Medical Biophysics

Introduction

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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 (Nobel laureate)*

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

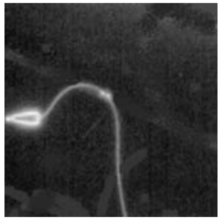
Questions we might ask:

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.

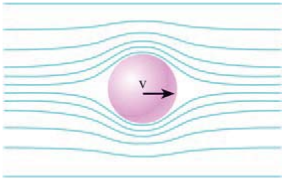
Drag coefficient of the spermatocyte

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:



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

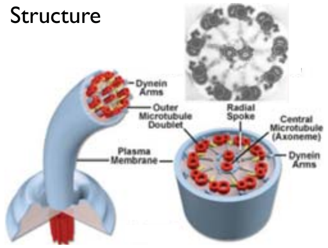
$$\gamma = 6 r \pi \eta = 6 \cdot 1.6 \times 10^{-6} (m) \cdot \pi \cdot 10^{-3} (Pas) = 3 \times 10^{-8} Ns/m$$

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

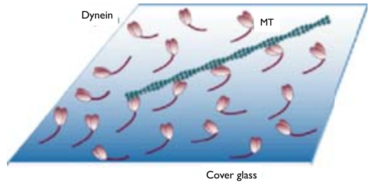
Mechanisms behind spermatocyte motility?

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

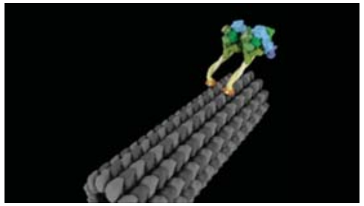
Structure



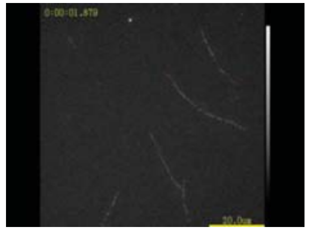
Functional test:
"In vitro motility assay"



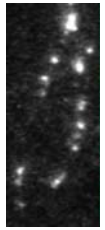
Fluorescence microscopy



"Drunken sailor" stepping mechanism



Microtubule moves over dynein



Dynein moves over microtubule

Lecture topics

Semester I.

1. Introduction. Radiations.
2. Biophysics of light
3. Geometric optics.
4. Optics of vision.
5. Structure of matter. Matter waves. Atomic and molecular interactions.
6. Many-particle systems. Boltzmann distribution. Gases, solids, liquid crystals.
7. Interaction of light with matter.
8. Luminescence.
9. Biomedical applications of fluorescence.
10. Lasers and their medical applications.
11. Atomic nucleus, radioactivity, isotopes.
12. Dosimetry.
13. Nuclear medicine
14. Signal processing

Semester II.

1. X-ray generation and properties
2. X-ray diagnostics
3. Medical applications of electricity
4. Thermodynamics
5. Diffusion, Brownian motion. Osmosis.
6. Fluid dynamics. Circulatory biophysics
7. Bioelectric phenomena. Resting potential
8. Sound, ultrasound. Muscle biophysics. Striated muscle, smooth muscle
9. Biophysics of sensory organs. Vision, hearing. Cardiac biophysics. Work of the heart. The cardiac cycle
10. Water, macromolecules, supramolecular systems.
11. Biomolecular structure and function. Fundamentals of NMR.
12. Biomechanics. Biomolecular and tissue elasticity
13. Pulmonary biophysics. Cardiac biophysics.
14. Physical foundations of physical examination.

Complexity

Dimensions of Living Systems

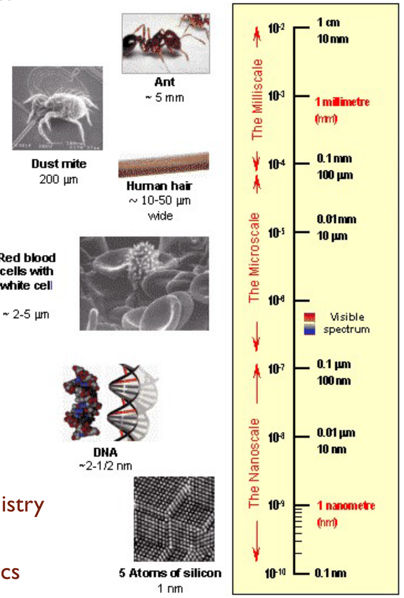
Thermodynamics — 10^{23} Atoms

Mesoscale — 10^{10} Atoms

10^{3} Atoms

Quantum chemistry — 10^{1} Atoms

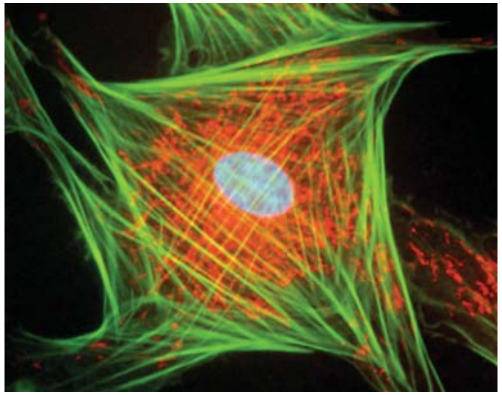
Quantum physics — 10^{0} Atom

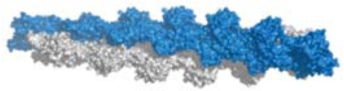


Prefixes

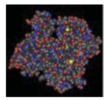
yotta	Y	10^{24}	named prefix every three orders of magnitude
zetta	Z	10^{21}	
exa	E	10^{18}	
peta	P	10^{15}	
tera	T	10^{12}	
giga	G	10^{9}	
mega	M	10^{6}	
kilo	k	10^{3}	
hekto	h	10^{2}	named prefix every order of magnitude
deka	da	10^{1}	
deci	d	10^{-1}	
centi	c	10^{-2}	
milli	m	10^{-3}	named prefix every three orders of magnitude
mikro	μ	10^{-6}	
nano	n	10^{-9}	
piko	p	10^{-12}	
femto	f	10^{-15}	
atto	a	10^{-18}	
zepto	z	10^{-21}	
yocto	y	10^{-24}	

Length scale of the living cell

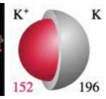




Actin filament (d=7 nm)

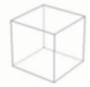


G-actin (d=5 nm, cc~100 μM)



Potassium ion (d=0.15 nm, cc~150 mM)

Simplified cell model: cube

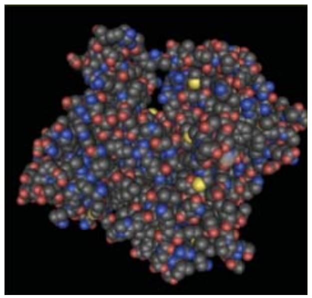


	Cell: cube with 20 μm edge	Analogue - **Lecture hall:** cube with 20 m edge
Size of actin molecule	5 nm	5 mm
Number of actin molecules	~500 thousand	~500 thousand
Average distance between actins	~250 nm	~25 cm
Size of potassium ion	0.15 nm	0.15 mm
Number of potassium ions	$\sim 10^9$	$\sim 10^9$
Average distance between K^+ ions	~20 nm	~2 cm

Deficiencies of the model:
- concentrations vary locally
- dynamics: constant motion and collisions
- interactions, many types due to dynamics

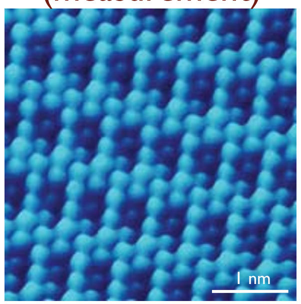
Can we explore the smallest parts of a biomolecular system?

Model



Structural model of globular actin
gray - C; red - O; blue - N; yellow - S

“Reality” (measurement)



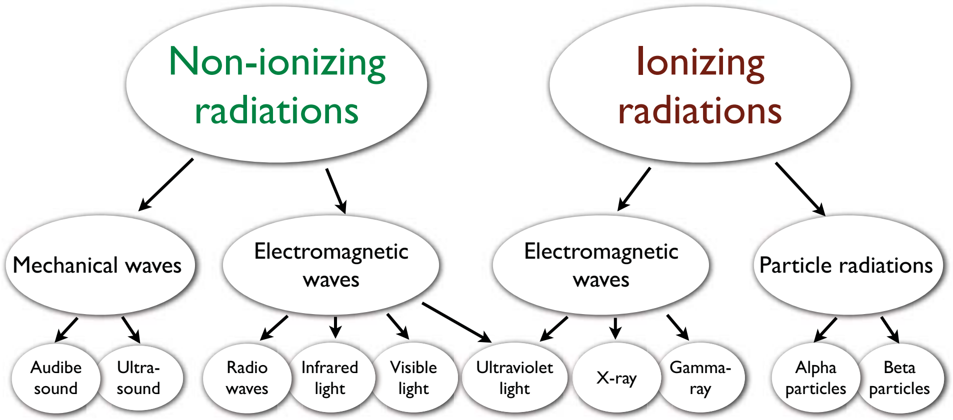
Oxygen atoms on the surface of a rhodium single crystal (scanning probe microscopic image)

Radiation is everywhere

Emission spectrum of the H-atom

Source ⟶ Radiation ⟶ Irradiated object

Types of radiation



Radiation = propagating ***energy***

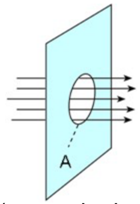
In the form of waves or subatomic particles, emitted by an atom or body as it changes from a high energy state to a lower energy state.

Energy, *E*: $[E]$ = J (Joule)

Radiant flux; radiant power: $$P = \frac{\Delta E}{\Delta t}$$ $[P]$ = W (Watt)

ΔE: energy carried during Δt time

Radiant intensity:



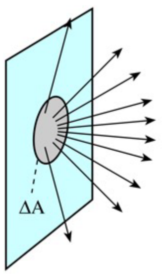
$$J = \frac{P}{A} = \frac{1}{A}\frac{\Delta E}{\Delta t}$$ $[J]$ = W/m^2

A: area (perpendicular to the direction of energy propagation)

Parameters of radiometry

Radiance

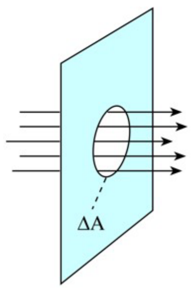
$$M = \frac{\Delta P}{\Delta A} \quad \left[\frac{W}{m^2}\right]$$



Power radiated by unit area into a solid angle of 2π.

Radiation intensity

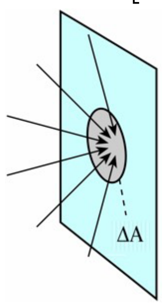
$$J_E = \frac{\Delta I_E}{\Delta A} \quad \left[\frac{W}{m^2}\right]$$



Power propagating through unit area.

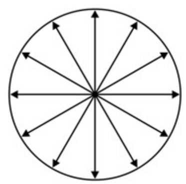
Irradiance

$$\varepsilon = \frac{\Delta P}{\Delta A} \quad \left[\frac{W}{m^2}\right]$$

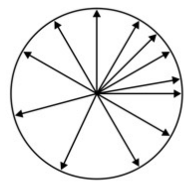


Power incident on a surface of unit area (radiation may arrive from all directions).

Directionality of radiation

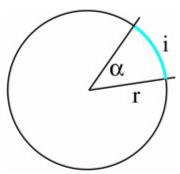


isotropic source



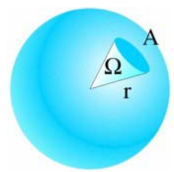
anisotropic source

Radian, steradian



$$\alpha = \frac{i}{r}$$

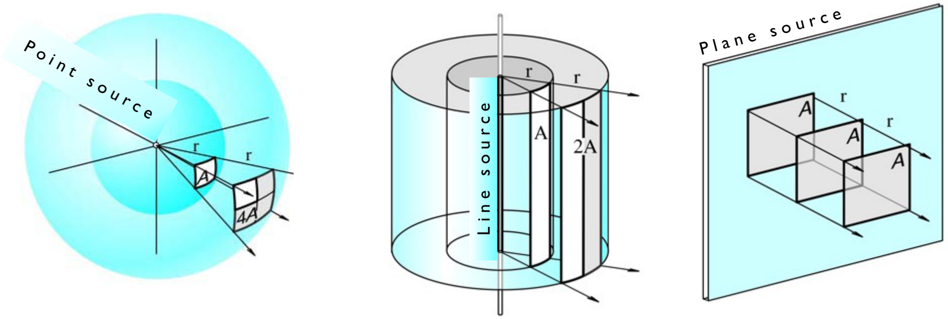
angular measure (radian):
arc length/radius;
full circle: $2r\pi/r = 2\pi$



$$\Omega = \frac{A}{r^2}$$

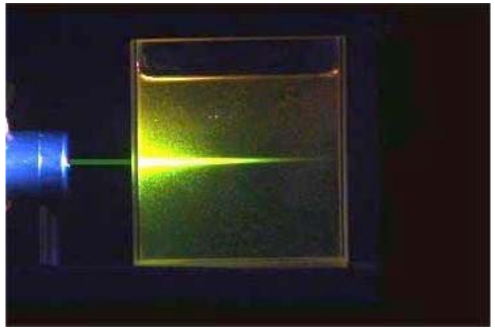
solid angle (steradian):
surface area/square of radius;
total solid angle (sphere): $4r^2\pi/r^2 = 4\pi$

Radiant intensity as a function of the geometry of radiation source



$A_{sphere} \sim r^2$ $A_{cylinder} \sim r$ A=constant

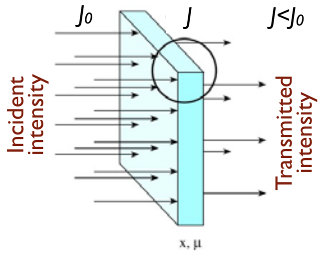
As radiation travels through matter, its intensity decreases

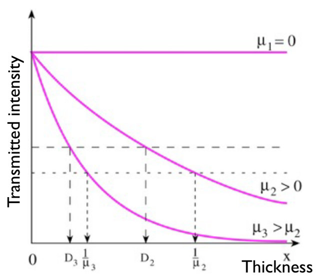


(Radiation that exits is weaker than the one that enters)

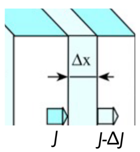
Is there a simple, general law to describe this phenomenon?

General radiation attenuation law





$\Delta J \sim J$; $\Delta J \sim \Delta x$; $\Delta J \sim \mu$

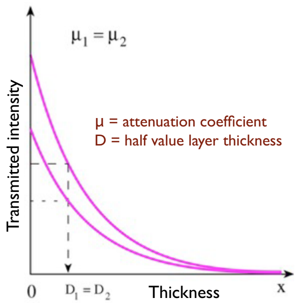


A given quantity (J) and its change (ΔJ) are proportional:

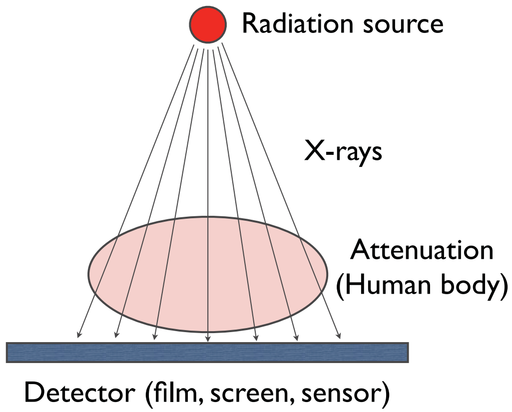
$\Delta J = -\mu \Delta x J$

Exponential function:

$J = J_0 e^{-\mu x}$



Medical relevance?



Chest x-ray