Another Introduction to Quantum Computing

Gustavo A. Bezerra (Koruja)
Programa de Educação Tutorial - Ciência da Computação UFRN
https://gustavowl.github.io/
gustavowl@lcc.ufrn.br

April 11, 2019

Table of contents

1. Introduction
2. Nowadays
3. Scratching The Surface of Quantum Algorithms
4. Related Fields of Study
5. Some References
6. Conclusion

Introduction

Motivation

- Nature is described by the laws of Quantum Mechanics;
    - Quantum Mechanics for modelling system;
    - Classical vs Quantum;
- Computer components' size limitation;
    - Moore's Law;
    - Physical limit;
    - Quantum phenomena.

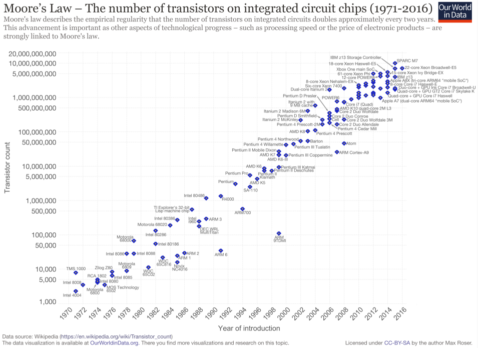


Figure 1: Graph illustrating Moore's law.
Image downloaded from `https://en.wikipedia.org/wiki/Moore%27s_law` on March 15, 2019.

History - An Overview

- 80's: Feynman;
- Today: Solid theoretical basis;
  - [1] [2] [3] [4];
- From Science to Companies;
- News.

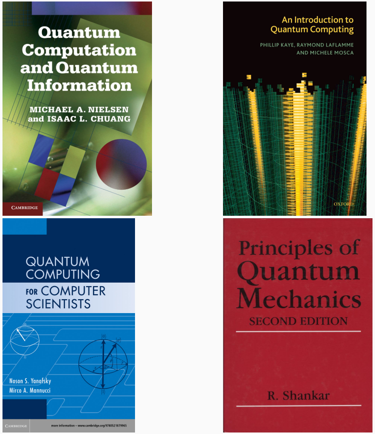


Figure 2: Some reference books.

Background - A Bit of Information

- Computers process information (Information Technology);
- Information is physical;
- Classical computer information: *bit*;
- From circuits to higher levels of abstraction.

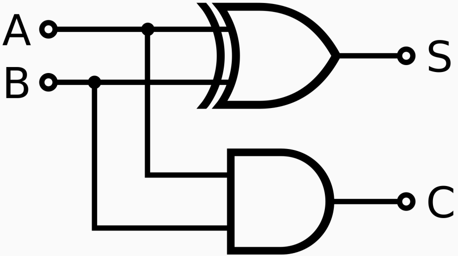


Figure 3: Half adder circuit.
Image downloaded from https://en.wikipedia.org/wiki/Adder_(electronics) on March 15, 2019.

Background - A Qubit of Information

- Computers process information (Information Technology);
- Information is physical;
- Quantum computer information: *qubit* (**Qu**antum **bit**);
- From circuits to no level of abstraction;
- Back to assembly good old days.

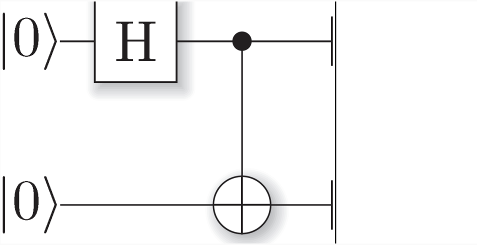


Figure 4: Quantum circuit to generate a Bell state.
Image downloaded from https://en.wikipedia.org/wiki/Bell_state on March 15, 2019.

Meta Frame

- Talk objectives;
  - Destroy the idea of "Perfect" Computing;
  - Brief overview on Quantum Computing.

Nowadays

Science

- Solid theoretical basis;
- Constant researches;
- Conferences;
  - List of conferences;
  - International Conference on Quantum Computing;
- Partnership with companies.

Companies

- Why are companies interested?
  - Money;
  - To accelerate;
  - Though costly, some Quantum Algorithms are faster than Classical;
  - Quantum Supremacy;
- Quantum Computers will probably be hybrid. Why?
  - Costly;
  - Qubits are unstable (Engineering challenge);
  - Avoid interactions;
  - Extreme conditions: $\frac{1}{10}$ K.

Companies

- Companies own Quantum Computers;
    - Around 50 companies (hardware and software);
    - IBM;
    - Google;
    - D-Wave.

Companies - IBM

- 50 Qubits;
- IBM-Q Experience;
- Qiskit.

Figure 5: IBM's Quantum Computer.
Image downloaded from https://www.technologyreview.com/s/609451/ibm-raises-the-bar-with-a-50-qubit-quantum-computer/ on March 14, 2019.

Companies - Google

- Claimed 72 Qubits;
- No news ever since.

Figure 6: Google's Quantum Processor.
Image downloaded from https://www.technologyreview.com/s/610274/google-thinks-its-close-to-quantum-supremacy-heres-what-that-really-means/ on March 14, 2019.

Companies - D-Wave

- 2048 qubits;
- Specific purpose.

Figure 7: D-Wave's 2000Q.
Image downloaded from https://www.dwavesys.com/d-wave-two-system on March 15, 2019.

Doesn’t it look familiar?

- Back To The Futur... Past;
  - Quantum Computers occupy a lot of space;
  - Assembly analogous;
  - Limited access;
  - Few People capable of extracting its full potential;
  - Computers are owned by Organisations.

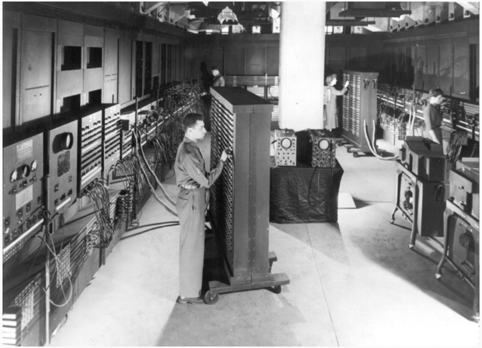


Figure 8: ENIAC.
Image downloaded from https://en.m.wikipedia.org/wiki/ENIAC on March 14, 2019.

Comparing To The Past

- Future is *not* precisely predictable. This is...
  - Exciting!
    - Promising Future;
    - Unknown applications;
  - Troublesome!
    - Unforeseen issues;
    - Over-excitement.

Over-excitement

- News;
  - Superficial explanation;
  - Advantages highlighted;
  - Problems not mentioned;
  - Reader concludes: Quantum Computing will save the World!
- Some examples;
  - No, scientists didn't just "reverse time" with a quantum computer - MIT Technology Review;
  - Announcing the Microsoft Quantum Network - Microsoft Quantum.

Beware of Hype Cycle!

- Analogous to the beginning of the "Computer Era";
    - Initial studies (calculations, business purposes);
    - Science Fiction, Unrealistic expectations;
    - Disappointment (more Science Fiction);
    - More studies;
    - Unforeseen applications (bank transactions, games);
- Artificial Intelligence Winters;
    - 1974-1980, 1987-1993;
- Disappointment is coming...

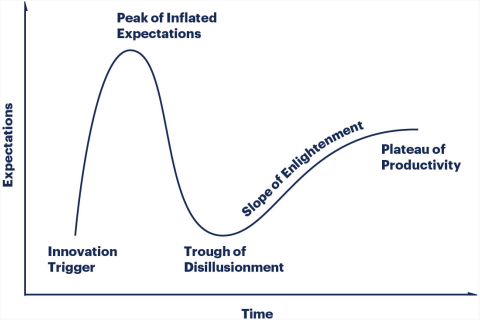


Figure 9: The Hype Cycle.
Image downloaded from https://www.gartner.com/en/research/methodologies/gartner-hype-cycle on March 14, 2019.

Scratching The Surface of Quantum Algorithms

Scratching The Surface of Quantum Algorithms

- Why are Quantum Computers interesting?
- Parallelism and Quantum Parallelism;
- Quantum superposition and Schrödinger's cat;
- There is *no* perfect analogy;
- The best way to understand Quantum Mechanics is...

Mathematics!

- Linear Algebra time!

4.6.3 Equations 2.208 and 2.209

When I firstly read these equations I thought there was a possibility that an extra explanation would be necessary. This thought raised, most likely, because I was unaccustomed to Tensor Product Properties and the Reduced Density Operator.

Using $|AR\rangle$ as defined in Equation 2.207:

$$|AR\rangle\langle AR| = \left(\sum_i \sqrt{p_i}\,|i^A\rangle\,|i^R\rangle\right)\left(\sum_j \sqrt{p_j}\,\langle j^A|\,\langle j^R|\right) \tag{130}$$

$$= \left(\sum_i \sqrt{p_i}\,|i^A\rangle \otimes |i^R\rangle\right)\left(\sum_j \sqrt{p_j}\,\langle j^A| \otimes \langle j^R|\right) \tag{131}$$

$$= \sum_{ij} \sqrt{p_i p_j}(\ |i^A\rangle \otimes |i^R\rangle\ )(\ \langle j^A| \otimes \langle j^R|\ ) \tag{132}$$

Then, by applying the properties as similarly defined in Equation 2.46:

$$\sum_{ij} \sqrt{p_i p_j}(\ |i^A\rangle \otimes |i^R\rangle\ )(\ \langle j^A| \otimes \langle j^R|\ ) = \sum_{ij} \sqrt{p_i p_j}\,|i^A\rangle\langle j^A| \otimes |i^R\rangle\langle j^R| \tag{133}$$

Therefore, using the definition of the Reduced Density Operator (Equation 2.178):

$$tr_R(|AR\rangle\langle AR|) = tr_R\left(\sum_{ij} \sqrt{p_i p_j}\,|i^A\rangle\langle j^A| \otimes |i^R\rangle\langle j^R|\right) \tag{134}$$

$$= \sum_{ij} \sqrt{p_i p_j}\,|i^A\rangle\langle j^A|\, tr(|i^R\rangle\langle j^R|) \tag{135}$$

Figure 10: Snippet of Quommentaries.

Image extracted from https://github.com/gustavowl/quommentaries on March 15, 2019.

Double Slit Experiment - Try To Keep It “Simple"

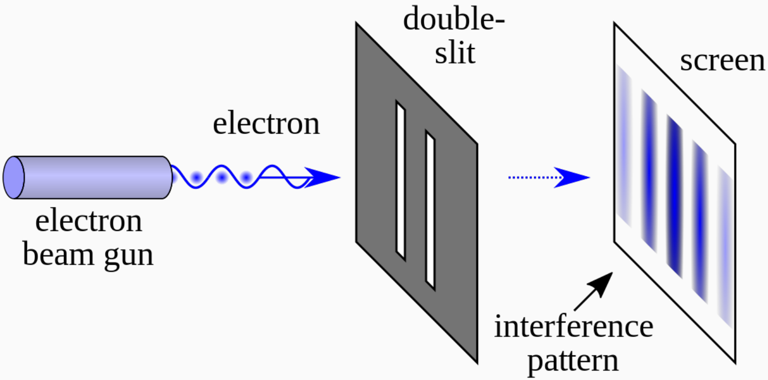


Figure 11: Double slit experiment.
Image downloaded from https://en.wikipedia.org/wiki/Double-slit_experiment on March 15, 2019.

An Outer Space Analogy

- Two alien friends: Nawibo, and Odeerg;
- North or South Pole;
    - Nawibo: relative position;
    - Odeerg: Poles.

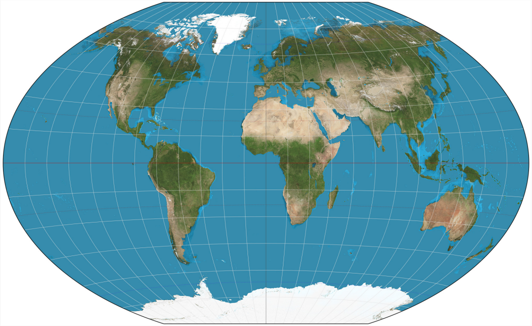


Figure 12: World Map.
Image downloaded from https://en.wikipedia.org/wiki/World_map on March 15, 2019.

Bloch Sphere

- Nawibo describes a state;
- Odeerg measures a state;
- Qubit as a vector, $|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$, where $\alpha, \beta \in \mathbb{C}$, and $|\alpha|^2 + |\beta|^2 = 1$;
- Qubit as a point on the Bloch sphere, $|\psi\rangle = cos\frac{\theta}{2} |0\rangle + e^{i\varphi} sin\frac{\theta}{2} |1\rangle$, where $\theta \in [0, \pi]$, and $\varphi \in [0, 2\pi)$;
- Schrödinger's cat.

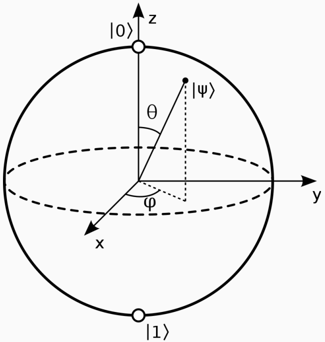


Figure 13: Qubit representation on a Bloch sphere.

Image downloaded from https://en.wikipedia.org/wiki/Bloch_sphere on March 15, 2019.

Confused? Do It Yourself

- First chapter of *An introduction to Quantum Computing* by Kaye, Laflamme and Mosca [2];
- Mach–Zehnder interferometer;
    - Why complex numbers are necessary.

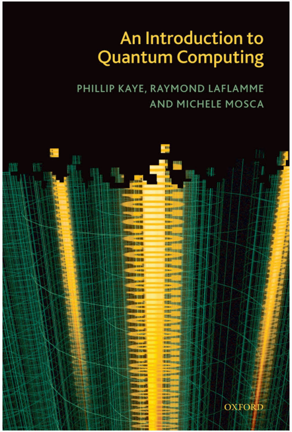


Figure 14: An Introduction to Quantum Computing's book cover [2].
Image downloaded from https://books.google.com.br/ on March 15, 2019.

Back To Quantum Parallelism

- Use superposition to compute all possible values at once;
- $|\psi\rangle = \frac{|0\rangle+|1\rangle}{\sqrt{2}}$ (equatorial line);
- Apply the desired operations;
- Verify the results;
  - Verify = measure;
  - Information loss;
  - Workaround.

Case Study: Quantum Teleportation

- Entangled state $|\beta_{00}\rangle = \frac{|00\rangle+|11\rangle}{\sqrt{2}}$;
- It is necessary to send classical information;
- Avoids faster than light information transmission.

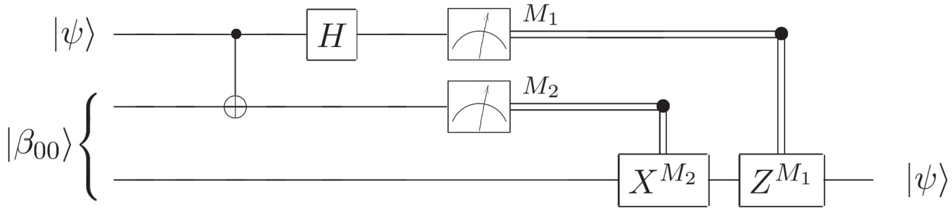


Figure 15: Quantum Teleportation Circuit.
Image from Nielsen and Chuang's Book Section 1.3.7 [1] on April 08, 2019.

Case Study: Grover's Algorithm

- Amplitude Amplification;
- $O(\sqrt{n})$ unsorted database search;
- Grover Iteration;
  1. Phase shift;
  2. Inversion about the mean.

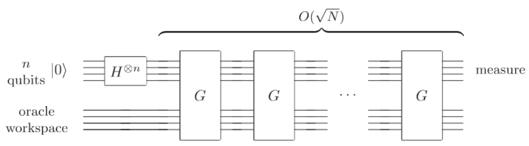


Figure 16: Grover's Algorithm.
Image extracted from *Quantum Computation and Quantum Information*'s Section 6.1.2 [1] on April 09, 2019.

Case Study: Grover's Algorithm

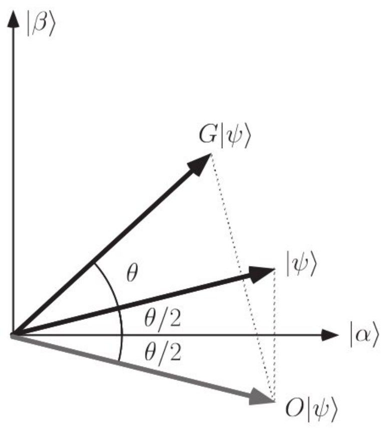
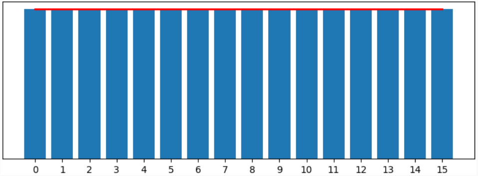
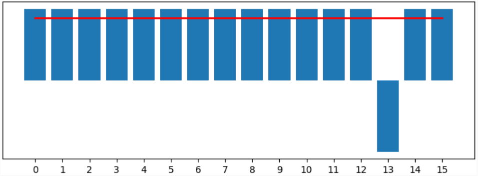


Figure 17: Grover Iteration Geometric visualisation.
Image from Nielsen and Chuang's Book Section 6.1.2 [1] on April 09, 2019.

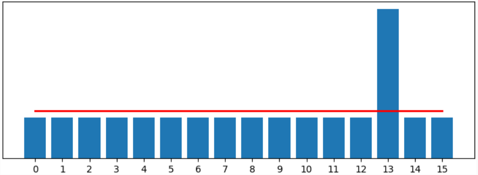
Case Study: Grover's Algorithm



(a) Initial state in superposition.



(b) Phase shift.



(c) Inversion about the mean.

Figure 18: Grover Iteration action on the state's amplitude [2].

A Few More Interesting Facts

- Quantum Mechanics And Linear Algebra Consequences;
- Interesting properties regarding Quantum Circuits;
- Quantum Circuits are reversible;
    - Unitary Operators;
    - No loss of information (if not measured);
- No fan-in;
- No fan-out;
    - No-cloning Theorem.

Related Fields of Study

Quantum Information

- Information representation;
- Information transmission;
- Cryptography;
- Error-correction.

Quantum Logic

- Logic is the basis of Computer Science;
- Quantum Logic is another type of logic;
  - Fuzzy;
  - Modal;
  - Universal;
- "Simpler" version for Quantum Turing Machine;
- Not directly related to Quantum Computing.

Some References

- *Quantum Computation and Quantum Information* by Nielsen and Chuang [1];
- *An introduction to Quantum Computingby Kaye, Laflammeand Mosca* by Kaye, Laflammeand Mosca [2];
- *Quantum Computing for Computer Scientists* by Yanofsky and Mannucci [3];
- *Principles of Quantum Mechanics* by Shankar [4].

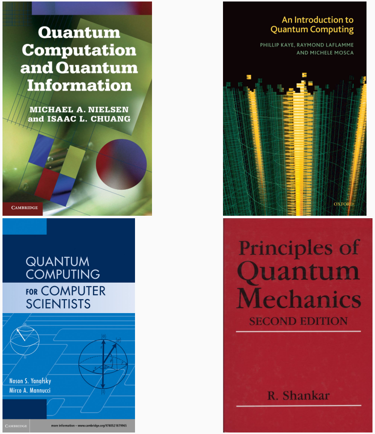


Figure 19: Some reference books.

Where To Study?

- LNCC;
- UFC - LATIQ;
- UFCG - IQuanta;
- UFRJ;
- UFRN;
  - ECT;
  - IIP.

Conclusion

Conclusion

- Hype Cycle;
    - Get ready for disappointment;
    - Unpredictable future;
- Quantum Computing is difficult;
    - Strong Mathematical basis required;
    - Steep learning curve;
    - Develop a Quantum Algorithm is challenging;
    - It is hard to debug.

References

- M. A. Nielsen and I. Chuang, "Quantum computation and quantum information," 2002.
- P. Kaye, R. Laflamme, M. Mosca, *et al.*, *An introduction to quantum computing*. **Oxford University Press, 2007.**
- N. S. Yanofsky and M. A. Mannucci, *Quantum computing for computer scientists*. **Cambridge University Press, 2008.**
- R. Shankar, *Principles of quantum mechanics*. **Springer Science & Business Media, 2012.**

Questions?

- About me;
  - Blog: $|\psi\rangle$ence $|\varphi\rangle$ction;
  - **E-mail: gustavowl@lcc.ufrn.br**;
  - Github: gustavowl;
  - **Website: gustavowl.github.io/**;
    - Slides will be uploaded here.

- About PET-CC;
  - Facebook: fb.com/petccufrn;
  - Instagram: @petccufrn;
  - LinkedIn: PET-CC UFRN;
  - **Website: petcc.dimap.ufrn.br**;
  - **YouTube: PET Ciência da Computação UFRN**.