

2. RADIATION

MIKLÓS KELLERMAYER

RADIATION IS EVERYWHERE



Emission spectrum of the H-atom



Orion Nebula



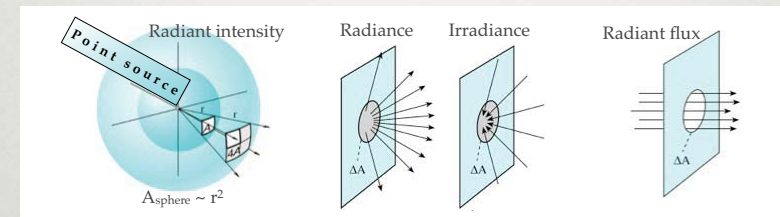
Source → Radiation → Irradiated object

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

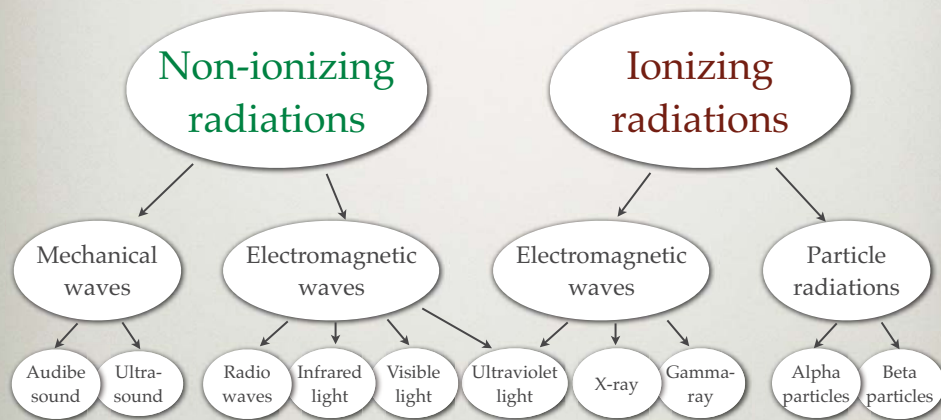
RADIATION FUNDAMENTALS

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.

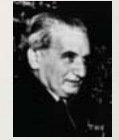


Quantity	Symbol	SI unit	Abbr.	Notes
Radiant energy	Q	joule	J	energy
Radiant flux	Φ	watt	W	radiant energy per unit time, also called <i>radiant power</i>
Radiant intensity	I	watt per steradian	Wsr^{-1}	power per unit solid angle
Radiance	L	watt per steradian per square metre	$\text{Wsr}^{-1}\text{m}^{-2}$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

TYPES OF RADIATION



OSCILLATIONS ARE SOURCES OF WAVES



Theodore von Kármán
1881-1963



Kármán vortex street

Tacoma Narrows Bridge ("Gallop'n' 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.



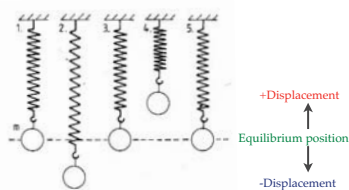
Tacoma Narrows Bridge today

OSCILLATION

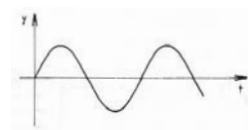
Movement (or change) that has a periodic component

Simple Harmonic Oscillation (SHO):

oscillation that can be described with sine function



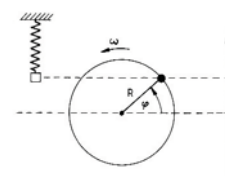
Mass on a spring



Displacement vs. time

DISPLACEMENT VS. TIME FUNCTION OF SHO

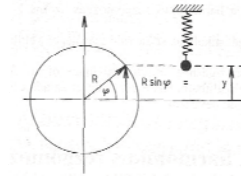
Simple harmonic oscillation and uniform circular motion are related



$$y = R \sin \varphi$$

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

y is maximal at $\sin \varphi = 1$
Maximal displacement: "amplitude(A)"



Since, from circular motion,

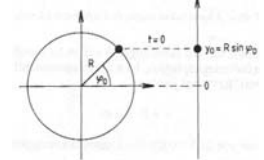
$$\varphi = \omega t$$

ω = angular velocity

we may write:

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

If at the beginning of examination $\varphi \neq 0$



$$y_0 = A \sin \varphi_0$$

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

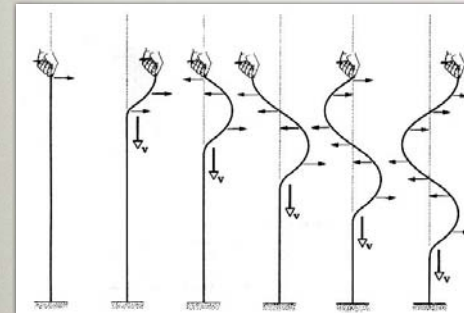
$$y = A \sin\left(\frac{2\pi}{T}t + \varphi_0\right)$$

TYPES OF WAVES

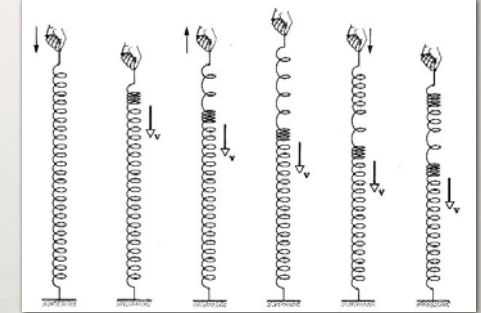
- According to **source**:
 1. Mechanical: elastic deformation propagating through elastic medium
 2. Electromagnetic: electric disturbance propagating through space (vacuum)
- According to **propagation dimension**:
 1. One-dimensional (rope)
 2. Surface waves (pond)
 3. Spatial waves (sound)
- According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



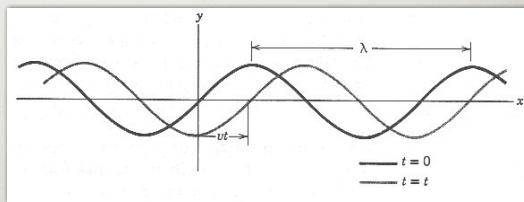
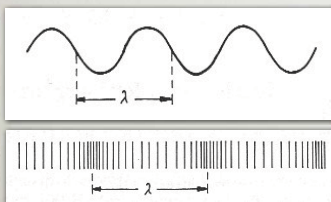
2) **Longitudinal** (direction of oscillation is parallel to direction of propagation, e.g., sound)



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

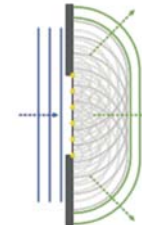
Huygens-Fresnel principle:
every point of a wavefront is the source of further waves



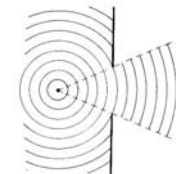
Christiaan Huygens
(1629-1695)



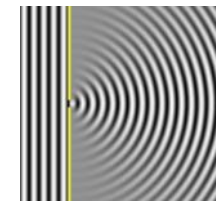
Augustin-Jean Fresnel
(1788-1827)



Slit much greater than the wavelength (λ)

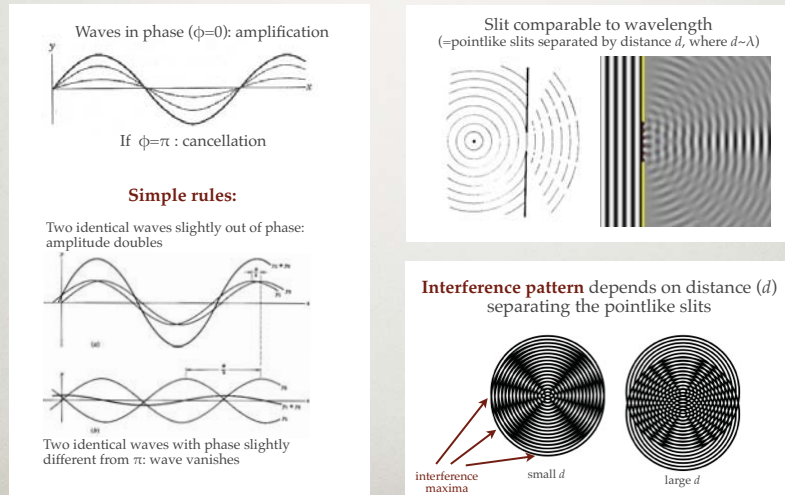


Slit much smaller than wavelength (λ)



WAVE PHENOMENA II. INTERFERENCE

Principle of superposition



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.



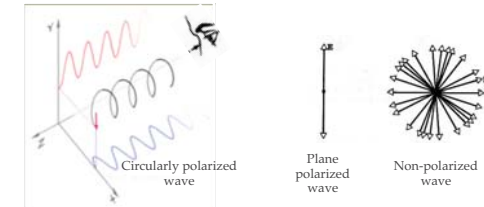
Polarization of Mechanical waves



Polarization of Electromagnetic waves

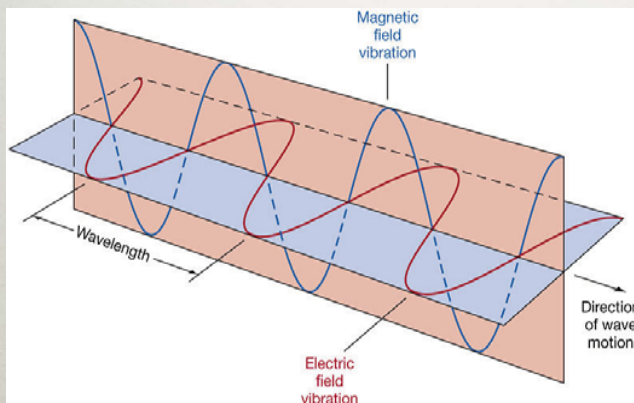


Head-on view of polarization plane:



THE ELECTROMAGNETIC WAVE

Electromagnetic disturbance propagating in space
No elastic medium is required.



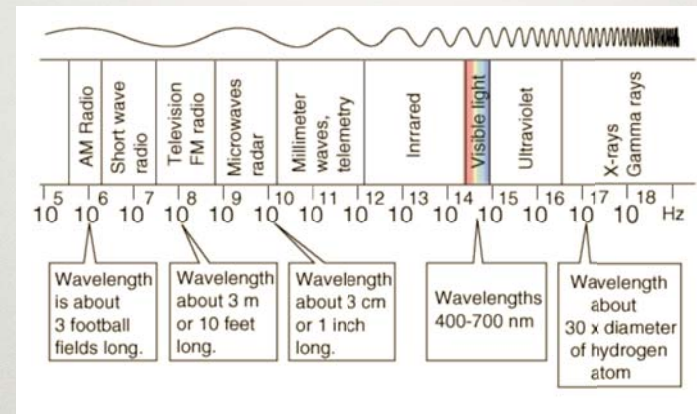
James Clerk Maxwell
(1831-1879)

Light is an electromagnetic wave.
Propagation velocity:

$$c = \lambda f$$

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

THE ELECTROMAGNETIC SPECTRUM

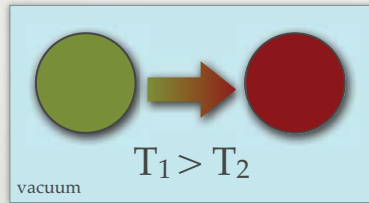


- N.B.: 1) "spectrum" = function (intensity of EM radiation as a function of energy)
2) "electromagnetic spectrum" = types of radiation as a function of energy

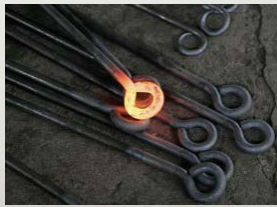
“BLACK-BODY” RADIATION

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-temperature
object

KIRCHOFF'S LAW

Objects not only emit radiation but absorb it as well!

Ratio of spectral emissive power and
absorptivity is constant

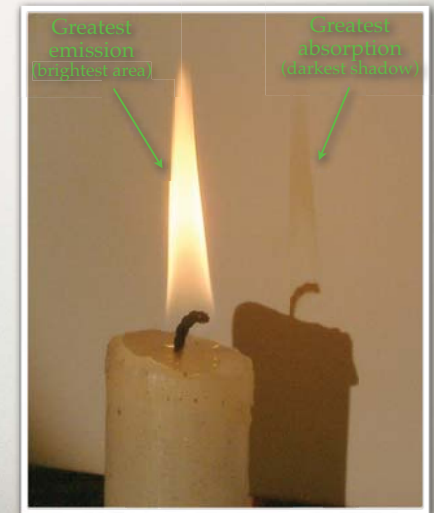


Gustav Robert Kirchhoff
(1824-1887)

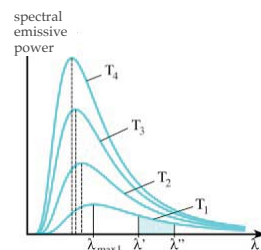
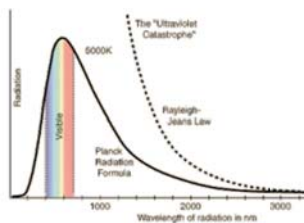
$$\frac{M_{\lambda i}}{\alpha_{\lambda i}} = \frac{M_{\lambda j}}{\alpha_{\lambda j}}$$

For a black body (BB):

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



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



Wilhelm Wien
(1864-1928)

Planck's law of
radiation:
 $E = hf$



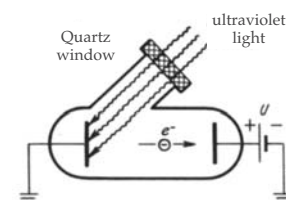
Max Karl Ernst Ludwig Planck
(1858-1947)

PHOTOELECTRIC EFFECT: THE EXPERIMENT

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



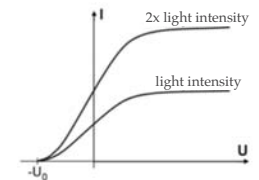
Wilhelm Hallwachs
(1859-1922)



Measurements, observations



Philipp Lenard/
Léonard Filop
(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

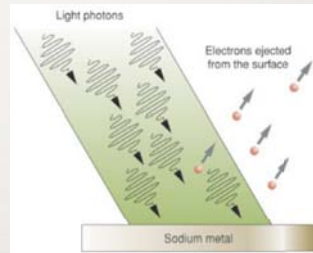
THE EXPLANATION

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:

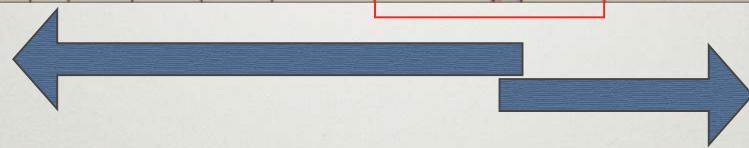
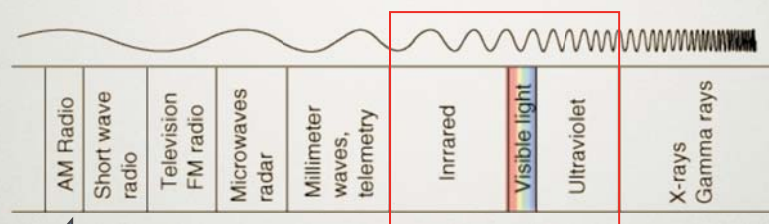
- Diffraction
- Interference
- Polarization

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 photon!):

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

Wavelength of particle ("de
Broglie wavelength"):

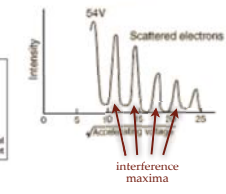
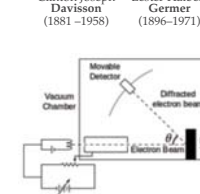
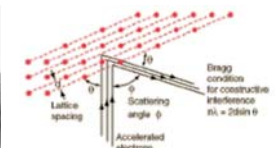
$$\lambda = \frac{h}{mv}$$

Davisson-Germer experiment



Clinton Joseph
Davisson
(1881-1958)

Lester Halbert
Germer
(1896-1971)



The electron is a wave!

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



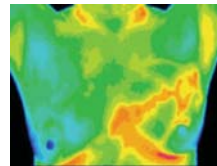
Bullet: for $m=1$ g and $v=1$ kms⁻¹,
 $\lambda = 6 \times 10^{-34}$ m!!

APPLICATIONS I.

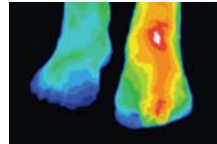
Black-body radiation: Thermography, infradiagnostics



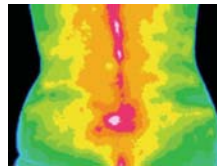
"Seeing through" non-absorbing layer



Breast screening, breast carcinoma



Inflammation



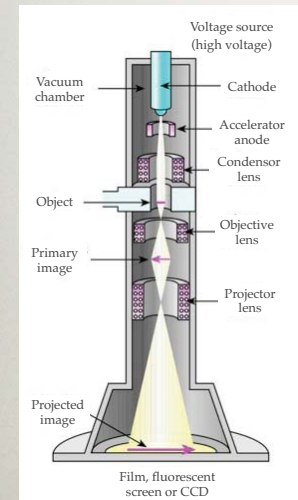
Chronic musculoskeletal stress (pain)



Airport thermography during swine flu pandemic

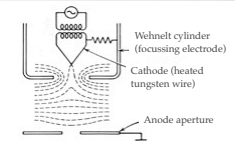
APPLICATIONS II.

Matter waves: Electron microscope

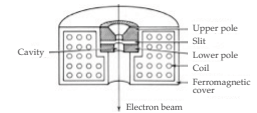


Transmission electron microscope (TEM)

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:

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

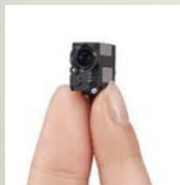
d =smallest resolved distance
 λ = "de Broglie" wavelength
 α =angle between the optical axis and the direction of the magnetic field

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

APPLICATIONS III.

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

Light detection, image recording, CCD camera



Harvesting and transformation of light energy



Light amplification



Silence of the lambs night vision scene

SUMMARY

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