Superconducting Qubit Design Workshop 2025

Quantum Design Engineering Initiative (QEDi)

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About me

Vamsi Sridharbabu

- Cohort A of the Quantum Communications and Quantum Computation CDT at UCL
- Starting the 2^{nd} year of my PhD supervised by Prof. Paul Warburton
- MSc in Physics with Quantum Dynamics at Imperial College London
- BSc in Physics at Imperial College London

Workshop Curriculum

- Day 1:
  - Introduction to Quantum Mechanics
  - Quantum Systems
  - Workshop 1: Simulating Quantum Systems using QuTiP
  - Superconducting Circuits
- Day 2:
  - Circuit QED
  - Workshop 2: Designing a Transmon chip using Qiskit Metal
  - Workshop 3: EM simulations of the chip using Elmer FEM
  - Guest Lecture: Fabrication of Superconducting Devices (Leon Guerrero)
  - Careers Panel
  - Networking (Drinks at the Institute Bar!)

Intro to Quantum Mechanics

QEDi Day 1 Lecture 1
15/09/2025
Vamsi Sridharbabu

Lecture 1 Content

- Background on Quantum Computing
  - Use cases of Quantum Computing
  - Quantum Computing industry in the UK and globally
- Fundamentals of Quantum Mechanics
  - History of quantum
  - Wavefunction
  - Dirac Notation
  - Schrödinger's Equation
  - Brief look at Entanglement

Why do we want Quantum Computers?

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

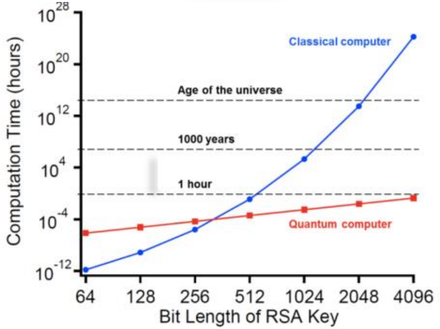
Received May 7, 1981

"Can you do it with a new kind of computer – a quantum computer? Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind."

- Richard Feynman (1981)

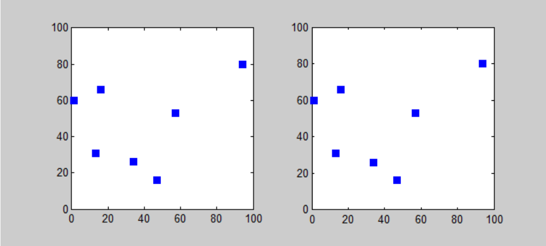
Limitation with Classical Computing

Breaking RSA Encryption



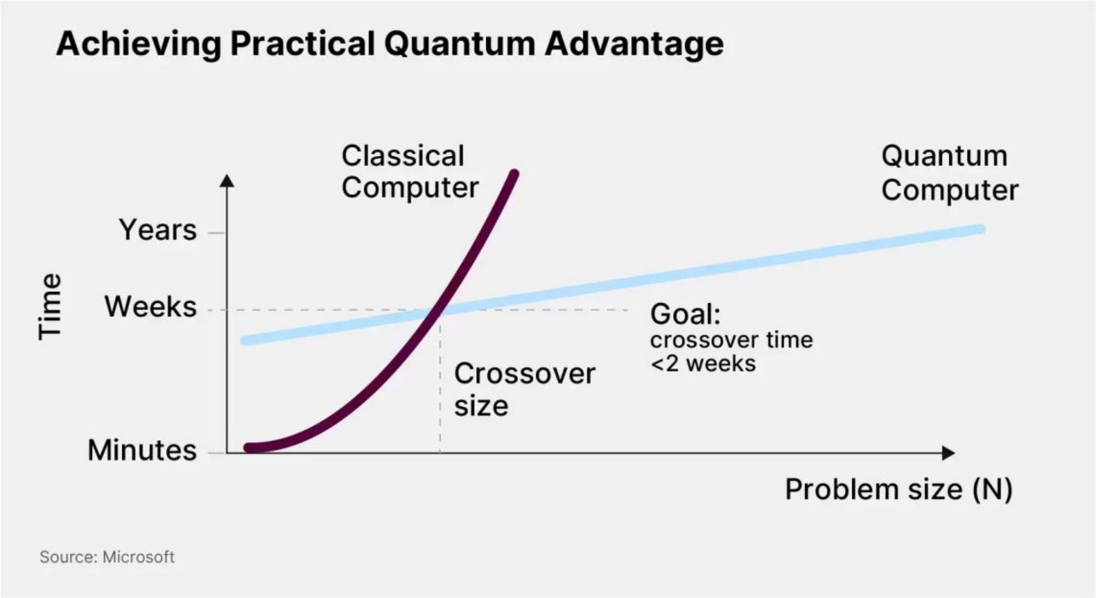
- RSA is a standard encryption protocol used by banks and other corporations to store secure data.
- This is an integer factorization problem.
- RSA-2048 is currently not breakable classically, but is under threat by quantum algorithms (Shor's Algorithm)

Travelling Salesman Problem



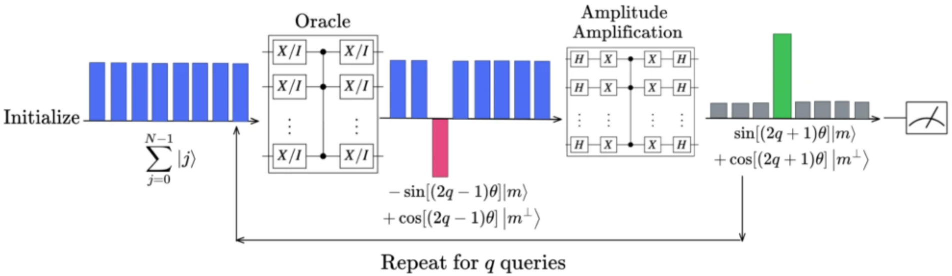
- This is an NP-hard combinatorial problem in classical computing.
- Quantum solvers aim to solve this by finding the ground state minima in the energy landscape. The optimum route has the lowest cost i.e. the global minimum.
- The scaling is dependent on the algorithm depth but is much lower than the classical case.
- Quantum Annealing and Quantum Approximate Optimization Algorithm (QAOA) are some quantum solver methods.
- The solvers can struggle with finding a minima if the initial parameters are in the wrong region of the energy landscape. This is the **barren plateau problem**.

Where is Quantum Advantage?

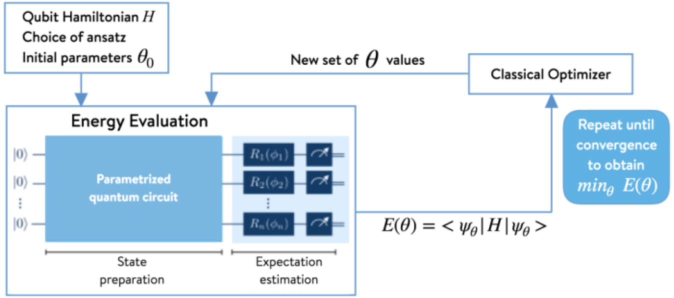


- Many problems scale exponentially in time on a classical computer.
- Quantum computers can reduce this to a polynomial scaling.
- Hence, reducing the time cost from decades to days of computing time.

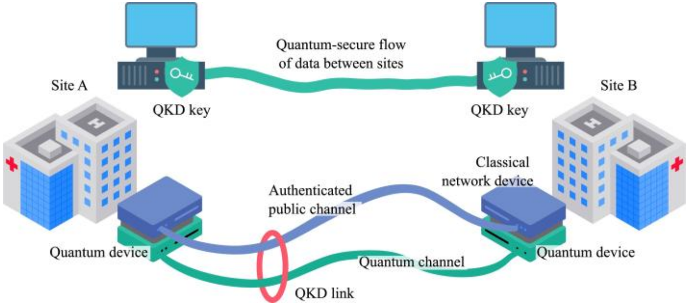
Quantum Algorithms



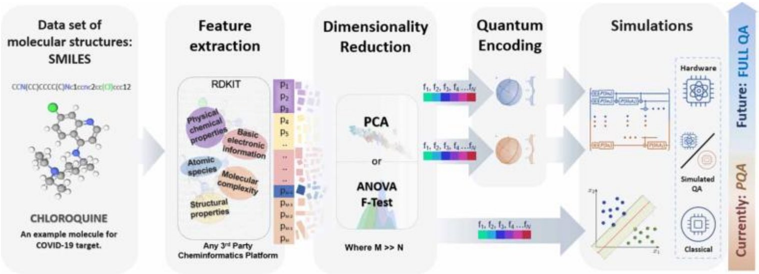
Grover’s Search Algorithm



Variational Quantum Eigensolver



BB84 Quantum Key Distribution Protocol



Quantum Machine Learning Models

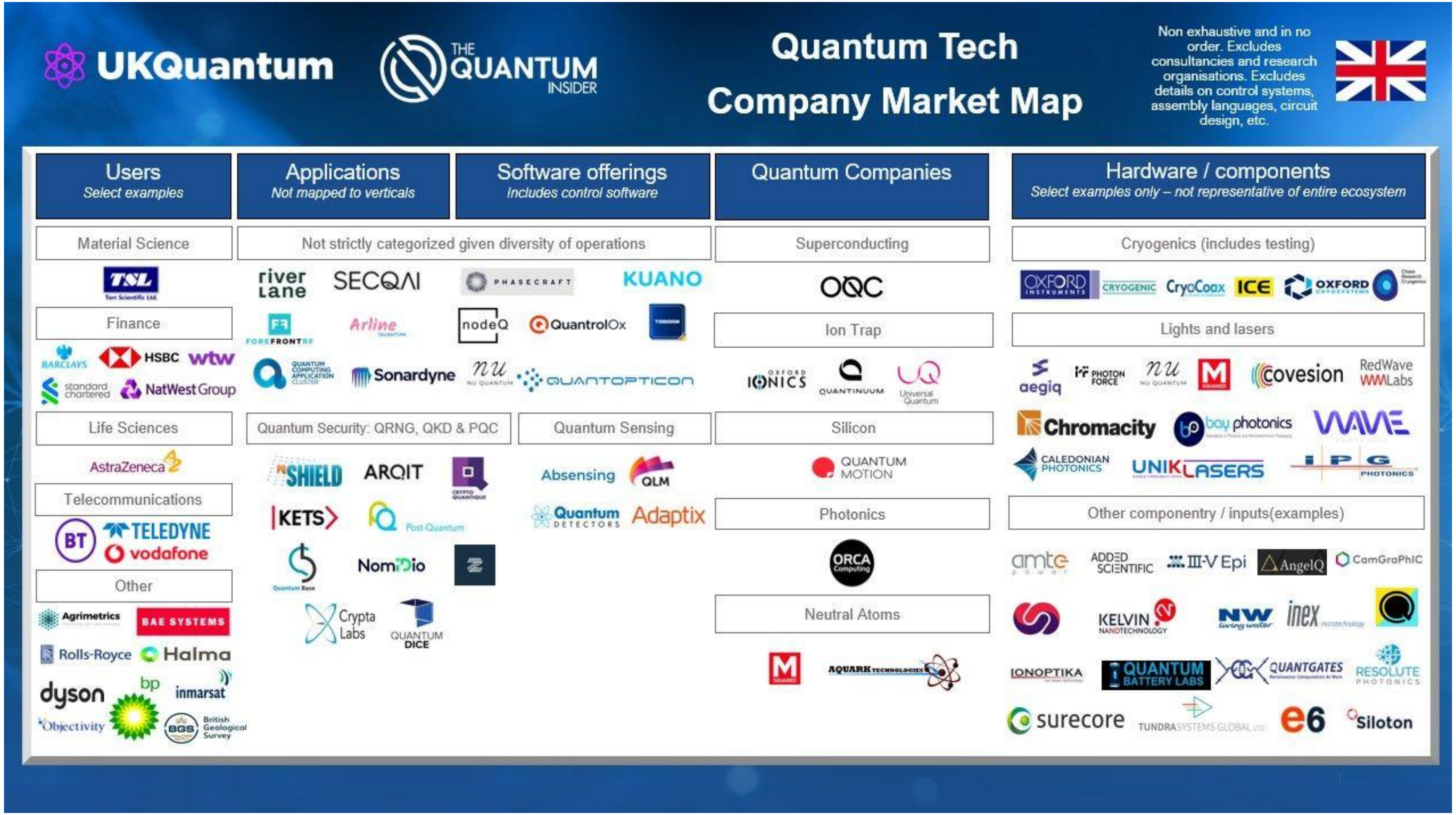
Quantum Computing in the UK

UKRI National Quantum Computing Centre

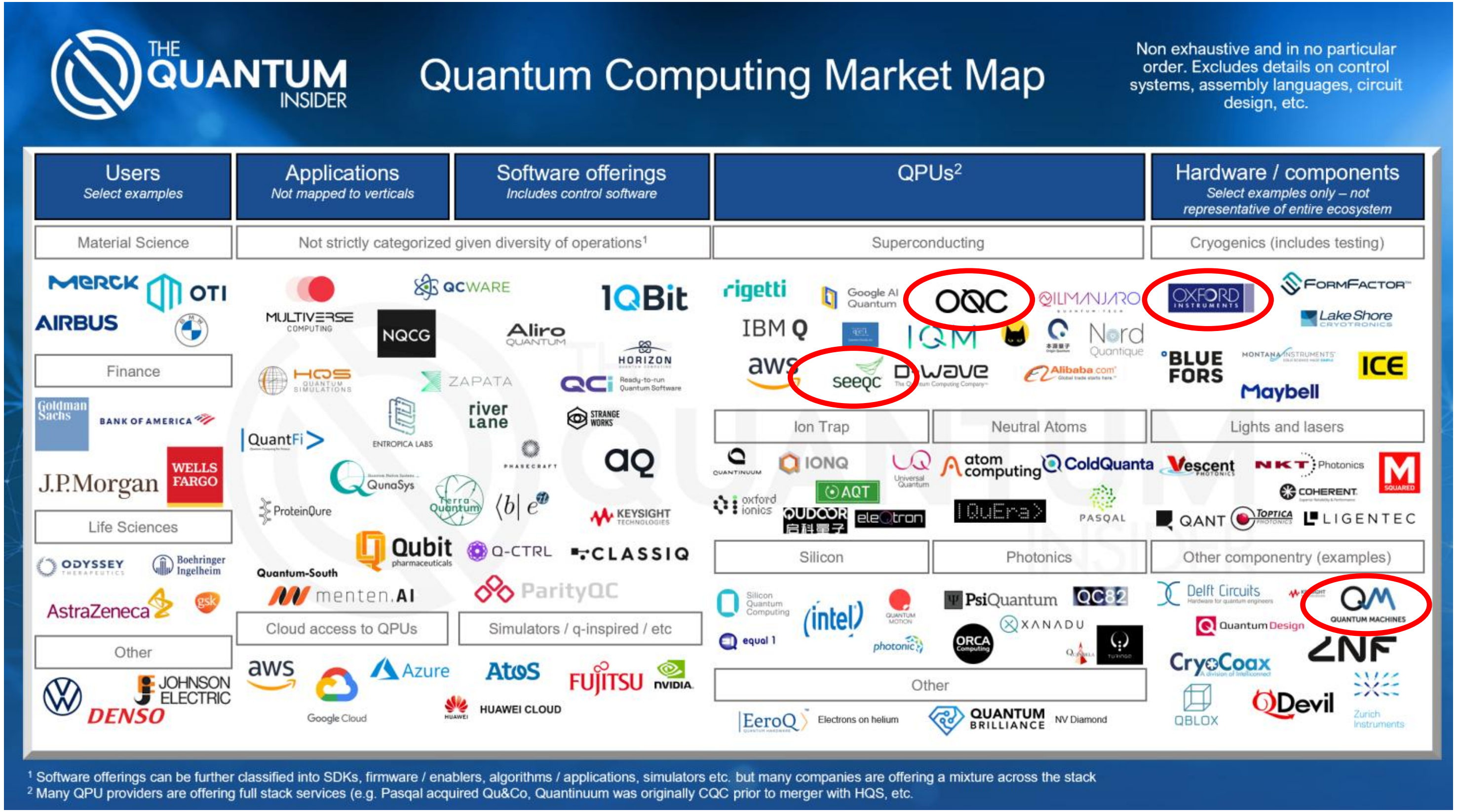
The UK government invested £650 million to accelerate the impact of quantum computing in various sectors.

- **Mission 1:** Develop UK-based quantum computers capable of 1 trillion operations, surpassing classical supercomputers.
- **Mission 2:** Deploy the world's most advanced quantum network, pioneering the future quantum internet.
- **Mission 3:** Integrate quantum medical sensors in the NHS for early diagnosis and treatments of chronic illnesses.
- **Mission 4:** Provide precise, satellite independent positioning for vehicles, including aircraft using miniaturized quantum sensors.
- **Mission 5:** Enhance infrastructure monitoring across transport, telecommunications, energy and defence with mobile, networked quantum sensors.

Quantum Industry in UK



Quantum Industry Global



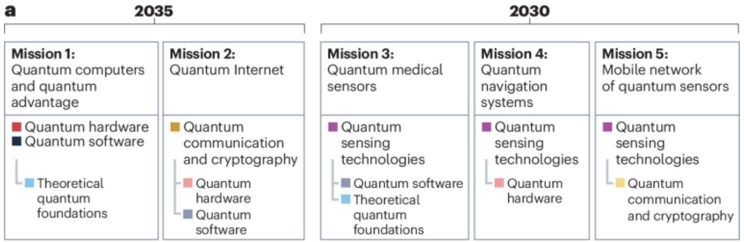
Brief study on the skill gap in UK's quantum industry

Down to Business | Published: 26 March 2025

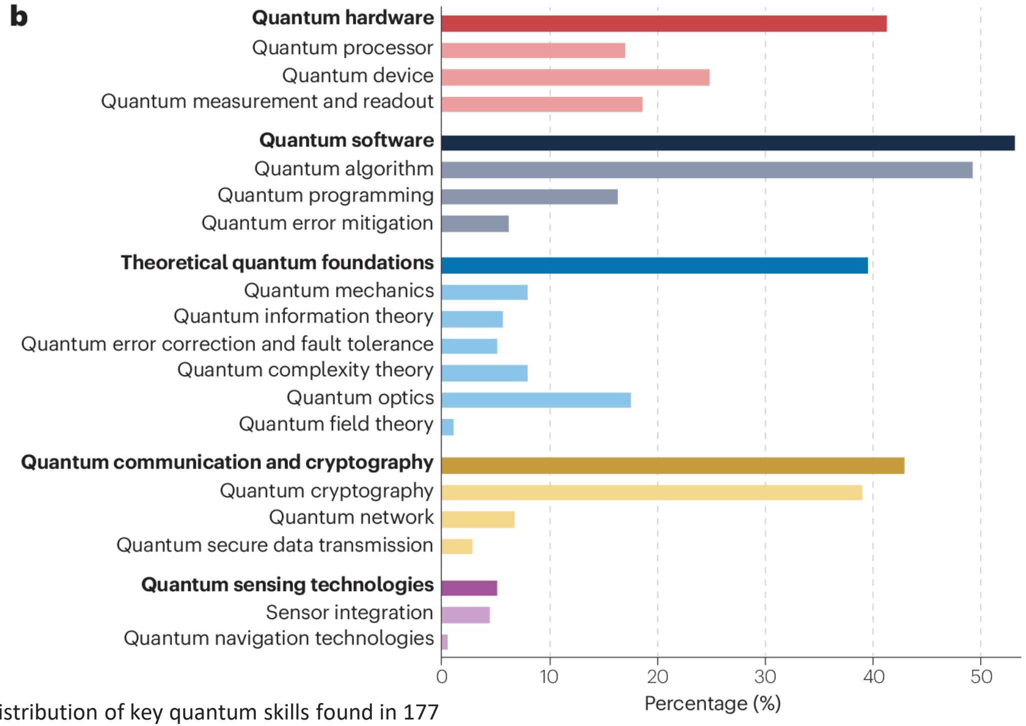
Assessing the skills gap for the UK's quantum missions

Josephine Hunout, Shey Dylan Lovett, Jessica Wade & Isabella von Holstein

Nature Reviews Physics 7, 171–173 (2025) | Cite this article

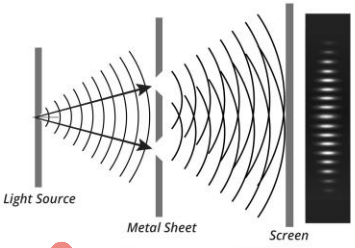


Addressing this challenge requires both short-term and long-term strategies. In the immediate term, targeted retraining programmes can help engineers and researchers transition into quantum roles, whereas stronger industry–academic partnerships and government incentives can accelerate workforce growth. However, long-term success

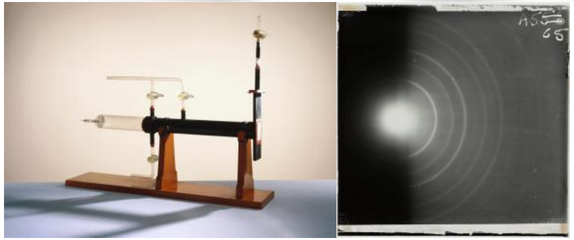


a, Key quantum skills aligned with each quantum mission and their deadline. **b**, Distribution of key quantum skills found in 177 LinkedIn job postings (UK, August–October 2024). Dark shades represent skill categories; light shades indicate sub-skills.

Intro to Quantum Physics



1801: Young's Double-Slit Experiment (Thomas Young)

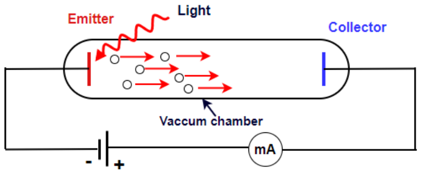


1927: Electron Diffraction (George Paget Thomson & Alexander Reid)

1924: De Broglie proposes the idea of **matter waves.**

A lot more happened here… (we will talk about them later)

1887: Photoelectric Effect (Heinrich Hertz)

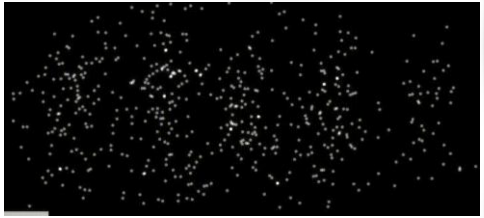


1905: Albert Einstein states that lights come in discrete packets of energy called ***"quanta"*** to describe the photoelectric effect.

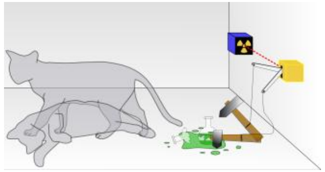
1926: Erwin Schrodinger publishes the **matter wave equation** and derives the energy spectrum of hydrogen.

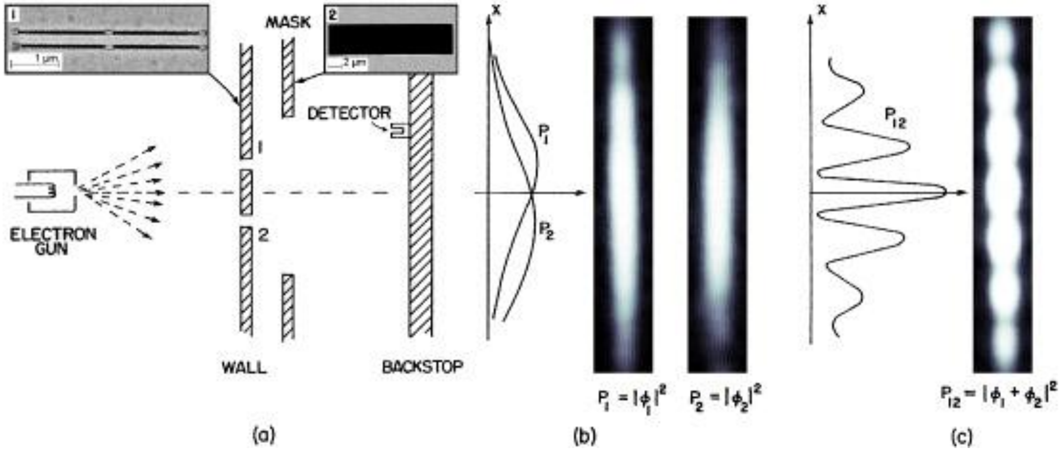
1928: Hans Bethe solves Schrodinger's equation to explain electron diffraction.

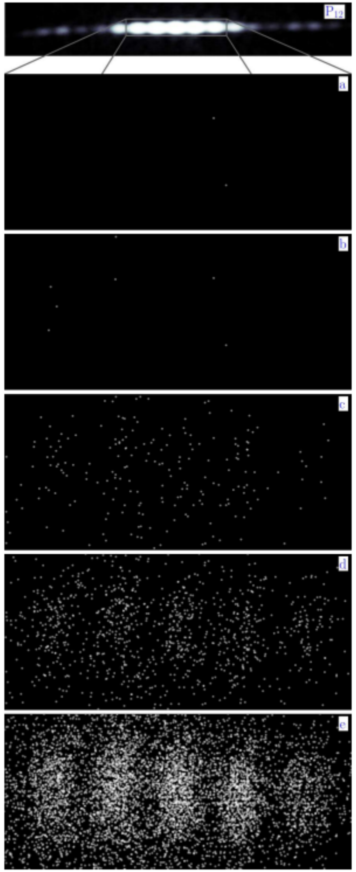
2013: Double-Slit Electron Diffraction (Roger Bach et al 2013 New J. Phys. 15 033018



Superposition







- The slit an electron takes is probabilistic. *We do not know which one was chosen!*
- The final pattern is composed of the *matter waves* diffracting from both slits ***interfering*** with each other.
- Hence the final pattern is a **superposition** of the matter waves from both slits.

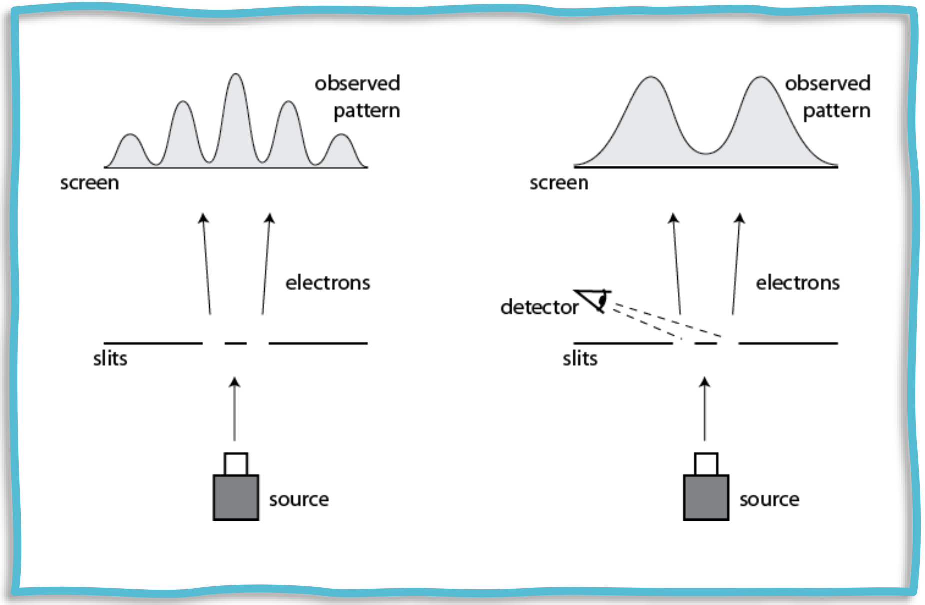
Wavefunction

- The "matter wave" is called the wavefunction of a particle: $\psi(x) = |\psi(x)|\, e^{i\varphi}$

- **Magnitude** of the wavefunction is $|\psi(x)|$
- **Phase** of the wavefunction is φ (determines interference effects)

- **Probability density function** (PDF) of the particle's position: $P(x) = |\psi(x)|^2$

- Measuring the particle's position will collapse the wavefunction to a specific point.
- This is called **wavefunction collapse**.



Dirac Notation

Ket/Column Vector:

$$|\psi\rangle \Leftrightarrow \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{pmatrix}$$

Bra/Row Vector:

$$\langle\psi| \Leftrightarrow \begin{pmatrix} c_1^* & c_2^* & \cdots & c_n^* \end{pmatrix}$$

Inner Product/Dot Product:

$$\langle\psi|\phi\rangle = (\langle\phi|\psi\rangle)^*$$

$\langle\psi|\phi\rangle = 0$ Not Orthogonal

$\langle\psi|\psi\rangle = 1$ Orthogonal

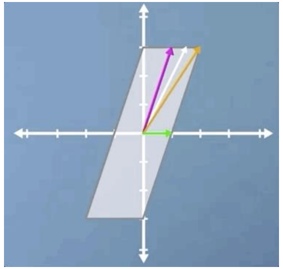
Outer Product:

$$|\psi\rangle\langle\phi| = \begin{pmatrix} a \\ b \\ c \end{pmatrix} \begin{pmatrix} d^* & e^* & f^* \end{pmatrix} = \begin{pmatrix} a \cdot d^* & a \cdot e^* & a \cdot f^* \\ b \cdot d^* & b \cdot e^* & b \cdot f^* \\ c \cdot d^* & c \cdot e^* & c \cdot f^* \end{pmatrix}$$

Quantum Operators/Observables

$$\hat{A}|\psi\rangle = |\phi\rangle$$

Operators define physically observable quantities.



Eigenvalue equation (if $|\psi\rangle$ is an eigenvector): $$\hat{A}|\psi\rangle = \lambda|\psi\rangle$$

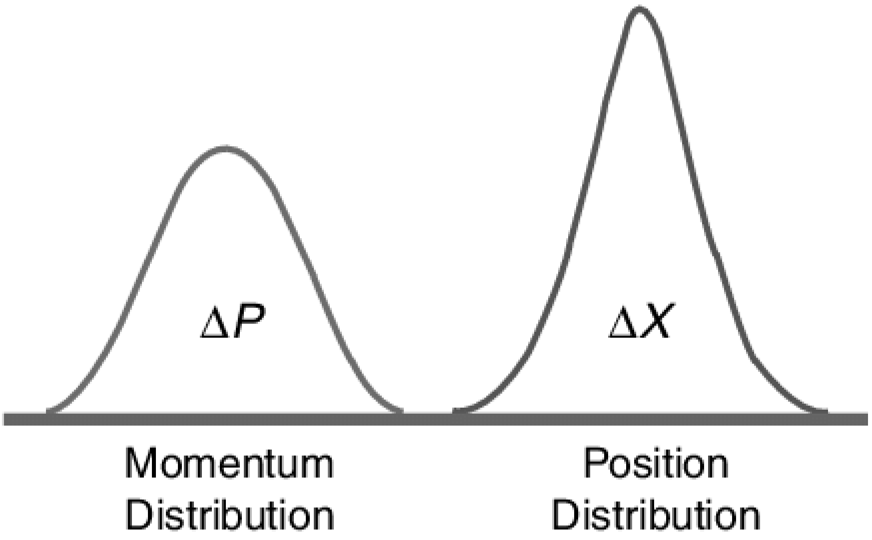
Expectation value: $\langle\psi|\hat{A}|\psi\rangle$

Operators obey commutation relations: $\hat{A}\hat{B} \neq \hat{B}\hat{A}$ (You can't measure both quantities simultaneously)

Note: If not in the same subsystem (Hilbert space), then they can freely commute.

Position-momentum commutation relation: $$[\hat{X},\hat{P}] = \hat{X}\hat{P} - \hat{P}\hat{X} = i\hbar$$

Heisenberg Uncertainty



$$\boxed{\Delta x \Delta p \geq \frac{\hbar}{2}}$$

Time Dependent Schrödinger's Equation:

$$\boxed{i\hbar \frac{d}{dt}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle}$$

The Hamiltonian

Describes the total energy of the system!

$$\hat{H} = \hat{T} + \hat{V}$$

Time Dependent Schrodinger's Eq:

$$i\hbar\frac{d}{dt}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle$$

Time Independent Schrodinger's Eq:

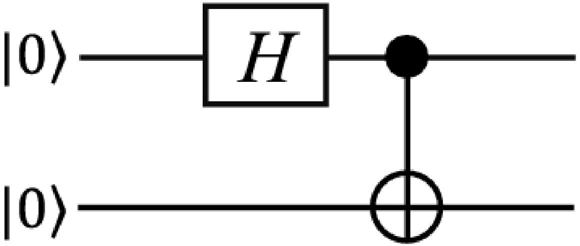
$$\hat{H}|\Psi\rangle = E|\Psi\rangle$$

- Hermitian operators conserve some quantity after transformation.
- The Hamiltonian is Hermitian and it conserves energy.

$$H = H^\dagger = (H^T)^* \longrightarrow U(t) = e^{-i\hat{H}t/\hbar}$$

Entanglement

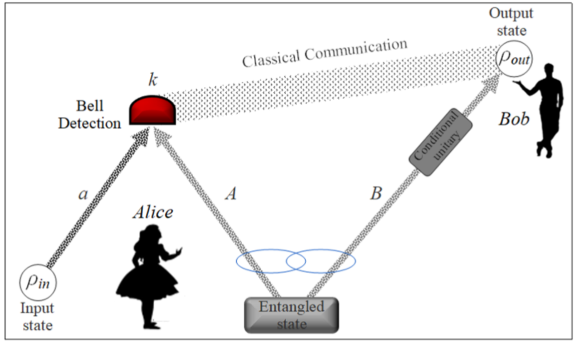
This is a Hadamard Gate
(Not the Hamiltonian)



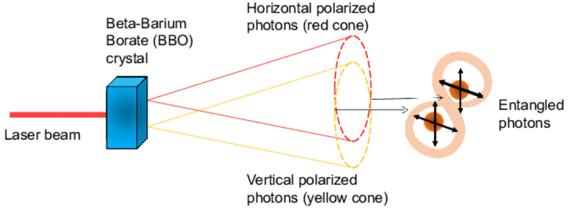
$$\rightarrow \frac{|00\rangle + |11\rangle}{2}$$

Controlled Not Gate

- Applies the σ_x gate conditionally



Quantum teleportation



Entangled photon pair generation

We will not cover entanglement in this series of workshops. But we will have a look at how some of these gates work.

Summary

- Quantum computing is an exciting field!
- The wavefunction describes the wave-like properties of particles.
- Quantum states can be represented in Dirac notation.
- Physical properties are observables, can be expressed as matrices.
- Full information about two non-commutable observables cannot be measured simultaneously.
- The Schrodinger’s Equation evolves the wavefunction in time, according to the Hamiltonian (total energy of the system).
- Quantum objects can be entangled over large distances!

Quantum Systems

QEDi Day 1 Lecture 2
15/09/2025
Vamsi Sridharbabu

Lecture 2 Content

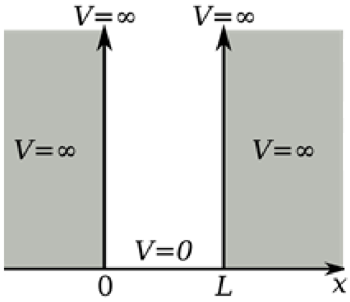
- Particle in a Box
- Spin
- Quantum Harmonic Oscillator
  - QHO Eigenstates
  - Annihilation and Creation Operators
- Qubit
  - Pauli Matrices
  - Bloch Sphere
  - Driven Qubit Model
  - Characterising the Qubit's Decoherence and Dephasing
- Scaling up to a Quantum Computer

Particle in a Box and Energy States

$$\hat{H} = \hat{T} + \hat{V}$$

$$\hat{T} = \frac{\hat{P}^2}{2m} = \frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}$$

$$\hat{V} = \begin{cases} 0 & \text{for } 0 < x < L \\ \infty & \text{otherwise} \end{cases}$$



Schrodinger's Equation:
(Inside the well)

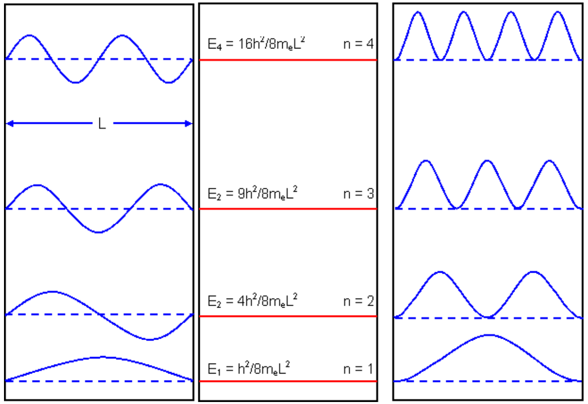
$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2} = E\psi(x)$$

Wavefunction:

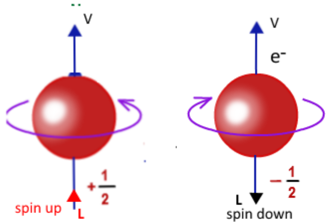
$$\psi_n(x) = \sqrt{\frac{2}{L}}\sin\left(\frac{n\pi x}{L}\right)$$

Energy Levels:

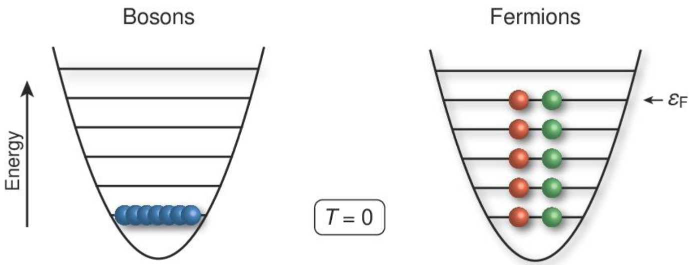
$$E_n = \frac{n^2h^2}{8mL^2} \quad n = 1, 2, 3, \ldots$$



Spin



Spin in an intrinsic property of quantum systems.
They act like angular momentum vectors. (Note: They are not actually spinning!)



Bosons: Integer spin systems

- E.g. photons, Higgs boson, Cooper-pairs etc.
- Form *Bose-Einstein Condensate* i.e. many can occupy a single state

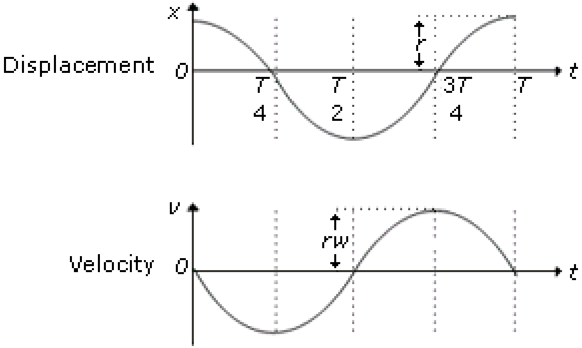
Fermions: Half-Integer spin systems

- E.g. electrons, neutrons, protons etc.
- *Pauli Exclusion Principle* states two fermions with identical properties cannot occupy the same state.

The two spin states (up and down) are usually degenerate (same energy).
However, fermions can act as 2-level systems under a magnetic field due to the *Zeeman energy splitting.*
This causes the two spin states (up and down) to have different energies forming a qubit. (quantum dots)

Harmonic Oscillator (Classical)

$$F = m\frac{d^2x}{dt^2} = -kx \longrightarrow \begin{cases} x(t) = A\cos(\omega t - \varphi) \\ v(t) = \dfrac{dx}{dt} = -\omega A \sin(\omega t - \varphi) \end{cases}$$



$$V(t) = \frac{1}{2}kx(t)^2$$

$$T(t) = \frac{1}{2}mv(t)^2$$

Classical Hamiltonian:

$$H(t) = T(t) + V(t)$$

Quantum Harmonic Oscillator

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2}k\hat{x}^2$$

Wavefunction:

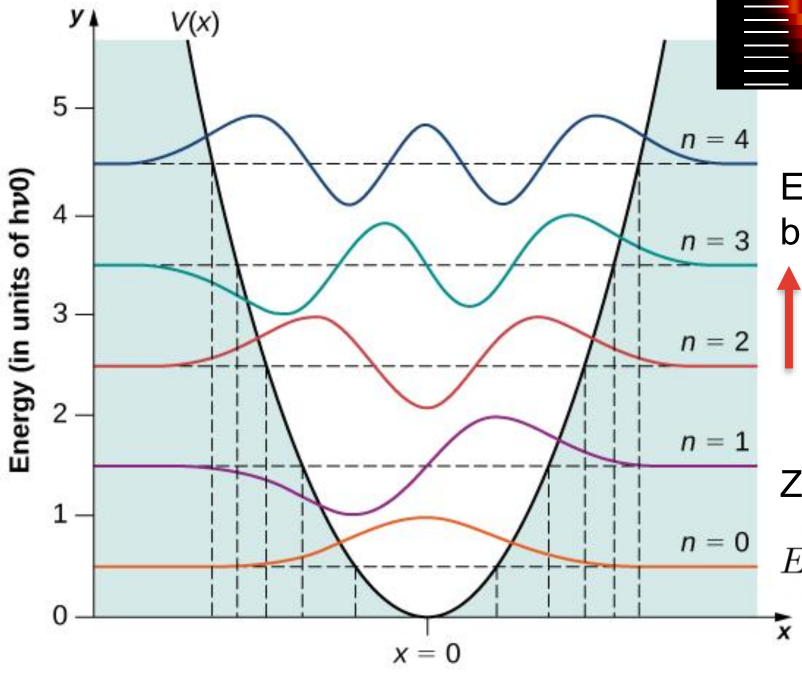
$$\psi_n(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \frac{1}{\sqrt{2^n n!}} H_n\left(\sqrt{\frac{m\omega}{\hbar}}x\right) e^{-\frac{m\omega x^2}{2\hbar}}$$

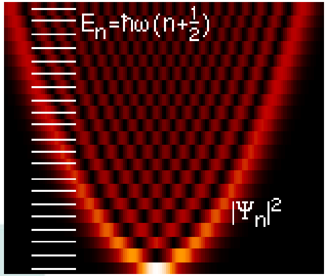
Energy States:

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

Fock/number states: $|n\rangle$

(*n* number of photons in the system)





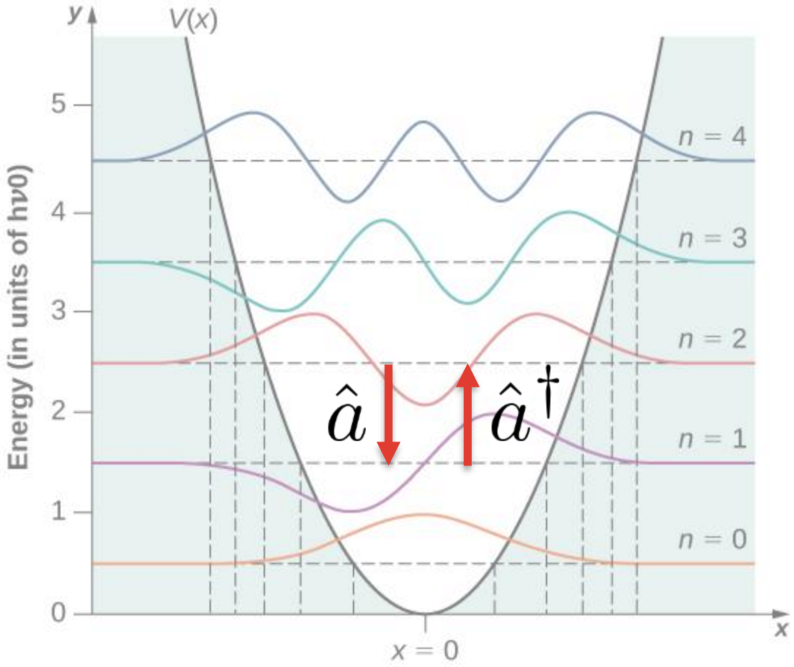
Energy spacing between states

$\hbar\omega$

Zero-point energy

$$E_0 = \frac{1}{2}\hbar\omega$$

Annihilation and Creation Operators



Annihilation Operator: $a = \sqrt{\frac{m\omega}{2\hbar}}\left(\hat{x} + \frac{i}{m\omega}\hat{p}\right)$

Creation Operator: $a^\dagger = \sqrt{\frac{m\omega}{2\hbar}}\left(\hat{x} - \frac{i}{m\omega}\hat{p}\right)$

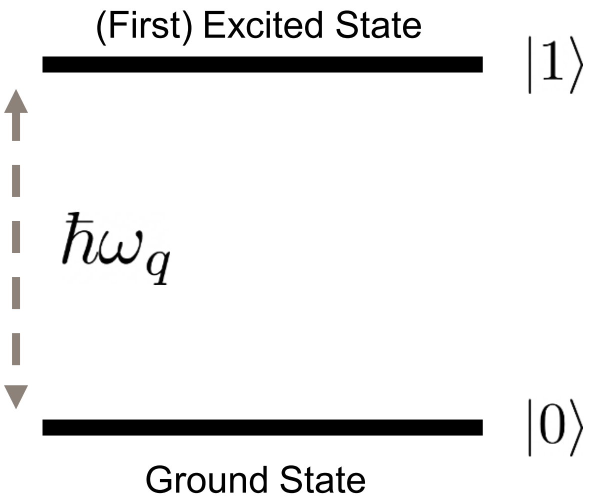
$$[a, a^\dagger] = aa^\dagger - a^\dagger a = 1$$

$$\hat{a}|n\rangle = \sqrt{n}|n-1\rangle$$

$$\hat{a}^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$$

Number Operator: $\hat{n}|n\rangle = a^\dagger a|n\rangle = n|n\rangle$

Qubit



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

Probability of State 0: $|\alpha|^2$
Probability of State 1: $|\beta|^2$

Born's Rule:

$$|\alpha|^2 + |\beta|^2 = 1$$

Pauli Matrices

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

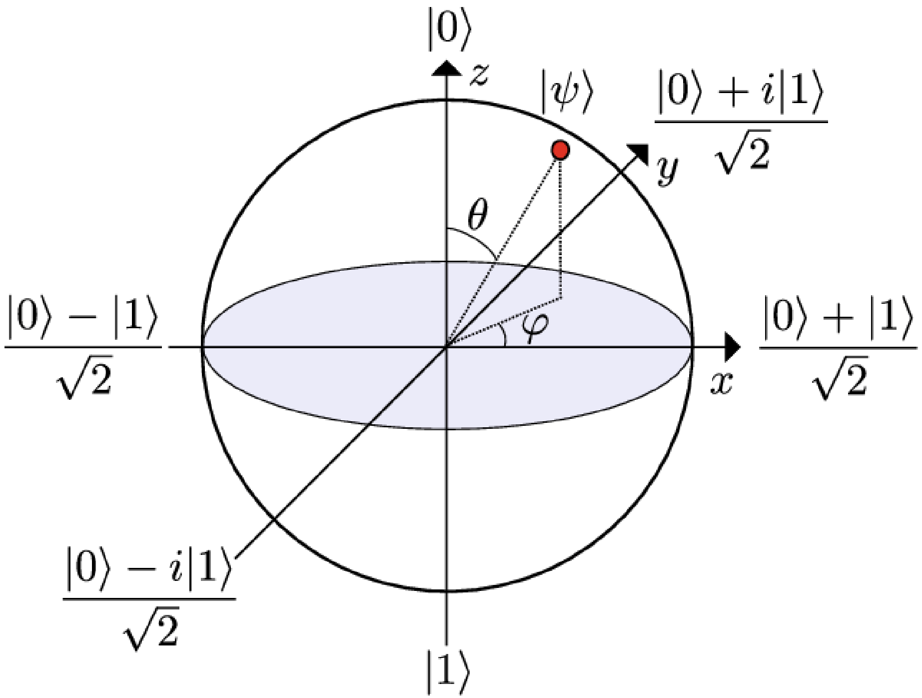
$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\hat{\sigma}_z|+\rangle = |+\rangle$$
$$\hat{\sigma}_z|-\rangle = -|-\rangle$$
$$\hat{\sigma}_x|+\rangle = |-\rangle$$
$$\hat{\sigma}_x|-\rangle = |+\rangle$$
$$\hat{\sigma}_y|+\rangle = i|-\rangle$$
$$\hat{\sigma}_y|-\rangle = -i|+\rangle$$

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

The Bloch Sphere



- The Bloch sphere can only represent 2-level systems like the qubit
- Each axis corresponds to the eigenstates of each Pauli matrix
- The ends of each axes represent the +1 and -1 eigenstates

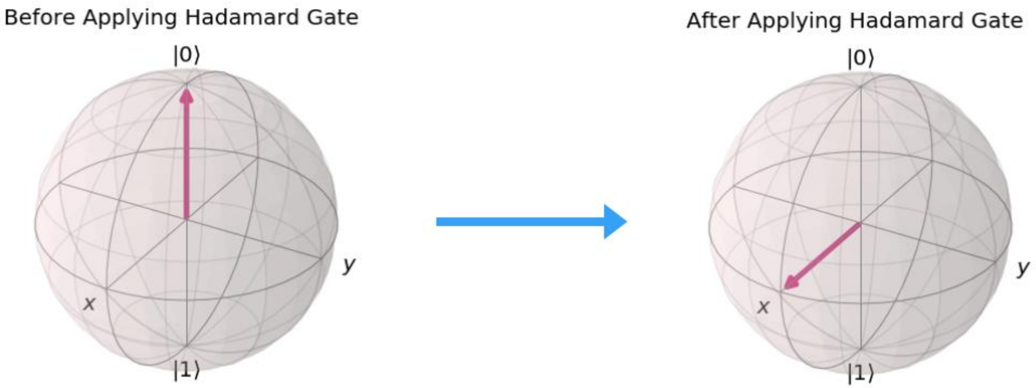
Representation of the state:

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

Hadamard Gate

$$H_2 = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} = \frac{1}{\sqrt{2}}\left(|0\rangle\langle 0| + |0\rangle\langle 1| + |1\rangle\langle 0| - |1\rangle\langle 1|\right)$$

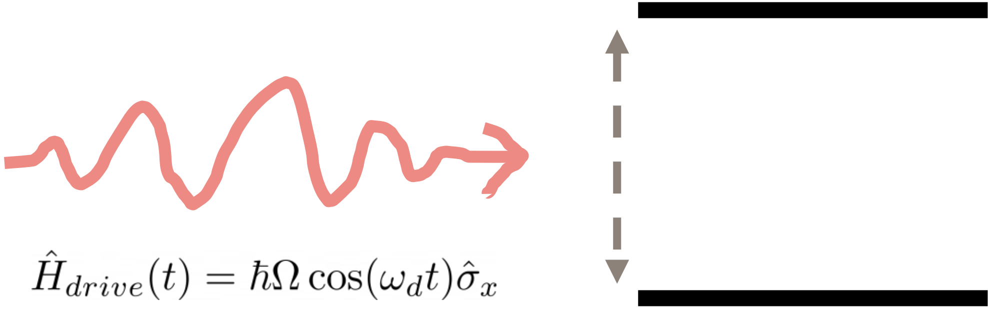
Do not confuse this with the Hamiltonian! This is a different H!



This operator transforms your state from the Z-basis (|0> and |1>) to the X-basis (|+> and |->).

Hence, generates an equal superposition.

Driven Qubit Model



$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\hat{H}_{qubit} = \frac{-\hbar\omega_q}{2}\hat{\sigma}_z$$

$$\hat{H}_{drive}(t) = \hbar\Omega\cos(\omega_d t)\hat{\sigma}_x$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Rotating Frame of ω_d +
Rotating Wave Approximation

$$\hat{H}(t) = \frac{-\hbar\omega_q}{2}\hat{\sigma}_z + \hbar\Omega\cos(\omega_d t)\hat{\sigma}_x \longrightarrow \hat{H}(t) = -\frac{\Delta}{2}\hat{\sigma}_z + \frac{\Omega(t)}{2}\hat{\sigma}_x$$

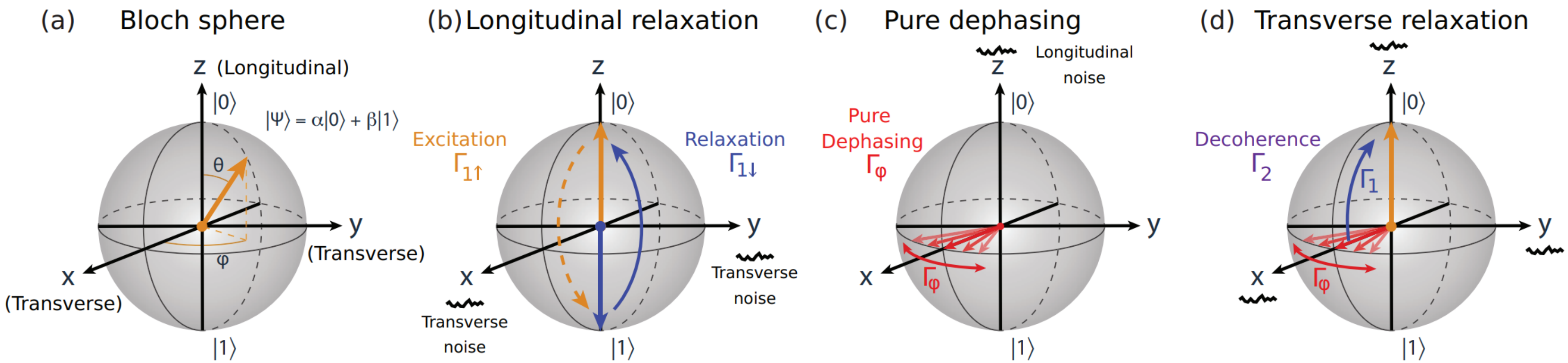
$$\omega_d \approx \omega_q$$

$$\Omega \ll \omega_q$$

$$\Delta = \omega_q - \omega_d$$

We will come back to this in the workshop!

Decoherence and Dephasing



$$\Gamma_2 = \frac{\Gamma_1}{2} + \Gamma_\phi$$

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

Energy relaxation time: $T_1 = \frac{1}{\Gamma_1}$

Total dephasing time: $T_2 = \frac{1}{\Gamma_2}$

Density Matrix and the Master Equation

The off-diagonal matrix elements tell us about the decoherence effects

Density Matrix: $$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| = \begin{pmatrix} \rho_{00} & \rho_{01} \\ \rho_{10} & \rho_{11} \end{pmatrix}$$

Lindblad's Master Equation: $$\frac{d\rho}{dt} = \underbrace{-\frac{i}{\hbar}[H,\rho]}_{\text{Unitary Evolution}} + \underbrace{\sum_k \left(L_k \rho L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho\} \right)}_{\text{Dissipative Terms}}$$

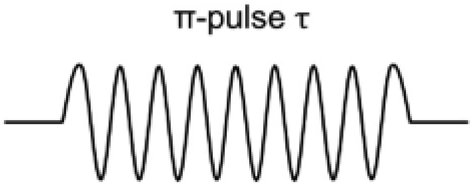
L_k are the Lindblad Operators. They describe the processes causing the dissipation.

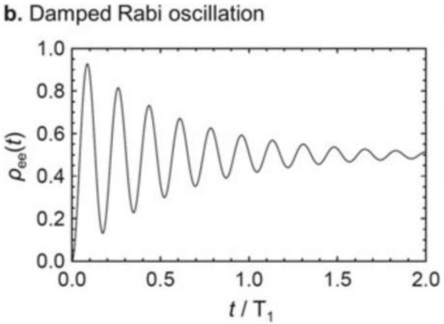
Eg. Photon emission, thermal losses, quasiparticles etc.

Rabi and Ramsey Measurement

Rabi Measurement

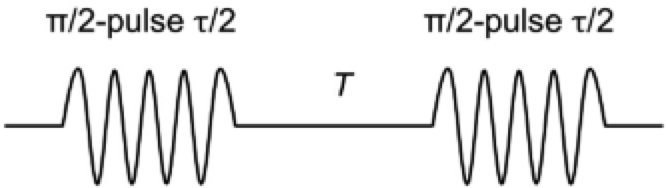
Estimates the T_1 time of the qubit.

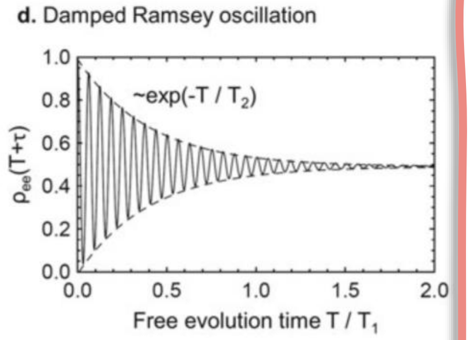




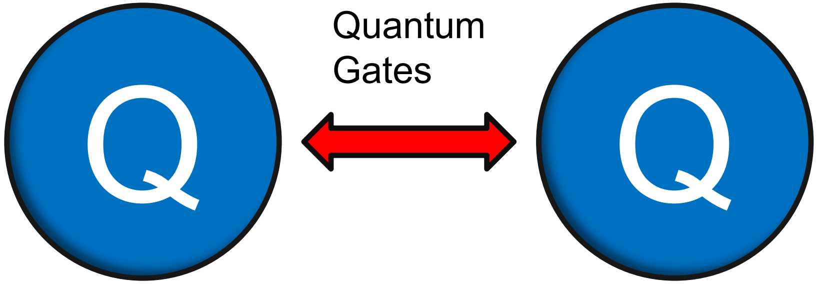
Ramsey Measurement

Estimates the T_2 time of the qubit.



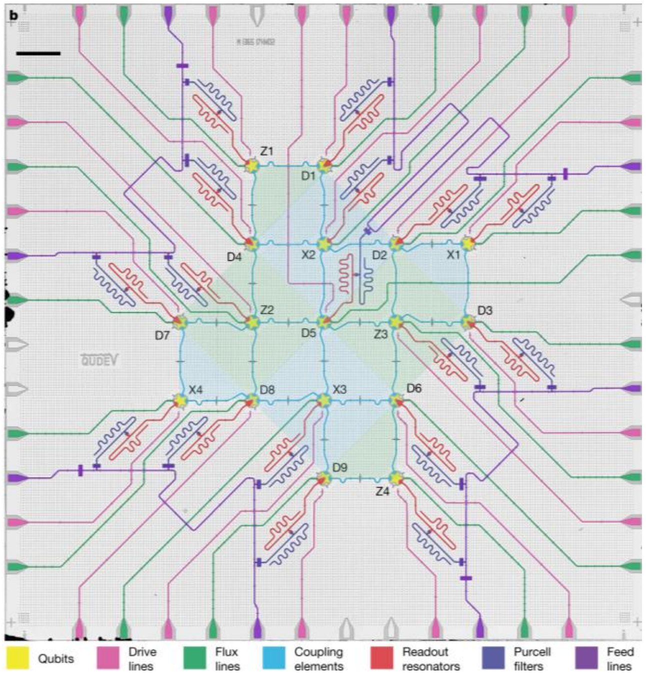


Qubits to Quantum Computer



Still required:
- Qubit-qubit interactions
- Two qubit gate protocols
- Qubit readout

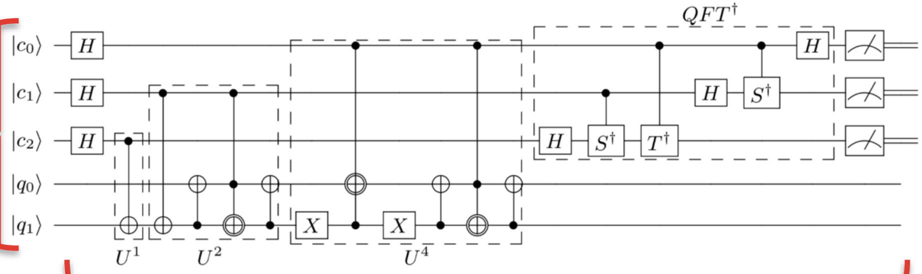
The physical implementation of the above will depend on the type of qubit platform.



Krinner et al (2021): Superconducting Qubit (ETH Zurich)

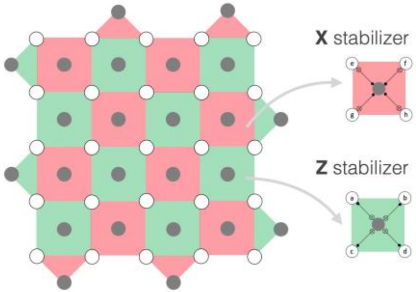
Real World Algorithm Designs

No. of Qubits



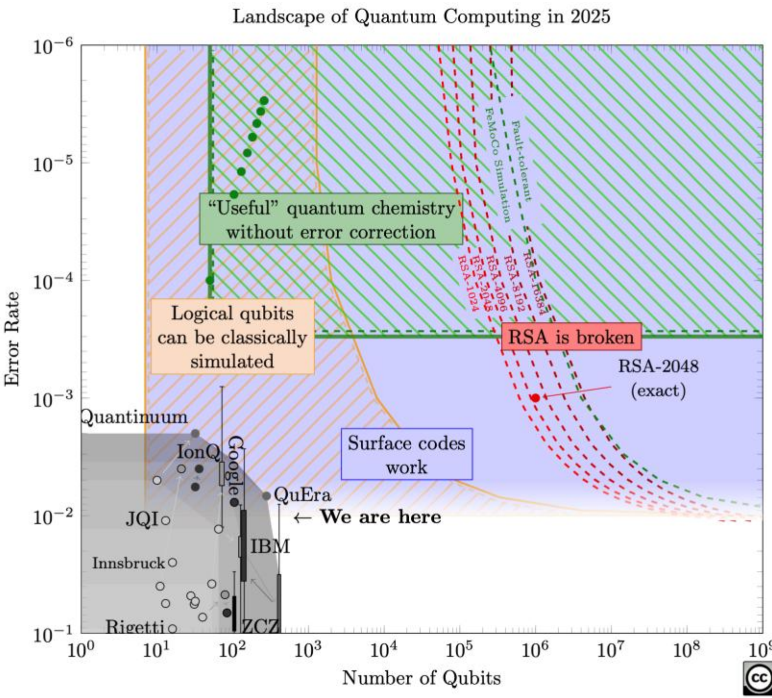
Algorithm Depth

Quantum Error Correction



Define logical qubits, which are a collection of physical qubits.

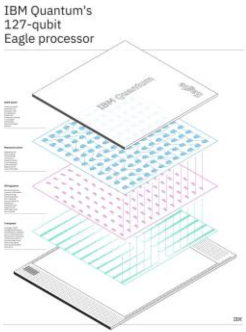
These reduce error rates by performing stabilizer measurement to identify error events and undo them.



Scalability of Quantum Computers

Scaling this is a challenge

Google Willow



IBM Eagle

Hardware Challenges:
- Fabrication yield
- Input-output wiring
- Cryogenics
- Qubit coherence times
- Connectivity

Algorithmic Challenges:
- Error Correction
- Algorithm depth
- Classical overhead

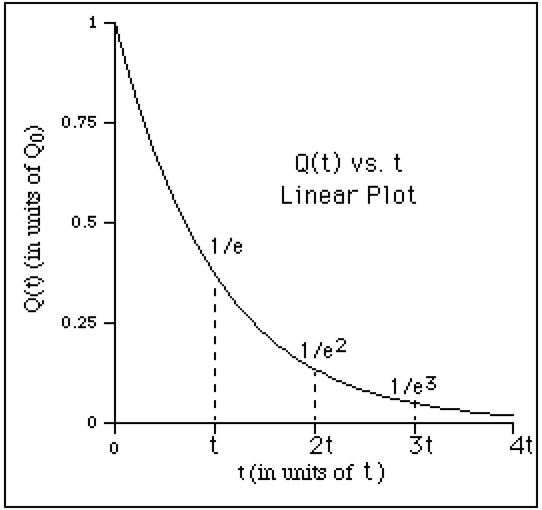
And many more…!

Summary

- Discrete energy states in a potential
  - Infinite potential well
  - Quantum harmonic oscillator
- Annihilation and creation operators
- Representing a qubit on a Bloch sphere
- Types of decoherence and dephasing
  - Simulation using the Lindblad Master Equation
  - Measurements using Rabi and Ramsey
- Requirements and challenges of scaling up to a fault tolerant quantum computer.

Workshop 1: QuTiP

https://github.com/vamsisridhar/QEDi-Superconducting-Qubit-Workshop-2025


1
0.75
0.5
0.25
0
Q(t) (in units of Q0)
Q(t) vs. t
Linear Plot
1/e
1/e2
1/e3
0
t
2t
3t
4t
t (in units of t)