127th STATISTICAL MECHANICS CONFERENCE
SHORT TALK SCHEDULE

SESSION A: Monday December 16, 2024 8:40am - 9:45 am

A1: David Roth, Yeshiva University

Title: Network of Networks with heterogeneous k-core percolation and hyper-links

Coauthors: Sergey Buldyrev, Bo Tong

Abstract : We study the cascading failures in systems of any number of networks connected to each other via groups of supply links which we call hyperlinks. The individual supply links of a hyperlink connect individual nodes belonging to the pair of networks connected by this hyperlink. Such a system is called a network of networks (NON), and a NON that based on the idea of mutual percolation has been studied for the case of dependency hyperlinks. The present model is the generalization of the heterogeneous k-core percolation for the NON, where any number of hyperlinks can be directional and any number of them can be bidirectional. We will show that, by utilizing generating function formalism, the cascading process can be modeled by a set of recursive relations that are generalizations of previously studied relations in heterogeneous k-core percolation. We show that the order in which failures propagate throughout the system does not matter for determining the final fraction of functional nodes, which depends only on the NON topology. We show that, in the NONs, there can be more than one transition point, defined as the discontinuous jump in the fraction of functional nodes at the end of the cascade as the strength of the initial attack on one of the networks gradually changes, and critical point, defined as when transition is between continuous and discontinuous. We further generalized previously studied criteria for the transition points and critical points in the bipartite network to these NONs, and compare the phase diagrams of NONs with multiple critical points to the phase diagrams of protein solutions.

A2: Matthew Marko, Marko Motors LLC

Title: Updates on the prototype development of a Stirling cycle solar generator, using the intermolecular Van der Waals forces to boost the thermodynamic efficiency

Abstract: A pending patent (18,888,204) was recently submitted to the USPTO, utilizing pistons and cylinders to effectuate a heat engine cycle. This cycle utilizes the large specific heat capacity of the cylinders to have near-isothermal compression and expansion, as well as utilizing near-isentropic compression and expansion to reduce and increase the working fluid temperature; similar to the theoretical Carnot cycle. This approach is utilized to increase the practical thermodynamic efficiency of the heat engine, generating useful motive power from small temperature differentials. The engine was designed to utilize non-ideal carbon dioxide gas, so as to further boost the thermodynamic efficiency by taking advantage of the temperature-dependence of the intermolecular attractive Van der Waals forces, as demonstrated in an earlier effort (DOI: 10.1038/s41598-022-11093-z).

A3: Jaeuk Kim, Princeton University
Generation of Dense Disordered Stealthy Hyperuniform Sphere Packings
Coauthors: Salvatore Torquato

Abstract: Disordered stealthy hyperuniform (SHU) packings are exotic amorphous two-phase materials endowed with novel optical, transport, and mechanical properties. We create such packings via a modified collective-coordinate optimization scheme that includes a soft-core repulsion in addition to the standard "stealthy" pair potential. Here, we demonstrate that 3D SHU packings with soft-core repulsions attain substantially higher packing fractions compared to those without soft-core repulsions, and the resulting structures range from disordered jammed packings to polymer-like linear hard-sphere chains as the stealthiness parameter χ varies. Thus, our results offer a new route for discovering novel disordered hyperuniform two-phase materials with unprecedented high density

A4: Murray Skolnick, Princeton University
Predictive Effective Conductivity Formulas for a Class of Two-Phase Materials
Coauthors: Salvatore Torquato

Abstract: Two-phase heterogeneous materials arising in a variety of natural and synthetic situations exhibit a wide-variety of microstructures and thus display a broad-spectrum effective physical properties. Given that such properties of disordered materials generally depend on an infinite-set of microstructural correlation functions that are typically unobtainable, in practice, one must consider rigorous bounds and approximations on the effective properties that depend on a limited set of nontrivial microstructural information. Over two decades ago, Torquato [1] derived such an approximation for the effective thermal/electrical conductivity of two-phase microstructures that perturb about those that realize the well-known self-consistent formula; a key feature of such microstructures being phase-inversion symmetry. Moreover, he predicted that this approximation, which depends on up to three-point correlations, should accurately estimate the conductivity of symmetric-cell materials with spherical cells. Here, we show via extensive numerical simulations that this virtually unexamined approximation predicts accurately the effective conductivities of various two- and three-dimensional two-phase microstructures, including symmetric cell materials with square and cubical cells, as well as certain model disordered microstructures both with and without phase-inversion symmetry. Additionally, we exactly derive the ranges of phase volume-fractions in which this approximation lies between the tightest three-point bounds. Predictions of this approximation in the limit of perfectly insulating and superconducting phases, as well as connections to the percolation thresholds of the microstructures will also be discussed.

A5: Žiga Krajnik, New York University
Title: Anomalous fluctuations in charged single-file systems and integrable spin chains
Coauthors: Takato Yoshimura, Enej Ilievski, Johannes Schmidt, Vincent Pasquier, Tomaž Prosen

Abstract: We introduce charged single-file systems and discuss their anomalous charge fluctuations. The full counting statistics of such systems out of equilibrium generically undergoes first and second order dynamical phase transitions, while equilibrium typical fluctuations are non-Gaussian and follow a universal distribution. Similar phenomenology of dynamical criticality is observed in equilibrium fluctuations in easy axis and isotropic regimes of an integrable spin chain. While the easy axis regime does not manifestly satisfy a single-file kinetic constraint, it nevertheless supports the non-Gaussian distribution of the charged single-file class. The dynamical spin structure factor at the isotropic point matches that of the Kardar-Parisi-Zhang universality class while spin fluctuations are anomalous but distinct from those of the Kardar-Parisi-Zhang universality class.

A6: Xiangyi Meng, Rensselaer Polytechnic Institute
Title: **Distinct statistical characteristics of quantum communication networks**
Abstract: Network science emerged around the year 2000, two decades after the birth of the Internet. As a result, much of its focus has been on explaining (rather than designing) the statistical and structural properties of real-world networks, such as scale-freeness and small-world behavior. However, with the quantum Internet still in its early stages, the question arises: can network science actively contribute to the design of large-scale quantum communication networks from first principles? In this talk, I will explore how quantum communication networks can differ fundamentally from their classical counterparts, especially when incorporating various quantum elements like quantum memories, entanglement routing paradigms, and the intricate challenge of multipartite entanglement. These components have the potential to enhance quantum networks not just at the point-to-point level, but at the synergistic, network-wide scale, revealing novel statistical characteristics. This may open the door to a comprehensive, globally integrated (re)design of quantum communication systems—guided by the principles of network science.

A7: Gregory Dignon, Rutgers University
Title: Statistical Inference of Patterning Parameter Distributions in Intrinsically Disordered Proteins
Coauthors : Arjun Singh, Ali Ukperaj
Abstract : Intrinsically Disordered Proteins (IDPs) are proteins which do not assume a single stable folded structure, but rather populate an ensemble of coil-like or molten globule conformations. Their solution behavior can be roughly characterized by various size-related properties including radius of gyration, polymer scaling exponent and end-to-end distance. Predicting these properties directly from sequence is of general interest to the community. The composition and patterning of amino acids in the sequence play a large role in dictating the solution behavior of IDPs. Here we develop a probabilistic approach to calculating the range of possible values of certain charge and hydropathy patterning parameters that are predictive of IDP solution behavior, and can be calculated based on pairwise distance distributions of

different types of amino acids in a sequence. To validate this approach, we generate thousands of sequences having the same composition and directly calcualte out the distribution of patterning parameter values. We find that the probabilistic approach give decent agreement with the brute-force approach at a fraction of the computational cost. This is useful for design of new amino acid sequences with particular sequence properties.

A8: Miaohua Jiang, Wake Forest University
Title: Sinai-Ruelle-Bowen entropy and laws of thermodynamics
Abstract: Based on the Gallavotii-Cohen Chaotic Hypothesis, we model the process in which a nonequilibrium thermodynamic system evolves to its equilibrium as a gradient flow of the Sinai-Ruelle-Bowen entropy defined on the space of transitive Anosov maps. In low-dimensional cases, we prove the basic postulate and the second law of thermodynamics.

A9: Benjamin Sorkin, Princeton University
Title: Second Law of Thermodynamics without Einstein Relation
Coauthors: Haim Diamant, Gil Ariel, and Tomer Markovich
Abstract: Materials that are constantly driven out of thermodynamic equilibrium, such as active and living systems, typically violate the Einstein relation. This may arise from active contributions to particle fluctuations which are unrelated to the dissipative resistance of the surrounding medium. We show that in these cases the widely used relation between informatic entropy production and heat dissipation does not hold. Consequently, fluctuation relations for the mechanical work, such as the Jarzynski and Crooks theorems, are invalid. We propose a temperature-like variable which restores this correspondence and gives rise to a generalized second law of thermodynamics, whereby the dissipated heat is necessarily nonnegative and vanishes at equilibrium. The Clausius inequality, Carnot maximum efficiency theorem, and relation between the extractable work and the change of free energy are recovered as well.

A10: Ronald Fisch
Title: **Adaptive Boundary Conditions and the Interface Energy Scaling Exponent of the Ising Spin Glass**
Abstract: Using a more physical boundary condition (BC) than periodic and/or antiperiodic, a simple argument leads to the scaling law $\theta_i = 2*\theta_m$, where θ_m is the familiar McMillan exponent for the interface energy of an Ising spin glass, defined by the absolute value of the energy difference between applying periodic and antiperiodic BCs to some finite sample in one direction and periodic BCs in the remaining directions. The exponent θ_i is the exponent which characterizes the actual energy scaling for a domain wall in a D-dimensional nearest neighbor Ising spin glass of size L^D below its freezing temperature, T_c.

A11: Harman Preet Singh, SISSA (Trieste)
Validity of edge linear response for 2d topological insulators
Coauthors: Marcello Porta

Abstract: For a class of non-interacting quantum Hall lattice systems on a cylinder, we consider the edge density and current dynamical responses to a time-adiabatic density-type perturbation, in the infinite volume and zero temperature limit. We prove the validity of the linear response for such quantities, thus justifying Kubo's formula. Further, we explicitly evaluate them solely in terms of spectral data at the Fermi points, and of the profile of the perturbation. The proof of validity of linear response on the physically relevant time-scale relies on a precise analysis of the imaginary-time Duhamel series, and in particular on a cancellation for the scaling limit of the higher order correlation functions describing the nonlinear response, also related to bosonization. The precise form of the linear response coefficient is then fixed by lattice conservation laws. Based on part of arXiv:2411.04023, a joint work with Marcello Porta.

A12: Alexander Migdal, IAS
Duality of fluid mechanics and Solution of Decaying Turbulence.

Abstract: I will describe the duality of incompressible Navier-Stokes fluid dynamics in three dimensions, leading to its reformulation in terms of a one-dimensional momentum loop equation. The decaying turbulence is a solution of this equation equivalent to a string theory with discrete target space made of regular star polygons and Ising degrees of freedom on the sides. This string theory is solvable in the turbulent limit, equivalent to the quasiclassical approximation in a calculable background. As a result, the spectrum of decay indexes is analytically computed and agrees very well with real and numerical experiments. Among the decay indexes there are complex conjugate pairs related to zeros of the Riemann zeta function. The Kolmogorov scaling laws are refuted. The momentum loop equation does not have finite-time blow-up solution

SESSION B: Tuesday, December 17, 2024 8:30 am- 9:45 am

B1: Daniel Swartz, MIT

Title: How host mobility patterns shape antigenic escape during viral-immune co-evolution

Coauthors : Natalie Blot, Caelan Brooks, Eslam Abdelaleem, Martin Garic, Andrea Iglesias-Ramas, Michael Pasek, Thierry Mora, and Aleksandra M. Walczak

Abstract: Viruses like influenza have long coevolved with host immune systems, gradually shaping the evolutionary trajectory of these pathogens. Host immune systems develop immunity against circulating strains, which in turn avoid extinction by exploiting antigenic escape mutations that render new strains immune from existing antibodies in the host population. Infected hosts are also mobile, which can spread the virus to regions without developed host immunity, offering additional reservoirs for viral growth. While the effects of migration on long term stability have been investigated, we know little about how antigenic escape coupled with migration changes the survival and spread of emerging viruses. By considering the two processes on equal footing, we show that on short timescales an intermediate host mobility rate increases the survival probability of the virus through antigenic escape. We show that more strongly connected migratory networks decrease the survival probability of the virus. Using data from high traffic airports we argue that current human migration rates are beneficial for viral survival.

B2: Leonardo Goller, SISSA

Title: π-flux phase stability in Z_2 lattice Gauge theory coupled to fermionic matter

Coauthors : Marcello Porta

Abstract: The Flux Problem is a famous problem in condensed matter physics, solved by Lieb. It states that the magnetic flux through each plaquette of a square lattice in 2d (with either OBC/PBC or PBC/PBC) that minimizes the ground state energy of a system of free electrons at half-filling is π. Such phase, called π-Flux Phase, is known to display emergent Dirac-like low energy excitations. What happens when we couple the system to a dynamical Z_2 gauge field whose energy is minimized by 0 flux per plaquette? In this talk, we prove the stability of π-Flux Phase by showing, using Reflection Positivity techniques, that the energy of the fermions at half-filling in a background of N monopoles increases extensively in N. As an application, we compute explicitly the zero temperature diamagnetic susceptibility and the conductivity of the gauge theory, and we show that they coincide with the ones of massless Dirac fermions.

B3: Shengkai Li, Princeton University

Title: Memory-induced spontaneous symmetry breaking

Abstract: We explore memory-driven dynamics in a society of autonomous spinning robots, where agents exchange and process opinions based on memory and distinct personalities. We gave each agent one of two possible opinions ($+$ or $-$) and a distinct personality. We start with a simple yet commonly observed way to change opinion, namely following the majority after asking around. We observed that agents with small memory will stay at an even mixture of both opinions, while agents with memory size larger than a critical number, the collective will unavoidably reach a consensus. When the society is added with more reality, such as introduction of stubborn constant agents can

assimilate all other agents given the ratio is larger than a critical number; introduction of an agent always goes against the majority will oscillate the demography intermittently.

B4: Peter Morse, Seton Hall University
Title: A generalized form of shear and its utility in storing material memory
Coauthors: Elisabeth Agoritsas, Collin Doyle
Abstract: Under a sufficiently small shear a material will deform elastically and have entirely reversible behavior. However, beyond a critical value, the response of the material will become nonlinear and the material can be trained to hold a mechanical memory of its driving. This process has been studied extensively, but in practice, a global shear only allows a small number of mechanical memories to be stored. It is thus reasonable to ask whether orthogonal memories can be stored, and if so, how many? By adapting a localized shear to jammed sphere packings---whose response can be predicted through the mean-field theory of glasses---we can form highly localized and fully decoupled memories. In this talk, I will discuss our ongoing efforts to characterize these memories.

B5: Zhiyue Lu, UNC Chapel Hill
Non-equilibrium Response Relations Beyond Steady States
Coauthors: Jiming Zheng
Abstract: Fluctuation-dissipation relations elucidate the response of near-equilibrium systems to environmental changes, with recent theoretical advancements focusing on non-equilibrium steady states (NESS). While the response theory for steady states is well-developed, a general and interpretable response relation for systems evolving far from steady states has remained an open challenge. We derive a universal response relation that is valid arbitrarily far from equilibrium and NESS. The response equality provides a unified perspective on how systems respond to environmental perturbations by explicitly characterizing the relation between the system's responsiveness and the irregularity of its internal fluctuations, which we denote as "dynamical discrepancy." By connecting response to measurable kinetic properties, our theory offers new insights for understanding and designing responsive behavior in far-from-equilibrium systems ranging from biological sensory processes to responsive materials.

B6: Rahul Chacko, University of Pennsylvania
String-like Rearrangements Induce Mobility in Supercooled Liquids
Abstract: Dynamical heterogeneity is a signature phenomenon of deeply supercooled liquids and glasses. Here, we demonstrate that the spatiotemporal correlations between local relaxation events that underpin it are the result of local relaxation events raising the likelihood that other relaxation events subsequently occur nearby, confirming a widely held, but until now unsubstantiated, belief that dynamical facilitation is responsible for dynamical heterogeneity. We find that mobility is propagated through the entrainment of particles into elementary string-like

rearrangements, known as microstrings, and not through perturbing the structure surrounding these rearrangements.

B7: Francisco Hernandez, University of Fribourg
Transverse spreading Anderson Localization in two-dimensional disordered correlated dielectric materials with bandgap regimes
Coauthors: Luis S. Froufe-Perez and Frank Scheffold
Abstract: Using numerical simulations, we investigate the transverse spreading of a focused beam across various realizations of 2D Stealthy Hyperuniform (SHU) materials composed of parallel-aligned dielectric \noteFS{no silicon here} rods within a rectangular slab geometry. For frequencies far from the bandgap, rapid spreading to the slab edges suggests diffusive behavior. Conversely, tight transverse confinement of the transmitted intensity near the gap indicates the presence of Anderson localization. We identify all transport regimes of the SHU-transport phase diagram —bandgap, pseudotunneling, Anderson localization, and diffusion—to rationalize our findings.

B8: Georgios Gounaris, University of Pennsylvania
A Paradox in Physical Networks of Diffusive Exploration
Coauthors: Eleni Katifori
Abstract: Time is a critical factor in numerous physical systems that rely on complex networks to ensure navigability among their components. From human-made transportation networks that seek to optimize routes between stations, to transport of particles in porous media and biological networks, intricate structures and active motion mechanisms ensure low mean first passage times (MFPT) between the target regions. Yet, random walkers can get lost within complex networks and stray from the desired target. This leads to a fundamental question: What is the best architecture that makes a graph optimally searchable? Traditionally, it has been assumed that small-world architectures with numerous shortcuts between distant nodes are ideal. Counter-intuitively, for diffusive exploration of spatially embedded networks, we find that the addition of a link can worsen the total search time between all pairs of nodes, akin to the well-known Braess paradox where increasing a system's capacity reduces its efficiency. This highlights that the topological advantage gained from the extra pathway can be negated by the diffusive delay required to traverse the length of the shortcut, as dictated by the mean squared displacement of anomalous diffusion. We generalize, developing an optimization scheme according to which each edge adapts its conductivity in order to minimize the total mean first passage time. This unveals a crossover in the optimal architecture: for super-diffusive motion, the optimal graph features long-range links, while for sub-diffusive propagation geometrical nearest connections are preferred. Ultimately, we explore how multiple propagation speeds can mitigate the impact of "Braessian edges" inspired by the ingenious strategies of intracellular transport networks that utilize diffusion over short distances and motor-driven ballistic motion over longer ones.

* Publication reference: Braess's Paradox Analog in Physical Networks of Optimal Exploration, Phys. Rev. Lett. 133, 067401

B9: Jianxi Gao, Rensselaer Polytechnic Institute
Network Science for AI
Co- Authors: Chunheng Jiang, Zhenhan Huang, Tejaswini Pedapati, Pin-Yu Chen, Yizhou Sun, & Jianxi Gao
Abstract: Machine learning influences numerous aspects of modern society, empowers new technologies, from Alphago to ChatGPT, and increasingly materializes in consumer products such as smartphones and self-driving cars. Despite artificial neural networks' vital role and broad applications, we lack systematic approaches, such as network science, to understand their underlying mechanism. In this talk, I will briefly introduce our work on using network science tools to evaluate the performance of neural networks. First, we develop a mathematical framework that maps the neural network's performance to the network characters of the line graph governed by the edge dynamics of stochastic gradient descent differential equations. This framework enables us to derive a neural capacitance metric to universally capture a model's generalization capability on a downstream task and predict model performance using only early training results. Secondly, we map the original neural network to a graph based on its information propagation. We find that the degree of this network quantifies its performance and achieves zero-shot learning. It frequently outperforms the state-of-the-art approaches.

B10: Maxim Lavrentovich, Worcester State University
Title: Stripe formation in driven binary mixtures with repulsive interactions
Coauthors: G. E. F. Oliveira, R. Dickman, R. K. P. Zia
Abstract: We investigate a phase-separating binary mixture of diffusive particles with short-range repulsive interactions under uniform drive in two and three dimensions. We find elongated domains - stripes or lamellae in the ordered phase and finite strips in the disordered phase - perpendicular to the drive direction, with their characteristic size inversely proportional to the drive strength. This behavior is observed in multiple models, including the driven Widom-Rowlinson lattice gas and its corresponding mean field theory. We propose and analyze a continuum theory of such systems, demonstrating that fluctuations are essential for domain formation in the disordered state. We discuss the features of these systems, including large density fluctuations and cusps in the static structure factor for small wavevectors.

B11: Aaradhya Pandey, Princeton University
Title: **Multivariate version of the Ghirlanda-Guerra identity and an application**
Abstract: In this talk, we will introduce Ghirlanda-Guerra identities in the context of mean-field spin glasses, and prove a multivariate version. As an application, we will resolve some aspects of the problem of limiting spectra of the matrix of spin correlations coming from mean-field spin glasses.

B12: Bruno Renzi, Università degli Studi di Milano Statale
Free energy universal finite temperature correction in non-solvable quantum chains
Coauthors: Alessandro Giuliani, Vieri Mastropietro and Venanzio Alessio Santini
Abstract: It was conjectured by Affleck and Blöte-Cardy-Nightingale that the leading finite temperature correction to the free energy in a quantum chain is universal and simply related to the central charge and the effective velocity of the system. This has been established in few exactly solvable models. We prove it for a class of weakly interacting non-solvable quantum chains by means of fermionic Renormalization Group methods.

B13: Simone Fabbri, SISSA (Trieste)
Universality of the Topological Phase Transition in the Haldane-Hubbard Model
Coauthors: Alessandro Giuliani, Robin Reuvers (Roma Tre University)
Abstract: One central problem of Solid State Physics is the study of the transport coefficients of many-electrons systems. It is known that Quantum electron systems, in presence of an external magnetic field and a gap in the energy spectrum, exhibit a transverse conductance which is quantized at integer values, in units of e^2/h. This phenomenon is known as Integer Quantum Hall Effect (IQHE), and in the last decades its stability under disorder and weak inter-particle interactions has been shown too. In our work we investigate the nature of the `topological phase transition', i.e. the phase transition between two different (integer) values of the Hall conductivity. We focus on a remarkable prototype of 2D lattice system for the study of the IQHE, the Haldane-Hubbard model, which is obtained from the standard Haldane model by adding a weak, generalized, Hubbard interaction. We study the semi-metal phase transition from the normal insulating phase to a non-trivial Quantum Hall phase, and we prove that at the transition the conductivity is quantized at the symmetric average between the two insulating phases nearby, universally with respect to the interaction. Our result is obtained by a rigorous renormalization group approach, combined with the knowledge of the universality for the insulating phases of the model, which in turn relies on exact lattice Ward identities.

B14: Robert Ziff, University of Michigan
Percolation and filtering in porous media
Coauthors: Salvatore Torquato, Michael Klatt
Abstract: When particles such as spheres are pushed together, a random closed packed or maximally random jamming (MRJ) state is reached. While a fluid will obviously flow through the system, finite-size particles moving in that fluid must be sufficiently small to make it through --- thus, there is a percolation transition depending on the relative diameter of the flowing spheres and the jammed spheres. We find that the critical value of the ratio is about 0.278. We use a Voronoi construction around the packed spheres to find the pore throats through which the moving particles must pass through. We can also look at other arrangements of the jammed spheres, including regular crystalline arrays.