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Biology 3550
Physical Principles in Biology
Fall Semester 2016

Final Exam
12 December 2016

100 points total
Be sure to show your work, convert your answers to decimal form and include correct units in all of your answers!

1. (15 pts) Two students, Bob and Alice, are studying probability by flipping coins.

   (a) Each student flips the same coin 10 times. Bob sees the following sequence of outcomes, where "h" represents heads and "t" represents tails:

   `h-t-h-h-t-t-h-t-h-t`

   while Alice sees:

   `h-h-h-h-h-h-h-h-h-h`

   Assuming that the coin is "honest", which, if either, of these two outcomes is more likely? Explain your reasoning.

   (b) After the last of her coin flips shows heads, Alice offers Bob a bet: If the next flip comes up heads, she will pay Bob \$2, but if it comes up tails, Bob will pay Alice \$1. Should Bob accept this bet (assuming that everything is on the up-and-up)? Why or why not?

Name:________________________________

(c) For a sequence of 10 coin flips, what is the probability of seeing 10 heads in a row?

(d) What is the probability of seeing 5 heads and 5 tails, in any order?

2. (20 pts) At this time of year, many homes are permeated with the scent of pine trees, a scent that comes largely from pinene, a bicyclic terpene with a molecular mass of 136 Da. For the following, assume that the diffusion coefficient of pinene through air is $5\times10^{-6}\,\mathrm{m^2/s}$ and that the room in question has a temperature of 25°C.

(a) Calculate the RMS velocity of a pinene molecule at 25°C.

Name:________________________________

(b) Calculate the average distance traveled by a pinene molecule between collisions with other molecules in the atmosphere.

(c) Calculate the time, in hours, that a pinene molecule would have to diffuse in order for the RMS distance traveled along a specific direction to be 5 m.

Name:______________________________

(d) Is the time you calculated in part b consistent with your real-life experience? Why or why not? If your experience is not consistent with the time that you calculated, suggest an explanation for the discrepancy.

3. (15 pts) At chemical synapses, neurotransmitters are released from a neuron and diffuse across the synapse and bind to receptors on either another neuron or a muscle cell. Before being released, the neurotransmitters are stored in vesicles within the pre-synaptic neuron. For this problem, assume that the vesicles have a diameter of 50 nm and that the concentration of neurotransmitters within the vesicles is 200 mM.

(a) Calculate the number of molecules stored within a single vesicle.

(b) If the concentration of neurotransmitters in the cytoplasm of the pre-synaptic cell (outside of the vesicles) is 10 mM what is the entropy change for increasing the concentration within one vesicle from 10 mM to 200 mM?

(c) What is the minimum amount of work required to increase the neurotransmitter concentration in one vesicle from 10 mM to 200 mM, at 37°C?

4. (15 pts) Suppose that the vesicle described in the previous problem contains a pore that, when open, allows the neurotransmitter to diffuse across the membrane. Assume that the diameter of this pore is 5 nm and that its length is 4 nm. As specified in the previous problem, the concentration of neurotransmitters inside the vesicle is 200 mM and the concentration outside the vesicle is 10 mM. The diffusion coefficient of the neurotransmitter is $3{\times}10^{-10}\,\mathrm{m}^2/\mathrm{s}$.

(continued on the next page)

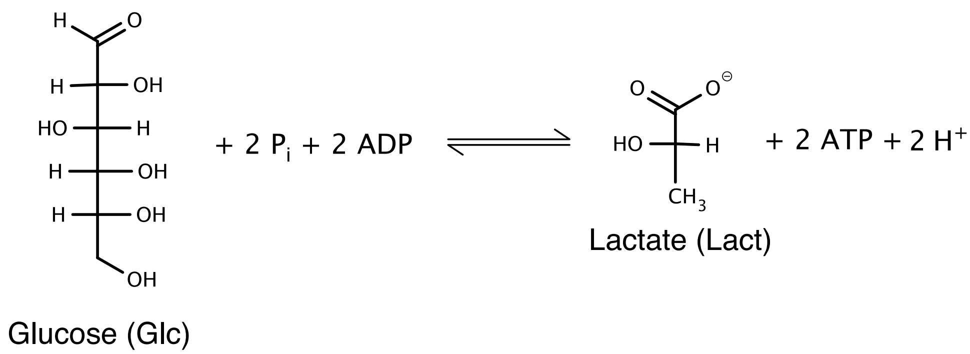
Name:______________________________

(a) Calculate the flux, J, of molecules diffusing out of the vesicle through one of the pore, when it is open.

(b) Estimate how long it would take for the concentration inside the vesicle to drop to that outside the vesicle if this pore were to open.

Name:____________________________

5. (20 pts) During periods of intense activity, the muscles of animals are unable to produce enough ATP through aerobic metabolism and instead rely on glycolysis to metabolize glucose and then convert pyruvate, the normal product of glycolysis, to lactate. The overall reaction for this process is shown below:



At pH 7 and 25°C, the standard free energy change ($\Delta G°$) for the overall reaction is -130 kJ/mol and the enthalpy change is 570 kJ/mol. For all of the following, assume that the temperature is 25°C and the pH is 7.

(a) Write the expression for the reaction quotient, Q, for this reaction (ignoring the 2 hydrogen ions).

(b) Calculate the value of Q when the overall reaction is at equilibrium.

Name:______________________________

(c) After a period of strenuous anaerobic exertion, the metabolite concentrations in the muscle are found to be:

$[\mathrm{Glc}] = 0.5\,\mathrm{mM}$
$[\mathrm{P_i}] = 1\,\mathrm{mM}$
$[\mathrm{ADP}] = 3\,\mathrm{mM}$
$[\mathrm{Lact}] = 25\,\mathrm{mM}$
$[\mathrm{ATP}] = 3\,\mathrm{mM}$

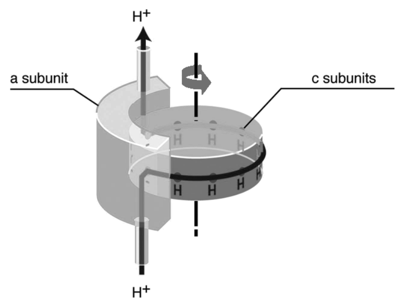
What is the free energy change for the overall reaction under these conditions?

(d) Do you expect the production of ATP to be favorable at the end of this period of exertion? Why or why not?

(e) What is the entropy change for the overall reaction under the conditions of part c?

6. (15 pts) In class, we discussed the mechanism of the ATP synthase found in mitochondria, chloroplasts and some bacteria. Although this enzyme probably did not evolve to function as a motor, it does use rotary motion to couple the favorable diffusion of H^+ ions across a membrane to the unfavorable synthesis of ATP from ADP and P_i.

   The drawing below is a representation of the the portion of the ATP synthase that is embedded in the lipid bilayer of a membrane.[1]



   Referring to the diagram above, explain how this structure is believed to couple the translocation of H^+ ions to rotary motion of the c-ring. Your answer should identify the critical steps of the process and should account for the direction of rotation indicated in the drawing. You may use additional space on the following page, but a longer answer will not necessarily result in a higher score (and may result in a lower one).

[1] Figure reproduced from Walker, J. E. (2013). The ATP synthase: the understood, the uncertain and the unknown. *Biochem. Soc. Trans.*, 41, 1–16. `http://dx.doi.org/10.1042/BST20110773`

Stop!

If you need more space, your answer is definitely too long!

Happy holidays and best wishes for the new year!

Possibly Useful Constants and Equations

Avogadro's number, $N_\mathrm{A} = 6.02\times10^{23}$
Gas constant: $R = 8.314\,\mathrm{L\cdot kPa\cdot K^{-1}mol^{-1}} = 8.314\,\mathrm{J\cdot K^{-1}mol^{-1}}$
Boltzmann constant: $k = 1.38\times10^{-23}\,\mathrm{J\cdot K^{-1}}$

$1\,\mathrm{N} = 1\,\mathrm{kg\cdot m\cdot s^{-2}}$

$1\,\mathrm{J} = 1\,\mathrm{N\cdot m} = 1\,\mathrm{kg\cdot m^2\cdot s^{-2}}$

$1\,\mathrm{L} = 10^{-3}\,\mathrm{m^3}$

$$\binom{n}{k} = \frac{n!}{k!(n-k!)}$$

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}}e^{-(x-\mu)^2/(2\sigma^2)}$$

$$\langle r^2\rangle = n\delta^2$$

$$\mathrm{RMS}(r) = \sqrt{\langle r^2\rangle}$$

$$\langle x^2\rangle = n\delta^2/2$$

$$\langle x^2\rangle = n\delta^2/3$$

$$D = \frac{\delta_x^2}{2\tau}$$

$$J = -D\frac{dC}{dx}$$

$$\frac{dC}{dt} = D\frac{d^2C}{dx^2}$$

$$E_{\mathrm{k},x} = mv^2/2$$

$$\mathrm{RMS}(E_{\mathrm{k},x}) = kT/2$$

$$\mathrm{RMS}(v) = \sqrt{kT/m}$$

$$D = \frac{kT}{6\pi\eta r}$$

$$\Delta E = q + w$$

$$\Delta S_\mathrm{sys} = \frac{q_\mathrm{rev}}{T}$$

$$\Delta S_\mathrm{surr} = -\frac{q}{T}$$

$$S_\mathrm{sys} = k\ln\Omega$$

$$\Delta S_\mathrm{sys} = nR\ln\frac{V_2}{V_1}$$

$$\Delta H = q_\mathrm{p}$$

$$\Delta F = \Delta E - T\Delta S_\mathrm{sys}$$

$$\Delta G = \Delta H - T\Delta S_\mathrm{sys}$$

$$\Delta G = \Delta F - w_\mathrm{p}$$

$$\Delta G^\circ = -RT\ln K_\mathrm{eq}$$

$$\Delta G = \Delta G^\circ + RT\ln Q$$