Physical Biology: Information Processing in Biological Systems
Physics 380/Biology 385/NBB 370/Physics 597
Fall 2011, Emory College

Professor: Ilya Nemenman
ilya.nemenman@emory.edu (best way to contact me)
Office Hours: Thu 2-3pm and by appointment

Class Web Page
http://www.menem.com/~ilya/wiki/index.php/Physics_380,_2011:_Information_Processing_in_Biology

Textbooks
There is <u>*no required single textbook*</u> that will cover all subjects discussed in the class. There will be lecture notes distributed on occasion electronically. We will be borrowing from the following books:

1. *Physical Biology of the Cell* by R Phillips, J Kondev, J Theriot (Garland Science, 2008)
2. *Biological Physics: Energy, Information, Life* by P Nelson (W.H. Freeman, 2003)
3. *Biophysics: Searching for Principles,* by W Bialek, available at http://www.princeton.edu/~wbialek/PHY562.html
4. *Theoretical Neuroscience: Computational and Mathematical Modeling of Neural Systems* by P Dayan and L Abbott (MIT Press, 2005)

Additional recommended reading:

1. *Random Walks in Biology,* by H Berg (Princeton UP, 1993)
5. *An Introduction to Systems Biology: Design Principles of Biological Circuits* by U Alon (Chapman and Hall, 2006)
6. *Spikes: Exploring the Neural Code* by F Rieke, Dd Warland, R de Ruyter van Steveninck, W Bialek (MIT Press, 1999)
7. E. coli *in motion* by H Berg (Springer, 2003)

All of these books will be on reserve, or will be available from me for short loans.

Required Software
Mathworks Matlab Student Edition (free on Emory computers) any version or Octave v 3.4 (Open Source) or greater is required.

Pre-requisites:

- Calculus (Math 111/112 or Math 115/116 or AP equivalent)
- Intro Physics (Phys 141/142 or Phys 151/152 or AP equivalent)
- Intro CS (CS110 or CS170 or instructor consent)
- Recommended prior classes: Intro Biology (Biol 141/142). It is recommended, but not required, that the students have some exposure to differential equations, probability, and statistics.

In this class, we will rely on mathematical modeling and computer simulations to achieve deep, physics-style understanding of certain biological phenomena. Therefore, it is important that you come ready with the needed mathematical and computational background. I don't expect you to be professional mathematicians or programmers, but you should be familiar with derivatives and integrals, and you should be able to write a simple computer program in your favorite computer language that would output a "Hello world!" sentence on a screen. There will be study sessions for the class where you will be able to remind yourself how to program, and where the TAs will review the needed math with you.

I expect that, working in groups, those of you with biology backgrounds will learn ideas of computing / modeling from your physics / mathCS peers, and the physicist will learn basic biology facts from the biologists.

Class structure

The teaching philosophy that I adhere to is:

> *I request a lot from my students, but also provide them with all the necessary resources to succeed in the class. As a result, students will work hard, but will likely learn more than in a typical class.*

In practice, this philosophy is implemented as follows.

<u>Lectures:</u> The class will be delivered in a traditional lecture form. However, each lecture will start with a set of questions that will test your understanding of the previous material. We will answer the questions collectively, and I expect that everyone will participate in the ensuing discussion. The questions will not be graded – so don't be afraid to answer incorrectly. Participation is key here.

<u>Homeworks:</u> We will have weekly homework problems. The assignments will be revealed typically in class on a Thursday and/or by email on a Friday. They will be due on Friday of the following week. The assignments will involve calculations and problems, like in physics and math classes, and numerical simulations, like in computational physics, biology, and chemistry classes. I expect that, to earn a high grade on your homework assignments, most of you will need to commit about 6 hours a week to them if you choose to work in groups and to attend support sessions. You may need to work a lot more if you choose to do it alone. If you start working on an assignment on the night before it's due, you won't have time to finish. Don't be discouraged if you cannot figure out a solution to a homework problem immediately: talk to your peers, attend support sessions (see below), or see me. The problems are meant to be challenging, but, as prior years have shown, they *are* all solvable if you expend a sufficient effort.

Some of the problems will be open-ended, and may result in research projects if studied deeply (see below). The open-ended sections will be marked clearly and will be graded for extra credit only. The course will be structured to accommodate both undergraduate and graduate students by providing two sets of homeworks with the appropriate levels of difficulty.

<u>Support Sessions:</u> To ensure that everybody can succeed in the class, we will have weekly evening problem solving session. The sessions will not be required, but I strongly encourage you to attend them. The time for the sessions will be chosen after a class survey. From time to time, we will have additional support sessions designed for review of background math, physics, and biology materials. These will be announced ahead of time.

Exams: There will be no midterm or final exams in this class.

In-class presentations: I will provide you with a list of original research papers relevant to the class. Each student (or a pair of students if we end up having more than 10 students in the class) will choose one paper from this list for a careful study. You will present the paper at one of the class meetings in the second half of the term. Your presentation will be about half an hour long, and it will be graded by me.

Projects: Some of the open-ended homework problems may be turned into research projects. I encourage you to explore these possibilities. Working on a project is not required. However, it is one of the best ways for you to ensure that I know you well enough to write a recommendation letter later on if you need one. It is also a great way to be introduced to research and to try to solve a cool problem that nobody has solved before. I will encourage you to work in groups; my hope is that some of us may be able to write a journal paper as a group after the class is over.

Grading

Homework assignments – 75% (14 assignments total)
Paper presentation – 25%
Extra credit problems – up to 10%
There are no exams and tests. In-class questions and projects (if any) will not be graded.
Your scores will convert to a letter grade as follows:

93.0 - 100 A
90.0 – 92.9 A-
87.0 – 89.9 B+
83.0 – 86.9 B
80.0 – 82.9 B-

with the pattern repeating for C and D grades; 59.9 or less is a failing grade.

Classes requiring rescheduling

Due to my travel in the Fall, 2011 semester, I will not be able to deliver the following lectures. These will either be taught by TAs, or will be rescheduled. Details will be announced as they become available.

Sep 13, 15, 29; Oct 25

Honor code

The Emory College Honor Code applies to all homework assignments.

Topics to be covered

This course will emphasize that all living systems have evolved to perform certain tasks in specific contexts. There are a lot fewer tasks and contexts than there are different biological solutions that the nature has created. The problems, which live on the intersection of physics and biology, are universal, while the solutions may be organism–specific. Focusing on physics-style mathematical models of biological processes allows us to uncover phenomena that generalize across different living organisms – something that traditional empirical approaches cannot do alone.

This course will try to take this point of view while analyzing what it takes to perform one of the most common, universal functions performed by organisms at all levels of organization: signal or information processing and shaping of a response (variously known as learning from observations, signal transduction, regulation, sensing, adaptation, etc.) Studying these types of phenomena poses a series of well-defined questions: How can organisms deal with noise, whether extrinsic, or generated by intrinsic fluctuations within them? How can organisms ensure that the information is processed fast enough for the formed response to stay relevant in the ever-changing world? How should the information processing strategies change when the properties of the environment surrounding the organism change? These biological questions are, in fact, physics problems. Equally importantly, they are problems that should be studied in the language of mathematics.

We will study these questions focusing on specific biological examples, including, in particular, bacterial chemotaxis, vertebrate vision, neural computation in insect brains, adaptation in bacterial populations, and certain behaviors of rodents.

Tentative lecture schedule

The schedule of topics covered during each lecture is subject to change. I will revise it periodically to reflect the pace of the class. The current schedule can be found on the class web site. Note that in-class presentations by students will start around week 8 or 9. These presentations will take some of the class time. They will result in a somewhat slower pace of the class in the second half of the semester.

Week 0. Introduction

1. Why study information processing in biology?
2. Introduction to the class structure and topics

Week 1-4. Random fluctuations limit the accuracy of information processing in biology

3. *E. coli* chemotaxis as a motivating example for introduction of concepts from probability theory.
4. Central limit theorem and the beauty of Gaussian random variables.
5. Random walks and diffusion in different dimensions and the search for transcription factor binding sites.

Week 5-7. Coping with random fluctuations

6. Vertebrate vision: linear response approaches to analysis of propagation of fluctuations through biological network. Biochemical enzymatic amplifiers.
7. Spatiotemporal averaging in vertebrate photoreceptors as a tool for noise control.
8. Thresholding and positive feedback as a noise suppression tool.
9. Collective behavior as noise suppression – from neurons to immune system.
10. First passage time and noise suppression in generation of neural action potentials.

Week 8-11. Quantifying the fidelity of information processing in biology

11. Bacterial gene expression as an information channel – introduction to information theory.
12. Is one bit a lot? What are the limits on information processing imposed by structure of biological systems, temporal structure of signals, and their intrinsic randomness?

13. Does biology care about bits? Information theory and bet hedging in population biology.

Week 12-14. Adaptation as a means of improving information transmission

14. Neural computation in fly vision: adaptation maximizes information transmission.
15. Flashback to chemotaxis and vertebrate vision – negative feedback as a mechanism for adaptation.
16. How fast can adaptation happen? Rats and birds as ideal detectors of change.