MCB137L/237L: Physical Biology of the Cell
Spring 2025
Homework 13: Final Project
(Due 5/6/25 at 2:00pm)

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1 Physical Biology of the Cell: Your Turn

This problem is one of the most serious ones of the whole course. Flippant or sarcastic answers to any of these questions will result in your problem set not being graded. In this problem, I want you to construct a thoughtful syllabus for how you would teach a course on Physical Biology. This a sophisticated course for those that are interested in the study of life and happy to bring any and all tools from mathematics, physics and computer science to bear on these questions. You have 15 weeks, two classes of 90 minutes each per week. Make sure to give a sense of whether your homeworks will involve computation, whether you will give an exam, etc. But more importantly, what is the content? What do you want students to leave the course with? What are the top five skills you want them to leave with? What are the top five insights you want them to leave with? You have 30 lectures, so I want to hear what each and every lecture will be about. How much Powerpoint? How many calculations on the blackboard.

2 Order of Magnitude Estimates

This final problem set involves a number of challenges in order-of-magnitude thinking. As a reminder, when doing street fighting estimates, the goal is to do simple arithmetic of the kind that all numbers take the values 1, few (f) or 10. few $\times$ few = 10, etc. Please do not provide estimates with multiple "significant" digits that are meaningless. Be thoughtful about what you know and what you don't know. You may use the Bionumbers website (http://bionumbers.hms.harvard.edu/) to find key numbers (examples are masses of amino acids (BNID 104877) and nucleotides (BNID 103828), the speed of the ribosome (BNID 100059), etc.), but please provide a citation to the Bionumber of interest as shown above if you do decide to use those numbers. If you have some other source for your numbers, please cite them. However, for many of these problems the essence of things is to do simple estimates, not to look quantities up.

Choose any 15 of the problems below and provide estimates in the style we have been doing all term or the style that can be found in the vignettes of *Cell Biology by the Numbers*. Remember, we are not fixated on your answers as much as on the clarity of your assumptions, your skill with 1, f and 10 arithmetic, your common sense and intuition. If after performing your estimate you want to comment on data and how your results jibe with that data, brief discussions are welcome. Try to spend less than 5 minutes on each of the questions — this is meant to be a fun, rapid drill in exercising your estimation skills.

1. Phosphorus in the life of a cell.

What is the fraction of the mass of a bacterial cell that is phosphorus?

2. Cows and dairy products.

How many cows are needed to meet the dairy needs of the world?

3. Cows and meat products.

How many cows are needed to meet the beef needs of the world?

4. pH and ion numbers.

At the typical pH of a bacterial cell, how many hydrogen ions does that correspond to?

5. Growth media for bacteria.

After 24 hours, a 1 mL tube will have roughly 10^9 bacteria in it. What mass of glucose was needed in the growth media to support that many cells?

6. Lipids per cell.

How many lipids are there in a bacterial cell?

7. Current in ion channels.

The ion channels that conduct charges across cell membranes and give rise to the action potentials that are the basis of thinking and muscle action open transiently. What is the current across such an ion channel (in pA units)?

8. Water in the Central Valley?

How much water is used to irrigate the Central Valley of California every year?

9. Mass of mRNA and proteins.

What is the mass of an mRNA and a protein?

10. Water uptake in dividing bacteria.

How many water molecules are taken up each second during the growth of a rapidly growing bacterium?

11. Water loss in cholera infection.

When infected by cholera, people have terrible diarrhea. How much water is there in the monolayer of cells of the small intestine?

12. Length of DNA in your cells.

What is the length of DNA in one of your cells?

13. Length of DNA you synthesize in your lifetime.

How many light years worth of DNA do you synthesize in your body over the course of a lifetime?

14. Molecules in aspirin.

How many molecules are there for each of your cells in a single aspirin pill?

15. Photoreceptors in your retina.

How many photoreceptors do you have in your retina?

16. Fertilizer use worldwide.

How many tons of fertilizer are used worldwide every year?

17. Phosphorus in fertilizer use worldwide.

How many tons of phosphorus are in all of that fertilizer?

18. Size of sequence space.

How many times the volume of our universe would it take to make a single copy of every 300 aa protein?

19. Number of genomes in the history of life.

How many genomes have there been in the history of life on earth?

20. Fraction of body mass in DNA.

What fraction of your body mass is DNA?

21. Chickens slaughtered.

How many chickens are slaughtered every year?

22. Number of humans born per year.

Make the spurious assumption of a steady state human population size and use Little's theorem to work out the number of humans born every year.

23. Earthworms and turnover of land.

Estimate the number of tons of dirt turned over per year in a hectare of land by earthworms.

24. Oxygen in headspace of falcon tube.

5 mL of bacterial culture over a 24 hour period will go from a single bacterium to 5×10^9 bacteria. During growth, these cells are shaken at 37 degrees C. How large a headspace in mL is needed in order to provide enough oxygen to grow the cells?

25. CO_2 production.

How much CO_2 is produced per cell cycle by a bacterial cell?

26. Human poop per day

How much human poop is generated per day?

27. Cow poop per day

How much cow poop is generated per day?

28. Land fertilized by poop.

How much land could be fertilized by all the waste of cows and humans?

29. Intuition for concentration.

If there is one copy of a molecule of interest per bacterial cell, what is the concentration in M units?

30. Volume of a human body.

In m^3 units, what is the volume of a human body?

31. Number of red blood cells in a human.

How many red blood cells in a human body?

32. Number of SARS-CoV-2 Virions.

At the height of the pandemic, what was the total number of virions circulating in the human population and what was their total mass?

33. Diffusion time in a neuron.

How long does it take a protein to diffuse the length of an axon?

34. Translation time.

How long does it take for a ribosome to translate all of the proteins that are needed to make another ribosome?

35. Body mass loss during migration.

How many grams of mass are lost by a bar-tailed godwit in its flight from Alaska to New Zealand?

36. Areas and volumes of your cells.

Crudely estimate the total (membrane) surface area, and total (cellular) volume, of all bacterial cells in your body (assuming they are rods like E coli). Do the same for your eukaryotic cells; how different are these bacterial & human values?

37. Powering a city with bacteria.

How many bacteria would be needed to power the energy needs of San Francisco, assuming all ATP production is efficiently allocated to urban human needs?

38. Food and mountain climbing.

What is the maximum height of a mountain you can climb after eating just a bowl of ramen?

39. Dropping animals.

A viral urban myth claims that squirrels can survive any falls, since they survive encounters with the ground at their terminal velocities. Is this really plausible? Give quantitative estimates in support of your reasoning.

40. Stomping microbes.

Given that there are $\approx 10^{30}$ bacteria on Earth, estimate the number of bacteria you will step on in a one-mile run through the forest or countryside.

3 Your Philosophy of Biology.

Choose to answer one of the following questions in a several paragraph discussion.

(a) The history of engineering has been characterized repeatedly by a transition from enlightened empiricism to rational design. For example, the flying buttresses of European cathedrals originally did not come from a deep understanding of the quantitative principles of structural mechanics. Now, companies like Boeing design their airplanes knowing very well what the stresses and strains are like within the materials from doing finite element calculations of elasticity. Give your position on the future of bioengineering and whether you think the field is currently in the enlightened empiricism stage or the rational design stage? Will medicine become a rational design topic and do you think it should?

(b) The mantra of this course is that quantitative data demands quantitative models. Explain in what sense modern biology has become quantitative and defend the mantra as a tool for understanding biological phenomena.

4 A Feeling for the Organism: Your Turn

Pose an order of magnitude problem about real world biology and then make the corresponding estimate. Please take this seriously and try to build on everything we have done the entire term. Formulate a particular "I wonder" question that you find exciting and that you imagine others will find interesting as well. Then, make clear statements about what assumptions you need to make in order to construct the relevant estimate. Once you obtain your estimate, make a rational discussion of why the values take the values they do and how you think this corresponds to what we know from data.