2.9.2024

Exercises for Module BIO1 – The physical principles of life

Question 1:

a) Estimate how much ATP your body produces every day. Base this estimate on a daily energy uptake of 2000 kcal, and assume that about half of this energy is converted into ATP. It takes about 30 kJ/mol to synthesize ATP from ADP and phosphate. How does this amount of ATP compare to a typical human body weight? How is this possible?

Question 2:

Neurotransmitters are small molecules that are used by higher organisms to transmit signals, for example between nerve cells and muscle cells. They have diffusion coefficients of the order of 10^{-9} m^2/s.

a) How long does it take for a molecule of dopamine (a type of neurotransmitter) to diffuse through the space between two brain cells ("synaptic cleft"), which is approximately 20 nm? How long to diffuse through a nerve cell (ca. 100 µm diameter)?

b) A typical protein molecule has a diameter that is approximately 10 times larger than a dopamine molecule. What is the diffusion coefficient of such a protein molecule? How long does it take for this protein to diffuse the distances in a) (20 nm and 100 µm)?

c) You play football and decide to kick the ball. Your brain releases a spike of neurotransmitters. How long would it take for these neurotransmitters to diffuse from your brain to your leg? Do you think this is how your brain communicates with your leg? If not, how does it do it?

d) Chemotaxis. This question is taken from the book "Physical Biology of the Cell" by Rob Phillips. Bacteria use swimming to seek out food. Imagine that the bacterium is in a region of low food concentration. For the bacterium to profit from swimming towards a region of more food, it has to reach there before the diffusion of food molecules makes the concentration in the two regions the same. Here we find the smallest distance that a bacterium needs to swim so it can outrun diffusion. Using Python, make a plot of the distance travelled by the bacterium as a function of time, at a velocity of v=30µm/s. Plot on the same figure the diffusion distance as a function of time (D = 5e-10 m^2/s). Starting from what distance does it make energetic sense for the bacterium to swim towards the food? Bonus question: How many sugar molecules would the bacterium need to find at its destination in order for this trip to be worth its effort? Assume for this estimate that the bacterium is a sphere with 1 µm radius, and that the expended energy is solely dissipated by drag forces.

Question 3:

Organisms can live even under very high stress environments, such as in saturated salt solutions (see Figure below). Under such conditions, the water molecules inside the cell have a very high tendency to flow out of the cell as they try to “dilute the salt solution in the environment”, which is a pretty hopeless undertaking...

Figure 2: Algal blooms turn a salt lake in China red and purple.

a) Calculate the osmotic pressure of a saturated sodium chloride solution at 25°C, (26.3% by weight, density 1.202 kg/l) assuming that it behaves like an ideal solution.

b) How do you think microorganisms living in such conditions (e.g. dead sea) can adapt?

Question 4:

The highest trees in the world are the coastal redwoods of Northern California, which can reach heights of well above 100 m. The fundamental limit on how high a tree can grow is given by the need to transport water with dissolved nutrients all the way up to the top of the tree. Capillary action plays an important role in this transport. Jurin's law describes the maximal height of a liquid column inside a thin capillary under the action of gravity.
a) Plug reasonable numbers for the properties of water (surface tension, density) into the equation for Jurin's law. Assume a contact angle $\Theta \approx 0$, i.e. a very hydrophilic surface. What is the characteristic length (or rather thickness) scale for the thinnest capillaries you obtain from your calculation?
b) What other physical processes play a role in the water transport in very tall trees?

Question 5:

Blood flow. Here we will estimate the average blood flow velocity through a thin capillary (diameter 5 µm). The pressure drop is ca. 3000 Pa per cm through such a capillary. Use the formula of the average flow rate (volume/time) from the lecture slide and the viscosity of water (0.001 Pa s) to calculate the average flow speed (m/s) of blood through such a capillary. The actual measured rate is 0.5 mm/s. Comment on the difference.