MEDICAL BIOPHYSICS

BIOPHYSICS OF LIGHT

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

Wave: propagating oscillation

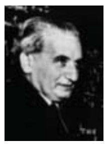
What is an oscillation?

Example:
Tacoma Narrows Bridge

Tacoma Narrows Bridge ("Gallopin' Gertie")
- (*"Gertie the Dinosaur"* (1914), cartoon, Winsor McCay)
- Opening: July 1, 1940.
- During wind (50-70 km/h): oscillation for hours
- Oscillation amplitude initially 0.5 m, then, after snapping of a suspension cable, up to 9 m!
- Collapse: November 7, 1940.

(Explanation of the effect)

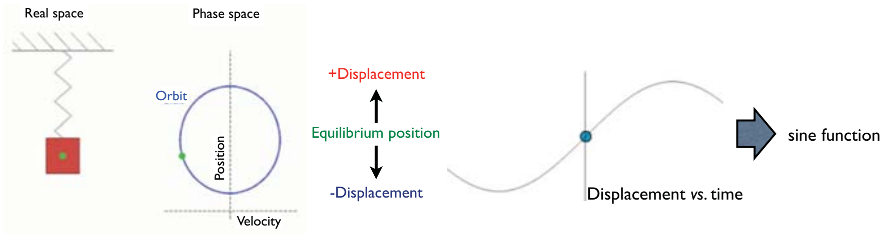
Kármán vortex street

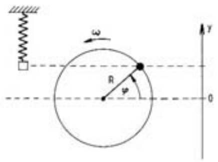


Theodore von Kármán
1881-1963

Harmonic oscillation

Restoring force acts on a system displaced out of equilibrium (e.g., mass on a spring).





ϕ = phase angle at time *t*
y = displacement at time *t*
ω = angular velocity (ϕ/t)
R = length of rotating unit vector
= maximal displacement (amplitude)

$$y = R\sin\varphi$$

Because ϕ = ω*t*: $y = R\sin(\omega t)$

If the initial phase angle (ϕ_0) differs from 0: $y = R\sin(\omega t + \varphi_0)$

Because angular velocity (ω) is the full circular orbit (2π) per period (*T*): $y = R\sin(\frac{2\pi}{T}t + \varphi_0)$

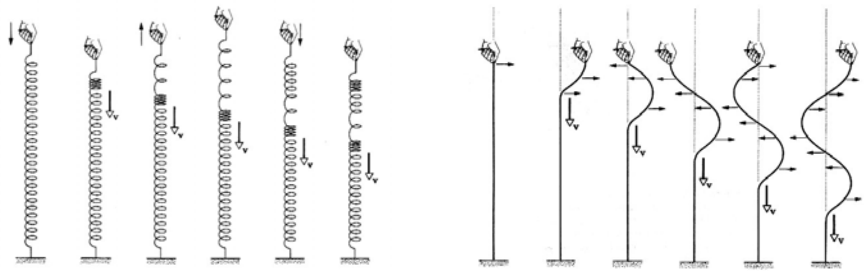
Important parameters of the propagating wave:
- **Period** (*T*)
- **Frequency** (*f*=1/*T*)
- **Velocity** (*v*, *c*)
- **Wavelength** (λ): distance covered in a period:

$$\lambda = cT = \frac{c}{f}$$

Types of waves

- According to source:
  1. Mechanical: elastic deformation propagating through elastic medium
  2. Electromagnetic: electric disturbance propagating through space (vacuum)
- According to propagation dimension:
  1. One-dimensional (rope)
  2. Surface waves (pond)
  3. Spatial waves (sound)
- According to relative direction of oscillation and propagation:

1. Longitudinal   2. Transverse



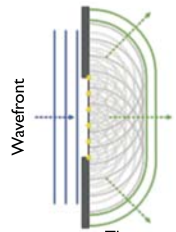
Wave phenomena I.

Diffraction

Huygens-Fresnel principle:
every point of a wavefront is the source of further waves

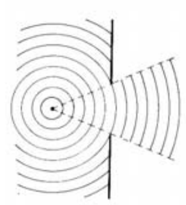
Christiaan **Huygens** (1629-1695)

Augustin-Jean **Fresnel** (1788–1827)

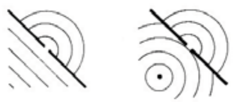


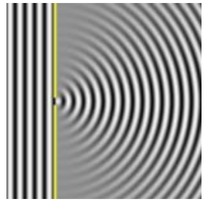
The wave appears in the "shaded" areas, too.

Slit much greater than the wavelength (λ)



Slit much smaller than wavelength (λ)





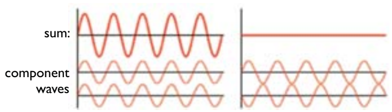
Wave phenomena II.

interference

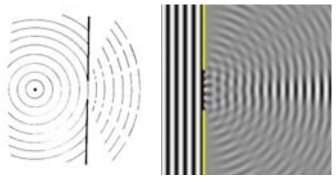
Principle of superposition

Waves in phase (φ=0): amplification

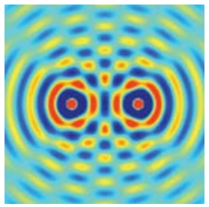
If φ=π : cancellation



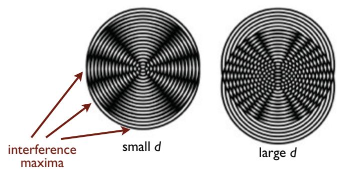
Slit comparable to wavelength
(=pointlike slits separated by distance *d*, where *d*~λ)



Interference of waves emerging from two point sources.



Interference pattern depends on distance (*d*) separating the pointlike slits



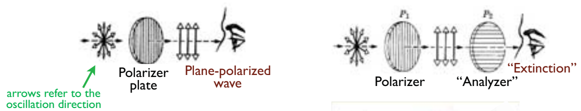
Wave phenomena III.

Polarization

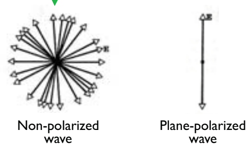
- **Polarization:** oscillation is oriented in some *preferred* direction
- **Birefringence** is related to polarization: anisotropic propagation velocity
- Only ***transverse*** waves can be polarized.

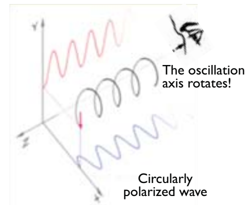
Polarization of Mechanical waves

Polarization of Electromagnetic waves



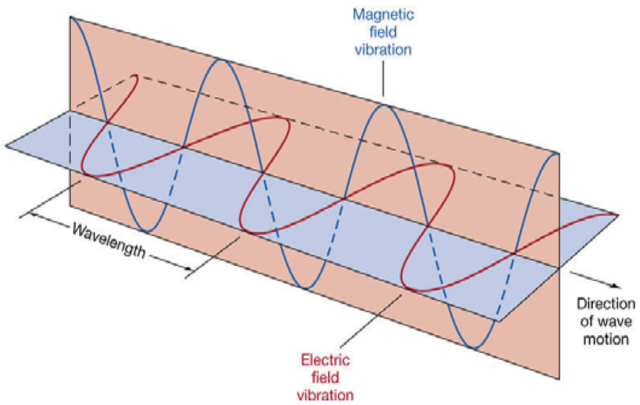
Polarization can be understood by observing the head-on view of the wave:





Light: electromagnetic wave

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



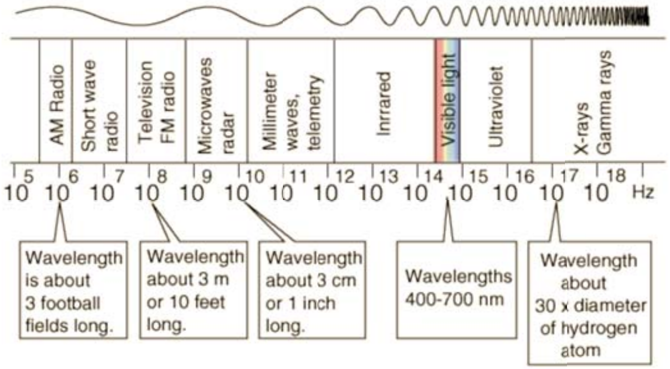
James Clerk **Maxwell**
(1831-1879)

Light is an electromagnetic wave.
Propagation velocity:

$$c = \lambda f$$

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

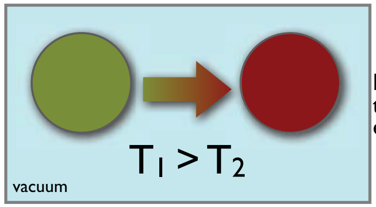
The electromagnetic spectrum



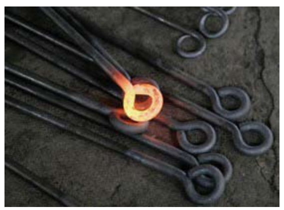
N.B.: 1) *"spectrum"* = function (intensity of EM radiation as a function of energy)
2) *"electromagnetic spectrum"* = types of radiation as a function of energy

"Black-body" (Thermal) radiation

One way of generating of light (besides *luminescence*)
Electromagnetic radiation emitted from all matter due to its possessing thermal energy



Heat exchange, temperature equilibration



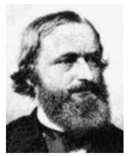
- High-temperture objects emit light.
- The greater the temperature of the body, the smaller the wavelengths that appear in its emission spectrum.

... what is a "black body"...?

A black body absorbs all the light falling on it

Objects not only emit radiation but absorb it as well.

Ratio of spectral emissive power (*M*) and absorptivity (α) is constant (Kirchoff's law):



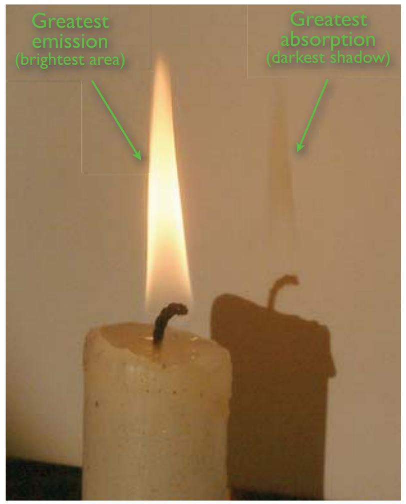
Gustav Robert **Kirchoff**
(1824-1887)

$$\frac{M_{\lambda i}}{\alpha_{\lambda i}} = \frac{M_{\lambda j}}{\alpha_{\lambda j}}$$

For a black body (BB):

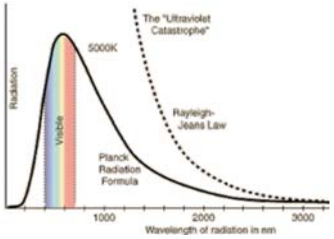
$$\alpha_{\lambda BB} = 1$$

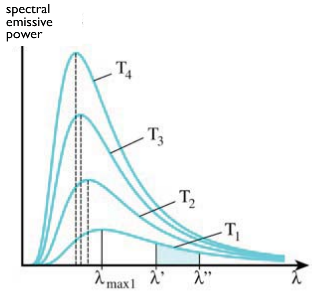
- That is, the black body absorbs all light that it is exposed to (nothing is reflected).
- The black body is an ideal object for investigating temperature-dependent emission.



Black-body radiation

Properties and inferences





Stefan-Boltzmann law:

$$M_{BB}(T) = \sigma T^4$$

M_{BB} = emissive power, area under emission spectrum.

Wien's displacement law:

$$\lambda_{max} T = const$$

Planck's law of radiation:

$$E = hf$$

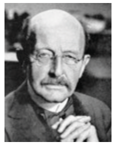
h = Planck's constant (6.626 x 10^{-34} Js).

Meaning: energy is absorbed and emitted in discrete packets (***quanta***).

Jozef Stefan (1835-1893)

Ludwig Eduard **Boltzmann** (1844-1906)

Wilhelm **Wien** (1864-1928)



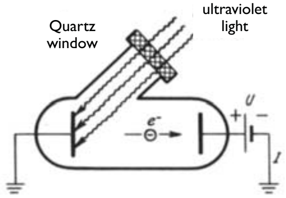
Max Karl Ernst Ludwig **Planck** (1858-1947)

What happens if an object is illuminated with light?

Photoelectric effect: The experiment

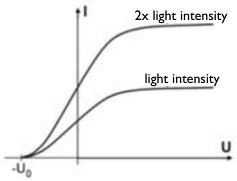
Hallwachs-effect:
Upon UV illumination, negative charges leave the metal surface

Wilhelm **Hallwachs** (1859-1922)



Measurements, observations

Philipp **Lenard**/ Lénárd Fülöp (1862-1947)



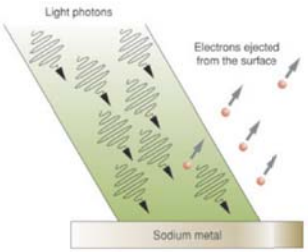
- Electron emission: instantaneous upon illumination
- Electron emission only in high-frequency (e.g., blue, UV) light
- No electron emission in low-frequency (e.g., red) light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

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 (6.62·10^{-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!

Christiaan **Huygens** (1629-1695)

Sir Isaac **Newton** (1643-1727)

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)

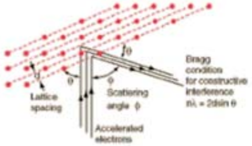
$$mc^2 = h \cdot \frac{c}{\lambda}$$

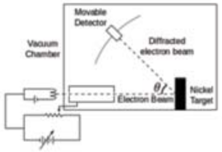
Momentum of particle (or phtoton!):
$$P = \frac{h}{\lambda}$$

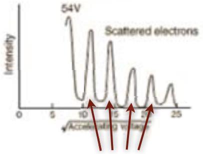
Wavelength of particle ("de Broglie wavelength"):
$$\lambda = \frac{h}{mv}$$

Davisson-Germer experiment

Clinton Joseph **Davisson** (1881 –1958)   Lester Halbert **Germer** (1896–1971)







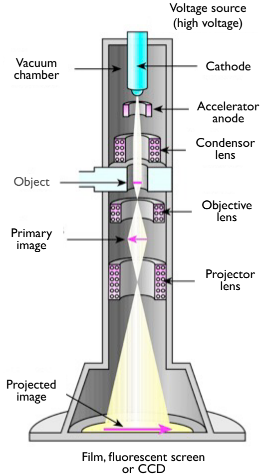
The electron is thus a *wave*!

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!!

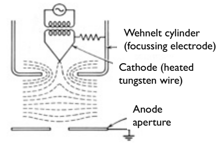
Applications I.

Matter waves: Electron microscope

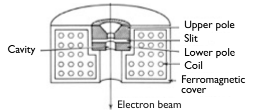


Transmission electron microscope (TEM)

Ray source: electron gun



Focussing: 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~ 0,005 nm (=5 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