The 3rd International Workshop on Post-Moore Era Supercomputing
November 11, 2018

Argonne NATIONAL LABORATORY

HYBRID QUANTUM-CLASSICAL COMPUTING ARCHITECTURES

MARTIN SUCHARA

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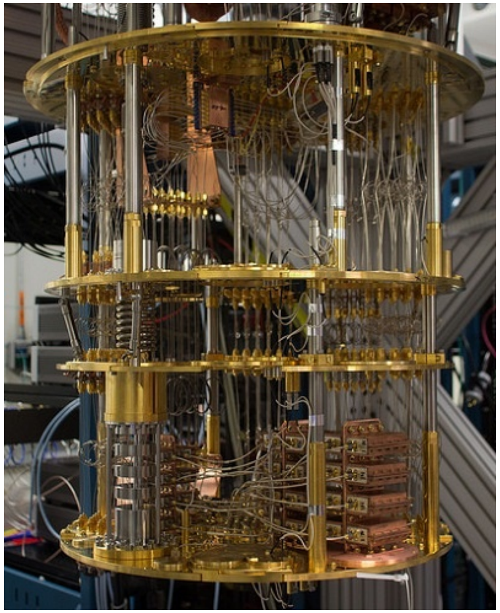
BUILDING QUANTUM COMPUTERS IS REALLY HARD!

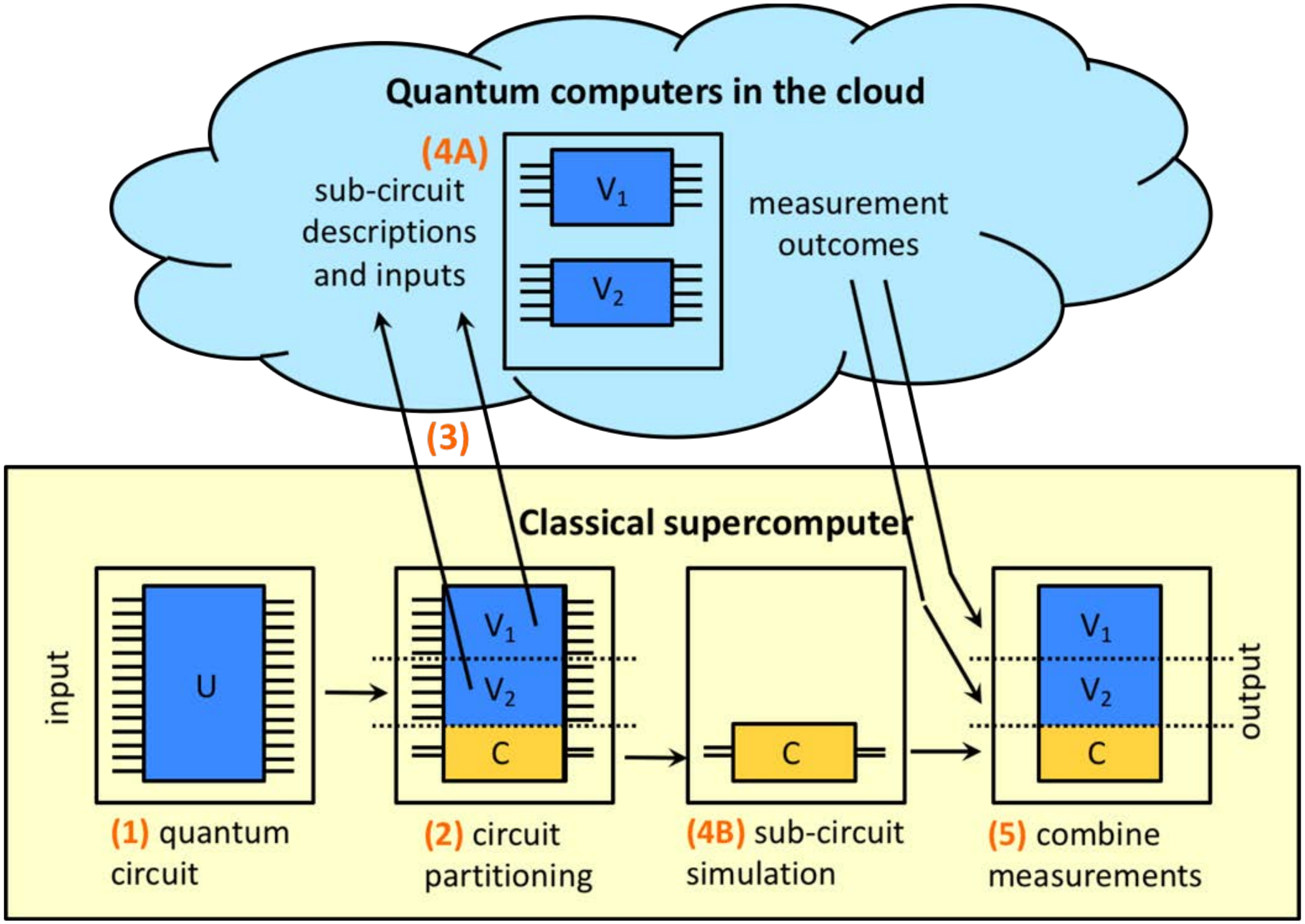


IBM Q superconducting quantum computer

- We have witnessed 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 qubits are steadily improving but will always be a fundamental challenge

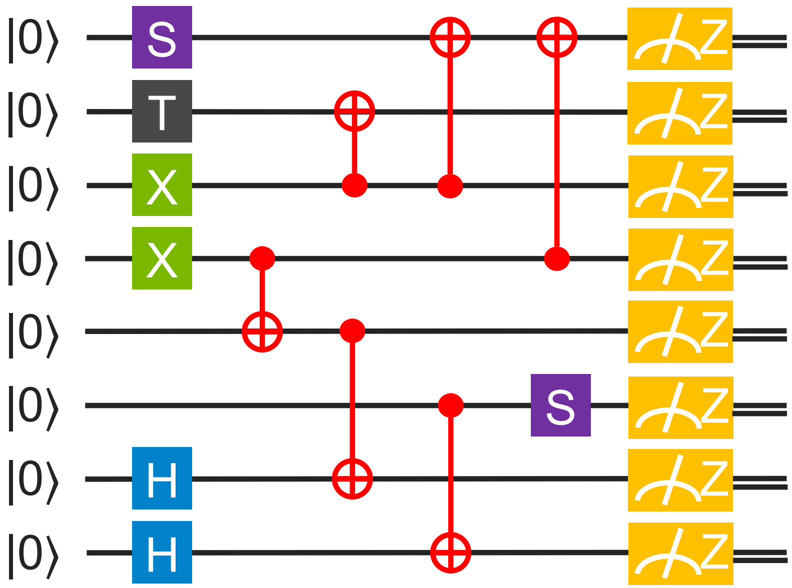
How can we use unreliable quantum processors of intermediate size to reliably solve large computational problems?

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

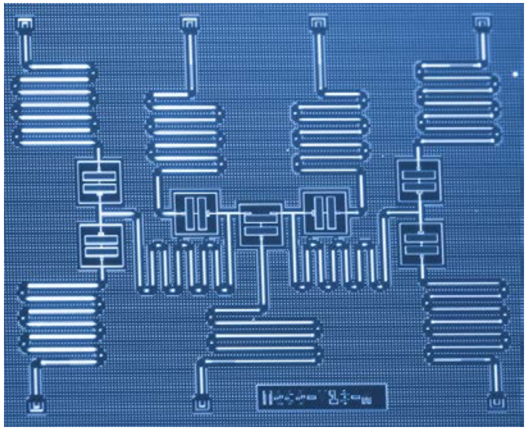


ALTERNATIVE 1: CUT A LARGE QUANTUM CIRCUIT INTO MULTIPLE SUB-CIRCUITS

Original quantum circuit:

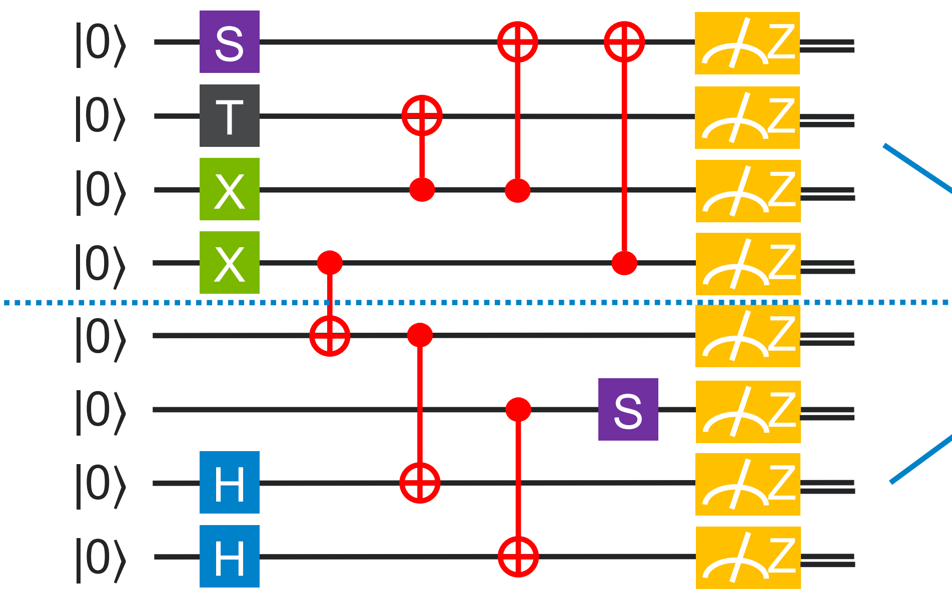


- Evaluate this circuit on a device with 7 qubits?



ALTERNATIVE 1: CUT A LARGE QUANTUM CIRCUIT INTO MULTIPLE SUB-CIRCUITS

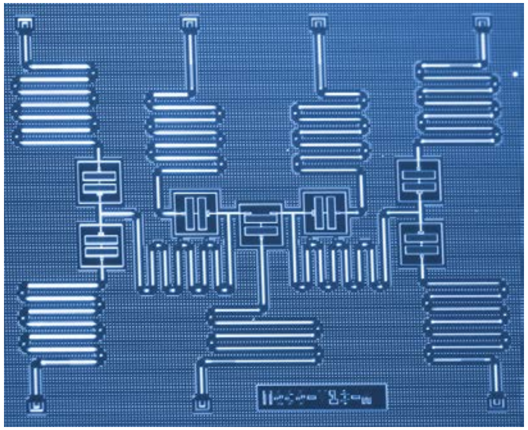
Processor A



Processor B

- *Bravyi, Smith, Smolin, Phys. Rev. X, 2016*
- *Harrow, Ozols et al., Semantic Scholar and private communication*

- Evaluate this circuit on a device with 7 qubits?



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

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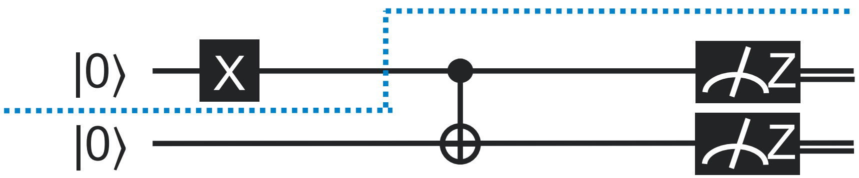

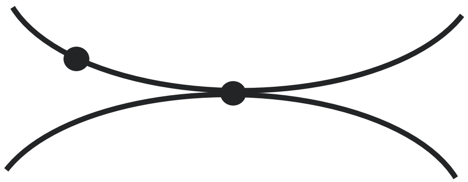

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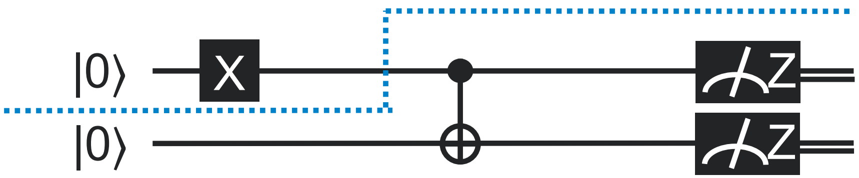
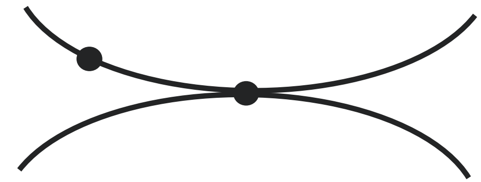
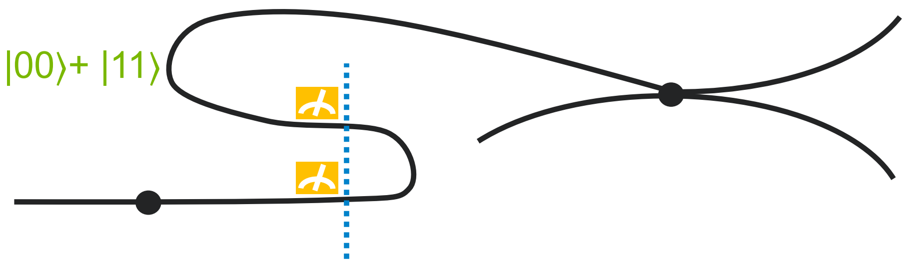




$|\Phi\rangle = \sum_i |i\rangle|i\rangle$ $\quad I = \sum_i |i\rangle\langle i|$ $\quad \langle\Phi| = \sum_i \langle i|\langle i|$



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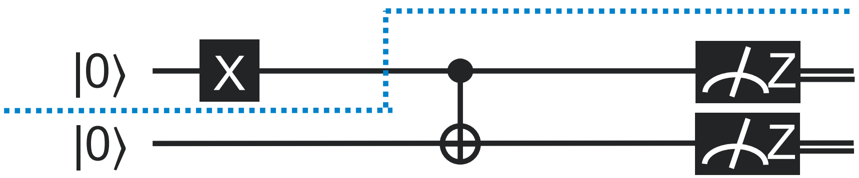

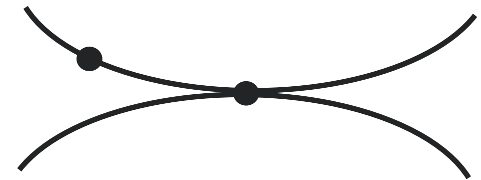

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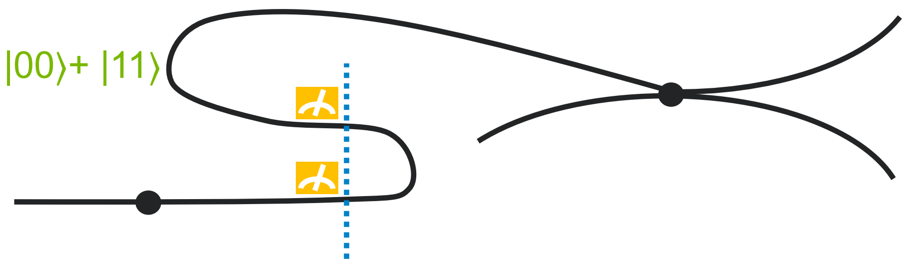
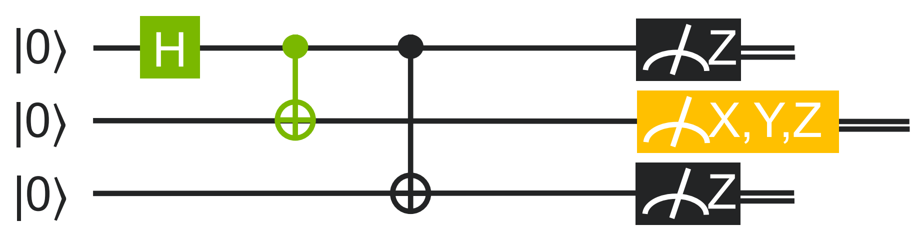


Fragment B



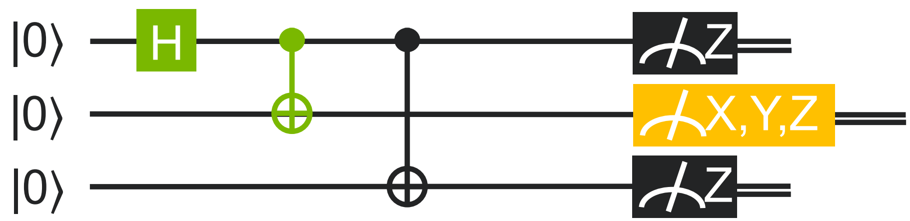
Fragment A

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



The probabilities you expect:

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

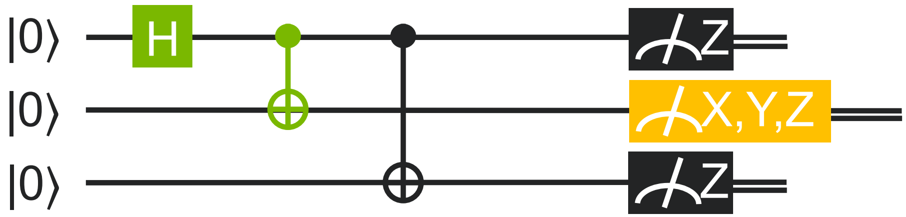
Outcome	X	Y	Z
0 0 0	0.25	0.25	0.5
0 1 0	0.25	0.25	0
1 0 1	0.25	0.25	0
1 1 1	0.25	0.25	0.5

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

Fragment B



Results with a quantum simulator:

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

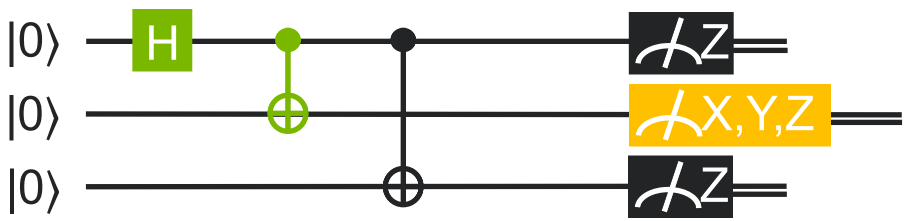
Outcome	X	Y	Z
0 0 0	0.25	0.27	0.5
0 1 0	0.26	0.25	0
1 0 1	0.24	0.25	0
1 1 1	0.25	0.23	0.5

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.:

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

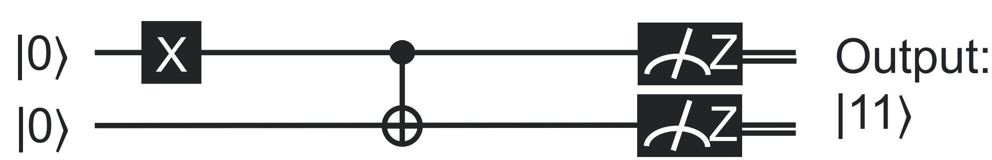
Outcome	X	Y	Z
0 0 0	0.25	0.25	0.5
0 1 0	0.25	0.25	0
1 0 1	0.25	0.25	0
1 1 1	0.25	0.25	0.5

*1 if same, *-1 if different

*-1 if same, *1 if different

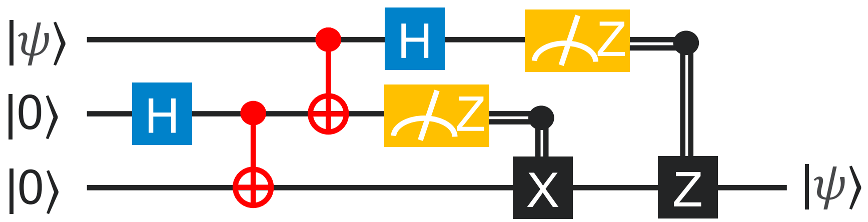
*2 if same, *0 if different

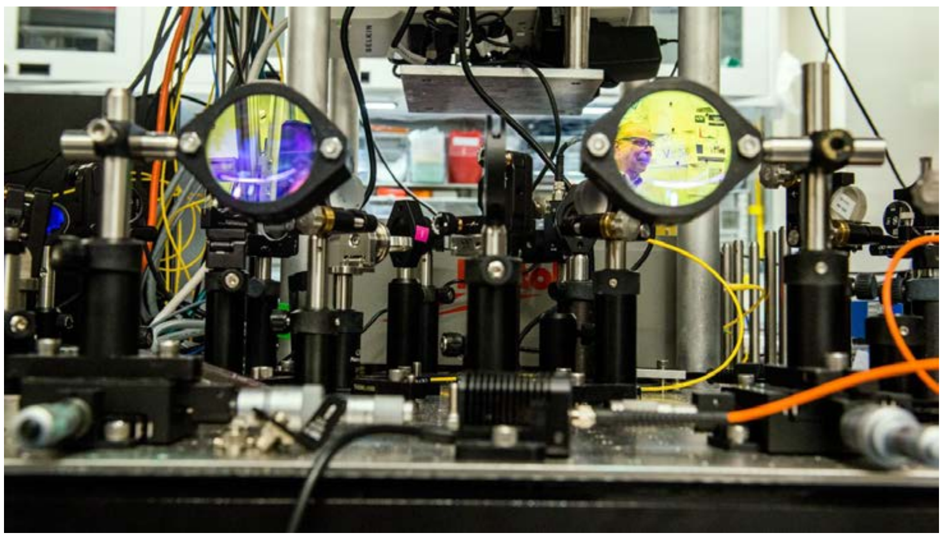
Outcome	Estimate
0 0	0
0 1	0
1 0	0
1 1	1



ALTERNATIVE 2: TELEPORT SOME QUBITS BETWEEN QUANTUM PROCESSORS

Quantum teleportation circuit:





Optical table demonstrating the principles of quantum teleportation in the Awschalom Lab (University of Chicago and Argonne)

- Quantum teleportation allows to transmit quantum state between two network hosts
- Requires distribution of entangled particles followed by classical communication
- Experimental demonstrations
- 30-mile teleportation network under construction at Argonne

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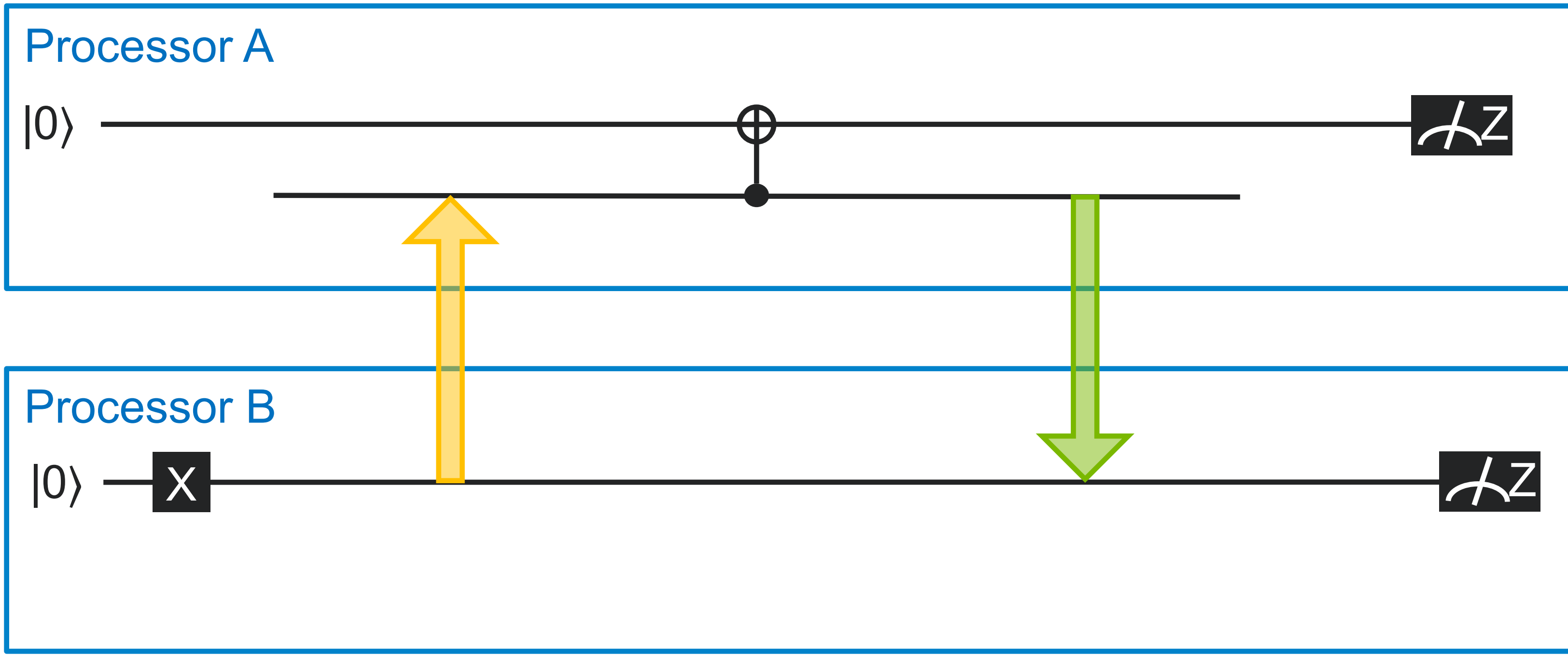

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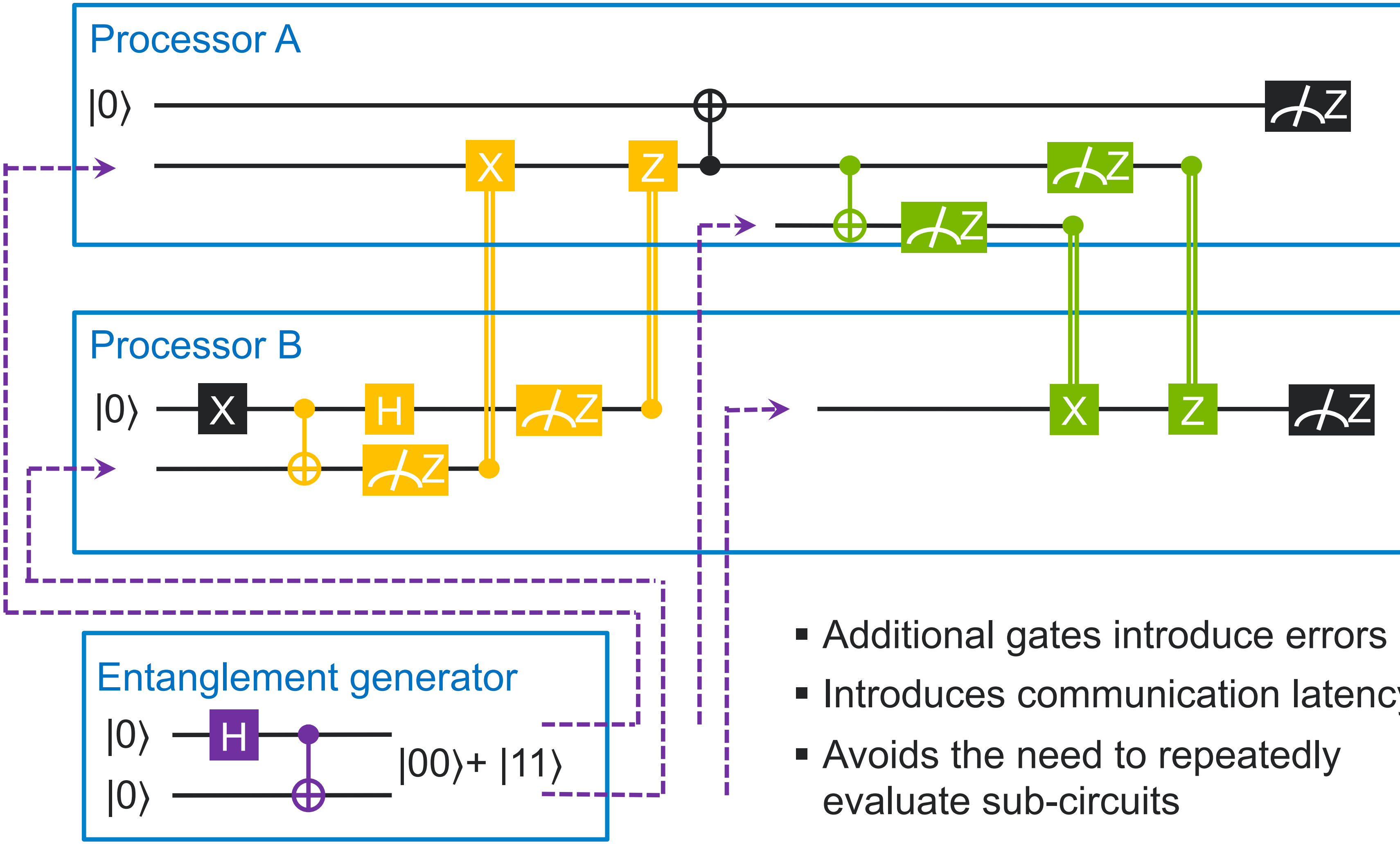
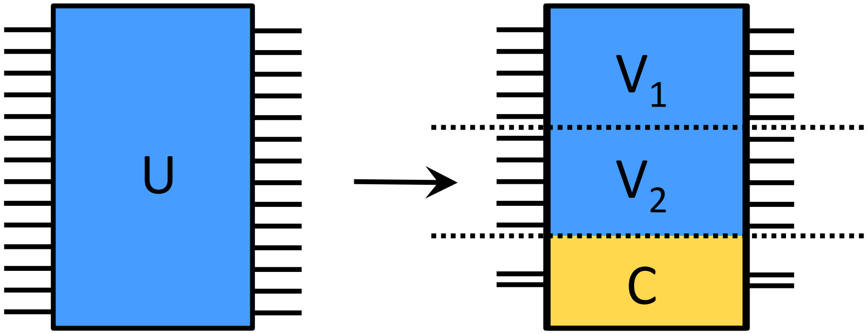
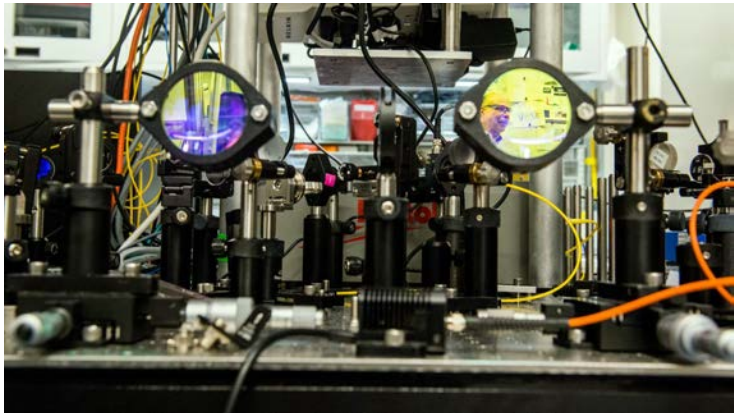


- Additional gates introduce errors
- Introduces communication latency
- Avoids the need to repeatedly evaluate sub-circuits

SUMMARY AND FUTURE WORK





- Uses small quantum processors to evaluate large circuits
- Can be done now
- Circuits must be cleanly separable
- Exponential cost depends on number of gate cuts

- New potential application for quantum teleportation networks
- Teleportation will be imperfect and will introduce latency
- Linear scaling of overhead

- Which quantum algorithms are suitable for these techniques, and which should be simulated classically?

THANK YOU!

POSTDOCTORAL AND SUMMER STUDENT POSITIONS AVAILABLE

- Requisition number 405345 on www.anl.gov
- For inquiries send email to msuchara@anl.gov

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