

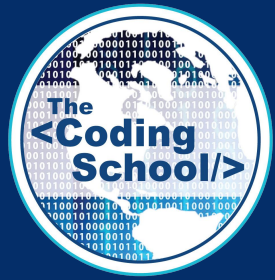
INTRO TO QUANTUM COMPUTING

LECTURE #24

Near-term Quantum Algorithms

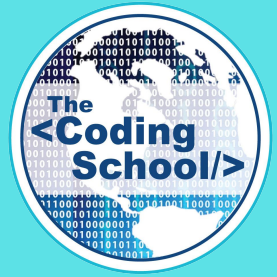
Amir Karamlou

05/02/2021



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ANNOUNCEMENTS

THE QUANTUM ALGOS LANDSCAPE

Deutsch-Jozsa

First theoretical demonstration of quantum advantage!



Uses an Oracle

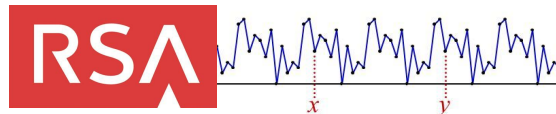
$$O(1) \ll O(2^n)$$

Exponential Quantum Speedup!

QUANTUM ADVANTAGE

Shor's Algorithm

Super-polynomial speedup for factoring using the QFT!



Cracking RSA Requires Factoring & Period Finding



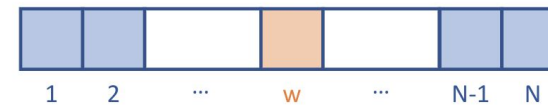
The Quantum Fourier Transform Encodes Frequency in Phase

$$O(\log(n)^3) \ll O(n^{1.9})$$

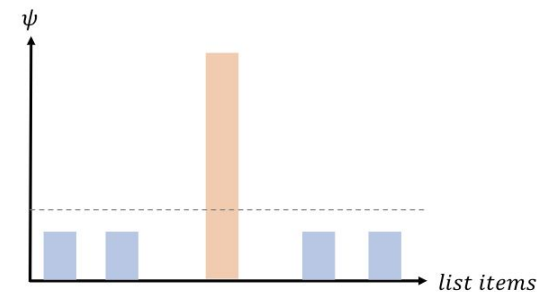
Super-Polynomial Quantum Speedup!

Grover Search

Quadratic speedup for search using amplitude amplification!



Unstructured Search



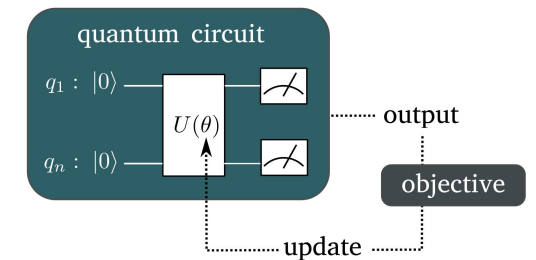
Leverages Amplitude Amplification

$$O(\sqrt{n}) \ll O(n)$$

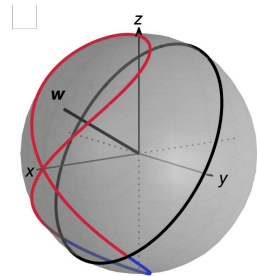
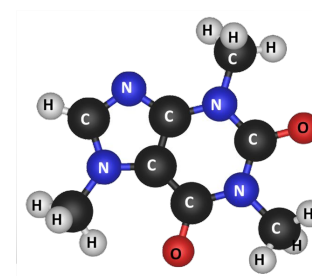
Quadratic Quantum Speedup!

Near-Term Algos

Applications of noisy, small available quantum devices!



Hybrid Quantum-Classical Algos



Using Quantum to Solve Important Problems!

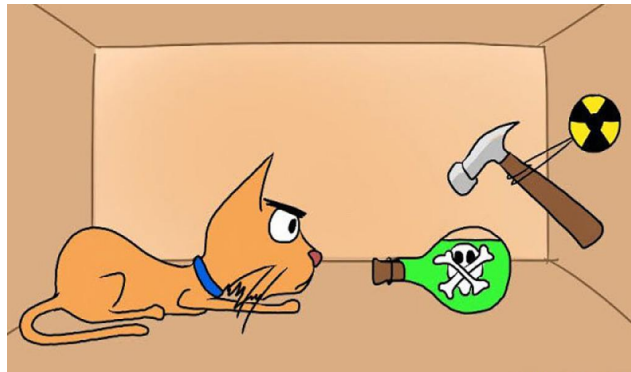
How to program a quantum computer today

- The error in present day quantum computers get out of hand for large quantum circuits
- Largest number factored using Shor's algorithm: 35
- We can't run any of the algorithms discussed without error correction for a meaningful instance
- Near-term algorithms take these restrictions into account when programming a quantum computer

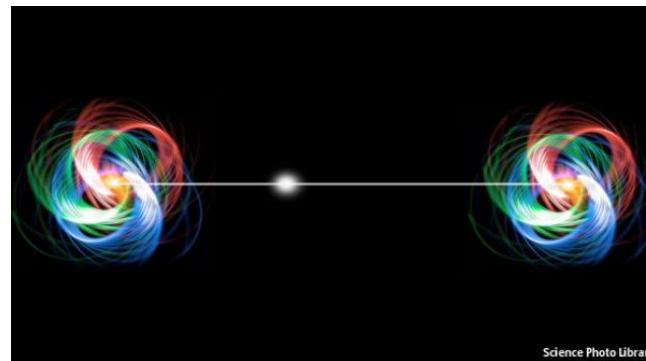
What do we need for running algorithms

- Many qubits
- Either with no noise (error), or error-corrected
- And:

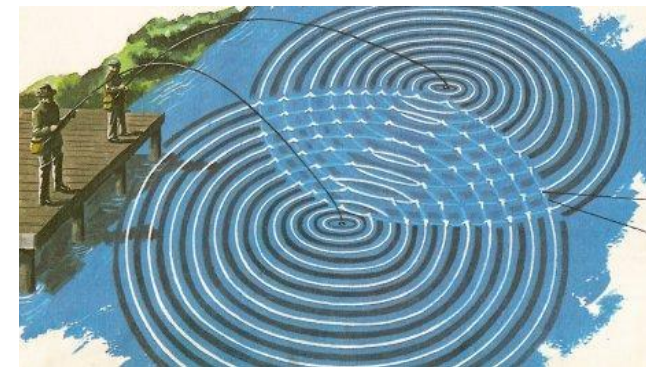
SUPERPOSITION



ENTANGLEMENT

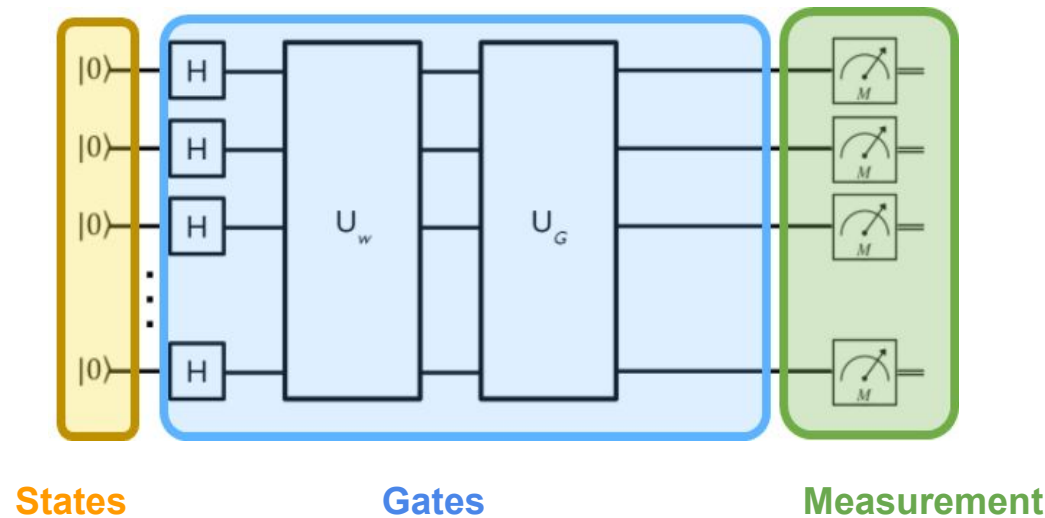


QUANTUM INTERFERENCE



Properties of a Quantum Computer

- Enough* qubits to run algorithms
- A way to fix errors if they occur
- A set of gates that are “universal”
- Capability to readout the state at the end of the algorithm



Motivation

What we want for quantum computing:

- No errors (no noise, error correction, perfect gates)
- No limitations on the number of qubits
- No limitations on the number of gates (circuit depth)

What we have:

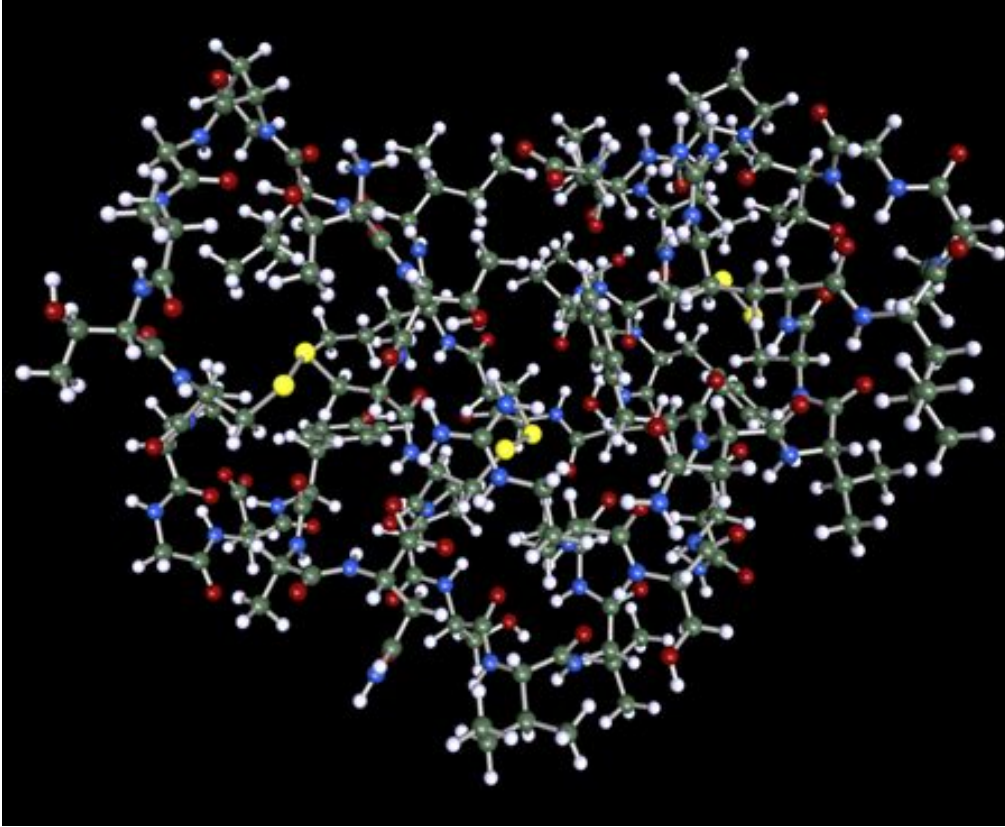
- Limited number of qubits (50-200)
- No error correction -> limited circuit depth
- Known as “noisy intermediate-scale quantum (**NISQ**)” or simply “Near-term quantum” devices

State of the art quantum processor

Today's state of the art quantum computers:

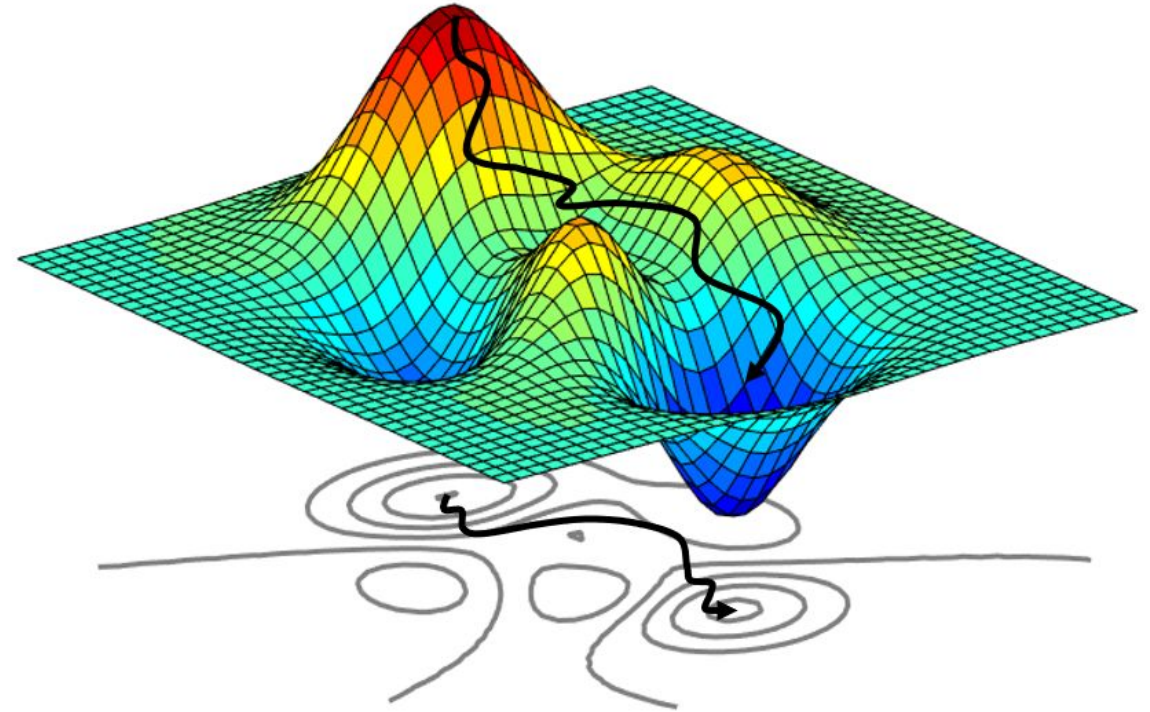
- Superconducting quantum processors
- Number of qubits: 50-100
- T_1 , T_2 ~ 50-100 microseconds
- two-qubit gate fidelity: 99.4%
- No demonstration of useful quantum advantage

What can we do with near-term computers?



Find the most stable configuration of a molecule

Use cases: medicine, farming, material design



Better optimizing complex problems

Use cases: finance, scheduling, machine learning



Classical-Quantum hybrid algorithm

Idea: Let's combine the small quantum computers that we have with the classical processing power that's available to gain an advantage!

Step into our Classical-Quantum Factory



This is the stuff they
don't show in
Despicable Me...

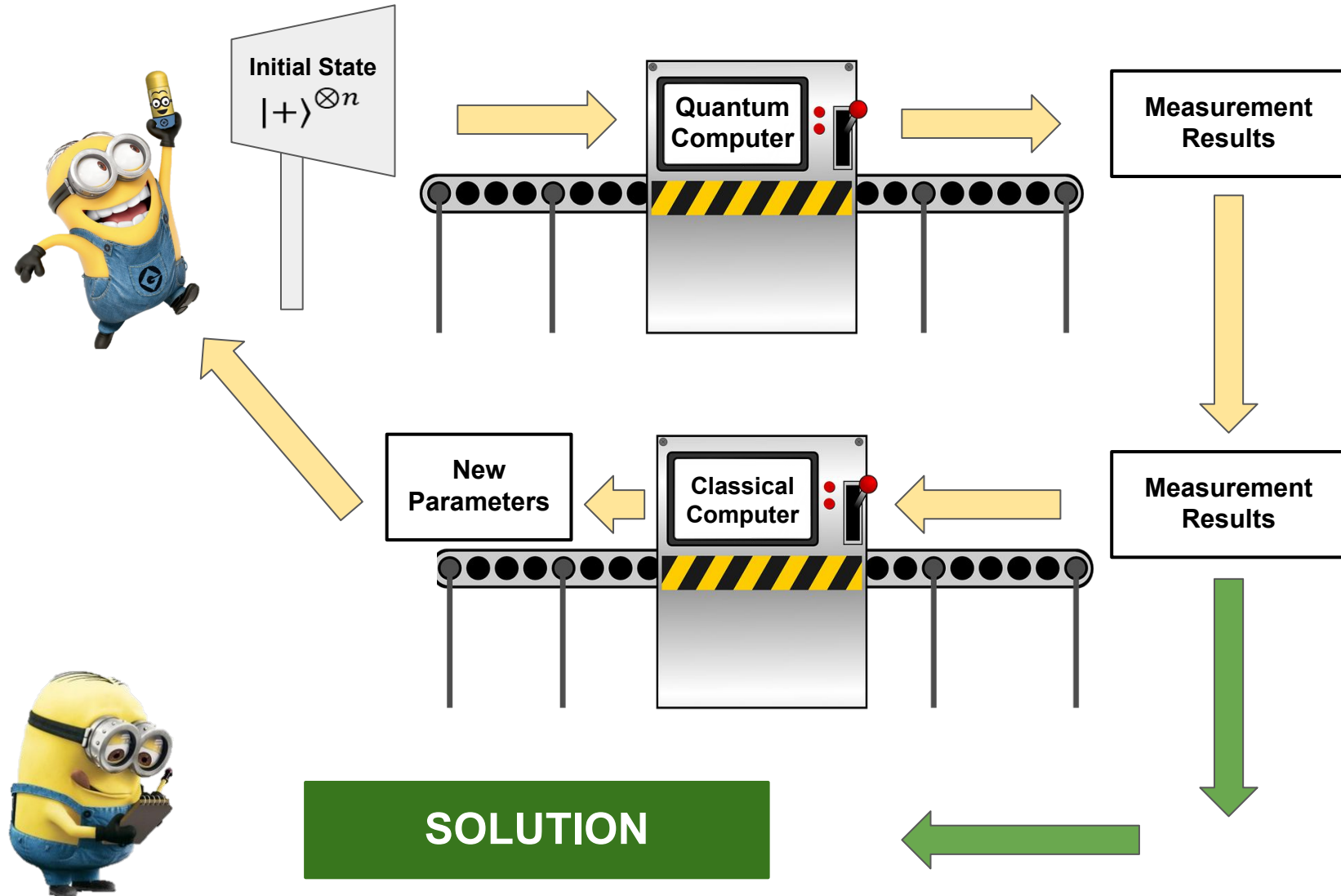


Step into our Classical-Quantum factory

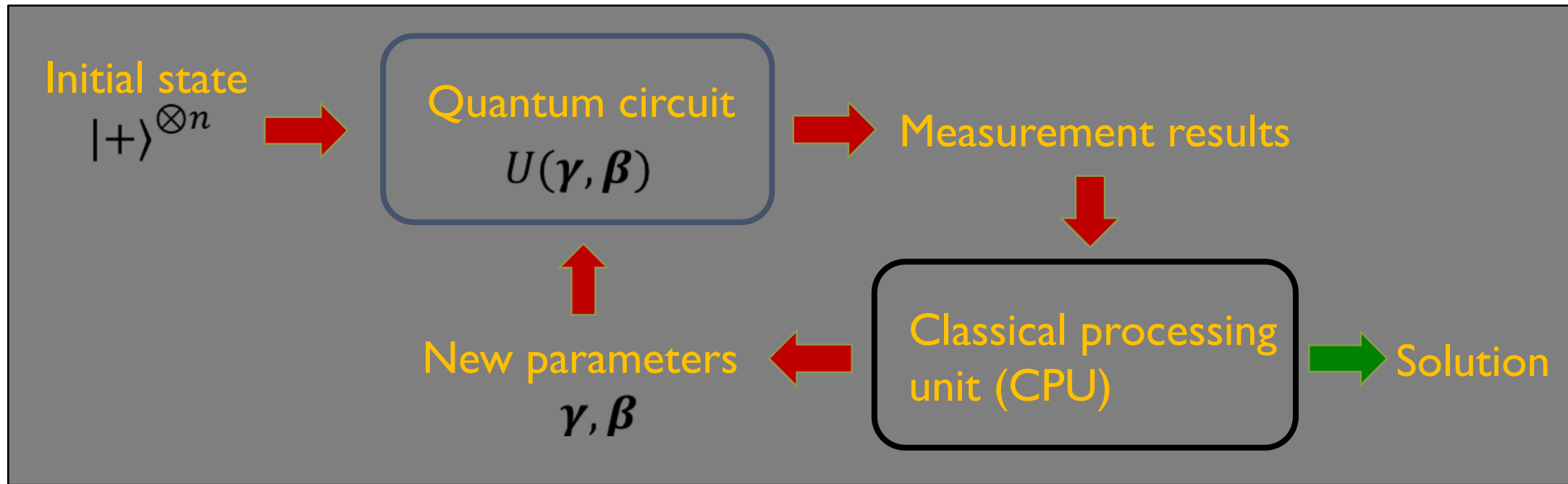
QC: quantum computer
CC: classical computer

- **QC:** run your quantum circuit
- **QC:** send the results of your circuit to CC
- **CC:** figure out how to modify the circuit
- **CC:** send new instructions to QC

Repeat!

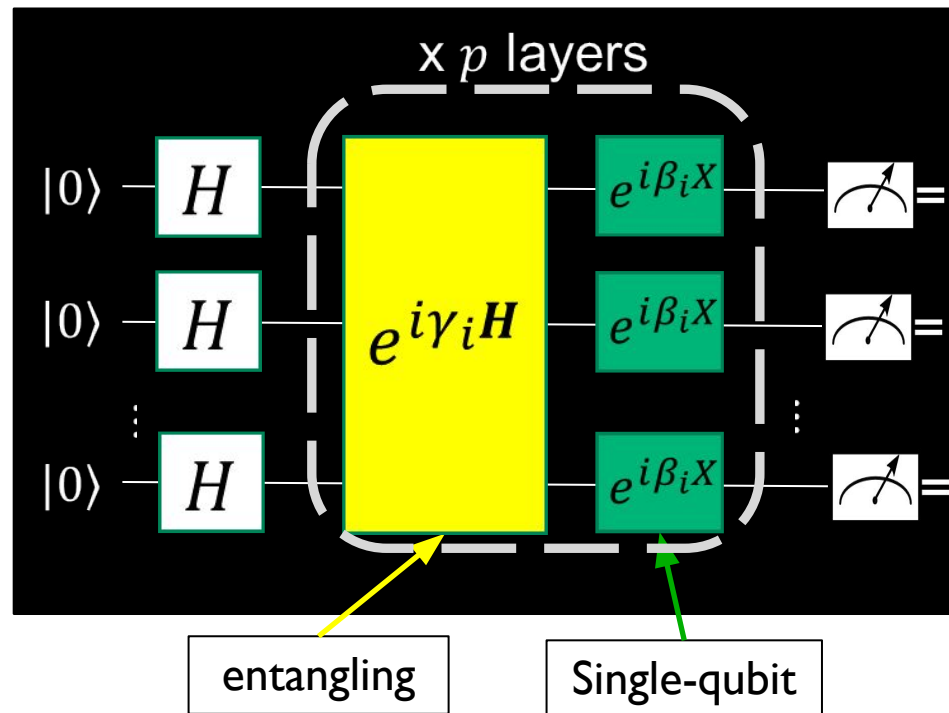


The workflow

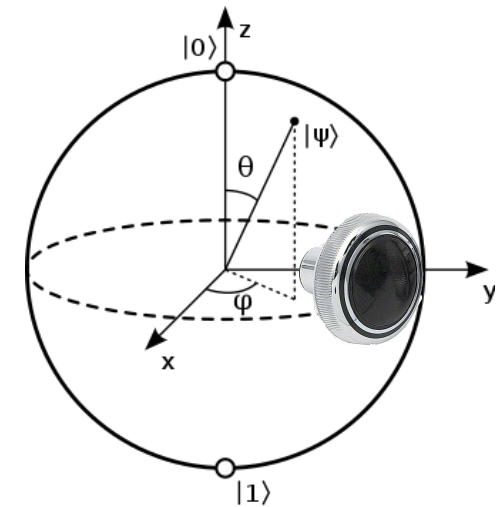


Variational quantum circuits

idea: Let's use “tunable” (variational) quantum circuits



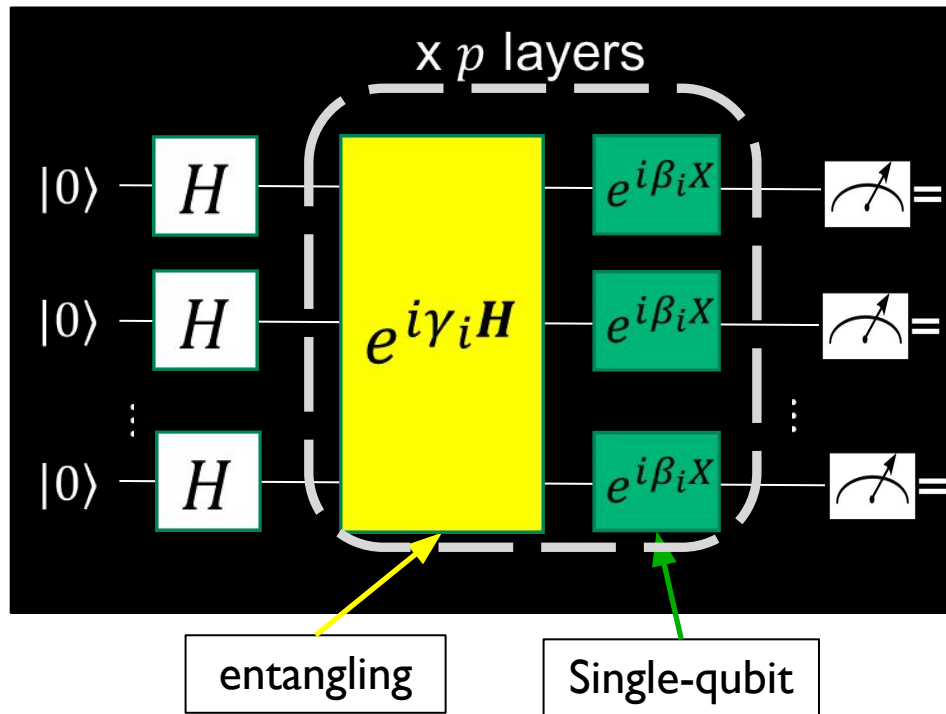
We have noisy qubits and gates, so we try to compensate by adding tunable parameters



Variational quantum circuits

The tunable circuit template is called an ansatz

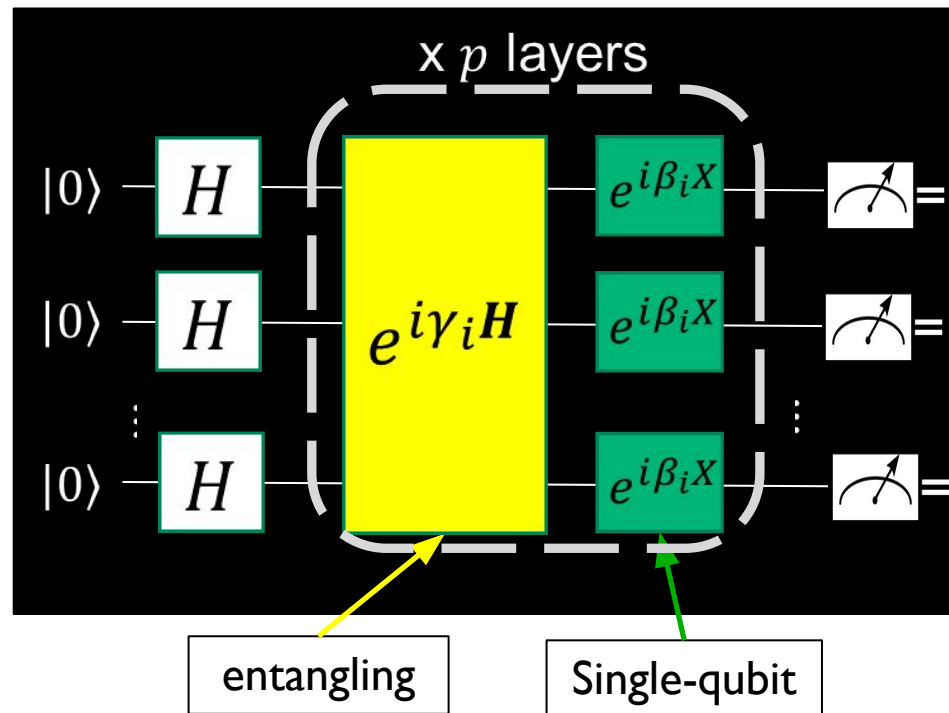
We fill in the template with our choice for the tunable parameters!



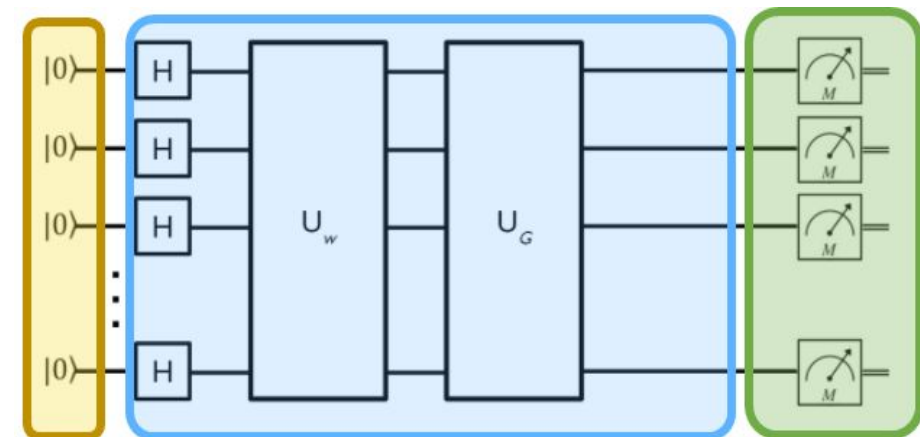
Variational quantum circuits

The circuit for Grover's was pre-fixed

But we can change the parameters of the variational circuits



Similar to Grover's algorithm circuit:



The tunable circuit template is called an ansatz

Classical-Quantum hybrid algorithms

Few notes:

- Variational circuits are a heuristic approach, trying to imitate amplitude amplification
- Not every variational circuit is created equal
 - expressibility: how many different quantum states can we produce with our ansatz
- The art of variational classical-quantum algorithms is coming up with good ansatz

Classical-Quantum hybrid algorithms

Two famous variational algorithms:

- Variational Quantum Eigensolver (VQE)
 - Used for continuous systems (e.g. chemistry simulations)
- Quantum Approximate Optimization Algorithms (QAOA)
 - Used for combinatorial optimization

Recent breakthroughs!

ARTICLE

Received 9 Dec 2013 | Accepted 27 May 2014 | Published 23 Jul 2014

DOI: 10.1038/ncomms5213

OPEN

A variational eigenvalue solver on a photonic quantum processor

Alberto Peruzzo^{1,*†}, Jarrod McClean^{2,*}, Peter Shadbolt¹, Man-Hong Yung^{2,3}, Xiao-Qi Zhou¹, Peter J. Love⁴, Alán Aspuru-Guzik² & Jeremy L. O'Brien¹

LETTER

doi:10.1038/nature23879

Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets

Abhinav Kandala^{1*}, Antonio Mezzacapo^{1*}, Kristan Temme¹, Maika Takita¹, Markus Brink¹, Jerry M. Chow¹ & Jay M. Gambetta¹

PHYSICAL REVIEW X **6**, 031007 (2016)

Scalable Quantum Simulation of Molecular Energies

P. J. J. O'Malley^{1,*}, R. Babbush^{2,†}, I. D. Kivlichan³, J. Romero³, J. R. McClean⁴, R. Barends⁵, J. Kelly⁵, P. Roushan⁵, A. Tranter^{6,7}, N. Ding², B. Campbell¹, Y. Chen⁵, Z. Chen¹, B. Chiaro¹, A. Dunsworth¹, A. G. Fowler⁵, E. Jeffrey⁵, E. Lucero⁵, A. Megrant⁵, J. Y. Mutus⁵, M. Neeley⁵, C. Neill¹, C. Quintana¹, D. Sank⁵, A. Vainsencher¹, J. Wenner¹, T. C. White⁵, P. V. Coveney⁷, P. J. Love⁶, H. Neven², A. Aspuru-Guzik³ and J. M. Martinis^{5,1,‡}

LETTER

<https://doi.org/10.1038/s41586-019-1040-7>

Error mitigation extends the computational reach of a noisy quantum processor

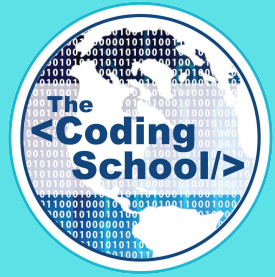
Abhinav Kandala^{1*}, Kristan Temme¹, Antonio D. Córcoles¹, Antonio Mezzacapo¹, Jerry M. Chow¹ & Jay M. Gambetta¹

QUANTUM COMPUTING

Hartree-Fock on a superconducting qubit quantum computer

Google AI Quantum and Collaborators^{*†}

The simulation of fermionic systems is among the most anticipated applications of quantum computing. We performed several quantum simulations of chemistry with up to one dozen qubits, including modeling the isomerization mechanism of diazene. We also demonstrated error-mitigation strategies based on N -representability that dramatically improve the effective fidelity of our experiments. Our parameterized ansatz circuits realized the Givens rotation approach to noninteracting fermion evolution, which we variationally optimized to prepare the Hartree-Fock wave function. This ubiquitous algorithmic primitive is classically tractable to simulate yet still generates highly entangled states over the computational basis, which allowed us to assess the performance of our hardware and establish a foundation for scaling up correlated quantum chemistry simulations.



10 MIN BREAK!

Quantum Approximate Optimization Algorithm (QAOA)

A variational quantum algorithm used for combinatorial optimization problems

Candy shop problem

What is combinatorial optimization?

Problem: What is the best combination of food items within 300 yen that maximizes the total satisfaction score?
(No food item can be selected more than twice.)

						
Score	5	7	10	3	4	6
Price (yen)	105	170	180	50	130	130



Score	15
Price	285

The optimal solution



Score	17
Price	350

Not a solution, since the total price exceeds 300 yen.

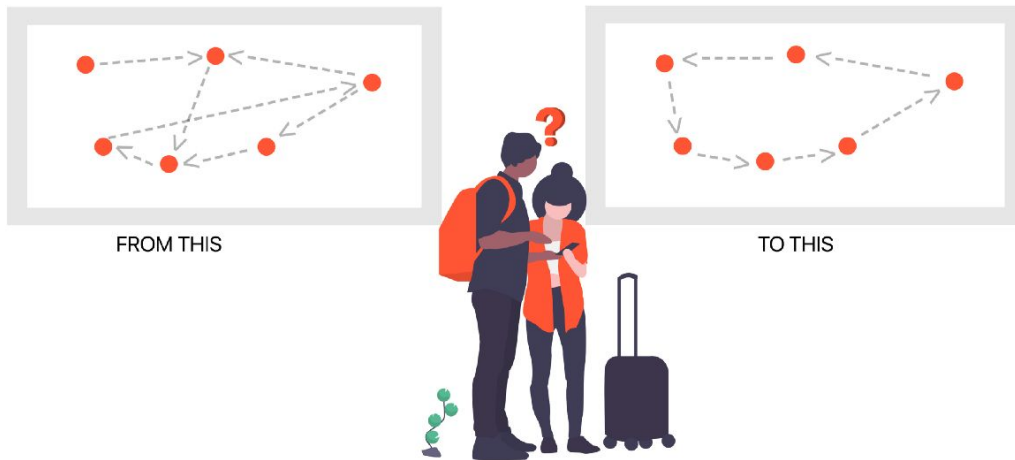


Score	12
Price	285

A feasible solution
(Not optimal)

Optimization in industry

Traveling Salesman Problem



Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?

Nurse Scheduling Problem

	Day 1			Day 2			...	Day 7			Number of shifts
Shifts	M	E	N	M	E	N	...	M	E	N	
Nurse 1							...				6
Nurse 2							...				7
Nurse 3							...				7
Nurse 4							...				7
.....
Nurse J							...				6
Number of nurses assigned	15	18	13	13	18	13	...	13	14	13	314



How can we find an optimal way to assign nurses to shifts within a set of hard and soft constraints, such as allowing no more than two consecutive shifts, considering nurses who are on vacation, and assigning nurses who work well together?

Combinatorial optimization

Let's consider we have:

- n bits
- m clauses (conditions)

Example:

- 3 bits: b_1, b_2, b_3
- 2 clauses:
 - $3*b_1 - 2*b_2 + b_3$
 - $b_1 + b_2 + b_3$

What are some values for b_1, b_2 , and b_3 that minimize the value of the clauses?

Combinatorial optimization

Cost function: tells us what the cost for different values of the bits are

We can define the cost function as the sum of our clauses!

Back to our example:

- 3 bits: b_1, b_2, b_3
- 2 clauses:
 - $3*b_1 - 2*b_2 + b_3$
 - $b_1 + b_2 + b_3$

Cost function: $C(b_1, b_2, b_3) = [3*b_1 - 2*b_2 + b_3] + [b_1 + b_2 + b_3] = 4*b_1 - b_2 + 2*b_3$

Combinatorial optimization

Goal: find values for the bits (b1,b2,b3) that minimize (or maximizes) the value of the cost function!

How can we do it?

One idea: Let's try every single combination of 0s and 1s

Problem: The problem grows exponentially with the number of bits :(

QAOA is a heuristic quantum algorithm for tackling this problem!

Back to the Classical-Quantum Factory



The Classical-Quantum Factory just hired a new team of purple minions. The problem? The purple and yellow minions do not speak the same language. **They cannot understand each other.**

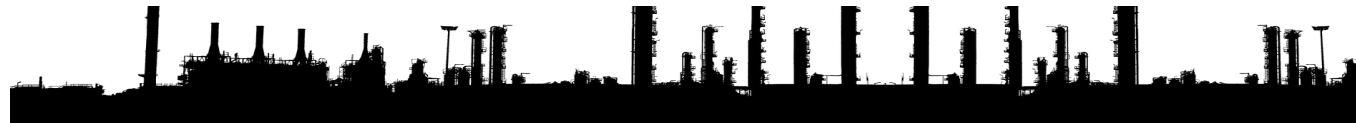


Back to the Classical-Quantum Factory



Once they were given **translating devices**,
both teams could work together!

Like teams of minions, we can translate between classical bits and qubits.



Translating from bits to qubits

We need to “translate” the problem from classical bits to qubits

Let’s map the value of a bit to an operator for a qubit

Using this mapping we can turn a classical cost function into a quantum Hamiltonian, which a quantum computer understands

Translating from bits to qubits

Let's map the value of a bit to an operator for a qubit

$$b_k \mapsto \frac{1}{2}(1 - Z_k)$$

Translating from bits to qubits

Example: $C = b_1 * b_2$

$$b_k \mapsto \frac{1}{2}(1 - Z_k)$$

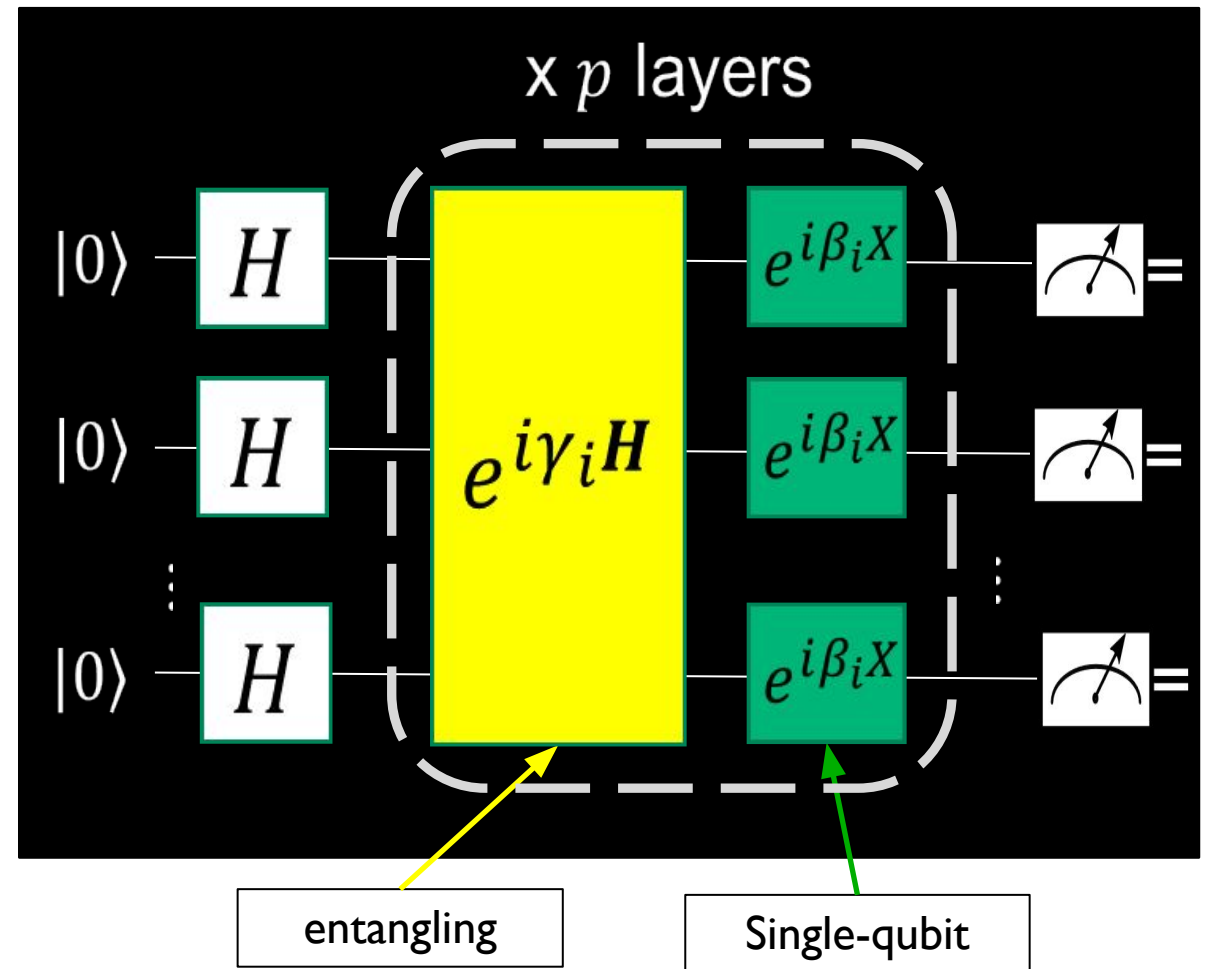
Translating from bits to qubits

Example: $C = b_1 \text{ xor } b_2$

$$b_k \mapsto \frac{1}{2}(1 - Z_k)$$

QAOA circuit

1. Map cost function to a Hamiltonian H
2. Entangling unitary of the template (ansatz)
3. Single-qubit unitary of the template (ansatz)
4. Measurement

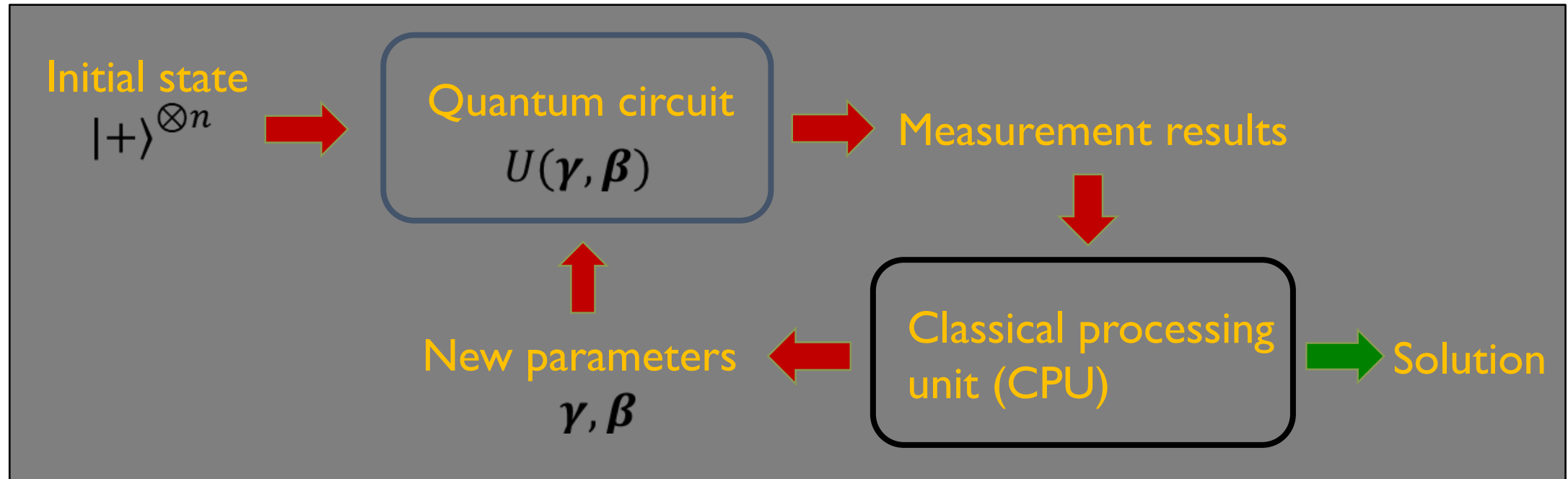


QAOA

How to make the entangling layer using our gates?

QAOA workflow

Find the optimal parameters that minimize the expected value of the cost Hamiltonian:



This is an active area of research!!

A Quantum Approximate Optimization Algorithm

Edward Farhi and Jeffrey Goldstone

Center for Theoretical Physics

Massachusetts Institute of Technology

Cambridge, MA 02139

Sam Gutmann

ARTICLES

<https://doi.org/10.1038/s41567-020-01105-y>

nature
physics

 Check for updates

Quantum approximate optimization of non-planar graph problems on a planar superconducting processor

Quantum approximate optimization is computationally universal

Seth Lloyd

Departments of Mechanical Engineering and Physics

Massachusetts Institute of Technology

Xanadu

Analyzing the Performance of Variational Quantum Factoring on a Superconducting Quantum Processor

Amir H. Karamlou^{1,2,*}, William A. Simon^{1,*}, Amara Katabarwa¹,

Travis L. Scholten³, Borja Peropadre¹, and Yudong Cao^{1,†}

¹Zapata Computing, Boston, MA 02110 USA

²Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA and

³IBM Quantum, IBM T. J. Watson Research Center, Yorktown Heights, NY 10598

(Dated: March 11, 2021)

Looking forward

Want to learn more?

- The original QAOA paper: <https://arxiv.org/abs/1411.4028>
- QAOA in the Qiskit Textbook: <https://qiskit.org/textbook/ch-applications/qaoa.html>
- First ever VQE demonstration: <https://www.nature.com/articles/ncomms5213>
- VQE in the Qiskit Textbook: <https://qiskit.org/textbook/ch-applications/vqe-molecules.html>

Looking forward

What's next?

- Variational circuits can be executed on near-term quantum computers
- Use your knowledge to design and execute your own variational circuit
- Combine your quantum resources with your classical algorithms
- Experiment!

Special thanks to

Our All-Stars!!



Katie



Sarah

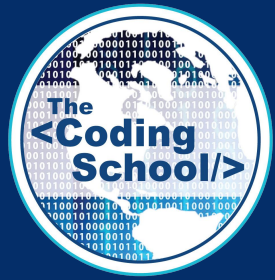


Rachel



Kiera

Welcome to you quantum journey!



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