Quantum Computing

Professor Lloyd Hollenberg

IBM Q Hub @ The University of Melbourne,
ARC Centre for Quantum Computation &
Communication Technology
Outline

Introduction – quantum logic and information processing

Quantum search 101 – the QUI system

Quantum error correction and scale-up

Quantum factoring, HPC simulations

Emerging quantum computers, “supremacy”

IBM Q Hub @ UoM – research highlights

Quantum computing and HEP
Quantum computing: drivers

Hard problems: generally scale poorly with (classical) CPU resources, technology plateau (Moore’s Law final gasp)

Conventional transistor miniaturization ...the end of Moore’s Law is nigh

Quantum computers based on the laws of quantum mechanics circumvent limitations of classical information processing

space of quantum apps being explored
e.g. optimisation, finance, AI, materials...
Quantum information...the important bits

Quantum superposition – multiple possibilities existing at the same time

Quantum measurement – collapse to one possibility when ”observed”

Quantum entanglement – observation of one part affects another part

\[ |00\rangle + |11\rangle \]

\[ \frac{1}{\sqrt{2}} \]
Quantum logic

Classical logic: bit by bit

Classical NOT gate

\[ \begin{array}{c|c}
A & B \\
\hline
0 & 1 \\
1 & 0 \\
\end{array} \]

Classical AND gate

\[ \begin{array}{c|c|c}
A & B & C \\
\hline
0 & 0 & 0 \\
0 & 1 & 0 \\
1 & 0 & 0 \\
1 & 1 & 1 \\
\end{array} \]

Quantum logic

Quantum NOT gate → both bits flipped at same time

Quantum logic: bit by bit

\[ \begin{array}{c|c|c|c}
A & B & C & \text{in} \\
\hline
|0\rangle & |1\rangle & |0\rangle \\
\end{array} \]

Quantum logic: bit by bit

\[ \begin{array}{c|c|c|c}
A & B & C & \text{out} \\
\hline
|1\rangle & |0\rangle & |1\rangle \\
\end{array} \]
Quantum logic

Classical logic: bit by bit

Classical NOT gate

Classical AND gate

Quantum logic

Quantum Hadamard gate → create superpositions

Quantum Controlled-NOT: all 2-bit strings at same time
Quantum logic

Classical logic: bit by bit

Classical NOT gate

\[
\begin{array}{cc}
A & B \\
0 & 1 \\
1 & 0 \\
\end{array}
\]

Classical AND gate

\[
\begin{array}{ccc}
A & B & C \\
0 & 0 & 0 \\
0 & 1 & 0 \\
1 & 0 & 0 \\
1 & 1 & 1 \\
\end{array}
\]

Quantum logic

Quantum Hadamard gate → create superpositions

\[
|0\rangle \rightarrow \frac{|0\rangle + |1\rangle}{\sqrt{2}}
\]

Quantum Controlled-NOT: all 2-bit strings at same time

Quantum gates in combination create generalized superpositions → entanglement
Quantum logic

Classical logic: bit by bit

Classical NOT gate

<table>
<thead>
<tr>
<th>A</th>
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Classical AND gate

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Quantum logic

Quantum Hadamard gate → create superpositions

\[ |0\rangle \xrightarrow{H} \frac{|0\rangle + |1\rangle}{\sqrt{2}} \]

Quantum Controlled-NOT: all 2-bit strings at same time

Quantum gates in combination create generalized superpositions → entanglement
Quantum information processing

- Logic gates between qubits perform mathematical operations on binary data.
- Complex entangled states created → binary data are quantum “linked”.
- Quantum interference amplifies probability of desired output (answer).
Quantum information processing

- Logic gates between qubits perform mathematical operations on binary data.
- Complex entangled states created $\rightarrow$ binary data are quantum “linked”.
- Quantum interference amplifies probability of desired output (answer).
UoM: Quantum User Interface (QUI)

Welcome to QUI
A quantum computer is the ultimate black box. Our quantum user interface is here to help.

Quantum computing is fast becoming reality. With or without a quantum physics background, if you are interested in how quantum computers work and learning how to program them, our quantum user interface (QUI) is designed to help make sense of it.

QUI is an intuitive programming and simulation environment designed to enable users to visualize and understand the inner workings of a quantum computer. Program and follow your quantum code, every step of the way.

Watch the QUI Overview Video and try it out!

Please note, QUI operates best on desktop Google Chrome or Firefox.

quispace.org
UoM: Quantum User Interface (QUI)

UoM QC programming and simulation environment for teaching, research, outreach

quispace.org
Quantum search 101 – needle in a haystack

**Problem:** alphabetical phone book, given a number find the name...

**Classical:** $N$ entries $\rightarrow$ on average $\sim N/2$ tries (look-ups).

**Quantum:** Quantum search ("Grover's algorithm") $\sim \sqrt{N}$ tries

**Example:** imagine our data-base (the phone book) is all eight 3-bit numbers $\rightarrow$ search on one entry (say the number 5 = 101)

"Database" in superposition:

$$|\psi\rangle = \left(\frac{1}{\sqrt{2}}\right)^3 (|000\rangle + |001\rangle + |010\rangle + |011\rangle + |100\rangle + |101\rangle + |110\rangle + |111\rangle)$$

"Oracle" marks 101 state:

$$|\psi\rangle = \left(\frac{1}{\sqrt{2}}\right)^3 (|000\rangle + |001\rangle + |010\rangle + |011\rangle + |100\rangle - |101\rangle + |110\rangle + |111\rangle)$$

"Inversion" amplifies probability of the marked 101 state.

Quantum search algorithm manipulates the amplitudes so that the probability of the result is amplified – i.e. magnifies the needle…
Quantum error correction and scale-up

Quantum logic is extremely vulnerable to decoherence and control errors...

Essential dilemma:

How do you correct if measurement collapses state?

Quantum Error Correction!

Redundancy & gates → more errors → error threshold

Topological QEC on 2D array (surface code)

Kitaev 1997, Raussendorf/Harrington 2007

Threshold >1% (Wang et al 2011)

TQEC is a game changer, but still 1000’s of physical qubits per logical qubit

1D: QEC threshold \(~10^{-7}\) (Skopek 2007)

2D: QEC threshold \(~10^{-5}\) (Svore et al 2005)

2D architectures:
(e.g. Hill, LH et al Sci Adv. 2015)
Quantum factoring algorithm (Shor)

The quintessential example: semi-prime factoring...

Kleinjung et al (2009): RSA768 1,500 core-yrs

\[ p \times q = N \]

Digicert (SSL): to crack 2048 bit key → (>>age of Universe) core-yrs

Shor’s quantum factoring algorithm → “quantum easy”

QC: 2048 bit case → thousands of logical qubits (& QEC) → c. 10m physical qubits

Quantum Advantage: some years before QC outperforms HPC on RSA problems... meanwhile:

Post-quantum Cryptography

Impact of full-scale QC on current and future crypto-systems (e.g. RSA) → high

→ NIST Post-Quantum Cryptography Standardization project
Classical simulations of quantum circuits

Shor’s quantum factoring algorithm for a $l$-bit semi-prime, $N = p \times q$:

**Hilbert space dimension**: $3l$ qubits $\rightarrow 2^{3l}$ complex amplitudes (i.e. $2^{3l} \times 2 \times 8$ bytes)

**Our method**: Matrix Product State (MPS)…storage $\sim$ entanglement

- Simulated up to **60 qubits**: $N = 961,307$, $l = 20$
- MPS actual: 5184 cores, 13.8 TB, 8h (Pawsey HPC Centre)

**Challenge**: sample from the distribution $P(s)$ by simulating $3l$ qubit circuit output

**NB**: Full Hilbert space for 60 qubits: 18 exabytes $\rightarrow$ Shor’s algorithm is very frugal with entanglement...
Meanwhile: quantum computers emerge

2016: IBM provides cloud access to QC hardware, programming interface

2017: IBM Network Q

Major players: Rigetti, Google, IonQ, Microsoft, Intel, D-Wave,…

2019: “System One” IBM state-of-the-art

Stand-alone QC systems (20 → 53 qubits), fully programmable

Nov 5 2019: Qiskit software stack supports access to AQT ion-trap QC

Google.com: quantum circuit sampler machine

“Quantum supremacy”

→ 54-qubits beat HPC for simulating QC circuits (Google)
→ 200 sec (QC) vs. 10,000 yrs (HPC) [Nature Oct 23 2019]

IBM: more like 2.5 days on HPC [arXiv:1910.09534]

Big goal: “Quantum advantage”

→ beat HPC on a useful problem (if/when?)
Quantum algorithms and applications: NISQ era

Quantum algorithms exist for a range of problems: optimisation, sampling, system simulation...

Key question: quantum advantage in NISQ era?

NISQ: Noisy Intermediate Scale Quantum (Preskill)

New era, old strategy: adapt quantum algorithm to purpose...

e.g. quantum search algorithm → bioinformatics (2000)

NISQ: instead of “big data”, think “big models”...

→ applications in HEP...
Effect of quantum logic gate errors: simulations

Instantaneous Quantum Polynomial circuits:

Semi-random phase gates

\[ T_n = \exp\left(\frac{\lambda_n T}{8}\right) \]

\[ T_{mn} = \exp\left(\frac{\lambda_n T}{8} Z_m Z_n\right) \]

Determine output prob. distribution

Example: 10 qubit IQP circuit

MPS simulations (Pawsey Supercomputer Centre)
(Z-errors, qubit reduction technique)

Results: evidence for cross-over at \(\sim 0.4\%\) gate error rate
Specific to IQP, but possibly indicative for phase intensive calculations
(and close to where hardware is at...)
How fast are things moving?

Quantum computing literature:

Journal club – no longer 1-2 papers/week, now deal with c.50 new/interesting abstracts per week...

Start-up status: pre-2017 and present (courtesy S. Devitt)
The IBM Q Network launched in Dec 2017...
IBM Quantum Experience

Sign in to IBM Q Experience

What is IBM Q Experience? Learn more

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Twitter | LinkedIn | Email

Quantum search 101 on IBM Q

Pick a backend (vigo = open)

Actually runs this circuit...

Results – QASM simulator
Quantum search 101 on IBM Q

Pick a backend (vigo = open)

Actually runs this circuit...

Results – Vigo
Research at UoM Q Hub: highlights (2018/19)

Sam Tonetto (PhD) et al:
Semi-prime factoring via QAOA on IBM Q
\[
\text{cost fn } = \text{bitwise}(N-p.q)^2
\]
-> some problem reduction shortcuts...

Gary Mooney (PhD) et al:
Entangled 20 qubit graph state on IBM Q (GM et al, Sci Rep 2019)

Greg White (PhD) et al:
Procedure to improve CNOT gate
-> demonstrated fidelity increase on IBMQ [- Nov arXiv]
Larger systems – scaling up NISQ

As they scale the important factors in a quantum computer are:

- Gate errors
- Qubit connectivity
- Number of qubits

Combined quantitative measure: “quantum volume”

Determines the overall length (“depth”) of a quantum circuit before the “en-scrambling” of results...

Possibly quantum advantage in specific problems for 100-1000 qubit systems within 5 years...maybe.

IBM Q 53 qubit device “Rochester”
Related to HEP...(not exhaustive)

Simulation of quantum systems → variational approaches (VQE)
e.g.
→ chemistry problems (Kandala et al Nature 2017)
→ error mitigation techniques (Kandala et al Nature 2018)

Lattice gauge theory on QC: Byrnes and Yamamoto PRA 2006
QC and quantum field theory: Jordan, Lee, Preskill 2012-2018
LGT and QC review: Banuls et al arXiv:1911.00003)

QAML: Higgs-signal-versus-background machine learning optimization
problem → ground state of an Ising spin model (Mott et al, Nature 2017)

HEP engagement with QC:
openlab.cern/quantum-computing-high-energy-physics
**Quantum Information Science and Technology @ UoM**

**Staff**
- Lloyd Hollenberg
- David Simpson
- Charles Hill

**Postdocs**
- Mina Barzegaramiriolya
- Nikolai Dontschuk
- Liam Hall
- Brett Johnson
- Jean-Philippe Tetienne
- Muhammad Usman

**Admin**
- Rose Cooney
- Maureen Luna

**Students**
- David Broadway (PhD)
- Alister Chew (MSc)
- Aidan Dang (PhD)
- Matt Davis (QUI)
- Spiro Gicev (MSc)
- Robert De Gille (PhD)
- Erin Grant (PhD)
- Alexander Healey (PhD)
- Michael Jones (MSc)
- Timothy Kay (MSc)
- Scott Lillie (PhD)
- Julia McCoey (PhD)
- Gary Mooney (PhD)
- Viktor Perunicic (PhD)
- Sam Scholten (MSc)
- Maiyurenthan Srikumar (MSc)
- Daniel Sutherland (QUI)
- Sam Tonetto (PhD)
- Di Wang (MSc)
- Greg White (MSc)
- Yi Zheng Wong (MSc)
- Alex Zable (ME/QUI)

and many collaborators…

**Quantum computing:**
- quantum information
- large-scale architectures
- device simulations
- IBM Q Hub & applications

**Quantum sensing:**
- new sensing protocols
- quantum hyperpolarisation
- bio-imaging applications
- 2D materials imaging

**More information:**
- Group: blogs.unimelb.edu.au/quantum-technology
- UoM research: pursuit.unimelb.edu.au/special_reports
- IBM Q Hub @ UoM: research.unimelb.edu.au/QuantumHub
- QUI: QUIspace.org
- CQC2T: cqc2t.org