The Abdus Salam International Centre for Theoretical Physics

CONICET | Universidad Nacional de Mar del Plata | ICYTE

INSTITUTO DE INVESTIGACIONES CIENTÍFICAS Y TECNOLÓGICAS EN ELECTRÓNICA

Quantum Computing: Introduction and Emulation

Agustin Silva

- Quantum Mechanics
  - History
  - Classical vs Quantum
  - Quantum Properties
- Quantum Computer
  - Quantum Devices
  - Complexity Theory
  - Quantum Hardware
  - Programming Languages
- Quantum Computing
  - Quantum Bits
  - Quantum Gates
  - Quantum Circuits
- Quantum Algorithms
  - Quantum Teleportation
  - Deutsch-Jozsa
  - Grover's Search
  - Quantum Fourier Transform
  - Shor Factorization
- Quantum Everywhere
  - Quantum Cryptography
  - Quantum Game Theory
  - Quantum Machine Learning
  - Quantum Simulations
- Emulation of Quantum Algorithms

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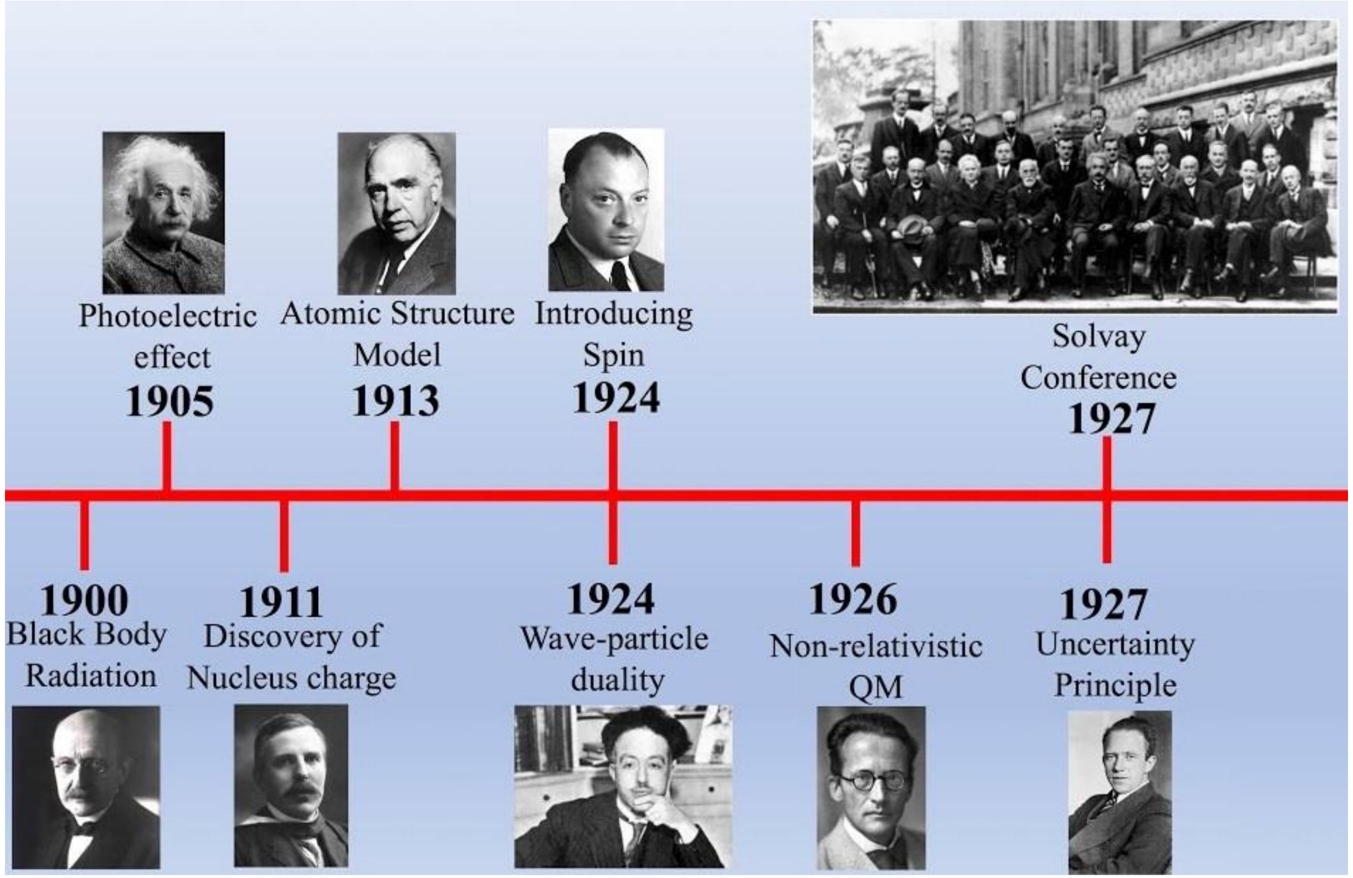
- **Emulation of Quantum Algorithms**

A little bit of History:



Classical Mechanics

- Macroscopic
- Newton's laws
- Continues Energy values
- Experiments are deterministic
- Certainty in position and momentum

Quantum Mechanics

- Microscopic
- Schrodinger's equation
- Discrete Energy values
- Experiments are probabilistic
- Uncertainty in position and momentum

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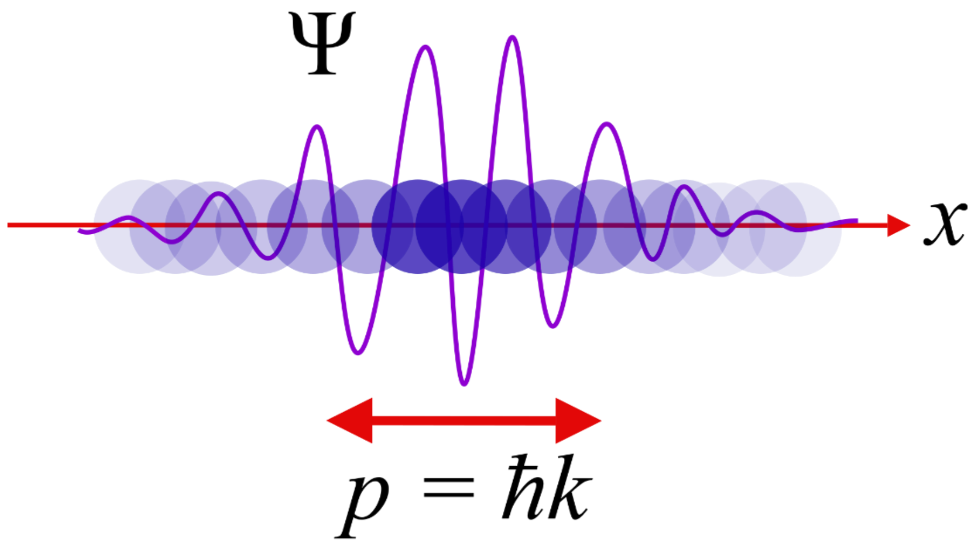
Some Quantum Properties:

- Wave Function
- Measurement
- Superposition
- Deconherence
- Entanglement



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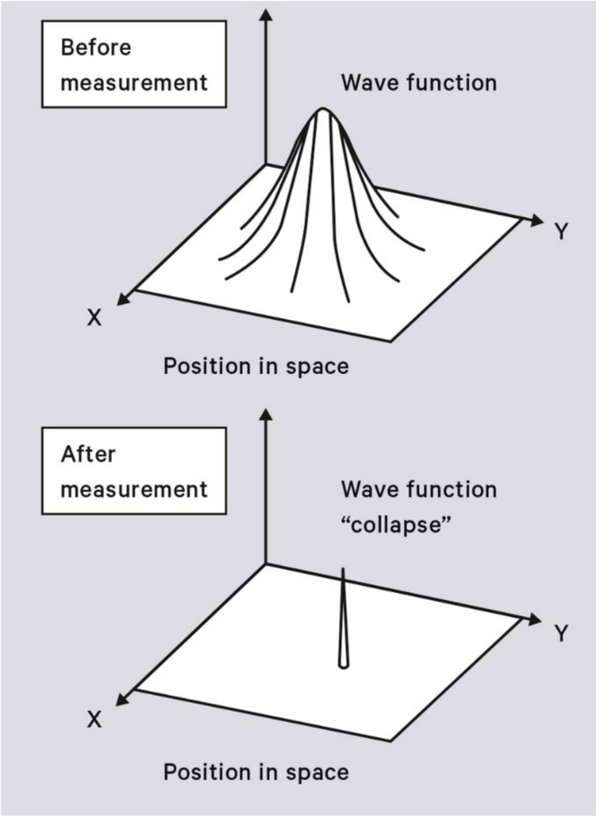

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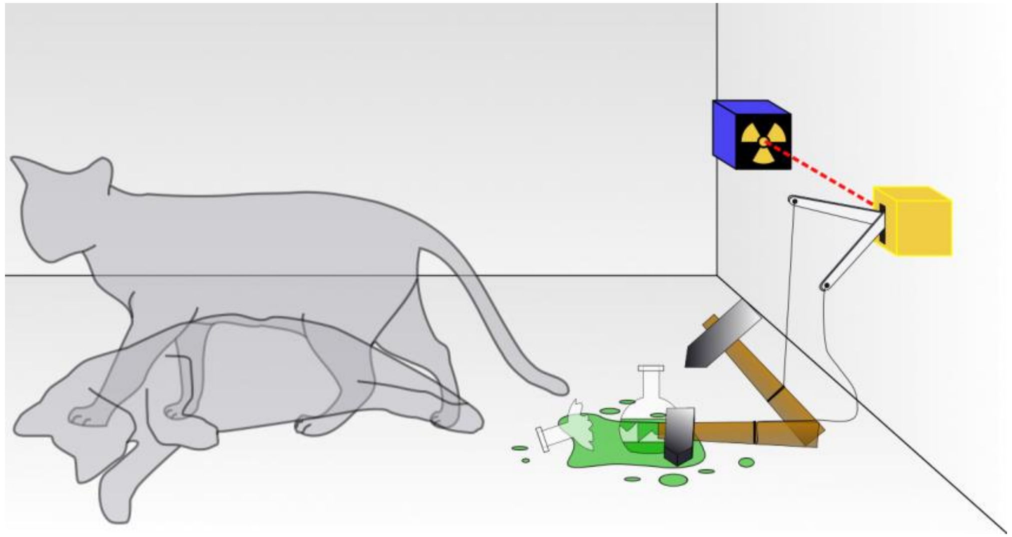

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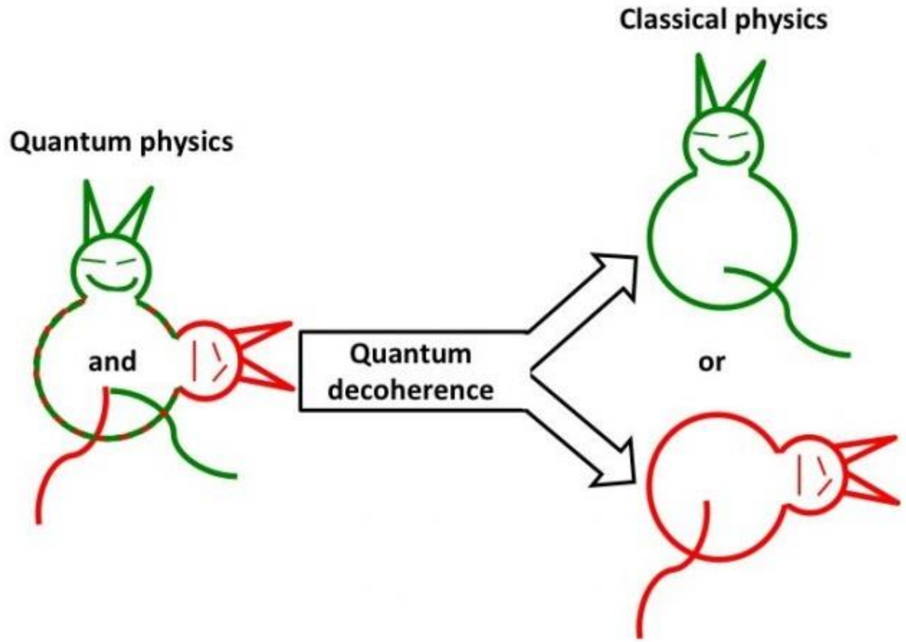

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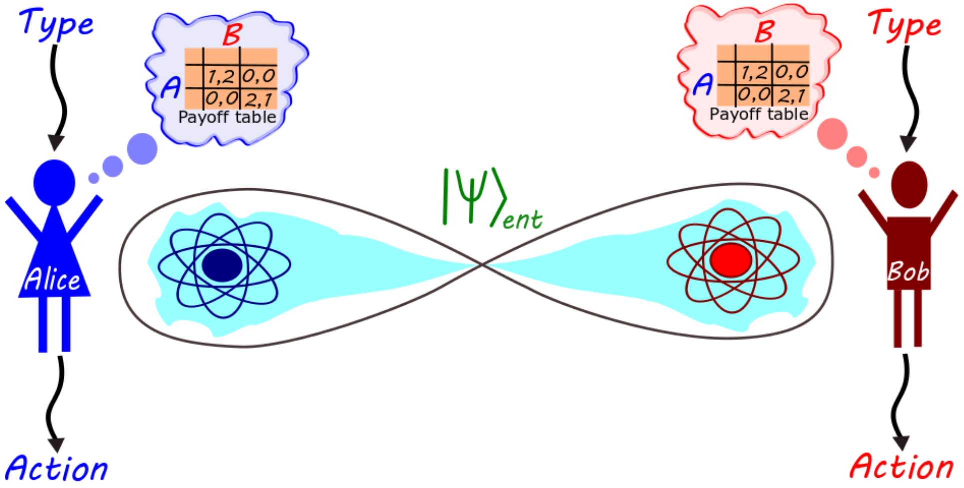
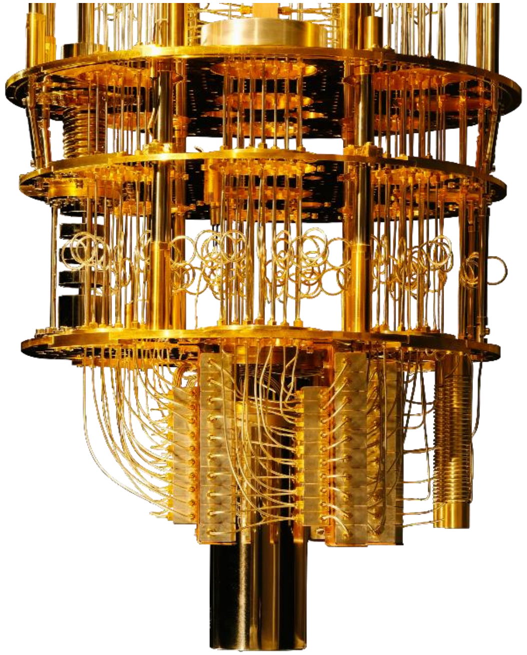


Quantum Computers

- Quantum Devices
- Complexity Theory
- Quantum Hardware
- Programming Languages



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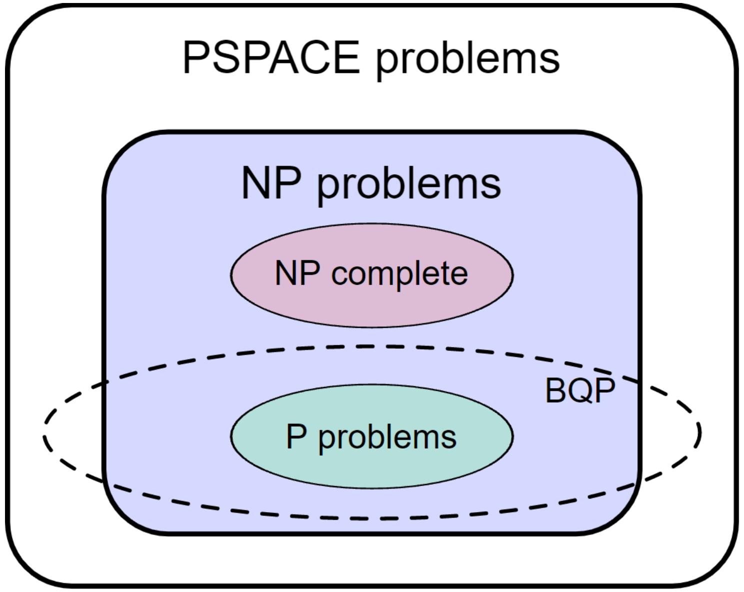

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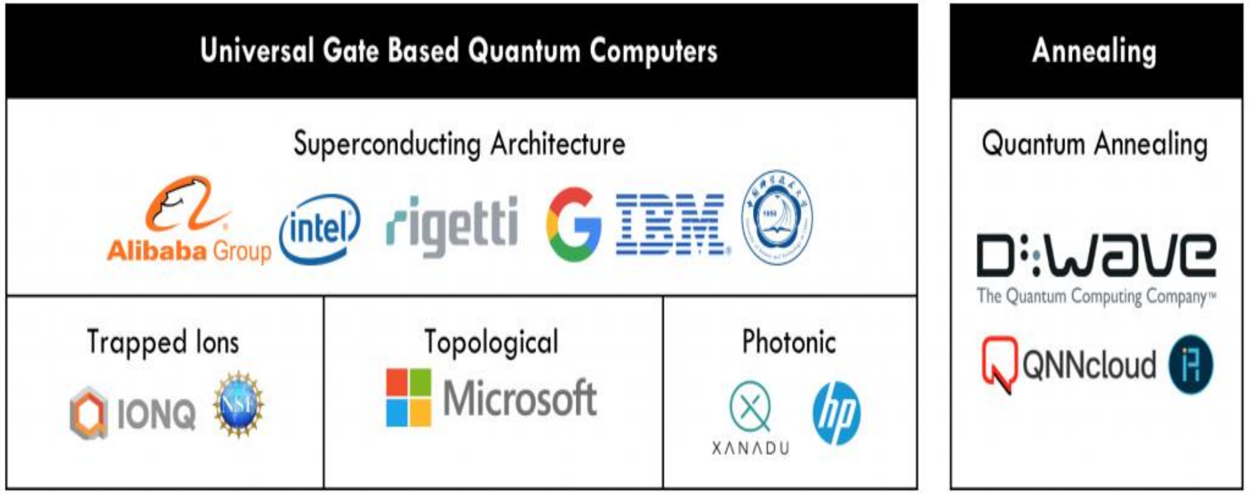

Quantum Computers

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PENNY LANE

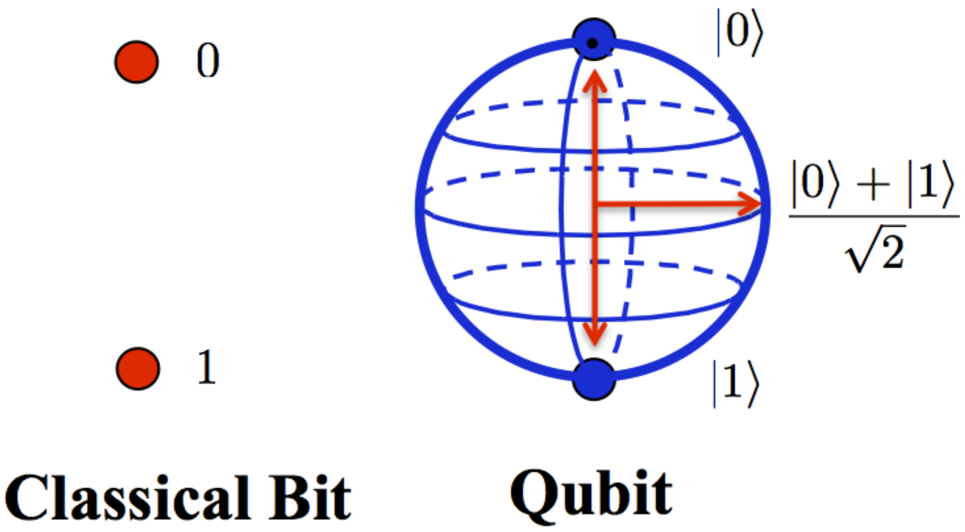
Cirq

SILQ

Ocean

Quantum Bits

- Classical vs Quantum bit
- Dirac notation
- Formal definition
- Bloch Sphere



Quantum Bits

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$\|\psi\rangle$	• Vector. Also known as Ket
$\langle\psi\|$	• Vector dual of $\|\psi\rangle$ (Bra)
$\langle\varphi\|\psi\rangle$	• Inner product between $\|\varphi\rangle$ and $\|\psi\rangle$
$\|\varphi\rangle\|\psi\rangle$	• Tensor product
$\langle\varphi\|A\|\psi\rangle$	• Inner product between $\|\varphi\rangle$ and $A\|\psi\rangle$

Quantum Bits

- Classical vs Quantum bit
- Dirac notation
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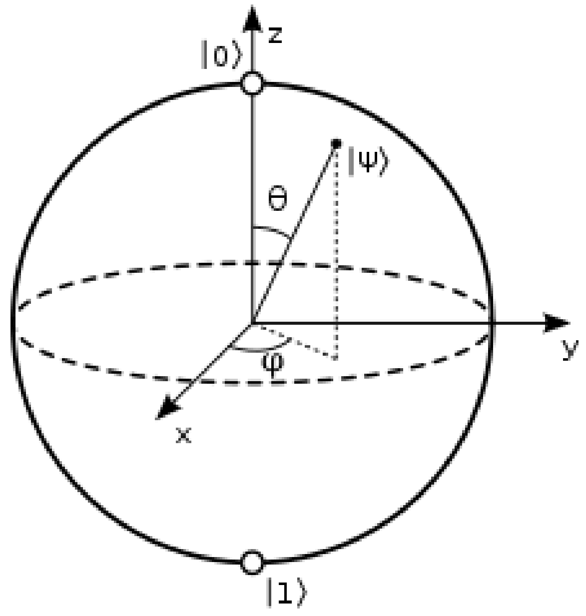
$$|\psi\rangle := \alpha\,|0\rangle + \beta\,|1\rangle = \begin{pmatrix}\alpha \\ \beta\end{pmatrix};$$

$$|\alpha|^2 + |\beta|^2 = 1.$$

Quantum Bits

- Classical vs Quantum bit
- Dirac notation
- Formal definition
- Bloch Sphere



$$|q\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

Quantum Gates

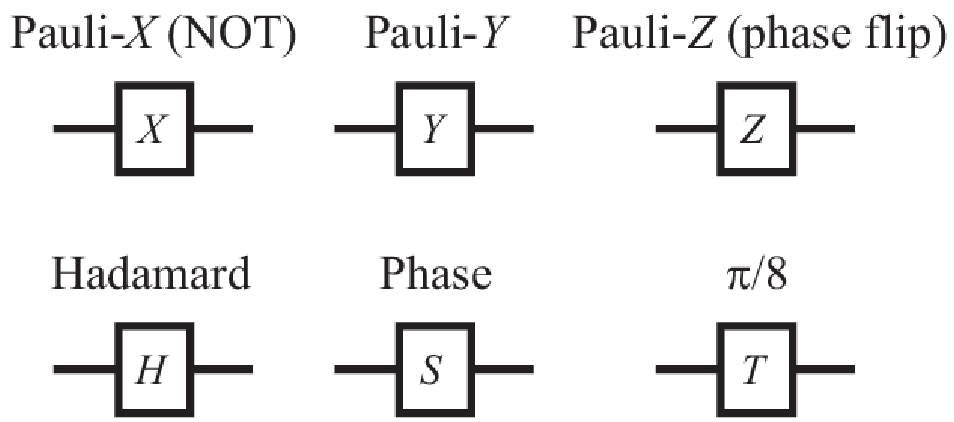
- Schrodinger equation
- Unitary matrix
- General one-qubit gate
- Multiple qubit gates

$$i\hbar \frac{d}{dt}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle$$

Quantum Gates

- Schrodinger equation
- Unitary matrix
- General one-qubit gate
- Multiple qubit gates

$$UU^{\dagger} = U^{\dagger}U = I$$



Quantum Gates

- Schrodinger equation
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- Multiple qubit gates

$$U(\theta, \phi, \lambda) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -e^{i\lambda}\sin(\frac{\theta}{2}) \\ e^{i\phi}\sin(\frac{\theta}{2}) & e^{i(\phi+\lambda)}\cos(\frac{\theta}{2}) \end{bmatrix}$$

$$U(\tfrac{\pi}{2}, 0, \pi) = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} = H$$

Quantum Gates

- Schrodinger equation
- Unitary matrix
- General one-qubit gate
- Multiple qubit gates

$$X \otimes H = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \otimes \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$= \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \times \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} & 1 \times \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \\ 1 \times \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} & 0 \times \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \end{bmatrix}$$

$$= \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix}$$

Quantum Circuits

- Universal gate set
- Linear vs Nonlinear evolution
- Measurement gate
- No-cloning theorem

$$U \equiv R_Z(\alpha) R_Y(\beta) R_Z(\gamma)$$

&

$$\{R_x, R_y, R_z, Ph, \mathrm{CNOT}\}$$

$$\{H, S, T, \mathrm{CNOT}\}$$

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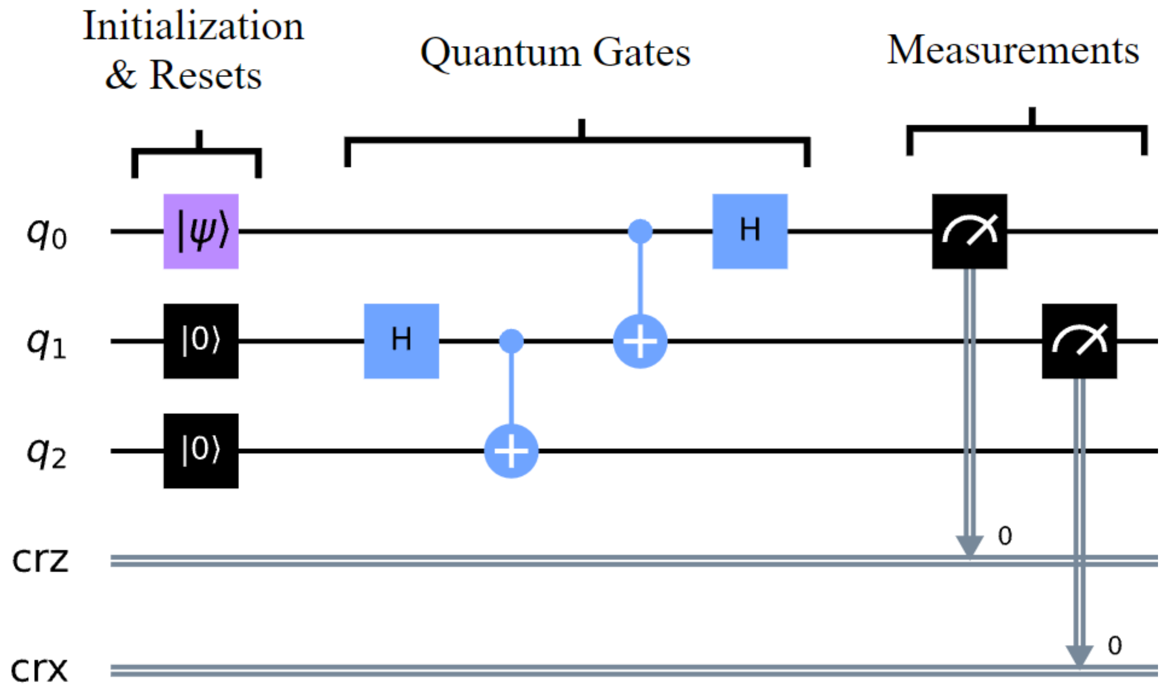

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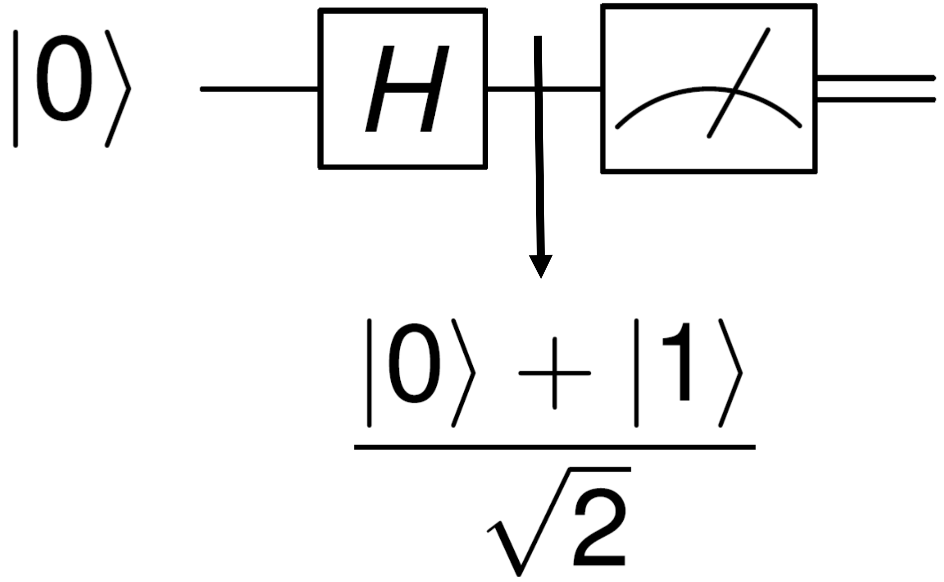

Quantum Circuits

- Universal gate set
- Linear vs Nonlinear evolution
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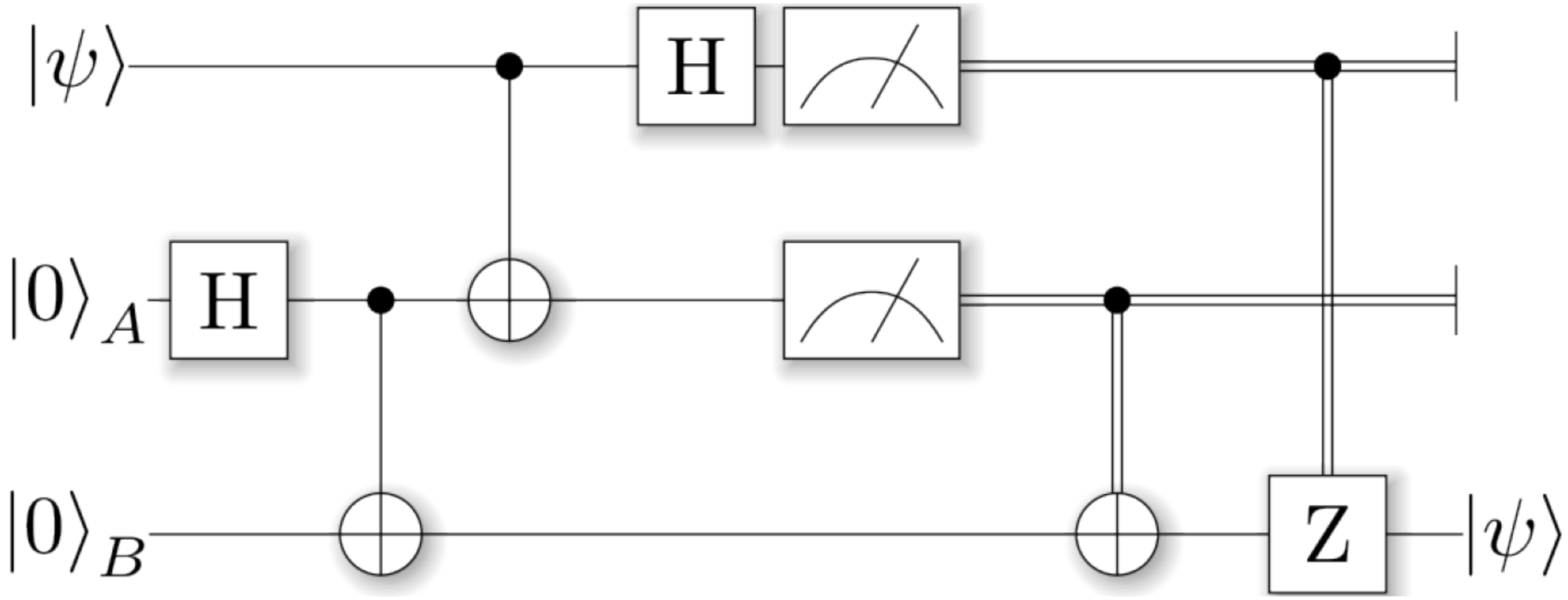
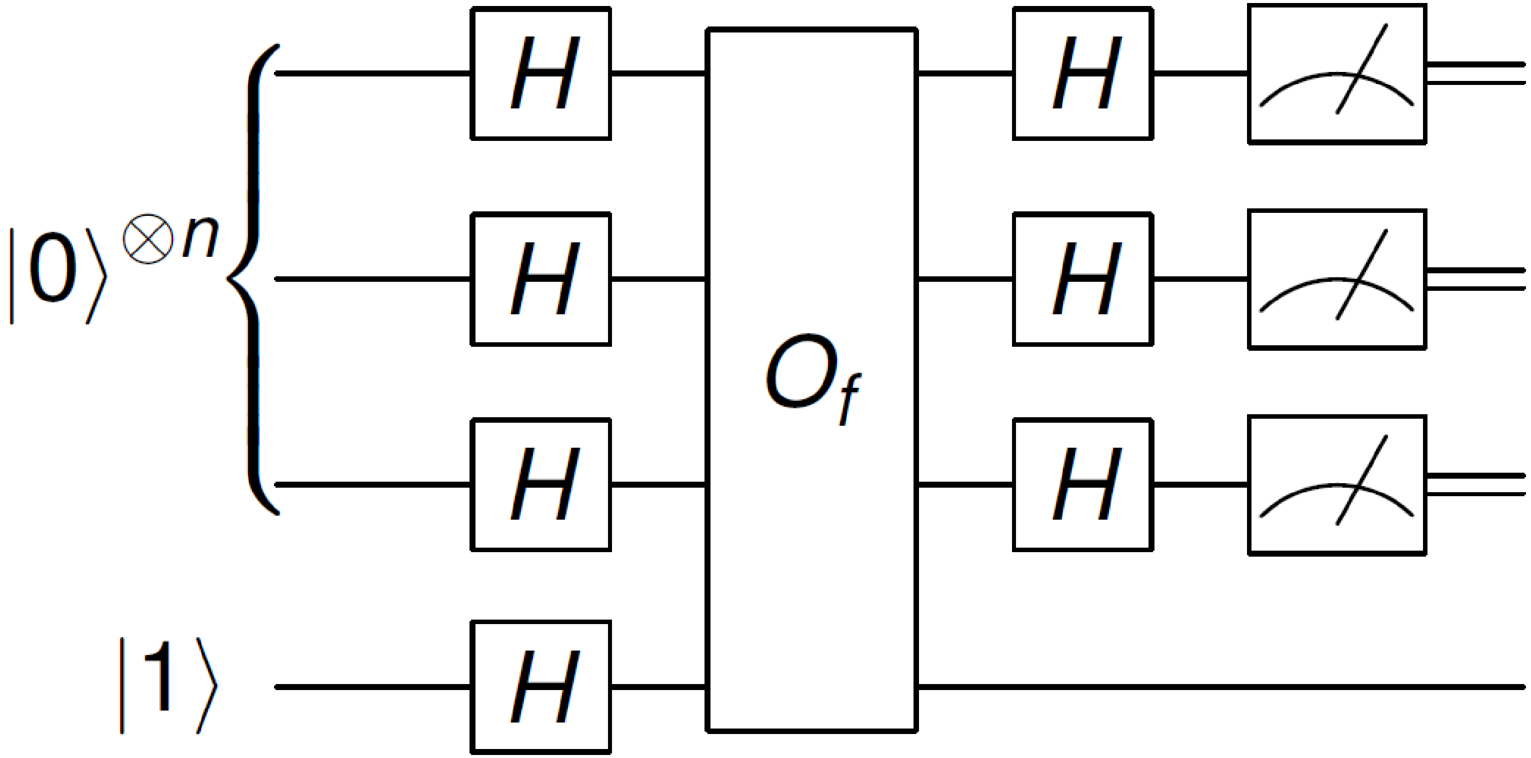
$$U|\psi\rangle|0\rangle \neq |\psi\rangle|\psi\rangle$$

<Let’s prove it with what we know>

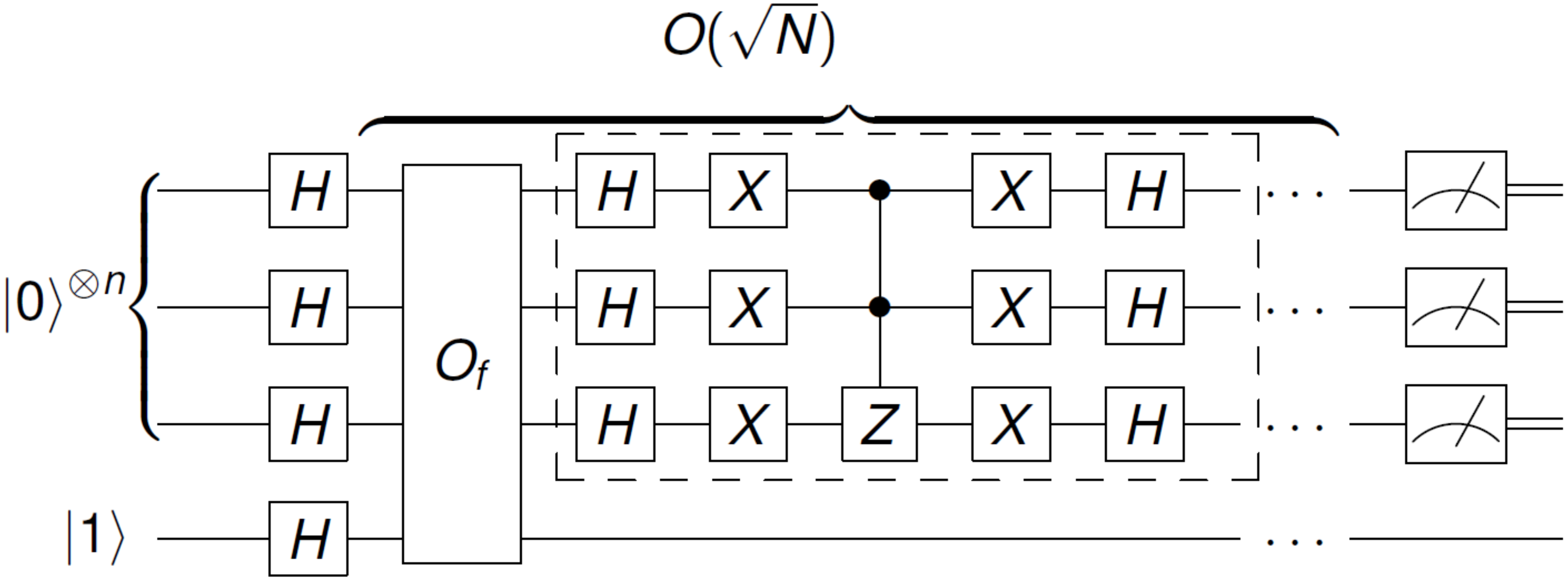
Quantum Algorithms: Quantum Teleportation



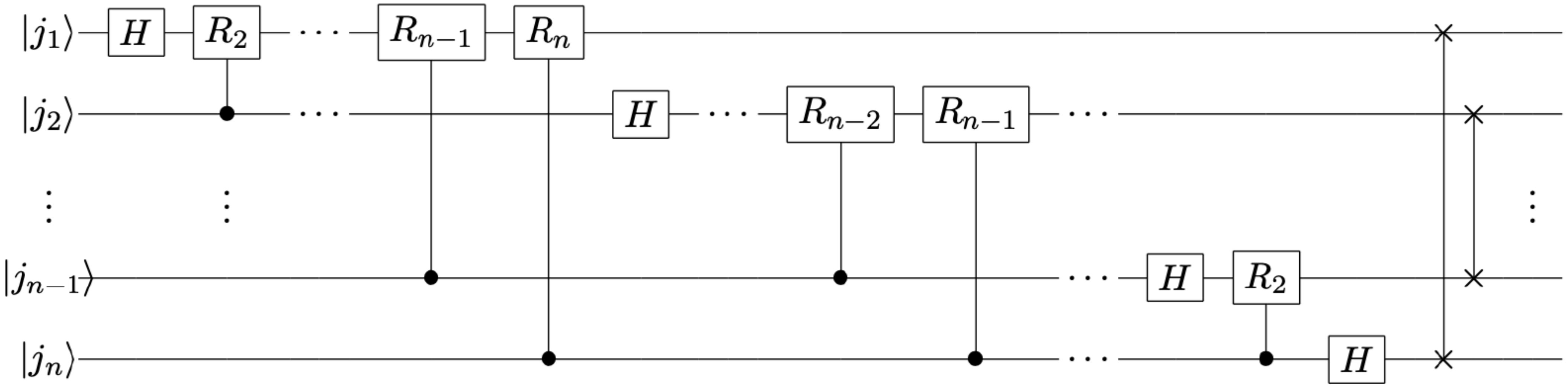
Quantum Algorithms: Deutsch-Jozsa algorithm



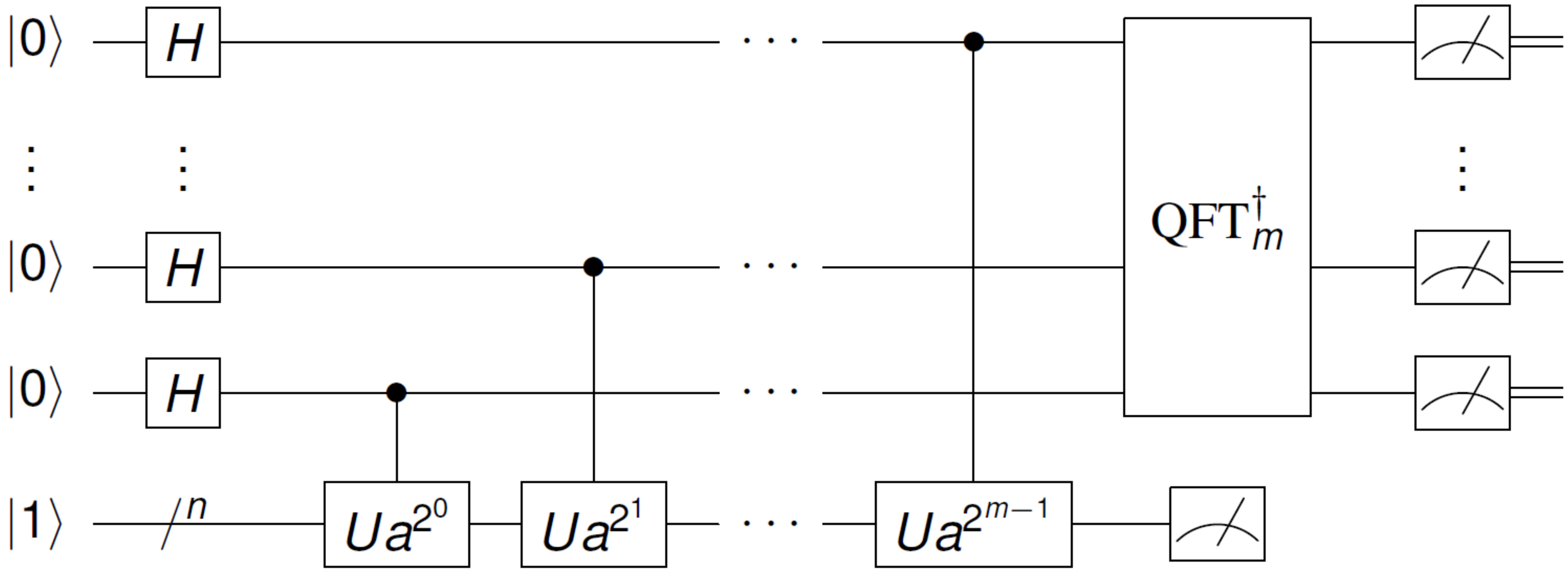
Quantum Algorithms: Grover's algorithm



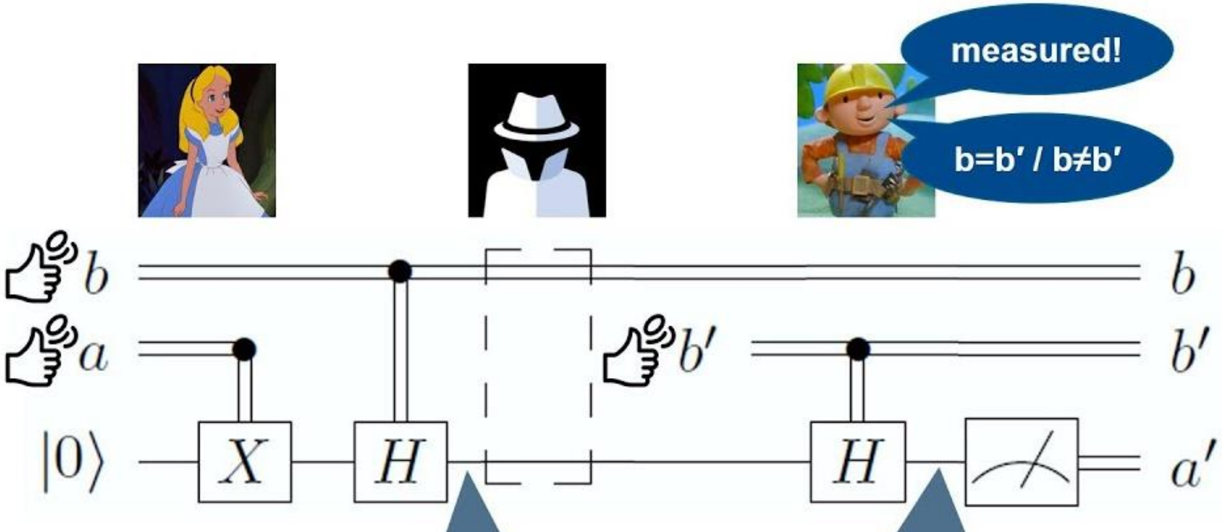
Quantum Algorithms: Quantum Fourier Transform



Quantum Algorithms: Shor's algorithm



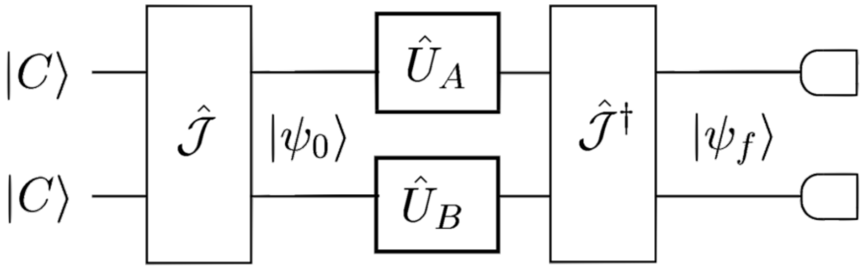
Quantum Cryptography

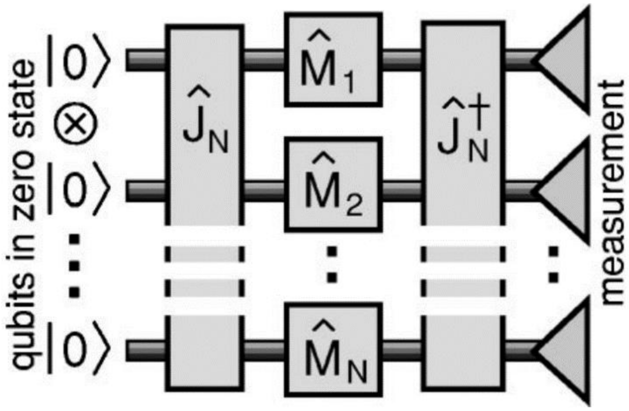


a	b	$\|\psi\rangle$
0	0	$\|0\rangle$
0	1	$\|+\rangle$
1	0	$\|1\rangle$
1	1	$\|-\rangle$

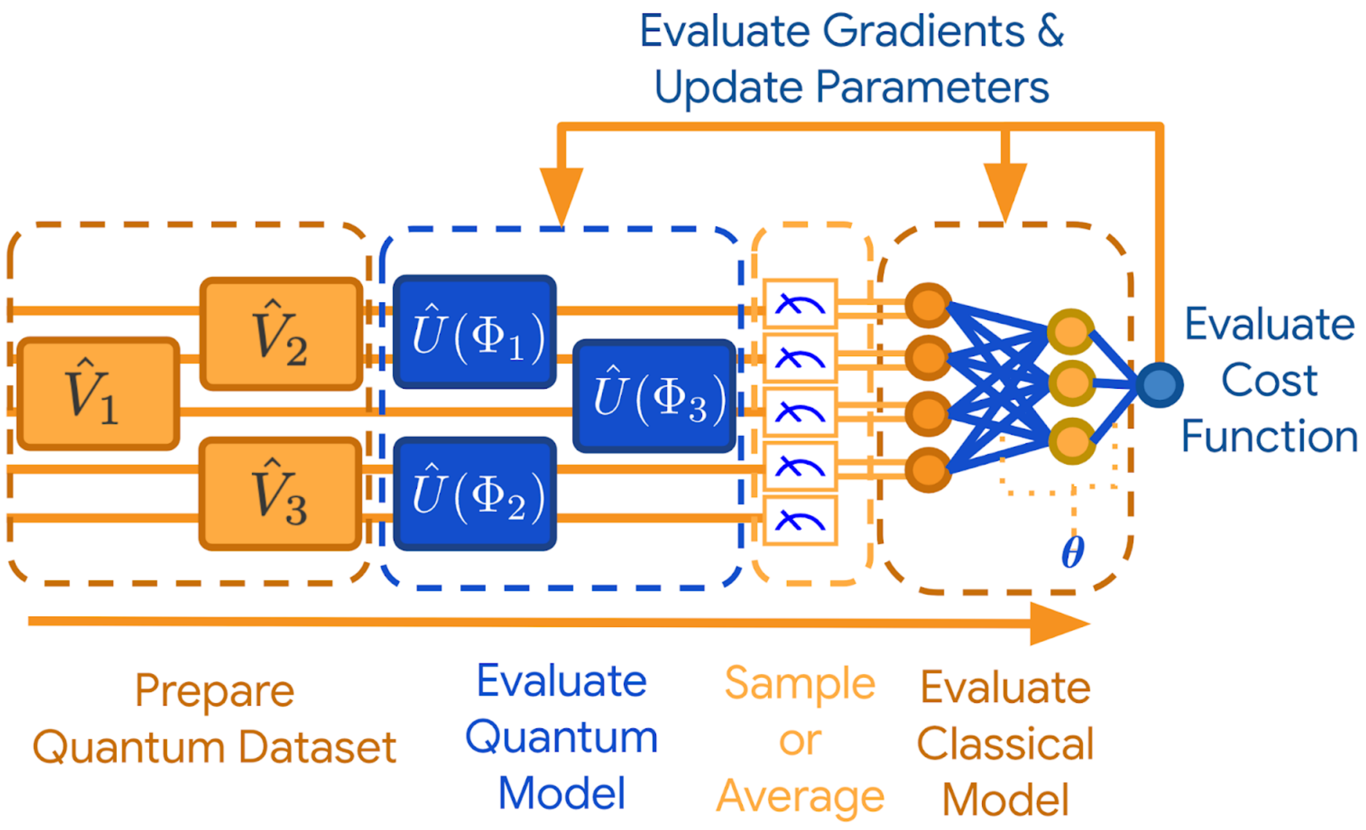
a	b	b'	$\|\psi'\rangle$
0	0	0	$\|0\rangle$
~~0~~	~~0~~	~~1~~	~~$\|+\rangle$~~
~~0~~	~~1~~	~~0~~	~~$\|+\rangle$~~
0	1	1	$\|0\rangle$
1	0	0	$\|1\rangle$
~~1~~	~~0~~	~~1~~	~~$\|-\rangle$~~
~~1~~	~~1~~	~~0~~	~~$\|-\rangle$~~
1	1	1	$\|1\rangle$

Quantum Game Theory

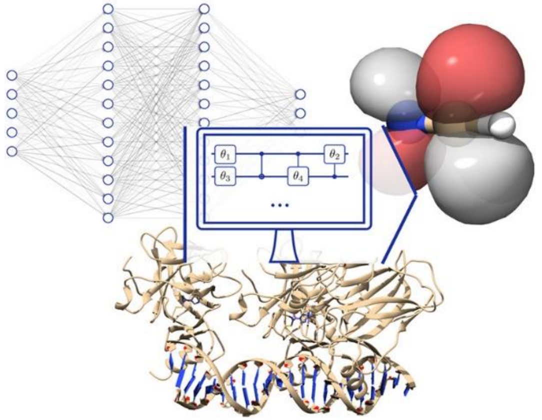




Quantum Machine Learning



Quantum Simulations



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain.

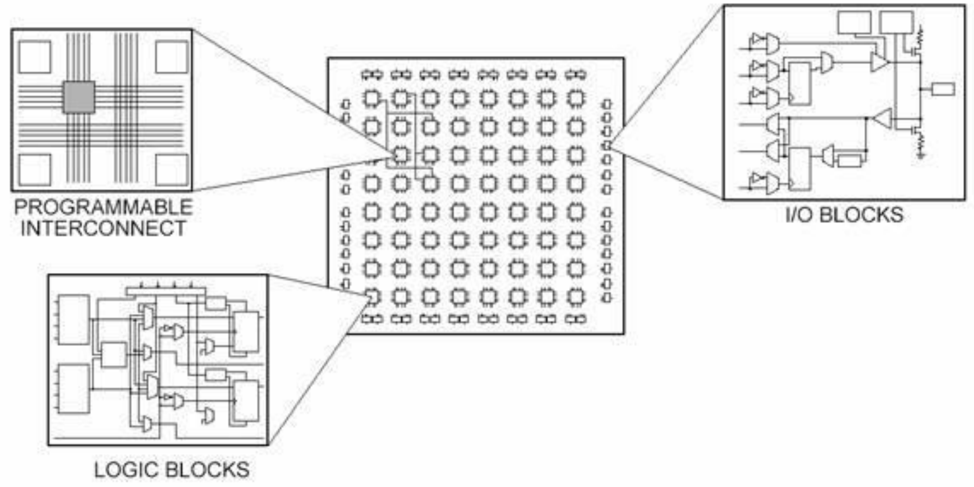
He and I have had wonderful, intense, and interminable arguments, and my argument is always that the real use of it would be with quantum mechanics, and therefore full attention and acceptance of the quantum mechanical phenomena—the challenge of explaining quantum mechanical phenomena—has to be put into the argument, and therefore these phenomena have to be understood very well in analyzing the situation. And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.

Questions:

- Why do we even need quantum computers?
- Are QC just trying all possibilities at the same time?
- Why are quantum computers so hard to build?
- What do we do in the meantime?

Why FPGAs?

- Parallelization capacity
- Handling fix point operations
- Take advantage of its blocks
- Memory manage



Questions?

Thank you very much!