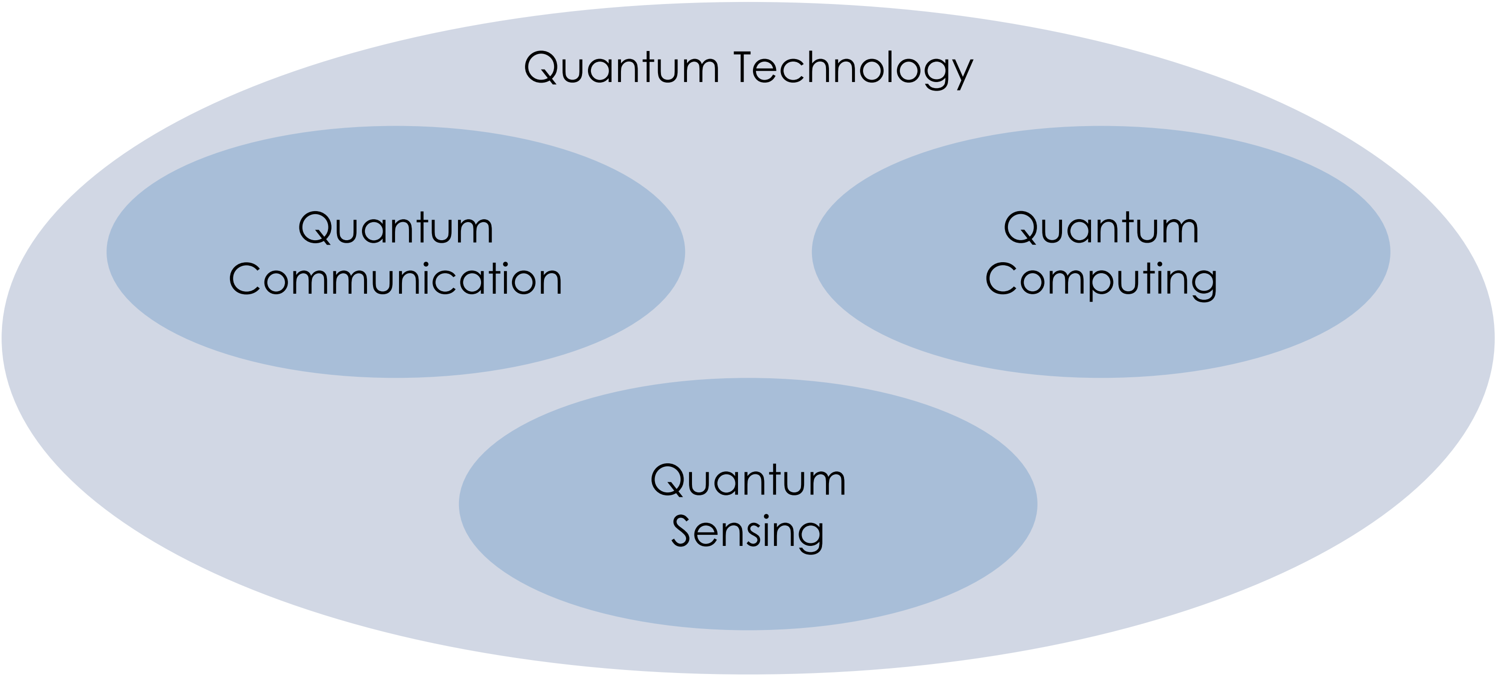
THE QUANTUM INTERNET: CONCEPT, INFRASTRUCTURE, CONNECTIVITY, FEASIBILITY

Dr Tiff Brydges
(Tiff Brydges-Harrington)

Quantum Technologies Group

MOTIVATION



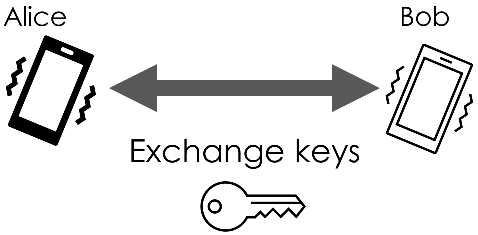
Major Interest: Security/Encryption

SECURE COMMUNICATION

Encryption is pivotal to many aspects of modern-day life (Instant Messaging, Banking, etc)

Users exchange keys, which can be used to encrypt and decrypt information

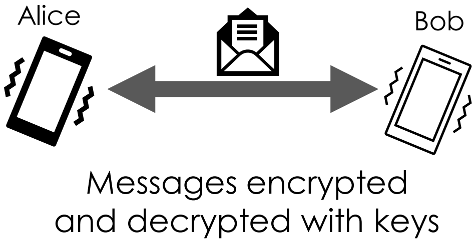
Many modern-day encryption algorithms depend on cracking the key being a *hard problem*



Threats: Quantum computers, or efficient classical protocols

Generally, eavesdroppers can't be detected

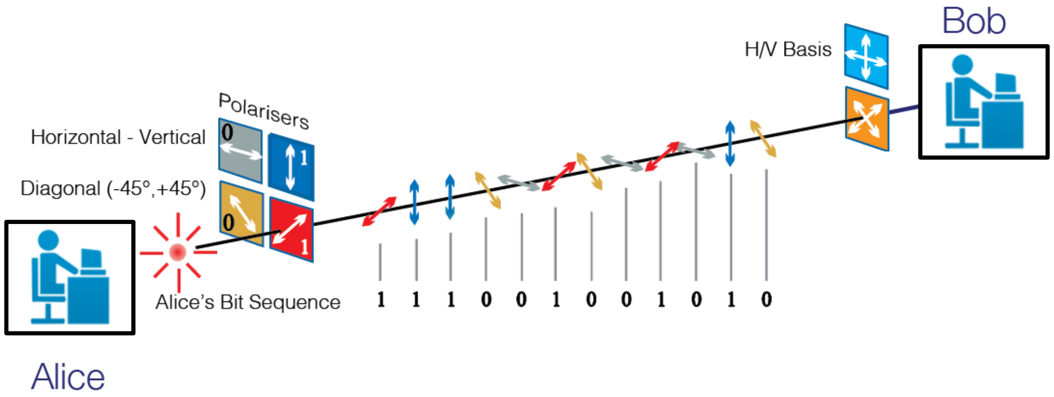
Messages can be intercepted without the users realising



SECURE COMMUNICATION

Popular Solution: Quantum Key Distribution (QKD)

QKD can lead to increased security compared to classical methods



Security guaranteed by physics (not by how hard a problem is to solve)

Eavesdroppers can be detected

By measuring the quantum state, eavesdroppers fundamentally alter the outcomes, which can be detected by Alice and Bob

Natural carrier to use: Photons

Can be sent through fibre network and free-space

BIG PICTURE: A SECURE GLOBAL NETWORK

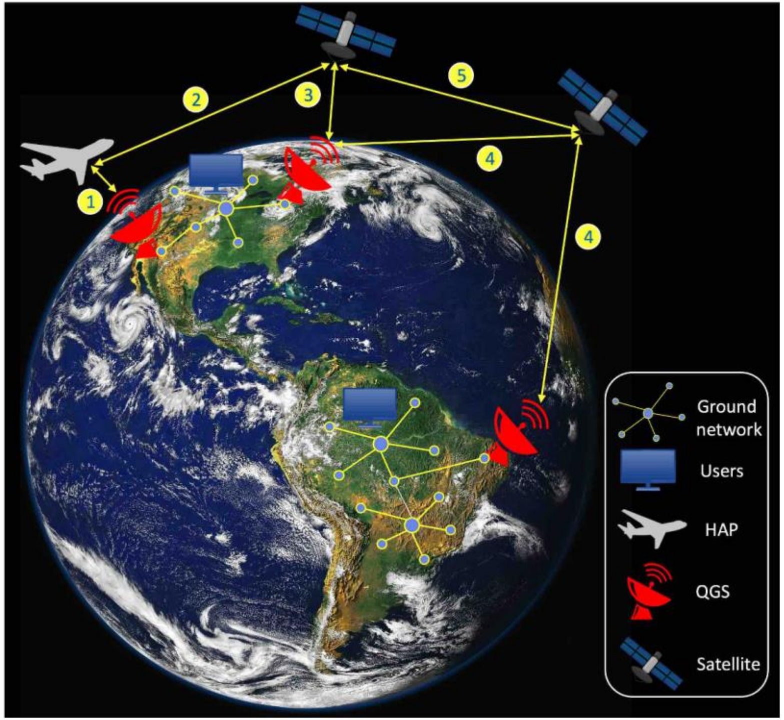
Networks which allow e.g. secure communication via QKD or similar

- Satellites
- Drones
- Fibre-Based Ground Networks

Some Requirements:

- Use existing fibre infrastructure
- Co-exist with existing communication channels
- **Require use** of classical communication channels

The goal is not to replace, but to co-exist!

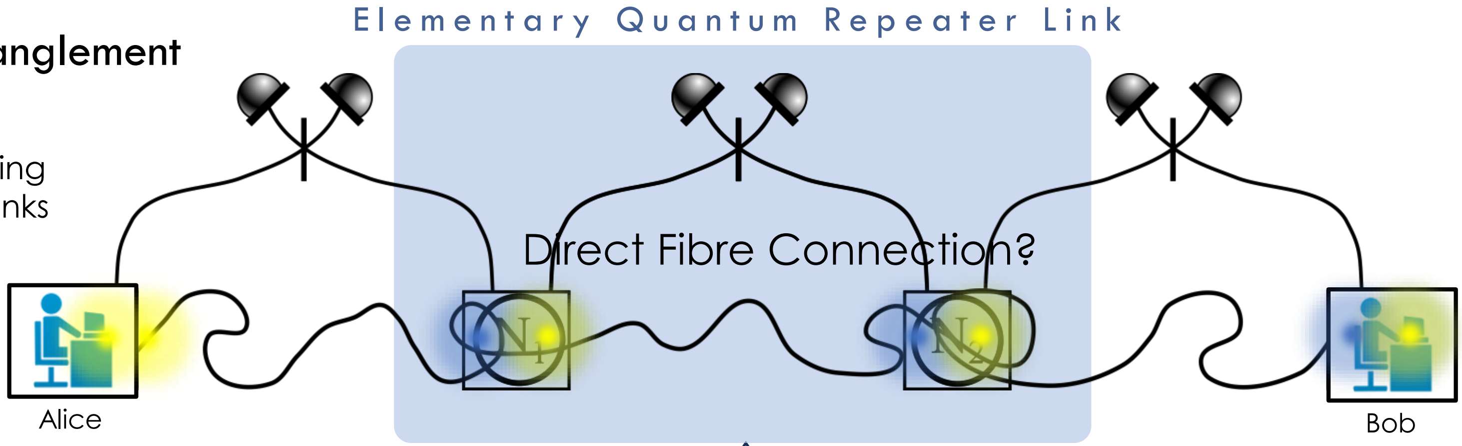


Credit: Jennewein et al, Canadian journal of physics 2023

HOW TO MAKE A QUANTUM NETWORK

Distribution of Entanglement

Fibres are **lossy**, meaning long-distance, direct links are **unfeasible**



Standard signal repeaters (e.g. amplifiers) can't be used[1]

Solution: Quantum Repeaters[2]

Split direct transmission channel up into many smaller elementary **quantum repeater links**

Elementary Link (in a laboratory) → Country-Wide Networks (Swiss QCI) → Continent-Wide Network (Euro QCI) → Global Quantum Network (Satellite Links)

[1] W. K. Wooters & W. H. Zurek, Nature, 299, pp.802-803 (1982)
[2] N. Sangouard *et al.*, *Rev. Mod. Phys.*, 83, pp.33-80 (2011)

NECESSARY RESOURCES

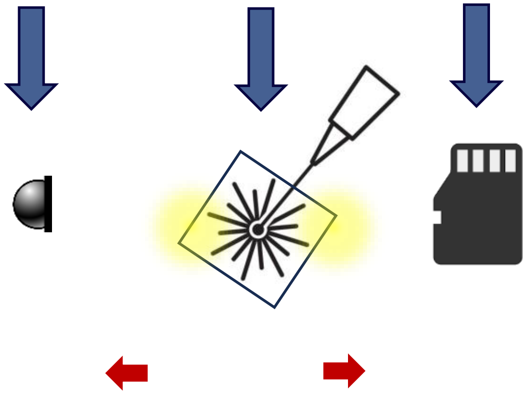
Build an Elementary Entanglement-Based Quantum Repeater Link

Quantum Repeater Node

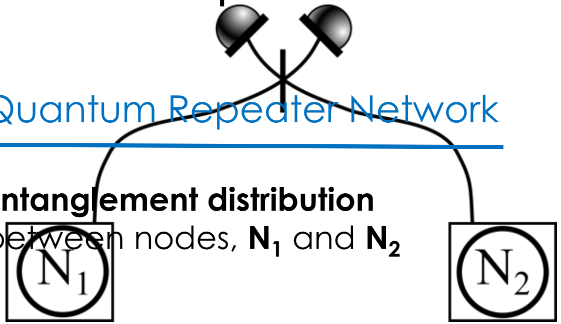
Photon Detectors

Photon Source

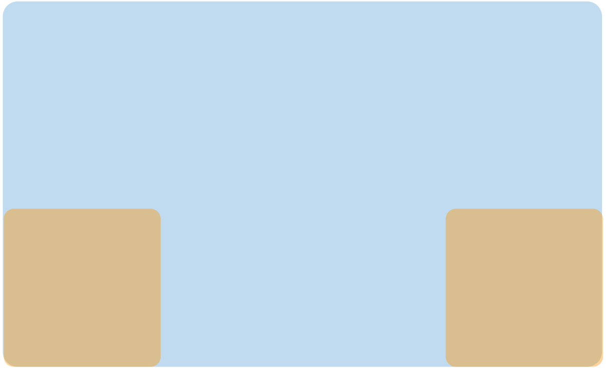
Quantum Memory



Quantum Repeater Network



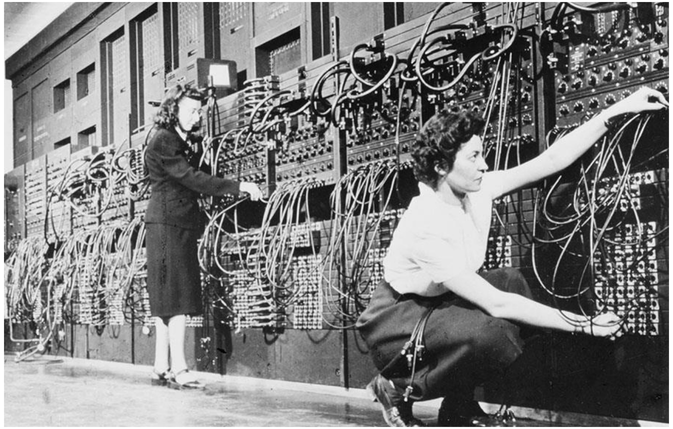
Entanglement distribution
between nodes, $\mathbf{N_1}$ and $\mathbf{N_2}$



A BIG STEP FORWARD: INTEGRATION

The ENIAC (1946)

(Electronic Numerical Integrator and Computer)

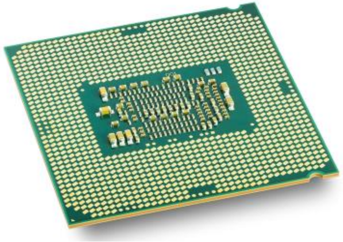


Credit: U.S. National Archives Education Updates

- 18,000 vacuum tubes
- 10,000 capacitors
- 6,000 switches
- 40 nine-foot-tall panels

500 FLOPS[1]

Typical Consumer-Grade Desktop Processor (Today)



- i7 processor has >1 billion transistors (2012)
- Footprint: A few cm^2
- Barely needs a small fan

10^9 FLOPS

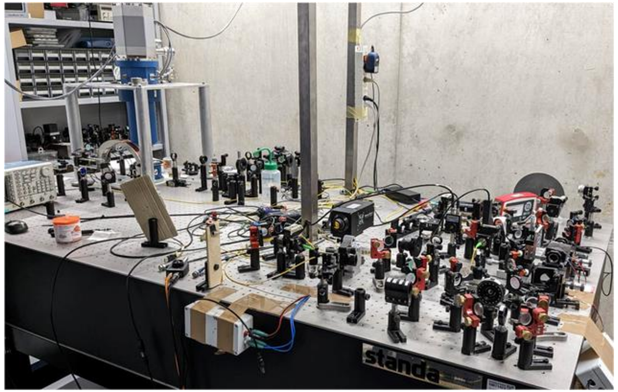
Transistors & Integrated Circuits

[1] Floating Point Operations per Second

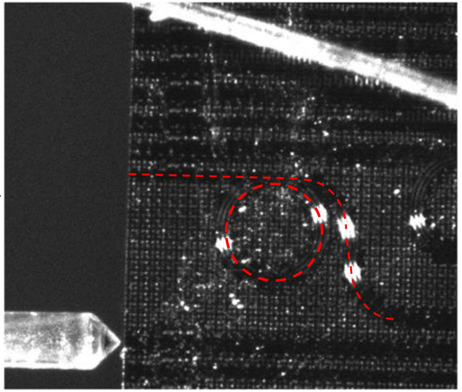
KEY ADVANTAGE

Bringing laboratory experiments closer to real world **implementation** and **application**

Current implementations are **unsuited** for **practical application**: using large, bulky setups



Instead, make use of **integrated technologies**



Potential to lead to **field deployable** technologies

Integrated Photonics provides the solution:
compact, stable, practical, and **commercially viable**

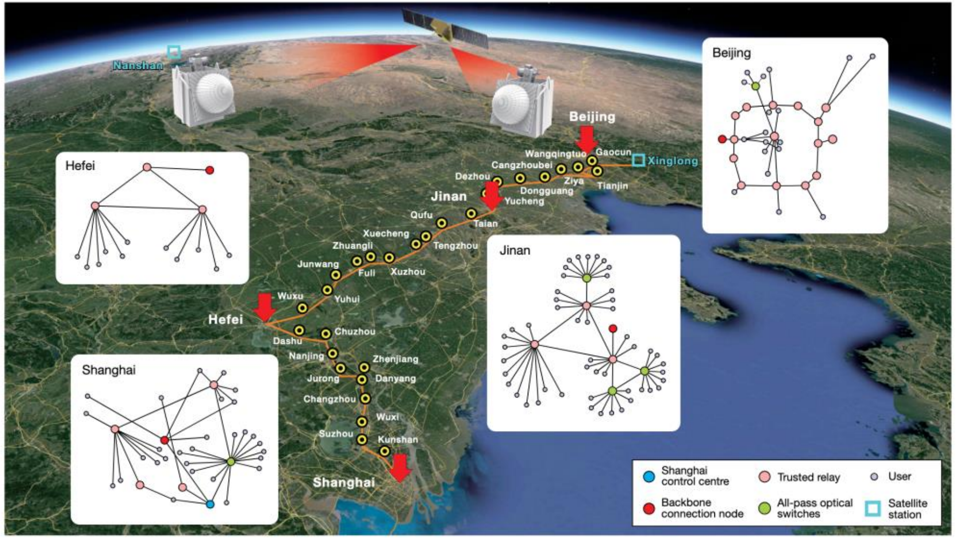
STATE OF THE ART

Quantum Key Distribution over 4600km[1]

Link connects multiple metropolitan areas via fibre and space-based connections

No Quantum Repeaters:
Uses ‘trusted nodes’, which are a security weak-point (need to be guarded)

Enough for a Video Call?
Not quite: 48 kilobits per second
Standard is ~1 megabits per second



Credit: Chen et al, Nature, **589**, 214-219, (2021)

[1] Chen et al, Nature, **589**, 214-219, (2021)

STATE OF THE ART

Elementary Quantum Repeater Link (Delft/Hanson group)[1]

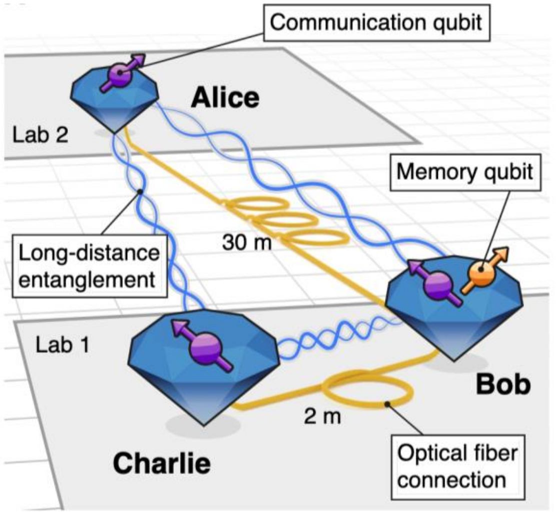
Connected two end users, Alice and Charlie, via an intermediate node, Bob (N_1)

Nodes are small/integrated

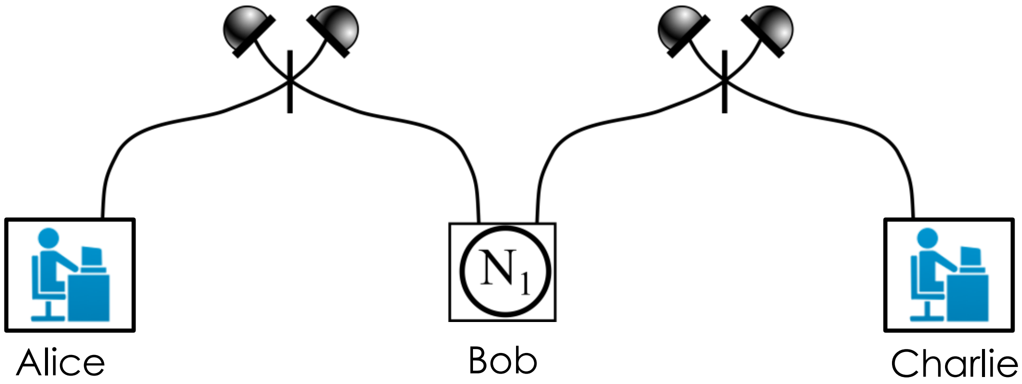
Proof-of-Principle Phase

Still lab-based

Very slow: 3-way node entanglement every 90 seconds



Credit: Pompili et al, Science, 372, 259-264 (2021)



[1] Pompili et al, Science, 372, 259-264 (2021)

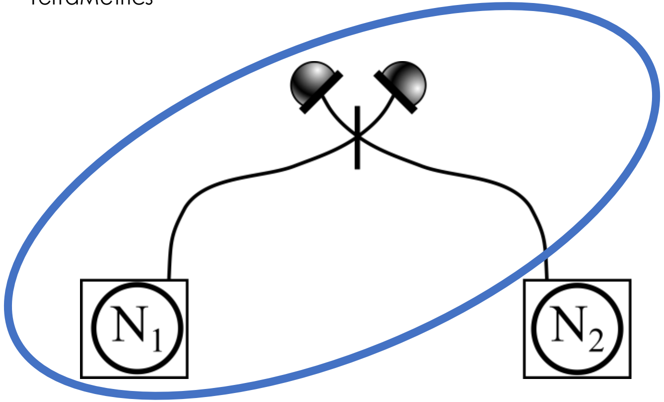
STATE OF THE ART

Distribution of entanglement over Barcelona (ICFO/de Riedmatten group)[1]

Credit: Google Earth Data SIO, NOAA, U.S. Navy, NGA, GEBCO. Image © 2023 TerraMetrics

Metropolitan-scale link

Repeater-style system



Slow (~1 event per second)

Still only in Proof-of-Principle Phase

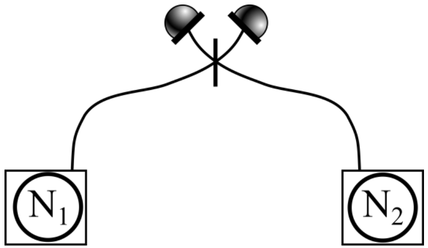
Predominantly bulk, no integration

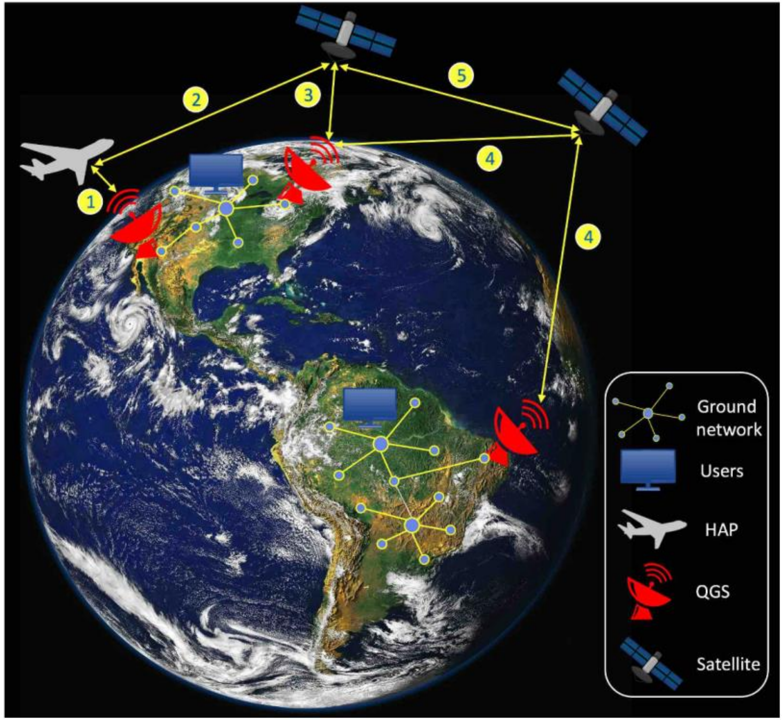
[1] Rakonjac et al., Optica Quantum, **1**, 2 (2023)

SUMMARY

Critically Need to Develop:

- Integrated, miniaturised, low-loss systems
- On-demand photon sources
- Better quantum memories (longer storage times, higher efficiency)





Credit: Jennewein et al, Canadian journal of physics 2023

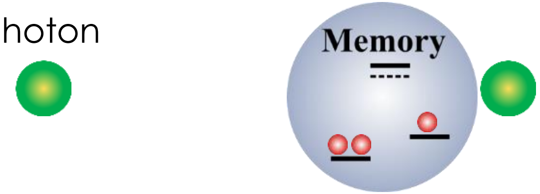
Excellent Overview: Jennewein et al. "QEYSSat 2.0 - White Paper on Satellite-based Quantum Communication Missions in Canada", Canadian Journal of Physics 2023

QUANTUM MEMORIES

Temporary Storage: Quantum analogue of cache memory in classical CPUs

Store a quantum state and preserve it in time

Photon



Promising Platform[1]

Solid Crystals doped with Rare-Earth Ions

Store single photon in frozen ensemble of ions trapped in crystal lattice

Incident photon absorbed

Photon stored in energy levels of ion

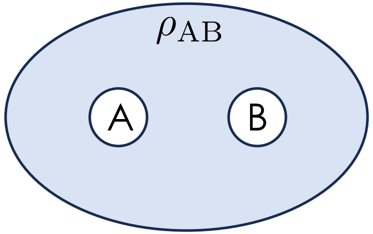
Readout photon preserves all properties of incident photon

[1] M. Afzelius *et al.*, Physics today, **68**(12), 42-47 (2015)

BELL STATES & MEASUREMENTS

Need to measure state of two-particle system (joint measurement)[1]

For two-particle system → 4-Dimensional Space → **Bell Operator Basis**



Bell States: Four two-qubit states which are *maximally entangled*

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_{A}|1\rangle_{B} \pm |1\rangle_{A}|0\rangle_{B})$$

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_{A}|0\rangle_{B} \pm |1\rangle_{A}|1\rangle_{B})$$

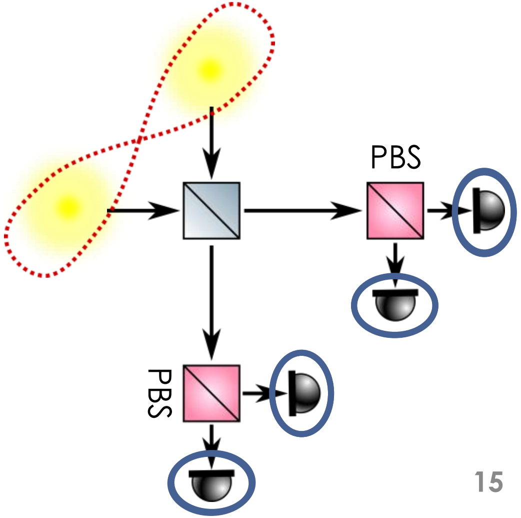
Bell State Measurement

$$|\Psi^{-}\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$$

$$|\Psi^{+}\rangle = \frac{1}{\sqrt{2}}(|HV\rangle + |VH\rangle)$$

'Which Bell state is this pair in?'

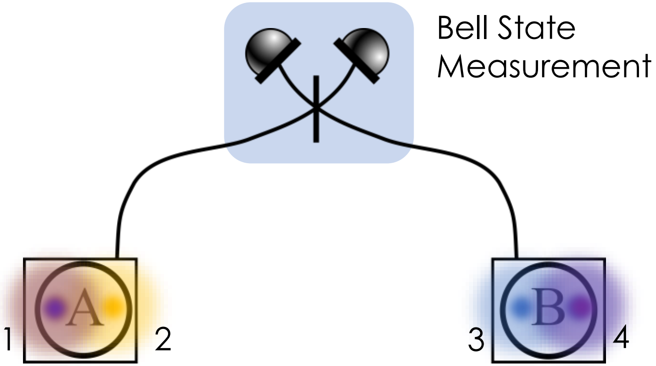
Get a unique detector click pattern*



[1] H. Weinfurter, Europhys. Lett., **25**(8), 559-564 (1994)

ENTANGLEMENT SWAPPING

Uses of Entanglement



$$|\Psi^-\rangle_{A} = \frac{1}{\sqrt{2}}(|0\rangle_{A_1}|1\rangle_{A_2} - |1\rangle_{A_1}|0\rangle_{A_2})$$

$$|\Psi^-\rangle_{B} = \frac{1}{\sqrt{2}}(|0\rangle_{B_3}|1\rangle_{B_4} - |1\rangle_{B_3}|0\rangle_{B_4})$$

Entanglement shared between A and B

Total State is: $|\Psi^-\rangle_{A}|\Psi^-\rangle_{B}$

Measure 2 and 3 in e.g. $|\Psi^-\rangle_{A_2B_3}$ → 1 and 4 become entangled → **Even though they've never met!**

NEXT STEPS

Main Goal:
Implement Entanglement Distribution

Major Stages:

1. Time-Bin Entanglement Swapping

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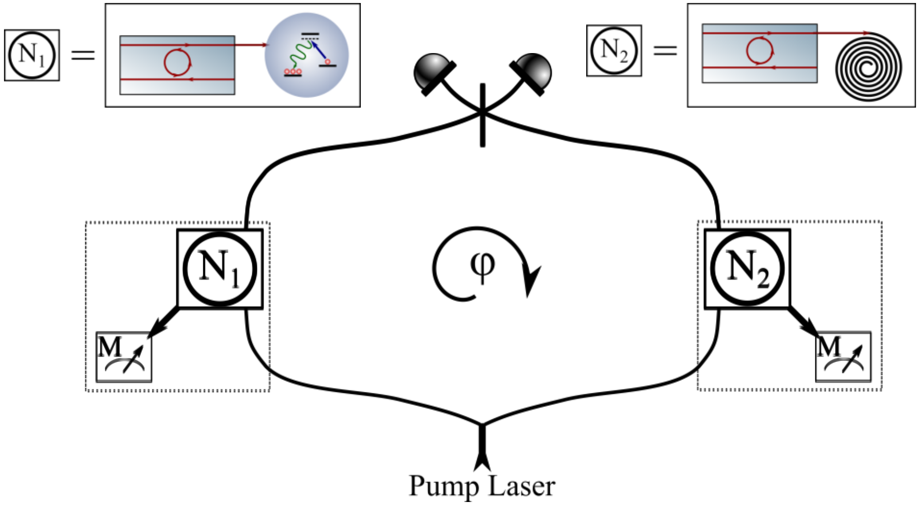
   First Synchronisation/Stabilisation of two quantum nodes

2. Path-based Entanglement Swapping

   ⬇

   Phase stabilisation of large quantum network



FINAL SCHEME

Include QFC in Entanglement Swapping Scheme

Flexibility to interface between multitude of different atomic systems

Major Stages:

1. Demonstrate QFC with MRRs between telecom/memory wavelengths

2. Integrate QFC in path-entanglement schemes from WP2

⇩

Phase stabilisation of QFC in quantum networks