Physical Biology: Information Processing in Biological Systems

TTh 10:00-11:15, Math & Science Center, E116

Course numbers:
PHYS 380.001
BIO 385.000
NBB 370.002

Professor:
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Blackboard: TBA

Textbooks

There is *no required single textbook* that will cover all subjects discussed in the class. There will be lecture notes distributed on occasion. We will be drawing heavily 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)

Pre-requisites:

Calculus I, II and working knowledge of probability. It is recommended, but not required, that the students have some exposure to differential equations. This being said, the necessary knowledge will be delivered during the lectures. Exposure to physics at the level of Phys 141/142 and to biology at the level of Bio 141/142 is recommended. However, no formal training in these fields is required.

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. Thus a lot can be understood about the physical structure of biological systems by focusing on understanding of why they do what they do in addition to how they do it on molecular or cellular scales. In particular, this way we can uncover phenomena that generalize across different organisms, thus increasing the value of the experiments and building a coherent understanding of the underlying physiological processes.

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 physical phenomena poses a series of well-defined questions: How can organisms deal with noise, whether extrinsic, or generated by intrinsic fluctuations within molecular components of information processing devices? 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, if asked at the molecular and cellular scale, become physics problems.

We will study these questions focusing on specific biological examples, including, in particular, vertebrate vision, microbial chemotaxis, small neuronal networks, and bet hedging in bacterial populations and in behaving rodents.

The course will be structured to accommodate both undergraduate and graduate students by providing two sets of homeworks with the appropriate level of difficulty.

Grading:
There will be no midterm or final exams in this class. Homeworks will be assigned weekly. Some of the problems will be open-ended, and may result in research projects if studied deeply. Each student will be assigned to read a paper relevant to the course and to present it at one of the class meetings in the second half of the class. The grade for the course will be determined by the performance on the non-open-ended parts of the homeworks and at the research papers presentations.

SI/problem session:
The class will have a recommended evening problem solving session to be scheduled at a later time. The session will not be required.

Tentative syllabus (subject to change):

Week 1 - 4.
1. Life is information processing
  i. Introduction to the main model systems
    a. Controlling noise: Vertebrate vision

  b. Amplifying noise: Randomness in population biology
  c. Efficient signal encoding: Adaptation in microbial chemotaxis
  d. Extracting relevant features: Motion estimation in the blowly
  e. Learning in a changing environment: Rat foraging behavior
 ii. Information theory primer
  a. Entropy and mutual information
  b. Data processing inequality
  c. Efficient encoding and prediction
  d. A gambling primer

Weeks 5-6

2. Controlling noise
 i. Linear filtering
 ii. Enzymatic amplifiers: gain vs. time
 iii. Impedance matching
 iv. The numbers game: population codes in immune system and brains

Weeks 7-8

3. Amplifying noise
 i. Rare events in excitable and metastable systems
 ii. When few govern many: from bacteria to spikes in neurons
 iii. Minority games and optimal investment strategies: from antibiotic resistance to foraging

Week 9-10

4. Efficient signal encoding
 i. Linear adaptation in bacterial chemotaxis
 ii. Adaptation as Bayesian decision making
 iii. Adaptation as optimal information encoding: from slime mold to flies

Week 11-12

5. Extracting relevant features
 i. Adaptation to time, variance, and other nonlinear features in fly vision
 ii. Receptive fields choice and information maximization
 iii. Optimizing for prediction, thresholding, and other nontrivial computation

Week 13-14

6. Learning in a changing environment
 i. Learning changes optimally
 ii. Learning to learn
 iii. Critical periods in learning as a Bayes-optimal behavior