Programming a Quantum Computer

A paradigm shift

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⟨C|Q|T⟩

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INFORMATION TECHNOLOGY **DELHI**

THE QUANTUM INSIDER

Quantum Computing Market Map

Non exhaustive and in no particular order. Excludes details on control systems, assembly languages, circuit design, etc.

Users
Select examples

Material Science
Merck, OTI, AIRBUS, BMW

Finance
Goldman Sachs, BANK OF AMERICA, J.P.Morgan, WELLS FARGO

Life Sciences
ODYSSEY THERAPEUTICS, Boehringer Ingelheim, AstraZeneca, gsk

Other
VW, JOHNSON ELECTRIC, DENSO

Applications / Software offerings
Not mapped to verticals / *Includes control software*

Not strictly categorized given diversity of operations[1]
MULTIVERSE COMPUTING, QCWARE, NQCG, 1QBit, Aliro QUANTUM, HORIZON, HQS QUANTUM SIMULATIONS, ZAPATA, QCi Ready-to-run Quantum Software, ENTROPICA LABS, river lane, STRANGE WORKS, QuantFi, PHASECRAFT, aq, QunaSys, Terra Quantum, ⟨b| e, ProteinQure, KEYSIGHT TECHNOLOGIES, Qubit pharmaceuticals, Q-CTRL, CLASSIQ, Quantum-South, menten.AI, ParityQC

Cloud access to QPUs
aws, Google Cloud, Azure

Simulators / q-inspired / etc
Atos, FUJITSU, NVIDIA, HUAWEI CLOUD

QPUs[2]

Superconducting
rigetti, Google AI Quantum, OQC, QILIMANJARO QUANTUM TECH, IBM Q, IQM, Nord Quantique, aws, seeqc, D-Wave The Quantum Computing Company, Alibaba.com

Ion Trap
QUANTINUUM, IONQ, Universal Quantum, AQT, oxford ionics, QUDOOR, eleQtron

Neutral Atoms
atom computing, ColdQuanta, QuEra, PASQAL

Silicon
Silicon Quantum Computing, intel, QUANTUM MOTION, equal 1

Photonics
PsiQuantum, QC82, XANADU, photonic, ORCA Computing, Quandela, TuringQ

Other
EeroQ Electrons on helium, QUANTUM BRILLIANCE NV Diamond

Hardware / components
Select examples only – not representative of entire ecosystem

Cryogenics (includes testing)
OXFORD INSTRUMENTS, FormFactor, Lake Shore CRYOTRONICS, BLUE FORS, MONTANA INSTRUMENTS, ICE, Maybell

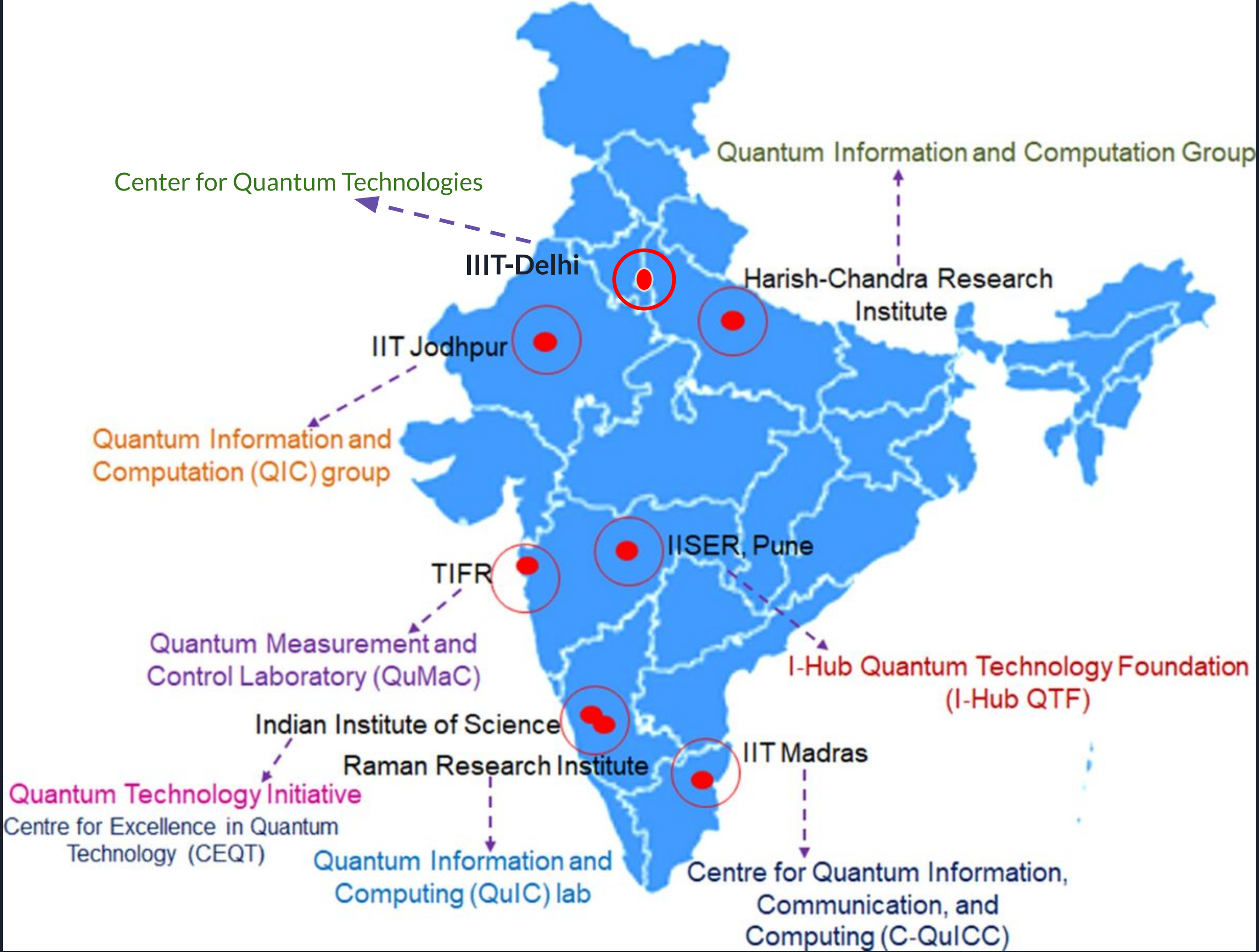
Lights and lasers
Vescent PHOTONICS, NKT Photonics, M SQUARED, COHERENT, QANT, TOPTICA PHOTONICS, LIGENTEC

Other componentry (examples)
Delft Circuits Hardware for quantum engineers, KEYSIGHT, QM QUANTUM MACHINES, Quantum Design, CryoCoax A division of Intelliconnect, ZNF, QBLOX, QDevil, Zurich Instruments

[1] Software offerings can be further classified into SDKs, firmware / enablers, algorithms / applications, simulators etc. but many companies are offering a mixture across the stack

[2] Many QPU providers are offering full stack services (e.g. Pasqal acquired Qu&Co, Quantinuum was originally CQC prior to merger with HQS, etc.

Quantum in India



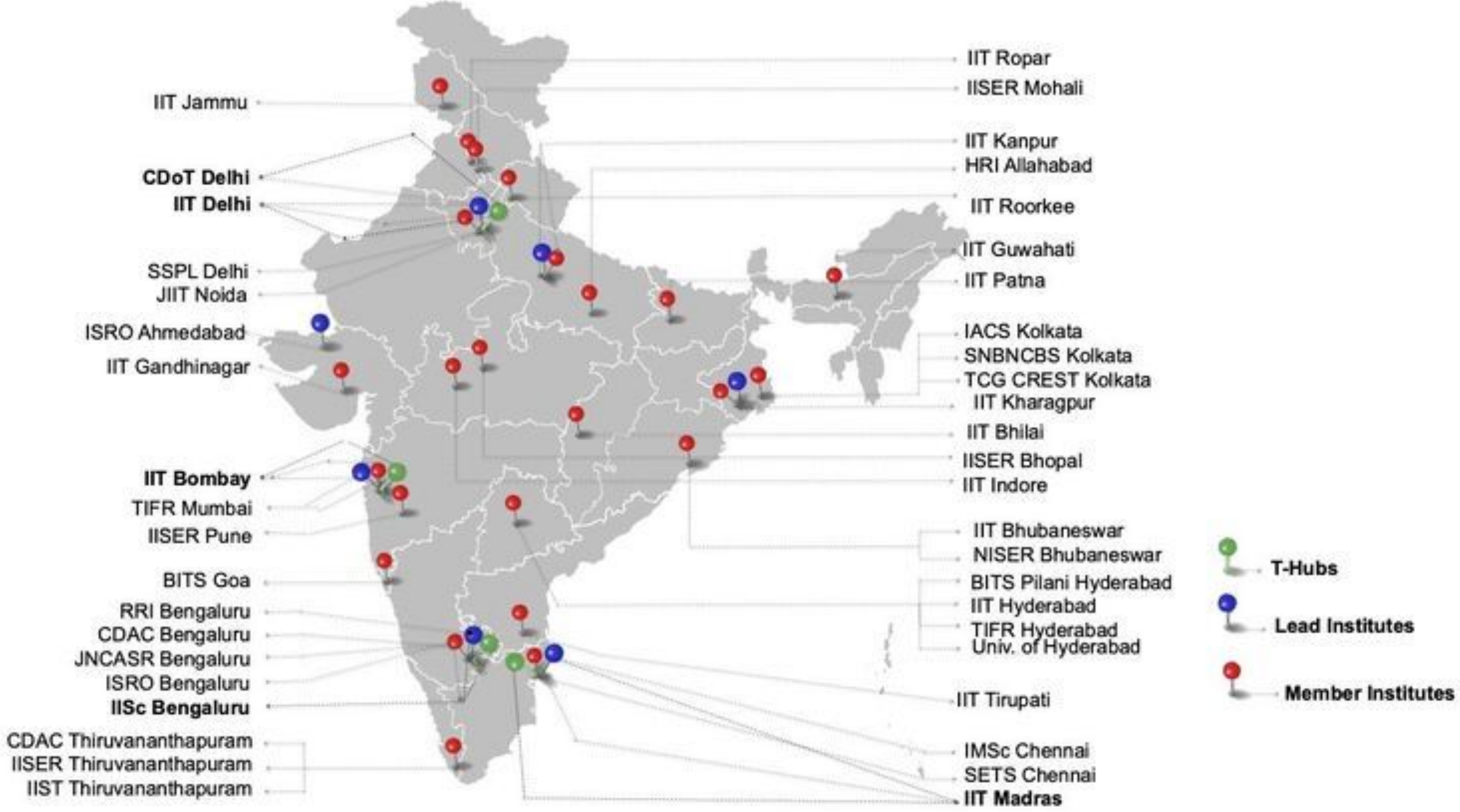
4 Thematic Hubs of NQM

Quantum Computing @ IISc Bangalore (involves IIIT-Delhi)

Quantum Communication @ IIT Madras

Quantum Sensing and Metrology @ IIT Bombay

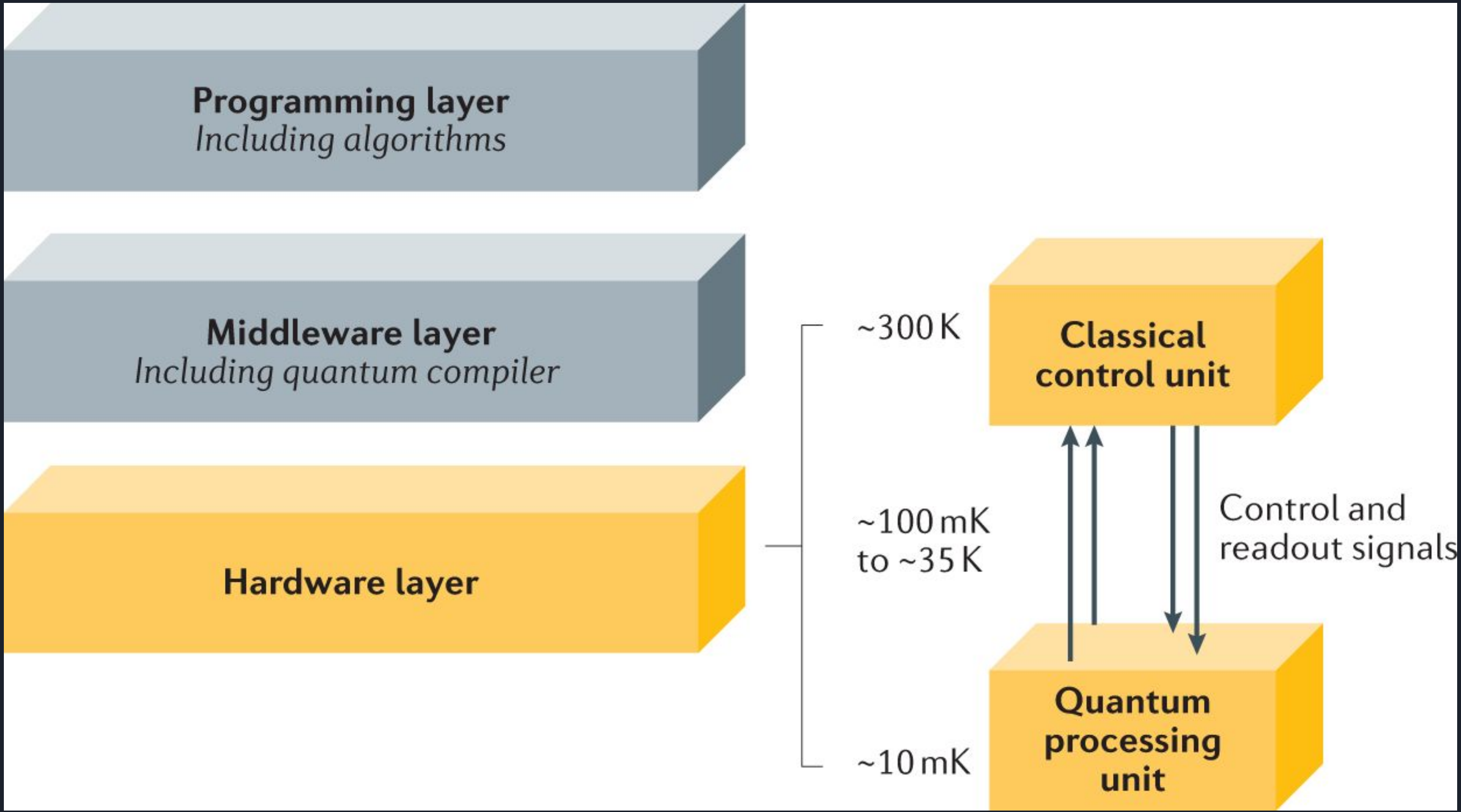
Quantum Materials and Devices @ IIT Delhi



- 43 Institutions (Lead & Member) from 17 states and 2 UTs involved in the 17 proposals

Education Programs

★ B.Tech. Minor @ IIIT-Delhi
★ B.Tech. Minor @ IIIT-Delhi
★ Sponsored M.Tech. @ IIT Madras
★ M.Tech. @ IISc Bangalore
★ M.Tech. @ IIT Jodhpur
★ M.Tech. @ DIAT Pune
★ M.Tech. @ IIST Trivandrum
★ M.Tech. @ PEC, Punjab
★ Certificate course @ IIT Delhi



Quantum Computing Stack

Donati, G. A look at the full stack. *Nat Rev Phys* 3, 226–228 (2021) https://en.wikipedia.org/wiki/List_of_quantum_processors

Available QPU

Company	Technology of qubits	Architecture
IBM	Superconducting	Gate-based
Google	Superconducting	
Intel	Superconducting & semiconductor spin	
IonQ	Trapped ion	
Quantinuum	Trapped ion	
Rigetti	Superconducting transmon	
SpinQ	Nuclear magnetic resonance (NMR)	
Xanadu	Nanophotonics	
DWAVE	Superconducting	Quantum annealing

How to access QPUs ?

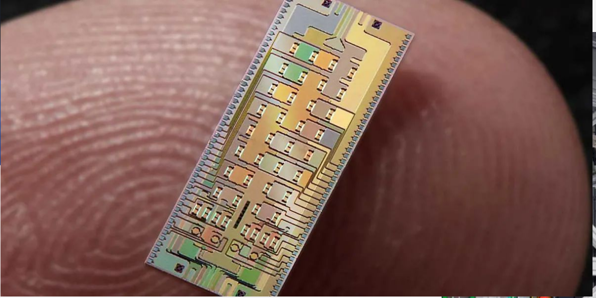
Amazon Braket Pricing

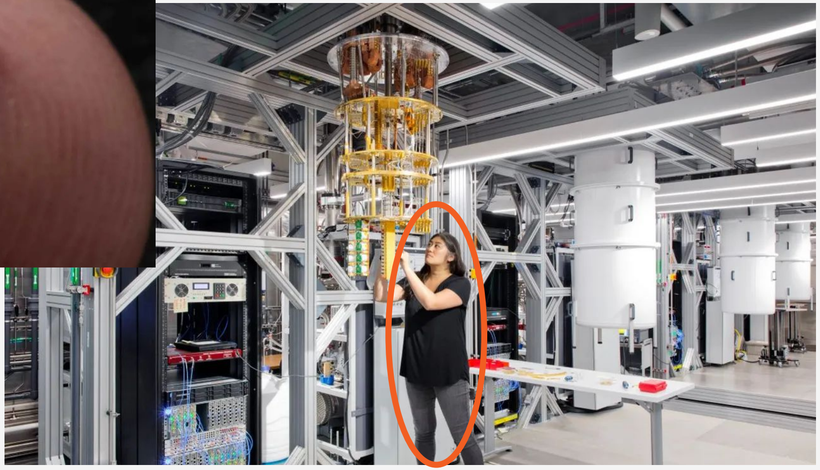
Hardware Provider	D- Wave	D- Wave	IonQ	Rigetti
QPU Family	2000Q	Advantage	IonQ device	Aspen-8
Per-task price	$0.30000	$0.30000	$0.30000	$0.30000
Per-shot Price	$0.00019	$0.00019	$0.01000	$0.00035

1 run involving 1000 shots ~ Rs 26/-

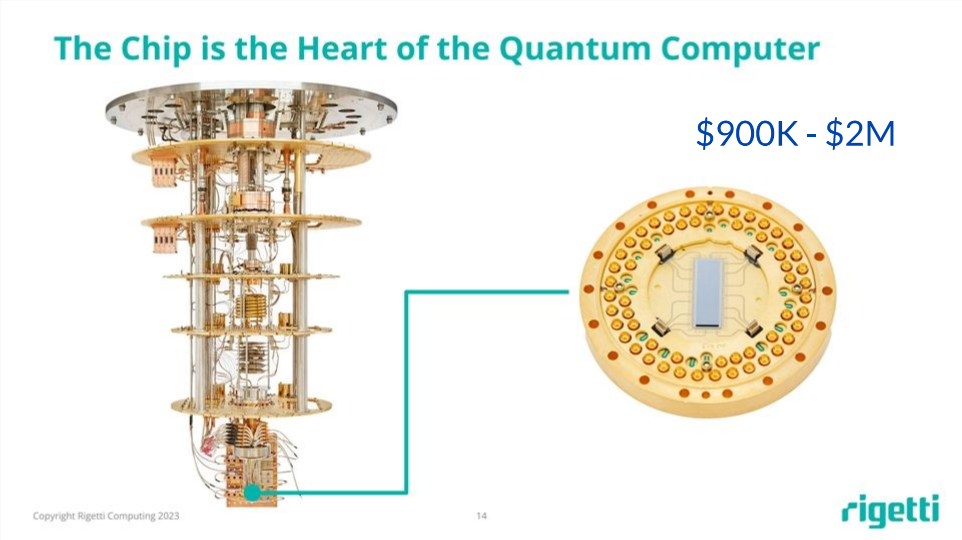
Leap D'Wave Leap allow free trial access

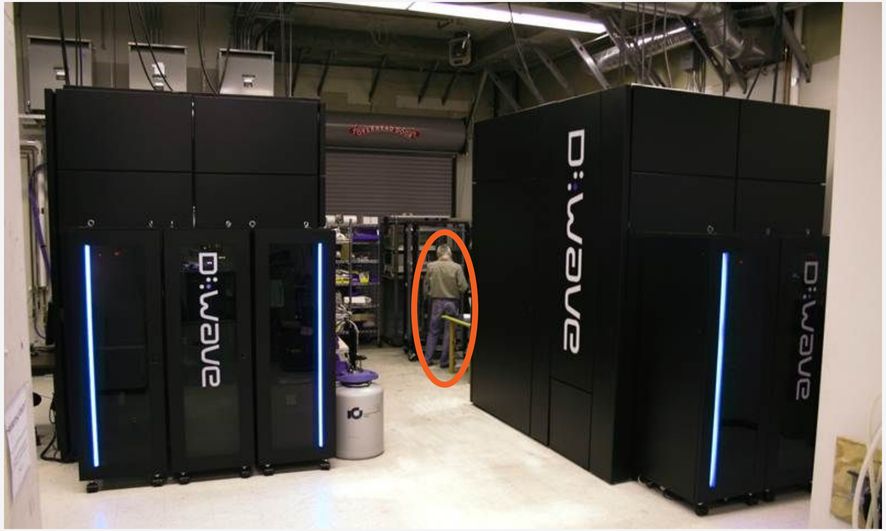
IBM Quantum Platform IBM allows (limited) free access

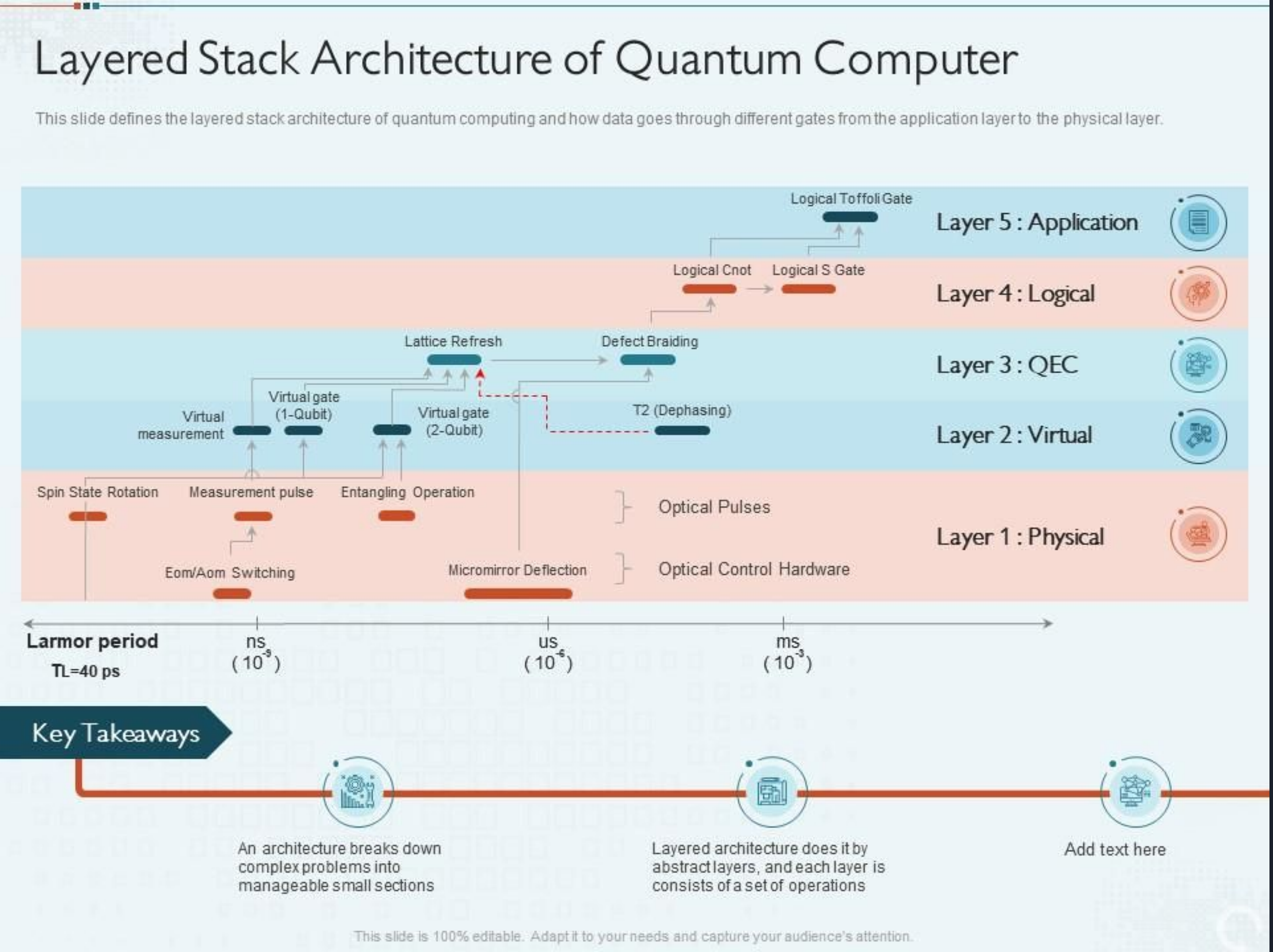





$9K - $58K
My personal stand-alone room temperature 2-qubit quantum computer


The Chip is the Heart of the Quantum Computer
$900K - $2M
Copyright Rigetti Computing 2023
14
rigetti


D:Wave
D:Wave
D:Wave



QPU Speed

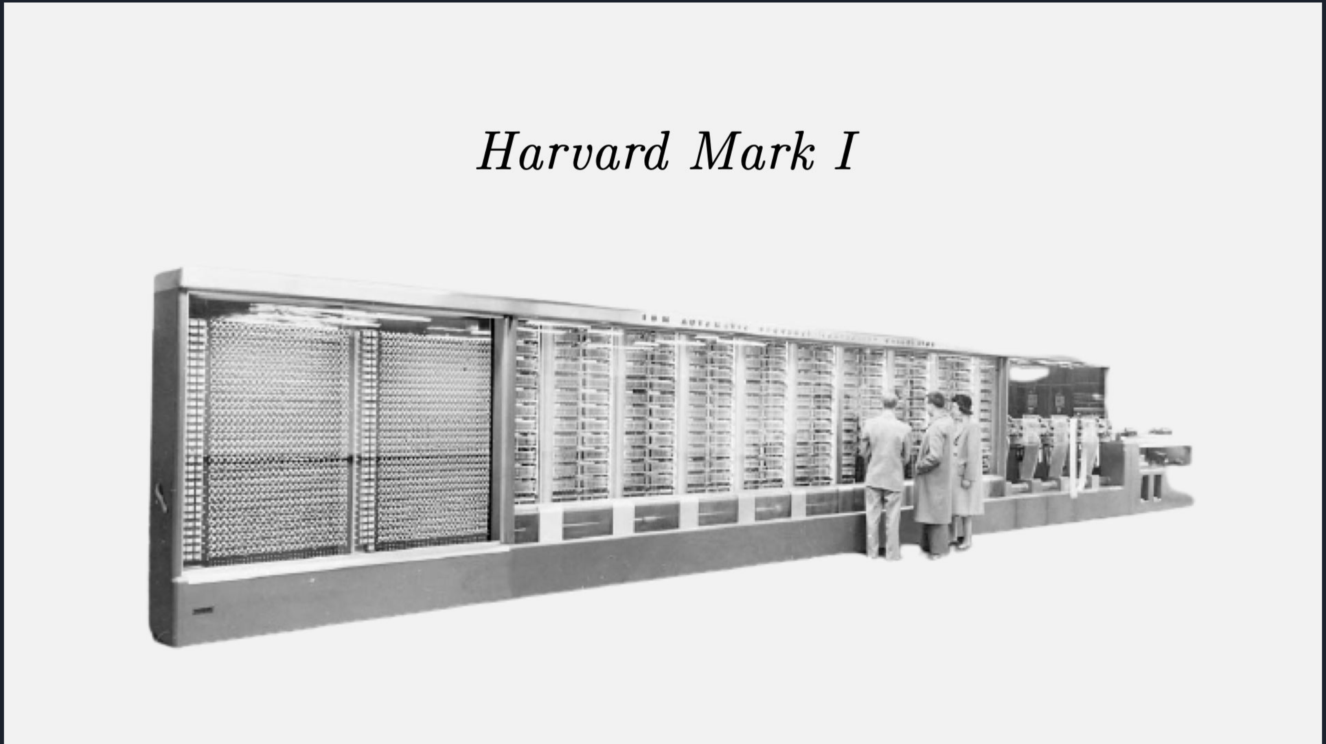
<u>Variable operations</u>

Physical rate < 1 - 0.1 GHz
Logical rate ~ MHz

<u>Variable read</u>

Physical rate ~ MHz

First generation CPU



Specification

- \+ : 0.3 sec
- x : 6 secs
- ÷ : 15 secs
- sin, cos, etc. : 1 min +

- Operated on 72 73-bit registers

- 51 ‘ x 8 ‘ x 2 ‘
- 4.3 ton

A simple program

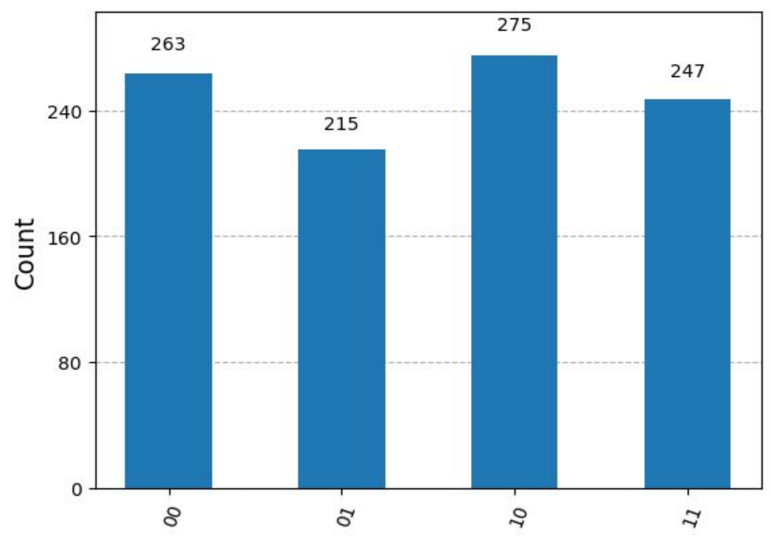
Assume both qint and int are 2-bit datatypes.

```
1.   qint myvar1 = 00;
2.   myvar1.Hadamard();
3.   int abc = myvar1.get(); // measure in QPU assembly languages
```

abc will be:

- 00 with probability ¼
- 01 with prob. ¼
- 10 with prob. ¼
- 11 with prob. ¼

Running this for 1024 “shots”, we observe something like



Probability is important!

A simple program

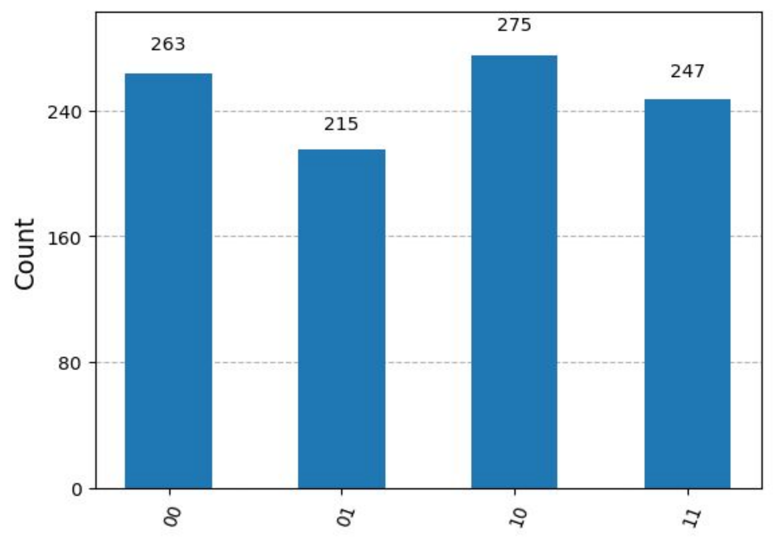
Assume both qint and int are 2-bit datatypes.

```
1.   qint myvar1 = 10;
2.   myvar1.Hadamard();
3.   int abc = myvar1.get(); // measure in QPU assembly languages
```

abc will be:

- 00 with probability ¼
- 01 with prob. ¼
- 10 with prob. ¼
- 11 with prob. ¼

Running this for 1024 “shots”, we observe something like

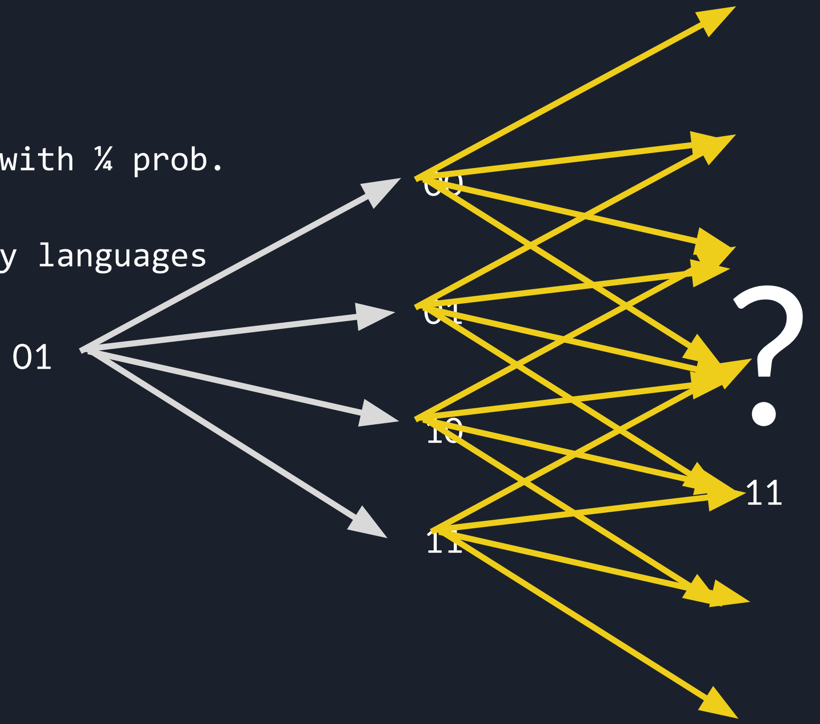


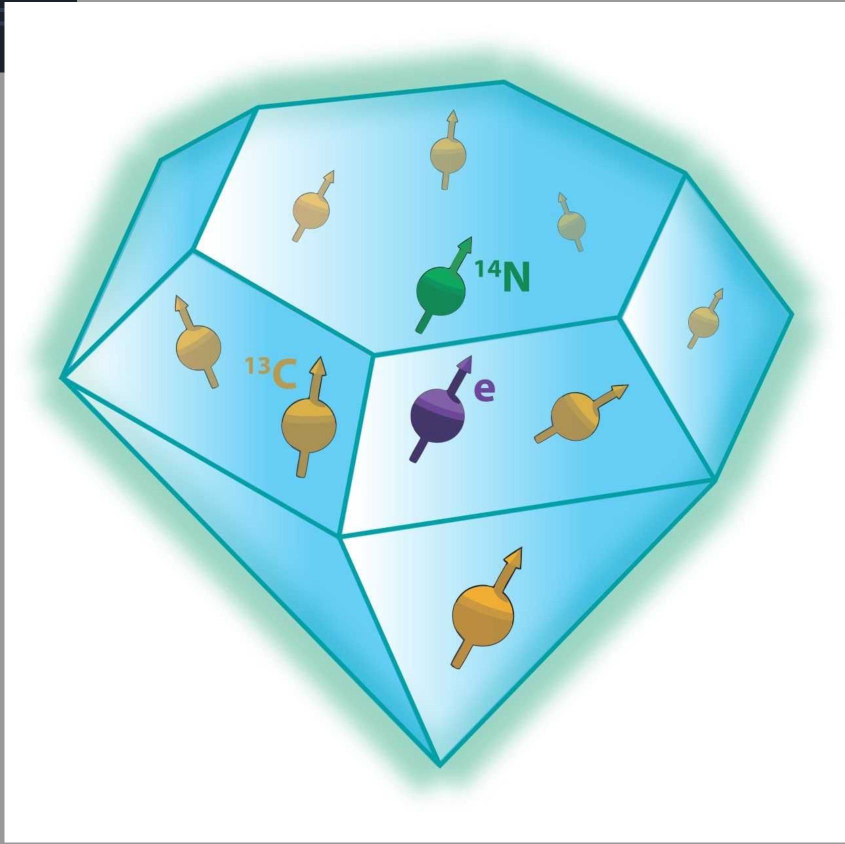
Same observation for myvar1 = 01 or 11

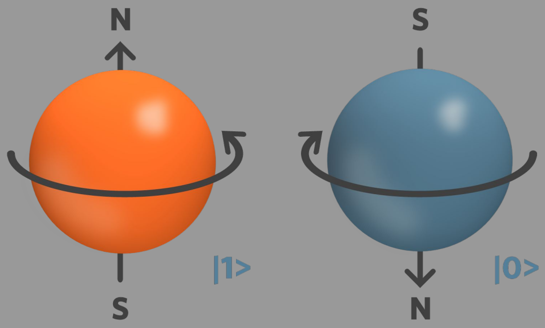
Quantum is more than probabilistic comp.

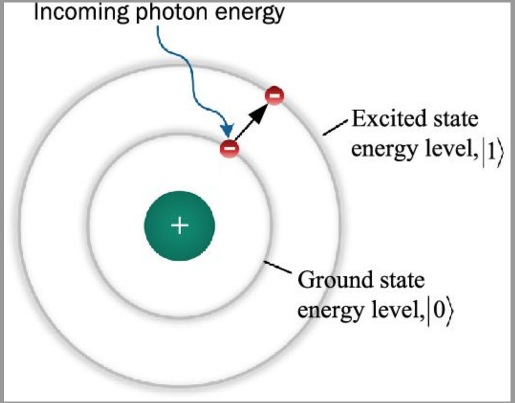
```
1.   qint myvar1 = 10;
2.   myvar1.Hadamard();
     // myvar1.get() will return 00 or 01 or 10 or 11 with ¼ prob.
3.   myvar1.Hadamard();
4.   int abc = myvar1.get(); // measure in QPU assembly languages
```

What will be abc? **10** !









Quantum-mechanical implementation of Qubits

Quantum mechanical variables

Linear algebra is important!

$$\begin{pmatrix}1\\0\\0\\0\end{pmatrix} \quad \begin{pmatrix}0\\1\\0\\0\end{pmatrix} \quad \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \quad \begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

qint myvar1 = 00 01 10 11

1-qubit register is a complex vector in a 2-dimensional Hilbert space
2-qubit register is a complex vector in a 4-dimensional Hilbert space
10-qubit register is a complex vector in a 1024-dimensional Hilbert space

Linear algebraic view of variables

$$\begin{pmatrix}1\\0\\0\\0\end{pmatrix} \quad \begin{pmatrix}0\\1\\0\\0\end{pmatrix} \quad \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \quad \begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

qint myvar1 = 00 01 10 11

Hadamard matrix H:

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

1-qubit operation is multiplication by 2 x 2 unitary matrix.
2-qubit operation is multiplication by 4 x 4 unitary matrix.
10-qubit operation is multiplication by 1024 x 1024 unitary matrix.

Linear algebraic view of variables

$\begin{pmatrix}1\\0\\0\\0\end{pmatrix}$ $\begin{pmatrix}0\\1\\0\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\1\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\0\\1\end{pmatrix}$

qint myvar1 = 00 01 10 11

Hadamard matrix H: $\frac{1}{2}\begin{pmatrix}1 & 1 & 1 & 1\\ 1 & -1 & 1 & -1\\ 1 & 1 & -1 & -1\\ 1 & -1 & -1 & 1\end{pmatrix}$

1-qubit operation is multiplication by 2 x 2 unitary matrix.
2-qubit operation is multiplication by 4 x 4 unitary matrix.
10-qubit operation is multiplication by 1024 x 1024 unitary matrix.

$$\frac{1}{2}\begin{pmatrix}1 & 1 & 1 & 1\\ 1 & -1 & 1 & -1\\ 1 & 1 & -1 & -1\\ 1 & -1 & -1 & 1\end{pmatrix}\begin{pmatrix}1\\0\\0\\0\end{pmatrix} \rightarrow \frac{1}{2}\begin{pmatrix}1\\1\\1\\1\end{pmatrix}$$

qint(00).Hadamard()

qint(01).Hadamard()

$$\frac{1}{2}\begin{pmatrix}1 & 1 & 1 & 1\\ 1 & -1 & 1 & -1\\ 1 & 1 & -1 & -1\\ 1 & -1 & -1 & 1\end{pmatrix}\begin{pmatrix}0\\1\\0\\0\end{pmatrix} \rightarrow \frac{1}{2}\begin{pmatrix}1\\-1\\1\\-1\end{pmatrix}$$

qint.get() : Quantum Measurement

$$\begin{pmatrix} 0.5 \\ -0.5 \\ 0.5 \\ -0.5 \end{pmatrix} \longrightarrow 0.5 \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} - 0.5 \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} + 0.5 \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} - 0.5 \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

After measurement,

- value of register changes to 00 with probability $(½)^2$ = ¼
- value of register changes to 01 with probability $(-½)^2$ = ¼
- value of register changes to 10 with probability $(½)^2$ = ¼
- value of register changes to 11 with probability $(-½)^2$ = ¼

A quantum operation is manipulation of probability vectors !

Comparison with vector processors & MATLAB

How to store and operate on vectors of size 2^{100} ?

⅛	⅛	⅛	⅛	⅛	⅛	⅛	⅛

Requires 8 floating point registers. A 2^{100}-dimensional vector will require 2^{100} floating point registers.

But 2^{100} is more than the number of atoms in our universe !!!

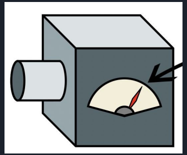
However, the quantum-mechanical description of a 100-qubit register is a 2^{100} dimensional vector (*).

A 100-qubit register is typically implemented using …

100 ions or 100 electrons or 100 photons (100 quantum mechanical particles.

Destructive interference

$$\begin{pmatrix}0.5\\-0.5\\0.5\\-0.5\end{pmatrix} = 0.5\overset{00}{\begin{pmatrix}1\\0\\0\\0\end{pmatrix}} - 0.5\overset{01}{\begin{pmatrix}0\\1\\0\\0\end{pmatrix}} + 0.5\overset{10}{\begin{pmatrix}0\\0\\1\\0\end{pmatrix}} - 0.5\overset{11}{\begin{pmatrix}0\\0\\0\\1\end{pmatrix}}$$



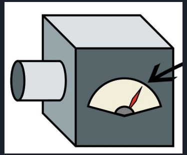
00 w/p $(0.5)^2$ = ¼

01 w/p $(-0.5)^2$ = ¼

01 w/p $(0.5)^2$ = ¼

11 w/p $(-0.5)^2$ = ¼

$$\begin{pmatrix}0.5\\-0.5\\0\\-0.707\end{pmatrix} = 0.5\underset{00}{\begin{pmatrix}1\\0\\0\\0\end{pmatrix}} - 0.5\underset{01}{\begin{pmatrix}0\\1\\0\\0\end{pmatrix}} + 0\underset{10}{\begin{pmatrix}0\\0\\1\\0\end{pmatrix}} - 0.707\underset{11}{\begin{pmatrix}0\\0\\0\\1\end{pmatrix}}$$



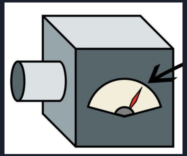
00 w/p $(0.5)^2$ = ¼

01 w/p $(-0.5)^2$ = ¼

11 w/p $(-0.707)^2$ = ½

QC: inherently “probabilistic” & vectorized

$$\begin{pmatrix}0.5\\-0.5\\0\\-0.707\end{pmatrix} = 0.5\underset{00}{\begin{pmatrix}1\\0\\0\\0\end{pmatrix}} - 0.5\underset{01}{\begin{pmatrix}0\\1\\0\\0\end{pmatrix}} + 0\underset{10}{\begin{pmatrix}0\\0\\1\\0\end{pmatrix}} - 0.707\underset{11}{\begin{pmatrix}0\\0\\0\\1\end{pmatrix}}$$

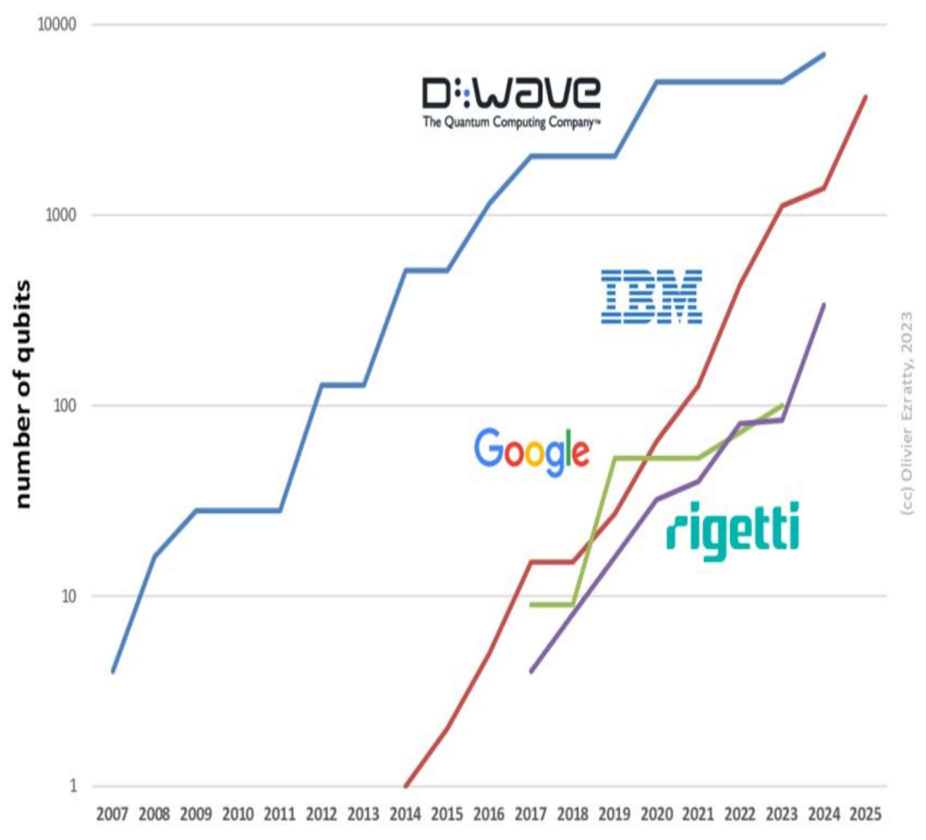


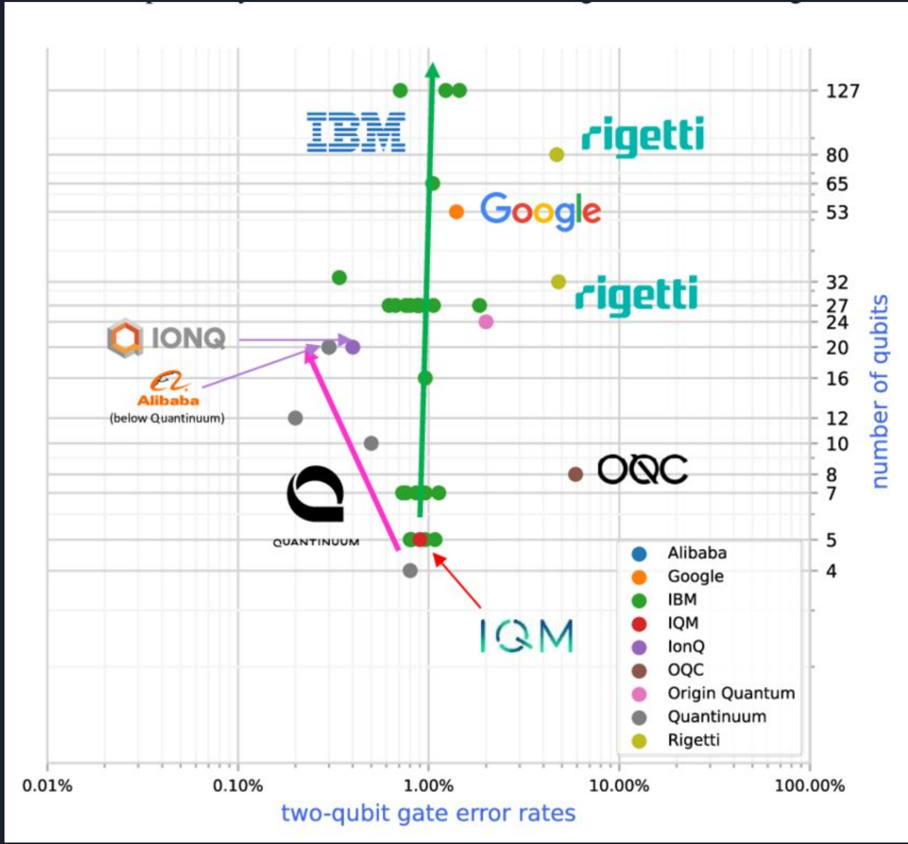
00 w/p $(0.5)^2 = ¼$

01 w/p $(-0.5)^2 = ¼$

11 w/p $(-0.707)^2 = ½$

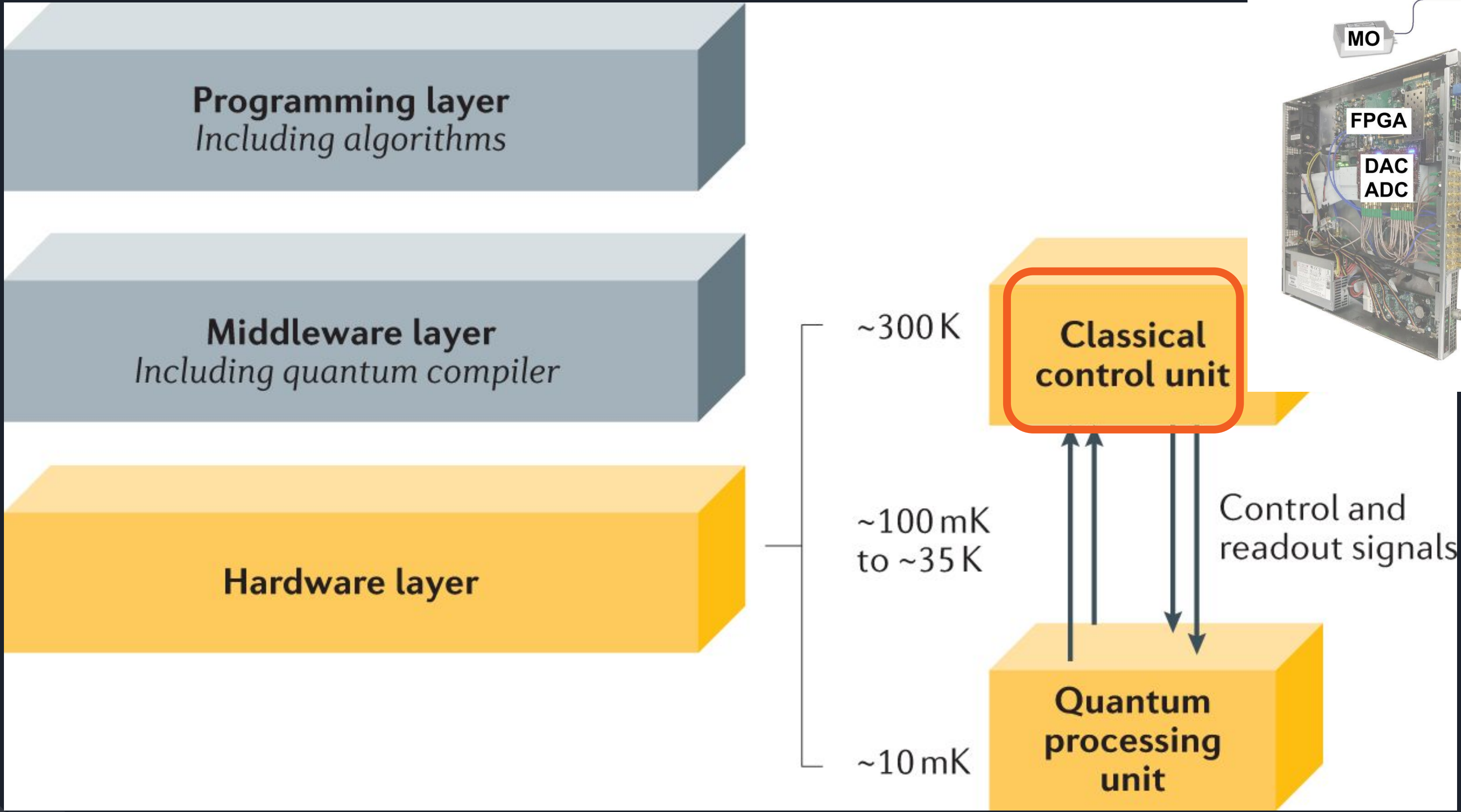
- Implemented as a quantum-mechanical property of 1 electron / neutron / photon / etc.
- State of n particles can be represented by a 2^n-dimensional vector
  - Essentially, storing 2^n complex numbers (with unit norm)
- When measured, values changes to one of the “basic” values with probabilities depending on the vector coordinates
- Unlike probability vectors, coordinates can be negative (actually, complex numbers)
  - **Destructive interference:** Operations can “cancel out” basic values, thus lowering the probability of observations

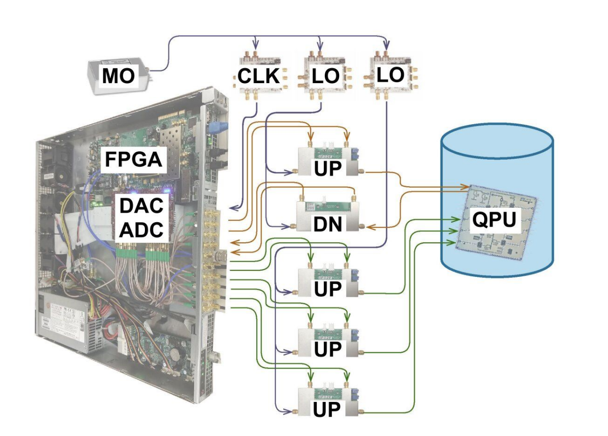




The Qubit Race: Current Quantum Processing Units

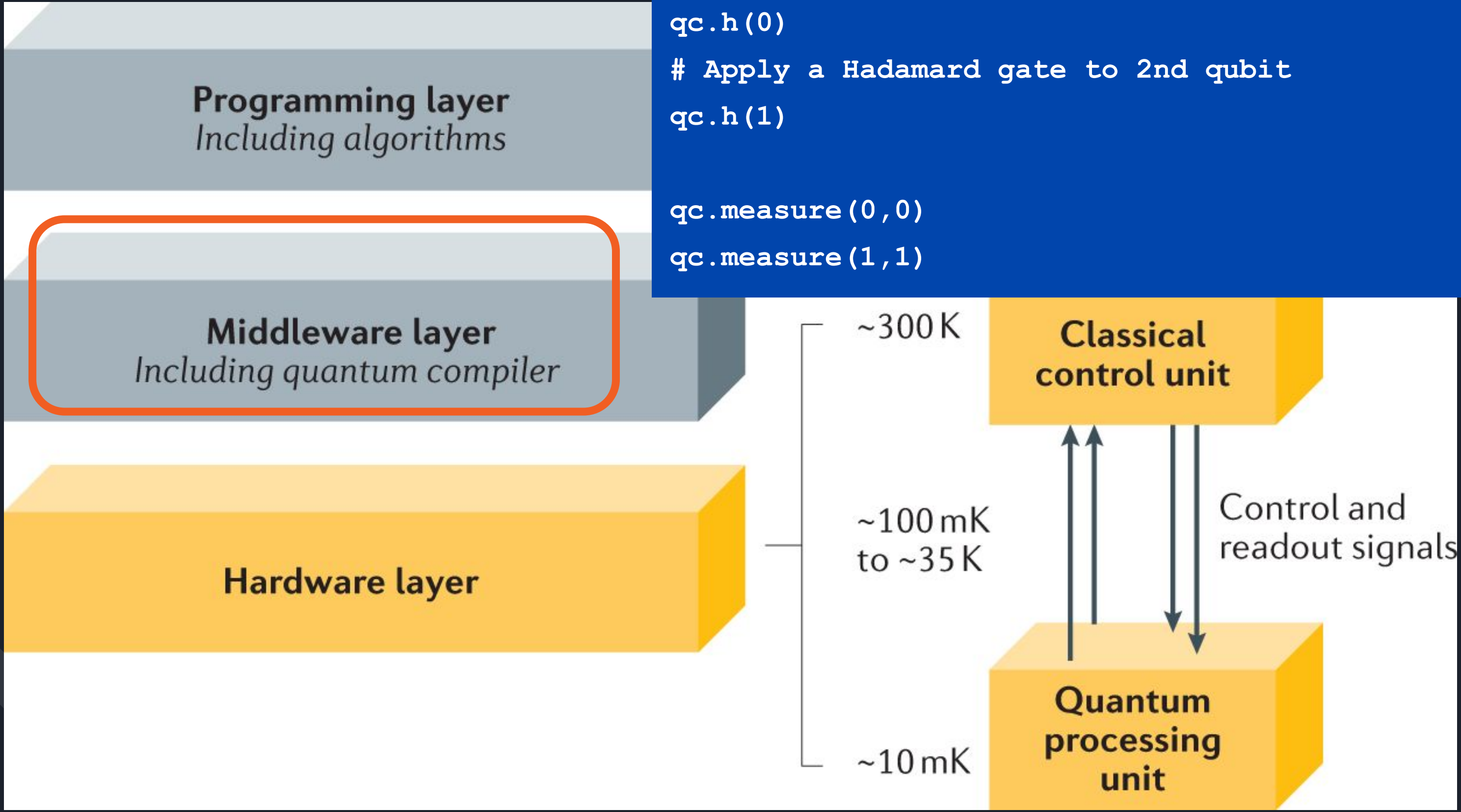
Ezratty, Olivier. (2023). Is there a Moore's law for quantum computing?.





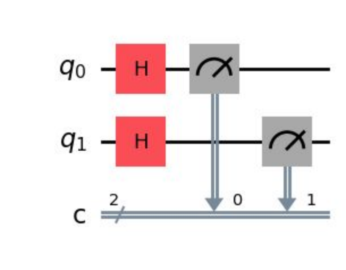
Quantum Computing Stack

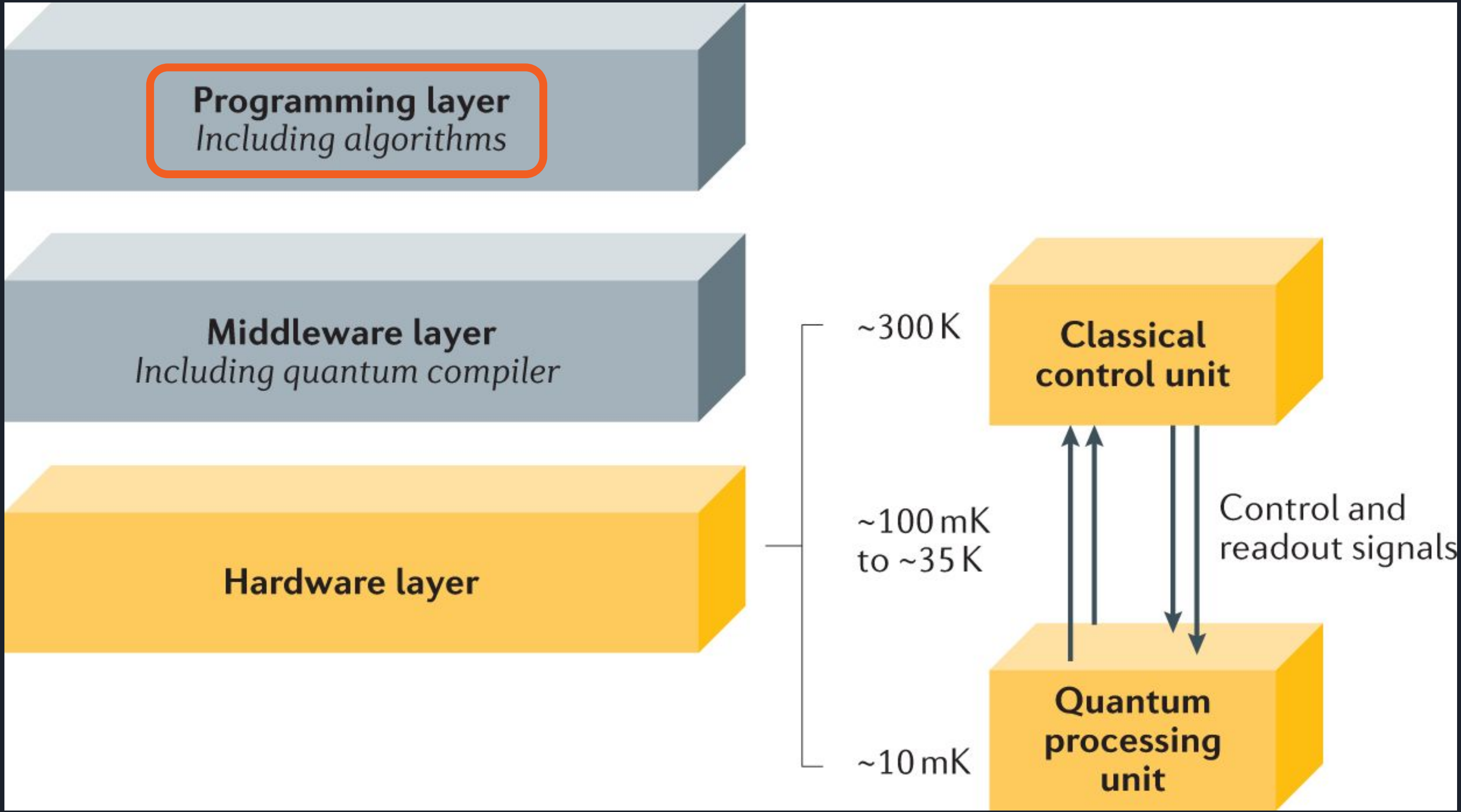
Donati, G. A look at the full stack. *Nat Rev Phys* 3, 226–228 (2021)




```
from qiskit import QuantumCircuit
qc = QuantumCircuit(2,2) # 1 quantum register, 1 classical
register
# Apply a Hadamard gate to 1st qubit
qc.h(0)
# Apply a Hadamard gate to 2nd qubit
qc.h(1)

qc.measure(0,0)
qc.measure(1,1)
```

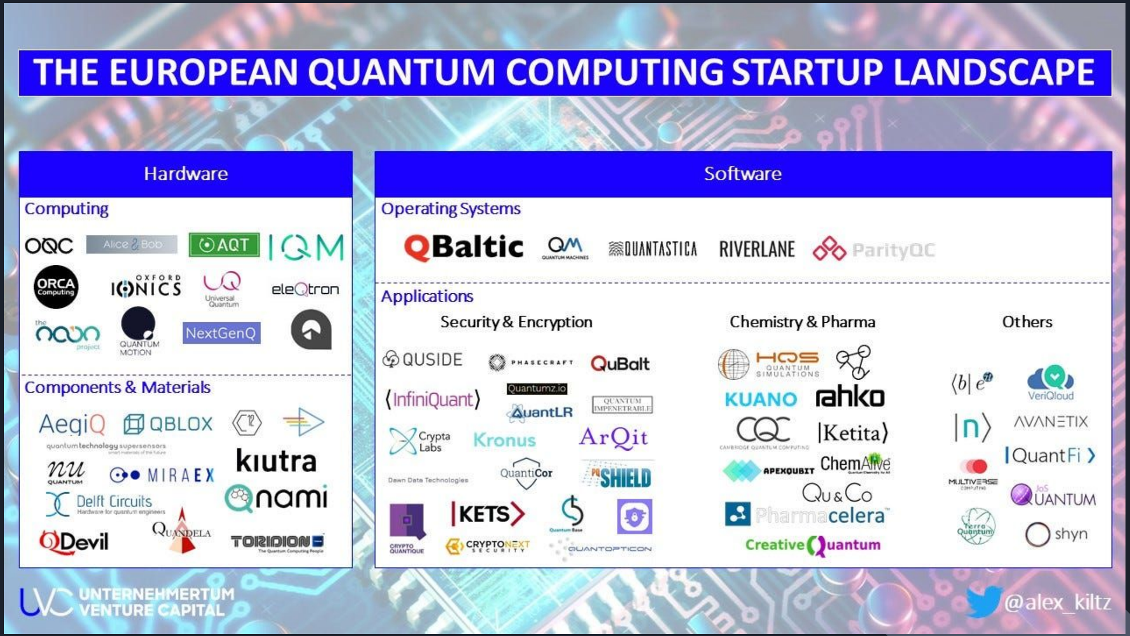



Programming layer
Including algorithms
Middleware layer
Including quantum compiler
Hardware layer
~300 K
~100 mK
to ~35 K
~10 mK
Classical
control unit
Quantum
processing
unit
Control and
readout signals

Quantum development ecosystem

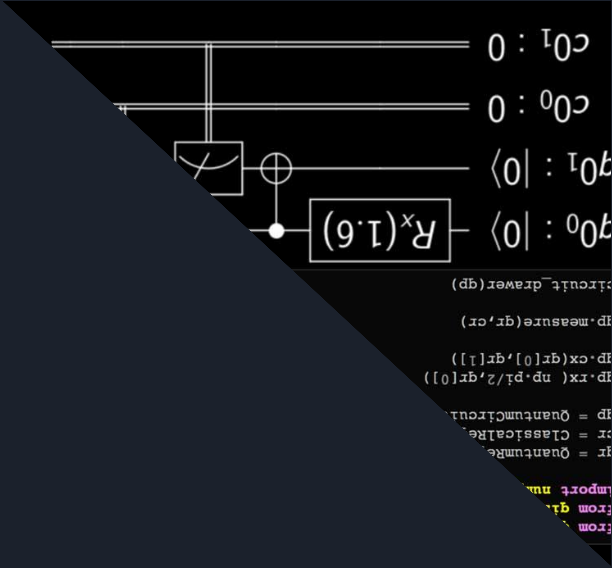
Many programming languages.
Lot of libraries.
Active community.
Several tutorial, blogs, open Github projects,

SDK
Qiskit by IBM
Ocean by D-Wave
Strawberry Fields & Pennylane
Forest by Rigetti
Circ by Google
QDK by Microsoft
CUDA-Quantum by NVIDIA



Quantum Algorithms for …

Traditional CS problems



Quantum Algorithm Zoo

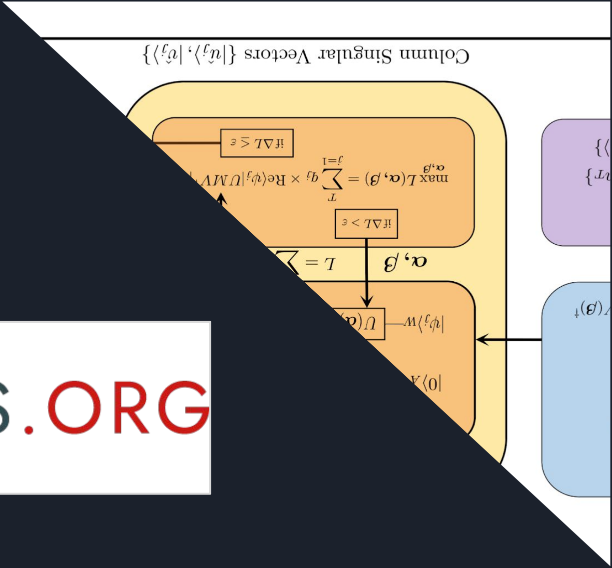
Number theoretic algorithms
Linear algebraic algorithms
Algebraic algorithms
Sorting, searching, …
Graph algorithms
String algorithms
Group-theoretic algorithms
Linear programs
Semi-definite programs
…

https://quantumalgorithmzoo.org/

Quantum algorithms for ...

Data analysis

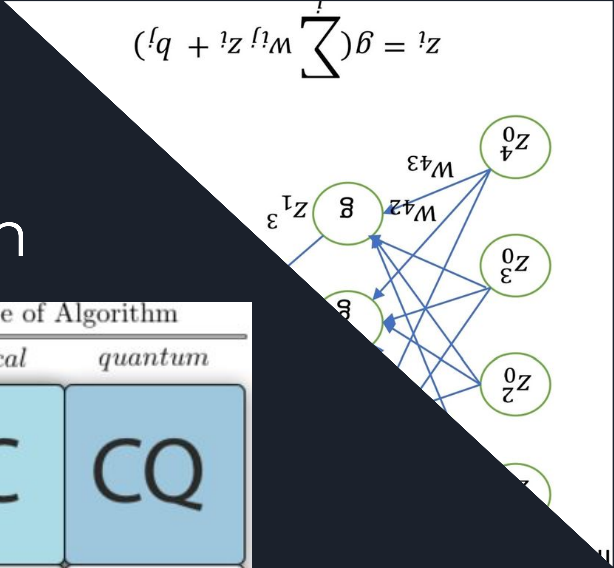
QUANTUMALGORITHMS.ORG



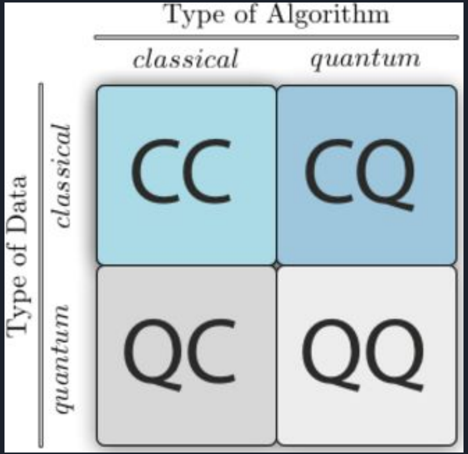
- Singular-value estimation based algorithms
- Monte-carlo techniques
- PCA and other dimensionality reduction methods
- Clustering algorithms like k-means, k-median, ...
- Matrix operations like inversion, solving linear system, ...

Quantum algorithms for ...

Machine learning & optimization



https://en.wikipedia.org/wiki/Quantum_machine_learning



Quantum-enhanced reinforcement learning
Quantum annealing
Training Boltzmann machines
Quantum convolutional neural networks (QCNN)
Dissipative QNN
Quantum generative adversarial networks (QGAN)
Hidden quantum markov models
Quantum graph neural networks
Quantum physics-inspired neural networks (QPINN)

Quantum Online Portfolio Optimization

Input: n, s, η, T, C, δ

Initialize $U_{\rho^{(0)}} = \mathbb{I}$, $\tilde{I} = 1$ and $q^{(1)} = (1, \cdots, 1)$, $U_{q^{(1)}} = \mathbb{I}$.

for $t = 1$ to T **do**

$q_{\max} \leftarrow$ Find the largest element of $q^{(t)}$ using $U_{q^{(t)}}$ and quantum maximum finding [56] with success probability $1 - \frac{\delta}{4T}$.

$\tilde{Z}^{(t)} \leftarrow$ Estimate the norm of $\frac{q^{(t)}}{q_{\max}}$ using $U_{q^{(t)}}$, $q_{\max}$, Lemma 2, and Lemma 3(i), with relative error $\epsilon_Z = \frac{\eta^2}{r_{\min}^2}$ and success probability $1 - \frac{\delta}{4T}$.

$U_{w^{(t)}} \leftarrow$ Prepare quantum circuit for approximating $|\tilde{w}^{(t)}\rangle$ of the quantum state $|w^{(t)}\rangle$, where $w^{(t)} = \frac{q^{(t)}}{\|q^{(t)}\|_1}$, using $U_{q^{(t)}}$, $q_{\max}$, $\tilde{Z}^{(t)}$, Lemma 2, Lemma 3(ii), with success probability $1 - \frac{\delta}{4T}$.

$\Gamma, W, V \leftarrow$ Determine using Lem. 5 applied to $\tilde{w}^{(t)}$ with probability $1 - \frac{\delta}{4T}$.

$i_1^{(t)}, \cdots, i_s^{(t)}$ Perform multi-sampling using Γ, W, V and Lemma 6 with probability $1 - \frac{\delta}{4T}$.

Invest the amount $1/s$ in each asset $i_1^{(t)}, \cdots, i_s^{(t)}$ at cost C each.

Wait until end of day.

Receive price relative oracle $U_{\rho^{(t)}}$.

$\rho^{(t)}_{j^{(t)}} \leftarrow$ Query $U_{\rho^{(t)}}$ with $|j^{(t)}\rangle|0\rangle$.

$\tilde{I}^{(t)} \leftarrow$ Estimate $\tilde{w}^{(t)} \cdot \rho^{(t)}$ using $U_{w^{(t)}}$, $U_{\rho^{(t)}}$, and Lemma 4, with relative err success probability $1 - \frac{\delta}{4T}$.

$U_{q^{t+1}} \leftarrow$ Prepare quantum circuit to compute $q^{(t+1)} = \exp\left(\eta \sum_{t'=1}^{t} \frac{\rho^{(t')}}{\tilde{I}^{(t')}}\right)$ usi Lemma 2.

end for

Output: $LS^Q_{\text{samp}} := \frac{1}{T} \sum_{t=1}^{T} \log\left(\frac{1}{s} \sum_{\ell=1}^{s} \rho^{(t)}_{i^{(t)}_\ell}\right)$.

Name	Alg.	Regret	Run time
Online	1	$\frac{1}{r_{\min}}\sqrt{\frac{\log n}{2T}}$	$O(Tn)$
Sampling-based Online	2	$\frac{2}{r_{\min}}\sqrt{\frac{\log n}{2T}}$	$O(T^2 n \log \frac{T}{\delta})$
Approximate Sampling-based Online	3	$\frac{8}{r_{\min}}\sqrt{\frac{\log n}{2T}}$	$O\left(Tn + \frac{T^2}{r_{\min}} \log \frac{T}{\delta}\right)$
Quantum Online	4	$\frac{12}{r_{\min}}\sqrt{\frac{\log n}{2T}}$	$\tilde{O}\left(T^3 \sqrt{\frac{n}{r_{\min}}} \log^{1.5}\left(\frac{1}{\delta}\right)\right)$

Solving Knapsack using Annealing

N = 4   W = 5

Wt:	1	2	4	5
Val:	5	4	8	6

$x_\alpha = 1$ if good α (weight w_α, cost c_α) is included:

$$H = A\left(\mathcal{W} - \sum_\alpha w_\alpha x_\alpha\right)^2 - \sum_\alpha c_\alpha x_\alpha$$

$\mathcal{W}$ encoded by auxiliary variables y_i ($i = 0, \ldots, M = \lfloor \log W \rfloor$):

$$\mathcal{W} = \left(W + 1 - 2^M\right) y_M + \sum_{i=0}^{M-1} 2^i y_i$$

choose $A > \max(c_\alpha)$.

Knapsack: Given values [v1 … vn] and weights [w1 … wn] and a weight limit W on the knapsack, find the largest possible total value from items that can fit in the knapsack.

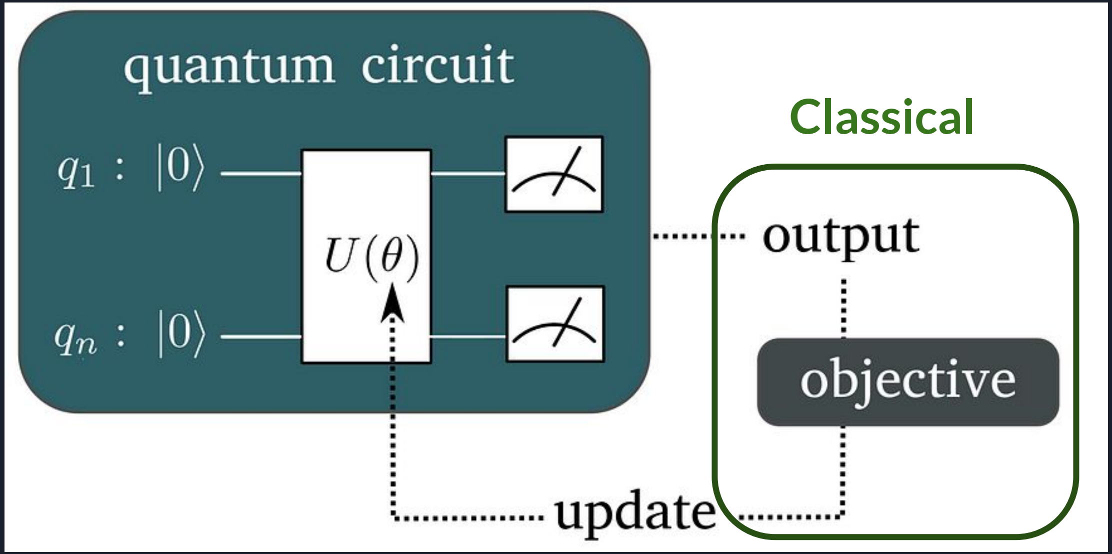
Equivalent optimization problem:

Variable xi = 1 if i-th item can be included, and 0 otherwise

max v1 x1 + v2 x2 + … vn xn
subject to: w1 x1 + w2 x2 + … + wn xn <= W

Quantum Annealers (e.g., DWave 2000Q) can solve a QUBO reformulation of the such optimization problems.

PQC (Parameterized Quantum Circuit)



PQC algorithms for …

- Quantum neural networks
- Quantum variational eigen-solver
- Quantum approximate algorithms for NP-complete problems

Popular Primitives	Popular Subroutines	Other Primitives
QFT [31]	QPE [32]	QITE [33]
AA [34]	QAE [35]	Q. Lanczos [36]
QA [37]	Grover [38]	Variational QSVD [39]
VQE [40]	QLSAs [30, 41–44]	Bayesian QPE [45]
HSs [46–51]	QSVT [52]	Hadamard Test [53]
Block Encoding [49]	QSP [54]	Hilbert-Schmidt Test [55]
BS [56]	Szegedy's QW [57]	Q. Hierarchical Clustering [58]
Swap Test [59]	SKW's QW Search [60]	Q. Distance Classifier [61]
	Adiabatic Search [62]	Q.-Enhanced Markov-Chain Monte Carlo [63]
	D. & H. Minimization [64]	Simon's Algo. [65]
	Q. Counting [66]	Fermionic QFT [67]
	Q. Monte-Carlo Integral [68]	QCA for Q. Electrodynamics [69]
	Gaussian BS [70]	Q. Final State Shower [71]
	Ising-QUBO [72]	Free-Q.-Field-Theory Ground State [73]
	QAOA [74]	Q. Fock Space Dynamics [75]
	QSDP [76]	Dirac-Equation QW [77]
	Dihedral HSP Algo. [78]	
	Shor [79]	

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Why quantum ?

Fundamentally different point of view! Backed by quantum mechanics.

10 qubits represent a distribution over 1024 elements ≡ 1024-sized “stochastic” vector

+

Distribution allows “negative” probabilities ⇒ Cancellation of probabilistic scenarios

+

Certain impossibility results advocated by quantum mechanics

Classically impossible tasks are now possible.

Better speedup compared to classical techniques.

Better quality of optimization solutions.

Why not (yet) quantum ?

Early stages.

No Quantum RAM (yet)!

Lots of errors - T1, T2, Gate, Readout, …

No clear case of quantum supremacy!

Perceived learning curve.

Thank you!

https://braqiiit.github.io/