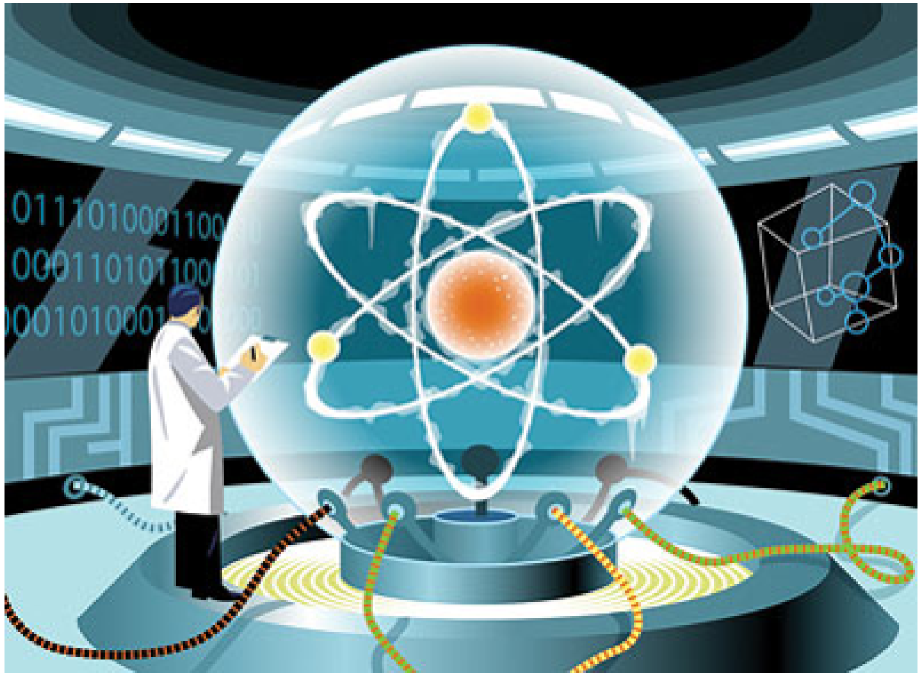
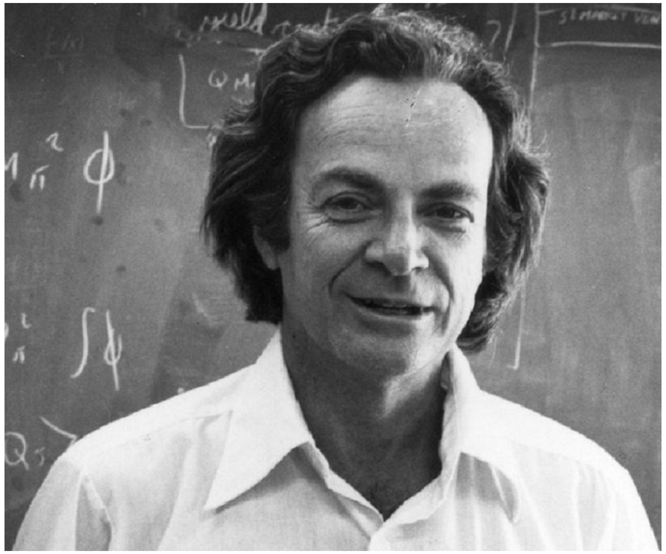
Quantum Computers
Callenges and Applications



Sandy Irani
Computer Science Department
UC Irvine

The Origins of Quantum Computing



"Simulating Physics with Computers"
Richard Feynman

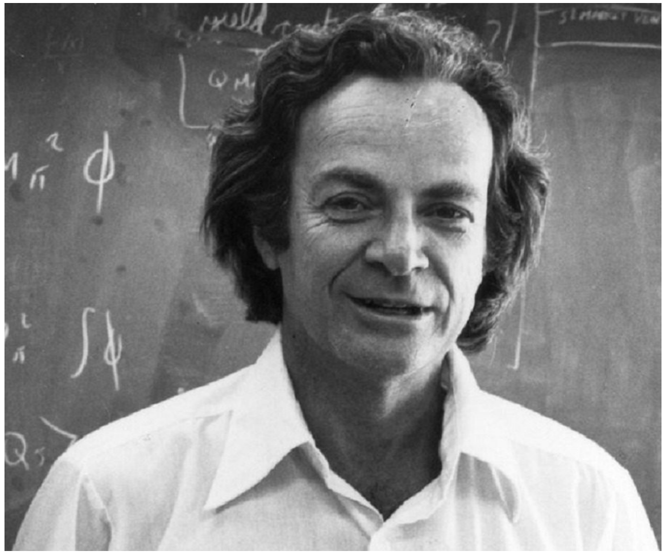
Keynote talk: 1st Conference on Physics and Computation, MIT, 1981

(Image credit: https://www.pma.caltech.edu/content/pma-glance)

The Origins of Quantum Computing

”Simulating Physics with Computers”
Richard Feynman

Keynote talk: 1st Conference on Physics and Computation, MIT, 1981



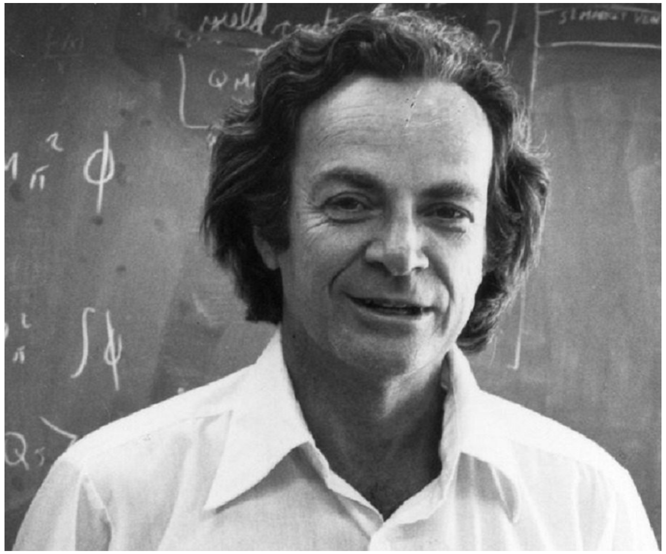
Can classical and/or quantum physics be simulated by a classical computer?

(Image credit: https://www.pma.caltech.edu/content/pma-glance)

The Origins of Quantum Computing

”Simulating Physics with Computers”
Richard Feynman

Keynote talk: 1st Conference on Physics and Computation, MIT, 1981



Can classical and/or quantum physics be simulated by a classical computer?

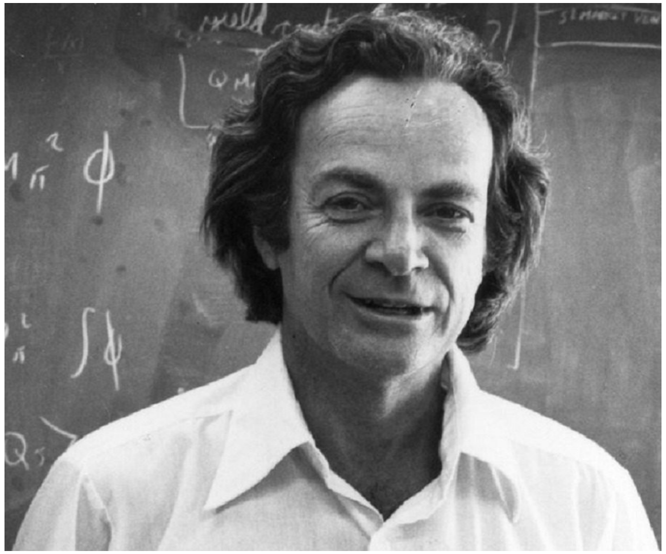
Can quantum physics be simulated by a quantum computer?

(Image credit: https://www.pma.caltech.edu/content/pma-glance)

The Origins of Quantum Computing

"Simulating Physics with Computers"
Richard Feynman

Keynote talk: 1^{st} Conference on Physics and Computation, MIT, 1981



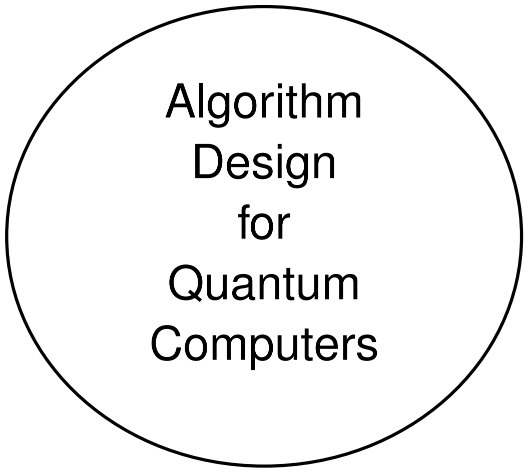
Can classical and/or quantum physics be simulated by a classical computer?

Can quantum physics be simulated by a quantum computer?

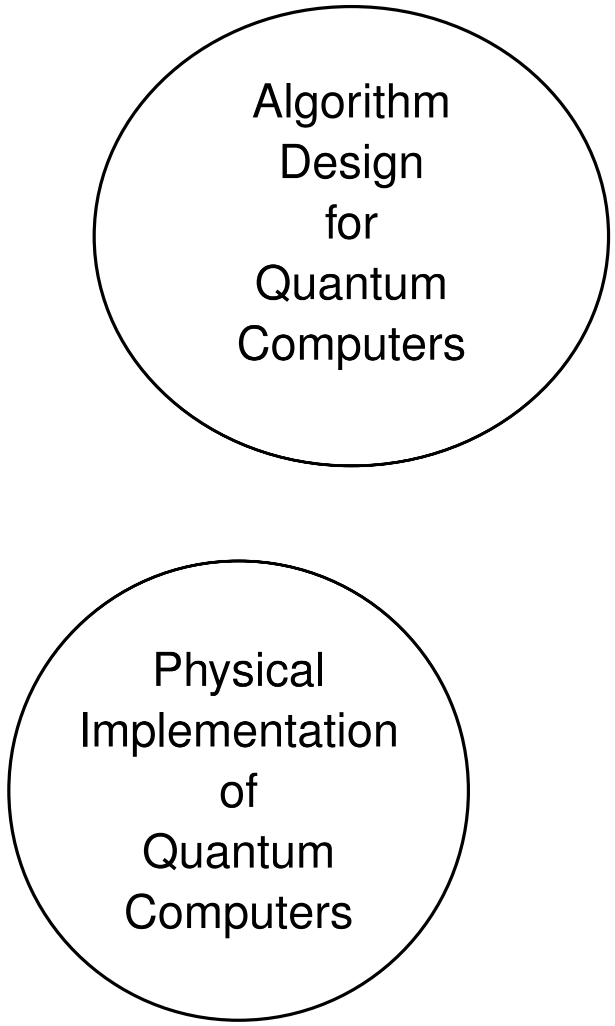
Can a universal quantum simulator be built?

(Image credit: https://www.pma.caltech.edu/content/pma-glance)

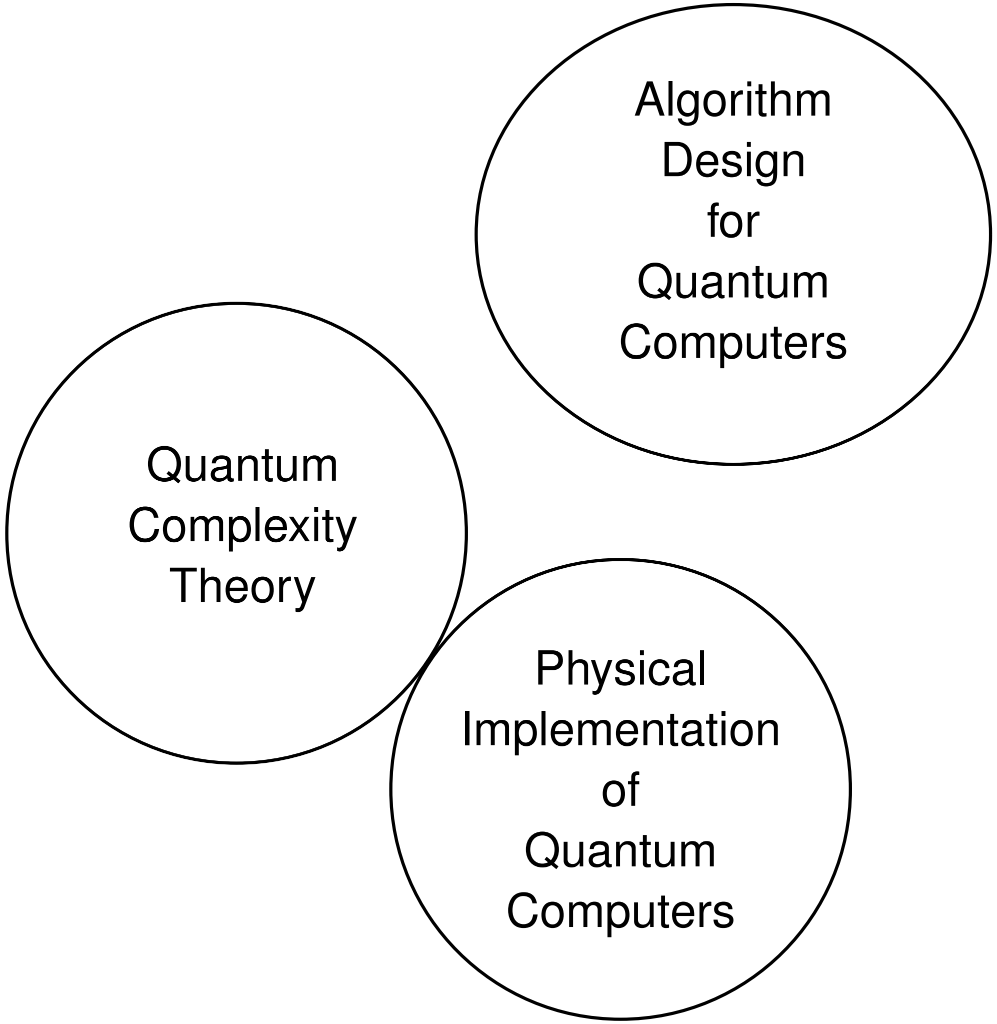
Quantum Computation



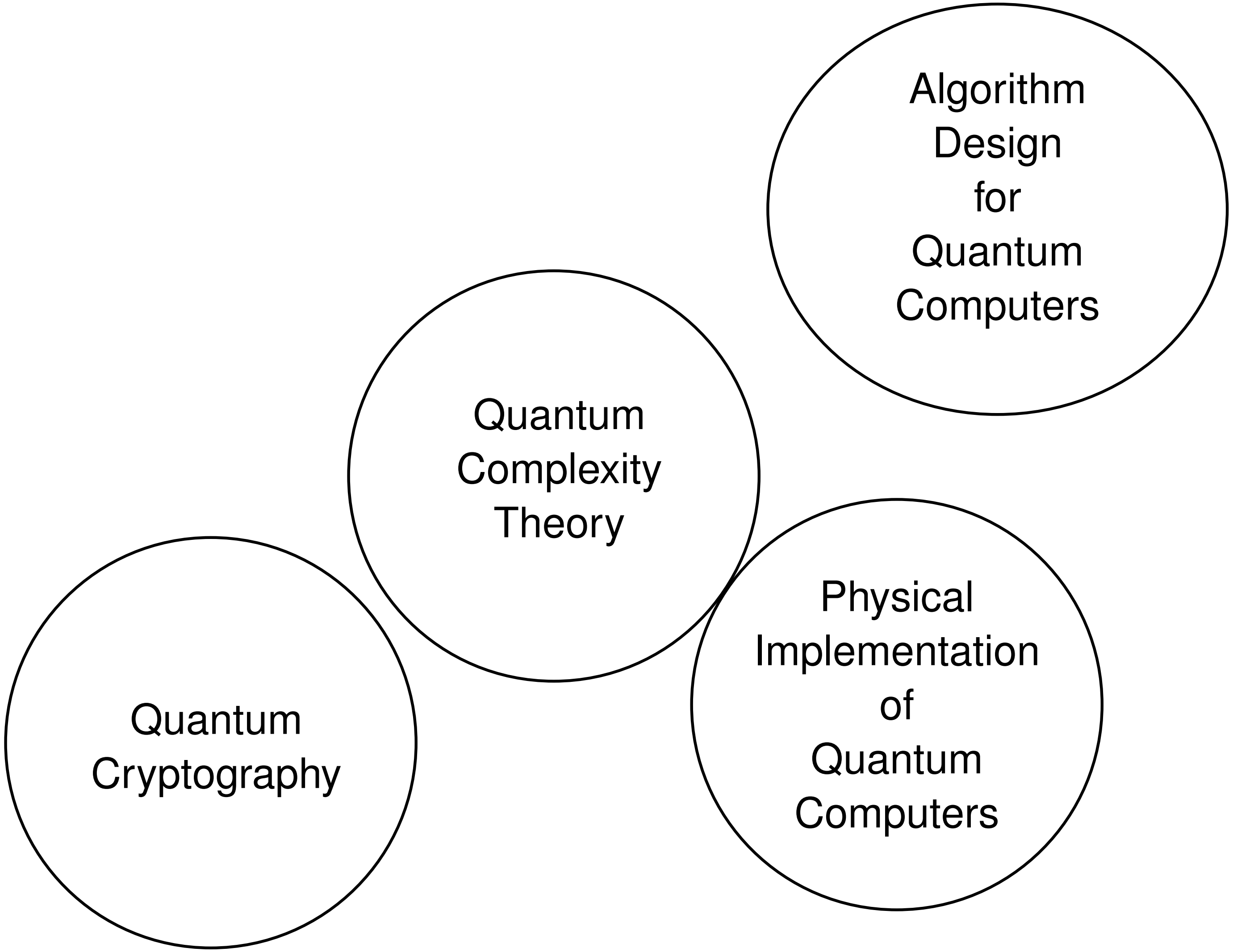
Quantum Computation



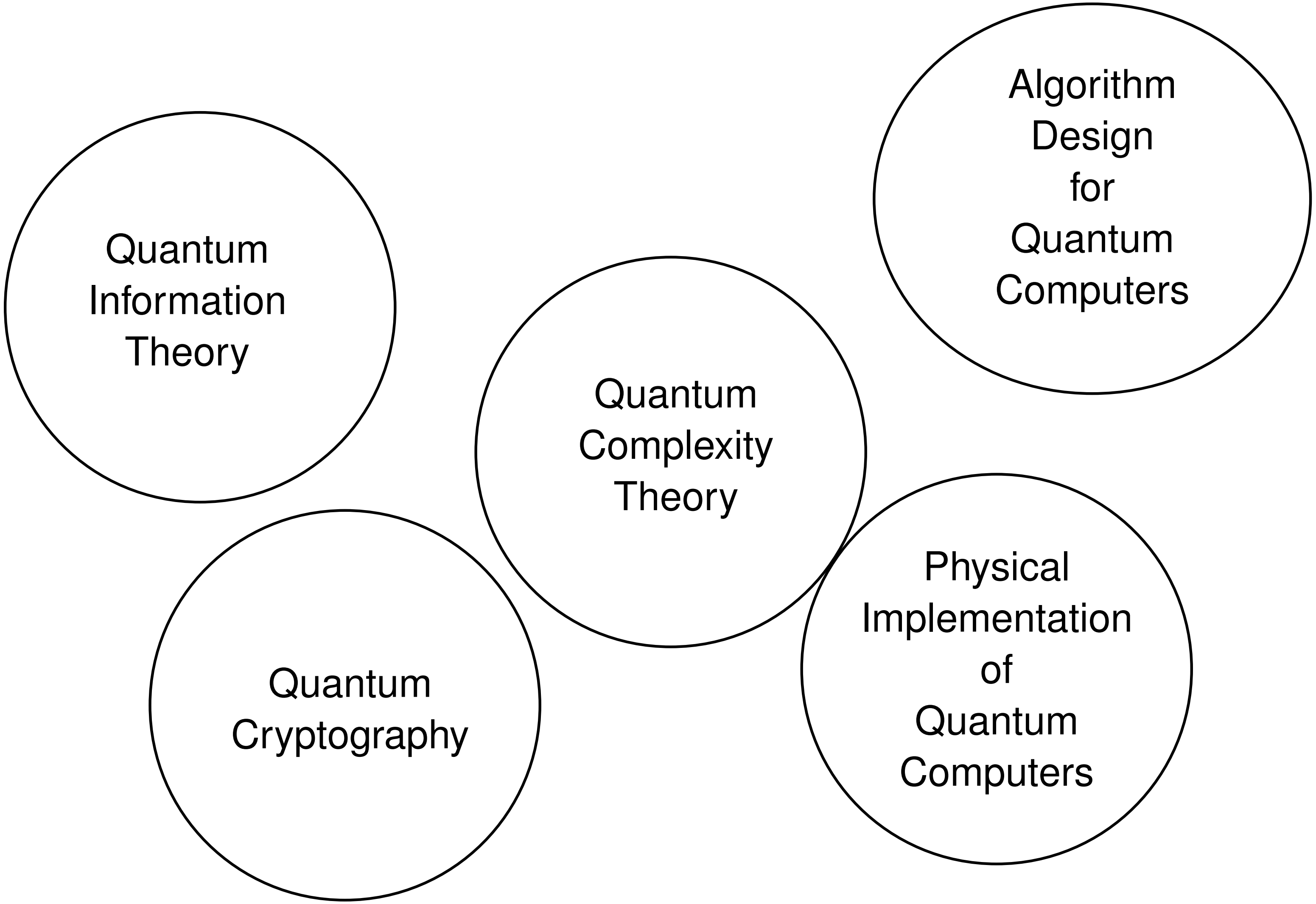
Quantum Computation



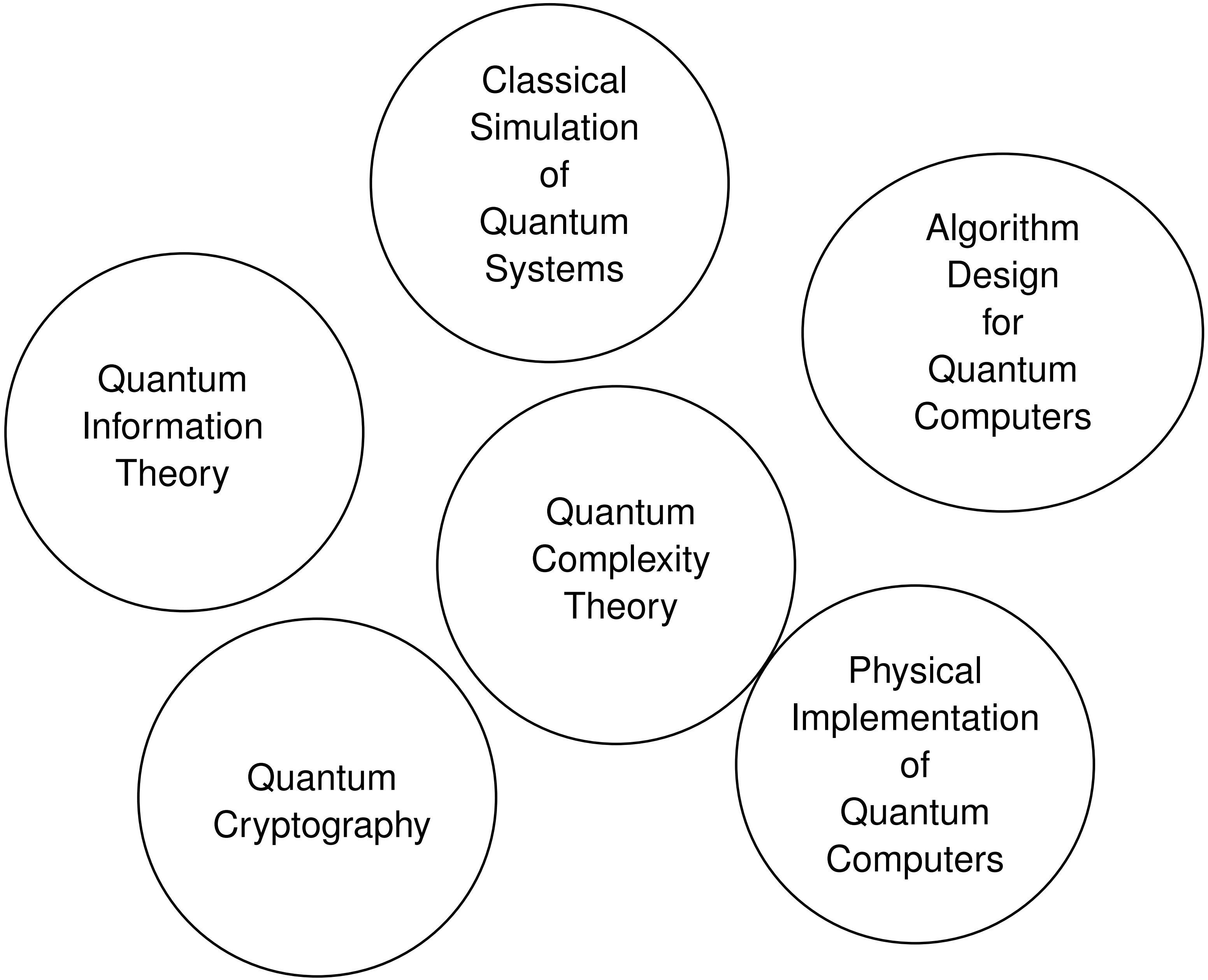
Quantum Computation



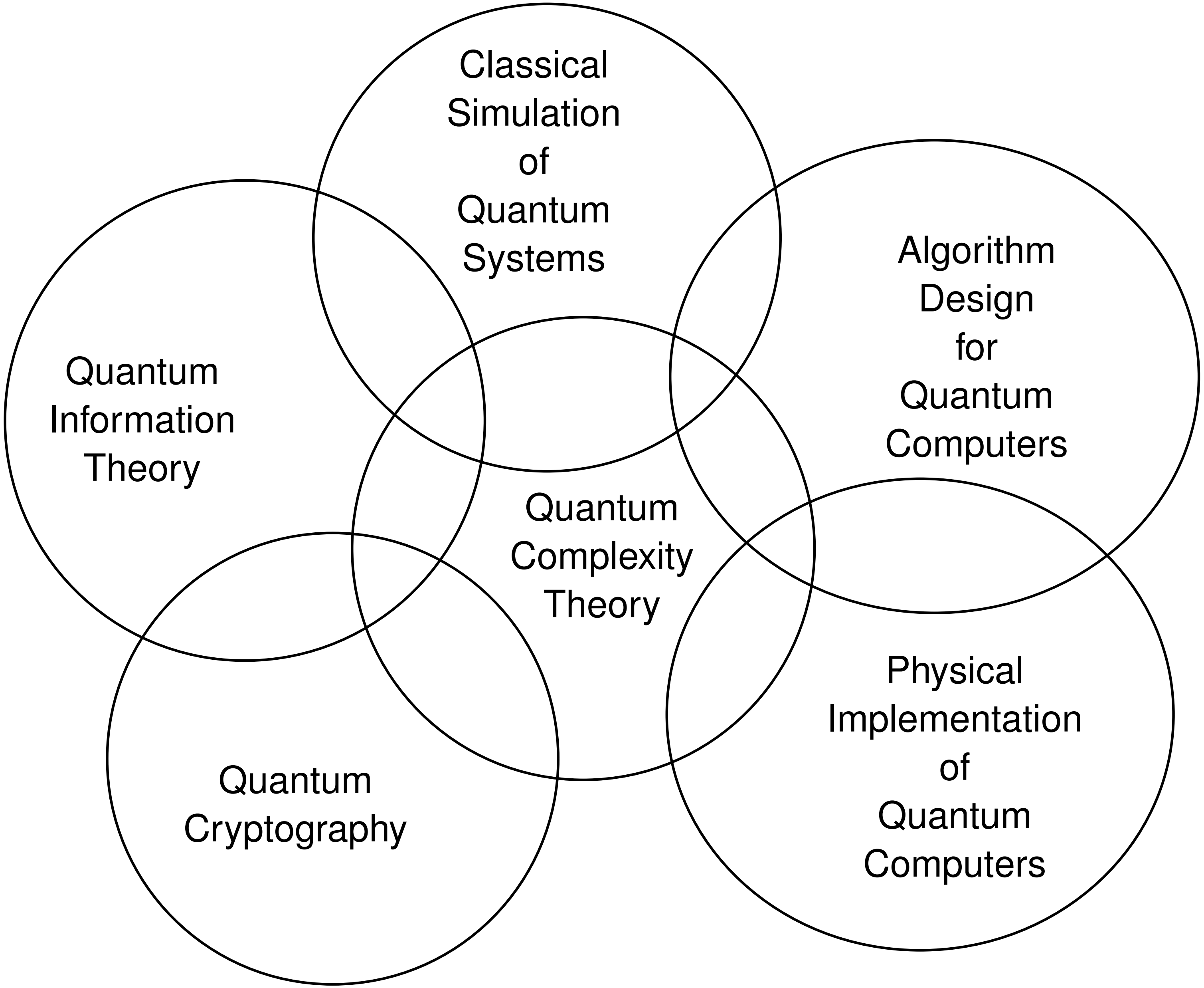
Quantum Computation



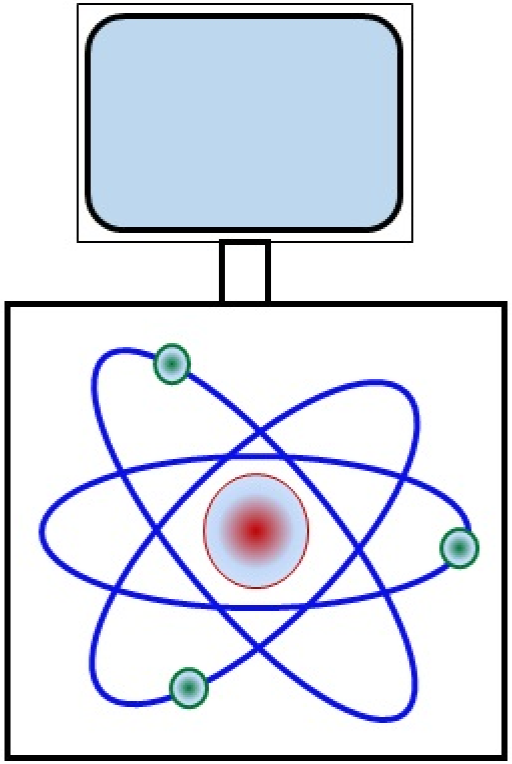
Quantum Computation



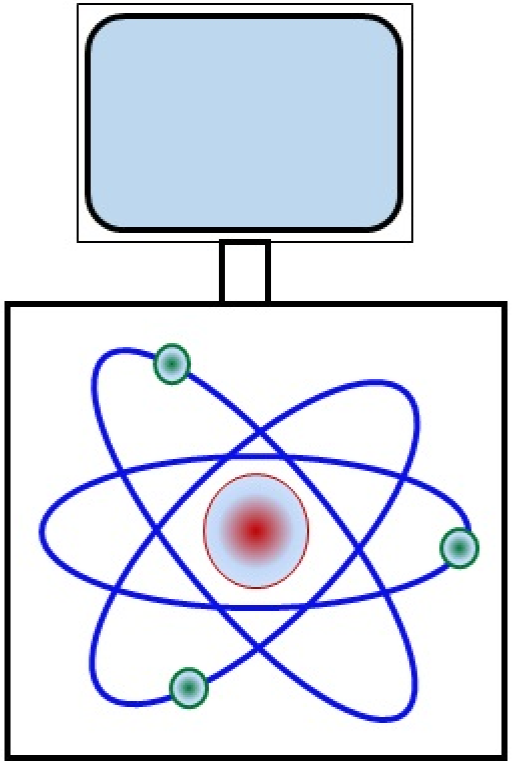
Quantum Computation



What can we compute with a quantum computer?



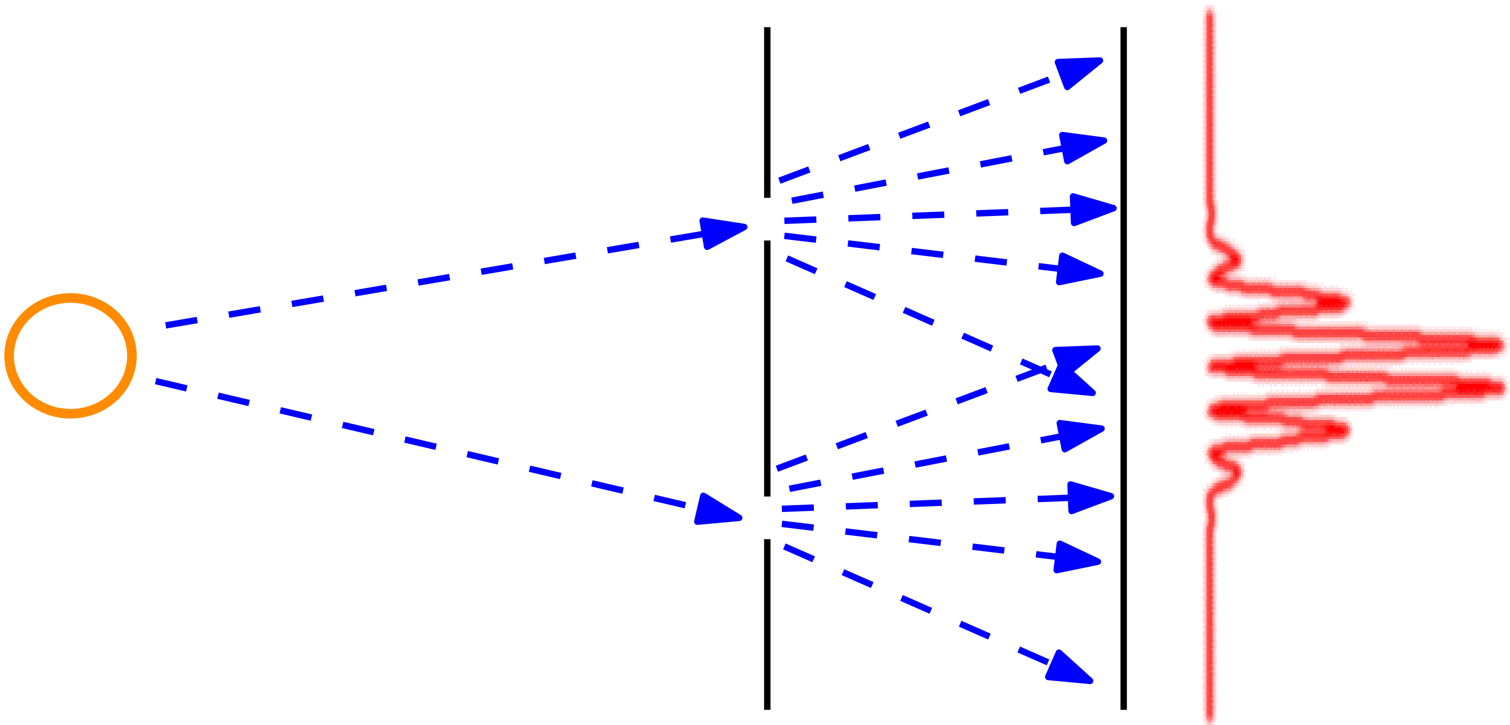
What can we compute with a quantum computer?



Universal QC with error correction

NISQ: Noisy Intermediate-scale Quantum Computer

Quantum Mechanics: "Probability with Minus Signs"



Quantum Information: 1 qubit

A bit of classical information: state is 0 or 1

Quantum Information: 1 qubit

A bit of classical information: state is 0 or 1

A quantum bit can be partially in state $|0\rangle$ and state $|1\rangle$:

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

α_0 and α_1 are complex numbers.

Quantum Information: 1 qubit

A bit of classical information: state is 0 or 1

A quantum bit can be partially in state $|0\rangle$ and state $|1\rangle$:

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

α_0 and α_1 are complex numbers.

Atfer measurement:

0 with probability $|\alpha_0|^2$....afterwards the state has collapsed to $|0\rangle$

1 with probability $|\alpha_1|^2$....afterwards the state has collapsed to $|1\rangle$

Quantum Information: *n* qubits

State is a superposition over $N = 2^n$ possible states:

$$|\psi\rangle = \sum_{x \in \{1,\ldots,2^n\}} \alpha_x |x\rangle$$

Quantum Information: *n* qubits

State is a superposition over $N = 2^n$ possible states:

$$|\psi\rangle = \sum_{x \in \{1,\ldots,2^n\}} \alpha_x |x\rangle$$

To express a state with 200 qubits requires 2^{200} complex numbers.

Quantum Information: *n* qubits

State is a superposition over $N = 2^n$ possible states:

$$|\psi\rangle = \sum_{x\in\{1,\ldots,2^n\}} \alpha_x |x\rangle$$

To express a state with 200 qubits requires 2^{200} complex numbers.

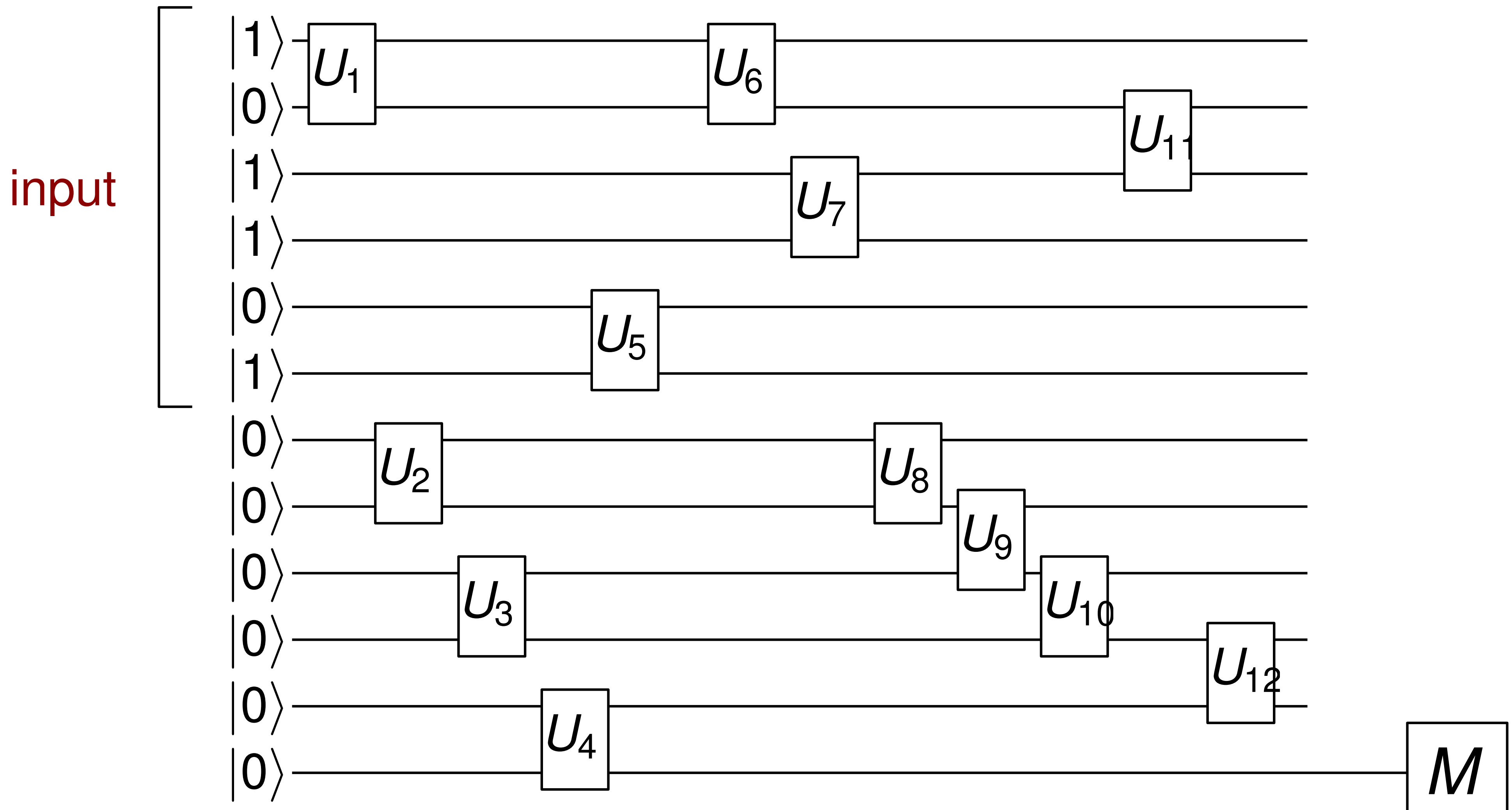
We have very limited access to this wealth of information:

If all n qubits are measured, state collapses to $|x\rangle$

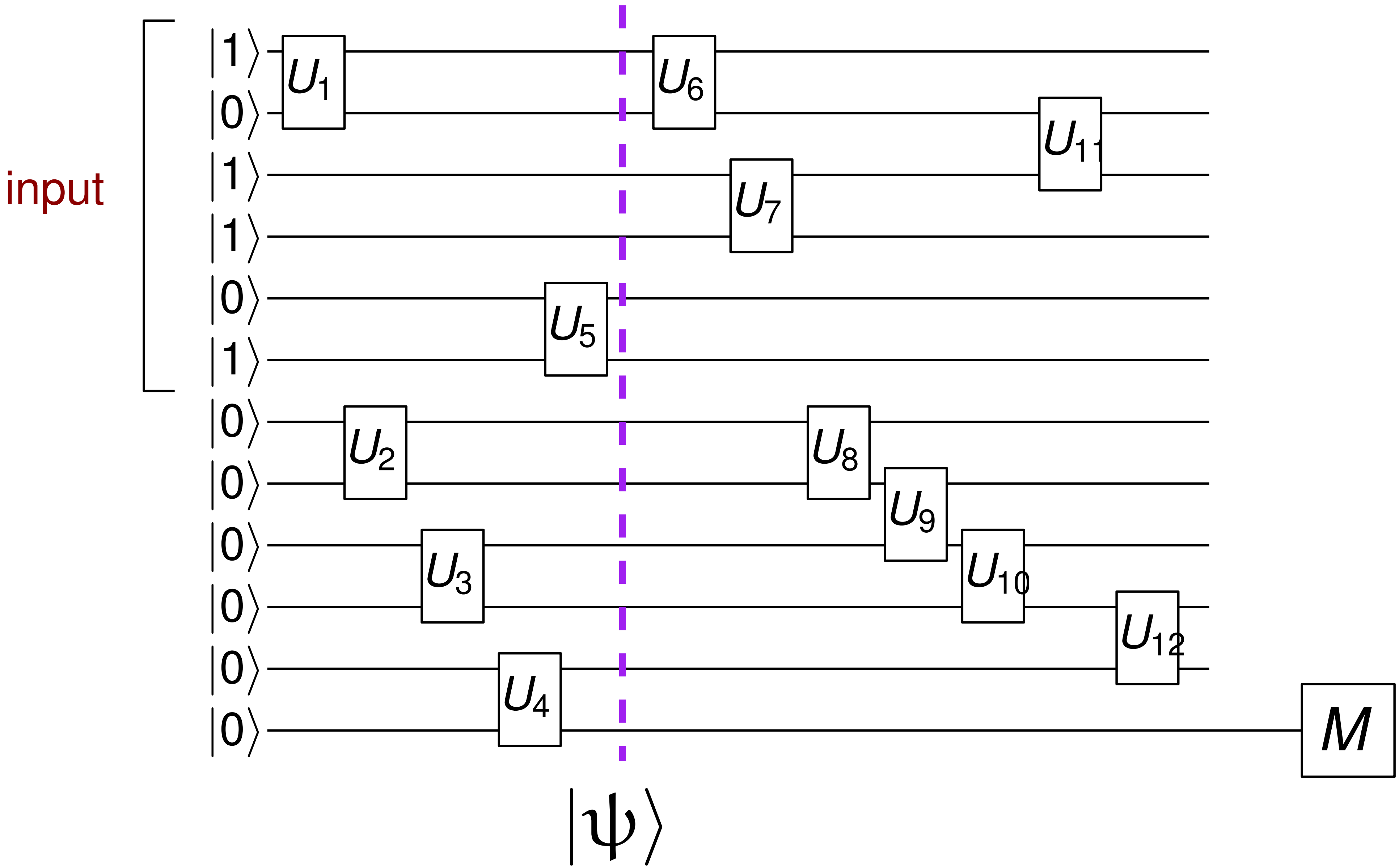
Exponentially many answers but only one can be observed.

Quantum speed up comes from algorithms that use negative interference to boost the amplitude of the correct answer.

Quantum Circuits



Quantum Circuits



Adiabatic Quantum Computing

[Farhi, Goldstone, Gutman, Lapan, Lundgren, 2001]

Start State:
Ground state of an "easy" Hamiltonian

Desired State:
Ground state of final Hamiltonian

$$H_s \longrightarrow H_f$$

$$H(t) = (1 - t)H_s + tH_f \quad t \in [0, 1]$$

Adiabatic Quantum Computing

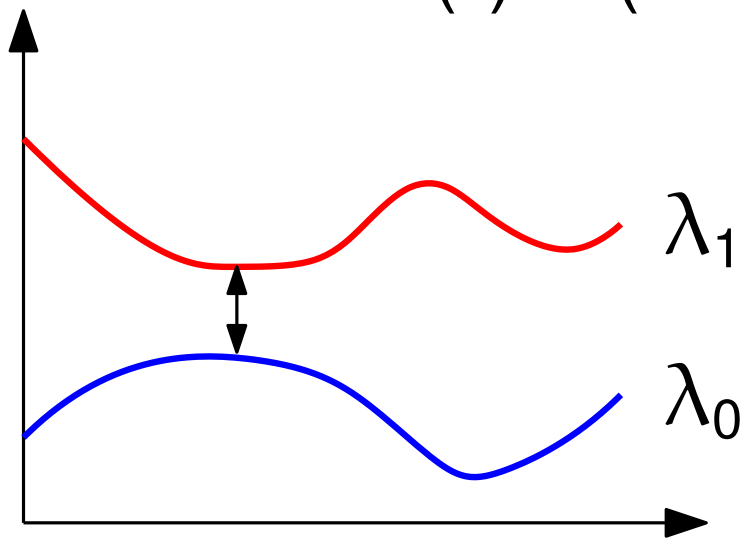
[Farhi, Goldstone, Gutman, Lapan, Lundgren, 2001]

Start State:
Ground state of an "easy" Hamiltonian

Desired State:
Ground state of final Hamiltonian

$$H_s \longrightarrow H_f$$

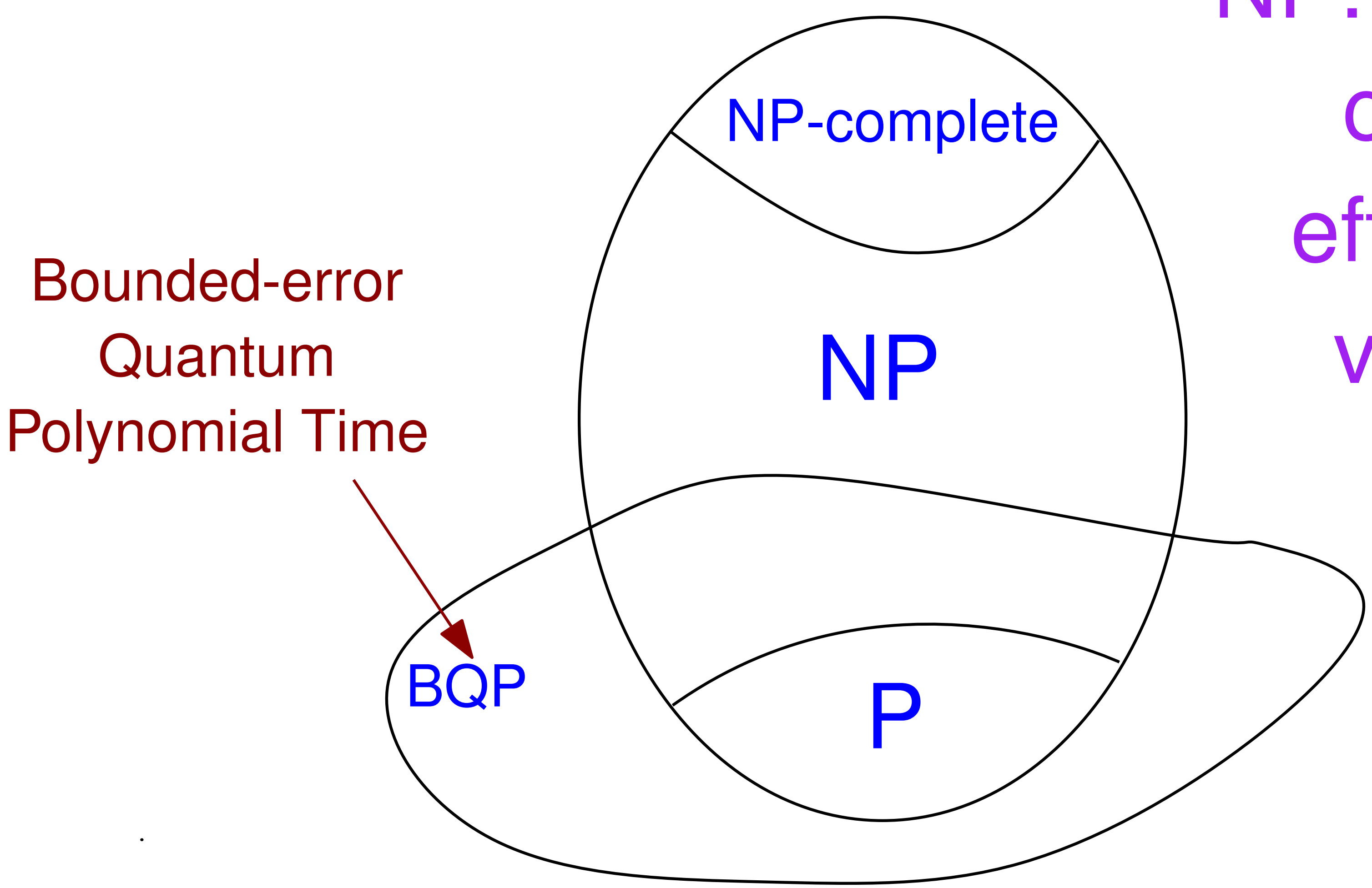
$$H(t) = (1 - t)H_s + tH_f \quad t \in [0, 1]$$



Running time is $\Omega(1/\text{poly}(\lambda_1 - \lambda_0))$

Can be exponential:
[van Dam, Vazirani, 2001]

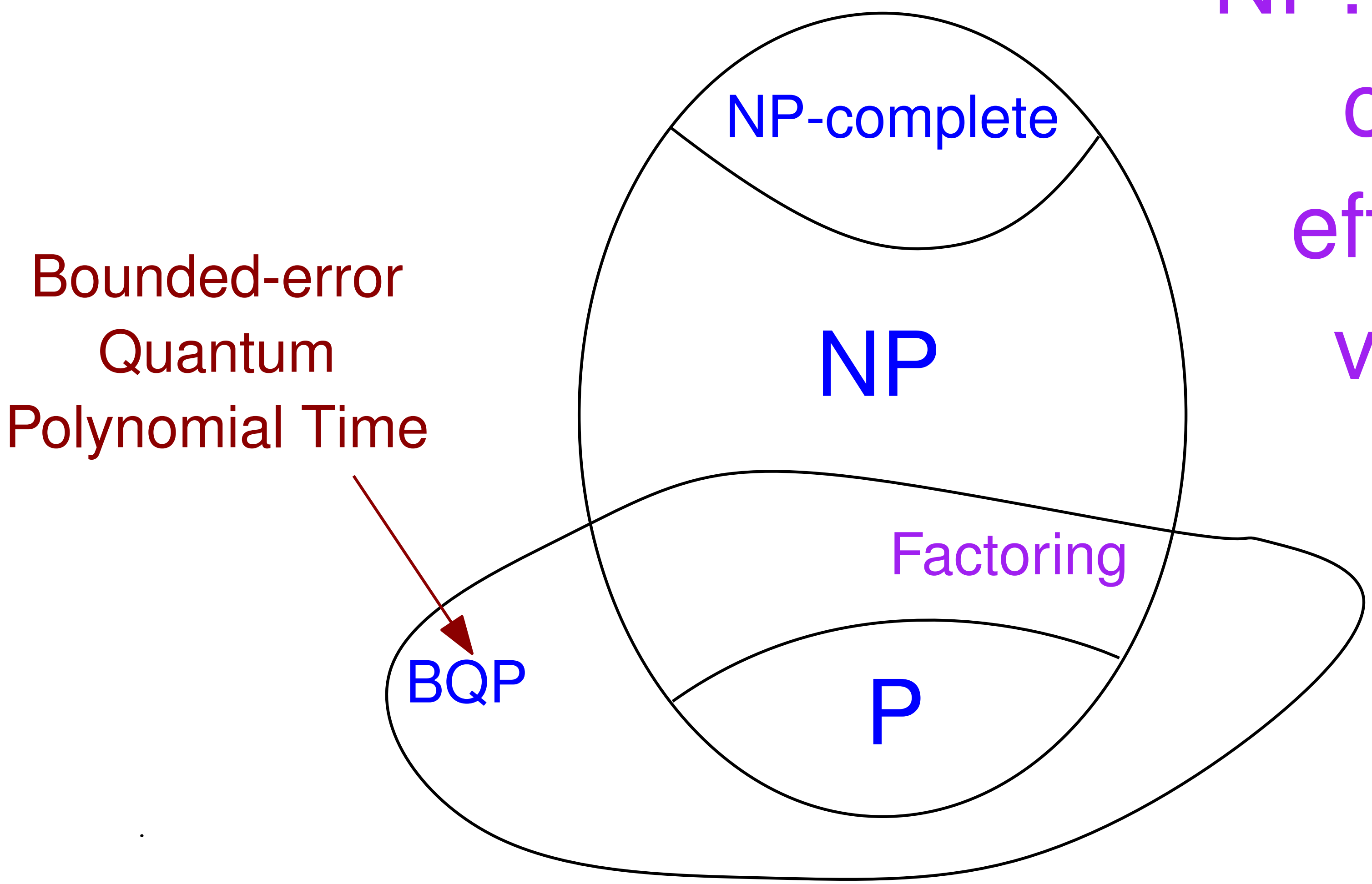
Quantum Complexity Classes



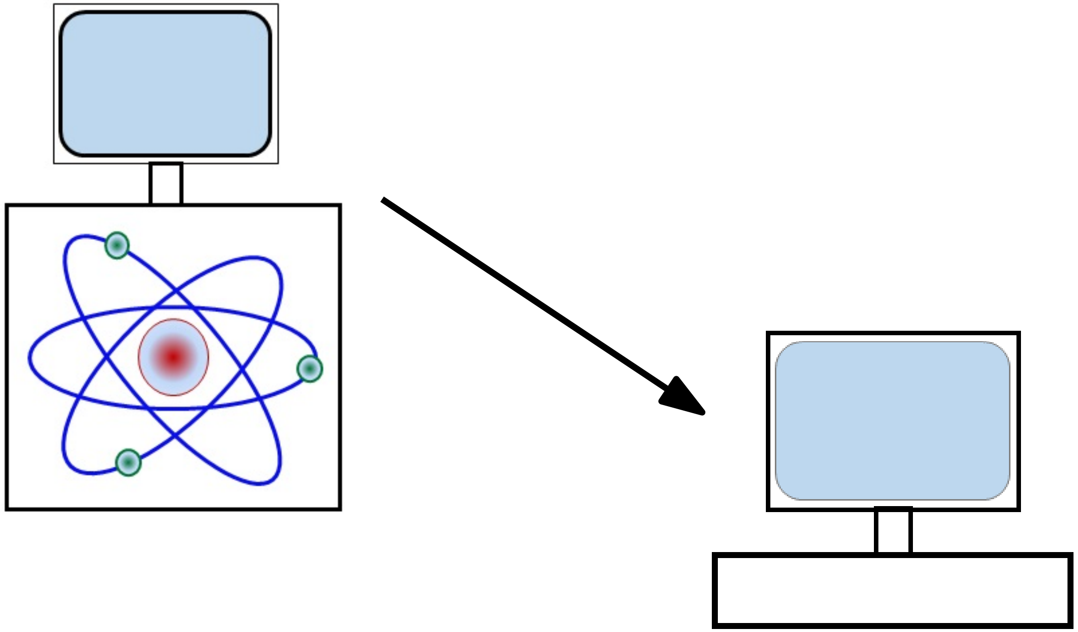
NP: solutions can be efficiently verified

Quantum Complexity Classes

NP: solutions can be efficiently verified



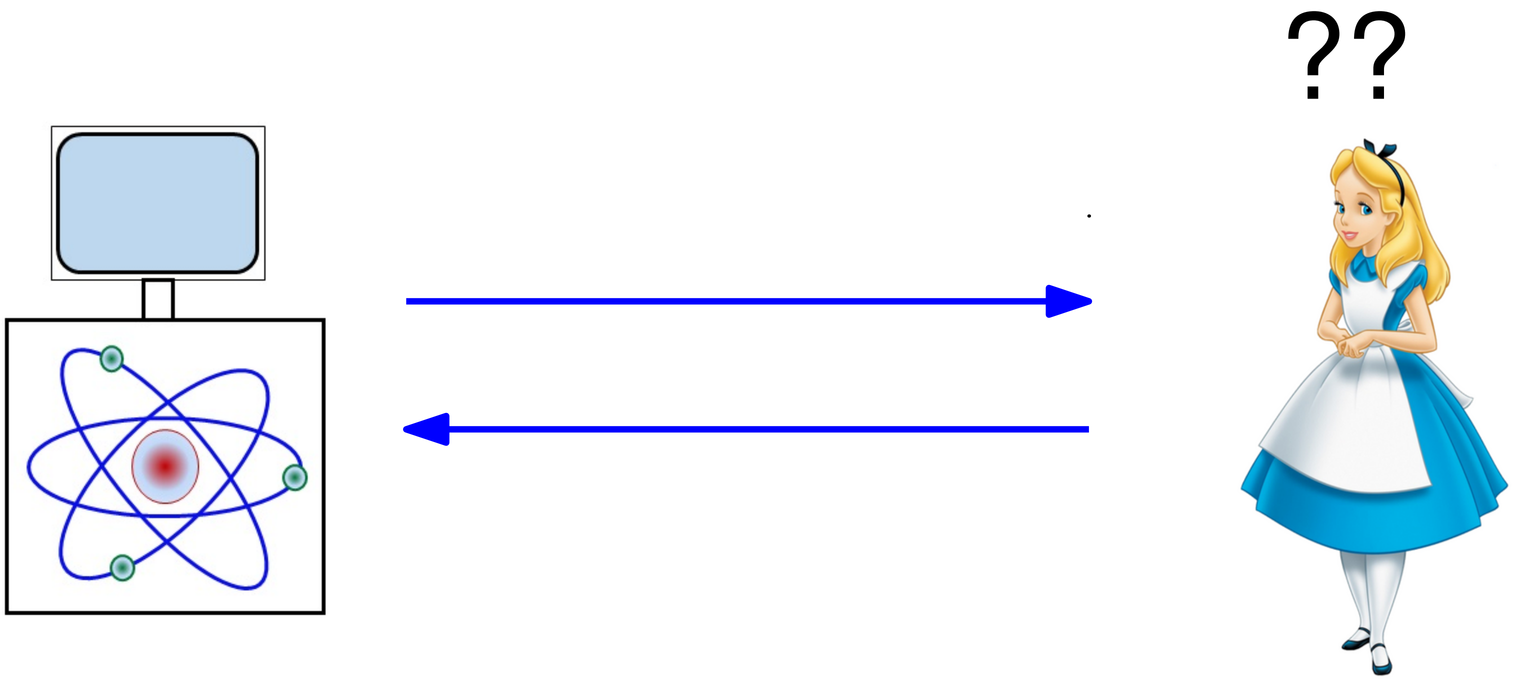
Quantum Supremacy



Can we devise a problem that is specifically designed to show that quantum computers are more powerful than classical computers?

Good candidate: sampling from a distribution that is the output of a random quantum circuit.

Quantum Verification



How can a classical computer verify that a quantum computer has obtained the correct answer to a computational problem?

[Mahadev 2018]

[Aharonov, Ben-Or, Eban] [Broadbent, Fitzsimons, Kashefi] [Reichardt, Unger, Vazirani]

Simulating the dynamics of quantum systems over time

Simulating the dynamics of quantum systems over time

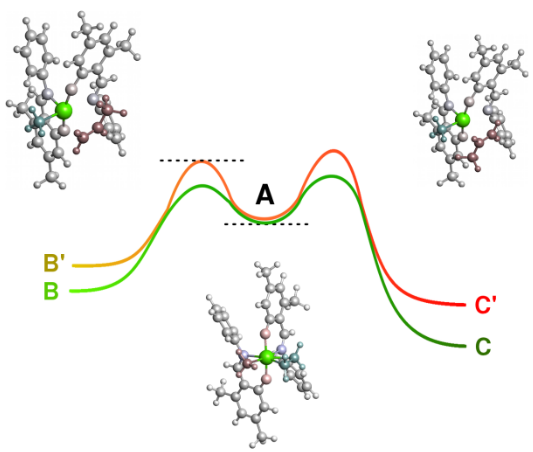
$$|\psi(0)\rangle \longrightarrow \boxed{i\hbar \frac{d|\psi\rangle}{dt} = H|\psi\rangle.} \longrightarrow |\psi(t)\rangle$$

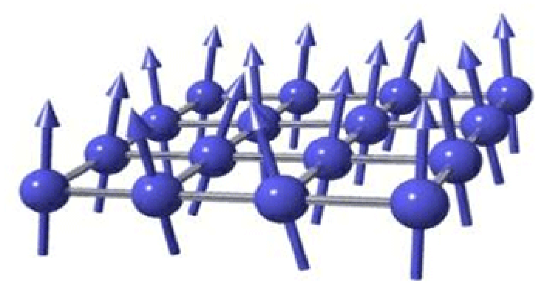
$$= e^{-iHt}|\psi(0)\rangle$$

Simulating the dynamics of quantum systems over time

$$|\psi(0)\rangle \longrightarrow \boxed{i\hbar \frac{d|\psi\rangle}{dt} = H|\psi\rangle.} \longrightarrow |\psi(t)\rangle$$

$$= e^{-iHt}|\psi(0)\rangle$$

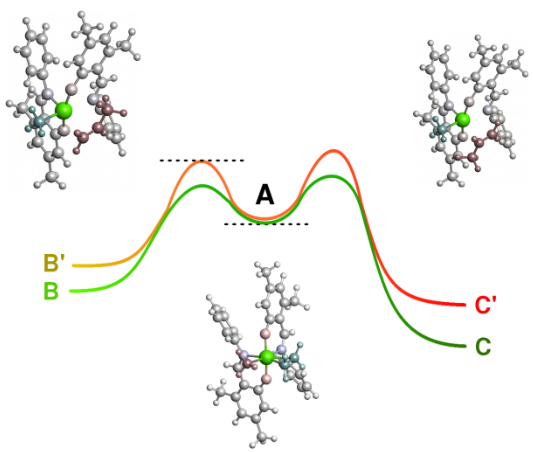


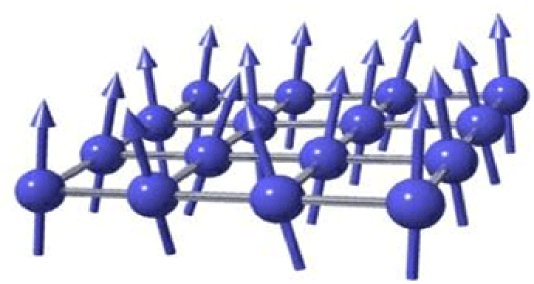


Simulating the dynamics of quantum systems over time

$|\psi(0)\rangle \longrightarrow$ $$i\hbar \frac{d|\psi\rangle}{dt} = H|\psi\rangle.$$ $\longrightarrow |\psi(t)\rangle$

$= e^{-iHt}|\psi(0)\rangle$





[Lloyd 1996] [Berry, Childs, Cleve, Kothari, Somma 2015]
[Haah, Hastings, Kothari, Low 2018] [Low Chuang 2016, 2017]

QAOA: Quantum Approximate Optimization Algorithm

$B(\beta_p)C(\gamma_p), \ldots, B(\beta_1)C(\gamma_1)|\psi\rangle$

Alternate the different ”amounts” of the same two operations.

One operation alters the current solution

One operation favors ”better” solutions.

The entire algorithm is parameterized by the vector $(\beta_p, \gamma_p, \ldots, \beta_1, \gamma_1)$

Use a classical algorithm (like gradient descent) to find the vector that produces the best solution.

[Farhi, Goldstone, Gutmann]

Thank You!