Quantum Computing: Principles, Challenges, and Outlook

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Outline

- What started it all?
- What is quantum information and what are qubits?
- Why can quantum computing be faster?
- What are the types of quantum computers?
- What do the Di Vincenzo criteria teach us?
- How can we compute if quantum information is so fragile?
- What about compilers for quantum algorithms?
- Closing speculations

Physics of Computation Conference, Endicott House MIT May 6-8, 1981

Rolf Landauer, IBM – co-organizer

Richard Feynman, Cal Tech

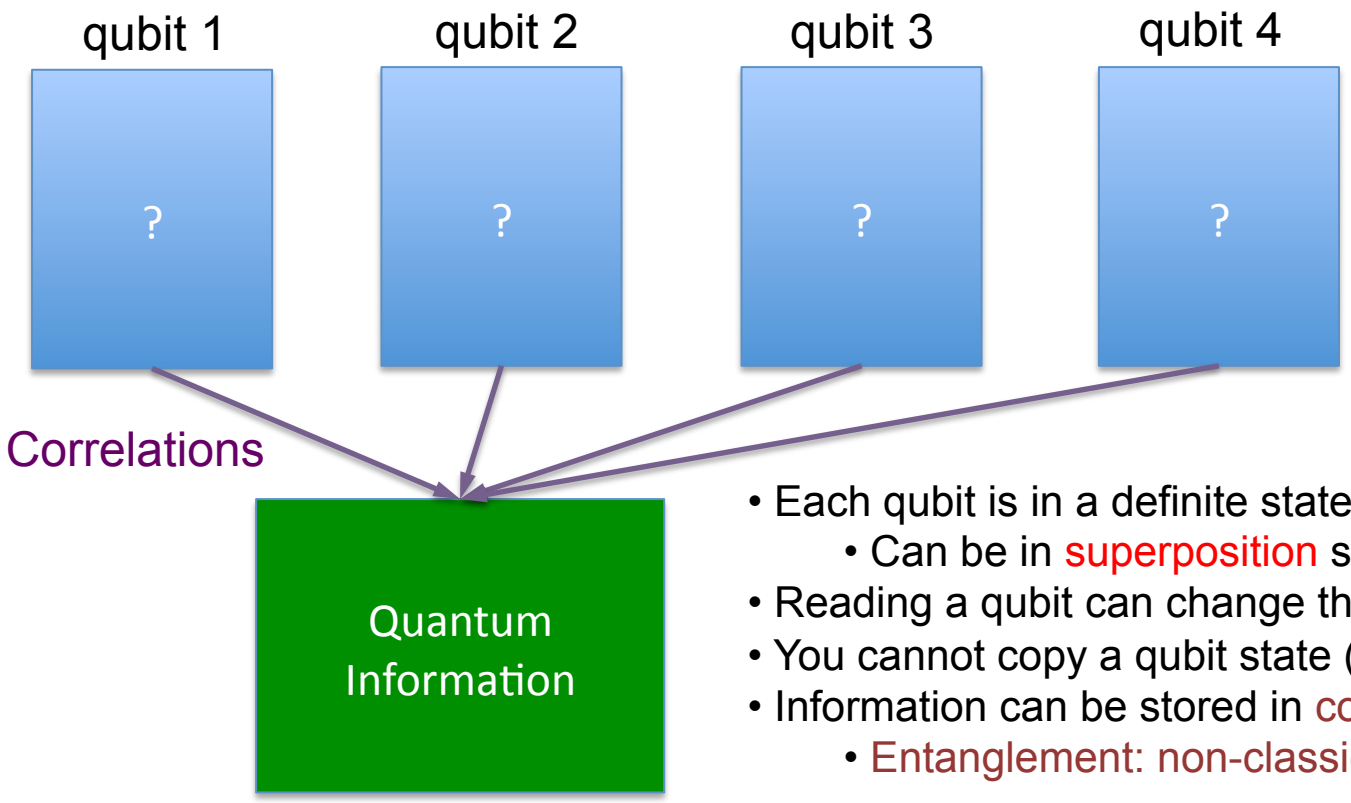
"… nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

- Richard Feynman at Physics of Information conference, 1981

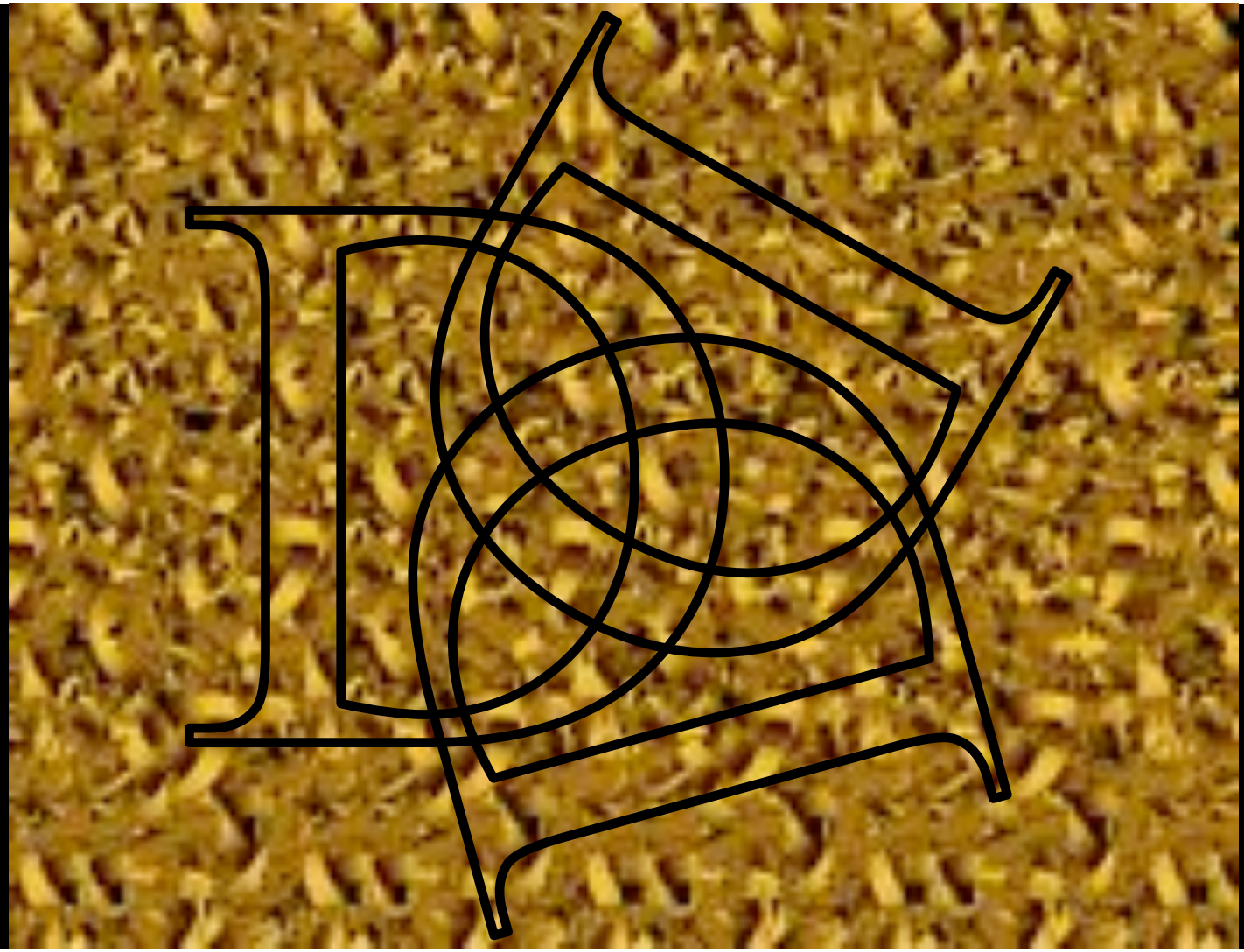
Classical Information

- Each bit is in a definite state, 0 or 1
- Reading a bit does not change the state
- You can copy a bit
- All of the information of a bit is stored in that bit

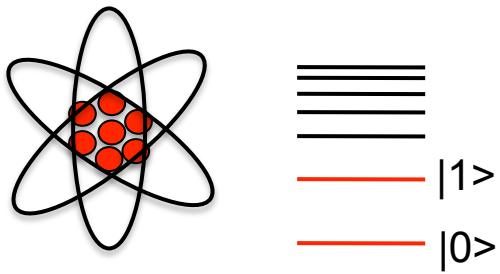
Quantum Information



- Each qubit is in a definite state
  - Can be in superposition state – 0 and 1
- Reading a qubit can change the state
- You cannot copy a qubit state (no cloning)
- Information can be stored in correlations of qubits
  - Entanglement: non-classical correlation



Example of Qubit



single atom

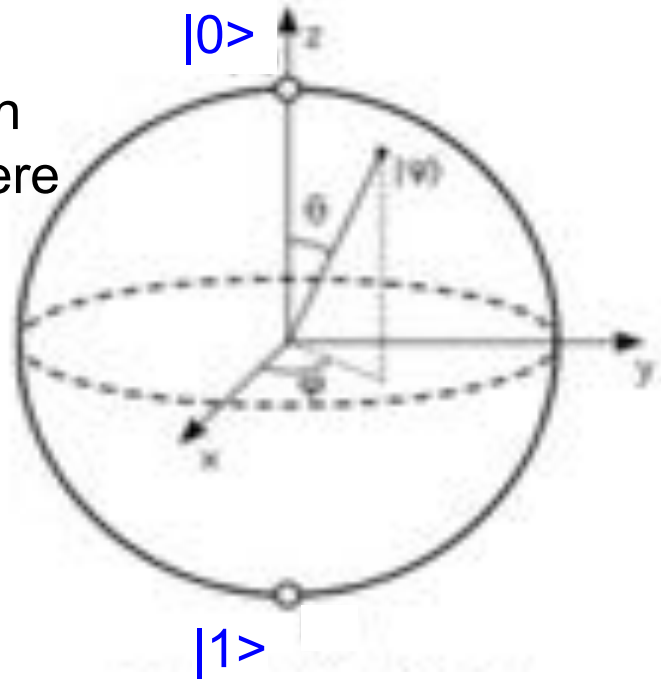
Atom can be |0> or |1> state, or it can be simultaneously in both states !!

superposition

BUT, the atom <u>is</u> in a definite state…

How do we describe a qubit state?

Bloch Sphere



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

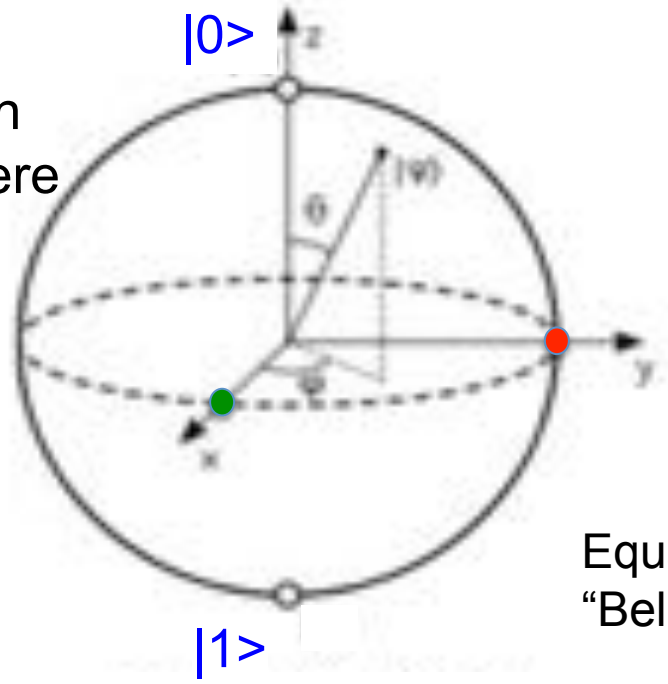
$$\alpha = \cos\left(\frac{\Theta}{2}\right)$$

$$\beta = e^{\iota\phi}\cos\left(\frac{\Theta}{2}\right)$$

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

Qubit Superposition States

Bloch Sphere



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

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

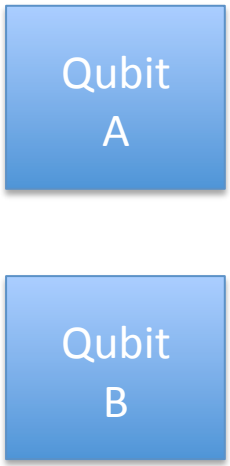
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)$$

Equator = equal superposition of |0> and |1> = "Bell States" with different phases, ϕ

Measuring a superposition state: sometimes get |1>, sometimes |0>…

Measuring Qubits- What Do We See?

Measure repeatedly

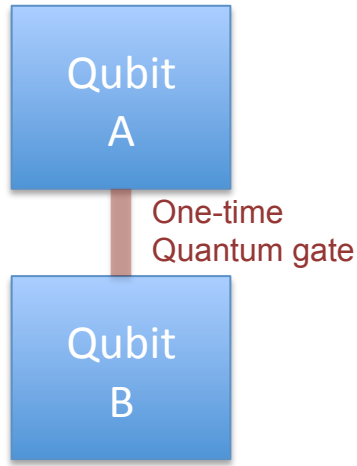


#	A	B
1	1	0
2	0	1
3	0	0
4	1	0
5	1	1
6	0	1
7	1	0
8	0	1

Superposition
Not entangled

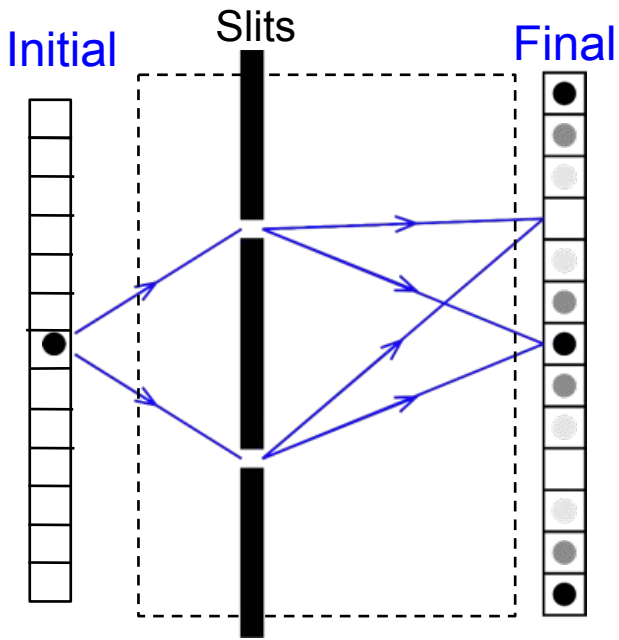
#	A	B
1	1	1
2	0	0
3	0	0
4	1	1
5	1	1
6	0	0
7	1	1
8	0	0

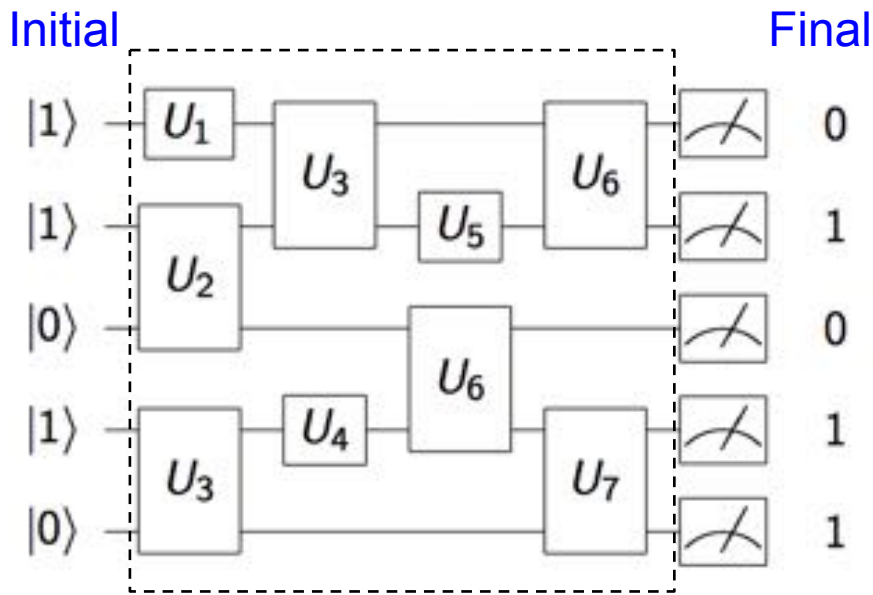
Entangle and measure



Superposition
Entangled – 100% correlated !!!

Analogy to Describe Quantum Algorithms





Quantum correlations:
1) coherent light
2) superposition – photon senses slits
2) interference gives slit separation

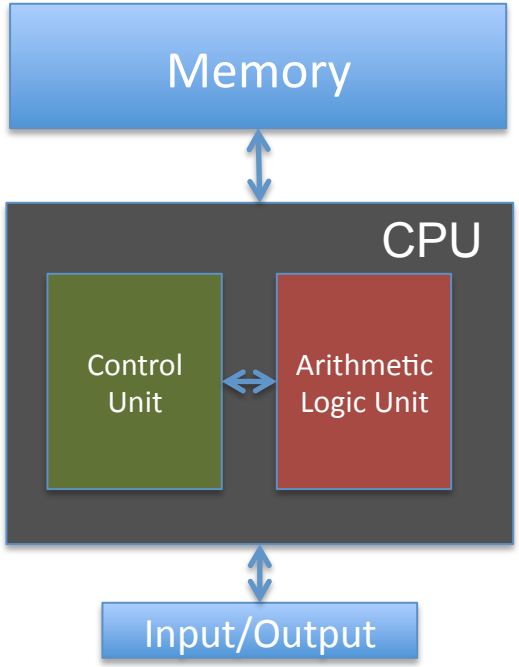
Quantum algorithms:
1) long-lived quantum states
2) superposition and entanglement
3) interference determines answer

Why are Some Quantum Algorithms So Fast?

- Superposition: each qubit in 2 states simultaneously
- Entanglement: qubits share information, so
  - N entangled qubits in superposition states span 2^N states
- Interference:
  - Constructive interference enhances correct answer – ONLY 0 or 1 at end.
  - Destructive interference suppresses incorrect answers
- Power grows exponentially with number of qubits
  - Doubles with each added qubit
    - Compare to linear growth of conventional: double by doubling the number of bits…
- BUT this means qubits need interaction choreography…

High-Level Architectures

Conventional

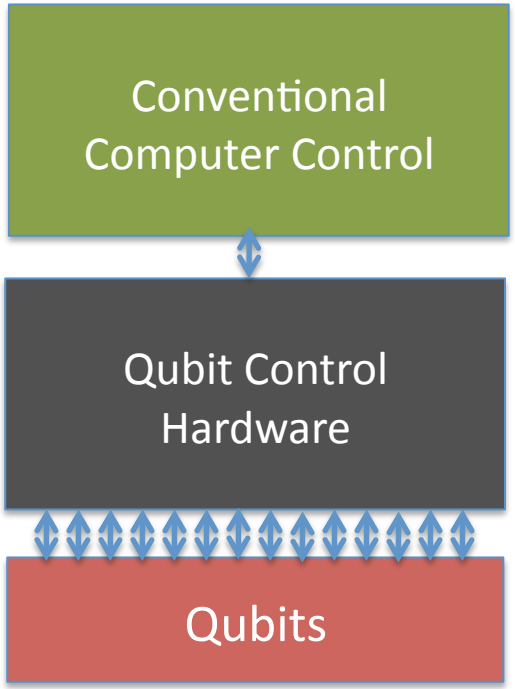


Rent's rule: pins = k T^{β}

T = number transistors

$0.5 < \beta < 0.8$

Quantum



Nothing like Rent's rule-
every qubit controlled

The three known types of Quantum computing and their applications, properties, and computational power.

Quantum Annealer

The quantum annealer is least powerful and most restrictive form of quantum computers. It is the easiest to build, yet can only perform one specific function. The consensus of the scientific community is that a quantum annealer has no known advantages over conventional computing.

APPLICATION
Optimization Problems

GENERALITY
Restrictive

COMPUTATIONAL POWER
Same as traditional computers

Analog Quantum

The analog quantum computer will be able to simulate complex quantum interactions that are intractable for any known conventional machine, or combinations of these machines. It is conjectured that the analog quantum computer will contain somewhere between 50 to 100 qubits.

APPLICATIONS
Quantum Chemistry
Material Science
Optimization Problems
Sampling
Quantum Dynamics

GENERALITY
Partial

COMPUTATIONAL POWER
High

Universal Quantum

The universal quantum computer is the most powerful, the most general, and the hardest to build, posing a number of difficult technical challenges. Current estimates indicate that this machine will comprise more than 100,000 physical qubits.

APPLICATIONS
Secure computing
Machine Learning
Cryptography
Quantum Chemistry
Material Science
Optimization Problems
Sampling
Quantum Dynamics
Searching

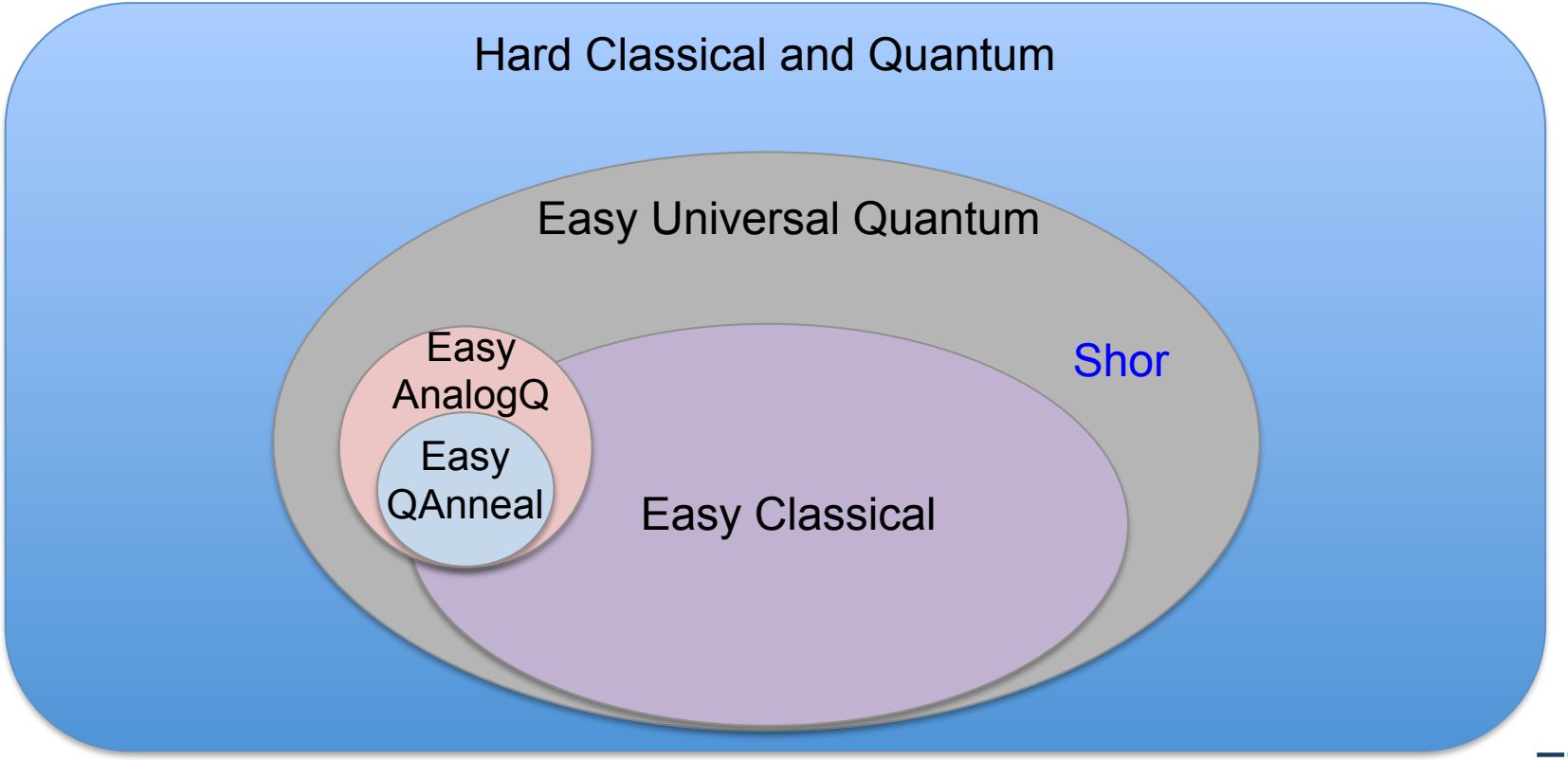
GENERALITY
Complete with known speed up

COMPUTATIONAL POWER
Very High

EIV Research

Graphic by Carl De Torres for EIV Research

Classes of Problems

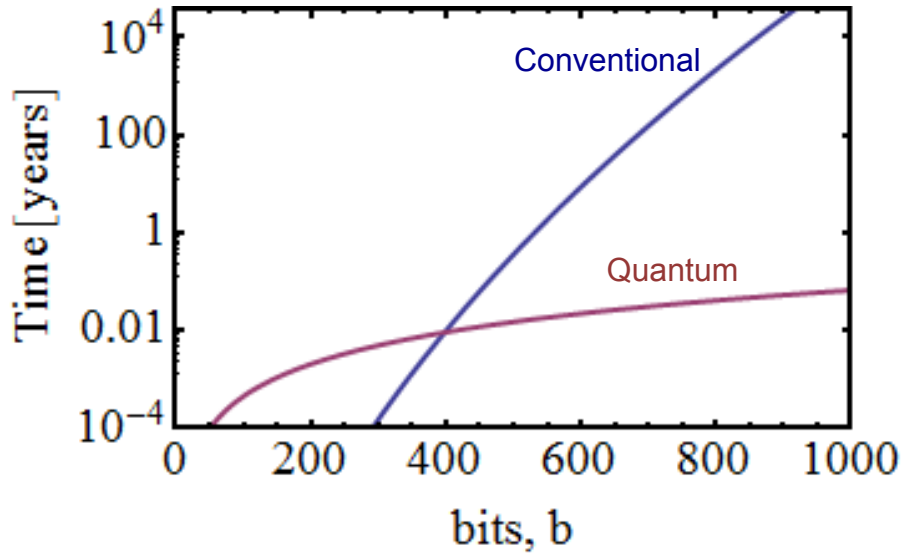


Shor's Algorithm

Factor a number into primes:

$$M = p * q$$

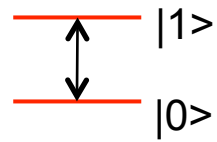
Classical	Quantum
$t \sim \exp(O(n^{1/3} \log^{2/3} n))$	$t \sim O(n^3)$



P. W. Shor, \Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer," SIAM Journal on Computing, no. 5, p. 1484.

The DiVincenzo Criteria for Universal Quantum Computers

1. Well-defined qubits



2. Initialization to a pure state $|000\ldots0\rangle$

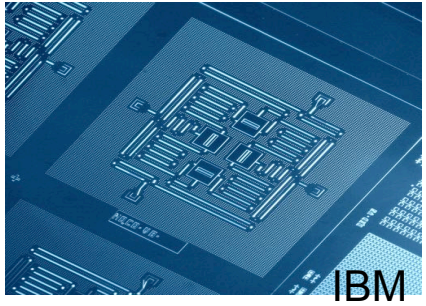
3. Universal set of quantum gates

4. Qubit-specific measurement $\langle 0011000| M |0001100\rangle$

5. Long coherence $T_1/T_g \sim 10{,}000$

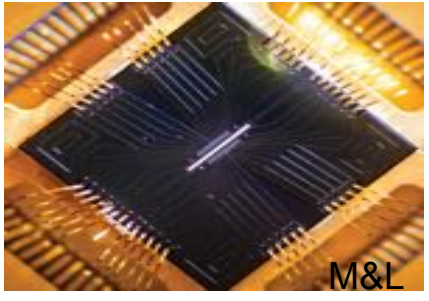
David DiVincenzo, Fortschrift der Physik, (2000)

1. Well-defined Qubits: Example Technologies

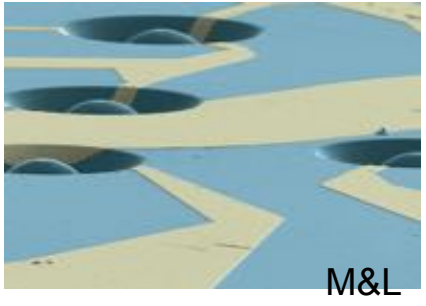


Superconducting Qubits

Transmon, Flux, Phase

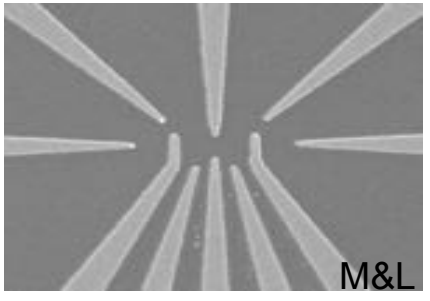


Trapped Ions



Engineered Defects

NV Centers in Diamond

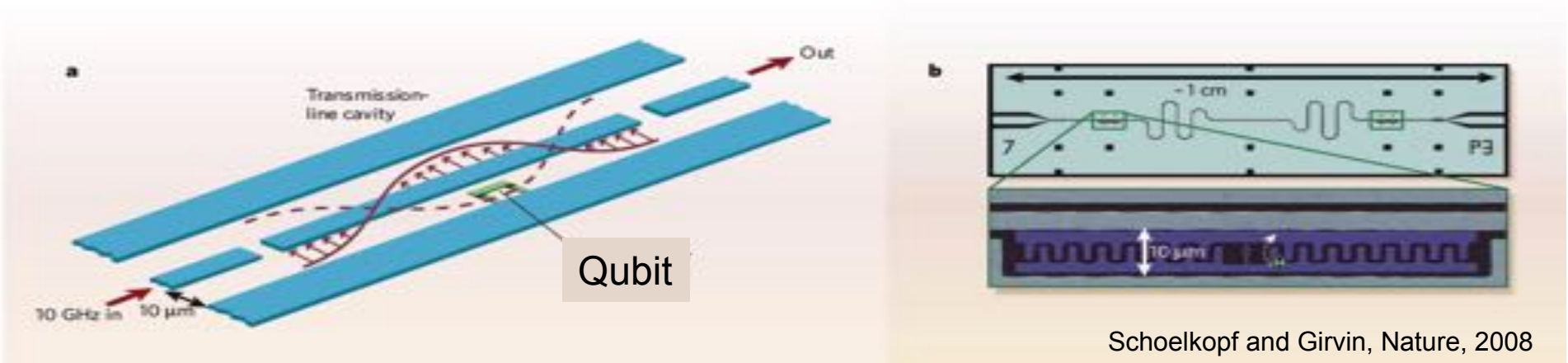


Quantum Dots

- All technologies have well-defined states that are used for |0> and |1>
  - $E_{|1>} - E_{|0>}$ is unique
- Technologies differ in fundamental physical mechanisms limiting T_1, T_2

M&L: Morton and Lo, IEEE Spectrum, 8/2104

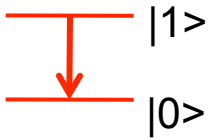
2. Initialization to a Pure State



Schoelkopf and Girvin, Nature, 2008

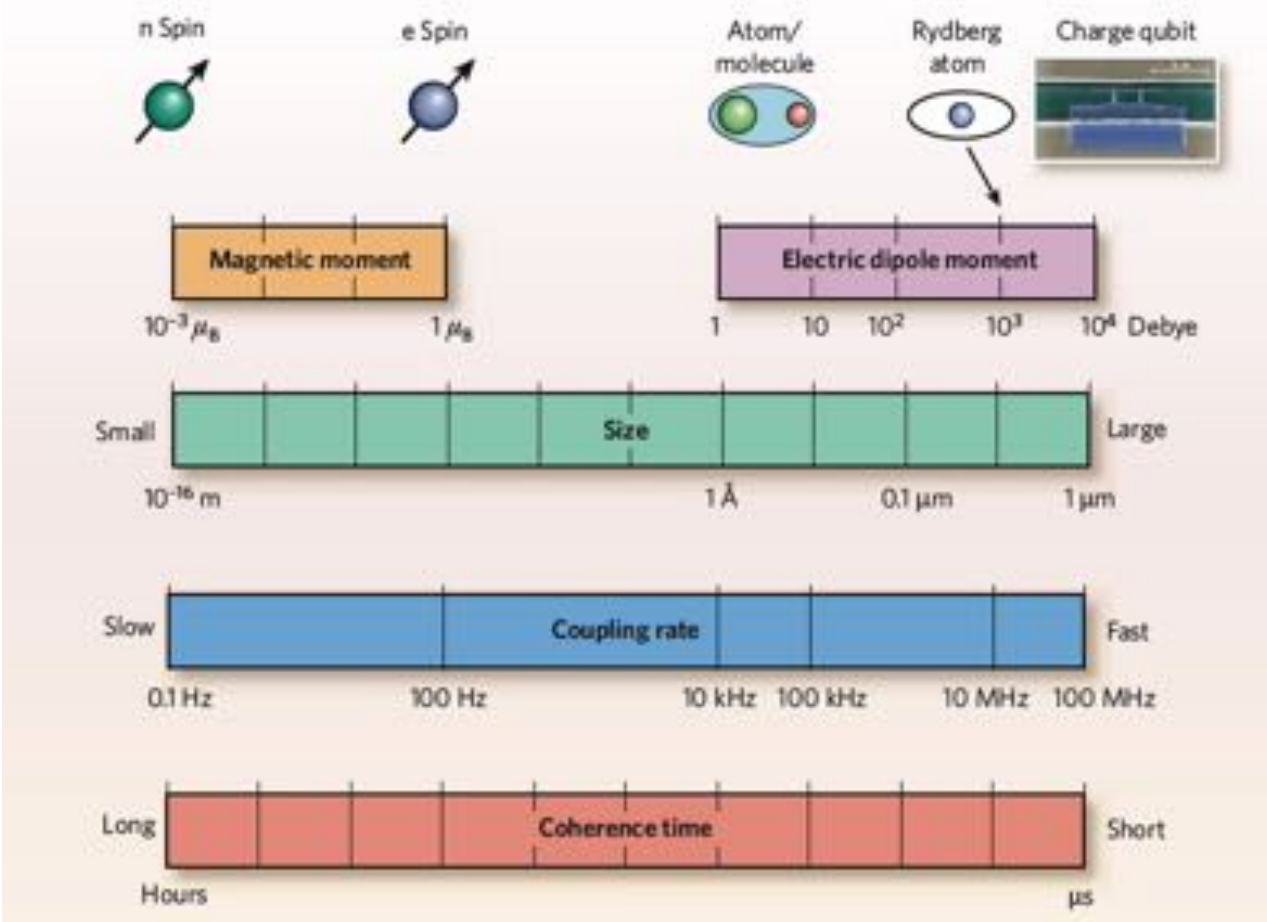
Initialization:

- Wait > T1, qubit thermalizes to |0>
- Control state with EM pulses to force |0>



Wait $>T_1$

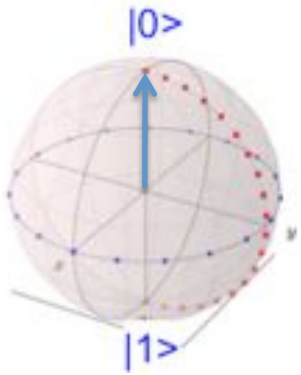
2. How Easy is Qubit Controlled?

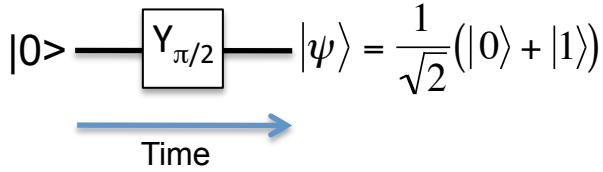


Schoelkopf and Girvin, Nature, 2008

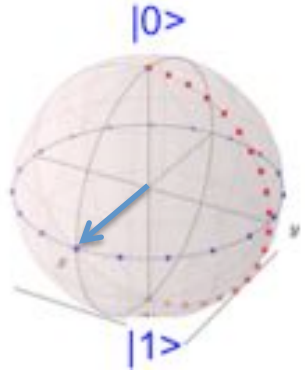
3. Quantum Gates – Introduction – Single Qubit Gate

qubit 1
Before



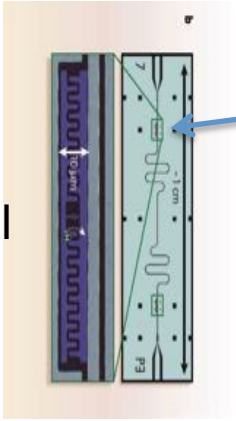


$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



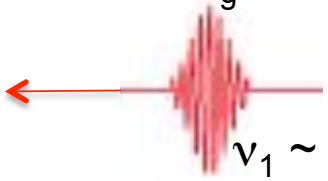
qubit 1
After -
Superposition

Physical



ν_1
Qubit 1

T_g ~ 10-20ns



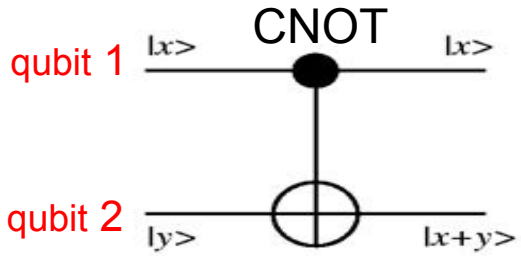
ν_1 ~ 6 GHz

1. Set initial states of Qubit to |0>
2. Apply specific RF pulse to Qubit 1 at its resonant frequency, ν_1

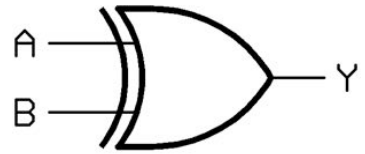
3. Quantum Gates – Introduction – 2 Qubit Gate

A quantum CNOT gate: (this entangles the qubits)

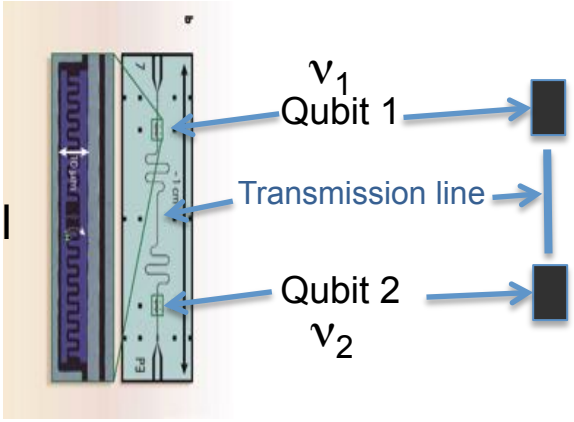
Logical



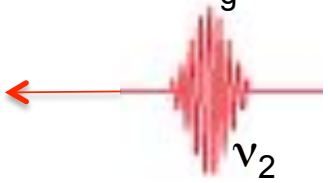
Like conventional xor



Physical



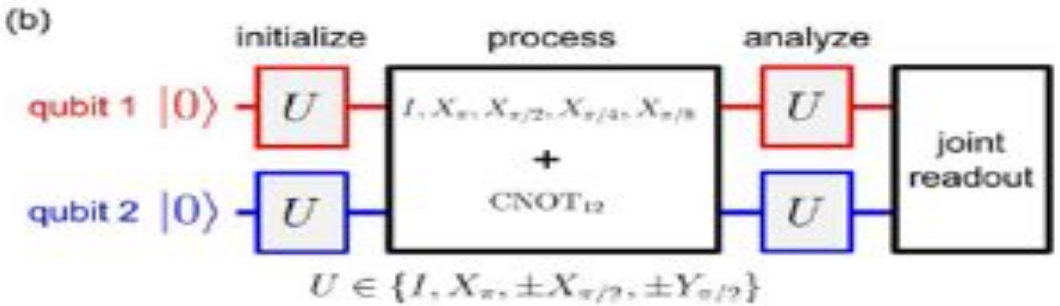
T_g ~ 30-100ns



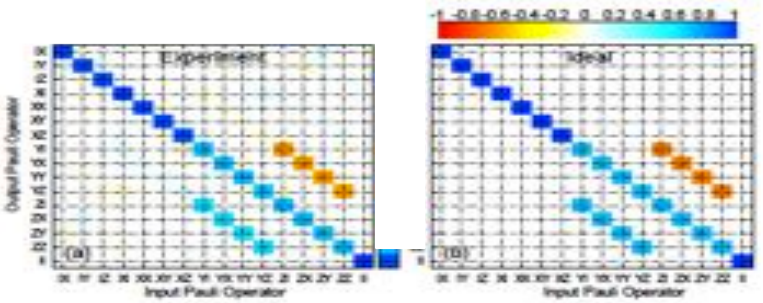
1. Set initial states of Qubits
2. Apply RF pulse to Qubit 1 at the frequency of Qubit 2

3. Universal Set of Quantum Gates

- Validation of Complete Set of Quantum Gates approaching fault tolerant threshold (fix by error correction)



Gate Operations



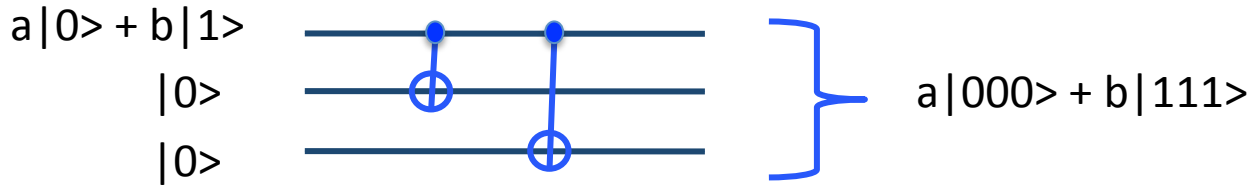
Experiment Ideal

(Chow, Jerry M., et al. *Physical review letters 109.6 (2012): 060501.*)

- Consequences for computation:
  - Control requires access to each qubit
  - Therefore, device density limited by fanout, not qubit size…

4. Qubit Specific Measurement: SPAM

- Improving state preparation
  - Calibrate gate control
  - Calibrate out unwanted interactions
- Improving unreliable measurement
  - Measure qubit state for a longer time and average (noise in qubit measurement)
  - Repeat calculation and average outcome (1-bit answer problems)
  - Apply "Quantum FAN-OUT" and majority voting

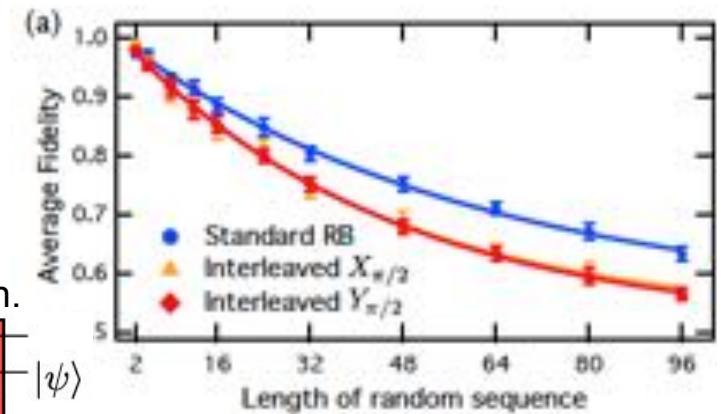


State Preparation And Measurement (SPAM) is critical

4. How Do You Validate A Quantum Gate?

- Accurately measure SPAM, try to calibrate everything perfectly
- THEN measure gate,
- Then remove measurement errors to find gate error?

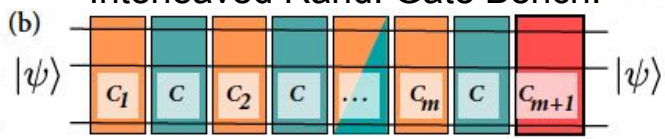
Take a breath and think:
<u>Randomized Gate Benchmarking</u>



Randomized Gate Benchmarking

- Choose random set of N+1 Clifford gates
- End reset gate (computed)
- Measure fidelity
- Repeat and average

Interleaved Rand. Gate Bench.

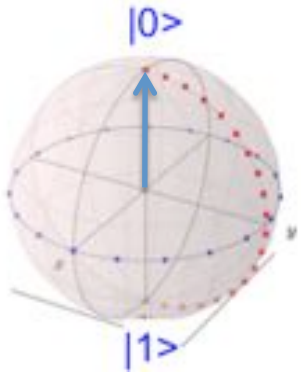


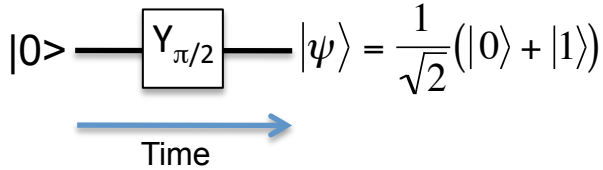
- Choose random set of Cliffords
- Interleave gate of interest (green)
- End reset gate (computed)
- Measure fidelity
- Repeat and average

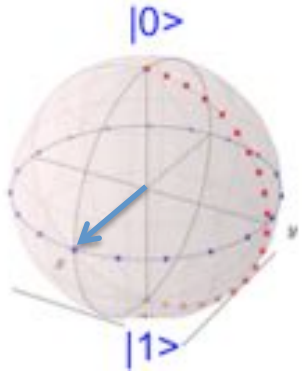
Magesan et.al., arXiv:1203.4550v2 [quant-ph] 19 Mar 2014

4. Quantum Gate Fidelities

Single Qubit Gates



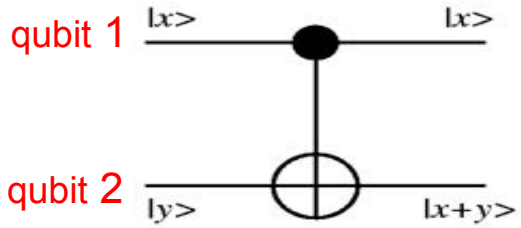




99.95% Fidelity

Two Qubit Gates

Logical CNOT

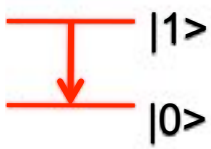


99.1% Fidelity

At fidelities required to begin experimenting with surface code

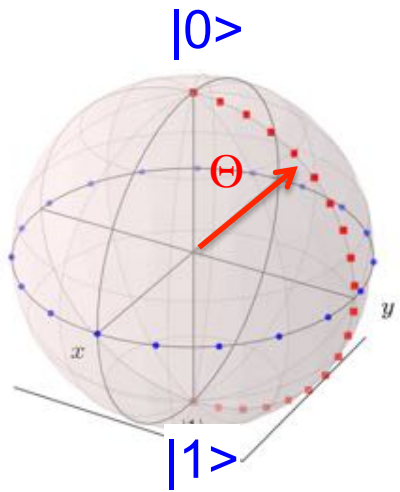
5. Long Coherence-- Preserve Magnitude

Preserve Magnitude = Latitude on globe



T_1

θ changes



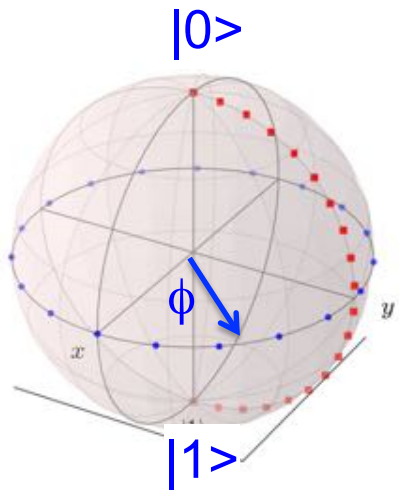
T_1 = How long "latitude" preserved

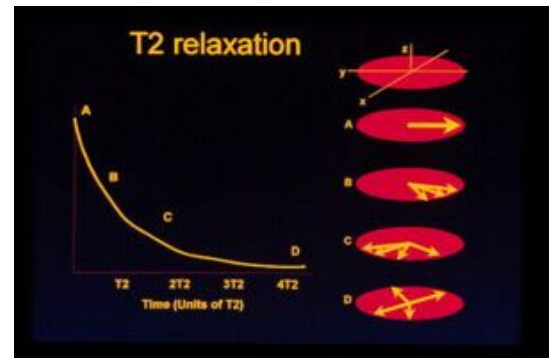
5. Long Coherence-- Preserve Phase

Preserve <u>Phase</u> = Longitude on globe

T_1

θ changes





T_2

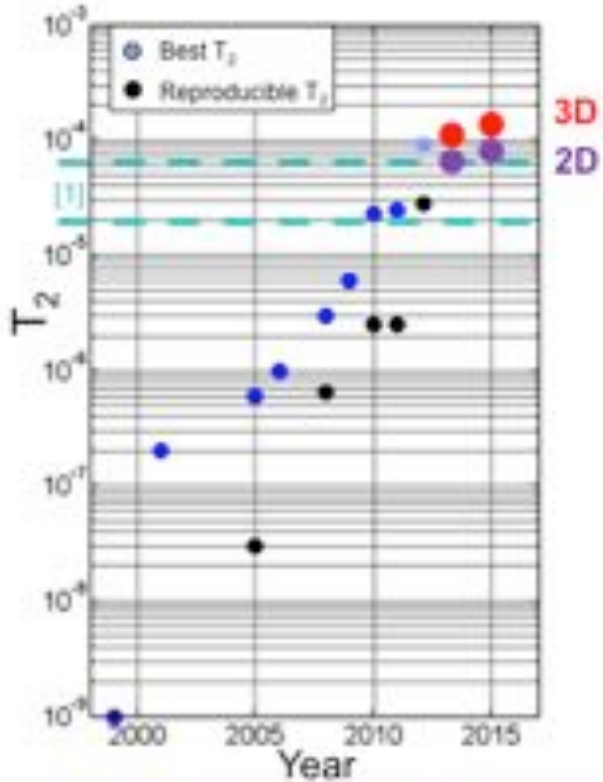
ϕ changes

T_1 = How long "latitude" preserved

T_2 = How long "longitude" preserved

Want $T_2 \Rightarrow T_1 >> T_{\text{quantum operation}}$

5. Superconducting Qubit Coherence Progress



Remarkable progress over the past decade

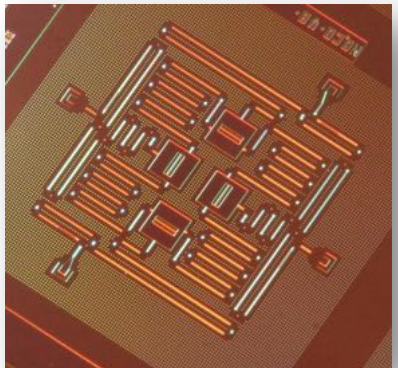
- Understand charge noise e.g. [1]
- Materials e.g. [2,10]
- Microwave environment [3]
- Design and geometries e.g. [4,10]
- 3D transmon [5]
- IR Shielding [6,7],
- Cold normal metal cavities and cold qubits [8]
- High Q cavities [9]

$T_{1,2}/T_g$ > 1,000 now

[1] Koch et. al. PRA **76**, 04319 (2007)
[2] J. Martinis *et al.*, PRL **95** 210503 (2005)
[3] Houck et. al. PRL **101**, 080502 (2008)
[4] K. Geerlings *et al.*, APL 192601 (2012)
[5] H. Paik *et al.*, PRL 107, 240501 (2011)
[6] R. Barends *et al.*, APL **99**, 113507 (2011)
[7] A. Corcoles *et al.*, APL **99**, 181906 (2011)
[8] C. Rigetti *et al.*, PRB **86**, 100506 (2012)
[9] M. Reagor *et al.*, arXiv:1302.4408 (2013)
[10] J. Chang et al. APL 103, 012602 (2013)

[1] Noise threshold for surface code QEC assuming 30-100ns gate time

Why Quantum Information is Fragile

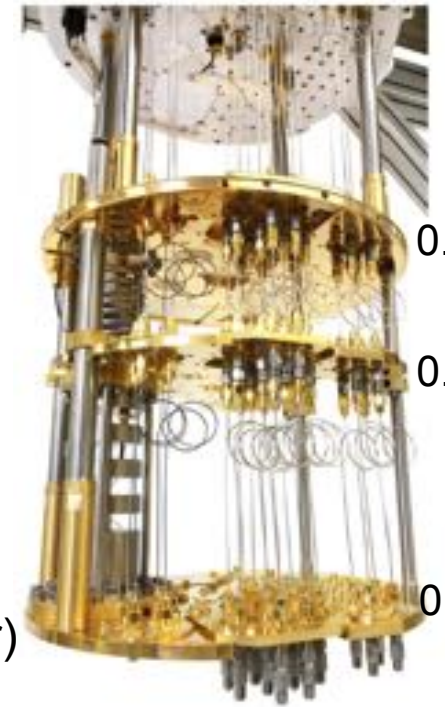


Qubit chip

Qubits “trap” and control state of single microwave photon or atom

Energy state >> Thermal energy, RF noise OR you lose qubit state.

- This is why we operate at 0.02 Kelvin…
- Why cryostat (refrigerator) is well-shielded…

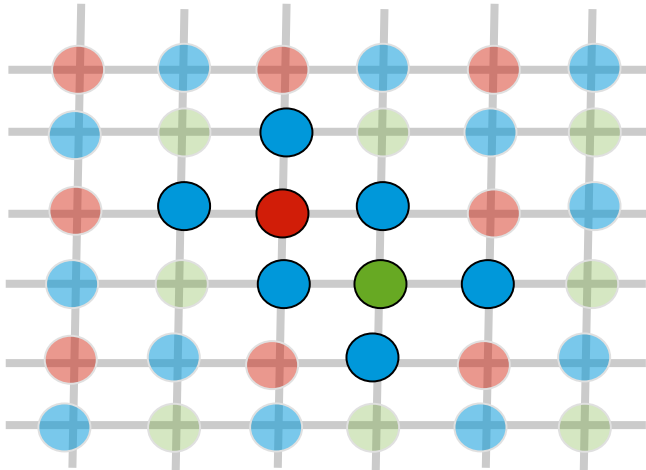


Cryostat (refrigerator)

Need to understand errors and apply error correction…

The Surface Code: Protecting Quantum Information by Error Correction

Bravyi



Qubit Legend:

Data

Ancilla – phase parity

Ancilla – magnitude parity

Surface Code of Bravyi and Kitaev:

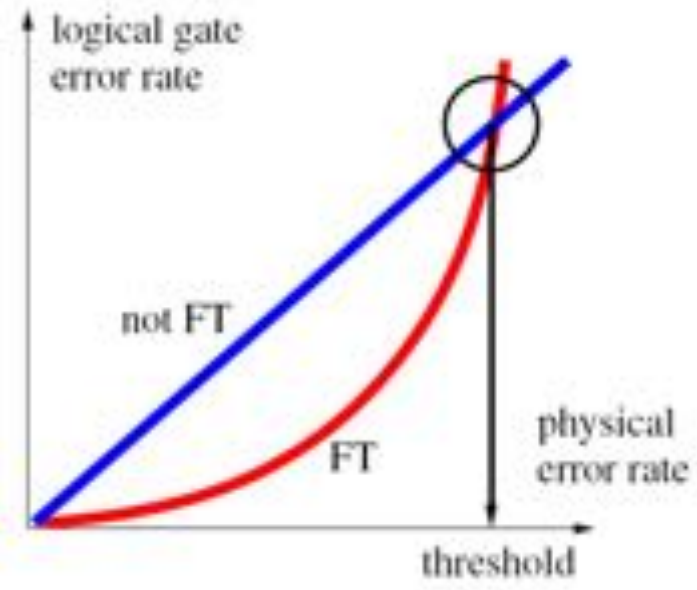
- Measure Green ancilla qubits for phase parity, red for magnitude parity
- Data qubits never directly measured
- Repetitive application of code used to correct errors on data qubits

[1] Bravyi, Sergey B., and A. Yu Kitaev. "Quantum codes on a lattice with boundary." *(1998).*
[2] Fowler et al., PRA (2009)

Error Suppression with Surface Code

Large scale quantum computing possible in principle, despite decoherence, control inaccuracy, and systematic error in physical implementations

- Error rates 10^{-2} – 10^{-6}
- Arbitrary low logical error rates don't require large numbers of physical gates

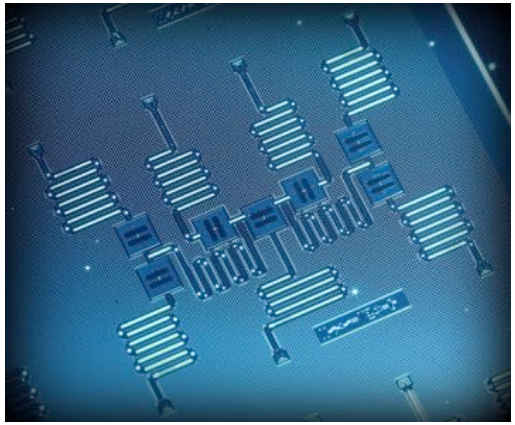


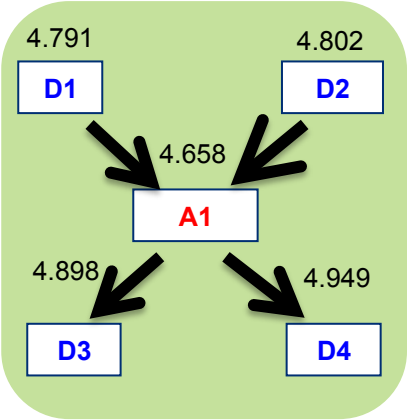
Are there better quantum codes?

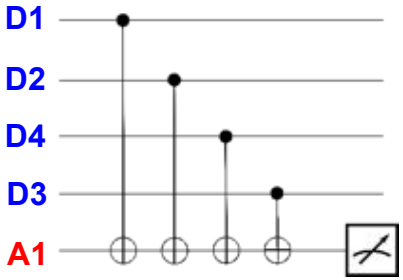
Are there better ways of implementing decoders?

Progress Demonstrating Code

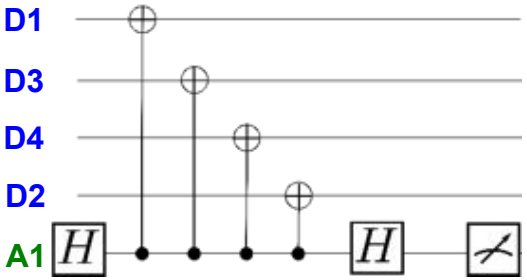
MQCO completed January 2016: demonstrated 5-qubit surface code parity check







ZZZZ (mag) parity



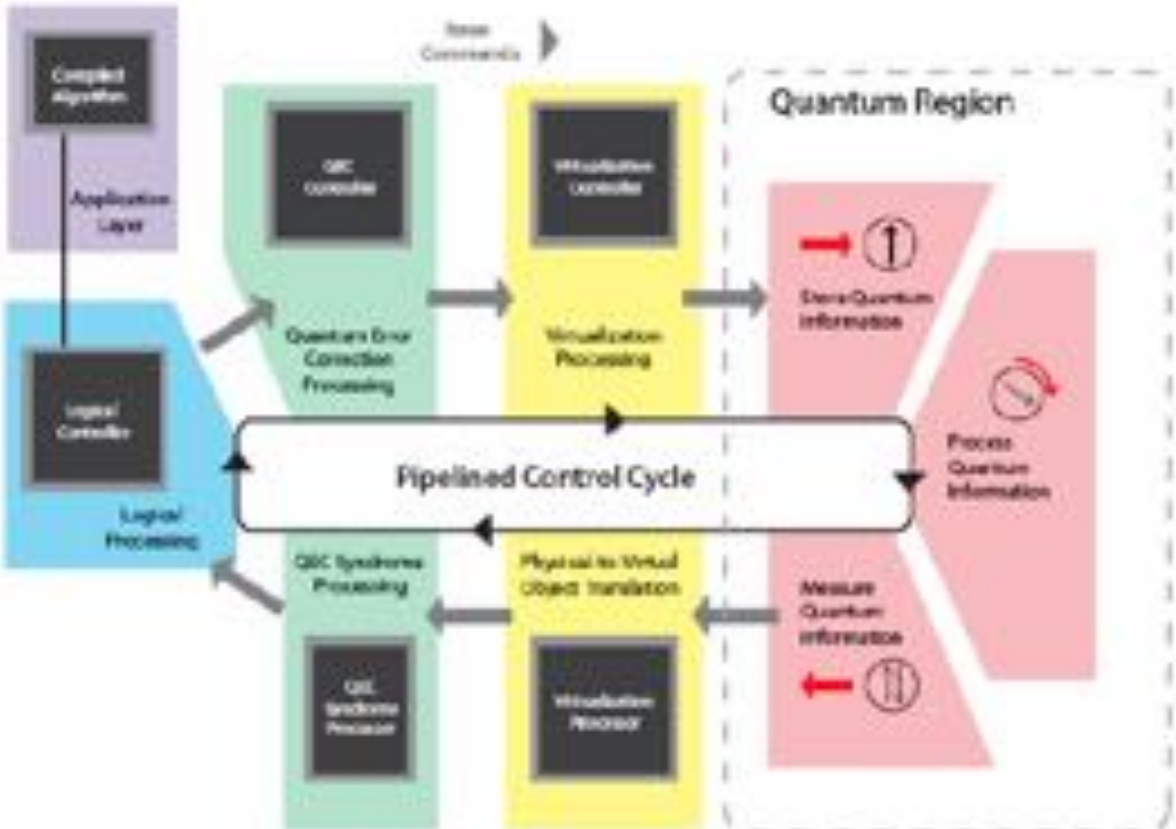
XXXX (phase) parity

First ever demonstration:
mean of correct probability = **0.774/0.795**

IARPA LogiQ program: first Logical Qubit (just begun)

Corcoles et.al., Nature Communications **6**, (2015)

Controlling a Universal Quantum Computer Using Surface Code



N. Cody Jones et. al., arXiv:1010.5022 [quant-ph] Oct. 24, 2010

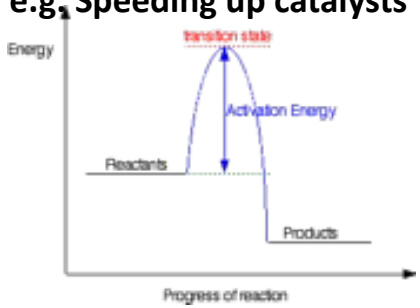
Compilers for Quantum Algorithms

- Examples of quantum languages and compilers:
  - QUIPPR
  - LIQ*Ui*|> - Microsoft
- Approach: take high-level description in C#, F#, etc. and convert to quantum algorithm
- Compilers must preserve quantum rules
  - General rules:
    - States are superpositions
    - Operators are unitary transformations
    - Two-qubit gates cause entanglement
    - Measurement is destructive
    - Cannot copy a quantum state (no cloning theorem of quantum mechanics)
  - Must know group theory of gates
- Optimizing compilers are a work in progress
- BUT problems may need mapping before compiling…

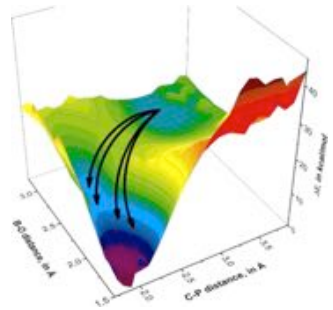
Example: Solve Quantum Chemistry Problems

Goal: Analog simulation for the **electronic structure problem**

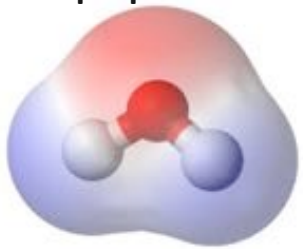
Reaction rates
e.g. Speeding up catalysts



Reaction pathways



Molecule geometry
e.g. H2O bond properties

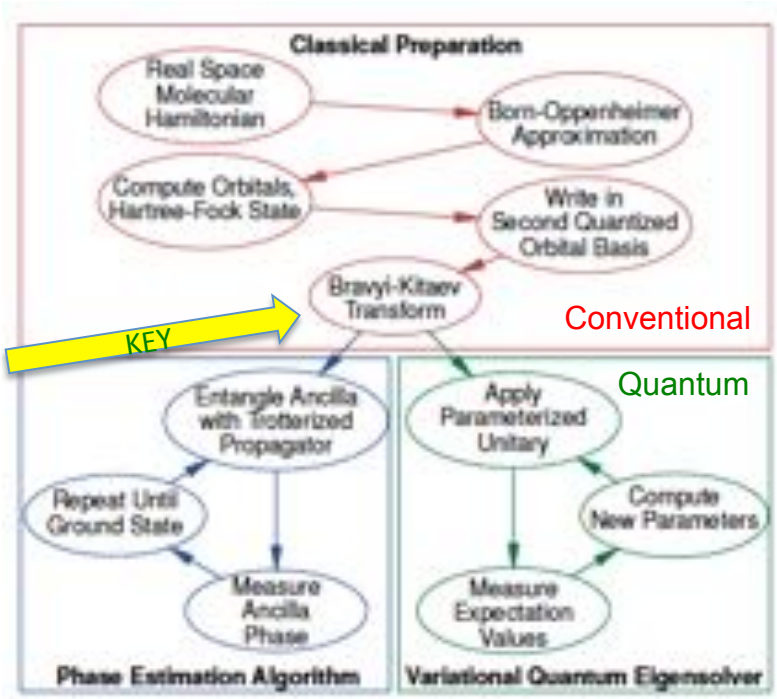


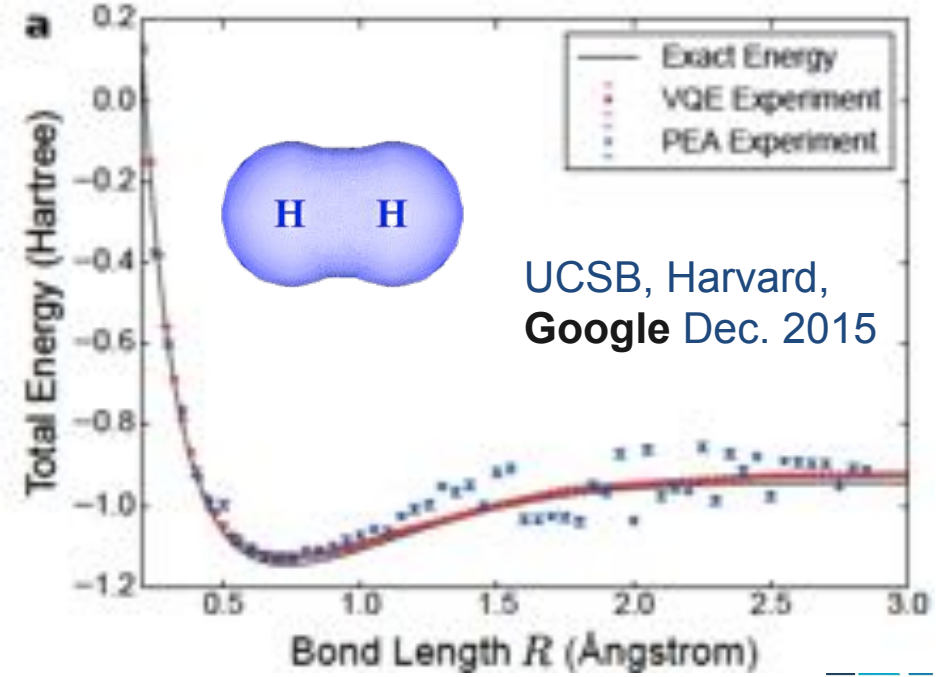
$|\psi(\theta)\rangle$

$$E_{min} = \min_{\theta} \langle \psi(\theta) | H | \psi(\theta) \rangle$$

Approach for Solving Quantum Chemistry Problems

1. Map electronic quantum states of atom to qubit quantum states
2. Run digital (or analog) quantum simulator to find answer in qubit basis
3. Transform back to original atomic quantum state representation

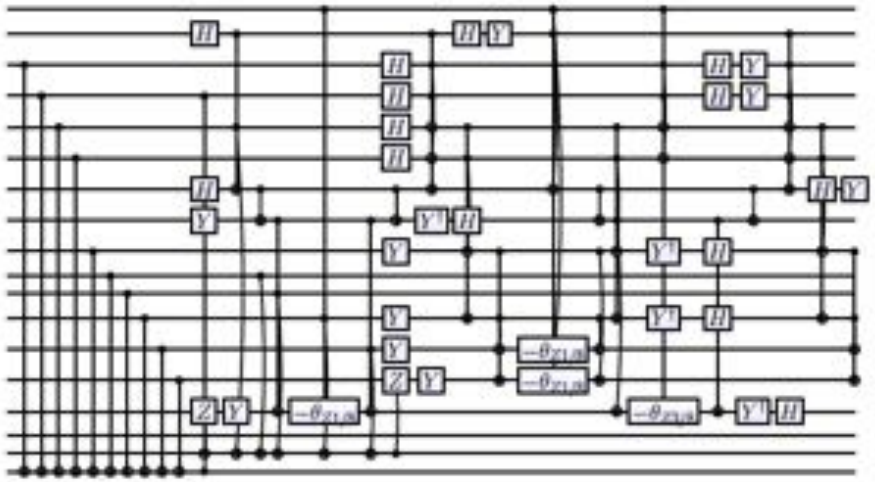




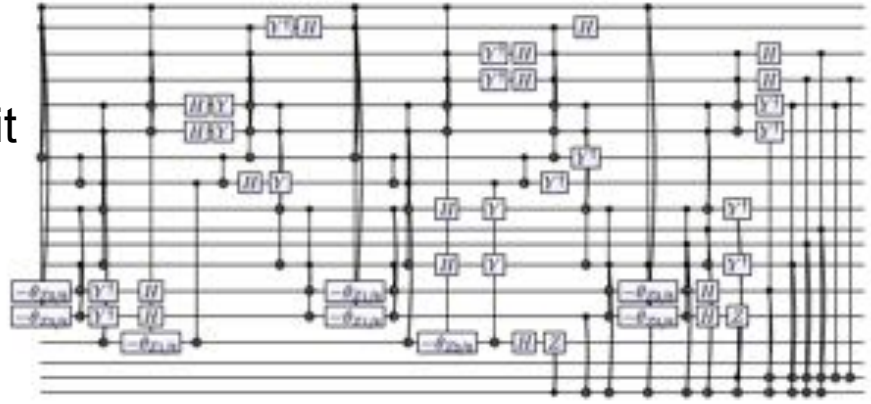
S. Bravyi and A. Kitaev, Annals of Physics, 298, 210 (2002),

Optimization Is Important !

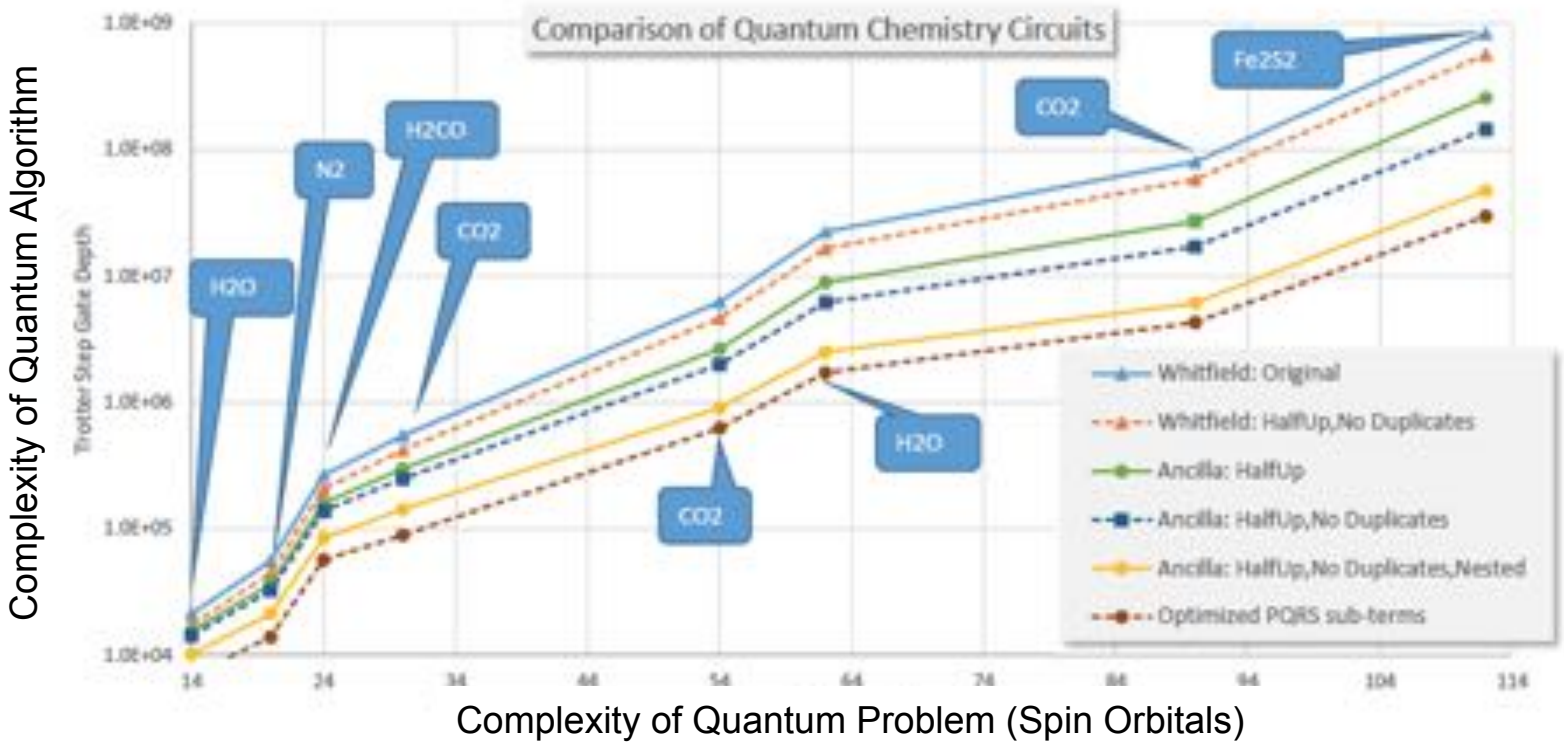
Original circuit



Optimized circuit



Hastings, Wecker, Bauer, Troyer, “Improving Quantum Algorithms for Quantum Chemistry,” 2014 (arXiv: 1403.1539v2)



Troyer: there are problems that we believe can be solved with a universal quantum computer which we cannot be solved in a reasonable time by any conventional computer.

Hastings, Wecker, Bauer, Troyer, “Improving Quantum Algorithms for Quantum Chemistry,” arXiv:1403.1539v2 [quant-ph] 23 Mar 2014

Closing Speculations and Assertions

- The first quantum simulations solving intractable problems ~ 5 years
  - Molecular
  - Fermionic quantum problems (engineer superconductors)
  - Etc.

  These are the problems that Feynman envisioned.
- We will be able to build a universal quantum computer
  - We do not know when– certainly more than 10 years because of complexity
- When we have a small universal computer, it will spur new algorithms
- The ultimate technology will look very different than what we have today