Superconducting qubit: The transmon - Leonardo DiCarlo

Today I will give you an introduction to quantum computing with superconducting quantum circuits; more specifically, quantum computing with transmon quantum bits or qubits in the circuit quantum electrodynamics architecture.

Superconducting qubits differ in two important ways from truly quantum two-level systems provided to us by nature, such as the spin of an electron or the spin of certain nuclei, like Carbon 13 or Silicon 29.

First, they are multi-level systems, not unlike the electronic levels in atoms. Multi-level quantum systems can be used effectively as qubits by confining all dynamics to two quantum levels, usually the ground state and the first excited state of the system. Second, these qubits are circuits that we fabricate ourselves! This has advantages and disadvantages. On the bright side, we have freedom to design! In a sense, we can play 'god' designing artificial atoms. However, fabrication uncertainty keeps us from making any two qubits the same! For this reason, we like to say that qubits have individual personality! While the form of the Hamiltonian describing them quantum mechanically is well known, the parameters of this Hamiltonian cannot be perfectly targeted in fabrication. This has interesting implications for scaling up our quantum processors, which I will discuss in a later video.

But back to design. Superconducting qubits generally consist of superconducting electrodes, or islands, that are interconnected by Josephson junctions. The Hamiltonian typically consists of two non-commuting contributions, one capacitive and one inductive. The first tends to localize Cooper pairs. The second favors their tunnelling from one island to another, in other words, their hopping.

There exist numerous varieties of superconducting qubits: the charge qubit, the flux qubit, the phase qubit, the fluxonium, and many more. These qubit types differ in terms of the number of superconducting islands, the number of junctions, and, also importantly, the relative energy scales of the capacitive and inductive terms. Typically, superconducting qubits work in the frequency range between 4 and 8 GHz, approximately. This frequency, let's call it f_{01}, is related via Planck's constant to the energy difference E_{01} between the quantum levels that we assign as states 0 and 1. f_{01} is also the frequency of the microwave pulses that we need to induce coherent transitions between these levels.

In this course, we will focus on the transmon, a derivative of the charge qubit. The transmon is the superconducting qubit that we specialize on in QuTech. In its simplest form, the transmon consists of two islands interconnected by one junction. Those of you familiar with circuits, particularly the electrical engineers, will recognize that the transmon looks, well, just like a parallel combination of one capacitor and one inductor. In other words, an *LC* oscillator! This gets us most of the way there, so let's take a look.

The Hamiltonian for the *LC* oscillator consists of two terms that are each quadratic with respect to one variable:

The capacitive term is quadratic on the charge accumulated on one island (the opposite charge is accumulated in the other). The inductive term is quadratic on the flux through the inductor. This charge and this flux do not commute. In fact, they are canonically conjugate variables.

A direct correspondence between this Hamiltonian can be made to that of the simple harmonic oscillator by mapping flux to the position of the mass and charge to the mass' momentum. Physics students will thus not be surprised to learn that the spectrum of the quantized *LC* oscillator is perfectly harmonic: levels are equally spaced in energy! This equal spacing is given by a familiar formula: one over root LC.

But unfortunately, a harmonic spectrum does not a good qubit make! It is very difficult to confine the dynamics to just two levels, so 'leakage' out of the qubit subspace is a permanent threat.

That is why the transmon differs from the *LC* oscillator in a fundamental way. In the transmon, the inductance is provided by a Josephson junction and not by a typical coil inductor. The inductive energy for the junction is not quadratic, but a cosine function of the generalized flux through it. This difference has important consequences for the spectrum: crucially, it disrupts the harmonic spectrum in ways that are very practical.

At typical parameter values deep in the so-called transmon regime, where the energy scale of the inductive term is much larger than that of the charging term and let's say, for the frequency f_{01} of about 6 GHz, the transition from the first to the second-excited state is lower by approximately 300 MHz. This difference is sufficient in practice to confine the dynamics to the lowest two levels, our qubit subspace, when performing single-qubit gates with pulses of duration about 20 ns. Brian will discuss the implementation of single-qubit gates in detail.

As a final note, we build our transmon not from one but two Josephson junctions in parallel. This gives us the possibility to tune the inductive element and thereby the qubit transition frequency, by threading a magnetic flux through the loop defined by the two junctions.

We can do this independently for each qubit and on nanosecond timescales. This capability is the workhorse enabling two-qubit gates. Adriaan will present these in a later video.