Caltech
Student-Faculty Programs

Alumni Weekend: Session 1 Abstracts

Mapping the human speech cortex with a multi-scale foundation model
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Mentors: Edward Chang, Ueli Rutishauser, and Shailee Jain

Understanding how the human brain processes speech is essential for uncovering the neural basis of communication, a cornerstone of social interaction, culture, and cognition. While prior studies have linked specific brain regions to distinct speech features, a large-scale investigation of global brain dynamics and fine-grained spatial organization across many individuals has not yet been conducted. The Chang Lab is building the first large-scale AI-based simulation of the human speech cortex, enabling accurate, high-resolution predictions of population-level electrocorticography (ECoG) responses to naturalistic language. Leveraging over 50,000 ECoG electrodes recorded from more than 180 participants, this model captures shared structure in speech-evoked neural activity across individuals and brain regions. The model's powerful generalization capabilities enables two novel downstream applications. First, we use unsupervised learning techniques to uncover how speech is functionally organized in the brain. By clustering the raw ECoG activity and the model's internal representations, we identify groups of electrodes that respond similarly to different speech features using a hypothesis-free, data-driven approach. Second, we use the learned ECoG model that captures population-level activity to bootstrap the prediction of single-neuron firing in the speech cortex, recorded using high-density Neuropixels probes. This allows us to link population-level dynamics to single-cell responses, elucidating how speech is encoded across multiple spatial scales. Overall, this work aims to uncover novel insights into the multi-scale neural architecture of speech perception across individuals.

Designing synthetic microbial communities for sustainable nitrogen delivery in the rhizosphere
Elisa S. Grillo
Mentors: Gözde S. Demirer, Chiara Berruto, and Eugene Li

To reduce reliance on chemical fertilizers a synthetic microbial community capable of converting atmospheric nitrogen to plant available nitrate was developed. The community is composed of both nitrogen-fixing and nitrifying bacteria, including *Azotobacter vinelandii*, *Nitrosomonas europaea*, *Nitrobacter winogradskyi*, and *Nitrobacter hamburgensis*. Growth and nitrogen production were assessed with monoculture and coculture experiments, using colorimetric assays to track nitrogen levels in the form of ammonium, nitrite, and nitrate. Initial results have guided media optimization to support compatibility between strains. Future directions include implementing these microbial communities in both hydroponic and soil-based plant systems to assess nitrogen delivery, as well as investigating chemotactic behavior of *A. vinelandii* to identify unique attractants that will then be engineered to be secreted by plant roots to improve colonization efficiency. These efforts aim to lay the groundwork for a developed synthetic community capable of targeted nitrogen delivery to plant roots.

Multimodal modeling and prediction of neuromuscular fatigue for intelligent control during functional electrical stimulation of a murine hindlimb
Keyu Wan
Mentors: Shriya Srinivasan, John O. Dabiri, and Patrick Pariseau

Functional Electrical Stimulation (FES) has become a crucial method for restoring movement in individuals with neurological impairments. By delivering controlled electrical pulses to muscles, implanted FES systems can produce coordinated movements that mimic voluntary actions. However, the effectiveness of FES is often constrained by the onset of muscle fatigue, a phenomenon in which muscle fibers gradually lose their ability to sustain forceful contractions under repeated stimulation. This gradual decrease in force output occurs much more rapidly during FES than for natural, nerve-mediated muscle activation. The aim of this project is to investigate neuromuscular fatigue dynamics in rat hindlimb by integrating force, electromyography, and muscle length signals under controlled electrical stimulation. Experimental protocol involves implanting recording and stimulation electrodes in anesthetized rats to evoke and monitor leg muscle activity across varied stimulation waveforms and amplitudes. Experimental datasets demonstrate correspondence between physiological responses and stimulation profiles, enabling robust modeling of fatigue progression. Multimodal data were processed for eventual training of deep learning models for predictive fatigue analysis and adaptive control strategies. This work demonstrates the feasibility of integrating physiological sensing and machine learning to achieve fatigue-aware control of muscle stimulation, with potential applications in neuromuscular rehabilitation, wearable exoskeletons and neural prosthetic systems.

Calibrating land models using FLUXNET observation data: Investigating the variation of vegetation parameters with environmental conditions
Thanhthanh V. Nguyen
Mentors: Tapio Schneider and Julia C. Sloan

Land vegetation greatly affect the atmosphere via the flux of carbon, water, and energy that occurs during photosynthesis. In order to develop a new, state-of-the-art Earth System Model (ESM) that better simulates the biogeochemical and physical interactions on Earth, CliMA (the Climate Modeling Alliance) aims to also develop a novel Land System Model (LSM) that uses the fluxes of vegetation recorded by global FLUXNET site towers to more accurately parameterize plant-photosynthesizing components. For this project, we built the structure for running single-site parameter calibration, where we first simulate a FLUXNET tower with its corresponding information for soil, plant structure, etc. We then pass the outputs through CliMA's EnsembleKalmanProcesses.jl optimization algorithm to identify which parameters are primarily responsible for the fluxes in the atmosphere attributing to photosynthesis. We also aim to create a process to calibrate all FLUXNET sites simultaneously, allowing us to better isolate and build an accurate set of these parameters.

Profiling misinformation susceptibility in the American electorate
Samantha Chang
Mentors: R. Michael Alvarez and Mitchell Linegar

Misinformation has become a persistent influence in American political life, with false claims spreading widely especially during elections, public health crises, and major news events. This study investigates which groups within the American electorate are most susceptible to misinformation by using the Misinformation Susceptibility Test (MIST) index, a validated measure based on how people respond to news headlines. Drawing from a large, nationally representative survey, we analyze how susceptibility varies by age, education, political affiliation, ideology, and media consumption. We find that while many Americans accurately identify false claims, a significant portion struggles to do so, especially on politically charged topics. Regression models show that susceptibility is not evenly distributed: Republicans and very conservative respondents are more likely to believe misinformation and misidentify factual statements as false, especially on items aligned with their ideological views. In contrast, Democrats and liberals tend to score higher, especially on items involving public health and political narratives. These patterns reveal how misinformation belief clusters within certain groups, providing insights into how misinformation intervention strategies can be better tailored towards these groups.

A unified phase-space framework for measurement-device-independent quantum key distribution

Sujay Champati
Mentors: Maria Spiropulu and Raju Valivarthi

We develop a unified theoretical framework for measurement-device-independent quantum key distribution (MDI-QKD) that combines phase-space modeling with realistic system imperfections. Coherent state pulses are represented as Gaussian states with covariance matrices and displacements, and their evolution through beamsplitters, phase modulators, and lossy channels is described via symplectic transformations. Using this formalism, we derive analytic coincidence probabilities for Hong–Ou–Mandel interference at the measurement station, incorporating detector dead time, dark counts, and partial temporal overlap between time bins. These results yield closed-form expressions for basis-dependent gains and error rates, providing a foundation for decoy-state analysis and secure key-rate estimation under realistic conditions. Our optimized key rates outperform previous simulations due to the improved accuracy of phase space computations. To complement the physical model, we implement high-speed classical post-processing with LDPC and Cascade reconciliation, followed by GPU-accelerated Toeplitz hashing for privacy amplification. Finally, we outline extensions of this framework to model longer-distance MDI-QKD using two-mode squeezed vacuum sources and to generalize the protocol to multi-party scenarios based on GHZ-state measurements.