Quantum Internet
a long term vision

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The premise

- We would like to architect a quantum internet, which can generate entanglement -- of any *kind, rate and quality*, based on requirements imposed by application(s) – simultaneously between (potentially multiple) user groups with hybrid nodes (space, various ground based – different qubit technologies), on demand

A long term vision

- Long baseline interferometer assisted by distributed GHZ states
  - Telescope receivers are small quantum processors
  - Teleported gates over the quantum internet (blind)
- Distributed LIGO stations enhanced by multimode entangled squeezed states of light
- Quantum secured communications (QKD, SPIR, Auctions, …)
- Photonic sensors (local entanglement, and distributed)
- Distributed quantum “computing”
  - search/optimization problems (autonomous vehicles, personalized medicine?)
  - Use entanglement across hybrid models of QC? (e.g., adiabatic + circuit model)
- **Quantum internet is a shared resource – medium that supports all of the above and more: forward compatible and adaptable**

Link

- What kind of entanglement should the network supply?
  - CV vs. DV. “CV” is a vague term: squeezed light, cat-basis, GKP, … [for the rest of the discussion we will assume DV two-photon two-qubit entanglement]
  - Can “CV apps” use DV entanglement?
- Should a link strive to establish (some generic form of) entanglement of a certain rate and quality (e.g., Fidelity), or should it strive to encode a stream of qubits into a coded stream of qubits and transmit it one way, over the link?
  - Classical comms overhead
    - Bandwidth
    - Latency
    - Synchronization
    - Asymmetry (uplink vs. downlink)
    - Modality (lasercom, internet, wireless RF, …)
  - Quantum processor requirement
  - Quality requirement of entanglement (before and after purification)

One Way	Two Way
Error correction (overhead)	Distillation and purification (overhead)
Links are individually error corrected	Links may be purified to a certain “point"

Link (continued)

- Memory/processor requirements
  - Quantum logic needed for distillation-purification (two-way) versus error correction encoding and decoding (one-way)
  - Efficiency of coupling of photon with memory
  - Coherence time (relates to: classical communications latency, purification protocols, and network protocol related considerations)
  - CV entanglement: memory requirements may be more severe
- Multi-channel encoding
  - Spectral encoding: what requirements does it impose on memory, transduction, frequency conversion needs, application-interoperability, …
- The quantum internet could have subnetworks architected one-way (short-haul terrestrial), and other subnetworks architected two-way (e.g., long haul terrestrial, satellite networks)

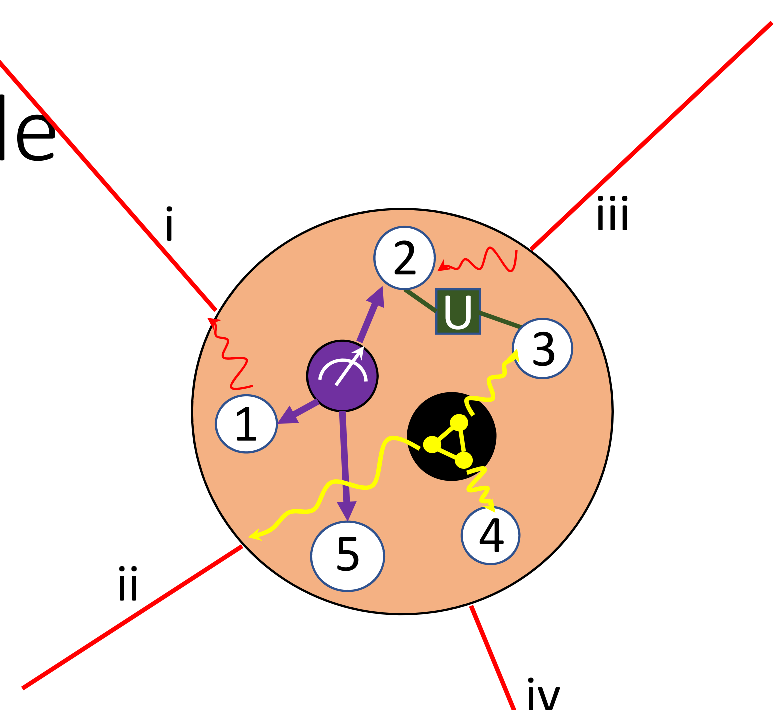
Device requirements

- Memory/processor requirements

Modality	Capability
Trapped ion	Logic
Color center	Photon interface
Superconducting	Coherence times
All-photonic	Depth
Rare-earth doped crystals	bandwidth
Ensemble memory	CV (multi-level) compatibility

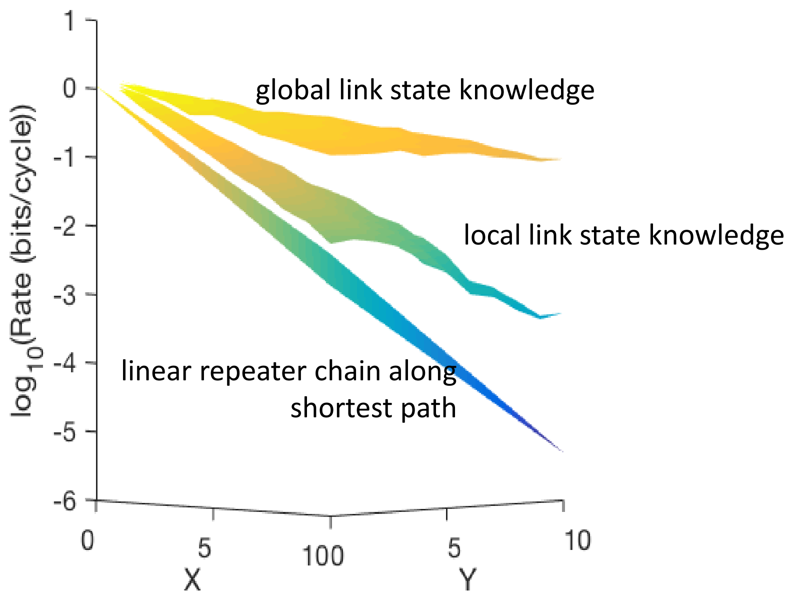
- Detector requirements
  - With SPDC entanglement sources, High-efficiency PNR detection is an important technology
  - Wavelength compatibility
  - Bandwidth
  - Spectrally-resolved detection (if using multi-spectral encoding)

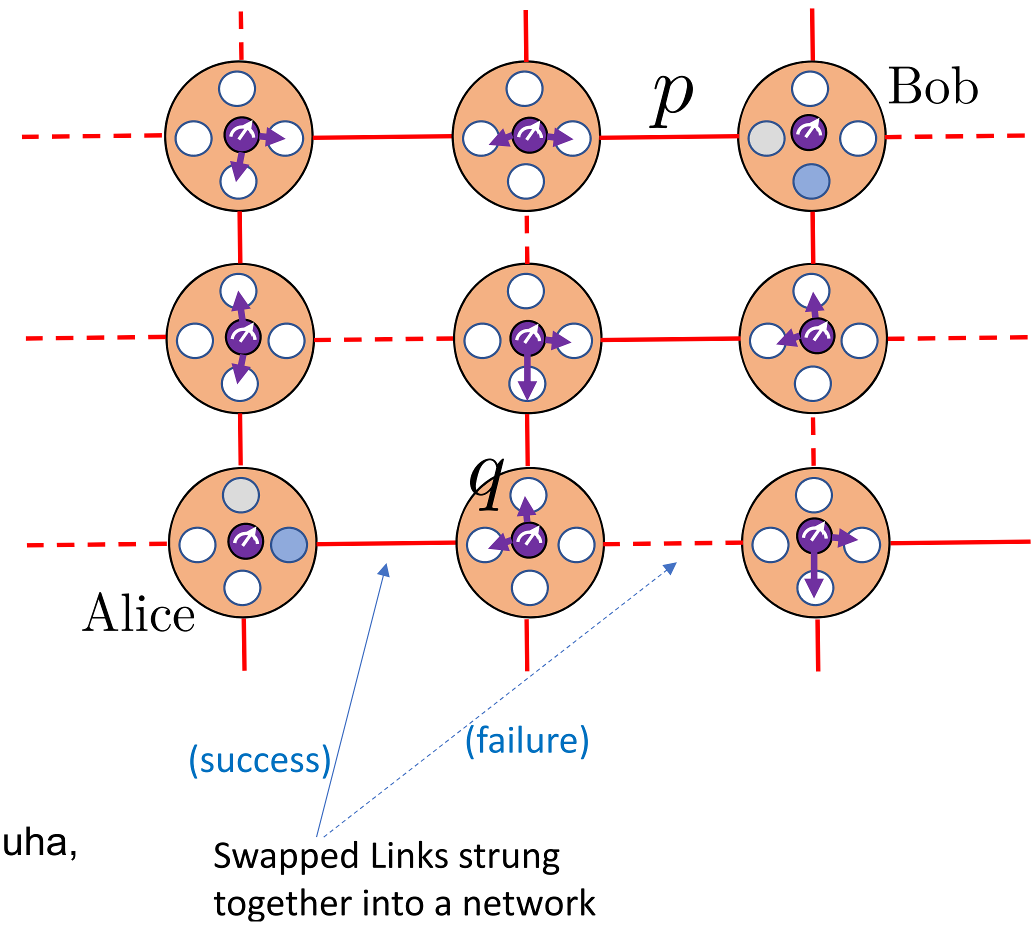
A quantum network node



- Quantum memories: loading and readout (transduction, interafce)
- Multi-qubit quantum projective measurements
- Quantum logic on across qubits held in QMs
- Multi-photon entanglement sources
- Classical computing and communications interface

Routing entanglement





Routing entanglement in a quantum internet
Pant, Krovi, Towsley, Tassiulas, Jiang, Basu, Englund, Guha,
Nature NPJ Quantum Inf. (2019)

Network level considerations: metrics

- What are the right quality metrics?
  - Throughput/latency/bandwidth
  - Do we need better metrics, tied to application level needs?
- Network tomography
  - Minimal set of end-to-end probes+measurements to get good estimates of end-to-end network-level performance metrics
- Network design
  - Where to place the nodes?
  - How to best provision resources?

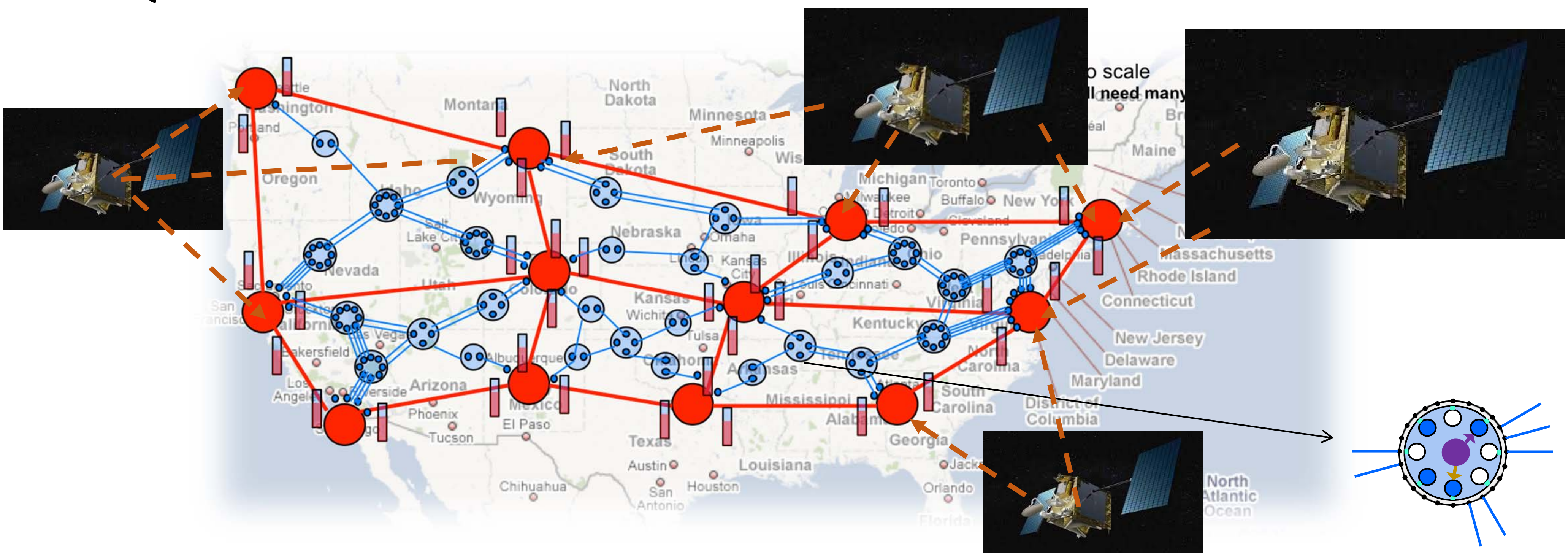
Routing of entanglement

- Routing protocols
  - Classical communications
    - Local link state knowledge versus k-hop knowledge? BW and latency requirements on classical communications will be different. Is it worth it, or should network protocols be designed that only assume "local link state knowledge"
  - Bell measurements versus multi-qubit measurements
    - Is it important to have multi-qubit joint measurement capability?
    - Color centers, Ions, SC and all-photonic: different capabilities
    - When should we "stop" purification, and go ahead with swaps (2, or more qubits)?
  - Multi-site entanglement
    - Should the network strive to perfect end-to-end bi-partite entanglement generation, and *then* convert link-level entanglement generation into multi-site entanglement; or whether the network protocol be amenable to "directly", in a more resource-efficient way, generate multi-site entanglement (e.g., for the VLBI application)?
    - If the latter, does the network node need more functionality?
  - Supporting multiple entanglement flows with hybrid nodes and links

The "near term" architecture development

- What network capabilities can be obtained with:
  - SPDC sources, linear optics, switches, memory (ion, color center), SNSPDs (with PNR capabilities?), modulators, WDM, SoA lasercom capability (+ associated PAT, AO, etc.)?
  - Even with the above constraints, there are *many* open questions on optimized, network architecture, the right network level metrics, entanglement routing protocols, etc.
- Top-down study also important
  - With the "best" network design, which devices and metrics should be emphasized

Quantum network architecture considerations



- **Network resource allocation:** Routing, scheduling to support multiple flows
- **Network management**: Network tomography, control
- **Network design**: Where to place the nodes under resource constraints
- **Network protocol stack:** Routing (TCP, IP), Security, Authentication