Proposed PHYS 590 Research Thesis Topics, 2022

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The Blohm lab uses a combination of computational models and experimentation to understand sensory-motor processes in the brain - we do neuro-physics (http://www.compneurosci.com/). Proposed projects require knowledge in numerical methods.

1. Design, implement and analyze an artificial neural network that performs multi-sensory integration in a causal fashion. Multi-sensory integration is combining redundant information (e.g. you can localize a dog by hearing it bark and by seeing it; and both). However you don't want to combine unrelated information (e.g. seeing a dog and hearing a meow).
2. Design and implement spiking neural network models to investigate distributed computational principles, such as synchronization in oscillatory sub-nets, entrainment of oscillations, stochastic facilitation, and their consequence for macroscopically measurable electro-magnetic signals, such as measured with Electroencephalography (EEG) or MEG.
3. We are open to suggestions from students with specific other interests feel free to contact me!

Joseph Bramante (joseph.bramante@queensu.ca)

1. **Theory and analysis for heavy dark matter**

   The hunt for dark matter continues at underground experiments, with gamma ray detectors in space, and using rich datasets that catalog the structure and history of our universe. Certain kinds of heavy dark matter present unique signatures and detection opportunities. Projects along these lines include new analyses looking for super-nanoscale dark matter in publicly available data from underground search experiments, studies of dark matter's impact on interstellar gas clouds, and simulation of galaxy formation modified by dark matter that induces white dwarf explosions.
2. **Early universe cosmology and gravitational substructure**

   The coarse gravitational features of galaxies, galactic clusters, and the large scale structure of our universe have been established using myriad tracers of matter in our universe. However, there is the intriguing possibility that there is extra gravitational "substructure," detectable using a number of methods including weak lensing and stellar astrometry. Projects along these lines include developing theoretical models that describe early universe formation of extra substructure, developing new techniques to look for substructure using observation, and modeling the historic transit of dark matter substructures through the earth.

Tucker Carrington (Tucker.Carrington@queensu.ca)

All projects in my group involve using numerical methods to study properties of molecules. Possible topics include:

1. Develop new tools for using the Gaussian processes variant of machine learning to fit potential energy surfaces.
2. Develop new computational tools for studying inelastic molecular collisions in interstellar space.

Stéphane Courteau (courteau@queensu.ca)

1. **Is there a Universal Rotation Curve?**

   Our research group maintains the largest and most complete compendium of galaxy rotation curves with matching light profiles, in the world. The student will use this exceptional data base to investigate the unique, and possibly universal, mapping of RCs and light profiles via the method of Principal Component Analysis. We will investigate numerically whether there exists a simple mapping between the rotation curves, the surface mass density, the dark matter fraction, and other key structural parameters of galaxies.

   This coding-savvy project will exploit Python programming and the manipulation of very large data bases in the context of a state-of-the-art investigations of the interplay between luminous and dark matter in galaxies. This project is partly motivated by the paper:

   The universal rotation curve of spiral galaxies - I. The dark matter connection Persic, Salucci, & Stel 1996, MNRAS, 258, 27

2. **The Density Distributions of Mock Galaxies**

   Detailed studies of galaxy formation require clear definitions of the structural components of galaxies. Are galaxy bulges and disks truly distributed according to simplistic models, such as exponential disks and concentrated (de Vaucouleurs/Sérsic) bulges? This project uses light and stellar mass profiles for the simulated NIHAO galaxies to test if the commonly assumed density distributions of galaxy structural components fit mock galaxies.

   This study involves Python programming, numerical methods (e.g., least square fits), and some understanding of galaxy observations and simulations. This project is partly motivated by the papers:

   NIHAO VI. The hidden discs of simulated galaxies Obreja et al 2016, MNRAS, 459, 467

NIHAO XVI. The properties and evolution of kinematically selected discs, bulges, and stellar haloes Obreja et al 2019, MNRAS, 487, 4424

James Fraser (james.fraser@queensu.ca)

1. **Photonics at the Nanoscale**

   The new Nanophotonics Research Centre aims to explore photonics of nanoscale materials, with the goal of understanding new physics and developing new applications. We need help in designing, implementing, and testing new optical set-ups for the Centre. This is an in-lab research project that will help you develop your experimental optics, data collection, computer integration, and/or analysis skills. Your schedule will need to be sufficiently flexible that you can meet weekly with the team and supervisor. You will also need to follow university-mandated safety training to become a laser worker.

Jun Gao (jungao@queensu.ca)

1. **Polymer-based light-emitting devices** and **polymer solar cells** are attractive candidates for display, lighting and energy harvesting applications. Semiconducting polymers offer interesting electrical and optical properties, solution processibility, chemical tenability and mechanical flexibility that are unrivaled by conventional inorganic semiconductors. These 590 projects aim to explore the design, performance, and physics of these polymer photonic devices through fabrication and testing and/or modelling and simulation.

Guillaume Giroux (ggiroux@owl.phy.queensu.ca)

1. **The search for dark matter with the PICO bubble chamber**

   PICO is an international collaboration working at searching for dark matter at SNOLAB using superheated liquid detectors, or bubble chambers. The most recent iteration of the experiment, PICO-40L, is set to start taking data soon and will allow the exploration of new dark matter models. PICO-500 is the next generation, ton-scale bubble chamber, to be constructed at SNOLAB. Research topics are available in the fields of data analysis (dark matter search data and calibration data), detector simulation, detector design and R&D.

2. **The search for dark matter with the NEWS-G spherical proportional counters**

   NEWS-G is an international collaboration aiming at the detection of low-mass dark matter particles using spherical proportional counters (SPCs) installed in the deep underground laboratories of LSM in France, and SNOLAB in Canada. A 140-cm SPC made from ultrapure copper will soon be installed at LSM and SNOLAB and will have unprecedented sensitivity to light dark matter particles. Research topics include data analysis, detector simulation, and detector calibration using SPCs located at QueenÕs.

Sarah Sadavoy (sarah.sadavoy@queensu.ca)

1. **The role of magnetic fields in star formation**

   Magnetic fields can greatly affect the star formation process, from suppressing the formation of a planet-forming disk and multiplicity, to delaying collapse and setting the star mass. The most common way to probe magnetic fields is from polarized emission from dust grains. This project will use newly obtained dust polarization observations at 0.85 mm from the James Clerk Maxwell Telescope for small clouds. We will utilize standard techniques to measure the magnetic field strength from the polarization measurements. We will then use complementary observations at other wavelengths (from Herschel) and complementary molecular line emission from the literature to compare the magnetic energy to the gravitational potential energy and turbulent energy in the cloud and determine its dynamical state and whether or not the magnetic field is important to its evolution. We will also use these data to examine changes in the dust properties themselves and how those changes may affect the inferred magnetic field structure. This project will require using computer programming to apply model techniques such as a Monte Carlo Markov Chain (MCMC) and basic statistics.

Bhavin Shastri (bhavin.shastri@queensu.ca)

1. **Photonic neural networks for PDE solving**

   Neural networks have enabled applications in artificial intelligence through machine learning. Software implementations of neural networks on standard digital computers are limited in speed and energy efficiency. Photonics (optical physics) provides an entirely new way building computing platforms (i.e. processors) that use light (photons) instead of electric signals. By combining the high bandwidth and efficiency of photonic devices with the adaptive, parallelism and complexity like the brain, photonic processors have the potential to be orders of magnitude faster than electronic processors while consuming less energy. The goal of this thesis will be to design and implement neuromorphic photonic processor that can solve tasks such as partial differential equations (PDE) and optimizations problems, orders of magnitude faster than CPUs. This could be an open-ended project with potential to lead to a first-authored journal article. Expectation: student should be strongly self-motivated.

2. **Cryogenic compatible photonic network for computing**

   Quantum and superconducting single flux quanta (SFQ) computing platforms operate at cryogenic (4K) temperatures. Signals from these platforms are small (mV), ultrafast (GHz), and can decohere easily. Processing these signals for tasks such as qubit readout classification or dimensionality reduction, possess a serious challenge—as such tasks are most effectively performed with machine learning algorithms implemented on neural networks. However, processing these high bandwidth and small signals ex-situ in real-time is not possible with the latency associated in getting these signals out. The objective of this thesis will be to propose a low-temperature neural network enabled by nanophotonics (optical physics) and 2D materials like graphene. Specifically, this thesis will study devices such as graphene-based optical modulators as neurons and how they can be interconnected to form a cryogenic-compatible network.

Stephen Hughes (shughes@queensu.ca)

1. **Theory and computational projects in quantum optics**
2. **Theory and computational projects in electromagnetism and nanophotonics**
3. **Computational projects in inverse design and deep learning in photonics and quantum optics**

Kristine Spekkens (kristine.spekkens@rmc.ca)

1. **Probing Galaxy Evolution with Star-Forming Gas**

   How do galaxies like the Milky Way evolve? Where and how do they get their gas? How is their dark matter distributed? What is the fate of the smallest galaxies in the universe? All of these outstanding astrophysical questions can be probed using observations of the star-forming gas in nearby galaxies. This PHYS590 project will focus on one aspect within this broad theme, with the specific project tailored to the student's interest. Example projects include constraining the atomic gas content in the smallest and faintest known galaxies, searching new survey data for the ionised gas shreds of colliding galaxies, or writing code to derive the orbital velocities of the gas in Milky Way-like systems to measure dark matter.

Greg van Anders (gva@queensu.ca)

1. **Robust Distributed Systems Design**

   One of the challenges in distributed systems design is understanding the interactions between whole systems and consituent elements. One example of this is in the context of transportation networks. For example, how an airline manages traffic volumes and routes between destinations affects the design of individual aircraft components. State-of-the-art approaches to this problem attempt to optimize aircraft component design for fixed traffic, but it is difficult to understand how changes traffic lead to changes in component specifications. This project address this problem by using statistical physics techniques to understand how systems-level changes in network traffic exert forces on aircraft design.

2. **Lock-and-Key Design**

   Because living things are divided into cells, that organization means lot of different, functionally orthogonal chemical pathways need to play out in the same tiny, cellular reaction vessel. One of the ways that nature solves this problem is via Fischer's lock-and-key principle. This principle describes the interaction specificity between, enzymes and substrates, hormone and receptors, and drugs and various targets, among others. One of the things that make the lock-and-key principle work is geometric complementarity, but we don't have a complete understanding of how that works because complementarity coexists with chemical specific interactions (moeties in chemistry language) that also affect interactions. In this project we want to understand how to leverage purely geometric realizations of the lock-and-key mechanism to understand isolate the role of geometric complementarity in the molecular machinery of biochemical processes.

3. **Flashpoints in Land Use Change**

   The United Nations has reported that two key challenges humanity will face in this century are climate change and urbanization. A key problem in meeting both of these challenges is finding ways to address how people will change the way they use land. People typically approach land allocation via optimization techniques, however, optimization only works for problems that have a closed form where everyone agrees on the relative importance of all of the different forms of land use, which is never the case in practice. This project will use statistical physics techiques to study tradeoffs among priorities for land use to identify potential flash points where different desired uses are likely to come into contact.

4. **Artificial Intelligence: Shining Light into Black Boxes**

   Artificial intelligence provides an important set of algorithms for automating tasks that have typically been done by people. This can save human labour, however, evaluations done by machines can reproduce the discrimination exercised by human decision makers, which raises serious questions for applying machine learning to evaluate resumes, assess parole eligibility, screen graduate school admissions, etc. Figuring out how to remove these biases is difficult because part of the power of artificial intelligence is its black-box approach to achieving optimal behaviour. This project will use techniques from statistical physics to interrogate the ways that biased training data get encoded in artificial neural networks with the goal of working toward methodologies to reduce discriminatory outcomes.

5. **Nanoparticle self-assembly: Are good stabilizers good crystallizers**

   Self-assembly is an approach to nanomaterials development where basic material building blocks spontaneously form a target structure in solution without needing to be guided. Getting robust self-assembly requires two things: getting the building blocks to form the structure (kinetics), and then getting the structure to be stable once it has formed (thermodynamics). Recent work from our group has demonstrated how to solve the stability problem. However, getting the particles into the target structure is a separate problem. This project aims understand whether there is a relationship between nanoparticle designs that are good for thermodynamic stability and ones that are good for self-assembly kinetics. This project will involve computational work using industry-leading, open-source molecular simulation software.

Gregg Wade (Gregg.Wade@rmc.ca)

1. **Convection-driven decay of fossil magnetic fields in cool main sequence stars**

   Fossil magnetic fields - present at the surfaces of about 10% of main sequence A, B and O type stars - decline precipitously in frequency around spectral type F0 before being quickly replaced by dynamo fields at cooler temperatures. What is the origin of this abrupt transition in the qualitative character of stellar magnetism? We are testing the hypothesis that the hydrogen convection zone, growing with decreasing effective temperature, results in the systematic decay of fossil fields. This project will involve the analysis of new magnetic field measurements, as well as a systematic examination of TESS photometry and high resolution spectroscopy, to determine the magnetic and surface convective properties of a sample of cool magnetic A stars. Ultimately the results will be used to confront predictions of a new model of the interaction between fossil magnetic fields and convection.

Larry Widrow (widrow@queensu.ca)

1. **Galaxic Dynamics with Gaia**

   In June 2022, Gaia, a space telescope operated by the European Space Agency, will release astrometric data giving estimates for positions and velocities for 35 million stars in the disk of the Milky Way. Further data releases in the coming years will bring the number of stars with position and velocity information to 1 billion or about 1% of the stellar content of the galaxy. The Gaia phase space maps provide an unprecedented opportunity to probe the dynamics of our galaxy and test models for interactions between the stellar disk and the dark matter halo. The 590 project will use numerical N-body simulations and statistical modelling, including machine learning methods, to explore this data set. The project is suitable for a student with a strong interest in computational and mathematical physics. Course work in astrophysics, while useful, is not essential.

Alex Wright (awright@queensu.ca)

1. **The SNO+ Neutrino Experiment**

   The SNO+ experiment will study fundamental neutrino properties using a 780 tonne liquid scintillator target. In particular, we plan to study details of the neutrino-matter interaction by measuring low energy solar neutrinos; make a precision measurement of neutrino oscillation parameters by detecting anti-neutrinos produced by nuclear reactors; study the composition of the Earth's crust and mantle by measuring the geo-neutrinos; probe the development of a supernova explosion and study neutrino behaviour in high density matter by detecting the neutrinos from a supernova (should one occur while we are running!); and attempt to determine whether or not neutrinos are their own anti-particles and determine the absolute neutrino mass by searching for neutrinoless double beta decay.

   SNO+ has just been filled with liquid scintillator. We now plan collect a period of physics data before beginning to add the double beta decay isotope to the detector. PHYS 590 students will have the opportunity to be involved in the analysis of this data, with possible topics including detector simulations, event classification, event reconstruction, and analysis of calibration data.