2. Radiation

Miklós Kellermayer

Radiation is everywhere

Emission spectrum of the H-atom

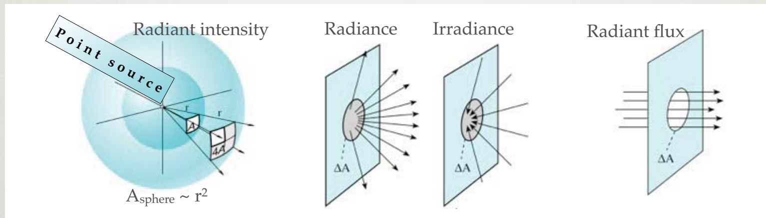
Source ⟶ Radiation ⟶ Irradiated object

Radiation

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

Radiation fundamentals

Radiation = propagating ***energy***, in the form of waves or subatomic particles, emitted by an atom or body as it changes from a high energy state to a lower energy state.

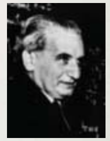


Quantity	Symbol	SI unit	Abbr.	Notes
Radiant energy	*Q*	joule	J	energy
Radiant flux	*Φ*	watt	W	radiant energy per unit time, also called *radiant power*
Radiant intensity	*I*	watt per steradian	$W \cdot sr^{-1}$	power per unit solid angle
Radiance	*L*	watt per steradian per square metre	$W \cdot sr^{-1} \cdot m^{-2}$	power per unit solid angle per unit *projected* source area. Sometimes confusingly called "intensity".
Irradiance	*E*, *I*	watt per square metre	$W \cdot m^{-2}$	power incident on a surface. Sometimes confusingly called "intensity".

Types of radiation

- Non-ionizing radiations
  - Mechanical waves
    - Audibe sound
    - Ultra-sound
  - Electromagnetic waves
    - Radio waves
    - Infrared light
    - Visible light
    - Ultraviolet light
- Ionizing radiations
  - Electromagnetic waves
    - Ultraviolet light
    - X-ray
    - Gamma-ray
  - Particle radiations
    - Alpha particles
    - Beta particles

Oscillations are sources of waves

Theodore **von Kármán**
1881-1963

Kármán vortex street

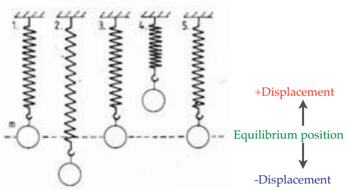
Tacoma Narrows Bridge ("Gallopin' Gertie")
(*"Gertie the Dinosaur"* (1914), cartoon, Winsor McCay)
Opening: July 1, 1940.
During wind (50-70 km/h): oscillation for hours
Oscillation amplitude initially 0.5 m, then, after snapping of a suspension cable, up to 9 m!
Collapse: November 7, 1940.

Tacoma Narrows Bridge today

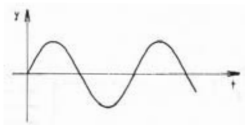
Oscillation

Movement (or change) that has a periodic component

Simple Harmonic Oscillation (SHO):
oscillation that can be described with sine function



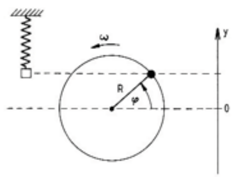
Mass on a spring



Displacement vs. time

Displacement vs. time function of SHO

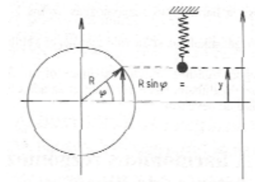
Simple harmonic oscillation and uniform cirular motion are related



$$y = R\sin\varphi$$

ϕ=phase angle at time t
y=displacement at time t

y is maximal at sinϕ=1
Maximal displacement: "amplitude(A)"



Since, from circular motion,

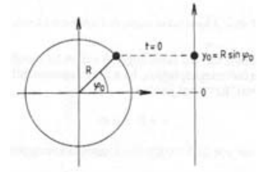
$$\varphi = \omega t$$

ω=angular velocity

we may write:

$$y = A\sin(\omega t)$$

If at the beginning of examination ϕ≠0



$$y_0 = A\sin\varphi_0$$

y_0=initial displacement
ϕ_0=initial angle (phase angle or phase shift)

$$y = A\sin(\omega t + \varphi_0)$$

Since $\omega = \frac{2\pi}{T}$

We may write

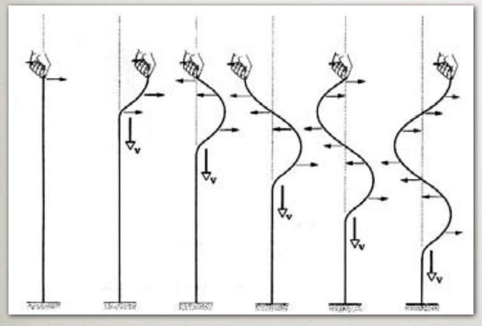
$$y = A\sin\left(\frac{2\pi}{T}t + \varphi_0\right)$$

Types of waves

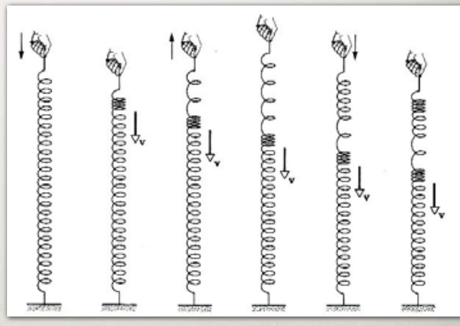
- According to source:
  1. Mechanical: elastic deformation propagating through elastic medium
  2. Electromagnetic: electric disturbance propagating through space (vacuum)
- According to propagation dimension:
  1. One-dimensional (rope)
  2. Surface waves (pond)
  3. Spatial waves (sound)
- According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

Relative propagation directions

1) **Transverse** (direction of oscillation is perpendicular to direction of propagation, e.g., light)



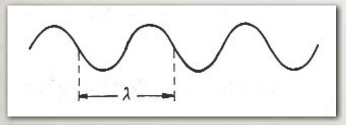
2) **Longitudinal** (direction of oscillation is parallel to direction of propagation, e.g., sound)

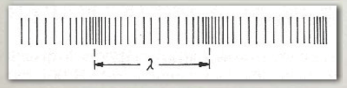


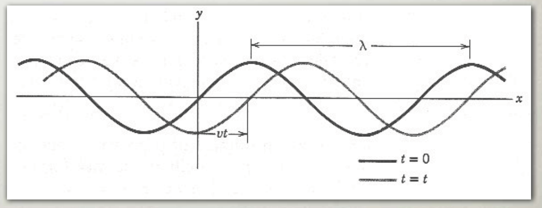
Parameters of a wave

- Harmonic waves: particles go through harmonic oscillations.
- Oscillation time (**period**): duration of a single oscillation (“T”).
- **Frequency**: inverse of period (f).
- The wave propagates with a given **velocity** (“phase velocity”, “v” or “c”)
- Distance between points of identical phase: “**wavelength**” (λ)

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





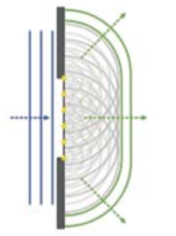


Wave phenomena I.
Diffraction

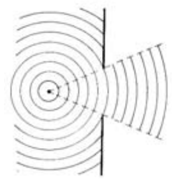
Huygens-Fresnel principle:
every point of a wavefront is the source of further waves

Christiaan **Huygens** (1629-1695)

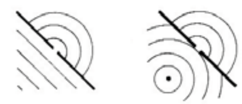
Augustin-Jean **Fresnel** (1788–1827)

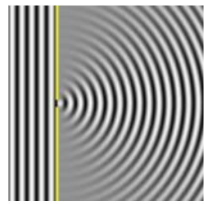


Slit much greater than the wavelength (λ)



Slit much smaller than wavelength (λ)

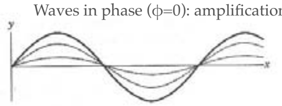




Wave phenomena II.
interference

Principle of superposition

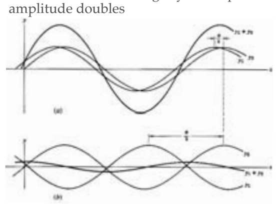
Waves in phase (ϕ=0): amplification



If ϕ=π : cancellation

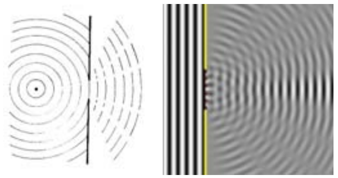
Simple rules:

Two identical waves slightly out of phase: amplitude doubles

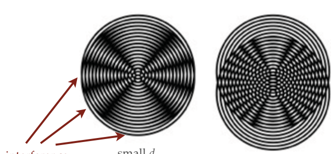


Two identical waves with phase slightly different from π: wave vanishes

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



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

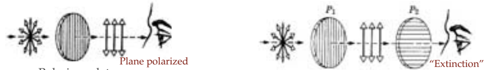


Wave phenomena III.
Polarization

- **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

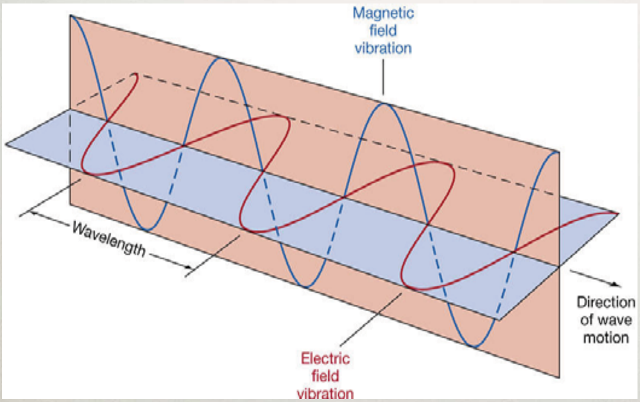
Polarization of **Electromagnetic** waves



Head-on view of polarization plane:

The electromagnetic wave

Electromagnetic disturbance propagating in space
No elastic medium is required.



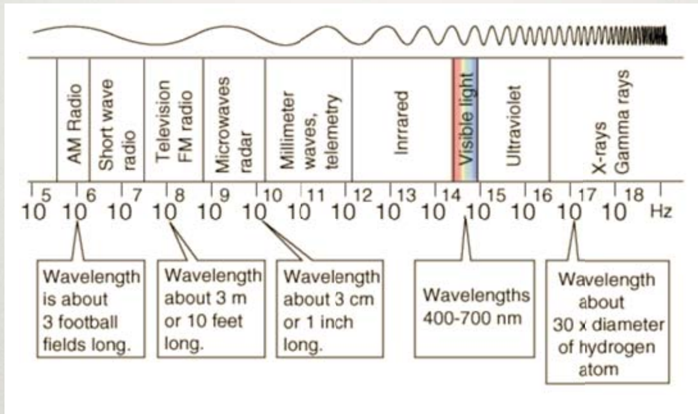
James Clerk **Maxwell**
(1831-1879)

Light is an electromagnetic wave.
Propagation velocity:

$$c = \lambda f$$

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

The electromagnetic spectrum



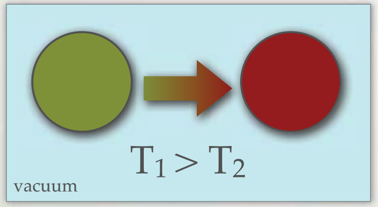
N.B.: 1) *"spectrum"* = function (intensity of EM radiation as a funciton of energy)
2) *"electromagnetic spectrum"* = types of radiation as a function of energy

"Black-body" radiation

Thermal radiation

One form of generation of light (besides *luminescence*)

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



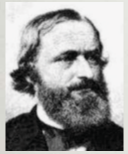
Heat exchange, temperature equilibration

Light emitted by high-temperture object

Kirchoff's law

Objects not only emit radiation but absorb it as well!

Ratio of spectral emissive power and absorptivity is constant

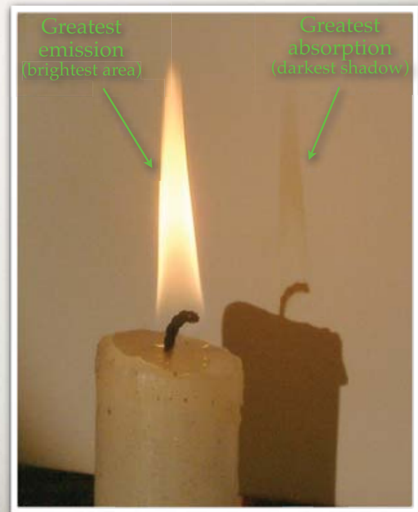


Gustav Robert **Kirchoff** (1824-1887)

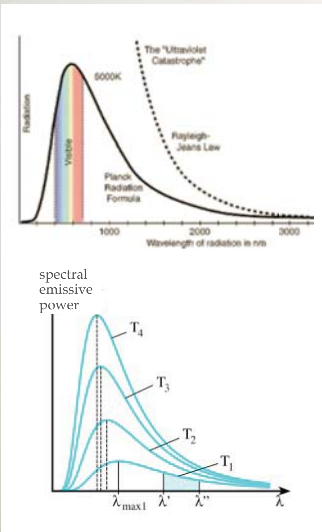
$$\frac{M_{\lambda i}}{\alpha_{\lambda i}} = \frac{M_{\lambda j}}{\alpha_{\lambda j}}$$

For e black body (BB):

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

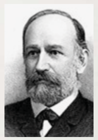


Black-body radiation

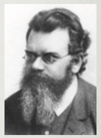


Stefan-Boltzmann law:

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



Jozef **Stefan** (1835-1893)



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

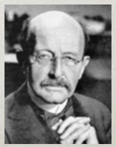
Wien's displacement law:

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

Wilhelm **Wien** (1864-1928)

Planck's law of radiation:

$$E = hf$$



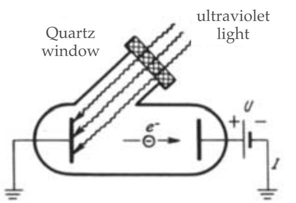
Max Karl Ernst Ludwig **Planck** (1858-1947)

Photoelectric effect:

The experiment

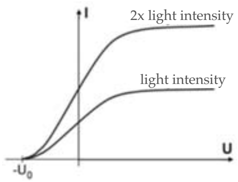
Hallwachs-effect:
Upon UV illumination, negative charges leave the metal surface

Wilhelm **Hallwachs** (1859-1922)



Measurements, observations

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

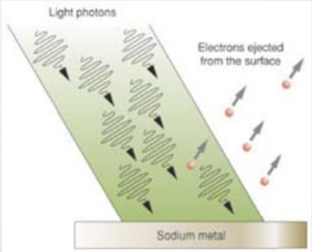


- Electron emission: instantaneous upon illumination
- Electron emission only in high-frequency (e.g., blue, UV) light
- No electron emission in low-frequency (e.g., red) light
- Photoelectric current: depends on light intensity
- Photoelectric current: does NOT depend on light color

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**

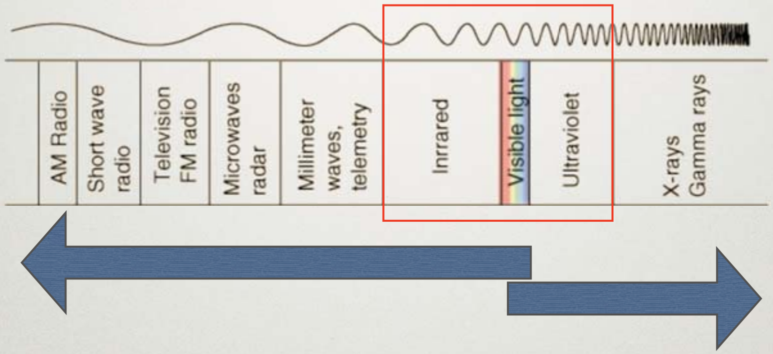
During propagation

Manifestations:
Diffraction
Interference
Polarization

During interactions

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

Light is a special range of the EM spectrum



Long wavelengths:
wave nature dominates

Short wavelengths:
particle nature dominates

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!):

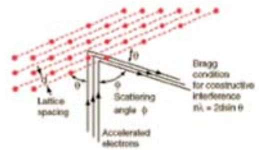
$$P = \frac{h}{\lambda}$$

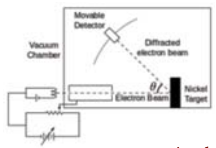
Wavelength of particle ("de Broglie wavelength"):

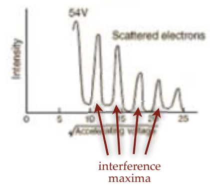
$$\lambda = \frac{h}{mv}$$

Davisson-Germer experiment

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







Az elektron hullám!

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

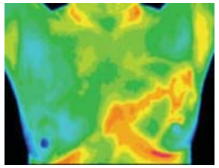
Bullet: for m=1 g and v=1 kms^{-1}, λ= 6 x 10^{-34} m!!

Applications I.

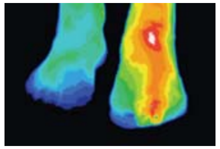
Black-body radiation: Thermography, infradiagnostics

"Seeing through" non-absorbing layer

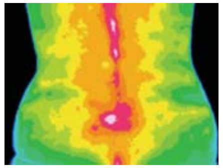
Airport thermography during swine flu *pandemia*



Breast screening, breast carcinoma



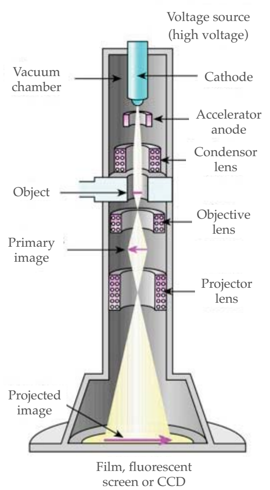
Inflammation



Chronic musculoskeletal stress (pain)

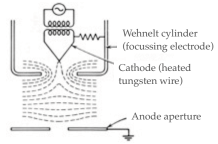
Applications II.

Matter waves: Electron microscope

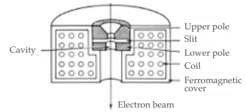


Transmission electron microscope (TEM)

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: $d \sim$ 0,005 nm (=5 pm).

Applications III.

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

Light detection, image recording, CCD camera

Harvesting and transformation of light energy

Light amplification

Summary

$$c = \lambda f \qquad E = hf \qquad \lambda = \frac{h}{mv}$$