(A Not So Technical) Introduction to Quantum Computation

What does it take to successfully use quantum computers?

Harold Ollivier

Outline

01

Quantum Computing

What is quantum mechanics?

Definition

Set of axioms used to describe reality (at the microscopic scale)

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1. State of a system is a normalized vector in a complex Hilbert space $\vec{u} \in \mathcal{H}$ — Information
2. Systems can be combined via tensor products $\vec{u}, \vec{v} \to \vec{u} \otimes \vec{v}$ — Scaling
3. Closed system evolutions are unitaries $\vec{u} \to U\vec{u}, \ U \in \mathcal{U}(\mathcal{H})$ — Processing
4. The probability of measuring $\vec{v}$ when starting $\vec{u}$ is $|(\vec{v}, \vec{u})|^2$ — Information retrieval

Direct consequences from axioms

Consequences: so what?

- It works! (Lasers, computers, GPS, etc. . .)

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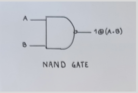

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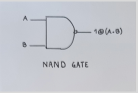

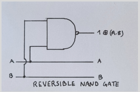

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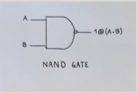

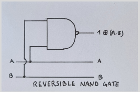

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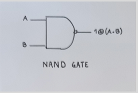

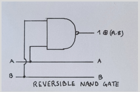

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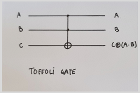

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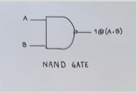

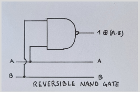

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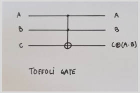

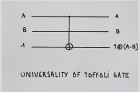

Is that it? Diving into superpositions

The Hadamard gate

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

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$$\vec{u}_0 \to \frac{1}{\sqrt{2}}(\vec{u}_0 + \vec{u}_1) \quad \vec{u}_1 \to \frac{1}{\sqrt{2}}(\vec{u}_0 - \vec{u}_1)$$

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One H gate behaves like a random number generator:

- $\Pr(\vec{u}_0|H\vec{u}_0) = \frac{1}{2} = |(\vec{u}_0|H\vec{u}_0)|^2$
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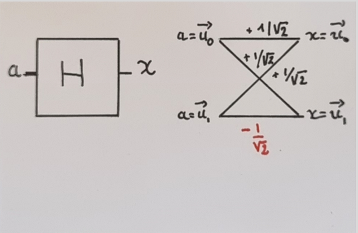
Two successive *H* gates behave like identity

$$\vec{u}_0 \xrightarrow{H} \frac{1}{\sqrt{2}}(\vec{u}_0 + \vec{u}_1) \xrightarrow{H} \frac{1}{2}(\vec{u}_0 + \vec{u}_1 + \vec{u}_0 - \vec{u}_1) = \vec{u}_0.$$

A different view of the Hadamard gate



We can compactly represent the computation of amplitudes

	$\mathbf{a}=0$	$\mathbf{a}=1$
$\mathbf{x}=0$	$1/\sqrt{2}$	$1/\sqrt{2}$
$\mathbf{x}=1$	$1/\sqrt{2}$	$-1/\sqrt{2}$

which we can rewrite $(-1)^{\mathbf{a}.\mathbf{x}}/\sqrt{2}$.

Using superpositions

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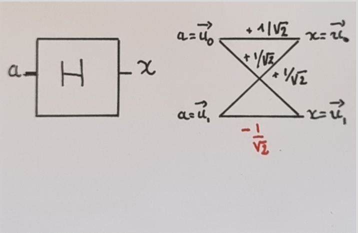

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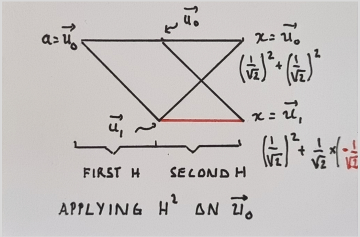
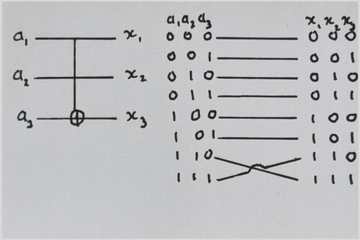
And its power



Because contributions (amplitudes) can be negative,

- Some paths add-up (constructive interference)
- Some paths cancel each other (destructive interference)

Toffoli gate



The amplitudes can also be computed in a very compact way:

$$\delta_{x_1,a_1} \times \delta_{x_2,a_2} \times \delta_{x_3,a_3 \oplus (a_1.a_2)}$$

i.e. is 1 when the input-output relation is satisfied, and 0 otherwise

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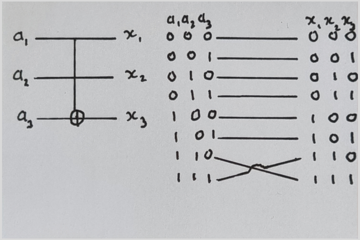

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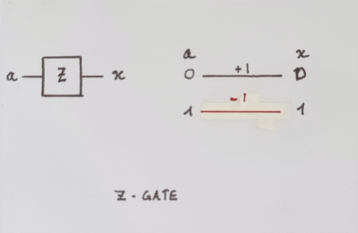
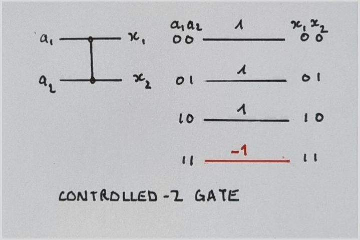
Z gate



The amplitudes are written:

$$\delta_{x,a} \times (-1)^a$$

CZ gate



For *CZ* the amplitude is $(-1)^{a_1 \cdot a_2} \delta_{a_1, x_1} \delta_{a_2, x_2}$

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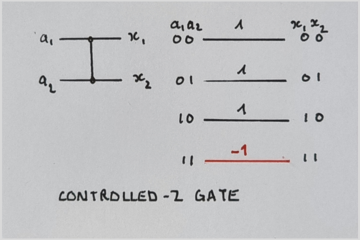

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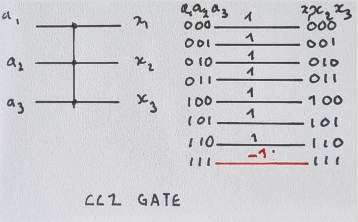
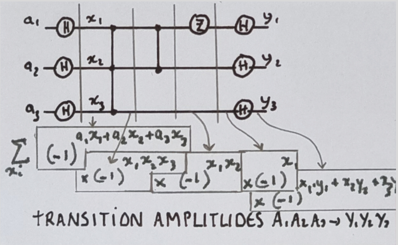


For *CCZ* it is $(-1)^{a_1 \cdot a_2 \cdot a_3} \delta_{a_1,x_1} \delta_{a_2,x_2} \delta_{a_3,x_3}$

Computing amplitudes for small circuits (recursively applying the formulas)



The power of superpositions

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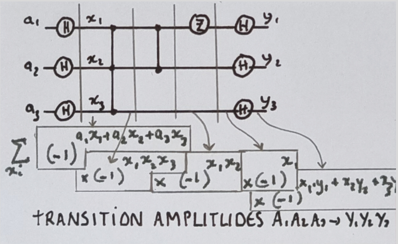

The transition amplitude from $a = \vec{u}_0^{\otimes n}$ to $y = \vec{u}_0^{\otimes n}$ corresponds to:

$$(\vec{u}_0^{\otimes n}, C_P \vec{u}_0^{\otimes n}) = \frac{1}{2^n} \sum_{x=(x_i)_i \in \{0,1\}^n} (-1)^{P(x)} = \frac{1}{2^n} (\#\{x : P(x) = 0\} - \#\{x : P(x) = 1\})$$

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Defining $gap(P)$ for P degree-3 polynomial

$$gap(P) = \#\{x : P(x) = 0\} - \#\{x : P(x) = 1\}$$

where $P = \sum \alpha_{i,j,k} x_i.x_j.x_k + \sum \beta_{i,j} x_i.x_j + \sum \gamma_i x_i$, and $\alpha_{i,j,k}, \beta_{i,j}, \gamma_i \in \{0, 1\}$.

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Hardness

- Classically computing $gap(P)$ is hard (in $PP \supset NP$)
- Computing $ngap(P) = gap(P)/2^n$ is also hard
- Quantum computers seem to do it with few gates: $ngap(P) = (\vec{u}_0^{\otimes n}, C_P \vec{u}_0^{\otimes n})$

The power of quantum computers is fragile

Exact computation of $ngap(P)$ is hard

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- It can become easy for additive approximation for classes of functions that remain hard multiplicatively

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- It can become easy for additive approximation for classes of functions that remain hard multiplicatively
- It can be easy when there is noise

Take home messages

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4. Useful QC algorithms need to be designed (or checked) on a case-by-case basis: no easy black-box approach
5. Keep in mind that we assumed perfect machines (without noise)

02

Current Impacts

Examples of algorithms using coherent QC (large machines, error free)

- Discrete log (exponential)
- Linear algebra with quantum encoded data (possibly exponential, mostly polynomial)
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- Variational Quantum Eigensolver (VQE): optimization problems recast as minimization of energy / QML
- Quantum Alternating Operator Ansatz (QAOA): combinatorial optimization
- Analog QC: physics simulations, optimization

Some quantum algorithms and more...

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Quantum cryptography (QKD)

- Protecting information with statistical security (ie. without hardness asumptions)

On cryptography

- 2016 NIST has started the process of changing the way public key crypto is done to become post-quantum (ie. quantum resistant)
- Calls issued, some protocols are being standardized
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On computing

- A lot of work is being done to pinpoint possible use-cases
- Assessment of the current power of quantum machines
  - Well chosen problem (hard for classical / easy for quantum): supremacy experiment
  - Useful problem (but brute force classical simulation): latest IBM Nature paper
  - Small scale proof of concept: hard to apprehend the scaling
- Trying to develop a GPU-like approach with HPC coupling

03

Looking into the future

Expected imapcts

Impact your client's businesses

- Need to account for crypto uncertainty
  - People store have long-term valuable documents
  - Need to properly upgrade security of systems before it's too late
- Ensuring that some computations are correct / trusting computations

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Impact on your own business

- Dependent on applications
- Algebra + optim: Quite general

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Current HW status

- In the hundred's of qubits non error corrected
- In a zone where there is some battle with classical computing (for well chosen problems)
- Many different architectures where some could potentially arrive faster than expected

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Bottlenecks

- Assessment of usefulness of QC requires reanalysing the full computational software stack
- Takes time and knowledge to know what you are trying to improve
- Improving over state of the art means you know what it is for your problem

What?

You can (should?) take actions now

- Get an idea with small scale hackathons (to get a first feeling)

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- Look where quantum can help
- Work with private companies (when getting inspiration from others / adapting something described elsewhere)
- Work with academic labs when you want to tackle something that (really) nobody has looked at before

04

Thank you! (time for questions)