MATH 6380R, Fall 2019: Topics in Theoretical Neuroscience

Instructor

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Office Hour by appointment.

Meeting Time and Venue

Monday and Wednesday (10:30am – 11:50am), Rm5506 Academic Building

Course description

Theoretical neuroscience aims to understand the principle mechanisms of brain function using mathematical models. It develops concepts and insights that has been crucial for experimental design and data interpretation. The technical challenges it faces, such as analyzing nonlinear systems with broadly interacted units, are also relatable to other application scenarios of mathematical modelling.

We will introduce classic models and results on the main topics of the field, including neural coding of sensory information, dynamics of neural circuits, decision making, memory, and learning. As a rapidly developing field with many open questions, we will also discuss the latest research in these topics.

Prerequisite

Linear algebra, multivariate calculus, ordinary differential equations, basic probability and statistics.
Experience in programming using python, MATLAB, etc. is required. No prior knowledge of neurobiology is formally required but is encouraged, and we will introduce the necessary background in the course.

No auditing policy: Please register. Commitment and participations are very important for this course.

Outline and weekly schedule

The course is organized into four modules on topics of coding, learning, decision, and dynamics. At the end of each module, we will have a journal club on the latest research on the corresponding topic, presented by a group of students (everyone will be assigned to one of such journal clubs).

Introduction: what is theoretical and computational neuroscience? [Sept 2]
I. Principles of sensory representations *[total 6 lectures]*

- Sensory representations and efficient coding theory [Sept 4]
- Entropy and max-entropy principle [Sept 9]
- The role of noise and the infomax, analysis for the Gaussian ensemble [Sept 11]
- Vision: natural image statistics, efficient coding and Independent component analysis (ICA) [Sept 16]
- Sparse coding and compressed sensing [Sept 18]
- Current topic: manifold and dimensionality of neural codes [Sept 23]

II. Learning in neuronal networks *[total 5 lectures]*

- Synaptic plasticity and principles of learning [Sept 25]
- Classification in linear systems, the perceptron [Sept 30]
- Support vector machines (SVM) and learning in the cerebellum [Oct 2]
- Gradient based learning [Oct 9]
- Current topics: biological plausible learning [Oct 14]

III. Neural models of decision and inference *[total 5 lectures]*

- Neuronal readout models, the role of neuronal correlations [Oct 16]
- Maximum likelihood and Bayesian decision and inference [Oct 21]
  Reinforcement Learning: Markov decision process(MDP), Bellman Theory [Oct 23]
- Temporal difference learning and the basal ganglia [Oct 28]
- Current topic [Oct 30]

IV: Network dynamics and computation *[total 8 lectures]*

- Dynamics of networks: fixed points, attractors and Lyapunov functions [Nov 4]
- Hopfield model of associative memory [Nov 6]
- Working memory and persistent neural activity [Nov 11]
- Neural integrators in motor and navigational systems, line attractors in neuronal circuits [Nov 13]
- Spatial processing: the ring network [Nov 18]
- Random networks, Excitation-inhibition balanced [Nov 20]
- Relation between connectivity structure and dynamics, chaos and computation in neuronal circuits [Nov 25]
- Current topic [Nov 27]

No class on Oct 10 (Chung Yeung Festival)

Intended Learning Outcomes

Upon successful completion of this course, students should be able to:
1. Know the main questions and models in theoretical neuroscience
2. Learn the analysis techniques discussed and can apply to other applied math scenarios
3. Develop mathematical modeling skills for interdisciplinary research

Evaluation

Credit points: 3

Assessment	Course ILOs
Homework 40%	1,2
Journal presentation 20%	1,3
Final project presentation and written report 40%	2,3

Final project

This is an important component of the course and is supposed to be a mini-research project. We will have a list of suggested topic where you can choose from. You can also propose your own project and seek approval from the instructor on or before November 15. You need to work on the projected independently and submit a written report by December 19. In addition, each of you will give a 10 min presentation. We will schedule the presentation during the Final Exam period.

Homework
There will be 4 sets of homework questions, involving both analytical derivations and computer programming. The homework problems are due two weeks after the assignment.

References
This course is highly influenced by and owes many of its topics and materials to the Computational Neuroscience course at Harvard University taught by H. Sompolinsky.

There is no textbook for the course. You are highly encouraged to take your own notes during the class for later reference. In the lectures, we will use a combination of slides and "chalk talk". We will post afterwards the slides and some typed notes as much as possible.

We will draw materials from the following textbooks and you are recommended to read the relevant chapters for extended discussions. They have been put on reserve in the library.

Theoretical Neuroscience by P. Dayan and L. Abbott
Introduction to the theory of neural computation by J. Hertz et al.
Neuronal Dynamics by W. Gerstner et al.

For a general introduction to neurobiology, a standard reference is:
Neuroscience: Exploring the Brain by M. Bear et al, which is also put on reserve.