Closing lecture Building Blocks of a Quantum Computer – part 1

This is the closing lecture of the first part of our series of lectures on the building blocks of a future quantum computer.

We started by introducing a stacked layer approach toward a future quantum computer. In part 2 of this MOOC we will focus on the higher layers of this stack. In addition we will also discuss the path toward a quantum internet. A quantum internet allows for communication between nodes where the security of the communication is dictated by the laws of quantum mechanics. In the first part of this MOOC, we mainly focussed on the lowest level, the quantum chip that forms the foundation.

The quantum chip is the quantum circuitry hosting the physical qubits. Physical qubits can be controlled to a superposition state and coupled together to create entanglement. These principles are on the basis of a quantum computer and quantum internet. The quantum mechanical state of a qubit is usually fragile and can suffer from environmental interactions and decohere over time. However, in order to do operations on these qubits it is essential that many operations can be done within the qubit coherence time. Theoretical predictions state that for practical fault tolerant quantum computing it will be necessary to perform thousands of operations within the qubit coherence time. While more sophisticated quantum error correction protocols are actively being studied, it is clear that good qubits are essential and that qubits need to be of high-fidelity.

Today, various qubits are being explored and investigated to reach this goal. In this series of lectures we have introduced to you several of the most promising qubit systems. Qubits based on the spin states of electrons or nuclei associated with defects or donors in silicon or diamond can reach very long coherence times. In materials with low net nuclear spins, detrimental magnetic interactions with the environment are small. In addition, the strong confinement leads to small overlap with other states. NV centers in diamond are particularly interesting, as they can be coupled to photons, providing an optical link between spin qubits that are distant from each other.

Spin qubits in quantum dots also exhibit very long coherence times, but they also offer the advantage of being manmade. This allows to realize qubits at a predefined location, which is clearly beneficial for scaling up the number of qubits. Superconducting transmons offer this advantage as well. In addition, they are larger and so, at least in the few-qubit regime, it is even easier to fabricate these types of qubits.

Large efforts are devoted to improving the qubit environment leading to qubits that become more and more isolated and thus to qubits with extended coherence. This is achieved by for example removing magnetic noise from nearby nuclear spins or electric noise stemming from charge defects in the substrate. In addition, clever qubit designs enable to decrease a qubit sensitivity to noise. For spin and superconducting qubits, sweet spots exist where to first order qubits are insensitive to certain noise. A special class of qubits exists that can be made intrinsically insensitive to some noise. These are called topological qubits and are qubits such as the ones based on emergent Majorana fermion states. These qubits could become exponentially less sensitive to local noise with increasing system size. That is, by increasing the separation between Majorana fermions, the qubits become more and more protected against local noise and can thus hold their coherence for a longer time. Today, we do not know what the best qubit platform will be and so there is an active race going on between all these different platforms. We also often find out that developments made in one platform can be implemented into other platforms and so all these activities strongly benefit from each other.

Where are we now with quantum computing? To answer this question, let's take a classical perspective. In the 1950s, electrical systems contained many components, each requiring to solder to numerous others. This clearly prevented to go to large numbers. Jack Morton, at the time vice president of device development at Bell labs, referred to this situation as the 'tyranny of numbers'. Quantum devices are now at a similar stage of maturity.

For classical electronics the solutions was the invention of the integrated circuit. The power and beauty of these systems become apparent if we compare the numbers of connectors at the outside of the chip to the number of active components inside the chip. Large grid arrays have a couple of thousand connectors, but these can address billions of transistors on a classical processor. This huge ratio between components and connectors is described by Rent's rule and this rule has been one of the main drivers behind Moore's law. It is thus most likely that we will require for practical quantum information applications the development of a 'quantum integrated circuit'.

Today's quantum devices require individual electronics and connects for each and every qubit. Increasing these systems to large numbers will clearly require a different scaling law. Concepts from classical memory technology, such as crossbar layouts where signals only have to come from the sides to address a large array, are now being proposed as an efficient way forward for quantum systems. These approaches come with their own challenges, but do provide a powerful method to avoid an interconnect bottleneck.

Interconnects are not the only challenge that need to be addressed. Every critical resource must be evaluated and optimized. In the figure here you see some fictitious qubit platforms. The functionality of each qubit platform is described according to its quantum volume. The usefulness of a platform will depend on the number of qubits available, but also on the amount of operations that can be executed on them. A system with only a few qubits is not powerful, even if they are of very high-fidelity. Likewise, a system containing many qubits of very low quality is also practically useless. The quantum volume takes this into account and is defined as the square of the lowest number of these two quantities. Increasing the quantum volume will enable to reach quantum supremacy, the era where quantum systems become too complex to be efficiently simulated with classical computers. Further increasing the quantum volume will enable to perform useful practical quantum simulations and finally to reach practical quantum computing. Nonetheless, while this is certainly a useful metric, the quantum volume does not provide the information whether a system is capable of reaching these applications.

This scalability aspect is described by the quantum extensibility of a system. Depending on all the resources, required at every position of the stack, a platform has the capability to scale up toward practical quantum information. Defining these resources is a crucial aspect for quantum information research today.

We have learned the aspects of some of these resources in the first part of this course, such as qubit decoherence. In part 2 of this course we will introduce the other building blocks of a quantum computer and show you the vision of a full-stack future quantum computer. In addition, we will also introduce to you the foundations of a quantum internet. What is required and where are we now? While building a quantum computer and quantum internet is perhaps the greatest scientific challenge of this century, you will also learn in part 2 why it is completely worth it and you will hear all the opportunities that arise once this becomes a reality.