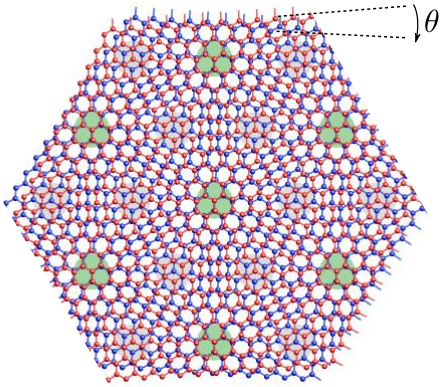
Available Master Thesis Topics

Scheurer group, University of Innsbruck, Summer 2021

Below is a list of a few currently available topics of master theses, along with a brief description. More topics are available, see here for a broader overview of our current research interests. If you are interested, please shoot me an email and we can discuss more – in person or via Zoom.

Superconductivity in graphene moiré systems

Graphene, a truly two-dimensional material consisting of a honeycomb arrangement of carbon atoms, has many interesting properties, probably best reflected in the 2010 Nobel prize of physics awarded for its experimental realization. In 2018, it has been demonstrated that new and even more exciting systems can be designed by stacking several graphene layers with a finite relative twist angle [1,2]. This leads to a spatial interference pattern – a so-called "moiré superlattice" (see figure) – with extraordinary electronic properties. Ever since, the study of graphene-based moiré systems has taken center stage in modern condensed matter research. Due to the almost endless possibilities of stacking and twisting graphene layers and their remarkable tunability, these systems are being established as flexible quantum simulators [3] of exotic many-body physics, e.g., realizing physics similar to high-temperature superconductors. The goal of this project is to elucidate the microscopic origin and form of the superconducting state hosted by these systems.

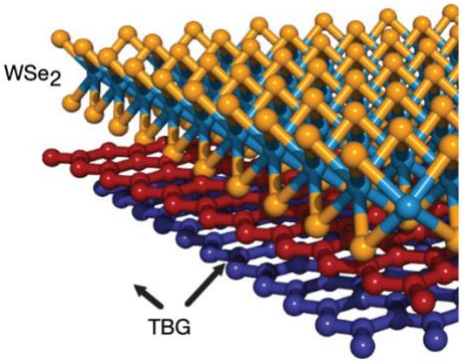


References and further reading:

[1] Gast, *Der Magische Winkel*, Spectrum der Wissenschaft, 2019.
[2] MacDonald, *Bilayer Graphene's Wicked, Twisted Road*, Physics **12**, 12 (2019).
[3] Kennes *et al.*, Nature Physics **17**, 155–163 (2021).

Spin-orbit-coupled moiré superlattices

In spin-orbit coupled systems, the real-space motion of electrons is correlated with the orientation of their spin. This has many interesting consequences for the electronic properties of a material, e.g., with crucial applications in spintronics [1]. Since the carbon atoms that graphene is made of are comparatively light (atomic number 6), spin-orbit coupling is weak in graphene and graphene-based moiré superlattices. However, moiré superlattices have also been built, see, e.g., [2] using related materials with heavier atoms, such



WSe_2 induces spin-orbit coupling in twisted bilayer graphene (TBG), adapted from [2]

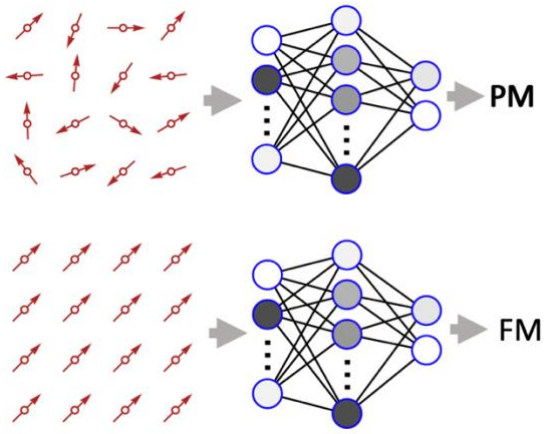
University of Innsbruck, Innrain 52, A-6020 Innsbruck
office: +43 512 507-52224 ▪ email: Mathias.Scheurer@uibk.ac.at ▪ web: uibk.ac.at/th-physik/mscheurer/

as transition-metal dichalcogenides, where spin-orbit coupling is large. Since the combination of superconductivity and spin-orbit coupling are important ingredients for topological superconductivity [3] with Majorana fermions – a possible route to topological quantum computing – we will explore different geometries of such systems in this project to realize a topologically non-trivial superconductor.

References and further reading:
[1] see Wikipedia article on spintronics.
[2] Arora *et al.*, Nature **583**, 379–384 (2020).
[3] Jason Alicea, Rep. Prog. Phys. **75**, 076501 (2012).

Machine learning of quantum many-body phases

The study of phase transitions is central to many fields of physics and chemistry. A classic example of a phase transition is the ferromagnet to paramagnet transition: in the paramagnetic phase (PM), the magnetic moments are disordered such that the sum over all these moments, the so-called magnetization M, is zero. In the ferromagnetic (FM) phase, on the other hand, these moments spontaneously choose a preferred direction and M becomes non-zero. Since the value of M characterizes the transition, it is referred to as its order parameter.



Traditionally, the order parameter is constructed by hand based on physical intuition and then tested for a transition exhibited by a model of interest. However, motivated by the success of machine learning in a wide variety of applications, physicists have recently started to explore whether the study of phase transitions can be automated by machine learning techniques. In the simplest example of a classical ferromagnet to paramagnet transition and "supervised training" (figure), this approach has been established to capture the transition well [1]; the task of capturing so called topological phase transitions [2], however, without a "regular" order parameter, and without supervision is more challenging, but approaches are being developed [2].

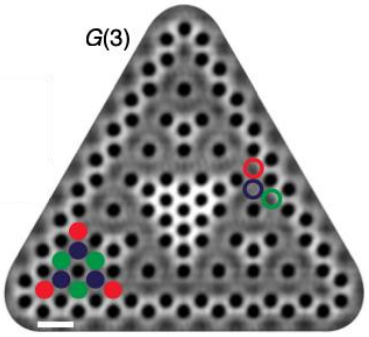
In this project, we will use machine learning to first capture the state of a many-body Hamiltonian, based on synthetic measurements, and then also use it to characterize the underlying phase.

References and further reading:
[1] Carrasquilla & Melko, Nature Physics **13**, 431 (2017).
[2] Rodriguez-Nieva & Scheurer, Nature Physics **15**, 790 (2019).

University of Innsbruck, Innrain 52, A-6020 Innsbruck
office: +43 512 507-52224 ▪ email: Mathias.Scheurer@uibk.ac.at ▪ web: uibk.ac.at/th-physik/mscheurer/

Quantum simulation via adatom design with STM

Scanning tunneling microscopy (STM) [1] not only allows to image surfaces of materials at the atomic scale, but also to controllably arrange atoms or molecule at the surface. In recent years, the deliberate placement of adatoms or molecules in, in principle, arbitrary geometrical arrangements has been established as a novel way of simulating two-dimensional electronic systems. For instance, Lieb lattices [2] and electrons in fractal geometry [3], see figure, have been realized in this way in experiment. The goal of this project is to study new geometries and simulate them theoretically to find a way of engineering novel electronic phases of matter in future adatom experiments.



Electrons in fractal geometry, adapted from [3]

References and further reading:

[1] see Wikipedia article on STM.
[2] Bercioux & Otte, Nature Physics **13**, 628–629 (2017).
[3] Kempkes *et al.*, Nature Physics **15**, 127–131 (2019).

University of Innsbruck, Innrain 52, A-6020 Innsbruck
office: +43 512 507-52224 ▪ email: Mathias.Scheurer@uibk.ac.at ▪ web: uibk.ac.at/th-physik/mscheurer/