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Introduction to Quantum Computing

XII KNMF Conference

April 4, 2024

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The three stages of computers: (1) Analogue

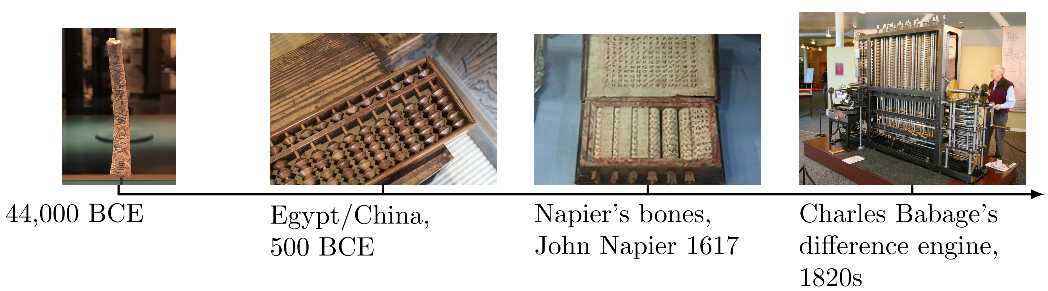


Figure 1: Analogue counting devices

The Analytical Engine – 1837 (concept)

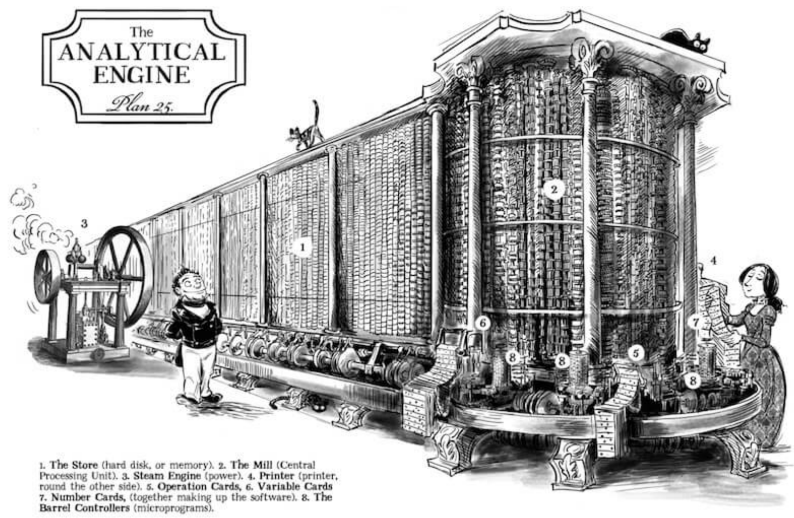


Figure 2: In 1837 Charles Babage proposed the first general purpose computer: the “analytical engine”. Legend: 1: memory, 2: the mill (CPU), 3: steam engine, 4: printer, 5: operation cards, 6: variable cards, 7: number cards, 8: barrel (controller)

1.1 Turing Machines

The three stages of computers: (2) Digital

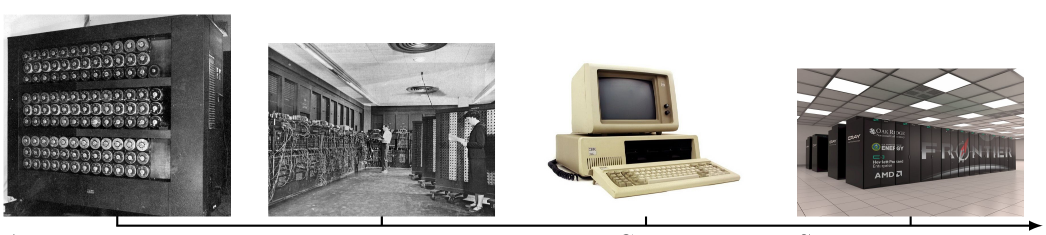


Figure 3: Digital Computers

The three stages of computers: (2) Digital

Figure 4: The fastest supercomputer in the world: Frontier, HPE CRAY EX235A, AMD OPTIMIZED 3RD GENERATION EPYC 64C 2GHZ – USA, Oakr Ridge – Rmax = 1.5 Exa Flops = 1.5×10^{18} Flops, using 21'000KwH – foto: Oak Ridge

1.2 Quantum Computers

The three stages of computers: (3) Quantum

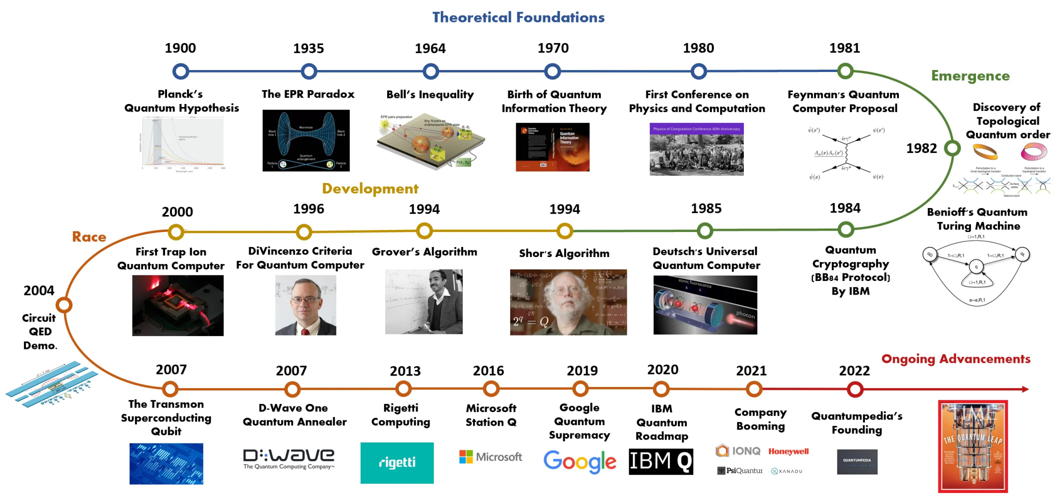


Figure 5: The timeline for quantum computers

2 Basics of Quantum Physics

The quantum world

Imagine a world where

- things are largely empty space (much more than 99.9999999999996% empty)
- things are waves and waves are things
- things can be in an infinite amount of places at the same time
- it is not possible to observe anything without changing what we observe forever and everywhere
  - so and event on one planet can influence reality in another galaxy, and
  - this influencing happens faster than the speed of light
- it is possible to get through walls even without sufficient energy to do so
- where no properties like color, softness, compassion, intelligence, cold, wet, etc. exists
- things have only mathematical properties
- vacuum is not empty

Could this world underlie our familiar and logical world?

2.1 Quantum states and superposition

Thomas Young's double slit experiment (1801)

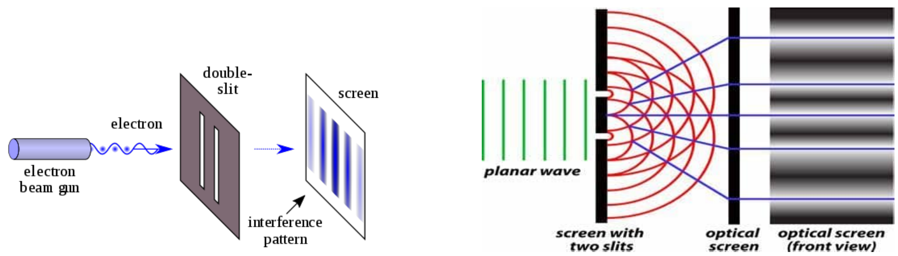


Figure 6: The double slit experiment. — (images licensed under Creative Commons CC0 1.0 Universal Public Domain Dedication and Creative Commons Attribution-Share Alike 3.0 Unported (author Fu-Kwun Hwang))

Schrödinger's Equation

Quantum entities are described by the Schödinger equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \hat{H}\Psi(\mathbf{r},t)$$

The probabilities to find the entity are then given by

$$P(\mathbf{r},t) = |\Psi(\mathbf{r},t)|^2$$

Superposition

The equation is linear, hence linear combinations of solutions are also solutions.

Example: Qubit

If an object can have a quantum state "up" or "down" with equal probabilities, then it is described by $\Psi = \frac{1}{\sqrt{2}}|up\rangle + \frac{1}{\sqrt{2}}|down\rangle$. When measured one state is observed.

Schrödinger's Cat thought experiment

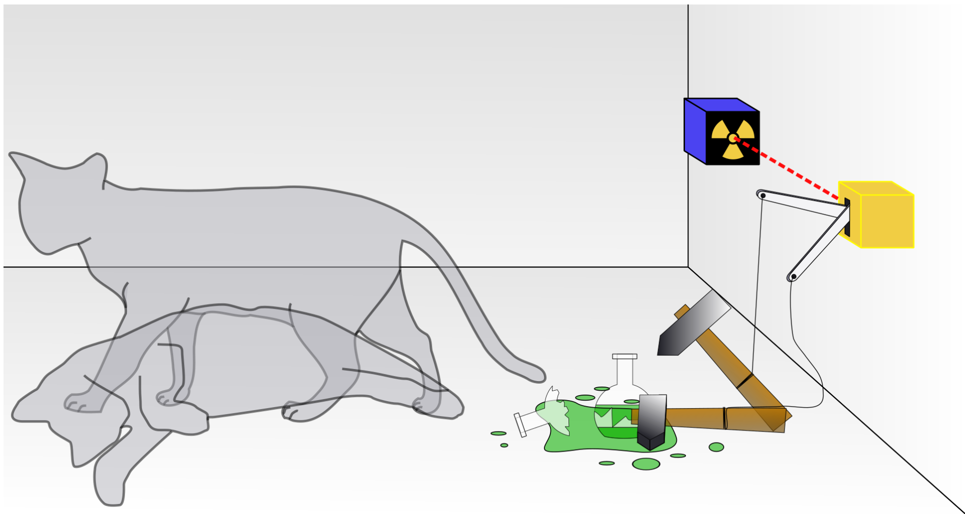


Figure 7: Poison is released when the radioactive atom decayes. As long as the box is not opened the radioactive atom is in superposition $\Psi_{atom} = \alpha_1 \left| decayed \right\rangle + \alpha_2 \left| not\ decayed \right\rangle$, and hence the cat must be $\Psi_{cat} = \alpha_1 \left| dead \right\rangle + \alpha_2 \left| alive \right\rangle$.

2.2 Quantum entanglement

Entanglement

A system of two qubits can be characterized by

$$\alpha_1 \; |00\rangle + \alpha_2 \; |01\rangle + \alpha_3 \; |10\rangle + \alpha_4 \; |11\rangle$$

where

- $|01\rangle$ means: the first qubit is $|0\rangle$ and the second $|1\rangle$
- $\sum_{i=1}^{4} |\alpha_i|^2 = 1$, with $\forall i : \alpha_i \in \mathbb{C}$

Figure 8: AI's interpretation of wedding rings in entanglement. Microsoft's copilot

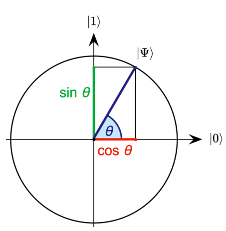
Entanglement
If two or more of α_i are non-zero, qubits are entangled if knowing one determines the state of the other.

Example
$\frac{\sqrt{2}}{2} \; |11\rangle + \frac{\sqrt{2}}{2} \; |10\rangle$ is not entangled
$\frac{\sqrt{2}}{2} \; |01\rangle + \frac{\sqrt{2}}{2} \; |10\rangle$ is entangled

Figure 9: AI's interpretation of entanglement. Microsoft's copilot

2.3 Quantum interference

Amplitudes and Probabilities



For a single qubit: unit sphere in $\mathbb{C}^2$ with the quantum state $\alpha_1|0\rangle + \alpha_2|1\rangle$ such that $|\alpha_1|^2 + |\alpha_2|^2 = 1$.
Notes

- The state can be re-written as $|\cos\theta|^2 + |\sin\theta|^2 = 1$, or $|\alpha_1|^2 = \cos^2\theta$ and $|\alpha_2|^2 = \sin^2\theta$.
- $|\alpha_1|^2$ is the probability of measuring $|0\rangle$ and $|\alpha_2|^2$ is the probability of measuring $|1\rangle$.

Amplitudes are Complex

Probabilities are real numbers and add up to 1, amplitudes are complex and the sum of absolute values adds up to 1. This allows for wave-like behaviour: interference.

Quantum Interference

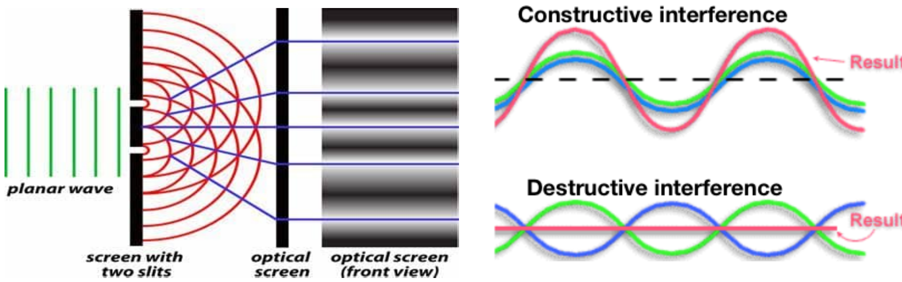


Figure 10: Quantum particles can influence others or themselves (via superposition) and disappear in certain places.

Well . . .

Is the universe local and real?

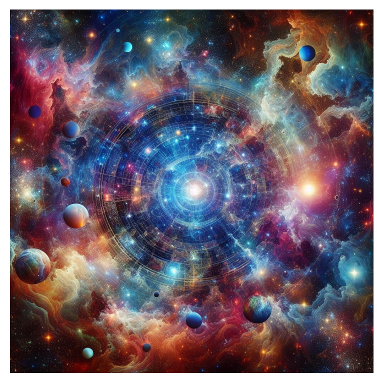


Figure 11: AI's interpretation of a universe that is not local nor real. Microsoft's copilot

3 Quantum Bits (Qubits)

3.1 Understanding Qubits

The QuBit

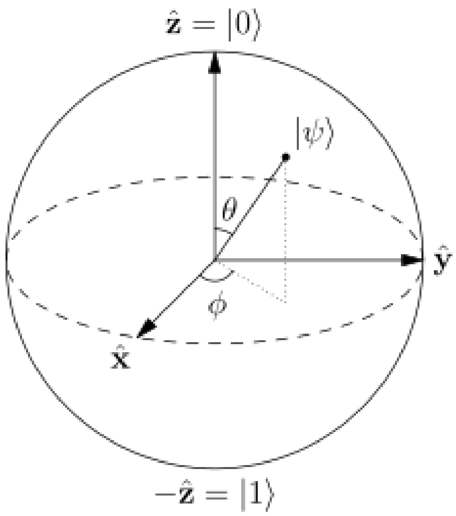


Figure 12: The qubit can be visualized on the Bloch-Sphere. Image licensed under Creative Commons

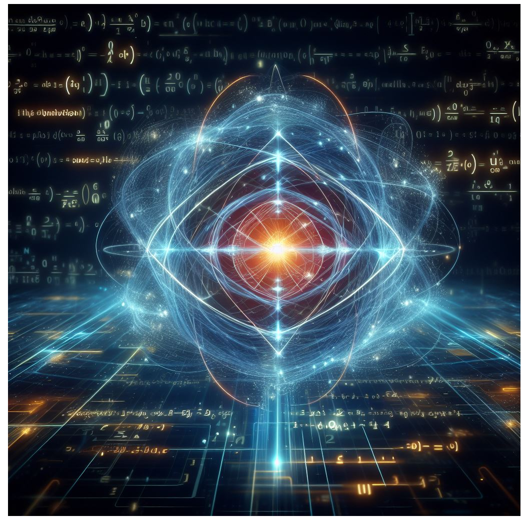


Figure 13: AI's interpretation of a qubit. Microsoft's copilot

4 Quantum Gates and Circuits

4.1 Differences between classical bits and qubits

Classical Computers

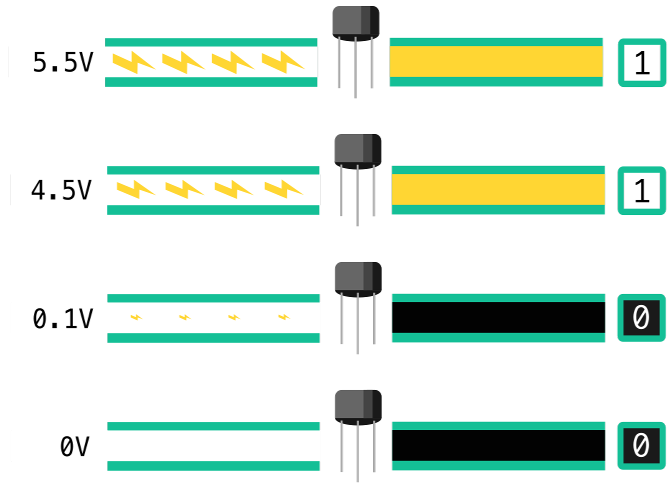


Figure 14: We use transistors to create logical states of 1 and 0.

Logical Gates

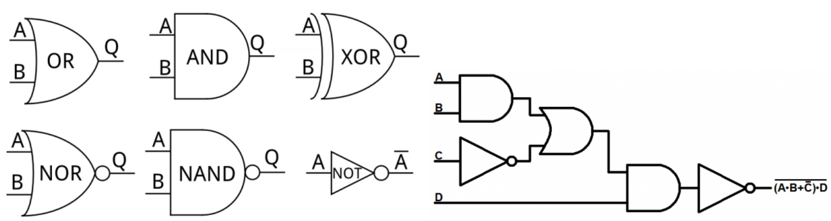


Figure 15: Those transistors are used to create logical gates that are in turn building blocks for logical circuits.

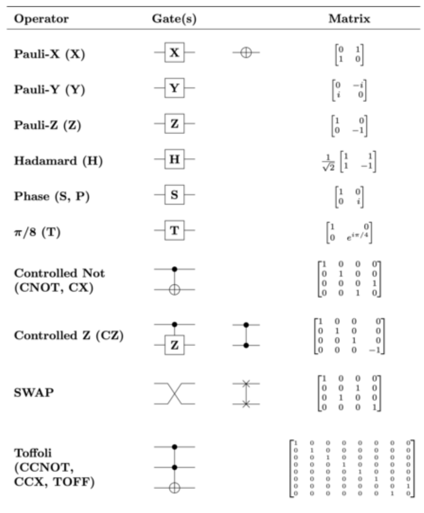
4.2 Introduction to quantum gates

Quantum Gates

quantum gate

a quantum logic gate (or quantum gate) is a basic quantum circuit operating on a small number of qubits.

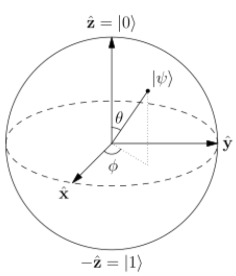
Examples of Quantum Gates



Operator	Gate(s)		Matrix
Pauli-X (X)	X	⊕	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & -1\end{bmatrix}$
SWAP			$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 0 & 1 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)			$\begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\0 & 1 & 0 & 0 & 0 & 0 & 0 & 0\\0 & 0 & 1 & 0 & 0 & 0 & 0 & 0\\0 & 0 & 0 & 1 & 0 & 0 & 0 & 0\\0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\0 & 0 & 0 & 0 & 0 & 1 & 0 & 0\\0 & 0 & 0 & 0 & 0 & 0 & 0 & 1\\0 & 0 & 0 & 0 & 0 & 0 & 1 & 0\end{bmatrix}$

Figure 16: Examples of popular quantum gates. There are in fact an uncountable infinity of quantum gates.

Examples of quantum gates on one qubit



The vector representation of $|a\rangle = \alpha_1|1\rangle + \alpha_2|0\rangle$ is $\begin{bmatrix}\alpha_1\\\alpha_2\end{bmatrix}$

Examples acting on one qubit:

A. Identity gate: $I = \begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$

B. Pauli X-gate (rotation around X axis): $X = \sigma_x = \text{NOT} = \begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$

C. Pauli Y-gate: $Y = \sigma_y = \begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$

D. Pauli Z-gate: $Z = \sigma_z = \begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$

Example of quantum gates: creating superposition

Hadamard Gate acts on a single qubit. It maps the basis states$|0\rangle \mapsto \frac{|0\rangle+|1\rangle}{\sqrt{2}}$ and $|1\rangle \mapsto \frac{|0\rangle-|1\rangle}{\sqrt{2}}$ (an equal superposition state if given a computational basis state).

The two states $(|0\rangle + |1\rangle)/\sqrt{2}$ and $(|0\rangle - |1\rangle)/\sqrt{2}$ are sometimes written $|+\rangle$ and $|-\rangle$ respectively. The Hadamard gate performs a rotation of π about the axis $(\hat{x} + \hat{z})/\sqrt{2}$ at the Bloch sphere, and is therefore involutory.

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

If the Hermitian ($H^\dagger = H^{-1} = H$) Hadamard gate is used to perform a change of basis, it flips $\hat{x}$ and $\hat{z}$. For example, $HZH = X$ and $H\sqrt{X}\ H = \sqrt{Z} = S$.

Example of a quantum gate on 2 qubits and entanglement

Controlled gates act on 2 or more qubits, where one or more qubits act as a control for some operation.

controlled NOT gate (or CNOT or CX)

acts on 2 qubits, and performs the NOT operation on the second qubit only when the first qubit is $|1\rangle$ (otherwise leaves it unchanged). With respect to the basis $|00\rangle, |01\rangle, |10\rangle, |11\rangle$ it is represented by the Hermitian unitary matrix:

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

4.3 Measuring Qubits

Measuring Qubits

Measurement = reduce the quantum states to a classical state.

Therefore, measurement is irreversible and not a quantum gate.

The probability of finding a state is the modulus of its amplitude[1]

$$if\ \Psi = \alpha|x\rangle + \dots,\ then\ P[|x\rangle] = |\alpha|^2$$

For example, measuring a qubit with the quantum state $\frac{|0\rangle - i|1\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix}$ will yield with equal probability either $|0\rangle$ or $|1\rangle$

4.4 Building quantum circuits

Building your first quantum circuit

See the presentation of IBM later today ;-)

[1]This is known as the Born rule and appears as a stochastic non-reversible operation as it sets with a given probability the quantum state equal to the basis vector that represents the measured state.

4.5 What are quantum computers really

What is a quantum computer?

Figure 17: Photosynthesis is possible thanks to quantum mechanics. – own photo 2014

An example of a simulation: the Fermiac

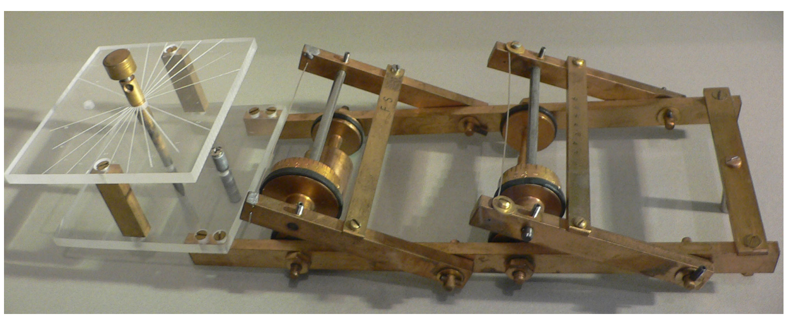


Figure 18: The FERMIAC, or Monte Carlo trolley, was an analog device invented by Enrico Fermi to implement studies of neutron transport. — image under Creative Commons Attribution-Share Alike 1.0

Aspects of Quantum Computing: Exponential Power

- qubit $\rightarrow$ 2 quantum states dimensions: $\alpha \left|0\right\rangle + \beta \left|1\right\rangle$

- 2 qubits $\rightarrow$ 4 states: $\alpha_1 \left|00\right\rangle + \alpha_2 \left|01\right\rangle + \alpha_3 \left|10\right\rangle + \alpha_4 \left|11\right\rangle$
- 3 qubits $\rightarrow$ 8 quantum state dimensions
- 6 qubits $\rightarrow$ 64 quantum state dimensions (card deck)
- 10 qubits $\rightarrow$ 1024 quantum state dimensions (810 listed companies on WSE)
- 20 qubits $\rightarrow 1.048576 \times 10^6$ quantum state dimensions (ca. number of all possible liquid investments)
- 60 qubits $\rightarrow 1.1529215 \times 10^{18}$ states (ca. 10^{19} grains of sand on earth)
- 175 qubits $\rightarrow 4.7890486 \times 10^{52}$ states (ca. 10^{50} atoms on earth)
- 275 qubits $\rightarrow 6.0708403 \times 10^{82}$ quantum states (ca. 10^{82} atoms in the visible universe)

Note: entanglement

To simulate quantum states on a Turing machine, we need to encode all possible entangled states too. The number of states in a quantum processor is 2^N, the complexity with entanglement scales as follows:

A. 10 qubits $\rightarrow$ 1,024 quantum states $\xrightarrow{\text{entanglement}}$ 16,000 Bits = 16 KB

B. 500 qubits $\rightarrow$ more quantum states than atoms in the visible universe $\xrightarrow{\text{entanglement}}$ not enough atoms in the visible universe

5 Quantum Algorithms

5.1 Overview of quantum algorithms

5.2 Examples: Shor's algorithm

Factoring

PGP relies on factoring large numbers

$$\begin{matrix}1\,7\,0\,1\,4\,1\,1\,8\,3\,4\,6\\0\,4\,6\,9\,2\,3\,1\,7\,3\,1\,6\\8\,7\,3\,0\,3\,7\,1\,5\,8\,8\,4\\1\,0\,5\,7\,2\,7\end{matrix} \text{ X } \begin{matrix}2\,0\,9\,8\,8\,9\,3\,6\,6\,5\,7\\4\,4\,0\,5\,8\,6\,4\,8\,6\,1\,5\\1\,2\,6\,4\,2\,5\,6\,6\,1\,0\,2\\2\,2\,5\,9\,3\,8\,6\,3\,9\,2\,1\end{matrix} = \begin{matrix}3\,5\,7\,1\,0\,8\,2\,5\,2\,2\,4\,7\,3\,7\,6\,6\,6\\7\,4\,4\,8\,4\,3\,0\,4\,9\,7\,5\,7\,7\,8\,5\,2\,7\\4\,0\,1\,8\,9\,5\,2\,0\,0\,1\,1\,5\,7\,2\,6\,1\,2\\0\,7\,9\,5\,8\,4\,2\,5\,7\,6\,3\,5\,5\,5\,0\,9\,7\\4\,6\,4\,0\,2\,6\,1\,4\,7\,7\,5\,5\,6\,7\end{matrix}$$

# digits	Supercomputer	Quantum comp.
10,000	0 s	56 s
100,000	0.6 year	2 min.
200,000	78,254 yrs	2 min.
300,000	449 mln. yrs	2 min.
400,000	72 x age of universe	3 min.

Factoring

Shor's Algorythm in quantum computers does not scale exponentially

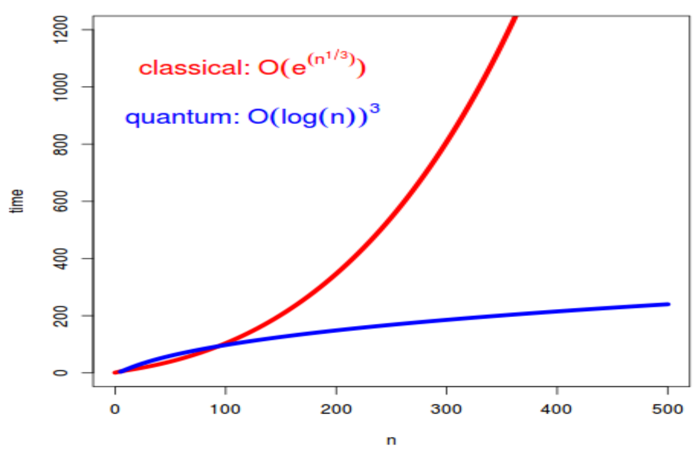


Figure 19: Time needed to factor large numbers in classical approach and with quantum computers

5.3 Examples: Grover's algorithm

Programming a Universal Quantum Computer

Lov Grover's Algorithm

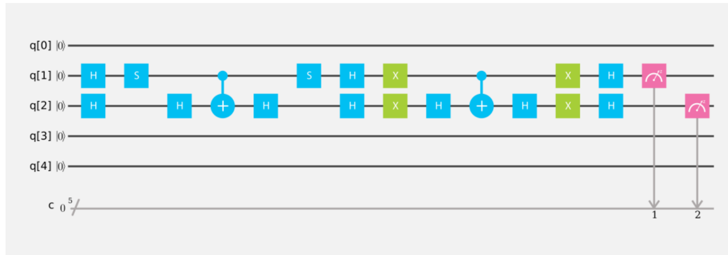
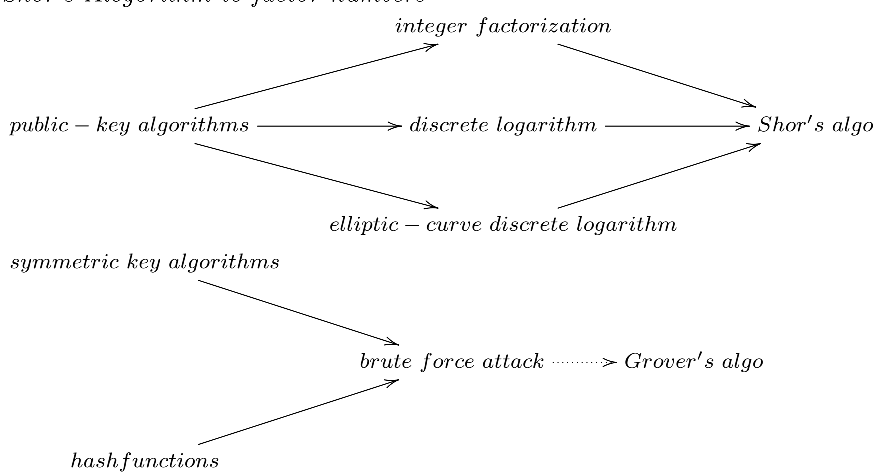


Figure 20: Grover's algorithm only needs $O(\sqrt{N})$ steps to find matching entry in unstructured data.

5.4 Note: Ciphering

Breaking Codes and Passwords

Shor's Alogorithm to factor numbers



5.5 Solving Sparse Large Linear Systems

Large Linear Systems

$$\begin{bmatrix} A_{11} & \dots & A_{1N} \\ \vdots & \ddots & \vdots \\ A_{M1} & \dots & A_{MN} \end{bmatrix} \times \begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} b_1 \\ \vdots \\ b_N \end{bmatrix}$$

with up to s non-zero A_{ij} per row/column and condition number k

Classical methods solve this in $O(Nsk)$ ... quantum algorithms need $O(log(N)sk)$

6 How to build a quantum computer

6.1 Models of Quantum Computing

Models of Quantum Computing

Gate Model

also Circuit Model. Uses entangled qubits and gates to execute operations

Measurement Based

set up entangled state over all qubits and then measure one by one

Adiabatic

start from flat energy surface and build up slowly, expect the system to stay in the lowest energy state

Annealing

not mathematically equivalent

6.2 Physical Realisations of Qubits

Physical Realisations of Qubits

Superconducting

typically a tiny line or loop of metal that behaves as one atom (eg. Google uses aluminium, IBM a mix of aluminium and niobium) – most popular (IBM, Google, Rigetti, Intel, etc.)

Trapped Ions

ions trapped (with electromagnetic fields) and manipulated using lasers or microwave radiation

Photon Polarization

The polarization of light is the qubitA photon moving along the z-axis has an associated electric field in the x-y plane, and the 2-dimensional quantity specifying this field is the polarization of the photon

Spin Qubits

Elementary particles and composite particles carry an intrinsic angular momentum called spin. The quantum mechanical spin state of an electron or proton can be used as qubits

Topological

using Majorano Zero-Mode Quasi-particles (sort of non-Abelian anyon)

Energy Levels of Hydrogen Atom

The electron in a hydrogen atom can be in its ground state or in an excited state.

6.3 Quantum Supremacy

Quantum Supremacy

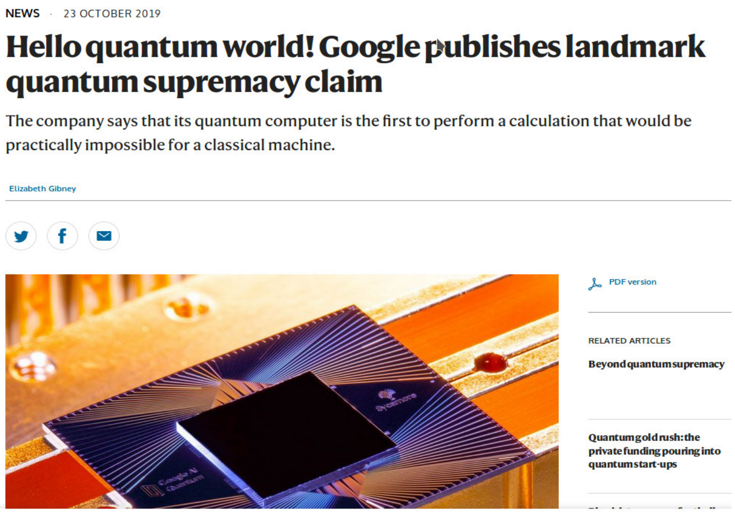
Definition 1 (quantum supremacy)**.** Quantum supremacy is the potential ability of quantum computing devices to solve problems that classical computers practically cannot.

Expectation: 50 sufficiently coherent q-bits needed for quantum supremacy.

Definition 2 (quantum advantage)**.** Quantum advantage is the potential to solve problems faster. In computational complexity-theoretic terms, this generally means providing a superpolynomial speedup over the best known or possible classical algorithm.

6.4 Current state of quantum hardware

Current State: Quantum Supremacy overconfident claims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Hello quantum world! Google publishes landmark quantum supremacy claim

The company says that its quantum computer is the first to perform a calculation that would be practically impossible for a classical machine.

Elizabeth Gibney

PDF version

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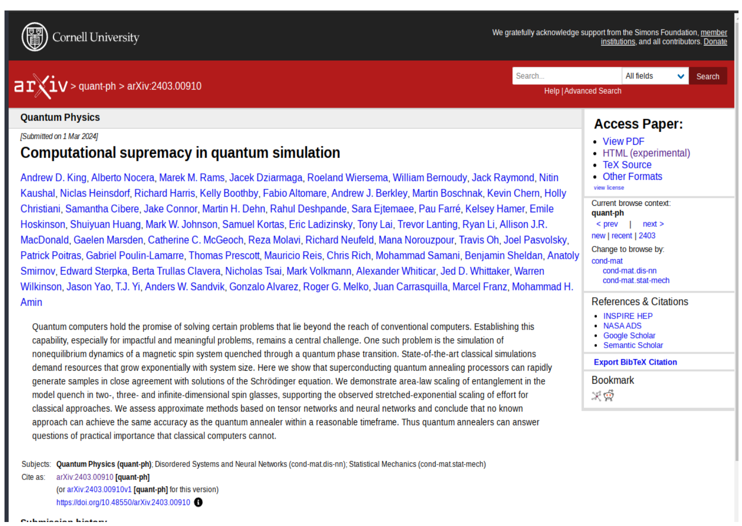
Quantum gold rush: the private funding pouring into quantum start-ups

Figure 21: Submitted, October 1st, 2024 – https://arxiv.org/abs/2403.00910

Current State: Quantum Supremacy with annealers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Quantum Physics

[Submitted on 1 Mar 2024]

Computational supremacy in quantum simulation

Andrew D. King, Alberto Nocera, Marek M. Rams, Jacek Dziarmaga, Roeland Wiersema, William Bernoudy, Jack Raymond, Nitin Kaushal, Niclas Heinsdorf, Richard Harris, Kelly Boothby, Fabio Altomare, Andrew J. Berkley, Martin Boschnak, Kevin Chern, Holly Christiani, Samantha Cibere, Jake Connor, Martin H. Dehn, Rahul Deshpande, Sara Ejtemaee, Pau Farré, Kelsey Hamer, Emile Hoskinson, Shuiyuan Huang, Mark W. Johnson, Samuel Kortas, Eric Ladizinsky, Tony Lai, Trevor Lanting, Ryan Li, Allison J.R. MacDonald, Gaelen Marsden, Catherine C. McGeoch, Reza Molavi, Richard Neufeld, Mana Norouzpour, Travis Oh, Joel Pasvolsky, Patrick Poitras, Gabriel Poulin-Lamarre, Thomas Prescott, Mauricio Reis, Chris Rich, Mohammad Samani, Benjamin Sheldan, Anatoly Smirnov, Edward Sterpka, Berta Trullas Clavera, Nicholas Tsai, Mark Volkmann, Alexander Whiticar, Jed D. Whittaker, Warren Wilkinson, Jason Yao, T.J. Yi, Anders W. Sandvik, Gonzalo Alvarez, Roger G. Melko, Juan Carrasquilla, Marcel Franz, Mohammad H. Amin

Quantum computers hold the promise of solving certain problems that lie beyond the reach of conventional computers. Establishing this capability, especially for impactful and meaningful problems, remains a central challenge. One such problem is the simulation of nonequilibrium dynamics of a magnetic spin system quenched through a quantum phase transition. State-of-the-art classical simulations demand resources that grow exponentially with system size. Here we show that superconducting quantum annealing processors can rapidly generate samples in close agreement with solutions of the Schrödinger equation. We demonstrate area-law scaling of entanglement in the model quench in two-, three- and infinite-dimensional spin glasses, supporting the observed stretched-exponential scaling of effort for classical approaches. We assess approximate methods based on tensor networks and neural networks and conclude that no known approach can achieve the same accuracy as the quantum annealer within a reasonable timeframe. Thus quantum annealers can answer questions of practical importance that classical computers cannot.

Subjects: **Quantum Physics (quant-ph)**; Disordered Systems and Neural Networks (cond-mat.dis-nn); Statistical Mechanics (cond-mat.stat-mech)

Cite as: arXiv:2403.00910 **[quant-ph]**
(or arXiv:2403.00910v1 **[quant-ph]** for this version)
https://doi.org/10.48550/arXiv.2403.00910

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Figure 22: Submitted, March 1st, 2024 – https://arxiv.org/abs/2403.00910

D-Wave

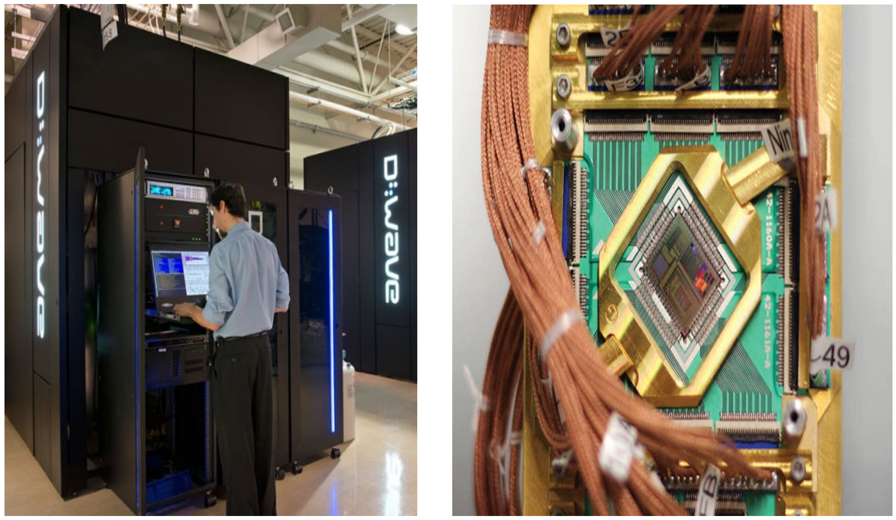


Figure 23: The quantum computer of D-Wave (pictures: D-Wave) – since 2007

Adiabatic Algorithm

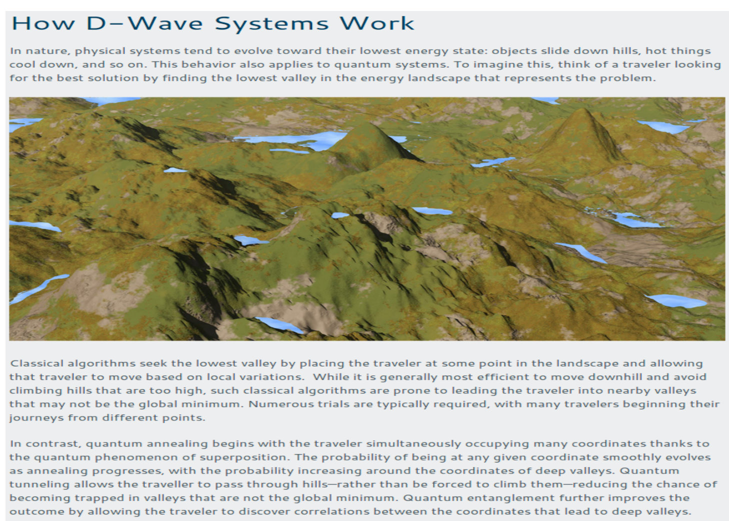
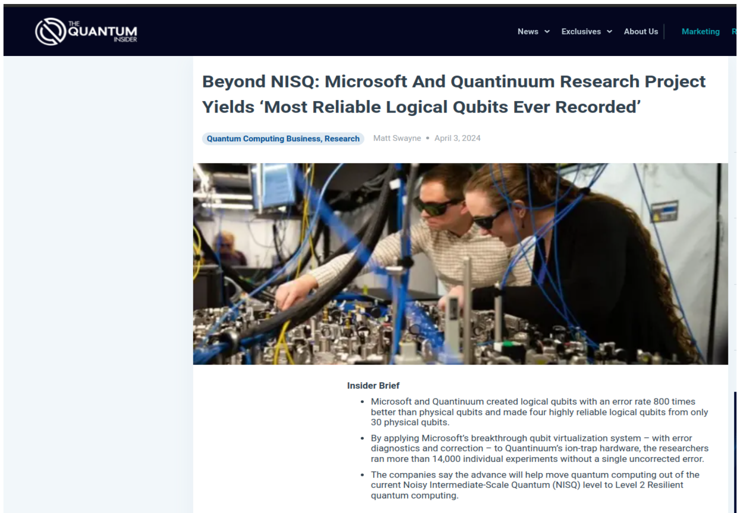


Figure 24: https://www.dwavesys.com/quantum-computing

Logical Quibits: recent progress: 2024-03-04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Beyond NISQ: Microsoft And Quantinuum Research Project Yields 'Most Reliable Logical Qubits Ever Recorded'

Quantum Computing Business, Research Matt Swayne • April 3, 2024

Insider Brief

- Microsoft and Quantinuum created logical qubits with an error rate 800 times better than physical qubits and made four highly reliable logical qubits from only 30 physical qubits.
- By applying Microsoft's breakthrough qubit virtualization system – with error diagnostics and correction – to Quantinuum's ion-trap hardware, the researchers ran more than 14,000 individual experiments without a single uncorrected error.
- The companies say the advance will help move quantum computing out of the current Noisy Intermediate-Scale Quantum (NISQ) level to Level 2 Resilient quantum computing.

Figure 25: https://thequantuminsider.com 2024-04-03 – also on https://blogs.microsoft.com and https://www.quantinuum.com.

7 Challenges in Quantum Computing

7.1 Decoherence and error correction

Decoherence

Coherence and Decoherence
Systems interacting with the environment in which they reside generally become entangled with that environment, a phenomenon known as quantum decoherence. This can explain why, in practice, quantum effects are difficult to observe in systems larger than microscopic.

Note: temperature

$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

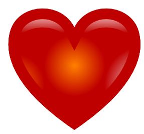
with:

- v_{rms} the average speed of a molecule in a gas in $\frac{m}{s}$
- $k = 1.38x10^{-23}\frac{J}{K}$
- T the temperature in Kelvin
- m the molecular mass in Kg

7.2 Scalability issues

Scalability

Each qubit needs a connection . . .



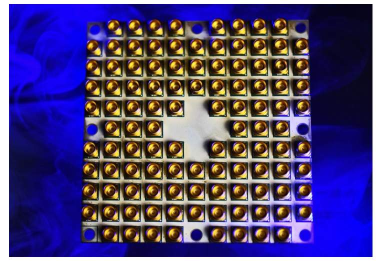


Figure 26: Intel Corporation's 49-qubit quantum computing test chip, "Tangle Lake," – 2018. Credit: Intel Corporation

8 Future of Quantum Computing

8.1 The Road-map

IBM's Road-map

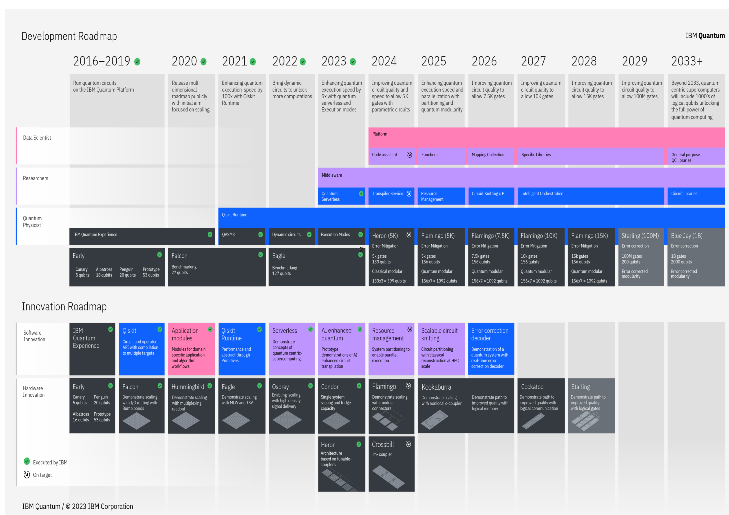


Figure 27: IBM's Quantum Roadmap (newsroom.ibm.com)

8.2 Potential applications

- **Quantum Physics modelling**: most obvious application is to understand quantum mechanical systems better

- **Biochemical modeling**: from determining the 3D shape of a protein to gene expression, the calculation of complex biological molecules to the atoms could revolutionize biotechnology research.
- **Climate modeling**: Climate models are extraordinarily complex and stretch the limits of what current supercomputers can do. A better understanding of the climate, with a finer calculation scale in the model, both geographically and in time, could help in understanding climate change risks.
- **Material Science**: Understanding quantum physics better and the reaction of materials down to individual atoms can open new designs for materials used in aerospace, batteries, 3D printing, manufacturing, etc.
- **Semiconductors, chip design, qubits**: Quantum computers could be used to make computer chips a lot more powerful. With "normal" chips now reaching the nanometre scale, quantum phenomena become increasingly problematic, and quantum computers might be needed to solve them.
- **Cryptography**: Quantum computers could potentially make all current cryptography methods obsolete. This is a serious concern for military, financial & IT systems. But at the same time, it could make cryptography even more secure.
- **Optimizations**: financial markets, traffic optimization, etc.

Figure 28: McKinsey Quantum Technology Monitor (April 2023) predicts USD 1.3 trillion in value by 2035 – source: https://www.mckinsey.com

Use cases in banking

- **Optimization**:
    A. portfolio optimization
    B. collateral optimization
    C. stress testing
    D. transaction settlement
    E. asset pricing
    F. ATM replenishment
- Machine Learning
    - fraud detection
    - credit scoring
    - synthetic data and data augmentation
- **Simulations**:
    - random number generator
    - Monte Carlo, LPDE simulations, etc.
    - asset valuation
    - ES and VaR calculations
- **Encryption**:
    - quantum key encryption
    - quantum currency
    - quantum blockchain

Resulting Advantages
quadratic to exponential speedup

- better risk management
- lower costs
- greener computing
- better forecasting
- more suitable investment
- etc.

Boston Consulting Group estimates a value of $42B to $67B for financial institutions

8.3 Case Study: HSBC

Why is HSBC interested

- Quantum computing could revolutionise financial services in areas like portfolio optimisation, fraud detection and cybersecurity.
- Quantum computers promise to deliver a step-change in computational power, with the potential to tackle highly complex tasks far beyond the capabilities of today's machines
- The quantum sector is estimated USD1.3 trillion in value by 2035

source: HSBC and quantum

HSBC's strategy

A. Working with a range of **organisations like IBM, Fujitsu and Quantinuum, leading academic institutions, and governmental organisations**, to put us at the forefront of the financial services industry in exploring how to integrate quantum computing into our products and services

B. Building a **dedicated quantum research team** and in-house team of PhD scientists at HSBC to formalise our use cases into deep research projects and develop patents and quantum products

C. **Bank-wide strategy**: Collaborating across business lines and functions to develop real world use cases to improve our processes and prepare for a quantum-secure economy

source: HSBC and quantum

Proofs of Concept in HSBC

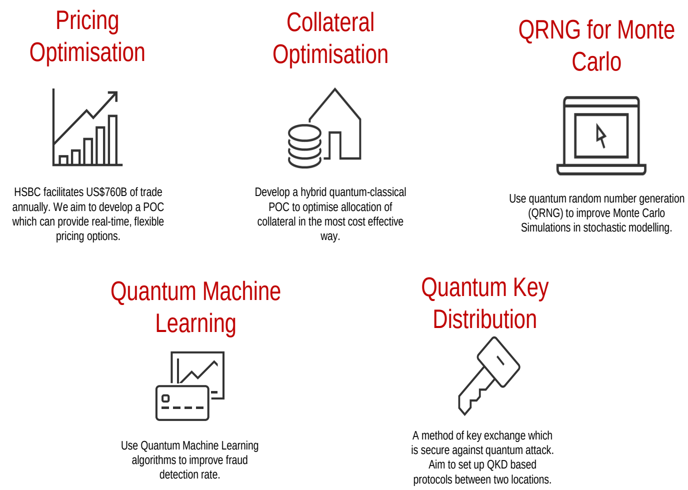


Figure 29: Proofs of concept in HSBC. source: HSBC and quantum

Quantum Key Distribution in HSBC

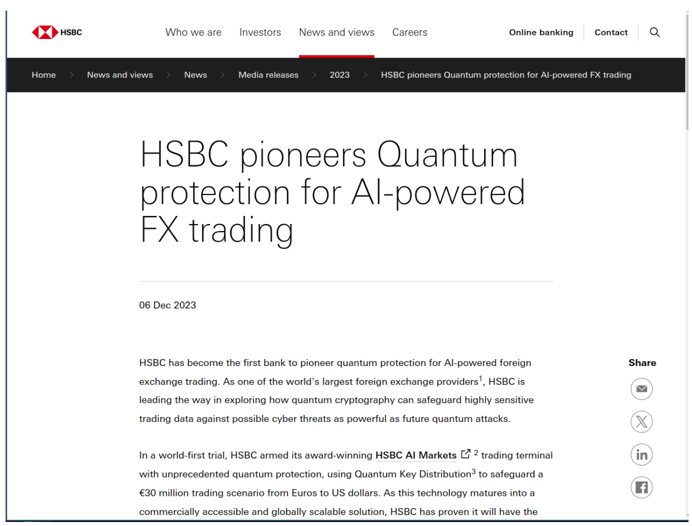


Figure 30: Proofs of concept in HSBC: quantum key distribution. source: HSBC and quantum

HSBC's Philip Intallura

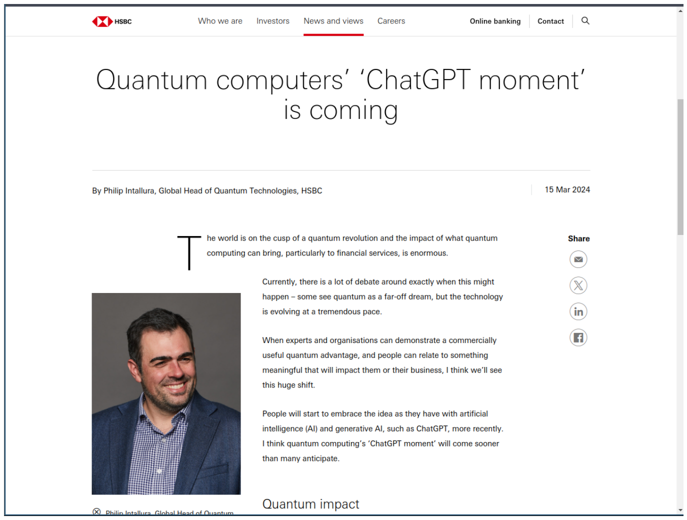


Figure 31: Proofs of concept in HSBC: quantum key distribution. source: HSBC news

9 Limits of Quantum Computers

9.1 Problem Complexity limits

Limits of Quantum Computers: Complexity Theory

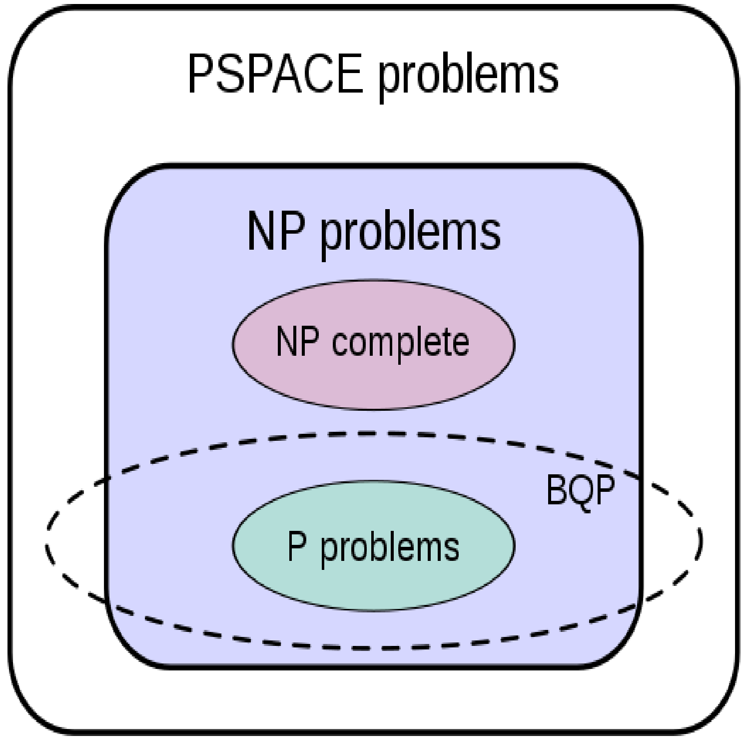


Figure 32: BQP –bounded-error quantum polynomial time– is the quantum equivalent of BPP –bounded-error probabilistic polynomial time

9.2 Limits in Applications

Turing Machines are Turing Complete

Turing Complete
A system is Turing complete if it can simulate any Turing machine, meaning it can compute any Turing-computable function. Essentially, it can perform any calculation that a computer with unlimited resources could. Most modern programming languages are Turing complete.

In practical terms, a Turing Complete system means a system in which a program can be written that will find an answer, although with no guarantees regarding runtime or memory use.

Quantum Computers are impractical for many applications
While a (theoretical) Quantum Turing Machine is Turing Complete, there are much practical barriers.

10 Conclusions

Conclusions: Q-Day is near

I predict that in 1 to 10 years quantum computers will bring us

- insight in quantum physics
- new medications, better batteries, better materials, etc.
- other encryption
- the ability to to gather more data and use it
- all kinds of optimizations, such as better optimized investment portfolios
- Artificial General Intelligence
- greener computing (e.g. bitcoin alone is responsible for 1.5% of the world's CO_2 production)
- but most exciting: ... answers to questions that we don't know yet.

Further Reading

- Michio Kaku, Quantum Supremacy: How the Quantum Computer Revolution Will Change Everything – order on Amazon.com
- McKinsey, McKinsey Quantum Technology Monitor, April 2023 – download
- McKinsey, 2020, "How quantum computing could change financial services" – download
- IBM, "The Quantum Decade" (e-book) – download
- E. Rieffel and W Polak, MIT Press, "Quantum Computing, a Gentle Introduction" – download
- Quantum Computing for the Quantum Curious, C. Hughes et al., Springer – download
- a list of books: download