Introduction to Medical Biophysics

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Objectives and methods of medical biophysics

Objectives:

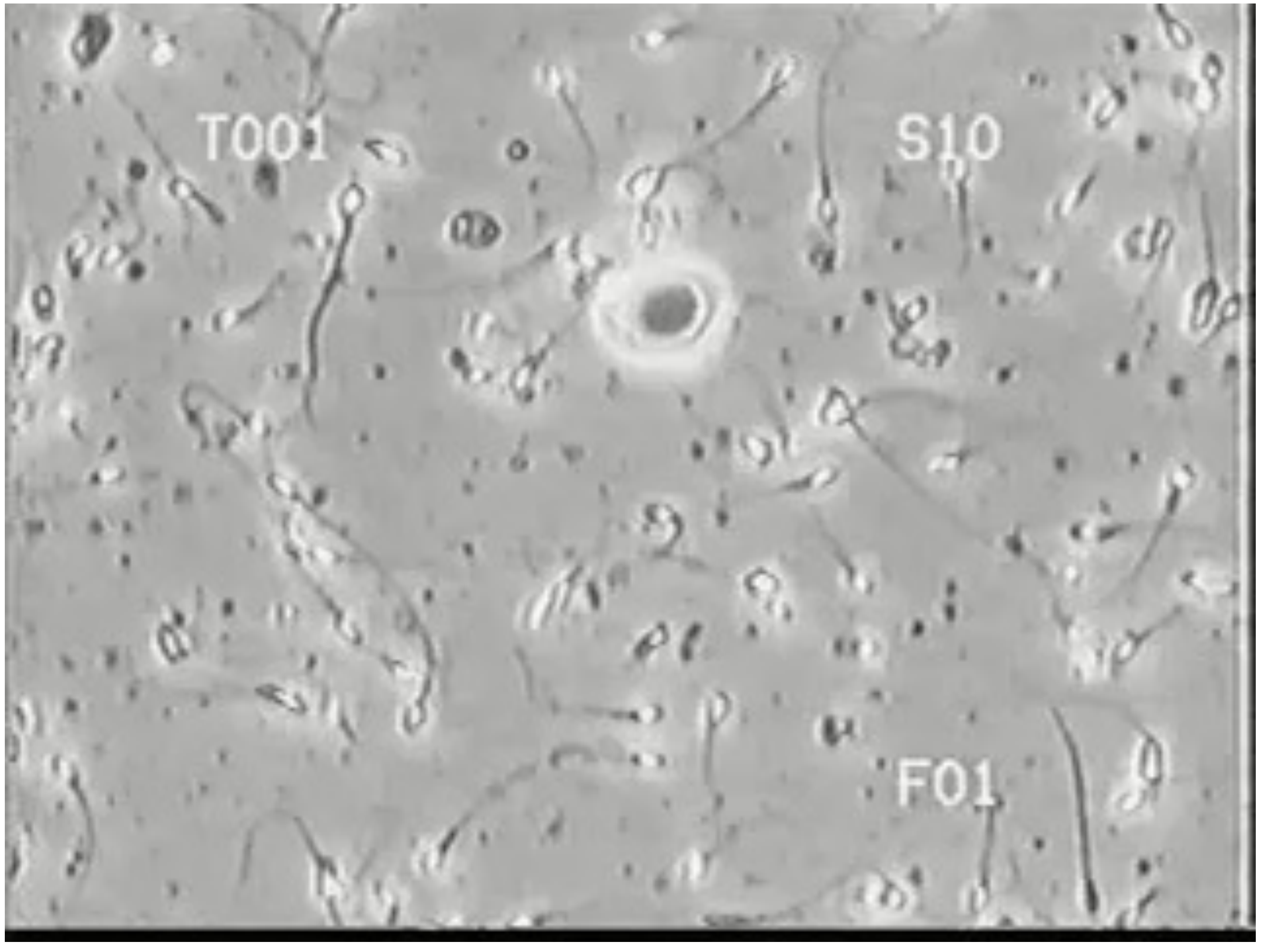
1. Provide a *physical* “description” of biomedical phenomena
2. Discuss and understand *physics*-based medical techniques

Methods:

Biomedical phenomena and processes are

1. quantified
2. simplified

1. Physical description of a biological phenomenon



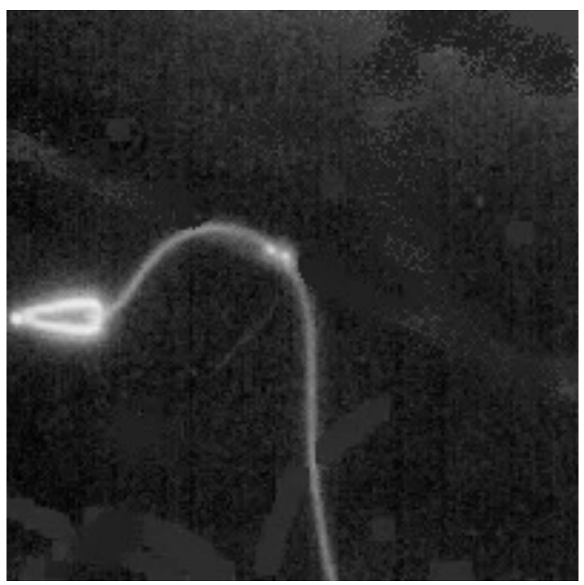
Questions we might ask:

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)? Can we build a predictive model?

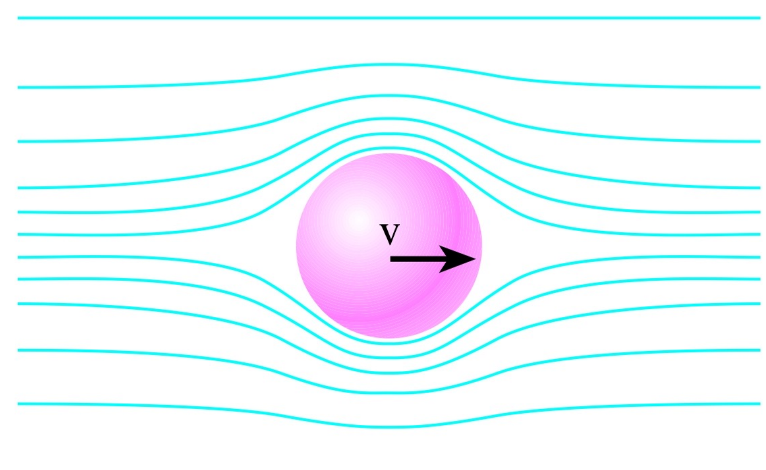
Drag coefficient of the spermatocyte

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:



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

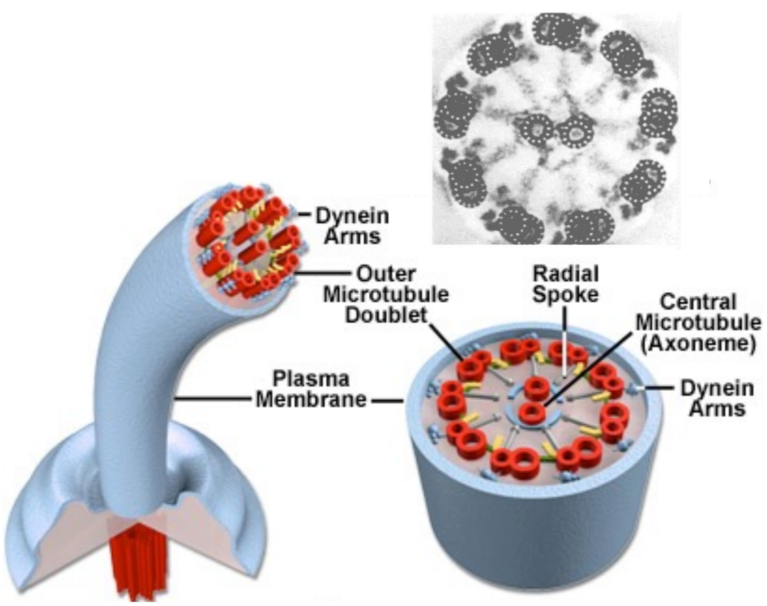
Friction coefficient: $\gamma = 6r\pi\eta = 6 \cdot 1.6\times10^{-6}(m) \cdot \pi \cdot 10^{-3}(Pas) = 3\times10^{-8}\,Ns/m$

Force: $F = \gamma v = 3\times10^{-8}\,Ns/m \cdot 5\times10^{-5}\,m/s = 1.5\times10^{-12}N = 1.5\,pN$

Mechanisms behind spermatocyte motility?

How does it happen (what is the exact mechanism)? Can we build a predictive model?

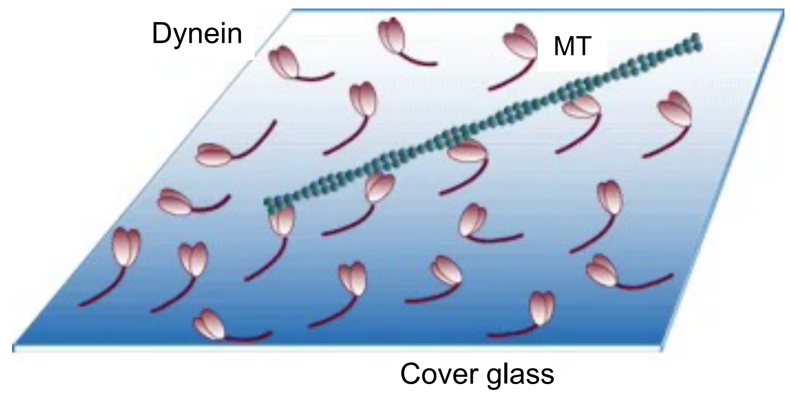
Structure of the sperm flagellum



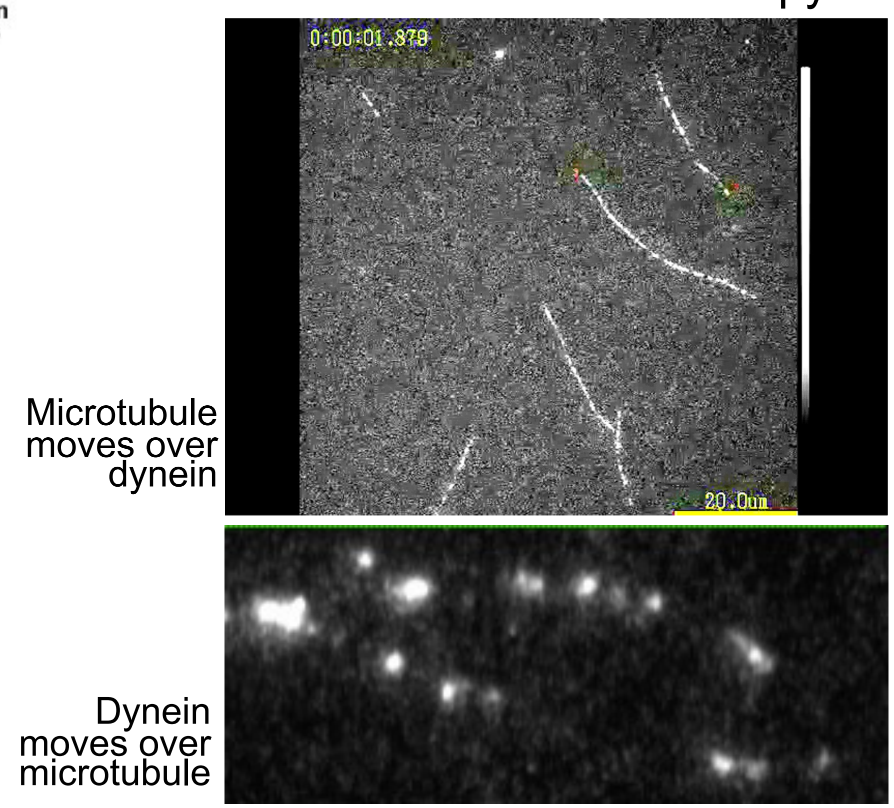
N.B.:

1. Let us collect all relevant information about the system under investigation.
2. Let us formulate testable questions.

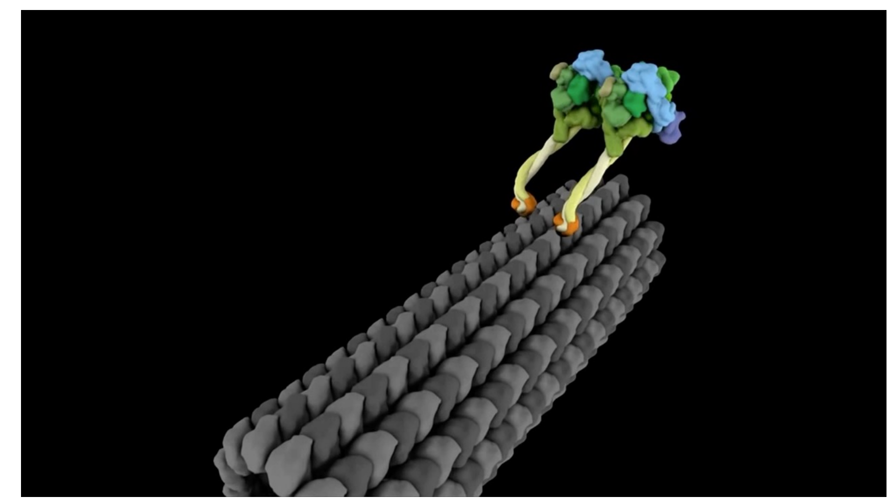
Functional test: "*In vitro* motility assay"



Fluorescence microscopy



Predictive model



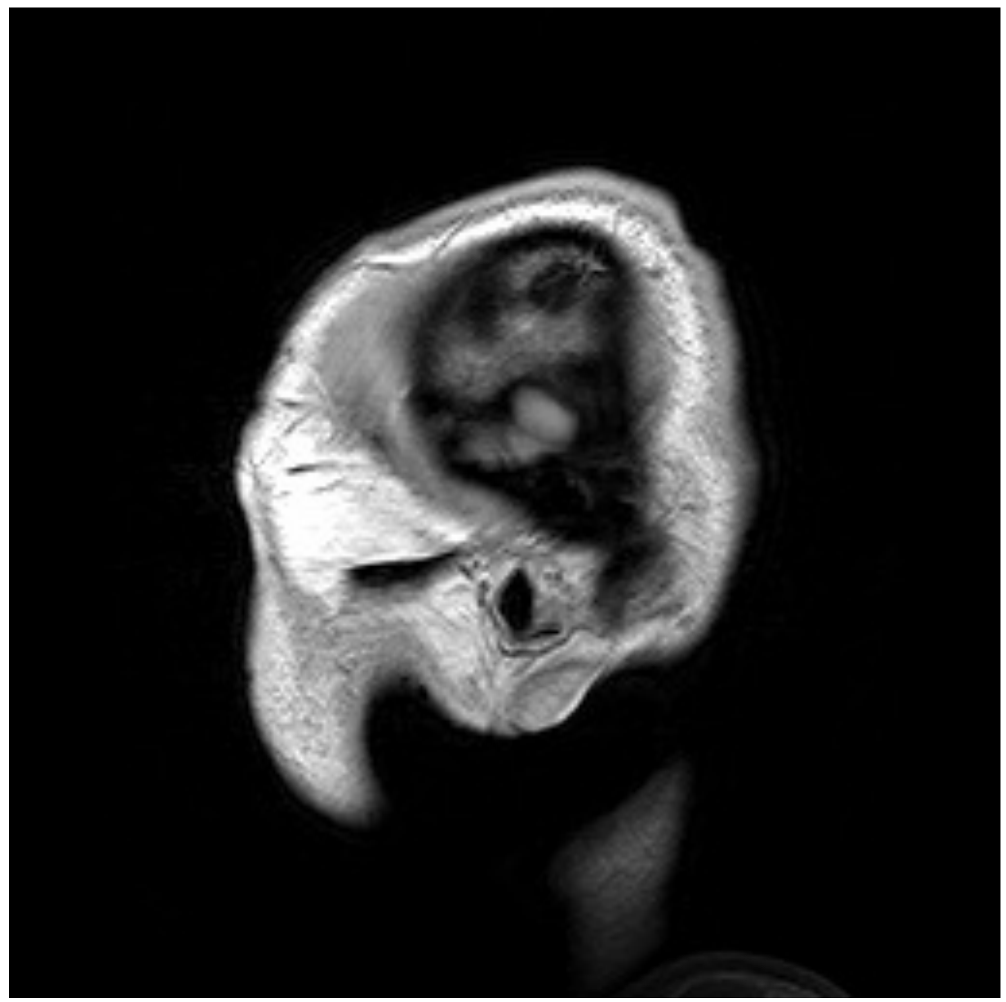
"Drunken sailor" stepping mechanism

N.B.:

1. model - grasps certain (but not all) important features of the system.
2. predictive - can make statements for generalized circumstances.

2. Understanding a physics-based medical technique

How does the MRI work?



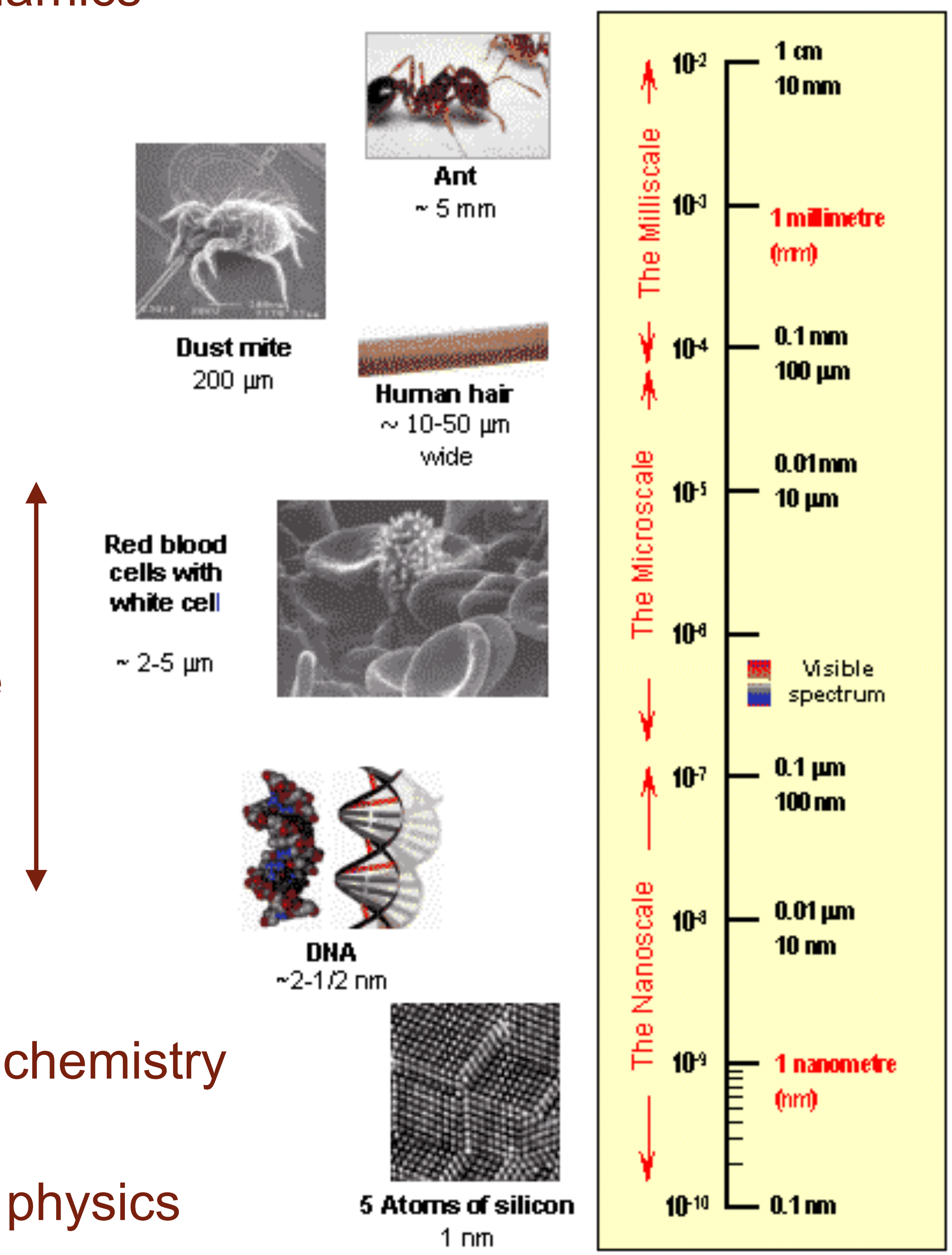
Questions we might ask:

1. What is this? (Magnetic Resonance Imaging)
2. What physical phenomena are utilized? (magnetism, radiations, absorption, emission)
3. What can MRI reveal about the human body? (structure, function, tissue composition)

1. Quantify…
Dimensions of Living Systems

Thermodynamics

10^{23} Atoms



10^{10} Atoms

Mesoscale

10^{3} Atoms

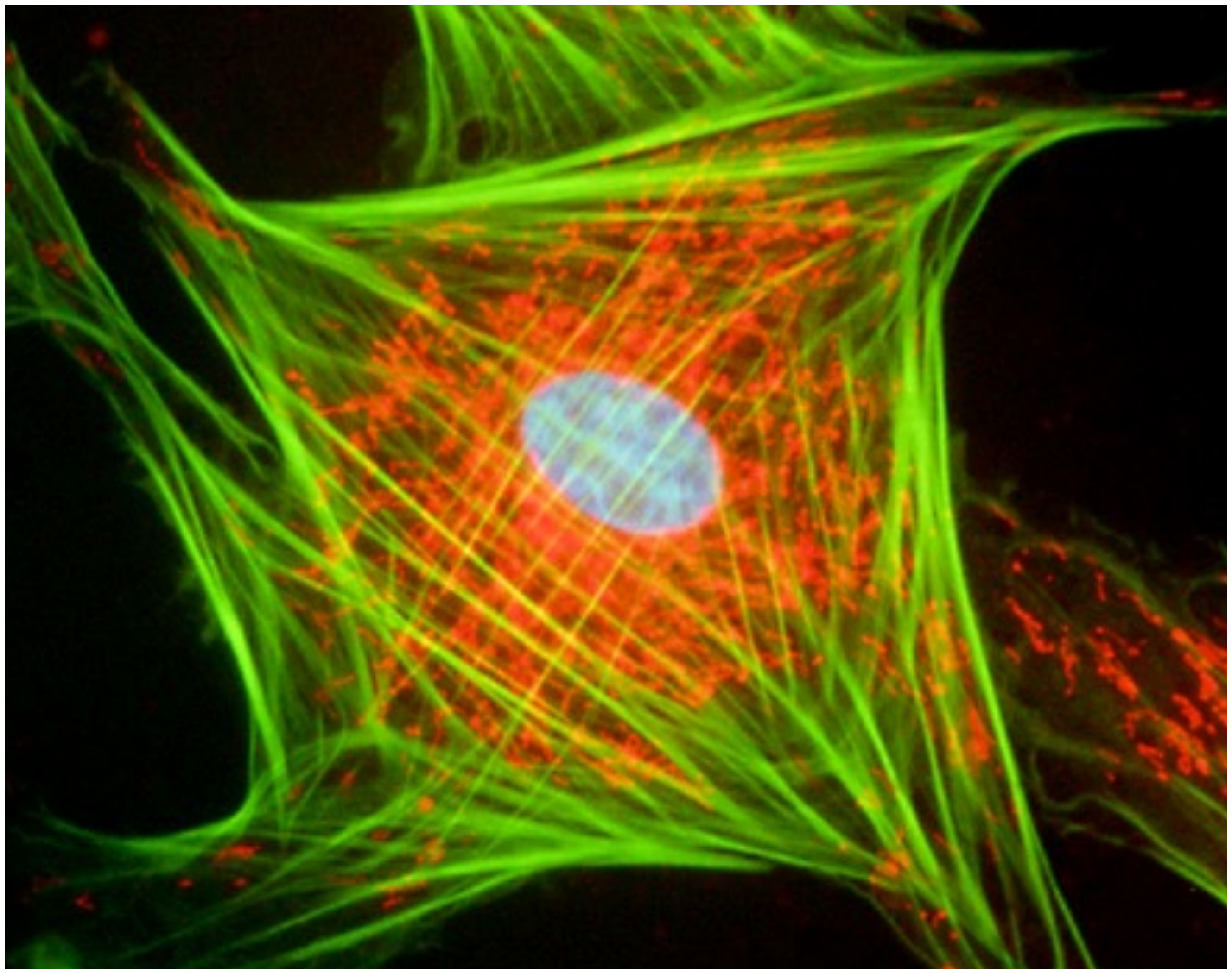
Quantum chemistry

10^{1} Atoms

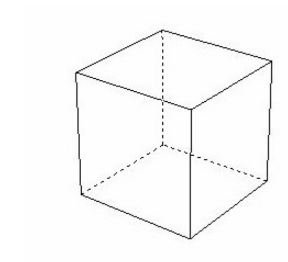
Quantum physics

10^{0} Atom

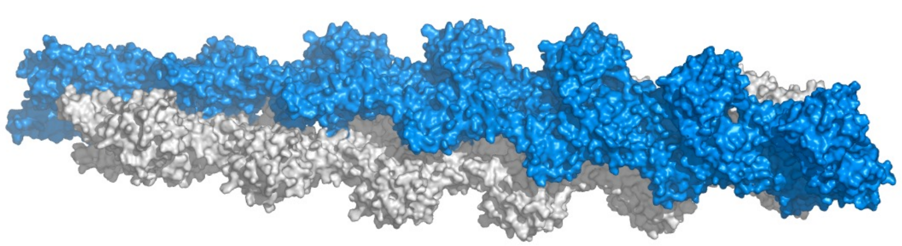
2. Simplify…
Model of the cell… and of a molecule…



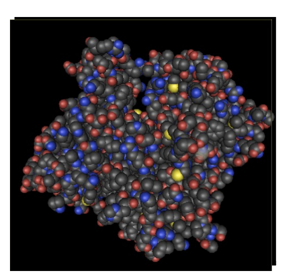
Simplified cell model: cube



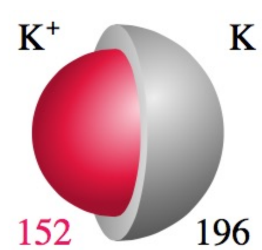
	Cell: cube with 20 µm edge	Analogue - **Lecture hall:** cube with 20 m edge
Size of actin molecule	5 nm	5 mm
Number of actin molecules	~500 thousand	~500 thousand
Average distance between actins	~250 nm	~25 cm
Size of potassium ion	0.15 nm	0.15 mm
Number of potassium ions	$\sim 10^9$	$\sim 10^9$
Average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



Actin filament (d=7 nm)



G-actin (d=5 nm, cc~100 µM)



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

Deficiencies of the model:

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

Lecture topics

Semester I.

1. Introduction. Radiations
2. Geometric optics
3. Wave optics
4. Dual nature of light
5. Structure of matter
6. Many-particle systems. Gases
7. Boltzmann distribution. Solids
8. Interaction of light with matter. Scattering, absorption
9. Thermal radiation, fluorescence. Laser
10. Atomic nucleus, radioactivity, isotopes.
11. Dosimetry.
12. Nuclear medicine
13. Signal processing

Semester II.

1. X-ray generation and properties
2. X-ray diagnostics
3. Thermodynamics
4. Diffusion, Brownian motion. Osmosis.
5. Fluid dynamics. Blood as a fluid
6. Bioelectric phenomena. Resting potential
7. Sound, ultrasound
8. Biophysics of sensory organs. Vision, hearing.
9. Water, macromolecules, supramolecular systems
10. Biological motion. Biomechanics
11. Biomolecular structure and function. X-ray diffraction, mass and IR spectrometry
12. Biomolecular structure and function. Fundamentals of MRI.
13. Blood circulation and cardiac function
14. Pulmonary biophysics. Physical foundations of physical examination.

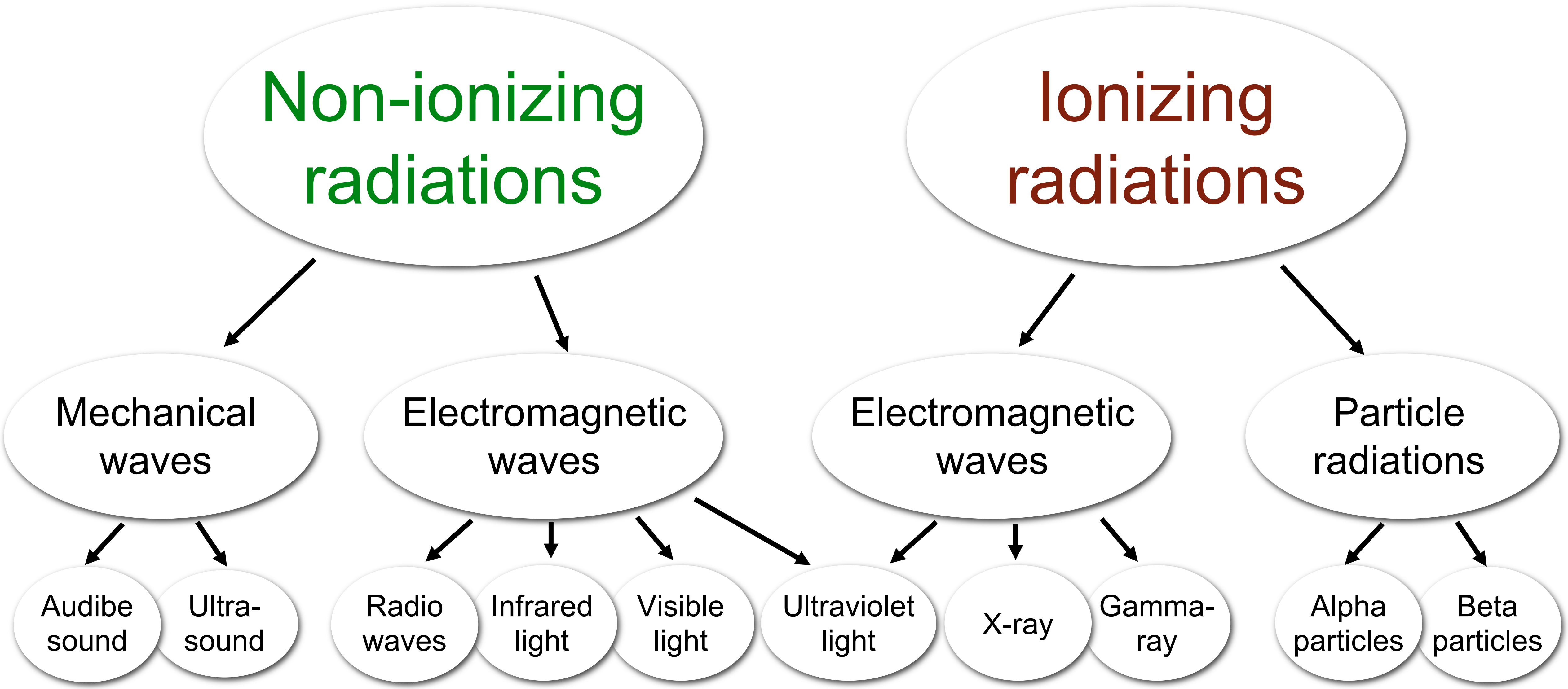
Radiation is everywhere

Emission spectrum of the H-atom

Orion Nebula

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)

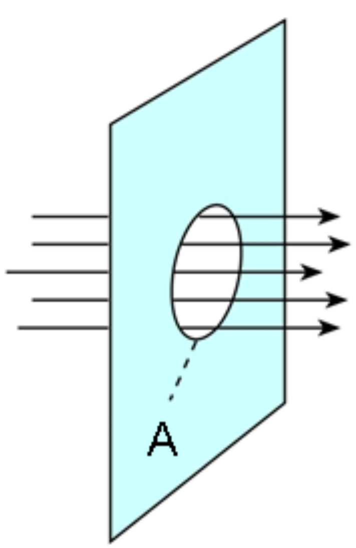
Radiant flux; radiant power:

$$P = \frac{\Delta E}{\Delta t}$$

$[P]$ = W (Watt)

ΔE: energy carried during Δt time

Radiant intensity



$$J = \frac{P}{A} = \frac{1}{A}\frac{\Delta E}{\Delta t}$$

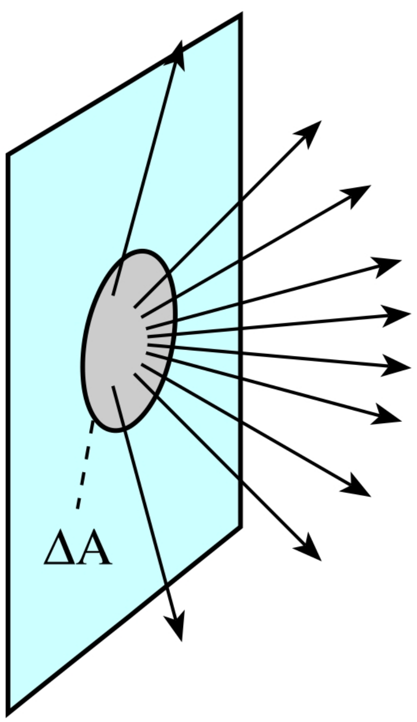
$[J] = \mathrm{W/m^2}$

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

Parameters of radiometry

Radiance

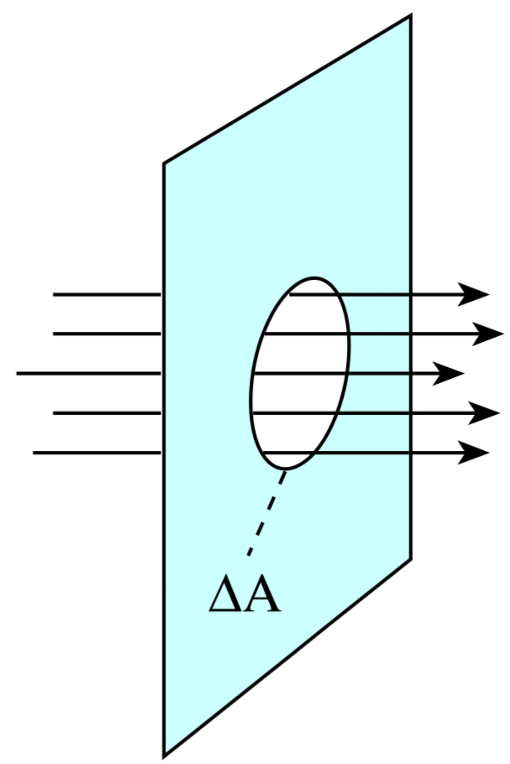
$$M = \frac{\Delta P}{\Delta A} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$



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

Radiation intensity

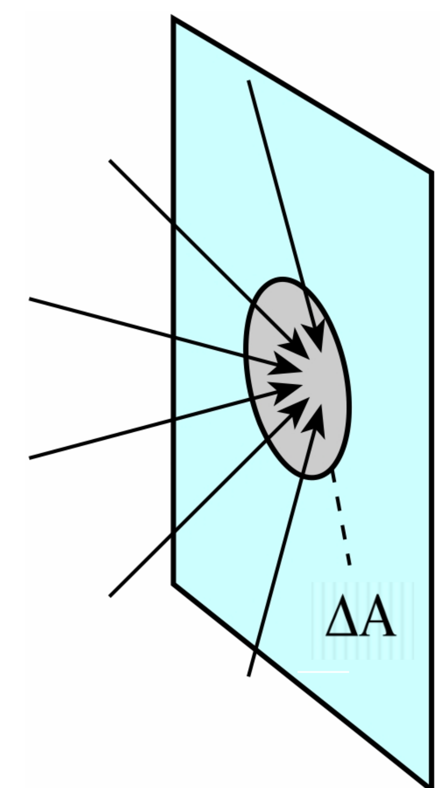
$$J_E = \frac{\Delta I_E}{\Delta A} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$



Power propagating through unit area.

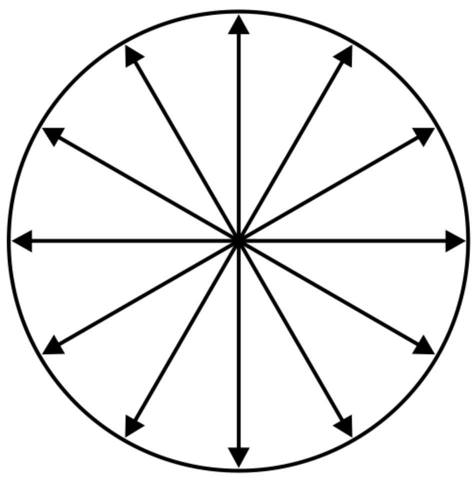
Irradiance

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

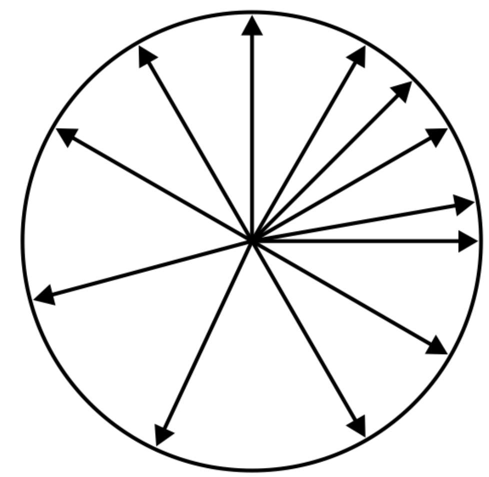


Power incident on a surface of unit area (radiation may arrive from all directions). (other symbol E_{inc})

Directionality of radiation

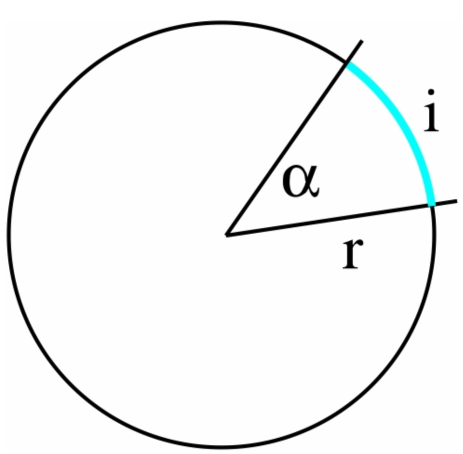


isotropic
source



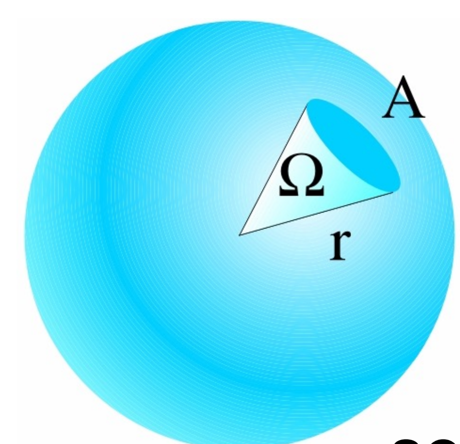
anisotropic
source

Radian, steradian



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

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

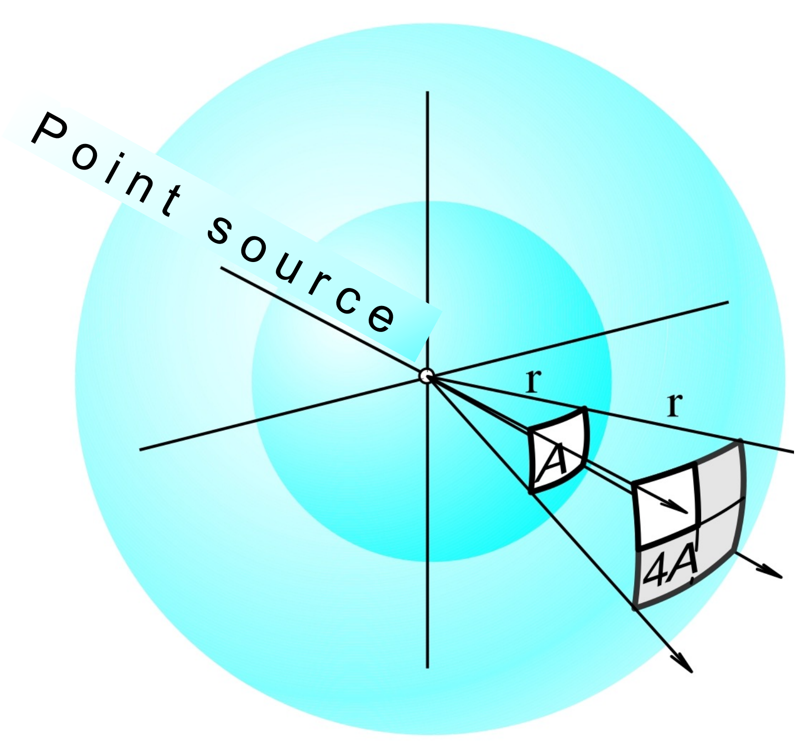


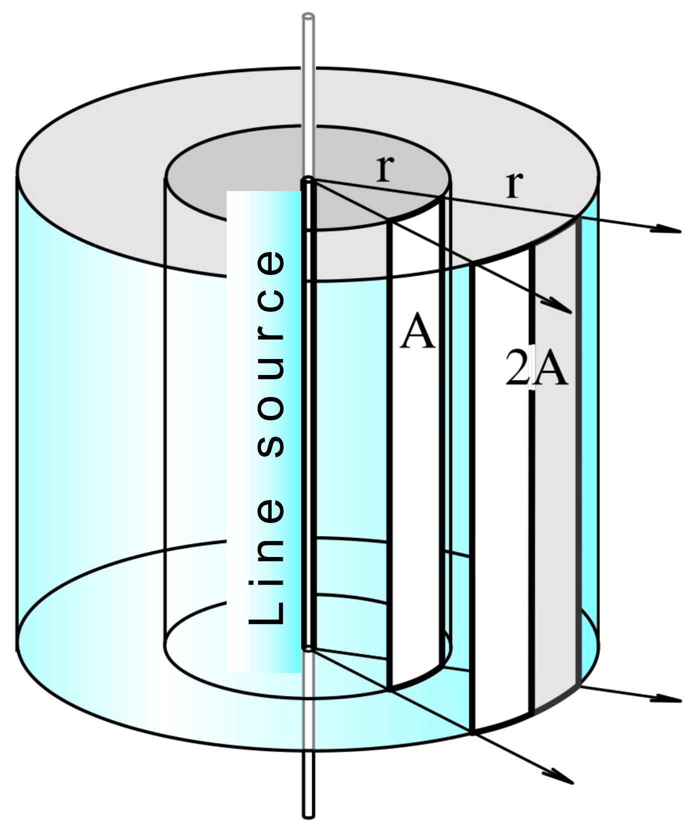
$$\Omega = \frac{A}{r^2}$$

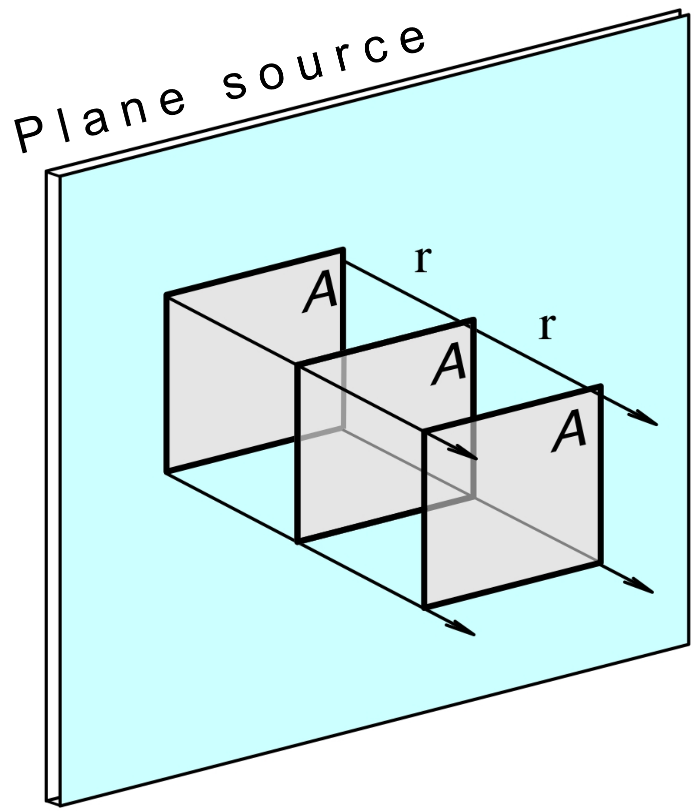
solid angle (steradian):
surface area/square of radius;
total solid angle (sphere):
$4r^2\pi/r^2 = 4\pi$

Radiant intensity as a function of the geometry of radiation source

Radiation is distributed on an imaginary surface (*A*) around the radiation source



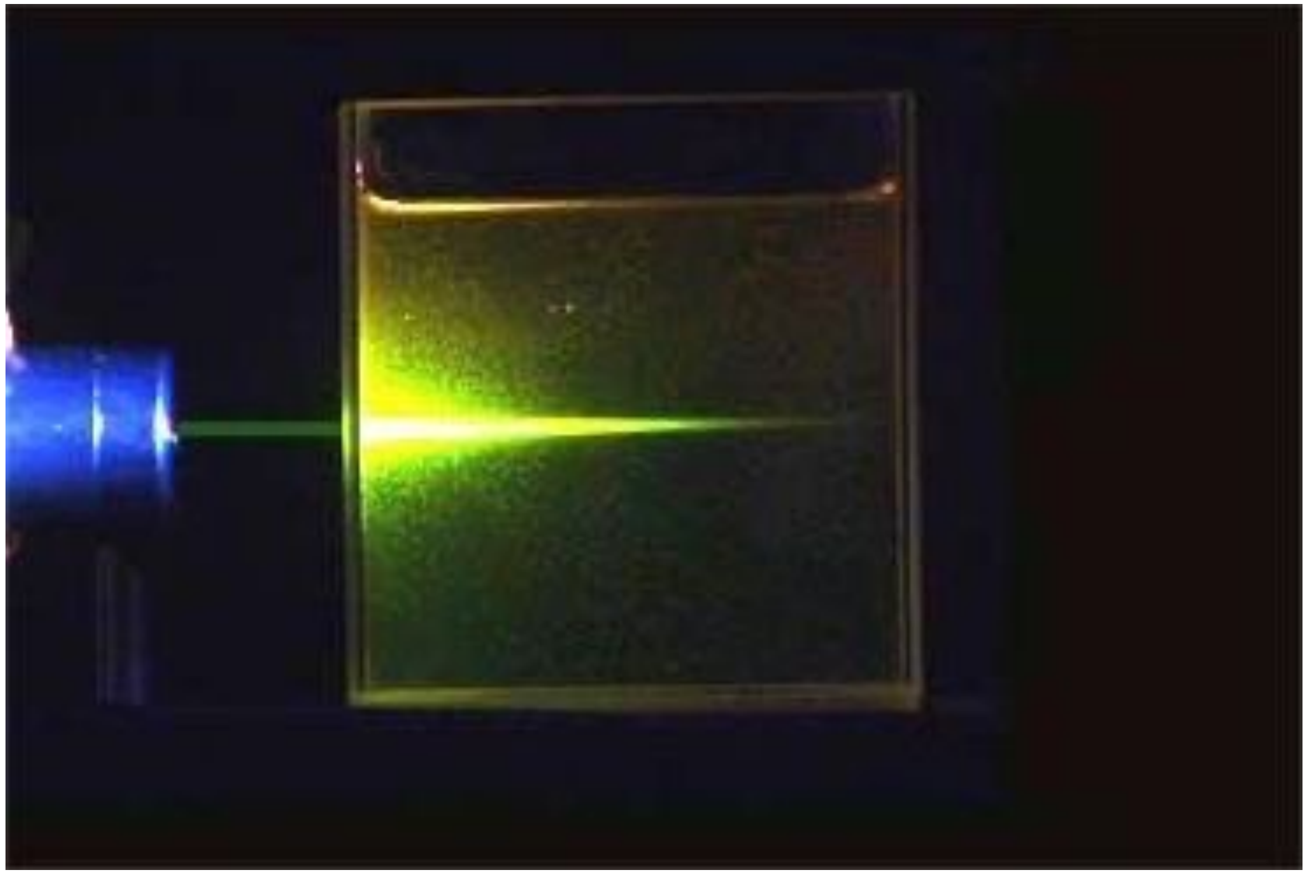




$A_{\text{sphere}} \sim r^2$ $A_{\text{cylinder}} \sim r$ $A = \text{constant}$

$E_{inc} \sim 1/r^2$ $E_{inc} \sim 1/r$ $E_{inc} = \text{constant}$

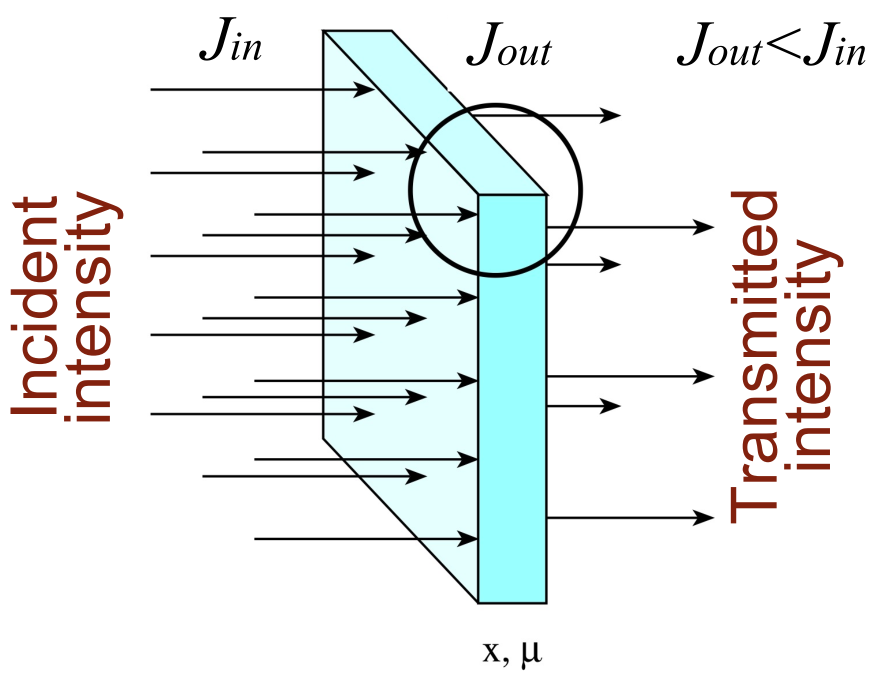
As radiation travels through matter, its intensity decreases

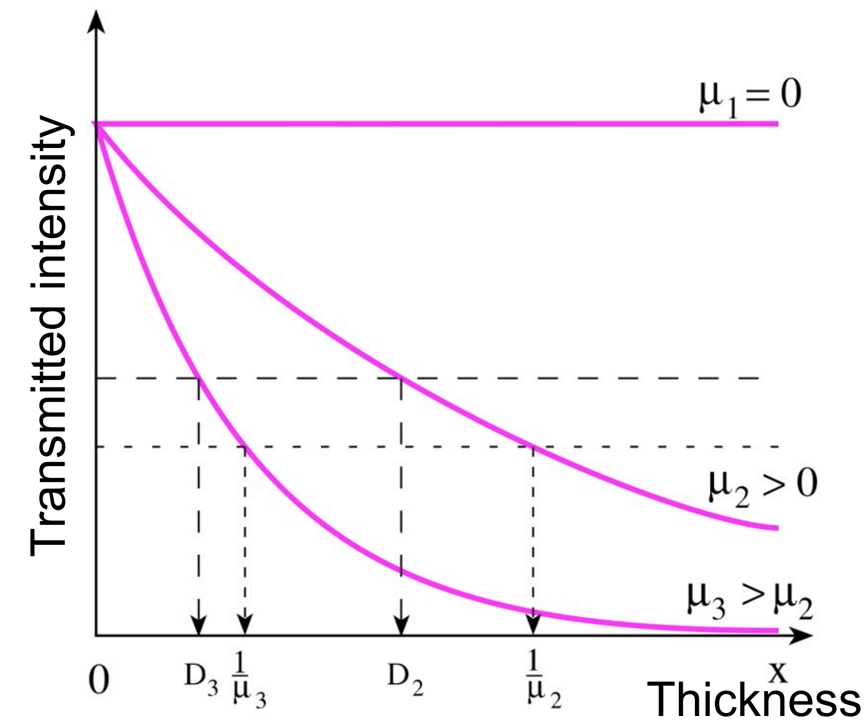


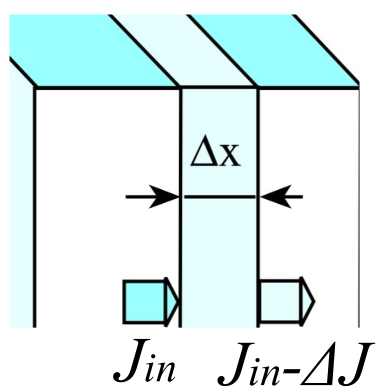
(Radiation that exits is weaker than the one that enters)

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

General radiation attenuation law







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

$$\Delta J=-\mu \Delta x J_{in}$$

Exponential function:

$$J_{out}=J_{in}e^{-\mu x}$$

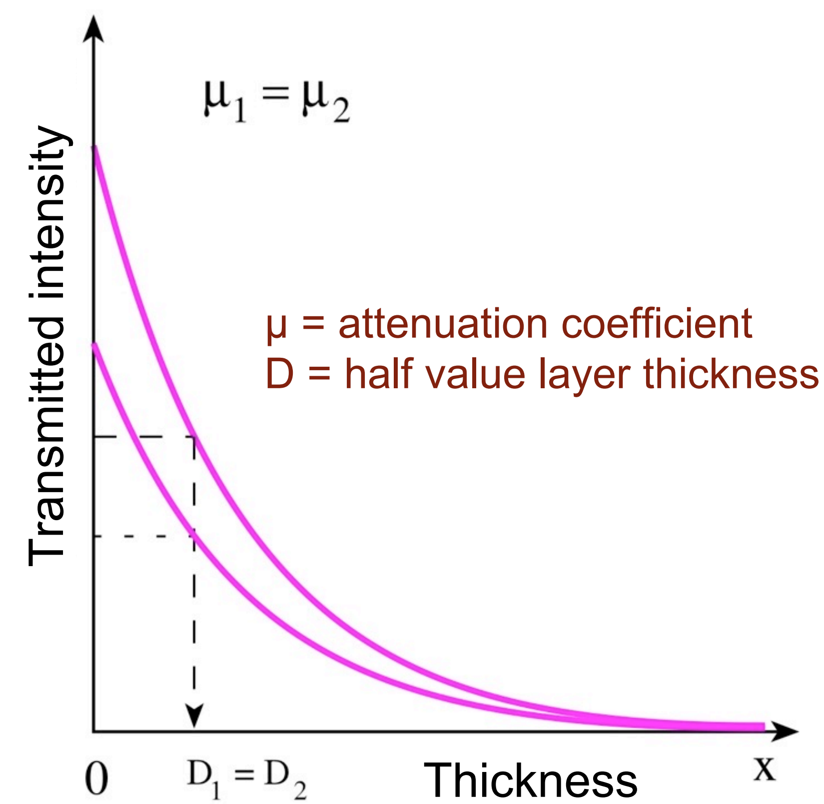
Properties of ΔJ:

$\Delta J \sim J_{in}$

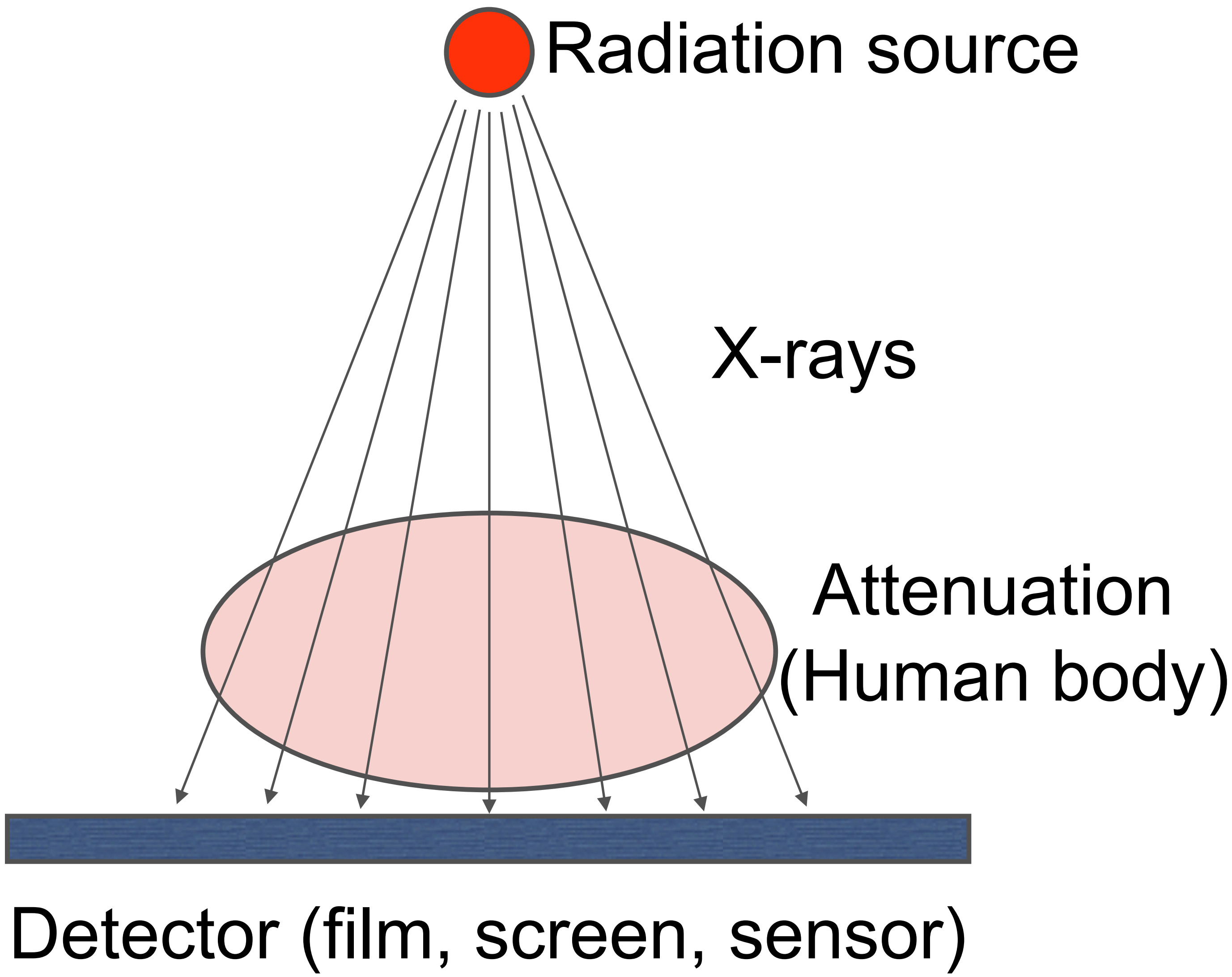
$\Delta J \sim \Delta x$

$\Delta J \sim \mu$

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



Medical relevance



Chest x-ray

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