The Noisy Era of Quantum Computing

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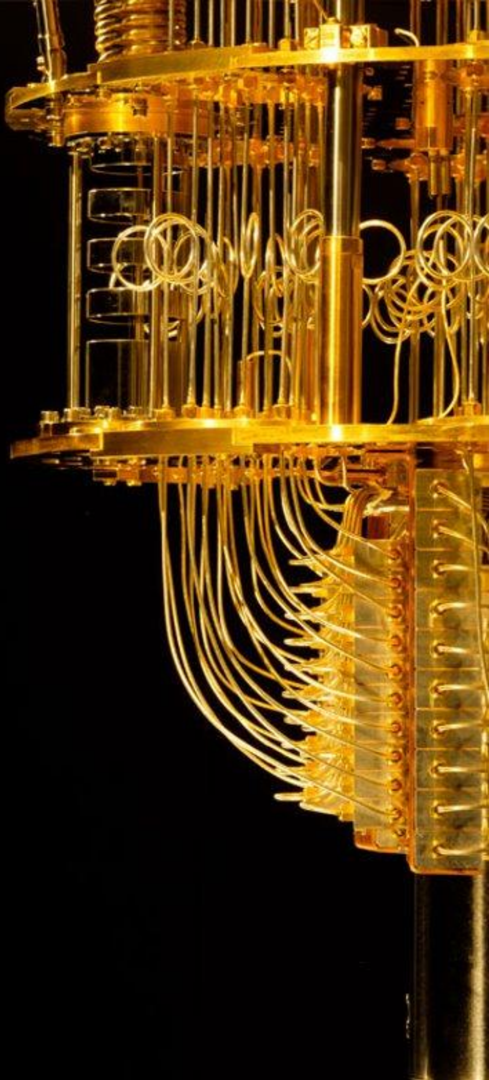


About Me

- **B-Tech (Hons.) in CS & MS by Research in CNS**
  Advisor - Professor Harjinder Singh
  Center for Computational Natural Sciences and Bioinformatics, IIIT-Hyderabad

- **Quantum Compute Researcher, QpiAI™ India Pvt. Ltd.**
  Developing a full software stack and algorithms for their CMOS based quantum hardware

- **Research Interests** → *Quantum Biology, Quantum Chemistry, Quantum Optimizations, Quantum Machine Learning*

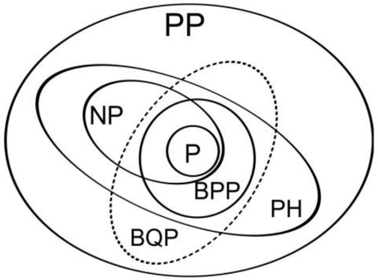
- **Research Work** → *Simulation, Development and Applications of NISQ Algorithms*

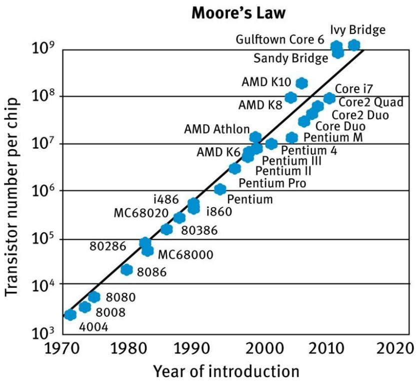
Utkarsh

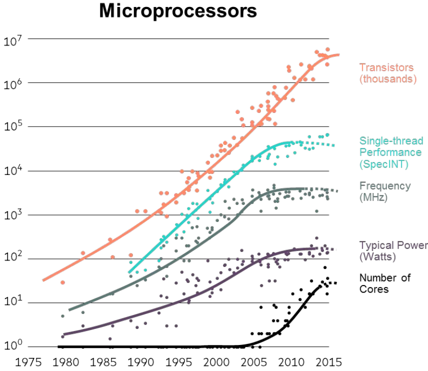
When I finally understand one equation in a QC paper

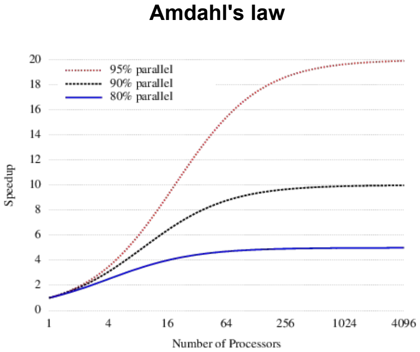
Me working on a problem during the quantum winters

Limitations of Classical Computers









Fundamental limits of computability

- Complexity Classes
- P, NP, NPC, BQP, PSPACE ...
- Bounded-Error Quantum Polynomial

Limits of miniaturization

- Quantum effects in electronics
- Economical limits over number of transistors - inter-transistor spacing

Energy considerations

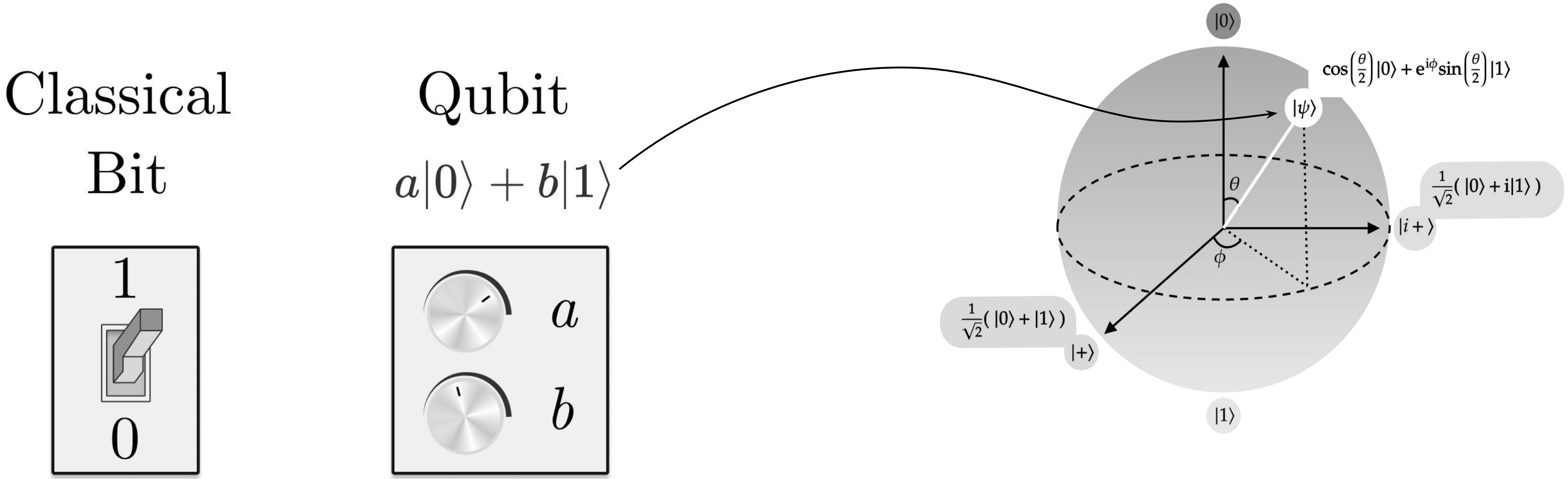
- Transistor scaling: heat
- Extreme energy consumptions
- Example: AI Model Training

Limits of Parallelization

- Limit to the speedup gained by running part of computation in parallel.

New model of computation? Analog computing, neuromorphic computing, *quantum computing*… ?

Quantum Computation



The state of a qubit is mapped to a point on the surface of Bloch sphere

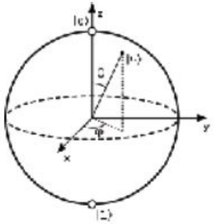
- $a \in C$, $b \in C$, $|a|^2 + |b|^2 = 1$
- a, b are probability amplitudes (can be negative)
- $P(|0\rangle) = |a|^2$ and $P(|1\rangle) = |b|^2$

If we can control individual quantum systems
We can use them as computational elements

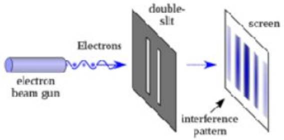
Superposition, Interference, Entanglement, Measurement

The feature of a quantum system whereby it exists in several separate quantum states at the same time.

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$



An individual particle can cross its own trajectory and interfere with the direction of its path.



$$A(|0\rangle + |1\rangle) = |0\rangle$$

constructive interference

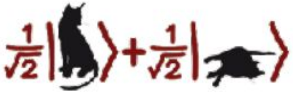
$$|\Psi\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad H|\Psi\rangle = \frac{H|0\rangle + H|1\rangle}{\sqrt{2}} = \frac{|0\rangle + |1\rangle + |0\rangle - |1\rangle}{2} = |0\rangle$$

destructive interference

Two particles become inextricably linked, regardless of how far apart they are.

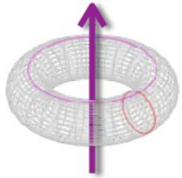
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Measurements are destructive $\hat{A}|\Psi\rangle = a|\Psi\rangle$



Three types of quantum computer

1. Digital quantum computers

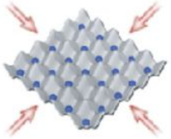


- The holy grail - a general-purpose Universal quantum computer
- Is extremely difficult to build
- **NISQ hardware** will not be fault tolerant - is it useful?

2. Quantum Annealer

- Solves a Hamiltonian ground-state problem
- Quantum speedups are currently a topic of scientific debate
- Easiest hardware to build if noise/temperature can be tolerated

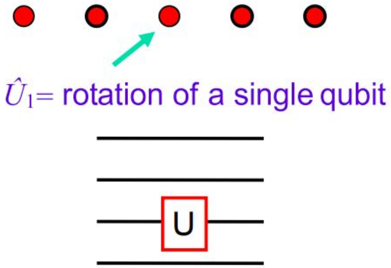
3. Analog Simulators

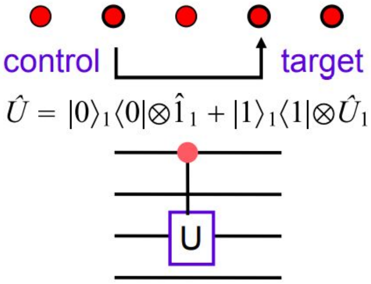


- Analog (unlike digital) computers simulate/emulate the equations of a physical system directly - using controlled quantum states.
- Applications lie in quantum chemistry, materials science
- Exist in many laboratories

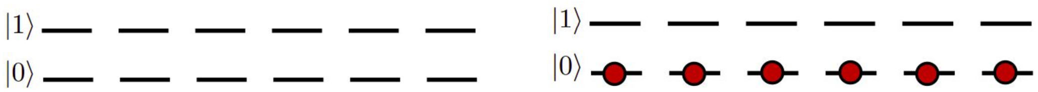
The DiVincenzo Criteria

- A **scalable** physical system with **well-characterized qubits**
- **Initialization** to a pure state, such as $|000...\rangle$
- **Decoherence times** longer than gate operation times
- A “**universal**” set of quantum gates
- **Readout**: a qubit-specific measurement capability
- Interconversion of **stationary** and **flying qubits**
- **Faithful transmission** of flying qubits between specified locations



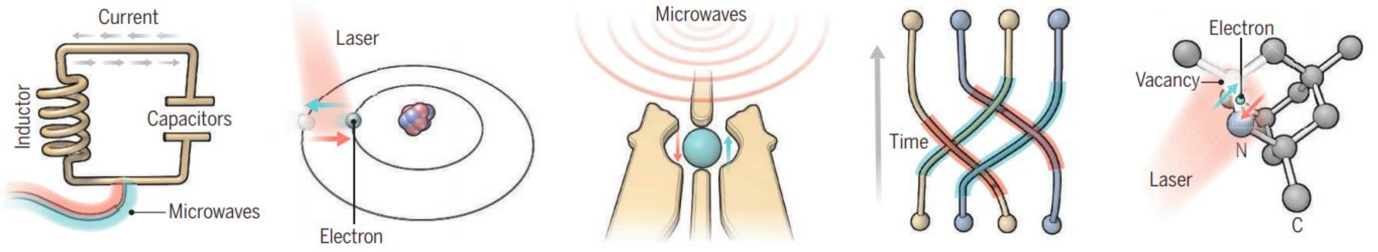


$$\hat{U} = |0\rangle_1\langle 0|\otimes\hat{1}_1 + |1\rangle_1\langle 1|\otimes\hat{U}_1$$



D. P. DiVincenzo “The Physical Implementation of Quantum Computation”, Fortschritte der Physik 48, p. 771 (2000) arXiv:0002077

Physical Implementation of Qubits



Coherence time for a single qubit superposition state

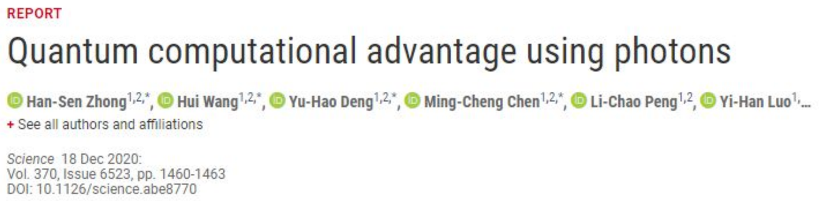
Highest reported gate fidelity for two-qubit logic gate operations.

Maximum number of qubits entangled and capable of performing two-qubit logic gate operations

	Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These “artificial atoms” are made by adding an electron to a small piece of pure silicon. Microwaves control the electron’s quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
⊕ **Pros**	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
⊖ **Cons**	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Credits: (GRAPHIC) C. BICKEL/SCIENCE; (DATA) GABRIEL POPKIN

The Noisy Era - I


REPORT

Quantum computational advantage using photons

Han-Sen Zhong[1,2,*], Hui Wang[1,2,*], Yu-Hao Deng[1,2,*], Ming-Cheng Chen[1,2,*], Li-Chao Peng[1,2], Yi-Han Luo[1,...]

+ See all authors and affiliations

Science 18 Dec 2020:
Vol. 370, Issue 6523, pp. 1460-1463
DOI: 10.1126/science.abe8770


Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

791k Accesses | **499** Citations | **6047** Altmetric | Metrics

Livemint

Why India is falling behind in the Y2Q race

To that end, in 2019, DST launched Quantum Information Science and Technology (QuEST), a programme wherein the government will invest ...

Jan 15, 2020

The Indian Express

Honeywell makes world's fastest Quantum Computer with quantum volume of 64

The quantum volume is a measurement that takes into account the number of quantum bits (or qubits) of a machine as well as their connectivity ...

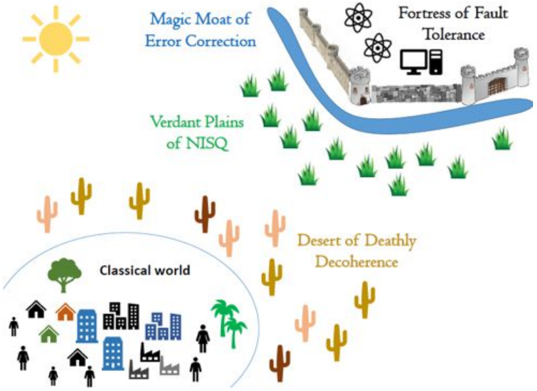
Jun 21, 2020

The Noisy Era - II

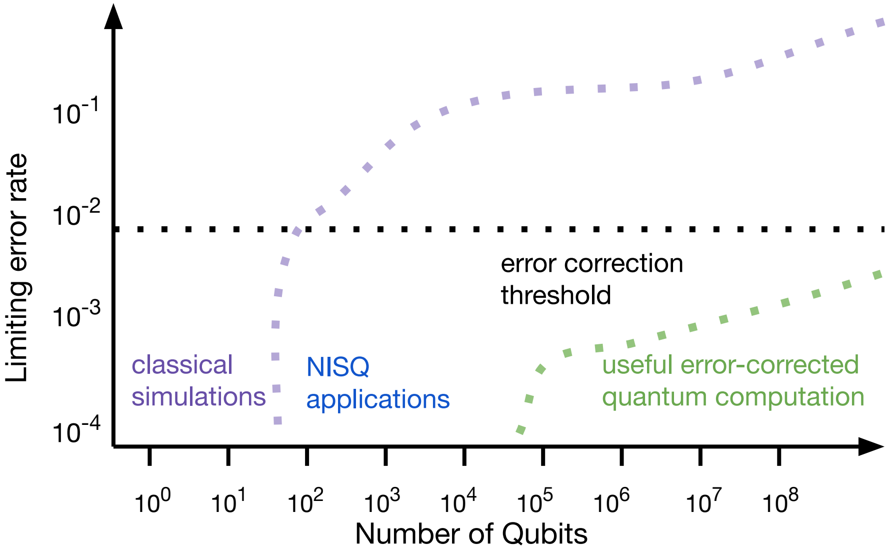
The Era of Noisy qubits a.k.a the Noisy Intermediate Scale Quantum (NISQ) Era -

1. A term coined by Prof. John Preskill
2. Limited numbers of **good** and **robust** qubits.
3. Limited **connectivity** of qubits.
4. Imperfect **control** over qubits.
5. **Coherent** and **incoherent** errors that limit quantum circuit depth.
6. Limited/Negligible **quantum error correction**.
7. Limited Gates can be applied (**low circuit depth**)
8. Speculated speedups.

John Preskill, Quantum Computing in the NISQ era and beyond, arXiv:1801.00862



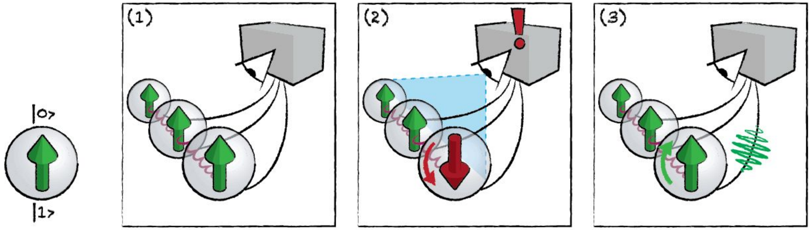
Credits - Graphic adapted from Daniel Gottesman's slides on Quantum Error Correction.



Understanding Preskill's Vision for NISQ Era

1. Opportunity to **experiment/test** NISQ computing
2. Unknown if speed-up for problems of broad interest will happen
3. Try **hybrid quantum-classical algorithms** for classical & quantum optimization
4. Experimental quantum computers will **accelerate** quantum algorithms/heuristic development
5. Design algorithms and their applications with **noise resilience** in mind
6. Quantum computers could be better at classically hard problems such as simulating dynamics of highly entangled many-particle quantum systems.
7. Focus on building quantum hardware with low gate-error rates
8. Near-term quantum platforms leverages payoff from future quantum computers.
9. Transformative quantum technologies likely must be fault-tolerant.

Quantum Error Correction (QEC)



Qubits: Imperfect operations or interaction with environment
Ideal qubits, physical qubits, logical qubits!

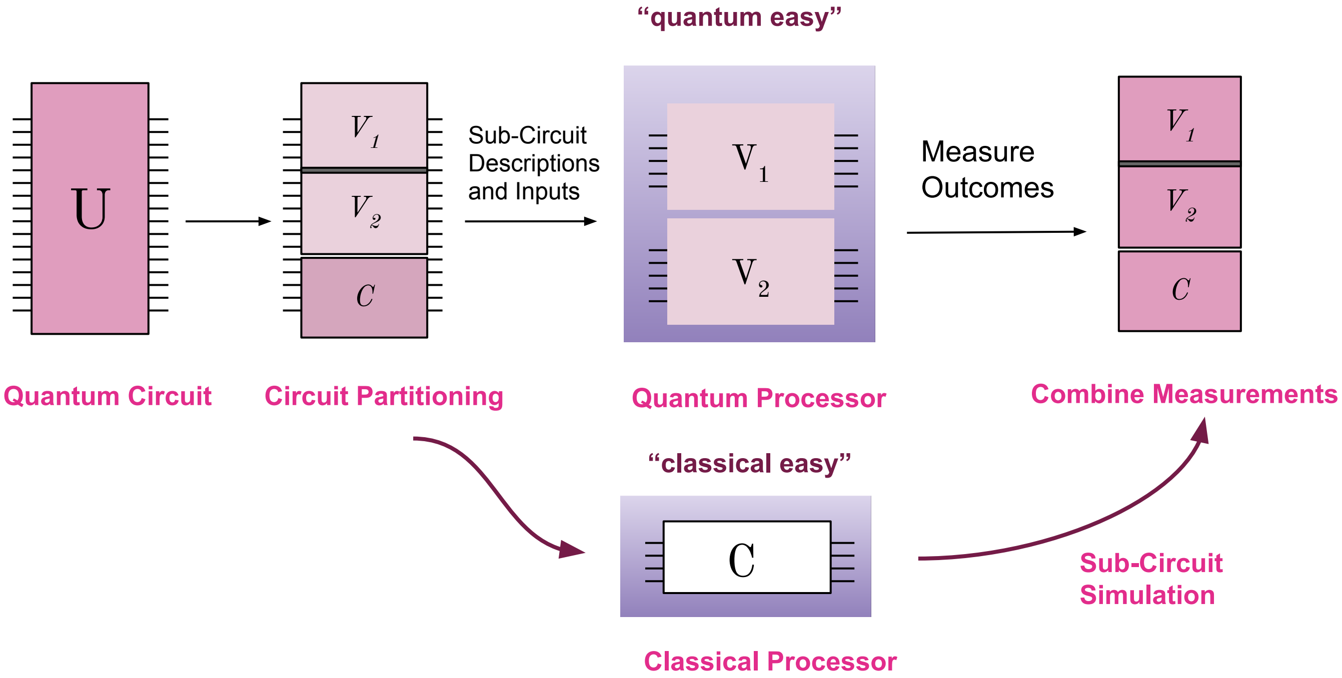
1. **Bit Flip** → Interchanges |0⟩ and |1⟩.
2. **Phase Flip** → Inverts the relative phase of |0⟩ and |1⟩. No classical analogue!
3. **Gate-Error** → Imperfections is logic gate operations.
4. **Decoherence** → Information about system is lost as it interacts with the Environment.
5. **Read-out Error** → Depolarization of qubits during readout.

Quantum Error Correction: Converts physical qubits into logical qubits (noise-resilient)
Fault-tolerant Universal Quantum Computer - proven exponential advantage
Threshold Theorem: scalability of quantum computers

Error Mitigation: Reduce noise in the system by hardware-specific insight.

Possible Solution: Since Quantum Error Correction requires high qubit-overhead, somehow make use of quantum processor limited. Use it as an accelerator.

Hybrid Quantum-Classical Architecture



“quantum easy”

Sub-Circuit Descriptions and Inputs

Measure Outcomes

Quantum Circuit

Circuit Partitioning

Quantum Processor

Combine Measurements

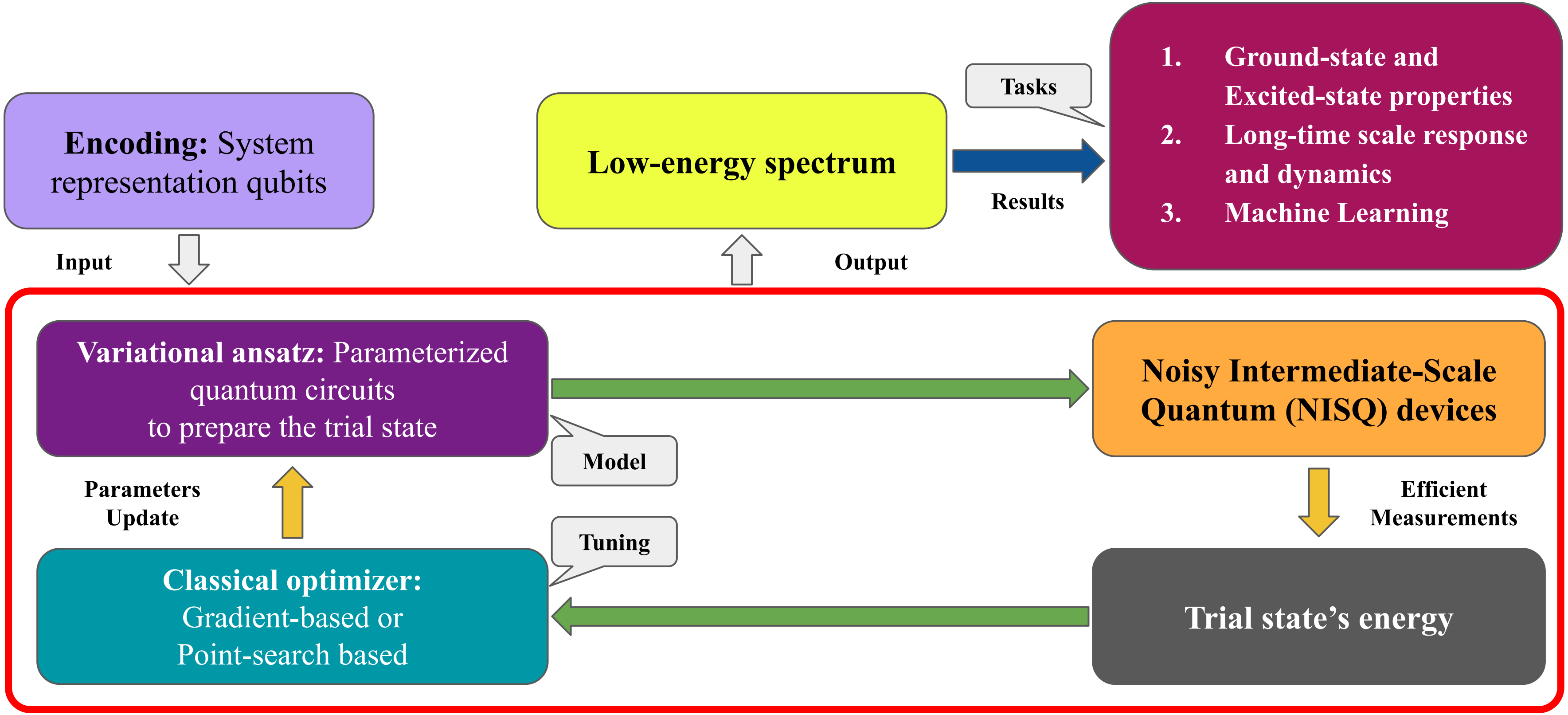
“classical easy”

Sub-Circuit Simulation

Classical Processor

n-qubit computations using n-k qubits
and additional classical resources

Variational Quantum Eigensolver (VQE)



Encoding: System representation qubits

Input

Low-energy spectrum

Output

Tasks

Results

1. Ground-state and Excited-state properties
2. Long-time scale response and dynamics
3. Machine Learning

Variational ansatz: Parameterized quantum circuits to prepare the trial state

Model

Noisy Intermediate-Scale Quantum (NISQ) devices

Parameters Update

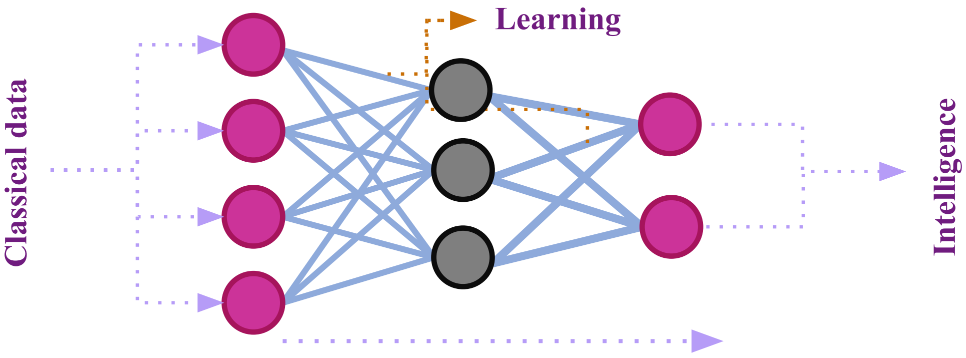
Efficient Measurements

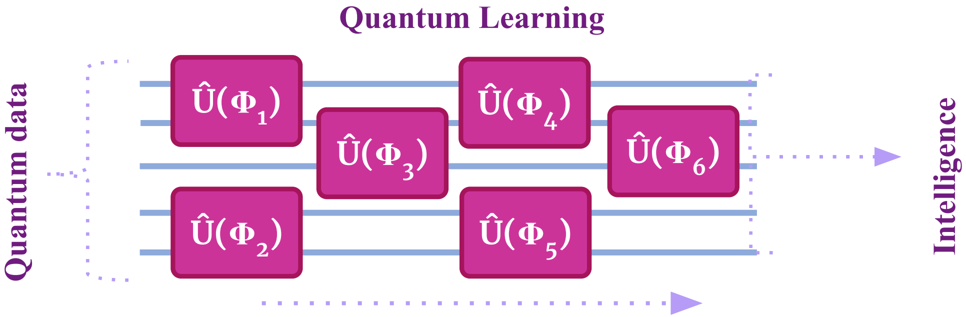
Tuning

Classical optimizer: Gradient-based or Point-search based

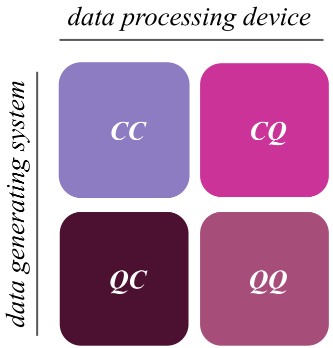
Trial state's energy

Hold on! This Feels Very Familiar





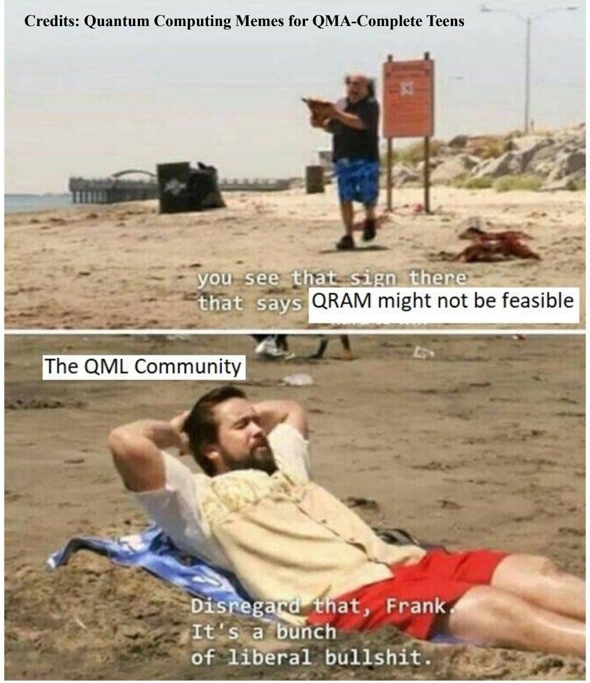
Modelling of Hybrid Neural Networks: Integrating Quantum and Classical Nodes



Our Focus: Quantum Machine Learning

QC - Learning Classical Data using Quantum Devices
QQ - Learning Quantum Data using Quantum Devices

C - classical,
Q - quantum



Credits: Quantum Computing Memes for QMA-Complete Teens

Quantum Optimization

- The natural description of a quantum optimization problem is to find the ground state of a N-body Ising Hamiltonian:

$$H^{\text{Ising}}(\psi) = \sum_{i} h_i\psi_i + \sum_{\langle i,j\rangle} J_{ij}\psi_i\psi_j + \sum_{\langle i,j,k\rangle} K_{ijk}\psi_i\psi_j\psi_k + \ldots$$

(The sum in brackets denote nearest neighbors)

ext. mag. 2-body 3-body

- Efficient **locality reduction** of H^{Ising} to a 2-local Hamiltonian can be seen as a QUBO:

$$f(x_1, \ldots, x_n) = -\sum_{m=1}^{N} c_m x_m + \sum_{1\leq m<n}^{N} J_{mn} x_m x_n, \quad \Longrightarrow \quad H^{\textit{2-local}}_{\text{Ising}} = -\sum_{j=1}^{N} h_j\sigma_j^z + \sum_{1\leq j<k}^{N} J_{jk}\sigma_j^z\sigma_k^z,$$

- **Adiabatic evolution** → *Initiate a spin-up state in X, which is fully entangled in Z and adiabatically evolve in s*

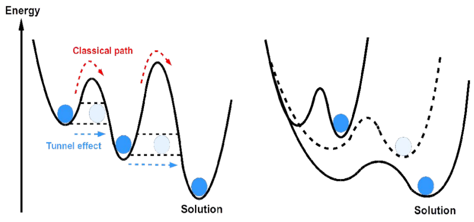
$$H(s) = (s-1)H^{\text{init}} + sH^{\text{problem}} \quad \Longrightarrow \quad U(T,0) \approx \prod_{j=1}^{p} \exp\{-i(1-s(j\Delta t))H_D\Delta t\}\exp\{-is(j\Delta t)H_P\Delta t\}.$$

- Adiabatic condition depends on energy gap of time-dependent Hamiltonian.

$$T \geq \mathrm{O}\left(\frac{\left|\left|H^{\text{init}} - H^{\text{problem}}\right|\right|^2}{\epsilon\min_{s\in[0,1]}\Delta(H(s))^3}\right)$$

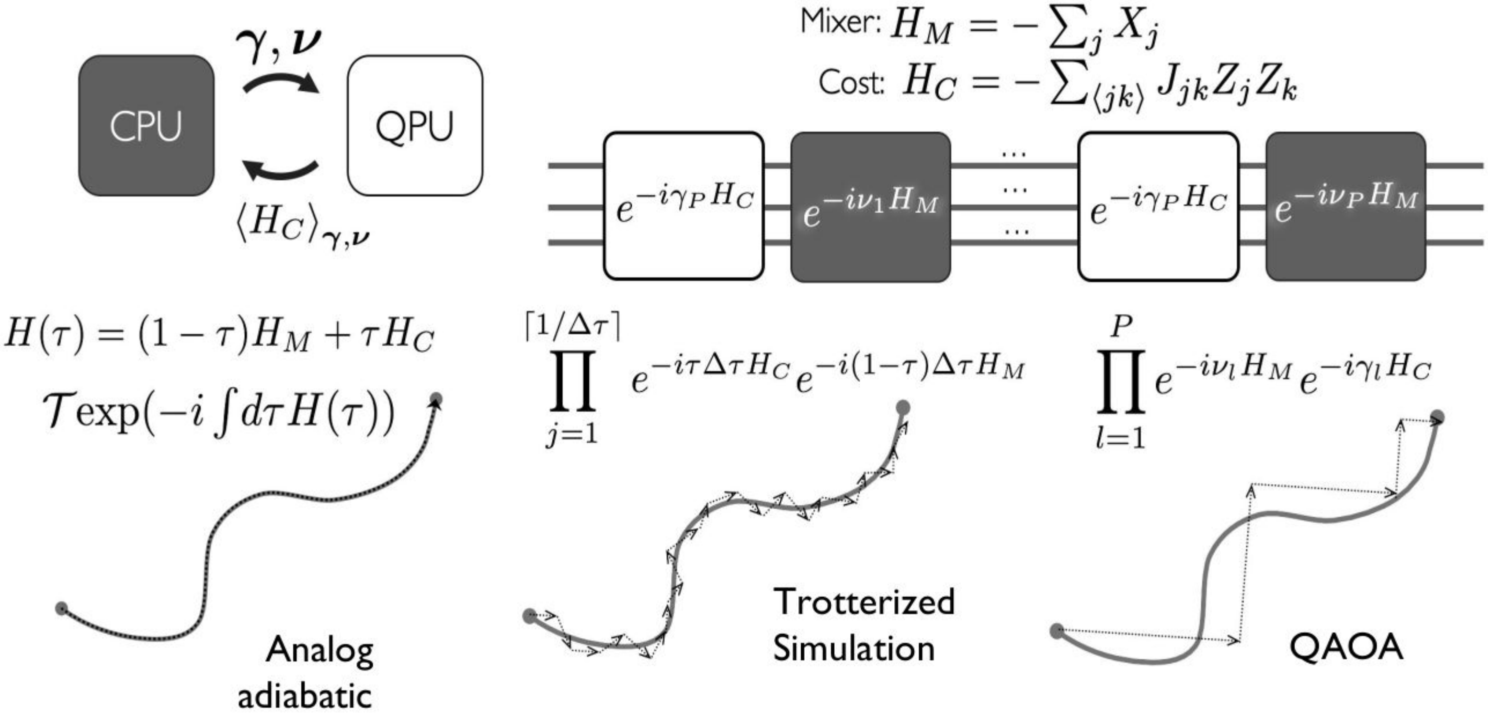
Approximate Quantum Optimization involves breaking this condition.

- Adiabatic quantum computing can solve problems that can be mapped to the Ising Model.



Quantum Tunnelling Adiabatic evolution

Quantum Approximate Optimization Algorithm



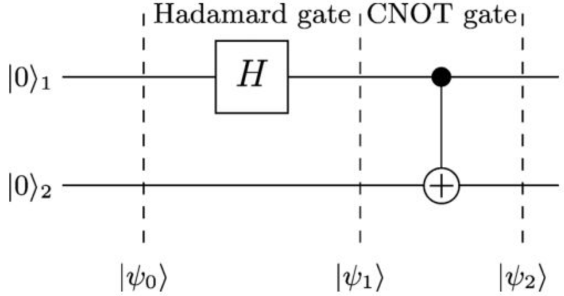
Quantum Software

1. **Quantum instruction sets**
    - OpenQASM
    - QUIL
    - BlackBird
2. **Pulse-control instruction sets**
    - QUIL-T
    - Open Pulse
    - Q-CTRL
3. **Quantum Programming Languages**
    - QCL
    - Q#
    - Silq
    - Quipper
    - Many More

Quantum Software Development Kits (SDKs)

1. Ocean → DWAVE
2. ProjectQ → Benjamin Group
3. XACC → LANL
4. Cirq, TensorFlow Quantum → Google
5. Forest → Riggeti
6. Orchestra → Zapata
7. QISKIT → IBM
8. Akaash → CDAC
9. t|ket> → CQC
10. Strawberry Fields, Pennylane → Xanadu
11. QDK → Microsoft

Naive Example



```
# Importing module for writing Quantum Programs
from pyquil.quil import Program
from pyquil.gates import X, Y, Z, H, CNOT
# Create a connection to the QVM
from pyquil.api import QVMConnection
qvm = QVMConnection()
# Initialize Program
p = Program(I(0), I(1))
# Add instructions
# H(0) - Hadamard on 0th qubit.
# CNOT(0, 1) - Target - 1st qubit
p.inst(H(0), CNOT(0, 1))
# Now index of Bell state needed
num = index #Replace it by int
if index/2 >= 1:
    p.inst(Z(1))
if index%2 == 1:
    p.inst(X(1))
print(p) #Print's P and inst. applied
print(qvm.wavefunction(p))
```

```
H 0
CNOT 0 1
Z 1
X 1
(0.7071067812+0j)|01> + (0.7071067812+0j)|10>
```

Quantum Compilation

Assume, $|\Psi\rangle$ is our quantum state, C is our classical state, G is our set of static gates, G` is our set of parametric gates, P is a sequence of instructions comprising our program, and κ is where we are in the program. Then, we define M = ($|\Psi\rangle$, C, G, G`, P, κ) as a Quantum Abstract Machine.

Goal of quantum compilation →

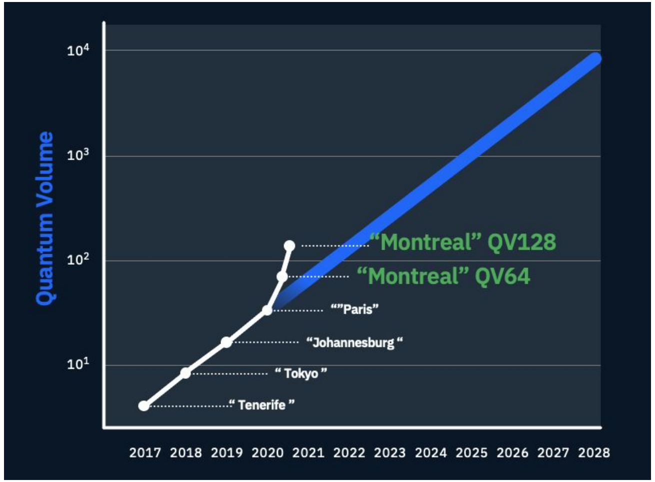
$$M_{\text{source}} \xrightarrow{f_0} M_1 \xrightarrow{f_1} M_2 \xrightarrow{f_3} \cdots \xrightarrow{f_n} M_{\text{target}}.$$

Optimized for the hardware

This uses a lot of heuristics -

1. **Decomposition** → Decompose all the higher order gates in the native bases gates. Then use algebraic identities, matrix-factorization methods or the Solovay–Kitaev algorithm.
2. **Routing** → Perform Qubit Allocation and efficient Qubit Movement using minimal number of SWAP gates.
3. **Approximate Compilation** → Estimate the total amount of error (using $||E_i|| \leq \epsilon$) for executing a series of gates computing U, and replace it with some other approximate series of gates computing U` which is contained in $\Pi_i(U_i + E_i)$.

Benchmarking - Quantum Volume

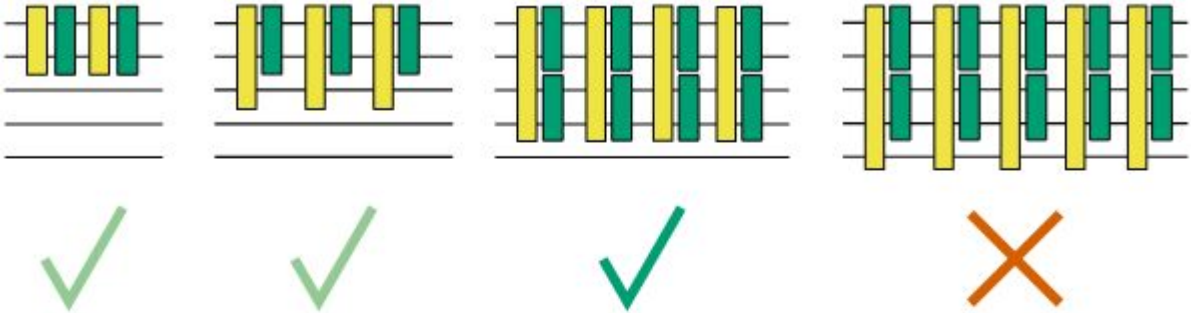


Quantum Volume $\mathbf{V_Q}$ for n-qubit quantum processor -

$$\log_2(V_Q) = \operatorname{argmax}_m \min(m, d(m))$$

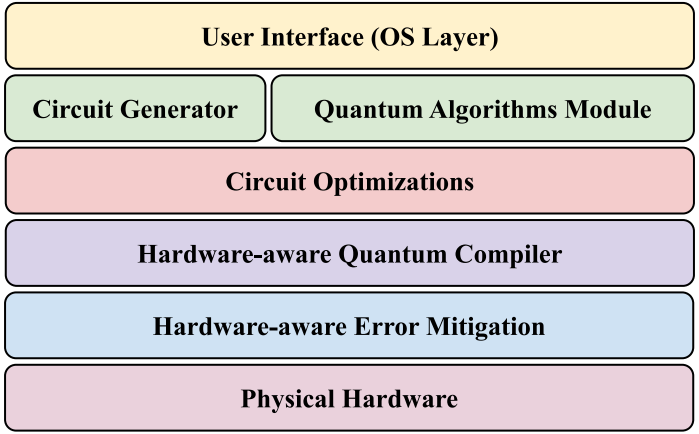
Where $m \leq n$ is number of qubits and $d(m)$ is the number of qubits in the largest square circuit for which we reliably sample output with a probability > ⅔

Example - Look at the following processor with $\log_2(V_Q) = 4$

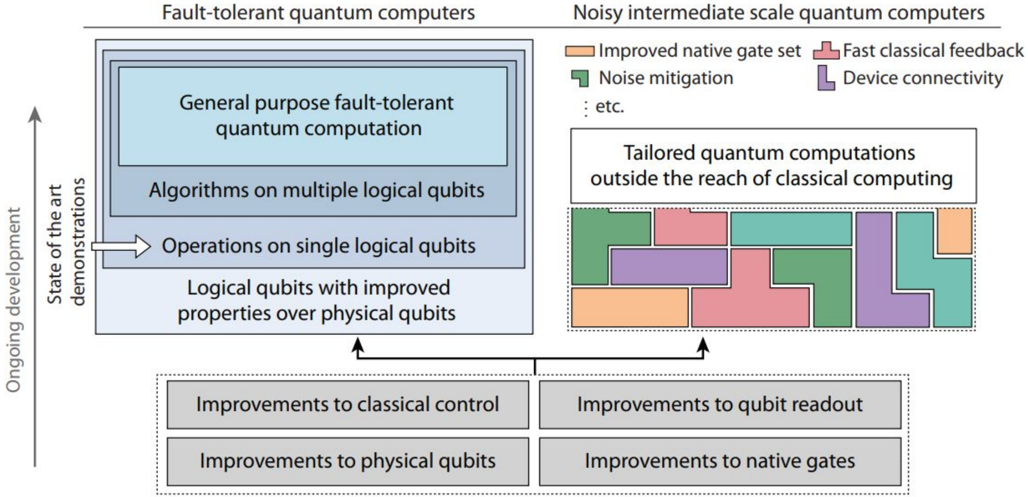


Quantum Stack

Credits - Superconducting Qubits: Current State of Play arXiv:1905.13641



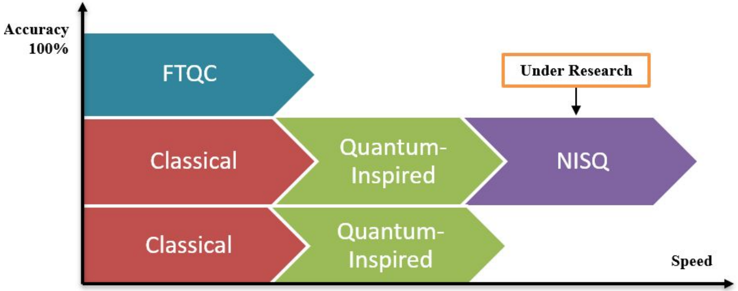
- User Interface (OS Layer)
- Circuit Generator | Quantum Algorithms Module
- Circuit Optimizations
- Hardware-aware Quantum Compiler
- Hardware-aware Error Mitigation
- Physical Hardware

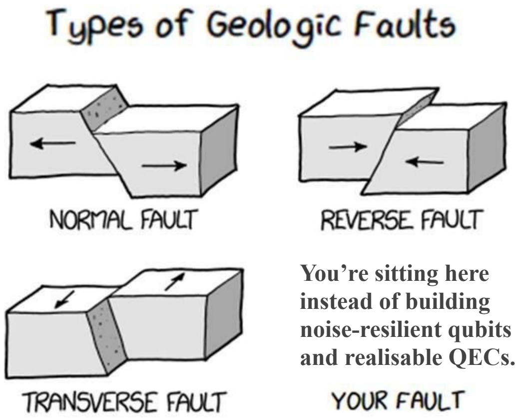


Path towards fault-tolerant quantum error-corrected quantum computers (left) as well as noisy intermediate scale quantum computing (right).

Quantum-Inspired Algorithms

- **Powering-up classical computations**
  - Concept from quantum physics, and sampling/query-access strategies
  - Results in probabilistic algorithms (with some specialized hardware)
    - Example: Annealing (AQC), Replica Exchange, Stochastic Neurons
- **De-quantized Algorithms**
  - Classical algorithms which proves their corresponding
    - quantum variants don't give exponential speedups
- **Examples**
  - Quantum-inspired evolutionary algorithms →
  - Quantum-inspired algorithms for linear algebra →
    - QIA for recommendation systems (Tang),
    - QIA for PCA and supervised clustering (Tang),
    - QIA for solving low-rank linear systems (Chia, Lin, Wang)
  - Quantum-inspired optimization algorithms → Ising Computing





You’re sitting here instead of building noise-resilient qubits and realisable QECs.

Thank You!

Questions?