LONG LIVE THE QUANTUM COMPUTER

Whatever the technology of the future may look like, there is little to no doubt quantum computers will be a significant part of it. A substantial amount of the research effort around the world is currently aiming at the development of those improved computing machines, which could be the next paradigm of technology, by allowing deeper atomic and molecular simulations and establishing a new age of cryptography. Some already claim having build a performant quantum computer, such as D-wave, a Canadian company located in Vancouver, going by the motto of *Welcome to the future*. Whether or not the quantum computing future is at our door, the device designed by D-wave can only perform one single type of calculation, and the quest for a universal quantum computer is far from finished.

Among the myriad of inspiring and original ideas of quantum computer design, the concept of **nuclear spins** in silicon **donors** is a promising candidate for many reasons. While silicon is the second most abundant material on earth's crust (after oxygen), it's also a perfect semi-conductor. It is one of the most studied element of the periodic table, with a huge community of specialists. Its application in most of modern electronics would make it quick and easy to develop a quantum computer industry. Silicon was the sparkle that ignited the digital revolution, and has a great potential to ignite a new one.

A silicon crystal is a great material by itself, but it can't accomplish much without other types of atoms in its structure. **Donors** are other elements intentionally mixed in very small quantity with silicon, such as phosphorus atoms. Those new elements don't ship alone; they provide an extra electron. This electron, in combination with the nucleus of the donor, forms the basis unit of the quantum computer, and is thus the equivalent of the transistor in classic computers. To be more precise, the spins of both the electron and the nucleus act as the unit of quantum information, or quantum bit (qubit for short). While the concept of spin still is mysterious to deal with, it can be replaced by a tiny magnet using imagination. This tiny magnet is a very special one though: it can aim at multiple directions at the same time, in a process called **quantum superposition**. This superposition is the root of the prodigious power of the quantum computer.

As a donor in a silicon crystal, a Phosphorus atom provides an extra electron.

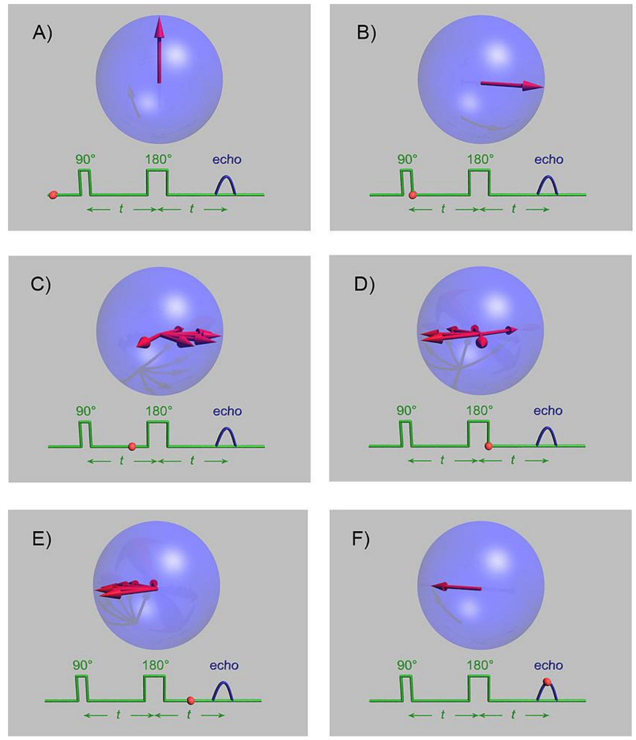
To get the best out of the silicon quantum computer, there must be no other spin around than those of the donors. Yet **natural silicon** is not without its own tiny magnets, and those have a tendency to hide the important donors. To get around this issue, it is required to purify the silicon to only one isotope, **silicon 28**. This isotope is comparable to void when interacting with the spins of donors, as it bears no effective spin. Purified silicon is difficult to create, but the effort was already spent. The **Avogadro project**, a research team dedicated to the definition of a more accurate and stable kilogram, used silicon 28 to create the world's roundest object. They were able to precisely count the number of silicon atoms in the sphere and define the kilogram based on the mass of a single silicon atom. The trimmings of this perfect sphere provide a perfect material to study the properties of spins as qubits. Donors are mixed with the very pure silicon 28 material at Pr. Mike Thewalt's laboratory, Simon Fraser University.

The world's roundest object, a sphere made of silicon 28.

To program a quantum computer, it is required to interact with the tiny magnets called spins. This is done using an external magnetic field with a method that goes by the name of nuclear magnetic resonance (NMR). NMR is a well explored field of physics. Developed in the late 40s, NMR spectroscopy saw its applications shift from physics to chemistry to medical imaging. Indeed, nuclear magnetic resonance is the science forming the basis of magnetic resonance imaging (MRI), a precious tool to medicine, especially for brain studies. Using this method often requires high magnetic fields provided by powerful superconducting magnets.

When applying an oscillating magnetic pulse at a spin, it will absorb a fraction of the energy from the field and re-emit it. The fraction of energy which is absorbed is directly related to the frequency of the magnetic field. A parallel can be drawn between this phenomenon and a child on a swing. If you want to push the child as high as possible, you need to push at a precise frequency. This precise frequency is the **resonance frequency**.

Using the correct frequency, it's possible to flip the tiny magnet from an upside direction to a downside direction. If the rotation is stopped in between, then the magnet is said to be in a **superposition state** of both up and down. While a spin is in a superposition state, it quickly loses its quantumness in a process called decoherence. After decoherence, it's not possible to use the spin for a qubit anymore, making decoherence a very important process to study and understand. The characteristic time of decoherence is noted T_2.



The Hahn echo sequence, a simple way to reduce the decoherence time T_2.
A: Initial spin aiming at one single direction.
B: Creation of a superposition state. The spin is aiming up and down at the same time.
C: Natural decoherence (loss of a pure quantum state) occurs.
D: All the states are flipped by 180 degrees
E: The states who travelled the fastest on the sphere are now the furthest from recombination.
F: The states recombine in a pure state once again.

In 1950, Erwin Hahn proposed a first sequence of magnetic pulses to avoid most of the decoherence. The sequence is shown on figure 2. At the beginning, a spin is aiming upwards (it is in the up state). A first 90° pulse pushes the spin in a superposition state (both up and down at the same time). Let this spin evolve naturally and decoherence process will start to show up. This is visually represented by the single arrow, a pure quantum state, splitting into multiple arrows, mixed states.

After a time t, a 180° pulse flips all arrows, and then they continue to deviate at the same speed. Wait t once again, and all the arrows will merge back into a single one; indeed, the 180° pulse make the fastest arrows travel a bigger distance on the sphere. In theory, this idea has no flaws, but experimentally it's not possible to get rid of all decoherence this way. If you were to repeat the same experiment with different t times, you would find a bigger decoherence every time. T_2 is the time t for which a substantial amount of quantumness has been lost.

The Hahn echo is an old idea that still proves itself useful today. However, it's possible to improve T_2 by a huge factor using alternative sequences. Those sequences combine flips in many directions and try to get the biggest T_2 possible. Part of Pr. Simmons group from Simon Fraser conducted simulations to compute the best combination of magnetic pulses. Among a myriad of results, a handful of sequences were shown to perform much better than others. Those sequences, when applied by a perfect source, would completely negate some types of errors. However, when the time came to put the simulations the test in a series of extremely recent experiments, they did not behave as expected. Some sequences outperformed the typically used sequence, which is a big win. Other sequences which were supposed to perform the best gave very poor results for some reason yet to be found.

The puzzle may not be solved yet, but once the pieces match together, this may be a great revolution for silicon quantum computing. Improving decoherence time is one of the biggest challenging surrounding the design of a quantum computer, and the results of the latest experiments are very promising.

Images are from Wikipedia and from Veritasium's YouTube channel.