# Medical Biophysics

## Biophysics of light

Miklós Kellermayer

# Mission of science

Better (eventually complete) understanding of the natural world
- uncovering scientific truths

Motivation:

"I think nature's imagination is so much greater than man's, she's never going to let us relax"

— *Richard P. Feynman*

Methods of approach:

***1. Scientific attitude:***
- Wondering (curiosity)
- Critical thinking (critique of *self* and peers)
- Asking and doubting

***2. Scientific method:***
- Observation
- Consideration
- Hypothesis
- ***Experiment***

„the test of any scientific idea is the ***experiment***"

# Medical biophysics

**Methodology:**

Biological processes are
1) simplified
2) quantified

**Objectives:**

1) *Physical* description of biomedical phenomena
2) Understanding of *physics*-based medical techniques

# Physical description of biological phenomenon

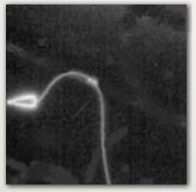
**Questions:**

1. How much force ($F$) is necessary for a spermatocyte to travel with a given velocity ($v$)?
2. How does it happen (what is the exact mechanism)? Building a predictive model.

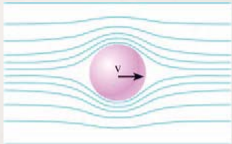
# Drag coefficient of the spermatocyte

How much force ($F$) is necessary for a spermatocyte to travel with a given velocity ($v$)?

Simplified spermatocyte model:
object with circular cross-section



**Stokes' Law:**



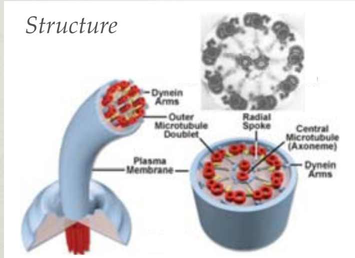

$$F = \gamma v = 6r\pi\eta v$$

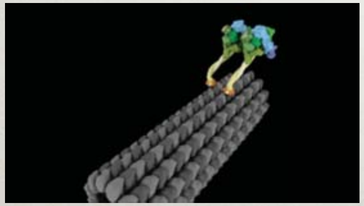
$$\gamma = 6r\pi\eta = 6\cdot 1.6\times 10^{-6}(m)\cdot \pi\cdot 10^{-3}(Pas) = 3\times 10^{-8}Ns/m$$

$$F = \gamma v = 3\times 10^{-8}Ns/m\cdot 5\times 10^{-5}m/s = 1.5\times 10^{-12}N = 1.5\,pN$$

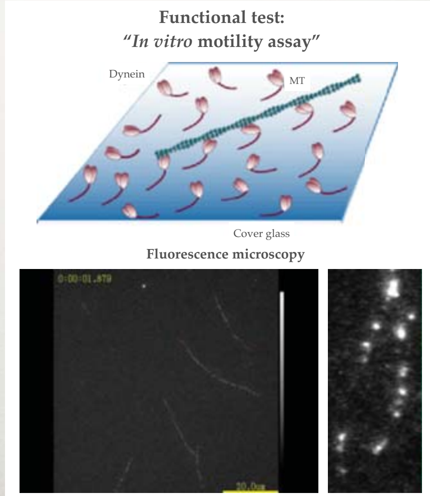
# Mechanisms behind spermatocyte motility?

How does it happen (what is the exact mechanism)? Building a predictive model.



"Drunken sailor" stepping mechanism




Microtubule moves over dynein

Dynein moves over microtubule

# Radiation is everywhere

Emission spectrum of the H-atom

Orion Nebula

Source ⟶ Radiation ⟶ Irradiated object

# Biophysics of light

- Light as wave. Wave phenomena.
- Electromagnetic waves, spectrum.
- Black body radiation. Planck's theory.
- Light as particle. Photoelectric effect.
- Dual nature of light.
- Matter waves. Electron as wave.
- Applications

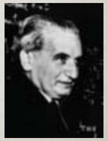
# Oscillations are sources of waves

**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)

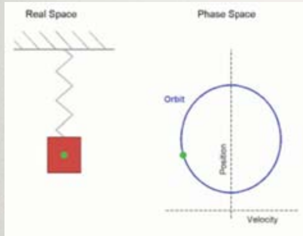
Kármán vortex street

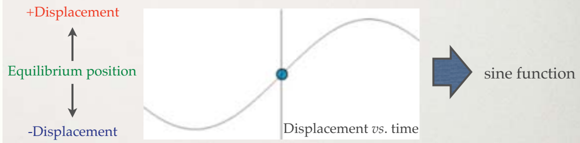


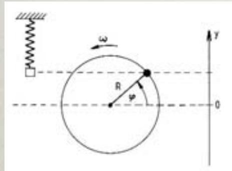
Theodore **von Kármán**
1881-1963

# Harmonic oscillation

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




$\varphi$ = phase angle at time $t$
$y$ = displacement at time $t$
$\omega$ = angular velocity ($\varphi/t$)
$R$ = length of rotating unit vector
= maximal displacement (amplitude)

$$y = R\sin\varphi$$

Because $\varphi = \omega t$: $y = R\sin(\omega t)$

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

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

Important parameters of the propagating wave:

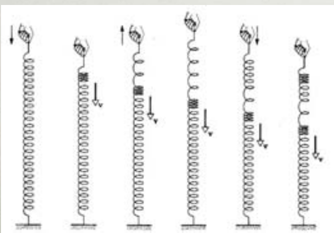
- **Period** ($T$)
- **Frequency** ($f$=1/$T$)
- **Velocity** ($v$, $c$)
- **Wavelength** ($\lambda$): distance covered in a period:

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

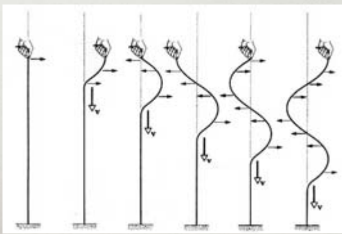
# Types of waves

- 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

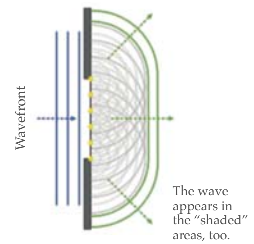


# Wave phenomena I.
## Diffraction

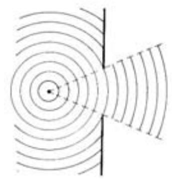
**Huygens-Fresnel principle:**
every point of a wavefront is the source of further waves

Christiaan **Huygens**
(1629-1695)

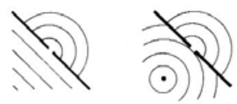
Augustin-Jean **Fresnel**
(1788–1827)

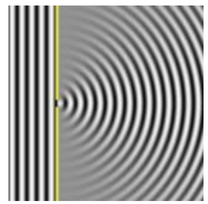



Slit much greater than the wavelength ($\lambda$)



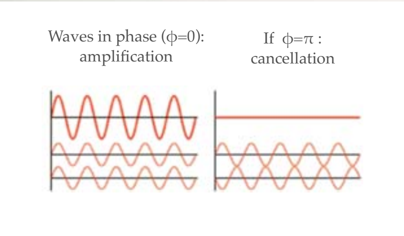
Slit much smaller than wavelength ($\lambda$)

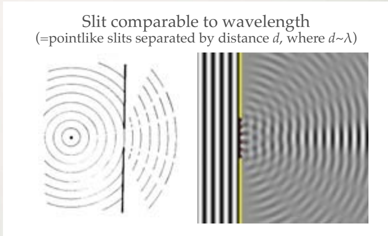




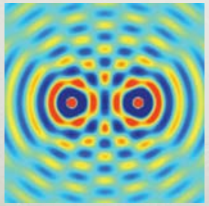
# Wave phenomena II.
## interference

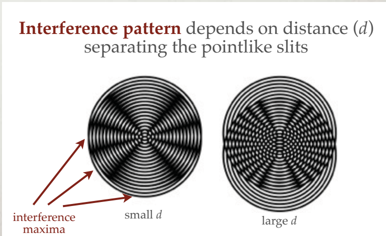
Principle of superposition




Interference of waves emerging from two point sources.





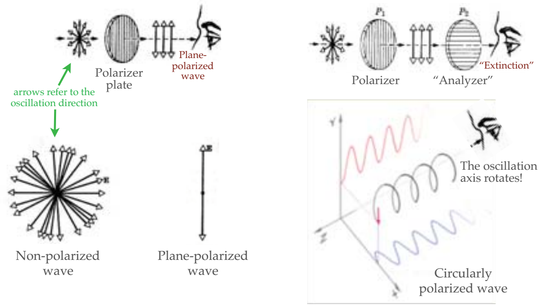

# Wave phenomena III.
## Polarization

- **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**

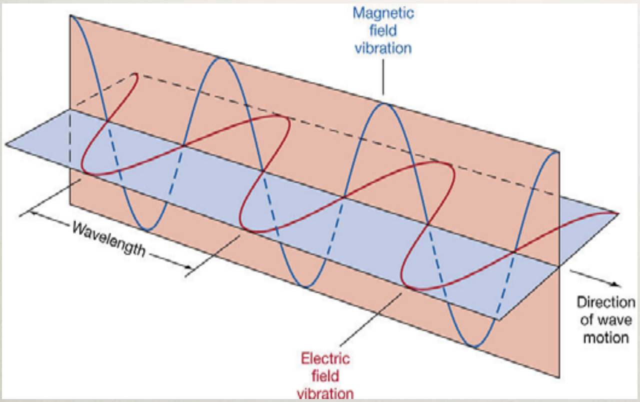

**Polarization of Electromagnetic waves**

**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 propagation.



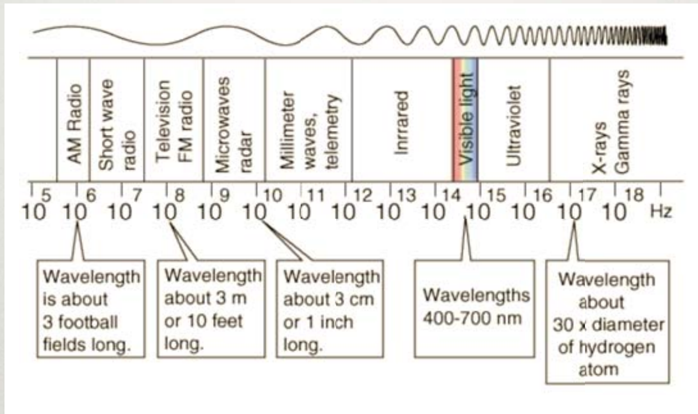

James Clerk **Maxwell**
(1831-1879)

Light is an electromagnetic wave.
Propagation velocity:

$$c = \lambda f$$

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

# The electromagnetic spectrum

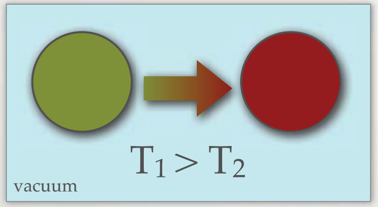



N.B.: 1) *"spectrum"* = function (intensity of EM radiation as a function of energy)
2) *"electromagnetic spectrum"* = types of radiation as a function of energy

# Generation of light:
## "Black-body" (thermal) radiation

One way of generating of light (besides *luminescence*)

Electromagnetic radiation emitted from all matter due to its possessing thermal energy



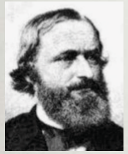

Heat exchange, temperature equilibration

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

# Kirchoff's law

Objects not only emit radiation but absorb it as well!

Ratio of spectral emissive power ($M$) and absorptivity ($\alpha$) is constant



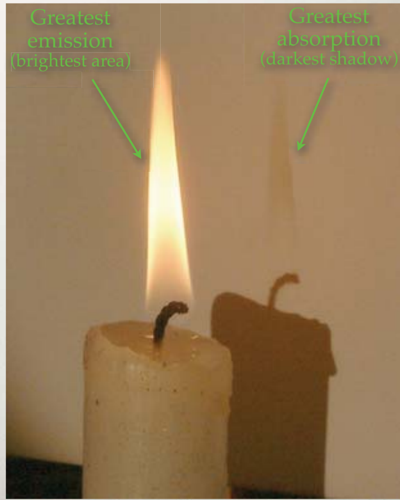
Gustav Robert **Kirchoff** (1824-1887)

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

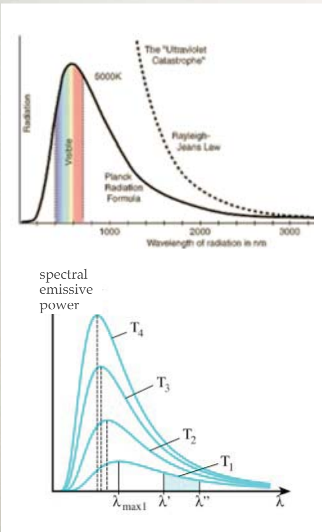
For a black body (BB):

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

- 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.



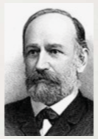

# Black-body radiation
## Properties and inferences



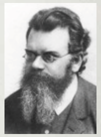

Stefan-Boltzmann law:

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

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



Jozef **Stefan** (1835-1893)



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

Wien's displacement law:

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

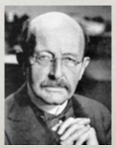
Wilhelm **Wien** (1864-1928)

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*).

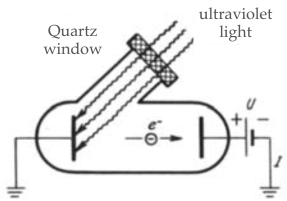


Max Karl Ernst Ludwig **Planck** (1858-1947)

# What happens if an object is illuminated?
## Photoelectric effect: The experiment

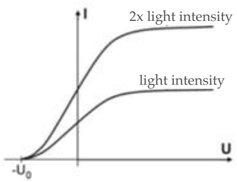
**Hallwachs-effect:**
Upon UV illumination, negative charges leave the metal surface

Wilhelm **Hallwachs** (1859-1922)




**Measurements, observations**

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

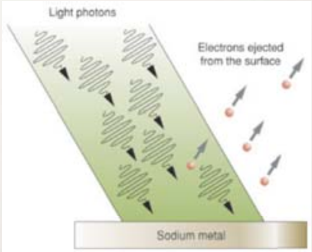



- Electron emission: instantaneous upon illumination
- Electron emission only in high-frequency (e.g., blue, UV) light
- No electron emission in low-frequency (e.g., red) light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

# 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

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)

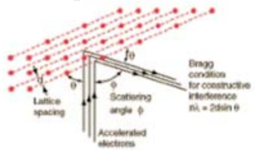
$$mc^2 = h \cdot \frac{c}{\lambda}$$

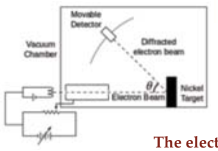
Momentum of particle (or phtoton!): $P = \dfrac{h}{\lambda}$

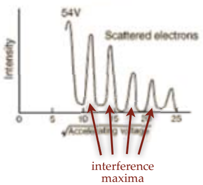
Wavelength of particle ("de Broglie wavelength"): $\lambda = \dfrac{h}{mv}$

**Davisson-Germer experiment**

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



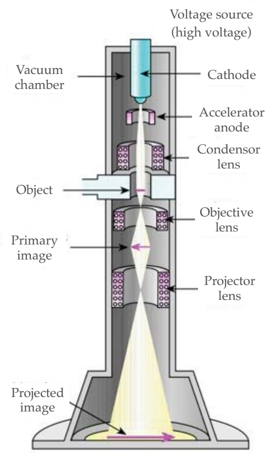

**The electron is a wave!**

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

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

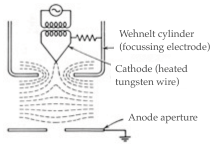
# Applications I.

## Matter waves: Electron microscope

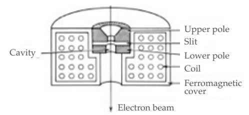



Transmission electron microscope (TEM)

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; $\alpha$=angle between the optical axis and the direction of the magnetic field

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

$d$=smallest resolved distance
$\lambda$="de Broglie" wavelength
$\alpha$=angle between the optical axis and the direction of the magnetic field

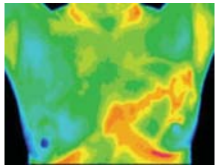
Based on the de Broglie wavelength the theoretical resolution is: $d \sim 0{,}005$ nm (=5 pm).

# Applications II.

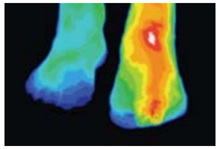
## Black-body radiation: Thermography, infradiagnostics


"Seeing through" non-absorbing layer

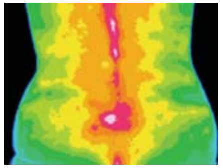
Airport thermography during swine flu *pandemia*



Breast screening, breast carcinoma



Inflammation



Chronic musculoskeletal stress (pain)

# 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*