The Hebrew University of Jerusalem
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# Understanding Quantumness And Testability.

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# Chapter 1

# Introduction

Many experts believe that quantum computing is a highly effective computation model. The consensus is that certain problems that are difficult for classical computers to solve can be effectively solved with quantum computers. One of the biggest challenges in simulation is chemical simulation. Although we have the ability to simulate the workings of electrical circuits, the durability of structures, and the flight of aircrafts, simulating the evolution of an 80-atom molecule over time is still beyond our capabilities, even with the assistance of the world's most powerful supercomputer. When it comes to simulating molecules, the classical method can be inefficient as it requires tracking a large number of variables in memory. However, quantum hardware, based on the principles of quantum mechanics, allows for a more efficient encoding of the molecule's structure, mimicking the way it exists in nature. Although it is unclear how to prove that classical algorithms cannot efficiently simulate molecules, we do know that quantum simulation is easily achievable and uses memory resources efficiently. Therefore, experts envision that in the future, drug development and materials engineering will become more systematic. Today, researchers proposing candidates for drugs or vaccines may have to wait a long time for approval, but in the future, simulations will provide real-time answers on a screen. This will be similar to the ease with which people share libraries of code or hardware, establish companies, and release products. As a result, we will see a complex and interconnected industry dealing with the development of drugs, materials, genetic engineering, and more.

Despite the undeniable superiority of the quantum computation model over the classical model, there remains a significant challenge: the implementation of the quantum computation model. The essential components of quantum hardware are prone to numerous errors, and currently, no quantum computers can overcome these errors. Even a slightly lengthy computation accumulates enough errors to render the final computation result incomprehensible. This issue is reminiscent of a problem faced by Von Neumann, one of the inventors of the classical computer, nearly a century ago. He asked if classical computation was possible despite the noise and answered affirmatively. It is worth noting that hardware has advanced considerably since then, but most of the ideas of "fault tolerance computation" have yet to be realized. However, many ideas are critical components of everyday products, such as the LDPC codes used for error correction in cellular communication in the G5 protocol. Researchers have also demonstrated that classical ideas can be generalized to quantum cases to enable "quantum fault tolerance computation." The ideas are based on a unique code encoding system that facilitates easy identification and correction of errors.

In addition to error correction codes, there are also codes that desinged to be tested effectively. To understand what testable codes are, Imagine in your head a puzzle in which all the pieces are

painted in exactly the same color. Such a puzzle will be called untestable if there is a placement of the pieces of the puzzle so that on the one hand it is worthwhile to reach it, half of the pieces must be swaped for obtaining the ”true placement” of the puzzle - that is, the correct way to put it together - but on the other hand there are a few discrepancies between the connections of the different parts. That is, you have to work a lot to get to the ”real placement,” but if you sample an arbitrary connection, there is zero chance that a contradiction will appear. Testable puzzles are the exact opposite; if a placement is very far from the ”true placement,” then an arbitrary test will most likely reveal it. The existence of good quantum codes and efficiently testable classical codes have been open questions for a long time. Although, it seems like, there is no direct connection between them, both have been obtained by the same one advanced construction that was developed only two years ago (2021). Hence, it is interesting to ask if this is a coincidence or if there is a deeper connection between the two that we no longer understand.

In this work, we review, end to end, the quantum error correction codes. Starting from an overview of classical codes, methods for constracting good codes, characterization of quantum noise and permutative quantum codes, to the advanced construction of good LDPC quantum codes. All this is alongside a review of testable codes. Finally, we present failed attempts in follow-up research, in particular, an attempt to reach the construction of testable classical codes without simultaneously developing good quantum codes. If we were able to isolate the results, it would indicate that the fact that both were obtained in the same constraction is completely coincidental. At the same time, we haven’t progressed far enough to suspect that there is a necessary connection reasonably.

The work assumes only a basic knowledge of linear algebra and combinatorics. So we believe that every computer science graduate will be able to enjoy reading it, understand the subject very well, and use it as a gateway for starting research in the field.