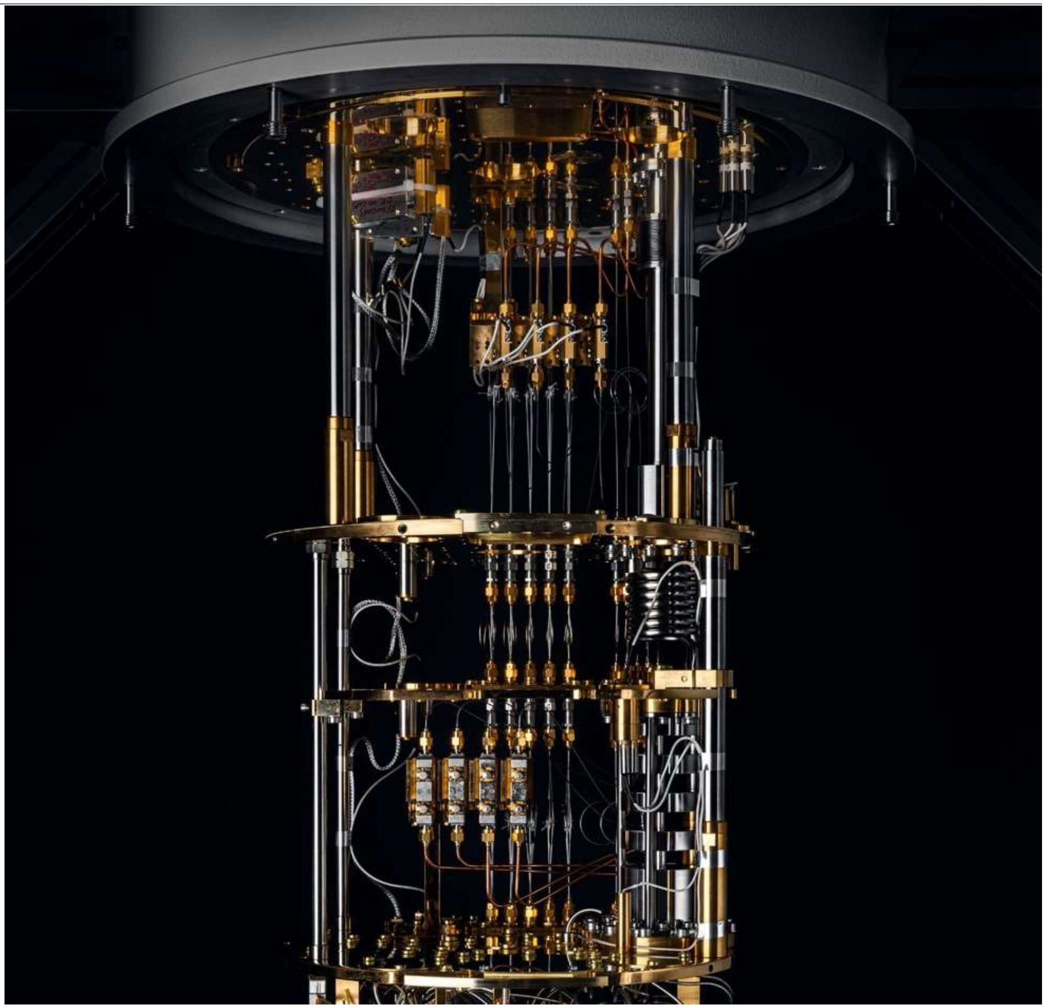
WE BUILD QUANTUM COMPUTERS

Introduction to Quantum Computing and its Applications



Dr. Mikio Nakahara

IQM Quantum Computers

www.meetiqm.com

IQM builds and delivers quantum computers

OUR MISSION

We build world leading quantum computers for the well-being of humankind, now and for the future.

285+
Experts one of the biggest quantum teams in Europe and the world.

On-premises & full access

3 systems sold and delivered to

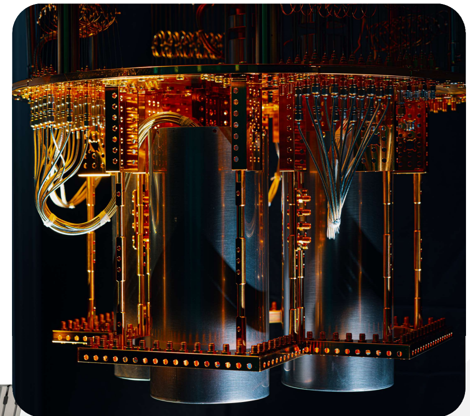
VTT

2 systems sold and delivered to

lrz

Spark sold to Julich SC

JÜLICH Forschungszentrum



Full-stack solutions with **co-design**

Own facilities → **fast turnaround**

IQM's Private Foundry: **600 m2**

200M€+ funding

European Investment Bank

EIC

European Innovation Council

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285+
experts

125+
PhDs

46+
nationalities

200M€
investment

On-premises & full access

Palo Alto - USA


EIB President Werner Hoyer & EIB Vice-President Thomas Östros handing over funding documents

IQM Product and Service Portfolio

On-premise / Product delivery

IQM Spark™

- quantum computer for research and education
- 5 or 20 tunable superconducting qubits with tunable couplers
- Hardware/Software access
- Fast delivery and affordable pricing

On-premise / Product delivery

IQM Radiance™

- State-of-the-art on-premise offering
- Up to 150 qubits
- Integration-layer to HPC centres

Service provider

IQM Services

- IQM Resonance - cloud offering
- IQM Academy
- Quantum education

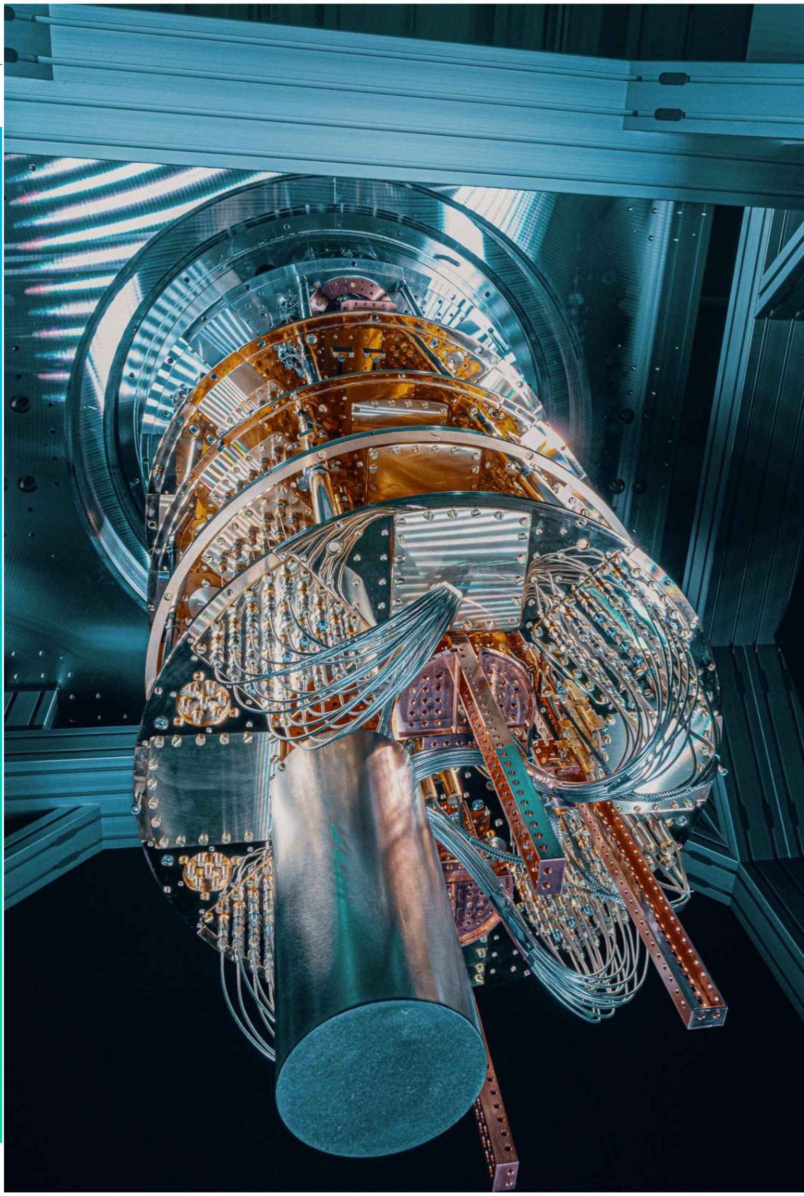
- Part I Overview
- Part II Near Term Quantum: Portfolio Optimization

Before we start our journey

1. Quantum computing will play more and more important roles in our society.
2. The unit of quantum information is qubit instead of bit.
3. The fundamental physics of our universe is quantum physics and relativity. The world we see is just a classical limit of these theories.
4. We don't see quantum phenomena in everyday life since it manifests itself only in a microscopic scale. But note that we doesn't exist without quantum theory. Our universe would not be created without quantum theory.
5. In contrast, we use relativity everyday through GPS and cellphone.

Outline

- Warm Up
- Foundations:
  Qubits, gates and superposition
- Quantum computing applications
- Current era of quantum computing
- IQM's approach to quantum computing
- Conclusion



Warmup: Sorting a list of numbers

Conventional Algorithm

1. Suppose n positive numbers are given. Sort them in increasing order.
2. Find the smallest number and put it the left end.
3. Find the smallest number in the rest and put it next to the smallest number.
4. Repeat it until all numbers are exhausted.
5. This takes $O(n^2)$ steps.

Sorting a list of numbers

8 2 5 3

Sorting a list of numbers

2 8 5 3

Sorting a list of numbers

2 3 5 8

Use spaghetti for sorting

Take-Home Message

1. Our spaghetti computer can sort n numbers in $O(n)$ steps.
   n steps to cut, 2 steps to grab and press them against a table. Pick up one by one takes n steps, hence $2n + 2$ steps.
2. Spaghetti computer is more efficient than digital computer.
   $O(n^2) \gg O(n)$ for $n \gg 1$.
3. How many steps it will take (computational complexity) depends on the resource you use. Quantum computer employes quantum system for computation.

Physics for Information Processing: Mechanical m-mail

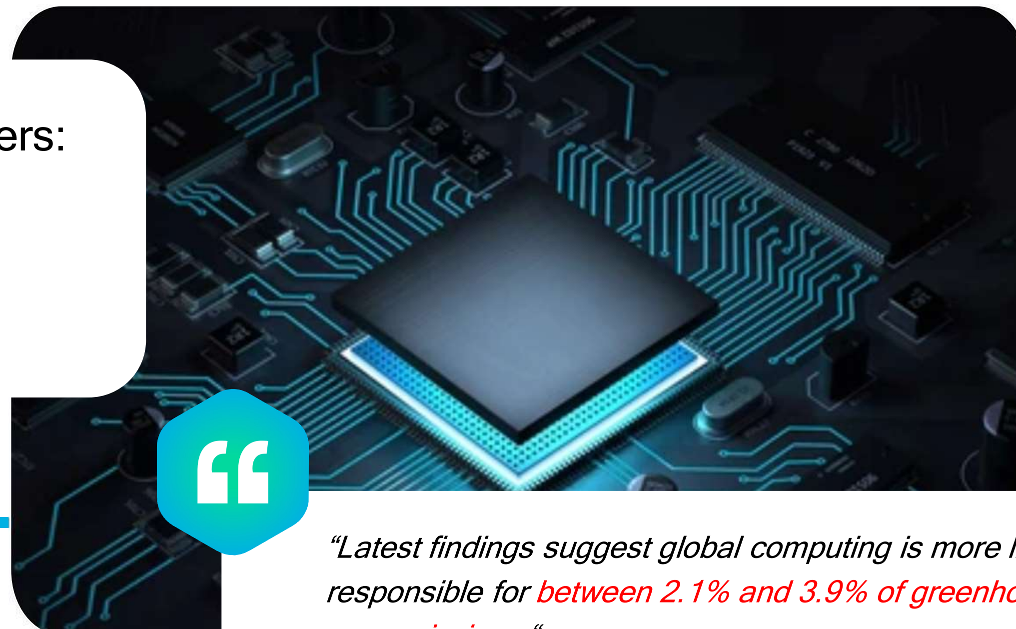
https://www.miraikan.jst.go.jp/exhibitions/future/internet/

A white ball represents 0 while a black ball 1.

There are problems a classical computer cannot (efficiently) solve

Problem with current computers:

- Intractable problems
- Fundamental limits
- Time & power limits



Current approach is not scalable!

"Latest findings suggest global computing is more likely responsible for between 2.1% and 3.9% of greenhouse gas emissions."

21=3*7; easy

1096623520809612220 27=52529305799*2087641373; harder

Quantum Sustainability

Current:

- 5 QB -> 15 kW
- 20 QB -> 32 kW
- 54 QB -> 34 kW
- 128 QB -> 49 kW
- ...

IQM CORE

- 5 QB
- 20 QB
- 54 QB
- ...

- Converging to ≈ 3.5×10^{-1} kW / QB

OPTIMIZE — ≈ 500 QB

- Higher electronics integration
- Cryocooler / compressor efficiency
- Cryogenic HW and cabling density

DEVELOP — ≈ 2000 QB

- Cryogenic electronics
- Wing and signal heat load reduction
- Cryocooler power need decrease

DISRUPT — ≈ 5000 QB

- On-chip electronics
- Heat load minimization per Qubit
- Highly integrated cryo system

	Current	≈ 500 QB	≈ 2000 QB	≈ 5000 QB
Electronics	≈ 1.3×10^{-1} kW / QB	≈ 2.0×10^{-2} kW / QB	≈ 5.0×10^{-3} kW / QB	≈ 1.0×10^{-3} kW / QB
Cryostat vacuum and pumping system	≈ 2.3×10^{-2} kW / QB	≈ 6.0×10^{-3} kW / QB	≈ 1.0×10^{-3} kW / QB	≈ 6.0×10^{-4} kW / QB
Cryo cooler / compressor	≈ 2.3×10^{-1} kW / QB	≈ 7.8×10^{-2} kW / QB	≈ 2.6×10^{-2} kW / QB	≈ 5.0×10^{-3} kW / QB
Total	≈ 3.8×10^{-1} kW / QB	≈ 1.0×10^{-1} kW / QB	≈ 3.3×10^{-2} kW / QB	≈ 6.8×10^{-3} kW / QB

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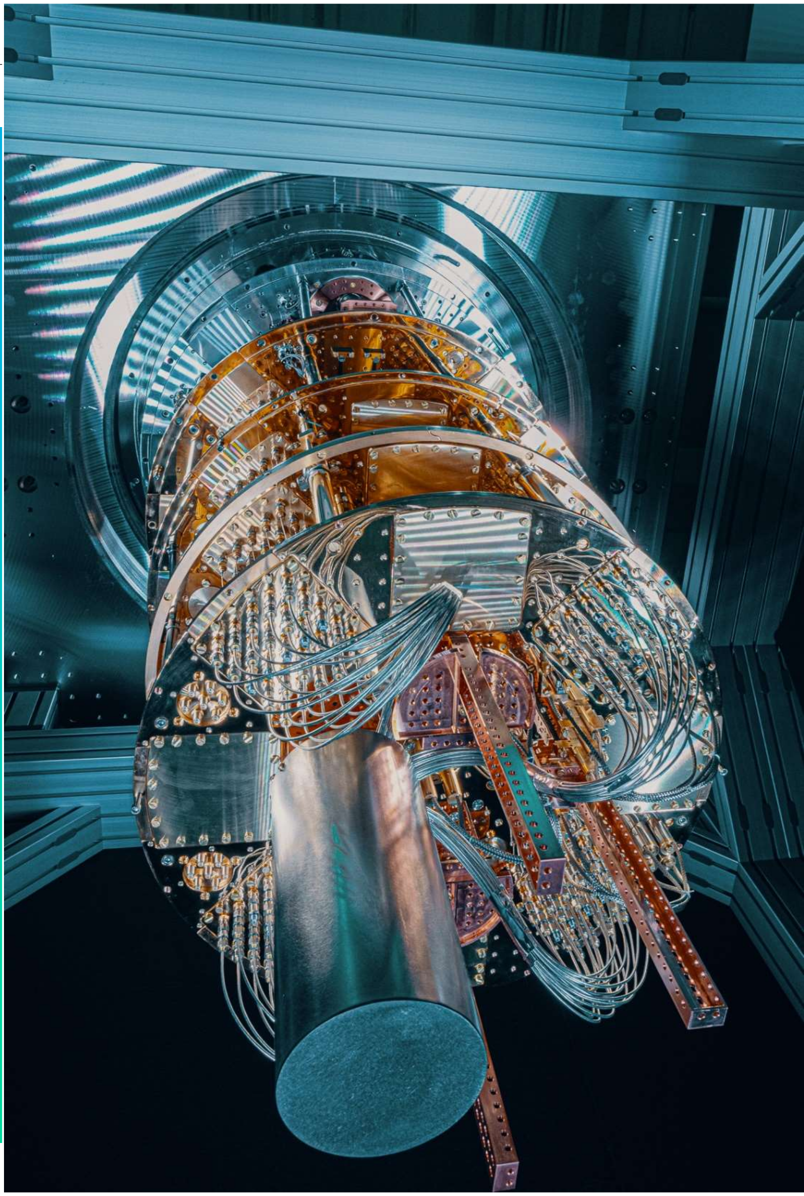
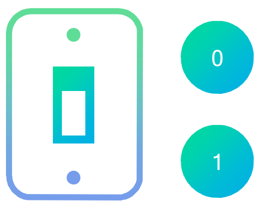


Classical Computer vs. Quantum Computer

Classical bit

2 distinct states

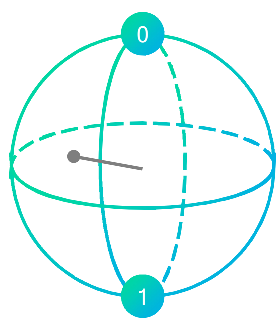


switch on/off

State can be measured repeatedly without affecting the state

Quantum bit = Qubit

Superposition of 2 basis states



Vector on the surface of a sphere

Measurement of the state projects it to 0 or 1 randomly and destroys the original superposition state

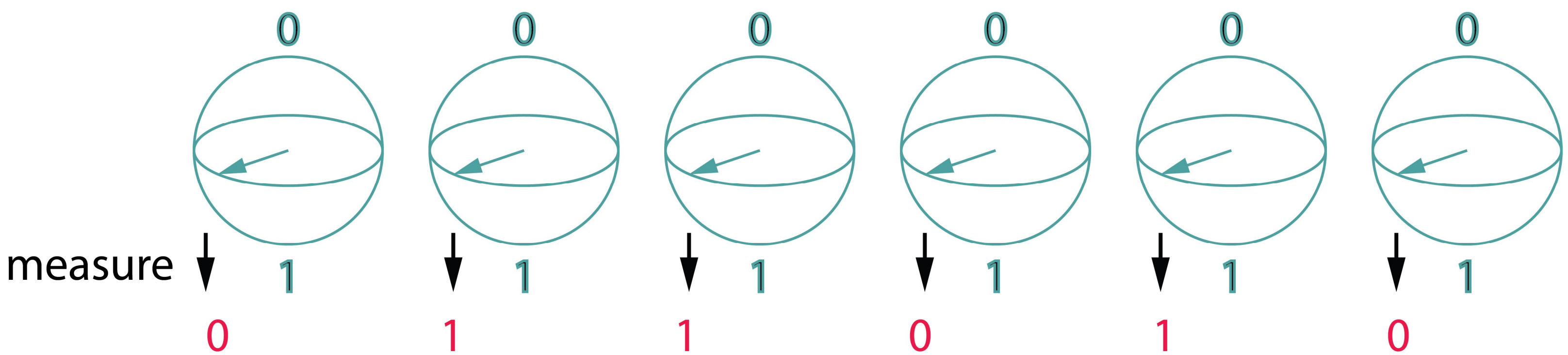
Classical Computer vs. Quantum Computer

- Measurement of a quantum state projects it to 0 or 1 randomly and destroys the original superposition state.
- If someone measures a qubit before you, the state will change to 0 or 1 when you measure it.
- Eavesdropping is detectable.
- Quantum key distribution (distributes classical encryption key securely: BB84). Already commercialized.

https://events.geant.org/event/453/contributions/436/attachments/273/408/2021-03-17_GEANT_Summary_Toshiba.pdf

Classical Computer vs. Quantum Computer

- Measurement of the state projects it to 0 or 1 randomly and destroys the original superposition state. Quantum random number generator.



- Most random number generators currently available are “pseudorandom number generators” based on some algorithm, potentially hackable.
- Quantum random number generator is already commercialized.

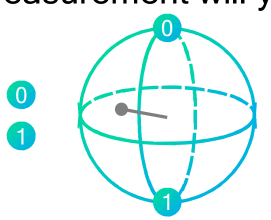
What is quantum computing?

Classical computer vs. Quantum computer

Quantum computers follow the rules of quantum physics.

Bit vs. Qubit (quantum bit)

A bit can be either 0 or 1, while a qubit can be in a superposition: qubit can be both 0 and 1 simultaneously. Measurement will yield either 0 or 1.



Two qubits can be entangled. Measuring one directly impacts the other.

→ 1 qubit can be in a superposition of 2 basis states

→ A 1 bit state can be just one out them

1Qubit

Basis states:

- 0
- 1

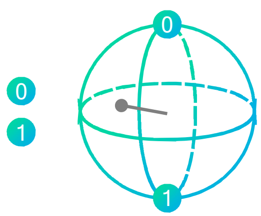
What is quantum computing?

Classical computer vs. Quantum computer

Quantum computers follow different rules than classical computers - those of quantum physics.

Bit vs. Qubit (quantum bit)

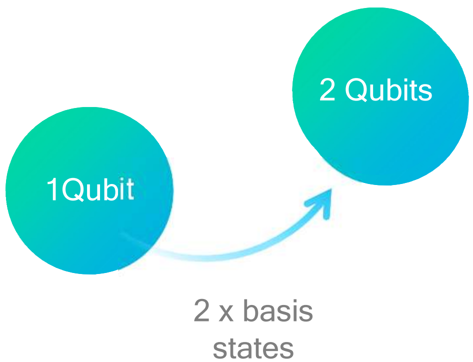
A bit can be either 0 or 1, while a qubit can be in a superposition: qubit can be both 0 and 1 at the same time. Measurement will yield either 0 or 1.



Two qubits can be entangled. Changing one directly impacts the other.

→ 2 qubits can be in a superposition of all 4 basis states

→ A 2-bit state can be just one out them



Basis states:

- 00
- 01
- 10
- 11

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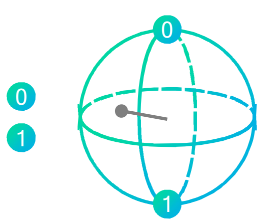
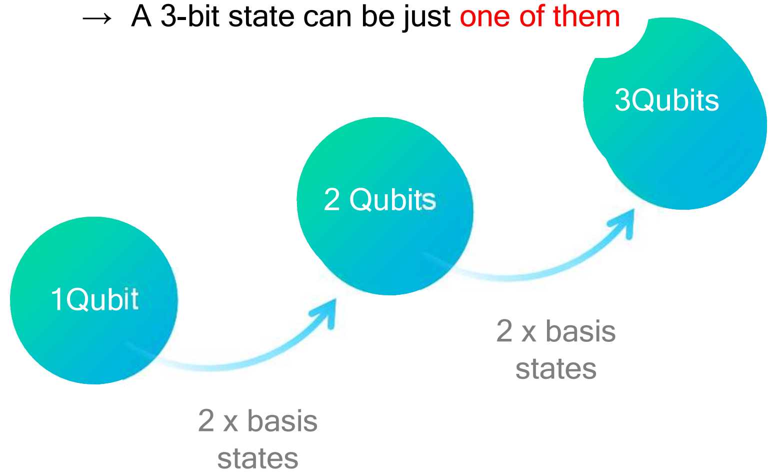


Two qubits can be entangled. Changing one directly impacts the other.

000	001	010	011
100	101	110	111

→ 3 qubits can be in a superposition of all $2^3 = 8$ basis states

→ A 3-bit state can be just one of them



Basis states:

- 000
- 100
- 010
- 110
- 001
- 101
- 011
- 111

What is quantum computing?

Classical computer vs. Quantum computer

Quantum computers follow different rules than classical computers - those of quantum physics.

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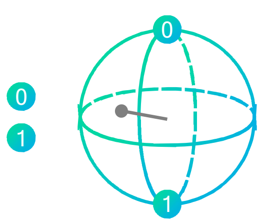

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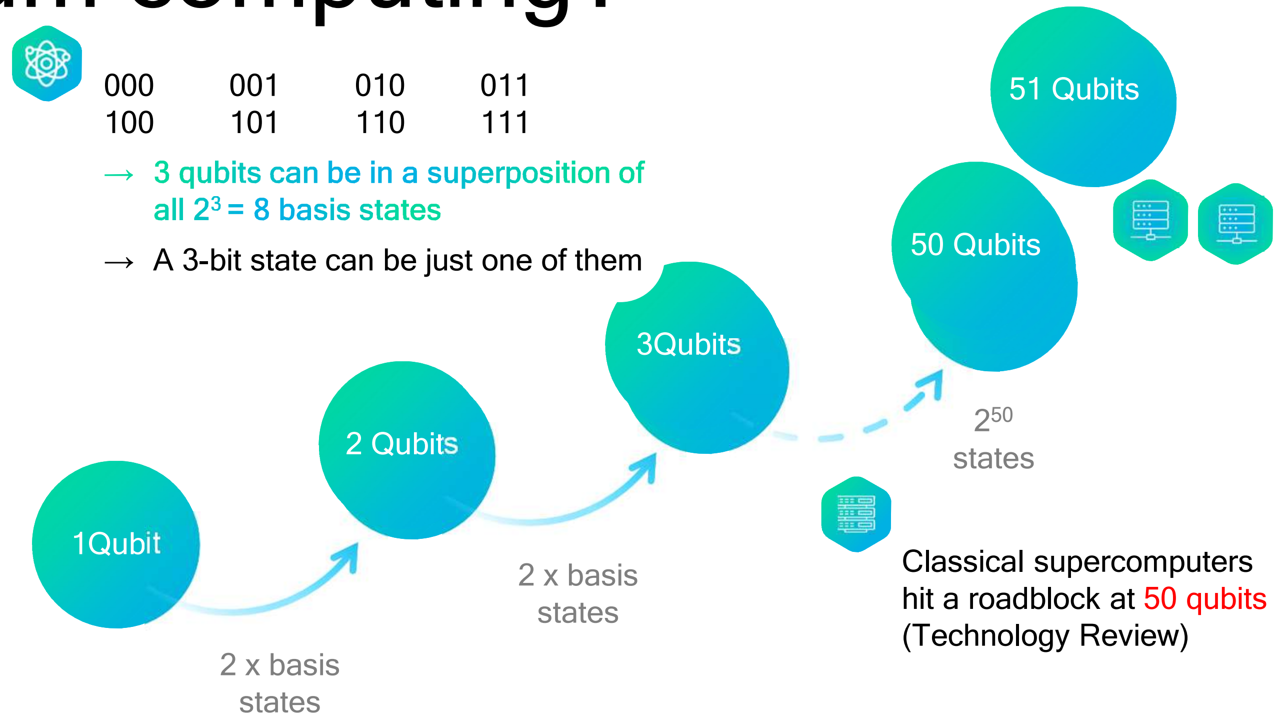

Classical supercomputers hit a roadblock at 50 qubits (Technology Review)

What is quantum computing?

000 001 010 011
100 101 110 111

→ 3 qubits can be in a superposition of all $2^3 = 8$ basis states

→ A 3-bit state can be just one of them

The Eddington number; the number of protons in the observable universe. Current estimates is approximately $10^{80} \sim 2^{270}$.

Classical computer vs. Quantum computer

Quantum computers follow different rules than classical computers - those of quantum physics.

Bit vs. Qubit (quantum bit)

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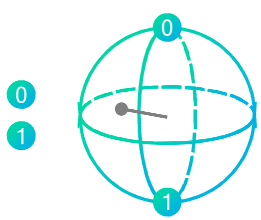

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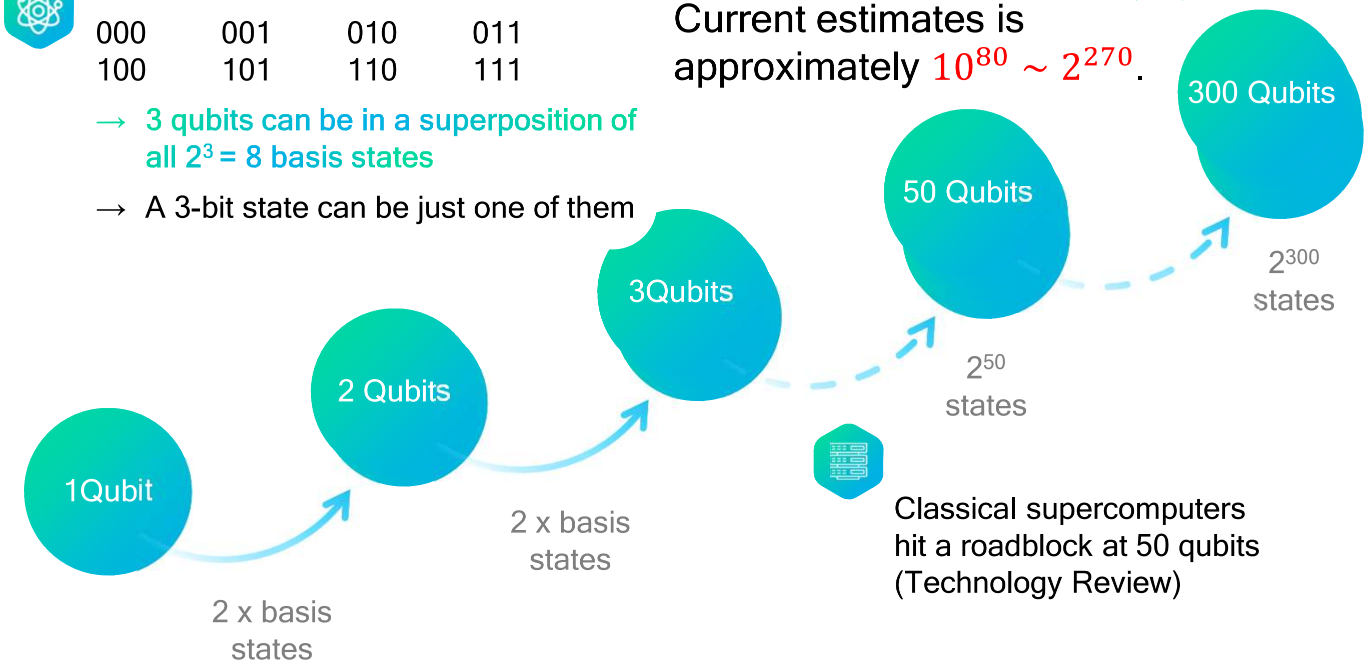


Classical supercomputers hit a roadblock at 50 qubits (Technology Review)

→ Exponential increase in computational capacity

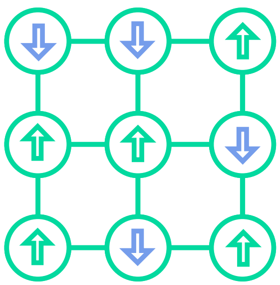
→ Enables new algorithms and solutions to previously intractable problems

But how to work with those qubits?

IQM

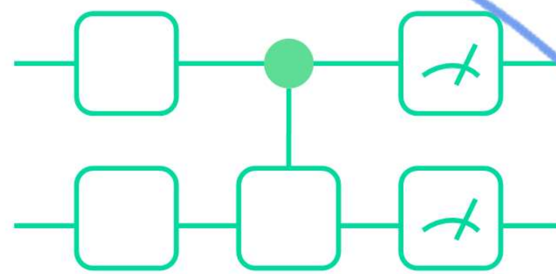
Different ways to work with qubits

Small magnets



Adiabatic Quantum Computing/Quantum annealing

designed for particular combinatorial optimization problems, which are reduced to finding the smallest number among 2^n numbers. This is trivial for $n = 4$ but highly nontrivial for $n = 300$ even with spaghetti.

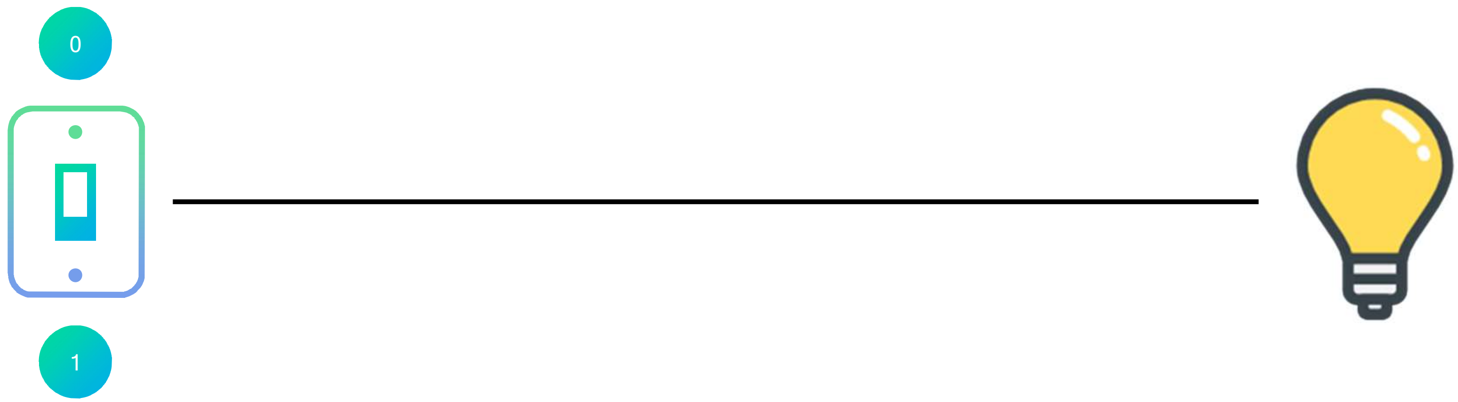


Gate-based quantum computing

designed for universal (quantum) computing

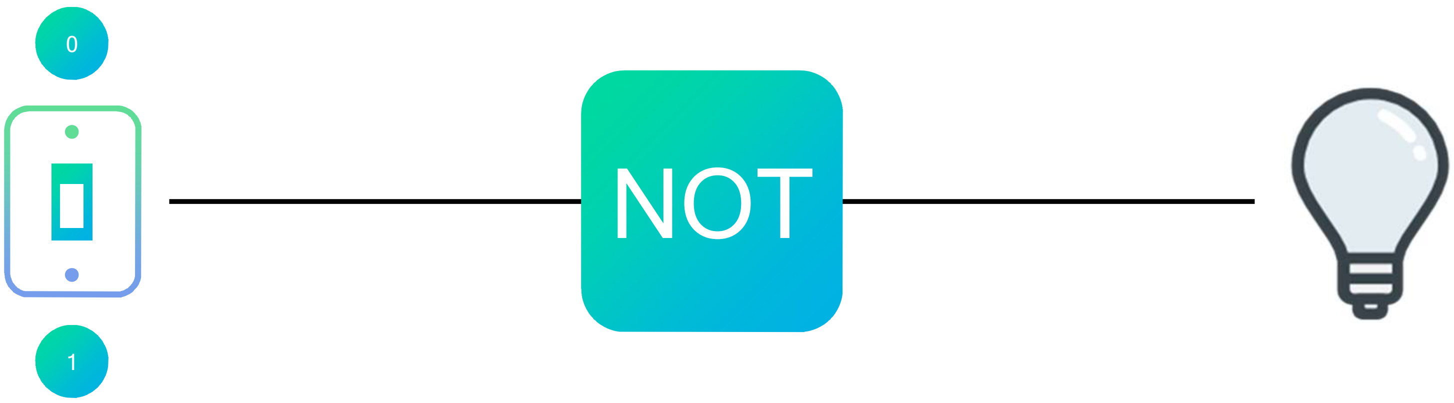
Conventional computer: bits

- Bits are the foundation of conventional computers



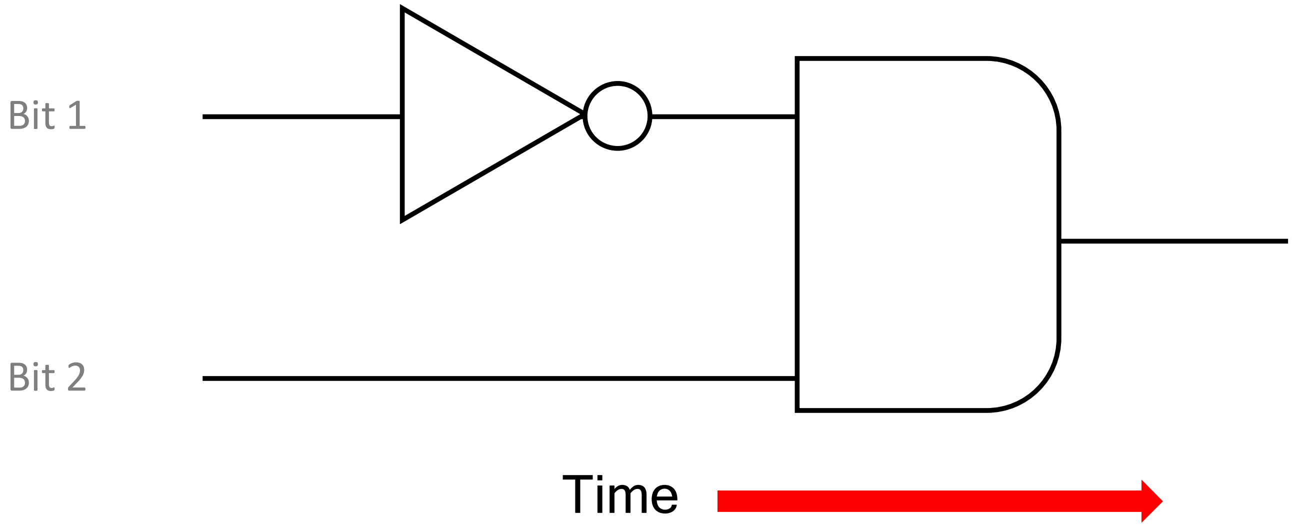
Conventional computer: working with bits

- Information processing is performed with the help of logical gates



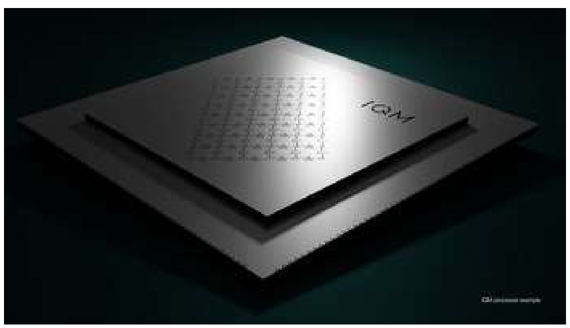
Conventional computer: algorithms

- Multiple gates form a (logical) circuit
- An algorithm is implemented in a sequence of gates
- Circuits are represented as a time sequence like musical score. A gate is a note.

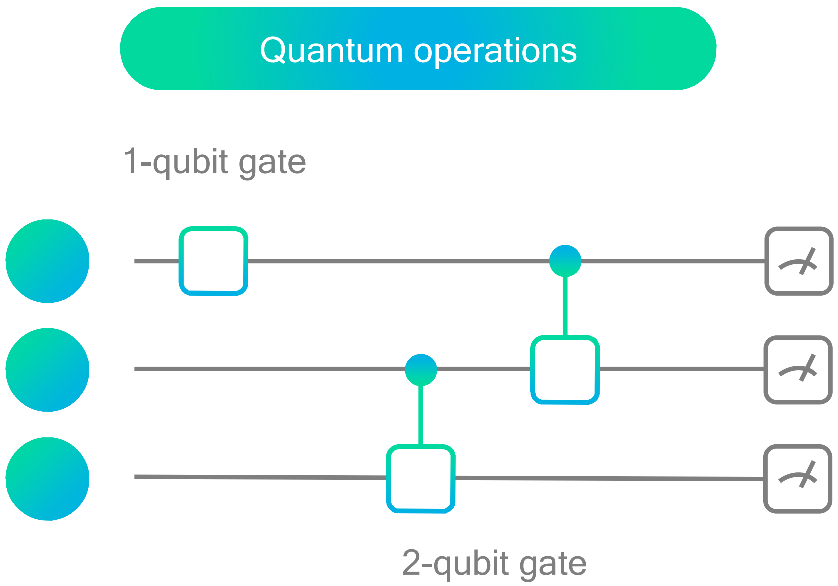


Quantum computers: algorithms

CPU



IQM QPU



Universality Theorem: Any quantum algorithm can be decomposed into 1- and 2-qubit gates

Quantum computing is reversible. Does not produce heat, does not require power. Power is required only for control electronics and refrigerator. (~ 30kW)

Superposition and Entanglement

X = 0 + 1 — X is a superposition of 0 and 1.

Measurement outcome of X is either 0 or 1.

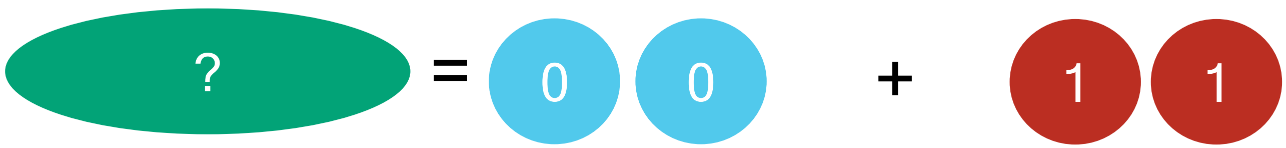
X X X = (0 + 1) (0 + 1) (0 + 1)

= 0 0 0 + 0 0 1 + ...

... + 1 1 1

XXX is called a tensor product of 3 Xs. Separable.

Superposition and Entanglement

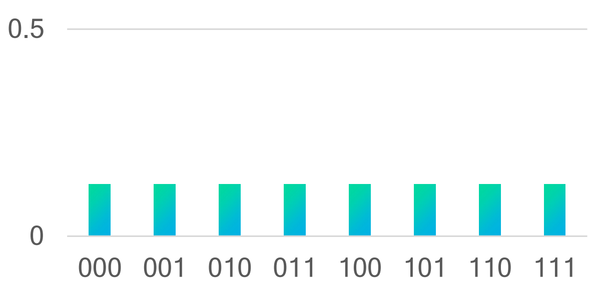


- If the first qubit is measured and 0 is obtained, the second qubit is also 0.
- If the first qubit is measured and 1 is obtained, the second qubit is also 1.

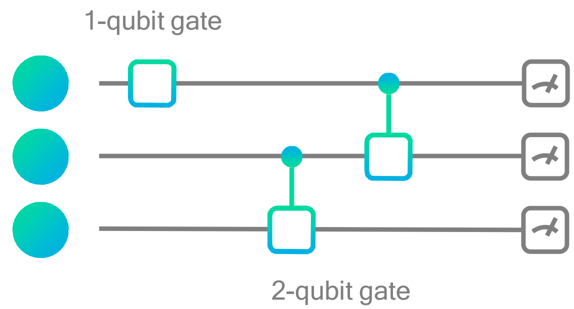
There are QKDs that make use of entangled states (E91, BBM92).
Eavesdropping changes an entangled state to a product state.

Quantum computing: algorithms

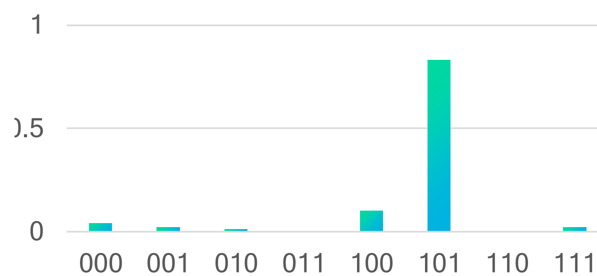
Prepare initial state



Quantum algorithm



Measurement outcomes



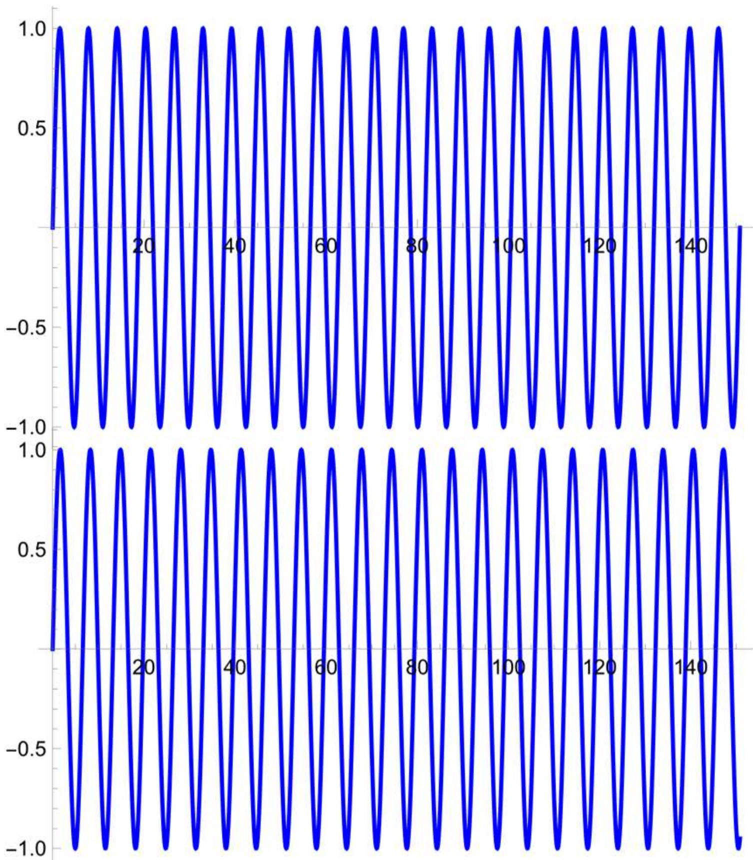
Prepare initial quantum state

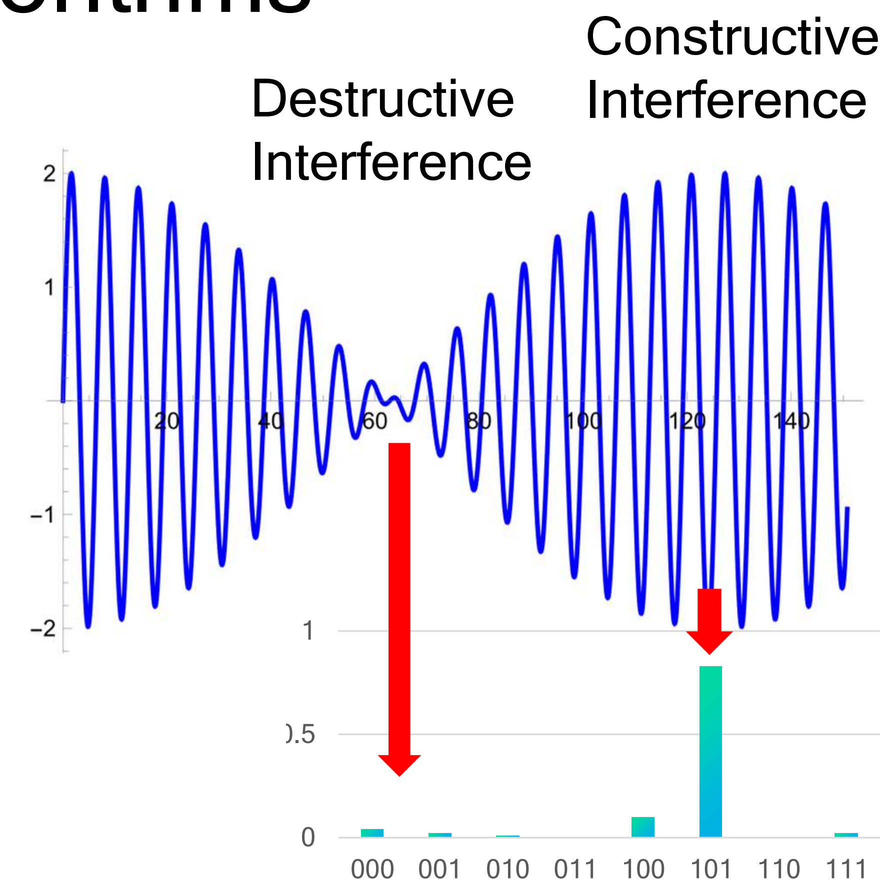
Use interference to make wanted outcomes more likely

Measure multiple times

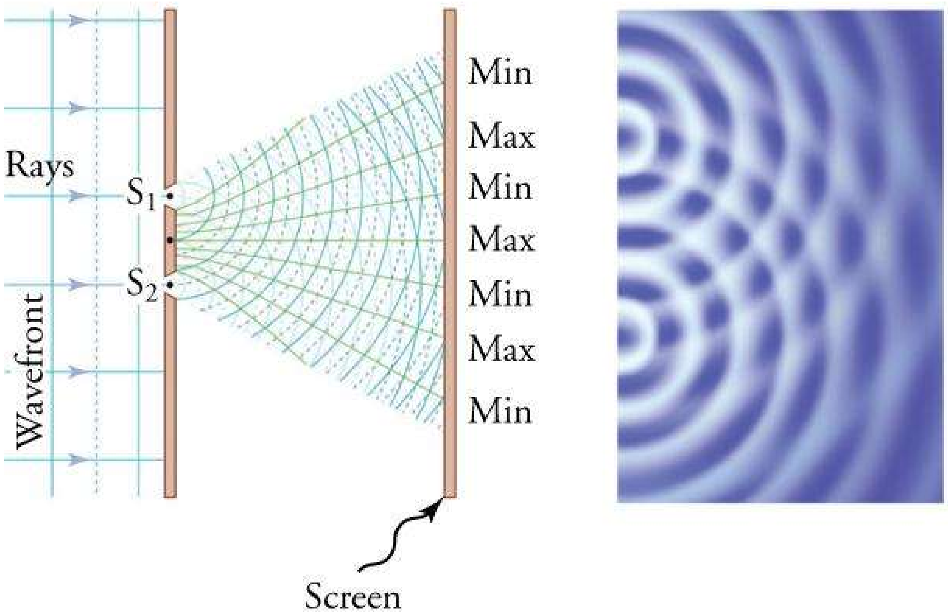
If the initial state is a superposition of 2^n states, the quantum circuit acts on 2^n states simultaneously! Quantum parallelism. $2^{270} \simeq 10^{80}$!

Quantum computers: algorithms

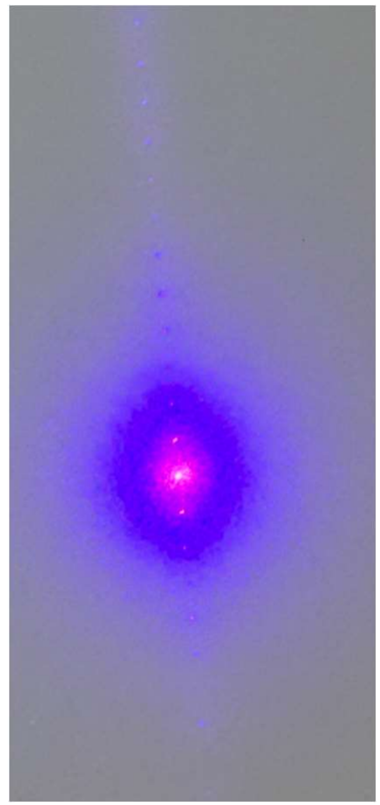


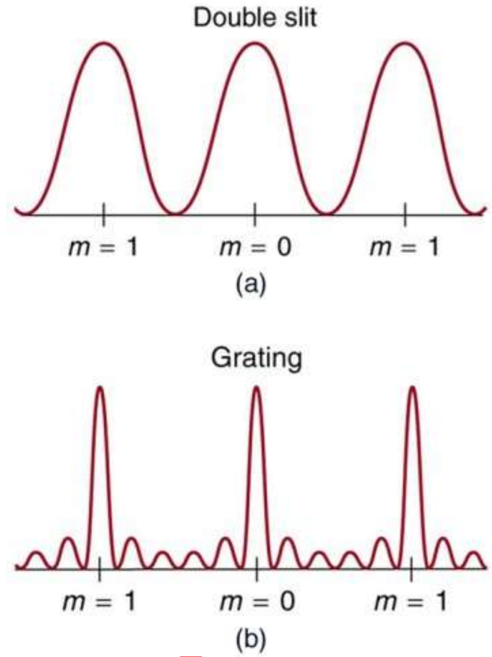


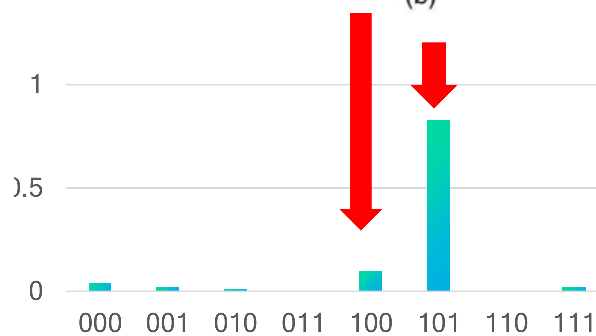
Quantum computers: algorithms



(a) (b)



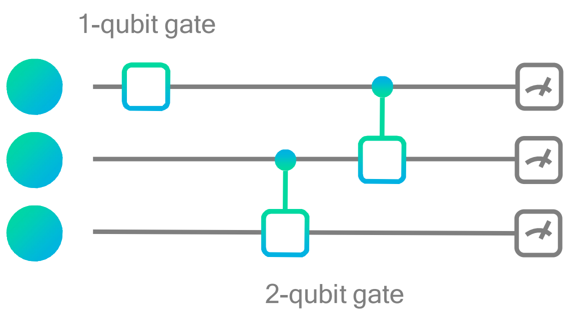




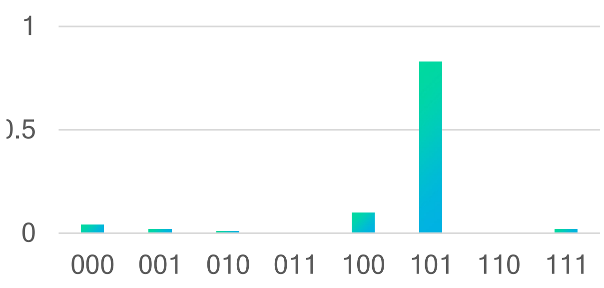
Quantum computers: algorithms

- Quantum algorithms leverage superposition and entanglement to enable new algorithms and manipulate qubits via quantum gates.
- Quantum algorithms explore a superposition of solution paths simultaneously. Quantum parallelism.
- Quantum algorithms use interference to amplify the likelihood of correct solutions to be measured, without knowing the solutions in advance.

Quantum operations

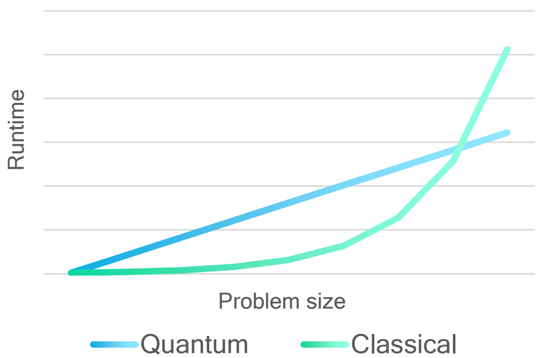


Measurement outcomes



Quantum algorithms vs. Classical algorithms

Quantum algorithms can provide up to exponential speedup for certain tasks in domains like simulation, optimization and machine learning.



Quantum computers do not speed up existing algorithms but allow new types of algorithms

Take-Home Message

- Unit of quantum information is qubit, which is a vector. As such, a qubit can be a superposition of 0 and 1.
- Multiple qubits can be entangled, which is not decomposable into a product of single qubit states. Separable states, which have classical analogue, are tiny, tiny fraction of qubit states. QC makes use of entangled states, which gives exponentially powerful computational power compered to its classical counterpart.
- Quantum algorithms are represented in terms of quantum circuits (quantum music score) by which the likelihood of the target state being measured is enhanced by interference.

Quantum circuit to decompose 21 into 3 and 7. From J J Vartieinen, A O Niskanen, M Nakahara and M M Salomaa, Phys. Rev. A 70, 012319 (2004).

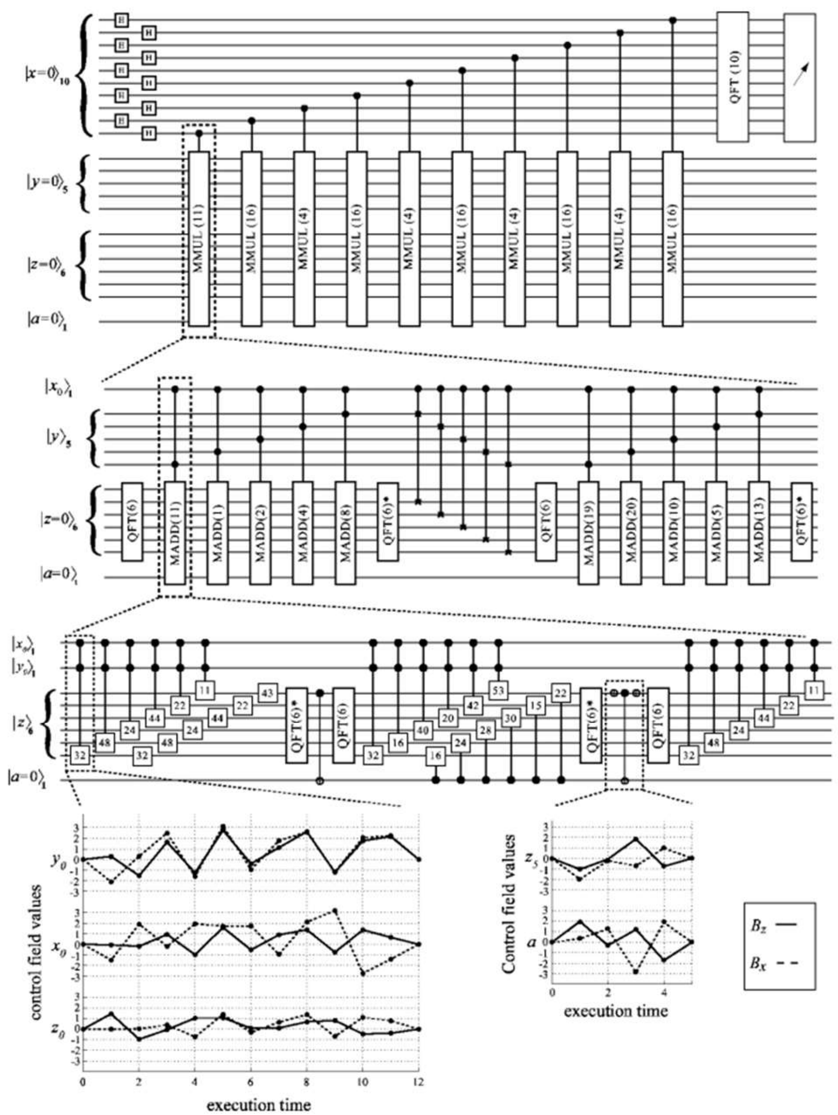
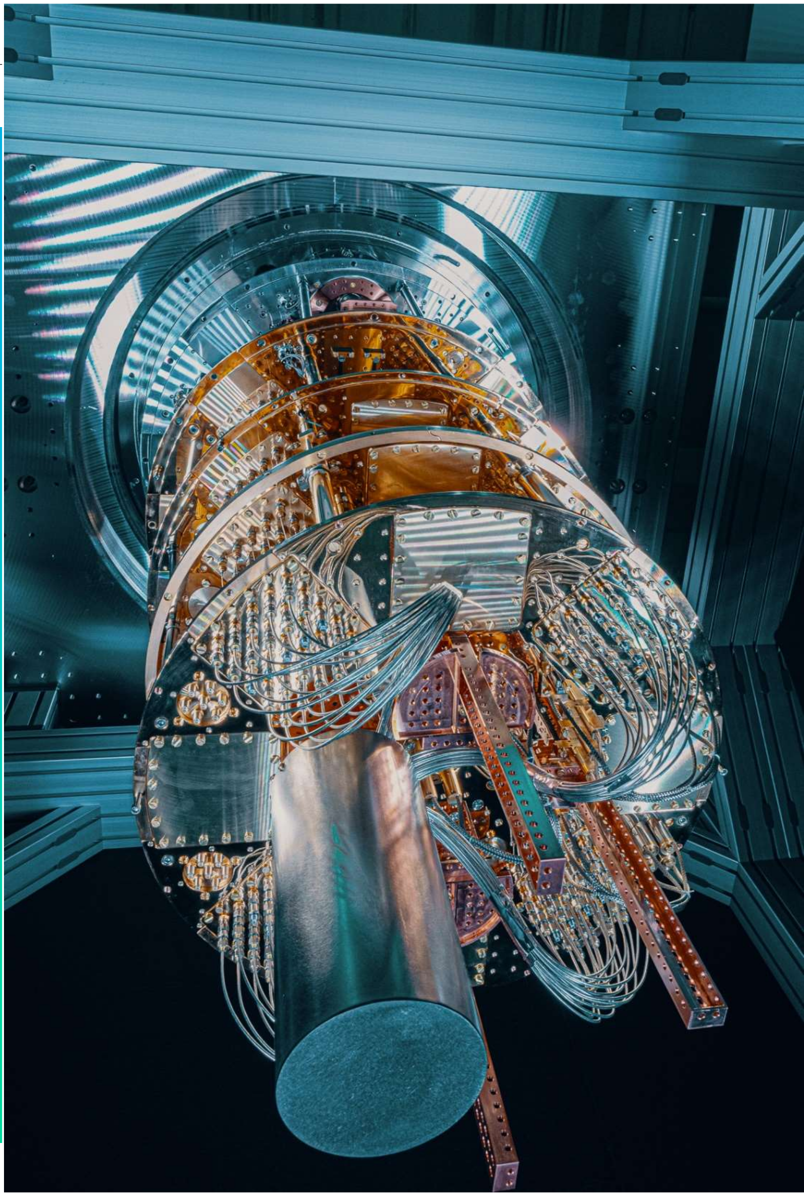


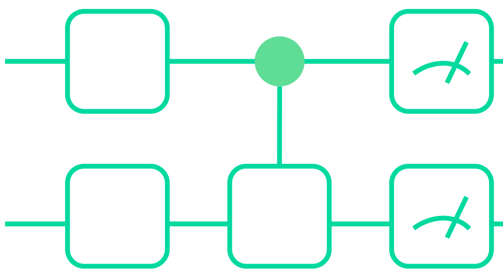
FIG. 5. Quantum circuit for Shor's algorithm factoring the number 21 with the parameter value $a=11$. The full circuit is shown topmost and the decompositions of the modular multiplier and adder blocks are indicated with dashed lines. The gates in the circuit have their conventional meanings, except that we denote a phase-shift gate by a box with a single number ϕ in it meaning that the phase of the state $|1\rangle$ is shifted by $e^{2\pi i\phi/2^n}$ with respect to the state $|0\rangle$. Two examples of numerically optimized parameter sequences are also shown.

Outline

- Getting started
- Foundations:
  Qubits, gates and superposition
- **Quantum computing applications**
- Current era of quantum computing
- IQM's approach to quantum computing
- Conclusion



Quantum computing applications encompass three areas



Quantum simulation

Material science, pharmacy, biology, chemistry, high energy physics

Optimization

Logistics, processes, portfolios, risks

Artificial intelligence / machine learning

Model training, pattern recognition

Use-cases across sectors

Healthcare

- Drug discovery, Simulation of molecular interactions
- Improved diagnostics on small data
- Catalyst & enzyme design
- Personalized medicine
- …

Energy

- Power grid optimization
- Energy distribution & demand management
- Demand forecasting
- Wind energy simulation
- …

Supply chain & logistics

- Supply chain & logistics optimization
- Capacitated vehicle routing
- Optimized itineraries
- …

Environment

- Climate simulation
- Solar power capture
- Carbon capture
- …

Finance

- Near-real-time risk assessment
- Portfolio optimization
- Derivative pricing
- …

Industrial goods

- Development of materials (e.g. Aerospace)
- Optimization of industrial designs (chips, sensors on car, …)
- …

Services

- Advertisement optimization
- Improved search
- …

Insurance

- Rating premium
- Risk analysis
- …

Retail

- Recommender systems
- Dynamic pricing
- …

QUANTUM COMPUTING EXPO TOKYO Participants (2022)

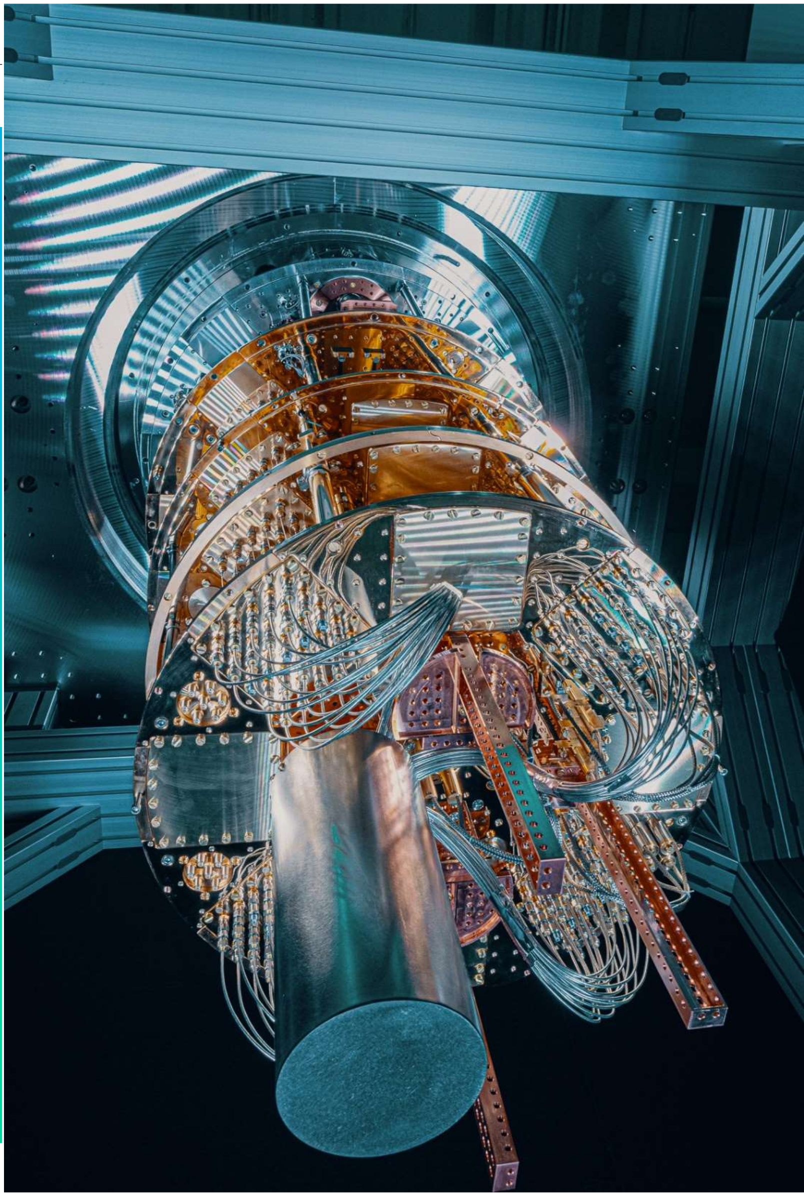
- https://www.nextech-week.jp/hub/en-gb/exhibit/qc.html

QUANTUM COMPUTING EXPO TOKYO Participants (2023)

- https://www.nextech-week.jp/hub/ja-jp/exhibit/qc.html

Outline

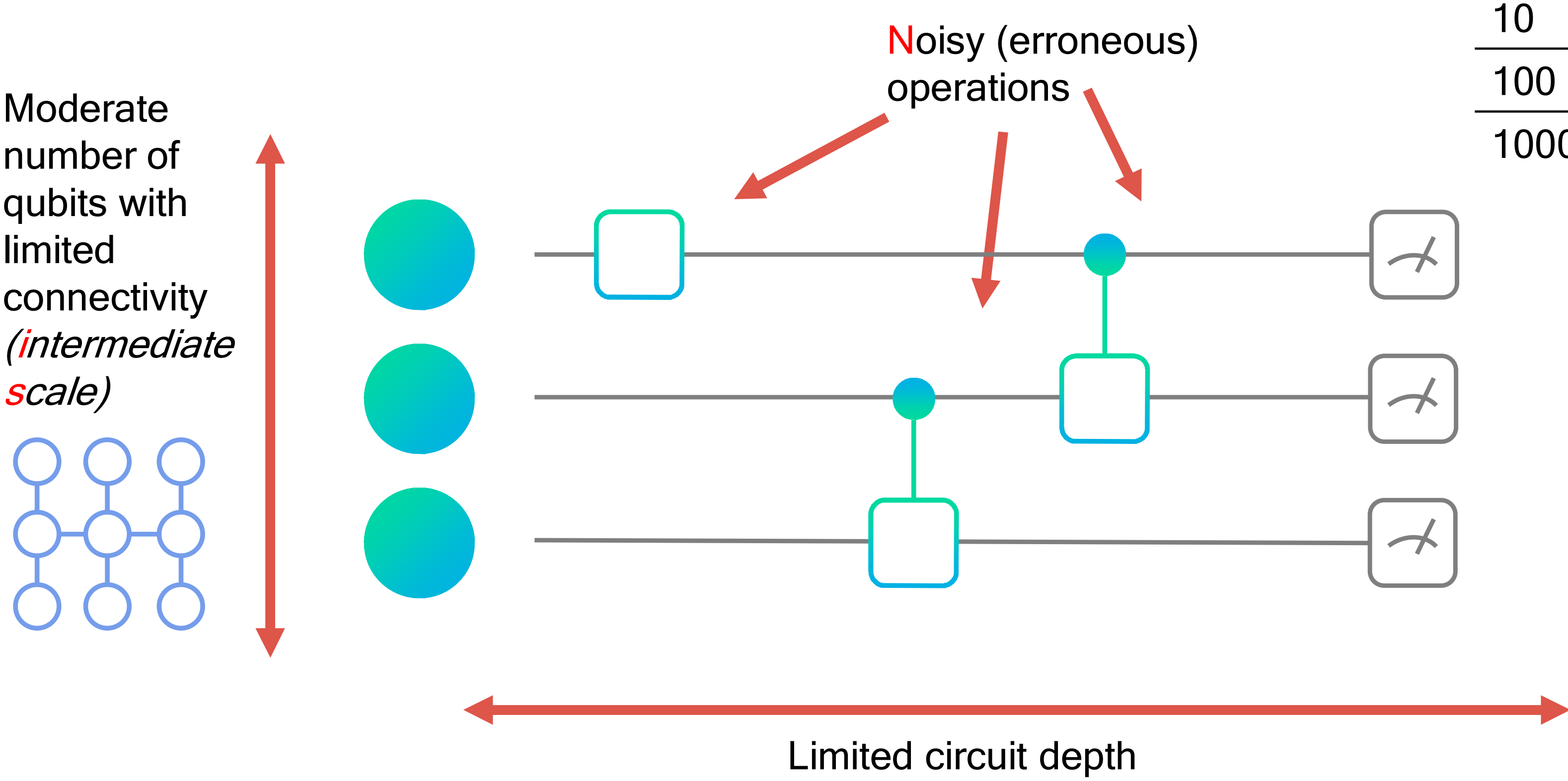
- Getting started
- Foundations:
  Qubits, gates and superposition
- Quantum computing applications
- Current era of quantum computing
- IQM's approach to quantum computing
- Conclusion



Quantum computers: NISQ era

# gates in algorithm	Algorithm fidelity
1	99.9%
10	99.0%
100	90.5%
1000	36.8%

Error rate: 1/1000 = 0.1%

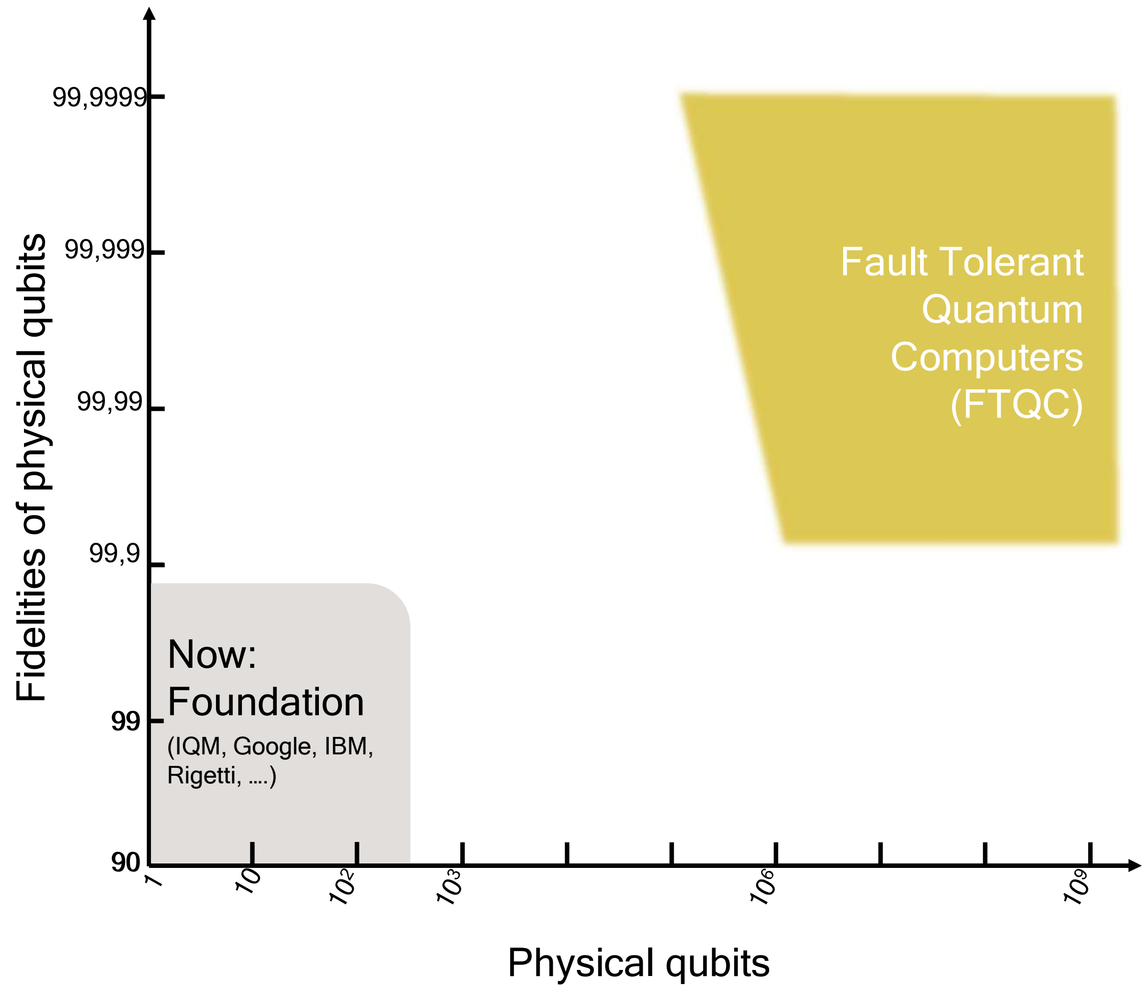


NISQ and FTQC

- Horizon: Fault Tolerant (FT) area

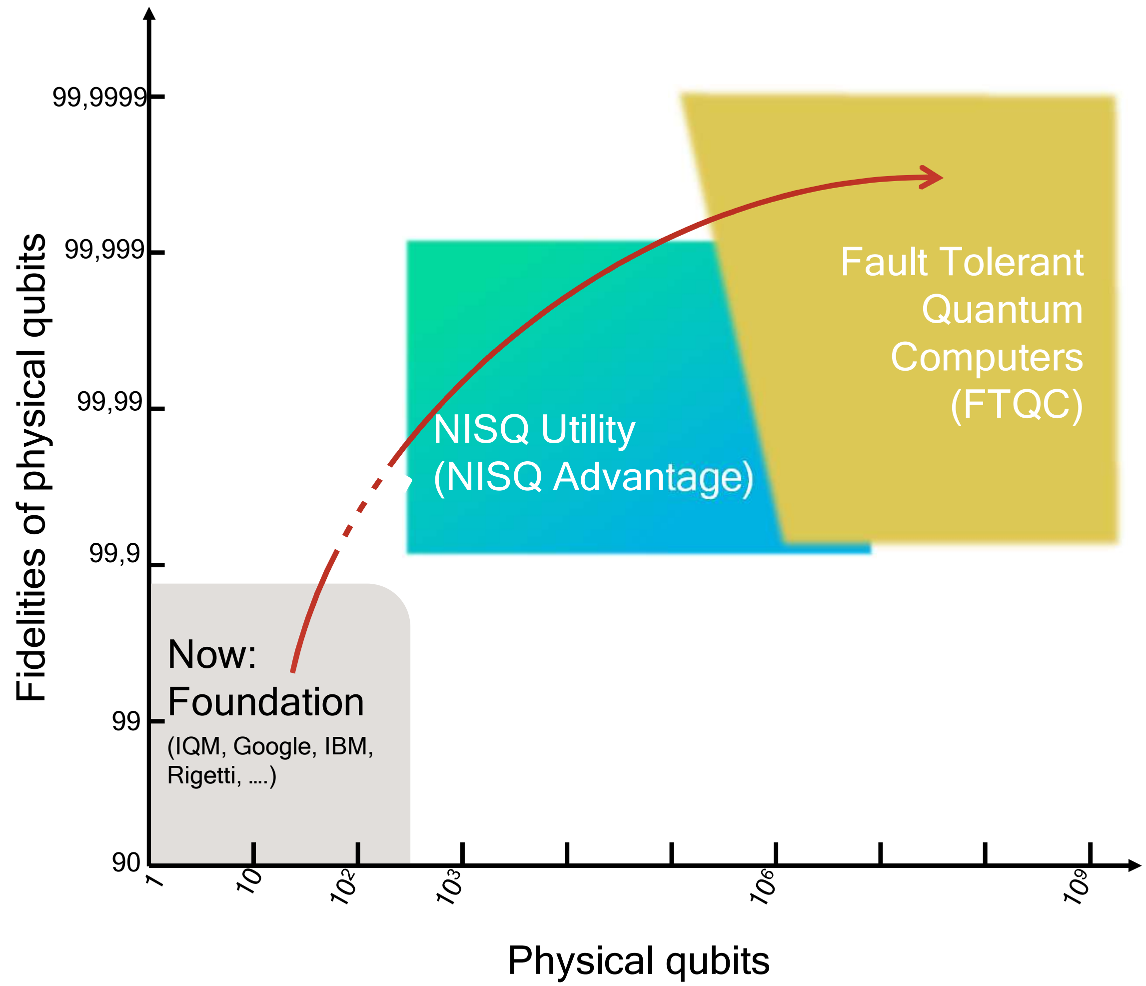
Why so complex?

- Error correction is based on redundancy
- 1 single fault tolerant logical qubit requires multiple physical qubits
- Noise needs to be reduced below a certain threshold



NISQ and FTQC

- Horizon: Fault Tolerant (FT) area
- But before that: Blue region (NISQ Advantage)
  - Hybrid approaches
  - Potential for NISQ quantum utility



Quantum Computing Is Becoming Business Ready (Boston Consulting Group)

https://www.bcg.com/publications/2023/enterprise-grade-quantum-computing-almost-ready

What can fault-tolerant quantum computer do?

- Prime number factorization cannot be done in polynomial time classically. It takes exponentially long time to factor $N = p \times q$.
- It takes billions of years to decompose a large N. This fact is utilized in the RSA cryptosystem. We can do internet shopping safely thanks to this.
- Shor's algorithm can factor a large composite number quantum mechanically in reasonable time.
- Fortunately, the algorithm requires a large number of qubits and FT gates, which is beyond the currently available NISQ QC.
- Are we safe for the time being? No! "Store now, decrypt later (SNDL)" attack.
- Post-Quantum Cryptography (PQC) is an active field of research.

https://en.wikipedia.org/wiki/NIST_Post-Quantum_Cryptography_Standardization
https://csrc.nist.gov/Events/2024/fifth-pqc-standardization-conference

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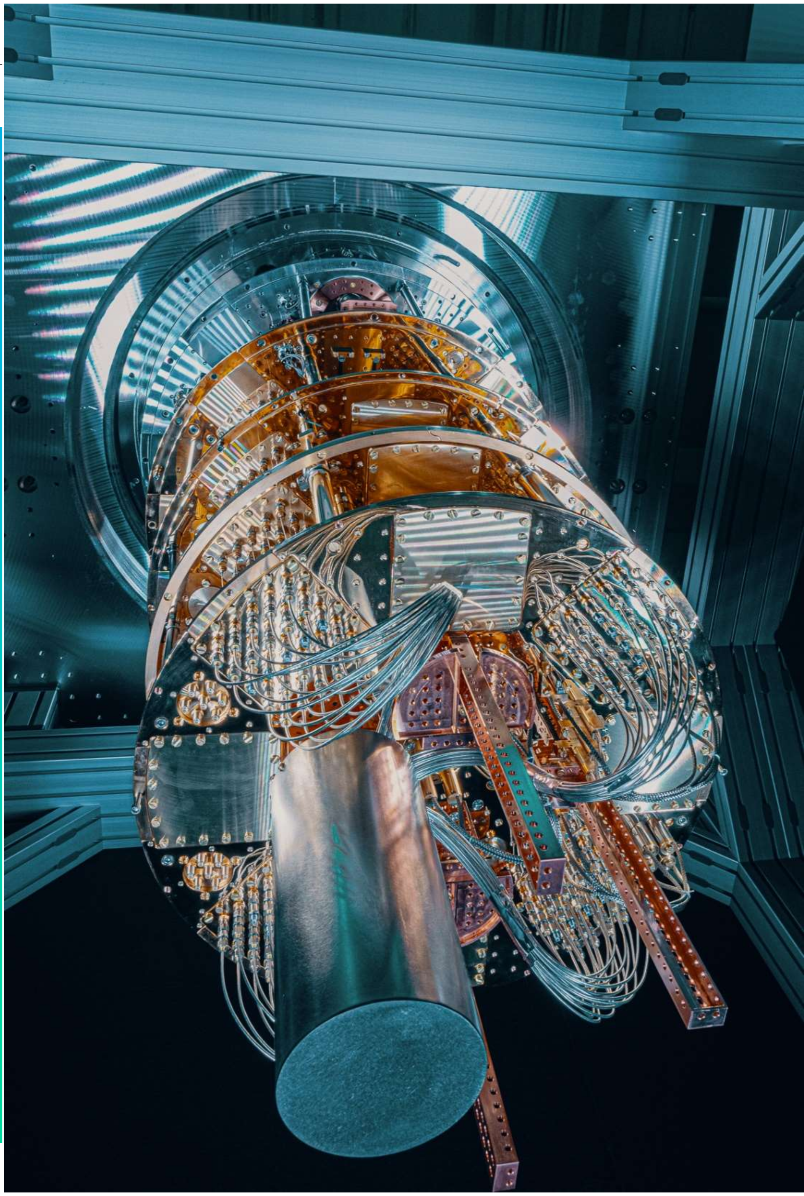


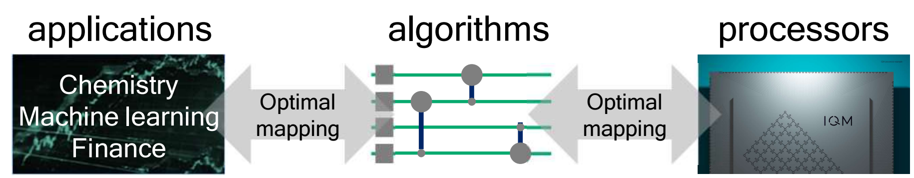
IQM: Unlocking early industry applications with the unique co-design approach

One-of-a-kind approach to industry applications

- Hardware efficiency through application-specific solutions (QuASICs) using a unique Co-Design approach

Faster time-to-market for industry applications

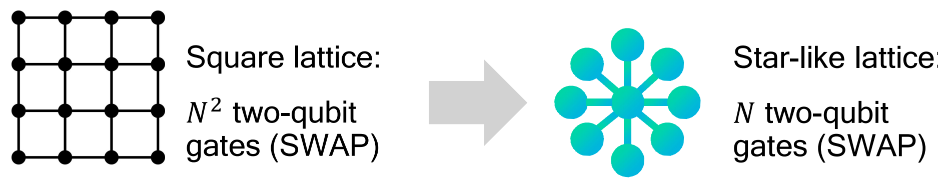
- Less qubits required compared to general-purpose approach
- Fewer gates required compared to general-purpose approach



Example: Algorithm for improving NMR imaging

- Adopted chip geometry to reduce hardware overhead

→ Better gate efficiency by using a star-shape chip geometry



Take-Home Message

- Full-fledged fault-tolerant QC is still beyond our reach.
- QC currently available is a NISQ (Noisy Intermediate-Scale Quantum) computer. There are many useful algorithms when it is combined with classical computer. Simulation of physical systems, optimization, machine learning etc.
- FT QC is expected to crack codes. Post Quantum Cryptography is an active area of research to fight against "store now, decrypt later" attack.
- QC produces enormous amount of business opportunities. Potential of $10-100B for each use case.
- IQM offers on-premises quantum computer while most vendors offer cloud services. On-premises quantum computer is mandatory when security must be guaranteed.

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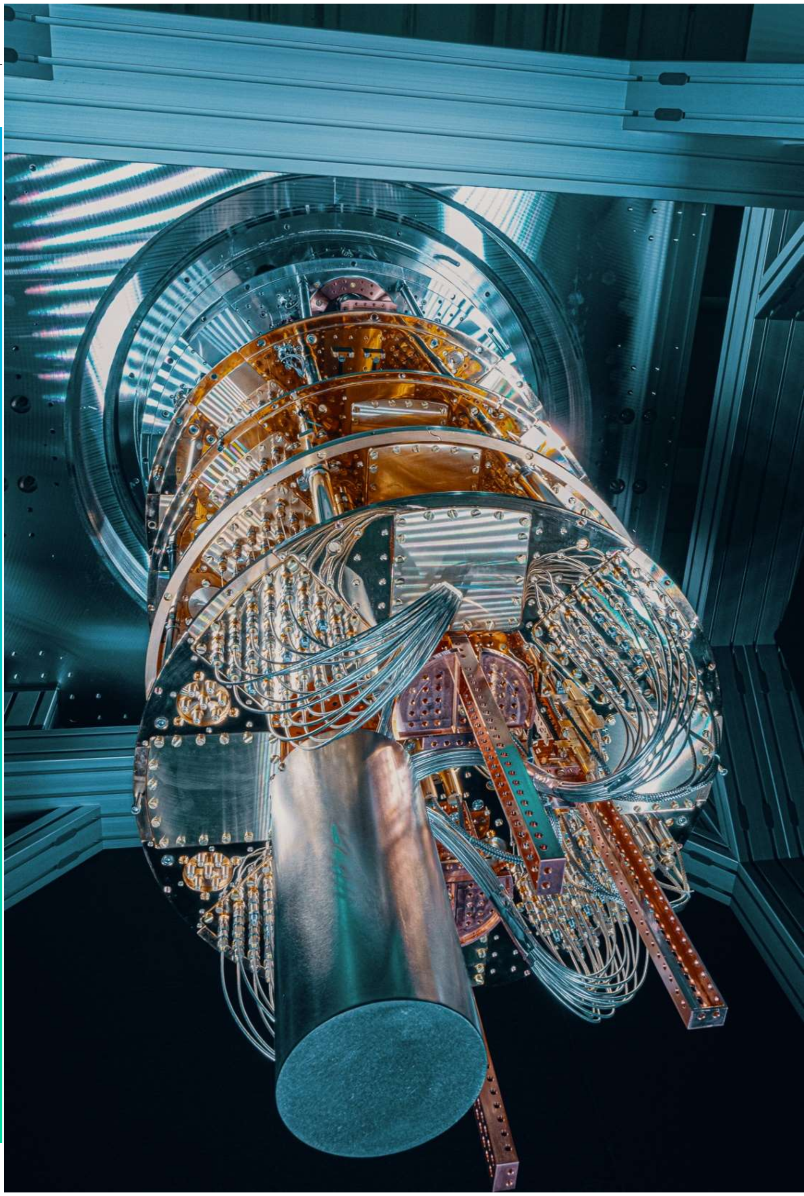
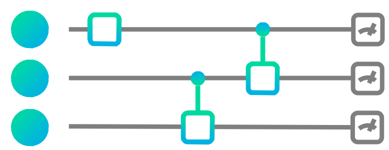
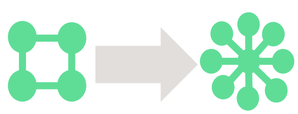


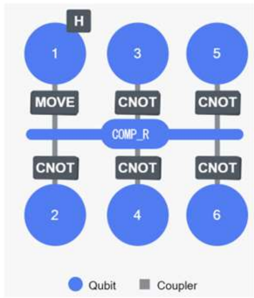
Conclusion

- Quantum computing can solve problems where conventional computers reach limits
- This requires clever algorithms that make optimal use of quantum properties of qubits

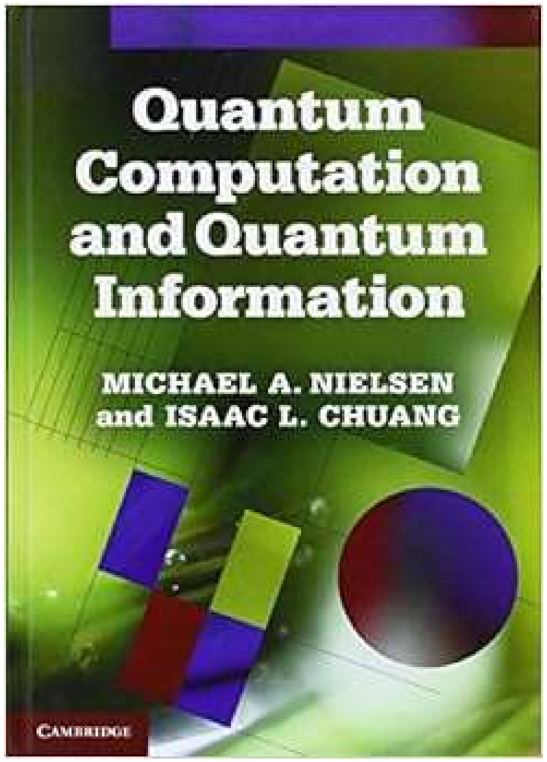


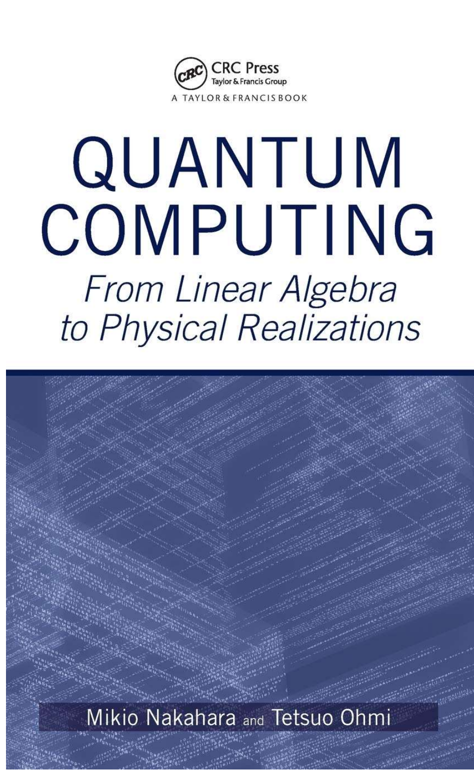
- Currently there are challenges to overcome; however, early adopters are prime to profit the most
- Co-Designing QuASICS as a mean to reducing the time to early industry applications

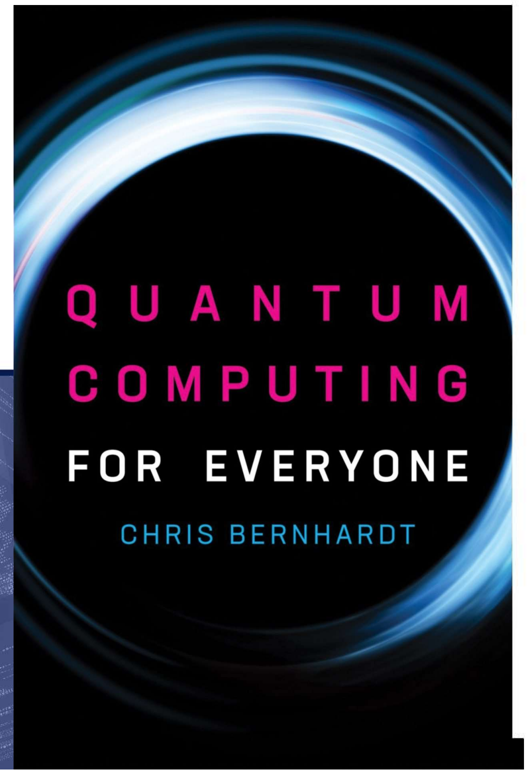


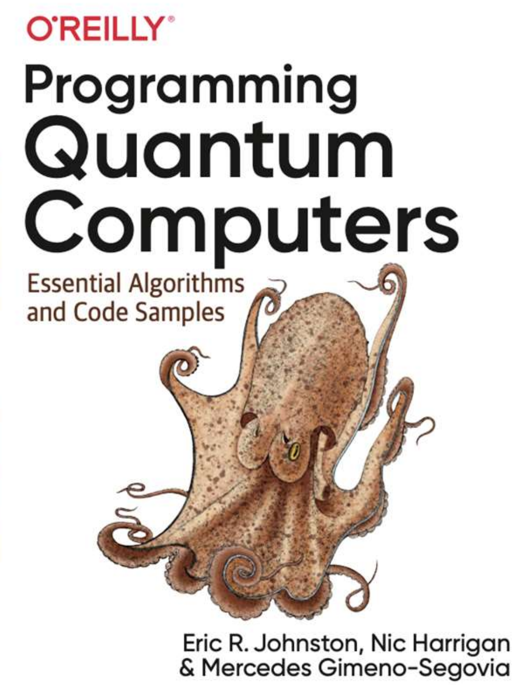


Recommended books









IQM

WE BUILD QUANTUM COMPUTERS

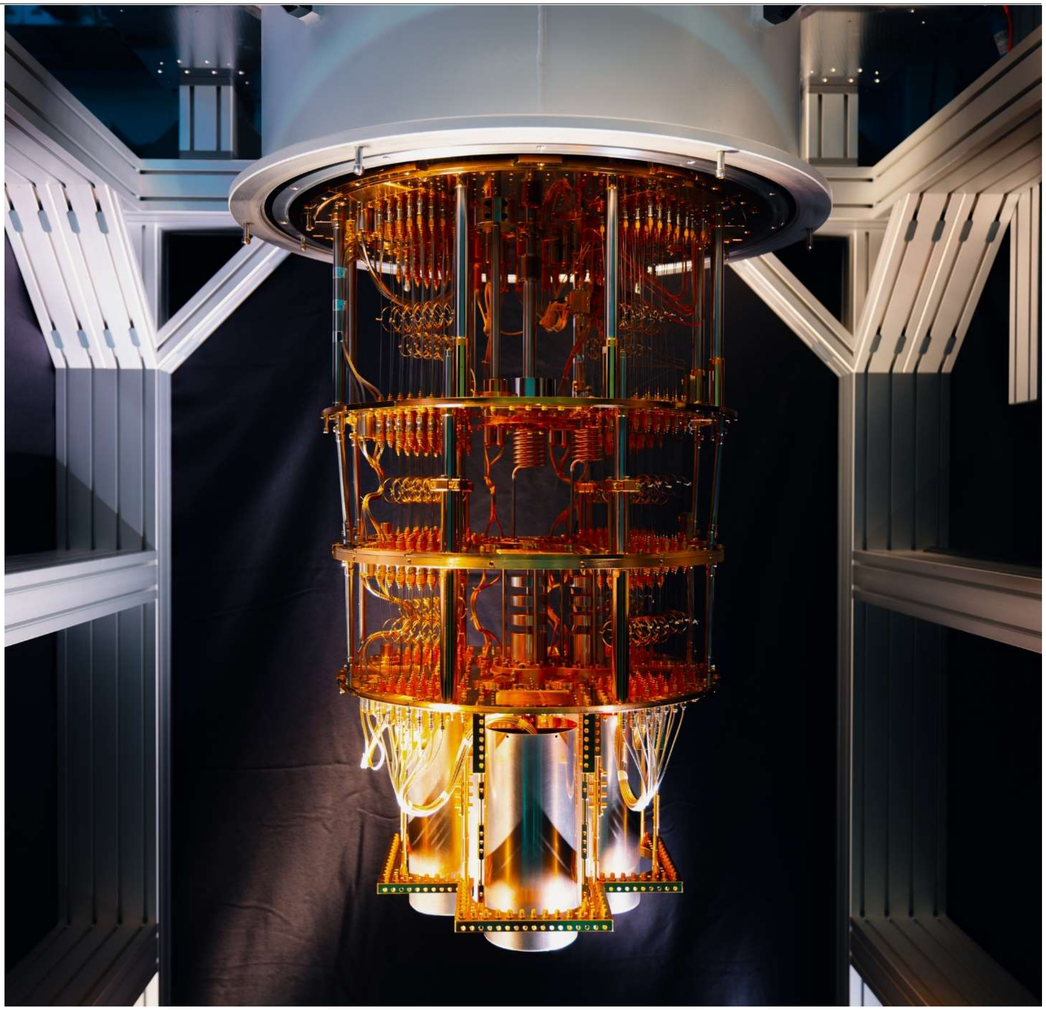
Part II
Quantum algorithms in the NISQ era: Portfolio Optimization

(slightly more technical)

Dr. Mikio Nakahara

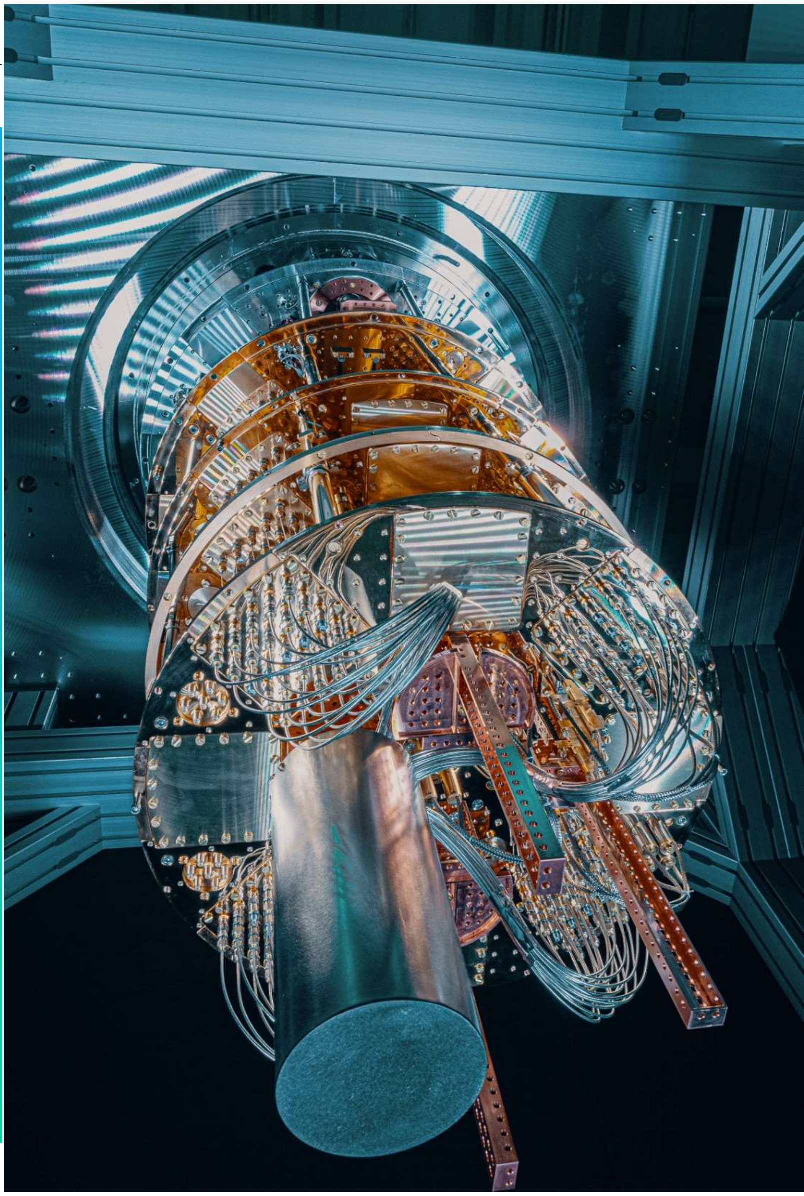
Quantum Education Manager, IQM

www.meetiqm.com



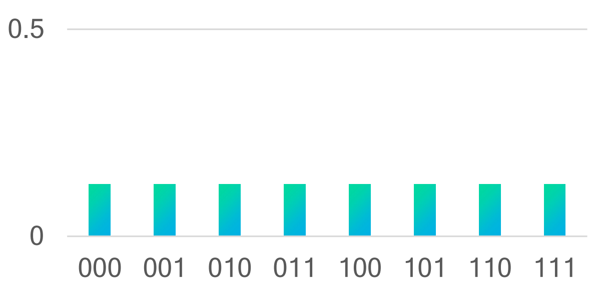
Outline

- Practical applications with quantum algorithms: algorithms for the NISQ era



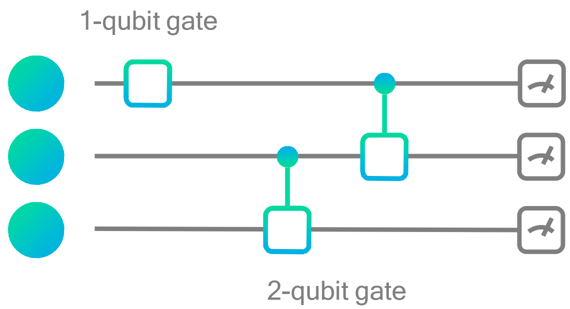
Quantum Algorithms, recap.

Prepare initial state



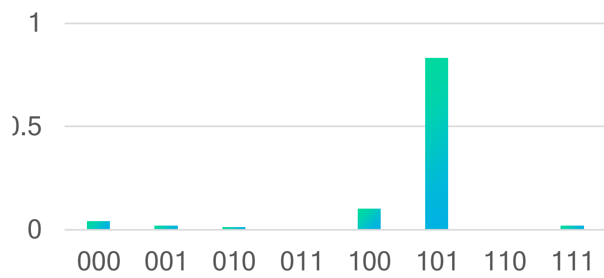
Prepare initial quantum state

Quantum algorithm



Use interference to make wanted outcomes more likely

Measurement outcomes

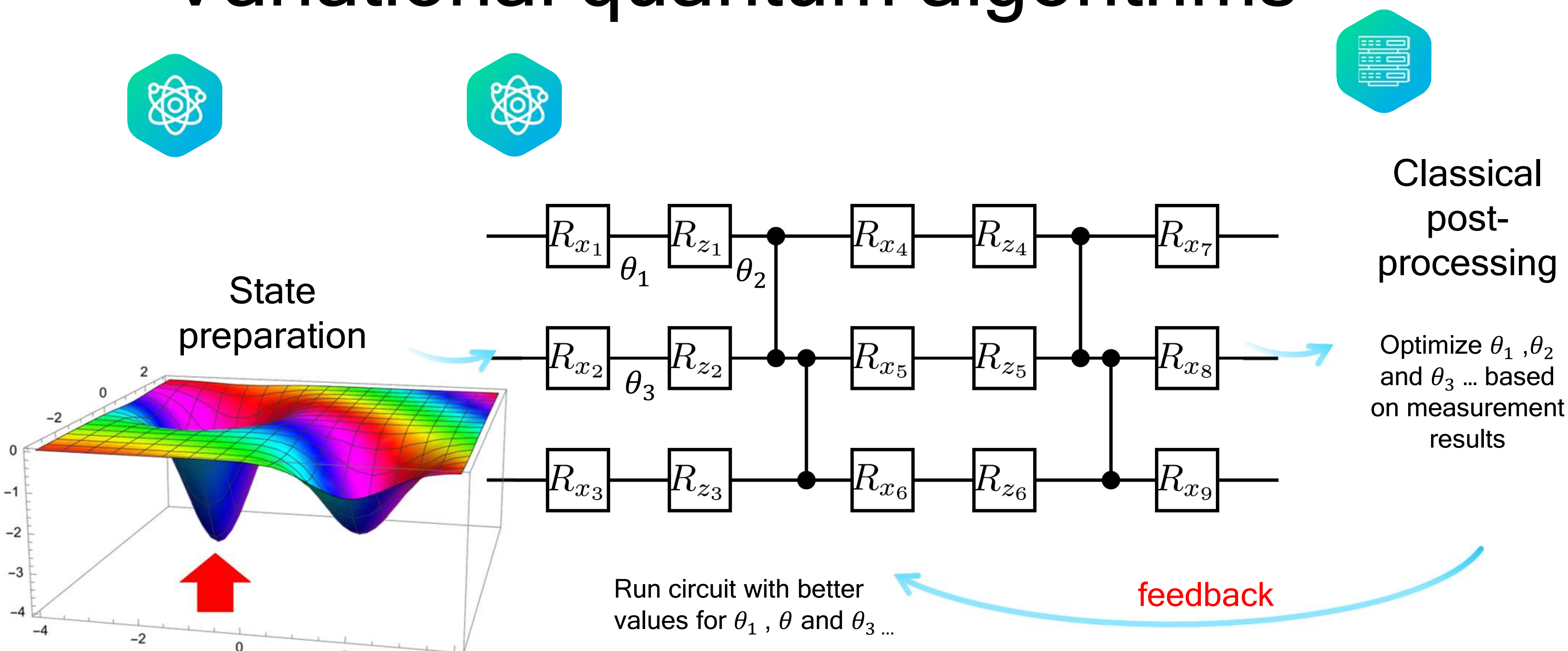


Measure multiple times

Near-term quantum algorithms

- They should solve useful problems
- They should require a moderate number of qubits
- They should work without error correction
- The circuit depth should be moderate

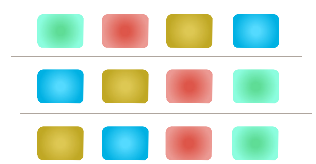
Variational quantum algorithms

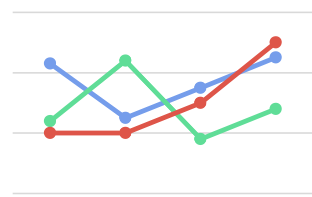


Cost function $f(\theta_1, \theta_2, \ldots)$ is easily evaluated with a quantum computer. It is minimized with a classical computer. Can get reasonable results without QECC.

Example: Optimization with a quantum computer

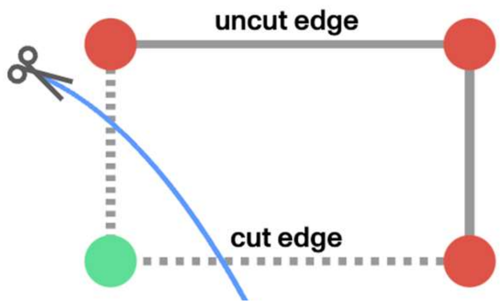
- Heuristic algorithm designed to find approximate solutions for combinatorial optimization problems
- Potential to be used to solve a wide range of combinatorial optimization problems, including:
  - Minimization: cost, distance, length of a traversal, weight, processing time, material, energy consumption, number of objects
  - Graph problems, such as finding best paths to travel
  - Scheduling problems, such as scheduling a set of jobs on a set of machines
  - Financial problems, such as portfolio optimization
  - Maximization: profit, value, output, return, yield, utility, efficiency, capacity, number of objects

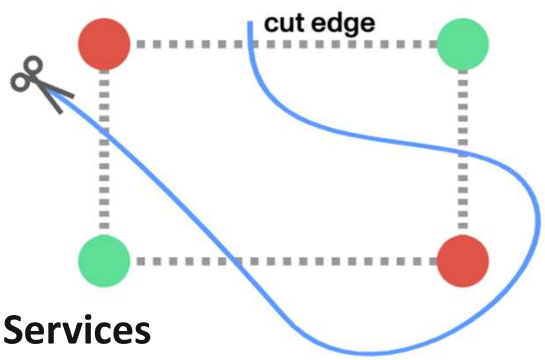


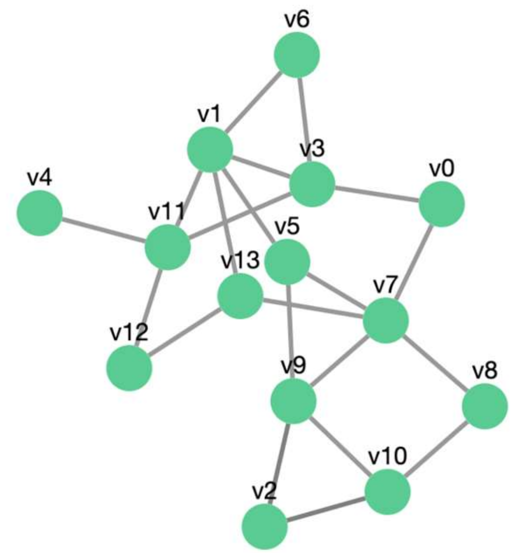


Example: Optimization with a quantum computer

Goals	Find two subsets of vertices so that the number of edges (the “cut”) connecting elements of subsets gets maximized.





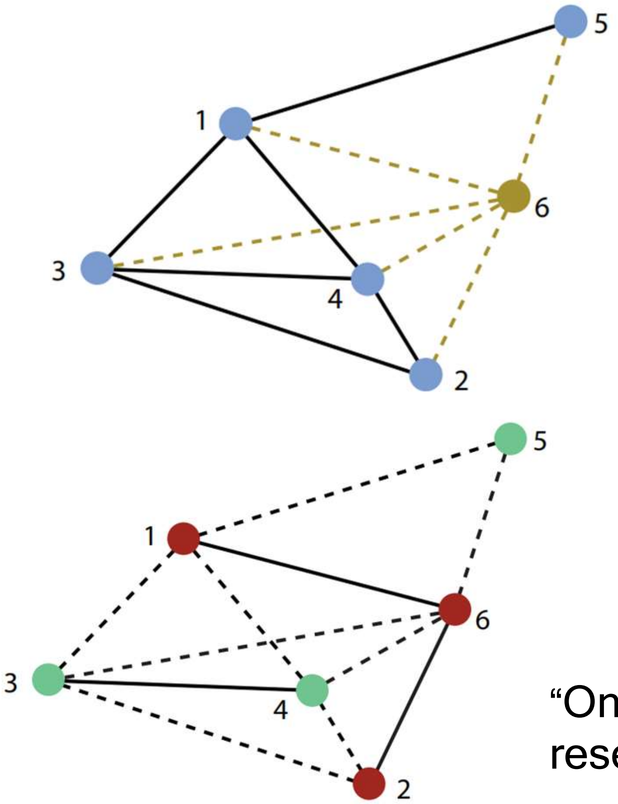


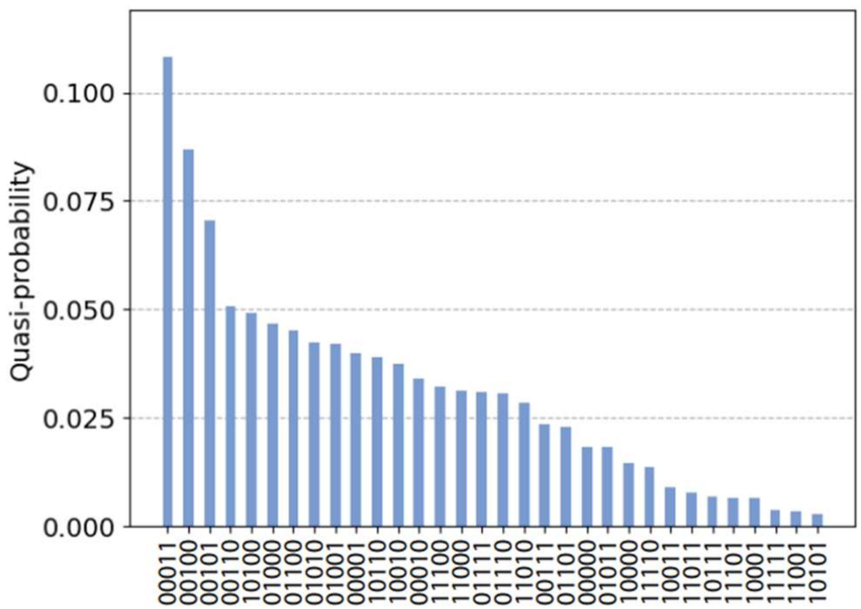
Potential Applications in Financial Services

1. **Fraud Detection**
2. **Portfolio Optimization**
3. **Credit Scoring**
4. **Network Security**

https://blog.algoanalytics.com/2023/04/20/business-applications-of-the-maximum-cut-problem/

Example: Optimization with a quantum computer



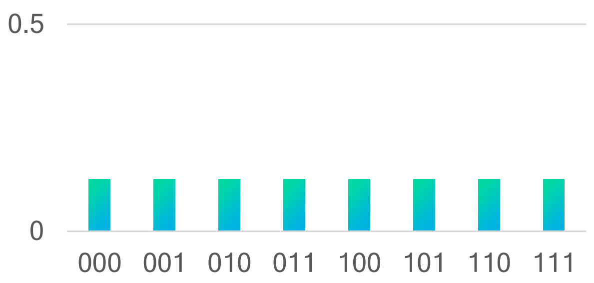


“On-premises superconducting quantum computer for education and research”, *EPJ Quantum Technology* **volume 11**, Article number: 32 (2024)

Example: Optimization with a quantum computer

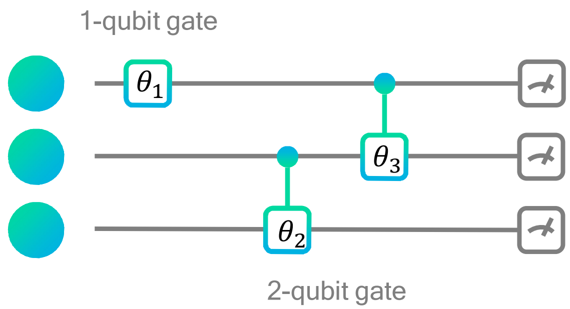
Optimize circuit parameters θ_1 ,θ_2 and θ_3 similarly to in deep learning

Prepare initial state



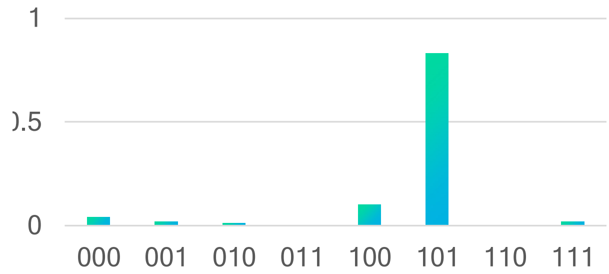
Prepare equal superposition where all outcomes are equally likely

Quantum algorithm



Apply a parametrized circuit

Measurement outcomes

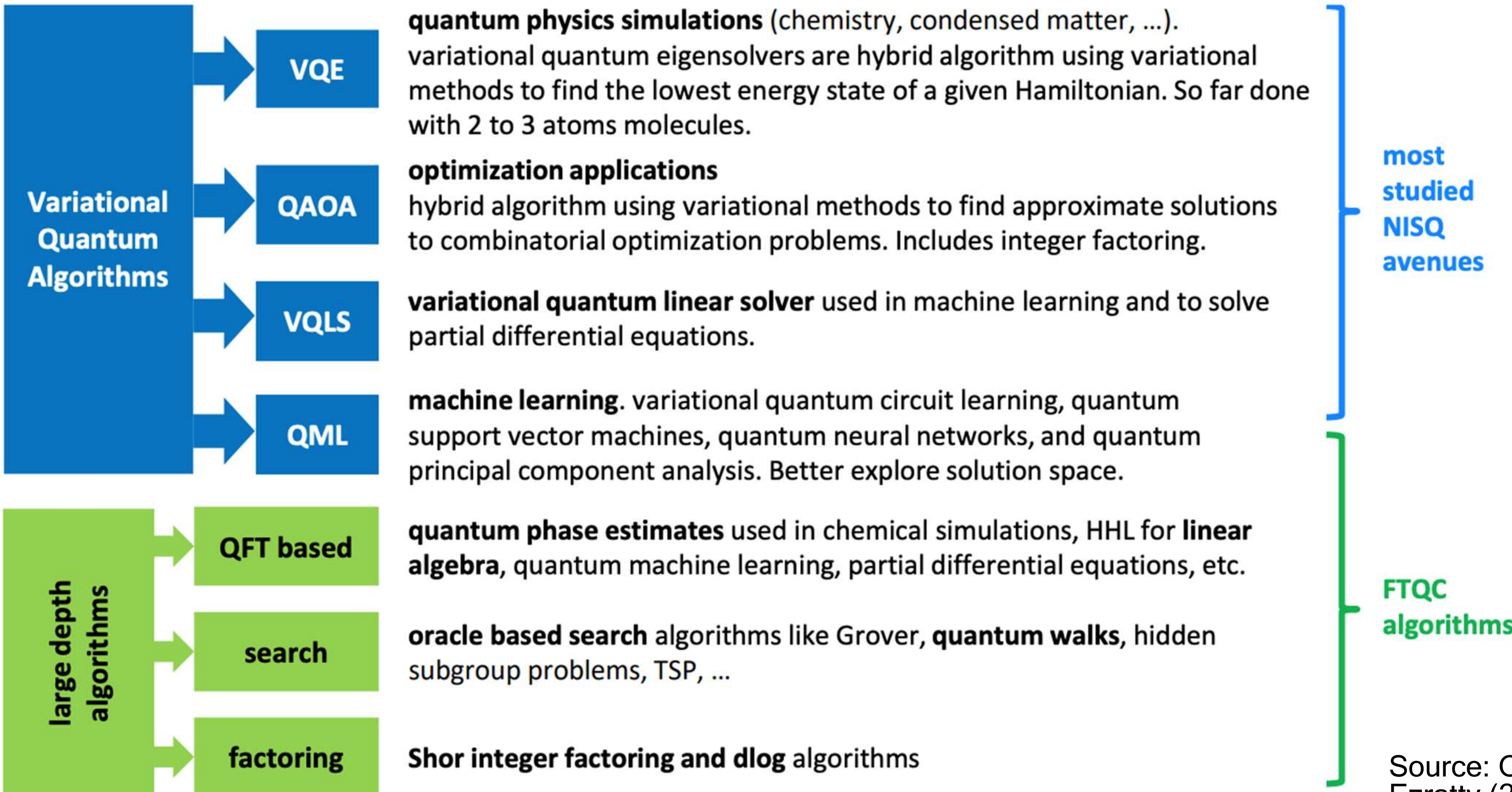


Measure outcome and calculate how good the average cut is

- Many optimization problems are reduced to find the lowest energy state of a type of magnet (Ising Model). Find the smallest element of a diagonal matrix.

1. Partitioning Problems
   - Number Partition
   - Graph Partition
   - Cliques
   - Reducing N to $\log N$ Spins in Some Constraints
2. Binary Integer Linear Programming
3. Covering and Packing Problems
   - Exact Cover
   - Set Packing
   - Vector Cover
   - Satisfiability
   - Minimal Maximal Matching
4. Problems with Inequalities
   - Set Cover
   - Knapsack with Integer Weights
5. Coloring Problems
   - Graph Coloring
   - Clique Cover
   - Job Sequencing with Integer Lengths
6. Hamiltonian Cycles
   - Hamiltonian Cycles and Paths
   - Traveling Salesman
7. Tree Problems
   - Minimal Spanning Tree with a Maximal Degree Constraint
   - Steiner Trees
   - Directed Feedback Vertex Set
   - Undirected Feedback Vertex Set
   - Feedback Edge Set
8. Graph Isomorphisms

A. Lucas, *Ising formulations of many NP problems*, Frontiers in Physics 2, 5 (2014).



Source: Olivier Ezratty (2023)

Simulation
- Fermionic Simulation
- Simulation of noisy quantum systems

Optimisation
- QAOA

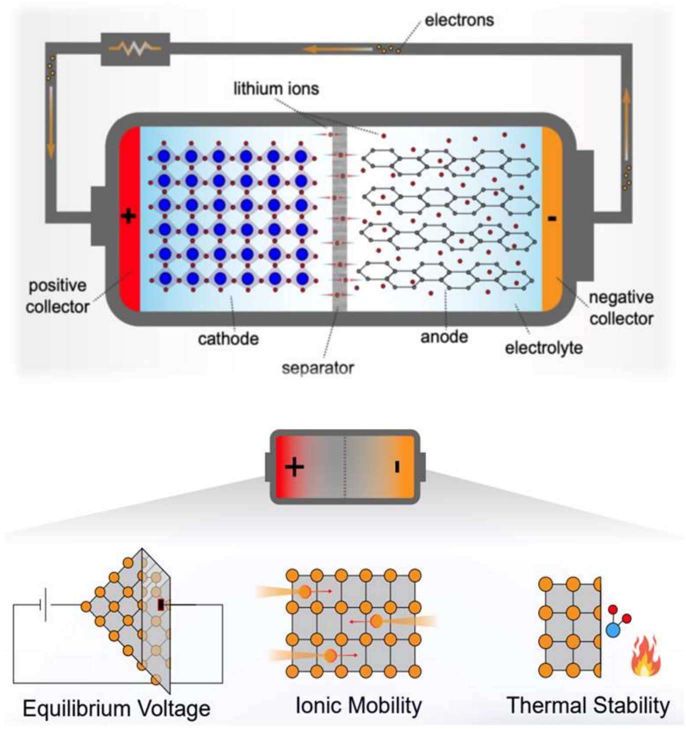
Partial Differential Equation
- Variational Quantum Simulation

Quantum Machine Learning
- Quantum Reinforce-ment Learning

Quantum Algorithm
- Quantum Error Correction
- Quantum Error Mitigation
- Qubit Routing
- ...

Real-world use-cases for different application areas

- Quantum Optimization: Power Plant Maintenance Scheduling with Energy Company
  Job-shop scheduling with resource constraints and specific time windows structure (QAOA variants)
- Quantum Simulation: Battery material design with Automotive Company
  Improve energy storage capabilities, charging and discharging speed and aging (Quantum Monte Carlo, DMFT)
- Quantum Machine Learning: Discovering Fraud with Insurance Company
  Anomaly detection in financial transactions to detect fraud such as money laundering



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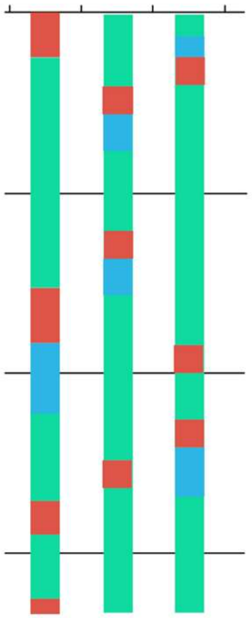

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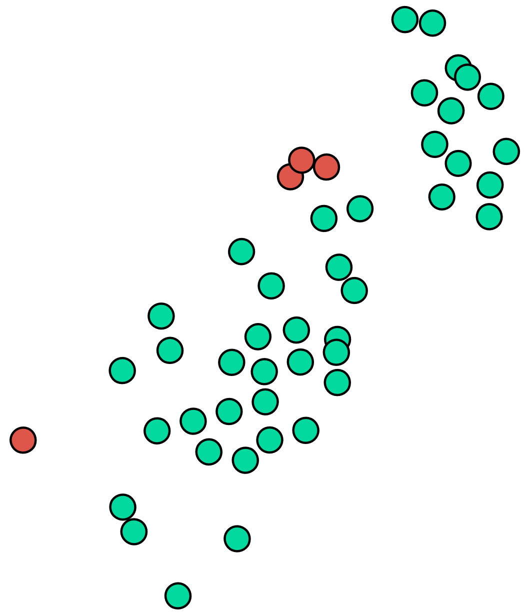


Example: Portfolio Optimization with QAOA

- Cost function $$F(z_1, z_2, \ldots, z_n) = q \sum_{i,j=1}^{n} z_i z_j \sigma_{ij} - (1-q) \sum_{i=1}^{n} z_i \mu_i, \quad z_i = 0, 1$$

Portfolio weights $z_i = 0$ or 1 of stock i, expected return μ_i, the covariance matrix of the stock returns σ_{ij}. q sets the risk preference of the investor: $q = 1$ if the investor wants to choose the portfolio with the lowest risk, irrespective of the return. $q = 0$ in the case of an aggressive investor who takes only the return of the stocks into account.

- Constraint for "feasible" portfolio, $\sum_{i=1}^{n} z_i = B$. The investment resource is limited.

$$F^{(A)}(z_1, \ldots, z_n) = F(z_1, \ldots, z_n) + A \left(\sum_{i=1}^{n} z_i - B \right)^2 .$$

The last term is the penalty to pay if $\sum_{i=1}^{n} z_i = B$ is not observed.

- Take $q = 0, 1/2$, and 1, $n = 5, B = 4, A = 10$ in the following.

Example: Portfolio Optimization with QAOA

From S. Brandhofer *et al.*, Benchmarking the performance of portfolio optimization with QAOA, Quantum Inf. Process. 22, 25 (2023).

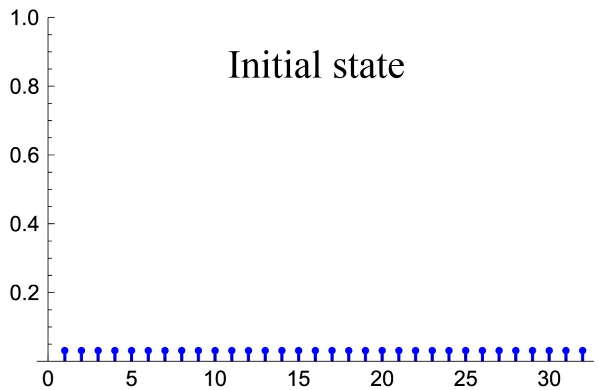
Table 2 Return vector μ_i for 5 assets chosen from the German DAX 30

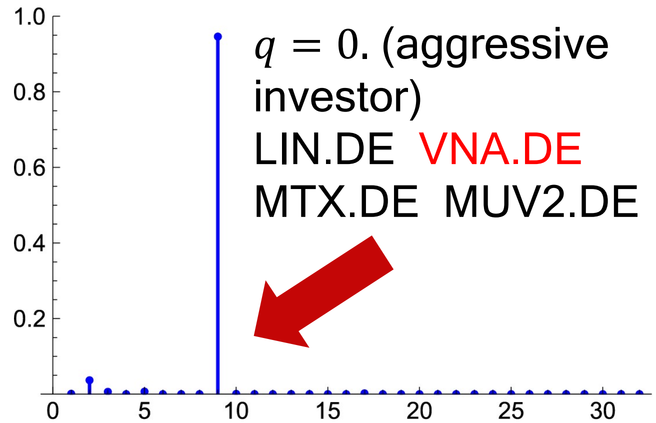
LIN.DE	BAYN.DE	VNA.DE	MTX.DE	MUV2.DE
0.26801758	−0.11724968	0.2109537	0.21523688	0.1128935

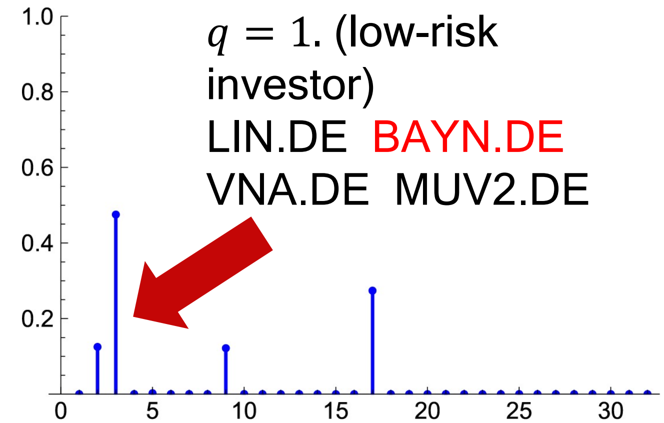
Table 3 Covariance matrix σ_{ij} for 5 assets chosen from the German DAX 30

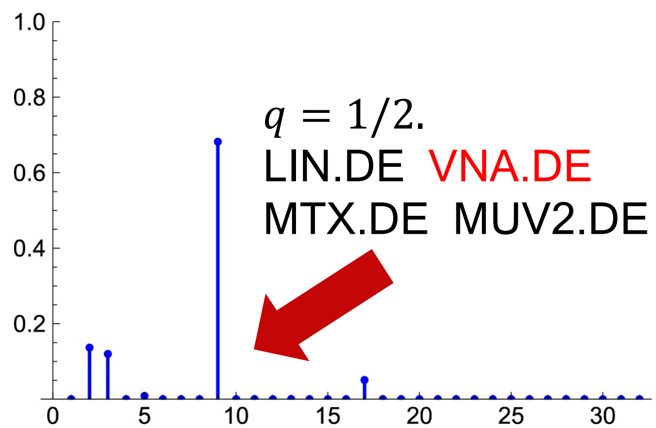
	LIN.DE	BAYN.DE	VNA.DE	MTX.DE	MUV2.DE
LIN.DE	0.21117209	0.03030933	0.00941277	0.02972179	0.02922818
BAYN.DE	0.03030933	0.08796365	0.01833403	0.0465302	0.04069187
VNA.DE	0.00941277	0.01833403	0.04971719	0.02303918	0.02051608
MTX.DE	0.02972179	0.0465302	0.02303918	0.13717214	0.05638483
MUV2.DE	0.02922818	0.04069187	0.02051608	0.05638483	0.06765634

Example: Portfolio Optimization with QAOA









Example: Portfolio Optimization with QAOA

q value	Stocks portfolio	cost
$q = 0$ (aggressive investor)	LIN.DE VNA.DE MTX.DE MUV2.DE	-0.00238912
$q = 1/2$	LIN.DE VNA.DE MTX.DE MUV2.DE	-0.807102
$q = 1$ (low-risk investor)	LIN.DE BAYN.DE VNA.DE MUV2.DE	0.713494

Conclusion: Quantum algorithms

- NISQ devices can run specific algorithms that might offer an edge over classical algorithms, even in the presence of noise.
- The prevalent paradigm for NISQ quantum algorithms, such as QAOA, is to prepare them for execution in a hybrid manner, utilizing both quantum and classical computing resources
- Quantum algorithms like QAOA are adaptable to a range of problems. Developing a deeper understanding of suitable problems and how they are mapped is essential
- Achieving early quantum advantage requires the strategic alignment of purpose-built algorithms with targeted problems and the compatible hardware

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- Easy to pick up, no previous knowledge required
- Highly interactive and engaging

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