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& TECHNOLOGY

OPERATING SYSTEMS & PARALLEL COMPUTING

Quantum Computing

Agenda

- Basic Concepts
- Quantum Algorithms
- Programming Languages
- IBM Quantum Experience

Basic Concepts

What is a quantum computer?

- A Quantum Computer makes use of the natural laws of quantum mechanics to carry out a calculation.

- Why do we need a quantum computer?
  - **Resolution of some specific problems** → Some problems cannot be treated with classical computer with full reliability.
  - **Performance** → Faster troubleshooting than a classical computer.

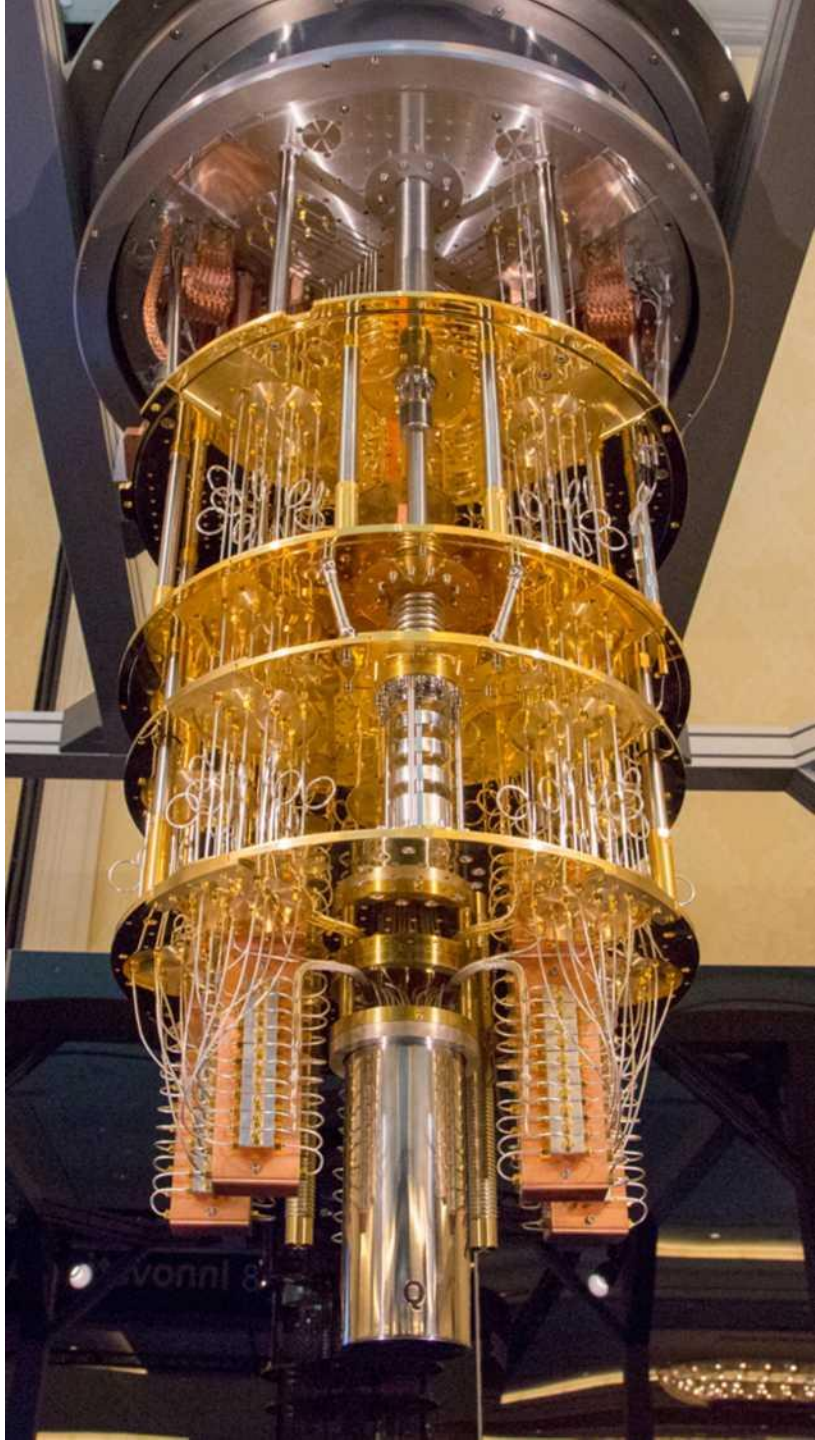
WHAT IS QUANTUM COMPUTING?

Quantum computer is not a faster computer!

In a quantum computer:

1. The information is stored in a quantum system
2. The computation is governed by quantum-mechanical phenomena.

It is fundamentally different from digital computers and .



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Quantum Computing Use Cases

Cryptography

Quantum computers are famous for code-breaking, but their real power may lie in making cloud computing more secure. Based on laws of physics, quantum computers have the potential to keep private data safe from snoops and hackers, no matter where it is stored or processed.

Medicine & Materials

•A quantum computer mimics the computing style of nature, allowing it to simulate, understand and improve upon natural things—like molecules, and their interactions and compounds-better than a classical computer. This ability could lead to new medical advances and materials discovery.

Machine Learning

•Quantum machine learning is an exciting and new area. Research indicates that quantum computing could significantly accelerate machine learning and data analysis tasks, such as training of classical Boltzmann machines, or topological analysis of big data. .

Searching Big Data

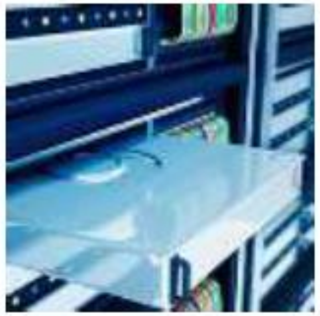
•A machine that can search the ever-growing amount of data being created, and locate connections within it, could have tremendous impact across many industries. Quantum computing offers the possibility of doing this significantly faster than classical computers. Further research will lead to the realization of this capability

Why build a Quantum Computer?

Quantum computing power* scales exponentially with qubits
N bits can exactly simulate log N qubits

This compute unit....

Commodore 64



AWS M4 Instance

1 Million x Commodore 64

Entire Global Cloud

1 Billion x
(1 Million x Commodore 64)

can exactly simulate:

10 Qubits

30 Qubits

60 Qubits

Why build a Quantum Computer?

Machine Learning

> Development of new training sets and algorithms

> Classification and sampling of large data sets

Supply Chain Optimization

> Forecast and optimize for future inventory demand

> NP-hard scheduling and logistics map into quantum applications

Robotic Manufacturing

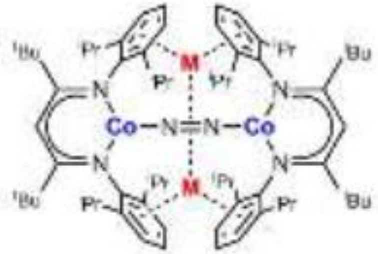
> Reduce manufacturing time and cost

> Maps to a Traveling Salesman Problem addressable by quantum constrained optimization

Computational Materials Science

> Design of better catalysts for batteries

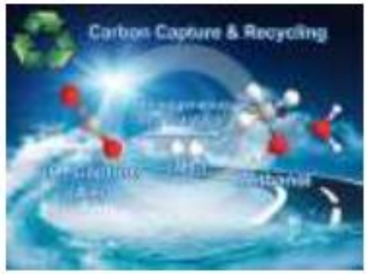
> Quantum algorithms for calculating electronic structure



Alternative Energy Research

> Efficiently convert atmospheric CO_2 to methanol

> Powered by existing hybrid quantum-classical algorithms + machine learning



What isn't on here: breaking RSA with Shor's algorithm

Quantum Explanation

- Generic video
  - https://www.youtube.com/watch?v=YgFVzOksm4o
- MIT Presentation
  - https://www.oracle.com/openworld/on-demand.html?bcid=6086803412001

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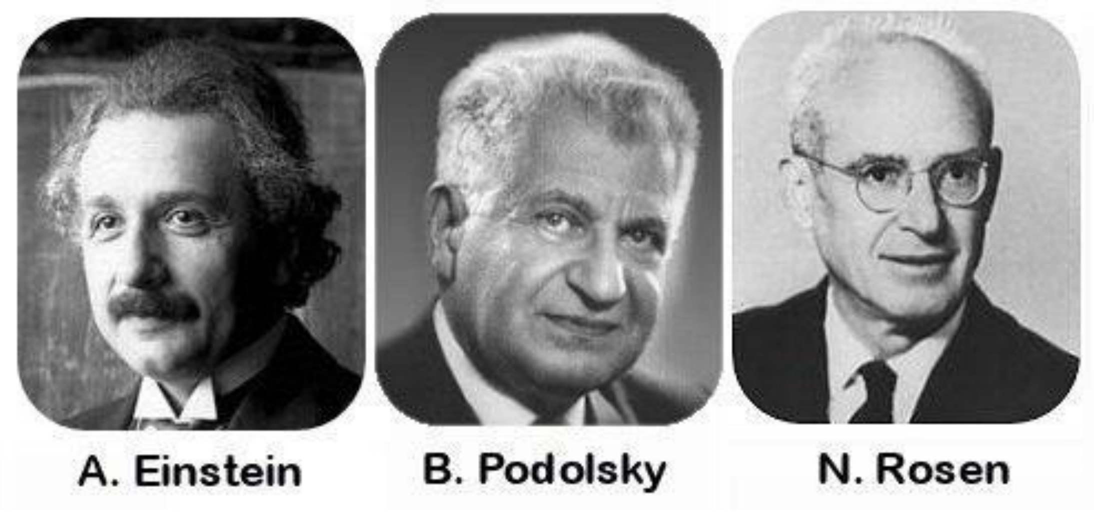
SHORT HISTORY

1935 The EPD Paradox

Albert Einstein, Robert Podolsky and Nathan Rosen question the quantum wave function as a complete description of physical reality

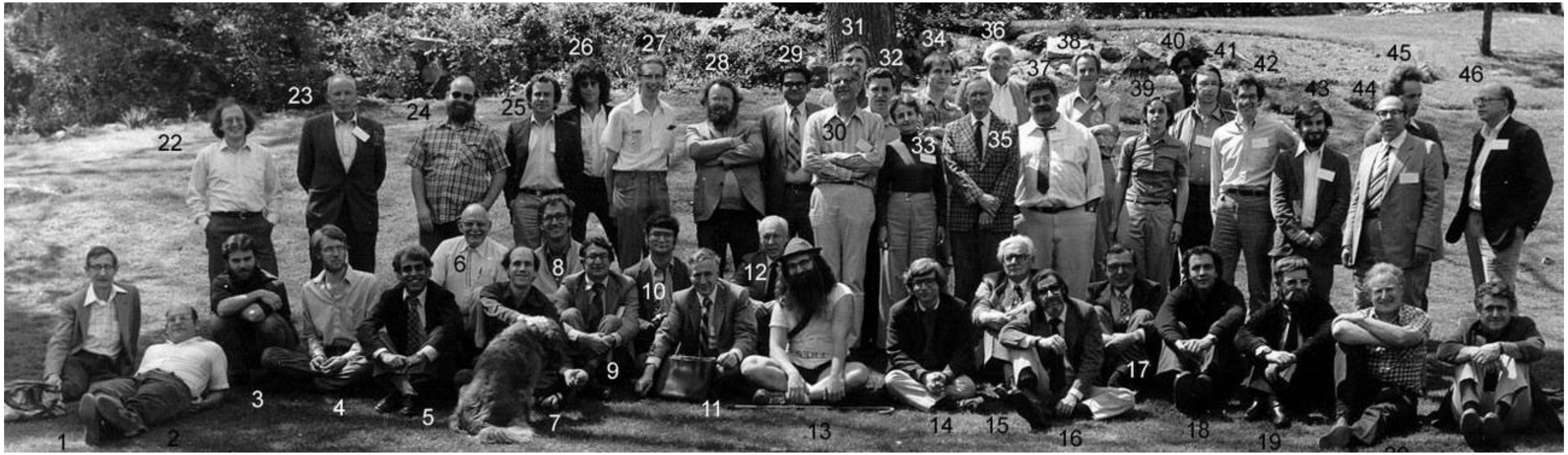


1970 The Birth of Quantum Information Theory

Notes taken from discussions between **Stephen Wiesner** and Charlie Bennet, when Charlie was still a graduate student at Harvard, possibly contains the first use of the phrase "quantum information theory" and the first suggestion for using entanglement as a communication resource. The notes go on to describe the principle of superdense coding, eventually published in 1992 by Stephen and Charlie, but this early version incorrectly states that the receiver can receive either of the encoded bits, but not both, whereas in fact both can be received, by an entanglement measurement.

1981 First Conference on the Physics of Computation

This first conference was co-hosted by MIT and IBM. During this conference, nobel prize winner Richard Feynman challenged computer scientist to develop a new breed of computers based on quantum physics. Ever since then, scientists have been grappling with the difficulty of attaining such a grand challenge



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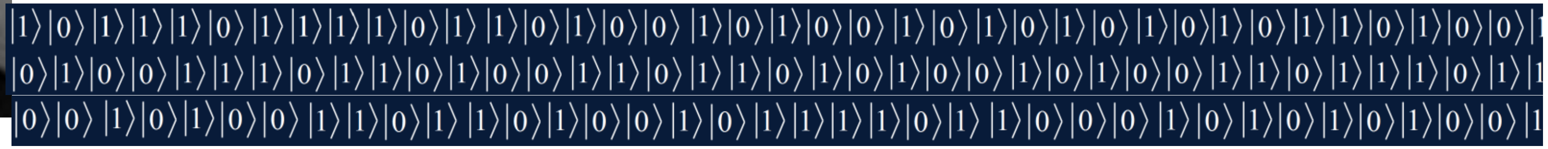
1984 Quantum Cryptography

Charles Bennettt and Gilles Brassard propose a cipher based on the fundamental laws of nature (quantum mechanics), rather than the status quo technique of assumed mathematical difficulty

0101001001100001010100101110101010101010101001000011110101010100101010101001010101010100100111101010111
0011110101010111010000100001111110101001100010111010010101010001111010010101011010101001010101100101001
0001010011101010001010001010100100010101011000101110101001010101000010111010101010010101010001010101001



1985 **Computador Cuántico Universal**

David Deutsch, described the first universal quantum computer

https://people.eecs.berkeley.edu/~christos/classics/Deutsch_quantum_theory.pdf

Quantum theory, the Church-Turing principle and the universal quantum computer

DAVID DEUTSCH*

Appeared in *Proceedings of the Royal Society of London A* **400**, pp. 97-117 (1985)†

(*Communicated by R. Penrose, F.R.S. — Received 13 July 1984*)

Abstract

It is argued that underlying the Church-Turing hypothesis there is an implicit physical assertion. Here, this assertion is presented explicitly as a physical principle: 'every finitely realizable physical system can be perfectly simulated by a universal model computing machine operating by finite means'. Classical physics and the universal Turing machine, because the former is continuous and the latter discrete, do not obey the principle, at least in the strong form above. A class of model computing machines that is the quantum generalization of the class of Turing machines is described, and it is shown that quantum theory and the 'universal

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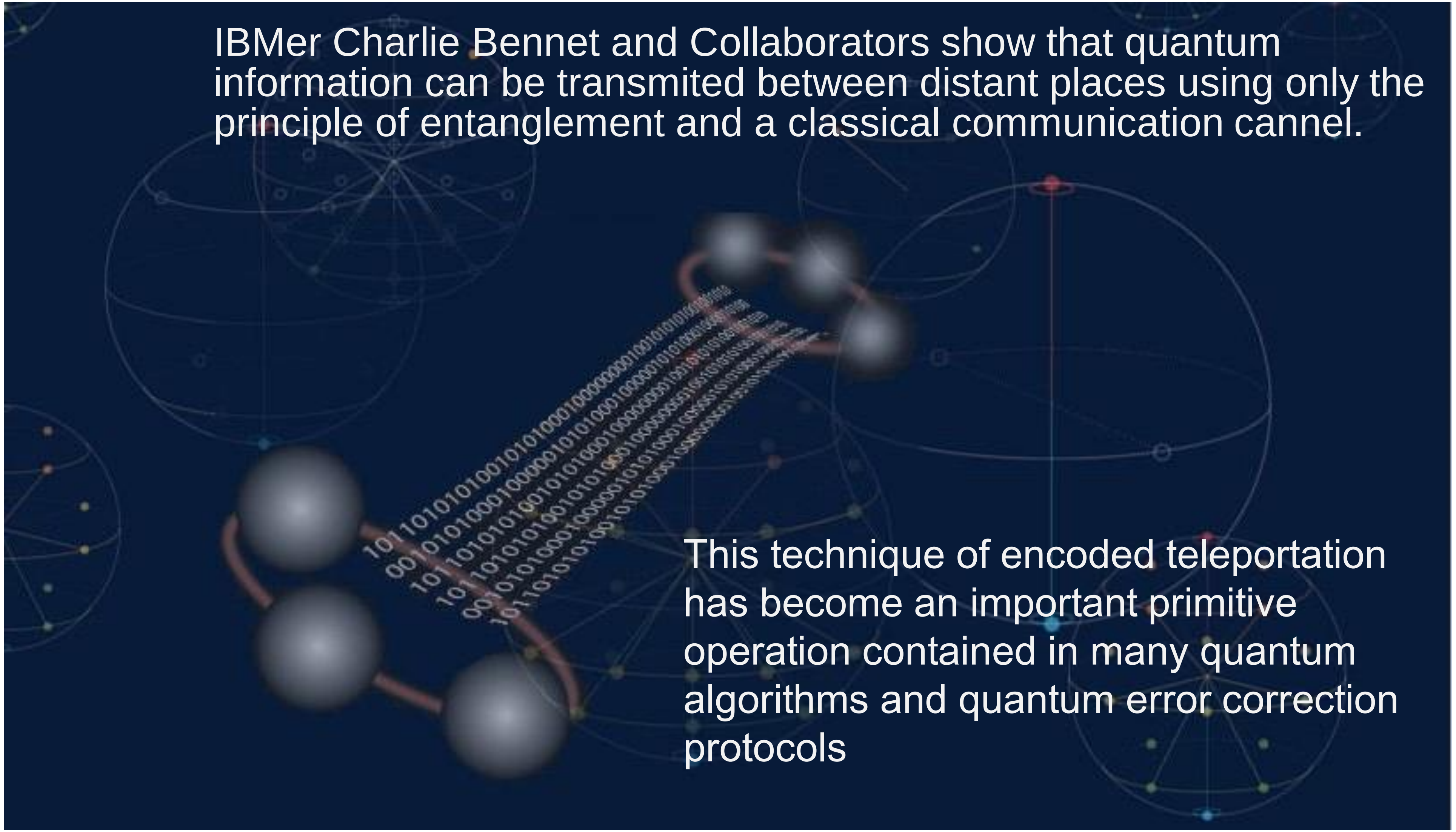
1993 Quantum Teleportation



IBMer Charlie Bennet and Collaborators show that quantum information can be transmited between distant places using only the principle of entanglement and a classical communication cannel.

This technique of encoded teleportation has become an important primitive operation contained in many quantum algorithms and quantum error correction protocols

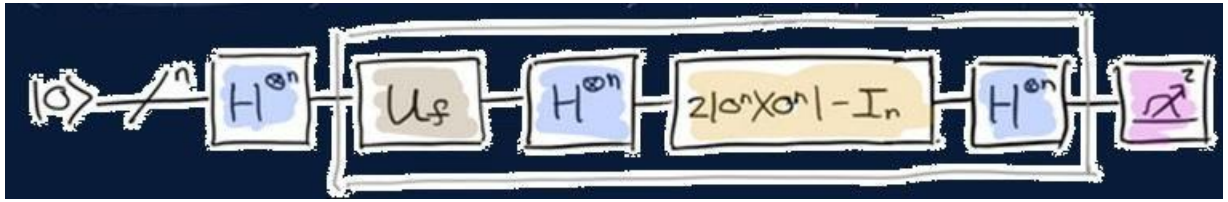
1994 Shor's Factoring Algorithm

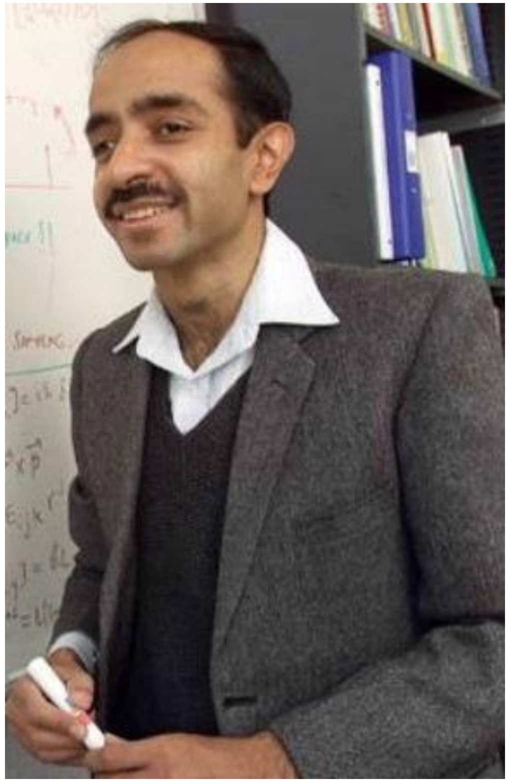
Peter Shor shows that is possible to factor a number into its primitives efficiently on a quantum computer. This problema is believed to be hard with a conventional computer.

Shor's algorithm was the first demostration that quantum computers are fundamentally more powerful than conventional computers, launching an explosion of both theoretical and experimental interest in the field

1996 Grover's Search algorithm

Using Quantum concepts, Lov Grover created an ultra-fast algorithm to search into non indexed databases





1996 DiVicenzo Criteria for Building a Quantum Computer

David DiVicenzo outlines the 5 minimal requirements he predicts are necessary for the physical implementation of a quantum computer. This list has known as the DiVicenzo Criteria and has influenced many experimental programs working on building a quantum computer. They are:

1. Well defined extendable qubit array
2. Preparable in the [0000…] ground state
3. A universal gate of quantum states
4. Long coherence times, much longer than the gate-operation time
5. Single-qubit measurement

arXiv:cond-mat/9612126v2 [cond-mat.mes-hall] 16 Dec 1996

TOPICS IN QUANTUM COMPUTERS

D. P. DIVINCENZO
IBM Research Division
T. J. Watson Research Center
Yorktown Heights, NY 10598 USA

Abstract. I provide an introduction to quantum computers, describing how they might be realized using language accessible to a solid state physicist. A listing of the minimal requirements for creating a quantum computer is given. I also discuss several recent developments in the area of quantum error correction, a subject of importance not only to quantum computation, but also to some aspects of the foundations of quantum theory.

1. What is a quantum computer?

I don't think that I will spend many words here saying why there has been a considerable growth of interest in the last couple of years in the subject of quantum computation. There has been a spate of reviews[1, 2, 3], semi-popular articles[4], and press accounts[5] giving, on the whole, a very good overview of the subject. At some level, the recent interest simply arises from the very traditional movement of computation into ever more miniature worlds, and what could be more miniature than the world of the single quantum? At another level, though, interest has arisen because the rules of quantum dynamics changes the rules of computation itself[6], in ways which we are still working to understand. You probably can't factor large numbers with any computer following, at the level of the logical operations, the laws of classical mechanics (which is to say, every computer ever operated up until now); with a computer, or a computation, obeying the laws of quantum dynamics, you just might be able to factor[7, 3]. This has drawn the attention of both the practical, problem-solving world, as well as that of those interested in further exploring and understanding the foundations of quantum theory itself.

2004 Circuit QED is Demonstrated

Robert Scholkopf and collaborators at Yale University invent Circuit QED, where a superconducting qubit is strongly interacted with a single photon in a microwave cavity. This is a ground-breaking result as it shows coherent interaciton of an artificial atom with a microwave photon, all on a chip. The work by the Yale team opened up many new possibilities and the circuit QED coupling scheme has become the standard for coupling and reading superconducting qubits as systems continue to scale.

2007 The Transmon Superconducting Qubit

The transmon superconducting qubit is invented by Robert Schoelkopt and collaborators at Yale University. It is a type of superconducting charge qubit designed to have reduced sensitivity to charge noise, a major obstacle for long coherence. it has subsequently been adopten by many superconducting quantum groups, including IBM.

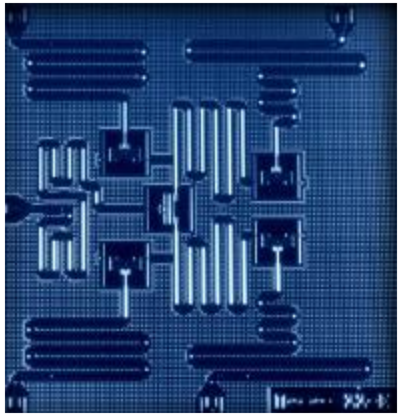
2012

Coherence Time Improved

Several important parameters for quantum information prodessing with transmon qubits are improved. The coherence time which is the amount of time that the qubit retain threir quantum state is extended up to 100 microseconds.

2016

IBM makes Quantum Computing Available on IBM Cloud to Accelerate Innovation



IBM scientists build a quantum processor that users can access through a first-of-kind quantum computing platform delivered via the IBM Cloud onto any desktop or mobile device. The cloud- enabled quantum computing platform, called IBM Quantum Experience, will allow users to run algorithms and experiments on IBM's quantum processor, work with the individual quantum bits (qubits) and explore tutorials and simulations around what might be possible with quantum computing.

March 2017

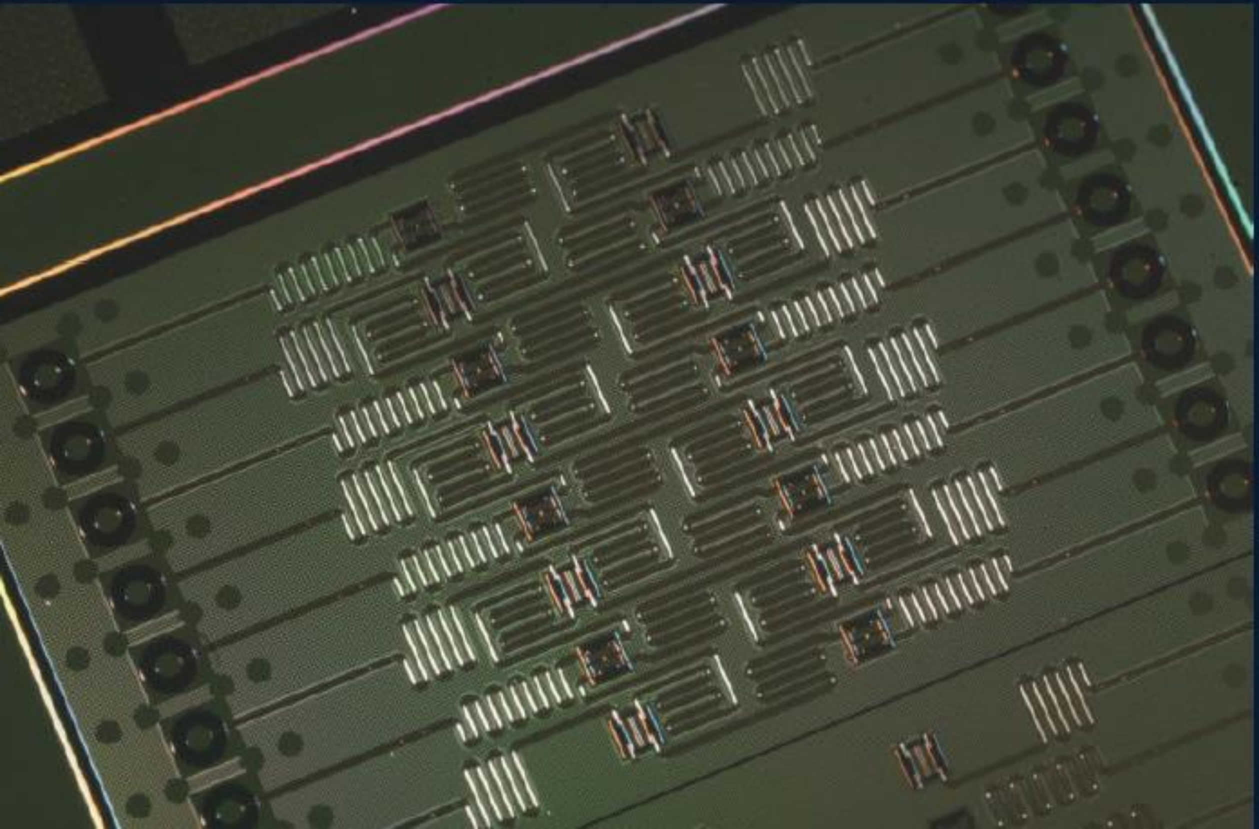
IBM announces IBM Q

IBM Q is the new line of Quantum Computers

IBM announces the building of a quantum computer of 50 qubits and that will offer services of quantum computation in the cloud

May 2017 **First Commercial Quantum Computer**

16 and 17 qubits universal quantum computers



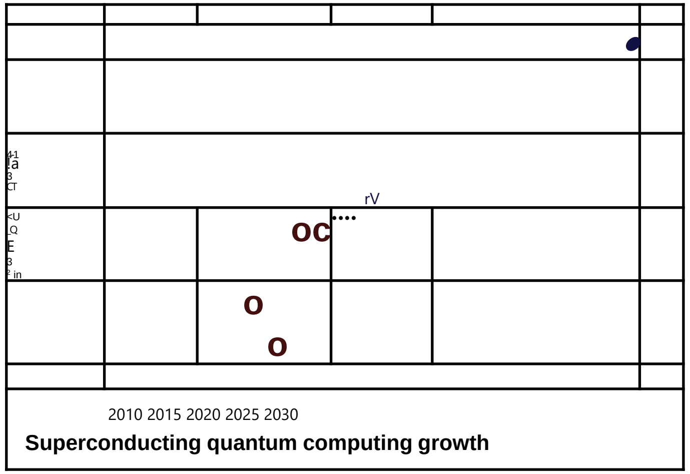
IBM says they are testing a new 17 qubits commercial quantum computing

IBM has discovered how to scale quantum architecture

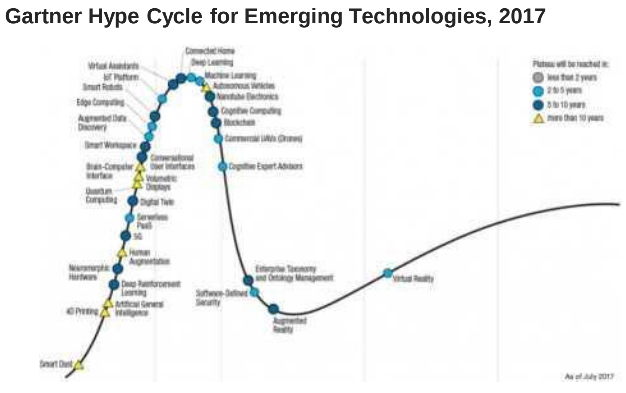
In three years it is planned to reach 50 qubits

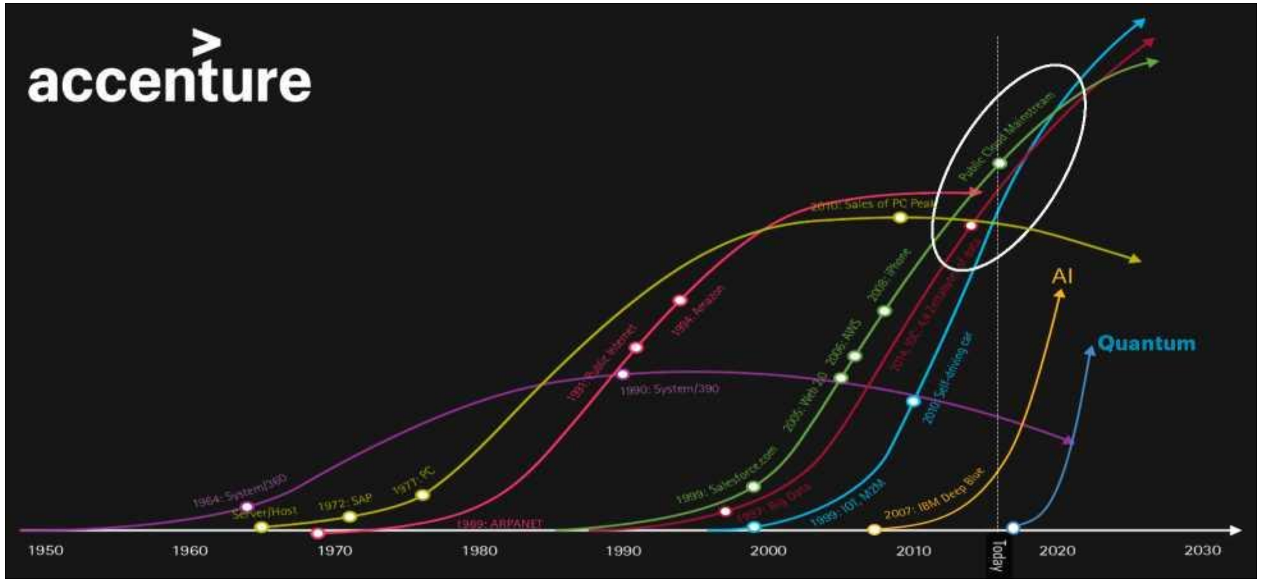
QUANTUM COMPUTING TIMELINE

[1959]	Richard Feynman: "There's Plenty of Room at the Bottom"
[1973]	Charles H. Bennett (IBM): introduce reversible logic
[1994]	Peter Shor (Bell Labs): an important algorithm to cryptography
[2000]	Alamos National Laboratory: first working 7-qubit NMR
[2007]	**D-Wave** : 8-qubit quantum annealing computer
[2016]	**IBM:** public launch of IBM Q Experience and a 5 qubit universal quantum computer.
[2017 -2018]	**IBM:** unveils a **50-qubit** quantum computer. **Microsoft:** releases Quantum SDK and a 40-qubit simulator. **Google:** announces a **72-qubit** quantum chip **Intel:** announces a **49-qubit** superconducting test chip.



Exponential growth of superconducting quantum computing technology





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FUTURE IS QUANTUM!

The promise of outperforming every classical computer to an extraordinary degree for certain tasks.

Change the world by solving problems that are intractable with today's technology.

Very likely to disrupt every industry in near future.

Market Situation:

- Public funds (2018): **US (\$1.3B), EU (€1.1B), UK (£240M), China (>\$10B)**, etc.
- Private sector: **IBM, Google, Intel, Microsoft**, and many startups.
- Big consultants, banks and industry: **Deloitte, KPMG, JPMorgan Chase, DAIMLER, Barclays**, **Accenture,** etc.

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Some Quantum Concepts

Basic Concepts in Quantum Mechanics

- **Uncertainty Principle**

  It is impossible to carry out a measurement on a system without disturbing the system

- **State Superposition**

  Every state can exists as any possible configuration in the states space

- **Quantum Entanglement**

  EPR Paradox – There's a relationship among the features of entangled particles.

- **State Decoherence**

  In a coherent state all the quantum properties remain on every component identified as being part of the system. Decoherence returns the individual identity to each component and drops off the quantum characteristics

Features of a Quantum Computer

1. Use of Quantum Bits or Qubits

2. Make use of Quantum Parallelism

3. Quantum Entanglement

4. Keeps coherence

What is a Quantum bit or Qubit?

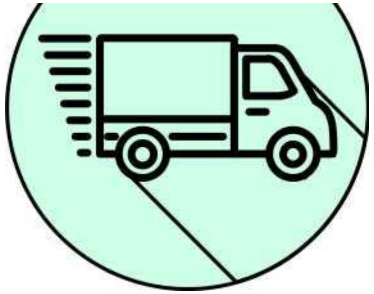
- A Qubit is the quantum concept of a bit

- It is either an element nor a device. A Qubit is a logical concept that can be implemented on a vast number of systems with a quantum behaviour.
- As a bit, the Qubit can be in two base states: 0 and 1.

However, a Qubit can work with all the possible combinations that can be built with these base states 0 and 1

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

IT IS ALL ABOUT COMPLEXITY



Computationally complex problems require more space and time. The difference in complexity can make a problem intractable.

There are many intractable problems (usually approximated!) Example:

- A UPS truck has to deliver **400 packets in Helsinki.** The TSP has complexity $0(2^{400})$

A quantum computer is not generally faster or parallel.

Quantum speedup:

- There are problems which are classically hard and quantumly easy!
- **Quantum speedup requires the existence of a corresponding quantum algorithm.**

An optimal traveling salesperson tour through Germany's 15 largest cities. It is the shortest among 43,589,145,600 possible tours visiting each city once.

THE FUTURE OF COMPUTING IS NOT DIGITAL!

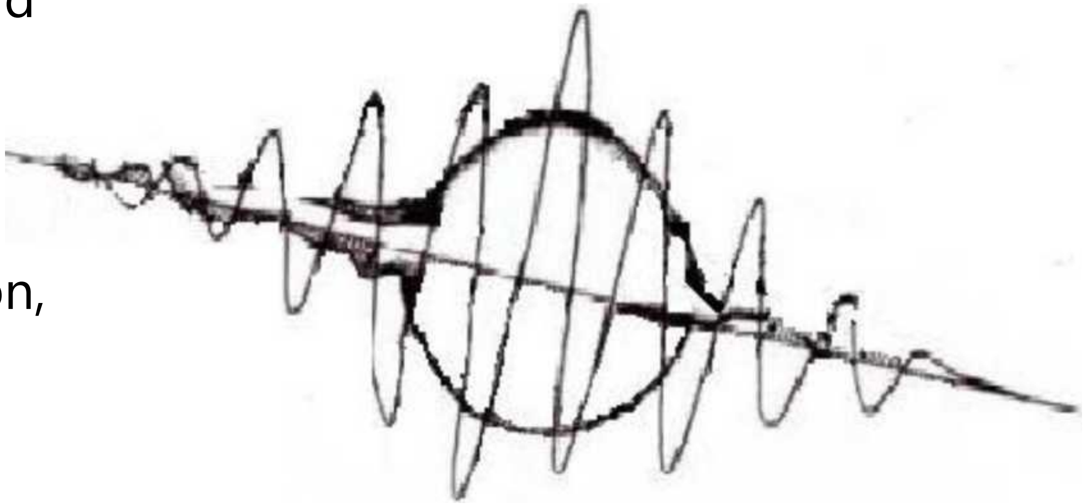
Quantum computing is not electronic

- It is not based on our current technology of electronics, semiconductor, …

- There are few technologies under development.
- The winning technology is not clear yet, but it should be one.

Quantum computing is not digital.

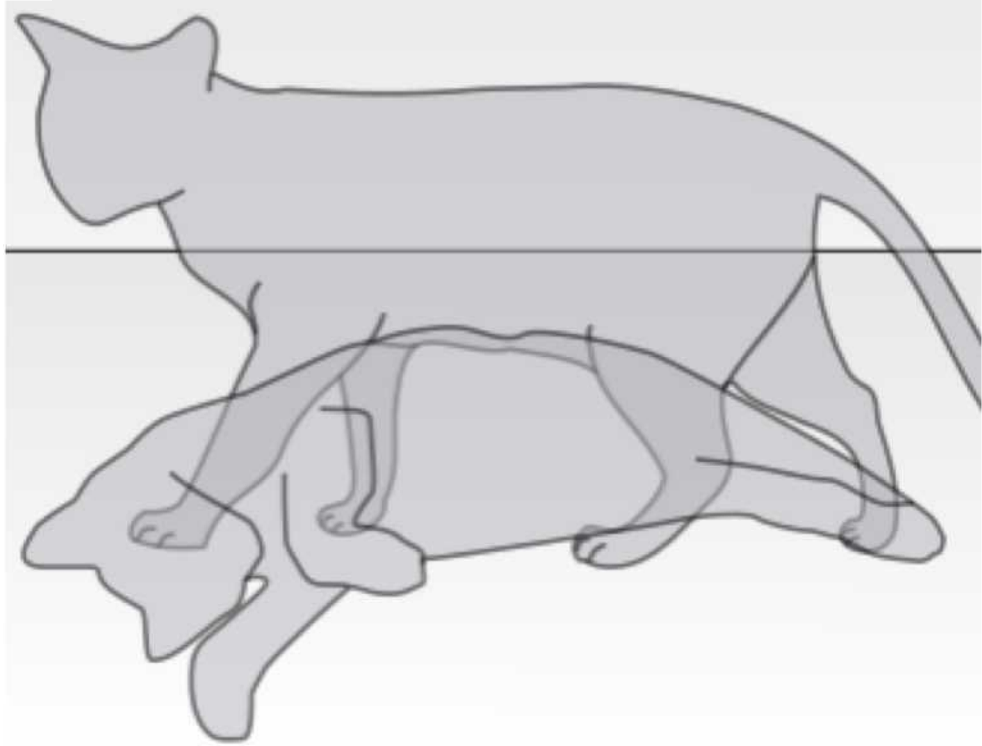
- It can be considered a type of analogue computation, i.e., not discretized.



It is probabilistic.

It is quite noisy nowadays.

DO NOT WORRY ABOUT QUANTUM PHYSICS



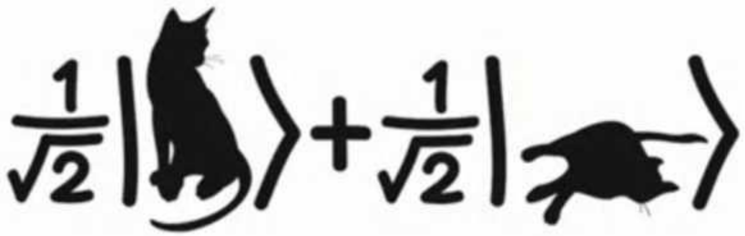
Superposition, Collapse, Entanglement, Teleportation

The physics can be difficult and subject to different interpretations.

Mathematics are simple and do not require interpretation.

Two important laws:

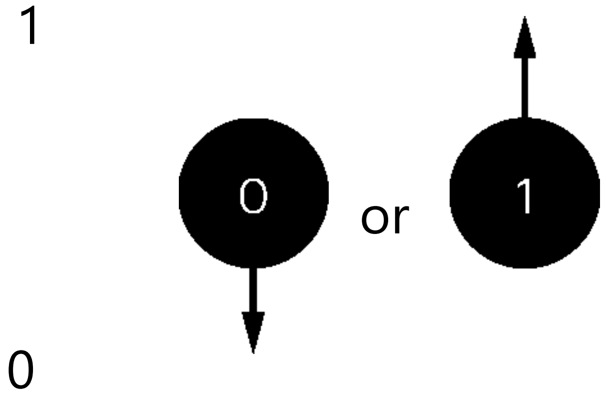
- Quantum operations are reversible.
- Measurement is irreversible



SOME TECHNICAL DETAILS! WHAT IS A QUBIT?

A SUPERPOSITION OF TWO QUANTUM STATES.

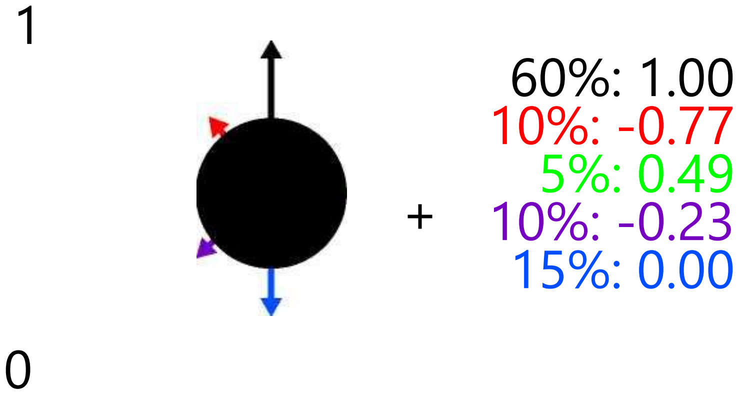
Classical



Discrete number of possible states: 0 or 1.

Deterministic: repeated computations on the same input will lead to thesame output.

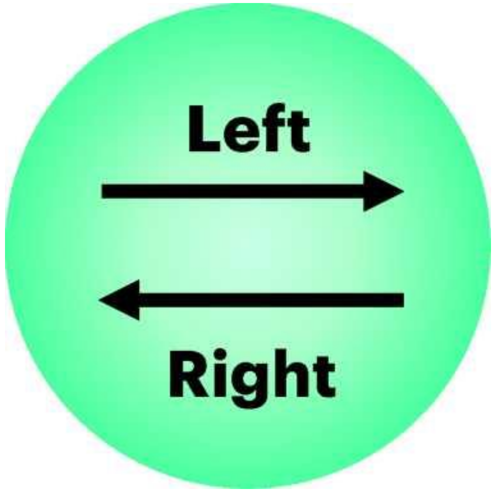
Quantum



Infinite (continuous) number of possible states.

Probabilistic: measurements on superposed states yield probabilistic answers (our confidence in these answers builds up through repeated computations) then reduced to 0 or 1.

MATHEMATICAL REPRESENTATION



A Qubit is a Linear combination of two or more states.

Qo _ o l - C ') + b\R)

$$a|0\rangle + b|1\rangle \rightarrow \begin{bmatrix} a \\ b \end{bmatrix}$$

Prob(go = l-L)) =

Prob(go = \ R }) = b 2

a 2 + b 2 = 1

MEASUREMENT

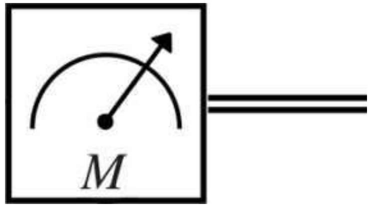
The state of a qubit is not accessible from outside.

Measurement is done in a basis.

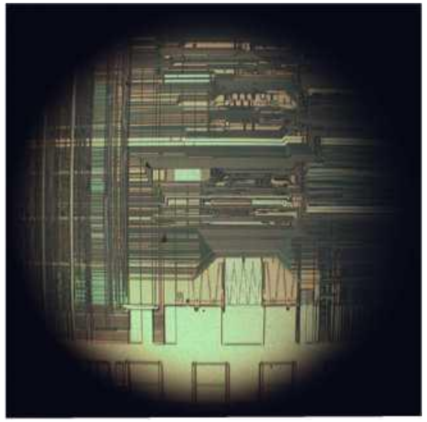
- Standard basis |0), |1).

- The state of a qubit collapses to one of the basis states.

Measurement is irreversible, hence not a quantum gate.



CLASSICAL COMPUTING: MODERN DIGITAL COMPUTERS

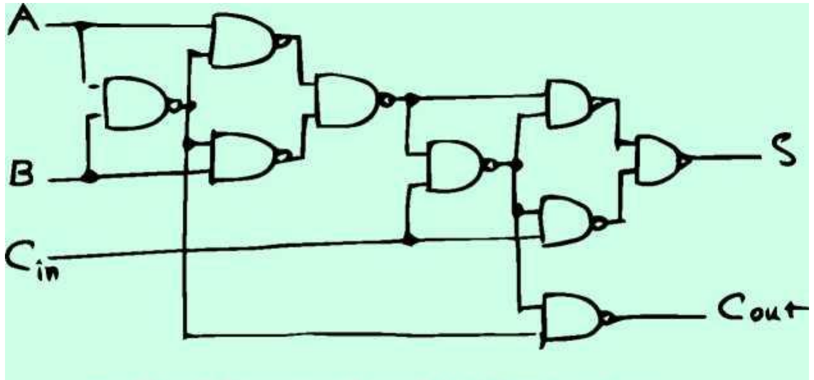


Electronic: using electrons to process information

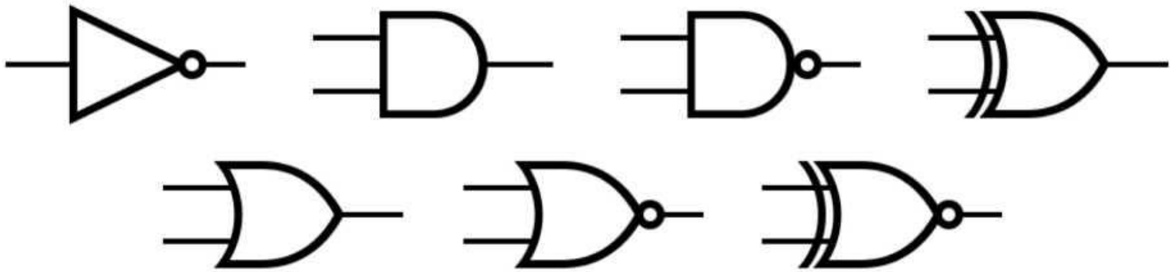
Digital: information units are bits (0/1)

Silicon-based transistor logic (MOSFET)

Basic gates: AND, OR, NAND, ... Universal gates: NAND, NOR Most system use a single universal



Full adder made of NAND gates



QUANTUM GATE MODEL for UNIVERSAL QUANTUM COMPUTER

1. A universal quantum computer made from simple gates.
2. Most common gates: 1-qubit and 2-qubit gates
3. Quantum logic gates are reversible.
4. Quantum logic gates are represented by unitary matrices.
5. Due to this inherent randomness (and also noise), the process is repeated and measured many times to find the probabilities of each state.

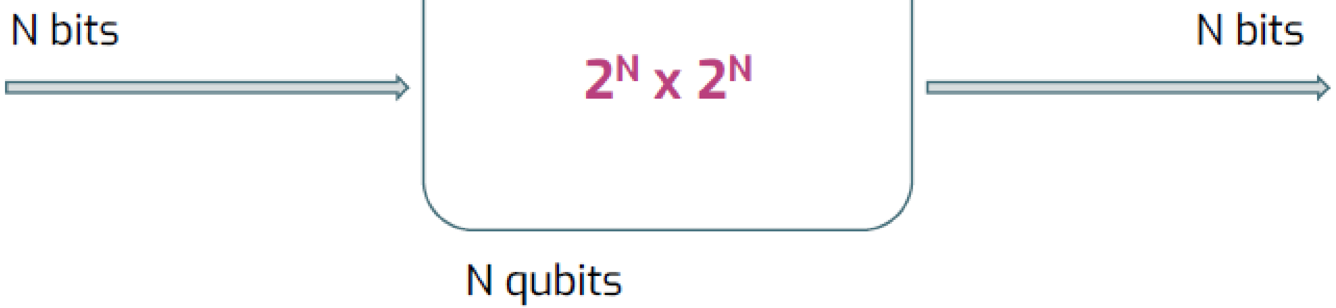
Why build a quantum computer?

For **N qubits** every time step (~100ns*) is an exponentially large **2^N x 2^N** complex **matrix multiplication**

Crucial details:

- limited number of multiplications (hundreds to thousands) due to noise
- not arbitrary matrices (need to be easily constructed on a QC)
- small I/O, **N-bits in and N-bits out**

The “big-memory small pipe” mental model for quantum computing



Quantum Operations

Quantum Gates

- A basic quantum circuit working on one or more qubits
- It’s equivalent to digital circuits logical gates lógicas

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

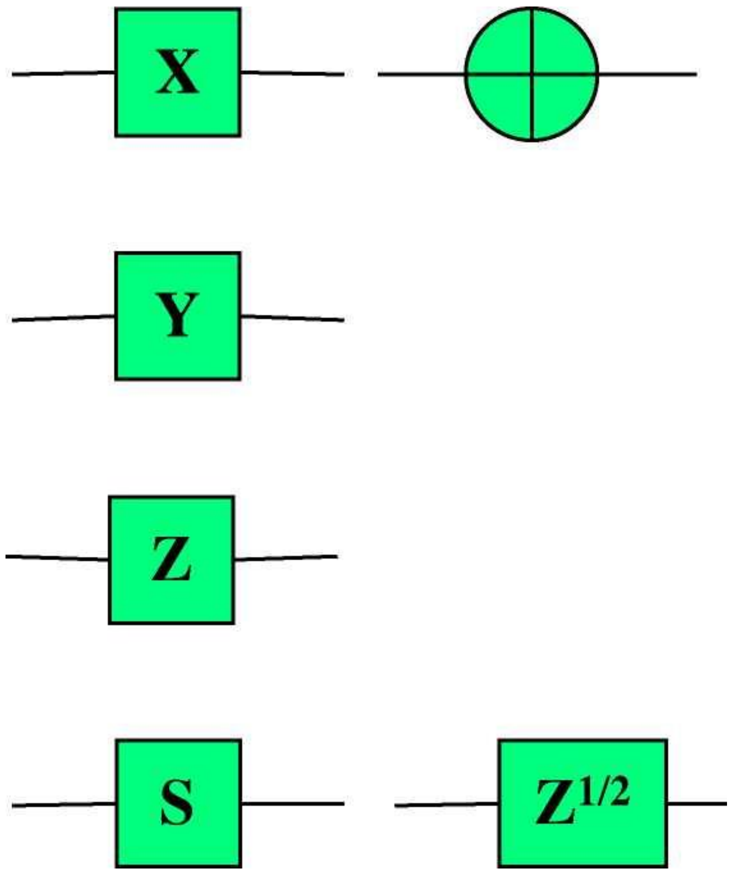
Hadamard Gate

1. Quantum Gates are reversible
2. Mathematically thery are represented by unitary matrixes
3. Los qubits on which they act must retain their quantum identity

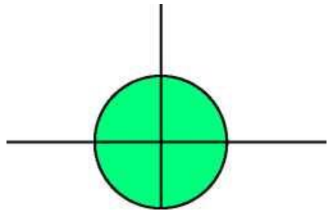
$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Controlled-NOT gate

Quantum Operations Examples



TWO-QUBIT GATES



With respect to the basis:

|00>,|01>,|10),|11>

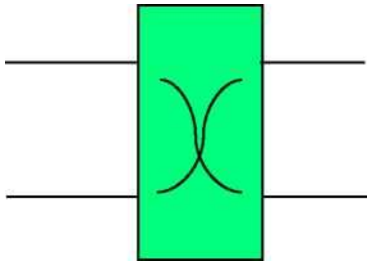
CNOT

1	0	0	0
0	1	0	0
0	0	0	1
0	0	1	0

CNOT GATE (A UNIVERSAL GATE)

It can be used to entangle and disentangle EPR states.

Any quantum circuit can be simulated to an arbitrary degree of accuracy using a combination of CNOT gates and single qubit rotations.



SWAP GATE

SWAP

1	0	0	0
0	0	1	0
0	1	0	0
0	0	0	1

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VECTOR SPACE AND ENTAGLEMENT

- **When multiple qubits interact the resulting state is in a vector space that contains all combinations of individual states.**

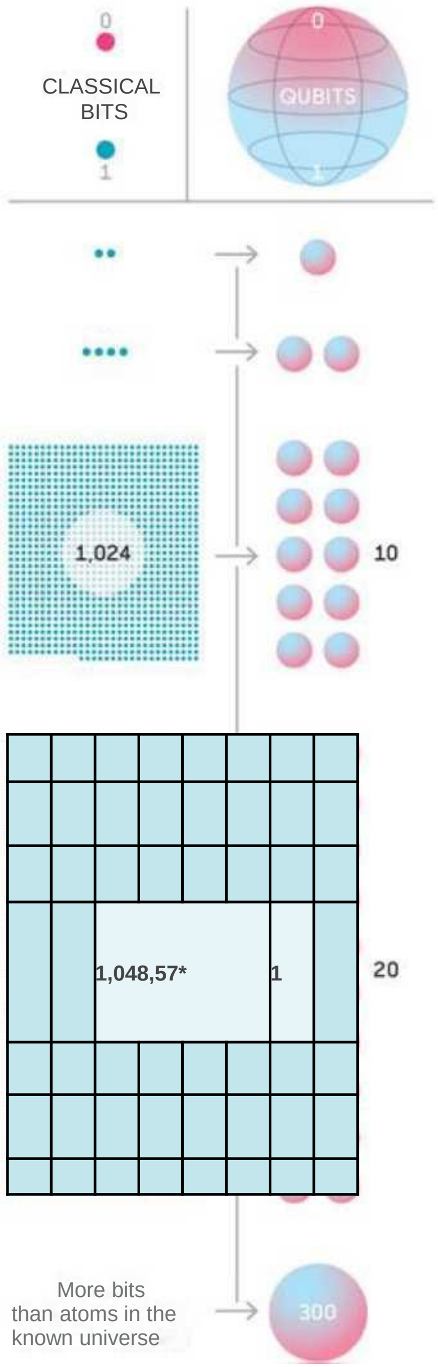
- **N qubits -> 2^N basis states**

- **Vector representation of two qubits in their joint vector space**

!oo|00) + !oi|01) + !oi|01) + !ii|H)

!oo
!01
!01
!1
&J

- **$|ab\rangle$ is the basis vector representing a state**



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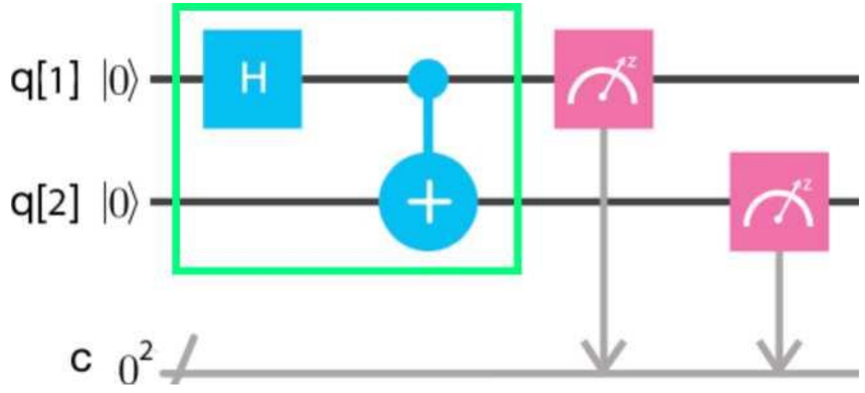
QUANTUM CIRCUIT



Quantum Circuit is composed of

- Quantum and classic registers
- Quantum gates
- Measurement gates

Example: Bell states ^cx ^oo,

1 1

- The first Bell state can be created using a Hadamard I^{00}) 7/^(1°) + I^{1}))!^{0}) (I^{00}) + gate and a CNOT gate.
- It creates and entanglement.
- Measurement of one qubit will assign one of two possible values to the other qubit instantly.

TWO MAIN TECHNOLOGIES

Adiabatic Quantum Computer

- Also known as **quantum annealing**
- **Approximate answers** to optimization problems.
- Cannot run standard quantum algorithms.
- Much larger machines available.

Universal Quantum Computer

Can solve **any classical or quantum algorithm** (E.g. IBM, Google).

Quantum **Gate Model** / Quantum Circuit.

Provides quantum **speedup for certain algorithms** developed.

Still very limited hardware.

Universal Quantum Computing

- Universal Quantum Computing requires entanglement for every qubit included in the system

- **Use Cases** → Secure Computing, Machine Learning, Criptography, Quantum Chemistry, Material Science, Optimization Problems, Sampling Quantum Dynamics, Searching.
- **Scope** → Wider scope
- **Computing Power** → Very High

The Universal Computing is the great challenge in quantum computing. It has the potential to be exponentially faster than traditional computers for a number of applications in the world of science and also in the world of business.

Adiabatic Quantum Computation

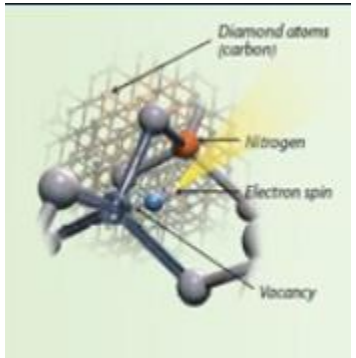
- Adiabatic Quantum Computation is based on the Adiabatic Theorem and requires at least a big set of qubist (but not all) to be entangled during process time.

- A very specific algorithm is implemented: "The Quantum Annealer"

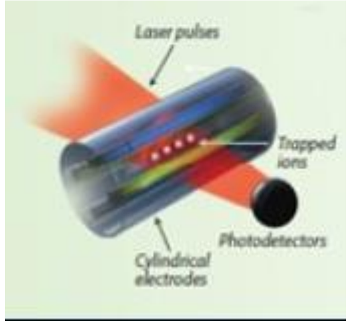
  - **Use Cases** → Optimization Problems
  - **Scope** → Restricted
  - **Computing Power** → Similar to current classical computers

Quantum Architecture

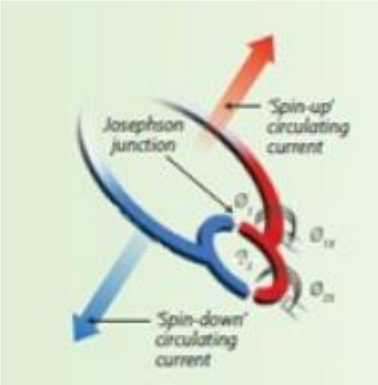
Type of Quantum Processors



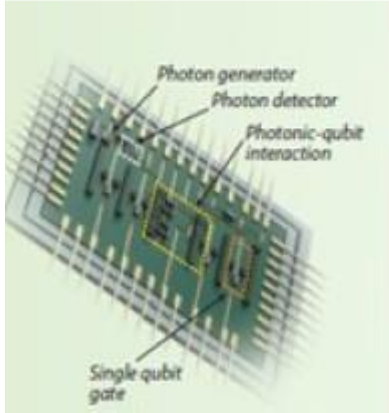
Spin Qubits – Electron or nuclear spins on a solid Substract.



Ion's Traps– Trap ions in electric fields



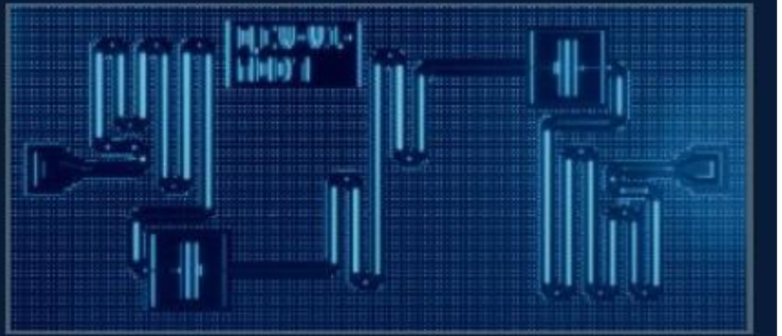
Superconducting Circuits – currents superposition around a superconductor.

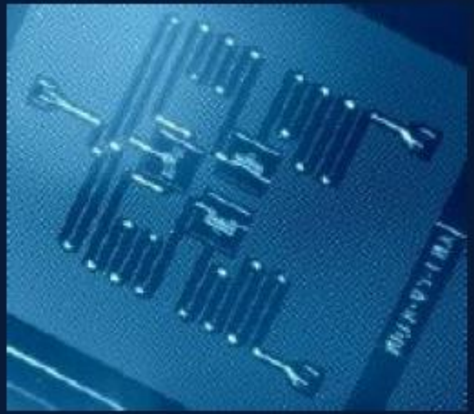


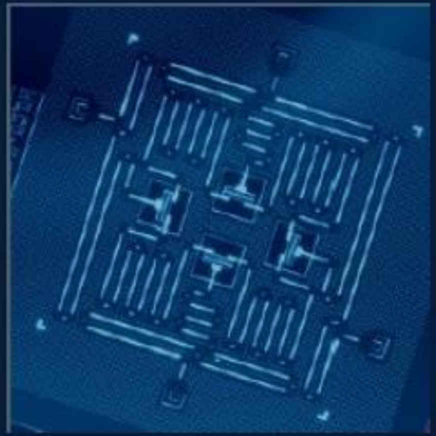
Photonic Circuits – The qubits are photons driven in in silicon circuits

Superconducting Qubits

Circuit QED: A superconducting qubit is strongly interacted with a single photon in a microwave cavity.

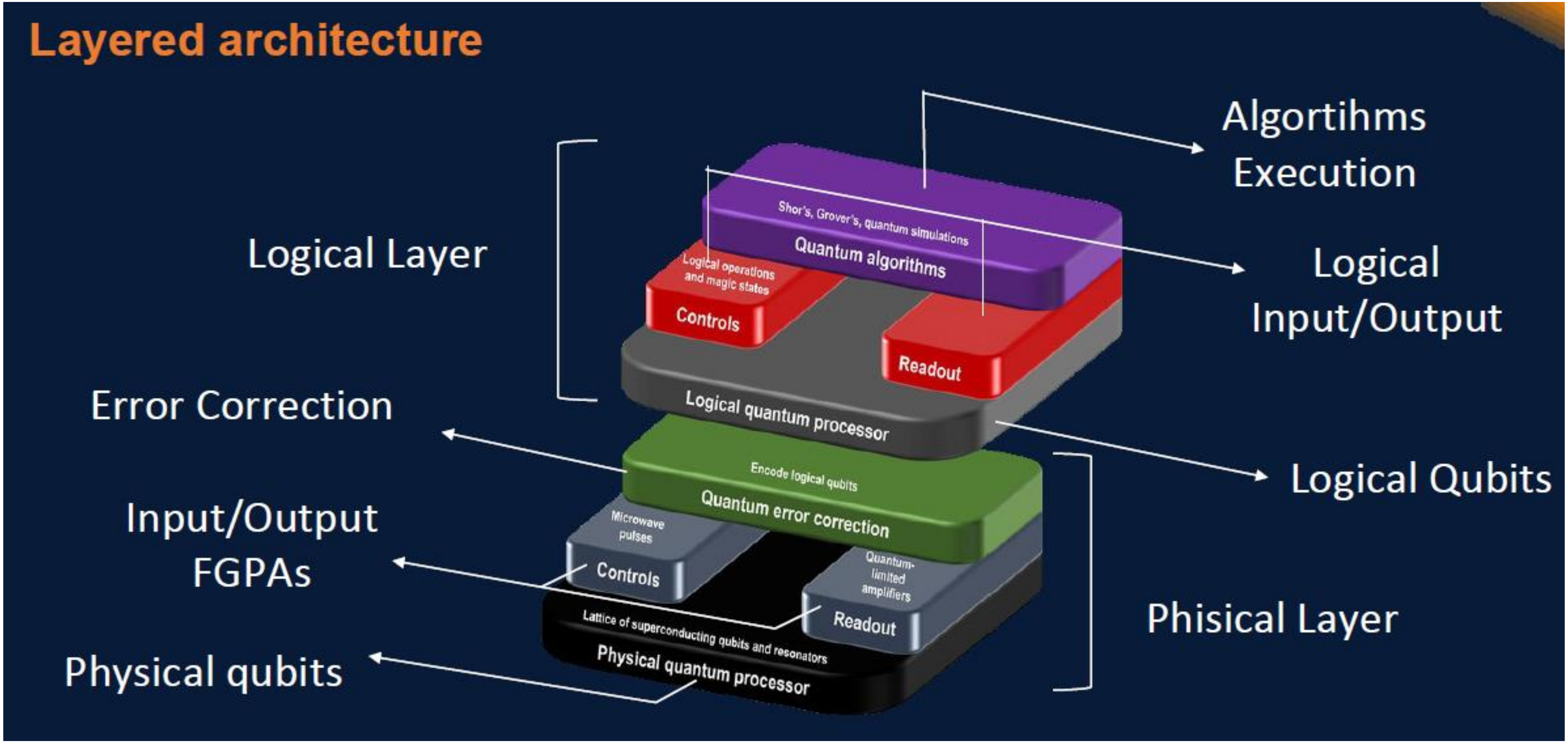






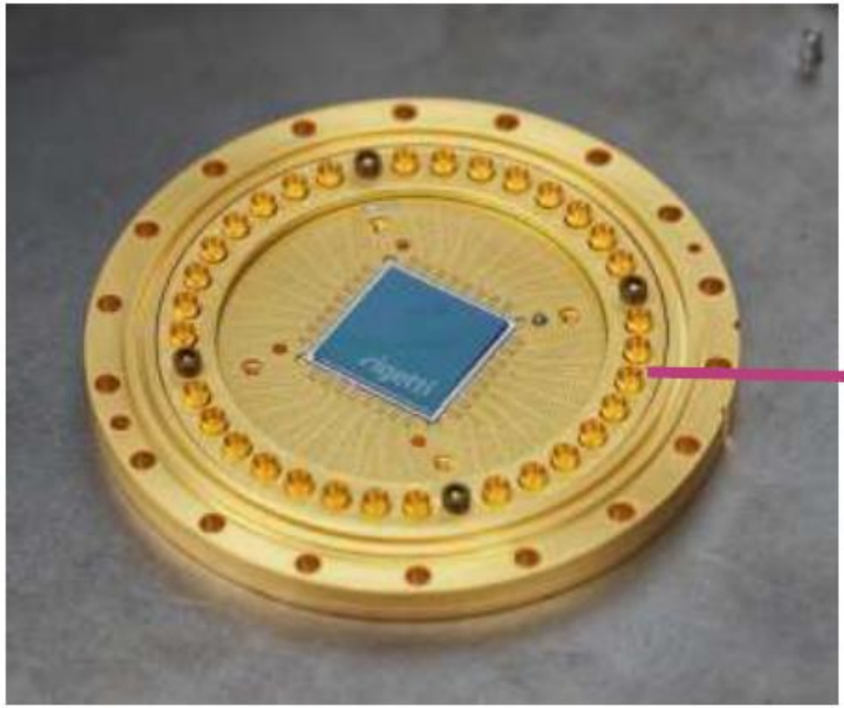
The circuit QED coupling scheme has become the standard for coupling and reading superconducting qubits as systems continue to scale.

Quantum Processor Architecture



Useful Quantum computation is Hybrid

Quantum computers have quantum processor(s) and classical processors



Quantum processor

Full quantum computing system

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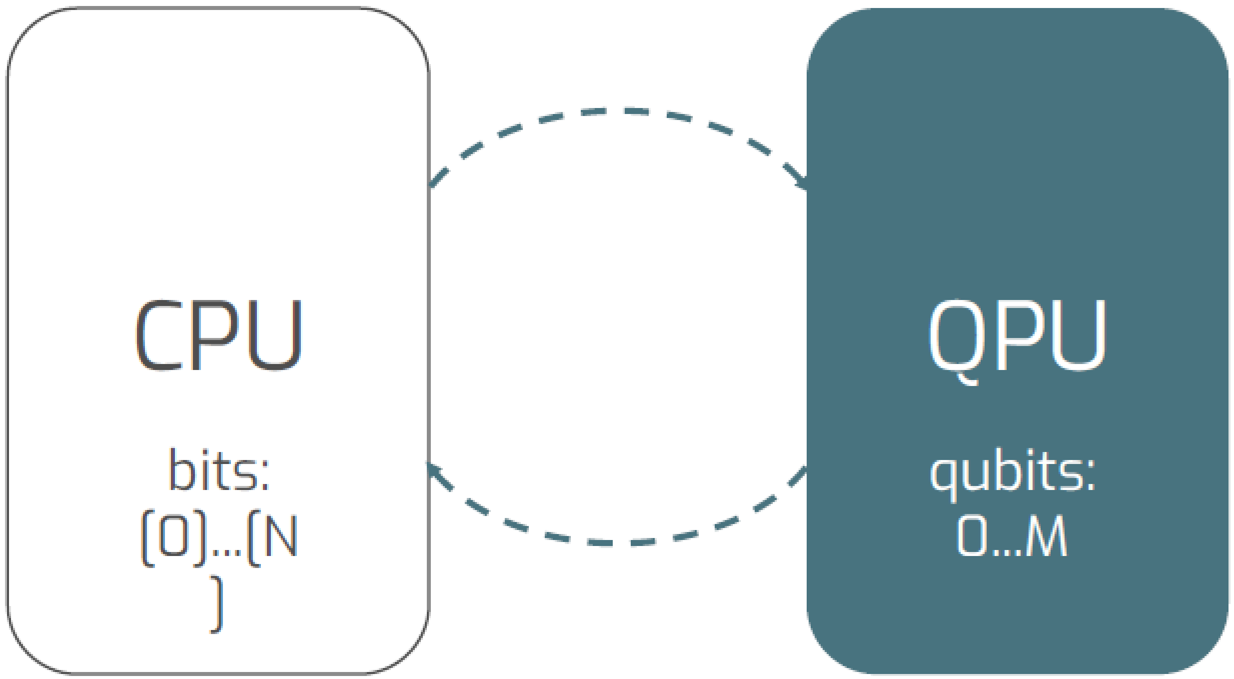
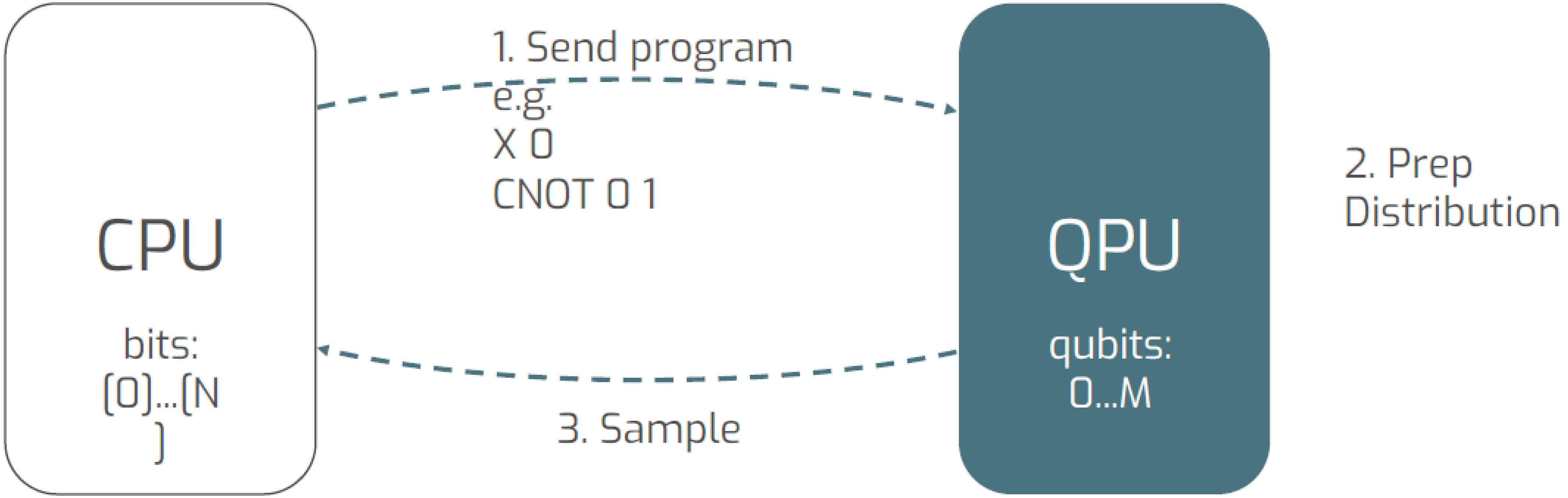
Useful Quantum computation is Hybrid



Forest is optimized for this with the Quil [01⟩ instruction set.

Useful Quantum computation is Hybrid

Quantum programming is preparing and sampling from complicated distributions



Quantum Algorithms

Quantum Algorithms

- **Deusch Algorithm** – Determines whether a function is balanced or unbalanced
- **Shor Algorithm** – Large numbers factorization
- **Grover Algoritm** – Search in unstructured spaces

Shor Algorithm

- Number of steps that a classic computer needs to run in order to find the prime factors of a number N of x digits

It grows exponencially with x

$$\boxed{\begin{array}{c} 937 \times 947 = N \text{ (easy)} \\ 887339 = p \times q \text{ (hard)} \\ \text{hardness of factoring is basis of RSA public key crypto:} \end{array}}$$

In 2001, IBM and Stanford University, executed for the first time the Shor algorithm in the first quantum computer of 7 qubits developed in Los Álamos.

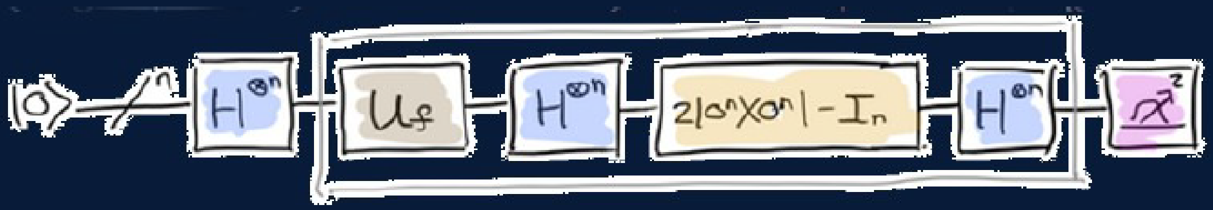
https://www-03.ibm.com/press/us/en/pressrelease/965.wss

Grover Algorithm

How many attempts need a data search in an unordered N-element database to locate a particular element??

An average of N/2 attemps are needed)

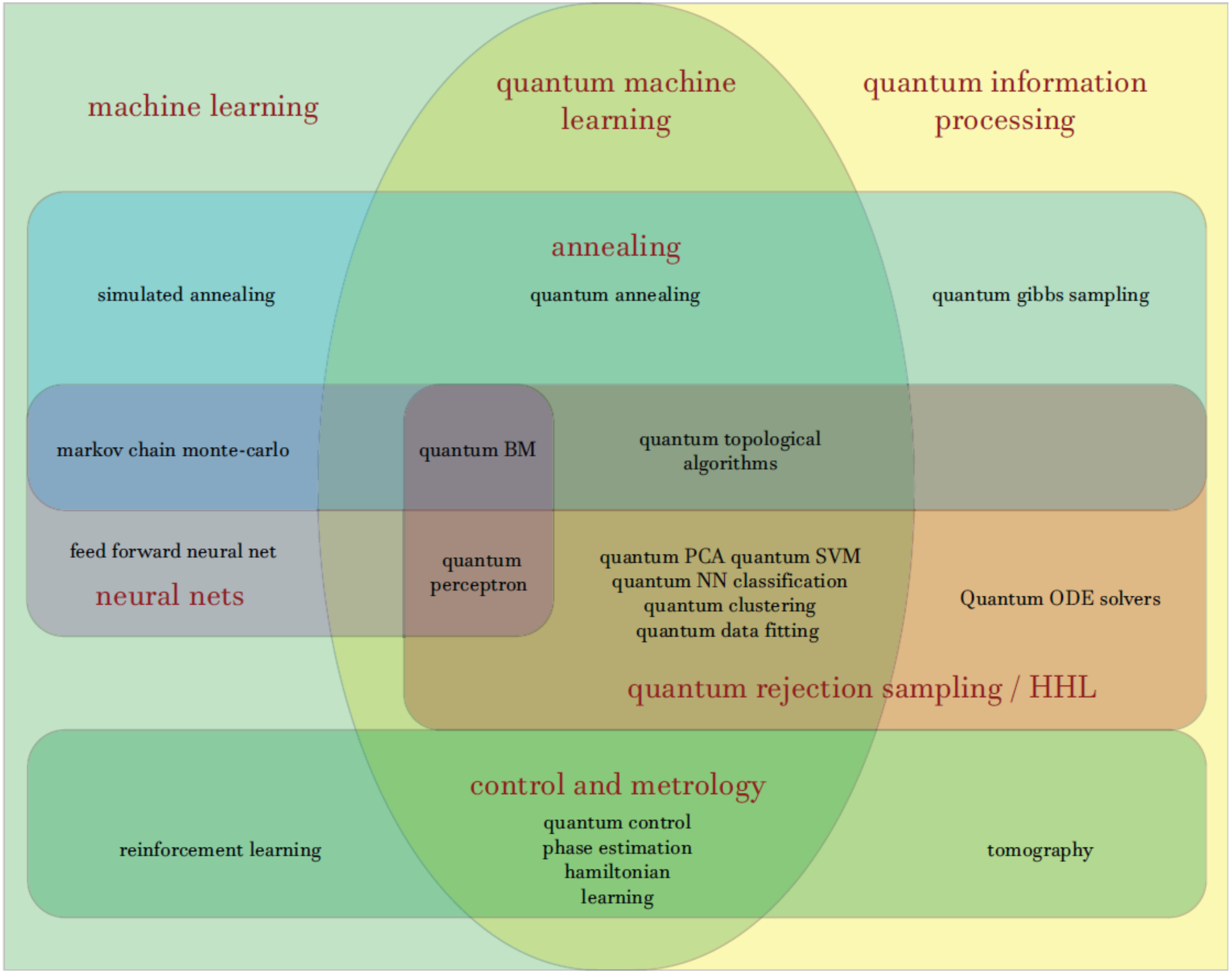
A quantum computing executing the Grover algorithm would run $\sqrt{N}$ attemps



http://www.dma.eui.upm.es/MatDis/Seminario4/AlgoritmoGrover.pdf

Quantum machine learning algorithms

https://arxiv.org/pdf/1409.3097.pdf



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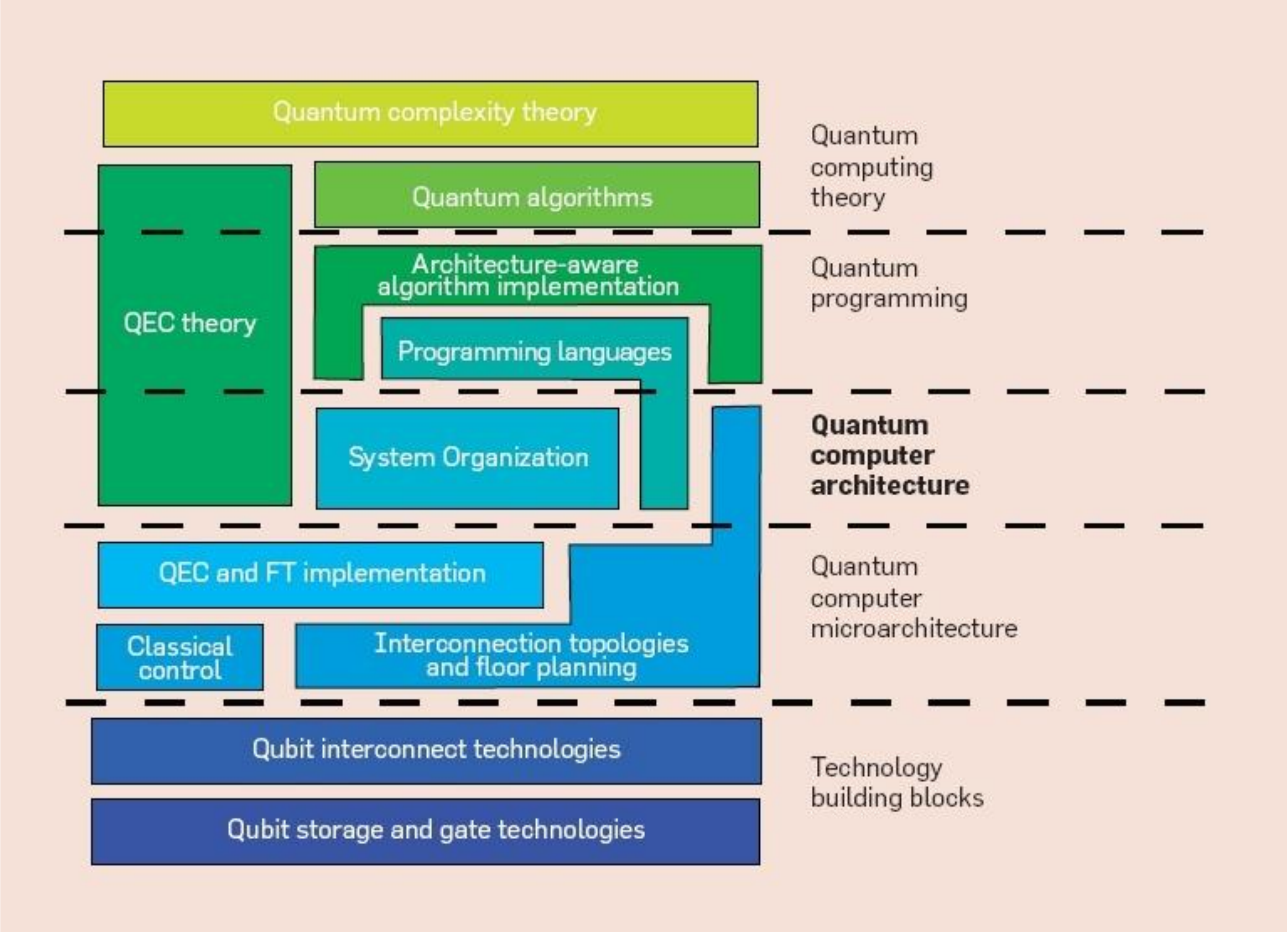
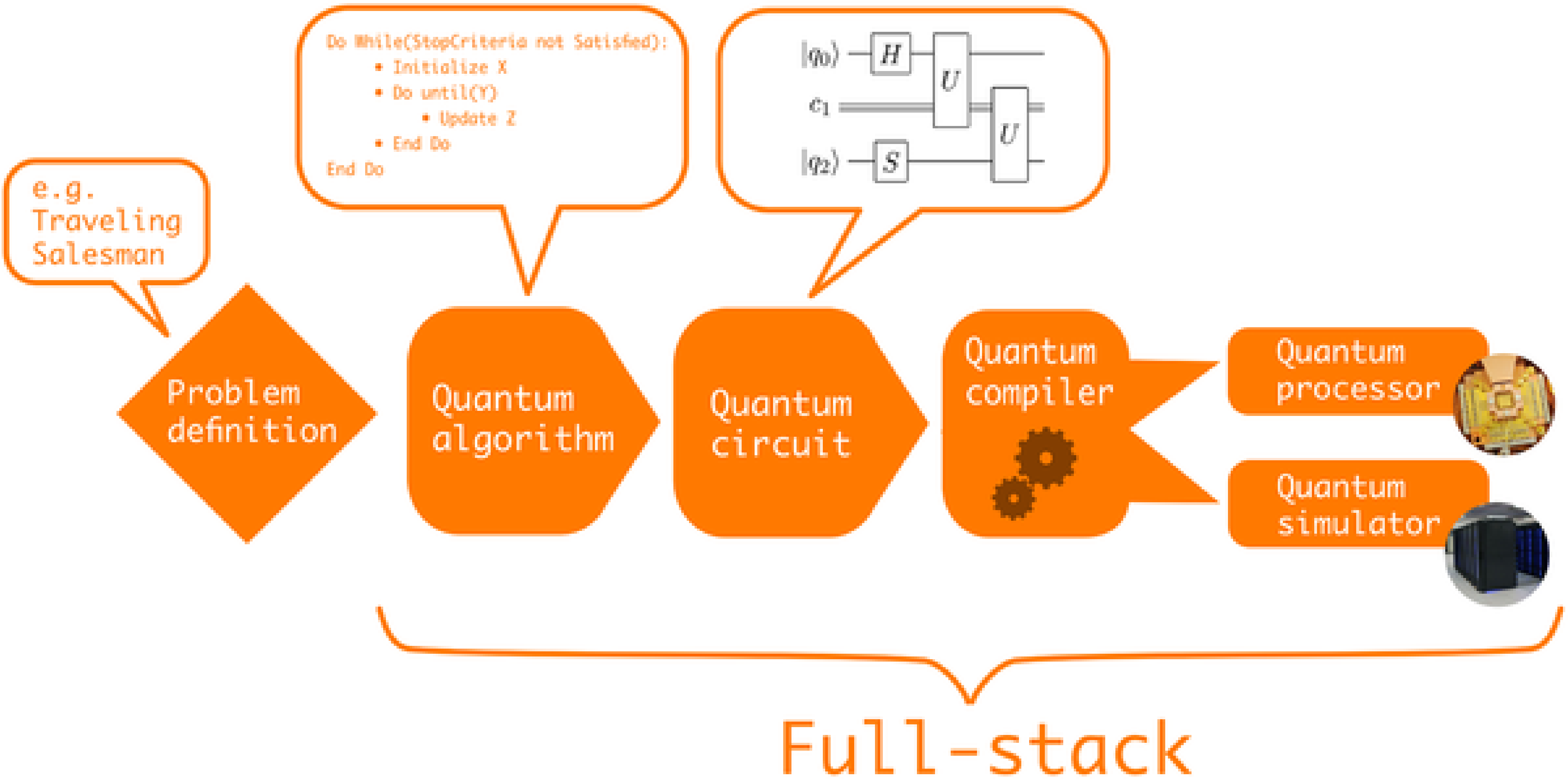
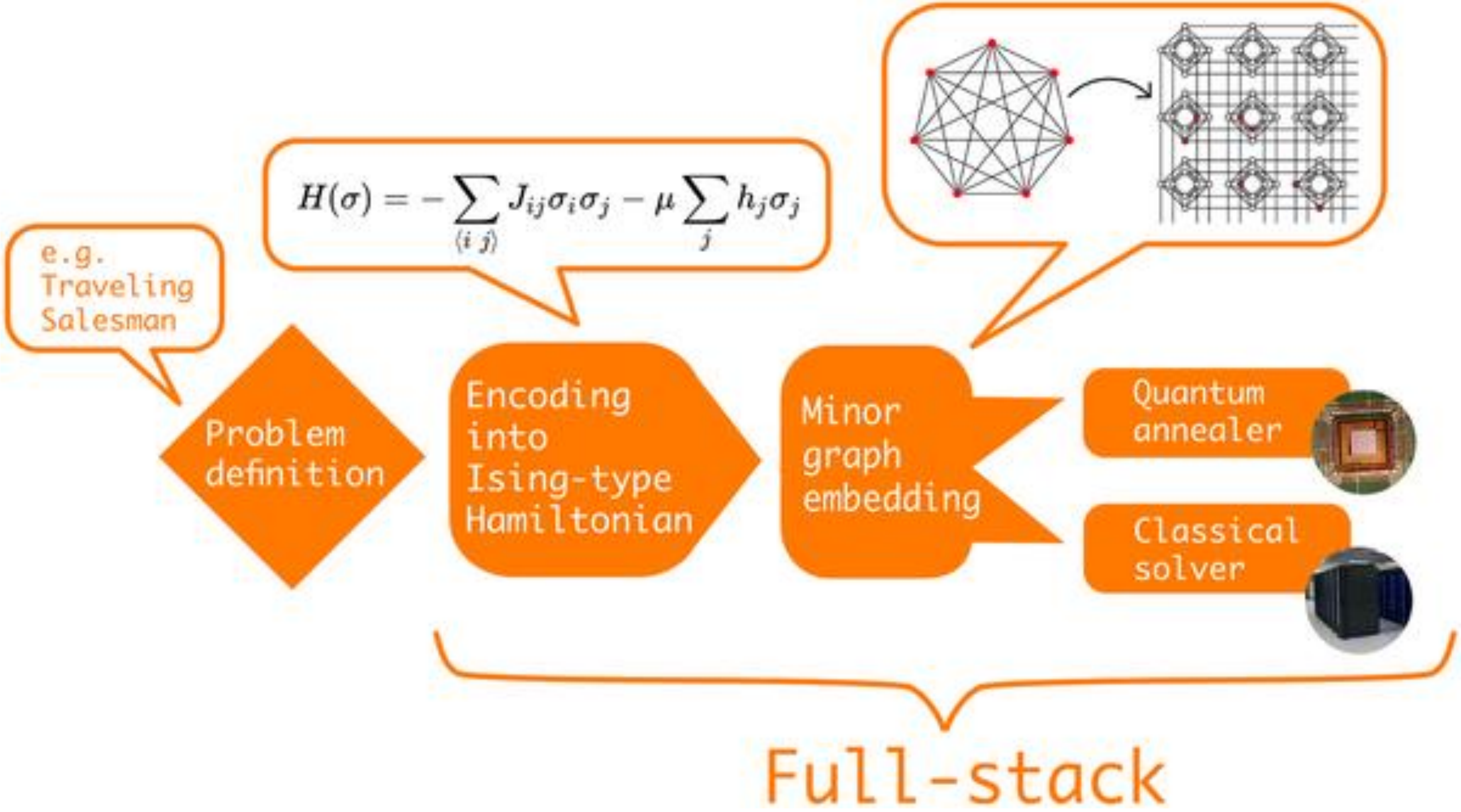
Quantum Architecture Levels



Visualization of a typical quantum algorithm workflow on a gate-model quantum computer.



Visualization of a typical quantum algorithm workflow on a quantum annealer



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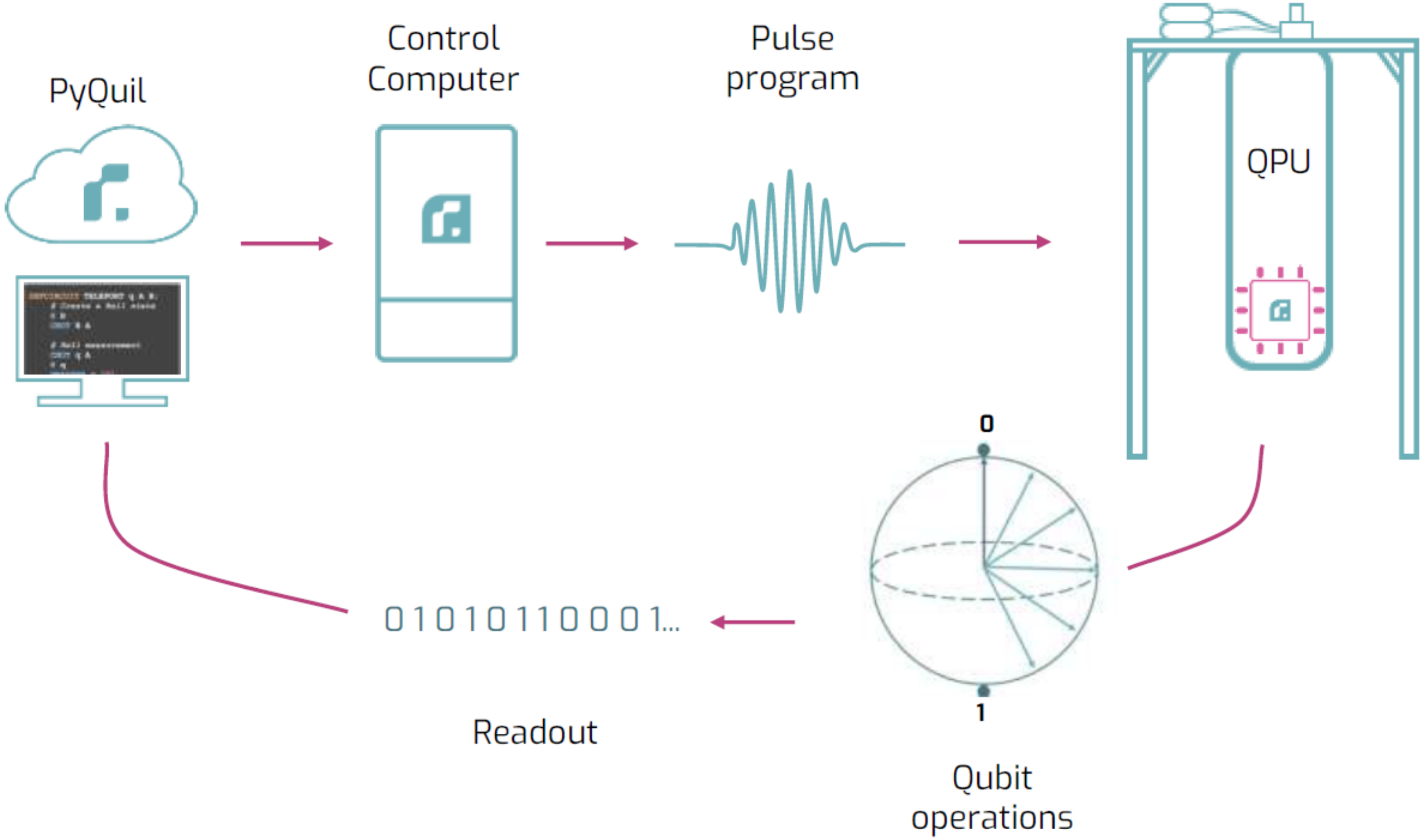
Quantum with Python

PyQuil: Quantum programming in Python

Forest: an Operating System for Quantum Computing
https://www.youtube.com/watch?v=SDQXGv1V2dc

https://github.com/rigetti/pyquil



QUANTUM PROGRAMMING - QISKIT

QISKIt

- **QISKIT (Quantum Information Science Kit) is an open-source quantum computing framework.**

  It is a Python SDK.

- **Backends: IBM Q computers, local and remote simulators**
- **The starting point for writing code is the QuantumCircuit.**
- Tutorial: https://qiskit.org/documentation/quickstart.html
- SDK reference: https://qiskit.org/documentation/ autodoc/qiskit.html

QISKIT SETUP JUPYTER NOTEBOOK

Navigate to

- Repo: https ://goo.gl/tsDH7V
- MyBinder: https://mybinder.ora/v2/ah/HassanNaseri/quantum-computina-handson/master

Open file: **hello_qiskit.ipynb**

QX_TOKEN =
M728624125ddfb3acc6485060d3c3bbd63e8c1373e65b3e8d1f2
9fd91417c75f7efa60cccd73f17669da651e24669c8a2865e7c1fc
efc01a3879dd5c735003244"
QX_URL = "https://quantumexperience.ng.bluemix.net/apiM from
qiskit import register register(QX_TOKEN, QX_URL)

Registring your credentials

- Needs API Token and the QX URL.
- Needs to be done only once.

Import the Qiskit SDK

from qiskit import QuantumCircuit, ClassicalRegister, QuantumRegister from
qiskit import available_backends, execute

QISKIT CODE EXAMPLE -HELLO WORLD

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Hello World!

1. Create registers
2. Create circuit
3. Add Hadamard gate
4. Add measurement
5. Plot circuit
6. Execute
7. Get results and print

```
from qiskit import QuantumCircuit, ClassicalRegister, QuantumRegister
from qiskit import available_backends, execute

print("Available backends: ", available_backends())

#    Create a Quantum Register with 1 qubit. The initial state is |0>
q = QuantumRegister(1)
#    Create a Classical Register with 1 bit. c = ClassicalRegister(1)
#    Create a Quantum Circuit qc = QuantumCircuit(q, c)

#    Add Hadamard gate to the qubit, putting it in superposition
state. qc.h(q)

#    Add a Measurement gate to see the state. qc.measure(q, c)

plot_circuit(qc)

job_sim = execute(qc, "local_qasm_simulator") sim_result =

job_sim.result()
```

Source code here:

https://mvbinder.org/v2/gh/HassanNaseri/quantum-computing-handson/master

```
print("simulation: ", sim_result)
print(sim_result.get_counts(qc))
```

QisKit

https://github.com/Qiskit/qiskit-presentations

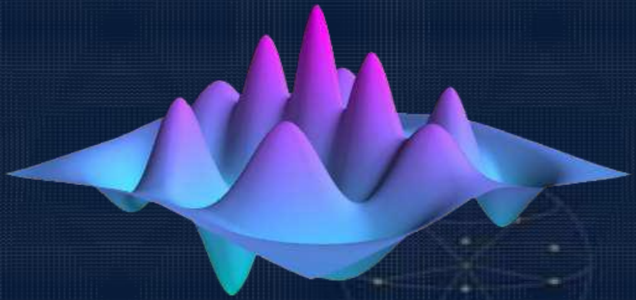
- Examples:
- SVM
  - https://github.com/Qiskit/qiskit-presentations/blob/master/2019-02-26_QiskitCamp/Aqua/qsvm_kernel_classification.ipynb

QuTIP: Quantum Toolbox in Python

http://qutip.org/tutorials.html

- Examples:
- https://nbviewer.jupyter.org/github/qutip/qutip-notebooks/tree/master/development/

The Python Quantum Toolbox

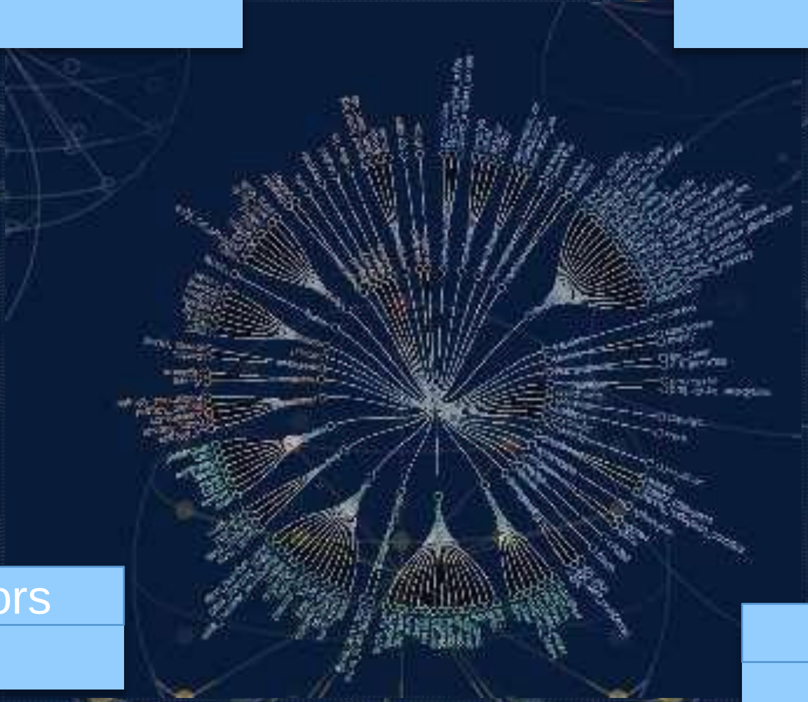


QuTiP – Is an object oriented open source framework for open quantum systems calculus

States

Temporal Evolution

Core Functions



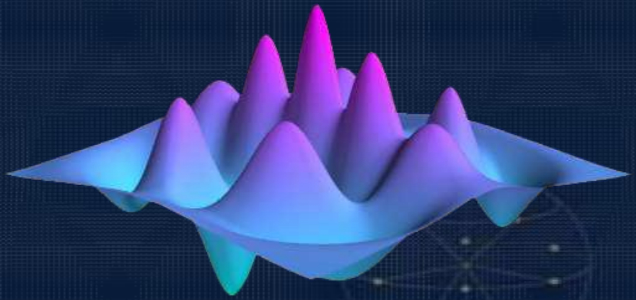
Visualization

Operators

Logic Gates

QuTiP Documentation: http://qutip.org/downloads/3.1.0/qutip-doc-3.1.0.pdf

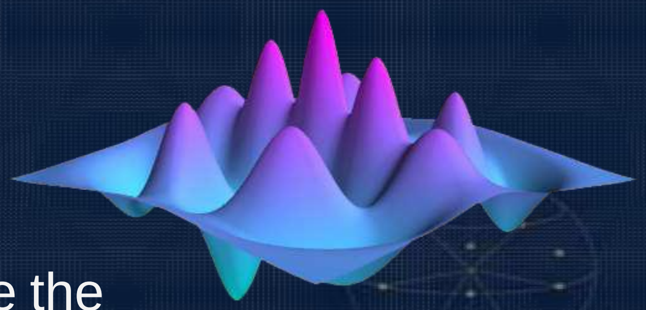
The Python Quantum Toolbox



- **Relationship between quantum concepts and their representation in QuTiP**

Quantum Concept	QuTiP Represenation
Quantum State or Wave Function Amplitude of probability that describes the state of the quantum system.	**Vectors and Matrices** Complex elements
Operators The Hamiltonian operator es the function that represents the total energy of a system and describes the energy of every possible state of the system. The operator represents physical observables	**Matrices** The operators are represented as matrices.
Equation of motion Describes how the states of the quantum system evolves in time.	**Diferential equations** Systems of coupled differential equations.
Observables and expected values Physical obsevables are quantities that correspond to operators	**Internal Product** The results are calculated as internal product between state vectors and matrices that represent operators, yielding as a result real numbers for physical observables

The Python Quantum Toolbox



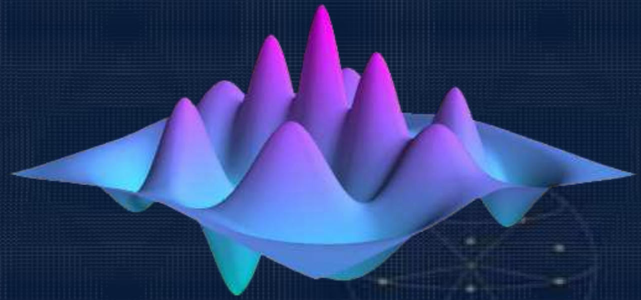
Objects and datatypes

`Qobj` provides the necessary structure to encapsulate the quantum operators and the vectors <bra| and |ket>

```
In [3]: Qobj()
Out[3]:
Quantum object: dims = [[1], [1]], shape = [1, 1], type = oper, isherm = True
Qobj data =
[[ 0.]]
```

Data	Q.data
Dimensions	Q.dims
Shape	Q.shape
is Hermitian?	Q.ishermIs
Type	Q.type

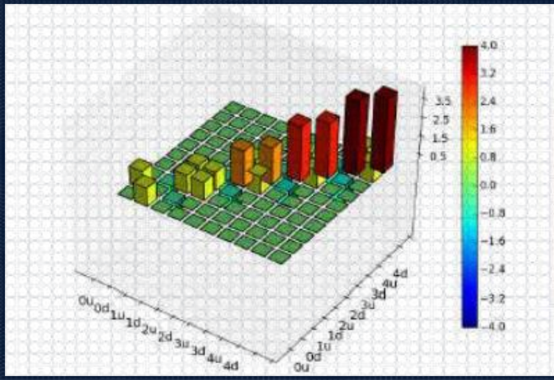
The Python Quantum Toolbox

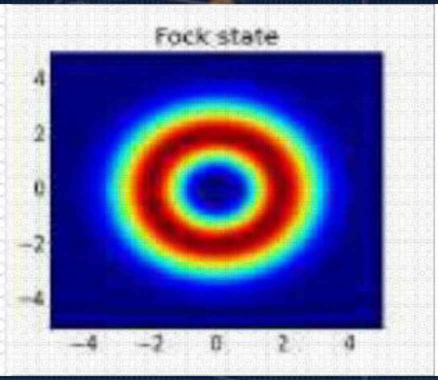


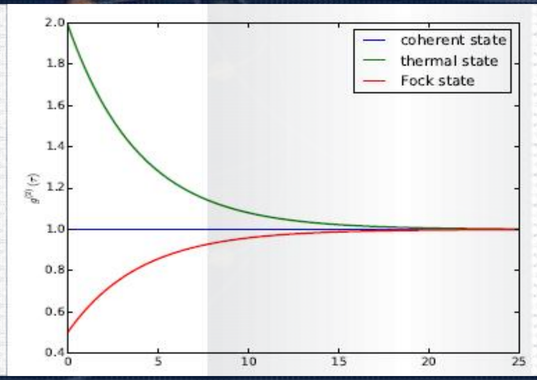
- Visualization capabilities

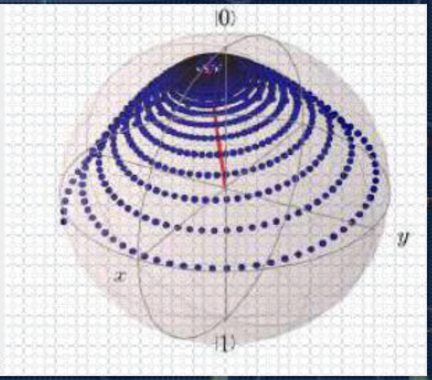
- Function for Distribution of Probability
- Operators Visualization
- Quantum Process Tomography

- 2D & 3D histograms
- Color Maps
- Lineal Graphs
- Bloch Sphere representation









A multithreaded, distributed, GPU-accelerated simulator of quantum computers

- https://quest.qtechtheory.org/
- https://github.com/QuEST-Kit/QuEST

More Quantum

QUANTUM ALGORITHMS - FOR UNIVERSAL COMPUTERS

Three categories of quantum algorithms:

1. **Quantum Fourier transform (QFT) (exponential speedups)**

   Shor's algorithm: factorization of prime numbers
   Quantum algorithm for linear systems of equation

2. **Amplitude amplification (quadratic speedups)**

   Grover's algorithm: searches an unstructured database

3. **Quantum walks**

   Graph optimization algorithms.

It is difficult to design a new Quantum algorithm!

APPLICATION AREA: CRYPTOGRAPHY

Cryptography Threat

RSA public key cryptosystem is based on complexity of solving a math problem.

Shor's algorithm on a large quantum computer can breaK it in a short time.

Such a computer could be available in 10 years.

- Many other cryptosystems are also at risk.

Responses

- Improving our current security practices

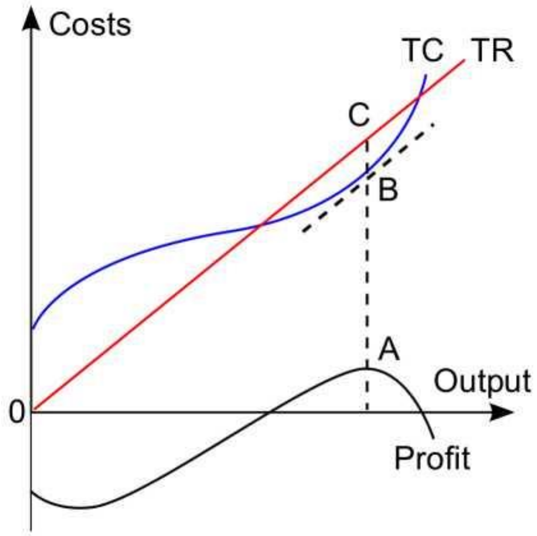
Post-quantum cryptography

Quantum communications

APPLICATION AREA : OPTIMIZATION AND MACHINE LEARNING

Mathematical optimization deals with finding the best solution to a problem.

- Examples: Portfolio optimization, Risk minimization



Optimization methods are the building blocks of machine learning and AI solutions.

Example techniques:

- **Quantum data fitting (regression)**
- **Quantum semidefinite programming**
- **Quantum combinatorial optimization**
- **Quantum support vector machine**

Quantum computing has the promise of:

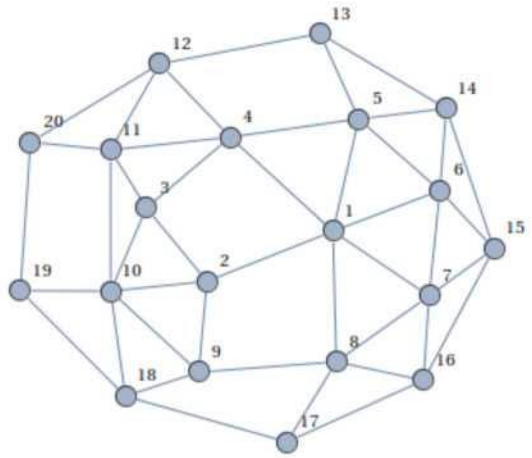
Solving problems which are classically infeasible

Obtaining a substantial speedup in optimization.

EXAMPLE - PORTFOLIO OPTIMIZATION

Portfolio optimization can easily become an intractable combinatorial optimization problem.

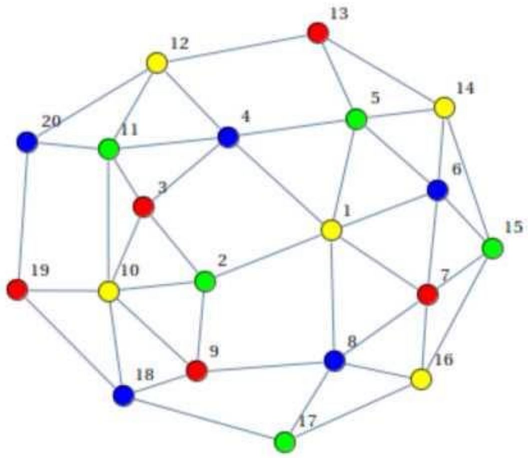
Example: Find portfolios containing only uncorrelated assets to minimize risk.



We represent the problem as a graph, where:

- Each asset corresponds to one node
- Each positive correlation is one edge

Each node color corresponds to one portfolio



Graph coloring problem: assign a color to each node avoiding a similar color on connected nodes.

Technique: Quantum annealing on a D-Wave machine

APPLICATION AREAS KEY DISTRIBUTION

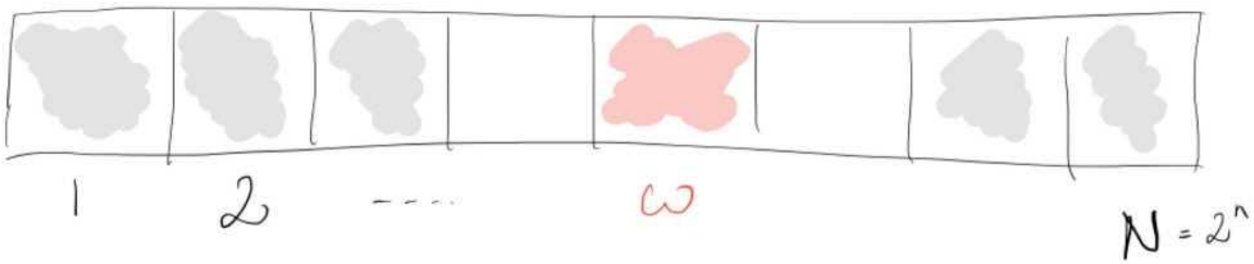
In Cryptography a secret key is used to encrypt/decrypt messages.

Key distribution is a mechanism to share a key between two parties in a secure manner.

Quantum entanglement provides a mechanism to distribute keys -completely tamper proof.

PROBLEM SETUP
UNSTRUCTURED DATABASE SEARCH

- We are searching for one item with a unique property in a large list of N items where there is no specific structure (e.g. order) in the dataset.



A list of! items. Only one has a unique property that we wish to locate; aka winner w.

- We have a check function to test if a given entry is winner or not, aka Oracle.
- Example: checking boxes one by one to find the only one box that contains an apple!

Conclusion

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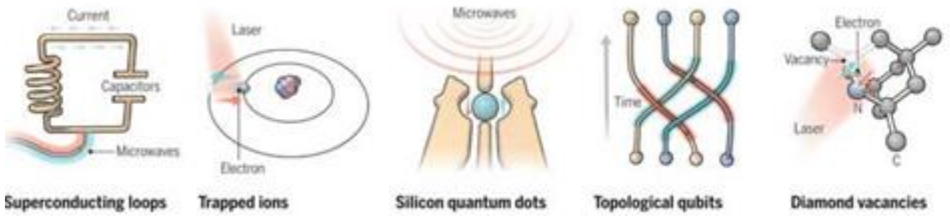
CONCLUSIONS: HARDWARE AND SOFTWARE



IBM Q
QISKit
Google AI
Cirq
Q#
Forest™ SDK

- **There is no standard architecture or de facto technology yet.**
- **Current computer are very limited:**
  - They are very few and fragile.
  - The have limited capacity.
  - The coherence time is short.
  - The technology is not fault-tolerant.
- **The progress has just started and it is believed to grow very fast!**

Plenty of things can/should be done before the ultimate hardware is ready.

Software development tools:

- IBM Q Experience
- Qiskit SDK
- Qiskit Aqua and other repositories: Aqua Chemistry, Aqua Optimization, Aqua Artificial Intelligence
- D-Wave: Internet API and programming libraries (C/C++, Python, and MATLAB)
- Microsoft: Quantum SDK, Q# (a new piece for Visual Studio) Azure simulator
- Google: Cirq (A python framework similar to Qiskit)

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Quantum on AWS

Amazon Quantum Solutions Labs

- https://aws.amazon.com/quantum-solutions-lab/

- Amazon Braket:
  - https://aws.amazon.com/blogs/aws/amazon-braket-get-started-with-quantum-computing/

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Microsoft Quantum

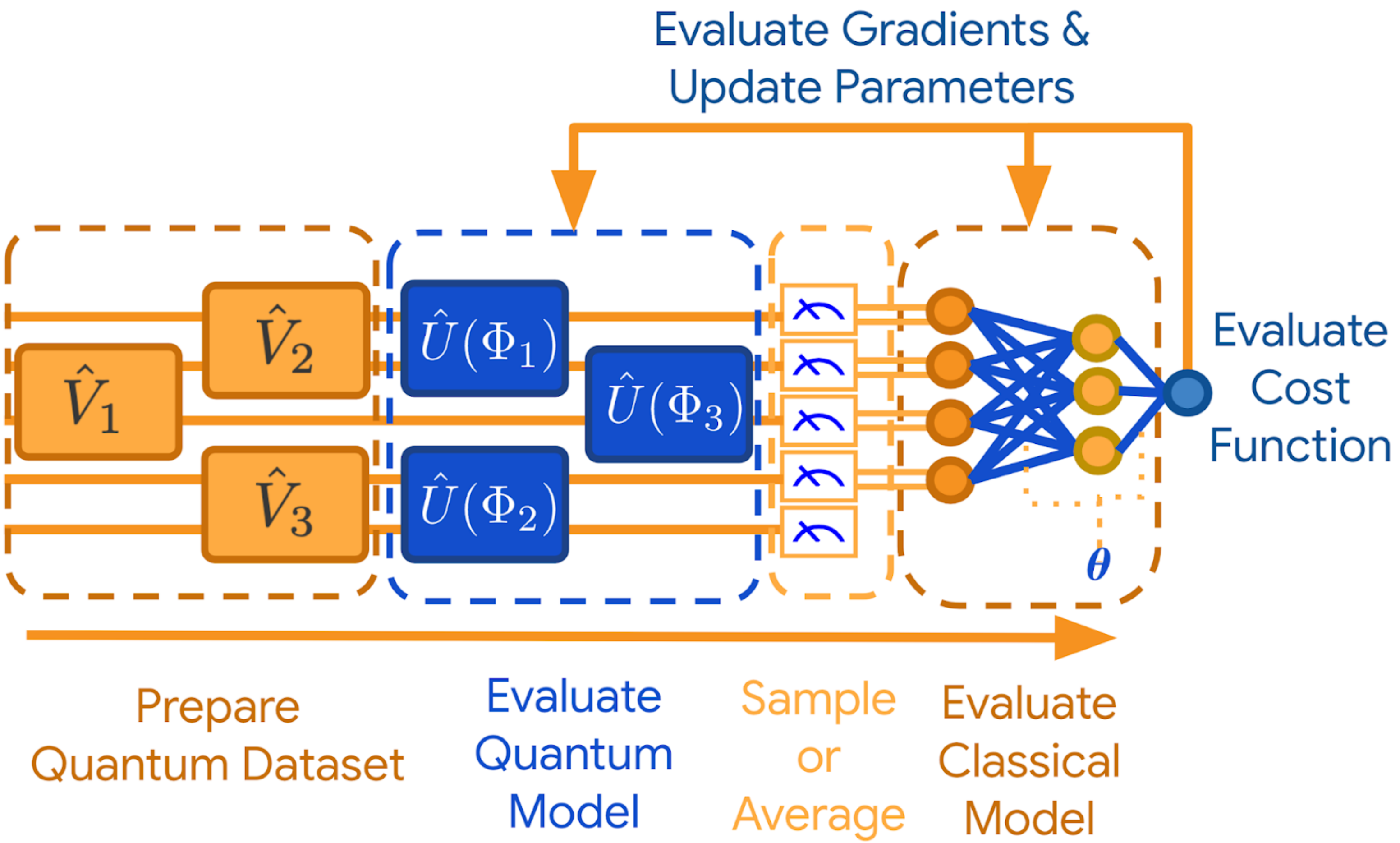
Azure Quantum

- Azure Development Kit:
  - https://www.microsoft.com/en-ca/quantum/development-kit
- Q#
  - https://docs.microsoft.com/en-us/quantum/?view=qsharp-preview

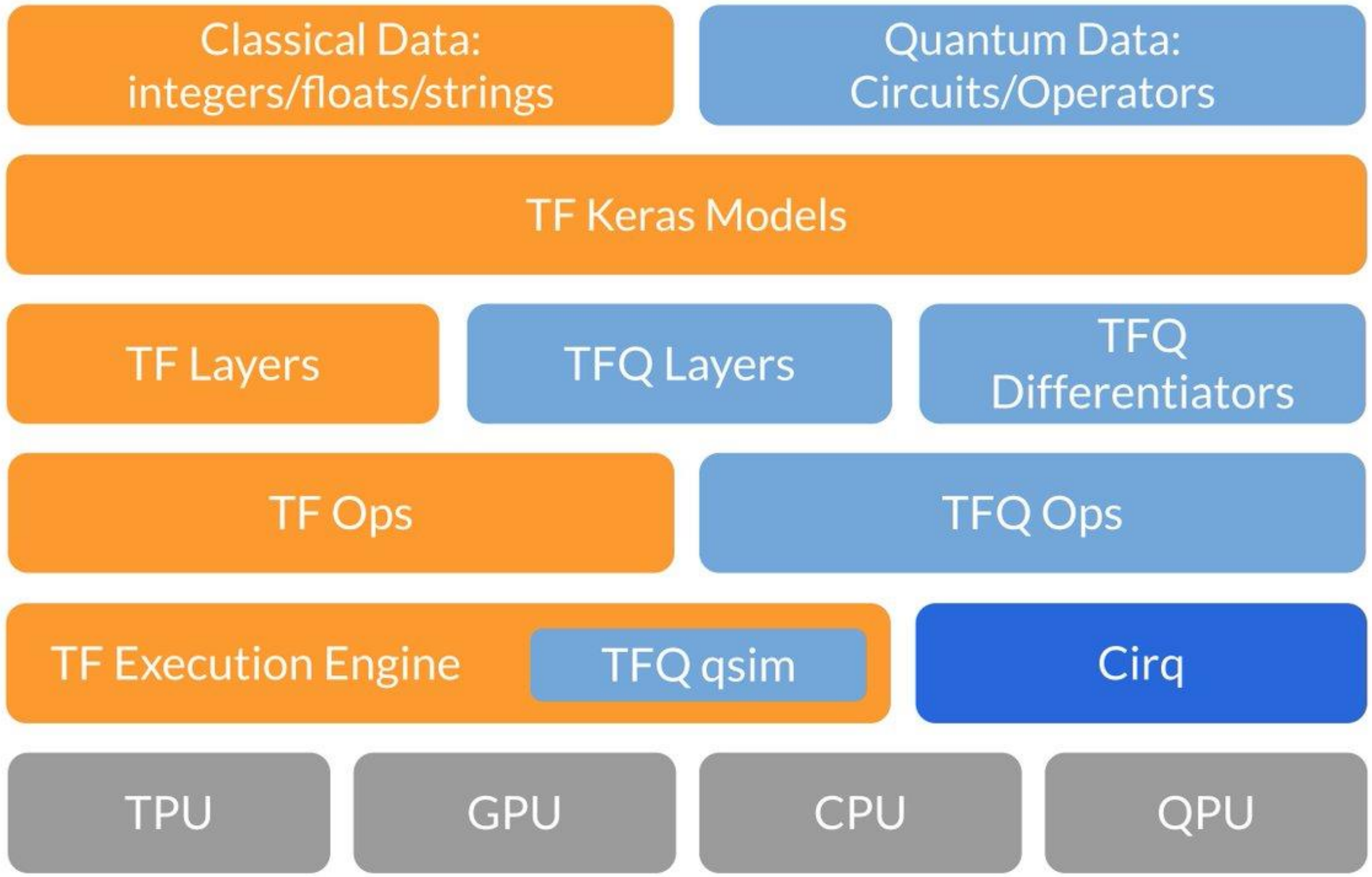
Google Quantum

TensorFlow Quantum

https://ai.googleblog.com/2020/03/announcing-tensorflow-quantum-open.html

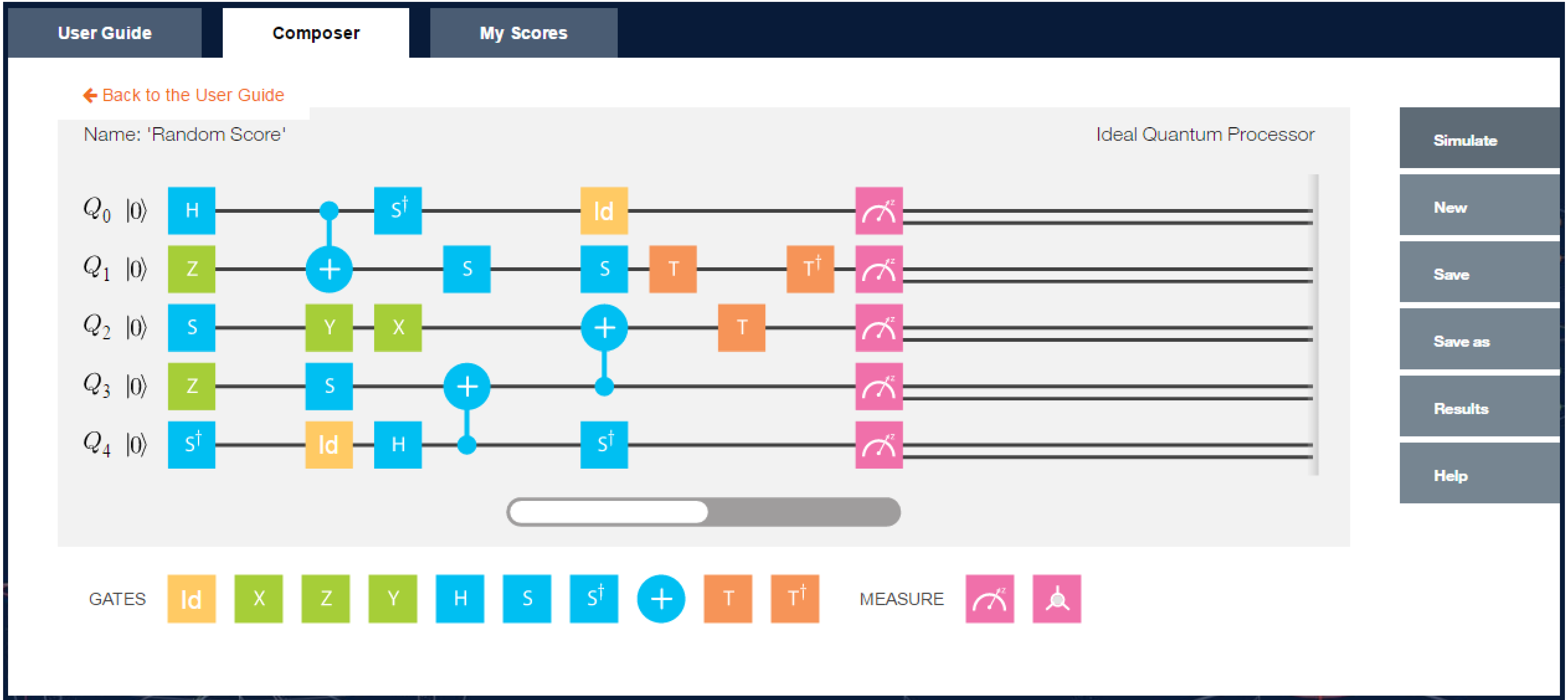


TensorFlow Quantum



Quantum on IBM

IBM Quantum Experience



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