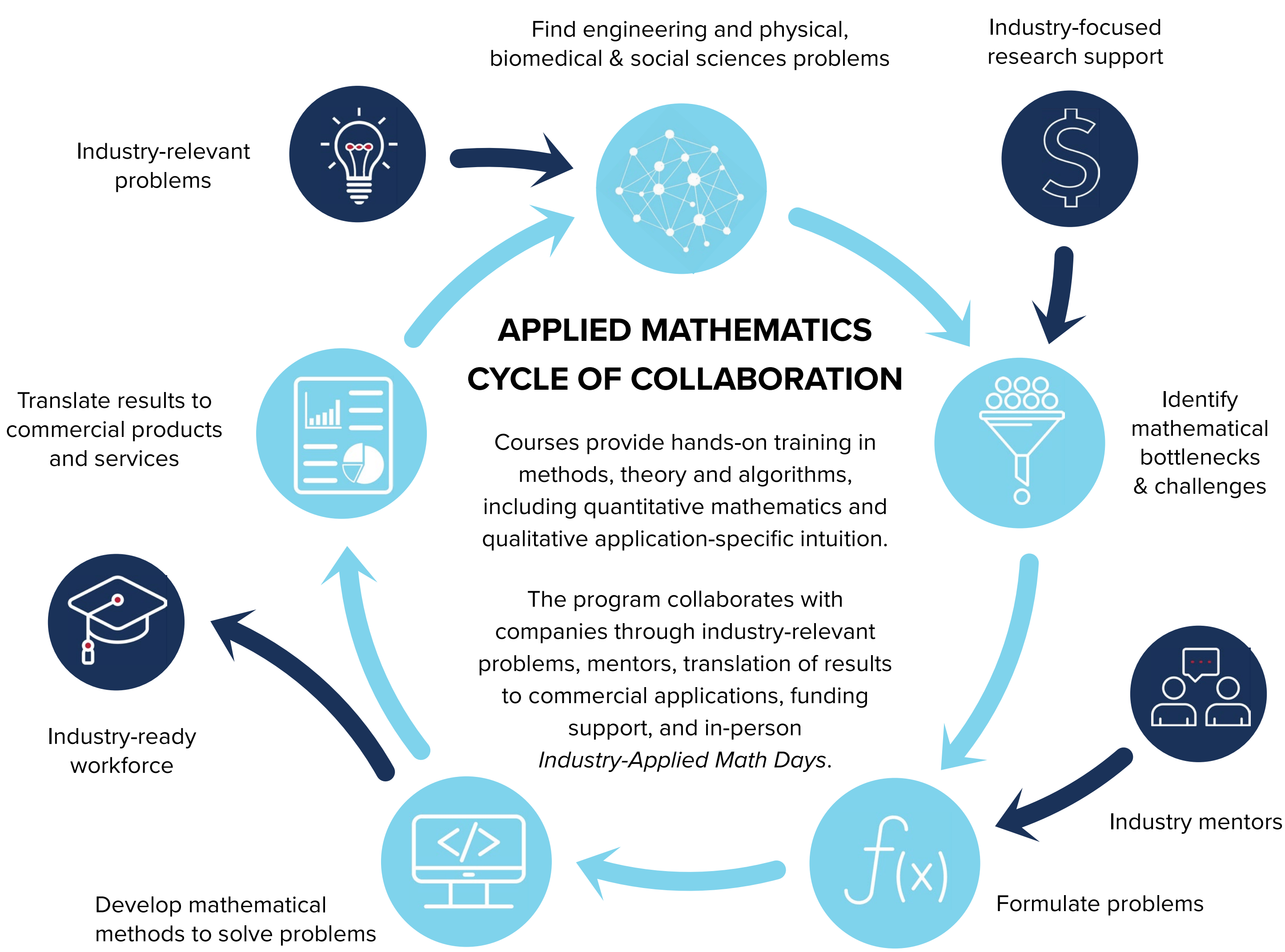
ARIZONA APPLIED MATHEMATICS

The applied mathematics graduate interdisciplinary program trains students across a broad range of mathematical disciplines and application areas. Core curriculum includes complex and Fourier analysis, ordinary and partial differential equations, optimization, probability and statistics, graphical models, and machine learning, including modern reinforcement learning techniques.

Students become well-versed in theory through an applied analysis course and gain extensive experience in computation through a numerical methods and algorithms course, including exposure to Markov-chain Monte-Carlo algorithms and neural networks. Beyond the core curriculum, students specialize in theoretical mathematics or work with affiliated faculty on applications in science & engineering

APPLIED MATH BY THE NUMBERS

8	27	65	130
COLLEGES	DEPARTMENTS	PHD STUDENTS	AFFILIATED FACULTY



APPLIED MATHEMATICS CYCLE OF COLLABORATION

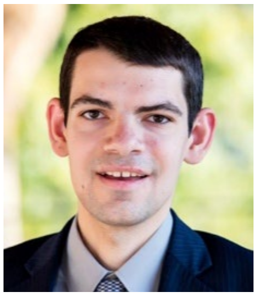
Courses provide hands-on training in methods, theory and algorithms, including quantitative mathematics and qualitative application-specific intuition.

The program collaborates with companies through industry-relevant problems, mentors, translation of results to commercial applications, funding support, and in-person *Industry-Applied Math Days*.

ARIZONA APPLIED MATHEMATICS

SELECTED APPLIED MATHEMATICS STUDENTS AND RESEARCH

MACHINE LEARNING FOR POWER & GAS



Rob Ferrando

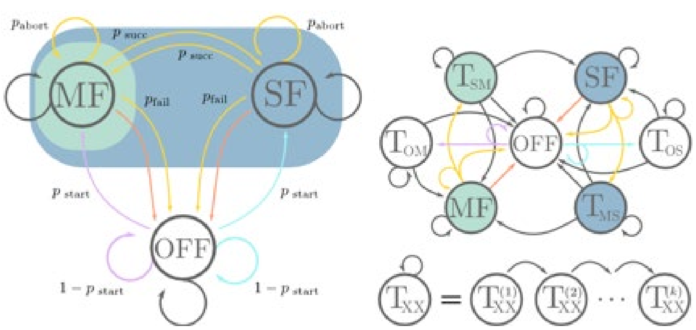
Advisor: Misha Chertkov
rferrando@arizona.edu

I use machine learning to develop surrogate models for stochastic optimization and control problems in interconnected power and gas systems, enabling efficient operation under rapidly fluctuating conditions and emergency scenarios.

Consider a power grid consisting of generators primarily powered by natural gas. I study the response to an emergency scenario precipitated by a sudden interruption to the gas supply.

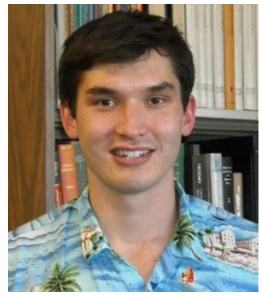
It is possible to transition units to a secondary fuel source, such as diesel, or to shut them off. The decision-making process is inherently challenging to rapidly balance the interests of the system operator—to minimize cost—and of customers—to maximize supply. As well, the power and gas systems operate on different time scales, and high-fidelity models require efficient numerical solution of a system of partial differential equations.

I use a Markov Decision Process framework to model the transitions and compare the performance of several policies guided by engineering intuition. I've proposed how to leverage deep reinforcement learning to iteratively recover an optimal policy. These solutions are relevant to isolated power grids both in the US and internationally.



Power system fueled primarily by natural gas: Stochastic transitions between generator statuses modeled as a Markov process (left). Intermediate transition states provided on the right.

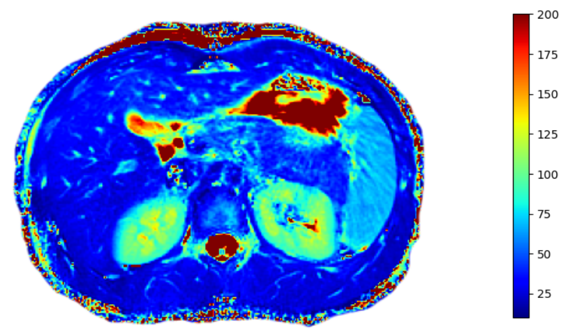
DEEP LEARNING ABDOMINAL MRI



Brian Toner

Advisors: Ali Bilgin & Maria Altbach
tonerbp@arizona.edu

I collaborate with Siemens to develop deep learning methods to reduce the time for abdominal MRI while maintaining high resolution imaging. The work involves cascaded unrolled networks with data consistency layers to accelerate respiratory-triggered T2 mapping of the abdomen using the radial TSE sequence. I am also interested in the radial GRASE sequence for improved fat suppression and quantification in T2 imaging.



Deep learning model MRI: We maintain high image quality and accurate T2 quantification, with reconstruction in 5 sec/slice compared to 45 min for compressed sensing.

NEURAL NETWORK FOUNDATIONS

Ben Stilin

Advisor: Kevin Lin
bstilin@arizona.edu

I use the perspective of dynamical systems, a highly developed field of mathematics, to better understand neural networks. Generally, NNs are poorly understood and, in most cases, we cannot explain NN predictions or provide strong performance guarantees, which limits the problems to which NNs can be applied.

I apply Mori-Zwanzig formalism from irreversible statistical mechanics to NN distillation to provide insight into how distillation methods work and to develop new algorithms.

ARIZONA APPLIED MATHEMATICS

NATURAL GAS SYSTEM MODELS

Criston Hyett
Advisor: Misha Chertkov
cmhyett@arizona.edu

We build and experiment with a realistic but reduced natural gas model of Israel. The system is unusual because (a) it is controlled from a limited number of points which are at, or close to, the gas extraction sites offshore; (b) control specifies average flux at inlet, not pressure; (c) there are no inland compressors to regulate pressure; (d) the gas-fired power system is the main consumer.

The nature of the system suggests that a special attention should be given to understanding dynamics driven by fast transients in gas consumption meeting intra-day variations in the electricity demand, and account for the increasing role of uncertain renewable generation (mainly solar).

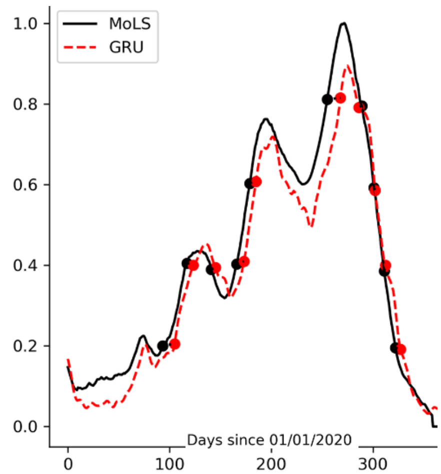
Based on the above, we pose and resolve a sequence of dynamic and control challenges, such as: How to time ramping up- and down- injection of gas to guarantee a healthy intra-day line-pack which meets both pressure constraints and gas-extraction patterns?

Our simulations use monotonicity properties of the natural gas flows which render robustness of our conclusions to the uncertainties of the edge withdrawals of gas.

MOSQUITO NEURAL NETWORKS

Adrienne Kinney
Advisor: Joceline Lega
akinney1@arizona.edu

Aedes-AI is a collection of neural network (NN) models of *Aedes aegypti* mosquito abundance, trained on synthetic data generated from a mechanistic model, in contrast to models of mosquito abundance that rely on noisy, real world trap data. Our NNs predict mosquito abundance with high skill and assess the impact of model architecture and data oversampling.



Mosquito abundance: The current mosquito landscape (MoLS) model (black solid curve) and our gated recurrent unit (GRU) NN model (red dashed curve). GRU is significantly faster than MoLS and can produce abundance estimates directly from local weather data.

MACHINE LEARNING-BASED REGRESSION & CLASSIFICATION

Many problems in industry and academia can be cast as regression or classification problems. Regression problems aim to predict numerical values from data, while classification aims to produce predictions of discrete classes from data. Machine learning techniques are effective tools for solving these kinds of problems on high-dimensional datasets, particularly when the relationship between input and prediction is complex. Many applied mathematics students use and develop state-of-the-art machine learning algorithms for solving scientific problems relevant to industry.

ARIZONA APPLIED MATHEMATICS

NEUROSCIENCE MACHINE LEARNING MODELS

Alexa Aucoin

Advisor: Kevin Lin
aucoin@arizona.edu

I am interested in data-driven modeling and interpretable machine learning (ML) with applications to neuroscience. My goal is to design an interpretable neural network (NN) to detect long-term changes in electro-physiological data from primate amygdala. Interpretability of NN decision-making informs our understanding of crucial biological mechanisms involved in encoding and decoding context in the brain. Previously, I worked on statistical ML algorithms with applications to neuroscience. I designed LSTM networks to classify spike-time data from primate amygdala. I explored how to leverage dynamical systems for NNs that are robust against variability in data representations.

COMPUTATIONAL MATERIALS DEVELOPMENT

Sheila Whitman

Advisor: Marat Latypov
sheilaw@arizona.edu

I develop computational techniques to help scientists develop materials with desired strength, elasticity and other properties. I use ML, computer vision, and natural language processing techniques. In my last project, I developed an automatic segmentation framework via a random forest model and a pre-trained convolutional neural network for a large and complex 3D printed metal artifact. I introduced a new statistical analysis tool, spatially-resolved chord length distributions, to analyze imperfect segmentation of microstructure constituents that include grains and melt pools.

In my current project, I explore the use of pre-trained vision transformers (ViTs) for material property prediction. While our framework is focused on training models to predict material properties from features extracted from the ViTs, I also develop multi-modal approaches to incorporate numerical compositions, microstructure images, and textual processing conditions into a single materials property prediction model.

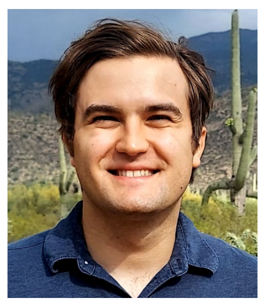
DEEP LEARNING IN ASTRONOMY

Jackson Zariski

Advisor: Kaitlin Kratter
jzariski@arizona.edu

The WIYN Telescope at Kitt Peak National Observatory hosts an extreme precision, optical spectrograph, known as NEID, built for exoplanet radial velocity studies. NEID has strict requirements on survey efficiency, stellar image positioning, and guiding performance, which exceed the native capabilities of the telescope's original pointing and tracking system. We developed a pointing system built on a recurrent NN and gradient-boosted tree, that does not rely on quasi-physical based pointing (e.g., TPoint) but rather informed by intrinsic properties of the pointing problem. Our models acquire targets with arcsecond-level accuracy with lower error bounds than the WIYN system.

ROBOT DESIGNS ADAPTED FROM NATURE



Ari Bormanis

Advisor: S. Venkataramani
abormanis@arizona.edu

Curly shapes in nature, like sea slug feet, arise from minimizing an elastic energy functional. I model surfaces as a map from the hyperbolic plane into 3D real space. The hyperbolic metric captures the idea that surface perimeters grow exponentially with their radius. I classify approx.-imate minimizers of this energy functional and topological defects to understand how moving such defects change surface shapes. I use my insights for robots that swim with small energy budgets.

MATHEMATICAL MODELS OF NEMATOCYSTS

I create and use mathematical 2D models of nematocysts—stinging cells in jellyfish tentacles—with the immersed boundary method to simulate fluid dynamics. I then numerically solve the Navier-Stokes equations that are coupled to structure interaction equations.

Addie Harrison

Advisor: Laura Miller | addieharrison@arizona.edu

ARIZONA APPLIED MATHEMATICS

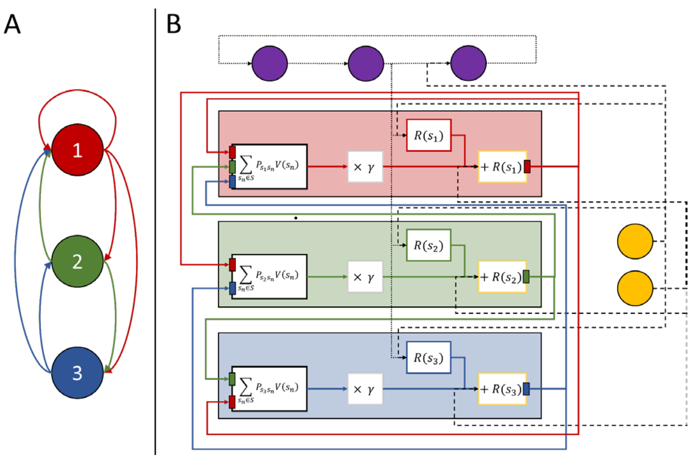
BRAIN-INSPIRED COMPUTING

Sarah Luca

Advisor: Misha Chertkov
sarahluca@arizona.edu

I develop scalable, energy efficient neuromorphic algorithms for Markov decision processes and brain-inspired learning algorithms for event/object detection on analog hardware. Markov reward processes are often studied in the context of Markov decision processes which are the mathematical basis for reinforcement learning.

We developed a spiking algorithm that estimates the state value function of a Markov reward process composed of circuits that perform streaming binary arithmetic. I evaluate scaling properties of our algorithms on Loihi 2 neuromorphic chips.



Example diagram: Algorithm (**A**) for a three-state Markov reward process (**B**). S. Luca et al. *Neuro-Inspired Computational Elements Conference*, San Diego, April 2024.

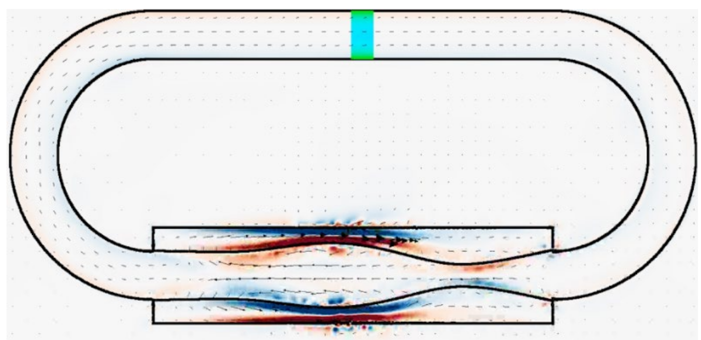
CFD WITH DEFORMABLE BOUNDARIES

Dunia Fernandez

Advisor: Laura Miller
dmfernandez@arizona.edu

I model fluid flow to explore how the embryonic heart, which starts as a simple tube, pumps blood without valves and how pumping and fluid behavior affect development. I use computational fluid dynamics (CFD) with the immersed boundary (IB) method to simulate and analyze fluid-structure interactions in 2D & 3D.

Specifically, I model dynamic suction pumping and peristalsis, which have been proposed as pumping mechanisms for blood flow in the embryonic tubular heart before valve development. By using CFD with IB, I capture the interaction between the heart and the blood to investigate the effects of flow rates, pressure gradients and shear stresses to understand mechanisms that drive early-stage cardiovascular development.



Applied computational fluid dynamics: I create models with movable boundaries to study dynamic systems like blood flow in tubular hearts.

NOISY PHYSICAL SYSTEM MODELS

Teddy Meissner

Advisor: Karl Glassner
tmeissner@arizona.edu

Given a set of noisy observations from a physical system, I look to model the system with differential equations. Since the set of possible models can be extremely large, the hardest part is to set up a regression problem based on noise assumptions and smartly evaluating only a small subset of these models. The main hurdle for this work lies in nonlinear optimization, where it is not clear how to efficiently optimize the problem.

ADAPTIVE LEARNING RATE OPTIMIZERS

Saheed Ganiyu

Advisor: Helen Zhang
saheedganiyu@arizona.edu

I work on ovarian cancer prediction and deep learning, where I focus on adaptive optimizers (AOs) due to their ability to adjust learning rates during training for fast convergence and to handle noisy gradients. I compare their strengths, limitations and adaptability to methods such as stochastic gradient descent, with an emphasis on accuracy, generalization and speed.

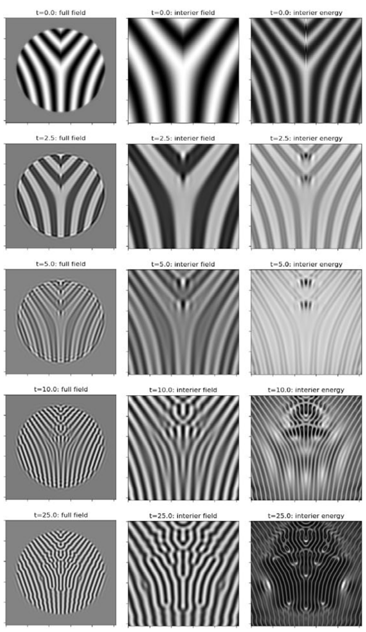
ARIZONA APPLIED MATHEMATICS

SYSTEMS IDENTIFICATION ALGORITHMS

Edward McDugald

Advisor: S. Venkataramani
emcdugald@arizona.edu

Systems identification seeks to deduce models and governing equations from data. For example, the trajectories of the planets result in the $F = m \cdot a$ equation. I seek to identify models that describe systems with as few points as possible. In general, PDEs do not have an analytical or easy-to-interpret solution. Often, interpretable approximations can be obtained using multiple scales and change of variables. Original PDE coordinates are called microscopic coordinates and those those of the approximation are macroscopic coordinates. Current algorithms extract microscopic models from data. However, no known methods can extract macroscopic models in general. I aim to develop macroscopic extraction algorithms using nonlinear oscillators and pattern forming systems.



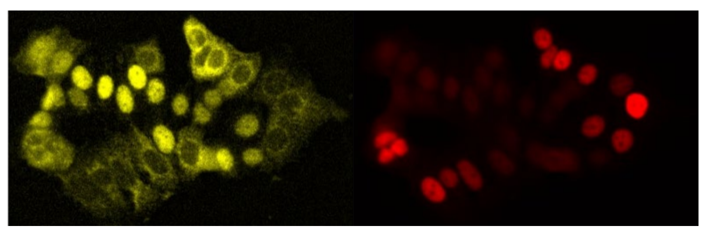
Swift-Hohenberg PDE on the circle: The initial condition has a small spatial wavenumber. **Left column:** full field; **middle:** zoomed in; **right**: microscopic energy density.

CELL COMMUNICATION NETWORKS

Woody March-Steinman

Advisor: Andrew Paek
wmarchsteinman@arizona.edu

I investigate communication networks within and between cells in response to oxidative stress, and the impacts of signal dynamics on cellular fate decisions to repair, die, or permanently exit the cell cycle. Much of the work involves single cell traces where we generate a multidimensional time series for each cell that includes information from spatial position to fluorescent marker luminosity. I classify each time series into a "fate bin" and evaluate features that lead to those classifications, making use of traditional time series analysis techniques and modern interpretable ML. I also produce regression predictions for time of cell death, duration of phase, and other quantifiable responses to treatment, while retaining explanatory power of these predictive models. Combining analysis insights with single cell transcription factor and gene expression data, I aim to generate and validate dynamical models of the signaling proteins involved in hydrogen peroxide stress response.



Multiple-input, multiple-output stress response communication networks: The same cells demonstrate mutually-exclusive activation of proteins under hydrogen peroxide stress.

MATHEMATICAL FRAMEWORKS TO UNDERSTAND NEURON NETWORKS

Marium Yousuf

Advisors: Jean-Marc Fellous & Misha Chertkov
myousuf@arizona.edu

The activity of neurons provides insights into how we navigate the space around us. I investigate replay and causality among neurons by simulating the activity of a network of neurons in the hippocampal area called the place cells. These cells spike (or fire) in response to visiting specific locations in any environment. I use the NEURON simulation environment to implement synapses with uncorrelated background noise for realistic neural behavior. The conductance of the synaptic currents is scaled by a connectivity matrix that can be controlled to introduce causality structures in subgroups of neurons. I compare results from three approaches designed to identify subgroups of neurons and their firing order. The first approach allocates spikes within a specified timeframe; the second leverages Fourier transform spectral analysis to analyze spiking in a frequency space; and the third extracts a directed acyclic graph that describes the causality relationship between neurons by capturing the underlying generative model using the Markov Decision Process.

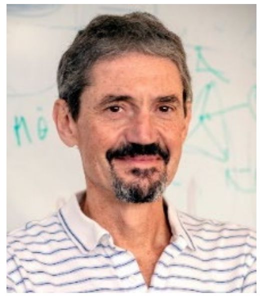
ARIZONA APPLIED MATHEMATICS

SELECTED APPLIED MATHEMATICS FACULTY & AFFILIATED FACULTY

Kailtin researches stellar and planetary system formation and evolution, using analytic and computational techniques to tackle topics including accretion disk dynamics, binary formation, few body dynamics, and planet-disk interactions. She collaborates with observers to discover extreme mass ratio binaries and very young multiple star systems.

Kaitlin Kratter, PhD

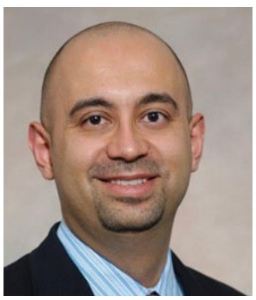
Professor, Astronomy
kkratter@arizona.edu



Misha's research, rooted in physics, lies in a diverse array of sciences, making use of machine learning, information and control theory, computer science, AI and operations research. He applies emerging AI tools to detect and mitigate rare, catastrophic events, such as a power grid collapse.

Misha Chertkov, PhD

Professor & Chair, Applied Mathematics
chertkov@arizona.edu



Ali's research interests include signal and image processing, image and video coding, data compression, and magnetic resonance imaging. He works at the intersection of disciplines, with appointments in Electrical & Computer Engineering and Biomedical Engineering.

Ali Bilgin, PhD

Assoc Professor, Electrical Engineering
bilgin@arizona.edu

Kevin's research includes nonlinear dynamics, computing, and applications such as data-driven modeling and model reduction, Monte Carlo methods, and dynamical problems in physics, biology, and engineering, especially computational neuroscience.

Kevin Lin, PhD

Assoc Professor, Mathematics
klin@arizona.edu

Laura studies locomotion and morphogenesis. She showed that the fluid dynamics in tiny insects during flight changes below a Reynolds number of about 40 which corresponds to changes in the vortex wake behind the wing and a drop in lift. She also studies the role of wing flexibility and bristles to reduce drag.

Laura Miller, PhD

Professor, Mathematics
lauram9@arizona.edu

Marat has a wide range of interests as they apply to materials science and engineering applications that include materials informatics, computational materials sciences through modeling and simulation, artificial intelligence, alloy design and materials process optimization.

Marat Latypov, PhD

Asst Professor, Materials Science & Engineering
latmarat@arizona.edu

INDUSTRY & NATIONAL LAB APPLIED MATH DAYS

A tradition since 1976, and revamped in 2019, Applied Math Days bring together working professionals and students, postdocs & faculty to tackle real-world problems. Professionals are encouraged to present their most pressing problems while academic presentation priorities are given to students and postdocs. Recent topics have included math as applied to space exploration, foundational AI, semiconductors, materials in extreme environments, and hypersonic flow. Applied math students secure internships and full-time positions at Los Alamos, Sandia, Lawrence Berkeley, Argonne, Pacific Northwest and Oak Ridge National Labs and companies that include Raytheon, Critical Path, Uber, Intel and Google.

For further information, contact Misha Chertkov, Chair, Program in Applied Mathematics | chertkov@arizona.edu