Intel Invited Talk Series
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HYBRID QUANTUM-CLASSICAL COMPUTING ARCHITECTURES

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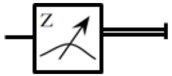
WHAT IS QUANTUM COMPUTING?

- New computing paradigm
  - Uses the rules of quantum mechanics to manipulate information
  - Exponential speedup for some problems: quantum simulation, factoring, quantum walks on graphs, etc.
  - Groundbreaking implications in computer security and cryptography

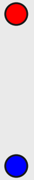
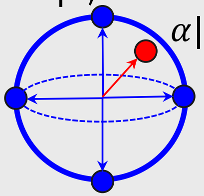
- Active research spans topics from quantum algorithms all the way down to device physics

- The race to build a quantum computer is now on

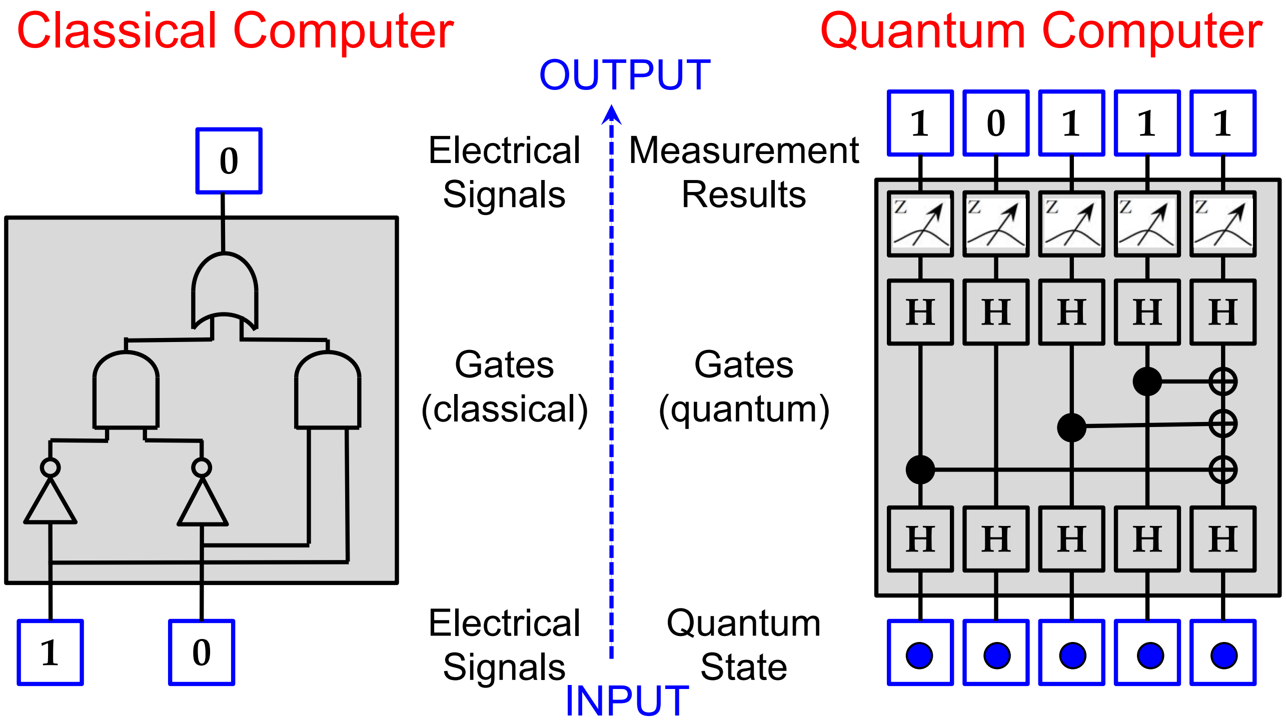
STORING AND MANIPULATING CLASSICAL VS. QUANTUM INFORMATION

- Qubit in state $\alpha|0\rangle + \beta|1\rangle$ where $|\alpha|^2 + |\beta|^2 = 1$
- Measuring qubit: $\alpha|0\rangle + \beta|1\rangle$ 

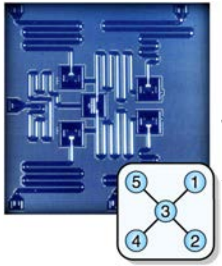
$\begin{cases} \text{get 0 with probability } |\alpha|^2 \\ \text{get 1 with probability } |\beta|^2 \end{cases}$
- Exponential state space increase with number of qubits

Classical bit:	Qubit:	2-qubit system:
		$\alpha\|00\rangle + \beta\|01\rangle + \gamma\|10\rangle + \delta\|11\rangle$

HOW A QUANTUM COMPUTER WORKS



HOW DO QUANTUM TECHNOLOGIES LOOK LIKE?

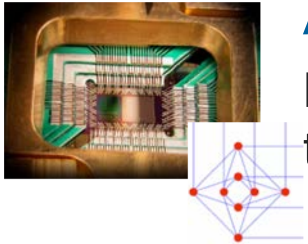


Superconducting qubits:

Josephson Junctions between superconducting electrodes

Ion traps:

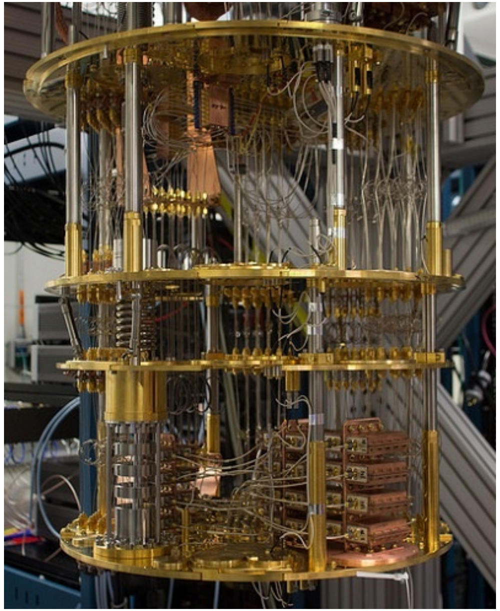
Ions trapped in electromagnetic field, gates performed by applying lasers



Adiabatic quantum computation:

Lattice of superconducting qubits that arrange themselves to solve an optimization problem

BUILDING QUANTUM COMPUTERS IS REALLY HARD!

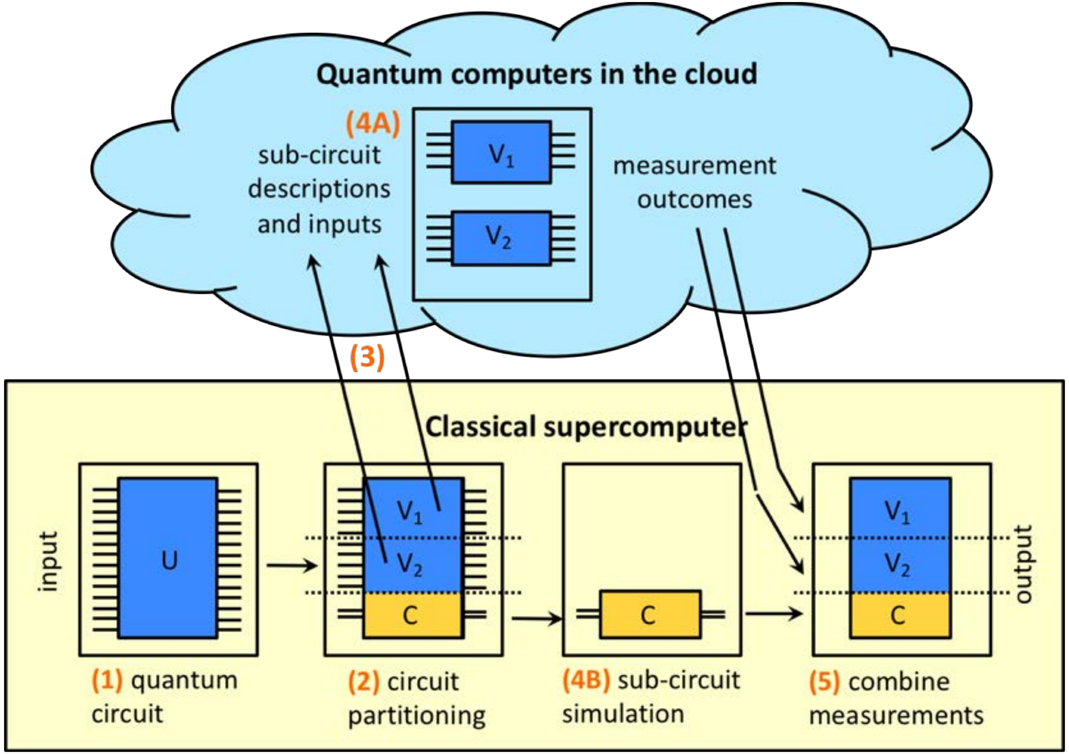


IBM Q superconducting quantum computer

- Remarkable technological advances in qubit manufacturing in the past few years but:
  - The cost to build quantum processors is extremely high
  - It is difficult to add qubits
  - Qubit coherence is improving but will always be a fundamental challenge

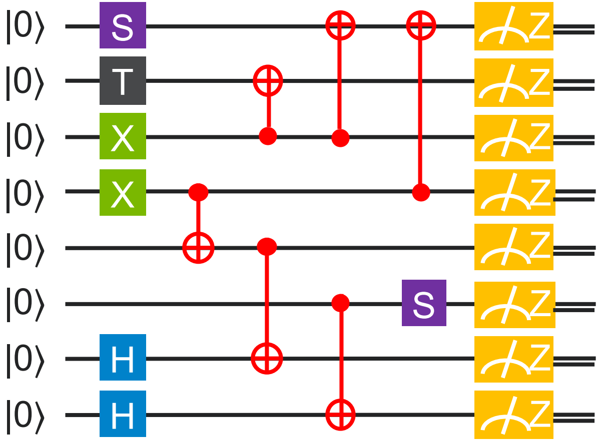
How can we use (multiple) unreliable quantum processors of intermediate size to reliably solve large computational problems?

WHAT WE WANT – USE SMALL QUANTUM PROCESSORS TO SOLVE LARGE PROBLEMS

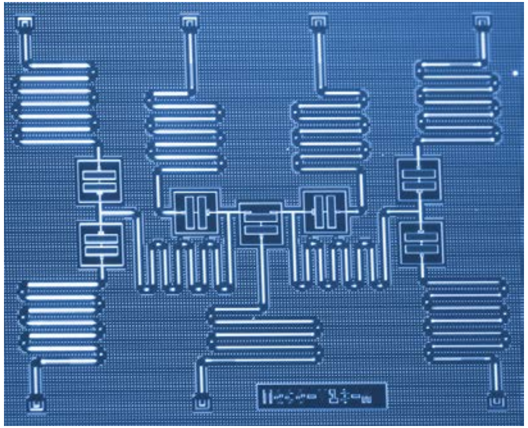


IDEA: CUT A LARGE QUANTUM CIRCUIT INTO MULTIPLE SUB-CIRCUITS

Original quantum circuit:

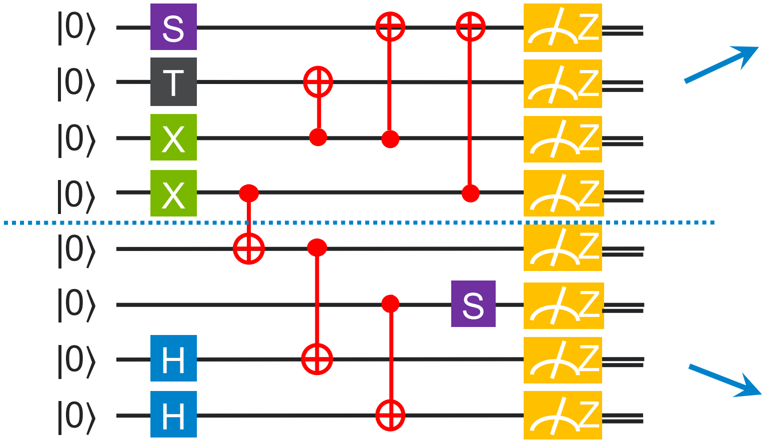


- Evaluate this circuit on a device with 7 qubits?

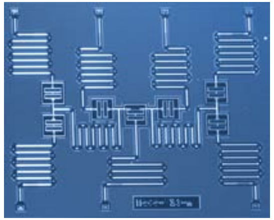


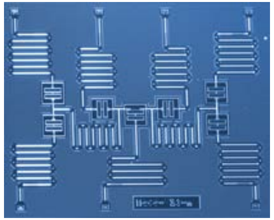
IDEA: CUT A LARGE QUANTUM CIRCUIT INTO MULTIPLE SUB-CIRCUITS

Processor A



Processor B





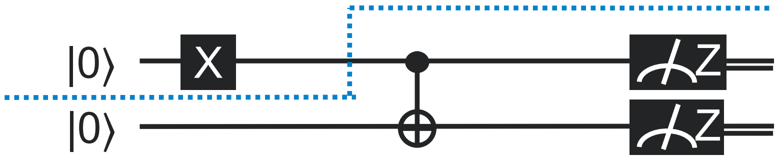
- Cost scales exponentially with number of wire and gate cuts
- Need to find a clean cut

➢ *Bravyi, Smith, Smolin, Phys. Rev. X, 2016*

➢ *Harrow, Ozols et al., Semantic Scholar and private communication*

IDEA: CUT A LARGE QUANTUM CIRCUIT INTO MULTIPLE SUB-CIRCUITS

Original circuit



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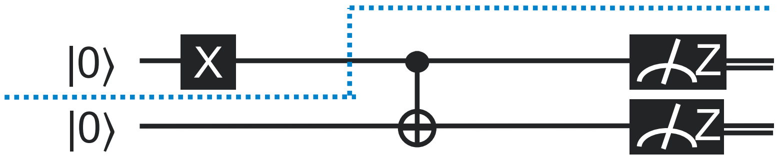

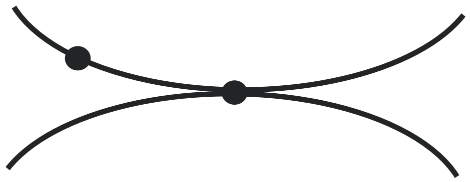

IDEA: CUT A LARGE QUANTUM CIRCUIT INTO MULTIPLE SUB-CIRCUITS

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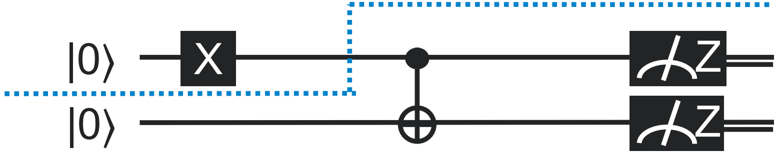
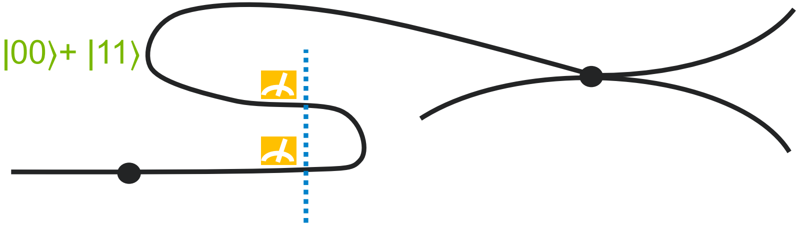
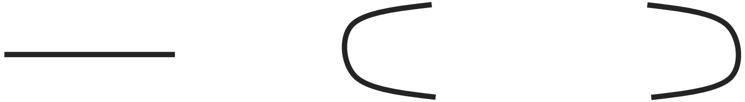


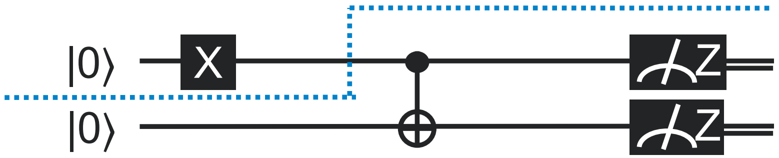




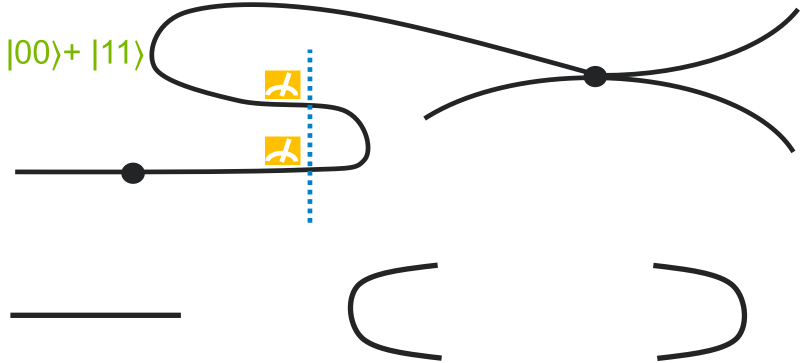
$$I = \sum_i |i\rangle\langle i| \qquad |\Phi\rangle = \sum_i |i\rangle|i\rangle \qquad \langle\Phi| = \sum_i \langle i|\langle i|$$

IDEA: CUT A LARGE QUANTUM CIRCUIT INTO MULTIPLE SUB-CIRCUITS

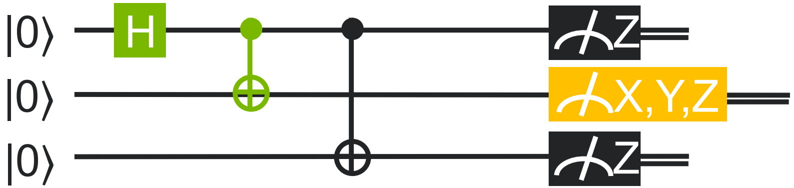
Original circuit



Fragment A



Fragment B



$I = \sum_i |i\rangle\langle i|$ $\quad|\Phi\rangle = \sum_i |i\rangle|i\rangle$ $\quad\langle\Phi| = \sum_i \langle i|\langle i|$

COMBINING THE OUTPUTS WITH CLASSICAL POSTPROCESSING

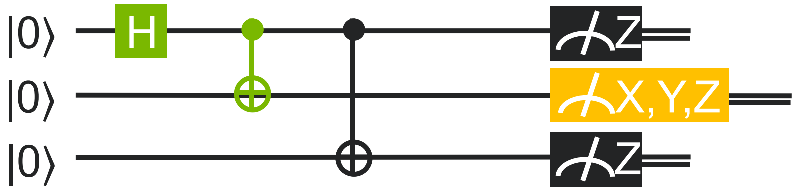
- Repeatedly run each circuit, perform measurements in the X, Y and Z bases, and record the measurement outcomes

Fragment A

The probabilities you expect:

Outcome	X	Y	Z
0	0.5	0.5	0
1	0.5	0.5	1

Fragment B



Outcome	X	Y	Z
0 0 0	0.25	0.25	0.5
0 1 0	0.25	0.25	0
1 0 1	0.25	0.25	0
1 1 1	0.25	0.25	0.5

COMBINING THE OUTPUTS WITH CLASSICAL POSTPROCESSING

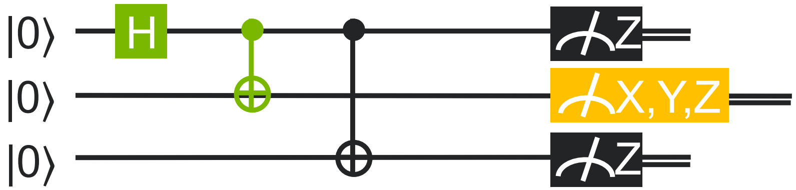
- Repeatedly run each circuit, perform measurements in the X, Y and Z bases, and record the measurement outcomes

Fragment A

Results with a quantum simulator:

Outcome	X	Y	Z
0	0.49	0.49	0
1	0.51	0.51	1

Fragment B



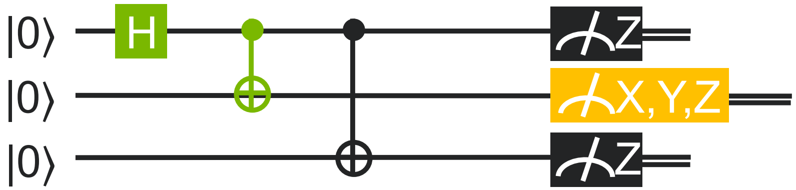
Outcome	X	Y	Z
0 0 0	0.25	0.27	0.5
0 1 0	0.26	0.25	0
1 0 1	0.24	0.25	0
1 1 1	0.25	0.23	0.5

COMBINING THE OUTPUTS WITH CLASSICAL POSTPROCESSING

- Repeatedly run each circuit, perform measurements in the X, Y and Z bases, and record the measurement outcomes

Fragment A

Fragment B



Results on a 16-qubit IBM Q processor:

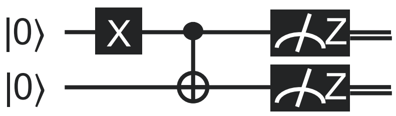
Outcome	X	Y	Z
0	0.52	0.56	0.05
1	0.48	0.44	0.95

Outcome	X	Y	Z
0 0 0	0.30	0.30	0.37
0 1 0	0.19	0.20	0.05
1 0 1	0.16	0.17	0.10
1 1 1	0.20	0.20	0.27

COMBINING THE OUTPUTS WITH CLASSICAL POSTPROCESSING

- Finally we combine the results using multiplicative factors from Harrow et al.:

Expected circuit output: |11⟩



Outcome	Estimate
0 0	0.001
0 1	0.000
1 0	0.000
1 1	0.999

Outcome	X	Y	Z
0	0.49	0.49	0
1	0.51	0.51	1

Outcome	X	Y	Z
0 0 0	0.25	0.27	0.5
0 1 0	0.26	0.25	0
1 0 1	0.24	0.25	0
1 1 1	0.25	0.23	0.5

*1 if same, *-1 if different

*-1 if same, *1 if different

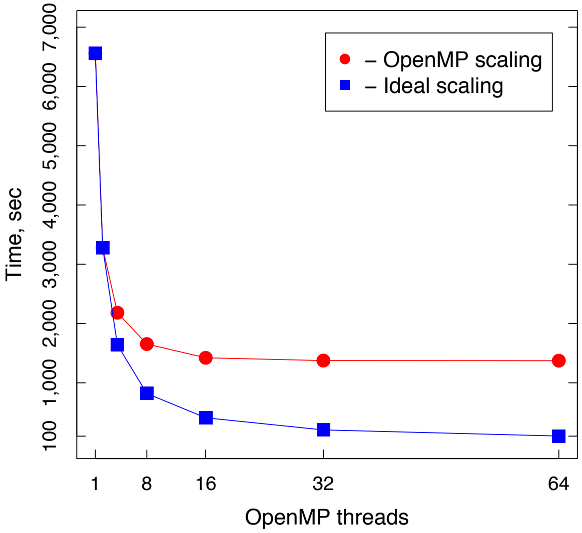
*2 if same, *0 if different

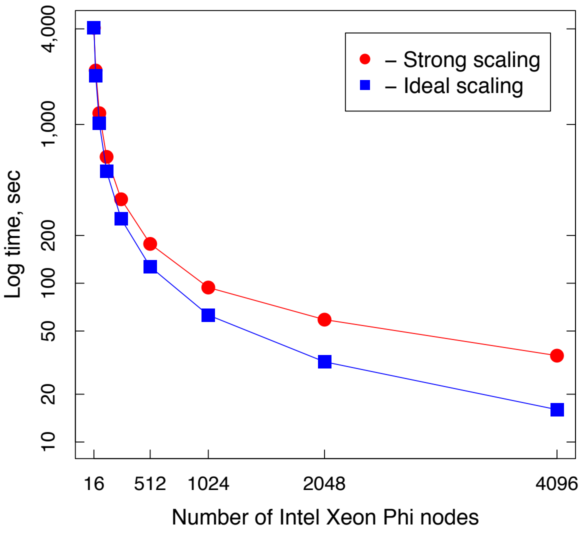
QUANTUM CIRCUIT EVALUATIONS WITH INTEL-QS ON THETA SUPERCOMPUTER

- Intel-QS is a freely available quantum simulator: https://github.com/intel/Intel-QS
- Code was ported and optimized for Cray/Intel supercomputer Theta at Argonne
- Simulator takes advantage of multi-core and multi-node architectures, parallelization with MPI and OpenMP
- State space increases exponentially with number of qubits

Qubits	Memory (GB)	Theta Nodes	Gate Time (sec)
35	788	512	458
40	25,216	16,098	796
45	806,912	515,136	1,632

QUANTUM CHEMISTRY CIRCUIT EVALUATION WITH INTEL-QS ON THETA SUPERCOMPUTER

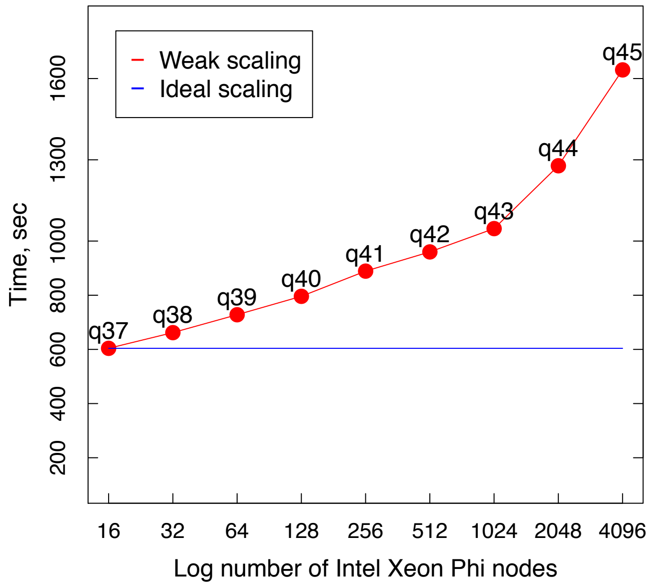




- Time to solution for a 30 gate circuit running on 30 qubits; 1 to 64 threads for 1 MPI rank shown
- Scales up to 32 threads

- Time to solution for a 35-qubit simulation with a single gate per qubit
- MPI rank varies from 1 to 4,096 with 64 OpenMP threads per rank

WEAK SCALING WITH NUMBER OF QUBITS AND GATE DEPTH - INTEL-QS ON THETA

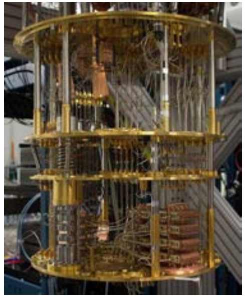


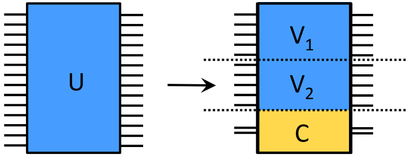
Gates	Time (sec)
2	563
4	1,068
10	645
501	1,050
100	2,028
200	3,089
400	~86,400 (est.)

- Time to solution vs. number of Theta nodes as the number of qubits increases
- Simple circuit: Hadamard gate on all qubits

- Estimating the number of gates that can be run in 24 hours (maximum time in queue)

SUMMARY: HYBRID QUANTUM-CLASSICAL COMPUTING APPROACH





- Can use quantum processors to evaluate circuit fragments with 20 to 50 qubits and gate depth ~100
- Circuits must be cleanly separable
- Exponential cost depends on number of gate cuts

- Intel-QS can simulate circuits with 35 to 45 qubits and gate depth up to ~400
- Allows accurate circuit evaluation without introducing noise
- Soon quantum supremacy may be achieved for some circuits

THANK YOU!