Potential Student Research Projects

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In this document, I describe a few potential student research projects. In general, I am interested in using mathematical modeling as a tool for uncovering mechanisms underlying biological phenomena. I am open to advising projects in the broad field of mathematical biology, but I specifically describe projects here in my research area of mathematical neuroscience.

Individual neuron dynamics

Several mathematical models exist to describe the membrane potential of an individual neuron. The most complicated of which is the set of Hodgkin-Huxley differential equations that includes nonlinear equations to describe each individual ion channel along the cell membrane. Investigations into the behavior of one cell in response to different input requires numerical integration (which can be done via MATLAB’s built-in ode45 function or a student’s own numerical integration scheme) and other simulation techniques to analyze the resulting behavior. Some potential applications of modeling an individual neuron could be:

1. to incorporate a variety of ionic channels into the Hodgkin Huxley model, potentially including stochastic components (e.g., channel failure), and investigating their effects of the membrane potential. Often, neurons in different regions of the brain are composed of different sets of ion channels. This project would include a literature search to find experimental measurements of the membrane potential of these different neurons and matching the model to those experiments.

2. to allow two neurons to communicate through either an inhibitory or excitatory synapse and perform an analysis on the observed behavioral changes that come with varying the parameters of the synapse strength and time scale of transmission. Depending on student interest, one could write a simplified version of the Hodgkin Huxley model (e.g., the Wilson-Cowan model) whose null-clines and phase portrait can be easily computed and analyzed. For different timescales of synaptic transmission, one might observe different steady-state behavior.

In each case, depending on the interest of the student, we would perform in-depth literature searches to find experimental behavior to check that the model is behaving as realistically as possible. In addition, one could introduce damage or disease to the model and use it to investigate different treatment protocols.
Population dynamics

Computational neuroscientists often model the behavior of a collection of neurons, rather than individual neurons, to understand the interaction between several regions of the brain. One can model the collective behavior of a population in terms of an average firing rate or average membrane potential. The resulting differential equations are often much simpler to analyze than those required for individual-neuron modeling. Potential student projects might include analytically investigating the resulting dynamical regimes of these systems and understanding how varying the type of interaction between populations of neurons can affect these dynamics. Some potential applications within this framework include:

1. modeling the interaction of populations of neurons responsible for sleep and wake dynamics. In particular, oscillations of varying frequencies often arise in the dynamics corresponding to states of REM or nonREM sleep. Students can examine how changing parameters in a population model can affect this oscillatory behavior and relate that to different observed sleep dynamics.

2. simulating a decision-making task using mutually-inhibiting populations of neurons. Modellers have had success describing interesting sensory phenomena such as binocular rivalry (when visual perception alternates between different images) and auditory segregated input (when auditory perception alternates between different frequencies) using mutually-inhibiting populations of neurons. Students can work within this framework to understand how the introduction of noise or more populations of neurons (excitatory and inhibitory) might affect the decision-making (alternating perception) properties of the network.

Data science

Due to the growing computational power and experimental designs, large sets of data can be generated or measured in very little time. Mathematicians are in a unique position to deal with this large quantity of data by helping to design tools for organizing raw experimental data and extracting key information. Neurons are noisy objects where multiple recordings often lead to different measurements. In order to extract key pieces of information (such as a preference for some sensory input), tools from signal processing are often applied, sometimes performing some averaging or smoothing over large sets of neurons, resulting in the loss of important, detailed information. A potential student project could be in applying different tools from signal processing to understand how different techniques lead to separate conclusions about the activity of the cells. The student might pay particular attention to the oscillation frequency or synchronization properties of a network of neurons and try to develop some tools that can guarantee that the features we observe are robust and not just due to the method of processing.

I have had experience mentoring students in simulating neuronal networks, detailed modeling of sensory cells including calcium and mechano-sensitive ion channels, and modeling the resulting force generated by a contracting muscle fiber. My own research spans topics from neuroscience, epidemiology, and data science of crime trends. I look forward to developing projects in any area of applied math where one can use equations (ODEs, PDEs, deterministic or stochastic) to describe and further understand interesting biological and physical phenomena.