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History, hype and how-to

Lourens van Niekerk

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History: foundations

1. 1901: Planck introduces quanta

2. 1913: Bohr's model of the atom

3. 1924: de Broglie introduces wave-particle duality

4. 1926: Schrödinger equation

5. 1927: Heisenberg's Uncertainty Principle

6. 1935: Einstein, Podolsky and Rosen define entanglement as the subject of the EPR paradox.

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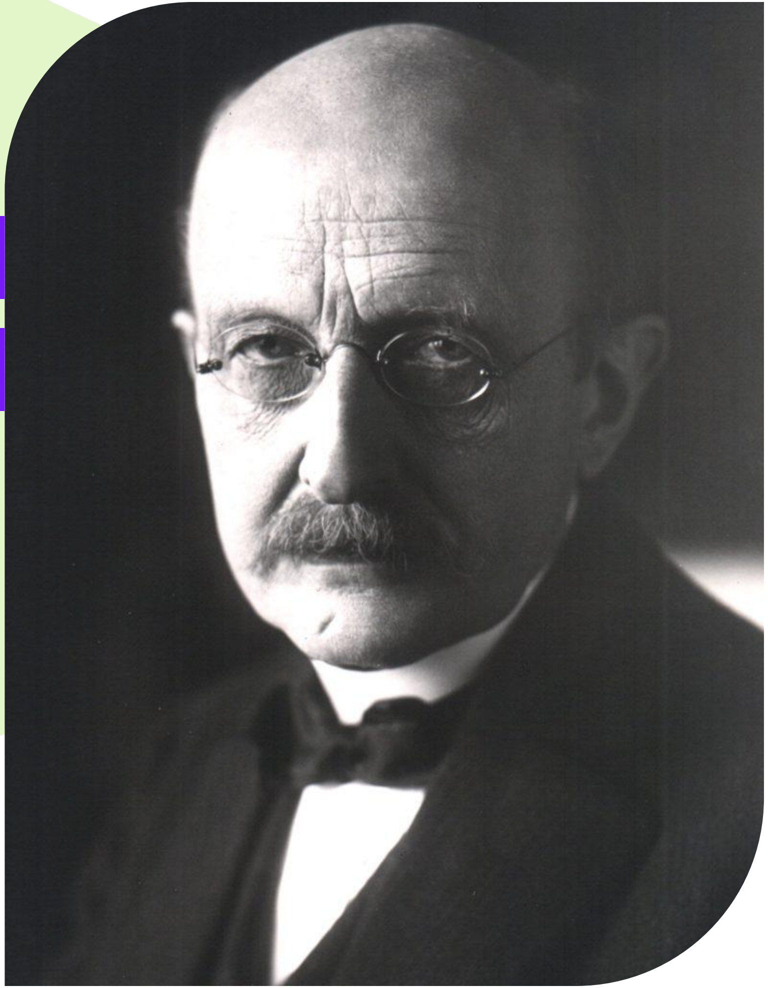
Max Planck

1901



He started the revolution with

"Ueber das Gesetz der Energieverteilung im Normalspectrum"

or

"About the law of energy distribution in the normal spectrum"

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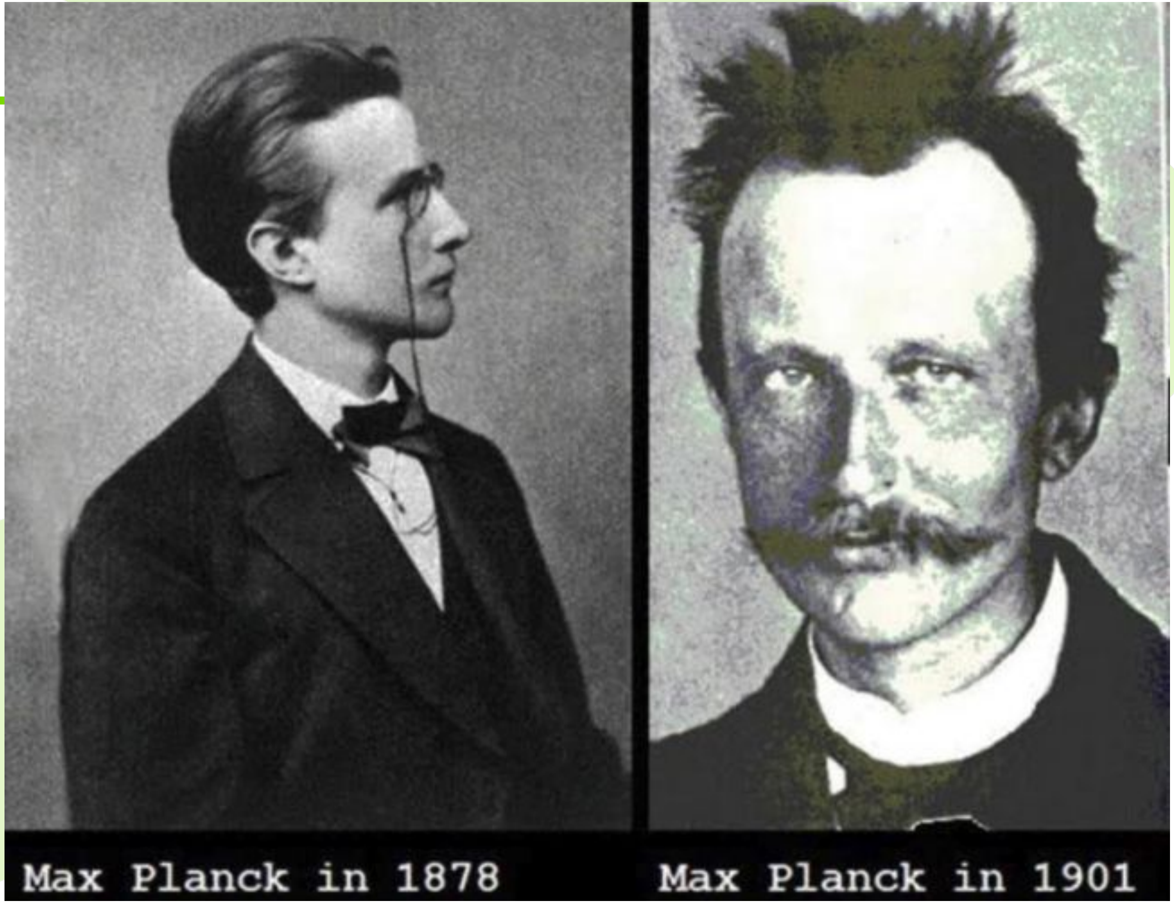
Quantum mechanics…

What it will do to you.

Don’t do it kids!



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History: concepts

1 1929: Mott uses quantum decoherence; Bohm defines it in 1951

2 1980: Benioff defines the qubit

3 1982: Wootters and Zurek prove non-cloning theorem

4 1985: Deutsch defines quantum Turing machine & quantum parallelism

5 1993: Bennett et al. proposes quantum teleportation (demonstrated 600m in 2004, and 144km in 2006, by Ursin et al.)

6 1995: QEC starts with Shor Code and Steane Code (1996)

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History: algorithms

1. 1985: Deutsch algorithm, upgraded to Deutsch-Josza algorithm in 1992, proves quantum can beat classical at least at 1 thing.

2. Quantum Fourier Transform: Deutsch suggests (1985), Shor defines (1994), Coppersmith improves (1994)

3. 1994: Shor's algorithm for factorization (demonstrated in 2001 by Vandersypen et al.)

4. 1996: Grover's algorithm for search problems

5. 2014: Peruzzo et al. define Variational Quantum Eigensolver

6. 2014: Farhi & Goldstone define QAOA (explored in 2000)

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History: computers

1. 1959: Feynman predicts a quantum computer in "There's plenty of room at the bottom" lecture. 1982: he actually suggests starting it.
2. 1995: First ever quantum logic gate demonstrated with a single trapped ion
3. 1996: Lloyd proves quantum computers to be able to simulate quantum systems
4. 1997: First quantum computer, done with nuclear magnetic resonance (NMR)
5. 2011: First sold computer - D-Wave One to Lockheed Martin
6. 2019: Google claims quantum supremacy (...it wasn't)

First demo of logic gate

- Notice the high decoherence!
- Interesting presentation too…

My favorite abstract ever from Lloyd's [1996 paper]:

"Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct."

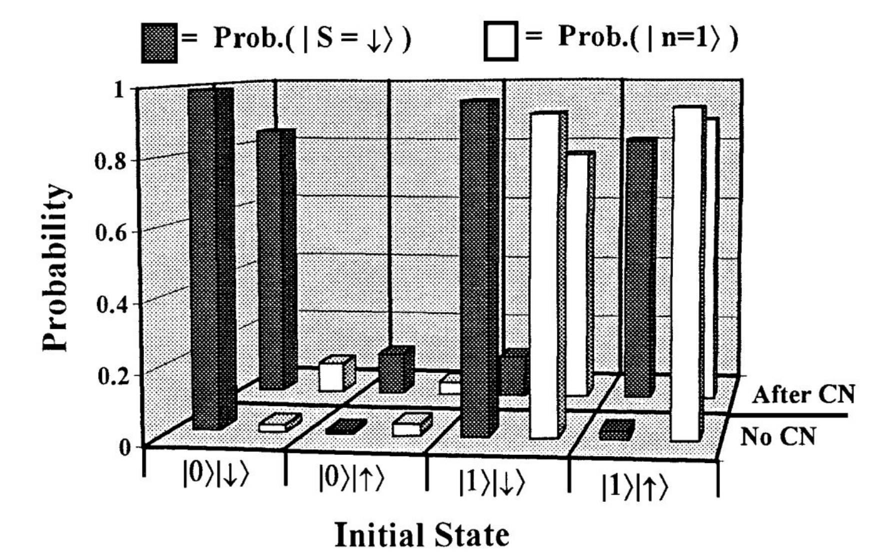


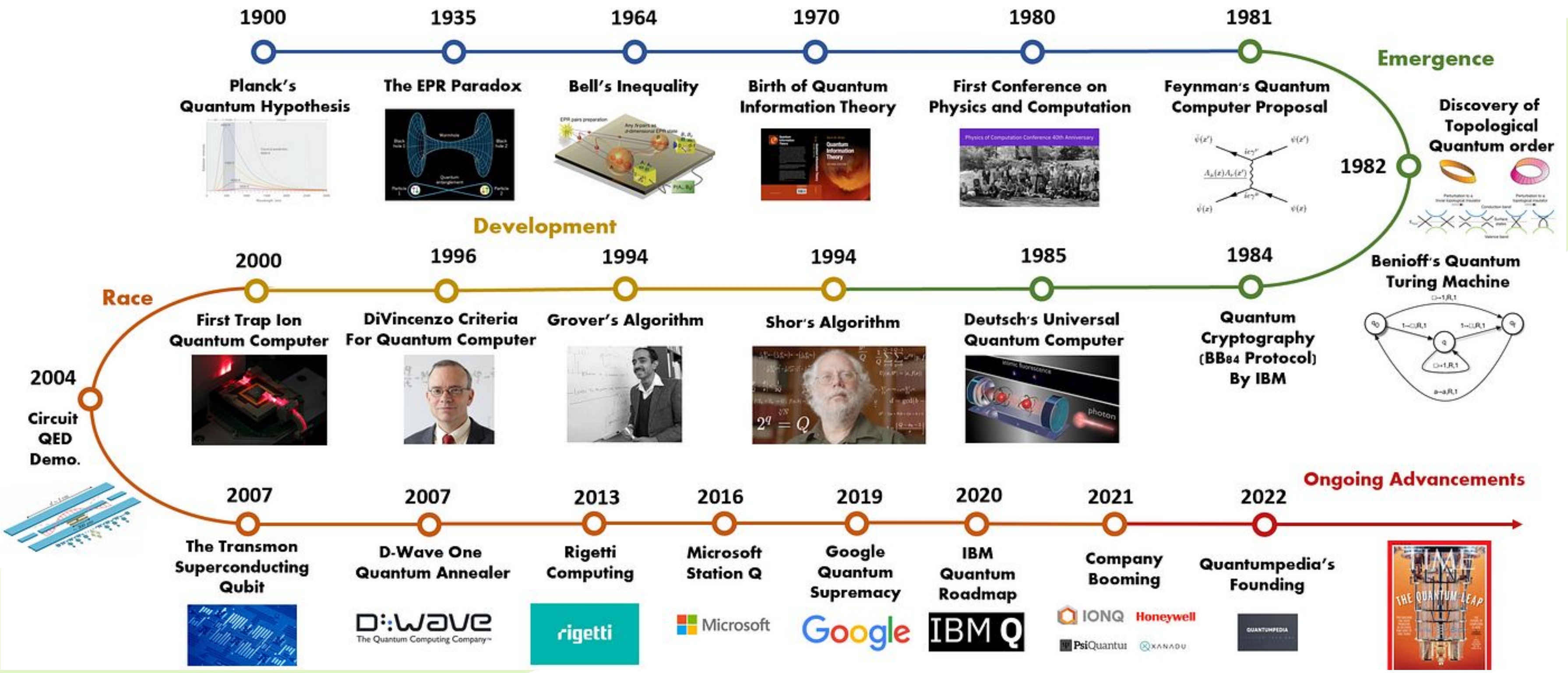
Fig 1: CNOT table (Monroe et al. 1995)

What about quantum neural networks?

- Subhash Kak (1 March, 1995) - "Quantum Neural Computing"
  - Proposes a quantum neural computer
- Independently, Ronald Chrisley also on 21 June, 1995 - “Quantum Learning”
  - Proposes neural network learning algorithm
- Purushothaman and Karayiannis (1996)
  - Coins the term ‘quantum neural network (QNN)’
- Kretzschmar et al. (2000)
  - Compares QNN with feedforward neural network (FFNN)

Nice overview

John Preskill also summarizes the history nicely in “[Quantum computing 40 years later](#)”



Credit: Quantum Computing Timeline by Anne Broadbent

History: modern

1. 2023: IBM develops first quantum computer with 1000+ qubits (IBM Condor)
2. Qiskit (IBM) is the most adopted quantum SDK
3. IQM has sold the most quantum computers.
4. IBM has largest ensemble of quantum computers globally, almost 80, most accessible via cloud
5. D-Wave has largest quantum annealer (5000+ qubits)
6. Quantinuum has highest Quantum Volume (2^{21})

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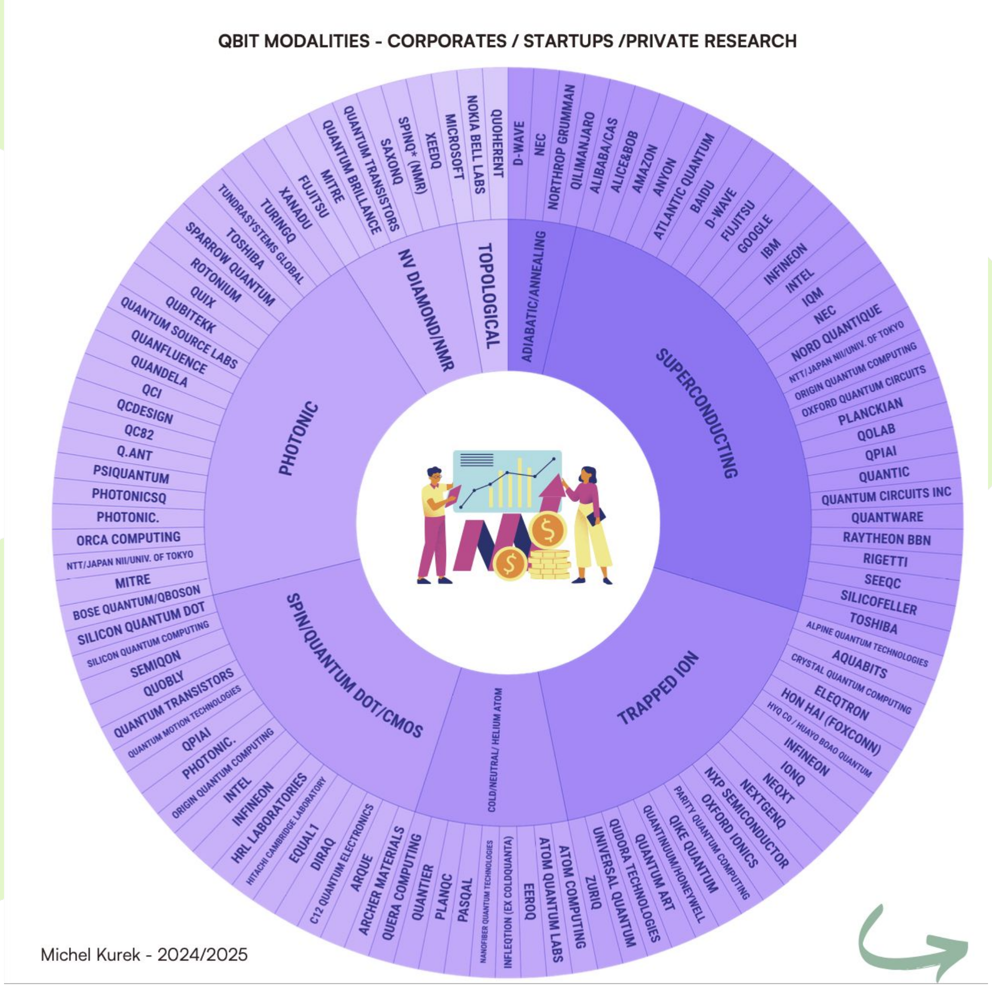
Company modalities

- Growing interest in
    - Photonic
    - Neutral atom
- Superconducting taking most space still



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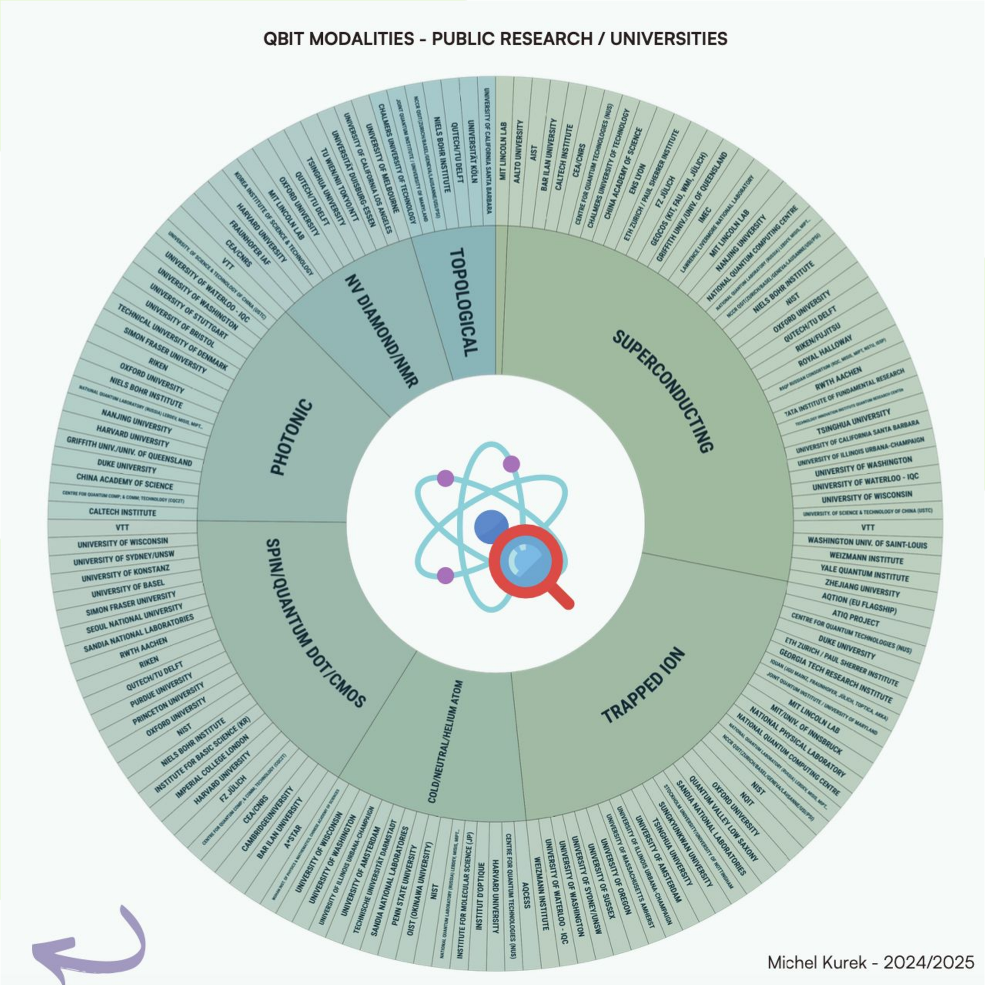
Institute modalities

- Closely the same, since companies pair with institutes
- Not much for annealing
- Germany highly represented



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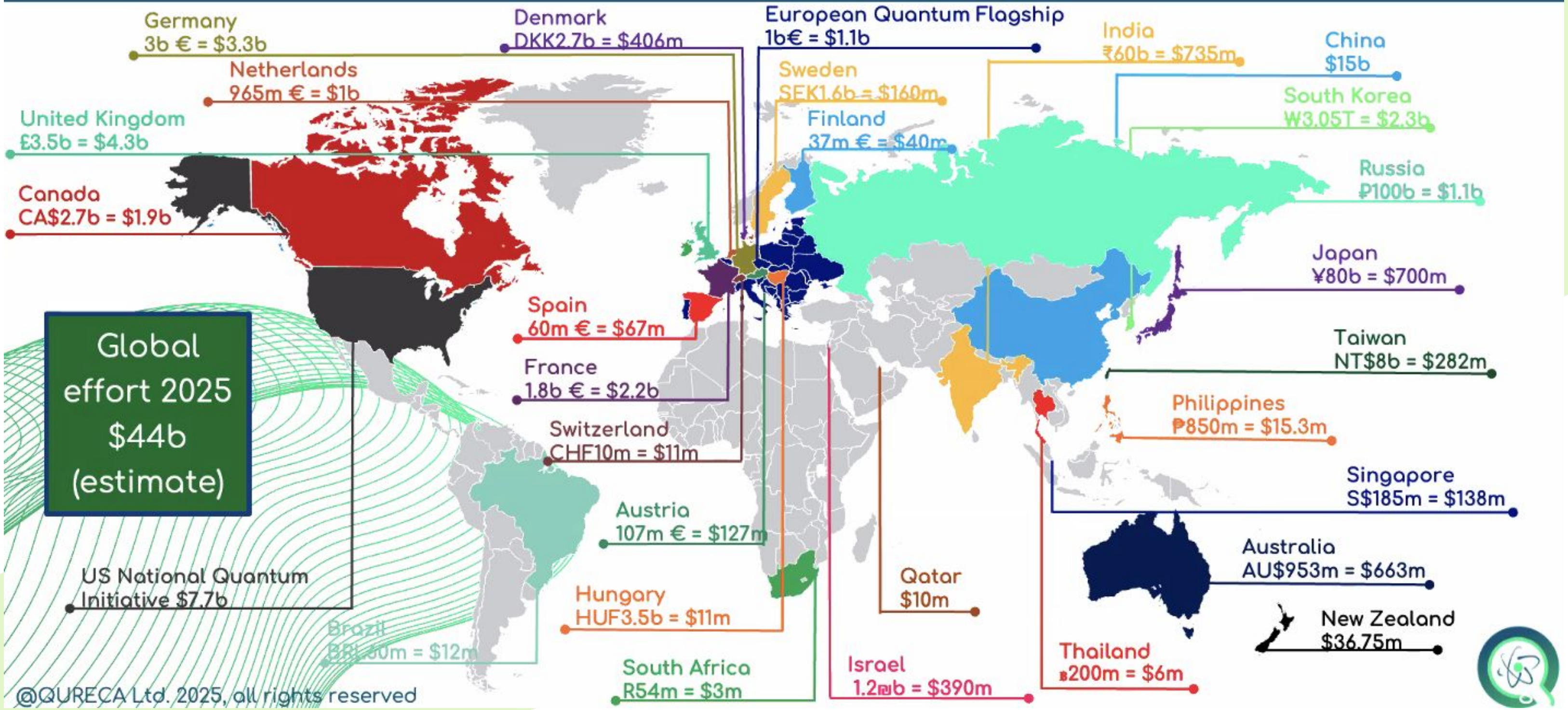
Quantum Effort Worldwide (public funding)



Credit: Qureca

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Addressing the hype

1

“Quantum is here!”

Companies lengthen timelines for new tech. Realistically, 5-10 years till real change.

2

“Quantum will shape the future”

Probably, but we don’t fully know yet in which areas and how much.

3

“Quantum is ‘rocket science’”

It need not be. AI is also complex at the core, but has become user-friendly.

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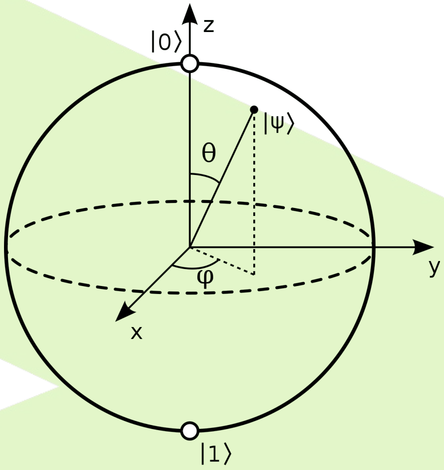
Recap the basics

- Qubits
    - basic quantum information container
    - (quantum) state (vector) of a qubit is a $\mathbb{C}^2$ vector $|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$ which is unitary $\rightarrow$ $|\alpha|^2 + |\beta|^2 = 1$
    - The computational basis states of a qubit are $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ $\rightarrow$ $|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$
    - Tensor products combine states $\rightarrow$ $\begin{bmatrix} \alpha_1 \\ \beta_1 \end{bmatrix} \otimes \begin{bmatrix} \alpha_2 \\ \beta_2 \end{bmatrix} = \begin{bmatrix} \alpha_1\alpha_2 & \alpha_1\beta_2 & \beta_1\alpha_2 & \beta_1\beta_2 \end{bmatrix}^T = |\psi_1\psi_2\rangle$
    - The state of n qubits is still unitary $\rightarrow$ $\langle\phi|\phi\rangle = \begin{bmatrix} \alpha_1^* & \dots & \alpha_{2^n}^* \end{bmatrix}^T \begin{bmatrix} \alpha_1 & \dots & \alpha_{2^n} \end{bmatrix} = 1$



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Recap the basics

- Gates
  - (Quantum logic) gates U are linear matrix operations, to transform states.
  - Gates are unitary → $U^\dagger = U^{-1}$ and $U^\dagger U = I = UU^\dagger$
  - Ex1) $H\,|0\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle = |+\rangle$

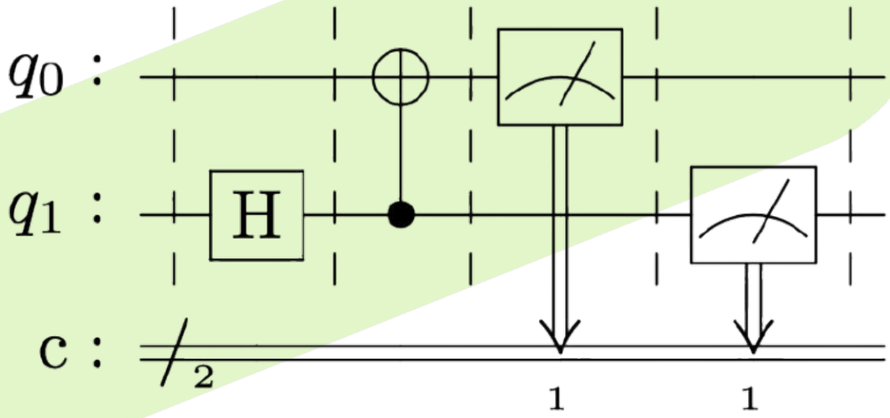
    Ex2) $CNOT\,|+0\rangle = \left[\begin{array}{cccc} \frac{1}{\sqrt{2}} & 0 & 0 & \frac{1}{\sqrt{2}} \end{array}\right]^T$

Gate	Symbol	Matrix
Pauli-X (NOT)	X	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
Pauli-Y	Y	$\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$
Pauli-Z (Phase flip)	Z	$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
S	S	$\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$
T	T	$\begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$
Hadamard	H	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$
Rotation Z	$R_z(\theta)$	$\begin{pmatrix} e^{-\frac{i\theta}{2}} & 0 \\ 0 & e^{\frac{i\theta}{2}} \end{pmatrix}$
Rotation Y	$R_y(\theta)$	$\begin{pmatrix} \cos\left(\frac{\theta}{2}\right) & -sin\left(\frac{\theta}{2}\right) \\ sin\left(\frac{\theta}{2}\right) & \cos\left(\frac{\theta}{2}\right) \end{pmatrix}$
Rotation X	$R_x(\theta)$	$\begin{pmatrix} \cos\left(\frac{\theta}{2}\right) & -isin\left(\frac{\theta}{2}\right) \\ -isin\left(\frac{\theta}{2}\right) & \cos\left(\frac{\theta}{2}\right) \end{pmatrix}$
CNOT		$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$
Swap		$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

Credit: ResearchGate

Recap the basics

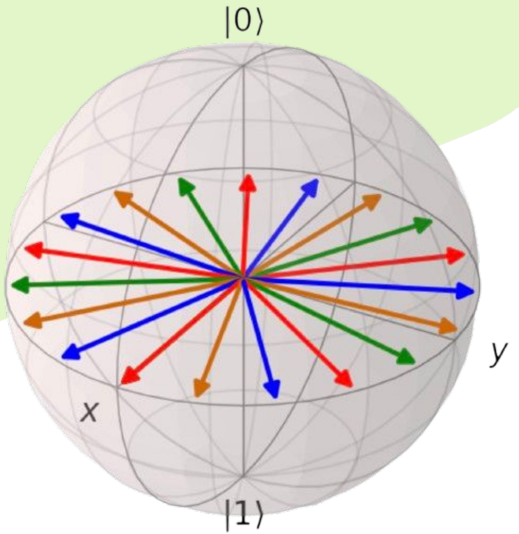
- Circuits
  - Represent quantum operations
  - Contain quantum & classical registers, gates and measurements
  - Measurements collapse to comp. bases by probability distribution
  - If $|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$, then $\mathbb{P}_{|\psi\rangle}(|0\rangle) = |\alpha|^2$



Recap the basics

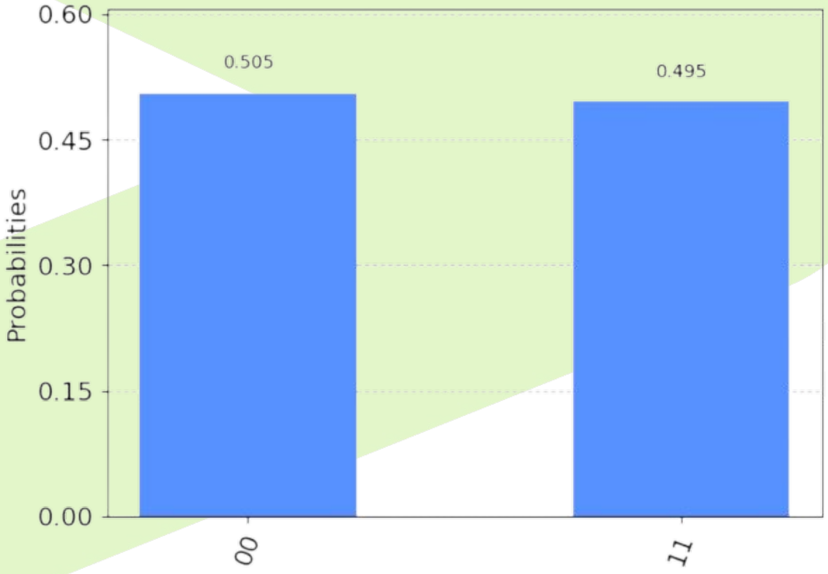
- Phase
  - The z-rotation of the state of a qubit
  - Change in (relative) phase does not affect (immediate) measurement probability distribution
  - Important to know for quantum Fourier transform (QFT)
  - Phase gate -> $P(\phi) = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{bmatrix}$
  - Global phase is something else and irrelevant to us…

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} -1 \\ 0 \end{bmatrix} = \begin{bmatrix} i \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1+i}{\sqrt{2}} \\ 0 \end{bmatrix}$$



Recap the basics

- Entanglement
  - When the measurement of one qubit affects the measurement of another
  - Hard to simulate classically; part of what gives quantum its potential



$$CNOT(I \otimes H)\,|00\rangle = CNOT[\tfrac{1}{\sqrt{2}}(|00\rangle + |01\rangle)] = \tfrac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

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Recap the basics

- Different states

Mixed	Pure
Only described by state density matrix	Described by state density matrix or statevector
ρ	$\|\psi\rangle$
Mixed if $trace(\rho^2) < 1$	Pure if $\rho^2 = \rho$ OR $trace(\rho^2) = 1$
$\begin{bmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{bmatrix}$	$\begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix} \sim \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} = \|+\rangle$
$\begin{bmatrix} \frac{1}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2} \end{bmatrix} = \frac{1}{2}\|00\rangle\langle 00\| + \frac{1}{2}\|11\rangle\langle 11\|$	$\begin{bmatrix} \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & \frac{1}{2} \end{bmatrix} \sim \begin{bmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ 0 \\ \frac{1}{\sqrt{2}} \end{bmatrix} = \frac{1}{\sqrt{2}}(\|00\rangle + \|11\rangle)$
Inside unit sphere	On unit sphere

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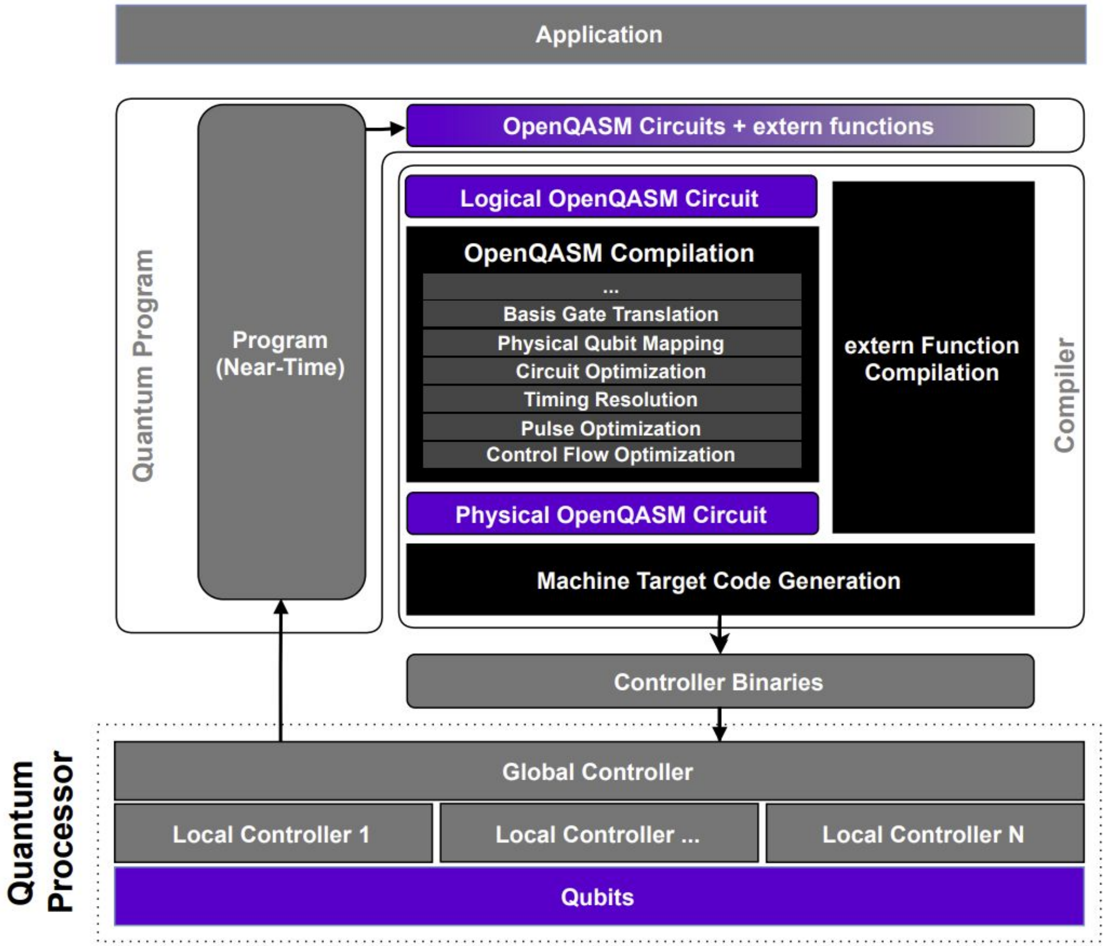
Recap the basics

- QASM
  - Full name: OpenQASM 3
  - Current industry standard for quantum intermediate representation (QIR)
  - Use to recompile among quantum SDKs e.g. Qiskit, Cirq, Qulacs, Pennylane, etc.



Credit: Cross et al. (OpenQASM 3 paper)

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Limitations

- Storage size

Acknowledgements

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Time to get down to business