MODELING BIOLOGICAL COMPLEXITY

Bard College Biology Seminar
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The goal of this course is to introduce tools from physics and mathematics that provide quantitative intuition for complex biological systems. Over the course of the semester, we will develop a number of examples—taken from both classical work and modern research—in pursuit of this goal. The course will be divided into four sections:

1. **Problems of scale** Why is it that a common field ant can support 5000 times its body weight but an Olympic power lifter can barely lift 3? Why do mice, men, and elephants all live a billion and a half heart beats before expiring? How did a NYC cat walk away from a 37-story fall with only a chipped tooth? And, why won't bacteria ever evolve fins? Beginning with Galileo, scientists have used physical reasoning to answer these, and related, questions. In the first part of the course, we will learn how the physical environment of an organism changes with its size and the evolutionary consequences of these differences.

2. **Structure from randomness** Biological systems and their environments are often so extraordinarily complex as to appear random. In the second part of the course, we will learn how random processes develop structure and patterns, how to recognize these patterns in the natural world, and how biological systems harness randomness. We shall take as inspiration examples including (i) the decay of organic material, (ii) neuron activity in the brain, (iii) motion of a bacterium in a chemical gradient, and (iv) morphogenisis.

3. **Geometry of interactions** From signaling pathways to food webs, from vascular networks to phylogenetic trees, from the spread of epidemics to the formation of thoughts, networks pervade biology. In the third part of the course, we will introduce networks and the tools that have been devised for their analysis. We will discuss generic mechanisms for network formation and growth and how the geometry of a network constrains its dynamics.

4. **Information and replication** Life differs from the base matter of traditional physics in that it replicates itself by means of a code. The great revolution of

twentieth-century biology was identifying the molecular basis of this code. The great challenge of the twenty-first century will be in understanding how information is coded in the brain. In the final portion of the course, we will introduce the physical definition of Information and discuss how it is stored and transmitted.

I Course Structure

We will have two types of classes. At the beginning of each section Alex will present a lecture on a new model or concept and outline its application to a series of papers. In the following several classes, groups of students will present papers related to this topic. In a presentation, students are responsible for understanding the aim, context, model, argument, conclusion, and figures. **Students are not responsible for explaining the equations.** Alex will explain the equations in each paper.

II Grading

The final grade will be based determined by the following:

Component	fraction of grade
2 presentations with summary and bibliography	50%
participation and statement of interest	10%
problem sets	10%
mini-review	15%
mini-presentation	15%

1. **Presentations** Each student will participate in two presentations. Below is a list of suggestions on how to give good presentation. One week after the presentation, each group will turn in a one paragraph (or so) summary of the paper and a short bibliography of useful sources for the biological context.

2. **Participation** Every student should read every paper. During the presentations, ask lots of questions.

3. **Statement of interest (SOI)** Contact Alex with a few sentences about your interests in biology. What do you want to learn about? This will help me guide you towards a paper for your mini-review and mini-presentation.

4. **Problem sets (PS)** I will pass out one problem set for each of the first three sections. These problem sets will require students to manipulate and understand the models. Feel free to work on these as a group and ask me for as much help as you need.

5. **Mini-review** Read a paper on your own that uses a mathematical or physical model to explore a biological problem. Write a summary (2-5 paragraphs) that explains what the paper is about, how the authors model it, what they learn, and any mistakes they make. Make this summary easy to read by a non-specialist. Your first draft of this will not be graded. Be sure you coordinate with me on finding a good paper.

6. **Mini-presentation** On the last day of classes, each student will give a five-minute presentation on the paper they read and answer questions from the class.

III How to give a good presentation

Student groups will be responsible for presenting most of the material in this course. These presentations will account for most of your grade. Before you do anything else, read the paper several times at least one week (ideally at least two weeks) before you are presenting it. These papers are not easy to read. Talk to Alex at office hours and coordinate a time to skype with him.

During the presentation, try to answer all of the following questions:

1. Tell us about the biological context for this paper. For example, if the paper is about flow of blood in the vascular system, tell us about what blood is made of, how it move, what the vessels are made of, how their material properties (e.g., elasticity) matter, and so forth. Don't tell us about blood in general, focus on the information that will help us understand this paper. This will require that you find more papers, reputable websites with useful animations, textbooks, etc. Provide us with a short bibliography of good sources.

2. What is your paper trying to understand? How does it fit into the context you just outlined? In preparation, write a paragraph or a few sentences that explains the goal and techniques of this paper. Write it such a way that it can be widely understood by non-scientists. During the presentation, this will be a good outline for introducing the paper to the group.

3. Present the main idea of the model. This will require some creativity. One good way of doing this is to draw pictures on the black board.
4. How do the authors use the model to answer the question they are interested in?
5. Walk us through each of the figures. Explain what the axes are. How did they get their data (if any)? What does the figure teach us? Explain any parts that are confusing to you. (Note: If "the whole figure" is confusing, be sure you spoke to Alex about it ahead of time.)
6. Alex is always happy to walk the group through the equations. Feel free to present them yourself. It will not effect your grade at all, but is very good practice.
7. What biological mistakes did the authors make in constructing their model? Do these mistakes invalidate their results?
8. If there is data, are there any interesting deviations from the model? What do these deviations teach us?

One week after your presentation, your summary and bibliography are due! You should do both before your presentation. The hope is that all of us, including you, will understand the paper better after your presentation. If this better understanding helps you write a better summary or leads you to a new source, that is great.

IV Calender

Date	Topic	Reading	Other
Aug 29	**What is a model?**		
Sept 5	**Introduction to Scaling**		PS 1 out, SOI due
Sept 12	The size of animals	[1]	
Sept 19	Walking on water	[2]	
Sept 26	How bacteria swim	[3]	
Oct 3	How trilobites saw	[4]	Mini-review topic due
Oct 10	**NO CLASS**		
Oct 17	**Introduction to Randomness**	[5]	PS 1 due, PS 2 out
Oct 24	How bacteria find food	[6]	
Nov 7	Randomness in evolution	[7]	Mini-review first draft due
Nov 14	**Introduction to Networks**	[8]	PS 2 due, PS 3 out
Nov 21	Vascular networks	[9]	
Nov 28	**Introduction to Information**		PS 3 due
Dec 5	The (wrong) genetic code	[10]	
Dec 12	Student Presentations		Mini-review final draft due

Bold face titles are presented by Alex

References

[1] J. B. Haldane, "On being the right size," *Harpers Magazine*, vol. 152, pp. 424–427, 1926.

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[4] E. Clarkson and R. Levi-Setti, "Trilobite eyes and the optics of des cartes and huygens.," *Nature*, vol. 254, no. 5502, pp. 663–667, 1975.

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[7] S. E. Luria and M. Delbrück, “Mutations of bacteria from virus sensitivity to virus resistance,” *Genetics*, vol. 28, no. 6, p. 491, 1943.

[8] A.-L. Barabási and J. Frangos, *FROM: Linked.* Basic Books, 2014.

[9] E. Katifori, G. J. Szöllősi, and M. O. Magnasco, “Damage and fluctuations induce loops in optimal transport networks,” *Physical Review Letters*, vol. 104, no. 4, p. 048704, 2010.

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