Educational Programs in QIS at UT Austin

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Outline

QIS Research at UT Austin
  Research Centers & Researchers

QIC Education Programs
  Student Mentoring
  Undergraduate & Graduate Courses

CQR Education Programs
  Quantum Computing FRI Stream
  Akins High School Pilot Course

Future Directions
  QIS Certificate Program
  UT edX Courses
QIS Research Centers at UT Austin

QIC
Quantum Information Center
Scott Aaronson, CS

CQR
Center for Quantum Research
Brian La Cour, ARL

Hook 'em Hadamards!

Over 40 faculty, students, & post-docs
**An Interdisciplinary Team of Researchers**

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Research Area</th>
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<tbody>
<tr>
<td>Scott Aaronson</td>
<td>CS</td>
<td>quantum algorithms and complexity theory</td>
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<tr>
<td>Seth Bank</td>
<td>ECE</td>
<td>novel detectors and photonic chips</td>
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<td>Elaine Li</td>
<td>Physics</td>
<td>experimental AMO light-matter interactions</td>
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<td>Feliciano Giustino</td>
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<td>Allan MacDonald</td>
<td>Physics</td>
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<td>Shyam Shankar</td>
<td>ECE</td>
<td>sensors and spintronics</td>
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<td>Brian La Cour</td>
<td>ARL:UT</td>
<td>quantum emulation, STEM education</td>
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<tr>
<td>Thomas Chen</td>
<td>Math</td>
<td>quantum field theory quantum dynamics</td>
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<tr>
<td>Emanuel Tutuc</td>
<td>MRC</td>
<td>confined quantum systems</td>
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... and many more!
QIC Educational Programs at UT

C S 395T Topics in Quantum and Classical Complexity Theory
Advanced graduate course taught by Prof. Aaronson

C S 378H Introduction to Quantum Information Science
Honors undergraduate course
Cross-listed as PHYS 341, M 371T, C S 377

Mentoring
Over a dozen post-docs, graduate students, and some very talented undergraduates!

CQR Educational Programs at UT

Quantum Computing FRI Stream

Part of the Freshman Research Initiative (FRI) under the College of Natural Sciences
Second year of a year-long program for 30 incoming CNS freshman:

Spring  Quantum Information Basics (C S 309 / PHY 108)
Summer  Experimental Quantum Optics (optional)
Fall    Quantum Programming (C S 378 / PHY 308F)

Funded by ARL:UT & National Science Foundation

Mentoring

Over a dozen post-docs, graduate students, and undergraduates working on sponsored research projects
CQR Educational Programs beyond UT

High School Pilot Course

A year-long course in Quantum Computing to begin Fall 2019
Pilot at Akins High School in Austin, TX
Taught by Akins staff and UT graduate students
Curriculum & materials provided by UT:
  Collaboration between CQR at ARL:UT and the STEM Center in UT Dept. Curriculum & Instruction
Funded by the Office of Naval Research STEM

Two sections now offered, 77 students have registered!
**Class Format**
- Active learning approach
- Mixture of lecture and in-class activities
- Assisted by peer mentors and graduate TA
- Just-in-time learning of necessary math
- Use of IBM Q Experience web interface
- Weekly homework assignments
- Two group projects and two exams

**Topics Covered**
- Photon polarization, all about qubits
- Born rule, active/passive measurements
- Cryptography, quantum key distribution
- Complex numbers, vectors, matrices
- Mixed states, decoherence, tomography
- Tensor products, entanglement, Bell states
- Teleportation, entanglement swapping

**Focus on Quantum Information**
FRI Stream – Summer Program

Optional program – not for credit
Fellowship & volunteer opportunities

Quantum State Tomography
  Class II CW laser as coherent light source
  Programmable waveplates and polarizers
  Avalanche photodiode photon detectors

Photon Entanglement (coming in 2019)
  Custom Type-I nonlinear source, detectors, and timing electronics from S-15
  Bell-CHSH inequality violations!

Connecting Theory to Reality
FRI Stream – Fall Semester

Class Format
- Hands-on quantum programming
- Explicit implementation of algorithms
- Learn-as-you-go Python programming
- Use of IBM API for hardware backend
- Independent Inquiry flag for UT
- Greater emphasis on projects and activities
- Mid-term and final exams

Topics Covered
- Intro to Python, IBM QISKit, Microsoft Q#
- Basic quantum algorithms, controlled gates
- Hamiltonian simulations, Boolean oracles
- Grover’s search algorithm, QAOA
- RSA encryption, Shor’s factoring algorithm
- Quantum error correction
- Stabilizer formalism, fault-tolerance

Focus on Quantum Programming
Understanding Superposition

Polarizing Filter

Polarizing Beamsplitter – Classical Light

Polarizing Filter

Polarizing Beamsplitter – Quantum Light
Virtual Quantum Optics Lab (VQOL)

Create your own realistic simulation of a quantum optics experiment!

Classical waves with real, stochastic vacuum modes

Deterministic detectors with amplitude threshold detection and dark counts

Results match what one observes experimentally.
QKD Project

BB84 protocol requires little background

Computer simulations of realistic photons

Implemented as classes in Java and Python
  Students are given code templates to aid development.
  Little to no prior coding knowledge needed

Teams of two develop Alice & Bob protocols

Code swapped with rival teams to play Eve
  Rival team can see all the flaws in your protocol.
  Reflects realistic assumptions in real QKD systems.

Try to steal the most key without being detected!

Photon class physical model:

\[
\begin{pmatrix}
a_H \\ a_V
\end{pmatrix} = \alpha \begin{pmatrix}
\psi_H \\ \psi_V
\end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix}
z_H \\ z_V
\end{pmatrix}
\]

Deterministic measurements:

Dark counts may occur.
A measurement in, say, the H/V basis gives one of four possible outcomes:

- \(|a_H| \leq \gamma, |a_V| \leq \gamma\) : no detections
- \(|a_H| > \gamma, |a_V| \leq \gamma\) : single H photon
- \(|a_H| \leq \gamma, |a_V| > \gamma\) : single V photon
- \(|a_H| > \gamma, |a_V| > \gamma\) : multiple photons
Quantum State Tomography Project

Prepare an arbitrary qubit state:

\[ U_3(\theta, \phi, \lambda) = \begin{pmatrix} \cos \frac{\theta}{2} & -e^{i\lambda} \sin \frac{\theta}{2} \\ e^{i\phi} \sin \frac{\theta}{2} & e^{i(\lambda+\phi)} \cos \frac{\theta}{2} \end{pmatrix} \]

General form of single-qubit mixed state:

\[ \rho = \frac{1}{2} \left( I + X \langle X \rangle + Y \langle Y \rangle + Z \langle Z \rangle \right) \]

-0.280 + 0.818i - 0.112i

Estimated Mixed State:

\[ \rho = \begin{pmatrix} 0.444 & -0.140 - 0.409i \\ -0.140 + 0.409i & 0.556 \end{pmatrix} \]

Ideal Mixed State:

\[ \rho = \begin{pmatrix} 0.346 & -0.238 - 0.412i \\ -0.238 + 0.412i & 0.655 \end{pmatrix} \]
An attenuated laser beam provide a “poor man’s” source of single photons.

A beam splitter acts as a Hadamard gates and creates two spatial modes.

A half-wave plate in the lower beam acts as a CNOT gate, changing $H$ to $V$.

Polarizing beam splitters and detectors are used to measure the four modes.
Bell Inequality Project

Using the IBM Q Experience, prepare a Bell state and measure the following:

\[ S = \left| \langle X \otimes T^\dagger XT \rangle + \langle X \otimes TXT^\dagger \rangle \right| + \left| \langle Y \otimes T^\dagger XT \rangle - \langle Y \otimes TXT^\dagger \rangle \right| = 2.12 > 2 \]
Bell Inequality Violations in VQOL

Entangled photon pairs are modeled as squeezed vacuum modes in a nonlinear crystal.

Half-wave plates allow Alice and Bob to choose different measurements independently.

Post-selection on coincident detections gives a violation of Bell’s inequality!
High School Pilot Program

Class Format
Modification of FRI stream, retooled for HS
More background on math, physics, etc.
Class meets 2-3 times/week over 1 year
Teacher assisted by UT graduate students
Use of custom GUI (not IBM Q Experience)
Analog quantum emulation hardware used
Study performance in other STEM courses

Topics Covered
Digital logic, linear polarization, Malus’s law
Qubits as photons, Born rule, QKD
Complex numbers, vectors, matrices
General qubit states, qubit gates
Multi-qubit states, entanglement
Teleportation, entanglement swapping
Quantum programming, Grover’s algorithm

Project Goal: Increase participation in STEM fields!
Signal Representation of Multi-qubit States

**Right Qubit**

- Signal
  - Amplitude (Volts/Hz)

**Left Qubit**

- Signal
  - Amplitude (Volts/Hz)

**Two-qubit State**

- Signal
  - Amplitude (Volts/Hz)

\[ |1\rangle_R = \sin(\omega_1 t) \]
\[ |0\rangle_L = \cos(\omega_0 t) \]
\[ |1\rangle_R |0\rangle_L = \sin(\omega_1 t) \cos(\omega_0 t) \]

Coherent sums yield superpositions and entangled states
Circuit Schematic for Single-Qubit Gates

Using standard analog electronics, any quantum gate can be implemented.
Quantum Emulation Device (QED)

clear

% Given an unknown Boolean function $f$ that maps one bit to one bit,
% determine whether it is constant $f(0)=f(1)$ or balanced $f(0)\neq f(1)$.

X = [0 1; 1 0]; % NOT gate
H = [1 1; 1 -1]/sqrt(2); % Hadamard gate

% initial hardware setup
n = 2;
qed = configureQED(n);
f = qed.f;
t = qed.t;

display('Initialize to the state $|0\rangle|0\rangle$.')
alpha = [1 0 0 0]';
psi = synthesisState(alpha, f, t, qed);
plotState(psi, f, t, 1);
display(' ')

display('Apply X (NOT) gate to qubit 1 (the')
psi = applyGate(X, 1, psi, f, t, qed);
plotState(psi, f, t, 1);
display('')

display('Apply H (Hadamard) gates to qubits')
for i = 0:1
    psi = applyGate(H, i, psi, f, t, qed);
end
plotState(psi, f, t, 1);
display('')

% Apply one of the four Boolean functions
% The quantum oracle Uf implements f such that
% $Uf|y, x\rangle = |x\oplus f(y), x\rangle$
% a = randi([0 3]);
switch a
    case 0
        display('Selected constant function')
    case 1
        display('Selected balanced function')
    case 2
        display('Selected odd function')
    case 3
        display('Selected even function')
end

Amplitude (Volts)

Amplitude (mV/ubar)
Future Directions

Scale High School Pilot
- Secure Texas Agency for Education (TEA) recognition for QC as an *innovative course*

UT Certificate in Quantum Information Science
- Transcript-recognized acknowledgment of student’s mastery in QIS
- Multidisciplinary coursework and keystone research project

UT edX Online Course for Freshmen
- Bring the FRI stream to the world with an online course targeted to freshmen

Partnerships with Industry
- Guest speakers, summer internships, sponsored research projects