In mathematical physics, the AdS/CFT correspondence is a conjecture according to which certain quantum theories (conformal quantum field theories or short CFTs, called the ”boundary”) can be described in a mathematically equivalent way in terms of theories of gravitation (called the ”bulk”) involving a negative curvature of spacetime (Anti-De Sitter spaces, AdS). This makes it an extremely powerful tool that allows translating questions about one side of the duality into questions about the theory on the other side of the duality, where they may be easier to solve with the available mathematical methods. For example, calculating the amount of quantum entanglement present in a physical system can be quite mathematically demanding. However, AdS/CFT maps this task to a geometrical problem conceptually similar to calculating the shape of a soap bubble, which in general is much easier than the usual calculation. This mapping is an example of what is called the ”holographic dictionary”, and AdS/CFT is an example of a ”holographic duality”.

However, despite its many successes, it is still somewhat unclear how big the family of theories for which the AdS/CFT conjecture can make reliable predictions actually is, and where the boundary of its applicability lie. Our central research question is hence:

Which predictions can holography make for realistic quantum systems, and conversely, which properties of such systems are indications of a holographic description existing?

To this end, we will follow a three-pronged research program on three interconnected aspects of AdS/CFT: the (A) universality of its applications, the (B) emergent nature of gravity in holographic applications, and the pivotal role of (C) quantum information theory in holography. Firstly, we will (A) investigate applications of AdS/CFT to open problems in quantum field theory and attempt to define criteria that distinguish field theories with a potential holographic description from those with no such description. Secondly (B), we will approach AdS/CFT duality as a kind of emergent gravity, i.e. as a mathematical framework where the laws of gravity arise from underlying rules. We will investigate how a dynamical, and potentially generalised, bulk geometry can be reconstructed from the boundary theory, and which insights into the nature of (quantum) gravity and black holes in the real world can be gained from this perspective. Thirdly (C), we will research the importance of concepts from quantum information theory in holography. Specifically, we will explore quantum entanglement and what role it plays in identifying theories with a holographic dual. Another main focus of this project will be the task of defining and calculating measures for how complex a given state is. We will explore precise definitions for this both in the bulk and on the boundary, and compare them to each other in order to add complexity as another entry to the holographic dictionary.

In this way, we expect to obtain fundamental criteria for distinguishing between putative boundary theories with or without holographic duals, i.e. determining what gives a field theory holographic properties. AdS/CFT is necessarily an interdisciplinary field with connections to quantum field theory, quantum information theory or condensed matter theory. If it was possible to show how and when AdS/CFT and holography can be applied confidently to systems and questions of real world relevance (and not only as a convenient conjecture to be taken on faith), it would have a significant impact on this and adjacent disciplines of physics. This would open up an entirely new tool set for researchers in these areas. Especially, the concepts surrounding complexity might have applications in the theory of quantum computations, an important emerging field of research at the moment. Additionally, if along the lines of direction B it is possible to uncover how at least some aspects of a bulk gravity theory can emerge from field theory degrees of freedom, it might help to provide indications for an emergent nature of gravity in the real world cosmos that we live in. This would be a significant step forward in the quest for a more fundamental understanding of the forces of nature and the nature of reality.