

An introduction written for a more general audience

The idea to utilize quantum physics for solving difficult computational tasks has spurred a lot of interest among both physicists and computer scientists. Once such a quantum computer is successfully built, it could carry out specific tasks exponentially faster than any computer used today. Using solid-state devices (resembling microchips) as the basic building blocks in the design of a quantum computer is particularly interesting, since these devices can be fabricated with a technology already prevalent in current computer chip fabrication. For a quantum computer architecture, it is necessary that the elementary units, the qubits, can communicate not only with their nearest neighbors, but also with more distant partners. This requirement can be satisfied via a quantum bus, similar to the bus used in a conventional computer, which establishes information transfer between different components. A natural candidate for such a quantum bus is a photon: Photons can travel over large distances without losing their quantum information. In our work, we have coupled two superconducting qubits via an on-chip cavity. The photons inside the cavity are not visible light photons but rather photons in the cell-phone frequency range. With our experiment we successfully demonstrate control over single qubits and a switchable two-qubit coupling.

Frequently asked questions

- What are the issues making the experiment challenging?

In order to successfully perform these experiments, we have to control electrical signals corresponding to one single photon. In comparison, a cell phone emits about 10^{23} (100,000,000,000,000,000,000) photons per second. Therefore, we need extremely good control over our device in order to isolate it from the environment. The experiments are performed at 10 milli Kelvin (10 milli degrees above absolute zero temperature, 273.13 degree celsius) such that the ambient thermal noise is small and cannot destroy the quantum information.

- What are the applications of this work?

The ultimate goal of this work is to realize a quantum computer. While, at present we are still far away from this goal, the current work marks an important step forward. In our paper we demonstrate a simple architecture which allows the coupling of several qubits in a non-local way, enabling arbitrary qubits to interact with each other. The architecture also makes possible the read-out of the states of any of the qubits via a single wire. This is termed “multiplexed read-out.” With such architecture it should be possible to couple more than 10 qubits. However, for a real quantum computer that can be used to tackle the most difficult of problems, even more qubits (hundreds up to thousands) will have to be fabricated and coupled in the future.

- How does this advance from previous demonstrations of chip-based qubits?

So far, single qubit manipulations and interactions that couple neighboring qubits have been demonstrated. In this work, we introduce an on-chip quantum bus coupled to the superconducting qubits located on the same chip. With this quantum bus it is possible to couple arbitrary qubits over long distances. We also use the cavity to control and read-out the qubits' states. In that way we are able to manipulate the qubits via only one single line, which reduces the complexity when coupling several qubits

The introduction of such a quantum bus provides the possibility of scalability to a network of multiple solid-state qubits.

- What are the next steps you will take with this work?
What is still missing for a quantum computer?

As one of the next steps, we will measure a full state-tomography of the two-qubit gate. This will help us to fully characterize the quality of our two-qubit gate and quantify the entanglement that is created between the qubits.

Furthermore, we are going to explore the advantages of our architecture and try to couple more than two qubits, a prerequisite for performing useful quantum algorithms. For a real quantum computer, many more coupled qubits have to be realized, at least hundreds if not thousands. The required number of qubits also increases due to additional error correction protocols, which have to be implemented in order to provide reliable calculations.

- Why solid state qubits/ why superconducting qubits?

The apparent advantage of a solid-state approach is the usage of standard existing chip technology for fabrication. This technology is inherently scaleable, such that once we can make one qubit, it is not difficult to fabricate larger numbers. The challenge will be to provide a reliable and switchable coupling between all of these qubits. Our work provides a major step forward in this direction by introducing a coupling that is long range and not restricted to nearest neighbors.

For a quantum bit it is very important that the energy is not lost in unknown or uncontrolled processes. In a superconductor, currents can flow without any resistance indefinitely, without losing any energy. Hence, the use of superconductors provides an advantageous scheme to build circuits that behave quantum mechanically.

- What are the advantages of circuit quantum electrodynamics (circuitQED)?

One advantage is the possibility to make use of existing chip technology for the fabrication of our quantum bits and quantum bus. Once a single qubit is fabricated, it is not difficult to make many more qubits. In that way a potential quantum computer can be made in a way resembling the fabrication of modern microchips.

The quantum electrodynamics aspect allows us to manipulate and control the interactions on a single photon level. Further, the coupling and read-out mechanisms can be understood in detail.

In such a system it is possible to convert the localized quantum information of a qubit into a photon, which travels at the speed of light. One can therefore call these photons “flying qubits,” which transport the information over large distances.

- What are virtual photons? Why do we use them?

The interaction between qubits is achieved in the following way: The transition frequencies of the two qubits are tuned to differ from the frequency of the cavity photons. In classical physics, such a situation would forbid the energy transfer between the qubit and a photon because of the energy mismatch. However, in quantum mechanics it is possible to break the energy conservation for a very short time, allowing the energy to be transferred from one qubit to the cavity and then to the other qubit. In this sense, the coupling is mediated via virtual photons. In distinction to real photons, virtual photons do not decay out of the resonator. As a result, we avoid processes where the energy can leak out of the system instead of being transferred from one qubit to the other qubit.

- Can you put more than 2 qubits in the resonator? How many?

Our work demonstrates the coupling of two qubits. However, it is straightforward to add qubits by placing more of them in the resonator. Since the cavity is used for multiplexed control and read-out of all the qubits, no additional hardware is required. This way we envision the coupling of at least 10 qubits with the cavity.

- Is this the first time two qubits have been coupled?

Superconducting qubits have been coupled before. In our work we demonstrate a new kind of coupling. Previous experiments were only able to couple qubits that were located physically next to each other. Our coupling allows non-nearest neighbor qubits to interact with each other via the cavity. The cavity therefore serves as a quantum bus for the qubits providing an interaction between arbitrary qubits.

- Is this the first quantum bus?

This experiment realizes a quantum bus for the first time in a solid-state system, i.e. on a chip. Quantum buses have been demonstrated for trapped ions with phonons and for atoms with photons.