Programming Quantum Computers (Introduction)

(**Subtrack of** Quantum Computing: An App-Oriented Approach)

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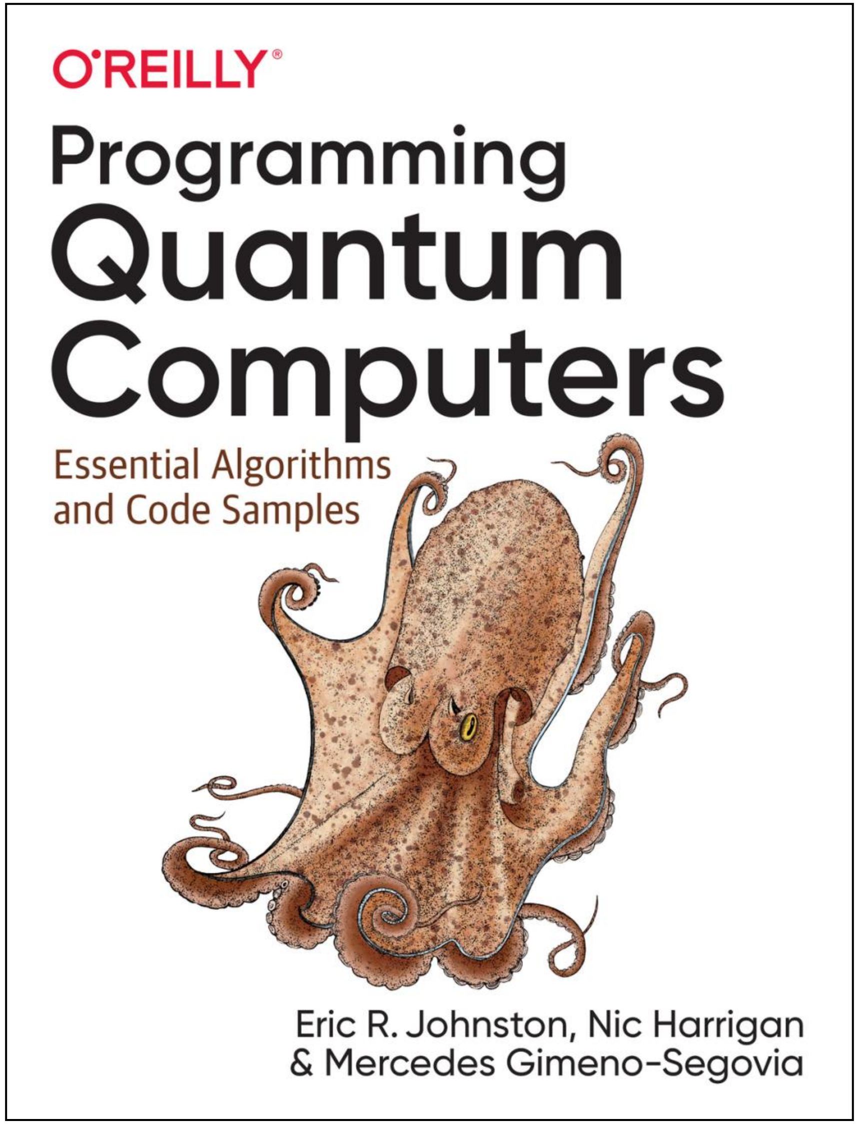
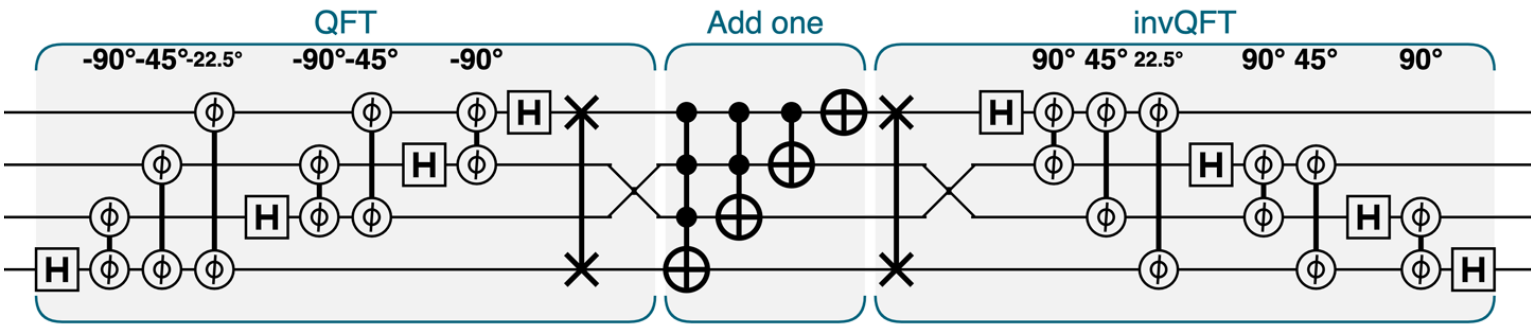

O'REILLY
Programming
Quantum
Computers
Essential Algorithms
and Code Samples
Eric R. Johnston, Nic Harrigan
& Mercedes Gimeno-Segovia

Quantum Computers are Real

- What are they useful for?
  - Let's discover, by programming them!

- A hands-on approach to programming QCs/QPUs.
  - By doing; i.e., by writing code & building programs.
  - Using simulators, since real QCs are harder-to-access (so far).

- Goals: Read, understand, write, and *debug* quantum programs.
  - Ones like the following.



PQC Outline (Tentative)

- **Introduction.**
  - **One Lect. (Ch. 1 & 2)**
  - **Qubits, Superposition, and One-Qubit Primitives.**

- Primitives.
  - One Lect. (Ch. 3 & 4)
  - Multiple Qubits and Entanglement.
  - A Program for Teleportation.

- Libraries.
  - Two Lects. (Ch. 5-8)
  - Arith. & Logic.
  - Amp. Amplification, QFT & Phase Est.

- Applications.
  - Two-Three Lects. (Ch. 9-13)
  - Real Data.
  - Search. Supersampling and QIP.
  - Shor's Factoring Algorithm, Quantum ML.

Lecture Outline

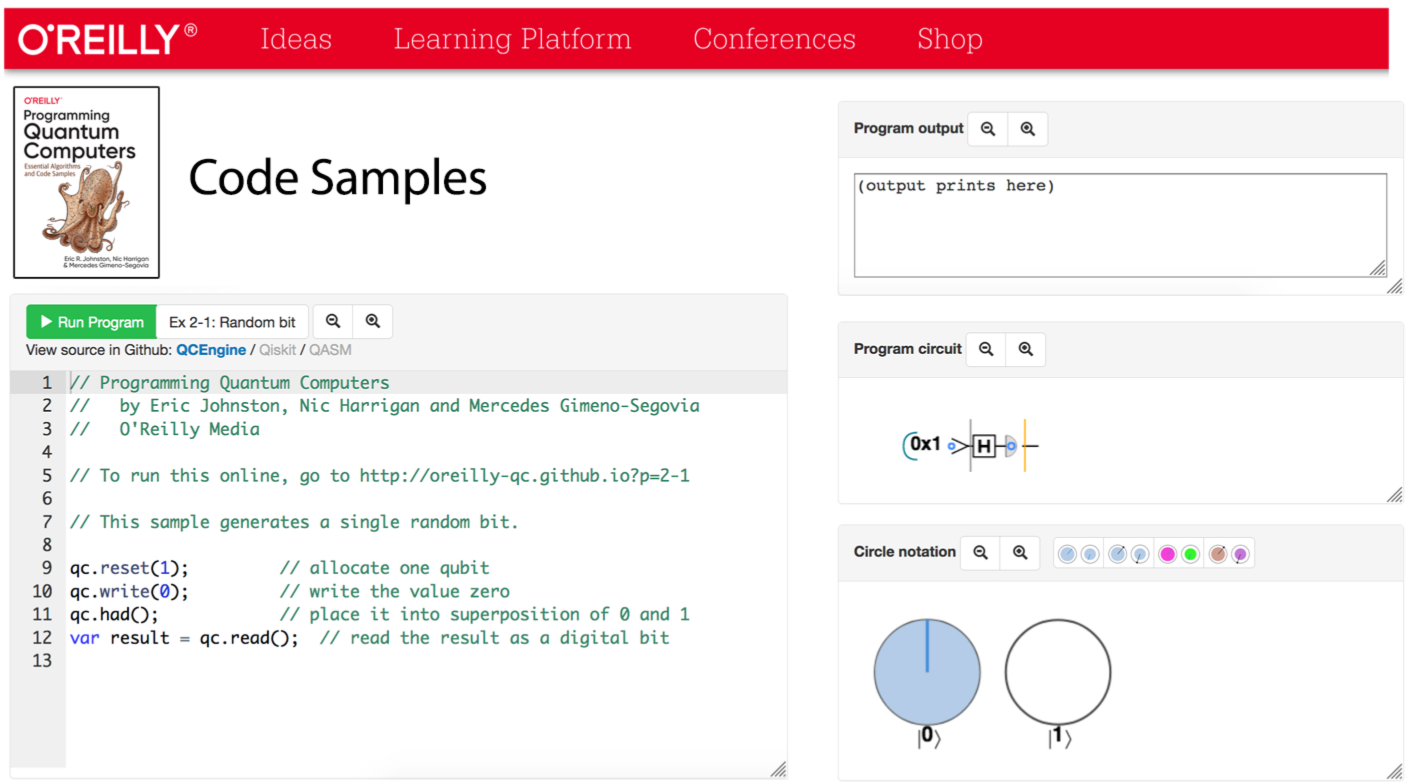
- Introduction & One Qubit Primitives.
  - QCEngine.
  - Qubits.
    - Physical, Logical. Bloch Sphere, Circle Notation.
  - Primitive Qubit Operations (PrimOps).
  - Simple Quantum Programs.
    - Random Generators, Quantum Spy Hunter.

Section I

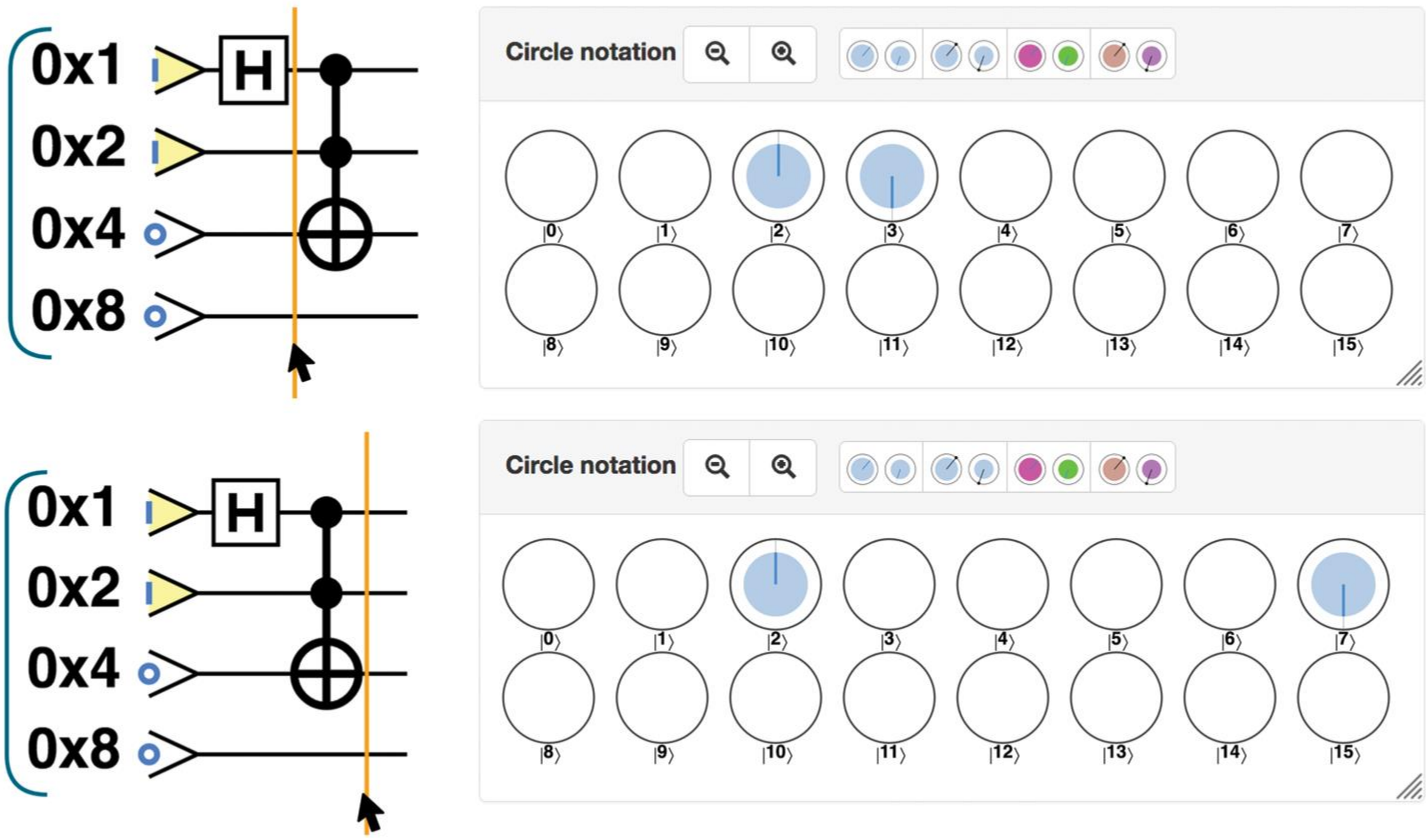
QCENGINE AND QUBITS

QCEngine: An Online Quantum Simulator

- https://oreilly-qc.github.io/

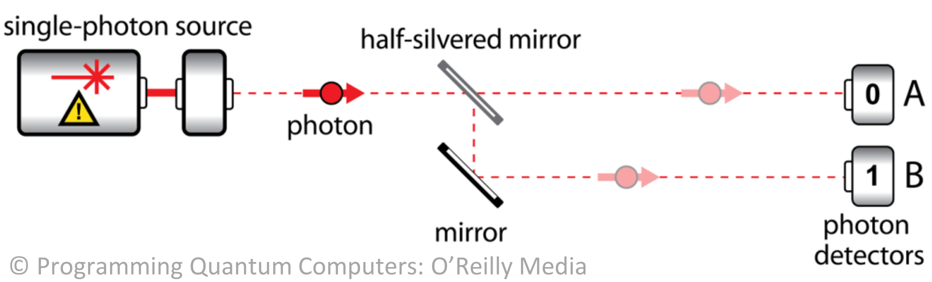


Debugging in QCEngine



What’s a Qubit?

- Qubit = Quantum bit.
- Physical/Concrete Qubits vs. Logical/Abstract Qubits.
- Physical Qubit: Photon, electron, ion, …
  - Needs physics knowledge.
  - Imperfect (decoherence). Needs error-correction.



What’s a Qubit?

- Logical Qubit:
  - Simpler (no physics).
  - Ideal (no worrying about errors).
  - May correspond to more than one physical qubit.
  - For programming, we use *logical* qubits.
    - Portable quantum programs, independent of underlying hardware.
  - Basic qubit values (quantum states):
    - Quantum_Zero $|0\rangle$ and Quantum_One $|1\rangle$.

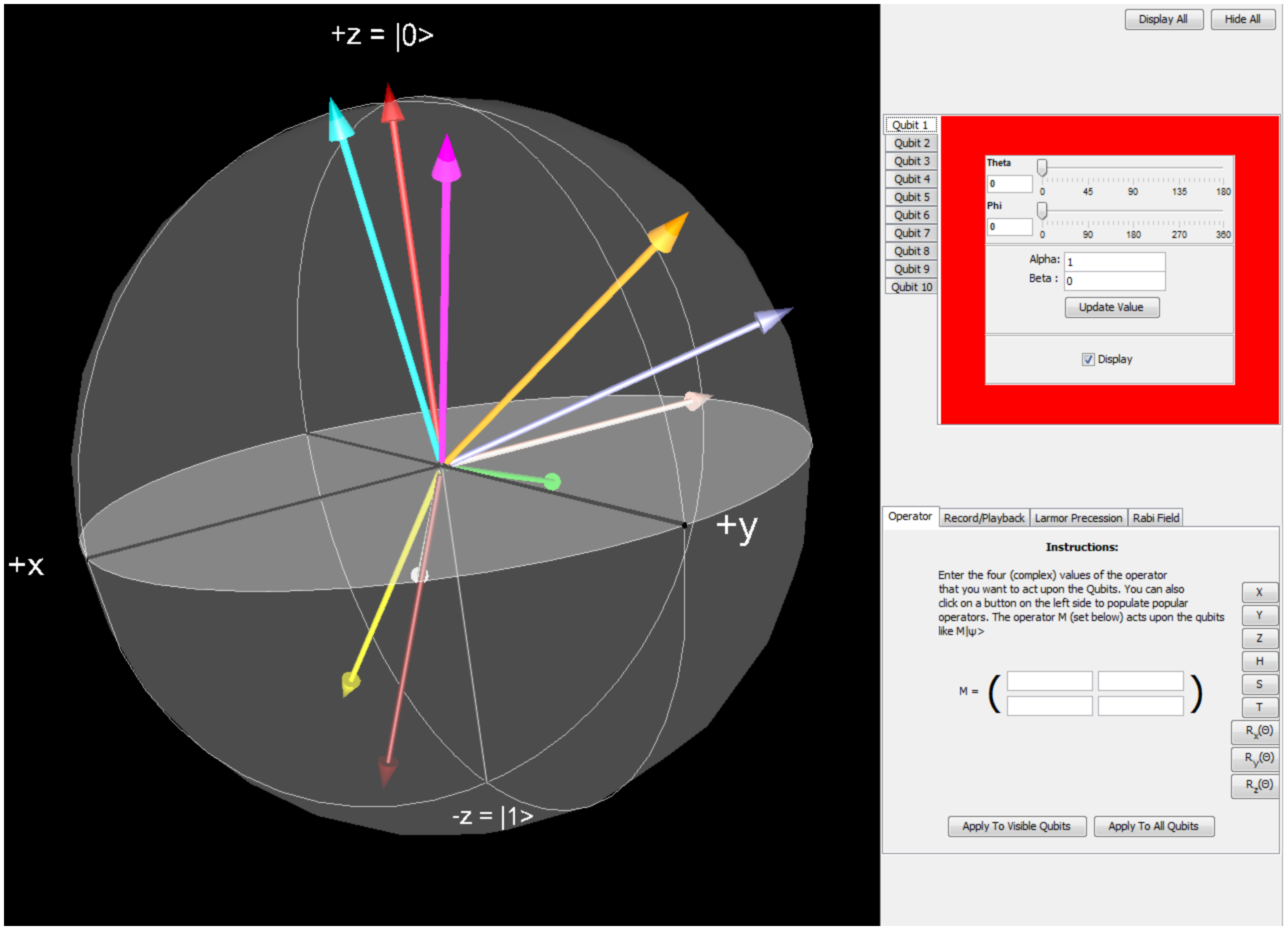
What’s a (Logical) Qubit?

- Superposition: $c_0|0\rangle + c_1|1\rangle$

- Circle-notation:
  - Complex numbers c, and their conjugates c^*.
  - Amplitude: $c = a + ib = re^{i\theta}$ ($i = \sqrt{-1}$; a, b, r, θ are reals)
  - Magnitude: $r = |c| = \sqrt{c \times c^*} = \sqrt{a^2 + b^2}$
  - Phase: $\theta = \tan^{-1}(b/a)$
  - Probability: $r^2 = a^2 + b^2$ (square of magnitude)
    - ${r_0}^2 + {r_1}^2 = 1.0$ (sum of probabilities)
  - Relative phase (difference between phases): $\theta_1 - \theta_0 | 360°$.

  - Visualizing Logical Qubits:
    - Bloch Sphere (Bloch Sphere Simulator, dotBloch App)
      - Three free variables (degrees of freedom) rather than four, or in fact just two (Theta and Phi).
    - To the rescue: **Circle-notation**
      - Visual, simple. No physics, no (complex) numbers!

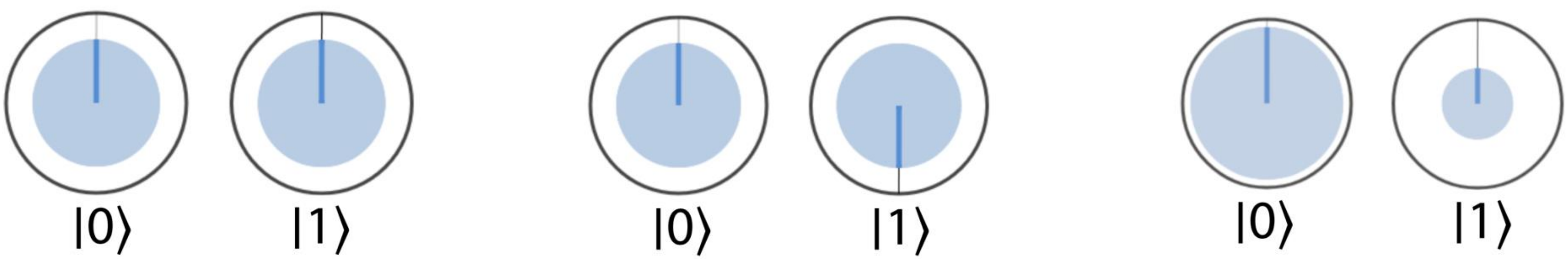
Bloch Sphere Simulator



Circle-Notation

- Conventional bits, and qubits *after* readout.

- Qubits *before* readout (superposition).

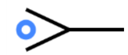


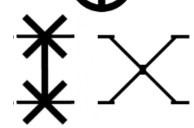
$0.707|0\rangle + 0.707|1\rangle$ $0.707|0\rangle - 0.707|1\rangle$ $0.95|0\rangle + 0.34|1\rangle$

Section II

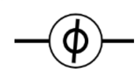
PRIMITIVE QUANTUM OPERATIONS AND SIMPLE QUANTUM PROGRAMS

Primitive Quantum Operations (PrimOps)

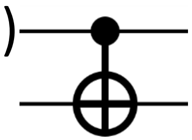
- **Read**  `val qc.read(t)`
- **Write**  `qc.write(t, val)`
- **No-Op** `qc.nop()`

- **Not**  `qc.not(t)`
- **Swap** (2 qubits)  `qc.exchange(t1|t2)`

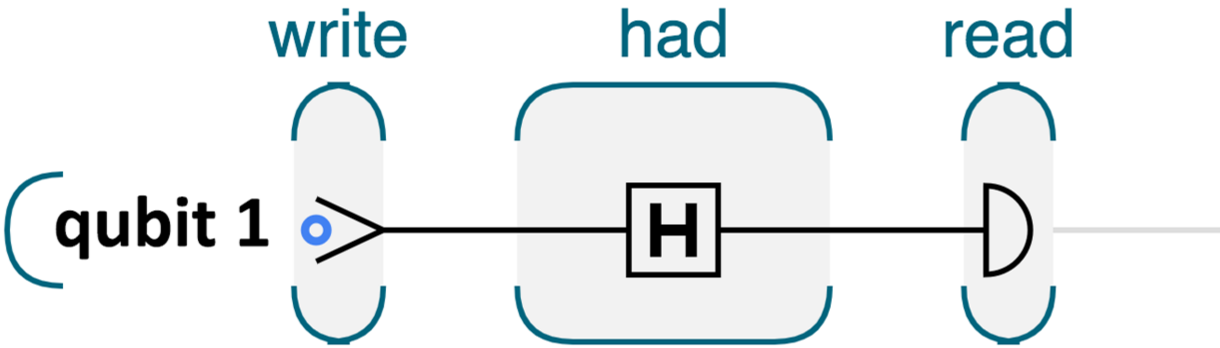
- **Hadamard** (Superposition) 

`qc.had(t)`
- **Phase** (deg.) 

`qc.phase(angle, t)`
- **Root-Not**  `qc.rootnot(t)`

- Cond. Op. (C-Not, C-Swap, C-Phase)  `qc.cnot(t,c)`
  - Multi-qubits (2 or more). `qc.cnot(t,c1|c2)`

Our First Quantum Program (Hands-on: Let's Play Online!)



Perfect Random Bit Generator

PrimOps: More Details

- **Read**: Converts a superposition to black/white (measurement). Random, according to probabilities.
  - Superposition, including phase, is irreversibly destroyed (Subsequent reads return same value).
- **Write**: Puts a definite black/white value (only $|0\rangle$ and $|1\rangle$ are allowed).
- **No-Op**: Does nothing (“time passage”).

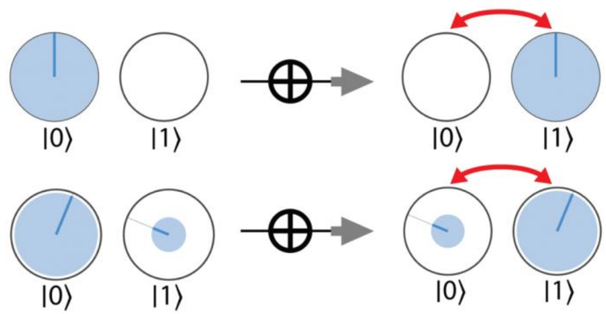
- **Not**: Flips/swaps probabilities and phase. Reversible.
- **Swap**: Exchanges states of two qubits.

- **Hadamard**: Puts into superposition ($|0\rangle$ goes to perfect 50%-50% superposition, $|1\rangle$ goes to same but with relative phase $180°$). Reversible. (Averaging. Best understood as matrix.)
- **Phase**: Shifts phase of $|1\rangle$ relative to that of $|0\rangle$.
  - **Rot-X** and **Rot-Y** (on Bloch sphere).
- **Root-Not**: Squared (repeated twice) gives **Not**.

- More into math? Complex vectors, matrices, linear algebra, tensor products, … .

PrimOps: More Details (using circle-notation)

- **Not**:



- Similarly for other primops.
  - **Phase**: Rotates $|1\rangle$ (right circle) counterclockwise.
  - **H** (**Hadamard**): Average and difference (matrix).
  - Any questions?

- Combinations/compositions, and equivalences.
  - Equiv. are basis for transformations and optimizations.
  - For example, $H \circ Z \circ H = \oplus$ and $H \circ \oplus \circ H = Z$.

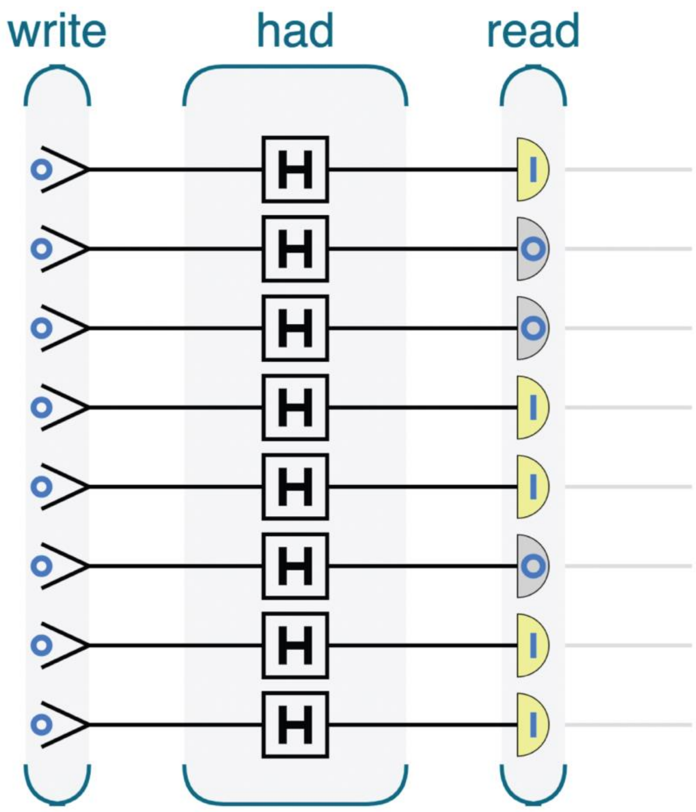
No ‘Copy’ Operation

- A fundamental counterintuitive property of QC.
  - Quantum states cannot be replicated.
  - Not even using entanglement. Originals are always destroyed.

- App-specific workarounds typically employed.

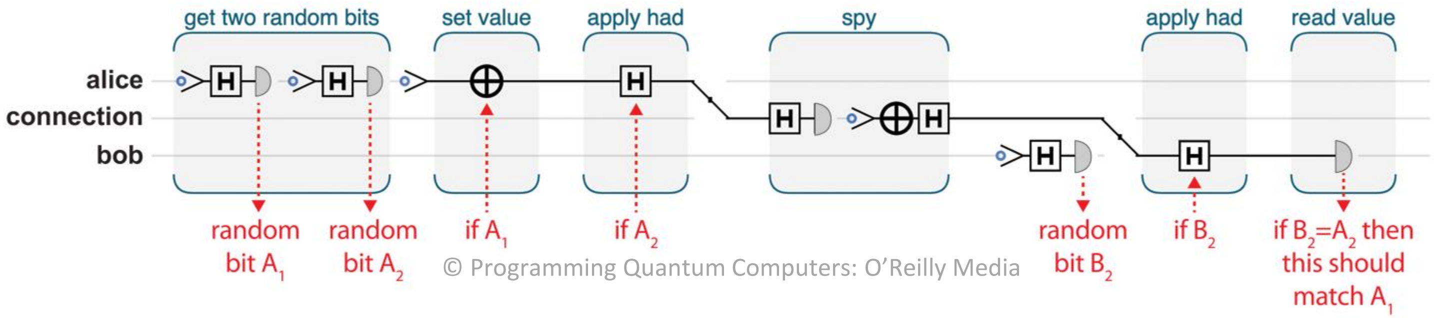
A Slightly More Advanced Program

- Can you guess what does program do?



Perfect Random Byte Generator

Quantum Spy Hunter



- Using the amazing laws of quantum physics/computing (e.g., no copy op.) to our advantage.

- Using 50 qubits, probability of spy *not* getting caught is less than $\frac{1}{1{,}000{,}000}$.
  - Precisely is $\left({}^{3}/_{4}\right)^{50}$.
  - Every 10 qubits divide the probability of not catching spy by more than 10 (precisely, by 17.75. Every 5 qubits divide by 4.2).

Discussion

Q & A

Next Lecture Appetizer!

- In next lecture:
  - Multi-Qubit Operations
    - Controlled Ops.
    - Entanglement.
  - Teleportation!
    - On IBM's quantum computer!

Thank You