A systems view of quantum computer engineering
II

Wednesday, September 16, 2020

Rutgers University

Yipeng Huang

Due Sunday, Sept. 20: read one of four articles. Share sketches / notes.

- Quantum Computing: Progress and Prospects. National Academies Report. 2019.
- Quantum Computer Systems for Scientific Discovery. NSF. 2019.
- Challenges and Opportunities of Near-Term Quantum Computing Systems. IBM. 2019.
- Quantum computer architecture: towards full-stack quantum accelerators. Delft. 2019.

Due Wednesday, Sept. 23: choices for class debates / presentations.

- The schedule for in-class debates and seminar paper presentations is ready:

- https://rutgers.instructure.com/courses/73314/pages/schedule-for-in-class-debates-and-presentations

- Expectation: for course credit, each student will give two 30-minute debate or stand-alone presentations.

- Due one week before each presentation: an outline (for your first presentation) or slides (for your second presentation) for feedback.

Due Wednesday, Sept. 23: choices for class debates / presentations.

- Due Wednesday, September 23: your ranking of six most preferred presentation dates and papers. (1=most desired, 6=less desired)

- You have the option of suggesting one article outside of the papers I selected, if you have something in mind. I will check to make sure it fits with class topic.

- Consider these factors when picking: your interests, your background (e.g., HPC, microarchitecture, device physics, etc.), time commitments (other class projects, research deadlines).

- Please use Friday 11am office hours, or by appointment, or email for guidance on what papers to read and present.

Due Wednesday, Sept. 23: choices for class debates / presentations.

- I will do my best to honor everyone's top picks.
- But I will also aim to have good distribution of topics among the paper options and across class days.
- Hopefully, asking you to pick six options will lead to good distribution, but if that is not the case, I may ask for another round of selection.

Class grading rubric will be as follows:

- 2 × 25 points on the presentations
- 2 × 25 points on the programming exercises
- Week-to-week, I may have 5-point assignments to encourage engagement and to spur discussion about the papers.

These two lectures: Broad view of open challenges in quantum computer engineering

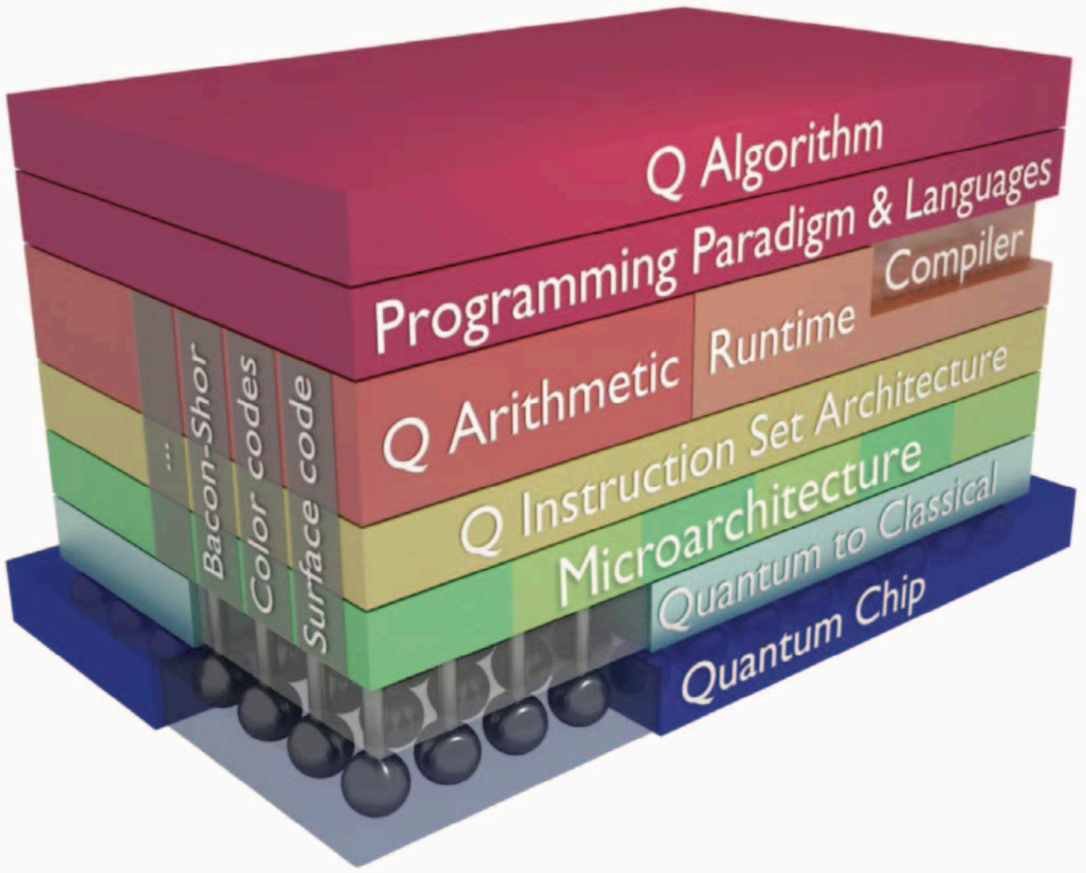


Figure 1. Overview of the quantum computer system stack.

A Microarchitecture for a Superconducting Quantum Processor. Fu et al.

- A complete view of full-stack quantum computing.
- In short, challenges are in finding and building abstractions.
- In each layer, why we don't or can't have good abstractions right now.
- Recent and rapidly developing field of research.

All the quantum computer abstractions we don’t yet have right now

0. Quantum computer support for quantum computer engineering
1. Fault-tolerant, error-corrected quantum algorithms
2. Mature, high level quantum programming languages
3. Universally accepted quantum ISAs
4. Uniform, fully connected quantum device architectures
5. Reliable quantum gates and qubits

Shor's integer factoring algorithm

Factoring underpins cryptosystems.

For number represented as N bits—

Classical algorithm: needs $O(2^{\sqrt[3]{N}})$ operations

Factoring 512-bit integer: 8400 years. 1024-bit integer: $13*10^{12}$ years.

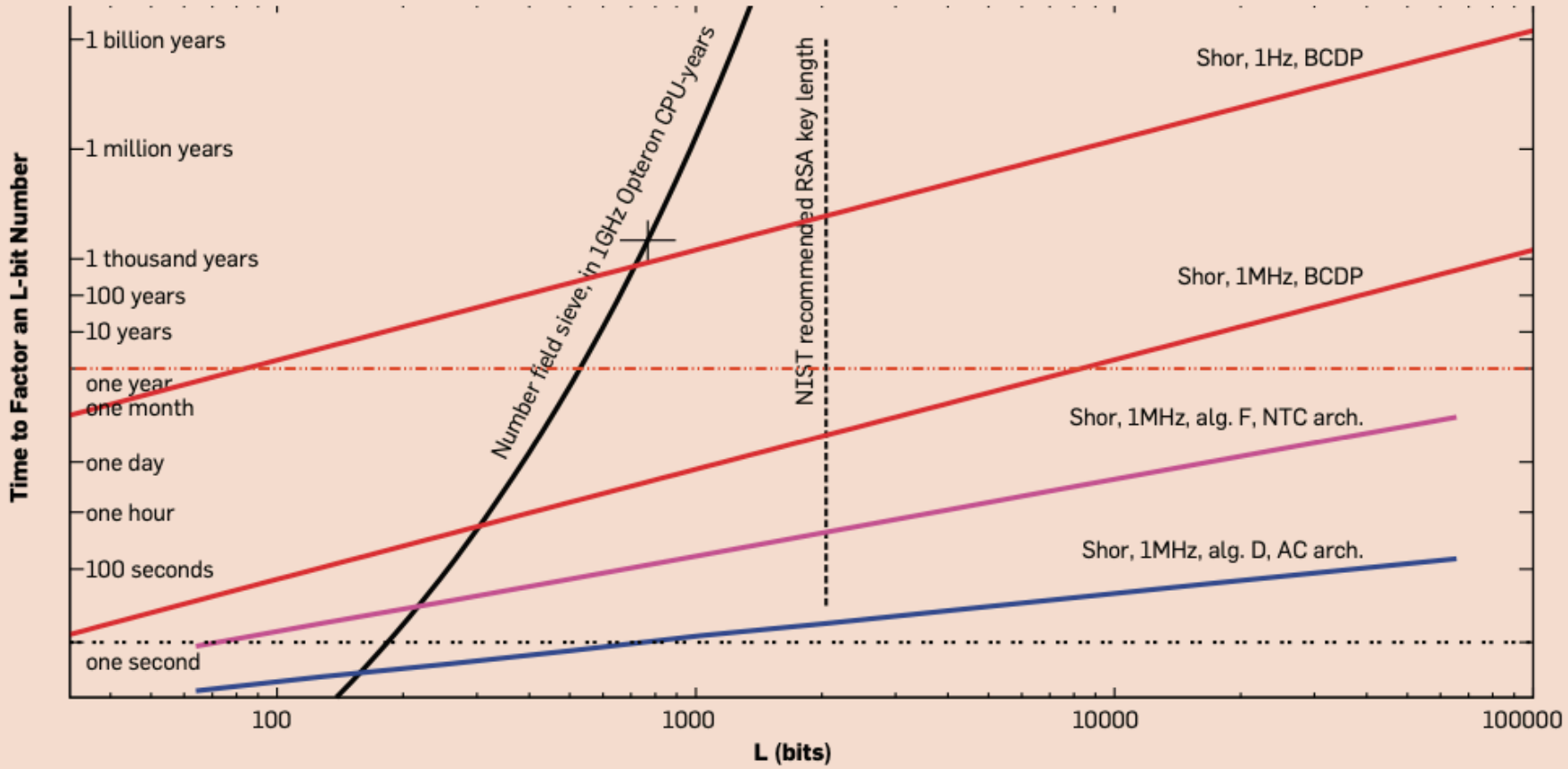
Quantum algorithm: needs $O(N^2 \log(N))$ operations

Factoring 512-bit integer: 3.5 hours. 1024-bit integer: 31 hours.

A Practical Architecture for Reliable Quantum Computers. Oskin et al.

Figure 1. Scaling the classical number field sieve (NFS) vs. Shor's quantum algorithm for factoring.[37]

The horizontal axis is the length of the number to be factored. The steep curve is NFS, with the marked point at $L = 768$ requiring 3,300 CPU-years. The vertical line at $L = 2048$ is NIST's 2007 recommendation for RSA key length for data intended to remain secure until 2030. The other lines are various combinations of quantum computer logical clock speed for a three-qubit operation known as a Toffoli gate (1Hz and 1MHz), method of implementing the arithmetic portion of Shor's algorithm (BCDP, D, and F), and quantum computer architecture (NTC and AC, with the primary difference being whether or not long-distance operations are supported). The assumed capacity of a machine in this graph is $2L^2$ logical qubits. This figure illustrates the difficulty of making pronouncements about the speed of quantum computers.



A Blueprint for Building a Quantum Computer. Van Meter and Horsman.

What are the societal impacts?

- Is it good to threaten the cryptosystems that underpin secure and private communications? No!
- But, current crypto systems rely on assumptions about hardness of tasks, such as factoring and discrete logarithm.
- Developments in quantum algorithms pushes the boundary of what we know is easy vs. hard.
- Spurs the development of more secure cryptosystems (lattices, etc.).

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Three abstraction challenges for quantum programming:

- ***Truly high-level quantum algorithm programming abstractions.***

- Widely adopted, high performance, open source source language.

- More expressive quantum intermediate representations.

What do we mean by high-level language?

```
// Create a list of strings
ArrayList<String> al = new ArrayList<String>();
al.add("Quantum");
al.add("Computing");
al.add("Programs");
al.add("Systems");

/* Collections.sort method is sorting the
elements of ArrayList in ascending order. */
Collections.sort(al);
```

High-level language hides all these concerns:

- Choice of sorting algorithm implementation and comparator function on Strings
- Encoding of Strings as binary numbers
- Memory allocation and deallocation for String storage
- Execution of Java code on different ISAs
- Correctness of library implementation
- …

- We want to get to that point with quantum programming

- Want to do things such as: initialize quantum data, perform search, without worrying about the detailed implementation

Grover's database search

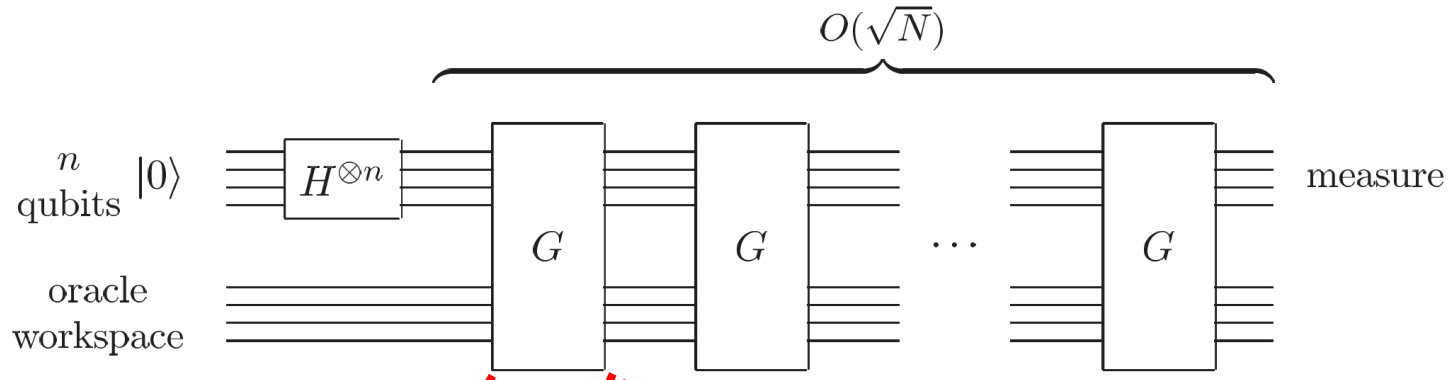
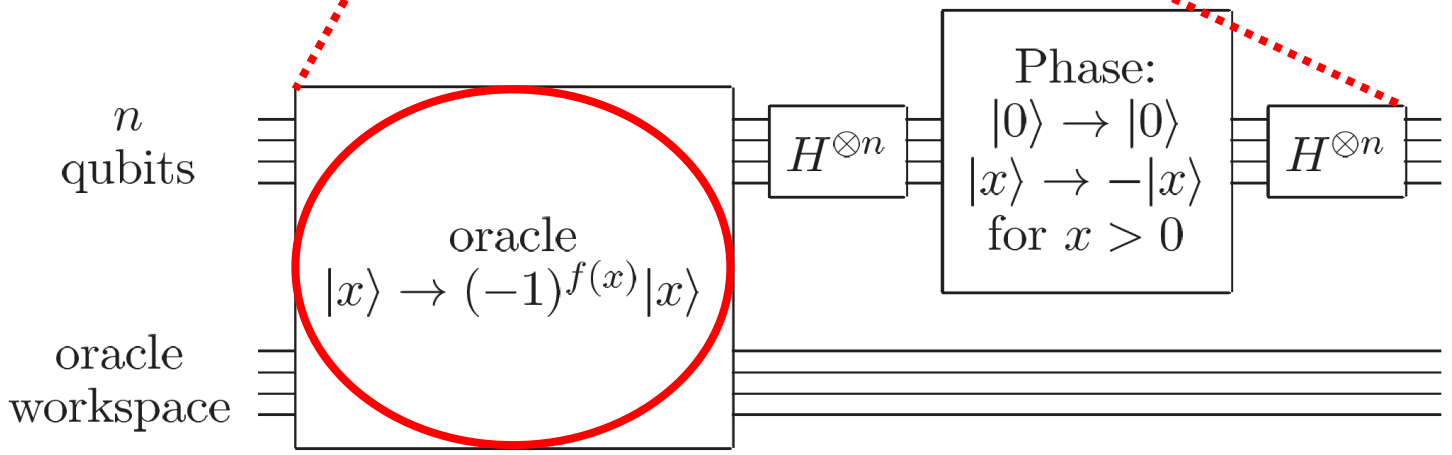


Figure 6.1. Schematic circuit for the quantum search algorithm. The oracle may employ work qubits for its implementation, but the analysis of the quantum search algorithm involves only the n qubit register.



Operations based on classical problem information

Figure 6.2. Circuit for the Grover iteration, G.

Nielsen and Chuang, p251

Table 7 Grover's amplitude amplification subroutine in two languages, showcasing QC-specific language syntax for reversible computation (rows 2 & 6) and controlled operations (rows 3 & 5).

	Scaffold (C syntax) [13]	**ProjectQ (Python syntax) [36]**

1	`int j;`
	`qbit ancilla[n-1]; // scratch register`
	`for(j=0; j<n-1; j++) PrepZ(ancilla[j],0);`
		`# reflection across`
		`# uniform superposition`

2	`// Hadamard on q`
	`for(j=0; j<n; j++) H(q[j]);`
	`// Phase flip on q = 0...0 so invert q`
	`for(j=0; j<n; j++) X(q[j]);`
		`with Compute(eng):`
		`  All(H) | q`
		`  All(X) | q`

3	`// Compute x[n-2] = q[0] and ... and q[n-1]`
	`CCNOT(q[1], q[0], ancilla[0]);`
	`for(j=1; j<n-1; j++)`
	`  CCNOT(ancilla[j-1], q[j+1], ancilla[j]);`
		`with Control(eng, q[0:-1]):`

4	`// Phase flip Z if q=00...0` `cZ(ancilla[n-2], q[n-1]);`	`  Z | q[-1]`

5	`// Undo the local registers`
	`for(j=n-2; j>0; j-)`
	`  CCNOT(ancilla[j-1], q[j+1], ancilla[j]);`
	`CCNOT(q[1], q[0], ancilla[0]);`
		`# ProjectQ automatically`
		`# uncomputes control`

6	`// Restore q`
	`for(j=0; j<n; j++) X(q[j]);`
	`for(j=0; j<n; j++) H(q[j]);`
		`Uncompute(eng)`

QDB: From Quantum Algorithms Towards Correct Quantum Programs. Huang and Martonosi.

Three abstraction challenges for quantum programming:

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- ***Widely adopted, high performance, open source source language.***
- More expressive quantum intermediate representations.

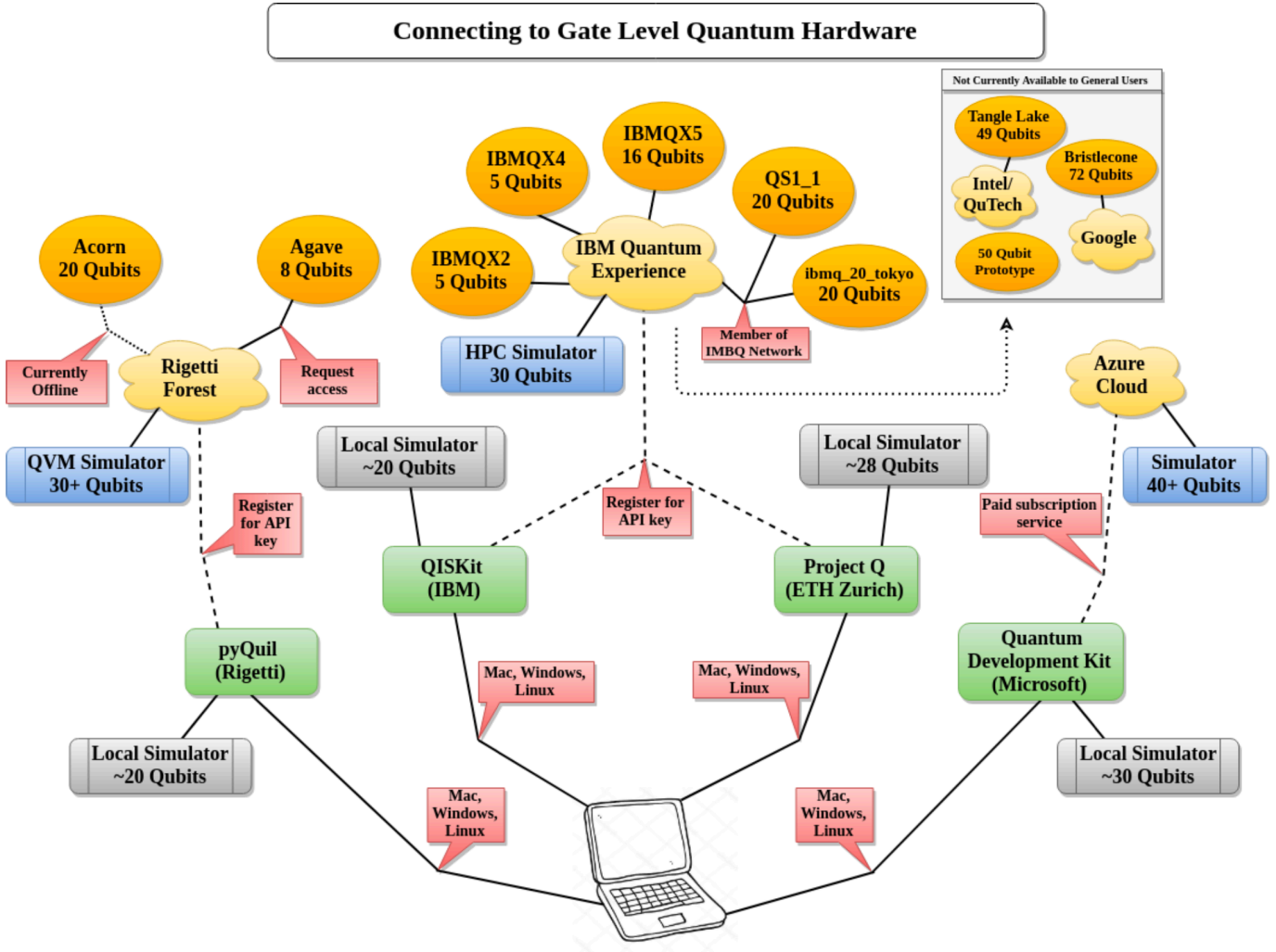

FIG. 1: A schematic diagram showing the paths to connecting a personal computer to a usable gate-level quantum computer. Starting from the personal computer (bottom center), nodes in green shows software that can be installed on the user's personal computer. Grey nodes show simulators run locally (i.e., on the user's computer). Dashed lines show API/cloud connections to company resources shown in yellow clouds. Quantum simulators and usable quantum computers provided by these cloud resources are shown in blue and gold, respectively. Red boxes show requirements along the way. For example, to connect to Rigetti Forest and use the Agave 8 qubit quantum computer, one must download and install pyQuil (available on macOS, Windows, and Linux), register on Rigetti's website to get an API key, then request access to the device via an online form. Notes: (i) Rigetti's Quantum Virtual Machine requires an upgrade for more than 30 qubits, (ii) local simulators depend on the user's computer so numbers given are approximates, and (iii) the grey box shows quantum computers that have been announced but are not currently available to general users.

Overview and Comparison of Gate Level Quantum Software Platforms. LaRose.

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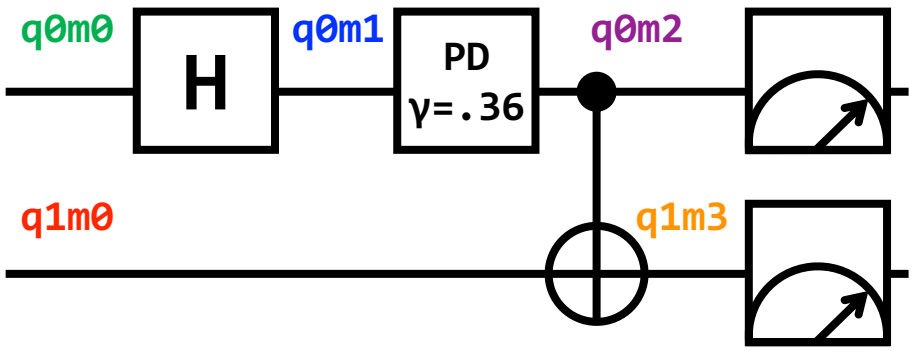
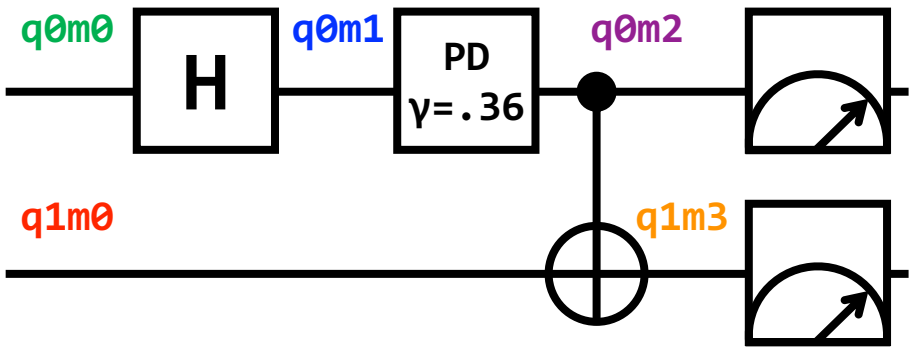

q0m0
H
q0m1
PD
γ=.36
q0m2
q1m0
q1m3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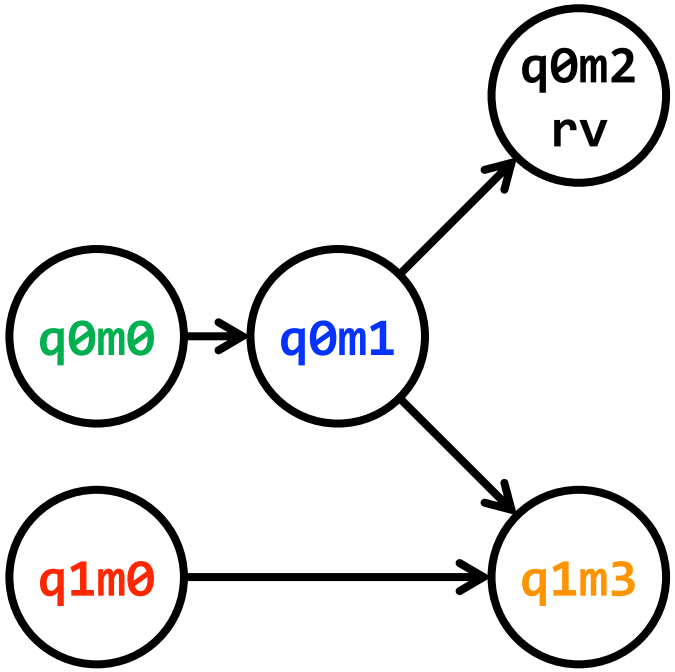
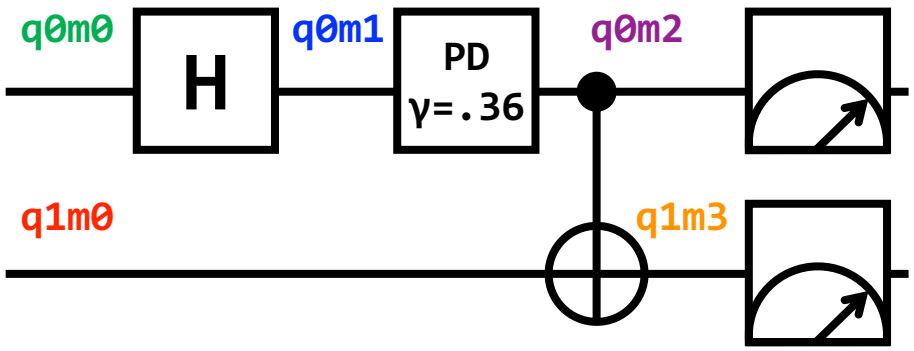
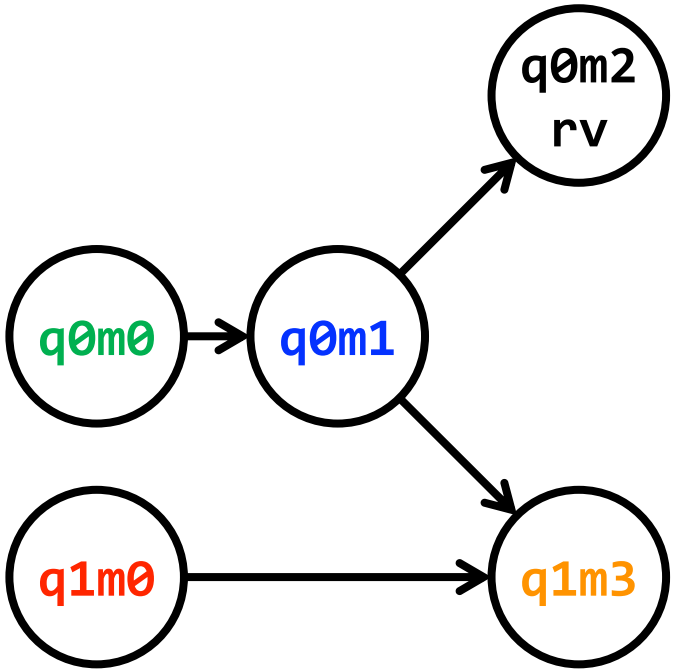
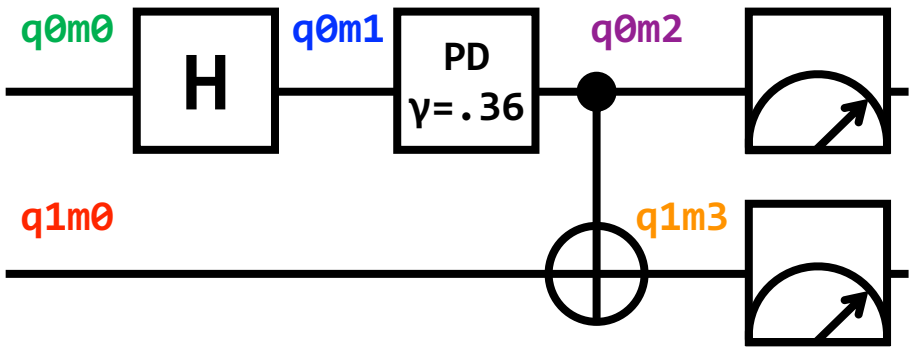
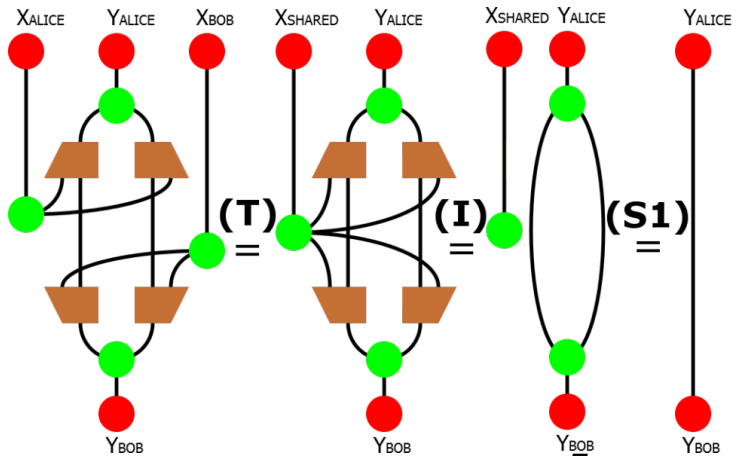

q0m2
rv
q0m0
q0m1
q1m0
q1m3



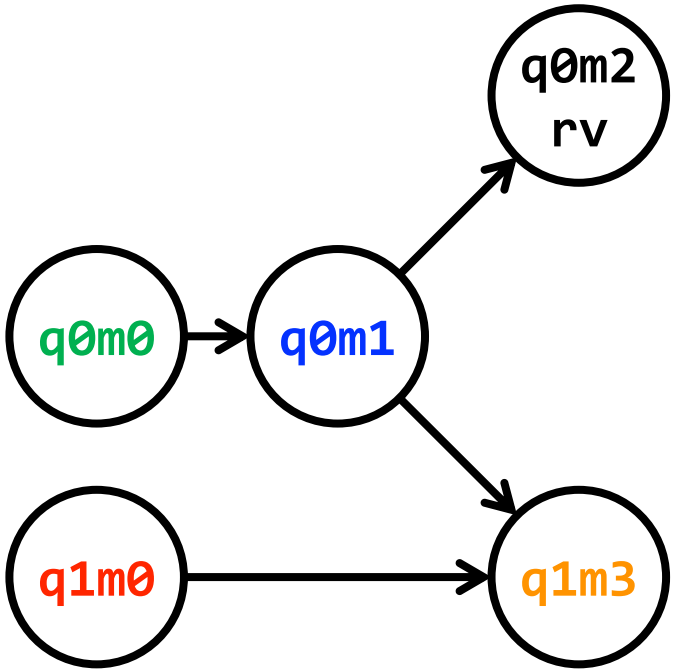


Qubits take on binary values; supply initial qubit values	$\texttt{q0m0} = \|0\rangle \oplus \texttt{q0m0} = \|1\rangle$ $\texttt{q0m0} = \|0\rangle$ $\texttt{q0m1} = \|0\rangle \oplus \texttt{q0m1} = \|1\rangle$	$\texttt{q1m0} = \|0\rangle \oplus \texttt{q1m0} = \|1\rangle$ $\texttt{q1m0} = \|0\rangle$ $\texttt{q1m3} = \|0\rangle \oplus \texttt{q1m3} = \|1\rangle$
Hadamard gate	$\texttt{q0m0} = \|0\rangle \wedge \texttt{q0m1} = \|0\rangle \implies +\frac{1}{\sqrt{2}}$ $\texttt{q0m0} = \|1\rangle \wedge \texttt{q0m1} = \|0\rangle \implies +\frac{1}{\sqrt{2}}$	$\texttt{q0m0} = \|0\rangle \wedge \texttt{q0m1} = \|1\rangle \implies +\frac{1}{\sqrt{2}}$ $\texttt{q0m0} = \|1\rangle \wedge \texttt{q0m1} = \|1\rangle \implies -\frac{1}{\sqrt{2}}$
Phase damping noise channel	$\texttt{q0m2rv} = 0 \oplus \texttt{q0m2rv} = 1$ $\texttt{q0m1} = \|0\rangle \implies \texttt{q0m2rv} = 0$	$\texttt{q0m1} = \|1\rangle \wedge \texttt{q0m2rv} = 0 \implies +0.8$ $\texttt{q0m1} = \|1\rangle \wedge \texttt{q0m2rv} = 1 \implies -0.6$
CNOT gate	$\texttt{q0m1} = \|0\rangle \wedge \texttt{q1m0} = \|0\rangle \implies \texttt{q1m3} = \|0\rangle$ $\texttt{q0m1} = \|0\rangle \wedge \texttt{q1m0} = \|1\rangle \implies \texttt{q1m3} = \|1\rangle$	$\texttt{q0m1} = \|1\rangle \wedge \texttt{q1m0} = \|0\rangle \implies \texttt{q1m3} = \|1\rangle$ $\texttt{q0m1} = \|1\rangle \wedge \texttt{q1m0} = \|1\rangle \implies \texttt{q1m3} = \|0\rangle$





Benchmarking ZX Calculus Circuit Optimization Against Qiskit Transpilation. Yeh et al.



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A small set of quantum gates are universal…

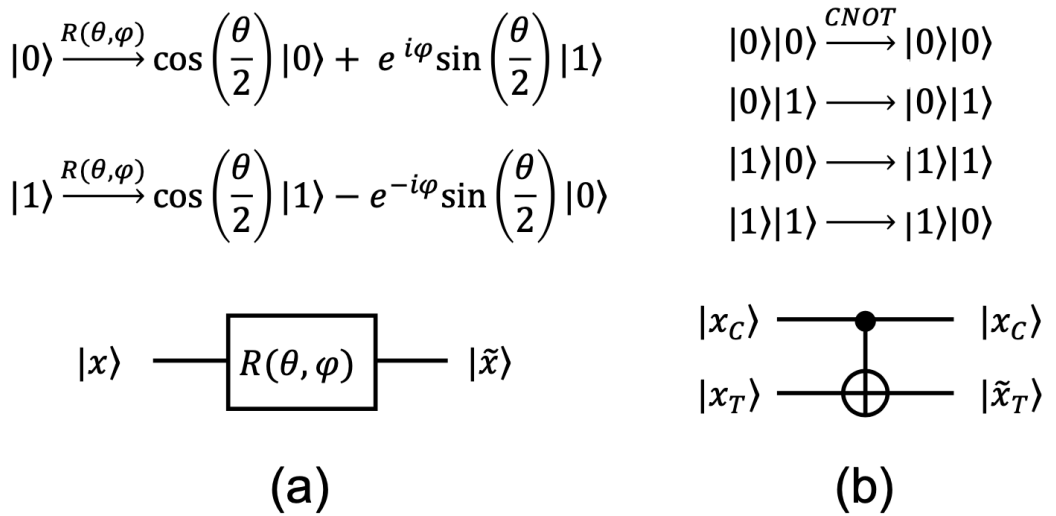
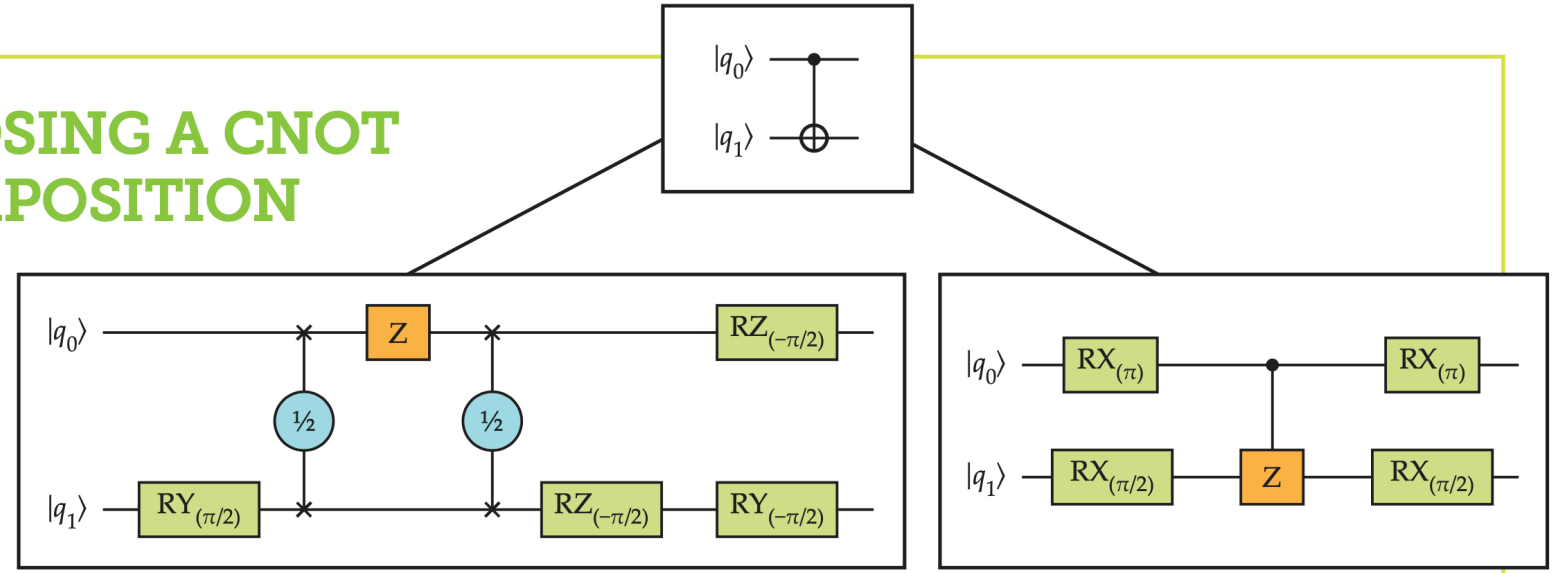


FIG. 1. The rotation and controlled-NOT (CNOT) gates are an example of a universal quantum gate family when available on all qubits, with explicit evolution (above) and quantum circuit block schematics (below). (a) The single-qubit rotation gate $R(\theta, \phi)$, with two continuous parameters θ and ϕ, evolves input qubit state $|x\rangle$ to output state $|\tilde{x}\rangle$. (b) The CNOT (or reversible XOR) gate on two qubits evolves two (control and target) input qubit states $|x_C\rangle$ and $|x_T\rangle$ to output states $|\tilde{x}_C = x_C\rangle$ and $|\tilde{x}_T = x_C \oplus x_T\rangle$, where $\oplus$ is addition modulo 2, or equivalently the XOR operation.

Quantum Computer Systems for Scientific Discovery. Alexeev et al.

…but those universal gates decompose various ways…

BOX 2. CHOOSING A CNOT GATE DECOMPOSITION



A logical controlled-NOT, or CNOT, gate is an entangling operation that flips the target qubit between 1 and 0 if the control qubit is in the 1 state. It must be decomposed into a sequence of native quantum gates for the qubit technology to perform the gate operation on the specific qubit system. Two possible decompositions are shown, where RX, RY, and RZ denote rotations around the *x*-, *y*- and *z*-axes, respectively. A system performance simulation could provide metrics to help choose which CNOT to incorporate into the specific design.

Depending on the fidelity of the single- and two-qubit gates in the circuits and on their speed, researchers may want to choose only one to implement the logical CNOT in the system. Depending on the performance of the qubits available at a particular point in the execution of the algorithm, it is also possible to choose a different logical CNOT sequence.

A systems perspective of quantum computing. Matsuura et al.

…and different quantum hardware support different gates.

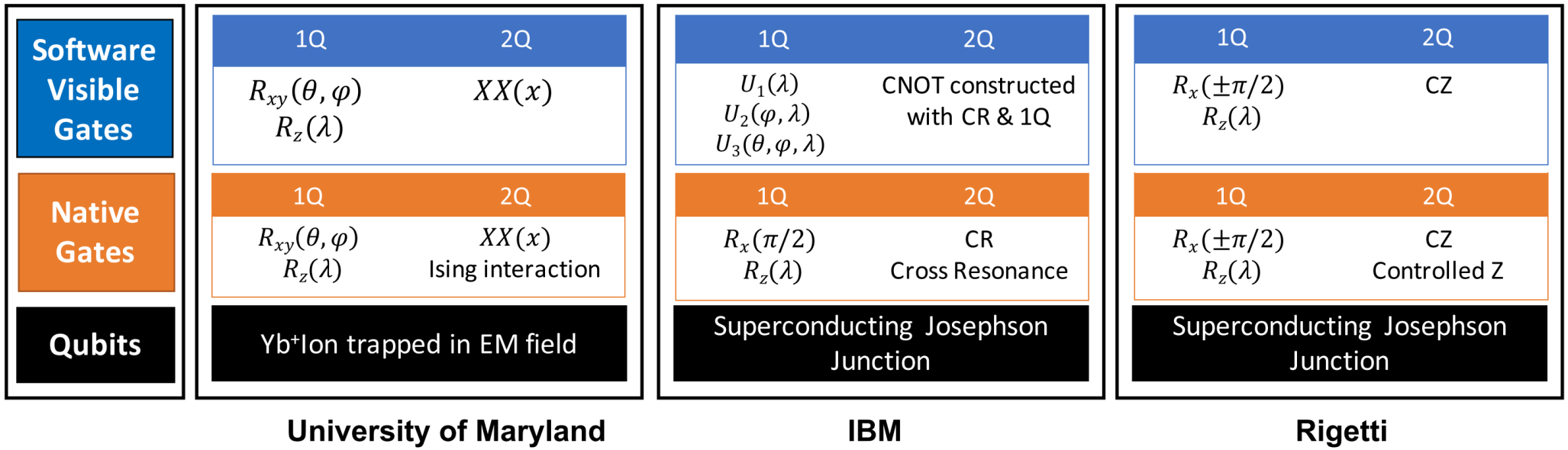


Figure 1. Hardware qubit technology, native gate set, and software-visible gate set in the systems used in our study. Each qubit technology lends itself to a set of native gates. For programming, vendors expose these gates in a software-visible interface or construct composite gates with multiple native gates.

Architecting Noisy Intermediate-Scale Quantum Computers: A Real-System Study. Murali et al.

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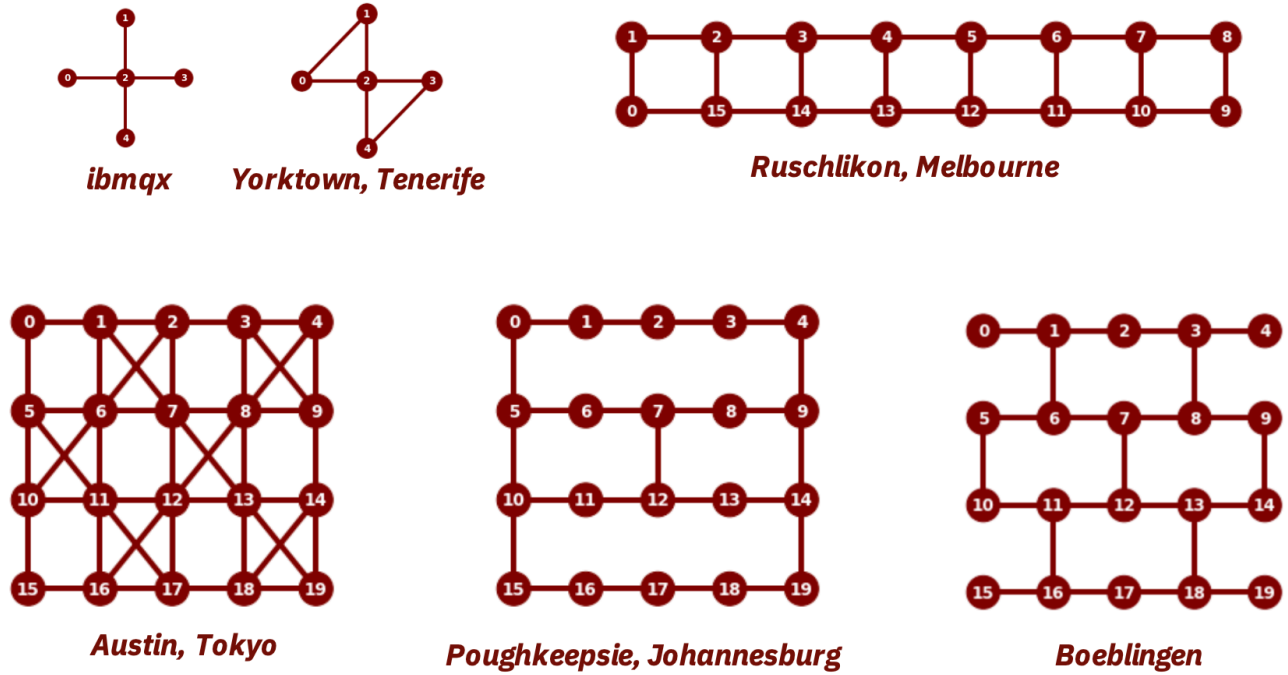

Fig. 1. Examples of several IBM cloud accessible devices. The top left 5-qubit device was the first one made available via the IBM Quantum Experience [40]. The one to the right of it was made available after including additional entangling gates between two pairs of qubits. A 16-qubit device was made available approximately a year after the first device. The devices in the bottom row show three variations of 20-qubit devices available to members of the IBM Q Network [41].

Challenges and Opportunities of Near-Term Quantum Computing Systems. Corcoles et al.

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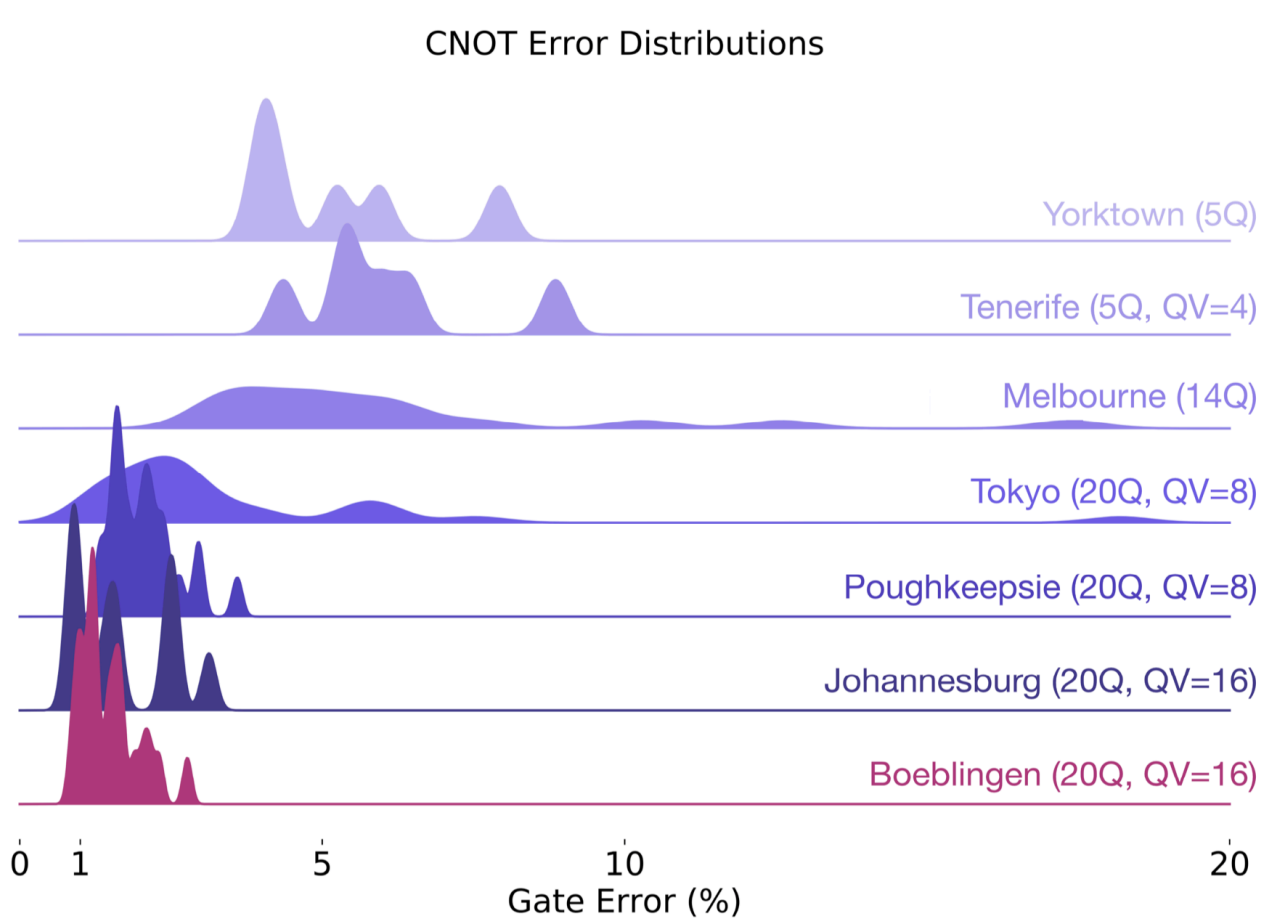

Fig. 2. Controlled-NOT (CNOT) gate error distributions for a variety of IBM devices. Beginning with the earlier devices (top rows), the average error rates remained quite large but have improved with continuing research. The bottom row represents the device shown in Fig. 4. The error reductions are the result of improved gate fidelities and increasing coherence times [44], [45], as well as a better understanding of spectator qubit errors.

Challenges and Opportunities of Near-Term Quantum Computing Systems. Corcoles et al.

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Position statement for this graduate seminar

- Quantum computer engineering has become important.
- Requires computer systems expertise beyond quantum algorithms and quantum device physics.