PHYSICS WITHOUT FRONTIERS

Physics Research and Education Bootcamps
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Quantum Information Science & Technology

Introduction

Quantum Computing – Lecture 1

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Centre Européen de Science Quantiques (CESQ)
Apr.2022

Université de Strasbourg

QUSTEC
Quantum Science and Technologies at the European Campus

Scope of the course

- *Five lectures of 1 hour*

  1) Introduction to Quantum Science & Technology

  2) From classical logic to quantum gates

  3) Quantum circuits & implementations

  4) Quantum algorithms & control

  5) Quantum error correction

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- *Recommended literature, tutorials & exercises*

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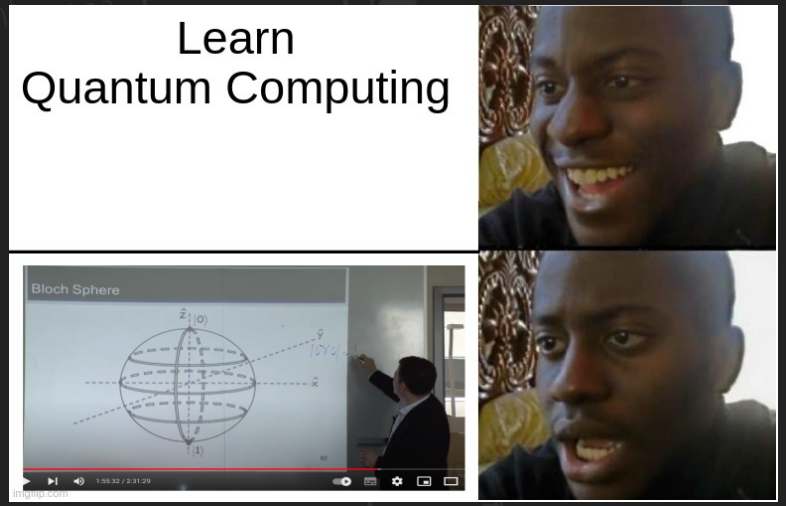

- *Questions & discussions along the talk*

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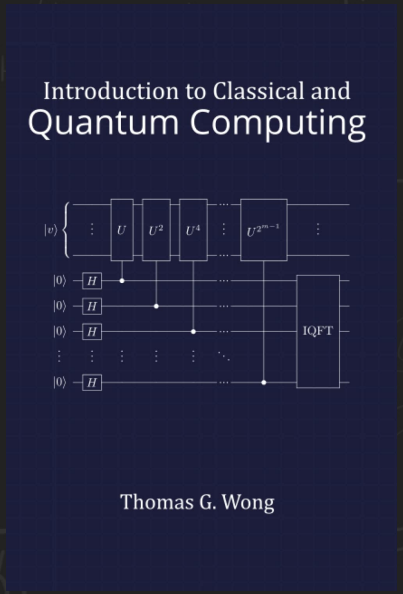

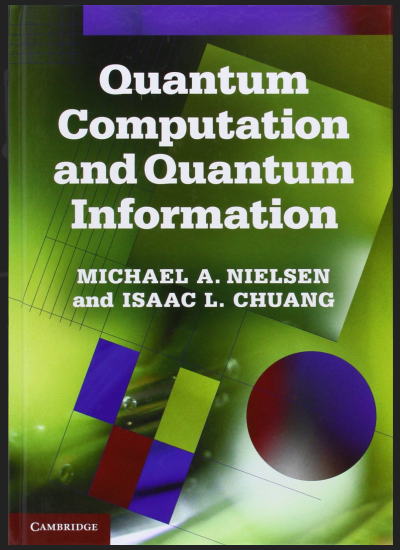

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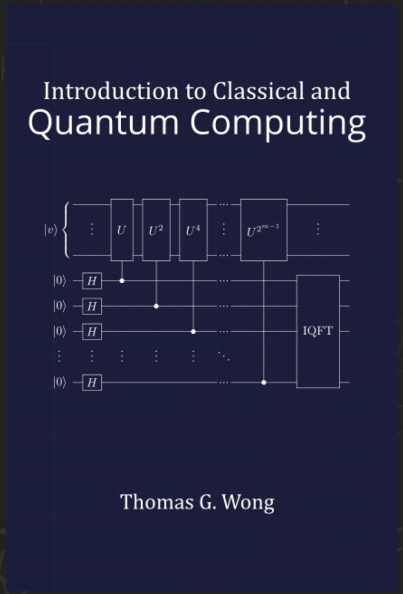
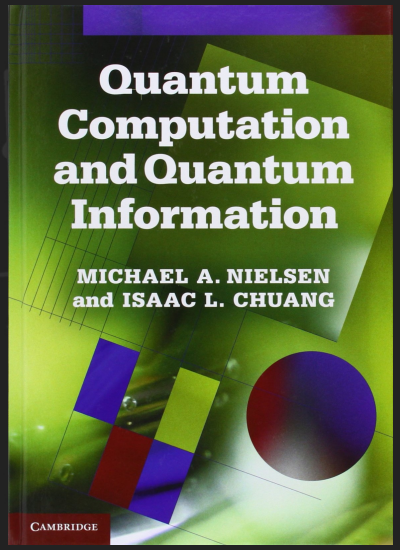
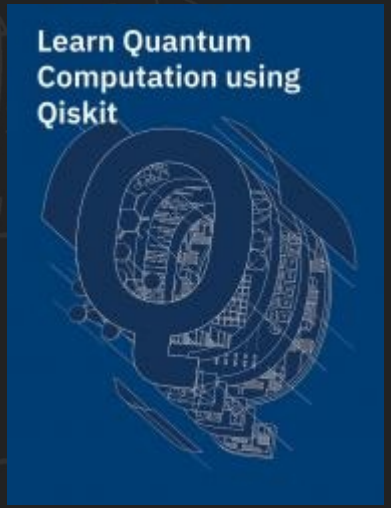
  https://qiskit.org/textbook/content/ch-ex/







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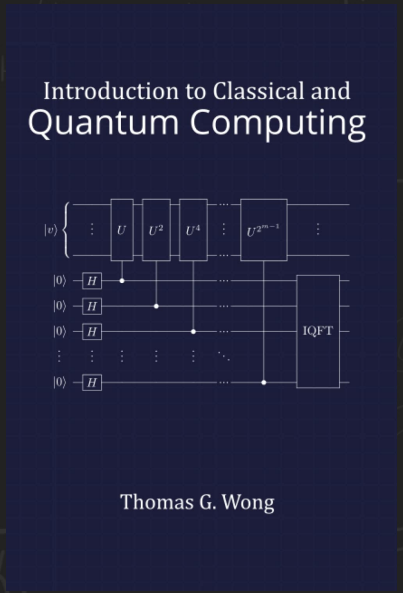
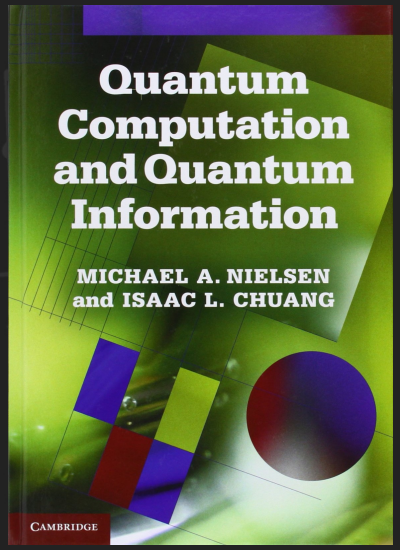
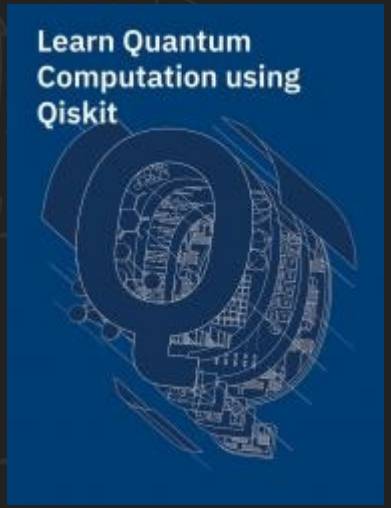
- *Forum*

  https://quantumcomputing.stackexchange.com/

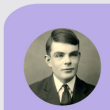






Quantum chat

Quantum



A. Turing

The class of functions computable by a Turing machine corresponds exactly to the class of functions which we would naturally regard as being computable by an algorithm.

A. Church

Can physics be simulated by a universal computer? [...] The full description of quantum mechanics for a large system with R particles [...] has too many variables, it cannot be simulated with a normal computer with a number of elements proportional to R [... but it can be simulated with] quantum computer elements. [...]

E. Schrödinger

R.P. Feynman

Can a quantum system be probabilistically simulated by a classical (probabilistic, I'd assume) universal computer? [...] If you take the computer to be the classical kind I've described so far [..] the answer is certainly, No!"

D. Di Vincenzo

We need a criteria! I have an idea

J. Preskill

For this talk, I needed a name to describe this impending new era, so I made up a word: NISQ. This stands for Noisy Intermediate- Scale Quantum.

Quantum Information Science & Technology

Quantum Computing

Quantum Simulation

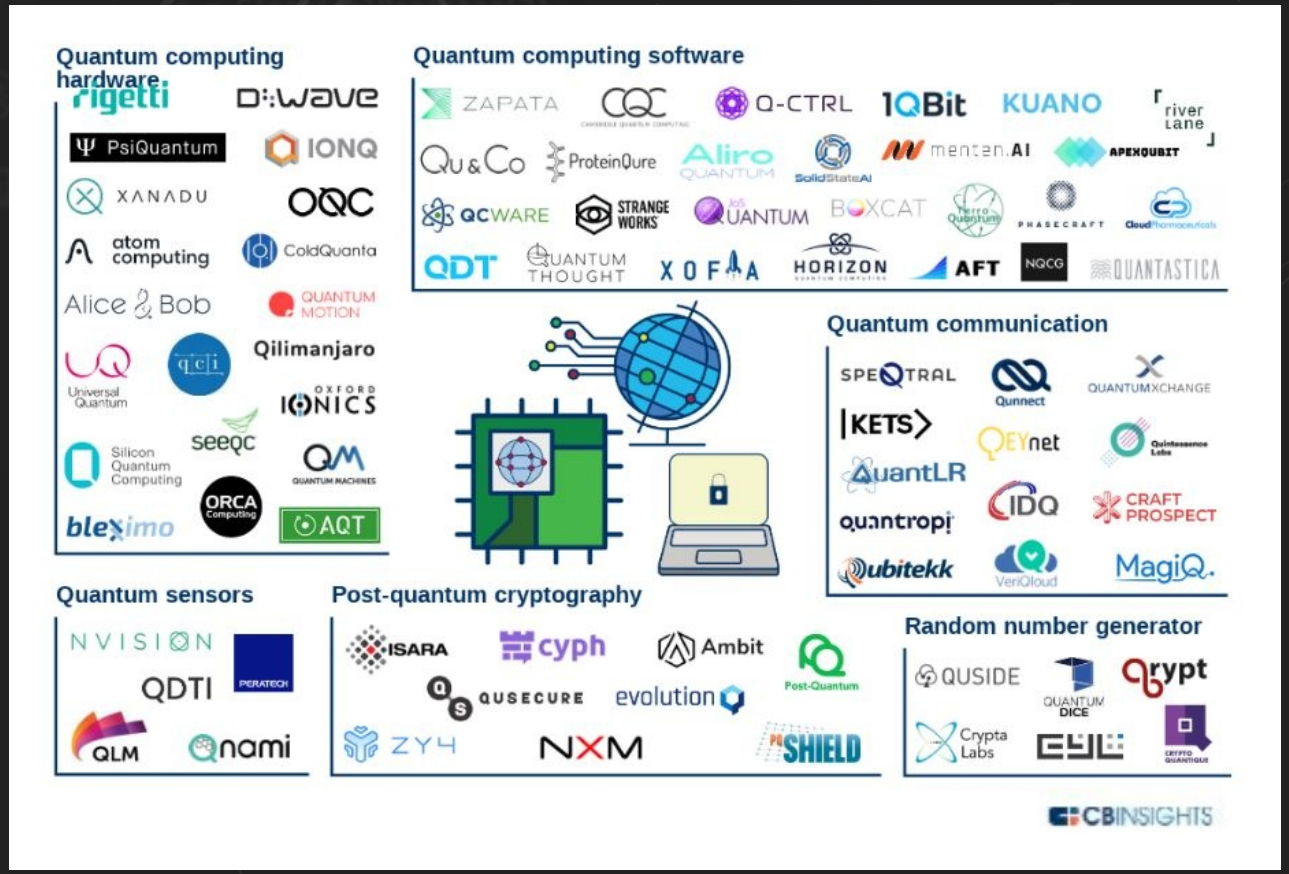
Quantum Communication

Quantum Sensing

Quantum Chemistry

Quantum Machine Learning

Quantum Information Science & Technology

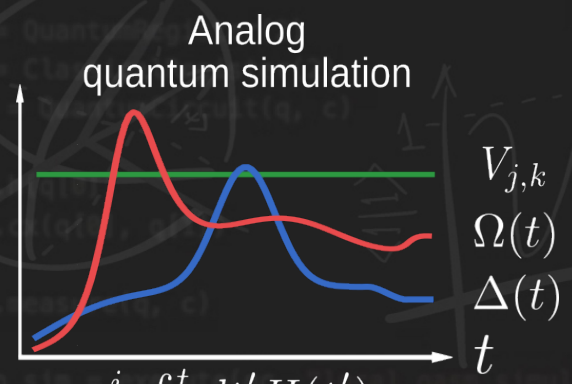


Quantum Information Science & Technology

$$|\text{Physics}\rangle + |\text{Engineering}\rangle + |\text{Math}\rangle + |\text{Chemistry}\rangle$$

Quantum Engineering ?

Quantum Simulators & Quantum Computers

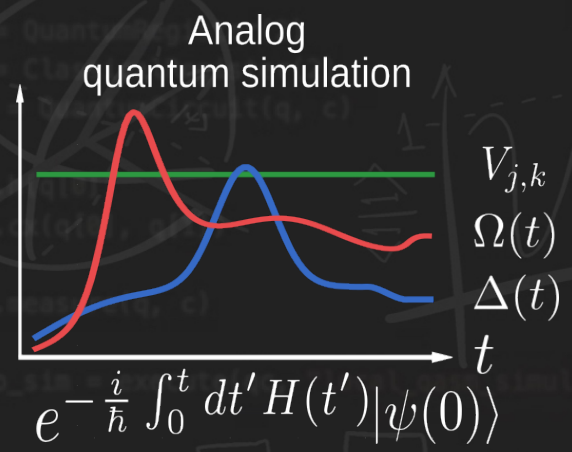


$$e^{-\frac{i}{\hbar}\int_0^t dt' H(t')}|\psi(0)\rangle$$

Analog quantum simulator (AQS): quantum physical system that mimics another quantum system or a specific class of models by closely *reproducing its Hamiltonian*.

AVS Quantum Science, 3(2), p.023501

Quantum Simulators & Quantum Computers



Analog quantum simulator (AQS): quantum physical system that mimics another quantum system or a specific class of models by closely *reproducing its Hamiltonian*.

Digital quantum simulator (DQS): similar to ***AQS*** but it encode the quantum state of the target system in a quantum register e.g., array of quantum bits (*qubits*), and simulate its time evolution by sequential *programmable quantum operations*.

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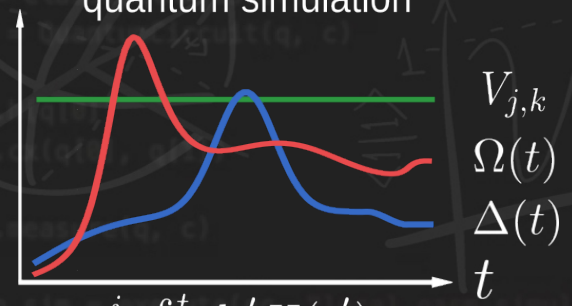
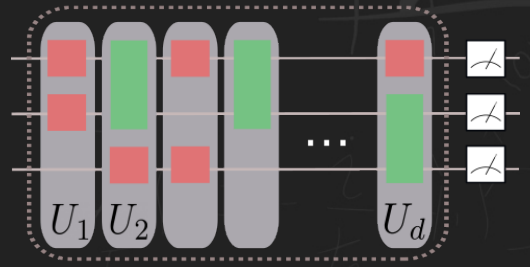
Quantum Simulators & Quantum Computers

Analog
quantum simulation



$$e^{-\frac{i}{\hbar}\int_0^t dt' H(t')}|\psi(0)\rangle$$

Digital quantum simulation
& quantum computing



$$\prod_i U_i(\Omega_i, \Delta_i, V_{j,k})|\psi(0)\rangle$$

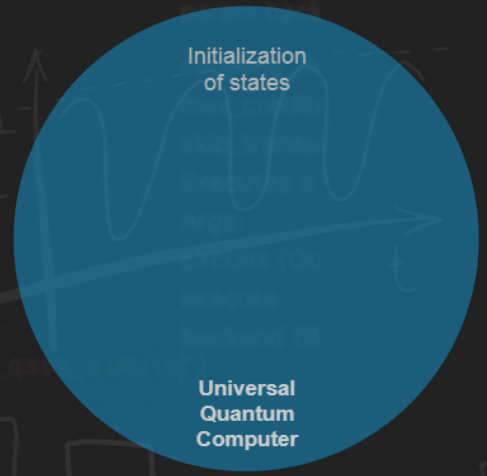
Analog quantum simulator (AQS): quantum physical system that mimics another quantum system or a specific class of models by closely *reproducing its Hamiltonian*.

Digital quantum simulator (DQS): similar to ***AQS*** but it encode the quantum state of the target system in a quantum register e.g., array of quantum bits (*qubits*), and simulate its time evolution by sequential *programmable quantum operations*.

Quantum computer (QC): takes ***DQS*** a step further, making use of a set of *fully addressable qubits and universal set of quantum logic gates* to implement quantum algorithms for solving classically intractable computational problems.

AVS Quantum Science, 3(2), p.023501

Criteria for Quantum Devices



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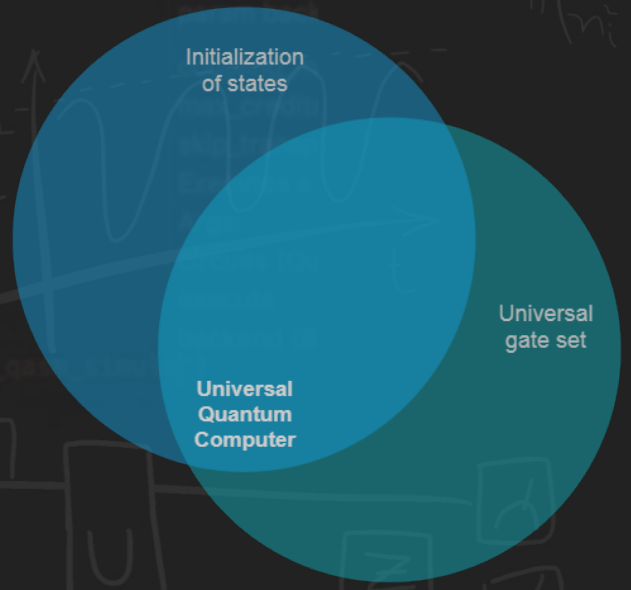

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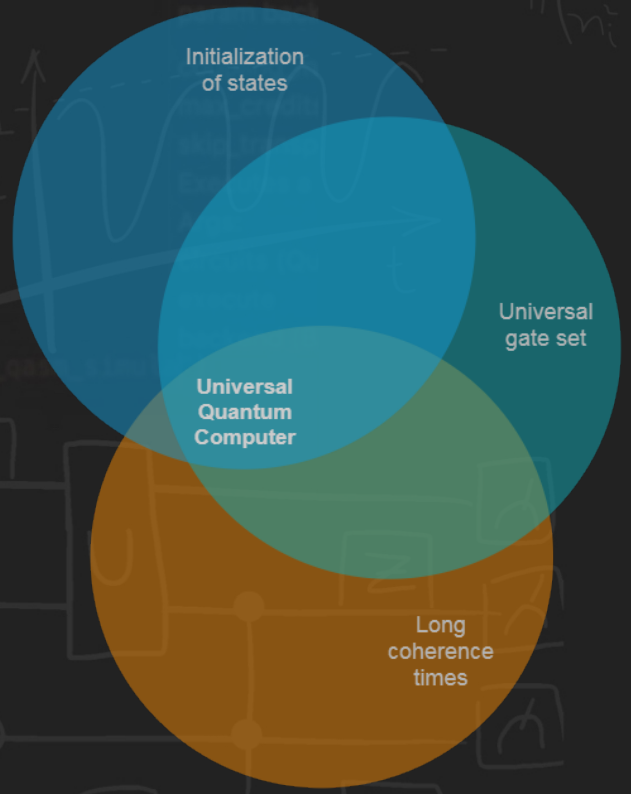

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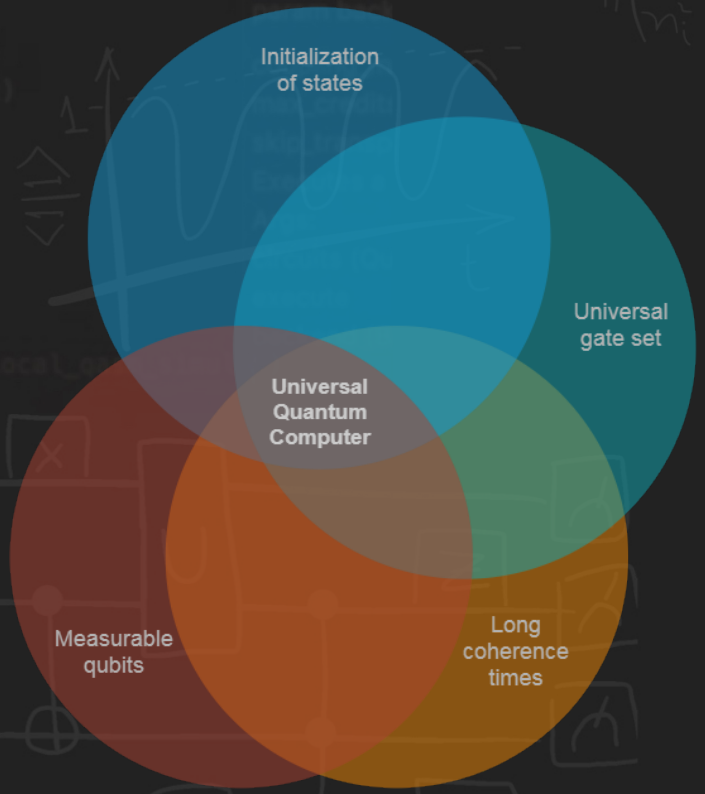

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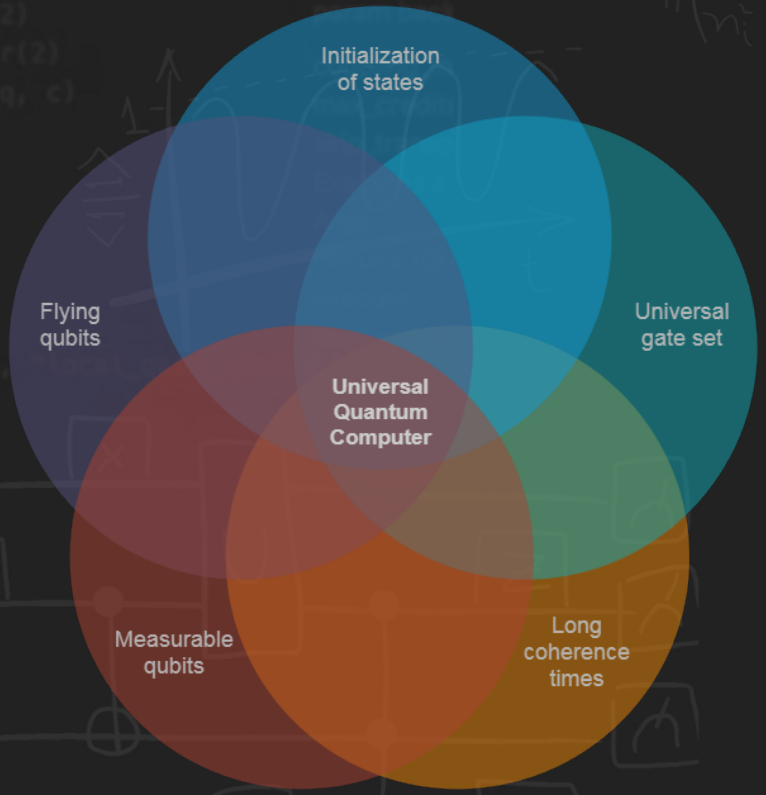

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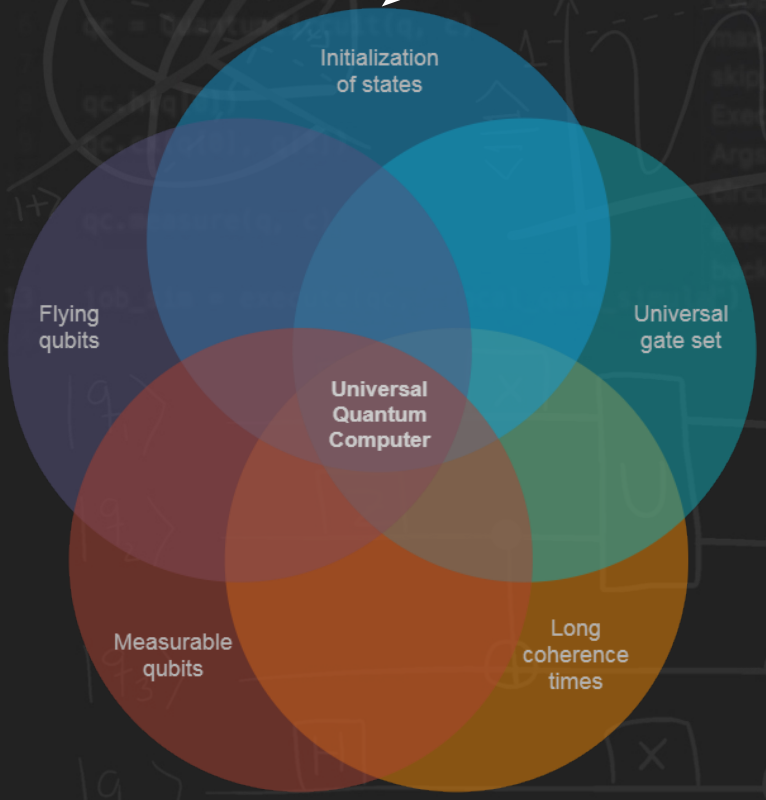

Universal Quantum Computer

D. P. DiVincenzo, Fortschritte der Physik: Progress of Physics 48, 771–783 (2000).

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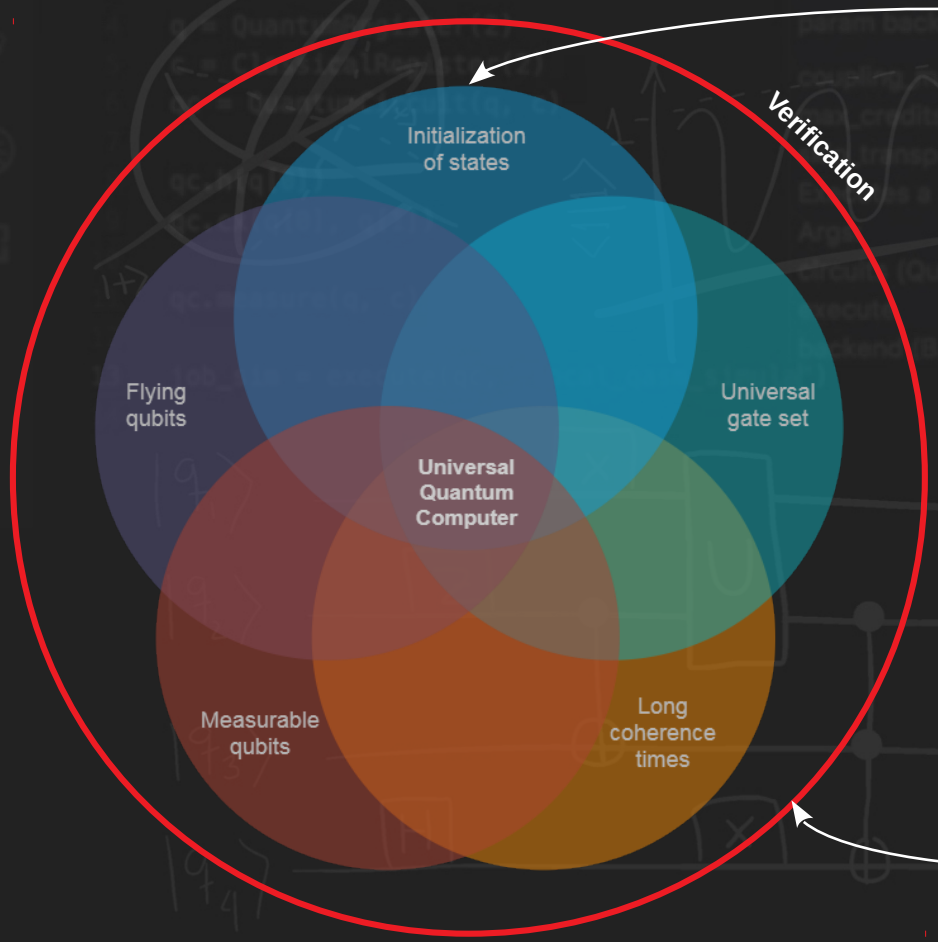

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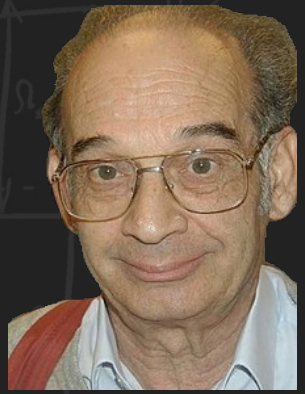
Quantum Simulators
Cirac, J. Ignacio, and Peter Zoller. Nature Physics 8.4 (2012): 264-266.

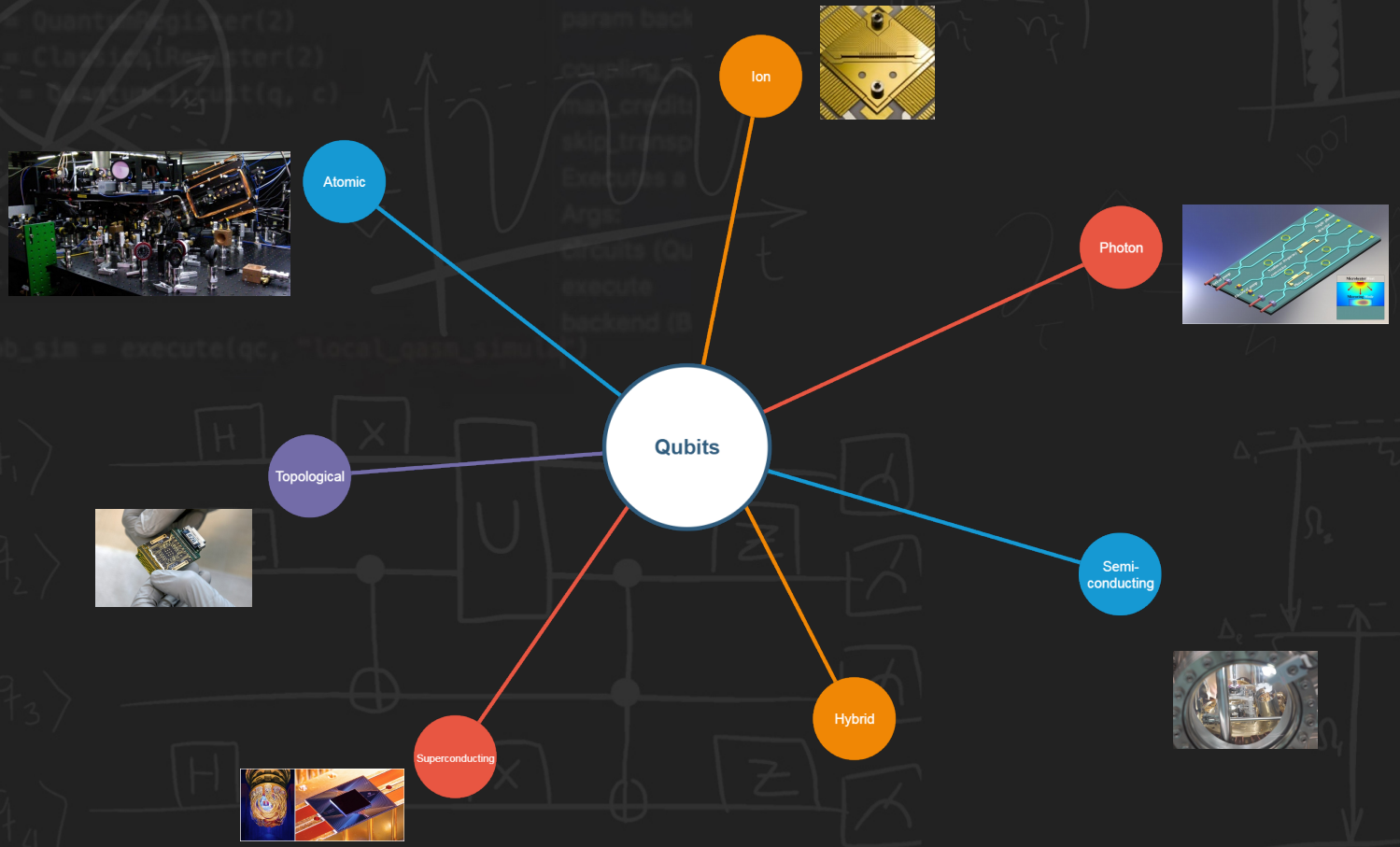
"The approach is pragmatic and strictly instrumentalist. This attitude will undoubtedly antagonize some readers, but it has its own logic: ***quantum phenomena do <u>not</u> occur in a Hilbert space, they occur in a laboratory.***" [1]

- Asher Peres



[1] **Book**: *Quantum theory: Concepts and Methods*

Quantum Register Zoo



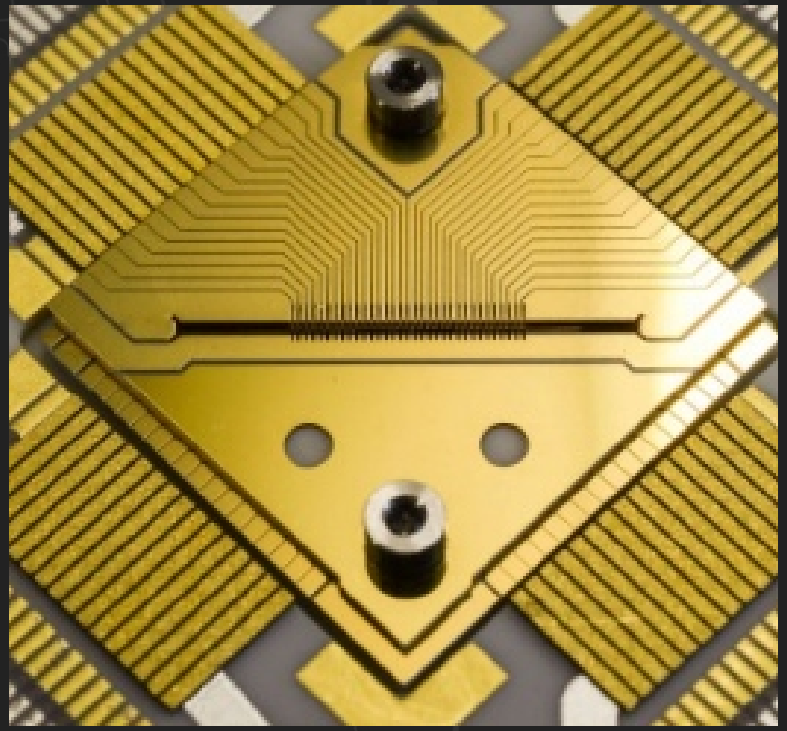
https://arxiv.org/pdf/1905.07240.pdf

Quantum Register Zoo

Trapped Ion Qubits

Using **atom-light interactions** , **electromagnetic fields** interactions and **phononic terms:**

$$\hat{\mathcal{H}} = \hbar\omega_0\sigma_z + \hbar\omega_z a^\dagger a - \vec{\mu}\cdot\vec{B}$$



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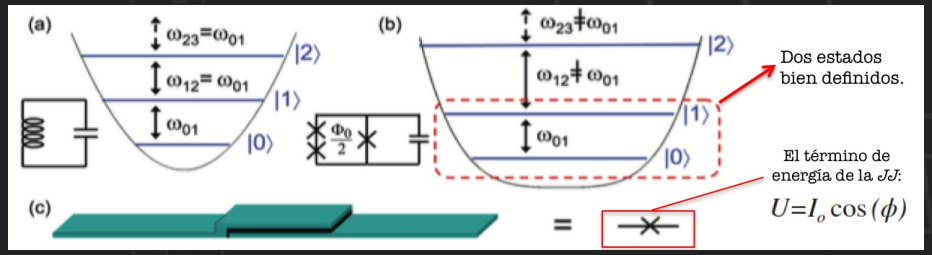
Quantum Register Zoo

Superconducting Qubits

Using **non-linear Harmonic Oscillators**

$$\mathcal{H} = \underbrace{\frac{\hat{Q}^2}{2C}}_{\text{Capacitor}} \underbrace{- E_J \cos\left(\frac{2\pi\hat{\phi}}{\phi_0}\right)}_{\text{JJ}}$$

$$\hat{Q} = 2e\hat{n} \quad \& \quad \hat{\Phi} = \frac{2\pi\hat{\phi}}{\phi_0}$$



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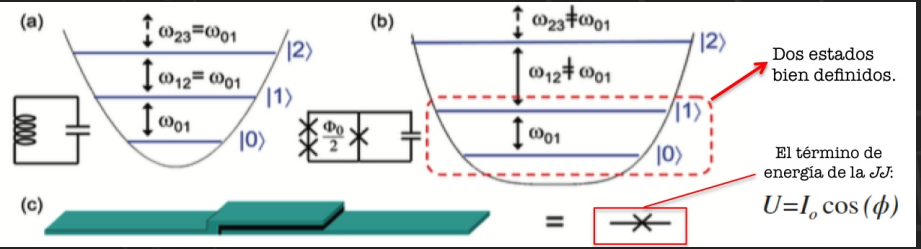
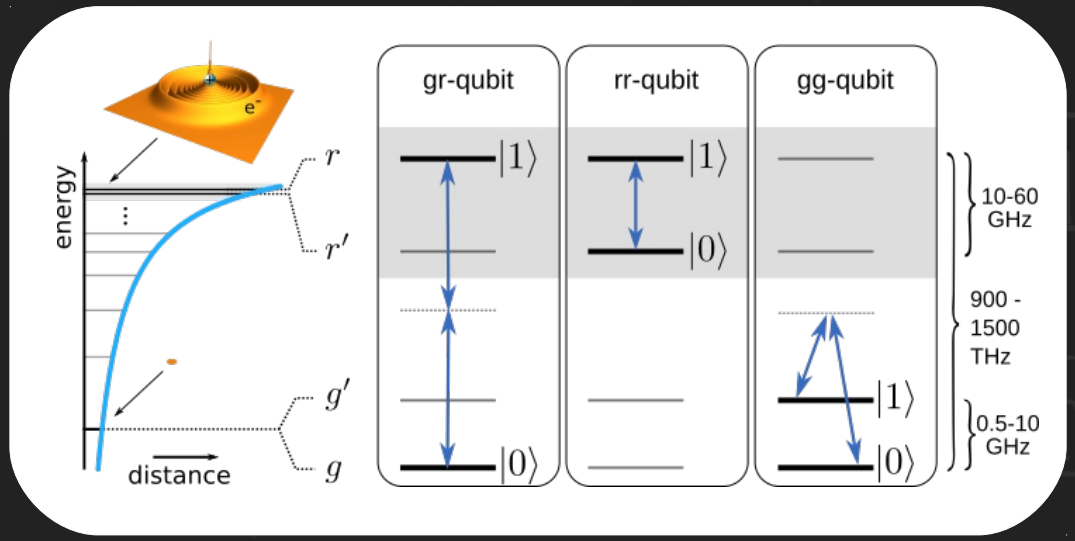


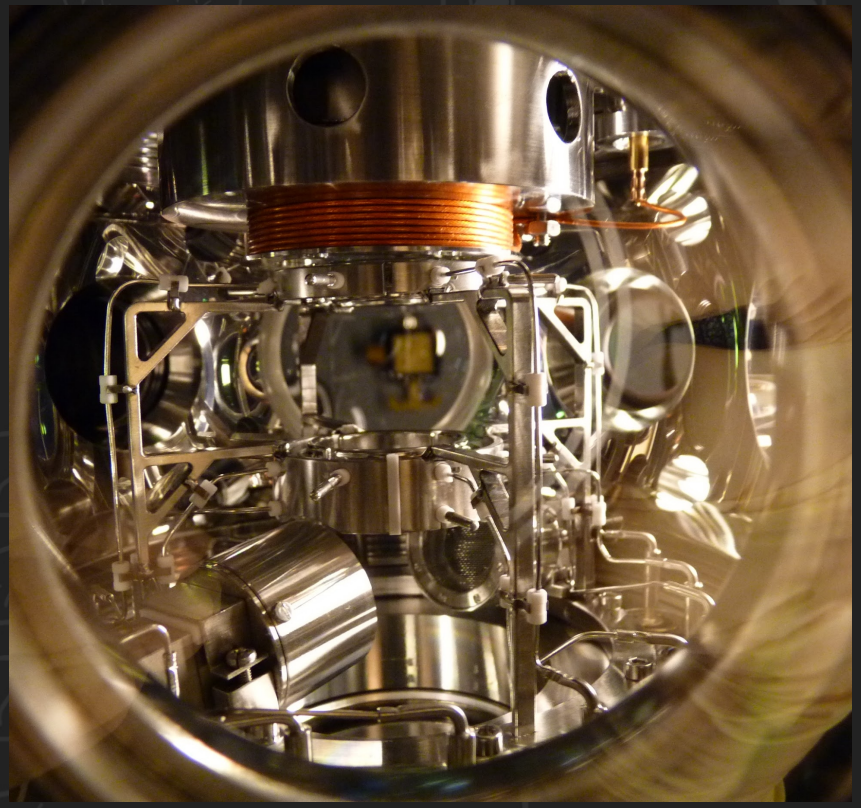
Quantum Register Zoo

Atomic Qubits

Using **atom-light interactions:**

$$\hat{\mathcal{H}}_j^{ab} = \left(\frac{\Omega_j(t)}{2} e^{i\varphi_j(t)} |a_j\rangle\langle b| + \text{h.c.} \right) - \Delta_j(t) |b_j\rangle\langle b|$$





AVS Quantum Science, 3(2), p.023501

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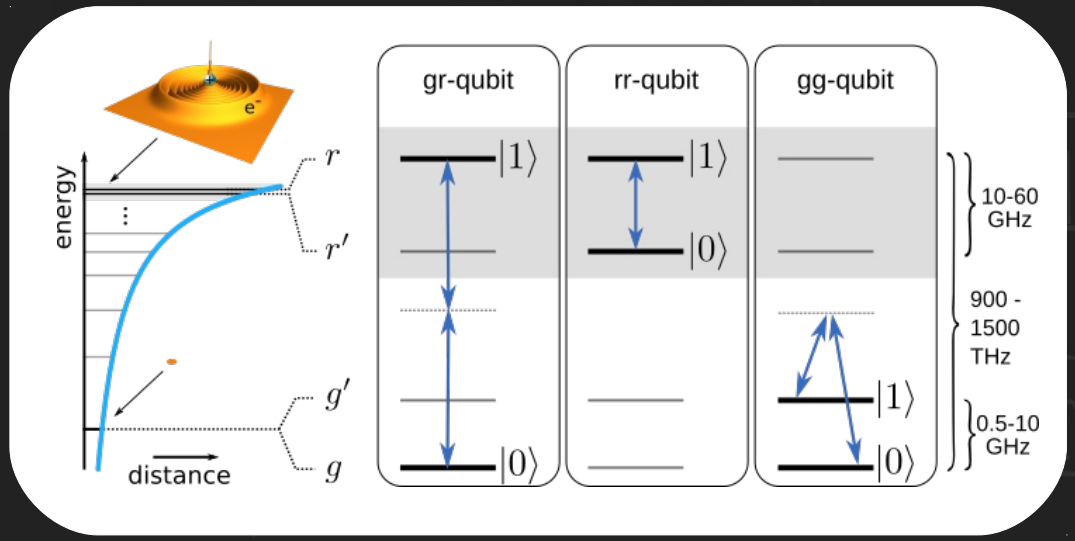

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Quantum Register Zoo

Photonic Qubits

Using photon **polarization**:

$$|\Psi\rangle = \alpha|H\rangle + \beta|V\rangle$$

$$|H\rangle = \int_{-\infty}^{\infty} d\mathbf{k} f(\mathbf{k}) e^{-iw_k t} \hat{a}_H^\dagger(\mathbf{k})|0\rangle_{\text{Vacuum}}$$

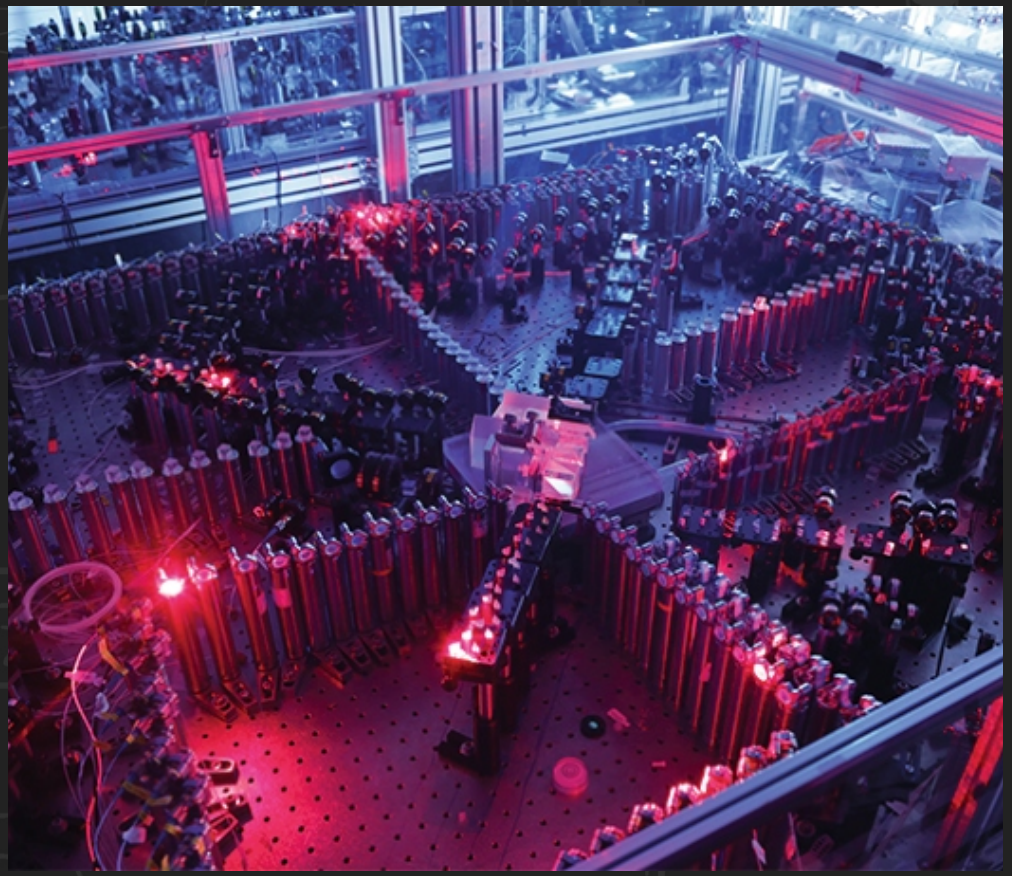
$$|V\rangle = \int_{-\infty}^{\infty} d\mathbf{k} f(\mathbf{k}) e^{-iw_k t} \hat{a}_V^\dagger(\mathbf{k})|0\rangle_{\text{Vacuum}}$$

Using photon **polarization**:

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

$$|0\rangle = \int_{-\infty}^{\infty} dz f\left(\frac{t - z/c}{\delta t_{ph}}\right) e^{-iw_0(t-z/c)} \hat{a}^\dagger(z)|0\rangle_{\text{Vacuum}}$$

$$|1\rangle = \int_{-\infty}^{\infty} dz f\left(\frac{t - z/c + \tau}{\delta t_{ph}}\right) e^{-iw_0(t-z/c+\tau)} \hat{a}^\dagger(z)|0\rangle_{\text{Vacuum}}$$



https://www.nature.com/articles/s41563-021-00953-0

More using: occupation number, dual-rail, orbital angular momentum

Quantum Register Zoo

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More using: occupation number, dual-rail, orbital angular momentum

Quantum Register Zoo

Semi-conducting Qubits

Use 6-bands k.p Hamiltonian:

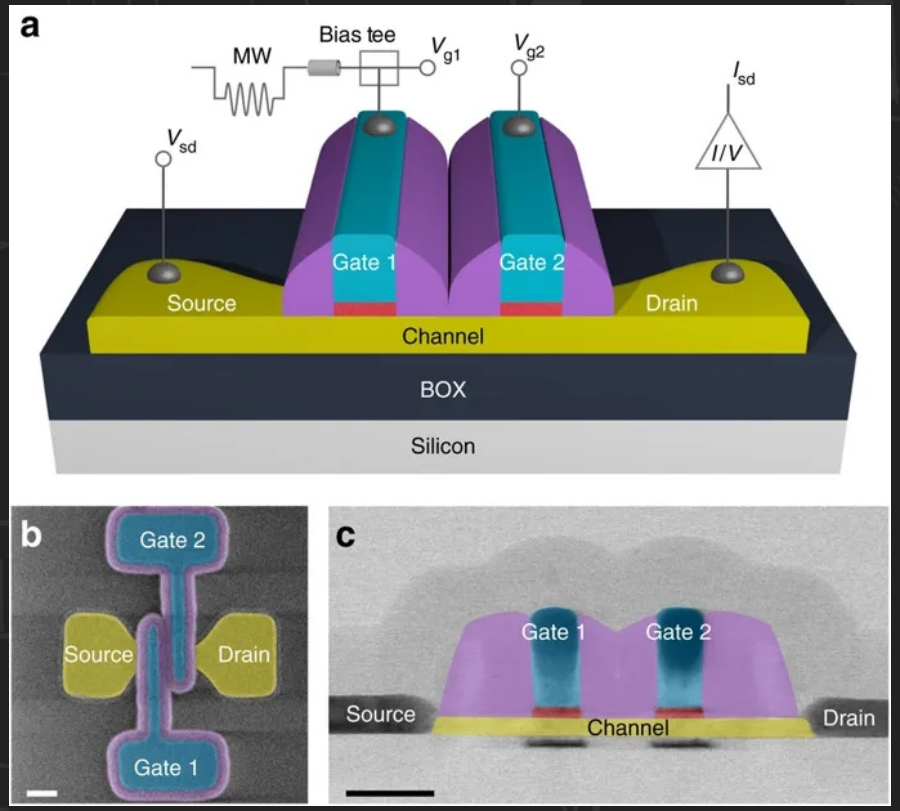
$$H_{6\mathrm{kp}} = -\begin{pmatrix} P+Q & -S & R & 0 & \frac{1}{\sqrt{2}}S & -\sqrt{2}R \\ -S^* & P-Q & 0 & R & \sqrt{2}Q & -\sqrt{\frac{3}{2}}S \\ R^* & 0 & P-Q & S & -\sqrt{\frac{3}{2}}S^* & -\sqrt{2}Q \\ 0 & R^* & S^* & P+Q & \sqrt{2}R^* & \frac{1}{\sqrt{2}}S^* \\ \frac{1}{\sqrt{2}}S^* & \sqrt{2}Q & -\sqrt{\frac{3}{2}}S & \sqrt{2}R & P+\Delta & 0 \\ -\sqrt{2}R^* & -\sqrt{\frac{3}{2}}S^* & -\sqrt{2}Q & \frac{1}{\sqrt{2}}S & 0 & P+\Delta \end{pmatrix}$$

$$P = \frac{\hbar^2}{2m_0}\gamma_1\left(k_x^2 + k_y^2 + k_z^2\right)$$

$$Q = \frac{\hbar^2}{2m_0}\gamma_2\left(k_x^2 + k_y^2 - 2k_z^2\right)$$

$$R = \frac{\hbar^2}{2m_0}\sqrt{3}\left[-\gamma_3\left(k_x^2 - k_y^2\right) + 2i\gamma_2 k_x k_y\right]$$

$$S = \frac{\hbar^2}{2m_0}2\sqrt{3}\gamma_3(k_x - ik_y)k_z.$$



https://www.nature.com/articles/ncomms13575

Quantum Register Zoo

Semi-conducting Qubits

Use 6-bands k.p Hamiltonian:

$$H_{6\mathrm{kp}} = -\begin{pmatrix} P+Q & -S & R & 0 & \frac{1}{\sqrt{2}}S & -\sqrt{2}R \\ -S^* & P-Q & 0 & R & \sqrt{2}Q & -\sqrt{\frac{3}{2}}S \\ R^* & 0 & P-Q & S & -\sqrt{\frac{3}{2}}S^* & -\sqrt{2}Q \\ 0 & R^* & S^* & P+Q & \sqrt{2}R^* & \frac{1}{\sqrt{2}}S^* \\ \frac{1}{\sqrt{2}}S^* & \sqrt{2}Q & -\sqrt{\frac{3}{2}}S & \sqrt{2}R & P+\Delta & 0 \\ -\sqrt{2}R^* & -\sqrt{\frac{3}{2}}S^* & -\sqrt{2}Q & \frac{1}{\sqrt{2}}S & 0 & P+\Delta \end{pmatrix}$$

$$P = \frac{\hbar^2}{2m_0}\gamma_1\left(k_x^2 + k_y^2 + k_z^2\right)$$

$$Q = \frac{\hbar^2}{2m_0}\gamma_2\left(k_x^2 + k_y^2 - 2k_z^2\right)$$

$$R = \frac{\hbar^2}{2m_0}\sqrt{3}\left[-\gamma_3\left(k_x^2 - k_y^2\right) + 2i\gamma_2 k_x k_y\right]$$

$$S = \frac{\hbar^2}{2m_0}2\sqrt{3}\gamma_3(k_x - ik_y)k_z.$$

https://www.nature.com/articles/ncomms13575