

# Introduction to Medical Biophysics

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inspired by prof. Miklós Kellermayer

# Objectives and methods of medical biophysics

## Objectives:

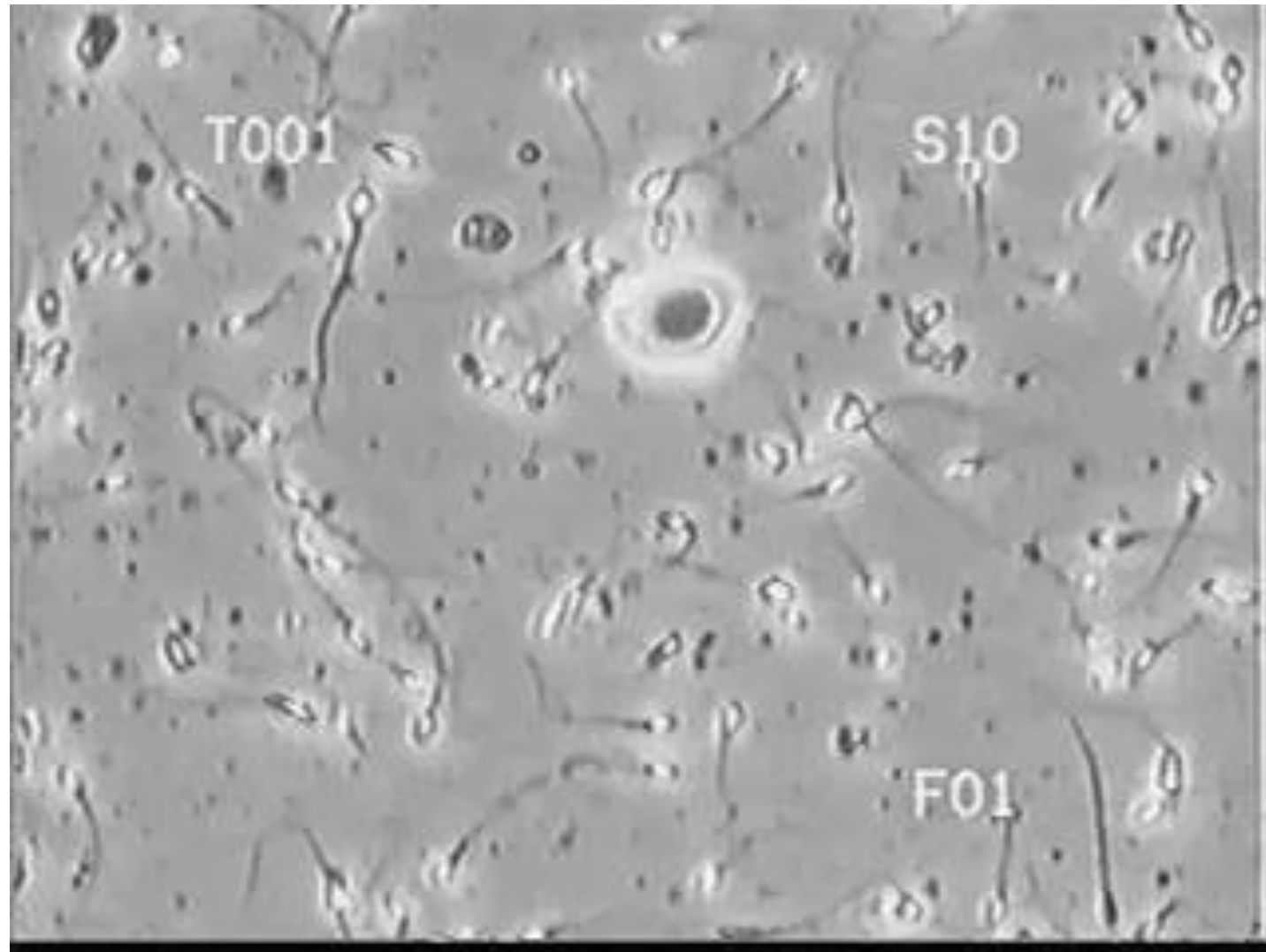
1. Provide a *physical* “description” of biomedical phenomena
2. Discuss and understand *physics*-based medical techniques

## Methods:

Biomedical phenomena and processes are

1. quantified
2. simplified

# 1. Physical description of a biological phenomenon



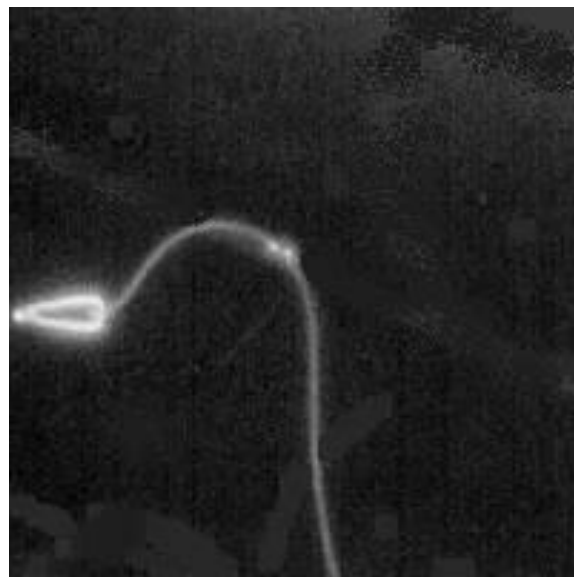
## Questions we might ask:

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

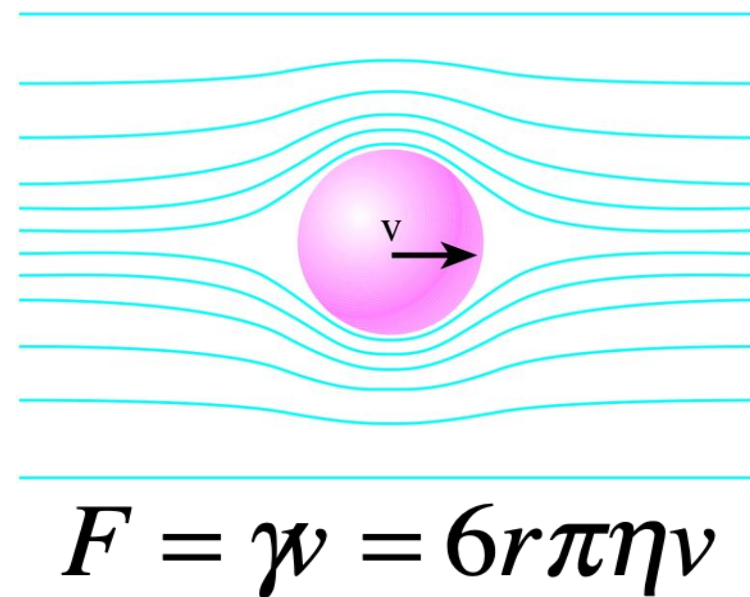
# Drag coefficient of the spermatoocyte

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

Simplified spermatoocyte model:  
object with circular cross-section



Stokes' Law:



Friction  
coefficient:

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

Force:

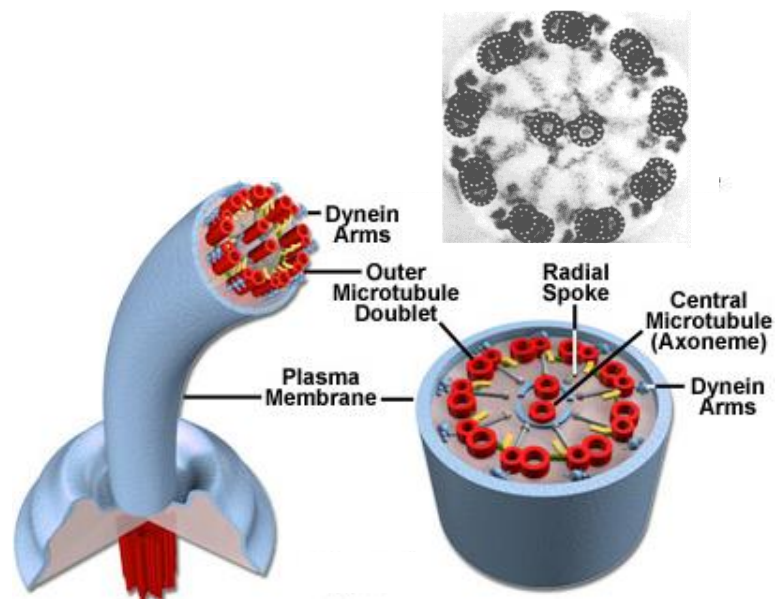
$$F = \gamma = 3 \times 10^{-8} Ns/m \cdot 5 \times 10^{-5} m/s = 1.5 \times 10^{-12} N = 1.5 pN$$



# Mechanisms behind spermatoocyte motility?

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

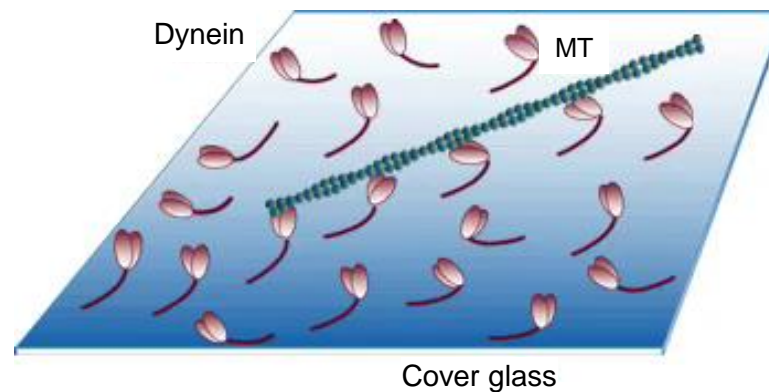
Structure of the sperm flagellum



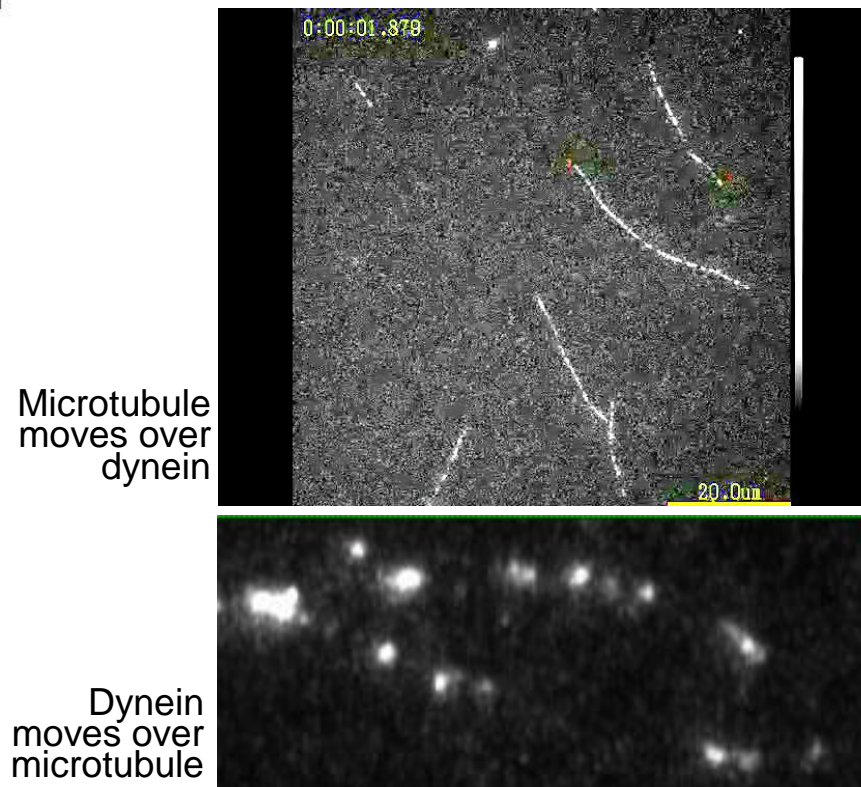
N.B.:

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

Functional test:  
“*In vitro* motility assay”



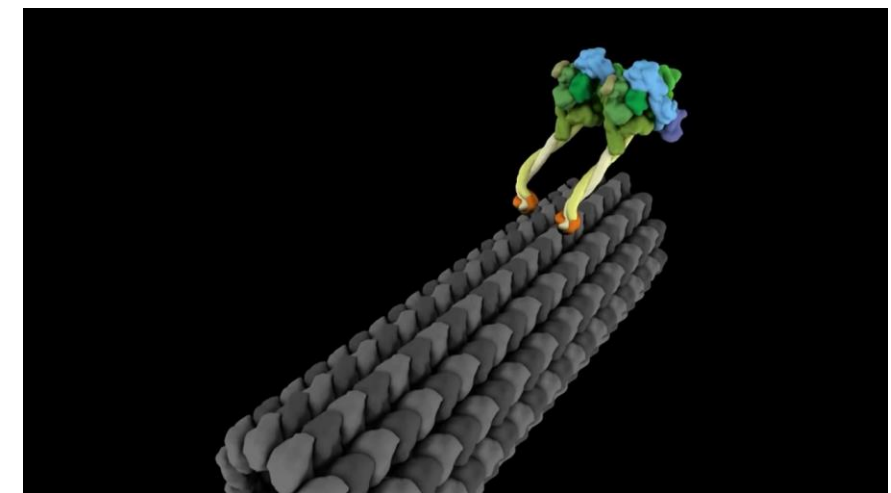
Fluorescence microscopy



Microtubule moves over dynein

Dynein moves over microtubule

Predictive model



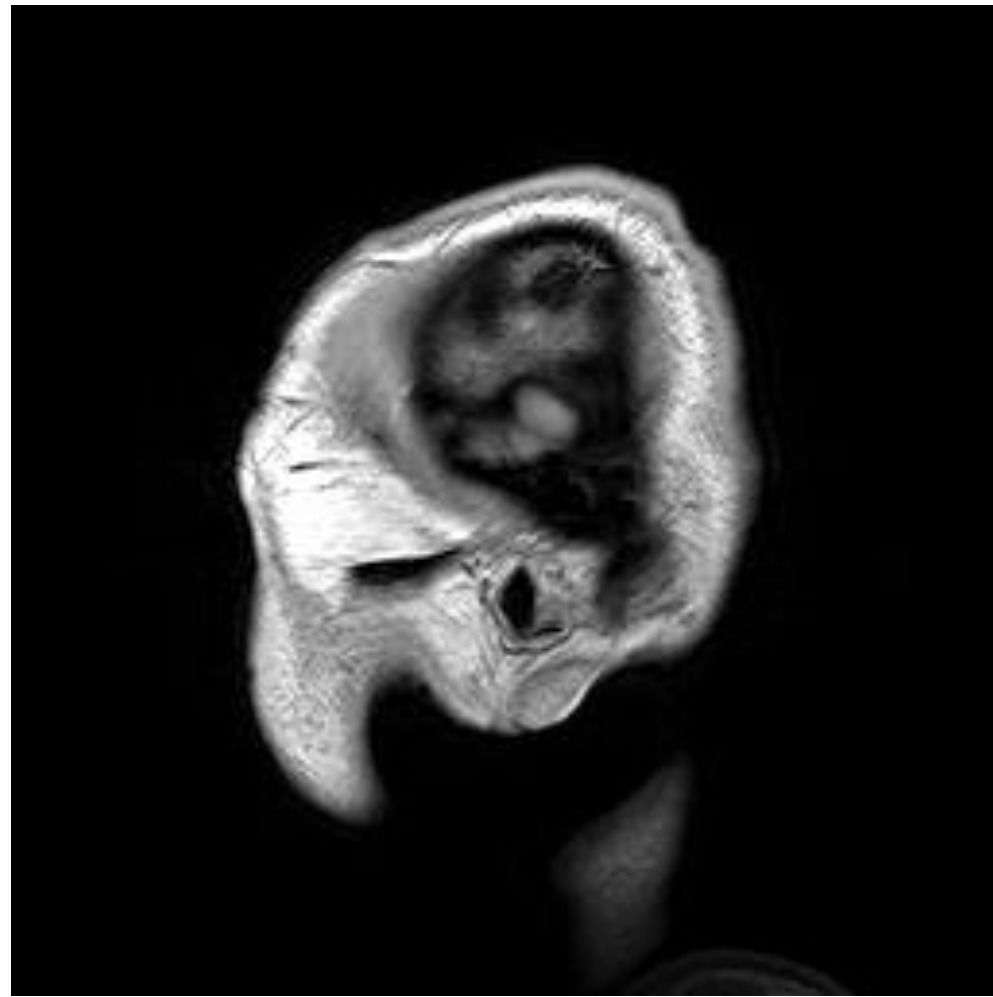
“Drunken sailor” stepping mechanism

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:**

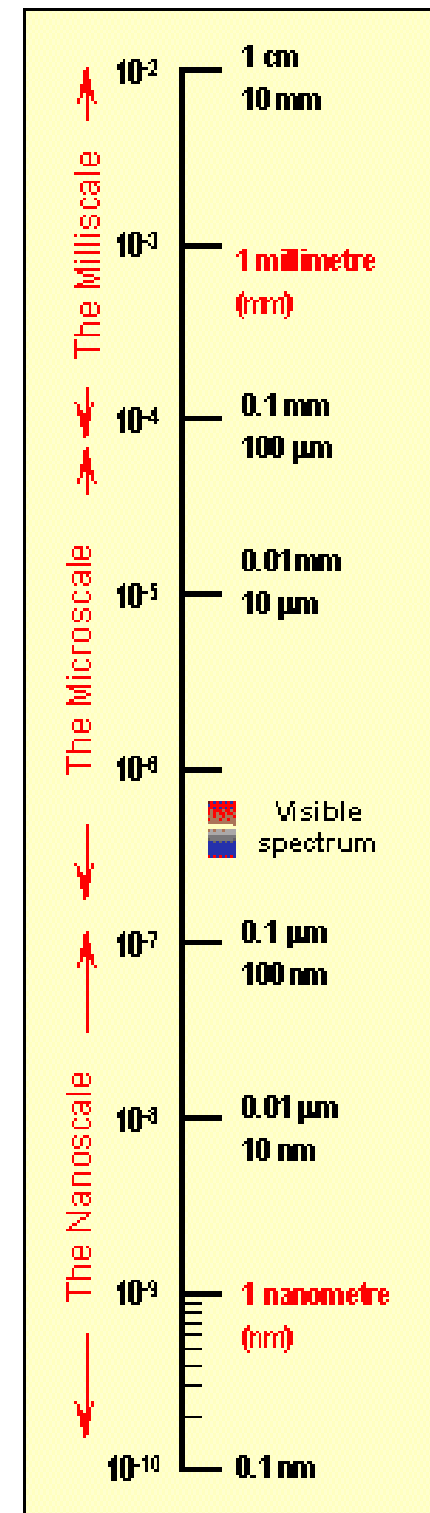
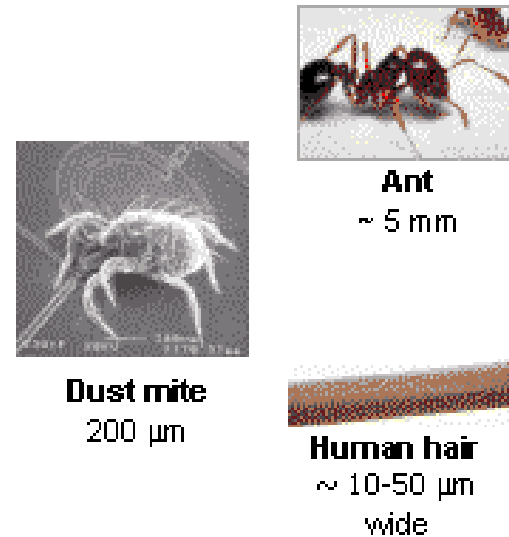
1. **What is this?** (Magnetic Resonance Imaging)
2. What **physical phenomena** are utilized? (magnetism, radiations, absorption, emission)
3. What can MRI reveal about the **human body**? (**structure, function, tissue composition**)

# 1. Quantify....

## Dimensions of Living Systems

Thermodynamics

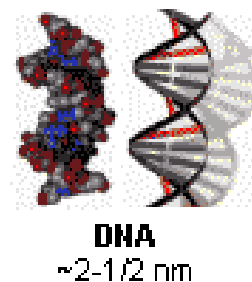
$10^{23}$   
Atoms



$10^{10}$   
Atoms

Mesoscale

Red blood cells with white cell  
~ 2-5  $\mu\text{m}$

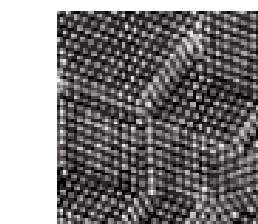


$10^3$   
Atoms

Quantum chemistry

Quantum physics

$10^1$   
Atoms



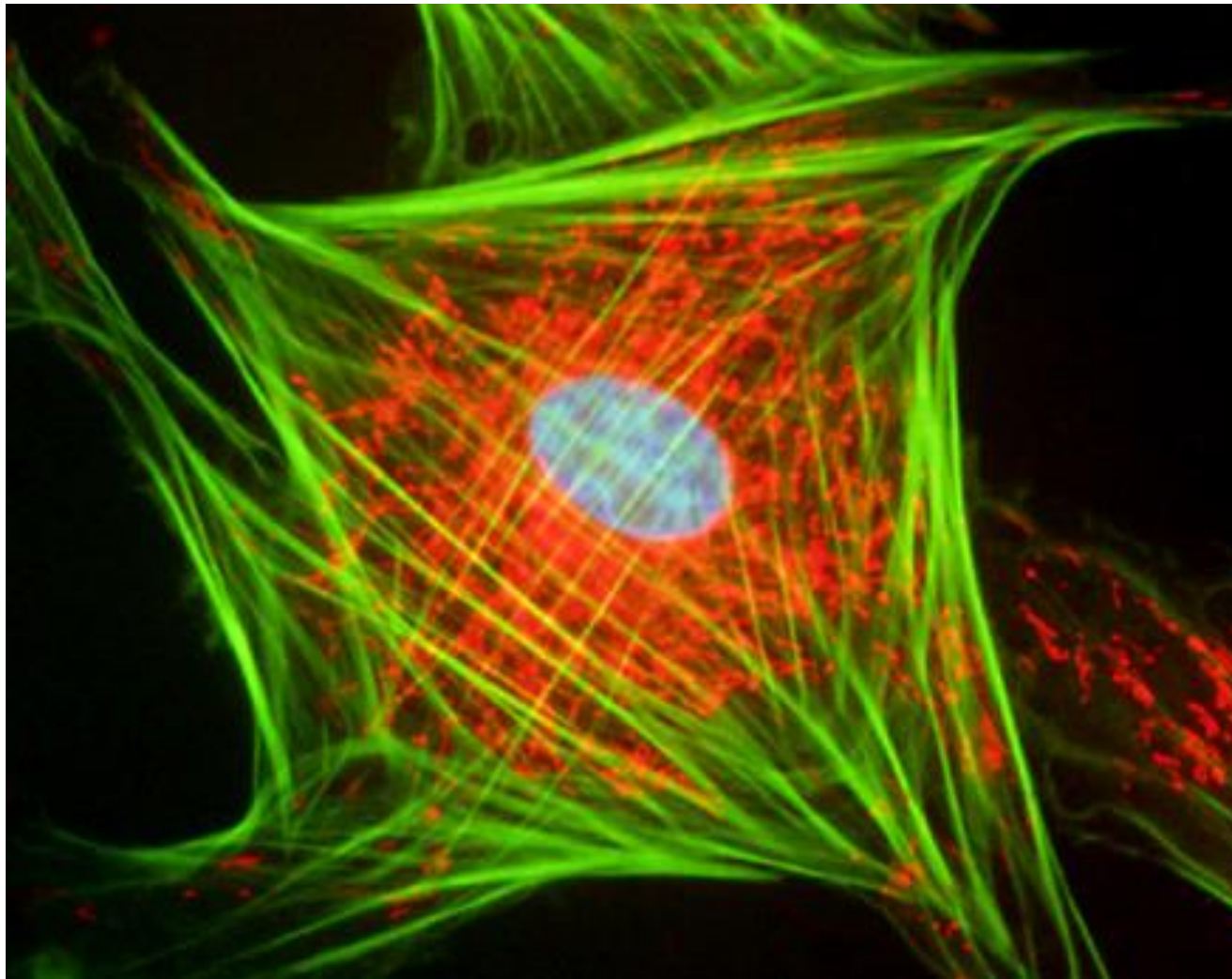
5 Atoms of silicon  
1 nm

$10^0$  Atom

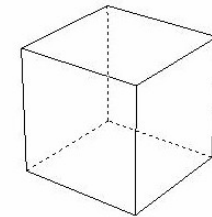


## 2. Simplify...

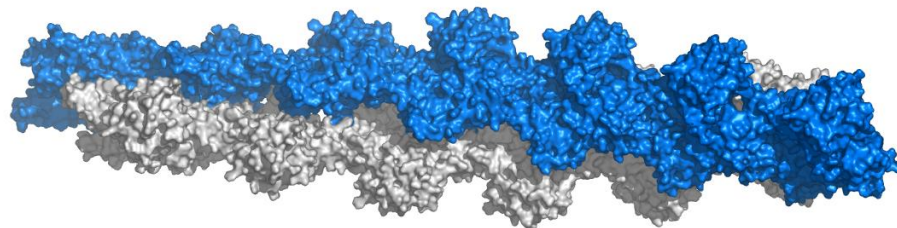
# Model of the cell... and of a molecule...



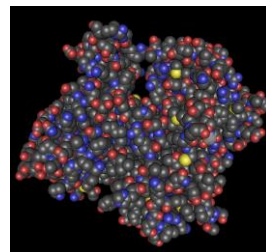
Simplified cell  
model: cube



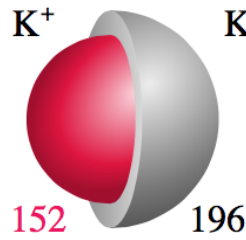
	<b>Cell:</b> cube with 20 $\mu\text{m}$ edge	Analogue - <b>Lecture hall:</b> cube with 20 m edge
Size of actin molecule	5 nm	5 mm
Number of actin molecules	~500 thousand	~500 thousand
Average distance between actins	~250 nm	~25 cm
Size of potassium ion	0.15 nm	0.15 mm
Number of potassium ions	$\sim 10^9$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



Actin filament ( $d=7$  nm)



G-actin  
( $d=5$  nm,  
 $cc \sim 100 \mu\text{M}$ )



Potassium ion  
( $d=0.15$  nm,  
 $cc \sim 150$  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.



Complexity

# Radiation is everywhere

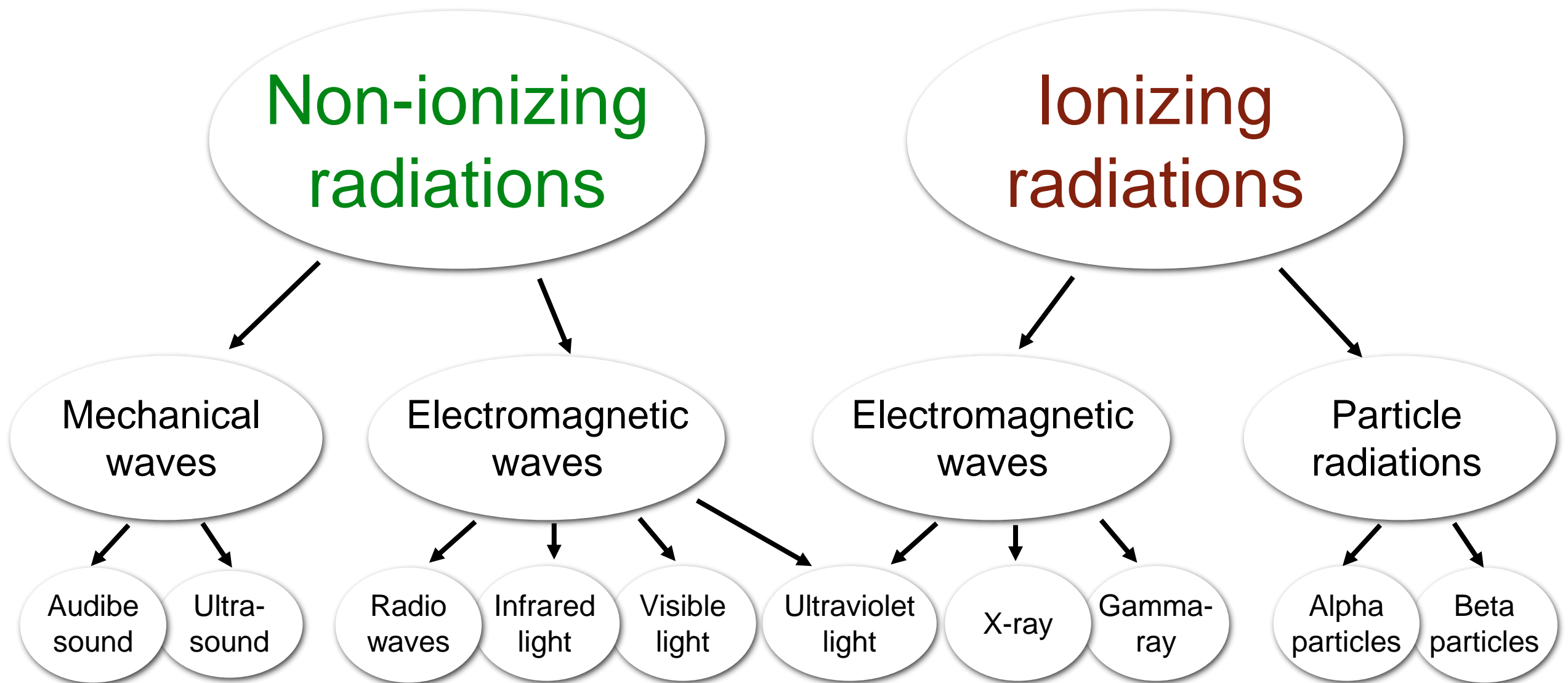


Emission spectrum of the H-atom



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,  $E$ :

$$[E] = \text{J (Joule)}$$

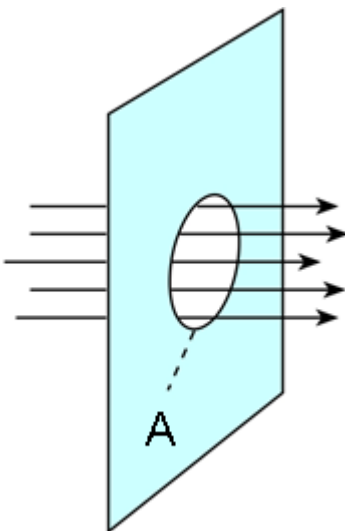
Radiant flux; radiant power:

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

$$[P] = \text{W (Watt)}$$

$\Delta E$ : energy carried during  $\Delta t$  time

Radiant intensity



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

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

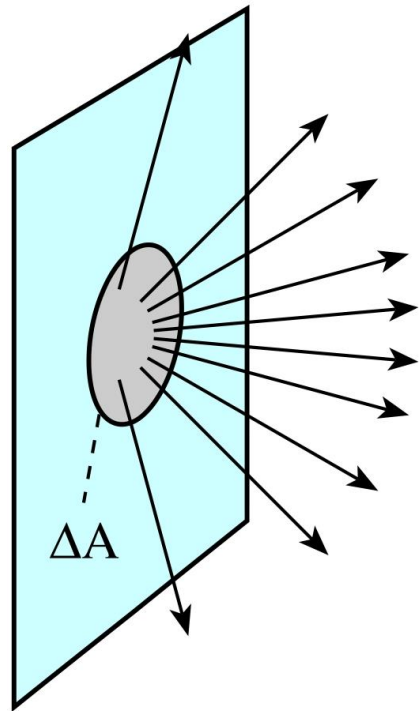
$A$ : area (perpendicular to the direction of energy propagation)



# Parameters of radiometry

## Radiance

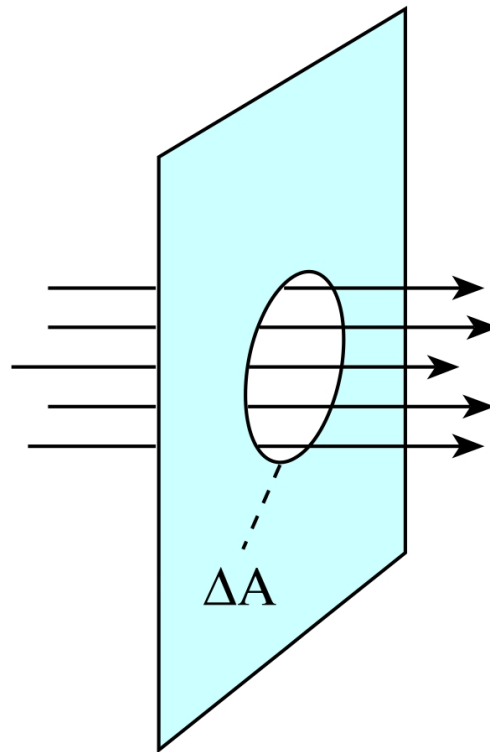
$$M = \frac{\Delta P}{\Delta A} \left[ \frac{\text{W}}{\text{m}^2} \right]$$



Power radiated by unit area into a solid angle of  $2\pi$ .

## Radiation intensity

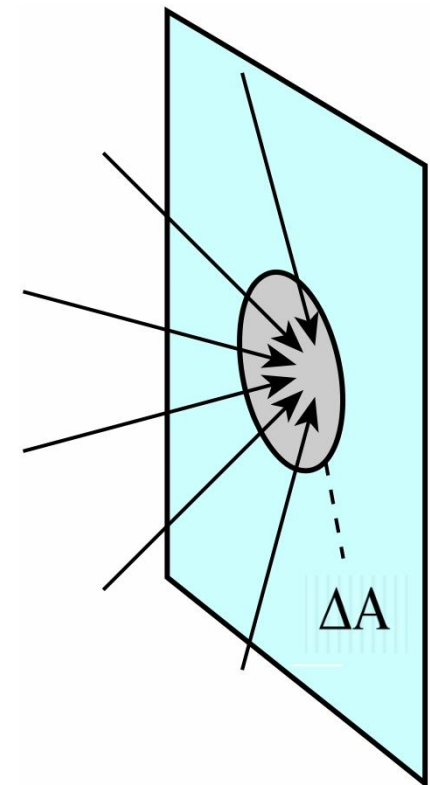
$$J_E = \frac{\Delta I_E}{\Delta A} \left[ \frac{\text{W}}{\text{m}^2} \right]$$



Power propagating through unit area.

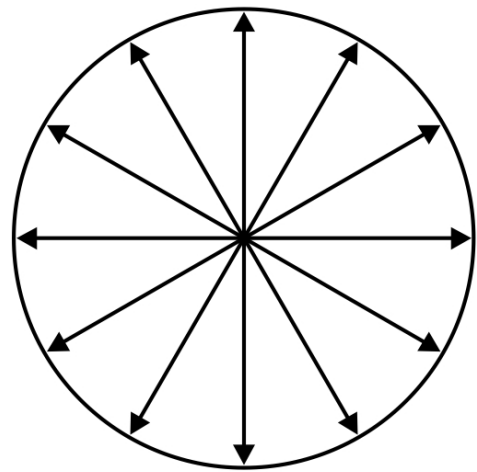
## Irradiance

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

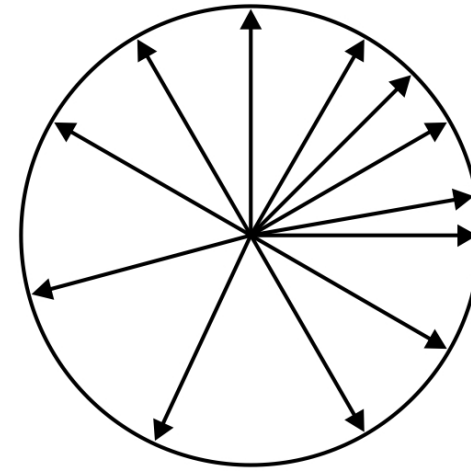


Power incident on a surface of unit area (radiation may arrive from all directions). (other symbol  $E_{inc}$ )

# Directionality of radiation



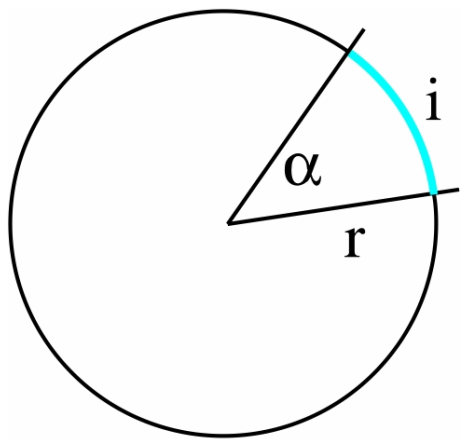
isotropic  
source



anisotropic  
source

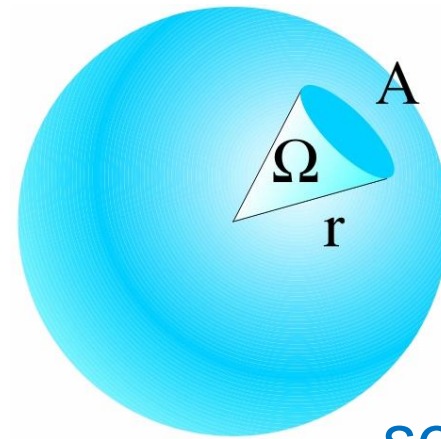
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## Radian, steradian



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

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

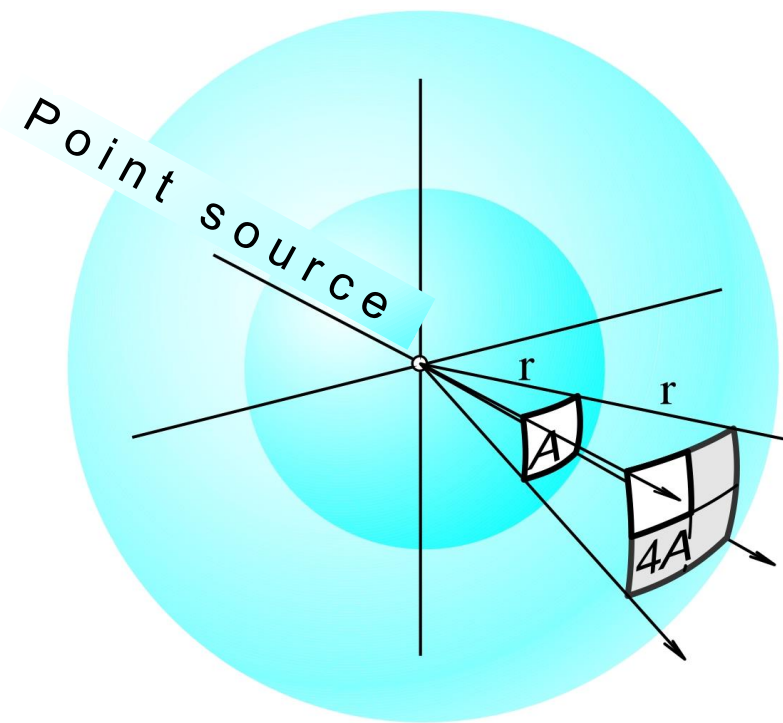


$$\Omega = \frac{A}{r^2}$$

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

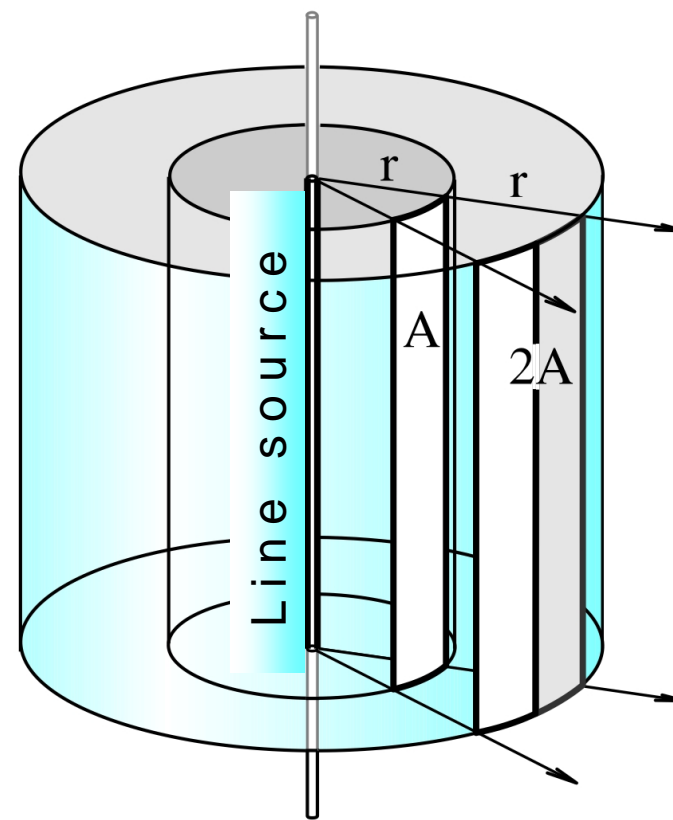
# Radiant intensity as a function of the geometry of radiation source

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



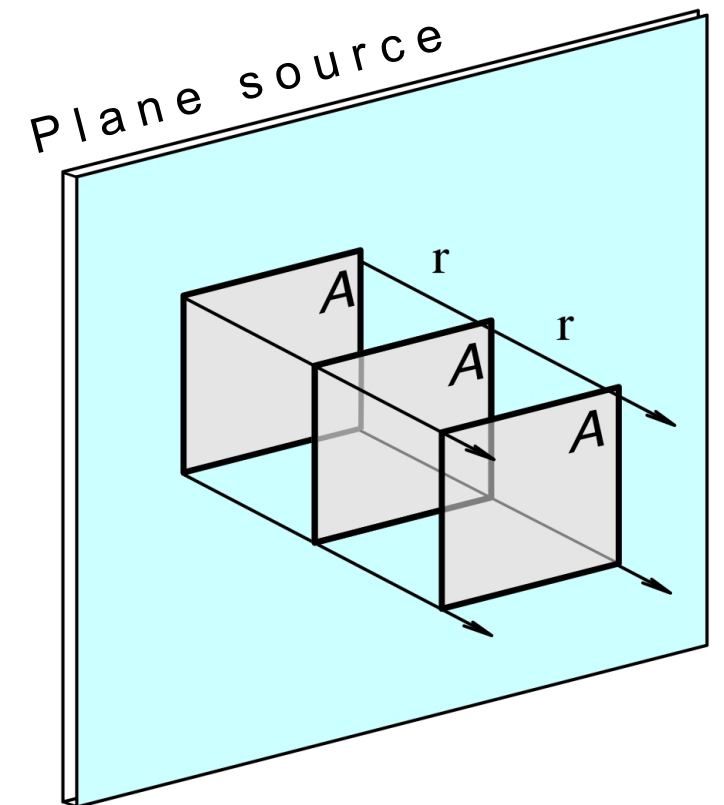
$$A_{\text{sphere}} \sim r^2$$

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



$$A_{\text{cylinder}} \sim r$$

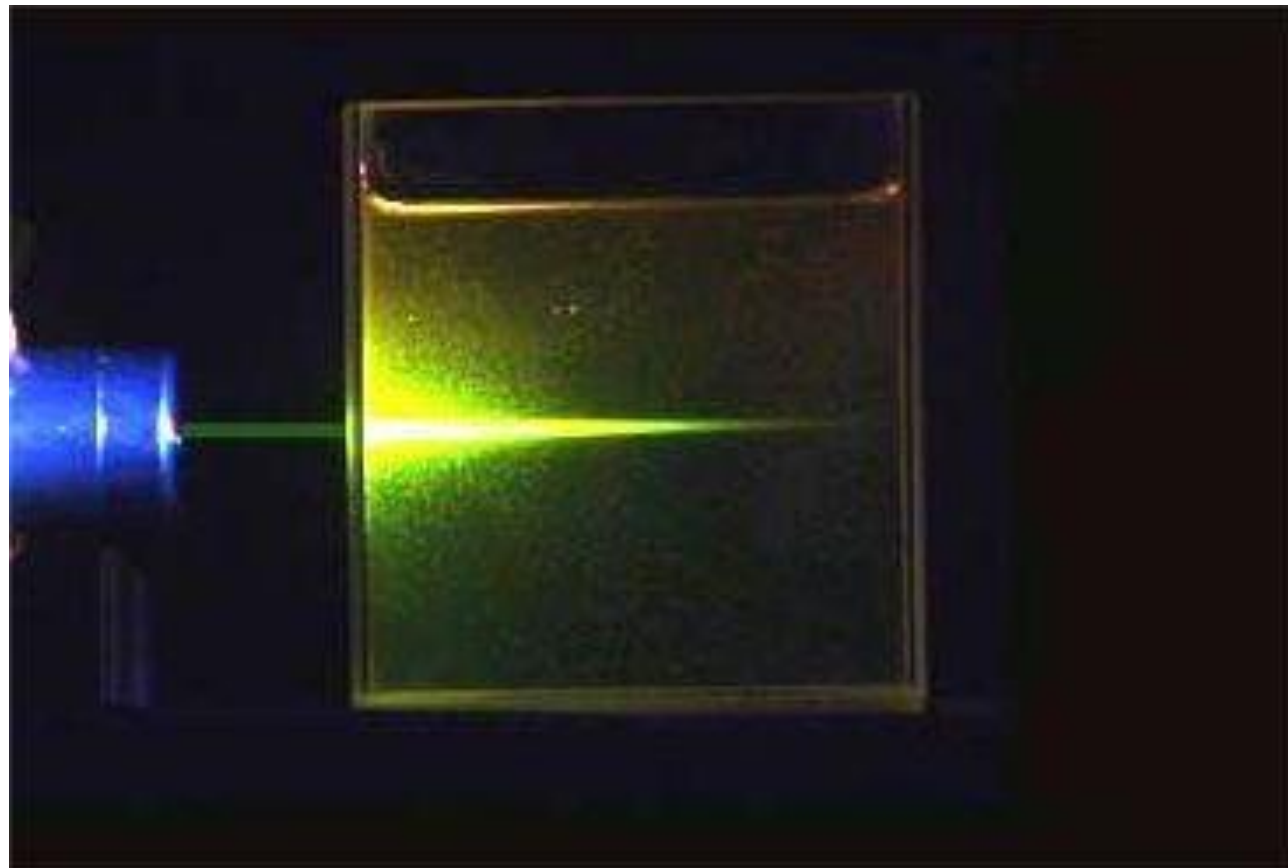
$$E_{\text{inc}} \sim 1/r$$



$$A = \text{constant}$$

$$E_{\text{inc}} = \text{constant}$$

# As radiation travels through matter, its intensity decreases

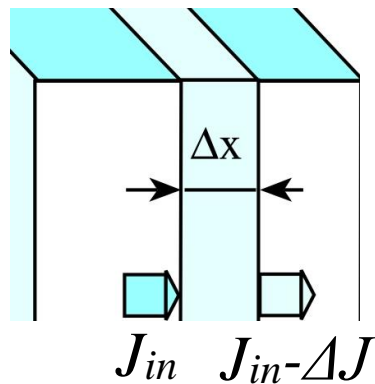
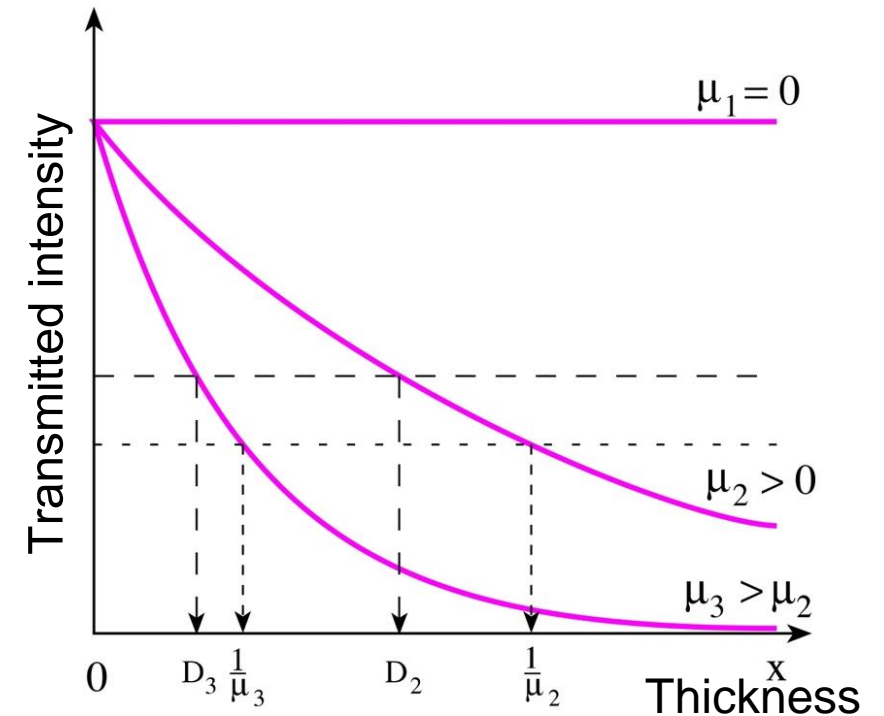
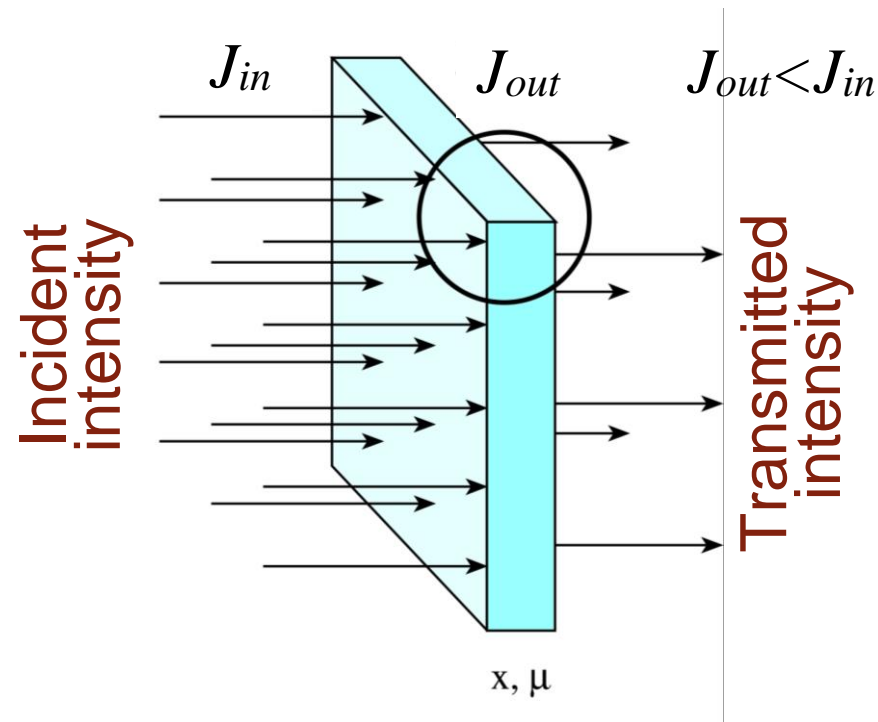


(Radiation that exits is weaker than the one that enters)

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



# General radiation attenuation law



A given quantity ( $J$ ) and its change ( $\Delta J$ ) are proportional:

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



Exponential function:

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

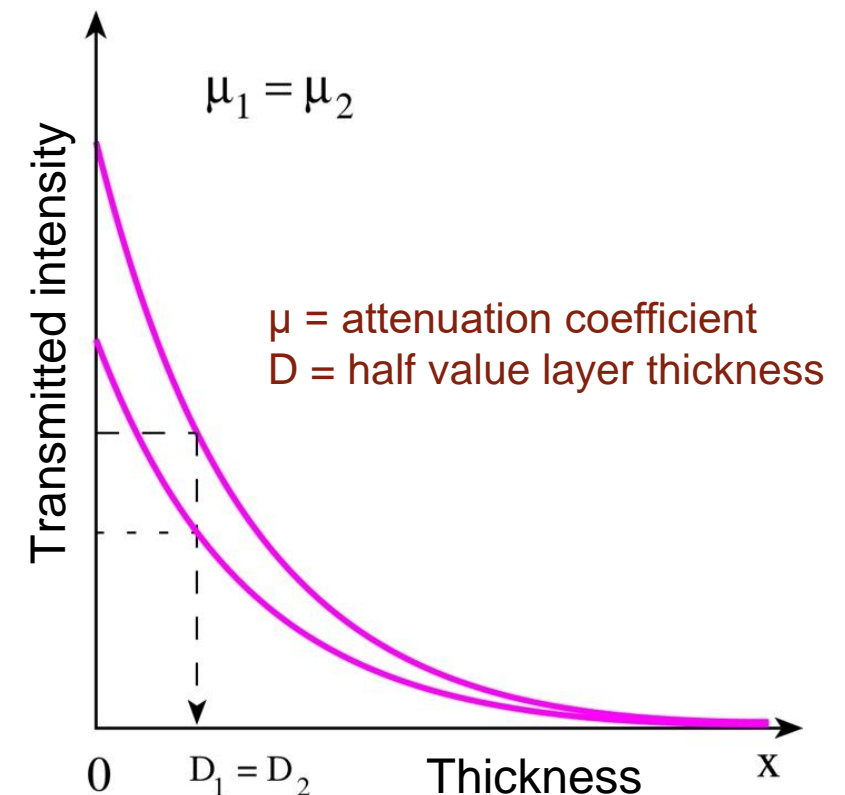
$$J = J_0 \cdot e^{-\mu x}$$

Properties of  $\Delta J$ :

$$\Delta J \sim J_{in}$$

$$\Delta J \sim \Delta x$$

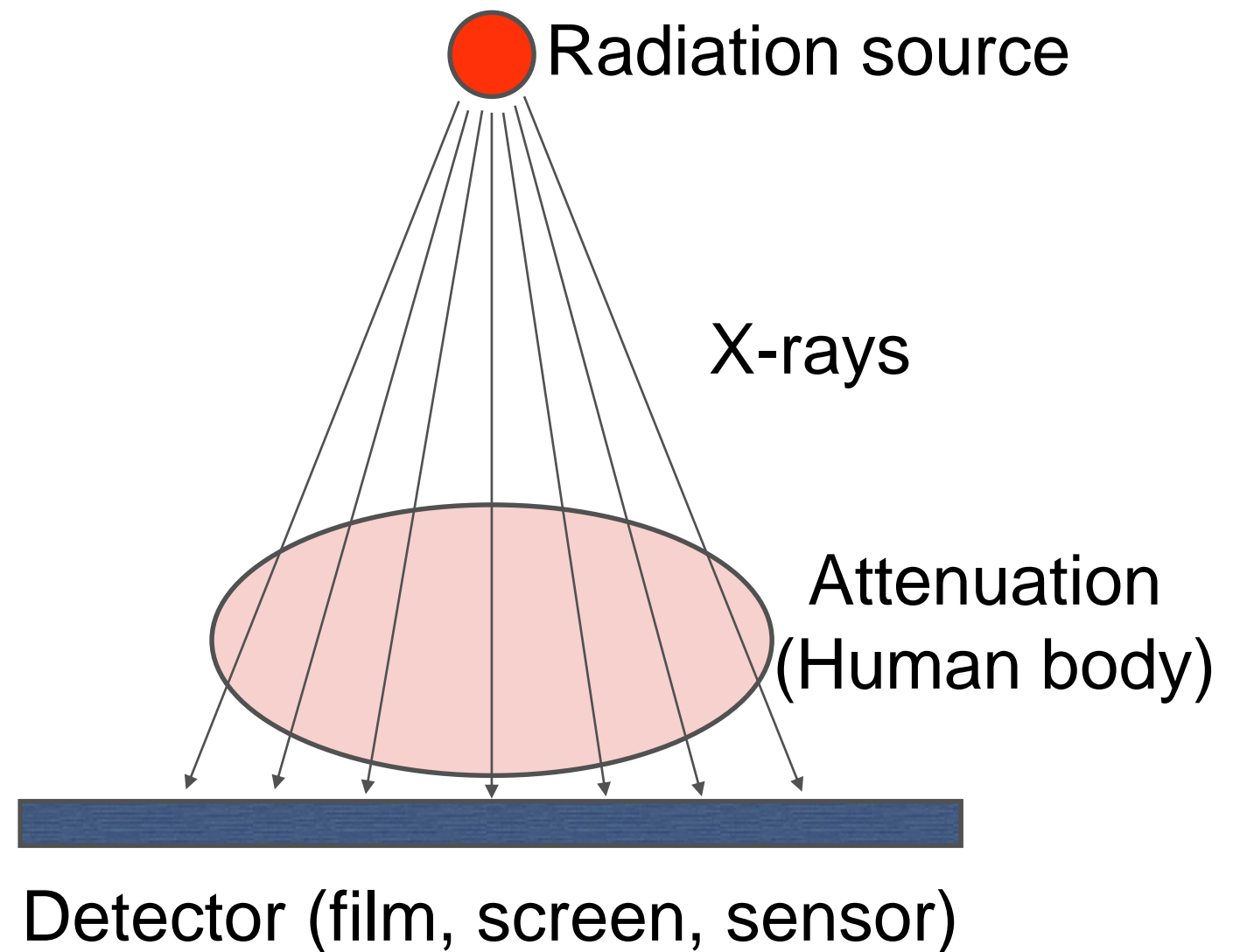
$$\Delta J \sim \mu$$



# Medical relevance



Chest x-ray



# FEEDBACK

