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Biology 3820
Physical Principles in Biology
Spring Semester 2010

Final Exam
2 May 2011

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

Some possibly useful constants:
The Boltzmann constant: $1.3806 \times 10^{-23}\,\mathrm{J \cdot K^{-1}}$
The gas constant: $8.314\,\mathrm{J \cdot mol^{-1} K^{-1}}$
Avogadro's number: $6.02{\times}10^{23}$

1. (15 pts) Suppose that you roll a conventional 6-sided die three times.

   (a) If the different possible outcomes of this experiment are defined as the specific sequences of numbers observed for the three rolls, *e.g.* (1,2,3), how many different possible outcomes are there for this experiment?

   (b) What is the probability that the sum of the three numbers from the experiment will be 3?

   (c) What is the probability that the sum of the three numbers will be 4?

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(d) What is the probability that all three of the numbers will be the same?

(e) What is the probability that the first two of the numbers will be the same?

2. (10 pts) A population of bacteria are swimming (independently) through a liquid with a velocity of $10\,\mu\text{m/s}$. Each bacterium changes directions every $1\,\text{s}$, on average.

   (a) What is the average (RMS) distance that the bacteria swim from their respective starting positions after $20\,\text{min}$.

   (b) Suppose that the bacteria were to increase their velocity to $20\,\mu\text{m/s}$, while still changing direction every $1\,\text{s}$. What would be the average distance after $20\,\text{min}$?

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(c) Suppose that the bacteria were to increase the time between changing directions, to 2 s, while keeping the velocity to 10 μm/s. What would be the average distance after 20 min?

3. (1 pts) Many animal cells are connected to their neighbors via structures known as gap junctions. These structures are formed by the close juxtaposition of the plasma membranes of adjacent cells, and the two cells are chemically linked via pores, called connexons, as illustrated in the figure below (Taken from The Molecular Biology of the Cell, by Alberts *et al.*):

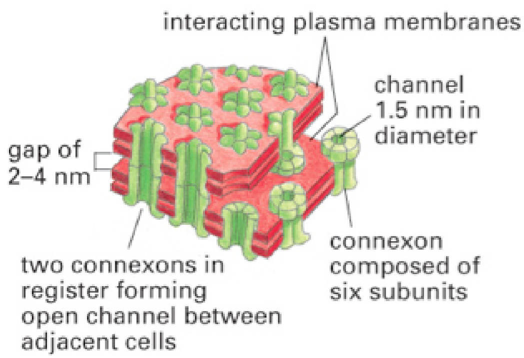

Figure 19–15. Molecular Biology of the Cell, 4th Edition.

The number of connexons in a gap junction can vary greatly, from just a few to several thousand. The pore formed by each connexon has a diameter of about 1.5 nm and a length of about 10 nm.

Gap junctions probably have a variety of specific functions in different cell types and tissues, but their general function appears to be to allow small molecules and ions to move rapidly between cells, thereby establishing a shared metabolic state.

Suppose that two cells are connected by a gap junction containing 200 connexons. A hormone, initially absent in both cells is suddenly synthesized in one of the cells, raising the concentration in that cell to 20 μM. Assume for the following that the diffusion coefficient for the hormone is $10^{-10}\,\mathrm{m^2s^{-1}}$.

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(a) Immediately after the concentration change in one of the cells, what is the concentration gradient (in units of $\mathrm{mol} \cdot \mathrm{m}^{-4}$) across one of the connexons?

(b) What will be the initial flux, in appropriate units, through the connexons?

(c) Calculate the total net number of hormone molecules that will diffuse across the entire gap junction in 1 s, assuming that the concentrations do not change significantly in that time.

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4. (15 pts) Now, consider the thermodynamic aspects of the diffusion of hormone molecules between the two cells. For the following, assume that the two cells have equal volumes and are not connected to any other cells. Also assume that the hormone molecules are initially uniformly distributed throughout the first cell.

   (a) If the cells are spherical and have a radius of $50\,\mu$m, and the initial concentration of hormone in one of the cells is $20\,\mu$M, what is the total number of molecules in the cell?

   (b) What is the total increase in entropy of the hormone molecules after they have completely equilibrated between the two cells?

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(c) What is the minimum amount of work that would be required to move all of the molecules back to just one of the cells, at 37°C?

5. (9 pts) Briefly describe the three major paramaters that determine the classical limiting resolution of a microscope objective, or other lens.

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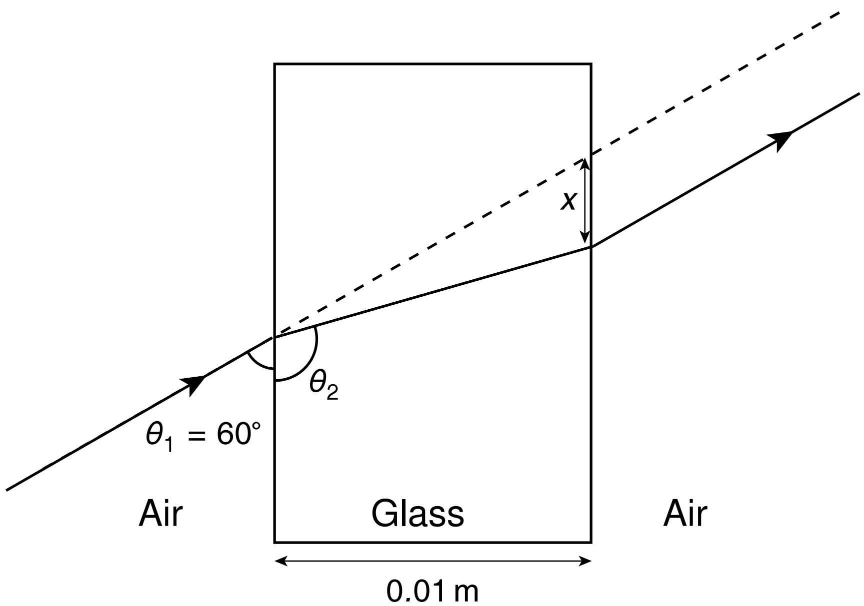
6. (15 pts) If a light ray passes from air through a block of glass and back into air, as illustrated in the drawing below, it will exit at the same angle as it entered, but will be displaced from the path that it would have followed in the absence of the glass (the dashed line):



For the following assume that the index of refraction of air is 1.00 and that of the glass is 1.33. Carefully draw and label in the diagram any additional lines or angles that you use in your calculations.

(a) For the example illustrated above, calculate the value of the angle θ_2.

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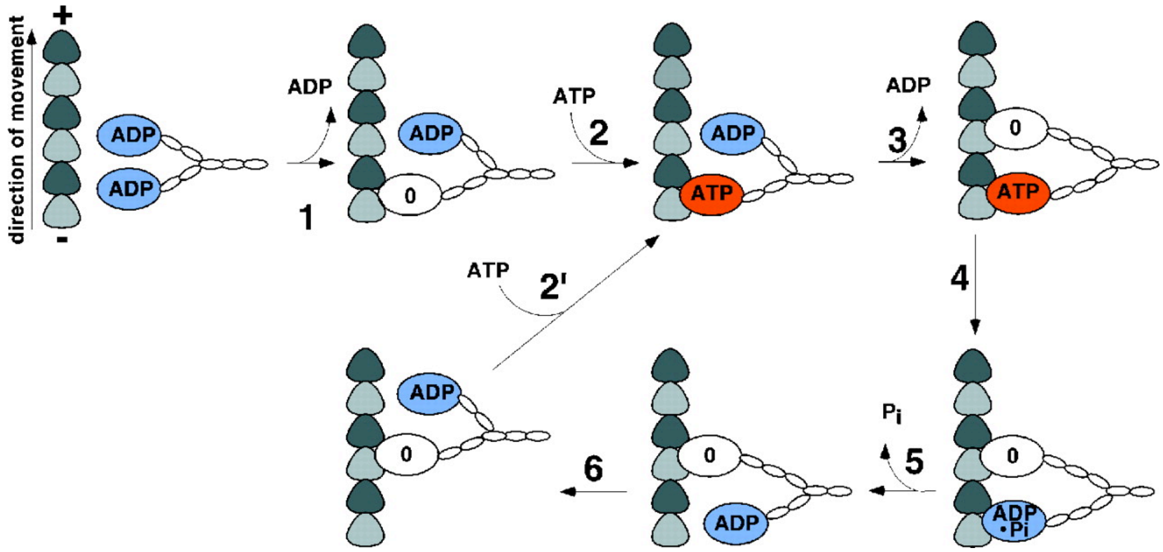
(b) Calculate the displacement of the entering and exiting rays, x in the drawing.

(c) If the light has a wavelength of 450 nm when it enters the glass, what will the wavelength be when it travels through the glass? What will the wavelength be when the light exits the glass?

7. (18 pts) In class, we briefly discussed kinesin, a molecular motor that moves along microtubules in eukaryotic cells. This motor shares several features in common with the two-headed myosins, but also differences. The figure below (taken from Brendza, K. M., Rose, D. J., Gilbert, S. P. & Saxton, W. M. (1999). *J. Biol. Chem., 274*, 31506–31514.) shows a model for the catalytic cycle of this motor:



The microtubule is illustrated in a simplified form, with only one row of tubulin subunits shown. There are two types of tubulin subunits, which alternate, and the kinesin heads bind between the two.

Though we did not discuss this cycle explicitly, you should be able to apply the general principles of molecular motors that we discussed in class to understand this mechanism.

(a) In the scheme above, there are three different states of the kinesin head, defined by the state of the nucleotide binding site ("O" indicates an empty binding site). For each of these states, listed below, indicate how the state of the nucleotide binding site influences the other properties of the molecule.

- Empty

- ADP-bound

- ATP-bound

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(b) Like myosin, kinesin moves in a preferred direction along its track, indicated as $- \rightarrow +$ in the diagram. In the scheme proposed above, in which step is the directionality established? What feature of the kinesin molecule determines the directionality?

(c) Suppose that a cell were depleted of ATP, but not ADP. In what state would you expect the kinesin to accumulate? Specify whether one or both of the heads would be bound to the microtubule, and explain your reasoning.

(d) Suppose that, in an in vitro experiment, you were to replace ATP with an analogue that could not be hydrolyzed. In what state would you expect the kinesin to accumulate? Specify whether one or both of the heads would be bound to the microtubule, and explain your reasoning.