Individual Major Proposal

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Class Year: 2021

Individual Major Advisor: Prof. Kevin Crisp

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Working Title: Computational Neuroscience

Description:

Computational neuroscience is an interdisciplinary discipline that studies the nervous system using computational approaches, including mathematics, statistics, computer simulations, and abstraction. Computational neuroscientists build models to better understand the functions and interactions of neurons and neural circuits to generate unanticipated hypotheses that are later tested using experiments. The models can be complex to imitate realistic responses of neural networks or simple to investigate general interactions between neurons. Computational neuroscience can also be employed to organize, analyze, and interpret huge datasets collected from lab experiments.

Questions:

How do neural circuits make decisions?

Is neural activity predictable?

What are some mechanisms of interactions between neurons that results in the behavior of neural networks?

What information can be extracted and reconstructed from neural activities?

How is information processed and stored in the brain? How is memory accessed?

How do the molecular mechanisms that underlie circadian rhythms generate a stable rhythm with the correct period?

How does a computational model of a random simple network behave in general?

How much affects would specific neurons, oscillators or circuits have to said network?

Can we come up with models that mimic the behavior of neural networks and circuits?

Courses

Neuroscience

NEURO 239 Cellular and Molecular Neuroscience (Currently Enrolled)

This course covers topics in Neuroscience including membrane biophysics, synaptic transmission and plasticity, intracellular signaling, sensory transduction, motor control systems, and development. The classes and labs will provide a systematic introduction to the discipline of neuroscience.

BIO 247 Animal Physiology (Completed)

In this course, students learn about basic systems that provide circulation, ventilation, movement, digestion, and waste removal. Students look at how these processes are coordinated by the nervous and endocrine systems. This course offers an integrative perspective of the nervous system and its interactions with other systems. In the lab, we used frogs and various chemicals like epinephrine, atenolol, propranolol, etc. to investigate the interactions between the nervous system and the endocrine system.

BIO 385 The Neuron (Completed)

This is a seminar course where students examine in depth the fundamental unit of the nervous system, the neuron. It introduces various functions of the neuron: electrical signaling, synaptic transmission, and directed growth and remodeling. This course will provide the physiological background for building computational models of individual neurons or interactions within a network.

BIO 387 Neuroethology (2021 Spring)

This is a new course offered next year. It blends ethology and neurobiology to understand proximal and ultimate causes of natural behaviors. Multiple case studies of invertebrate and vertebrate animal models will help me understand how the nervous system is involved and coordinates animal behavior, such as evading predators, finding prey, or finding mates.

Math

MATH 220 Elementary Linear Algebra (Completed)

This course investigates topics like matrix algebra, determinants, vector spaces, bases and dimension, linear transformations, and eigenvalues. Matrix operations can be used to simplify expressions of neurons and neural networks. This course provides a strong mathematical foundation for the major.

MATH 236 Mathematics of Biology (Completed)

In this course, students learn essential modeling techniques that are fundamental to the major, including formulation, implementation, validation, and analysis. Students learn to integrate mathematical theory, statistics, and computation to better understand a wide variety of biological systems. Many of the models in this class will involve solving differential equations with analytical and numerical solutions, which are frequently used in neural models.

Statistics

MATH 262 Probability Theory (Completed)

This course introduces the mathematics of randomness. Concepts of probability theory are crucial to understanding how the brain encodes, performs computations, and then decodes information gathered from the world. For instance, many aspects of human perceptual and motor behavior can be modeled with Bayesian statistics, which is one of the topics of this course.

STAT 272 Statistical Modeling (Completed)

In this course, students learn about the fitting and assessment of statistical models with application to real data. Statistical methods are used to analyze huge datasets in the realm of neuroscience. They will also be extremely helpful when trying to make sense of the results of our neuron models and neural networks.

MSCS 341 Algorithms for Decision Making (Completed)

This course introduces students to the subject of machine learning. The primary focus is the development and application of powerful machine learning algorithms applied to complex, real-world data. With the amount and type of data gathered in the field of neuroscience, new methods are needed for cohesive interpretations. Machine learning is a great addition to the arsenal of analysis tools for neuroscience investigations at multiple stages and levels.

Computer Science

CSCI 251 Software Design and Implementation (Completed)

This course provides an introduction to the structure and creation of computer software using the C++ programming language. This course introduces methods and ideas like pointers, dynamic programming, object-oriented programming, interface segregation principle that can be used to build and improve computational models. It also offers the probability of building interfaces for users that are not proficient in programming so that they can also participate in the computation side of neuroscience.

CSCI 253 Algorithms and Data Structures (Completed)

This course surveys standard algorithms and data structures with emphasis on implementation experience and complexity analysis. Implementing simpler algorithms and clearer data structures will greatly decrease the run time of computational models and offer further optimizations. The algorithms that I learned from this course, including DFS, BFS, and dynamic programming, have been extremely helpful in my current project working with Professor Crisp.

Senior Project

IS 392 Senior Project (2021 Spring)

Related Courses

MATH 230 Differential Equations I (Completed Audit)

MATH 330 Differential Equations II (Will Audit if possible)

MATH 320 Advanced Linear Algebra (Completed Audit)

MABIO 130 Exploring Biomathematics (.25) (2021 Spring)

CSCI 125 Computer Science for Scientists and Mathematicians (Completed)

CSCI 263 Ethical Issues in Software Design (Interested in taking)

CSCI 315 Bioinformatics	(Interested in taking)
BIO 315 Principles of Bioinformatics	(Interested in taking)
BIO 386 Animal Behavior	(Interested in taking)
PSYCH 238 Biopsychology	(Interested in taking)
PHYS 246 Electronics	(Interested in taking)
PHIL 231 Philosophy of Mind	(Interested in taking)

Rationale

Computational neuroscience is an interdisciplinary discipline that studies the nervous system using computational approaches, including mathematics, statistics, computer simulations, and abstraction. Computational neuroscientists build models to guide laboratory research in neuroscience as well as interpret huge datasets collected from experiments. Computational neuroscience is a rather new field that emerged a few decades ago and is coherent by itself. One of the ultimate goals of computational neuroscience is to be able to explain the everyday experience of conscious life. Several attempts have been made, but much of the work remains speculative.

Professors from the Biology and the Psychology department have been planning for a neuroscience major in the future, but the proposal is still in its infancy and will not be ready until years after I graduate. However, St. Olaf already has numerous courses and resources that will prepare me for an individual computational neuroscience major. Philosophy and religion have long been the major areas where people sought explanations for mind and consciousness. The Great Conversation Program at St. Olaf offers some excellent ideas about the nature and truth of being from philosophers like Socrates, Descartes, and Kant as well as theologians like St. Augustine, Aquinas, and Kierkegaard. I gained a good understanding of various traditional theological and philosophical frameworks that explain the relationship between body, mind, and the soul. Biology courses that have a strong focus in neuroscience are good opportunities to build a basic understanding of the underlying structure of the brain and the rest of the nervous system. Courses from Mathematics, Computer Science and Statistics provide the tools for a quantitative and bioinformatic approach towards neuroscience. A lot of interdisciplinary connections can be made, such as linear algebra, graph theory, algorithms, probability theory, random processes, and topology.

Computational Neuroscience has inspired ideas such as neural networks in the past and will have a lot of future potential in areas such as machine learning, AI, clinical trials, and biomedical research. These are areas that will produce evolutionary and global changes. With the enormous amount of data that is accumulated through research in the brain and the nervous system, quantitative methods are going to be essential. A major geared towards computational and bioinformatic skills will be the future of neuroscience. Thus, an individual major tailored to study computational neuroscience fits well with the global mission of St. Olaf.

Learning and other preparation

I was always fascinated by nature, by the delicacy and beauty it represents. This led to my interests in biology ever since middle school. For my college application essay, I wrote about a transition from drawing saffron flowers over the hills to looking at astrocytes, a type of brain cells, under the microscopes. Here's a short excerpt: "The fantastic colors and the intricate structures are in the childhood flowers, but also in the astrocytes, in the cells, in the minds of every one of us. The boy knew he was wrong thinking that interests in biology were so different from painting. In fact, both are representations and recreations of nature, creating a unity of color and beauty."

Coming into college, I discovered coding and fell in love. For a while I struggled between neuroscience and computer science, trying to choose one. Then I participated in a CURI research involving computational modeling with Professor Freedberg. I was astonished that simple computational models can capture the essence of a seemingly complex process of evolution in a population. The models can reveal general patterns that we overlooked in previous experiments and provide insight into future research. What if I can use computational modeling as a new perspective to look at neuroscience? I at once determined that computational neuroscience, an area that combines my love for the brain and enthusiasm for numbers, equations, and programming, is the perfect area for me. Since then I have been involved in several projects that deepened my understanding of computer science and neuroscience. Right now I am building models for Professor Crisp that investigate connections of a simple and random neural circuit to better understand the decision making process in leeches.

Senior Integrative Projects

The major goal of neuroscience is to understand how the brain works. One approach to the problem is to select a behavior and ask how the interconnected neurons and networks produce that behavior. A very useful animal for establishing the neuronal bases of behavior has been the leech. The swimming movements in the leech are believed to be controlled by a linear cascade. Layers of cells are connected in a hierarchical order to produce the behavior. Sensory neurons are connected to trigger/control neurons (also called command cells), which are connected to gating neurons, then the interneuron oscillator, and then finally the motor neurons. Command cells, such as Tr2, can potentially act as a toggle, eliciting swimming activities and halting them when activated. Gating cells, the third level in the cascade, can bring about changes in the swimming behavior when activated, such as the duration of swimming.

In this project, we are using computational models to imitate a simplified neural network that controls the swimming behavior in the leech. We constructed undirected graphs where each neuron is represented by a node and each connection by an edge. The neurons are stored in a vector, where each neuron can be represented by a state of either 1 or 0, 1 meaning activated and 0 not activated. Instead of setting up hierarchical neuron layers, we are using a novel approach with a random neural network and trying to investigate if the gating and command characteristics of the neurons could be the emergent property of the network. Rather than connected through layers, all neurons are randomly connected to each other. The simulations will run through numerous possible starting neurons and interconnections in order to identify cells with gating properties. These are cells that when forced on, will bring about different patterns in the network. We will analyze the probability and characterize the behavior of those “organically emergent gating cells” using different parameters. There are variations when we can increase the excitability of gating cells and thus lower their thresholds. In the future, we will hopefully determine the possibility of emergent commanding properties and identify cells with these properties.

The web portfolio is potentially in the form of a database. The simulations have the potential to create huge amounts of results that cannot be analyzed in one semester or a year. These data can be stored in a database (probably on a server from the computer science department, with the help of Prof. Richard Brown) for future use. We are currently exploring the possibility of using SQL databases or even graph databases.

The project is a synthesis of the various coursework that I have taken at St. Olaf. My neuroscience courses have provided me background contexts for concepts such as neural networks, command cells, and gating cells. The vectors and matrices used in the computations are concepts learned from my Linear Algebra courses. Programming the whole simulation requires the coding skills and algorithms knowledge I acquired from my computer science courses. The final product will probably be in the form of an academic report or paper. Hopefully we will get the paper published. Possible presentations opportunities include posters or even talks at neuroscience conferences.

Consultation

Research in our field can be done both online and offline. Even though computational neuroscience is a relatively new field, there are a variety of books that explain the core basis and concepts of computational neuroscience. Books like “An Introduction to Neural Networks” by James Anderson and “Introduction to the Theory of Neural Computation” by Hertz, Krogh, and Palmer will be great introductions to the field.

I met with librarian Audrey Gunn and we discussed some online resources for computational neuroscience. Online databases offered on the St. Olaf library website, such as

Web of Science, Biological Science, and Biosis Previews, can be used to find papers in our field. These databases have different focus and can be used simultaneously. Keywords such as "computation", "neuroscience", "neuron", "models", "stochastic", "deterministic", and other neuroscience terms can be used to find, modify, and narrow results. Upon finding a paper, we can look up full text through external websites that St. Olaf grants access to. We can look at cited references of this paper, other papers that cited this paper, and other papers that have shared references. We can also look for subject headings in the Medical Subject Headings website and then bring those headings into PubMed to search for related papers. We can use OneNote or Zotero to write up bibliography systematically and import them into Word or Google Doc. Zotero is especially easy to use and comes with a lot of citation styles.

Data gathering is essential in building brain models of all levels. For computational neuroscience, there are a lot of websites for dataset sharing. Collaborative Research in Computational Neuroscience, or CRCNS (https://crcns.org/) is a good resource to find data sets of the brain. It also provides some software tools that we can use to analyze data. Datasets can also be found from websites for specific projects, such as the Human Connectome Project (http://www.humanconnectomeproject.org/data/) and the Brain Genomics Superstruct Project (https://dataverse.harvard.edu/dataverse/GSP)

A *four-year course grid* or similar plan showing your schedule for completing your major and other graduation requirements. A course grid form is available at online or from the CIS office, or you can write up your own plan on a separate (single) page.