BME 4422: The Biophysics of Neural Computation

Instructor: Dr. Jorge Riera Diaz, PhD

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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:

<table>
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<tr>
<th>No.</th>
<th>Course Learning Outcomes By the end of this course, students should:</th>
<th>Corresponding Program Learning Outcomes</th>
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<tbody>
<tr>
<td>1</td>
<td>know the physiology of excitable cells, the most important neuronal circuit architectures as well as the mathematical tools to represent these cells and circuits</td>
<td>1, 2</td>
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<td>2</td>
<td>know the basic programming elements underlying neuronal computation</td>
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<td>3</td>
<td>know the working principles of artificial neural networks and their applications to perform modern research</td>
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<td>4</td>
<td>be able to understand a scientific paper, synthetize it and present it in front of other students</td>
<td>7</td>
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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: Neurotransmitters
- 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:
    o The Cumulative Electrotonic Length
    o The 3/2 Power Law
    o 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)


*Biophysics of Computation – Information Processing in Single Neurons. C. Koch, Oxford University Press, 1999*