BME 4422: The Biophysics of Neural Computation

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Office Hours: 11:00am-12:00am, Monday
Period: Spring 2015
Classroom: Academic Health Center 3 - 215
Time: Tue & Thu – 2:00 pm – 3:15 pm

Course description

This course will discuss the biophysics of neuronal computation for both biological and artificial neural networks. It will provide a detailed introduction to: **i)** the anatomy/physiology of excitable cells, **ii)** the major brain architectures and principles, and **iii)** the most relevant mathematical models for neural computation from single neurons to circuits. Therefore, this course will prepare the students to understand the main principles by means of which our brains work and computers recognize patterns, learn/plan actions, and interact with humans.

Course Outcome:

No.	Course Learning Outcomes By the end of this course, students should:	Corresponding Program Learning Outcomes
1	know the physiology of excitable cells, the most important neuronal circuit architectures as well as the mathematical tools to represent these cells and circuits	1, 2
2	know the basic programming elements underlying neuronal computation	1, 2
3	know the working principles of artificial neural networks and their applications to perform modern research	1
4	be able to understand a scientific paper, synthetize it and present it in front of other students	7

Prerequisites

Permission of Instructor

Grading

30% Assignments (4), 1% of the total grade will be deducted for assignments turned in late
35% Middle Term Exam
35% Final Exam
Grading scale: 95-100 A; 90-94.9 A-; 86-89.9 B+; 82-85.9 B; 79-81.9 B-; 76-78.9 C+; 72-75.9 C; 69-71.9 C-; 67-68.9 D+; 63-66.9 D, 60-62.9 D

Attendance

Attendance is mandatory but up to three classes can be missed without incurring penalties.

Tentative schedule (subject to change to better address goals)

L1: Introduction

- *Short History of Neural Computation*
- *Major Applications in Modern Times*
- *Open Discussion*

Part I- Neurons I

L2: Electrical Circuits

- *Capacitors and Resistors*
- *Kirchhoff Laws*
- *Norton-Thévenin Theorem*

L3: Membrane Equations

- *Resting Membrane Potential* ***(Nernst Equation, Laboratory)***
- *Thermodynamics Approaches*
- *Electrical Equivalent Circuits*

L4: The Hodgkin-Huxley Membrane Model

- *Voltage- and Ligand- Gated Ion Channels*
- *Borg-Graham's Generalizations*
- *The Action Potential*

L5: Information Propagation – Axons

- *The Cable Equation*
- *Myelinated Fibers: Impulse Conduction*
- *Ranvier Nodes: Structure and Function*
- *Conduction Velocity*

Assignment 1: Simulation of an AP using NEURON Software

L6: Recapitulation of Part I

Part II- Neurons II

L7: Information Transmission - Synapses

- *Types of Synapses*
- *Synaptic Vesicles: Neurotransmiters*
- *Post-synaptic Potentials: Excitatory and Inhibitory*

L8: Passive Synaptic Trees

- *Anatomical Features: Branches and Bifurcations*
- *Synaptic Efficacy/Strength*
- *Long-Term Potentiation/Depression*

L9: Synaptic Interactions

- *Excitation vs. Inhibition Balance (****up and down states****)*
- *Absolute vs. Relative Depression*
- *Shunting and Hyperpolarizing Inhibitions*

L10: Roles for Non-Excitable Cells

- *Support and Modulation by Glia Cells*
- *Neurotransmission Recycling by Astrocytes*
- *Cellular Metabolism and Active Transport*

Assignment 2: Paper Reading - Presentation

L11: Recapitulation of Part II

Midterm Exam

Part III- Neuronal Circuits I

L12: Large-Scale Circuits in the CNS

- *Sleep-Awake Thalamocortical Loop*
- *Circuitry for Space Memory*
- *Body Movement Control Loop & Reflex-Arc Circuit*

L13: Electrical Activity at the Mesoscopic Scale

- *Local Field Potentials & Current Source Density (CSD) Analysis*
- *Line Source Model*
- *Single/Multi – Unit Activity: Spike Sorting and Classification*

L14: *Semi-Realistic Models of Neuronal Excitability*

- *FitzHugh-Nagumo Model*
- *Morris-Lecar Model*
- *Integrate-and-Fire Model: Leaky and Exponential Versions*
- *Hindmarsh-Rose Model*

L15*: Multi-Compartmental Models of Neuronal Excitability*

- *Dimensionless Distance/Time Variables*
- *Linearization of Ionic Current Kinetics*
- *The Equivalent Cylinder Theorem*
- *Branches/Dendritic Attenuation:*
    - *The Cumulative Electrotonic Length*
    - *The 3/2 Power Law*
    - *The Termination Condition*

Assignment 3: Toolboxes for the Analysis of Extracellular Potentials

L16: Recapitulation of Part III

Part IV- Neuronal Circuits II

L17: Neural Oscillations

- *Feed-Back Loops*
- *Synchronization and Neuro-modulation*
- *Oscillatory Activity: Phase-Locked Vs. Spectral Perturbations*

L18: Small-Scale Circuits in the CNS

- *Different Types of Neurons*
- *Microcircuits in the Neocortex, Hippocampus and Cerebellum*
- *Major Working Principles of the Thalamus, Basal Ganglia and Spinal Cord*

L19: Neuronal Ensemble Models and Oscillators

- *Wilson–Cowan model*
- *Kuramoto model*
- *Mean field theory (Ermentrout-Kopell canonical model)*
- *"Synfire Chain" (Abeles)*

L20: Quantitative & Qualitative Analysis

- *Spectral Analysis*
- *Granger Causality Measures*
- *Nonlinear Oscillators: Bifurcation Analysis*

Assignment 4: Paper Reading – Presentation

L21: Recapitulation of Part IV

Final Exam

Textbooks (Recommended, not mandatory)

Theoretical Neuroscience – Computational and Mathematical Modeling of Neural System. P. Dayan and L.F. Abbott, MIT Press, 2005
Biophysics of Computation – Information Processing in Single Neurons. C. Koch, Oxford University Press, 1999