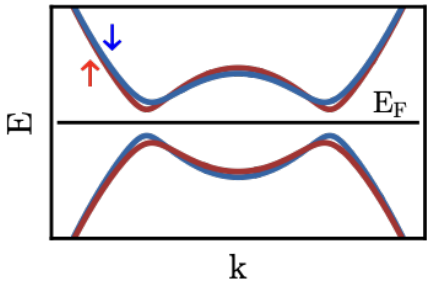
Bachelor/Master Thesis Projects 2027

Theory of Quantum Matter, Prof. Titus Neupert

Experimental fingerprints of altermagnetic superconductors

Altermagnetism was recently established as a third class of magnetism, complementing ferromagnetism and antiferromagnetism. Like antiferromagnets, altermagnets have a vanishing total magnetic moment. However, unlike antiferromagnets, where inversion combined with time-reversal symmetry protects doubly degenerate bands, the electronic bands in altermagnets are spin split despite the absence of a net magnetization. This is possible because the opposite spin sectors in altermagnets are related by spatial symmetry operations other than translations or inversion. Multicomponent superconductors can exhibit similar symmetry properties to those of altermagnets. However, it is unclear under which conditions the reduced symmetry leads to an altermagnetic-like spin splitting of the (Bogoliubov) band structure. The aim of this project is to identify experimental fingerprints of the altermagnetic symmetry breaking of unconventional superconductors.



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Keywords: Altermagnetism, unconventional superconductivity, Bogoliubov quasiparticles, spin-split band structure, symmetry breaking, experimental signatures.

Interplay of Magnetism and Superconductivity in a locally-noncentrosymmetric system

Magnetism and superconductivity often compete, yet they appear in close proximity in many materials, from heavy-fermion compounds to iron-based superconductors and cuprates. A particularly rich setting is that of locally noncentrosymmetric crystals, such as $CeRh_2As_2$ or $CeCoIn_5/YbCoIn_5$ superlattices, which are globally centrosymmetric but break inversion symmetry within a sublattice, such as an individual layer. The symmetry pattern produces an antisymmetric spin-orbit coupling that changes sign between sublattices. As a result, even- and odd-parity superconducting states can become nearly degenerate and field-tunable; the magnetic sector acquires anisotropic exchange (e.g., Dzyaloshinskii-Moriya-type) couplings, that favor specific spin orientations and sublattice structures; and novel couplings between the two orders can appear.

This project investigates which magnetic orders can emerge, and how they are modified, when superconductivity sets in near a magnetic transition in such a locally-noncentrosymmetric system. A central question of the project, then, is whether superconductivity can induce or stabilize exotic magnetic states, such as spin spirals, via the symmetry-allowed couplings.

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Keywords: Unconventional superconductivity, spin-orbit coupling, magnetic order, spin spirals.

Adaptive Selection of Loop Clusters for Long-Range Correlations in Tensor Networks

Projected entangled-pair states (PEPS) are a powerful tool for simulating strongly correlated quantum systems in two dimensions. Computing their physical properties, however, requires the approximate contraction of large tensor networks. Belief propagation (BP) provides an inexpensive approximation, while loop and connected-cluster expansions systematically correct its errors by incorporating correlations neglected by BP [1, 2].

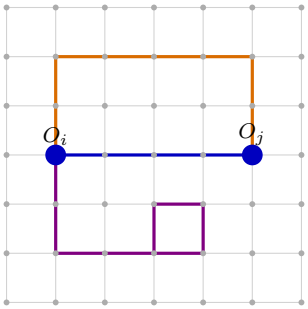


Illustration of candidate connecting structures on a square lattice. Shortest path (blue), longer detour (orange), and additional connected structure (violet).

A central computational challenge is deciding which clusters are worth including. Their number grows rapidly with cluster size, and selecting only the shortest paths between two measurement sites can omit important corrections. Conversely, many longer clusters may contribute negligibly to the desired observable.

Can their importance be estimated before performing their full tensor-network contraction?

In this project, you will investigate whether the importance of individual loop clusters can be predicted without explicitly computing their contributions. You will explore different selection strategies based on geometric properties, correlations, entanglement, and information available from BP. These approaches will be tested on realistic tensor-network states, comparing their accuracy in evaluating long-range correlation functions and their computational efficiency against conventional cluster-selection methods.

References

[1] G. Evenbly et al., Loop series expansions for tensor networks", 2026.

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[3] V. Gómez, J. M. Mooij, and H. J. Kappen, "Truncating the loop series expansion for belief propagation," *J. Mach. Learn. Res.* **8**, 1987–2016 (2007).

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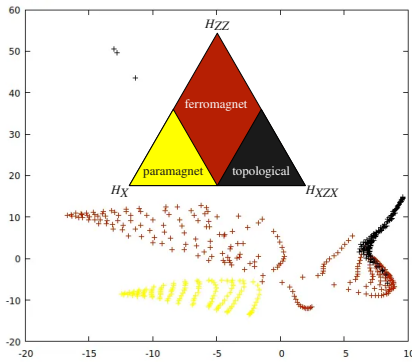
Keywords: Tensor networks, PEPS, belief propagation, loop-cluster expansion, entanglement, correlation functions, adaptive contraction.

Classification of topological phases with neural networks

Machine learning has had great success in classifying and recognising patterns in a variety of inputs. This includes classifying phases of matter based on data from experiments or simulations. However, there exist exotic phases known as topological phases, which are indistinguishable from trivial noninteracting states by straightforward local measurements, even though they carry intricate patterns of quantum correlations and entanglement.

The project consists of two, more or less independent, parts: depending on your interests, you may take either one (or both!).

Part 1: In this part of the project, you will explore whether machine-learning techniques can distinguish symmetry-protected topological (SPT) phases from conventionally ordered and disordered ones through the example of a spin-chain Hamiltonian. You will learn about principal component analysis (PCA) and variational autoencoders (VAEs), tools designed to extract similarities and differences from data, as well the DMRG algorithm for efficiently computing ground states of interacting quantum Hamiltonians. You will study whether these tools can distinguish the phases through conventional measurements (e.g., correlation functions).



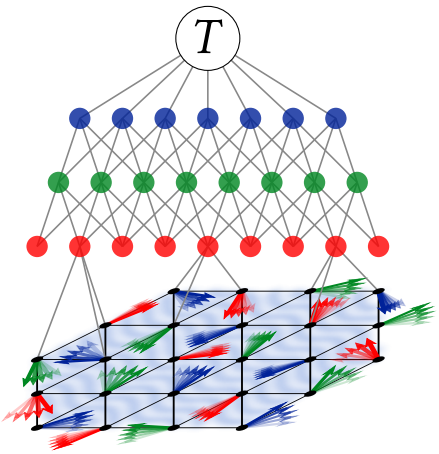
Part 2: In this part, you will explore how direct quantum measurements (i.e., samples from the Born probability distribution) may be used as input data. This part also involves learning about SPTs and DMRG as example systems to which to deploy the results. However, the focus is understanding the statistical and information theoretic principles underlying VAEs and designing one that works directly with the Born probability distribution.

If you'd like to work on one or both parts of the project, please send an email and share what motivates your interest. Please also mention which part of the project you are more interested in (both might be too much for one master's project), as well as any relevant background you may have in machine learning and/or condensed matter.

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Keywords: Machine learning, topological phases, variational autoencoder, probability theory.

Neural quantum states for lattice models of strongly correlated electrons

In the last few years, neural network wave functions have proven effective in describing many-body quantum systems. In particular, architectures such as FermiNet, PauliNet, and Psi-Former have been successful in tackling systems of interacting electrons in quantum chemistry. However, many important problems of condensed matter physics (e.g. the Hubbard model of high-temperature superconductivity) are defined on lattices: Adapting successful approaches from quantum chemistry to these problems comes with interesting new challenges.



In this project, you will develop such approaches for models of interacting electrons on a lattice, with a particular focus on efficient implementation of lattice symmetries and leveraging such symmetry-resolved data into a deeper understanding of the problem. The ultimate goal of the project is settling important open questions in the physics of strongly correlated electrons using large-scale, high-precision simulations.

In addition to learning about neural quantum states and challenging problems in the field of strongly-correlated-electron physics, you will gain experience with setting up simulations using the machine-learning frameworks JAX and NetKet

and find opportunities to collaborate with the wider machine-learning-for-physics environment in Zürich.

For this project, a good working knowledge of quantum physics, including second quantisation, is essential. Experience with programming in Python is also helpful.

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Keywords: Neural quantum states, machine learning, Hubbard model, quantum spin liquids, Slater determinants.

Generative machine learning for statistical mechanics

In recent years, generative machine learning has turned the world upside down. Closer to our interests, it is a promising solution to a central problem in computational physics: sampling. Monte Carlo simulations underpin much of our numerical understanding of thermodynamics, but at low temperatures, conventional sampling algorithms slow down or even become completely frozen. In principle, a generative model trained on the Boltzmann probability distribution offers a way out by producing independent samples at a low computational cost. However, simulating ordered phases runs into the same problem as conventional Monte Carlo: Generative models tend to mode collapse onto a particular ordered configuration, losing information about the phase as a whole [1].

Remarkably, the solution to this issue is to consider a harder problem: building a generative model to sample the Boltzmann distribution at all temperatures [2]. Due to the built-in continuity of neural networks, such a foundation model carries through phase transitions without restructuring the probability distribution (e.g. retaining only one ordered configuration), so it can generate samples throughout the phase diagram more reliably than a model optimised for a single temperature point!

In this project, you will design and deploy a generative foundation model to address open problems in the statistical mechanics of magnetism, where slow sampling impedes conventional Monte Carlo studies. In particular, you will design neural network architectures that incorporate the spatial symmetries of the problem, which both helps prevent mode collapse and improve the representation learned by the model.

In addition to learning about cutting-edge machine learning technqiues, such as normalising flows, interesting open problems in magnetism, you will gain experience with setting up simulations using the machine-learning frameworks JAX and NetKet and find opportunities to collaborate with the wider machine-learning-for-physics environment in Zürich, as well as experiments in real materials.

For this project, a good working knowledge of classical statistical mechanics is essential. Experience with programming in Python is also helpful.

References:

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Keywords: Generative machine learning, normalising flows, Monte Carlo sampling, statistical mechanics, frustrated magnetism.

Competing Orders in a Two-Dimensional Quantum Clock Model

Recent advances in infinite projected entangled-pair state (iPEPS) methods have made them powerful tools for studying two-dimensional quantum many-body systems. In this project, we will use iPEPS to investigate the ground-state phase diagram of a two-dimensional generalization of the quantum torus chain [1]. The model couples two conjugate clock variables and carries a projective representation of $\mathbb{Z}_q \times \mathbb{Z}_q$ per primitive cell. Its self-duality and Lieb–Schultz–Mattis-type constraint provide a framework for investigating competing symmetry-breaking orders and the critical theories that may describe their transitions. We will examine how increasing q affects this competition, exploring direct transitions, coexistence, and possible intermediate phases.

Through this project, you will learn state-of-the-art iPEPS techniques and develop numerical methods to identify quantum phases and characterize their transitions, with particular emphasis on continuous transitions and their critical behavior.

References:

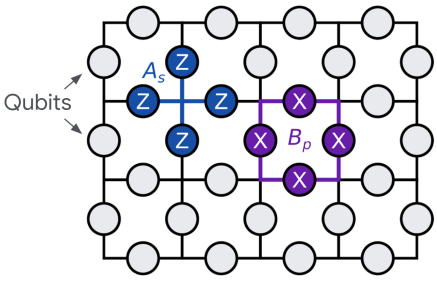
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Keywords: Quantum clock model, competing orders, quantum phase transitions, spontaneous symmetry breaking, self-duality, infinite projected entangled-pair states (iPEPS).

Microscopic models for foliated topological orders

Topologically ordered systems fall outside Landau's paradigm of ordered phases: they cannot be characterized by local order parameters but rather by global properties such as the ground state degeneracy on manifolds of different genus. Topological orders have been more or less classified in 2+1 dimensions using the language of fusion categories: topologically ordered systems in 2+1D are known to host "anyonic" quasiparticles which have exchange statistics beyond the standard fermion/boson dichotomy and which can be fused into other quasiparticles. A paradigmatic example of topological order is the toric code, a simple model of spin-1/2 degrees of freedom arranged on the links of a square lattice. In this project, we want to look at what happens when we take layers of toric code stacked on top of each other, and turn on interactions between them: what phases of matter can we obtain? We will start with the bilayer, and investigate both exactly solvable models as well as less engineered models using numerical techniques such as DMRG. Previous studies have shown the possibility of an anyon condensation induced transition, so the first goal will be to reproduce this result. We will then consider what happens for a more general class of models known as quantum double models. The goal of the project is not necessarily to produce new results but to obtain a good understanding of topological orders and anyon condensation using tractable microscopic models.



References:

1. Alexei Kitaev, *Annals of Physics*, **321**, 2, (2006)
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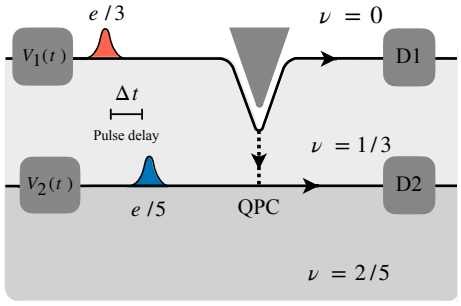
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Keywords: Topological order, toric code, tensor networks, renormalization group.

Levitons and collision noise in fractional quantum Hall edges

Observing quantum phenomena at the level of individual particles requires careful control. It is therefore natural that many introductory quantum mechanics experiments use optics. Photons interact weakly with one another, and mirrors and beam splitters allow their paths to be controlled while preserving coherence. Performing analogous experiments with electrons is more challenging, since electrons interact with their surroundings and with other electrons. Quantum Hall systems provide a useful setting for overcoming some of these difficulties. Their edges support channels along which excitations travel in a preferred direction. Bringing two such channels close together allows particles to tunnel between them, creating a beam splitter. Such devices make it possible to adapt familiar optical experiments to electrons and even to fractionalized qausiparticles known as Anyons.

A further ingredient is a source that prepares individual excitations. Levitov showed that Lorentzian voltage pulses with a suitably quantized time-integrated voltage can inject an electron into the Fermi sea without accompanying hole excitations [1]. These minimal-excitation states, called levitons, have since been produced experimentally [2]. The idea has also been extended to fractional quantum Hall edges [3], opening a route to controlled pulses in systems supporting Anyons. In this project, we will investigate such pulses in two inequivalent copropagating edge channels. We will study their partitioning and the current fluctuations generated when pulses arriving through the two channels overlap in time. Comparing pulses with equal voltage profiles and pulses carrying equal charge will allow us to identify what determines noise suppression when the incoming channels are physically different.



Inequivalent channels can carry different charges in response to the same voltage pulse, making it essential to distinguish the injected charge from the charge transferred through the tunneling contact. A particularly useful example is the pair of 1/3 and 1/15 edge channels of a $\nu = 2/5$ state. Their tunneling operator can be refermionized, yielding an exactly solvable model of a single tunneling contact. The project will begin with this geometry and calculate the currents and noise generated by the voltage pulses. Additionally, we will examine how interactions between the channels reshape the pulses before they reach the constriction, and whether adjusting the applied voltages can restore minimal noise. Familiarity with second quantization, scattering theory, and basic Green's function methods will be useful, while bosonization/ refermionization, and techniques for time-dependent transport will be developed during the project.

References:

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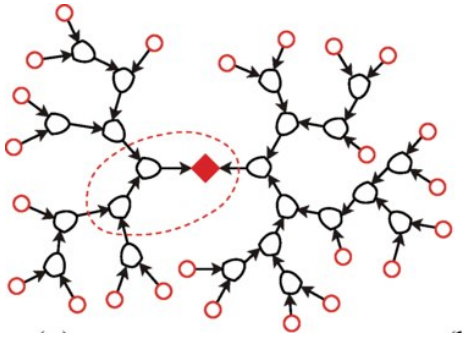
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Keywords: Fractional quantum Hall effect, chiral edge states, levitons, anyons, quantum point contacts, collision noise, electron quantum optics.

Global Correlation-Guided Optimization of Planar Tree Tensor Networks

Tensor networks are powerful numerical tools for studying quantum many-body systems. Their efficiency strongly depends on how the physical degrees of freedom are connected. While matrix product states arrange them along a chain, tree tensor networks (TTNs) allow for more flexible connectivity, potentially capturing complex correlation patterns more efficiently. However, finding a suitable tree topology remains a challenging problem.

An interesting possibility is to construct the network directly from global information about the quantum state, such as mutual information or connected correlation functions. Graph-based algorithms can use this information to identify strongly correlated degrees of freedom and organize them into hierarchical structures.



Example of a tree tensor network topology. Adapted from Ref. [1].

In this project, you will investigate **correlation-guided algorithms for constructing planar tree tensor networks**, comparing different information measures and tree reconstruction strategies. You will explore how the resulting topologies affect the accuracy and computational efficiency of quantum many-body simulations.

Beyond numerical optimization, the project will address a fundamental physics question: **Can the geometry of a reconstructed tree reveal the underlying correlation structure and quantum phases of matter?** You will investigate this question in representative quantum spin systems, such as disordered or frustrated magnets, and explore when pairwise correlations are sufficient to capture their entanglement structure. Potential applications also include finite-temperature von Neumann entropy calculations and efficient quantum data encoding for quantum computing.

References:

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3. M. J. Choi, V. Y. F. Tan, A. Anandkumar, and A. S. Willsky, "Learning Latent Tree Graphical Models,"J. Mach. Learn. Res. **12**, 1771–1812 (2011).

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Keywords: Tensor networks, mutual information, tree optimization, quantum correlations, quantum many-body systems