Fall 2019
How to build a brain: from channels to networks

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Description: Brain function is ultimately determined by ion channels that generate neuronal firing and by the synapses that allow information transfer between neurons in a network. To facilitate analyses of this extremely complex process, neuroscientists often use computer simulations to make predictions, design experiments, and importantly, to improve their intuition. In this course, students will build a network from the ground up. Using simulations, students will examine how biophysical properties affect the firing of neurons, how synapses and network architecture, control information flow, and how neural networks generate complex firing patterns. For some simulations, 'skeleton' Matlab programs will be provided, which the student can easily modify to explore the various processes that affect function; for some simulations, plug-and-play software with idealized full neuron models will be used for 'in silico experiments'.

Prerequisites:
Co- or pre-requisite: Cellular and Molecular Neurobiology, Behavioral Integrative Neuroscience or by permission of the instructor.

No programming experience is necessary. Students will be taught basic programming techniques in Matlab when needed or use Neurons in Action simulation environment.

Schedule:
Thursdays 2-4 pm in Meyer 760

Required Materials:
GL Fain: Molecular and Cellular Physiology of Neurons; chapters available for free at http://www.degruyter.com/viewbooktoc/product/430001
MatLab (License available for free through NYU)
JW Moore & AE Stuart: Neurons in Action; order it online:
http://neuronsinaction.com/home/main
HR Wilson: Spikes, Decisions and Actions (SDA). Basic Matlab codes provided by instructor and/or SDA. Free download of SDA:
http://cvr.yorku.ca/webpages/wilson.htm#book

Grading:
40% will be based on weekly homework assignments; 20% on project proposal (oral presentation); 30% on project (written & oral); and 10% on class participation. For the projects, students will formulate and then test their hypotheses by performing simulations.

Course Organization: Class meets once a week for 2 hours. The first hour will be a discussion of the assigned material. The second hour will be devoted to performing simulations.

Learning Goals: Upon completion of the course, students will be able to use computer simulations to explore cellular and network function.

1. (September 5): Introduction
Review of differential equations;
Euler method for solving differential equations
Matlab exercises:
Basic Matlab programming techniques: program structure, loops, vectors/matrices

2. (September 12): Passive properties of neurons; Nernst Equilibrium Potential
Review of passive properties of neurons, resting/equilibrium potentials, and membrane time constant.
Reading:
Fain, Chapt.2 (p. 31-45); handout for Nernst equation
Matlab exercises:
Using Euler method for modeling passive properties with resistors and capacitors in parallel; Na, K equilibrium potentials and resting potential
Homework: effects of membrane properties/ion concentration on voltage response.

3. (September 19): Biophysics of Action Potentials: Hodgkin and Huxley I
Using H&H experimentally-derived variables to model channel behavior
Reading:
Fain, Chapt.5 (p. 145-188);
Matlab exercises:
Modeling Sodium and Potassium conductances
Homework: Effects of H&H kinetics on macroscopic currents

4. (September 26): Biophysics of Action Potentials: Hodgkin and Huxley II
Relationship between H&H equations, action potential shape, and threshold
Reading:
Fain, Chapt.5 (p. 145-188);
Neurons in Action (NIA) exercises:
Introduction to NIA for action potential generation.
Running simulations to examine effects of changing H&H parameters
Homework: Input/output properties of H&H neurons

5. (October 3): Voltage spread and propagation in axons

Passive membrane: cable equation, voltage spread, length constant

Active (HH) membrane: action potential propagation, dependence of speed on diameter

Reading:

2 NIA tutorials : The passive axon; The unmyelinated axon

Fain, Chapt.5 (p. 145-188);

NIA exercises:

For passive axon: voltage time courses, spatio-temporal profiles – 'movies', estimating length constant

For unmyelinated axon: time courses, action potential temporal and spatial shape, estimating propagation speed

Homework: Dependence of length constant and propagation speed on biophysical properties: diameter and temperature.

6. (October 10): Biophysics of Synapses: Pre & Postsynaptic mechanisms

Mathematics of quantal hypothesis

Determinant of synaptic potential shape

Excitatory vs inhibitory synapses;

Reading:

Handout (Johnston & Wu chapter);

optional: Fain, Chapt. 9, 10;

Matlab exercises:

Conductance based synapses; Using convolution to generate synaptic trains

Homework: Effects of release probability, quantal content on synaptic potential; summation

7. (October 17): Cable models of neurons

Geometry and membrane properties affect action potential initiation and propagation in neurons.

Reading:

2 NIA tutorials: Axon diameter change; Site of impulse initiation

NIA exercises:

For Axon diameter change: effect of propagation into region of increased diameter – success or failure

For Site of impulse initiation: idealized neuron model with passive dendrite and active soma and axon; effects of timing and location of a synaptic input, and of soma size

Homework: "reflection" of propagating action potential; impulse initiation site depends on biophysical parameters.

8. (October 24): Coincidence detection/site of impulse generation

Some computational roles of dendritic neurons.

Reading:

2 NIA tutorials: Interactions of synaptic potentials on multiple dendrites; Coincidence detection

NIA exercises:

For Synaptic interactions on multiple dendrites: motoneuron model with axon, soma, and dendrites; effects of timing and location on summation of inputs
For Coincidence detection: model of neuron from auditory brain stem; ionic channel specializations, I_h and IK_lva for fast and precise coincidence detection
Homework: directional selectivity for sequential synaptic activation (Rall); tuning of temporal precision for coincidence detection

9. (October 31): Simple neuron models: Leaky-integrate-fire neurons
Replicating salient features of H&H neurons with simple models;
When/when not to use these simple models
Reading:
Handout (Naud et al., 2008, Biol Cybern. 99:335);
Matlab exercises:
Leaky-integrate-and-fire neurons and variants
Homework: Comparing LIF with HH neuron models

10. (November 7): Neural networks: feedforward configuration
How are signals propagated and transformed in networks
Reading:
Handout (TBD)
Matlab exercises:
simulating multilayer networks
Homework: none

11. (November 14): Introduction to firing rate models I:
Single E-E population, Firing rate framework, bistability, model for short term memory
Reading: SDA: sections 2.3, 6.4, 6.5; JR handout.
Matlab exercises:
Modify Matlab code to include recurrent excitation in network; sweep over input strength: bistability and hysteresis. Slow adaptation and network oscillations.
Homework: TBD

12. (November 21): Introduction to firing rate models II:
Homework: TBD

*****November 22: Written proposals for project due*****

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13. (November 28): Thanksgiving

14. (December 5): multiple population models.
Competition models: i-i network; Wilson-Cowan model of e-i network; phase plane representation of network dynamics
Reading:
SDA: for i-i: sections 6.7, 8.6; for e-i: section 8.2; and JR handouts
Matlab exercises:
Bistability in competition and decision-making models; slow adaptation leads to

alternating dominance as in perceptual bistability
Models of e-i networks: excitability, oscillations, bistability

Homework: TBD

15. (December 12): Student Presentation I

16. (exam week): Student presentations II