2021 PRIMES CONFERENCE ABSTRACTS

SATURDAY, OCTOBER 16
MATHEMATICS

SESSION 1: APPLIED MATHEMATICS

Yi (Alex) Liang

Predicting pandemics with stock market indicators

Mentor: Prof. James Unwin, University of Illinois at Chicago

Technical indicators are used by some stock traders to gain a competitive edge. These techniques are thought to provide insight as to the future evolution of the prices for stocks or sectors. Here we show that these same indicators can be applied to other systems of interest. Specifically, we examine the rate of new cases of COVID-19, thus providing a new set of tools for studying the spread of pandemics. We provide a quantitative assessment of MACD, RSI, and candlestick analyses, highlighting their statistical significance in making predictions for both stock market data and WHO COVID-19 data. Reliable short-term forecasting can provide potentially life-saving insights into logistical planning (and for regional analyses) to allocate additional resources such as hospital staff and equipment.

Linda He

A topological centrality measure for directed networks

Mentor: Lucy Yang, Harvard University

Given a directed network G, we are interested in studying the qualitative features of G which govern how perturbations propagate across G. Various classical centrality measures have been already developed and proven useful to capture qualitative features and behaviors for undirected networks.

In this talk, we use topological data analysis (TDA) to adapt measures of centrality to capture both directedness and non-local propagating properties in networks. We introduce a new metric for computing centrality in directed weighted networks, namely the *quasi-centrality* measure. We compute these metrics on trade networks to illustrate that our measure successfully captures propagating effects in the network and can also be used to identify sources of shocks that can disrupt the topology of directed networks.

Jeremy Yu

Gradient-enhanced physics-informed neural networks for forward and inverse PDE problems

Mentor: Dr. Lu Lu

Deep learning has been shown to be an effective tool in solving partial differential equations (PDEs) through physics-informed neural networks (PINNs). PINNs embed the PDE residual into the loss function of the neural network, and have been successfully employed to solve diverse forward and inverse PDE problems. However, one disadvantage of PINNs is that they usually have a limited accuracy even with many training points. Here, we propose a new method, gradient-enhanced physics-informed neural networks (gPINNs), for improving the accuracy and training efficiency of PINNs. gPINNs leverage gradient information of the PDE residual and embed the gradient into the loss function. We tested gPINNs extensively and demonstrated the effectiveness of gPINNs in both forward and inverse PDE problems. Our numerical results show that gPINN performs better than PINN with fewer training points. Furthermore, we combined gPINN with the method of residual-based adaptive refinement (RAR), a method for improving the distribution of training points adaptively during training, to further improve the performance of gPINN, especially in PDEs with solutions that have steep gradients.

Garrett Heller

Strichartz estimates and well-posedness for the one-dimensional periodic Dysthe equation

Mentor: Chengyang Shao

We discuss large deep water waves known as rogue waves and their governing equation, the Dysthe Equation. We explain the concept of well-posedness, and how we could use Strichartz type and multilinear estimates to show well-posedness of the Dysthe Equation. Further, we delve into the mathematical framework behind relevant estimates, including Fourier analysis and functional spaces.

Session 2: Algebra

Andrew Gu

Counting LU matrices with fixed eigenvalues

Mentor: Dr. Jonathan Wang

In this talk, we investigate two seemingly unrelated subjects in the realm of Linear Algebra. Namely, we consider the number of LU (lower-upper) matrices in a finite field with a certain set of distinct eigenvalues. Through this investigation, we determine a formula that makes use of partitions and their properties. Given this relation, we can make many interesting connections between different topics not just in mathematics, but in other fields of science as well.

Zifan (Atticus) Wang

Representation stability and orthogonal groups

Mentor: Arun Kannan

In this talk, we will motivate and introduce the concept of representation stability, a new area of research at the intersection of representation theory and algebraic topology. We discuss the framework that representation stability considers, and briefly explain our main result, a homological stability theorem with untwisted and twisted coefficients for orthogonal groups.

Karthik Seetharaman, William Yue, and Isaac Zhu

Regularities in the lattice homology of Seifert homology spheres

Mentor: Dr. Irving Dai

In this talk, we present an introduction to important concepts in low-dimensional topology, specifically in 3 dimensions, in order to understand the results of our project studying the lattice homology of Seifert homology spheres. We begin by introducing the central idea of manifolds and manifolds-with-boundary before moving to cobordism, an important topological problem concerning the classification of boundaries. We then introduce some examples of 3-dimensional manifolds, which are difficult to visualize. This is followed by an introduction of surgery, a process that allows for the construction of many 3-dimensional manifolds, including the family we are specifically interested in, Seifert homology spheres. The lattice homology is an invariant of certain classes of 3-dimensional manifolds that contains connections to homology cobordism, a specialization of cobordism in 3 dimensions that we are interested in. Specifically, it connects to the d-invariant and maximal monotone subroot, two invariants of homology cobordism which we discuss. To end, we state our results on the periodicity of these invariants under certain transformations of Seifert homology spheres.

Session 3: Algebra

Ilaria Seidel

Bounds on symmetric numerical semigroups

Mentor: Jeffery Yu

Numerical semigroups are combinatorial objects that are easy to define, but have rich connections to other fields. Certain families of numerical semigroups are of particular interest because of their connections to algebraic geometry. We focus on one such family known as symmetric semigroups. We analyze the rate of growth of the number of symmetric semigroups $N(g)$ with genus g. We state a conjecture about the behavior of the ratio $\frac{N(g+1)}{N(g)}$, depending on the residue of $g \pmod 3$. Finally, we generalize this conjecture to various other types of numerical semigroups.

Yanan (Nancy) Jiang, Benjamin Li, and Sophie Zhu

Factorization invariants of algebraic valuations of positive cyclic semirings

Mentor: Dr. Felix Gotti

We study some of the factorization invariants of the class of cyclic semirings. We focus on the additive structures of all atomic monoids of the form $\mathbb{N}_0[\alpha] = \{p(\alpha) : p(x) \in \mathbb{N}_0[\alpha]\}$, where α is a positive real algebraic number. We give the elasticity of non-finitely generated cyclic semirings and of a subset of finitely generated cyclic semirings restricted by the degree of the minimal polynomial of α and the cardinality of the set of atoms. We also study the omega-primality of cyclic semirings, and we provide the omega-primality for all cyclic semirings with positive real algebraic α between 0 and 1.

Sophie Zhu

Factorizations in evaluation monoids of Laurent semirings

Mentor: Dr. Felix Gotti

For $\alpha \in \mathbb{R}_{>0}$, let $\mathbb{N}_0[\alpha, \alpha^{-1}]$ be the semiring of real numbers $f(\alpha)$ with all $f(x) \in \mathbb{N}_0[x, x^{-1}]$, where $\mathbb{N}_0$ is the set of nonnegative integers and $\mathbb{N}_0[x, x^{-1}]$ is the semiring of Laurent polynomials with coefficients in $\mathbb{N}_0$. In this talk, we study various factorization properties of the additive structure of $\mathbb{N}_0[\alpha, \alpha^{-1}]$. We characterize when $\mathbb{N}_0[\alpha, \alpha^{-1}]$ is atomic. Then we characterize when $\mathbb{N}_0[\alpha, \alpha^{-1}]$ satisfies the ascending chain condition on principal ideals in terms of certain well-studied factorization properties. Finally, we characterize when $\mathbb{N}_0[\alpha, \alpha^{-1}]$ satisfies the unique factorization property and show that, when this is not the case, $\mathbb{N}_0[\alpha, \alpha^{-1}]$ has infinite elasticity.

Benjamin Li

A new class of atomic monoid algebras without the ascending chain condition on principal ideals

Mentor: Dr. Felix Gotti

In this presentation, we address several issues about atomicity and ACCP. A monoid is a collection of elements with an operation on it. It is atomic if every nonzero nonunit element factors into irreducibles. On the other hand, it satisfies the ACCP if every ascending chain of principal ideals is constant from one point on. Every integral domain satisfying the ACCP is known to be atomic. Although the converse does not hold in general, atomic domains without the ACCP are notorious for being very elusive and only a few classes have been discovered since A. Grams constructed the first example back in the seventies. We will discuss how to construct one of such integral domains using polynomial expressions with real exponents. This is a recent construction, and presumably one of the most elementary. This construction is part of a joint work with Felix Gotti.

Session 4: Applied Mathematics

Sheryl Hsu

The Power of Many: A Physarum *Swarm Steiner Tree Algorithm*

Mentor: Prof. Laura Schaposnik, University of Illinois at Chicago

We present a novel *Physarum* swarm approach to hard computational problems. *Physarum* swarms consist of computational models of many *Physarum* organisms, which are unicellular slime molds with the ability to form networks and fuse. We choose to demonstrate our new approach on the Euclidean Steiner tree problem, creating the *Physarum* Steiner tree algorithm. The *Physarum* Steiner tree algorithm utilizes a swarm of *Physarum* organisms which gradually find terminals and fuse with each other, sharing intelligence. The algorithm is also highly capable of solving the obstacle avoidance Steiner tree problem and is a strong alternative to the current leading algorithm. The algorithm is of particular interest due to its novel approach, time complexity, rectilinear properties, and ability to run on varying shapes and topological surfaces.

Alex Hu

Improved graph formalism for quantum circuit simulation

Mentor: Andrey Khesin

Improving the simulation of quantum circuits on classical computers is important for understanding quantum advantage and increasing development speed. In this project, we explore the stabilizer formalism through the lens of the graph formalism. We develop an improved algorithm for graph state stabilizer simulation and establish limitations on reducing the quadratic runtime of applying controlled-Pauli Z gates. We do so by creating a simpler formula for combining two Pauli-related stabilizer states into one. To better understand the linear dependence of stabilizer states, we characterize all linearly dependent triplets, revealing symmetries in the inner products. Using our novel controlled-Pauli Z algorithm, we improve runtime for inner product computation from $O(n^3)$ to $O(nd^2)$ where d is the maximum degree of the graph. In this talk, we discuss our results, including our unique and elegant canonical form for stabilizer states based on graph states to better represent stabilizer states, as well as improving upper bounds on the stabilizer rank of magic states.

Yash Agarwal

Convolutional encoder decoder network for the removal of coherent seismic noise

Mentor: Sarah Greer

Seismologists often need to gather information about the subsurface structure of a location to determine if it is fit to be drilled for oil. In a seismic experiment, a wave propagates from a source location, interacts with the underlying discontinuities in the subsurface, and arrives back to the surface to be recorded by receivers. This data is used to produce an image of the subsurface, which aims to show geologic structure below the area of interest. However, there may be coherent electrical noise in these datasets which is most commonly removed by disregarding certain frequency bands of the data with the use of a notch filter. Instead, we look at using a convolutional encoder decoder network to remove such noise by training the network to take the noisy shot record produced by the receivers as input and to give the denoised or "clean" shot record as output. Our results reveal that the convolutional encoder decoder network structure works quite well, removing almost all the coherent noise while still retaining most of the characteristics of the shot record.

Raymond Feng, Andrew Lee, and Espen Slettnes

Results on various models of mistake-bounded online learning

Mentor: Dr. Jesse Geneson, San Jose State University

We determine bounds between several variations of the mistake-bound model. In the first half of our presentation, we will discuss various bounds between the weak reinforcement model and the delayed, ambiguous reinforcement model. In both models, the adversary gives r inputs in one round and only indicates a correct answer if all r guesses are correct. The only difference between the two models is that in the delayed, ambiguous model, the learner must answer each input before receiving the next input of the round, while the learner receives all r inputs at once in the modified weak reinforcement model.

Then, we discuss a lower and upper bound on the maximum factor gap between the modified weak reinforcement model and the standard model, which is tight up to a factor of r and whose proof uses probabilistic methods and linear algebra techniques.

Lastly, we also introduce the relative position model, a related model where a learner attempts to learn a permutation from a set of permutations F by guessing statistics related to sub-permutations. We similarly define the notion of delayed, ambiguous, reinforcement, and demonstrate an optimal strategy for the adversary that mimics insertion sort and relates to prior models.

Session 5: Combinatorics

Atharva Pathak

Combinatorial aspects of the card game War

Mentor: Dr. Tanya Khovanova

We study a single-suit version of the card game War, played between two players Alice and Bob, on a finite deck of cards. When a player wins a round, they must put the two cards they win to the bottom of their stack. We consider randomly putting the two cards back and deterministically always putting the winning card before the losing card. The concept of a *passthrough* is defined, which refers to a player playing through all cards from some point in the game. We only consider games where Bob wins within his first passthrough, which we call single-use games. We show that single-use games can be decomposed into *blocks* where Alice begins with a single card. We give the probability that a random permutation of cards in the form of such a block is single-use.

We then show a bijection between the sequence of wins and losses for Alice in a block and full binary trees. A variety of results arise from these full binary trees, including counting win-loss sequences that end within k passthroughs for Alice and sequences that end in exactly k rounds. We touch on further results to count states that necessarily follow a win-loss sequence under random putback and states that end in a certain number of rounds.

Sophia Benjamin, Arushi Mantri, and Quinn Perian

On the Wasserstein distance between k-step probability measures on finite graphs

Mentor: Pakawut Jiradilok

We begin by introducing random walks, k-step probability distributions, and the notion of Wasserstein distance. We then consider random walks X, Y on a finite graph G with respective lazinesses $\alpha, \beta \in [0, 1]$. Let μ_k and ν_k be the k-step transition probability measures of X and Y. In our talk, we discuss the Wasserstein distance between μ_k and ν_k for general k. We consider the sequence formed by the Wasserstein distance at odd values of k and the sequence formed by the Wasserstein distance at even values of k. We first establish that these sequences always converge, and then we characterize the possible values for the sequences to converge to. We further show that each of these sequences is either eventually constant or converges at an exponential rate. By analyzing the cases of different convergence values separately, we are able to partially characterize when the Wasserstein distance is constant for sufficiently large k.

Anuj Sakarda, Jerry Tan, and Armaan Tipirneni

On the distance spectra of extended double stars

Mentor: Feng Gui

In this talk, we introduce the concepts of the adjacency and distance matrix, as well as the idea of graphs determined by their spectra. We explore previous results related to these concepts, as well as outline new results surrounding extended double stars and their distance spectra.

Session 6: Geometry

Andrew Du

Quaternion-based analytical inverse dynamics for the human body

Mentor: David Darrow

The human body provides unique challenges to model and study from a physics standpoint due to its mechanical complexity and the difficulty of obtaining measurements of internal dynamic quantities, leading to an oversimplification of models that ignore crucial anatomical parts. However, a number of critical applications require accurate inverse dynamic models of the human body, including medical treatment and simulation of human motion. In this talk, we discuss improvements to existing methods of inverse dynamics for the human body by presenting models that account for finer anatomical details with broader applicability than previously created ones through the application of recent quaternion methods and screw algebra.

Kevin Cong

Square tilings of translation surfaces

Mentor: Prof. Sergiy Merenkov, CCNY – CUNY

In this talk, we provide an introduction to square tilings on translation surfaces. We present Oded Schramm's results on square tilings of squares, obtained via a graph-theoretic approach. We also discuss square tilings of the torus, the simplest example of a translation surface. We then introduce and define translation surfaces. Next, we present our main results on the existence of square tilings of translation surfaces. We conclude by providing a summary and offering future directions to proceed.

Daniel Xia

A Minkowski-type inequality in AdS-Melvin space

Mentor: Prof. Pei-Ken Hung, University of Minnesota

In this talk, we consider the curvature of a one-dimensional curve from an alternative perspective, generalizing curvature to surfaces of higher dimensions through the concept of mean curvature. Out of the many interesting properties of the mean curvature, we focus on the classical Minkowski inequality. We also introduce the idea of a Riemannian metric, which allows us to work in more abstract spaces, such as non-Euclidean geometries. These new concepts allow us to consider a Minkowski-type inequality concerning surfaces in the AdS-Melvin space, which is the subject of our research.

Luke Robitaille

Topological entropy of simple braids

Mentor: Dr. Minh-Tam Trinh

This talk concerns *braids*, which are formed by "strands" wrapping around one another. In particular, we care about *simple braids* on n strands; these correspond in a natural way to permutations of $\{1, \ldots, n\}$. An important notion is *topological entropy*, which is zero for a braid that is "orderly," but positive for a braid that is "chaotic." Also we are interested in a certain map, called the *Burau representation*, which sends braids to matrices in a nice way. We investigate the proportion of simple braids on n strands that have positive topological entropy, as n grows large. We also present some conjectures regarding the images of simple braids under the Burau representation; these matrices are related to the topological entropy of the braid by a result of Kolev.

SESSION 7: ALGEBRA

Sushanth Kumar

Extending the restricted Lie algebra structure on the homology of a double loop space

Mentor: Adela Zhang

We begin by discussing the notion of homotopy equivalence and use it to define a multiplication on the loop spaces. We then extend the restricted Lie algebra structure on the mod 2 homology of a double loop space $\Omega^2 X$, given by the top Dyer-Lashof operation Q_1, to its bar construction. This gives rise to an operation on the E^1-page of the bar spectral sequence converging to the mod 2 homology of Ω^X.

Joshua Guo

On the Gauss-Epple homomorphism of B_n, and generalizations to Artin groups of finite type

Mentor: Kevin Chang

In this work, we introduce the Gauss-Epple invariant of braids, originally defined by Epple based on a note of Gauss, which we prove is well defined. We consider the Gauss-Epple invariant as an action of the braid group B_n on the set $\{1, ..., n\} \times \mathbb{Z}$ and as a group homomorphism from B_n to the symmetric group $\mathrm{Sym}(\{1, ..., n\} \times \mathbb{Z})$. We prove that this homomorphism factors through $\mathbb{Z}^n \rtimes S_n$ (in fact, its image is an order 2 subgroup of the previous group). We also describe the kernel of the homomorphism, including the probability that a random braid of a given length is contained in it. Furthermore, we discuss the *super-Gauss-Epple homomorphism* $B_n \to \mathbb{Z}^{\binom{n}{2}} \rtimes S_n$, which refines the Gauss-Epple homomorphism. We also describe a 1-cocycle of the symmetric group S_n on the set of antisymmetric $n \times n$ matrices over the integers that is related to the super-Gauss-Epple homomorphism. We then generalize these notions to Artin groups of finite type.

Ram Goel

Products of reflections in smooth Bruhat intervals

Mentor: Christian Gaetz

The finite symmetric group S_n is a Coxeter group, and is defined as the group of permutations of the set $\{1, \ldots, n\}$ with group operation the composition of permutations. We consider a partial order on the symmetric group known as the Bruhat order. A permutation is called smooth if the corresponding Schubert variety is smooth. It has been proven that a permutation is smooth if and only if it avoids the patterns 3412 and 4231. Gilboa and Lapid prove that in the symmetric group, multiplying the reflections below a smooth element w in Bruhat order in a "compatible order" yields back the element w. In this talk we investigate generalizations of this result to other finite Weyl groups and study finer properties of this decomposition of w. In particular, we prove that the product of reflections in a compatible order forms a saturated chain in Bruhat order.

Session 8: Computer Science

Rachel Chen

CryptoCuties: A new family of non-fungible virtual assets

Mentor: Jules Drean

We present CryptoCuties: a new family of non-fungible virtual assets that "live" on specialized secure hardware. Our scheme achieves a strong notion of digital ownership by relying on three main properties:

1) The owner of a valid CryptoCuties has inherent capabilities over the data structure in comparison to another user having an invalid copy of the CryptoCutie;

2) CryptoCuties can only be owned by one user at a time;

3) CryptoCuties can be traded offline through the use of trusted hardware and a specific exchange protocol. In particular, we do not require the use of a blockchain.

These properties are achieved by composing several cryptographic and hardware-security mechanisms. By binding a given CryptoCutie to a piece of hardware, using a constant sustenance requirement enforced by a new heartbeat mechanism, and embedding a proof of validity that can be verified offline by any user, we enforce a version of virtual ownership which makes duplicate copies unmodifiable and non-exchangeable. In other words, CryptoCuties are perishable data-structures that become invalid if not maintained with the right requirements. This creates a strong notion of virtual ownership.

Yavor Litchev

Distributed signature scheme with monotonic access pattern

Mentors: Yu Xia

A wide variety of digital signature schemes currently exist, from RSA to El-Gamal to Schnorr. More recently, multi-party signature schemes have been developed, including distributed signature schemes and threshold signature schemes. In particular, threshold signature schemes provide useful functionality, in that they require the number of participating parties to pass a threshold in order to generate a valid signature. However, they are limited in their complexity, as they can only model a threshold function. The proposed signature scheme (monotonic signature scheme) allows for the modeling of complex functions, so long as they are monotonic. This would allow for a much greater degree of access control, all while security and correctness are preserved.

Abigail Thomas

The implementation of model pruning to optimize zk-SNARKs

Mentor: Yu Xia

Zero-Knowledge Succinct Non-Interactive Arguments of Knowledge (zk-SNARK)s are used to convince a verifier that a server possesses certain information without revealing these private inputs. Thus, zk-SNARKs can be useful when outsourcing computations for cloud computing. The proofs returned by the server must be less computationally intensive than the given task, but the more complex the task, the more expensive the proof. We present a method that involves model pruning to decrease the complexity of the given task and thus the proof as well, to allow clients to outsource more complex programs. The proposed method harnesses the benefits of producing accurate results using a lower number of constraints, while remaining secure.

Simon Beyzerov and Eliyahu Yablon

Versatile anonymous authentication with Cloak

Mentor: Sacha Servan-Schreiber

This talk presents Cloak, a lightweight and versatile anonymous authentication tool. Authentication is enforced via two (or more) non-colluding Cloak servers which act as verifiers. Cloak servers authenticate users as being members of a group (e.g., a user is a student in a class) without learning any information beyond the resulting authentication status. We show that Cloak fits seamlessly into existing architectures for password-based authentication systems and is more versatile compared to anonymous credentials. Cloak easily extends to more complex applications such as two-factor, authenticated private information retrieval, and authenticated key exchange.

Session 9: Computer Science

Kunal Kapoor

Consensus under a dynamic synchronous model

Mentor: Jun Wan and Hanshen Xiao

With the advance of blockchain and cryptocurrency, the need for efficient and practical consensus algorithms is growing. However, most existing works only consider protocols under the synchronous setting. It is usually assumed that there exist at least h users who are always honest and online. This is impractical as honest users might alternate between online and offline states. In this paper, we adapt Byzantine Broadcast protocols to a dynamic synchronous model which features sleepy/offline users as well as information gaps. We do this by building off an approach centered around a Trust Graph, modifying key algorithms from previous works such as the post-processing algorithm to ensure correctness with the dynamic model. This allows the creation of a more fault-tolerant protocol.

Tanisha Saxena

A compromise between synchronous and asynchronous systems

Mentor: Jun Wan

This talk aims to solve the issue of inaccurate modeling within distributed systems. Previous work introduced the idea of slightly synchronous or partially synchronous systems, however, these are insufficient as they either have too much structure to be realistic or do not have enough structure as user actions are not entirely independent. In this talk, we create a separate model that combines the structure of both synchronous and asynchronous systems into a model that is resilient yet also realistic.

Akhil Kammila

An analysis of the Tor Handshake

Mentor: Kyle Hogan

The Tor network is one of the most important anonymous services as it enables users to bypass censorship restrictions, avoid being traced, and access the internet with true privacy. Tor uses a unique handshake to establish connections in its circuit. The handshake attempts avoid censorship by mimicking TLS, but practical methods to distinguish it may remain. The handshake also has high latency, which detracts from the user experience. There have been formal security analyses for TLS and QUIC, but Tor's handshake security has not been verified. Our work will present a security analysis of the Tor handshake protocol. The results will apply to handshakes where mutual authentication between Tor relays is required and to handshakes where a relay authenticates to a client. We will also propose changes to the Tor handshake protocol to improve its censorship resistance and latency.

Carl (Zifan) Guo

Studying the effectiveness of transformer models for analyzing low-level programs

Mentor: William Moses

The Transformer model has made many breakthroughs in the field of natural language processing, especially when one adopts transfer learning, the process of first pretraining then fine-tuning on a downstream task. Unlike natural languages that are somewhat tolerant of minor differences in word choices or ordering, the structured nature of programming languages means that program meaning can be completely redefined or be invalid if one token is altered. Whereas recent literature has examined how to use Transformer models on high-level programming semantics, this presentation explores the effectiveness of applying Transformer models to analyze various tasks when given low-level representations of programs that can shed light on better optimizing compilers. By evaluating results of two separate case studies, one that models LLVM intermediate representation (IR) and translates between C and LLVM-IR and another that analyzes basic blocks to estimate its throughput, we describe various changes in program representation, network architecture, and other modifications that we found to influence the effectiveness and the present limitations of Transformers on low-level code.

Session 10: Computer Science

Abhinav Mummaneni

Unsupervised contrastive learning with hard positive samples

Mentors: Prof. Suvrit Sra and Joshua Robinson

A key challenge in unsupervised contrastive learning is selecting the informative positive (similar) pairs for the encoder network to learn to be invariant between. Standard contrastive learning approaches sample a single positive pair. In this work we develop methods for generating harder positive pairs in the hope that they provide more useful learning signal. Our approach is to sample multiple similar inputs, and search over all pairs to find the hardest pair. Results thusfar show that our approach for selecting the hard positives results in higher accuracy on downstream tasks. On CIFAR10 we show an absolute accuracy increase of 0.9 when increasing the number of positives from two to three, and an increase of 3.1% when going from two positives to five. Although these results validate our central idea, we also find that our hard positive sampling approach is both memory and compute intensive. We therefore also discuss ideas for future work on decreasing the memory and compute cost such as using model distillation and a dynamic memory bank.

Jack (Qi Hao) Wang

Generalization of X-fields image interpolation model to higher dimensions

Mentor: Guillaume Leclerc

Generating images of the same scenes from different perspectives—whether that is from different points, from different angles, under varying illumination, or with other parameters—has a myriad of use cases, stretching from creating debug models to producing smooth videos. In the X-Fields model, hard-coded graphics tricks like lighting, 3D projection, and albedo are used to supplement neural networks in creating a differentiable map for the image parameters and the actual pixels using sample images and their corresponding coordinate values. Although X-Fields performs well on datasets of images concentrated on a 2D (x, y) plane relative to alternative interpolation methods, the original model cannot support broader use cases like the interpolation of images in different 3D (x, y, z) positions. After using the 3DB framework to generate 3D images and coordinates that we then pass through our dimensionally expanded version of the X-Fields model, we find that the new model can generate promising interpolation results with relatively sparse datasets and with large view angle changes; parameters such as learning rate, the bandwidth parameter in soft blending, and others have impact over the interpolation quality and construct trade-offs between training cost and interpolation quality; and that certain backgrounds (like the ocean) added to reference images can pose challenges for interpolation.

Michael (Yihao) Huang and Claire Wang

Efficient algorithm for parallel Bi-core decomposition

Mentors: Prof. Julian Shun and Jessica Shi

Many real-world statistics and problems can be modeled by graphs, such as user-product networks, social networks, and biological networks. Identifying dense regions within these graphs is useful for product-recommendation, spam identification, and protein-function discovery. k-core decomposition is a fundamental graph theory problem that discovers dense substructures of a graph. However, k-core decomposition does not directly apply to bipartite graphs, which are graphs that model the connections between two disjoint sets of entities. Bipartite graphs are widely used to model authorship, affiliations, and gene-disease associations, to name a few.

In this paper, we solve the analog of the k-core decomposition problem, which is the bi-core decomposition problem. Existing sequential bi-core decomposition algorithms are not scalable to large-scale bipartite graphs with hundreds of millions of edges. Therefore, in this paper, we develop a theoretically efficient parallel bi-core decomposition algorithm. Compared to existing parallel algorithms, our algorithm reduces the length of the longest dependency path of the computational graph which measures the asymptotic bound of a parallel algorithm given sufficiently many threads. We provide an optimized parallel implementation that is scalable and fast. Using 30 threads, our parallel algorithm achieves up to 34.8x self-relative speedup. Our code achieves up to 4.1x speedup compared with the best existing parallel algorithm.

Tanmay Gupta and Anshul Rastogi

Enhancing distributed tracing to order events

Mentor: Prof. Raja Sambasivan, Tufts University

Many modern online services rely on the interaction between different components that form a distributed system. Analyzing distributed systems is important in performance analysis (e.g. critical path analysis), debugging, and testing new features. However, the analysis of these systems can be difficult due to limited knowledge of how components work and the variety of services and applications that can be instrumented. The Mystery Machine uses log events across many traces to generate and refine a causal model with decreased instrumentation. We describe our efforts to replicate The Mystery Machine and discuss the limitations of its algorithm. We aim to expand on

The Mystery Machine's algorithm, employed by Chow et al., by using thresholds to increase the tolerance to violations in the formation of causal relationships.

Session 11: Computer Science and Computational Biology

Kevin Zhao

More than BERT: oLMpics on diverse language models

Mentor: Prof. Anna Rumshisky, Namrata Shivagunde, and Vladislav Lialin, UMass Lowell

Pre-trained transformers are at the core of natural language processing today. However, the understanding of their internal representations is still limited. Existing work has not explored models that significantly differ from BERT either architecturally or via the pre-training objective. In our work, we utilize the oLMpics benchmark for a diverse set of models including T5, BART, and ALBERT. Additionally, we adapt the oLMpics zero-shot setup for autoregressive models and evaluate GPT networks of different sizes. Our findings show that none of these models can resolve compositional questions in a zero-shot fashion. Additionally, we utilize attention norm analysis and demonstrate the evolution of representations in the models. We show that intuitive features like "age-MASK" attention do not contribute to the performance and finally demonstrate a new head-specialization phenomenon in T5 models that is caused by the Pre-Norm transformer architecture.

Christine (Ali) Yang

Linear classifiers and t-SNE for understanding relationships across cancer types

Mentor: Prof. Stefanie Jegelka and Alkis Gotovos

While cancers originating from different organs have significant differences, the molecular mechanisms behind them remain the same. We conduct a pan-cancer genome analysis using public data from the Cancer Genome Atlas to analyze similarities and differences across cancer types at the genetic level. Our results suggest that cancers from organs in a single organ system or originating from similar cell types are noticeably related even at the genetic level. We then use t-SNE to isolate the most significant pan-cancer genetic patterns and correlations between them.

Anish Mudide

Predicting mammalian conservation status from genome summary statistics

Mentor: Dr. Ayshwarya Subramanian, Broad Institute

The conservation status of a species is traditionally defined by ecological traits, such as population size and geographic range. Cataloging sufficient data for the world's millions of species has proven to be both time-consuming and expensive; even the most comprehensive system, the IUCN Red List of Threatened Species, has assessed just over 138,000 species. Given the rise of practical and economical genome sequencing, this talk explores how mammalian conservation status may be revealed via analysis of genomic features. In fact, the genome sequence of a species directly captures key markers of conservation status, such as regions of reduced genetic diversity and genetic load. Moreover, levels of inbreeding and historical population declines can be inferred via analyses of heterozygosity across the genome. While previous predictive models of conservation status have incorporated just ecological variables, these results from conservation genetics suggest that such models will benefit greatly from the inclusion of relevant genomic information.

Neil Chowdhury

Interplay between loop extrusion and compartmentalization during mitosis

Mentor: Sameer Abraham

During mitosis, DNA changes its physical structure from diffuse chromatin spread throughout the cell nucleus to discrete, compacted, cylindrical chromatids. This process is essential for cells to be able to transfer replicated chromosomes to the daughter nuclei. During interphase, chromatin is compartmentalized into heterochromatin and euchromatin, resulting in a visible signal in Hi-C contact maps. However, as the cell enters mitosis, this signal is disrupted, only to reappear after the cell divides. This talk explores the interphase and mitotic states by modeling DNA using polymer simulations. It is shown that loop extrusion, the mechanism underlying mitotic chromosome formation, can simultaneously be responsible for disrupting compartmentalization.

Vishnu Emani

Computational fluid modelling for surgical planning of single ventricle congenital heart defects

Mentors: Dr. David Hoganson and Dr. Vijay Govindarajan, Boston Children's Hospital

Single ventricle defects (SVD) refer to the collection of congenital heart defects in which one chamber of the heart remains weak or underdeveloped. Many surgical procedures, including the Fontan procedure and bilateral bidirectional Glenn, introduce non-natural blood pathways. In order to avoid defects such as Pulmonary Arteriovenous Malformations (PAVMs), the hepatic venous flow needs to be equally distributed to the left and right lungs. The purpose of this study was to evaluate the effects of various factors on hepatic flow distribution in Fontan and bilateral bidirectional Glenn patients. Idealized geometries were developed using Fusion 360 CAD software to model patient physiologies, assuming cylindrical, straight vessels. The geometries were varied with a collection of parameters, including vascular diameter, positioning of the Fontan conduit with respect to the vena cavae, and curvature of the Fontan conduit. Each parameter was varied at regular intervals, with the other variables constant. Computational Fluid Dynamic (CFD) simulations were executed on the idealized models, assuming laminar flow and no-slip boundary conditions, and massless particles were injected into hepatic veins with varied velocity boundary conditions. The hepatic particle distribution to each pulmonary artery was calculated and recorded. The results for Fontan curvature demonstrated no significant change in relative LPA hepatic flow as curvature increased. For both 1:1 and 1:1.5 SVC:IVC flow ratios, hepatic flow to the LPA ranged between 50% and 55%, and no consistent trend was observed. This result is not entirely surprising, given that the clinical range of Fontan curvatures is too small to have a significant impact on hemodynamic results. Results have yet to be gathered for other variables in bilateral bidirectional Glenn patients, but the same strategy will be applied. Overall, this study demonstrates the power of CFD as a tool for identifying factors that affect hepatic flow distribution in surgical management of SVD anatomies.

Arthur Hu and Powell Zhang

Remote interactions and effects on mental and physical health

Mentor: Prof. Gil Alterovitz

Loneliness remains a prominent issue when considering patients in long-term care as they are often isolated from a ready source of social interaction and may only receive infrequent visits from family. This problem has been exacerbated in recent years due to the COVID-19 pandemic which has drastically increased the difficulty of visiting care patients. To alleviate loneliness, video-calling devices were provided to facilitate online communication between veteran patients, their families, and their caregivers in a collaboration between the Red Cross Military and Veterans Caregiver Network and Facebook. We present an analysis of over 2000 patient and caregiver responses to loneliness surveys to determine the efficacy of these devices. Our results demonstrate that the devices have produced significant decreases in loneliness among both patients and their caregivers. Through expanded use both in this population and in others, it may be possible to further explore a number of additional benefits suggested by this initial work.

Sruthi Kurada and Victoria Yuan

Characterizing ergothioneine pathways and potential drug targets via intrinsically disordered protein analysis

Mentor: Prof. Gil Alterovitz

Ergothioneine (ERGO), a naturally occurring amino acid found mainly in mushrooms, is a powerful antioxidant which has attracted significant interest as a longevity drug in recent years. The concentration of ERGO in the human bloodstream tends to decrease with age, and this reduction has been associated with the onset of several diseases including mild cognitive impairment, Parkinson's disease, cancer, and cataracts. In this study, we aim to advance knowledge in the molecular pathways ERGO impacts, and characterize its potential drug targets via intrinsically disordered proteins (IDPs) analysis. We first conducted in vitro analyses, in which we identified differentially expressed IDPs that were significantly up or down regulated by ERGO. Secondly, we used in silico molecular docking to predict the binding affinity of ERGO with top IDP candidates. Through in vitro and in silico analyses, we identified 15 protein receptors with the highest interaction potential with ERGO. These receptors corroborate findings of previous studies linking the molecule to reduced inflammation, reduced risk of cancer, and neurological protection. In addition, we suggest new potential functions for ERGO, most notably decreasing blood-clotting and lowering calcium concentration in the muscle and bloodstream. This review outlines potential drug targets and pathways to be prioritized in further studies of Ergothioneine's therapeutic effect.

Session 13: Mathematics

Nathan Xiong

The master field and free Brownian motions

Mentor: Pu Yu

In this talk, we introduce free probability, a non-commutative analogue to classical probability theory, where independence is replaced by the notion of "freeness." This allows us to define the master field on the plane, a collection of non-commutative random variables indexed by loops in $\mathbb{R}^2$. The Makeenko-Migdal equations give us an efficient way to calculate the master field through a system of differential equations. Finally, we briefly discuss two-dimensional Yang-Mills theory and the motivation of our work.

Rishabh Das

Thermocapillary modulation of fluidic lenses in microgravity

Mentor: Dr. Valeri Frumkin

The fluidic shaping method is an exciting new technology that allows us to rapidly shape liquids into a wide range of optical topographies with sub-nanometer surface quality. The scale-invariance of the method makes it well suited for for space-based fabrication of large fluidic optics, allowing to overcome launch constraints that currently limit the size of space telescopes.

However, in microgravity, the fluidic shaping method typically produces simple spherical shapes, resulting in spherical aberrations that substantially reduce the maximal resolution of the optical component. In this talk I'll present how thermally generated variations in surface tension allow the fluidic shaping method to deviate from spherical surfaces, providing a much wider range of obtainable optical topographies. We derive a differential equation governing the steady-state shape of the liquid lens, and provide an analytic solution for the axisymmetric case where surface tension varies quadratically with the radius.