Quantum information: from the optics laboratory to the "real" world







Institute for **Quantum** Computing

Institute for Quantum Computing



 Founded 2001 at University of Waterloo

14 faculty
6 post-docs
~50 students
Always looking for more!



http://www.iqc.ca/

Optical JalktOutlinfermation

Quantum

Information

Nonlinear Optics

> Quantum Computation

Quantum Communication Quantum Metrology Quantum Foundations

Measurement- • induced nonlinearity

0

One-way quantum • computation

 Interferenceenhanced nonlinearity Linear optics entangling gates • Free-space entanglement distribution

0

Entanglement Purification Classical analogues of quantum interference Tomography

Weak measurement

 Multipartite entanglement

> Nonlocality tests

Quantum information Quantum bits can be 0 or 1 but also superpositions

> bit: 0 or 1 qubit: $\alpha |0\rangle + \beta |1\rangle$

 $|1\rangle = |V\rangle$



Photon Polarization Atomic Levels

Familiar quantum features

• Uncertainty principle





W. Heisenberg

Position

Momentum

No-cloning theorem

 $\xrightarrow{NOPE} \psi |\psi \rangle$ $|\psi\rangle|0\rangle$



Wootters





Dieks

...leads to ultimate cryptosystem

Automptidepper eithe astropper will eastropper eithe astropper will eastropper eithe astropper eithe astropper



C. Bennett, G. Brassard 1984

...leads to ultimate cryptosystem

Attempting either strategy will lead to errors in the detected signal Single photons are sent in one of two noncommuting basis states

Nor can the (f eavesdropper make identical copies of the state and make measurements on them (no-cloning)

An eavesdropper must make measurements to learn about the state, but cannot do so without disturbance (HUP)

More quantum features

Superposition

 A quantum system can be in many states at the same time

$$\left|\Psi\right\rangle = \frac{1}{\sqrt{N}} \left(\left|\psi\right\rangle_{1} + \left|\psi\right\rangle_{2} + \left|\psi\right\rangle_{3} + \ldots\right)$$



Interference

...more powerful computers



Feynman

Measupement results aneakes ta sapdoposex ceptf ablatoinsistaterence (replevestate to a algonitosis) ceanf aduces wheng answers tates

Deutsch

Entanglement

Anpentalgledastaténot entangled)

$$\begin{split} \left|\psi\right\rangle_{12} &= \frac{1}{\sqrt{2}} \left(\left|0\right\rangle_{1} \otimes \left|0\right\rangle_{2} + \left|1\right\rangle_{1} \otimes \left|1\right\rangle_{2}\right) \\ &= \left|00\right\rangle + \left|11\right\rangle \qquad \text{``Bell state''} \end{split}$$

 Foundation for most quantum information protocols

Optical photons as qubits

Polarization

Spatial modes







• Time-bin



Freq. encoding



Optical photons as qubits

The Bad

The Good

 Single-qubit operations

- Low decoherence
 No natural
- High speed
- Perfect carriers of quantum information

Easy to lose a photon
 No natural interactions/weak nonlinearities means 2-qubit operations are hard

The Ugly

 Linear optics proposals for scalable quantum computing are extremely complicated (~50-1000s of ancillas/elements per CNOT)

Entangled Photon Source



Type-II Down-conversion

Entangled Pair

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left(|H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2 \right)$$

H-Photon

Confused

Correlated V-Photon

Recent source advancements

 High-power UV laser diodes (cheap, easy to use -> UG lab!)

 Efficient single-mode coupling (longdistance, low divergence, free-space)

4-, 5-, and 6-photon entanglement
 Controllable entanglement - fundamental tests and quantum computing

State of the art

NumberuofepBoighteneasangled



Long-distance Entanglement distribution

Quantum source

Zeilinger Group

Not Pictured here: FS1&2: Michael Taraba FS2: Bibiane Blauensteiner, Alessandro Fedrizzi, Christian Kurtsiefer, Tobias Schmitt-Manderbach, Henning Weier, Harald Weinfurter Distributing Entanglement
 Photons are the ideal carriers

 Practical quantum communication needs shared entanglement over long distances

 Challenges: High efficiency (no cloning) and high background rejection (single photons)

Entanglement takes to the air

Freespace 1 (ALICE





Freespace 1 Results Measured S = 2.4 ± 0.1 (larger than 2 indicates entanglement) 15 Two links 500m & Coincidence Counts per second 100m 10 ~10 coincidences/s SMF-SMF coupling Time-stable channel 0 90 135 180 45 225 270

Polarization correlations Science (2003)

Polarizer Angle at Receiver B (Degrees)

The next step

• 500m to 7.8km (the atmosphere straight up is 7.3km thick)

No more cable

Light passed over a city – likely realworld scenario

Source telescope

15cm

From Source

Atmospheric fluctuations



Receiver module

150

PBS

٨/2

450

PBS

0

4.3

450

To detector

Practicalities

Absence of good single-photon sources

Can use quantum randomness to select state:



$$|HH\rangle + |VV\rangle$$
$$= |45,45\rangle + |-45,-45\rangle$$

 Triggered single photons, reduced "empty" pulses |0> and double photons |2>

Laser frequency monitoring unnecessary

Entanglement takes to the air again!

Freespace 2

Test Range (Laser Source)

Millennium City (BOB)

7.8km

Inst. f. ExperimentalPhysik

Vienna 🔒

Freespace 1 (ALICE) Freespace 1 (SOURC Freespace 1 (BOB)

Image © 2005 EarthSat Image © 2005 DigitalGlobe

iner Sternewarte (ALICE)





Freespace 2 Results

rte			22.5°	112.5°	67.5°	157.5°	
uffner Sternwa	•	0°	1469	5763	6500	1067	
	ice)	90°	4015	1305	1483	2959	
	(Al	45°	2171	9103	2633	6357	
		135°	5373	1701	6889	1090	
$\overline{\Sigma}$							

Millenium Tower (Bob)

S = 2.27±0.019 > 2 Quantum Correlations

Two links 7.8 km and 10⁻⁴km
 25 ccps found over time tags/internet
 Single-mode fibre to spatial-filter coupling
 14-σ Bell violation, all 16 meas. taken simultaneously
 Optics Express (2005)

Remaining challenges

Longer distances, Higher bit rates

Active components to compensate atmosphere

 Long-distance quantum interference (repeaters)

Full cryptography, different protocols

Moving targets (satellites, airplanes)

IQC free-space experiment

Gregor Weihs

Raymond Laflamme

Chris Erven



One-way quantum computation with a multi-photon cluster state

Photonic one-way quantum computation

- Philip Walther (Vienna→Harvard)
- Terry Rudolph (Imperial)
- Emmanuel Schenck (Vienna→ENS)
- Vlatko Vedral (Leeds)
- Markus Aspelmeyer (Vienna)
- Harald Weinfurter (LMU, Munich)
- Anton Zeilinger (Vienna)













One-way model



Algidiation (sprated medais under the temperated and the temperature of temperate

Raussendorff & Briegel, PRL 86, 5188 (2001) Optics: Neilsen; Browne/Rudolph

One-way quantum computing Cluster states can be represented by graphs Entanglement "bond" CPHASE $\left(+ \right)$ $\left(+ \right)$ $|0+\rangle+|1-\rangle$ 11(+)|÷)

Processing encoded information

How measurement can compute



Example of Feed-forward

• Equivalent quantum circuit

 $|\psi\rangle = R_z(\alpha)$

More general computations

Number of encoded gubits



Making cluster states





 $|\psi\rangle = |HHHH| + \langle HHVV \rangle + |VVHH \rangle - |VVVV \rangle$



Polarizing Beam-splitter Quantum "parity check"

V polarization

H polarization



The four-photon cluster



Clusters to circuits

Horizontal bond:



Clusters to circuits

 Multiple circuits using a single cluster

Different order of measurements



Two-qubit computations

Single & two-qubit operation

Single-qubit rotations

Two-qubit operations

0.25

0.0

-0.25



Fid ~ 83-86%

D.5 O.1 O.1 D.5 VY

> Separable Fid = 93% Tangle = 0

Entangled Fid = 84% Tangle = 0.65

42

HH HV VH

Grover's Algorithm

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Best Classical: O(N) queries Quantum: $O(\int N)$ queries



Conclusions and Future directions

 First demonstration of one-way quantum computation using cluster states

Experimental
 Larger cluster states = more complex circuits
 Feed-forward - two types - easy and hard

Theoretical

Different geometries and measurements
Higher dimensions

Summary

"Real" world

 First experiments demonstrating free-space entanglement distribution

Ideal world

First demonstration of Cluster State Quantum
 Computing - including the first algorithm



Australian Research Council

Clusters/Grover's Algorithm







Grover's algorithm

Quantum parallelism
 GA initializes the qubits to equal superposition of all possible inputs



Interference

 "Inversion about the mean" amplifies the correct element and reduces the others

 On a query to the black box (quantum database/phonebook), the sign of the amplitude of the special element is flipped

THANK YOU!









Australian Government

Australian Research Council