State of the Quantum Art

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Introduction

This is the **final week** of the course, as such it is meant to be **lighter** and more **challenging**. We will go over typical **models of computation**. Understand how all the theory we have been studying can actually be implemented - **how to build qubits** and quantum computers. Then, we will take a snapshot of the current state of the art as to the implementation of quantum computers, namely by analyzing the work all the **players** have showed.

Models of Quantum Computation

By now, we are aware that quantum mechanical properties of the world can be used to compute: *perform a transformation on a given input to produce the desired output.*

There are, however, many ways of doing so. These are the so-called **Models of Quantum Computation**. We will go over each of the main ones.

Models of Quantum Computation

Some considerations are required, however, namely:

- These models are interchangeable and equivalent in computational power
- Provide different approaches to problem solving, each with a set of problems that is more easily solved that are its *forte*

As such, each has its advantages and disadvantages but they each have their own distinct fascinating essence.

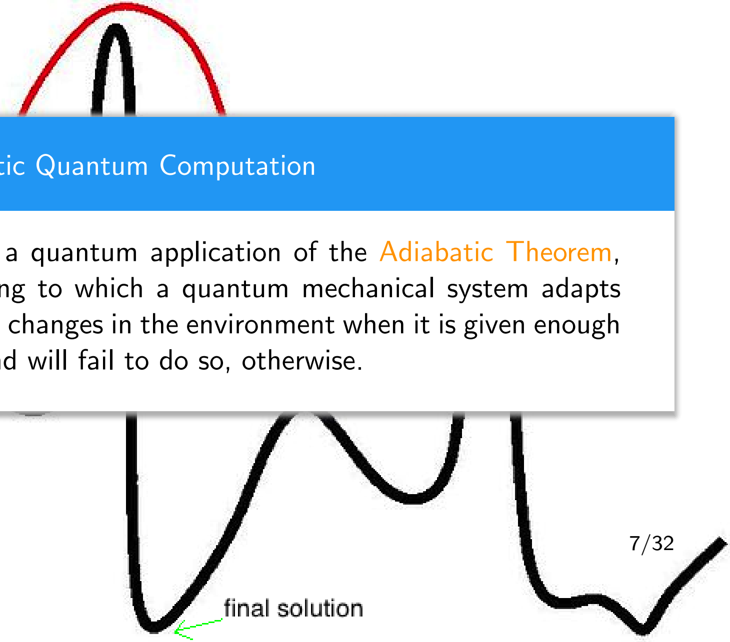
Quantum Circuit

Throughout this course, we have mainly focused on the *Quantum Circuit* Model, so you are in a better point to understand its explicit definition.

Computations are described as a sequence of gates, analog to classical circuits, that perform reversible transformations on a set of qubits, whose state is usually measured at the end.

Adiabatic Quantum Computation

This is a quantum application of the Adiabatic Theorem, according to which a quantum mechanical system adapts itself to changes in the environment when it is given enough time and will fail to do so, otherwise.



This is precisely what happens in metal and glass that is elevated to high temperatures and allowed to cool down slowly, so they can recrystallize into their natural organization, thus gaining some better mechanical properties. This process is called **annealing** and, as a matter of fact, Adiabatic Quantum Computation is also referred to (with some nuances) as **Quantum Annealing**.

Why is this interesting for Quantum Computing? Because we are able to generate a **Hamiltonian** whose **ground state** (the state of less energy) describes the final solution to our problem.

Take the SAT problem that we have already studied and think of it as a collection of constraints between variables (qubits) that can be implemented on a quantum system. We only specify the constraints and not the algorithm (this is already implicit!) and then we *adiabatically* evolve the system, meaning we bring it to lower and lower states of energy.

Can you think of a way of doing this?
One way is to cool the system, bring it (slowly) to lower temperature and then perform a measurement, which will encode the solution to our initial problem!

Measurement Based Quantum Computer (One-way)

This model focuses on using entanglement to describe graph-like relations between the quantum state and then performs individual and ordered measurements on qubits, until it obtains the solution to the problem. It should be noted that the result of a measurement on one of the qubits can determine if any further operations (like which basis to measure) will be necessary.

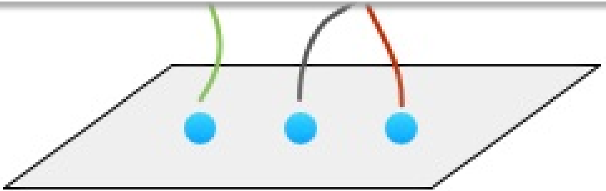
Cluster state

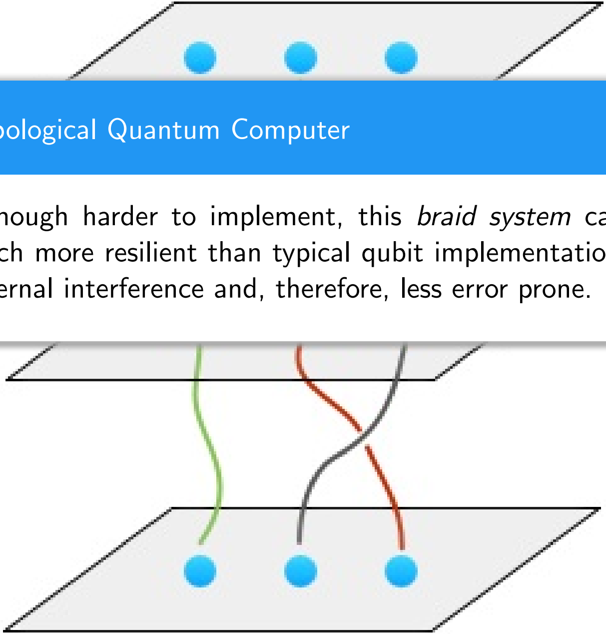
Measurement Based Quantum Computer (One-way)

The term **One-way** comes from the fact that there is a sequential logic behind the measurements and because the initial entangled state gets destroyed once a measurement is performed and what is left is to collect the correlated values of the previously entangled qubits, as we have already seen, and we get the solution!
The simplest physical implementations of such a system can usually be seen as a lattice of qubits.

Topological Quantum Computer

This last model is a bit more theoretical and has a few interesting properties, namely it employs quasiparticles that can be **braided** together in a two-dimensional spacetime, this is quite hard for the non-physics mind but it essentially means that the quantum particles can be connect by the equivalent of quantum gates, although these are inherent to the system.





Topological Quantum Computer

Although harder to implement, this *braid system* can be much more resilient than typical qubit implementations to external interference and, therefore, less error prone.

Building Quantum Computers

After all that we have seen and all that we know we haven't seen, quantum computing theory is extensive and promising, yet there is still the slight detail of **actually building** a quantum computer.

Unlike classical computers where the transistor has been the universal means for implementing circuits and handle bit information, there is no **one best** quantum equivalent so far. As a matter of fact, there are a lot of different approaches to this problem, each unique and each with both advantages and disadvantages.

Building Quantum Computers

Besides facing challenges in how to represent quantum states, the construction of quantum computers requires that those states:

- are stable enough that they can be operated upon and measured
- allow entanglement between qubits
- allow for easy setup and replication of experiments
- and so on

Implementing a Qubit

The atomic (literally) element of quantum computers can be implemented in various ways. The most commonly used are:

Individual ionized atoms *ion traps*, optical laser to trap (isolate) ions and using their electron's energy levels

Superconducting electronic circuits circuits cooled down to extremely low temperature so that harmonic behaviour appears

Spin qubits controlling the quantized orientation of electrons

Photons which can be used in many ways to achieve a qubit implementation (often involving other particles)

Quantum Decoherence

Besides being able to build the experimental setup to either trap ions or measure spin values, a problem that is common to most qubit implementations is that of **quantum decoherence**.

Quantum Decoherence

This phenomena describes the impact of **external interference** on the quantum states. In practice, the perfect isolation of these systems is extremely hard and so there is always interfering components, this can be: other **atoms** or **electrons**, **magnetic fields**, **energy fluctuations**, ... and so the coherence of the qubit, a necessary property for quantum computing to work, decays with ease.

Quantum Decoherence

The problem being that the more qubits there are in a system, the harder it is to guarantee the *goldilocks* state of just the **right amount of interference** to allow for other phenomena like **entanglement** and to prevent undesirable disturbances of the quantum system.

Quantum Error Correction

Like every problem invokes a solution, so does quantum decoherence result in another field of Quantum Computing, **Quantum Error Correction**.

This is a very active and widespread field of study and it tackles not only decoherence, but noise as well (errors from other experimental factors like tools).

Quantum Error Correction

Classical computing also has to deal with errors in information handling and communication, and Quantum Error Correction can be seen as the analogous for Quantum Computing. Instead of handling the quality of qubit implementation, it dwells on ideas of error **identification** and error **correction**, it also includes **gate-specific** analysis.

Industrial Standpoint - Race for Quantum

There are many **competitors** in this metaphorical race, and not only tech giants, a lot of academic institutions are quite well represented in the contest.

Let us begin by the tech giants, **IBM**, **Intel**, **Google**, **Microsoft** are just a few names of companies that have active R&D departments whose sole purpose is to create the best and largest quantum computer.

Industrial Standpoint - Race for Quantum

IBM had developed a 50qubit quantum computer by the end of 2017 and there are some rumours around a within-reach 70+qubit by the end of 2018. More than that, IBM has made available to the public, as we already know, through a few quantum computers with up to 14qubits and has some with 20 for rental.
Moreover, they have given Qiskit to the world, and we know how wonderful it is.

Industrial Standpoint - Race for Quantum

Intel has taken a more widespread approach and they have been traveling the world looking for places to invest, one of the most promising ones is QuTech in Delft. They also claim to have achieved a 49 qubit processor!

Industrial Standpoint - Race for Quantum

Microsoft has claimed to have topological qubits and is trying to make a services out of quantum computing through Azure. They have also come forward with a Quantum Development Kit.

Industrial Standpoint - Race for Quantum

Google has released, as of 2018, Bristlecone, a 70 qubit processor and they have also a large branch of Google AI dedicated to quantum research, along with secretive claims for new machine learning algorithms that run on quantum computers.

Another company, D-Wave Systems, which is a solely quantum company, as of 2018, sells **2000 qubit** processors as of 2018. These are supposed to be appropriate for Quantum Annealing techniques, especially dedicated to optimization problems. This does seem like a very large number, but let us not forget that quantity does not equal quality, and there is plenty of skepticism around their claims.

Industrial Standpoint - Race for Quantum

When Edward Snowden leaked information on the NSA, one of the findings in those documents was that of a secret project called Penetrating Hard Targets whose purpose was to build a Quantum Computer capable of breaking current encryption mechanisms. The current state of the project is unknown.

Industrial Standpoint - Race for Quantum

Moreover, the European Union has announced a 10 year funding program of more than one billion euros for research in quantum technologies

China, however, is spending billions of dollars to be on the frontier of this quantum race.

Industrial Standpoint - Race for Quantum

Clearly, there is immense at stake here, for quantum technologies represent a great tool, but also a great weapon, if there is one single entity in charge of it. So, global efforts must be put into making this a technology of the world and not of a company or super power, at least that is the author's conviction.

Closing Remarks

With any luck, you will have finished this course with a prickling sensation telling you not to stop here, for the amount of **possibilities**, **uncharted waters**, **untested hypothesis**, **unresolved problems**, **unformulated algorithms** along with the **power** you have witnessed, will have given you the right impression on quantum computing - it is **undoubtedly the next step**.

"If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet."

– Niels Bohr