Light: wave and particle

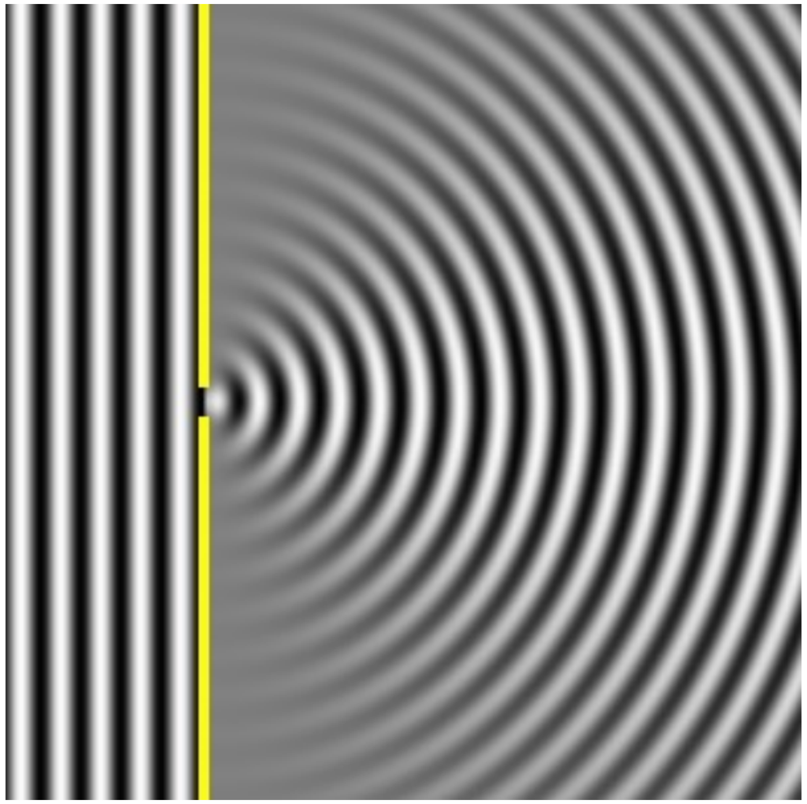
Miklós Kellermayer

Biophysics of light

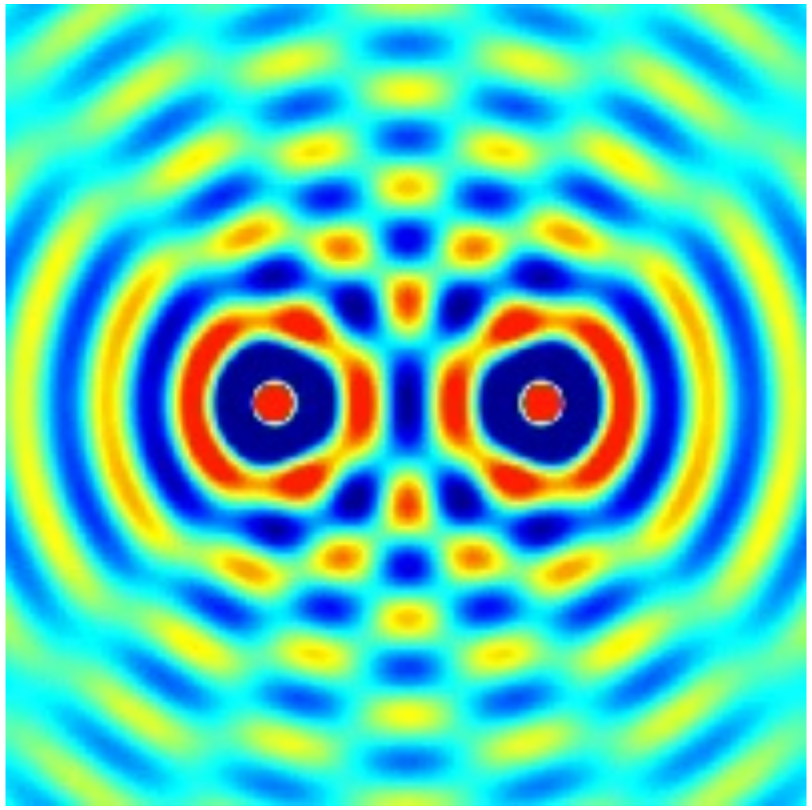
- Light as wave. Wave phenomena.
- Electromagnetic waves, spectrum.
- Light as particle. Photoelectric effect.
- Dual nature of light.
- Matter waves. Electron as wave.
- Applications

Light as wave: “wave phenomena” are displayed

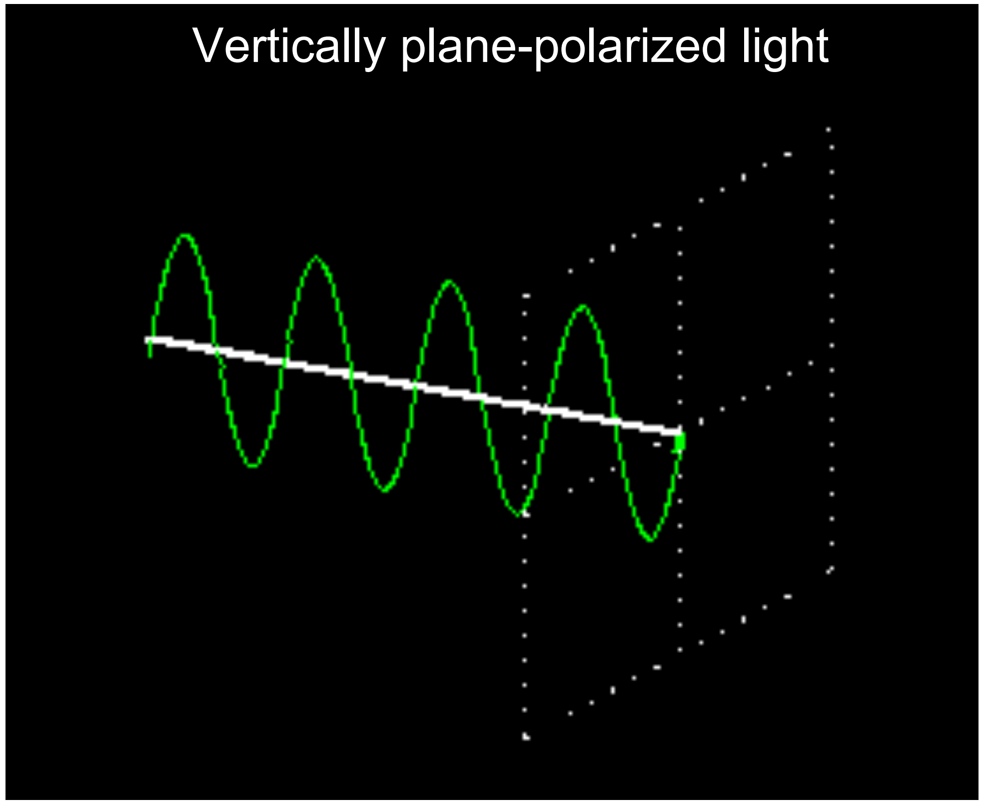
Diffraction	Interference	Polarization



Light “bends” into unexpected areas



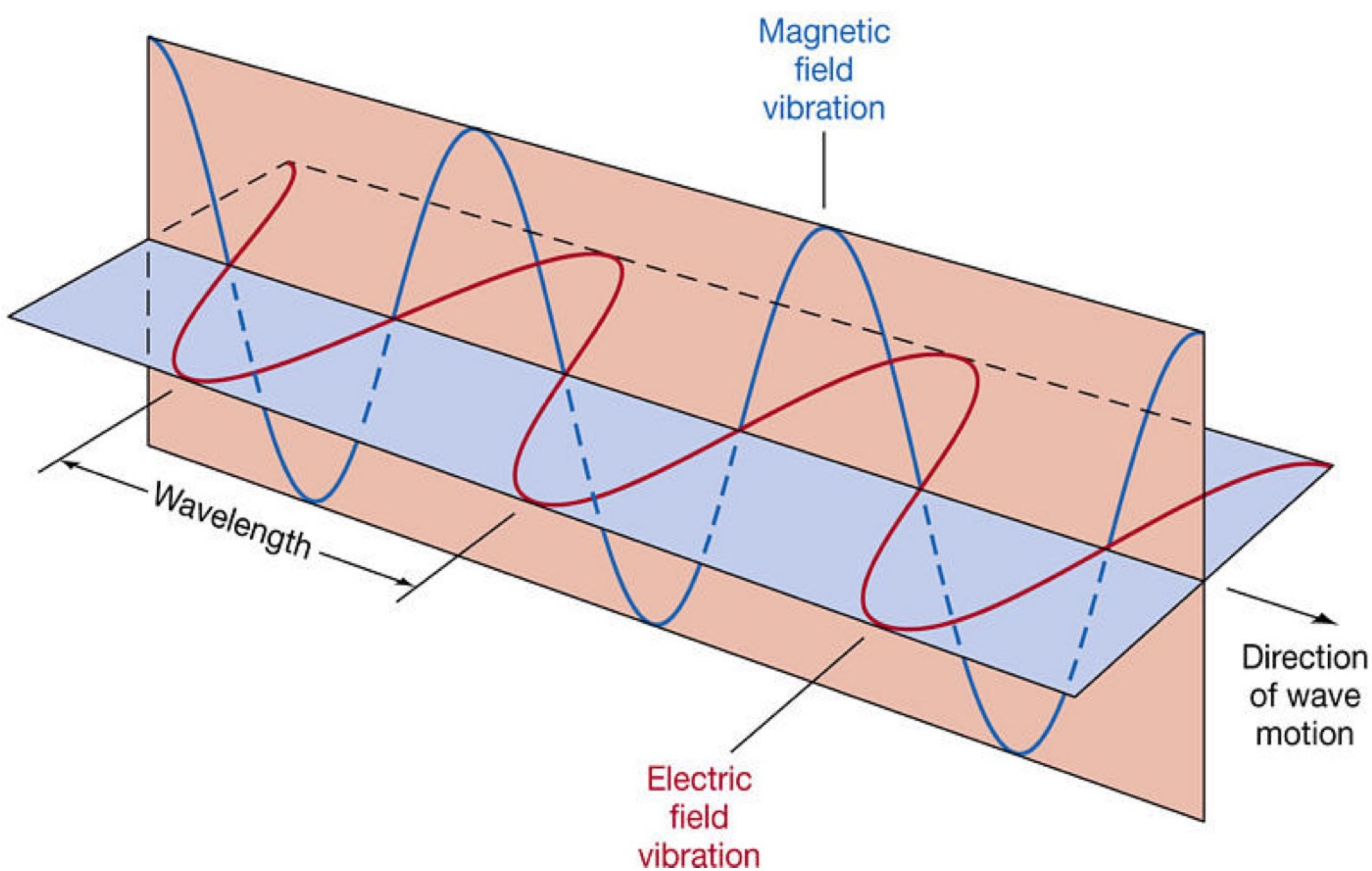
Spatial and temporal pattern of high- and low-amplitude regions



Oscillation occurs in a preferred direction

What kind of wave is light?
Electromagnetic wave

Electromagnetic disturbance propagating in space.
No elastic medium is required for its propagation.



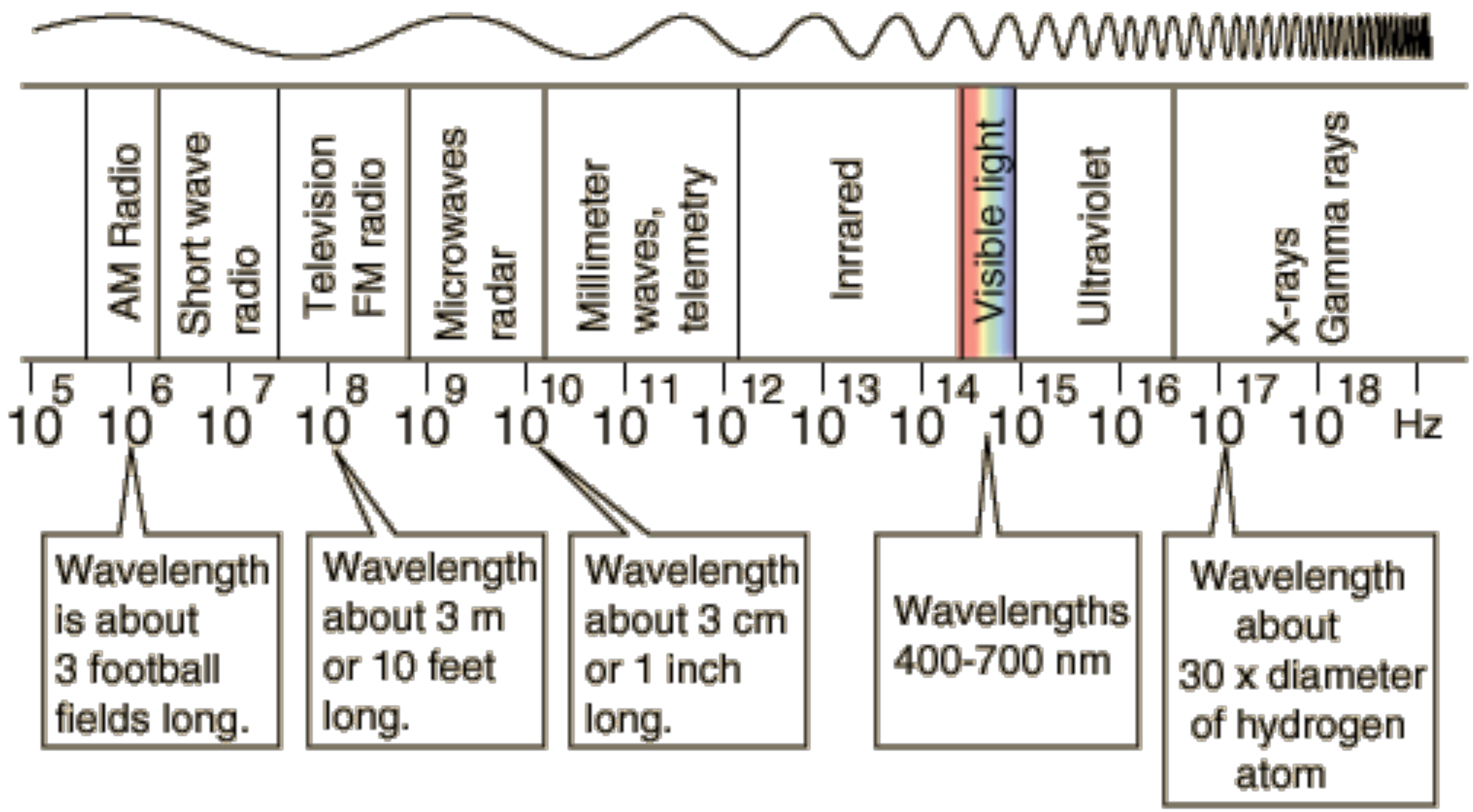
James Clerk Maxwell (1831-1879)

Propagation velocity:

$$c = \lambda f$$

c_{vacuum}=2.99792458 x 10^8 ms^{-1}

The electromagnetic spectrum



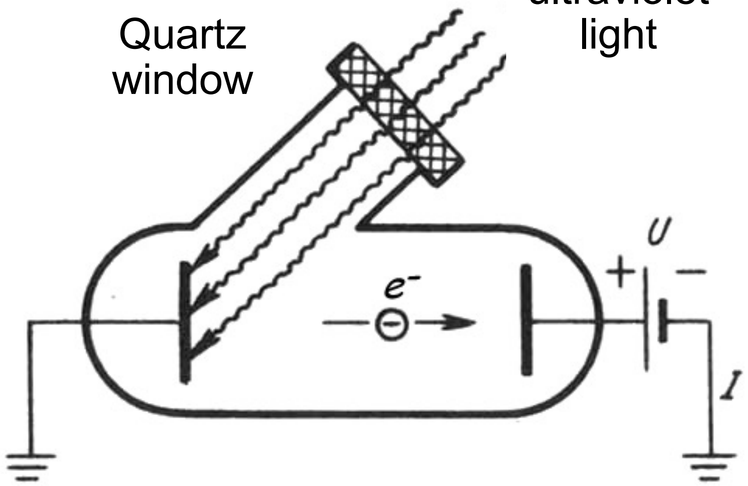
N.B.: 1) *"spectrum"* = function (intensity of EM radiation as a function of energy)
2) *"electromagnetic spectrum"* = types of radiation as a function of energy

What happens if an object is illuminated with light?

Photoelectric effect: The experiment

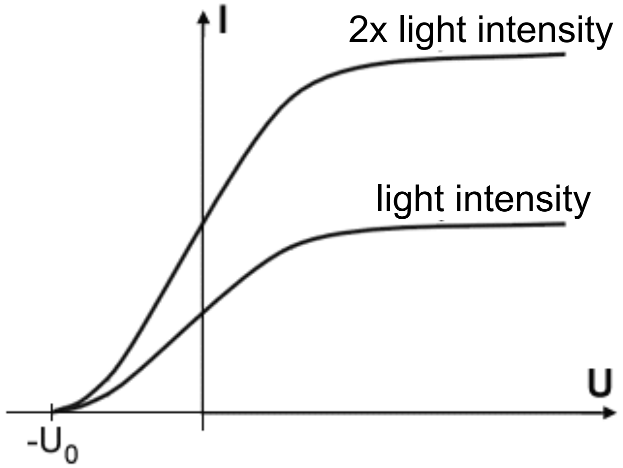
Hallwachs-effect:
Upon UV illumination, negative charges leave the metal surface

Wilhelm Hallwachs
(1859-1922)



Measurements, observations

Philipp Lenard/
Lénárd Fülöp
(1862-1947)



- Electron emission: instantaneous upon illumination
- Electron emission only in high-frequency (e.g., blue, UV) light
- No electron emission in low-frequency (e.g., red) light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

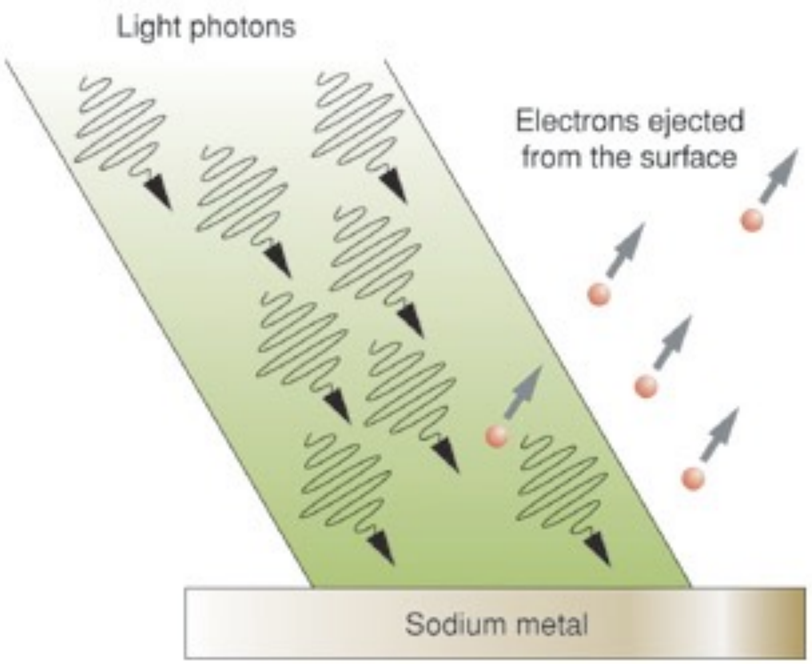
Photoelectric effect

The explanation

1905: *"Annus mirabilis"*

- photoelectric effect
- diffusion
- special relativity

Albert Einstein
(1879-1955)



$$E_{kin} = hf - W_{ex}$$

E_{kin} = kinetic energy of escaped electron
h = Planck's constant ($6.62 \cdot 10^{-34}$ Js)
f = frequency of light
hf = light energy = light quantum, *"**photon**"*
W_{ex} = work necessary for the escape of the electron from the atom

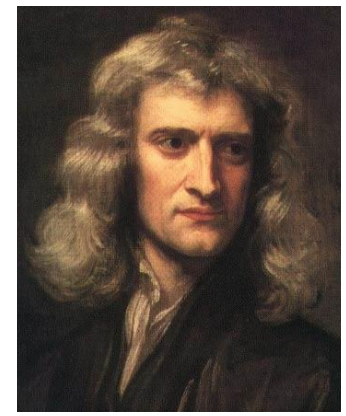
Photon:

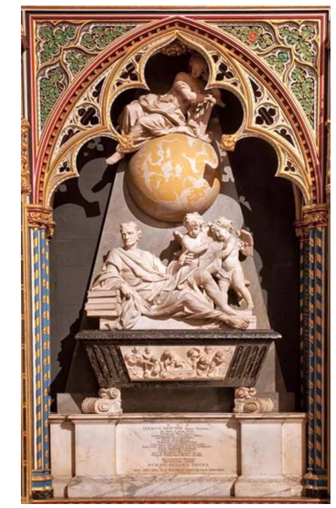
- travels with the speed of light (c) in vacuum
- does not exist at rest
- has momentum
- has no rest mass

Light is *at once* wave and particle!

Grote Kerk church, The Hague


Christiaan Huygens (1629-1695)


Sir Isaac Newton (1643-1727)


Westminster abbey

Wave ⟷ **Particle**

During propagation

Manifestations:
- Diffraction
- Interference
- Polarization

During interactions

Manifestations:
- Photoelectric effect
- Refraction
- Excitation, Ionization
- Compton scatter
- Pair production

If light can be a particle, then can a particle be a wave?

Matter waves: The electron as a wave

Einstein:
mass-energy equivalence

$$E = mc^2$$

Planck:
law of radiation

$$E = hf$$

Maxwell:
speed of light

$$c = \lambda f$$

Louis-Victor-Pierre-Raymond, 7th duc de Broglie (1892-1987)

$$mc^2 = h \cdot \frac{c}{\lambda}$$

Momentum of particle (or phtoton!):

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

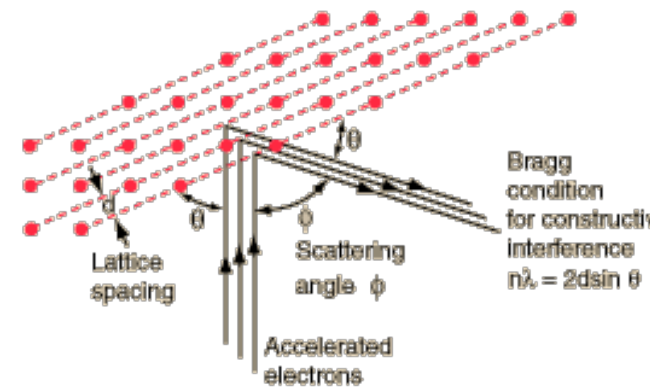
Wavelength of particle ("de Broglie wavelength"):

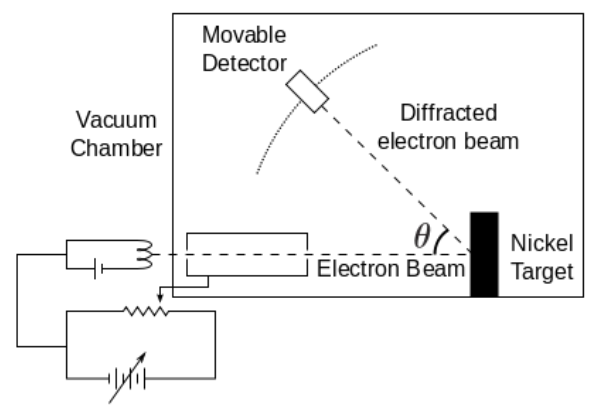
$$\lambda = \frac{h}{mv}$$

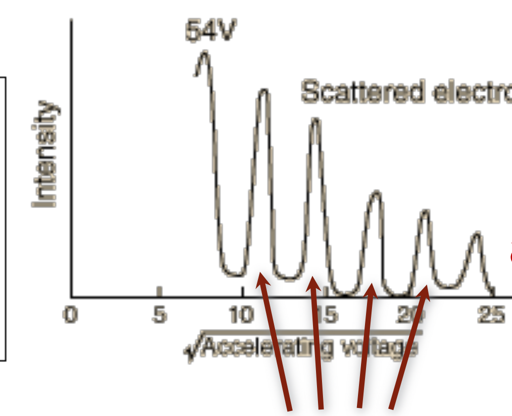
Davisson-Germer experiment

Clinton Joseph Davisson (1881 –1958)

Lester Halbert Germer (1896–1971)





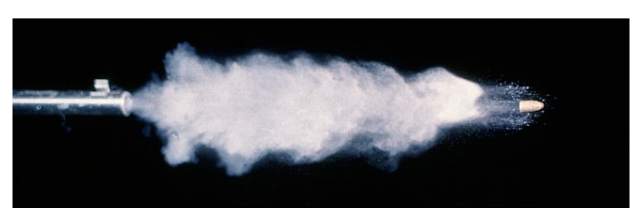


interference maxima

Interference pattern appears!

The electron is thus a ***wave***!

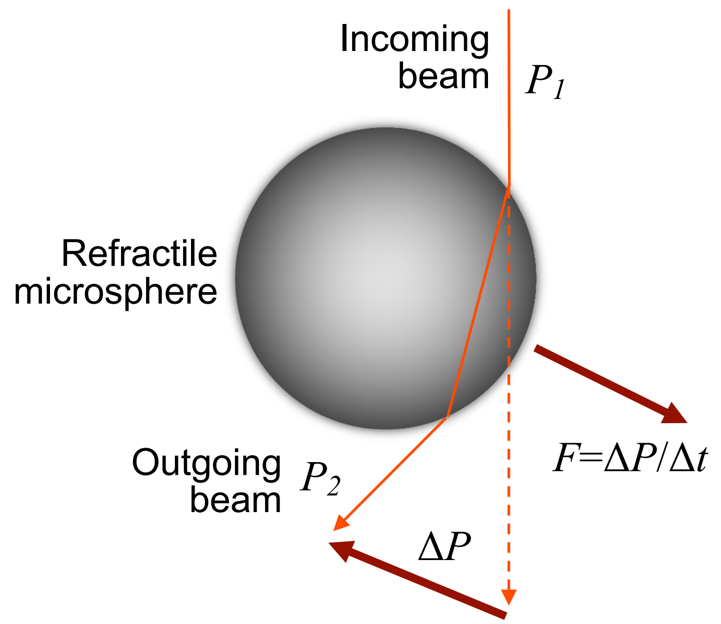
Why don't we experience the wave nature of macroscopic particles (e.g., bullet)?



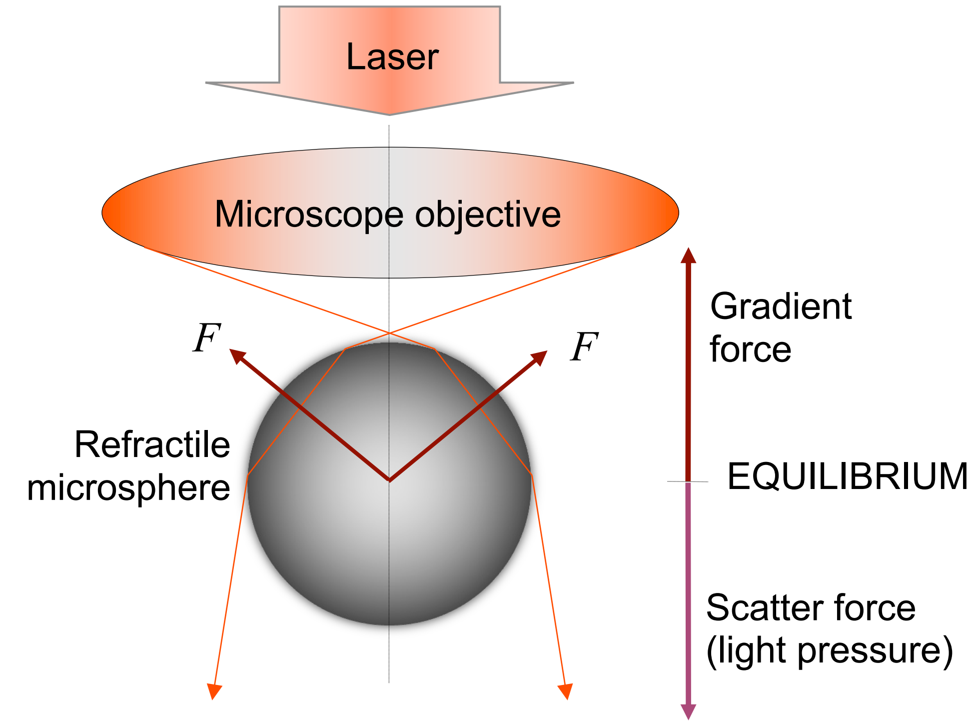
Bullet: for m=1 g and v=1 kms^{-1}, λ= 6 x 10^{-34} m!!

We can now better understand optical tweezers (applications I)

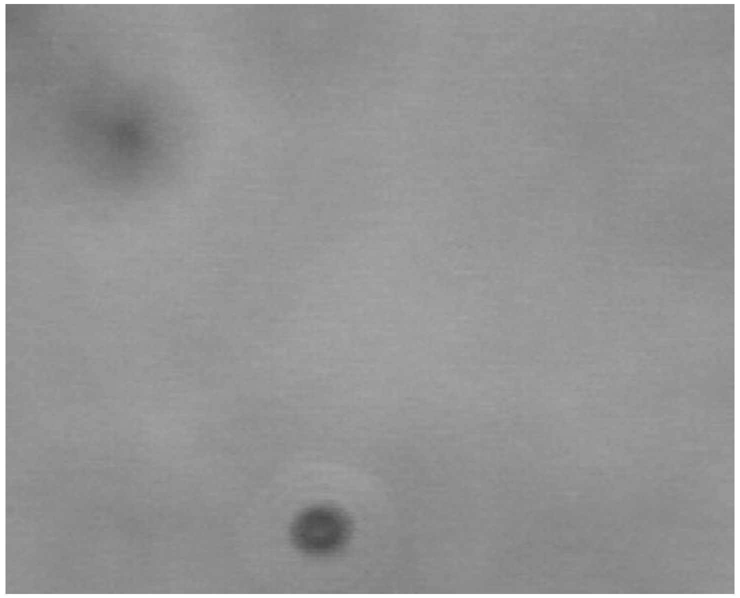
Refraction is accompanied by photonic momentum change (ΔP):



*Refractile particles may be **captured** with photonic forces:*



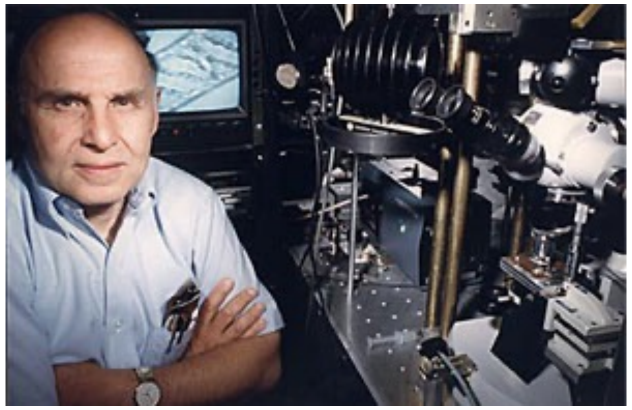
*In the **optical trap** a momentum change occurs between the photons and the trapped particle:*



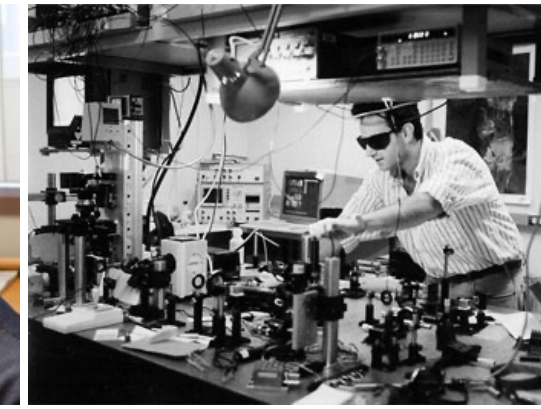
3 µm latex (polystyrene) microspheres in the optical trap

N.B.: the terms optical tweezers, optical trap, laser tweezers, laser trap are synonymous

Milestones of optical tweezers


Arthur Ashkin (Nobel-prize 2018)


J.Spudich


J.Finer

1970: Arthur Ashkin: optical tweezers

1991: J.Spudich, T.Yanagida, J.Molloy, single-molecule mechanics

1994: T.Yanagida, single ATP turnover on myosin

1994: K.Svoboda, S. Block, single kinesin mechanics

1996: C.Bustamante, D.Bensimon, DNA molecule stretch

1997: S. Chu, W.D. Phillips, C. Cohen-Tanoudji (Nobel-prize): atom cooling with laser

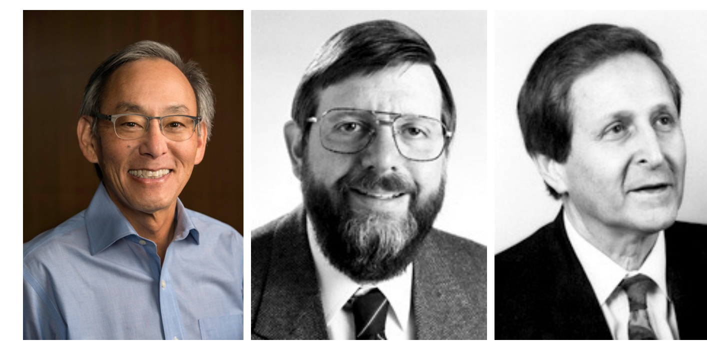
1997: M.Kellermayer, M.Rief, L.Tskhovrebova, protein molecule stretch

2000: Galajda P., Ormos O., microfabrication with optical tweezers, optically driven microscopic engines

2001: J.Liphardt, C.Bustamante, RNA molecule stretch

2002: Holographic optical tweezers (spatial light modulator, SLM)

2008: Bustamante, Tinoco: ribosome mechanics

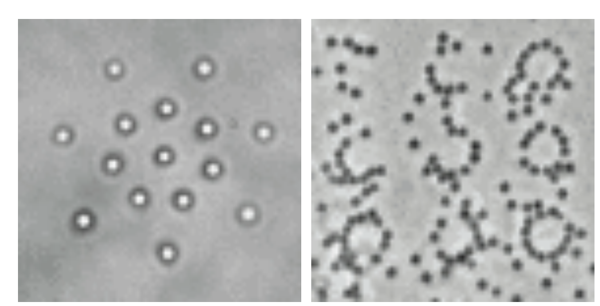

S. Chu, W.D. Phillips, C. Cohen-Tanoudji, Nobel-prize 1997


C.Bustamante

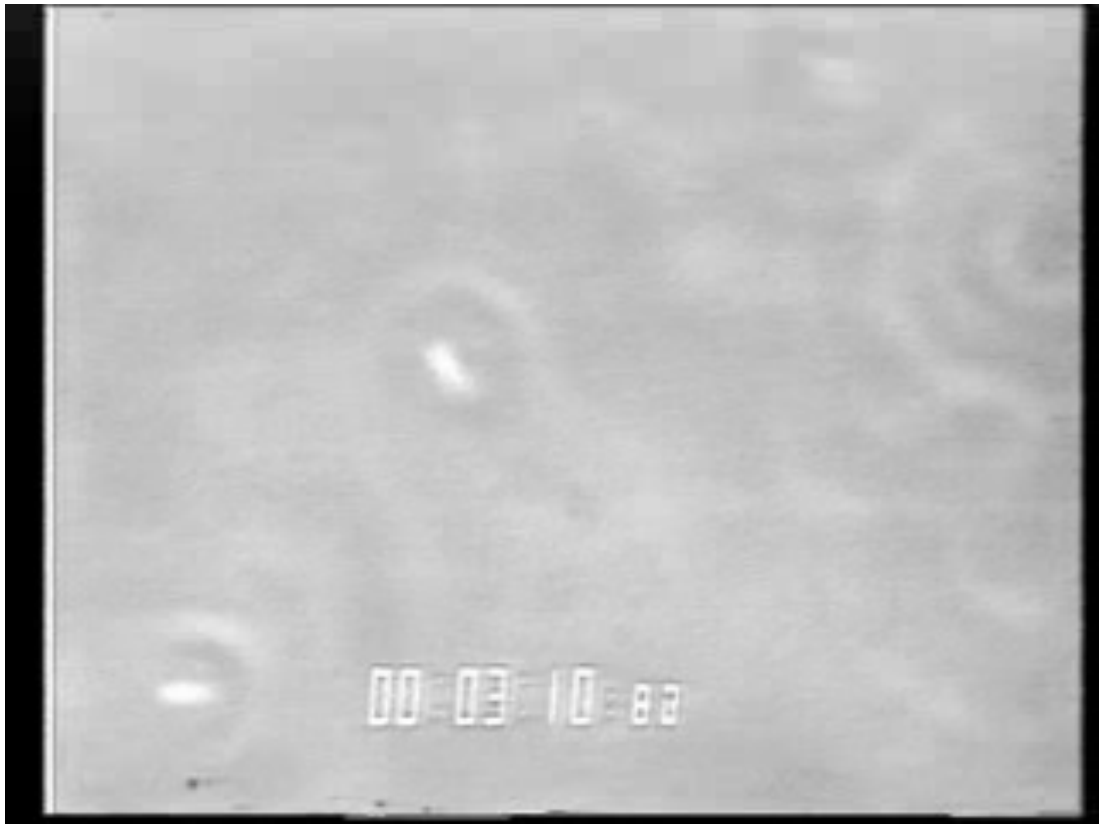

S. Block


J.Molloy


Microfabricated propeller


Simultaneous manipulation of multiple particles with holographic optical tweezers

Capturing cells with optical tweezers



Trapping of bacterial cells

The optical trap is 3D handle without a shaft:

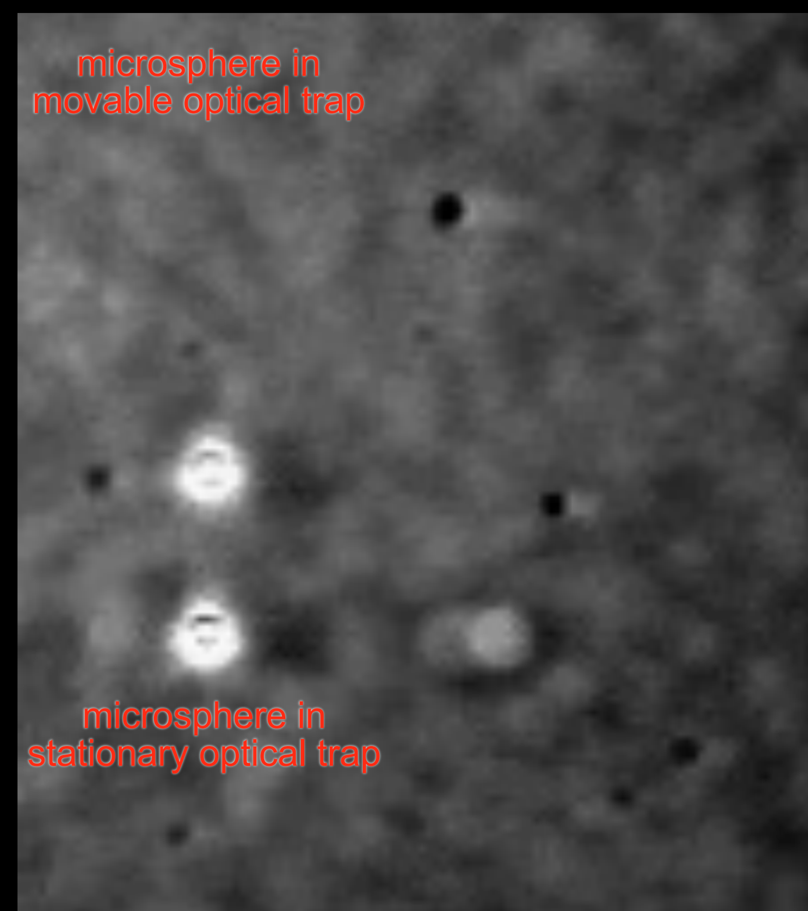
A knot can be tied on a molecular filament without releasing its ends

Actin filament

Fluorescence image

DNA

Phase contrast image

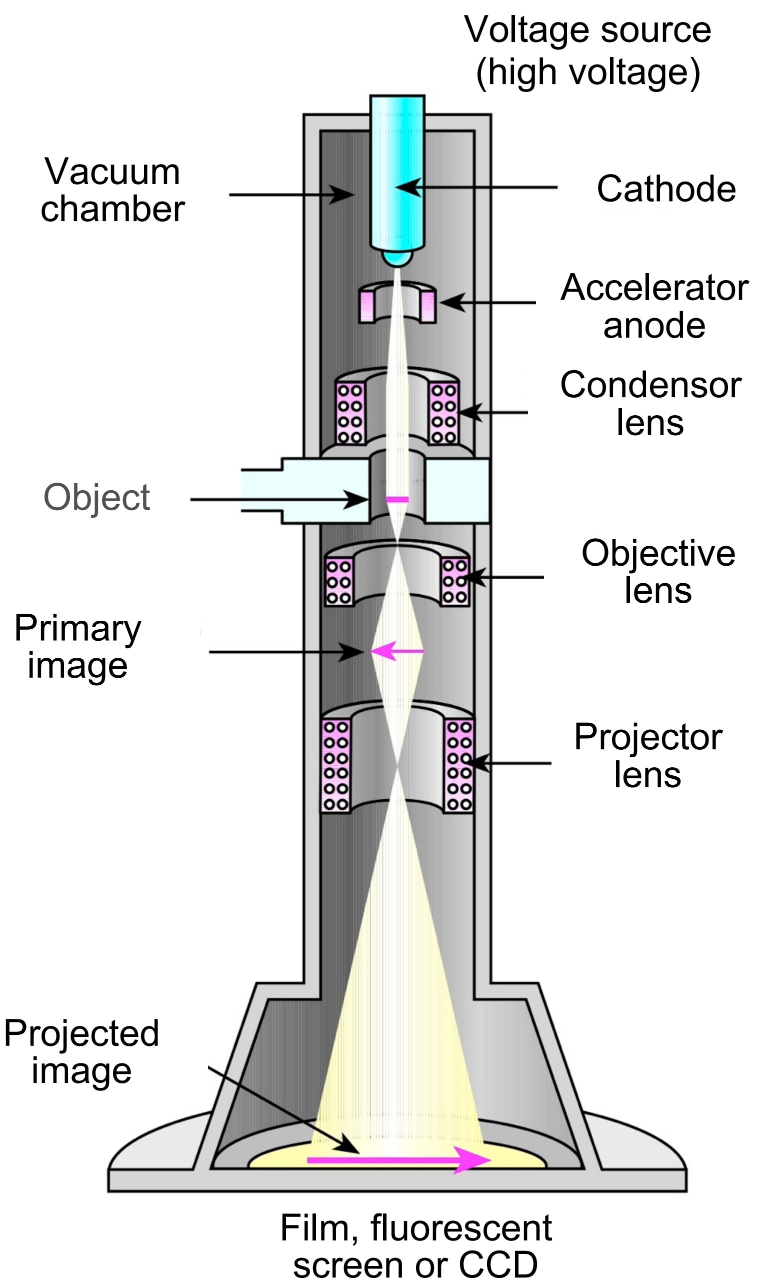


Fluorescence image

Arai et al. Nature 399, 446, 1999.

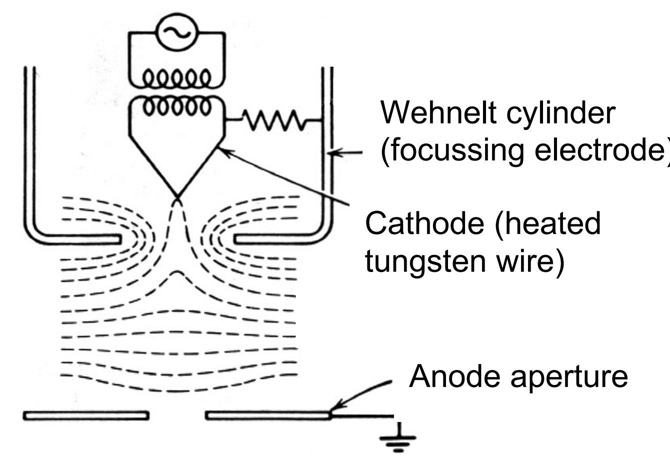
Applications II.

Matter waves: Electron microscope

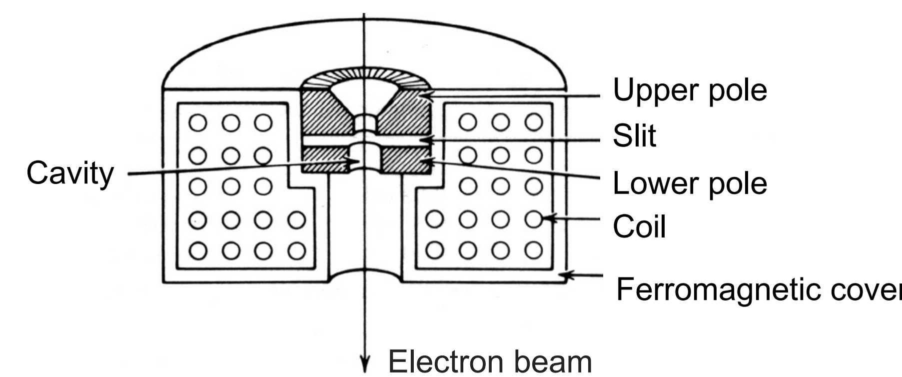


Transmission electron microscope (TEM)

Ray source: electron gun



Focusing: diverting the electron with magnetic lens



$$F = eBV_e \sin\alpha$$

F=force on the electron; e=electron's charge; B=magnetic induction; V_e=electron's speed; α=angle between the optical axis and the direction of the magnetic field

Resolution: $$d = \frac{\lambda}{\alpha}$$

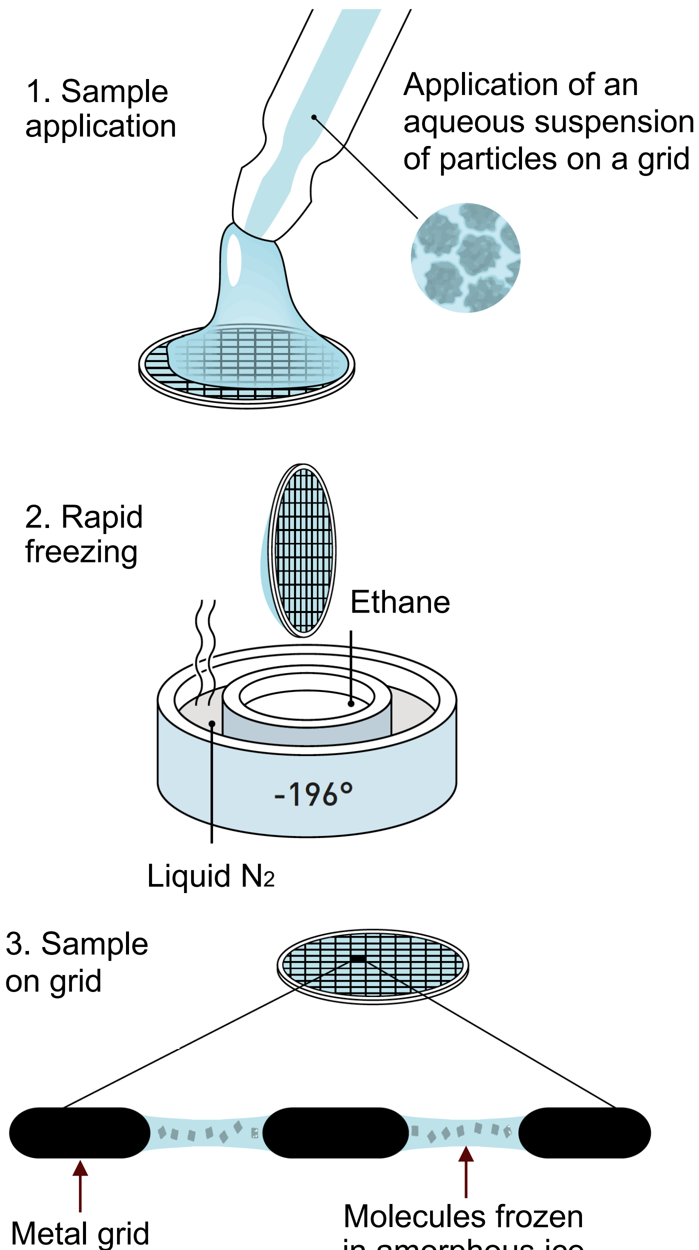
d=smallest resolved distance
λ="de Broglie" wavelength
α=angle between the optical axis and the direction of the magnetic field

Based on the de Broglie wavelength the theoretical resolution is: d~ 0,005 nm (=5 pm).

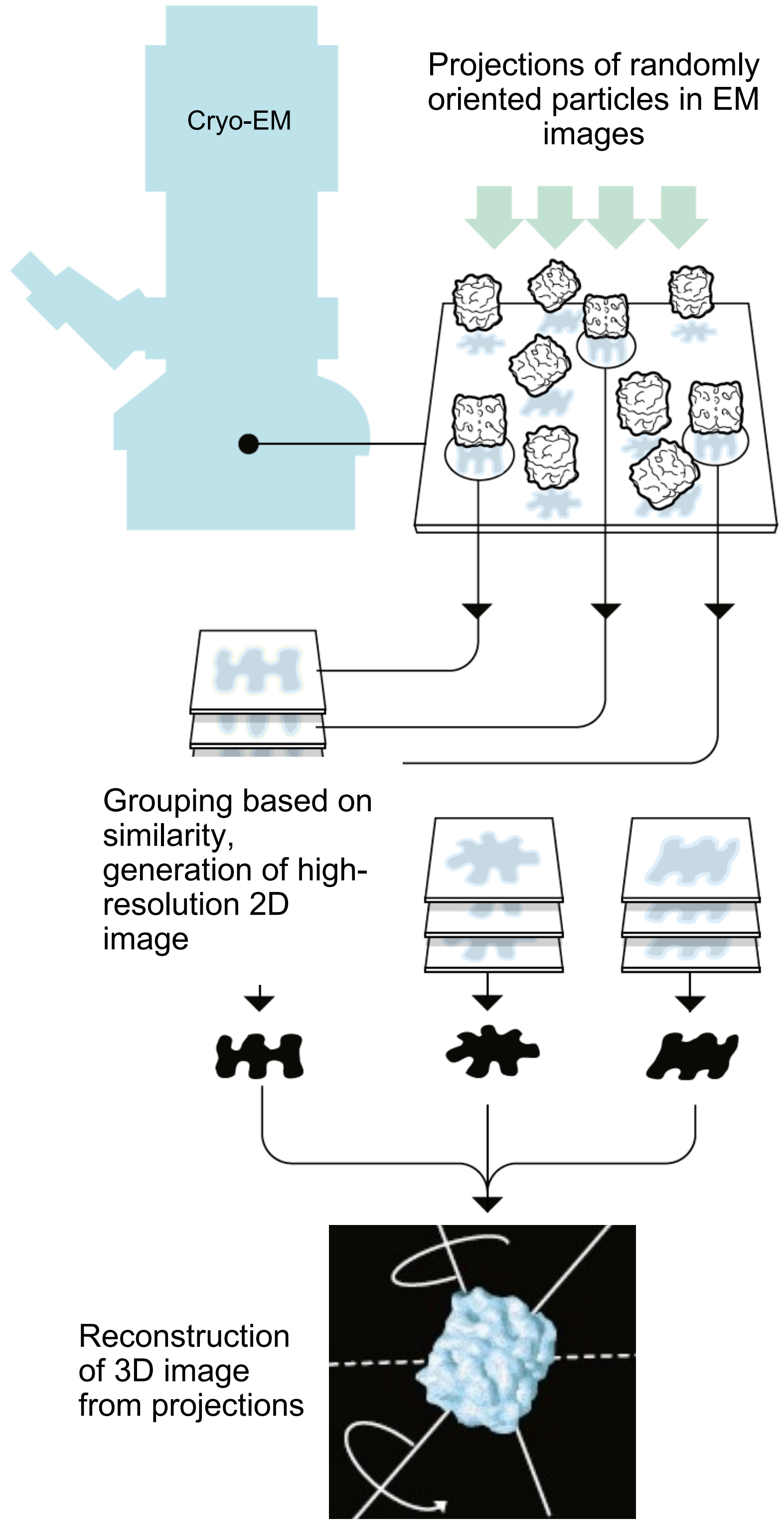
Cryo-electron microscopy (Nobel-prize 2017)

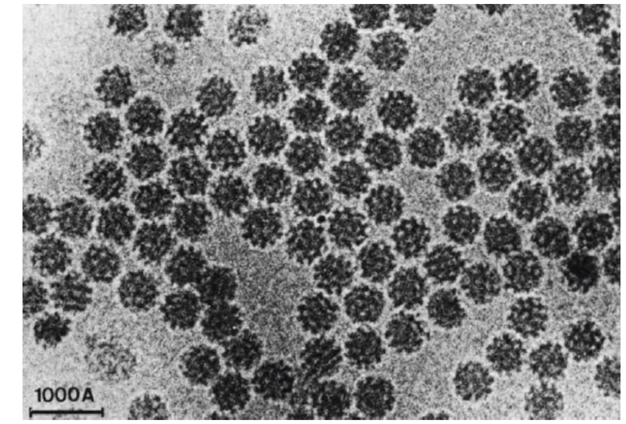
Jacques Dubochet, Joachim Frank, Richard Henderson

Sample preparation

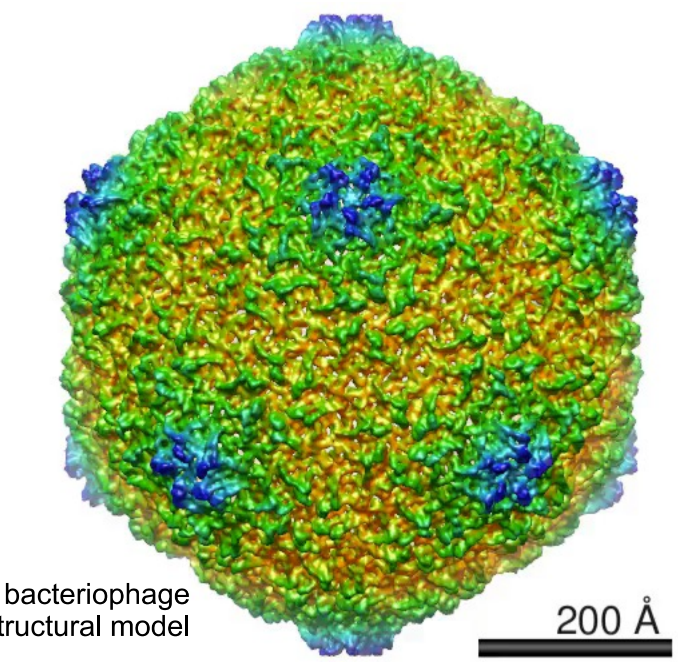


Cryo-EM imaging and structure reconstruction

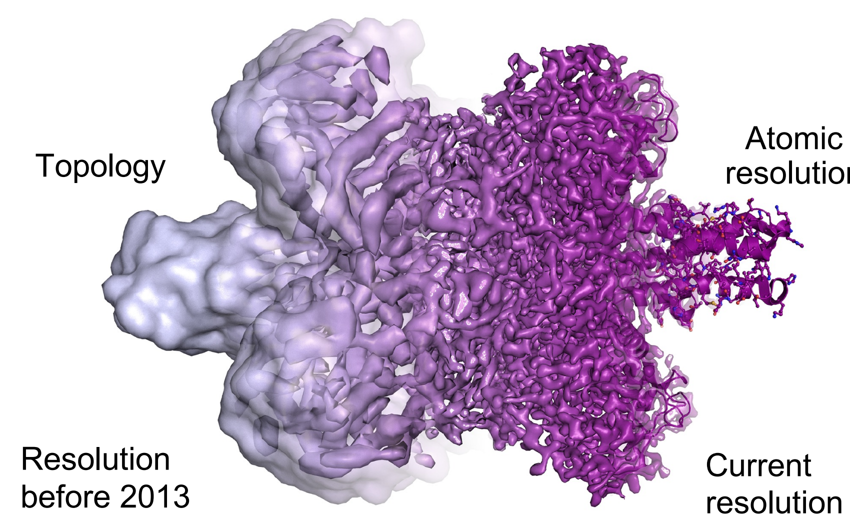




First cryo-EM image about viruses (Dubochet, 1984)



T7 bacteriophage structural model



Applications III.

Photoelectric effect: photodetection, photocell, CCD, etc, etc.....

Light detection, image recording, CCD camera

CCD chip in mobile-phone camera

Harvesting and transformation of light energy

Solar panels

Light amplification, intensification

Silence of the lambs night vision scene: Buffalo Bill wearing a night-vision goggle - a microchannel-plate intensifier

Feedback

https://feedback.semmelweis.hu/feedback/pre-show-qr.php?type=feedback&qr=FIT04MGEOLRD2GY4