Teaching Quantum Computing in High School

Anastasia Perry
Lewis University

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https://t2m.io/WyPJJm6Z8
IBM claims ‘quantum supremacy’ over Google with 50-qubit processor

House Passes Bill to Advance Quantum Science in the U.S.

Serious quantum computers are finally here. What are we going to do with them?
Current commercial efforts

- Google (superconducting loops)
- IBM
- Intel
- Rigetti
- IonQ (trapped ions)

Other companies…

- Academic efforts…
- D-Wave (quantum annealing)
- Fermilab superconducting RF cavities
“Nature isn’t classical . . . and if you want to make a simulation of Nature, you’d better make it quantum mechanical” (Richard Feynman, 1981)

**Superposition**
- A quantum system can exist in several states at the same time
- Measurement destroys superposition and only one state is observed with a certain probability

**Entanglement**
- If two particles are entangled, measuring the state of one gives information about the other.
Classical vs Quantum Information

Bits

1 and 0
On or off

Quantum Bits: Qubits

Spin up $|1\rangle$
Spin down $|0\rangle$

Superposition $|\Psi\rangle=\alpha|0\rangle+\beta|1\rangle$

For $n$ 2-state qubits there will be $k=2^n$ ‘bits’ of information

$|\Psi\rangle=\alpha_1|0...00\rangle+\alpha_2|0...01\rangle+\alpha_3|0...10\rangle+...+\alpha_k|1...11\rangle$

Amplitudes $\alpha_i$ are complex numbers.
Classical vs Quantum Gates

X, Y, Z, H (Hadamard)

CNOT - universal gate

- Irreversible
- Can be copied

- Reversible (Unitary Matrices)
- Cannot be copied

\[ f(2^n) \]
Applications

Quantum algorithms can solve certain problems more efficiently

➢ Shor’s factorization (1994) (polynomial speed)
➢ Grover’s search (1996)
➢ Quantum simulations
➢ Quantum network
➢ Quantum AI…..
Challenges

**Engineering:** hard to build, noise sensitivity, error

**Educational:** very abstract and non-intuitive, mostly theoretical

Quantum computers require not just different programming languages but a fundamentally different way of thinking about what programming is: “We don’t really know what the equivalent of ‘Hello, world’ is on a quantum computer.”

Knight, MIT Technology Review, 2018
How did I get involved in QC?

NOYCE TEACHING SCHOLARSHIP LEWIS
University

2018 summer Internship at Fermilab

My mentors: Jessica Turner, Joshua Isaacson, Ciaran Hughes

My collaborator: Ranbel Sun (Phillips Academy, Boston MA)

OBJECTIVES: Learn about QC,
Create materials to teach QC for High school students
Quantum Tic-Tac-Toe (Goff, 2006)

Introduces fundamentals of quantum mechanics:

- SUPERPOSITION
- MEASUREMENT
- ENTANGLEMENT

- Hands-on
- Used in undergraduate Quantum Mechanics courses at Purdue University (Hoehn at al, 2014)
IBM Q Experience

Beginners Guide
- FAQ for Beginners
- Introduction
- Getting Started
  - Histogram representation (Bar graph)
- The Weird and Wonderful World of the Qubit
- Single-Qubit Gates
  - Creating superposition
  - Introducing qubit phase
  - Summary of quantum gates
- Multi-Qubit Gates

Schrodinger's worm
Superposition using Interferometer

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Step-by-step Explanation</th>
<th>quantumphysics.iop.org</th>
<th>IOP Institute of Physics</th>
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</thead>
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**Interferometer experiments with photons, particles and waves**

- **Introduction**
- **Controls**

**Input**
- Classical particles
- Electromagnetic wave
- Single photons

**Beam splitter 1**
- Probability 50%

**Beam splitter 2**
- Probability 50%

**Detector 1**
- Probability 50%

**Detector 2**
- Probability 50%

**Coincidence counter**
- IN1 IN2

**Detected counts**
- Detector 1: $N_1 = 1$
- Detector 2: $N_2 = 2$
- Coincidences: $N_c = 0$

**Main controls**
- Fire
- Fast forward 100 counts
- Stop
- Insert beamsplitter 2

**Display controls**
- Label elements
- Show theoretical probabilities

**Clear measurements**
Stern-Gerlach Experiment

Lab activity about spin

Measurement basis

Cascade apparatus
Entanglement using SGA

Entanglement: The nature of quantum correlations

Source of particle pairs

Orientation of SGAs:
- X
- Z

Alice's SGA

Bob's SGA

Simulation

Source quantum state

\[ \frac{1}{\sqrt{2}} (|\uparrow \rangle_B - |\downarrow \rangle_B) \]

Product state

\[ \frac{1}{2} (|\uparrow \rangle_A + |\downarrow \rangle_A) (|\uparrow \rangle_B - |\downarrow \rangle_B) \]

Entangled state

\[ \frac{1}{\sqrt{2}} (-|\uparrow \rangle_A |\uparrow \rangle_B + |\downarrow \rangle_A |\downarrow \rangle_B) \]

Individual measurements

Total number of pairs: \( N_{\text{tot}} = 0 \)

<table>
<thead>
<tr>
<th>Alice</th>
<th>Probabilities</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{A+} = 0 )</td>
<td>( P_{A+} = \frac{N_{A+}}{N_{\text{tot}}} = \frac{0}{0} )</td>
<td>1.000</td>
</tr>
<tr>
<td>( N_{A-} = 0 )</td>
<td>( P_{A-} = \frac{N_{A-}}{N_{\text{tot}}} = \frac{0}{0} )</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Quantum Cryptography

Quantum key distribution (BB84 protocol) with spin $\frac{1}{2}$ particles

Display controls
- Show key generation
- Show key bits
- Show total errors

Main controls
- Send spin $\frac{1}{2}$ particles to Bob
- Single particle
- Continuous
- Fast forward 100 particles
- Let Eve intercept and resend particles
- Stop eavesdropping

Alice
- Basis: X
- Value: 1

Eve
- Basis: Z
- Outcome: 0

Bob
- Basis: Z
- Outcome: 0

Alice and Bob Same bases?
- Alice: NO
- Bob: NO
- Key: ERROR

Key
- Eve chose the wrong basis!

Most recent key bits (same bases)
- Alice: 0 0 0 1 0 0 1 0 0 1 1 1 1 1 1 1 1 0 1 0 0 1
- Bob: 1 1 1 1 1 0 0 1 1 0 1 1 0 0 0 1 0 0 0 0 0 0

Errors (all measurements)
- Total: $N_{tot} = 900$
- Key bits: $N_{key} = 436$
- Errors: $N_{err} = 108$
- Theoretical: $0.25 N_{tot}$
- Probability: $N_{err} = 0.248 N_{key}$
- Probability: 0.25
Conclusion and questions

1. Should we teach QC in High school physics?
2. Where would it fit in the public school curriculum?

Creating a quantum-smart workforce for tomorrow

- Encourage academia to consider quantum science and engineering as its own discipline, with needs for new faculty, programs, and initiatives at all levels
- Address education in the area of quantum science at an early stage, including elementary, middle and high school levels

Beyond the university, outreach to a broader audience will be essential. A strong comprehensive program in K-12 computational and scientific thinking featuring computer science and physics must start with developing interest at an early stage. A critical role can be played by industry, professional
Thank you!

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