MATR332 Physics of Biological Physics

University of Helsinki, Spring 2023
Examination: March 09, 2023 (5 exercises; maximum number of points is 30)

As to background information that is allowed during the examination:

- **MAOL or a guide with similar content is not allowed**
- **A sheet of notes ("lunttilappu") is not allowed**
- **Calculator is ok**

Questions are in English but you can write down your answers in English or Finnish.

Assignment 1 [max. 10 points]

Please consider the below statements and conclude whether they are true, or not. Further, *justify your reasoning.*

a) In a system under consideration, there is salt dissolved in a water liquid, interacting with a solid surface. The sodium ions of the salt are adsorbed (attached) to the charged surface. The temperature of the system is low, around 10 degrees Celsius. Now, if the system temperature is allowed to increase to reach room temperature (around 20 degrees Celsius), then changes in this system are capable of producing mechanical work.

b) Consider a medium-sized fish swimming in a lake. Suddenly, as this medium-sized fish eats a small-sized fish as one mouthful, it becomes a Huge fish: its size increases by 50%, but at the same time the velocity of the fish decreases by 50%. Despite these changes, the Reynolds number characterizing the motion of the fish remains constant.

c) You are working on your MSc thesis project. One of the tasks you need to do is to separate selected molecules (type A) from the other molecules (type B, C, ...) in this solution. To do this, you use sedimentation, and it works very well.

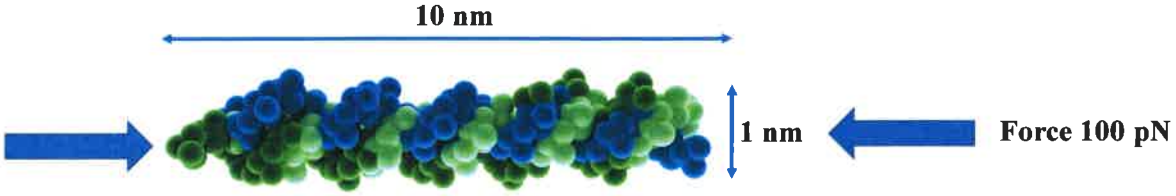
d) Consider molecules found on planet X in liquid nitrogen at a temperature of +73 K. Assuming that the forces between the molecules under these conditions on planet X are similar to forces in liquid water at +37 degrees Celsius on planet Earth, then this implies that on Earth these molecules would be almost 10 times bigger than on planet X.

e) You plan to use the equation of state of the ideal gas model to describe the behavior of a weakly interacting system, as the system temperature approaches zero Kelvin. Your 80-year-old grandmother (who has PhD in physics) says that "no chance, never going to work out". Your grandmother is right.

Assignment 2 [max. 5 points]

Collagen (see the attached image) is an important protein found, e.g., in connective tissue such as skin and bone. Its width (thickness) is about 1 nm, and its length is about 10 nm. It is quite rigid that is characterized by its Young modulus $K = 2$ GPa. If we apply a force of 100 pN on this molecule, then how much will the length of this molecule change?

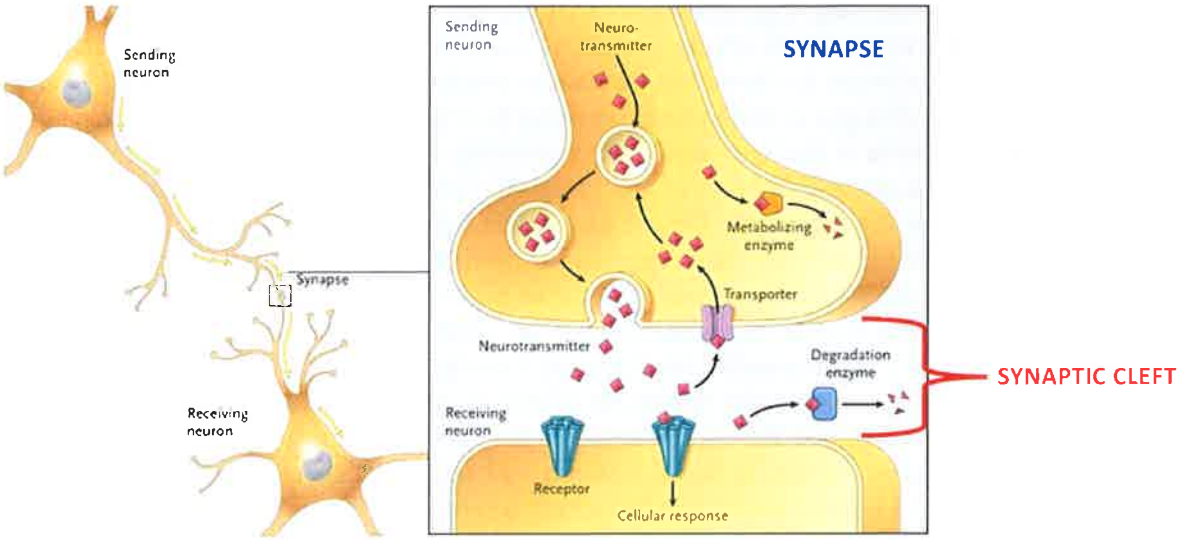
[Hint: The Young's modulus (E) is a property of the material that tells us how easily it can stretch and deform and is defined as the ratio of tensile stress (σ) to tensile strain (ε). where stress is the amount of force applied per unit area ($\sigma = F/A$) and strain is extension per unit length ($\varepsilon = dl/l$).]



Assignment 3 [max. 5 points]

When we decide to run, we must activate our muscles. The request for activation starts from our brain and propagates as a nerve impulse, and to activate the muscles in the feet, at least one meter of nerve propagation has to take place. This is not an immediate process, since even the best athletes have latency times of about 100 ms. One of the bottlenecks, slowing down nerve propagation, is to cross the synaptic cleft in a synapse (see the attached figure), since in nerve propagation the signal is transmitted by neurotransmitters that must cross the synaptic cleft. Their diffusion coefficient is about $D = 10^{-5}$ $\mathrm{cm^2/s}$, and it seems obvious that the diffusion length that neurotransmitters should move in time t is therefore 50 nm.

Based on these pieces of information, estimate the time it takes for neurotransmitters to cross the synaptic cleft. Is it a significant portion of the latency time?
[Hint: What are the dimensions of the diffusion coefficient? Length squared over time.]

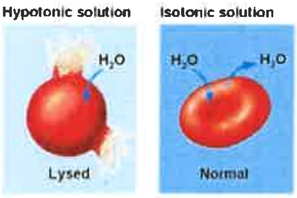


Assignment 4 [max. 5 points]

1. During the course we discussed how bacteria and fish swim, and how their swimming depends on the Reynolds number. Now, estimate how fast (or slowly) should you swim in water so that you would not have to care about inertia (such that friction would dominate how you move)? Keep again in mind that the viscosity of water is 1×10^{-3} $\mathrm{Ns / m^2}$, and now the temperature is 293 K.
2. Consider two imaginary polymers. Polymer A has a persistence length of 50 nm. Polymer B has a persistence length of 2 nm. Now imagine that you could grab the polymer at two points separated by 10 nm and bend it. Which polymer would be easier to bend and why? If you would use these two polymers as models for single- and double-stranded DNA, which one would be a better model for which? Why?

Assignment 5 [max. 5 points]

How much osmotic pressure (osmotic imbalance) does the cell membrane surrounding a cell withstand? To address this question, let us consider a cell exposed to an environment where there is a lower concentration of osmolites than inside the cell. Under these circumstances, water will flow through the membrane into the cell until the cell swells to a spherical shape, and further, if the concentration gradient of osmolites is large enough, the cell lyses (ruptures) and then reseals again due to line tension (see the attached figure: transition from isotonic to hypotonic conditions). The question is, what is the largest osmotic imbalance (in units of moles/liter, or number of particles/m^3) which the cell can withstand without rupture?



Hints:

- The stretch modulus of the cell membrane is $K = 0.16$ J/m^2.
- Lysis occurs when the cell membrane area is expanded by 2%.
- The area of the cell membrane is 150 μm^2.
- Please recall that membrane tension is the force per unit length acting on the cross-section of membrane, and the force arising from membrane tension must oppose the force arising from osmotic pressure.
- Look at the units of stretch modulus.

These might be useful:

Taylor expansion

$\sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!}(x-a)^n$

Boltzmann constant $1.380662 \cdot 10^{-23}$ J / K

1 amu = 1.66×10^{-27} kg (atomic mass unit)

Avogadro's number $6.022 \cdot 10^{23}$ 1/mol

permittivity of vacuum $8.85 \cdot 10\ ^{12}$ F/m (or coul^2/Nm^2)

permittivity of water $\approx$ 80 times that of a vacuum

charge on a proton $1.6 \cdot 10^{-19}$ coul

viscosity of water $\eta = 10^{-3}$ kg / ms

viscosity of syrup $\approx$ 3000 times that of water

mass density of syrup $\approx$ 1.4 times that of water

$\int_{-\infty}^{\infty} e^{-ax^2} \mathrm{d}x = \sqrt{\pi}$

$\log_a x = \frac{\log_b x}{\log_b a}$

$\frac{\mathrm{d}y}{\mathrm{d}t} + Ay = B$, where A, B are constants, is solved by $y = y(t_0)e^{At_0}e^{-At} - \frac{B}{A}e^{At_0}e^{-At} + \frac{B}{A}$ (t_0 = initial time)

Elementary charge:
e is about $1.6021766208(98) \times 10^{-19}$ C