

LIGHT: WAVE AND PARTICLE

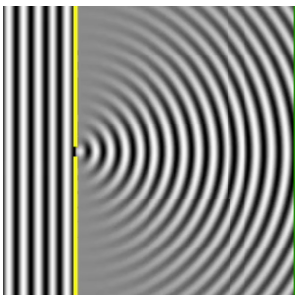
MIKLÓS KELLERMAYER

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

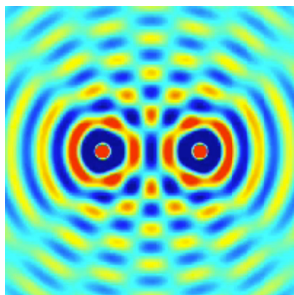
Light as wave:
“wave phenomena” are displayed

Diffraction



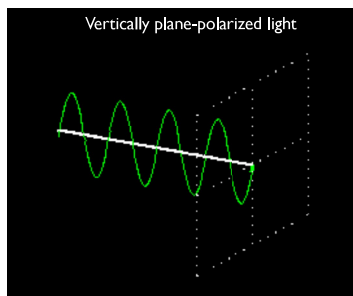
Light “bends” into unexpected areas

Interference



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

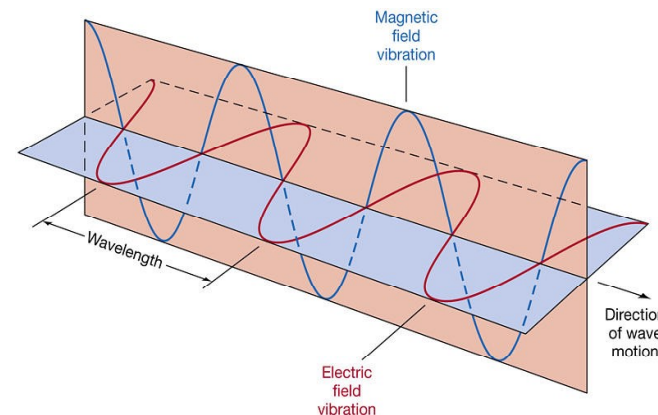
Polarization



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.



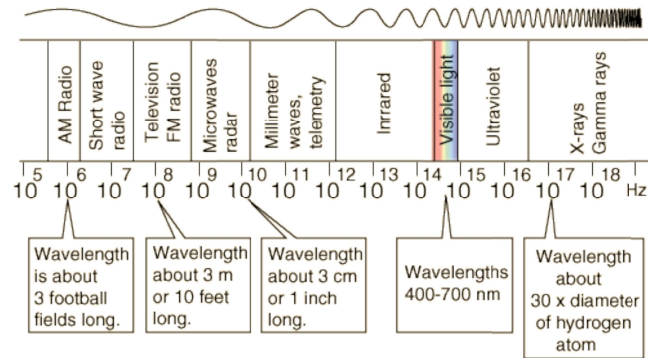
James Clerk Maxwell
(1831-1879)

Propagation velocity:

$$c = \lambda f$$

$c_{vacuum} = 2.99792458 \times 10^8 \text{ ms}^{-1}$

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

Photoelectric effect

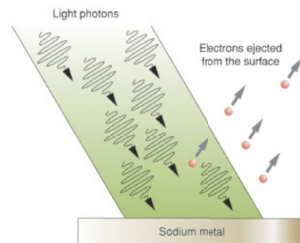
The explanation

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

What happens if an object is illuminated with light?

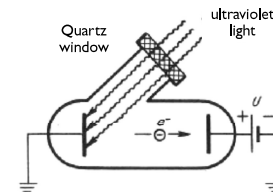
Photoelectric effect: The experiment

Hallwachs-effect:

Upon UV illumination, negative charges leave the metal surface



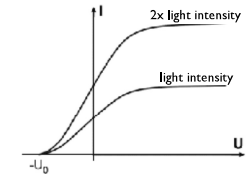
Wilhelm Hallwachs (1859-1922)



Measurements, observations



Philipp Lenard / Lenard-Füllp (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

Light is *at once* wave and particle!



Christiaan Huygens (1629-1695)



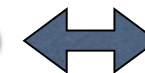
Sir Isaac Newton (1643-1727)



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 photon!):

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

Wavelength of particle ("de Broglie wavelength"):

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

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



Bullet: for $m=1 \text{ g}$ and $v=1 \text{ kms}^{-1}$,
 $\lambda = 6 \times 10^{-34} \text{ m!!}$

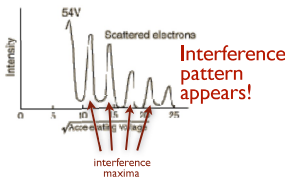
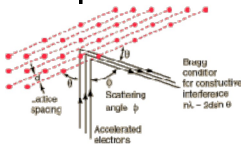
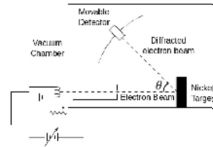
Davisson-Germer experiment



Clinton Joseph Davisson (1881-1958)



Lester Halbert Germer (1896-1971)

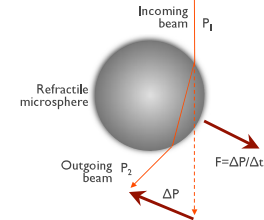


Interference pattern appears!

The electron is thus a wave!

We can now better understand optical tweezers

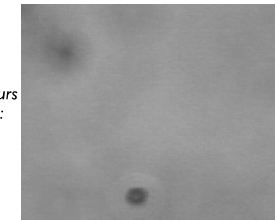
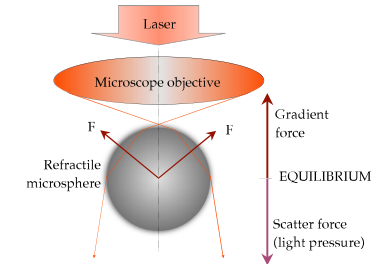
Refraction is accompanied by photonic momentum change (ΔP)
(Theory later):



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

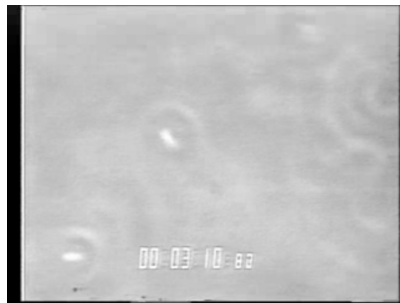
N.B.: the terms optical tweezers, optical trap, laser tweezers, laser trap are synonymous

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



3 μm latex (polystyrene) microspheres in the optical trap

Capturing cells with optical tweezers



Trapping of bacterial cells

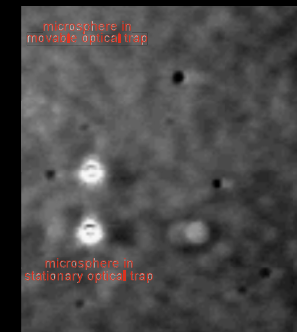
The optical trap is 3D handle without a shaft:
A knot can be tied on a molecular filament without releasing its ends

Actin filament

DNA

Phase contrast image

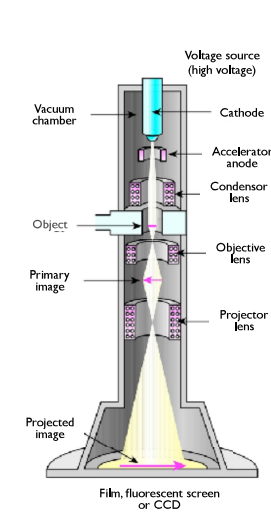
Fluorescence image



Fluorescence image

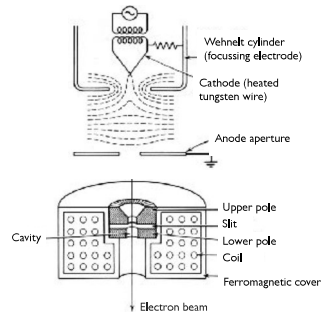
Applications I.

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 field; 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: $d \sim 0,005 \text{ nm}$ ($\approx 5 \text{ pm}$).

Applications II.

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