NOISY QUANTUM COMPUTERS ARRIVED

CAN WE PLEASE USE THEM?

JSC-JAHRESABSCHLUSSKOLLOQUIUM I MANPREET JATTANA

GATE-BASED

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QUANTUM COMPUTERS

Two types

→ **Gate based**

and

~~**Annealers**~~

GATE BASED QUANTUM COMPUTING

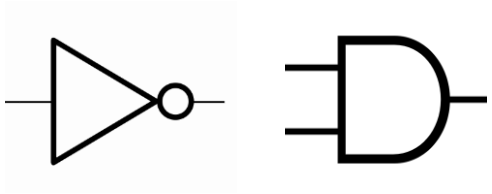
M. A. Nielsen and I. L. Chuang. Quantum Computation and Quantum Information: 10th Anniversary Edition. Cambridge University Press.

D. P. DiVincenzo. Phys. Rev. A **51**, 1015–1022.

Digital Gates:

1 bit: NOT

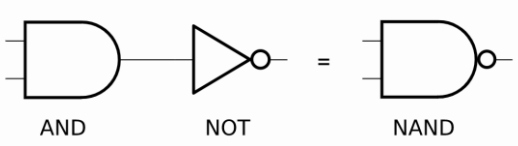
2 bits: AND



A	NOT A
0	1
1	0

A	B	A AND B
0	0	0
0	1	0
1	0	0
1	1	1

…and others.

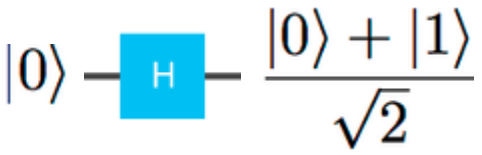


Quantum Gates:

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

X-Gate (NOT):

Hadamard (H-Gate):



…and others.

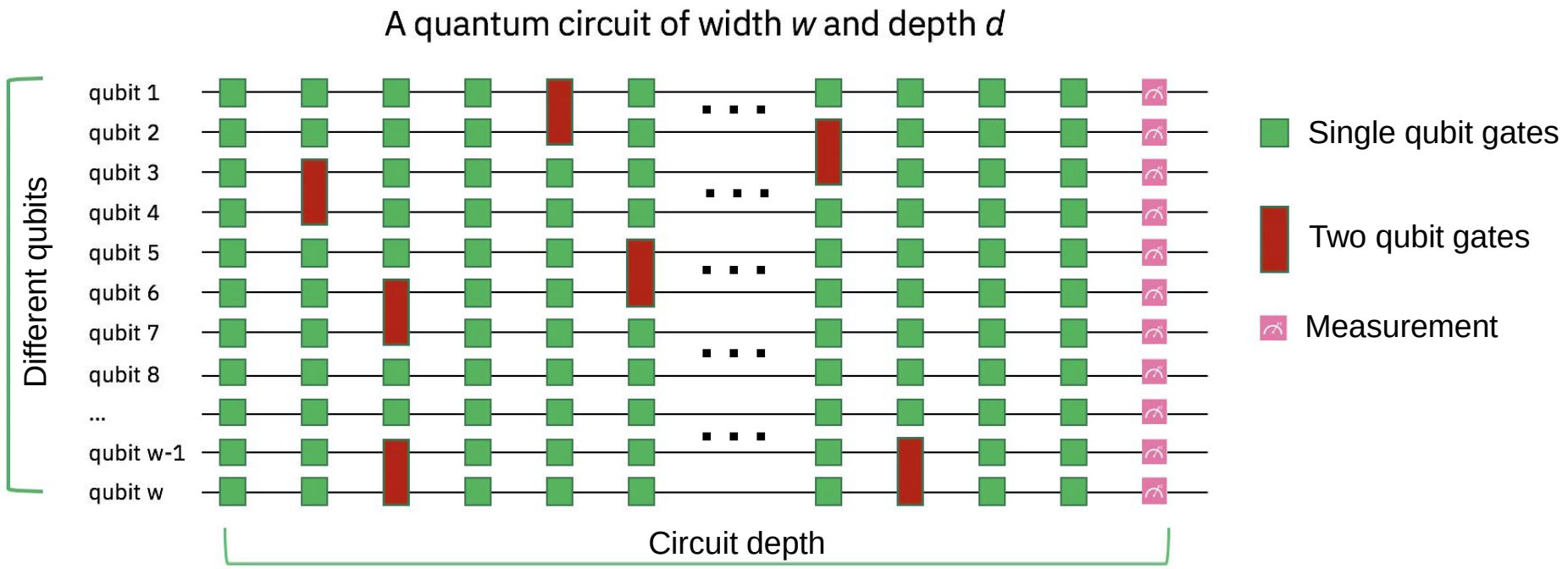
2 qubits: $\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$

CNOT:

…and others.

GATE BASED QUANTUM COMPUTING

Combining gates to form circuits

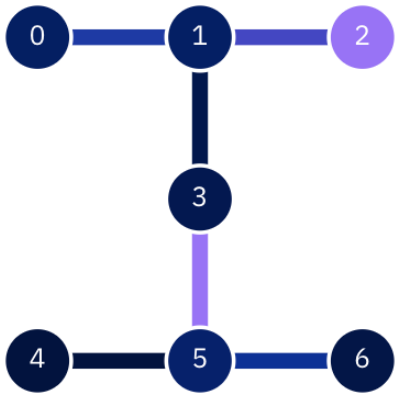


- Circuit is based on the implementation of some algorithm
- Current gate-based quantum hardware can accommodate small depth

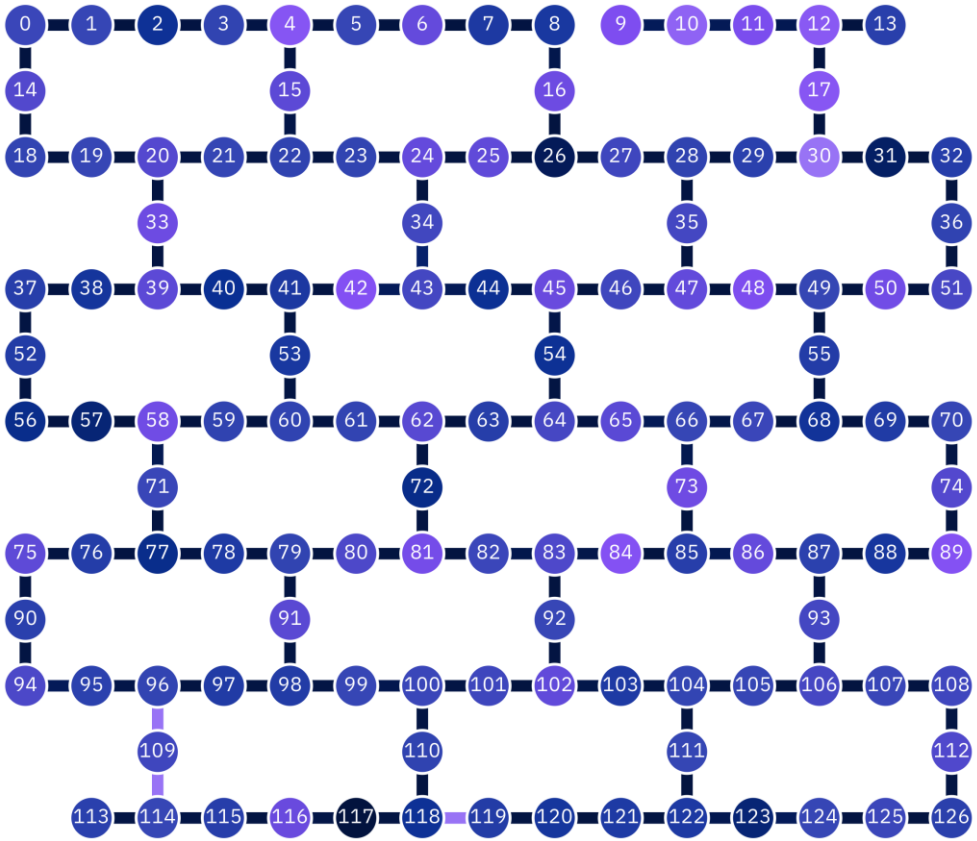
GATE BASED QUANTUM COMPUTERS

Superconductivity based and publicly available from IBM

- Largest announced: IBM Osprey with 433 qubits
- Available on cloud: IBM Washington with 127 qubits
- Available on cloud for free: 7 qubits



IBM Washington

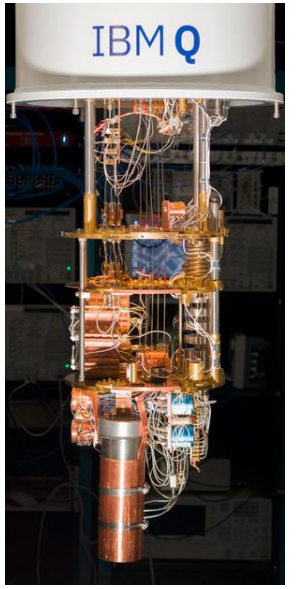


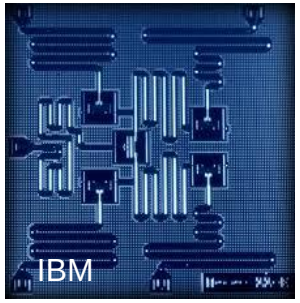
https://newsroom.ibm.com/2022-11-09-IBM-Unveils-400-Qubit-Plus-Quantum-Processor-and-Next-Generation-IBM-Quantum-System-Two

GATE BASED QUANTUM COMPUTERS

OPEN QUESTIONS

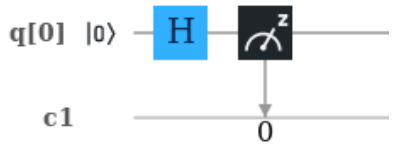
- More qubits or better qubits?
- How many ‘better qubits’ are good enough?
- Faster or more stable gate operations?
- Do we agree on what ‘quantum advantage’ is?
- Can we make practical use of noisy hardware?





ERROR PRONE COMPUTATION

All kinds of errors destroy the computation



- Error is present even by executing only a single gate
  - In state preparation, gate operation, and measurement
- An algorithm usually consists of hundreds of gates placed over several qubits
  - Expect propagation of error
- Error correction techniques require many more qubits than would be available in the near future

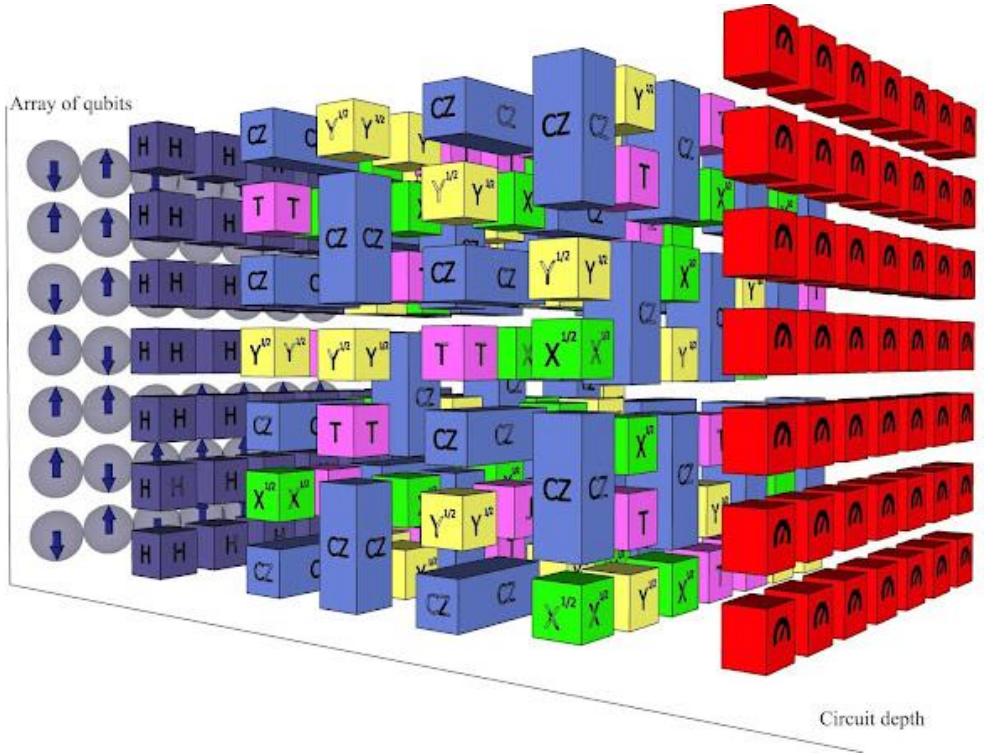
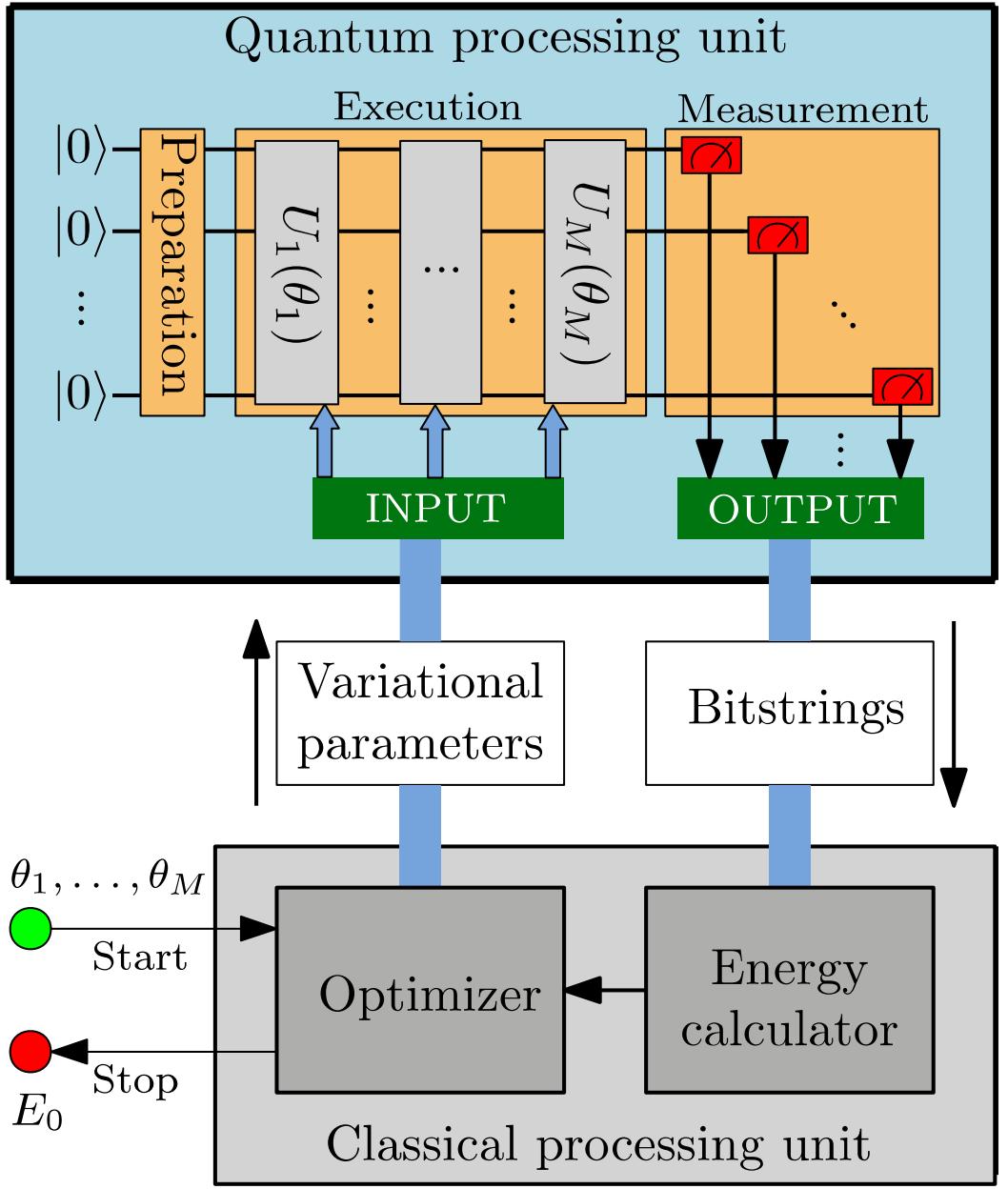


Image from: https://ai.googleblog.com/2018/05/the-question-of-quantum-supremacy.html

THE IDEA OF VARIATIONAL METHODS

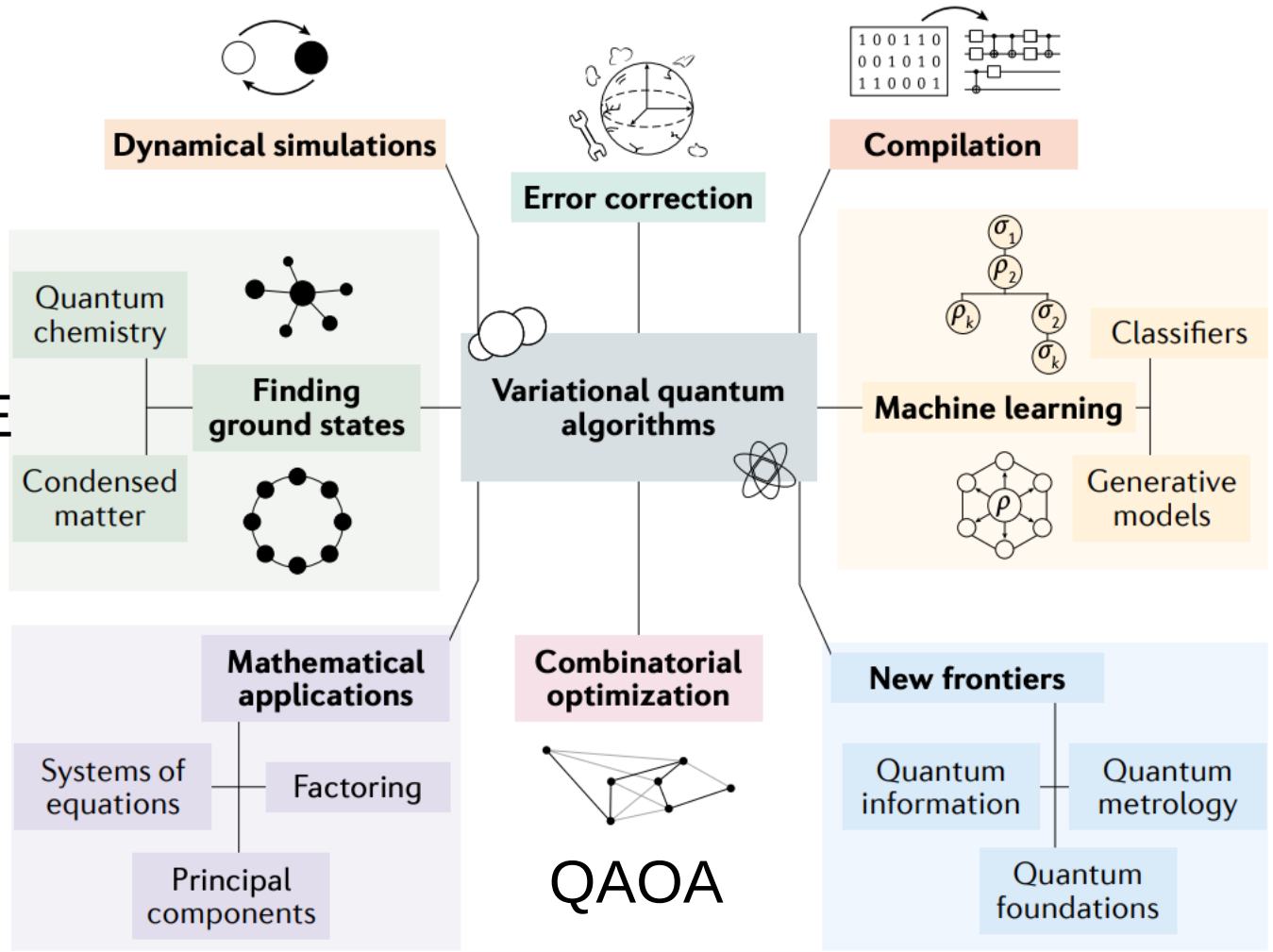
Combine quantum and classical computers

1. Prepare an initial state of the quantum unit and feed (a clever choice of) initial parameters
2. Execute the quantum circuit with those parameters and collect samples by repeating the execution
3. Collect sufficient samples to calculate the cost function to a required accuracy
4. Feed the output to an optimisation algorithm that proposes the next parameters
5. Repeat 2 to 4 until convergence



Phys. Rev. X **6**, 031007 (2016)

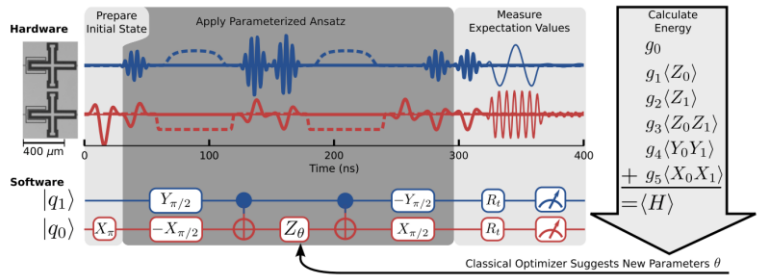
USES OF VARIATIONAL ALGORITHMS

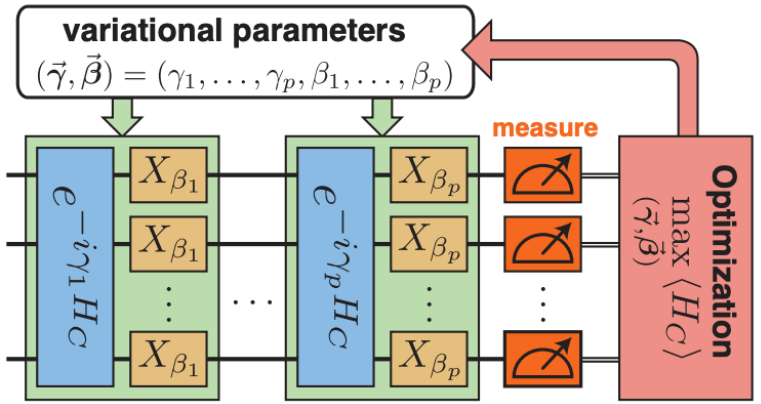


VQE

QAOA

Nature Reviews Physics volume 3, p. 625–644 (2021)

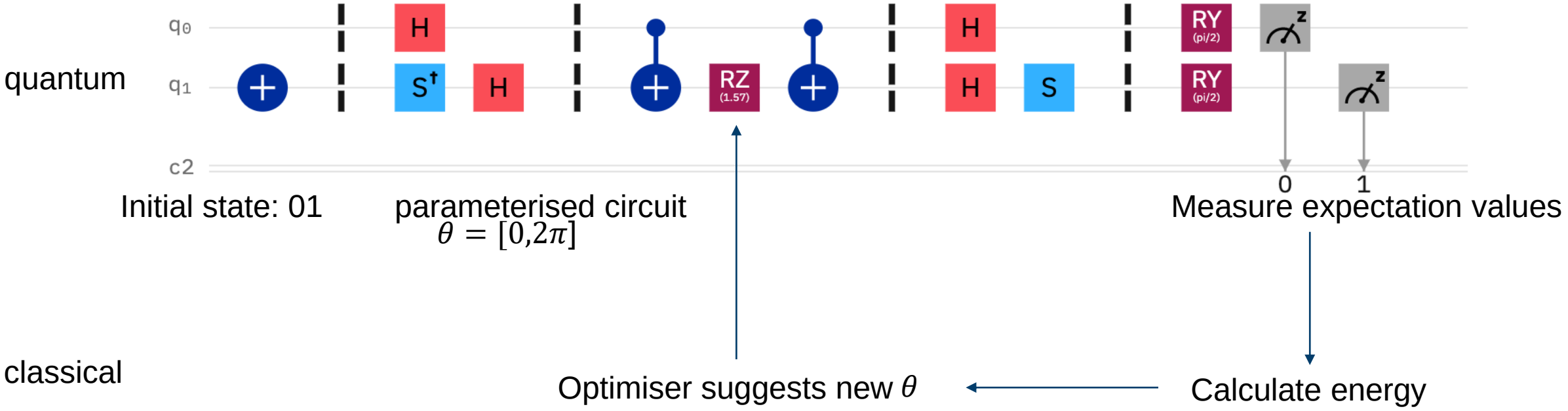




VARIATIONAL QUANTUM EIGENSOLVER (VQE)

Simple example of the hybrid (classical + quantum) mechanism

- Simple Hamiltonian: $H = X_0 X_1$, where X denotes the Pauli operator on the i-th qubit.
- We use only one parameter θ and can scan the parameter space.

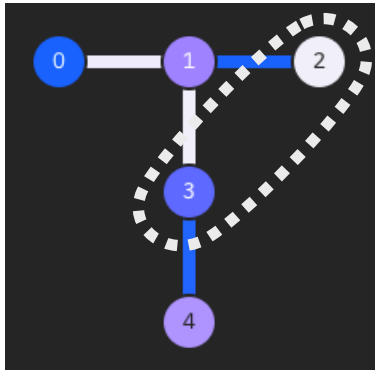


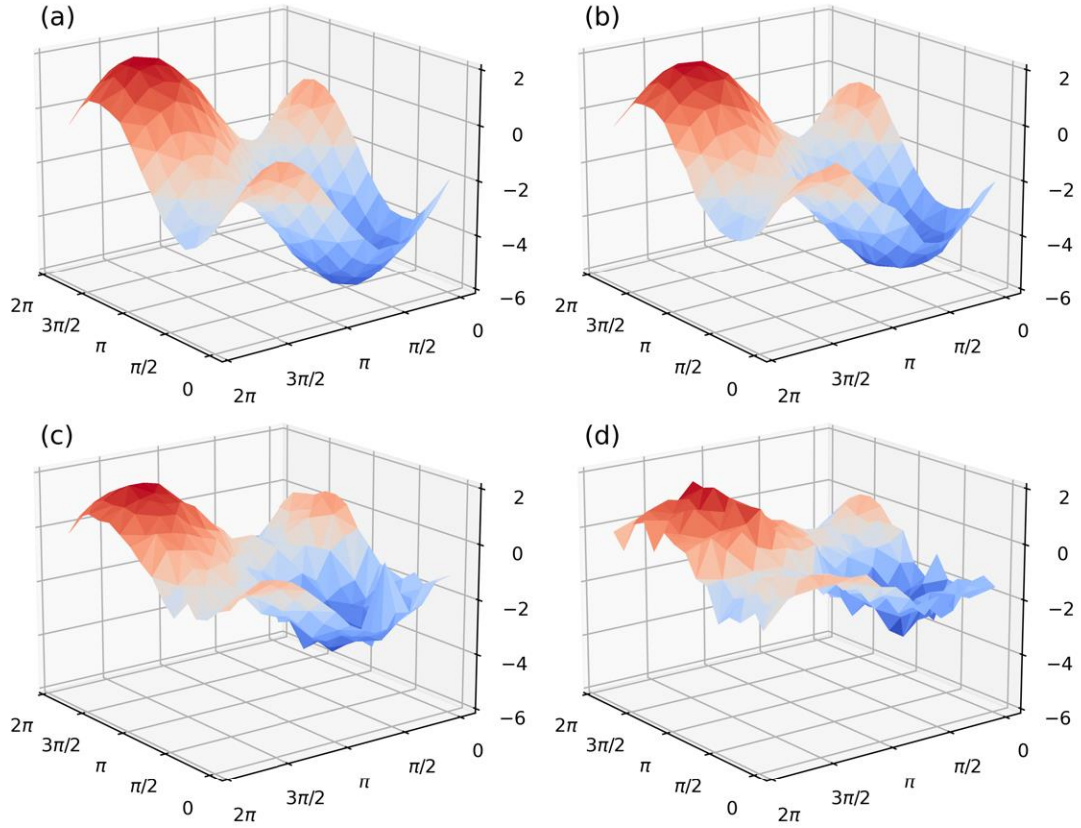
BENCHMARKING USING VQE

On IBM Q devices

- Using a 5-qubit device, we plot the energy landscape for a 2-parameter ansatz
- Problem is the *mean-field* model which is analytically solved

- (a) Ideal simulator
- (b) IBM Q Santiago (no swaps)
- (c) IBM Q Belem (no swaps)
- (d) IBM Q Belem (one swap)





CONCLUSIONS

- Gate-based quantum algorithms are severely restricted by current hardware specifications
- Hybrid quantum-classical algorithms can help use current generation hardware
- Problem-specific quantum computers (i.e. Annealers) appear more useful as of now
- Variational methods are ‘potentially useful’ but no quantum advantage yet

CONCLUSIONS

- Can we please use them?

  Yes, we can!

- Can we please use them for tasks not yet doable on classical computers?

  We're trying!