A systems view of quantum computer engineering

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Rutgers University

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Position statement for this graduate seminar

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

The role of abstractions in classical computing

What is an abstraction?

What are examples of abstractions?

Why are abstractions good and important?

The role of abstractions in classical computing

What is an abstraction?

What are examples of abstractions?

- APIs, Python, C, assembly, machine code (ISA), CPU-memory (von Neumann), pipeline, gates, binary, discrete time evolution

Why are abstractions good and important?

Hides details so that users & programmers can be creative

The role of abstractions in classical computing

Are abstractions always good?

What are examples of deliberately breaking abstractions?

The role of abstractions in classical computing

Are abstractions always good?

What are examples of deliberately breaking abstractions?

- Python calling C binary (Breaking interpreted high level PL abstraction)
- Assembly code routines (Breaking structured programming abstraction)
- FPGAs (Breaking ISA abstraction)
- ASICs (Breaking von Neumann abstraction)

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

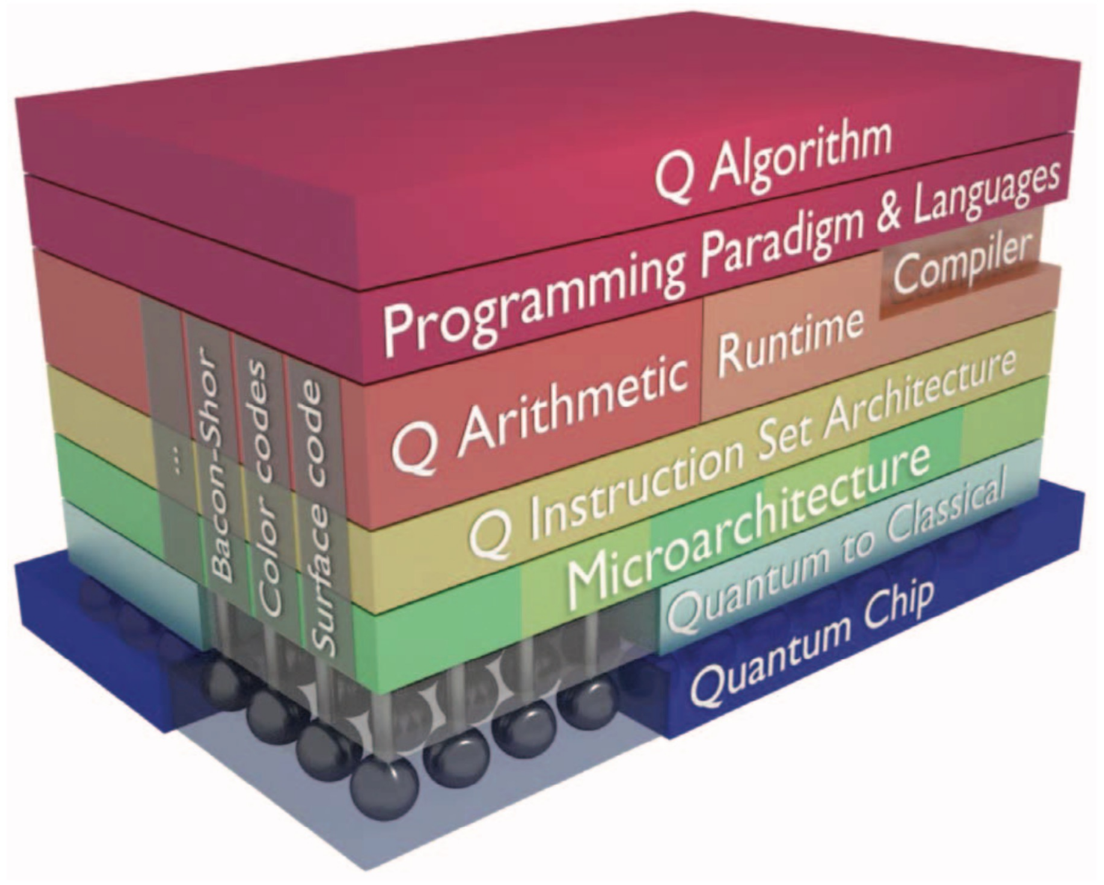

Figure 1. Overview of the quantum computer system stack.

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

1. Fault-tolerant, error-corrected quantum computers for algorithms
2. Programming: High level languages to aid algorithm discovery
3. Programming: Facilities for program correctness (debuggers, assertions)
4. Programming: Intermediate representations that aid analysis
5. Simulation: Support to validate and design next-gen quantum computers
6. Architecture: Standard instruction set architectures
7. Architecture: Memory hierarchy to store quantum data
8. Microarchitecture: Abundant and reliable quantum devices

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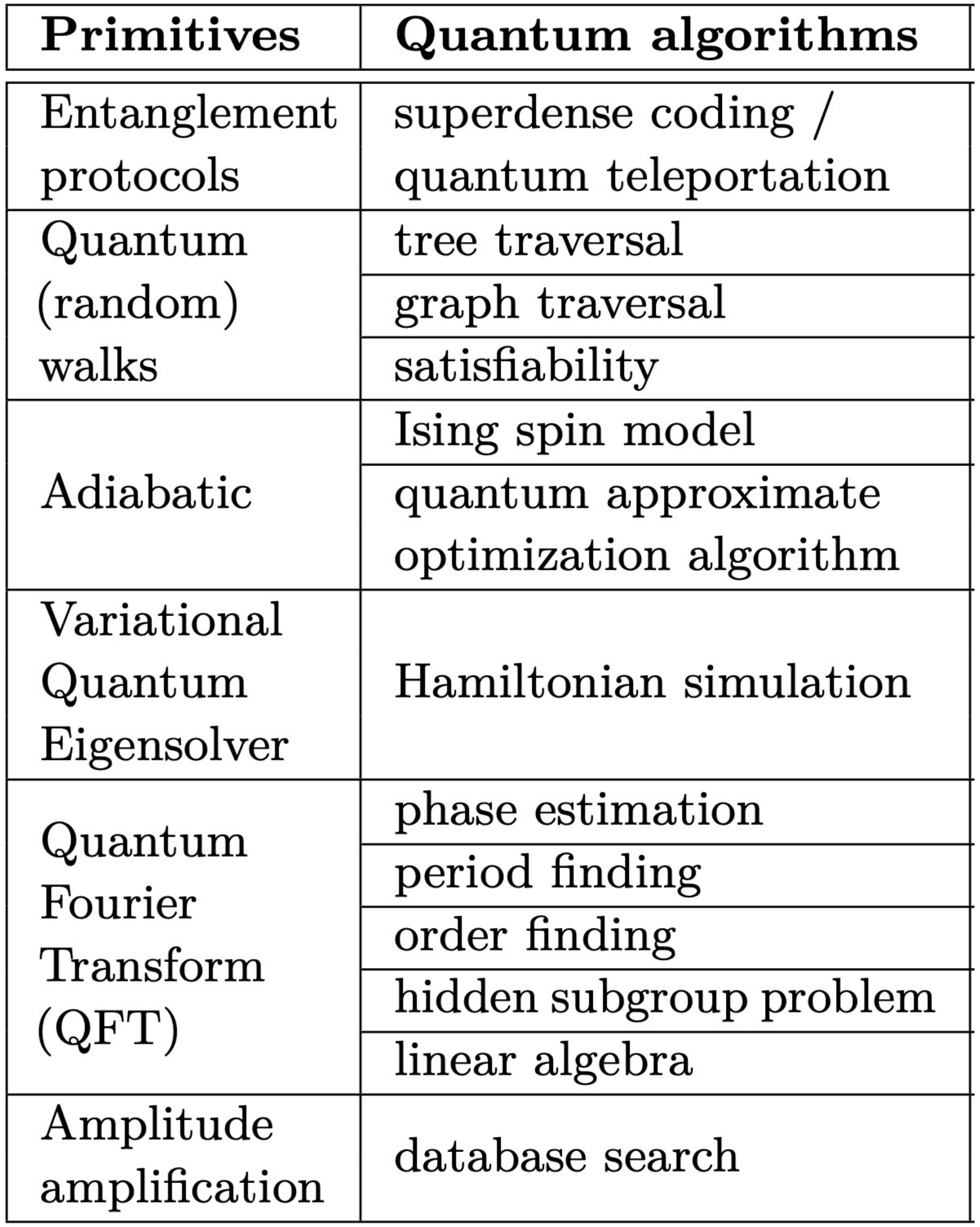
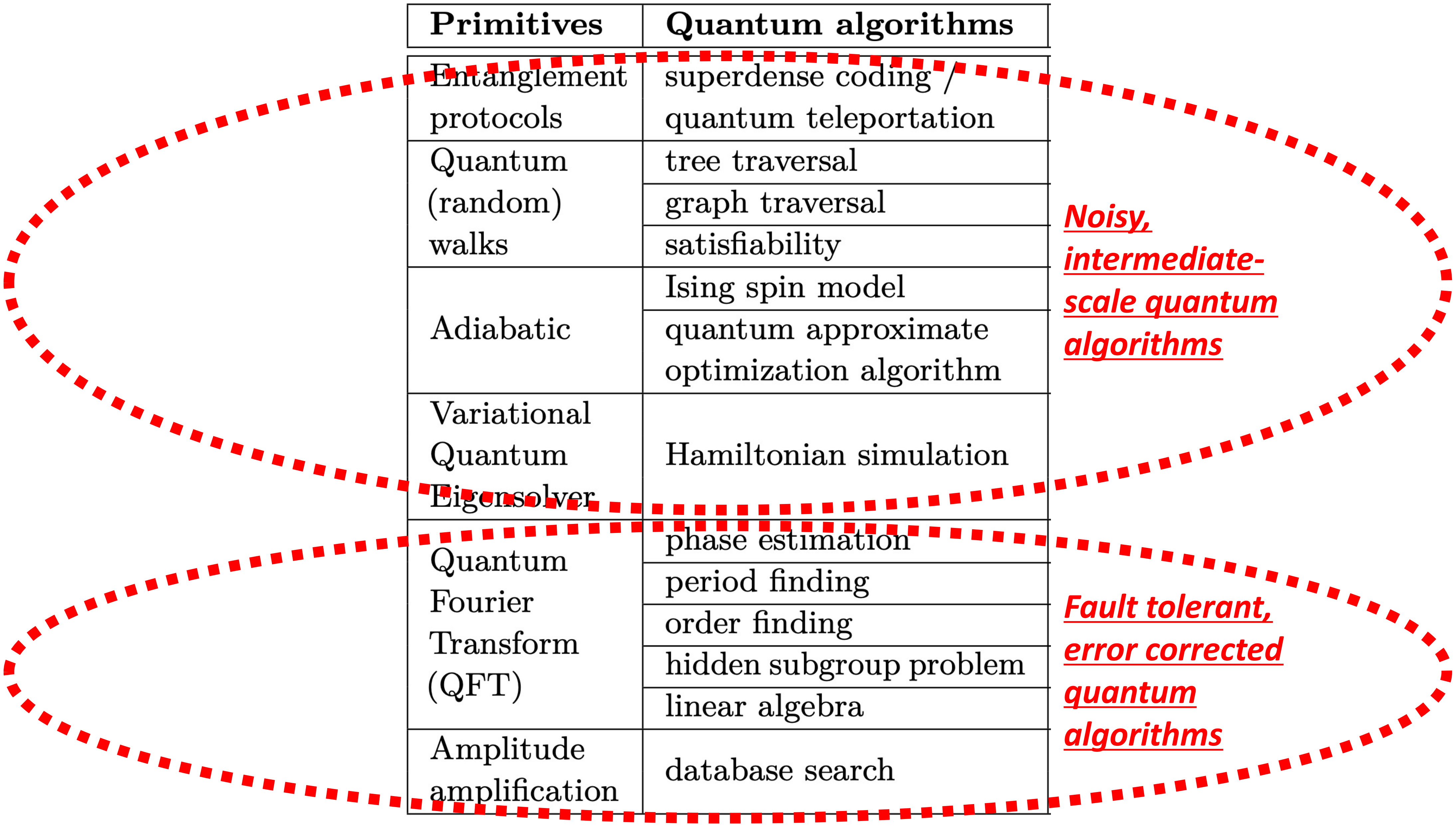


Primitives	**Quantum algorithms**
Entanglement protocols	superdense coding / quantum teleportation
Quantum (random) walks	tree traversal
	graph traversal
	satisfiability
Adiabatic	Ising spin model
	quantum approximate optimization algorithm
Variational Quantum Eigensolver	Hamiltonian simulation
Quantum Fourier Transform (QFT)	phase estimation
	period finding
	order finding
	hidden subgroup problem
	linear algebra
Amplitude amplification	database search

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



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Noisy, intermediate-scale quantum algorithms

Fault tolerant, error corrected quantum algorithms

Shor’s integer factoring algorithm

Factoring underpins cryptosystems.

For number represented as N bits—

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

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

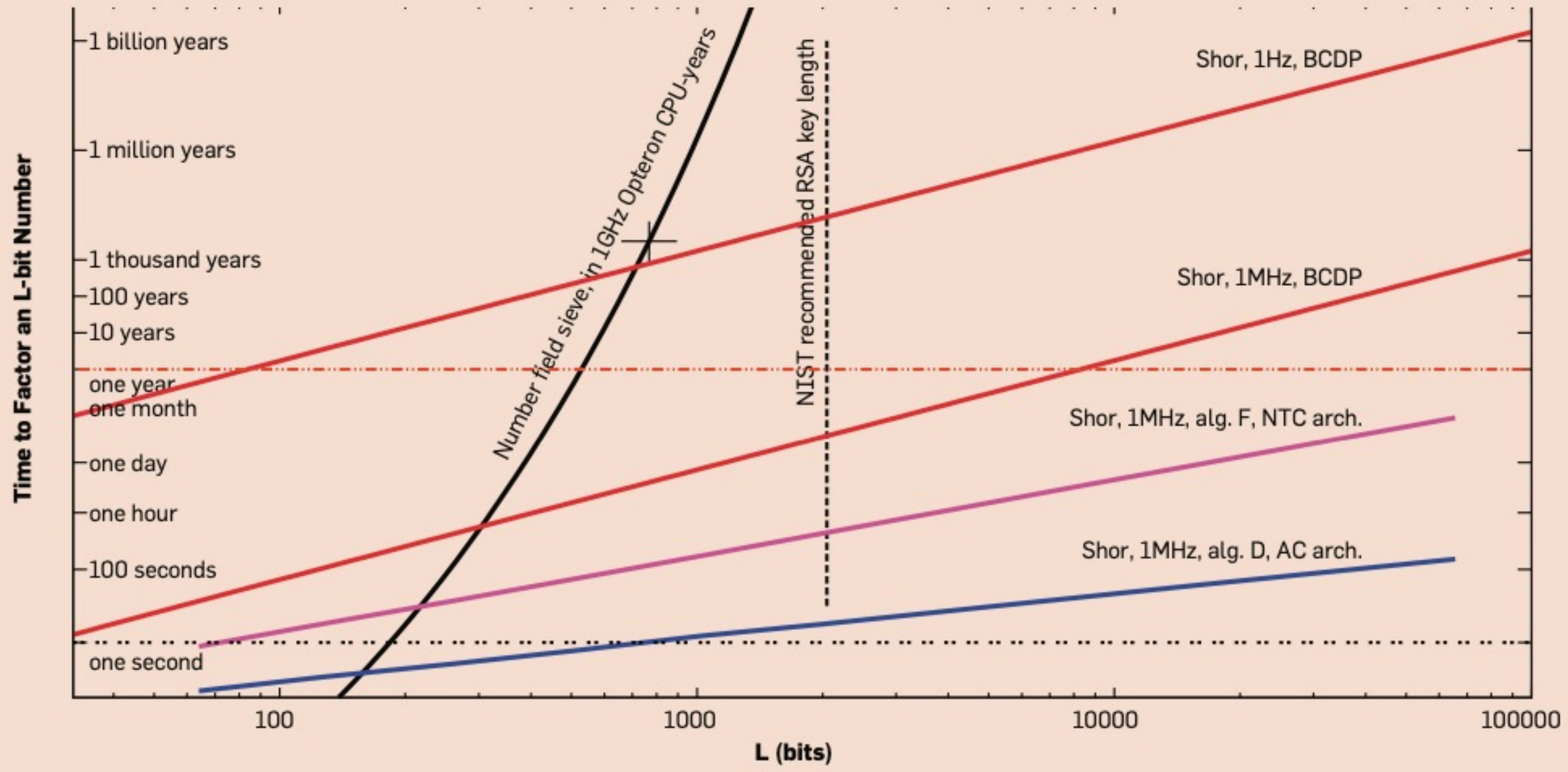
Quantum algorithm: needs $\boldsymbol{O(N^2 \log(N))}$ operations

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.

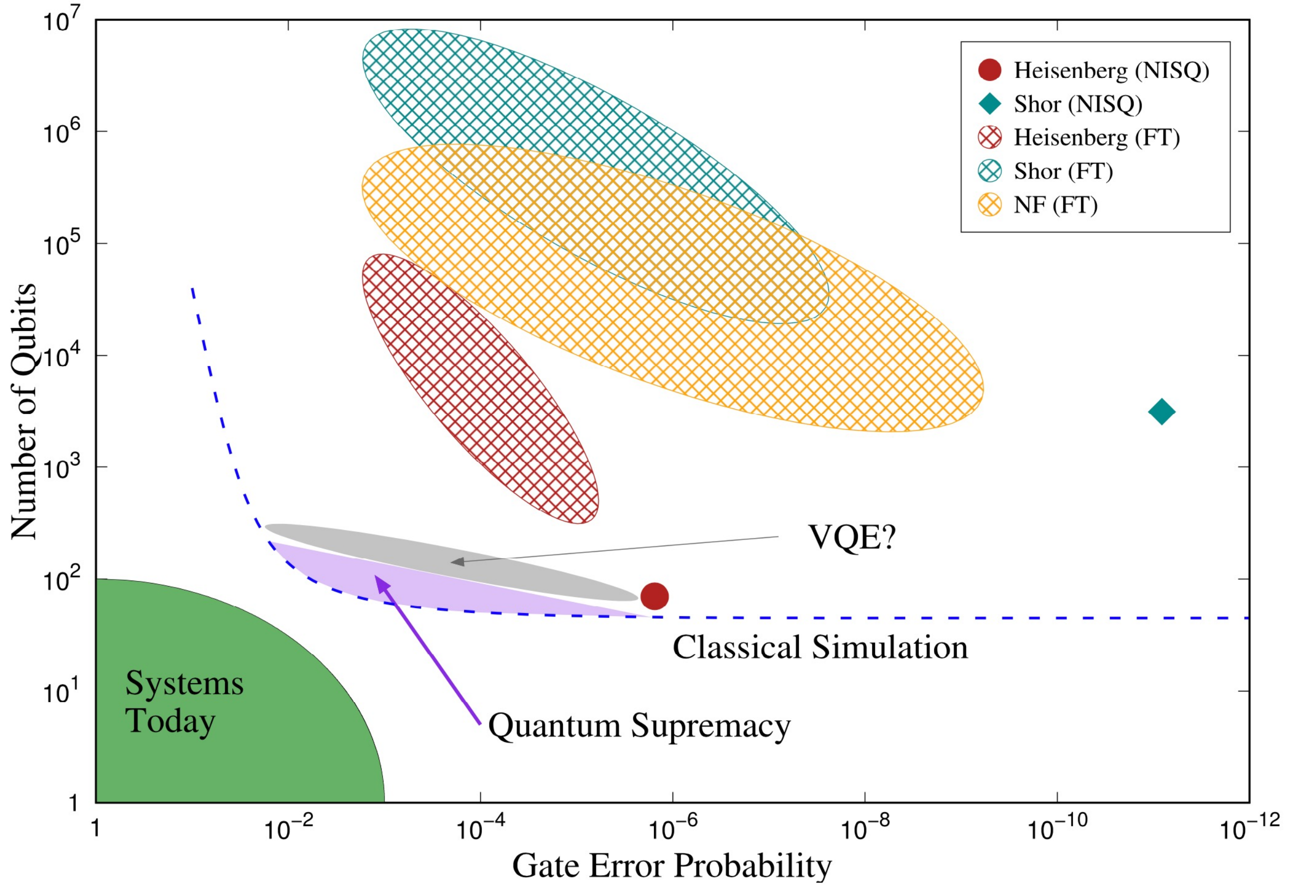
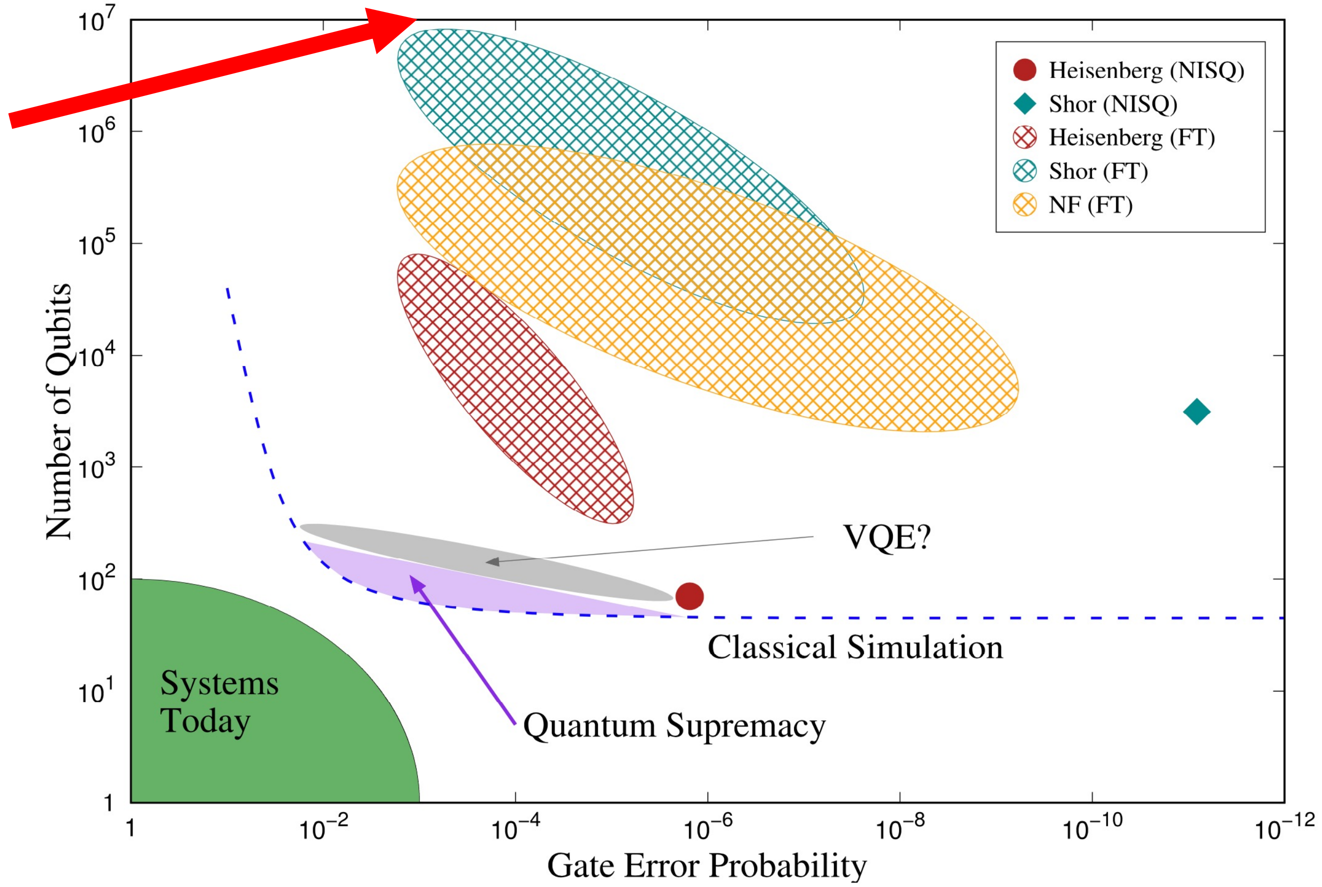


Fig. 2. ***Performance space of quantum computers, measured by the error probability of each entangling gate in the horizontal axis (roughly inversely proportional to the total number of gates that can be executed on a NISQ machine), and the number of qubits in the system in the vertical axis. Blue dotted line approximately demarcates quantum systems that can be simulated using best classical computers, while the green colored region shows where the existing quantum computing systems with verified performance numbers lie (as of September 2018). Purple shaded region indicates computational tasks that accomplish the so-called "quantum supremacy," where the computation carried out by the quantum computer defies classical simulation regardless of its usefulness. The different shapes illustrate resource counts for solving various problems, with solid symbols corresponding to the exact entangling gate counts and number of qubits in NISQ machines, and shaded regions showing approximate gate error requirements and number of qubits for an FT implementation (not pictured are the regions where the error gets too close to the known fault-tolerance thresholds): cyan diamond and shaded region correspond to factoring a 1024-bit number using Shor's algorithm [14], magenta circle and shaded region represent simulation of a 72-spin Heisenberg model [20], and orange shaded region illustrates NF simulation [21].***

An Outlook for Quantum Computing. Maslov et al.

How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits. Gidney and Ekerå. 2019.



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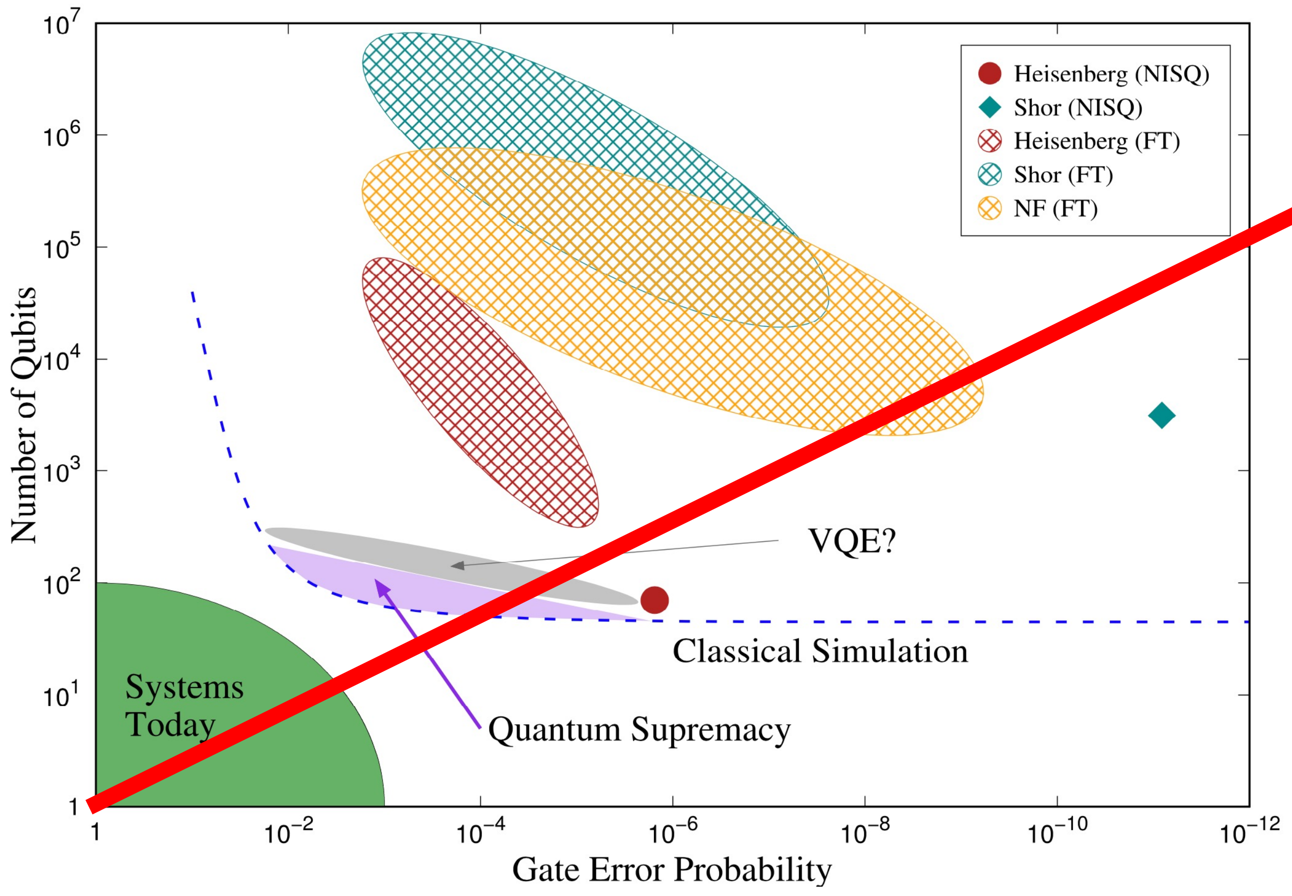

Need applications to motivate further research.

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Noisy, intermediate-scale quantum algorithms

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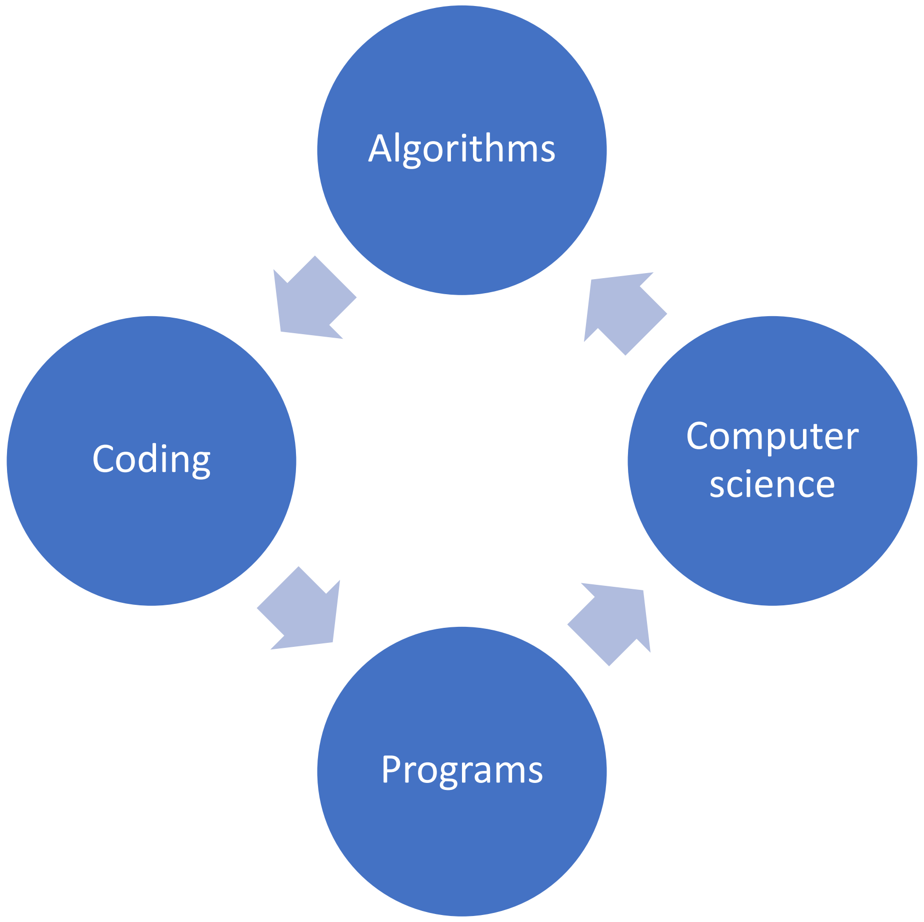
Underappreciated fact:
Programming languages aid discovery of algorithms



Underappreciated fact:
Programming languages aid discovery of algorithms

https://www.geeksforgeeks.org/random-walk-implementation-python/

Take classical random walks as an example. Notice:

1. Ease of going from 1D example to 2D example (reusable code).
2. Ease of generating a visualization.
3. Code and simulation reveals properties useful for new algorithms.

Underappreciated fact:
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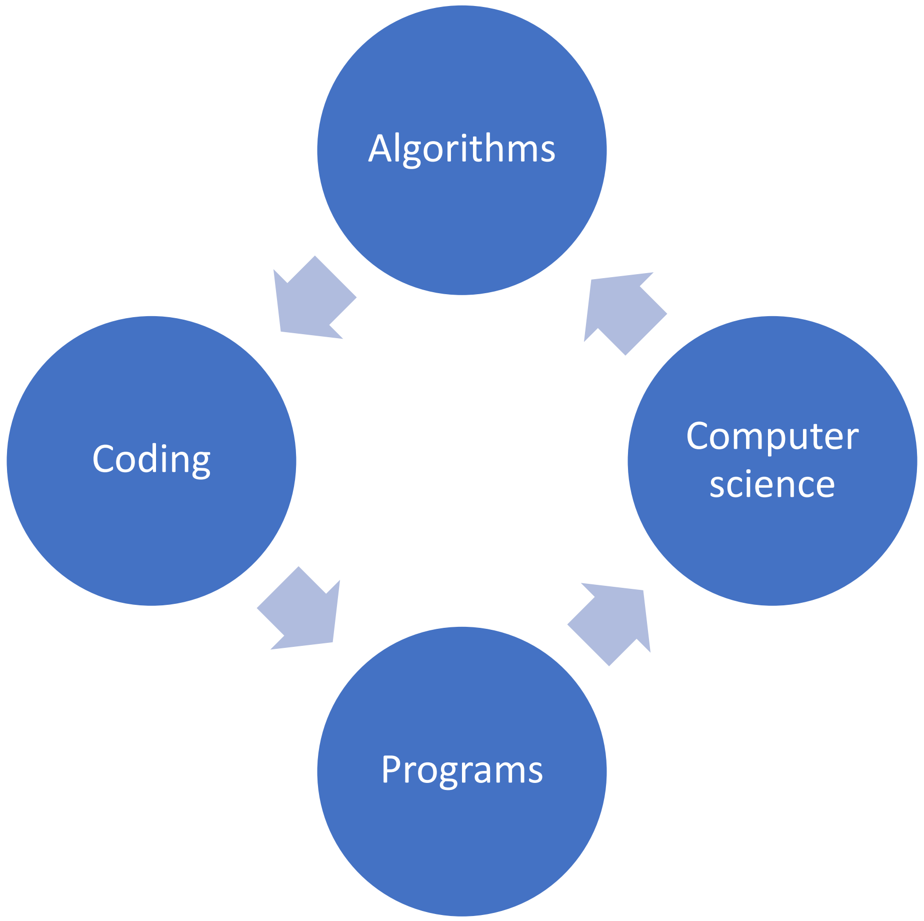


Specification of algorithm as a procedure

https://www.geeksforgeeks.org/random-walk-implementation-python/

Take classical random walks as an example. Notice:

1. Import library for random coin toss
2. Data structures for time series
3. Standard operators for increment and decrement

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

Programmers' time is scarce. Classical computing resources are abundant. Nonetheless, abstractions are expensive.

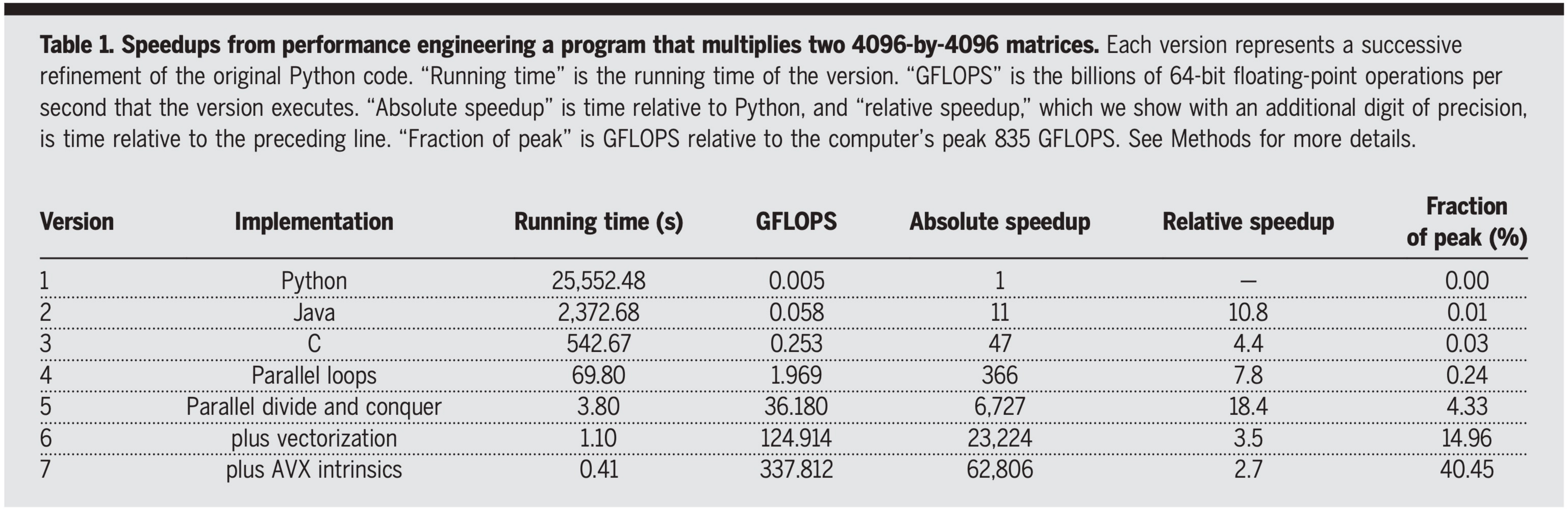
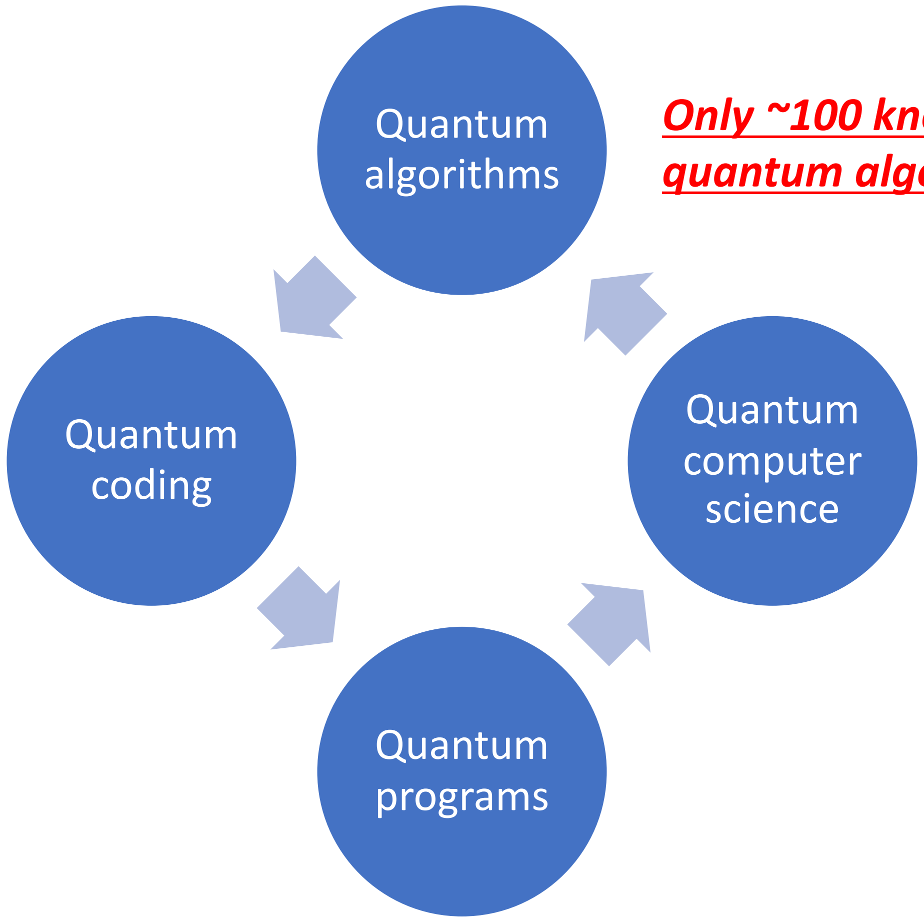


Table 1. Speedups from performance engineering a program that multiplies two 4096-by-4096 matrices. Each version represents a successive refinement of the original Python code. "Running time" is the running time of the version. "GFLOPS" is the billions of 64-bit floating-point operations per second that the version executes. "Absolute speedup" is time relative to Python, and "relative speedup," which we show with an additional digit of precision, is time relative to the preceding line. "Fraction of peak" is GFLOPS relative to the computer's peak 835 GFLOPS. See Methods for more details.

Version	Implementation	Running time (s)	GFLOPS	Absolute speedup	Relative speedup	Fraction of peak (%)
1	Python	25,552.48	0.005	1	—	0.00
2	Java	2,372.68	0.058	11	10.8	0.01
3	C	542.67	0.253	47	4.4	0.03
4	Parallel loops	69.80	1.969	366	7.8	0.24
5	Parallel divide and conquer	3.80	36.180	6,727	18.4	4.33
6	plus vectorization	1.10	124.914	23,224	3.5	14.96
7	plus AVX intrinsics	0.41	337.812	62,806	2.7	40.45

"There's plenty of room at the Top: What will drive computer performance after Moore's law?" Leiserson et al. Science. 2020.

Programming languages aid discovery of algorithms: Is it currently true for quantum computer science?



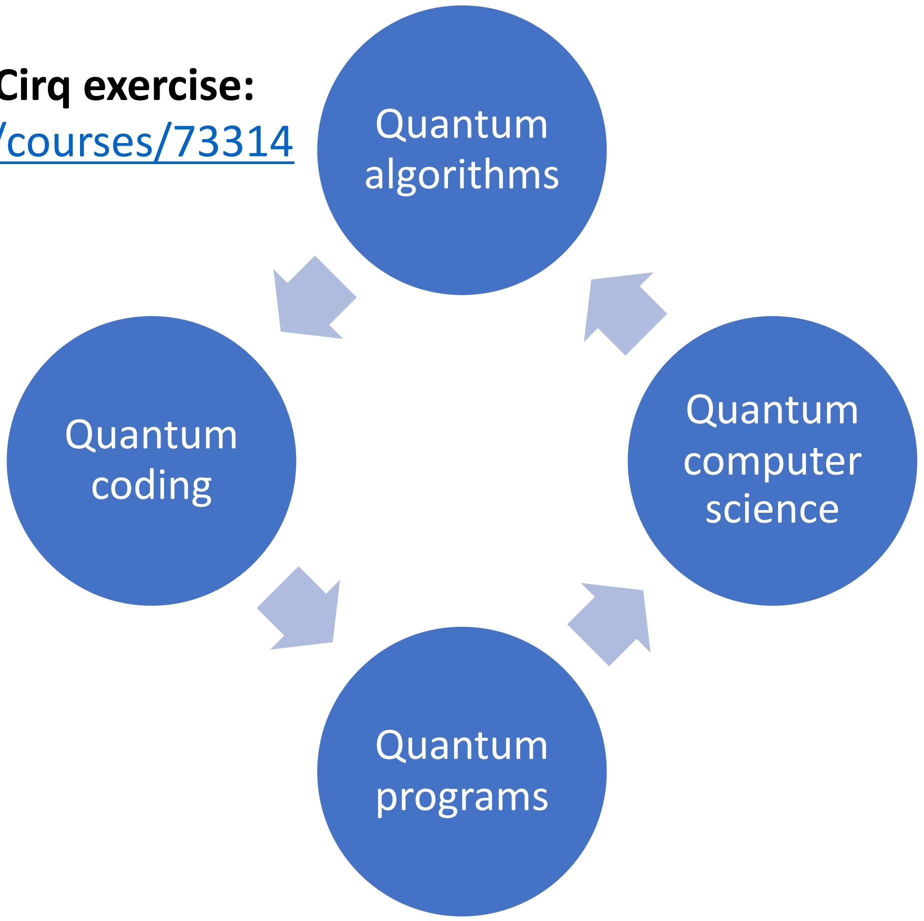
Only ~100 known quantum algorithms

Specification of quantum algorithm as a quantum procedure

As another example, QAOA on Cirq exercise:
https://rutgers.instructure.com/courses/73314/assignments/1017995

Need quantum equivalent of:
1. Partition representation
2. Edge constraints
3. Way to perturb partitioning

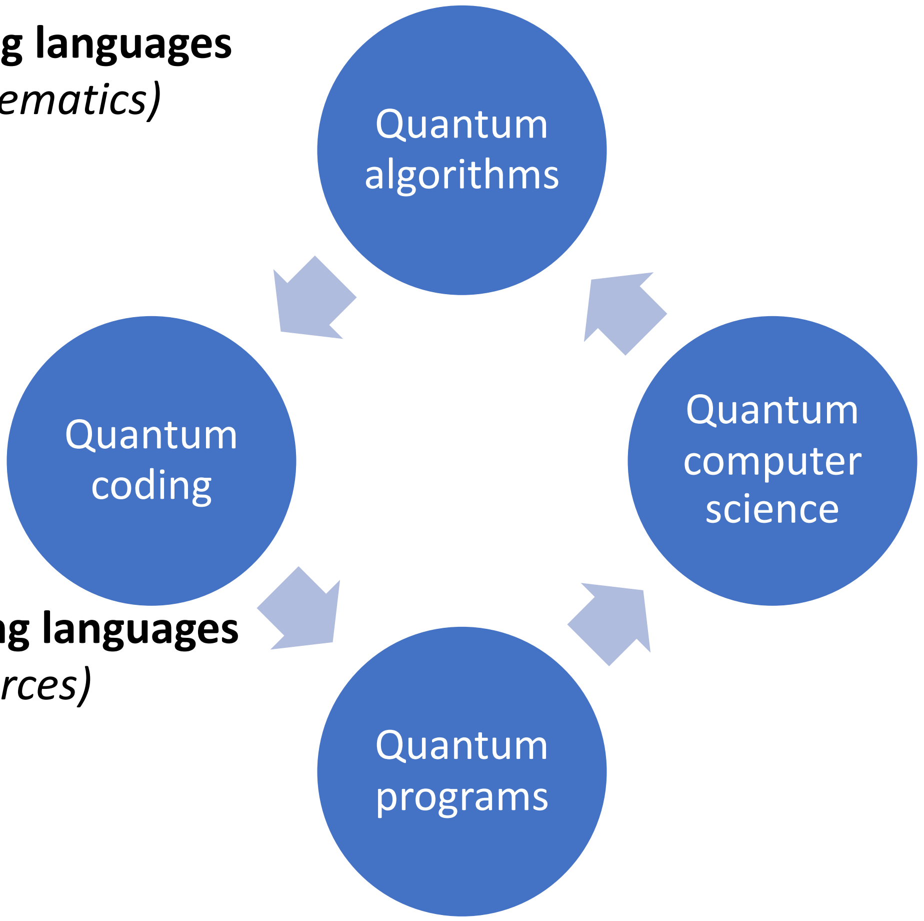
Gates to code that we can run.



Specification of quantum algorithm as a quantum procedure

Functional quantum programming languages
(emphasis on specifying the mathematics)
Microsoft Liquid
Quipper
QWIRE
Microsoft Q#
Etc.

Imperative quantum programming languages
(emphasis on specifying the resources)
Scaffold
Microsoft ProjectQ
Rigetti PyQuil
IBM Qiskit
Google Cirq
Etc.



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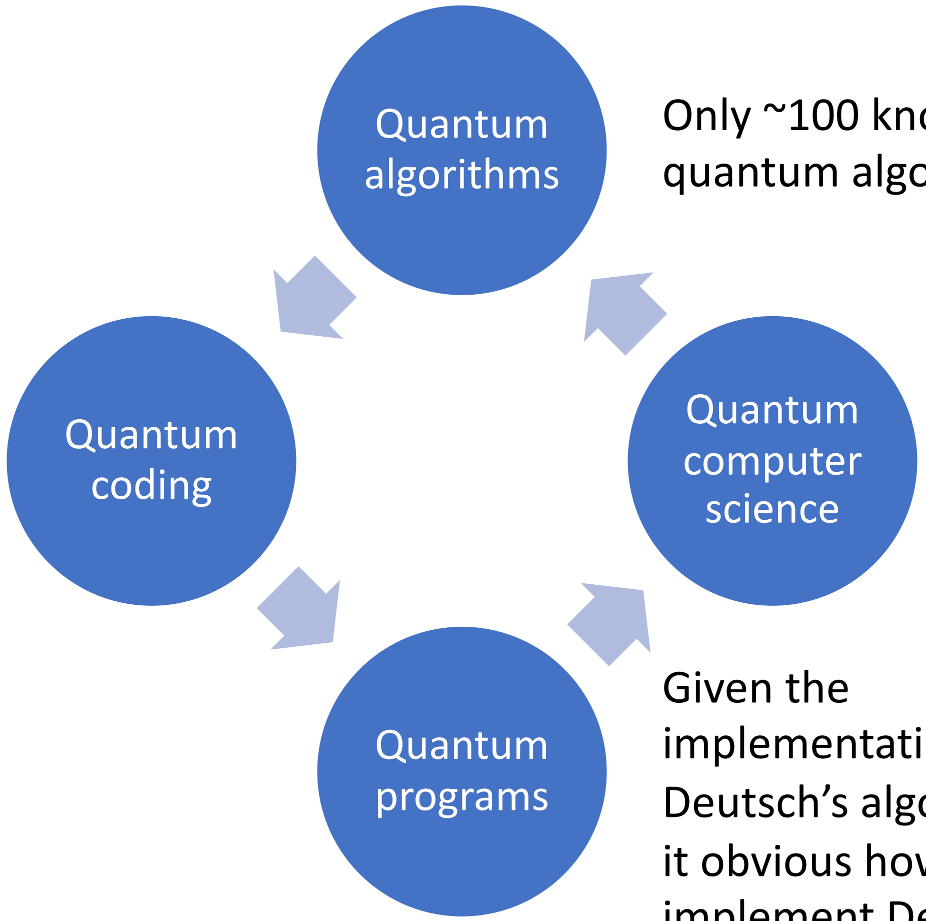
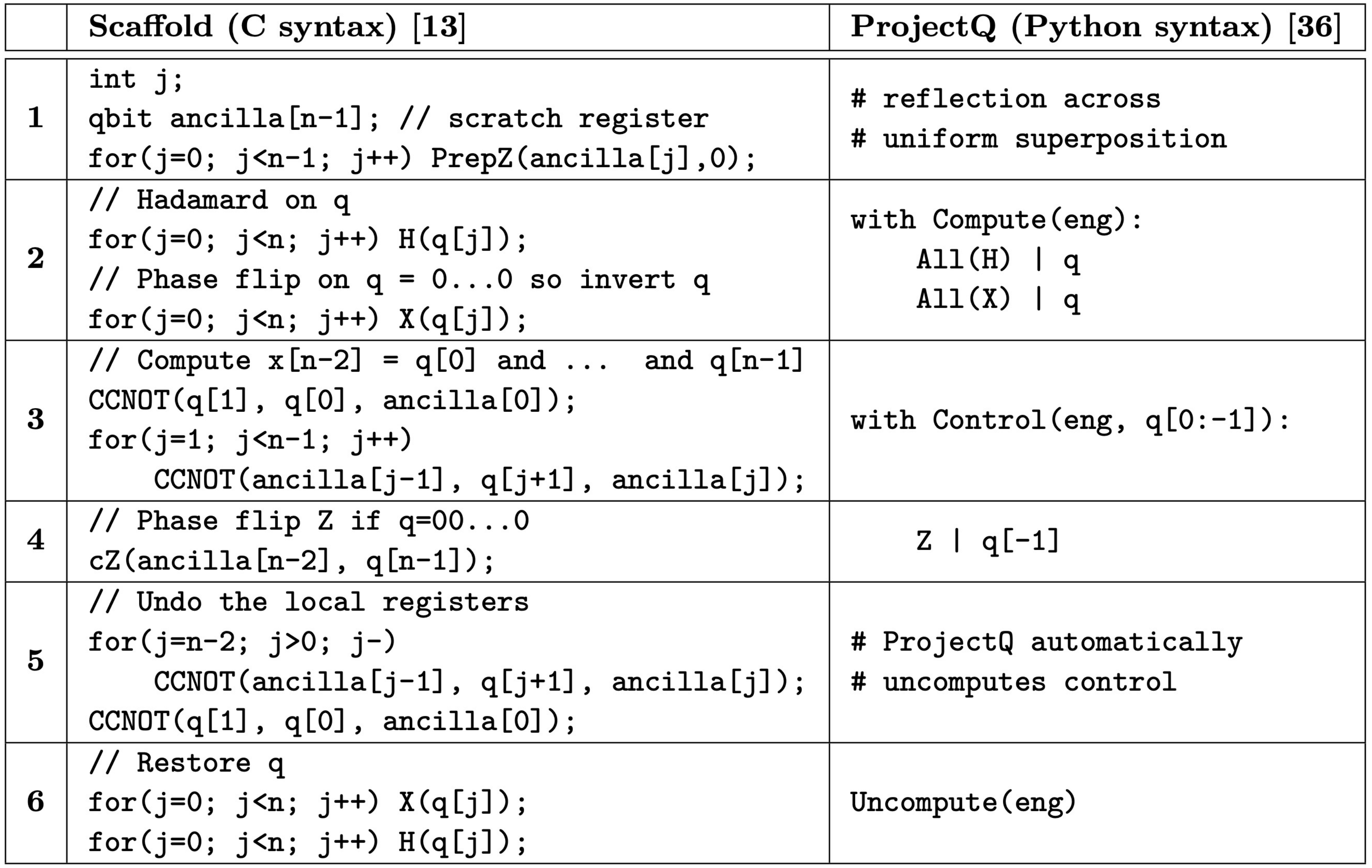


Only ~100 known quantum algorithms

Some progress in the past two years.
Qiskit Aqua
OpenFermion-Cirq
TensorFlow Quantum

Given the implementation for Deutsch's algorithm, is it obvious how to implement Deutsch-Jozsa's algorithm?

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)`

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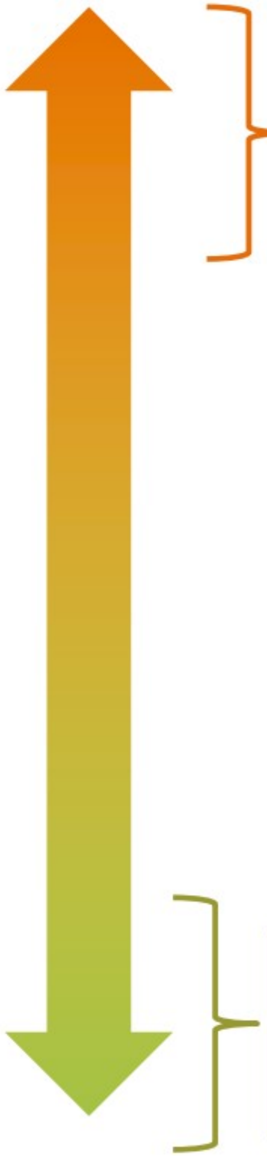
Approaches to Software Reliability

- Social
  - Code reviews
  - Extreme/Pair programming
- Methodological
  - Design patterns
  - Test-driven development
  - Version control
  - Bug tracking
- Technological
  - "lint" tools, static analysis
  - Fuzzers, random testing
- Mathematical
  - Sound type systems
  - Formal verification



Less "formal": Lightweight, inexpensive techniques (that may miss problems)

This isn't an either/or tradeoff… a spectrum of methods is needed!

Even the most "formal" argument can still have holes:

- Did you prove the right thing?
- Do your assumptions match reality?
- Knuth: *"Beware of bugs in the above code; I have only proved it correct, not tried it."*

More "formal": eliminate *with certainty* as many problems as possible.

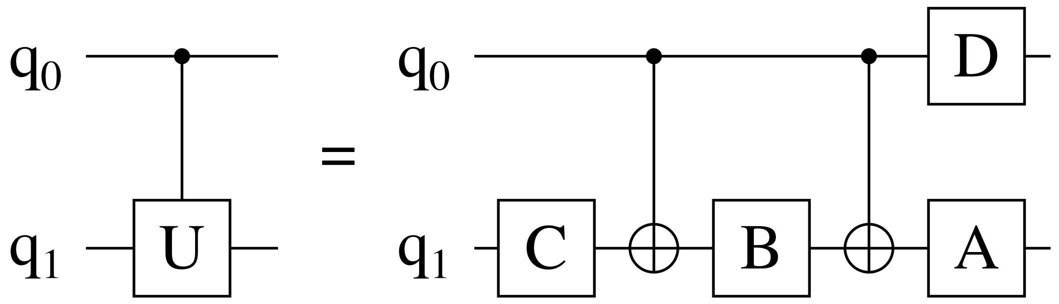
From: https://www.seas.upenn.edu/~cis500/current/lectures/lec01.pdf

Execution in target machine w/ facilities for validation

- Exception handling.
- Printf debugging.
- GDB breakpoints.
- Assertions.
- Etc.

- “Exception handling” (i.e., quantum error correction) is costly.
- No printf. No intermediate measurements.
- Can’t set arbitrary breakpoints.
- Few obvious assertions.

Even simple quantum programming bugs lead to non-obvious symptoms



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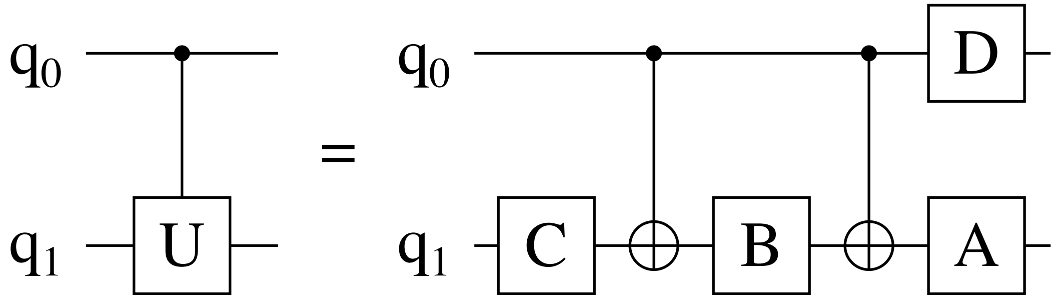
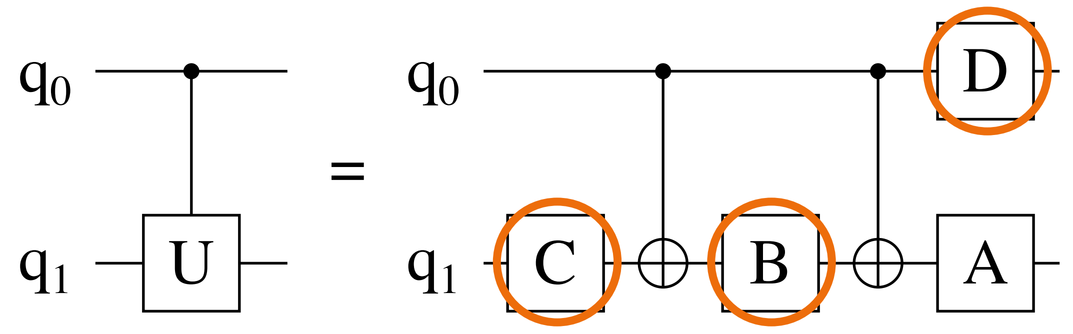


```
Rz(q1, +angle/2); // C
CNOT(q0, q1);
Rz(q1, -angle/2); // B
CNOT(q0, q1);
Rz(q0, +angle/2); // D
```

Even simple quantum programming bugs lead to non-obvious symptoms



Elementary single-qubit operations

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Rz(q1, +angle/2); // C
CNOT(q0, q1);
Rz(q1, -angle/2); // B
CNOT(q0, q1);
Rz(q0, +angle/2); // D
```

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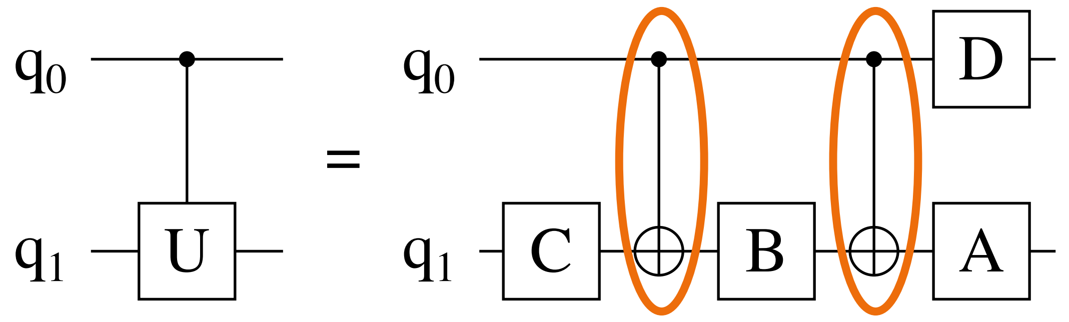
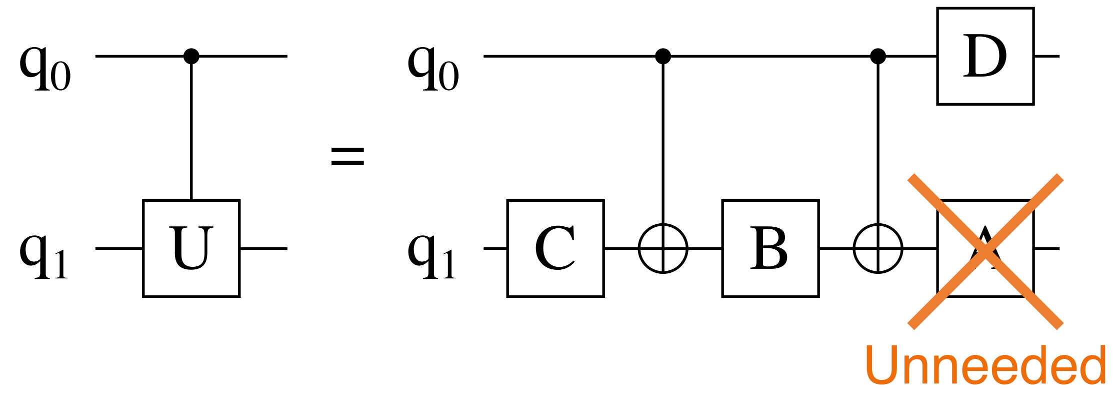


Elementary two-qubit operations

```
Rz(q1, +angle/2); // C
CNOT(q0, q1);
Rz(q1, -angle/2); // B
CNOT(q0, q1);
Rz(q0, +angle/2); // D
```
 Correct, operation A unneeded	

Even simple quantum programming bugs lead to non-obvious symptoms



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Correct, operation A unneeded

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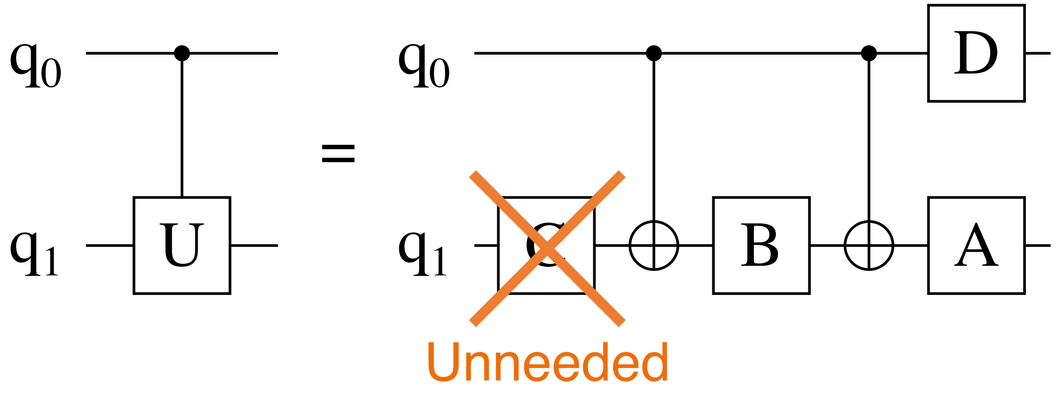

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**Correct,
operation A unneeded**
	`CNOT(q0, q1);`
	`Rz(q1, -angle/2); // B`
	`CNOT(q0, q1);`
	`Rz(q1, +angle/2); // A`
	`Rz(q0, +angle/2); // D`
	
	**Correct,
	operation C unneeded**	

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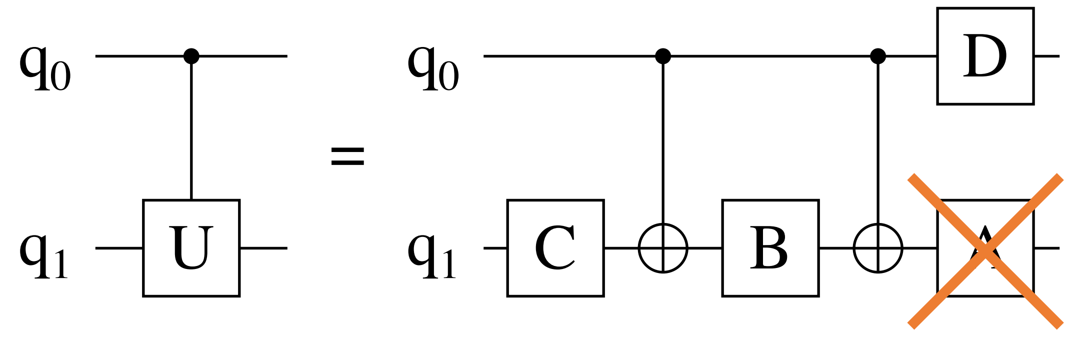

Unneeded?
But signs on angles wrong!

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	Correct, operation C unneeded
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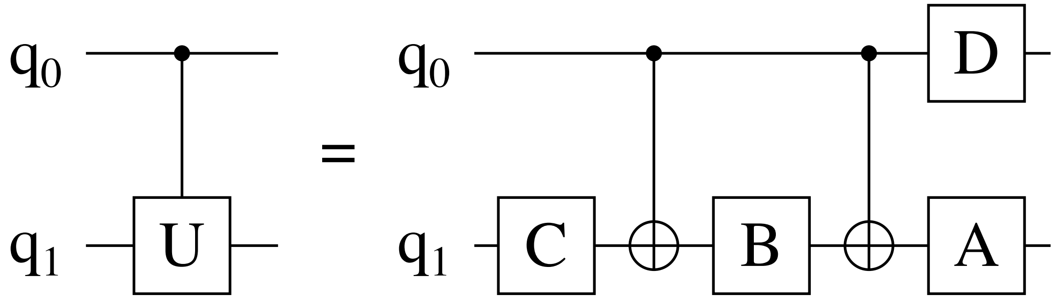
		`CNOT(q0, q1);`
		`Rz(q1, +angle/2);`
		`CNOT(q0, q1);`
		`Rz(q0, +angle/2); // D`
		
		Incorrect, angles flipped

Many ways to translate basic quantum operations to program code—many details to get right!

Even simple quantum programming bugs lead to non-obvious symptoms



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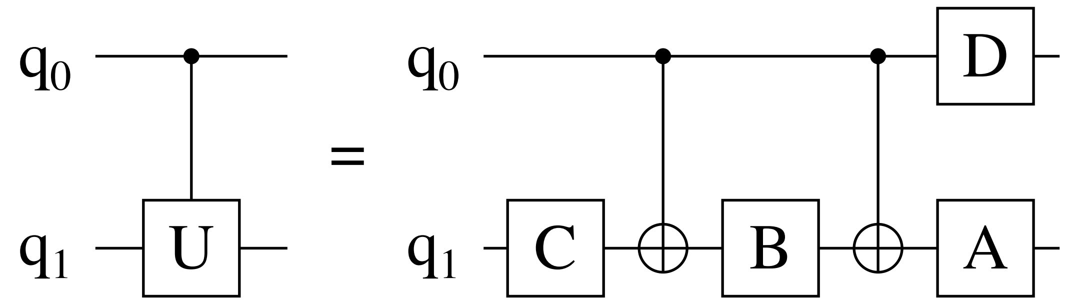
	`CNOT(q0, q1);`
	`Rz(q1, -angle/2); // B`
	`CNOT(q0, q1);`
	`Rz(q1, +angle/2); // A`
	`Rz(q0, +angle/2); // D`
		`Rz(q1, -angle/2);`
		`CNOT(q0, q1);`
		`Rz(q1, +angle/2);`
		`CNOT(q0, q1);`
		`Rz(q0, +angle/2); // D`

Correct, operation A unneeded	**Correct, operation C unneeded**	**Incorrect, angles flipped**
$\|11\rangle \rightarrow e^{i*angle}\|11\rangle$	$\|11\rangle \rightarrow e^{i*angle}\|11\rangle$	$\|11\rangle \rightarrow e^{-i*angle}\|11\rangle$

Even simple quantum programming bugs lead to non-obvious symptoms



```
Rz(q1, +angle/2); // C
CNOT(q0, q1);
Rz(q1, -angle/2); // B
CNOT(q0, q1);
Rz(q0, +angle/2); // D
```

Correct,
operation A unneeded

$|11\rangle \rightarrow e^{i*angle}|11\rangle$

```
CNOT(q0, q1);
Rz(q1, -angle/2); // B
CNOT(q0, q1);
Rz(q1, +angle/2); // A
Rz(q0, +angle/2); // D
```

Correct,
operation C unneeded

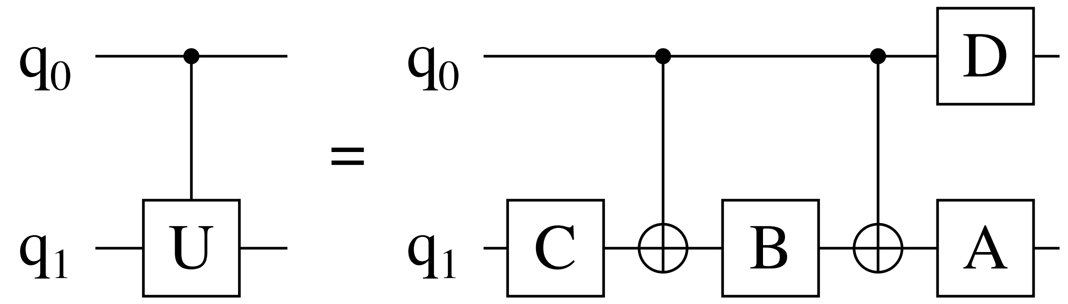
$|11\rangle \rightarrow e^{i*angle}|11\rangle$

```
Rz(q1, -angle/2);
CNOT(q0, q1);
Rz(q1, +angle/2);
CNOT(q0, q1);
Rz(q0, +angle/2); // D
```

Incorrect,
angles flipped

$|11\rangle \rightarrow e^{-i*angle}|11\rangle$

Even simple quantum programming bugs lead to non-obvious symptoms



```
Rz(q1, +angle/2); // C
CNOT(q0, q1);
Rz(q1, -angle/2); // B
CNOT(q0, q1);
Rz(q0, +angle/2); // D
```

Correct,
operation A unneeded

$$|11\rangle \rightarrow e^{i*angle}|11\rangle$$

```
CNOT(q0, q1);
Rz(q1, -angle/2); // B
CNOT(q0, q1);
Rz(q1, +angle/2); // A
Rz(q0, +angle/2); // D
```

Correct,
operation C unneeded

$$|11\rangle \rightarrow e^{i*angle}|11\rangle$$

```
Rz(q1, -angle/2);
CNOT(q0, q1);
Rz(q1, +angle/2);
CNOT(q0, q1);
Rz(q0, +angle/2); // D
```

Incorrect,
angles flipped

$$|11\rangle \rightarrow e^{-i*angle}|11\rangle$$

Detailed debugging of Shor's factorization algorithm

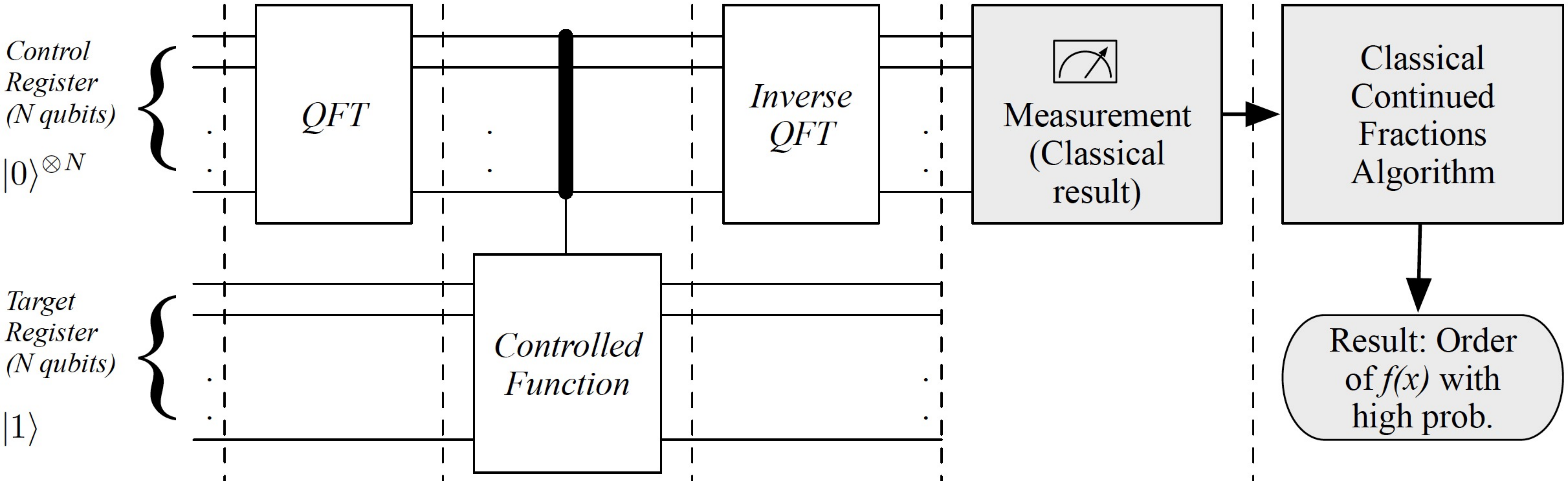
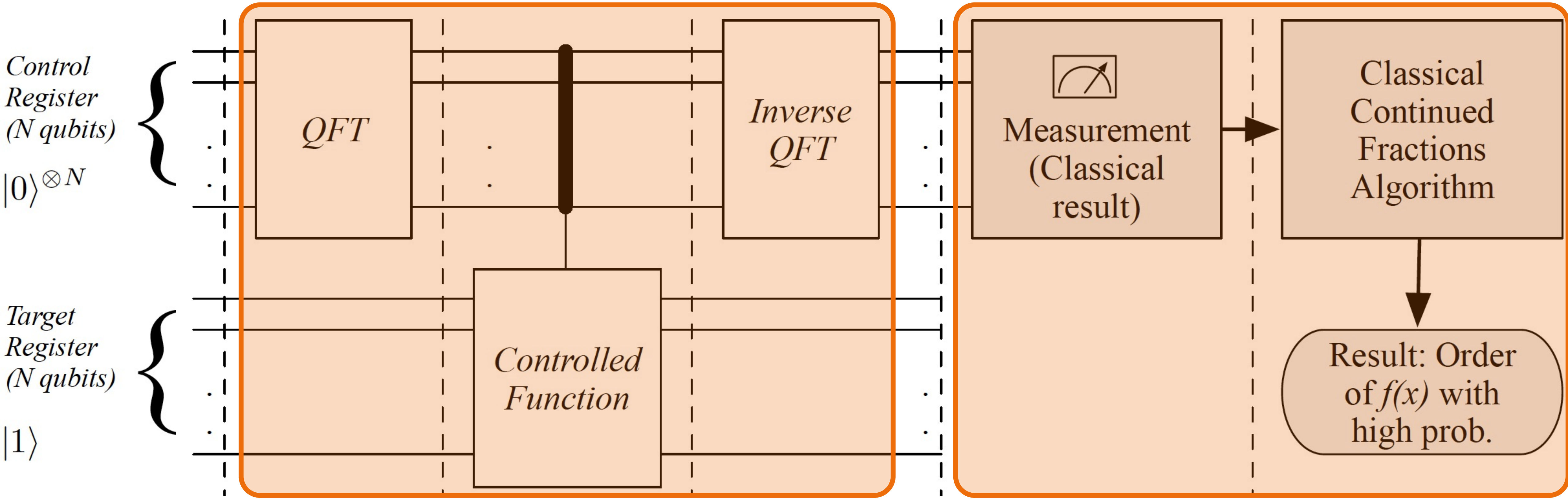

Control Register (N qubits)
$|0\rangle^{\otimes N}$
Target Register (N qubits)
$|1\rangle$
QFT
Controlled Function
Inverse QFT
Measurement (Classical result)
Classical Continued Fractions Algorithm
Result: Order of f(x) with high prob.

Image credit: Metodi, Faruque, and Chong, Quantum Computing for Computer Architects, 2nd Ed., p26

Detailed debugging of Shor's factorization algorithm

Quantum part of algorithm

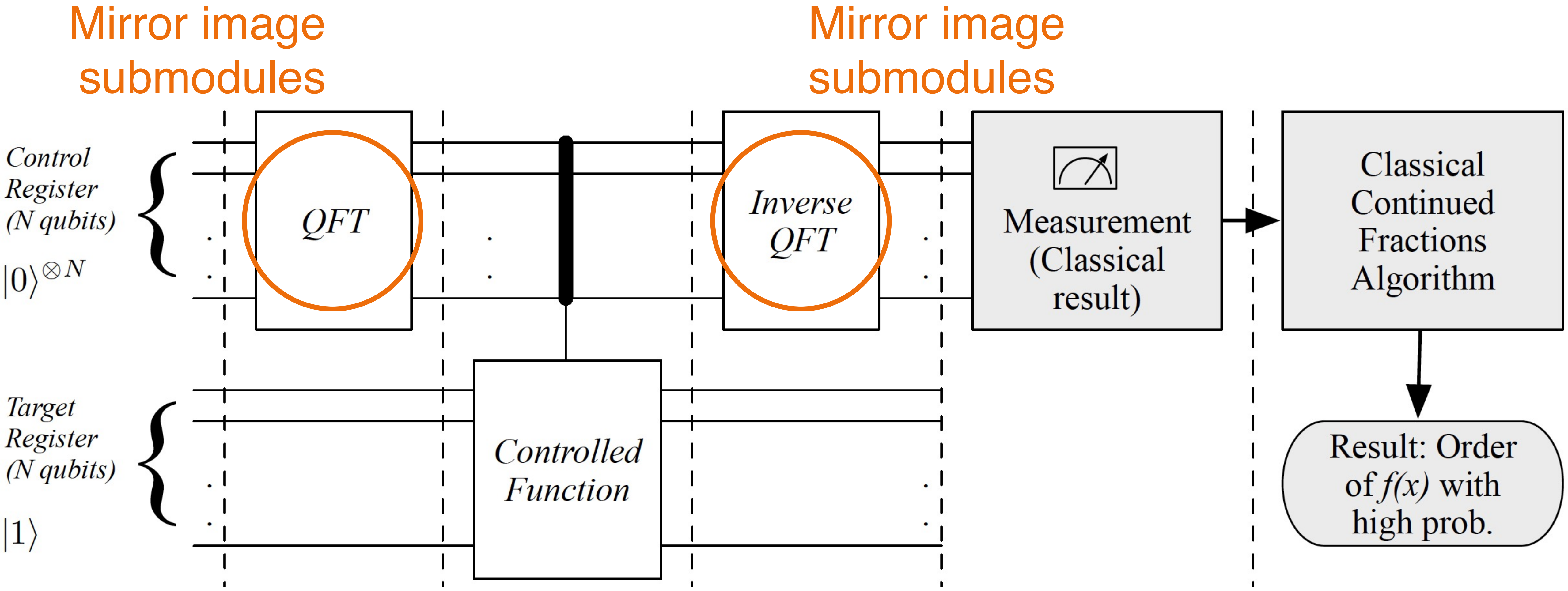
Classical post processing



Control Register (N qubits)
$|0\rangle^{\otimes N}$
Target Register (N qubits)
$|1\rangle$
QFT
Inverse QFT
Controlled Function
Measurement (Classical result)
Classical Continued Fractions Algorithm
Result: Order of f(x) with high prob.

Image credit: Metodi, Faruque, and Chong, Quantum Computing for Computer Architects, 2nd Ed., p26

Bug type 3-B: mistake in composing gates using mirroring


Mirror image submodules
Mirror image submodules
Control Register (N qubits)
$|0\rangle^{\otimes N}$
QFT
Target Register (N qubits)
$|1\rangle$
Controlled Function
Inverse QFT
Measurement (Classical result)
Classical Continued Fractions Algorithm
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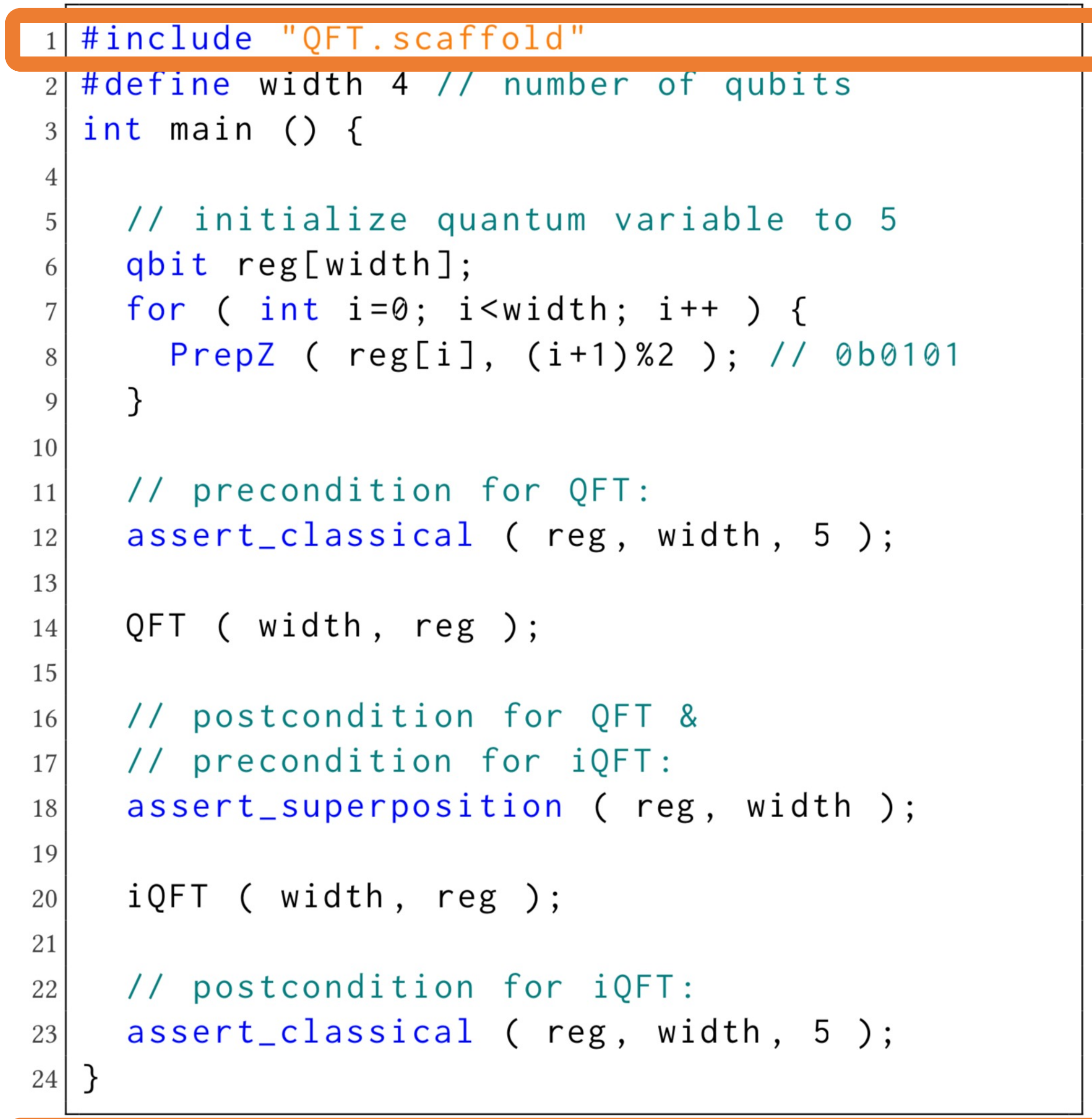

```
#include "QFT.scaffold"
#define width 4 // number of qubits
int main () {

  // initialize quantum variable to 5
  qbit reg[width];
  for ( int i=0; i<width; i++ ) {
    PrepZ ( reg[i], (i+1)%2 ); // 0b0101
  }

  // precondition for QFT:
  assert_classical ( reg, width, 5 );

  QFT ( width, reg );

  // postcondition for QFT &
  // precondition for iQFT:
  assert_superposition ( reg, width );

  iQFT ( width, reg );

  // postcondition for iQFT:
  assert_classical ( reg, width, 5 );
}
```

Listing 1: Test harness for quantum Fourier transform.

Assertions on classical & superposition states help us decide whether programs are correct

Testbench for quantum Fourier transform, consisting of controlled-rotations

```
#include "QFT.scaffold"
#define width 4 // number of qubits
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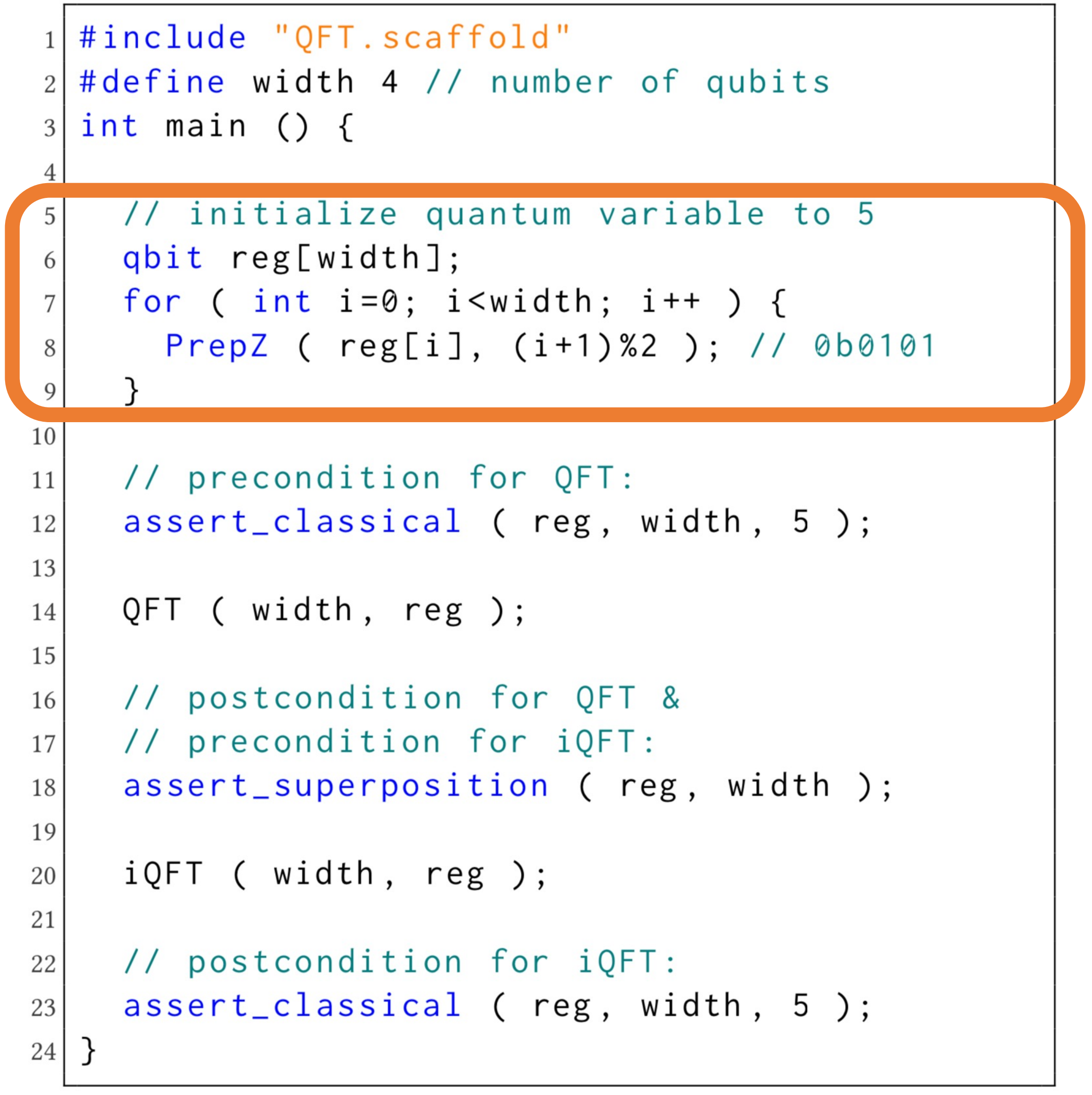
Listing 1: Test harness for quantum Fourier transform.

Assertions on classical & superposition states help us decide whether programs are correct

Testbench for quantum Fourier transform, consisting of controlled-rotations

QFT and iQFT should be inverses, but bug in controlled-rotations would lead to flawed inversion



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#include "QFT.scaffold"
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  for ( int i=0; i<width; i++ ) {
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  iQFT ( width, reg );

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}
```

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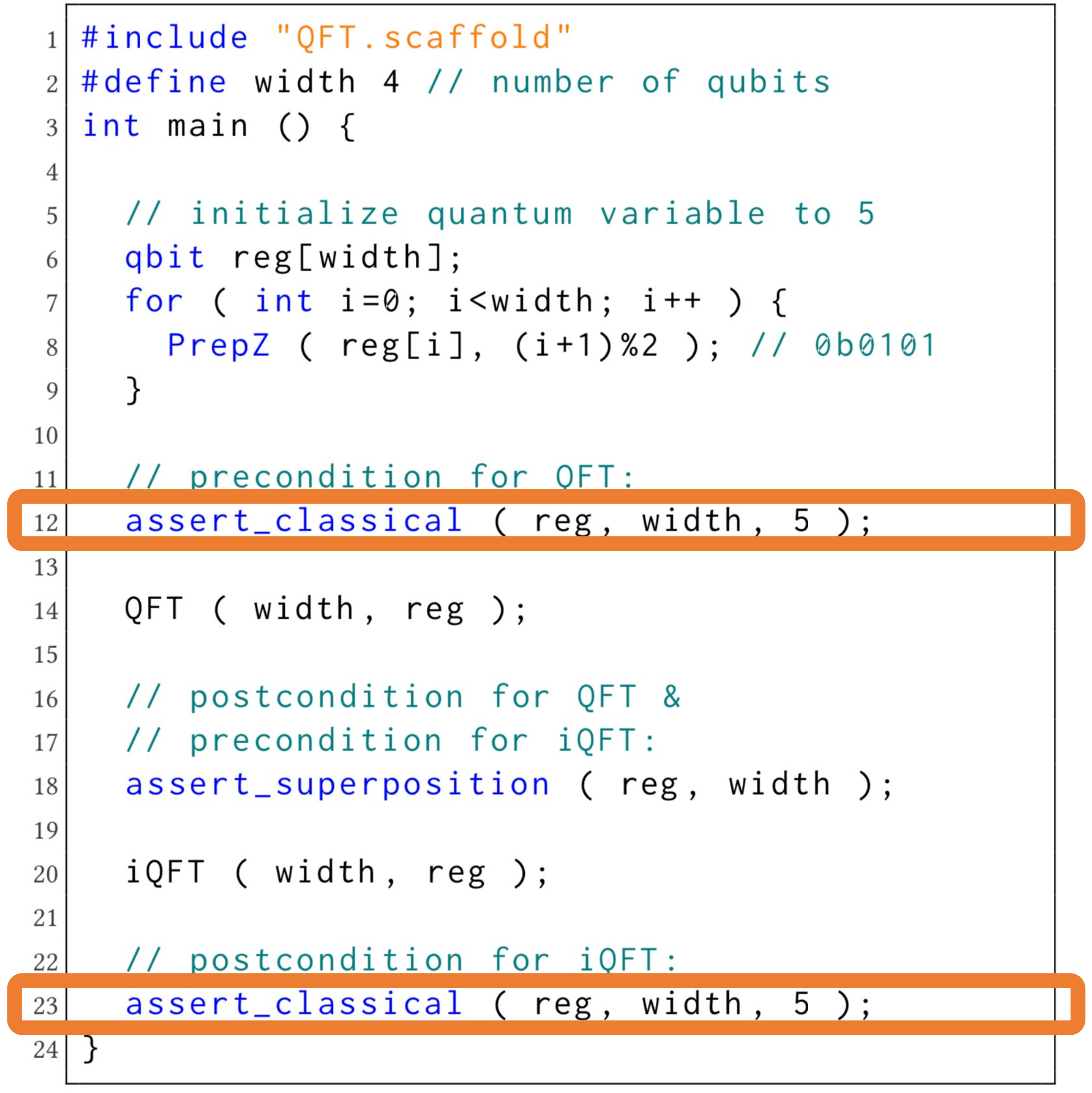

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```

Listing 1: Test harness for quantum Fourier transform.

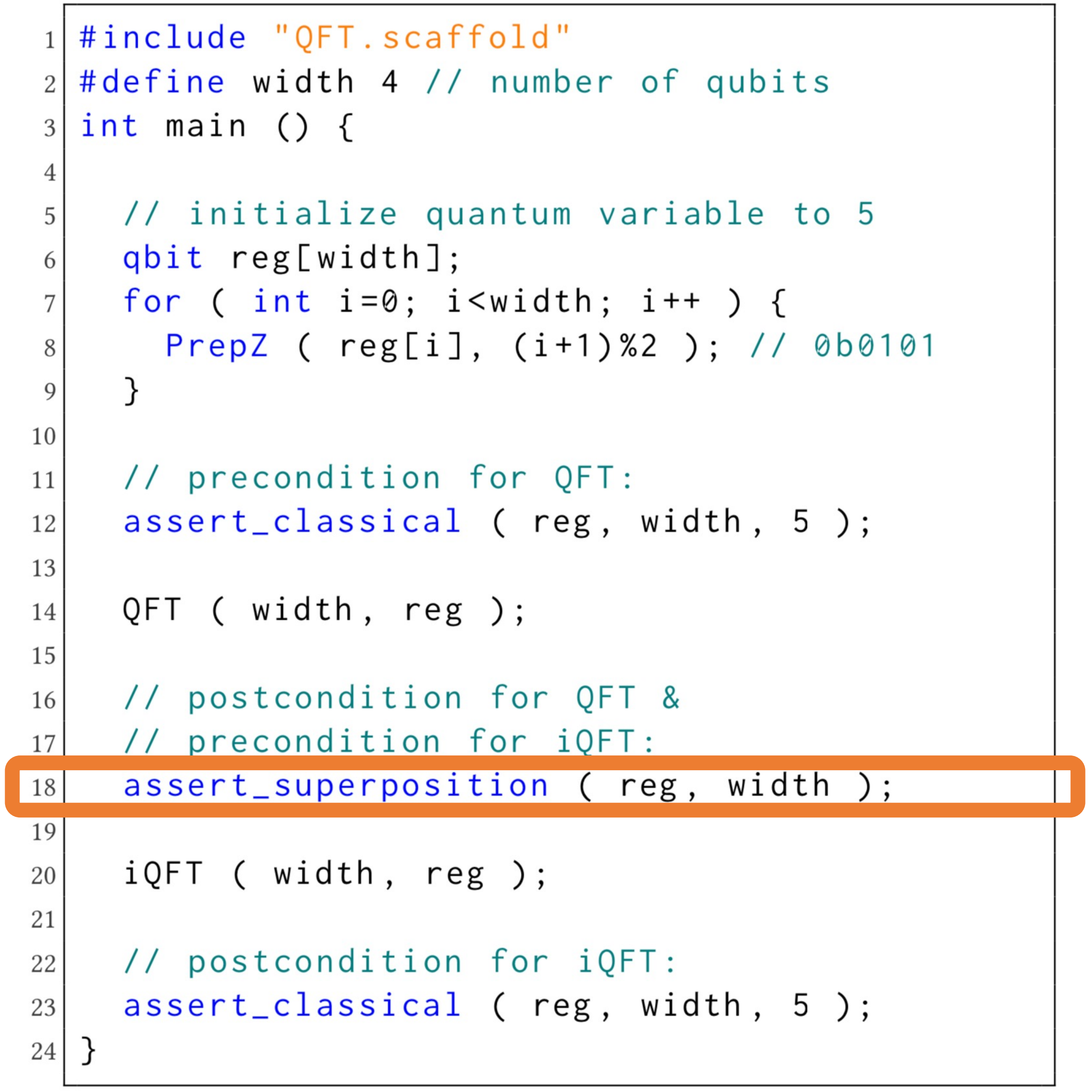
Assertions on classical & superposition states help us decide whether programs are correct

Testbench for quantum Fourier transform, consisting of controlled-rotations

QFT and iQFT should be inverses, but bug in controlled-rotations would lead to flawed inversion

Flawed inversion caught in failure of classical assertion based on Chi-squared tests

Assertions on classical & superposition states help us decide whether programs are correct



```
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#define width 4 // number of qubits
int main () {

  // initialize quantum variable to 5
  qbit reg[width];
  for ( int i=0; i<width; i++ ) {
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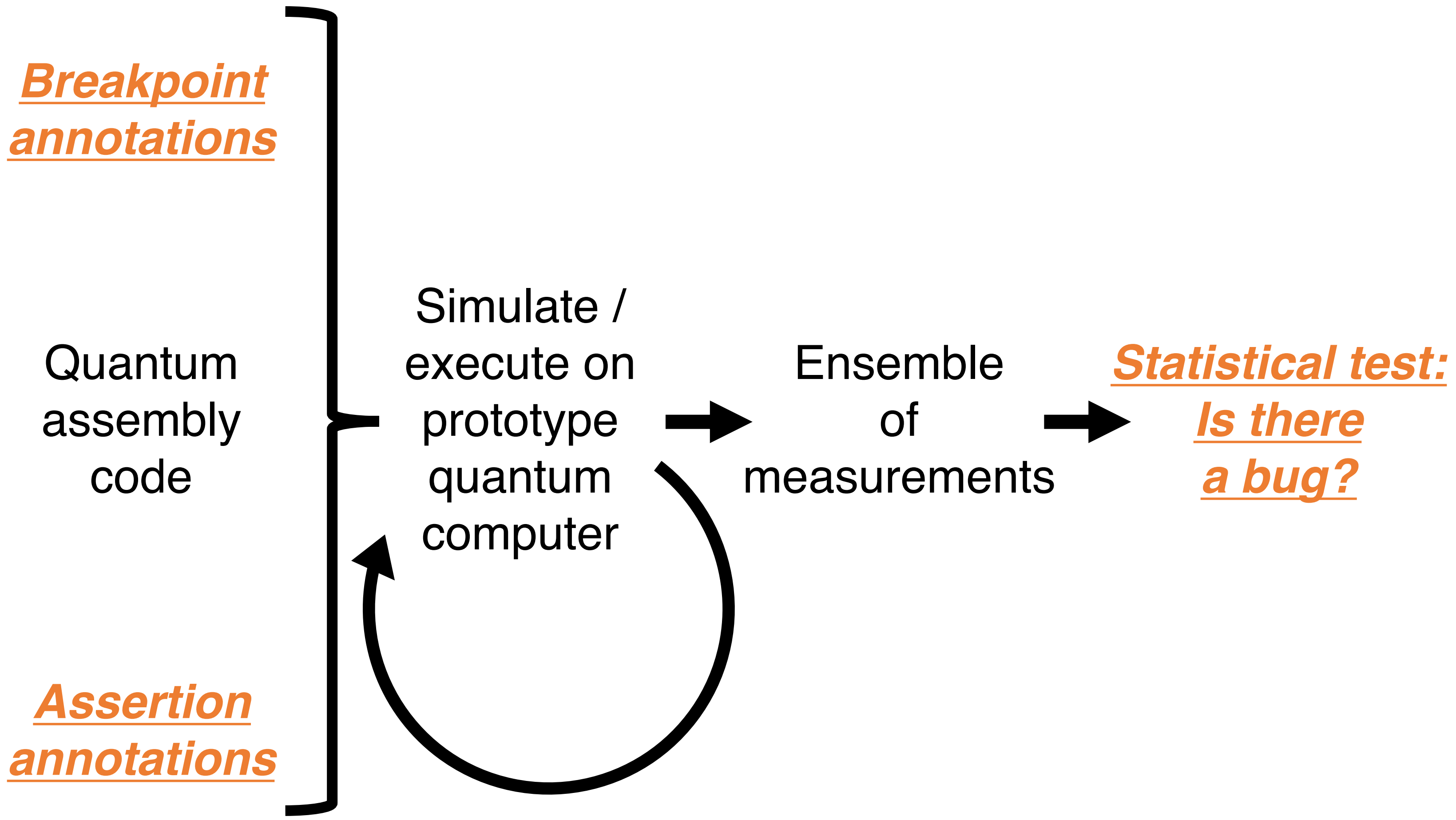
Listing 1: Test harness for quantum Fourier transform.

Testbench for quantum Fourier transform, consisting of controlled-rotations

QFT and iQFT should be inverses, but bug in controlled-rotations would lead to flawed inversion

Flawed inversion caught in failure of classical assertion based on Chi-squared tests

Toolchain for debugging programs with tests on measurements



Quantum program bug types

1. Quantum initial values
2. Basic operations
3. Composing operations
   A. Iteration
   B. Mirroring
4. Classical input parameters
5. Garbage collection of qubits

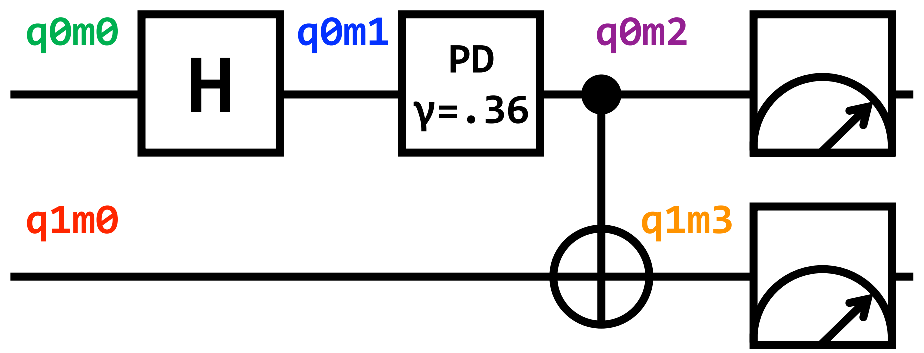
Defenses, debugging, and assertions

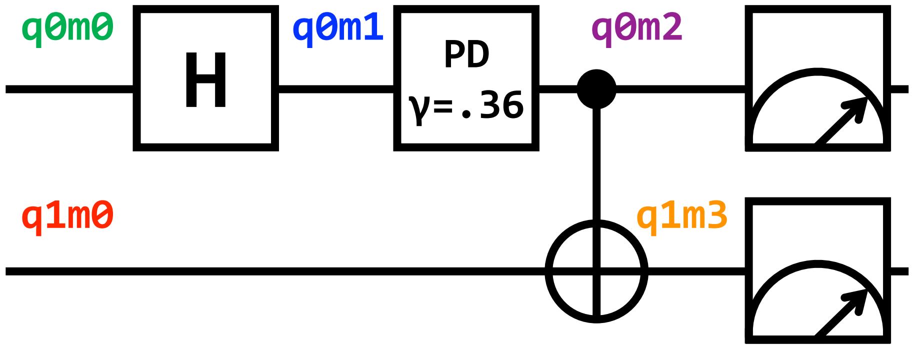
1. Preconditions
2. Subroutines / unit tests
3. Quantum specific language support
   A. Numeric data types
   B. Reversible computation
4. Algorithm progress assertions
5. Postconditions

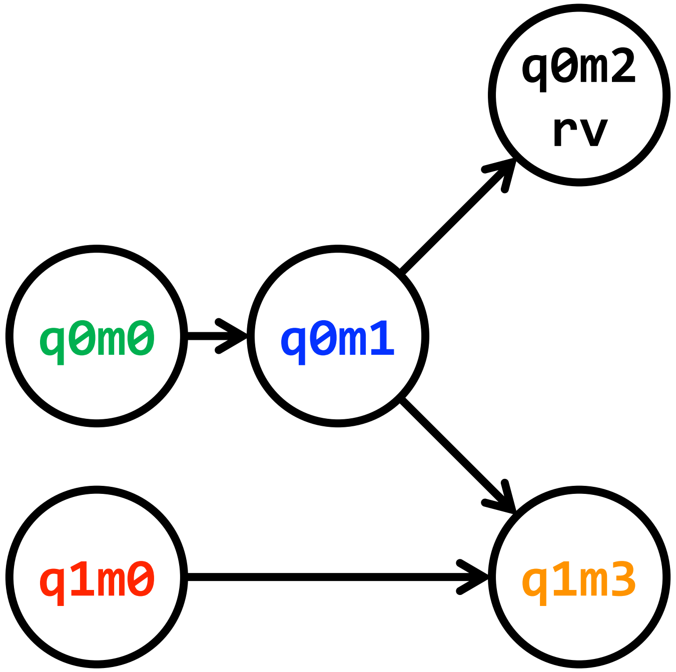
A first taxonomy of quantum program bugs and defenses.

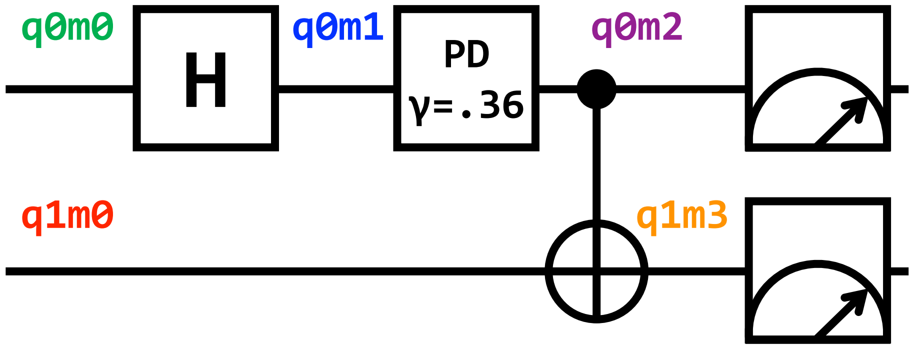
All the quantum computer abstractions we don’t yet have right now

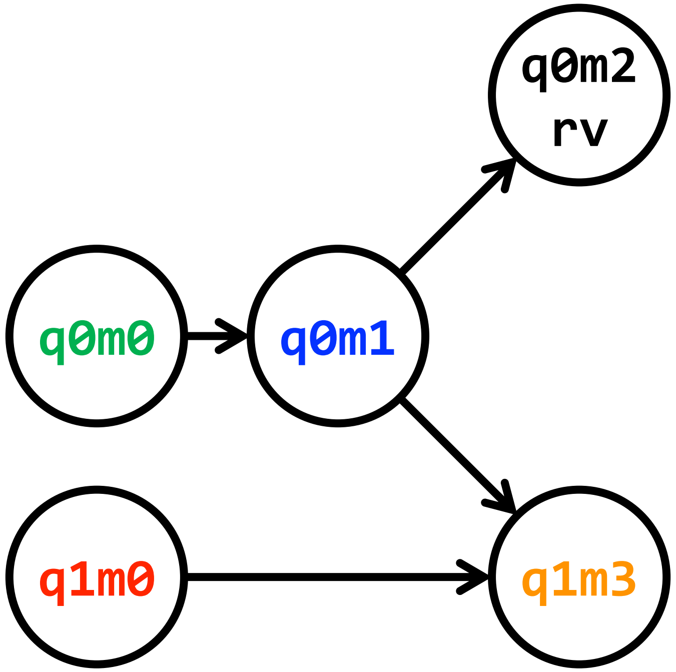
1. Fault-tolerant, error-corrected quantum computers for algorithms
2. Programming: High level languages to aid algorithm discovery
3. Programming: Facilities for program correctness (debuggers, assertions)
4. Programming: Intermediate representations that aid analysis
5. Simulation: Support to validate and design next-gen quantum computers
6. Architecture: Standard instruction set architectures
7. Architecture: Memory hierarchy to store quantum data
8. Microarchitecture: Abundant and reliable quantum devices


q0m0
H
q0m1
PD
γ=.36
q0m2
q1m0
q1m3

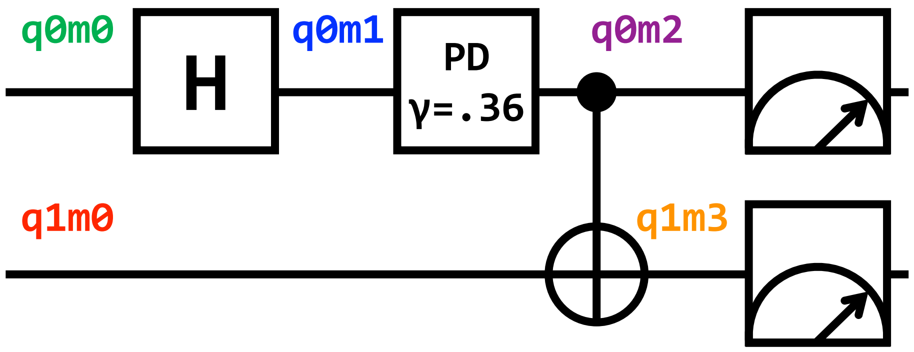

q0m0
H
q0m1
PD
γ=.36
q0m2
q1m0
q1m3

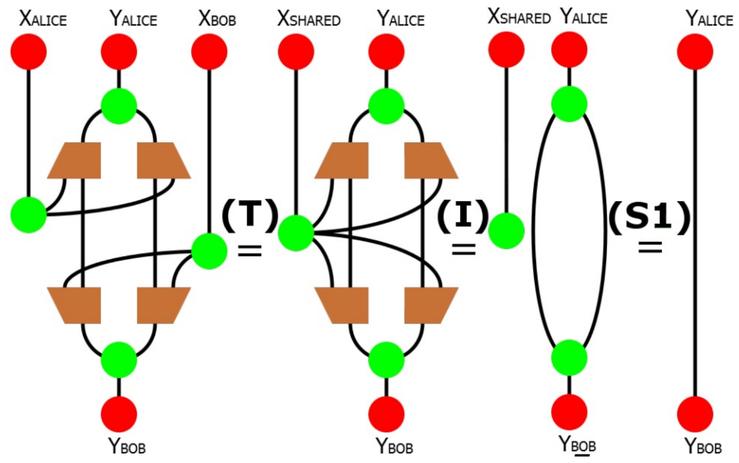

q0m2
rv
q0m0
q0m1
q1m0
q1m3



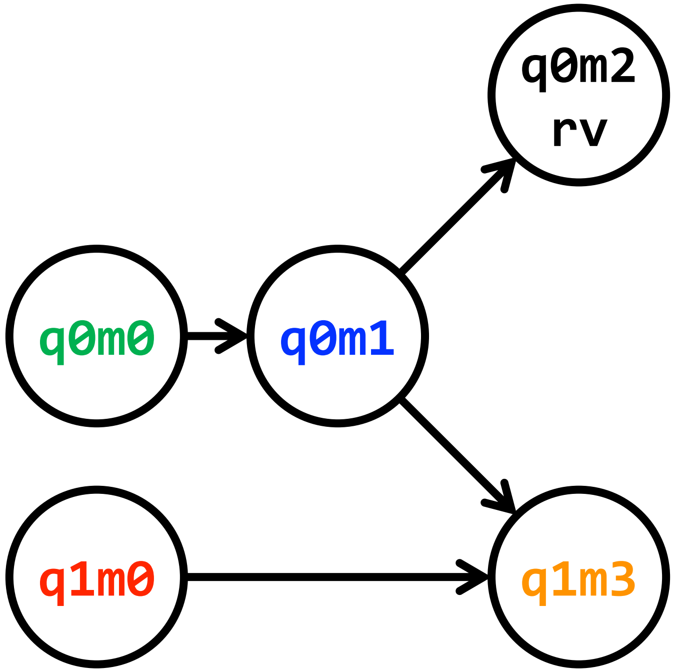


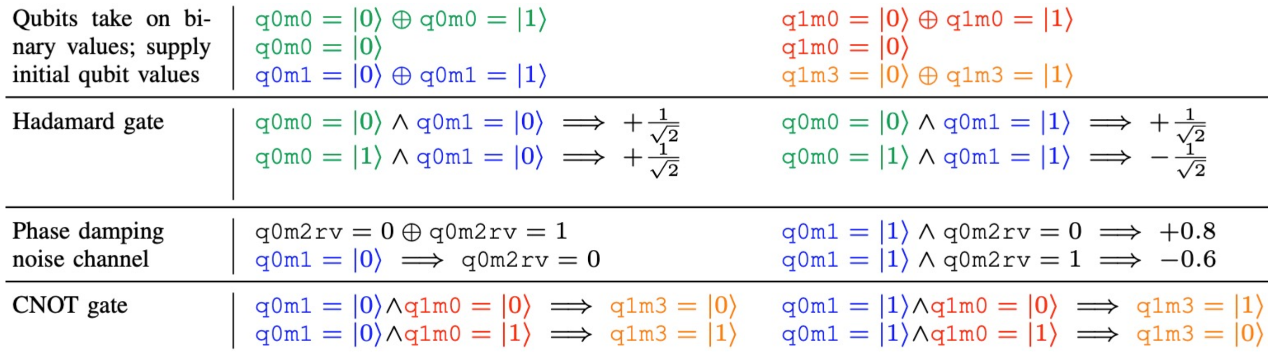
Qubits take on binary values; supply initial qubit values	$\mathtt{q0m0} = \lvert 0\rangle \oplus \mathtt{q0m0} = \lvert 1\rangle$ $\mathtt{q0m0} = \lvert 0\rangle$ $\mathtt{q0m1} = \lvert 0\rangle \oplus \mathtt{q0m1} = \lvert 1\rangle$	$\mathtt{q1m0} = \lvert 0\rangle \oplus \mathtt{q1m0} = \lvert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





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





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

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7. Architecture: Memory hierarchy to store quantum data
8. Microarchitecture: Abundant and reliable quantum devices

Role of simulation in classical computer engineering

- VirtualBox
- Gem5
- Synopsys / Cadence
- Spice

Warner Brothers Pictures

Why is simulation important?

- "Developing good classical simulations (or even attempting to and failing) would also help clarify the quantum/classical boundary."
—Aram Harrow
- Development and debugging of quantum algorithm implementations

Classical simulations of quantum computing

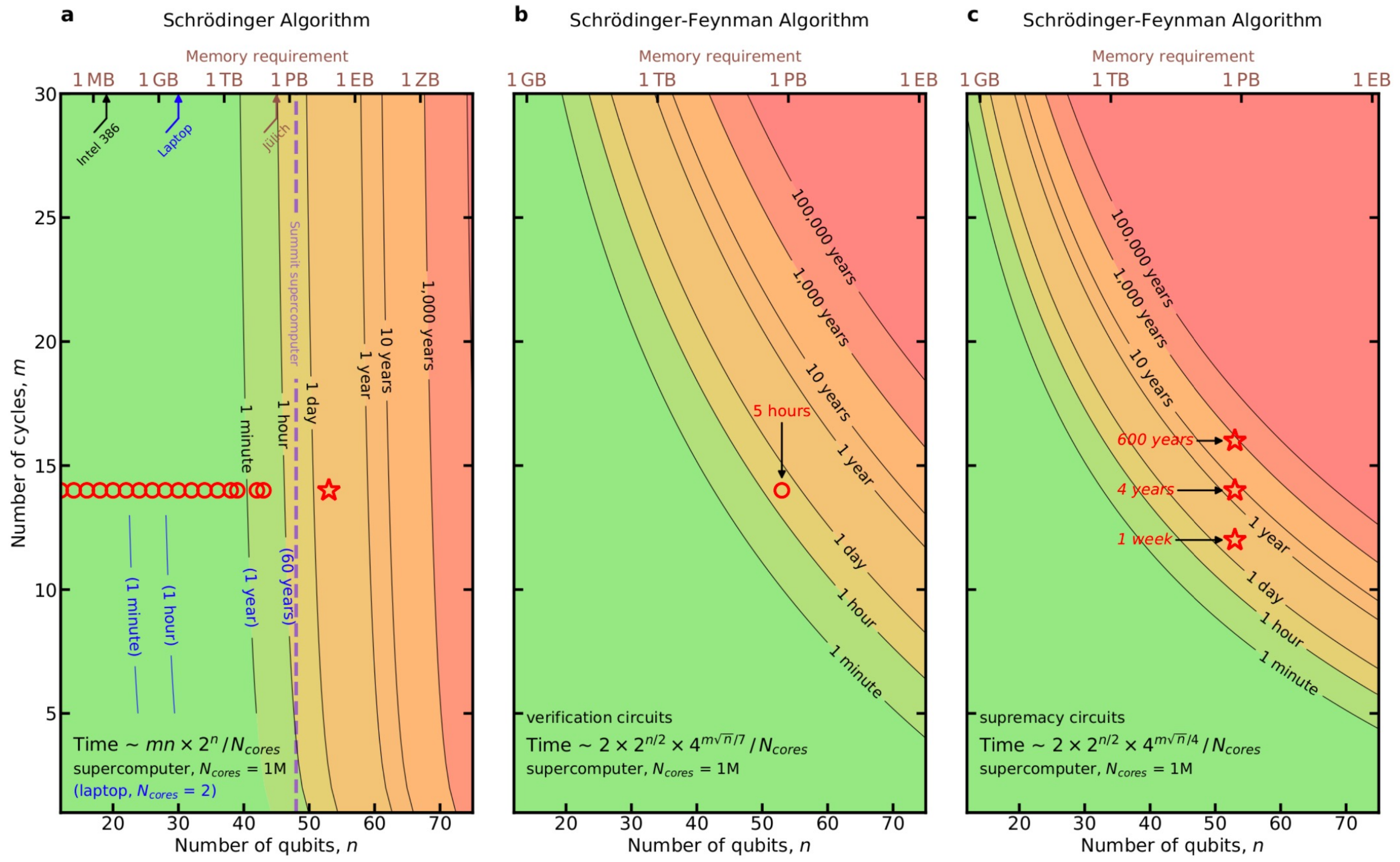

FIG. S40. **Scaling of the computational cost of XEB using SA and SFA. a,** For a Schrödinger algorithm, the limitation is RAM size, shown as vertical dashed line for the Summit supercomputer. Circles indicate full circuits with $n = 12$ to 43 qubits that are benchmarked in Fig. 4a of the main paper. 53 qubits would exceed the RAM of any current supercomputer, and shown as a star. **b,** For the hybrid Schrödinger-Feynman algorithm, which is more memory efficient, the computation time scales exponentially in depth. XEB on full verifiable circuits was done at depth $m = 14$ (circle). **c,** XEB on full supremacy circuits is out of reach within reasonable time resources for $m = 12$, 14, 16 (stars), and beyond. XEB on patch and elided supremacy circuits was done at $m = 14$, 16, 18, and 20.

Quantum supremacy using a programmable superconducting processor (supplement). Arute et al.

- Until we have quantum computer systems, building and testing quantum computers will rely on classical computer systems.

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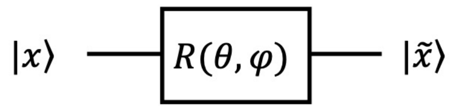
A small set of quantum gates are universal…

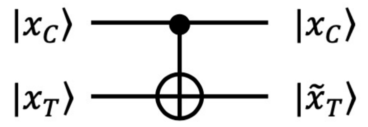
$$|0\rangle \xrightarrow{R(\theta,\varphi)} \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

$$|1\rangle \xrightarrow{R(\theta,\varphi)} \cos\left(\frac{\theta}{2}\right)|1\rangle - e^{-i\varphi}\sin\left(\frac{\theta}{2}\right)|0\rangle$$



(a)

$$|0\rangle|0\rangle \xrightarrow{CNOT} |0\rangle|0\rangle$$
$$|0\rangle|1\rangle \longrightarrow |0\rangle|1\rangle$$
$$|1\rangle|0\rangle \longrightarrow |1\rangle|1\rangle$$
$$|1\rangle|1\rangle \longrightarrow |1\rangle|0\rangle$$



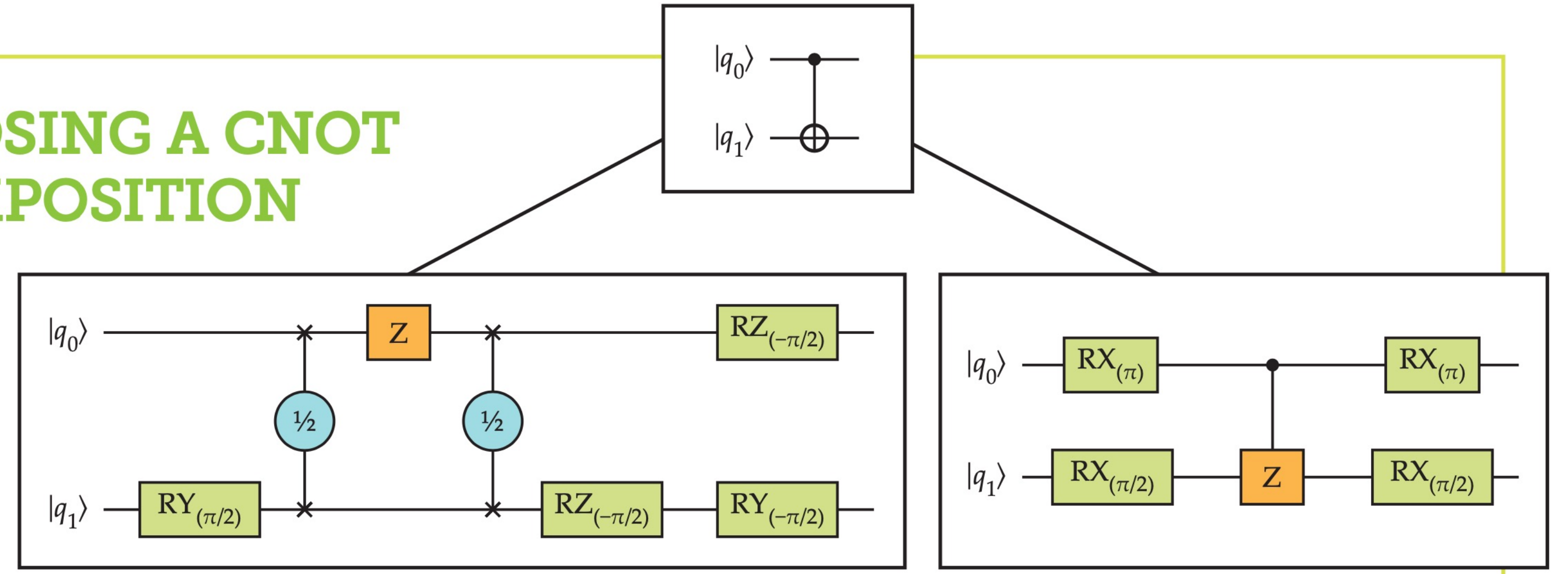
(b)

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

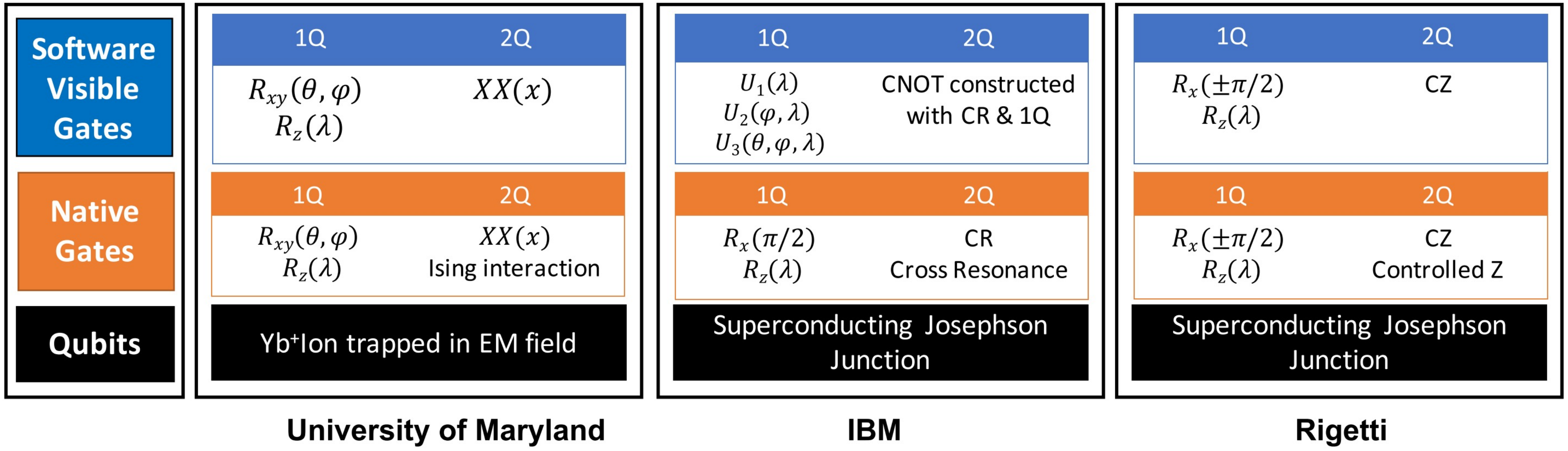


A logical controlled-NOT, or CNOT, gate is an entangling operation that flips the target qubit between 1 and 0 if the control qubit is in the 1 state. It must be decomposed into a sequence of native quantum gates for the qubit technology to perform the gate operation on the specific qubit system. Two 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.



	University of Maryland		IBM		Rigetti	
	1Q	2Q	1Q	2Q	1Q	2Q
Software Visible Gates	$R_{xy}(\theta,\varphi)$ $R_z(\lambda)$	$XX(x)$	$U_1(\lambda)$ $U_2(\varphi,\lambda)$ $U_3(\theta,\varphi,\lambda)$	CNOT constructed with CR & 1Q	$R_x(\pm\pi/2)$ $R_z(\lambda)$	CZ
Native Gates	$R_{xy}(\theta,\varphi)$ $R_z(\lambda)$	$XX(x)$ Ising interaction	$R_x(\pi/2)$ $R_z(\lambda)$	CR Cross Resonance	$R_x(\pm\pi/2)$ $R_z(\lambda)$	CZ Controlled Z
Qubits	Yb^+Ion trapped in EM field		Superconducting Josephson Junction		Superconducting Josephson Junction	

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.

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

1. Fault-tolerant, error-corrected quantum computers for algorithms
2. Programming: High level languages to aid algorithm discovery
3. Programming: Facilities for program correctness (debuggers, assertions)
4. Programming: Intermediate representations that aid analysis
5. Simulation: Support to validate and design next-gen quantum computers
6. Architecture: Standard instruction set architectures
7. Architecture: Memory hierarchy to store quantum data
8. Microarchitecture: Abundant and reliable quantum devices

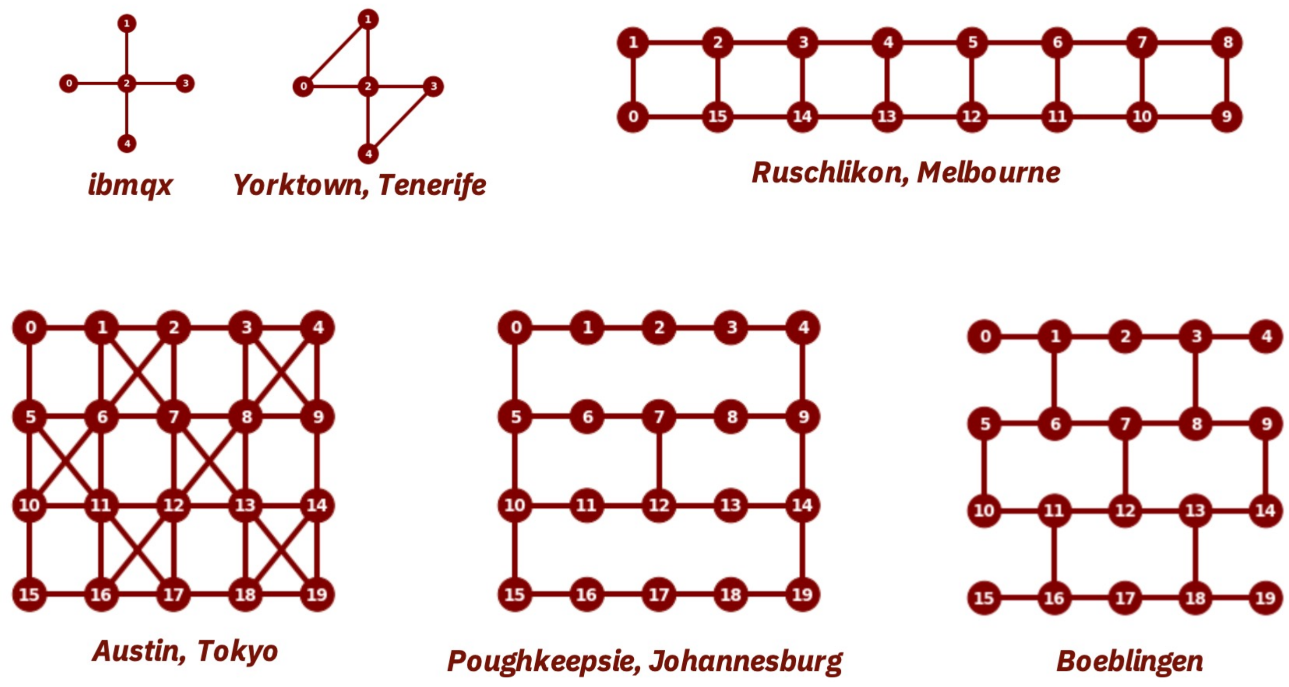


Fig. 1. Examples of several IBM cloud accessible devices. The top left 5-qubit device was the first one made available via the IBM Quantum Experience [40]. The one to the right of it was made available after including additional entangling gates between two pairs of qubits. A 16-qubit device was made 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.

Compiling quantum program abstractions to optimal quantum execution

Compilation for maximum correctness, while respecting constraints:

- variable qubit, operation, measurement reliability
- connectivity constraints
- parallelism

Will be topic of chapter on "extracting success."

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

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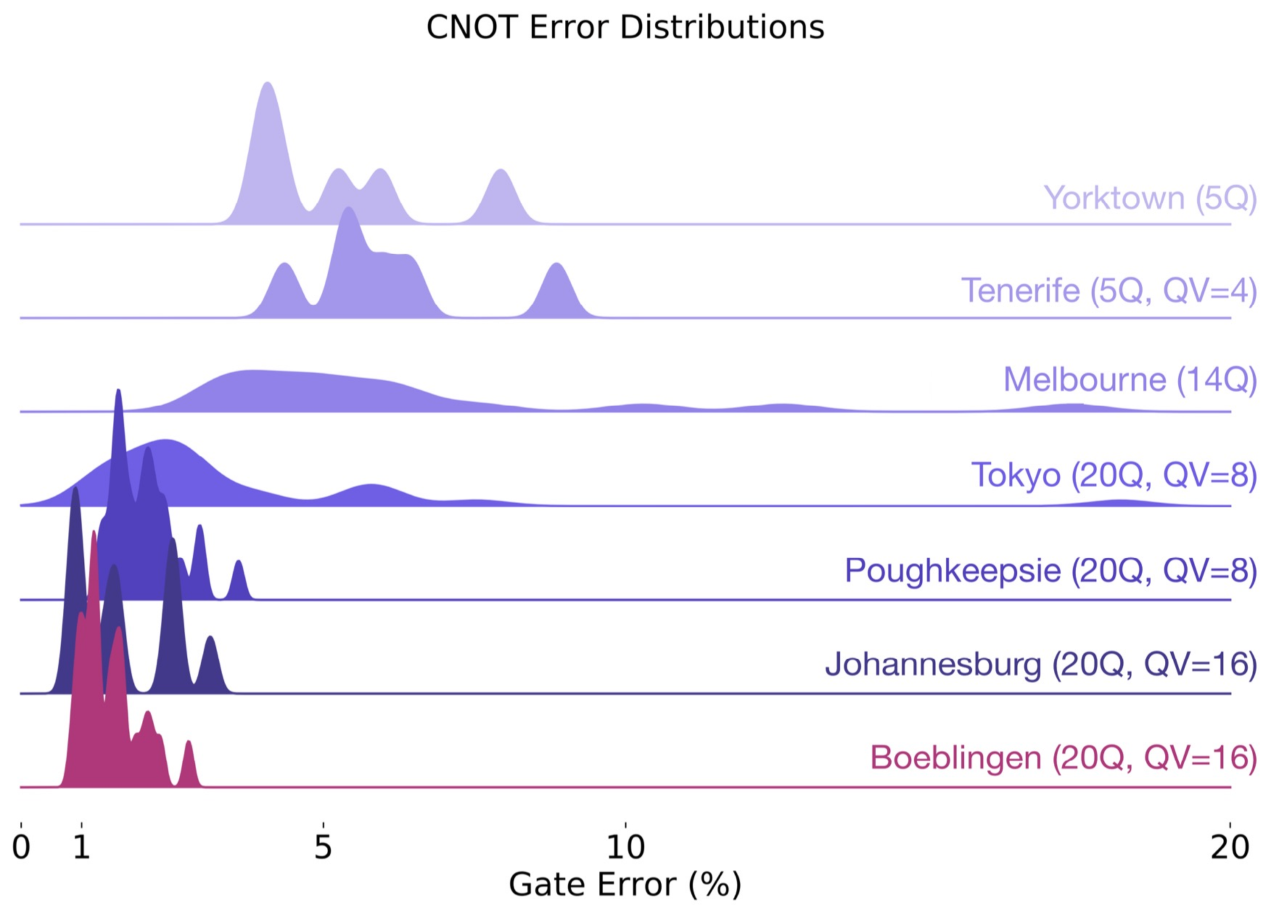


Fig. 2. Controlled-NOT (CNOT) gate error distributions for a variety of IBM devices. Beginning with the earlier devices (top rows), the average error rates remained quite large but have improved with continuing research. The bottom row represents the device shown in Fig. 4. The error reductions are the 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.

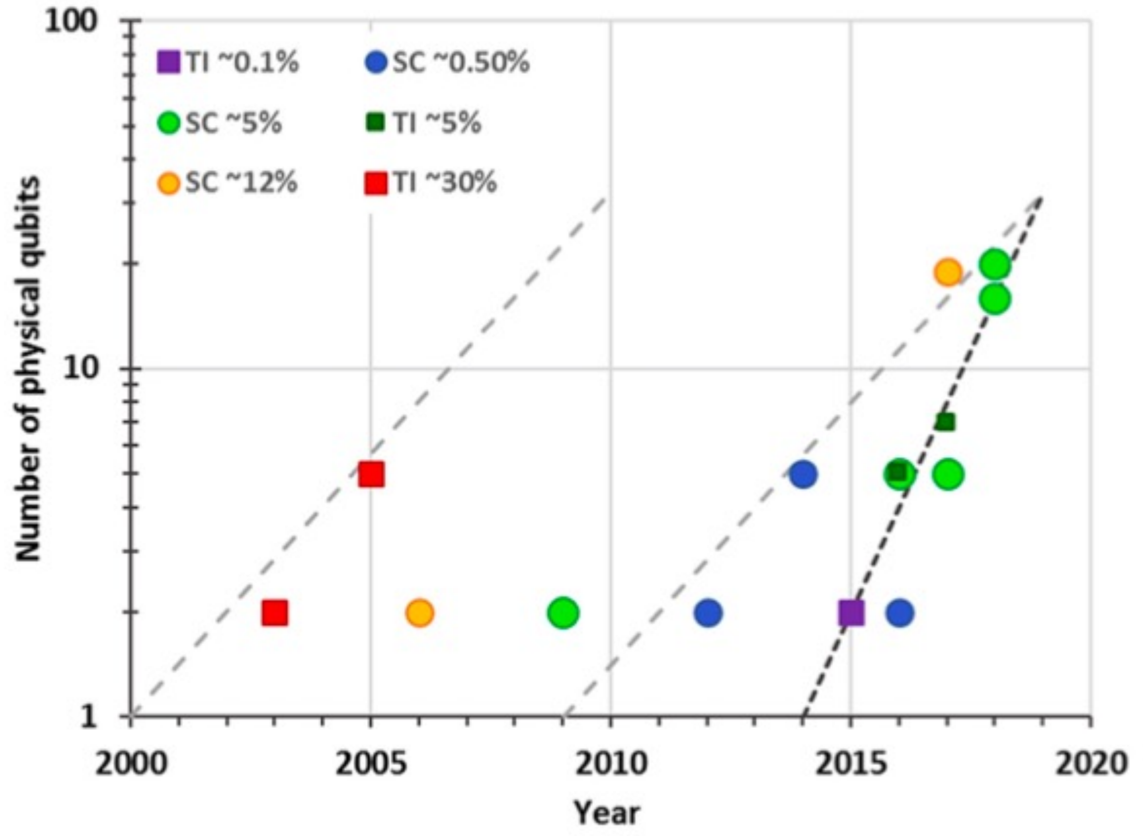


FIGURE 7.2 The number of qubits in superconductor (SC) and trapped ion (TI) quantum computers versus year; note the logarithmic scaling of the vertical axis. Data for trapped ions are shown as squares and for superconducting machines are shown as circles. Approximate average reported two-qubit gate error rates are indicated by color; points with the same color have similar error rates. The dashed gray lines show how the number of qubits would grow if they double every two years starting with one qubit in 2000 and 2009, respectively; the dashed black line indicates a doubling every year beginning with one qubit in 2014. Recent superconductor growth has been close to doubling every year. If this rate continued, 50 qubit machines with less than 5 percent error rates would be reported in 2019. SOURCE: Plotted data obtained from multiple sources [9].

Quantum Computing Progress and Prospects. National Academies Press.

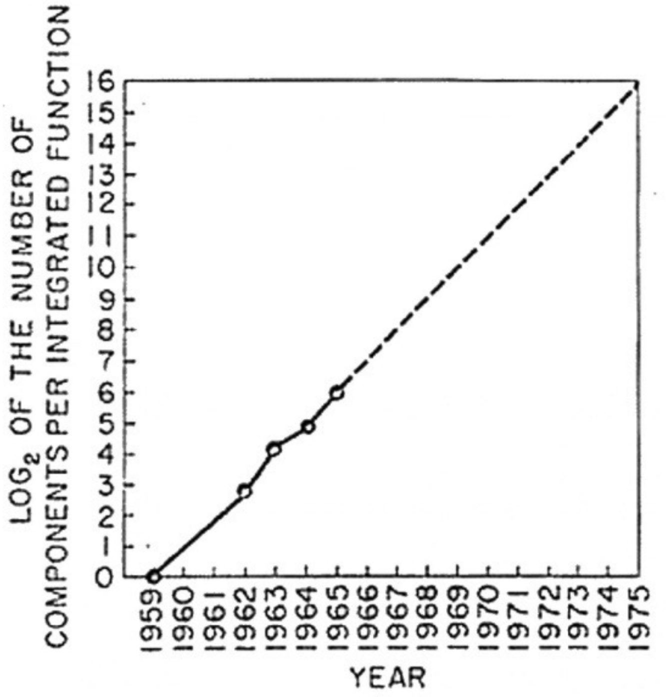
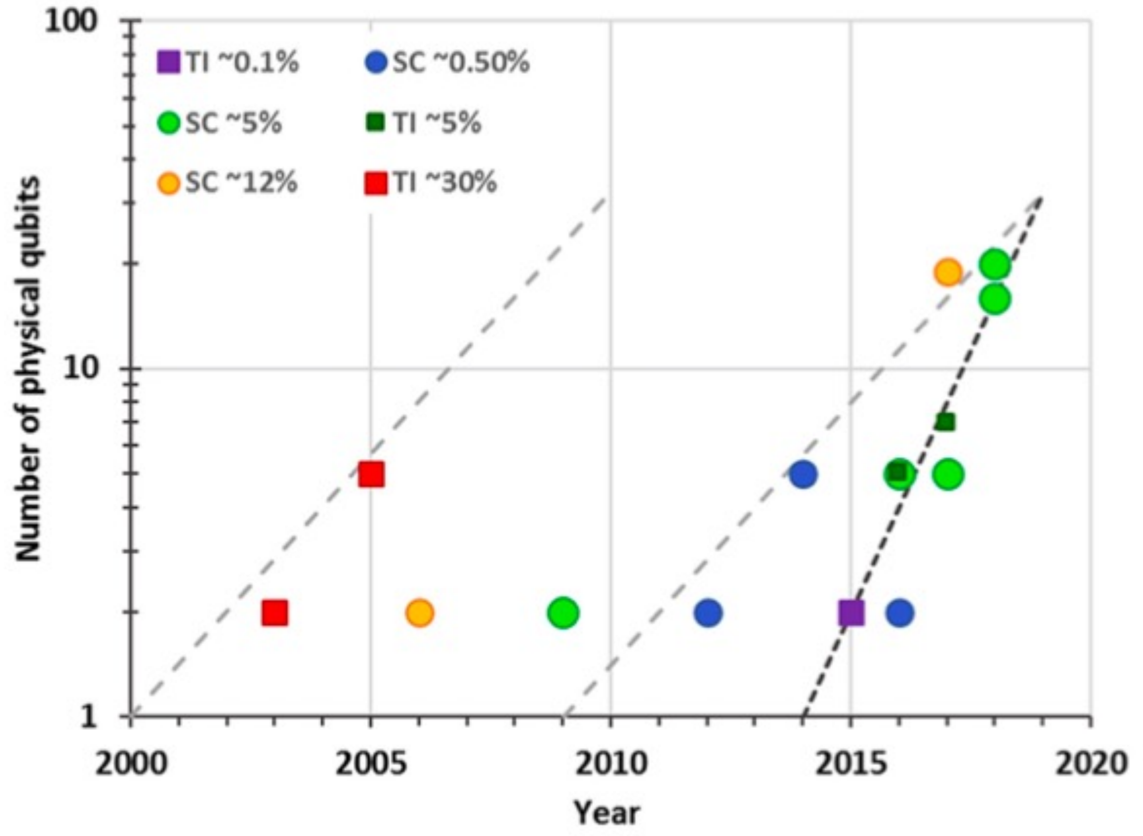


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

Intel



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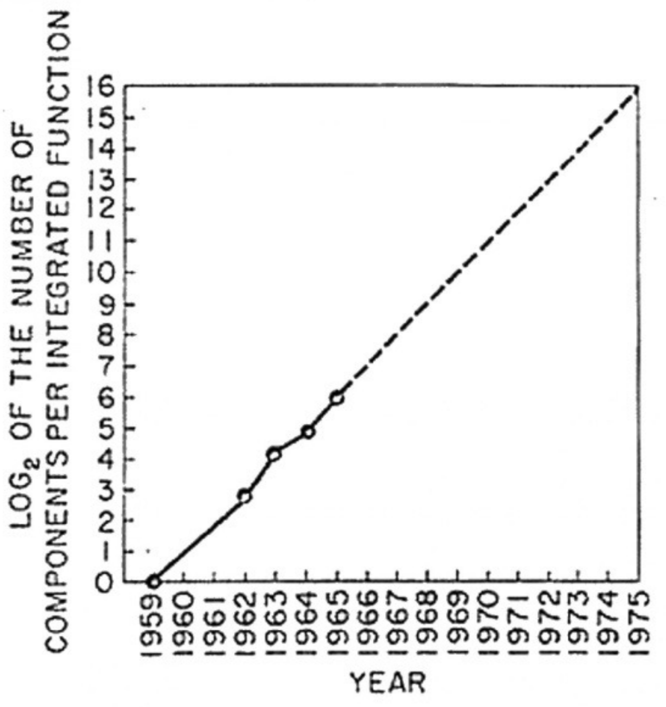
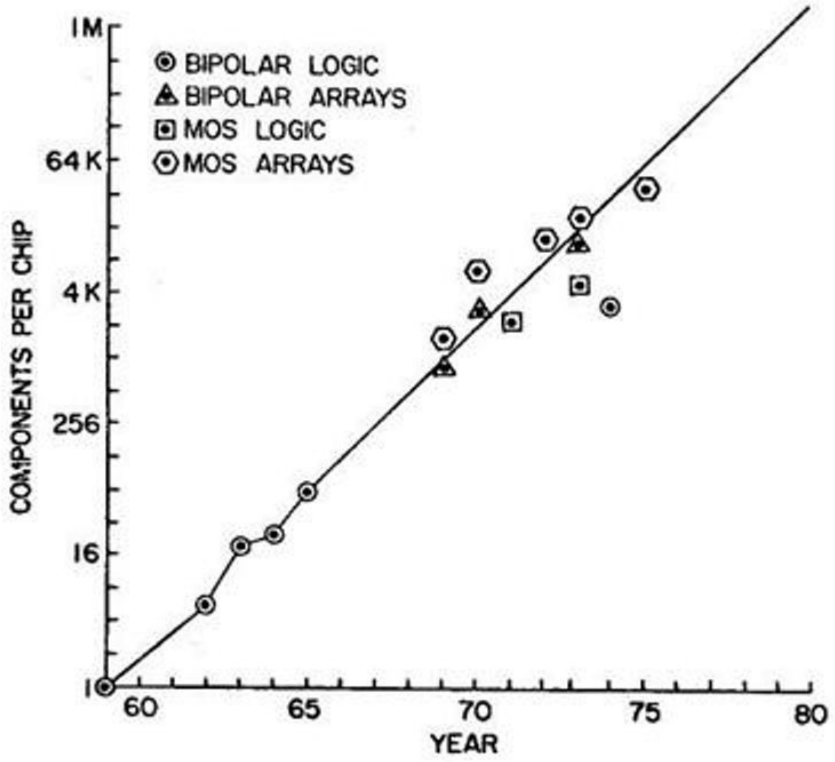


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

Intel



Computer History Museum

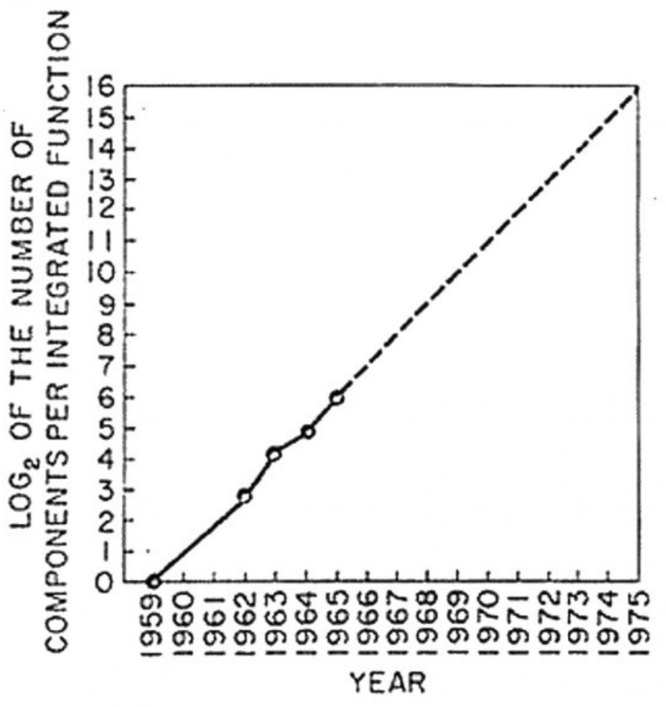
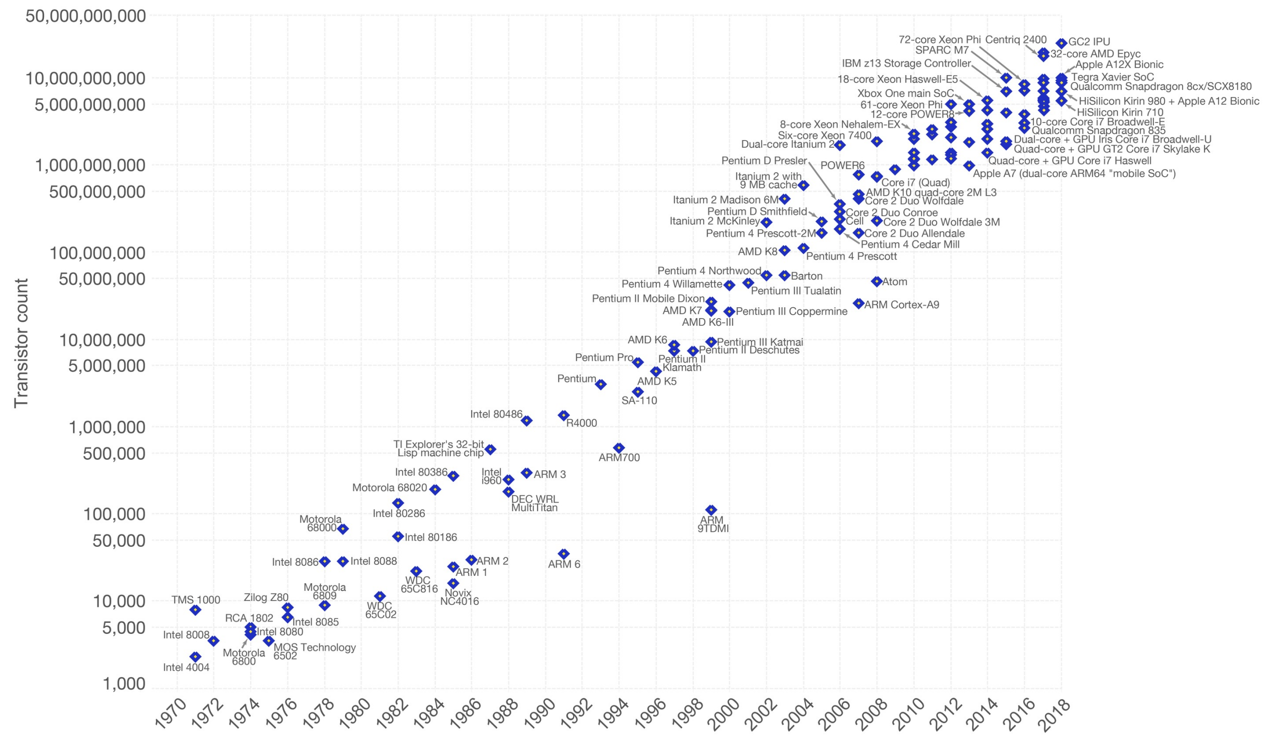


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

Intel

Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Wikipedia

Position statement for this graduate seminar

- Quantum computer engineering has become important.

- Requires computer systems expertise beyond quantum algorithms and quantum device physics.