Theoretical and Computational Neuroscience

[PHYS 585 / BE 530: Syllabus: Spring 2021]
Vijay Balasubramanian
TAs: Ron Ditullio, Cathy Li
Course Lecture: Synchronous, by Zoom 9-10:30 ET Tuesday, Thursday
Attendance required, Cameras On
Instructor Office Hours: Tuesday, 2-4 pm ET, by Zoom (subject to change)
TA Office Hours: Wednesday, 3-5pm ET, By Zoom (subject to change)
Version: January 16, 2021 (Adapted for the continuing Coronavirus pandemic)

Course description: This course will develop theoretical and computational approaches to structural and functional organization in the brain. The course will cover: (i) the basic biophysics of neural responses, (ii) neural coding and decoding with an emphasis on sensory systems, (iii) approaches to the study of networks of neurons, (iv) models of adaptation, learning and memory, (v) models of decision making, and (vi) ideas that address why the brain is organized the way that it is. The course will be appropriate for advanced undergraduates and beginning graduate students. It typically attracts a diverse group of students from the Schools of Arts and Science, Medicine, and Engineering: physicists, mathematicians, bioengineers, cognitive scientists, neuroscientists, BBB majors and more.

Pre-requisites: *Mathematics* -- A knowledge of multi-variable calculus, linear algebra and differential equations is useful for this course, although I will review essential methods for the benefit of students who have not had much prior exposure to this material. *Computation* -- Prior knowledge of MATLAB will be useful, but students will go through programming exercises to develop their skills. *Neuroscience* -- Basic knowledge of the architecture of the brain, and of the mechanisms of neural signaling, is useful. For the benefit of students from physics and bioengineering who lack formal training in neuroscience, the course will survey necessary material in class and in tutorial sessions.

Synchronous and asynchronous elements: Synchronous lectures will occur through Zoom, Tuesday and Thursday, 9-10:30 AM Eastern Time, and will be recorded. The TAs and I will hold office hours and discussion sessions at different times to give students an opportunity to ask questions about the course material and homework in smaller groups. Discussion sessions and office hours will not be recorded. Some asynchronous tutorials and lectures will also be made available. In each lecture, we will also have short refreshment and stretching breaks, and breakout sessions to help students in the class to get to know one another. One aim of the breakout sessions will be to enable students to make connections and find collaborators for homeworks.

Books: A good reference book for this class is P. Dayan and L.F. Abbott, *Theoretical Neuroscience: Computational and Mathematical Modeling of Neural Systems*, MIT Press, 2001. Students are not required to purchase it, but may find it useful to consult in conjunction with material that we cover in class. The Penn Libraries are making the text available as an eBook.

Canvas: I will post articles and tutorials on Canvas as needed, along with other course materials including assignments.

Computing Platform: Penn has a site license for MATLAB. You can buy a student copy for your own computer. You can also use Python, a free and powerful alternative computing platform.

Attendance: Attendance is required and will be assessed through participation in the Breakout Sessions (see below)

Breakout Sessions/Class Discussion: To reduce Zoom fatigue, to encourage participation, and to enable students to meet one another, I will organize a breakout session halfway in each lecture in which groups of students will be randomly assigned to breakout rooms. In some of these sessions you will be asked to discuss a pre-defined topic. The topic may be technical and related to the lectures, or may be just "something to think about", or something social intended to build camaraderie in a semester where we will not meet in person. Every breakout room will have an assigned scribe who should *write down the names of all the participants and the response to the prompt*. All the discussion groups will work in a shared Google Doc. The discussion responses will be assigned a grade out of 1.

Other policies: The course has a cameras-on policy during Zoom sessions, in order to facilitate discussions. If circumstances intervene (health-related, internet-connectivity-related etc.) which complicate your ability to participate in this way or submit assignments on schedule, let me know. This is a difficult year for everyone. Also let me know if you have any concerns, or if you are facing any challenges of which I should be aware.

Absences: Absences from class discussions will count against the participation grade unless you have a legitimate excuse. Preferably, contact me in advance if you will be absent, because I will be assigning members of breakout groups before class starts.

Late Homework: Late homeworks will only be accepted with a legitimate excuse or prior arrangement. (Talk to me, and tell me what is going on!) That said, please remember that there is a homework due every two weeks in the is class, and it will be difficult to keep up if you fall behind in the schedule

Graded work: There will be 7 problem sets in this class, consisting of analytical and computational exercises including analysis of neural data. Each homework will count for 10% of the final grade. The final take-home exam will count for 15%. The grades for breakout group responses will be equally weighted and will contribute 15% to the final grade. The homeworks in the class are challenging, and students are encouraged to work together. But please acknowledge your working partners in your solutions. You are also welcome to use the literature and online sources, but, again, please acknowledge your sources.

Topics Covered: Textbook chapters have been indicated where appropriate. Other material will be covered in class and in handouts.

1. Single Neurons
   a. Biophysics of spike generation and action potential propagation (Ch. 5 & 6)
   b. Neural coding and decoding – models of neural response, spike-triggered characterizations of response (Ch. 1 – 3)
   c. Measuring neural information (Ch. 4)
   d. Adaptation of neural responses
   e. Normative models of function
2. Neural Populations
   a. Receptive field maps
   b. Parallel Channels
   c. Correlations and interactions
   d. Network structure and computation (Ch. 7)
3. Higher level functions
   a. Memory – the Hopfield model
   b. Decision making and Bayesian analysis

   If there is enough time (most likely not), we might address

   c. Synaptic plasticity and learning (Ch. 8)
   d. Reinforcement Learning (Ch. 9)
   e. Representational learning (Ch. 10)

Statistical Topics Covered

While going through the computational neuroscience topics described above, we will also cover many topics in probability theory and statistics. These include:

1. Essentials of probability theory
2. Bayesian statistics and probability
3. Correlation and covariance
4. Principal components analysis
5. Statistical inference of models and decision making
6. Bias-variance tradeoffs and Fisher Information
7. Elementary game theory
8. Simple stochastic processes
   a. Statistical independence and Poisson processes
   b. Tests of Poisson statistics
   c. Statistical dependence and Markov processes
9. Information theory
   a. Definition of entropy and mutual information
   b. Techniques for measuring information
   c. Efficient coding theory
10. Elements of statistical learning theory
    a. Learning from statistical correlations
    b. Elementary machine learning