Poster Session Abstracts

Experimentation and development of a snake robot jamming gait
Diya Agarwal
Mentors: Howie Choset, Gunter Niemeyer, Andy Vu, and Bhaskar Vundurthy

Modular snake robots are essential tools for search and rescue applications due to their flexible structure and diverse locomotion capabilities. While existing gaits–modeled after biological snakes–allow the snake to navigate on flat surfaces and pipes, they often fail in unstructured environments, such as in rubble-filled voids or complex truss structures. This research addresses that gap by developing a biologically-inspired jamming gait, where the snake creates anchor points to move forward by pressing itself against uneven surfaces. This jamming technique supports the snake's weight and facilitates forward motion. The main objective is to use these static friction holds to develop a stable and controlled way to reach elevated surfaces in irregular or non-planar environments. To characterize this behavior, our main methodology involves a series of controlled experiments to determine optimal jamming configurations, strength, and repeatability by varying joint angles and contact forces. An adjustable 3D testing structure will be designed and constructed to facilitate these tests. While results are pending, this project will define parameters for a reliable jamming gait. This work will provide a foundational understanding of this novel locomotion and the capabilities of the snake robot, and offer further recommendations for its implementation in autonomous systems.

Comparative analysis of relative earthquake relocation methods: ReSpair and GrowClust3D.jl applied to the Bárðarbunga volcanic region
Levi J. Alderete
Mentors: Elias Heimisson and Ylse Anna De Vries

This project investigates two computational approaches for improving the relative relocation of seismic events: ReSpair, a MATLAB-based optimization method, and GrowClust3D.jl, a Julia-based clustering algorithm. The primary objective is to evaluate how each tool performs when applied to real seismic data, using the Bárðarbunga volcanic region in Iceland as a test case. The project integrates differential travel-time data with velocity models and applies iterative relocation routines under various threshold parameters. The ReSpair codebase was modified to enhance scalability and efficiency, allowing for systematic experimentation with event inclusion criteria. Preliminary results suggest that relocation accuracy and coverage are sensitive to parameter tuning, particularly threshold values controlling event clustering. Future work will refine these parameters and conduct quantitative comparisons of output catalogs from both tools. This study contributes to ongoing efforts in high-resolution earthquake mapping by providing insight into the comparitive and strength of a widely used relocation method and the developing ReSpair method.

Chiral allene formation via vinylcation intermediate
Ali S. Almosa
Mentors: Hosea Nelson and Yucheng Fu

Allenes are unique π-conjugated systems with axial chirality that make them valuable precursors for materials with circularly polarized luminescence and self-assembly properties. Current strategies for enantioselective allene synthesis rely heavily on metal-catalyzed transformations of alkynes, while purely organocatalytic approaches remain underdeveloped. In this work, we investigate a novel pathway to chiral allenes through vinyl cation intermediates, a high-energy species traditionally generated via solvolysis or vinyl triazene protonation. Building on recent advances in vinyl cation stabilization through strong Lewis acids and tailored leaving groups, we aimed to design ion-pairing catalysts capable of both promoting vinyl cation formation and imparting high enantioselectivity. Our synthetic efforts focused on preparing protected ion-pairing precursors, including MOM- and Me-protected dibromo intermediates, with characterization confirmed by NMR and high-resolution mass spectrometry. Although attempts at final catalyst formation using carborane coupling encountered challenges, our progress demonstrates the feasibility of stabilizing vinyl cations for asymmetric transformations. Ongoing work will optimize protecting groups and catalyst design to enable efficient, enantioselective chiral allene synthesis via this underexplored β-H elimination pathway.

Design and analysis of a 3D-printed gaseous oxide/liquid nitrogen resonance igniter in a bipropellant engine
Sophia-Marie N. Andrews
Mentor: Morteza Gharib

This project focuses on the design and testing of a gaseous oxide (GOX)/liquid nitrogen (LNG) resonance igniter and cavity. Moreover, we investigate its feasibility and performance for rocket propulsion applications, specifically focusing on its ability to provide reliable and efficient ignition. Ignition through a resonance igniter consists of sending compressed oxygen (GOX) through a nozzle, which travels at supersonic speed as an underexpanded jet; this is then sent into the cylindrical cavity, also known as the resonator, where both the temperature and pressure of the GOX rise significantly due to emission of shock-waves. Once mixed with the fuel in the combustion chamber, due to the oxidizer now being at an incredibly high temperature and pressure, this becomes sufficient enough to combust when coming into contact with the fuel. Therefore, the objective is to design, conduct CFD-based thermal-fluid analysis, and fabricate a Hartmann-Sprenger type resonance igniter under controlled gas inlet conditions, as well as a test setup with adjustable nozzle-cavity spacing. Experimental data suggests that such geometry amplifies acoustic pressure oscillations and thus enhances ignition potential. Future work will focus on transient high-speed diagnostics and refining the nozzle-cavity design to further validate reliability and efficiency.

Impact of bacterial community structure on plasmid conjugation efficiency assessed through colony-forming units
Ava K. Balanon
Mentors: Sujit Datta, Danielle Sclafani, and Pablo Bravo

By 2050, antibiotic resistance is projected to cause 10 million deaths annually, largely driven by horizontal gene transfer through plasmid conjugation. While conjugation dynamics are well studied in liquid cultures, natural microbial communities often grow in structured environments where spatial confinement and restricted motility may alter transfer efficiency. Thus, in this project, we analyze how bacterial community structures affect conjugation efficiency under the stress of antibiotics. We quantify plasmid transfer under three conditions: liquid LB media, well mixed granular hydrogel, and 3D-bioprinted hydrogel clusters of varying densities. We use *E. coli* strains expressing different fluorescent proteins to distinguish between recipient and donor cells. Then, we quantify conjugation efficiency by comparison of colony-forming unit counts on agar plates with and without antibiotics. We hypothesize that conjugation efficiency will be optimal at an intermediate hydrogel concentration where cells are confined long enough to interact but not so restricted that motility is inhibited, decreasing the total number of cell-cell contacts. This approach is used to clarify how spatial structure influenced the spread of plasmids and provided insight into the role of bacterial community structure and the evolution of antibiotic resistance.

A fully integrated optical alignment system for the Andor Spectrometer
Jonathan G. Barata
Mentors: George R. Rossman and Helen V. Evans

The Andor Spectrometer is a spectroscopy system that uses a wide range of wavelengths to analyze the absorption spectra of any mineral. The biggest hurdle in using the spectrometer is the fact that in order to focus light into the fiberoptic detector a series of stages need to be manually aligned to even get close to a smooth signal and proper alignment. To remedy this, we switched to a microscope that focuses light through a custom-made made optical system, using two concave lenses, into a 3D printed set up. The setup not only holds the detector at just the right distance from the lenses but also has a built-in compartment for a polarizer, which allows for comparison between polarized and unpolarized light. The microscope has a singular stage that can be manipulated via a joystick, meaning less room for error and more precise control over alignment. The stage, however, still needs to be aligned in a way that maximizes light through any given sample. We came up with a system that uses a photodiode, transimpedance amplifier, and a microcontroller to measure light output from the microscope and compare it with pre-calibrated values for every possible lens setting. This would then be run through a microcontroller to output an audible pitch scaled to the lens that indicated maximum alignment and thus proper light input to the detector.

Turning light into flow: Active matter driven microfluidic pumps
Rishi Bhargava
Mentors: Matthew W. Thomson and Hao Wang

Physiological processes like vascular remodeling and embryonic development occur under slow interstitial flow (~ μm/s). Conventional microfluidic pumps rely on rigid, non-biocompatible materials, limiting their use in live-cell biological models. This project introduces a new paradigm for biological modeling by developing a biocompatible, programmable microfluidic pump powered by a microtubule kinesin motor solution.

Five pump geometries were simulated *in-silico* and fabricated via Polydimethylsiloxane (PDMS) soft lithography. Negative control trials using M2B buffer and tracer beads (1 μm) showed low average speeds (1.5 – 3.6 μm/s), minimal directionality, and near zero flow rates (0.0001 – 0.0021 μL/min). One-way ANOVA revealed significant differences among controls ($F(4,86) = 3.11$, $p = 0.019$), likely due to residual loading pressure. A Welch's t-test confirmed that flow from a microfluidic syringe pump (average speed: 30.96 μm/s) was significantly greater than from any negative control ($t \approx -200.5$, $p < 10^{-120}$), demonstrating that any future flow observed in active matter experiments will result from active matter activity rather than experimental artifacts.

Active matter trials will continue once microtubule supply is restored. This work establishes validated experimental and computational frameworks. Future efforts will aim to optimize device performance and incorporate cells within PDMS to establish novel models for pathology.

Investigating the roles of macrophage sources in mouse digit tip regeneration and scarring
Beatrice K. Cai
Mentors: Kai Mesa, Lea A. Goentoro, and Emily A. Polk

Macrophages are essential for digit tip regeneration in mammals, yet the distinct roles of monocyte-derived versus tissue-resident macrophages remain unclear. Using a mouse model of distal (regenerative) and proximal (non-regenerative) digit amputations, we examined spatial and temporal distribution of macrophages and how macrophage origin influences regenerative outcomes. Two-photon live microscopy of *Csf1r-EGFP* mice reveals that regenerative wounds form a blastema enriched with rounded macrophages positioned near the wound edge, while non-regenerative wounds exhibit elongated macrophages and horizontally aligned extracellular matrix. To test the role of monocyte-derived macrophages, we use *Ccr2-RFP* (knock-in/knock-out) mice, which lack efficient Ccr2-dependent monocyte recruitment. Digits from heterozygous and homozygous mice are amputated and analyzed via cryosectioning, immunofluorescence, and image quantification using FIJI and Imaris. Preliminary results show smaller blastemas in homozygous mice along with diminished bone regrowth. These findings suggest that monocyte-derived macrophages promote blastema formation and structural regeneration, while resident macrophages alone may be insufficient to support full tissue repair. Understanding the distinct roles of macrophage subsets may inform future strategies to regulate the immune response and improve regenerative outcomes in mammalian wound healing.

Structural and functional characterization of the nucleocytoplasmic transport of MAPK14
Ioana M. Caraus
Mentors: André Hoelz and Chia-Yu Chien

Cells have evolved to thrive in constantly changing living conditions by rapidly detecting and responding to extracellular stress. The mitogen activated protein kinases (MAPKs) play a key role in the cellular response to a wide range of stimuli, by translating extracellular signals into a cascade of intracellular phosphorylation events. MAPK14 is one of the most extensively studied member of the MAPK family. Initially, it was believed that MAPK14 acts as a tumor suppressor, yet recent studies have revealed its tumor promoter activity. The apparent dual role of MAPK14 as a tumor promoter and suppressor made the attempts to develop anti-cancer therapies against MAPK14 unsuccessful, outlining the gaps in knowledge regarding the MAPK14 pathway – such as the transport of this protein through the nuclear pore complex. Nucleocytoplasmic transport of molecules is tightly regulated and dependent upon interactions with transport factors that facilitate cargoes to pass through the diffusion barrier formed by the FG-nucleoporins of the nuclear pore complex. By extensive recombinant protein expression and purification, pull-down assays were conducted and multiple transport factors binding to MAPK14 have been identified. These screening results will further serve as a basis for the structural elucidation of the MAPK14•transport factor complexes.

Existence and stability of traveling-wave solutions to a generalized Korteweg-de Vries-Burgers equation
Dora Chatterjee
Mentors: Jared C. Bronski, Omer Tamuz, and Vera Hur

This project expands upon the existence and stability of traveling-wave solutions to a generalized Korteweg-de Vries-Burgers equation. To be specific, the equation that we are looking at is the following:$(\Phi^2/2) - (1/2) = \Phi_x + v\Phi_{xxxx}$ which is a 5th order ODE. A related model, the Korteweg de Vries (KdV)-Burgers equation: $u_t + (u^2/2)_x = u_{xx} + vu_{xxx}$ with conditions $u(x, 0) = \Phi(x)$ was proposed by Whitham as a model for undular bores, a natural phenomenon where high tides at a river mouth lead to waves propagating upstream against the flow of the river. An undular bore is a type of dispersive shock wave that is formed when a disturbance in fluid evolves into a series of oscillations due to dispersion and nonlinearity. The reason why we would like to understand non-monotone bores is that they consist of complex wave structures that are difficult to capture in standard shock models. We have numerically constructed the bore profile and used it to verify the spectral condition that Blake, Bronski, Hur, and Zhao found in their paper. Specifically, we use spectral methods such as series expansion to conduct a matching of the left and right sides of $\Phi(x)$.

Knowledge transfer in ResNet and vision transformers: Investigating asymmetric data distributions and alternative training paradigms for computer vision
Shravani A. Deshmukh
Mentors: Pietro Perona and Fengqing Yu

In real-world settings, data often follows a long-tailed distribution, where a few “head” classes contain abundant examples while the majority of “tail” classes remain underrepresented. This imbalance raises critical questions about whether knowledge learned from head classes can transfer to improve tail-class recognition. In this project, we rigorously evaluate two leading architectures—ResNet-50 and Vision Transformers (ViTs)—across a range of head–tail splits. Our findings demonstrate that head classes do not aid tail classes in either architecture, confirming that no meaningful transfer of learning occurs from head to tail. This result highlights a fundamental limitation in current approaches to imbalanced classification and underscores the need for methods explicitly targeting the tail regime. As a step in this direction, we also implement a custom class-conditional GAN to generate synthetic images for tail classes, in place of large-scale diffusion models. While the impact of these GAN-based augmentations remains under evaluation, their inclusion provides a concrete pathway to test whether targeted synthetic data can address the lack of transfer and improve learning under extreme class imbalance

Optical phase stability in large-scale quantum networks
Elizabeth C. Ellison
Mentors: Maria Spiropulu, Andrew Cameron, and Si Xie

Quantum entanglement is a powerful feature of quantum mechanics that has valuable implementations within quantum communication. Quantum networks rely on quantum mechanical properties of single photons to transfer data between nodes, using entanglement to overcome classical limitations. Other encodings, such as the dual rail encoding, enable long distance communication but require strict control of the stability of the optical phase in fiber. Within our group, INQNET (Intelligent Quantum Networks and Technologies), entanglement has been achieved through multiple means (polarization, time-energy, etc.). There is a powerful new quantum key distribution protocol, twin-field, that can increase communication distances. The protocol only relies on a single photon making it through a fiber rather than requiring two photons to both successfully pass through fibers. Phase stabilization has significant implementation complexity, with our group previously only maintaining stabilization over centimeters in distance. This project aims to analyze phase fluctuations over a 2.5 km link at Fermilab. With an understanding of the magnitude and frequency of phase fluctuations in the link, a feedback loop can be built using QICK (Quantum Instrumentation Control Kit), a FPGA based system with closed loop controls capable of operating up to 1 MHz in rate.

Sparse graphical designs and the Kolm Pollak-EDE: Investigating the equity of spectral geometry
Jawhara A. Emhemed
Mentors: Catherine Babecki and Drew Horton

A graphical design is a framework that uses the eigenvectors of the graph Laplacian to find a small subset of nodes that efficiently represents the entire network, analogous to a quadrature rule for numerical integration. These designs are computationally tractable as they can be found by solving a linear program. In contrast, the Kolm-Pollak Equally Distributed Equivalent (EDE) is a metric that balances average outcomes with a penalty for inequality. We seek to understand if the graphical design solution is inherently equitable. To investigate this hypothesis, we compare our graphical designs to a facility location model that directly finds the most equitable placement of resources by optimizing the Kolm-Pollak EDE with an integer program. We test both models on theoretical and real-world graphs. Our results show that on highly symmetric graphs, the graphical design method can be suboptimal compared to the KPL model due to eigenspace multiplicity. However, in realistic models and even in these suboptimal cases, a graphical design is often fairly equitable and saves greatly on computational costs. This makes it a practical alternative for large-scale networks where both efficiency and fairness are desired.

The effect of non-instantaneous switching on time-modulated array performance
Nerissa A. Finnen
Mentors: Hua Wang, Ali Hajimiri, and Basem Ali

Time-modulated arrays (TMA) are an emerging subfield of phased array research. Phased arrays are valued for their electronic beam steering. Traditionally, a phase shifter controls the electromagnetic wave's phase to enable constructive interference of individual elements to form the desired beams. Instead, the TMA employs newly developed high-frequency switches that simplify beam steering by selective antenna activation. This ability lends itself to a wide range of applications from communication devices to high-resolution imaging and radar detection systems. This additional modulation period generates multiple beams that are absent in typical phased arrays. To harness this effect engineers develop switching patterns that optimize the lobes for specialized multibeam formations or sidelobe suppression that enhances a main beam. The switching schemes assume that changes between the on and off states occur instantaneously. In practice, switching takes time, introducing timing overlaps between antenna activation intervals that degrade the radiation pattern. This study investigates the effect of a finite switching period on TMA lobe patterns through analytical derivations and simulations. The simulations visualize lobe degradations that arise from the difference between analysis techniques. The results provide insights that can guide the design of future TMAs.

Design and implementation of a drop on demand (DoD) system for automated drop casting of a radiolytic precursor target
Sophia E. Gershaft
Mentors: Nick R. Hutzler and Phelan Yu

The Hutzler lab is presently studying the possibility of using ultracold, radium-containing molecules as a sensitive, next-generation platform for measuring possible time-reversal violating physics in the nuclear sector. The laser fluorescence spectroscopy experiment utilizes a target consisting of radium-226 salt drop cast onto a gold-plated copper substrate. The current manual drop casting technique results in an inhomogeneous target and an inconsistent yield of precursor to the vapor phase during laser ablation. Inconsistent amounts of atoms are introduced into the gas phase, which subsequently translates to fluctuations in spectroscopic intensity peaks. Thus, systematically addressing this problem would improve signal-to-noise ratio and sensitivity of the cryogenic spectrometer. Introducing a drop on demand (DoD) system allows for reproducibility and automation of the target preparation process. The DoD system was constructed, in which individual droplets are dispensed by a PipeJet nanoliter dispenser onto piezoelectric XY stages, allowing for a precise printing-like effect for target preparation. The system is operated by hardware controls using an ADC board and code written in LabVIEW.

Brown dwarfs in eclipse: A nested sampling approach to inferring internal temperature via broadband photometry
Aryan Gupta
Mentors: Andrew W. Howard and Steven Giacalone

Brown dwarfs occupy a curious middle ground in exoplanetary systems. Although they orbit host stars like exoplanets, their atmospheric structures and strong internal heat contributions resemble low-mass stars. Close-in brown dwarfs are especially valuable targets, as measuring their internal temperatures can offer key insights into their formation histories — whether they form through planet-like core accretion or star-like gravitational instability mechanisms. In this work, we extend the HELIOS radiative transfer code to generate a grid of 121 brown dwarf atmospheres of varying internal temperatures and heat redistribution efficiencies. From these models, we compute secondary eclipse depths across multiple observed photometric bandpasses. By comparing simulated and observed eclipse depths, we implement a nested sampling framework using Dynesty to retrieve posterior distributions for internal temperature and the heat redistribution efficiency. We also investigate how the uncertainties on internal temperature depend on the choice of photometric bandpasses used. Ultimately, this approach will enable us to estimate the internal temperatures of five close-in brown dwarfs, combining scheduled observations on Palomar's WIRC instrument with TESS archival data. These results may shed light on how intrinsic properties, such as mass and energy transport, influence the thermal evolution of brown dwarfs in stellar systems.

Spectral gap and mixing times in the repeated averages process on graphs
Nikash Gupta
Mentor: Lingfu Zhang

The repeated averages process is a stochastic averaging dynamics on graphs, with mixing times characterized for several structured families such as the complete graph, cycle, hypercube, and binary tree. A general expression applicable to all connected graphs, however, remains unknown. Existing conjectures propose that the mixing time is governed by the spectral gap of the graph Laplacian, but this relationship has not been fully established. We analyze specifically the L2 to L1 mixing time, focusing on graphs constructed by combining cliques and cycles. These constructions maintain rapid local averaging while introducing small spectral gaps, and the results suggest that they may mix faster than predicted, providing evidence that the conjectured dependence on spectral gap does not universally determine mixing behavior.

Mueller polarimetry of experimental interstellar dust analogs
Muhammed Halil
Mentors: Paul M. Bellan and Andre Nicolov

Interstellar asymmetric dust grains aligned with the magnetic field polarize starlight in the optical-to-infrared spectral range along the direction of minimum extinction. (Whittet 2022) Polarization measurements of interstellar dust are commonly used to study the magnetic field in the interstellar medium. (Andersson, Lazarian, and Vaillancourt 2015) Studies of the alignment process and dust polarization have been largely theoretical and simulation-based. This work aims to provide a laboratory foundation for interpreting astrophysical polarization observations. Experimental analogs of interstellar dust are created using the Caltech Ice Dust Plasma experiment. Ice grains are formed in a low-temperature (50–170 K), low-pressure (100–2000 mTorr) weakly ionized plasma, with an ionization factor (~ 10−6). Ice grains grow to sizes up to 700 μm, exhibit fractal morphology, and are continuously levitated due to plasma confinement forces. (Nicolov, Gudipati, and Bellan 2024) A dual-rotating polarizer Mueller polarimeter is constructed to measure the Mueller matrix of the ice cloud. By measuring the Mueller matrix of the dust cloud, we investigate how grain alignment correlates with spatial distribution, temperature, pressure, and evolution over time.

Probing substituent influence on reactivity and selectivity in Pd-catalyzed Michael spirocyclization
Daood I. Hashmi
Mentors: Brian M. Stoltz and Christian Strong

Spirocyclic compounds bearing vicinal quaternary and tertiary stereocenters are prevalent in natural products and medicinal chemistry, yet remain difficult to access with high selectivity. Building upon recent work from the Stoltz group, this project aims to expand the substrate scope of an enantioselective Pd-catalyzed Michael spirocyclization that forms spirocycles via Pd-enolate intermediates. In particular, we seek to evaluate the feasibility of forming seven-membered rings by modifying the tether length and substitution pattern of β-ketoester substrates. To date, we have synthesized and characterized a substrate bearing a seven-membered ring precursor with methyl-phenyl substitution at the formerly prenyl position. Reactivity studies under established Pd-catalyzed spirocyclization conditions are ongoing. Additional substrates featuring diverse substitution patterns are currently in progress. These efforts will inform future mechanistic studies and help establish design principles for accessing larger spirocyclic systems through Pd-enolates.

Rainbow on a chip: High-performance visible and short near-infrared laser sources based on germano-silicate ultra-low-loss photonic integrated circuits
Hanfei Hou
Mentors: Kerry J. Vahala and Haojing Chen

High-performance lasers spanning the visible and short near-infrared (NIR) spectrum (380–1100 nm) are essential for emerging quantum technologies, yet their chip-scale integration is hindered by high material loss at shorter wavelengths. Germano-silicate glass has recently emerged as a promising photonic integrated circuit platform with potential for ultra-low loss across this full band. Here, we demonstrated integrated visible and short NIR lasers based on germano-silicate optical microresonators using two complementary approaches. In spectral regions with available semiconductor gain media (infrared, red, green, and blue), single frequency, narrow-linewidth hybrid-integrated lasers are demonstrated using self-injection locking scheme, reaching record-low fundamental linewidths below 100 Hz. In the spectral ‘green gap’ (530–600 nm) where no suitable gain media exist, we explore frequency-converted lasers based on third-harmonic generation. Together, these results establish germano-silicate as a versatile platform for visible and short NIR integrated laser sources, with broad potential for quantum information and precision measurement applications.

Investigating improvements to sensitivity of next generation gravitational wave detectors with internal squeezing
Umran S. Koca
Mentors: Lee P. McCuller and Sander Vermeulen

Current generation gravitational wave (GW) detectors like LIGO/Virgo use frequency dependent external squeezing incident on the dark port of the interferometer to improve sensitivity to strains. Research has been done on internal squeezing, putting the squeezer within the IFO in the Signal Extraction Cavity (SEC). Internal squeezing can improve detection bandwidth and strain sensitivity at high frequencies while not impacting low frequency sensitivity. However, no previous study has tried to implement directional internal squeezing. My project tests squeezing fields propagating toward the arms while anti squeezing field returning from the arms. I use the GW simulation package Finesse, with realistic loss values for injection and readout losses as well as a squeezer crystal with tunable, directional phases and amplitudes. I demonstrate that while internal squeezing does not provide a sensitivity improvement for Cosmic Explorer unless internal losses are less than 0.01%, this design could improve the sensitivity of LIGO above 1 kHz using internal losses on the order of .1%.

Verifiably correct datasets in first-order logic for large language model reasoners
Henry B. Lane
Mentors: Matthew W. Thomson and Tony Yue Yu

Current Large Language Models (LLMs) reasoners achieve impressive results on a wide variety of cognitively demanding benchmarks, yet still display extremely brittle and often formally incorrect reasoning steps on complex tasks, default to heuristic strategies that neglect logical faithfulness, and often collapse under minor adversarial perturbations. A key limitation for current LLMs is the lack of diverse verifiably correct and fine-grained training data sets that contain not only problem statements, but also formal proof steps. Methods which generate synthetic data, such as those that leverage automated theorem provers to mine lemmas, often explore a highly restricted and narrow subset of first-order logic space. In this report, we detail a new approach to address generation of synthetic first-order logic datasets in sequent calculus and natural deduction, called FOLSeqGen that constructs intuitionistic first-order logic sequents by the iterative forward application of Gentzen's G3i rules, a variant of Sequent Calculus. The generator samples uniformly over the rule schema, yielding proofs with a diversity of inference steps. As the system iteratively constructs sequents from a given random axiom set, all derived sequents are guaranteed to be verifiably correct and contain a proof trace, demonstrating the derivability of the sequent.

Dissecting zebrafish hunting behavior using deep reinforcement learning-trained recurrent neural networks
Raaghav Malik
Mentors: Kanaka Rajan and Markus Meister

Understanding how neural systems give rise to complex natural behaviors remains a central challenge in neuroscience. Larval zebrafish present a powerful model for addressing this problem, combining rich ethological behaviors such as prey hunting with a compact, transparent brain. While experimental work from groups including Engert, Roy, and others has illuminated key sensorimotor motifs in zebrafish hunting, the computational mechanisms that underlie these behaviors remain poorly understood. In this project, we introduce a complementary modeling approach that leverages deep reinforcement learning (DeepRL) to train recurrent neural networks (RNNs) to perform naturalistic hunting in a simulated zebrafish environment. Our contributions are threefold: (1) we develop a flexible, biologically inspired simulation framework with virtual zebrafish agents that perceive, move, and hunt in an arena consistent with larval behavior; (2) we conduct detailed behavioral analyses that recapitulate key hallmarks of zebrafish ethology, including vergence-linked hunting, speed modulations, and stereotyped approach trajectories; and (3) we extract emergent RNN dynamics to gain insights into possible algorithmic implementations of the hunting program.

We demonstrate that our agents develop a convergence-before-turning hunting strategy, reproduce known statistics of prey capture maneuvers, and exhibit behaviorally distinct explore/hunt regimes. Eye vergence dynamics closely track behavioral state and align with experimental observations.

Finally, we explore interpretable alternatives such as probabilistic finite-state programs and compare them to the RNN-based control policies. This work highlights the utility of task-optimized RNNs as mechanistic hypotheses for animal behavior and opens avenues for integrating them with biological data to better understand sensorimotor transformations in the brain.

Development of an inducible acoustic biosensor for protease activity using Plum Pox Virus protease and engineered gas vesicles
Neev Mangal
Mentors: Mikhail G. Shapiro and Jee Won Yang

Abstract withheld from publication at mentor's request.

Investigating thermophoresis and self-thermophoresis of aerosols in microgravity for improved climate modeling
Ama A. Obeng
Mentors: Jeffrey L. Moran, John O. Dabiri, and Jacob Velazquez

Aerosols in Earth's atmosphere influence its climate in several ways, for example by absorbing sunlight, which tends to warm the planet, or reflecting it, which tends to cool the planet. The mechanisms by which aerosols are transported through the atmosphere remain incompletely understood, which limits the accuracy of climate models. This project will test whether thermophoresis (particle migration in response to a temperature gradient) is important in driving atmospheric aerosol transport. Samples will be launched to the International Space Station (ISS), where microgravity eliminates the settling of particles due to gravity. This approach isolates the contribution of thermophoresis to aerosol transport, monitored using optical microscopy. My contributions to this project primarily lie in selection, procurement, and characterization of the aerosols that will be sent to the ISS: these are carbon soot, sodium chloride, and silica. The ISS-based experiments will provide valuable data quantifying their response to known temperature gradients, enabling their thermophoretic mobilities to be characterized as functions of particle material and size. We will also test polystyrene microspheres half-coated in a metal, which we hypothesize will undergo "self-thermophoresis" by asymmetrically absorbing light (and converting it to heat), thus being one of the first examples of particle self-propulsion through air.

Generating synthetic neural data via conditional diffusion for broader applicability of brain-computer interfaces
Sanvi Pal
Mentors: Nishal Shah, Joel W. Burdick, and Siyuan Tao

A key application of brain-computer interfaces (BCIs) is decoding intracortically recorded neural signals generated during attempted speech, helping restore the ability to communicate for people with speech impairments. A crucial limitation of current speech BCI systems is the large amount of time a participant has to spend in collecting training data for the speech decoder. Generating synthetic data that faithfully models neural dynamics for a target phoneme sequence could potentially accelerate speech decoder training and enhance the generalizability of speech BCIs to new users. Latent Diffusion for Neural Spiking Data (LDNS) is an unconditional diffusion model trained on intracortical spike recordings from a BrainGate2 participant (T12), during attempted speech. We observed that an RNN speech decoder achieving around 25% phoneme prediction error rate on real data performs significantly worse on LDNS-generated neural activity, revealing the limitations of unconditional generation. We explored conditioning LDNS on phonemes in two ways. First, we used a GRU-embedding of the entire phoneme sequence to condition the LDNS model. Second, we converted the sequence of target phonemes into a sequence of phoneme probabilities at each time point and used an embedding of the instantaneous phoneme probabilities as an input to the LDNS at each time-step.

Characterizing redox dependent structural changes of RuBisCO
Joel Kai Chen Pang
Mentors: Karthish Manthiram and Luis Burgos

Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) is the most abundant soluble carbon-fixing protein found in photosynthetic organisms. Although the enzyme's structure and catalytic activity have been a subject of thorough investigation, limited advances relative to the wild type have been attained. In this work, we posited that a limited understanding of the protein's structural changes as a function of redox potential has hindered efforts in the field. We employed an electrochemical approach to establish fixed solution potentials. Additionally, to predict redox influences in our system, we modelled permeating oxygen via a reaction-diffusion model on COMSOL Multiphysics software. These findings further elucidate an underexplored space in biochemical studies and could provide new foundations for rational protein engineering efforts.

Stress-testing distributional reinforcement learning: Calibrated risk control and out-of-distribution robustness in Atari under a 1M-step budget
Guanni Qu
Mentors: Sergei G. Gukov and Muhammad A. Shehper

Distributional reinforcement learning models full return distributions rather than means, enabling uncertainty awareness and risk-sensitive control. I present a reproducible evaluation of C51 and QR-DQN under realistic stressors and generalization tests. The protocol standardizes compute (≤1M environment steps per task), seeds (3), and evaluation, and reports mean±sd across seeds. A small-control validation established internal validity and robust defaults (support aligned to return scale; ~51 atoms) and showed n-step returns improve sample efficiency over a matched DQN. Building on that baseline, I target visually rich domains (Atari tasks). These results provide actionable guidance on when Distributional RL's distributional heads matter and how to set support/atoms for calibrated, risk-aware decisions that generalize OOD.

Sparse autoencoder neural operators: Model recovery in function spaces
Ailsa X. Shen
Mentors: Anima Anandkumar and Bahareh Tolooshams

We frame the problem of unifying representations in neural models as one of sparse model recovery and introduce a framework that extends sparse autoencoders (SAEs) to lifted spaces and infinite-dimensional function spaces, enabling mechanistic interpretability of large neural operators (NO). While the Platonic Representation Hypothesis suggests that neural networks converge to similar representations across architectures, the representational properties of neural operators remain underexplored despite their growing importance in scientific computing. We compare the inference and training dynamics of SAEs, lifted-SAE, and SAE neural operators. We highlight how lifting and operator modules introduce beneficial inductive biases, enabling faster recovery, improved recovery of smooth concepts, and robust inference across varying resolutions, a property unique to neural operators. This perspective provides a foundation for interpreting neural operators through the lens of sparse representation learning.

Dissecting root thermomemory: Heat stress priming and elongation dynamics in *Arabidopsis* through automated phenotyping
Katherine W. Tam
Mentors: Trevor M. Nolan and Xiaohui Li

With wildfires and increased temperatures damaging natural and agricultural environments, the need to understand and enhance plants' abilities to survive and flourish upon exposure to extreme heat is crucial through the study of root elongation dynamics in *Arabidopsis thaliana* upon heat stress and priming. After the exposure to a single heat event, the plant establishes a thermomemory which allows them to survive a more extreme heat stress event and to recover in the days after. The effects of a variation in temperature and duration of these exposures in the context of root dynamics are quantified and assembled into a phenotype x treatment matrix through automated phenotyping.

Automated data gathering is implemented through Smart Plate Imaging Robots (SPIROs); the data analysis pipeline is performed through an independently developed root measurement and graphing model. Preliminary results show favorable root elongation during recovery after priming at 32ºC and stressing at 42ºC with substantial characterization within this temperature range. Additionally, intriguing yet ambiguous phenotypes have emerged which demonstrate the effects of extreme heat onto root systems and the amazing paths for recovery. This study establishes the experimental methodologies and baseline characterizations for future genetic dissections of root thermomemory.

Cold gas thruster design, analysis, manufacturing, and testing for roll control of a self landing rocket
Miigwan D. Tanner-Wostrel
Mentors: Morteza Gharib and Jack N. Caldwell

The goal of this project is to build a cold gas roll control thruster for a rocket in development at PARSEC. This is necessary because the gimballing of the rocket's main engine will control the rocket's attitude, with exception of roll. The propellant in use is nitrogen tapped from the main propellant pressurizing tank. Using isentropic flow equations, nozzle geometry is determined and a minimum length nozzle contour is generated in Matlab using the method of characteristics. Nozzles with JIC connections are 3d-printed from acrylic and a nozzle bench test rig is built to determine nozzle performances. Informed by bench test results, a thruster system is designed for use on the rocket and metal nozzles are 3d-printed. Beyond this project, the final thruster system design will be tested, and if generated torque is too little or system mass is too great, the design will be iterated upon.

Polymer synthesis in *Comamonas testosteroni* KF-1 under nitrogen depletion
Madison Elle C. Tongco
Mentors: Ludmilla Aristilde, Jared R. Leadbetter, and Xinyu Chen

Comamonas testosteroni, a bacterium isolated from wastewater, is known for its ability to degrade plastic-related compounds, as well as its ability to produce polyhydroxyalkanoates (PHAs) as valuable biopolymers with potential applications in plastic waste valorization. We grew *C. testosteroni* on nitrogen-limited media with gluconate as the source of carbon and analyzed PHA production via confocal microscopy and flow cytometry. We found that the stationary phase of nitrogen-limited cultures produced the highest levels of PHAs. We quantified PHA monomers along with possible glycogen synthesis via liquid chromatography-mass spectroscopy (LC-MS). We obtained only medium-chain-length PHAs, with no short-chain-length PHAs and negligible levels of glycogen. Our findings thus illustrate the preferential production of selective polymers in gluconate-grown *C. testosteroni* under nitrogen-limited conditions.

Uncovering prospective planning and subgoal representation in human neurons
Samuel W. Xie
Mentors: John P. O'Doherty and Cooper Grossman

To understand how the human brain plans multiple steps ahead, this project investigates model-based hierarchical reinforcement learning (MB-HRL) using high-resolution intracranial recordings during epilepsy patients' performance of the Space Taxi task. Unlike fMRI, intracranial recordings provide sub-millisecond temporal resolution of single-neuron activity, enabling the study of how neurons encode intermediate subgoals during decision-making. Because information in the brain is often represented in a distributed fashion across neural populations, decoding analyses are a powerful tool for probing these representations. In certain regions, we are able to decode subjects' upcoming choices *before* they occur, and this accuracy improves with increased neural dimensionality—particularly in regions such as ACC and PRV. The project focuses on decoding plans for sequential choice during the early stages of the task to uncover prospective planning. Additional analyses explore cross-condition generalization and the geometric structure of neuron population activity using metrics such as parallelism scores. Challenges include dataset limitations that necessitate aggressive trial subsampling, potentially reducing classifier performance. Nevertheless, decoding analyses and population correlations offer promising insight into how neurons encode subgoals and value information. This work builds on prior studies of MB-HRL by applying decoding and representational geometry techniques to human electrophysiological data, providing new insight into how the brain structures future-directed planning.

Towards building a "toolbox" for the synthesis of bicyclo[3.2.1]octanes
Zhehao Zhang
Mentors: Sarah E. Reisman and Kala Youngblood

The Grayanane diterpenoids possess diverse bioactivities such as analgesic, antifeedant, anti-inflammatory, antinociceptive, and cAMP and ion channel inhibitory effects. The bicyclo[3.2.1]octane ring system found in the Grayananes remains a challenging project in natural product total syntheses, and existing methods are often hindered by racemic synthesis, limited access to oxidation patterns, or minimal synthetic divergence. Here, we report progress towards developing strategies for synthesizing bicyclo[3.2.1]octane systems with oxidation patterns found in complex grayananes with accessible cross-coupling handles. We can also envision access to a diverse set of bioactive grayananes through synthesizing differently functionalized bicyclo[3.2.1]octanes followed by coupling to a more conserved west-side fragment.