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The **Networking** in Quantum Networking

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Personal history (DARPA Quantum Network)

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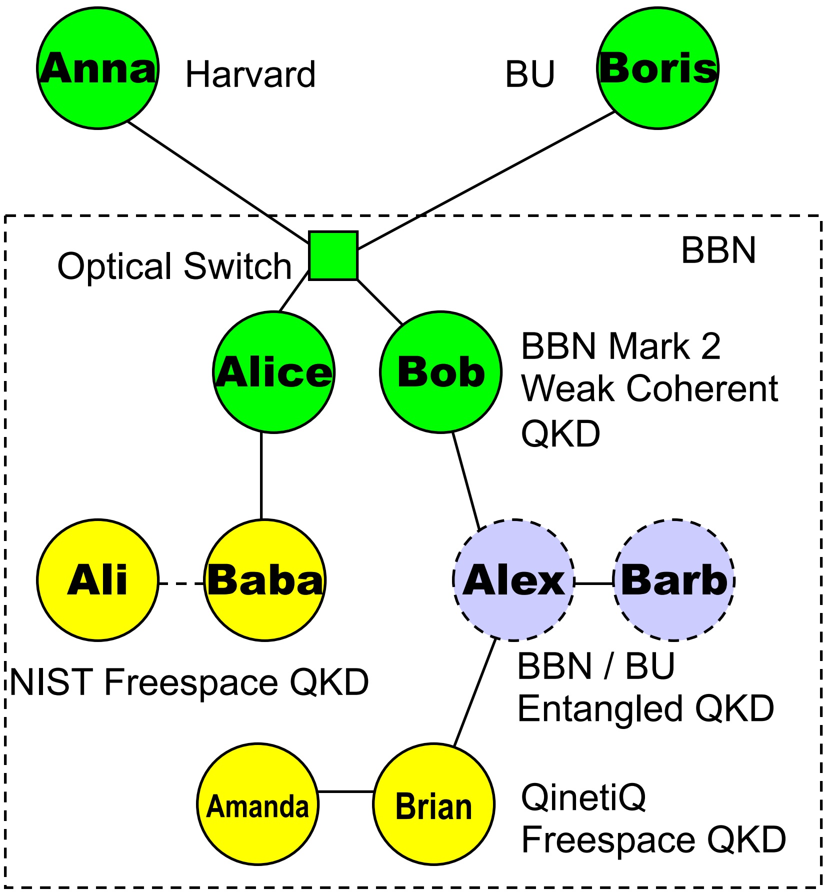
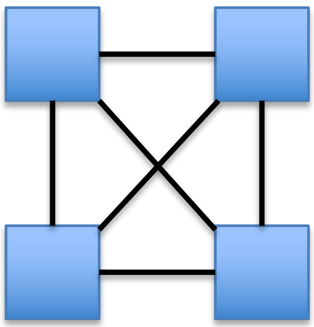


8 Nodes Running 24x7 in DARPA Quantum Network
And 2 More Running in Hardware Emulation

- Snapshot circa 2006
  - Multiple QKD technologies
  - Shared software protocol stack
  - Allows graceful evolution
- QKD Networking
  - Key Relay via trusted intermediaries for distance & bridging incompatible technologies
  - Passive optical switches for compatible endpoints

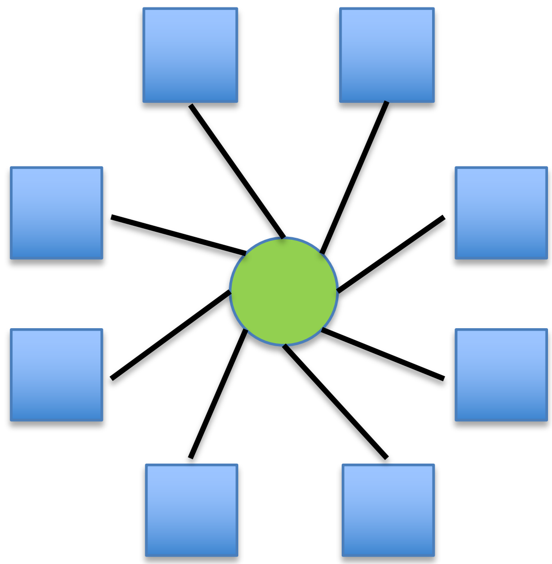
Some typical shapes of networks



Bus / Mesh

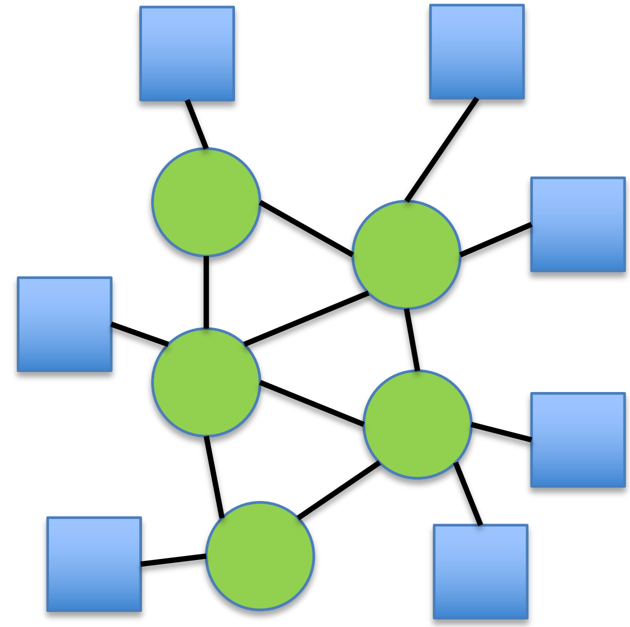
All endpoints directly connected (could be multimode fiber at various λ)

Endpoint Switch



Star

Central switch
Example: MAN (Metropolitan Area Network)
GPON λ: 1490, 1310 nm
XGPON λ: 1577, 1270 nm
EPON λ: 1575, 1260 nm



Arbitrary graph

Interconnected switches
Examples:
Campus networks
National networks
Telecom λ: 1550 nm

Some possible shapes of quantum networks

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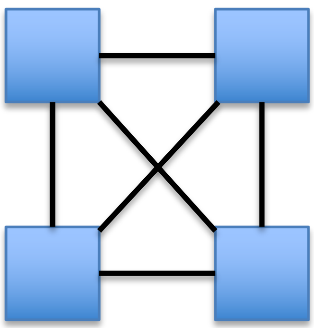
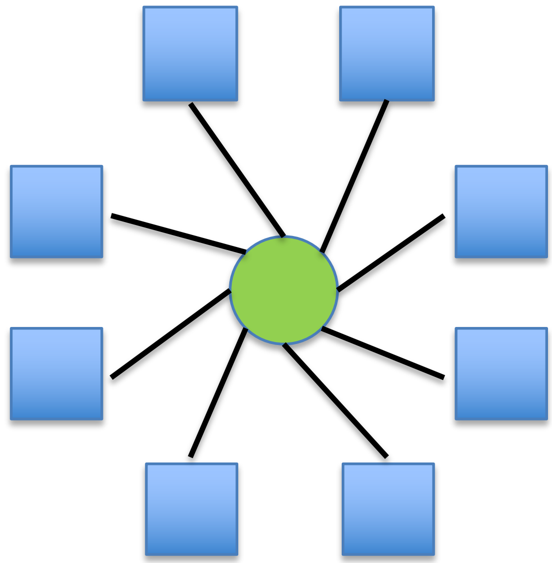
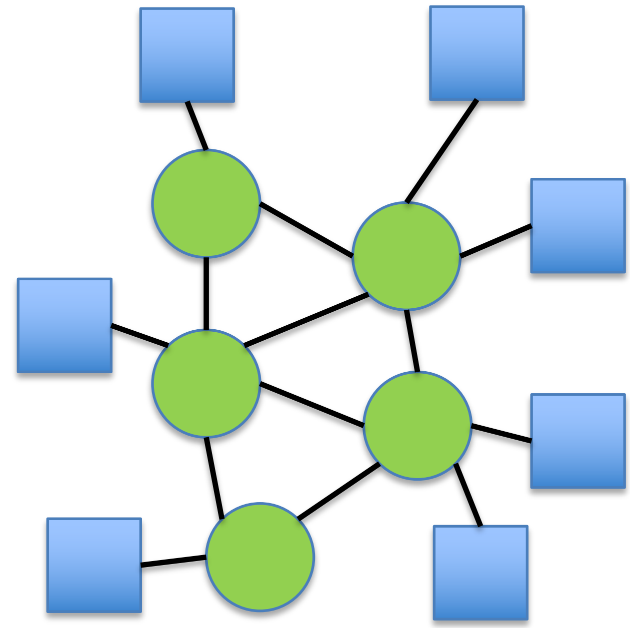




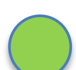


Small lab
All Q. computers directly connected

City
Central quantum repeater

Regional network
Mesh of quantum repeaters to interconnect quantum computers

Quantum computer



Quantum repeater

Who does what in a network ?

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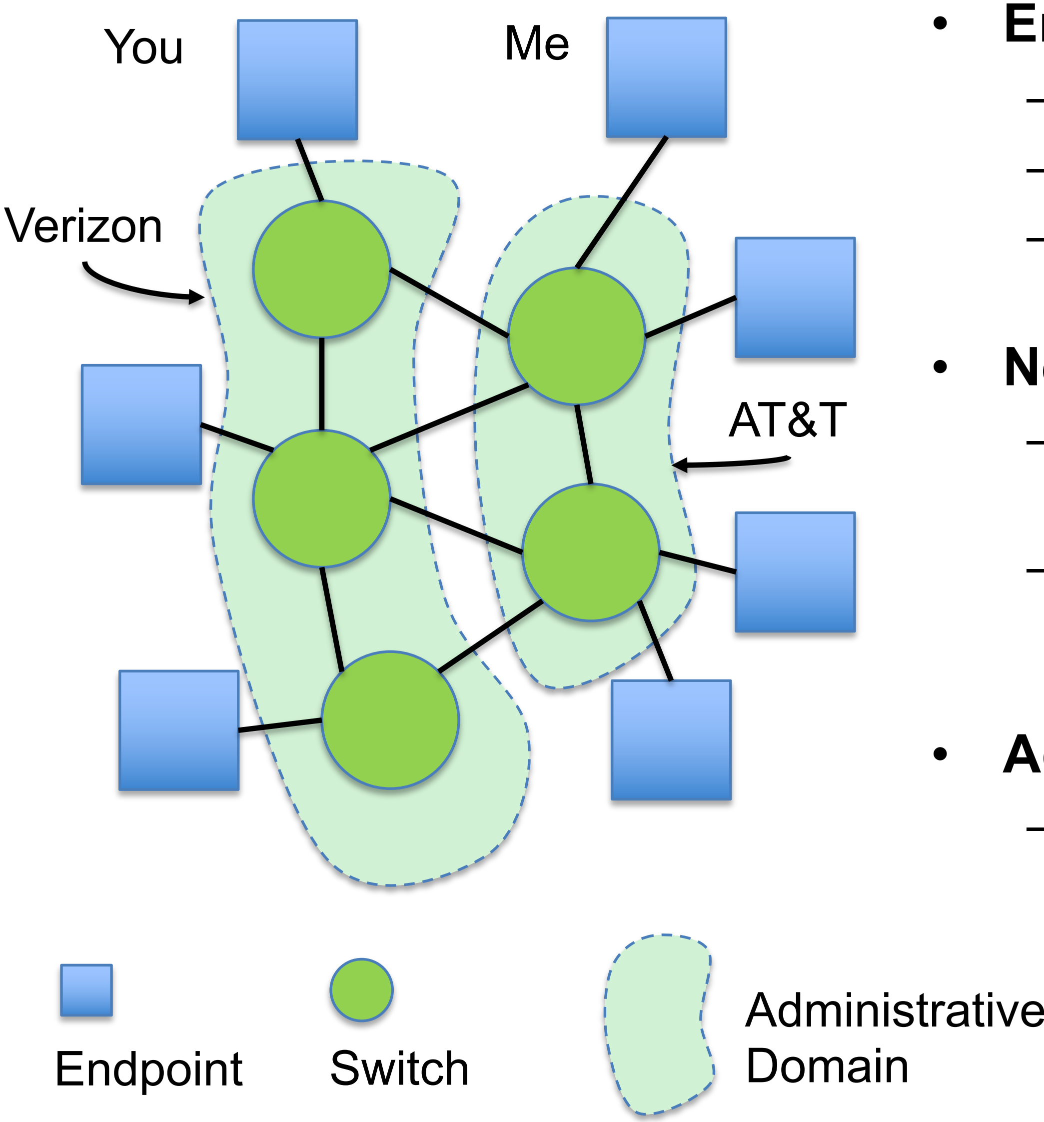

- **Endpoints**
  - Implement the applications
  - Do all the useful work
  - Examples: cell phones, laptops, servers
- **Network switches**
  - Provides connectivity between endpoints
  - Examples: cellular base stations, Ethernet switches, IP routers, …
- **Administrative domains**
  - Different parts of the network are owned and operated by different organizations

Key network interfaces

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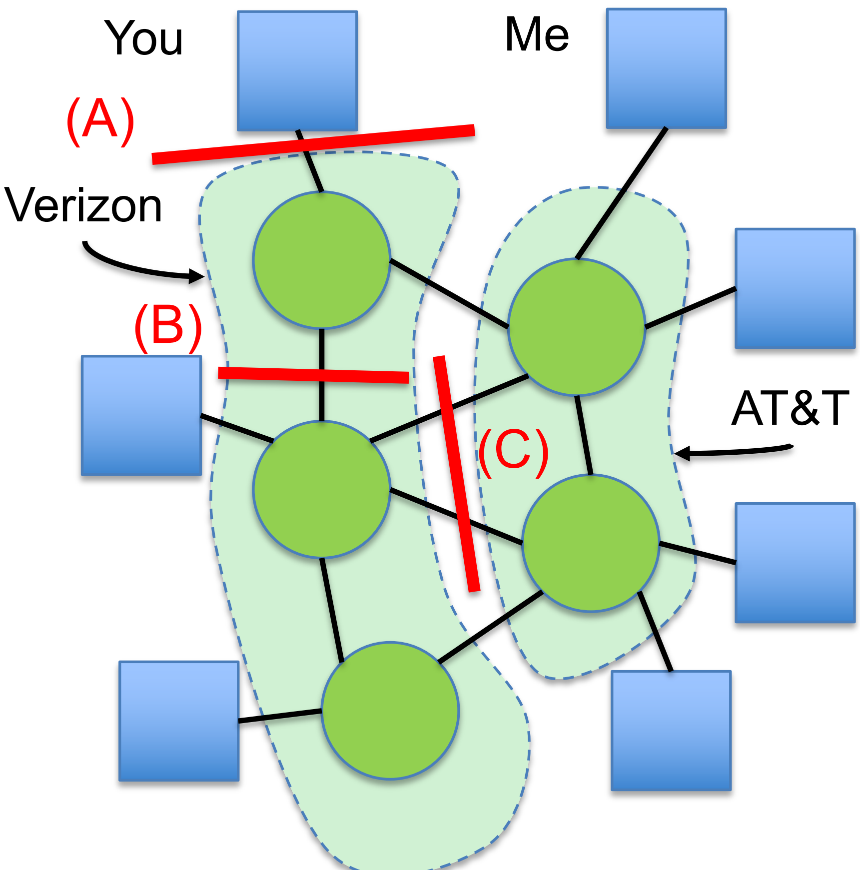

- **(A) Endpoint to switch**
  - Permits endpoint to "plug into" the network
  - Highly standardized so that a wide variety of endpoints can use the network
- **(B) Switch to switch within an administrative domain (AD)**
  - Generally standardized by equipment makers, but can vary considerably between operators
- **(C) AD to AD**
  - Reveal as little as possible about each domain's internal structure

Key network interfaces – a quantum example

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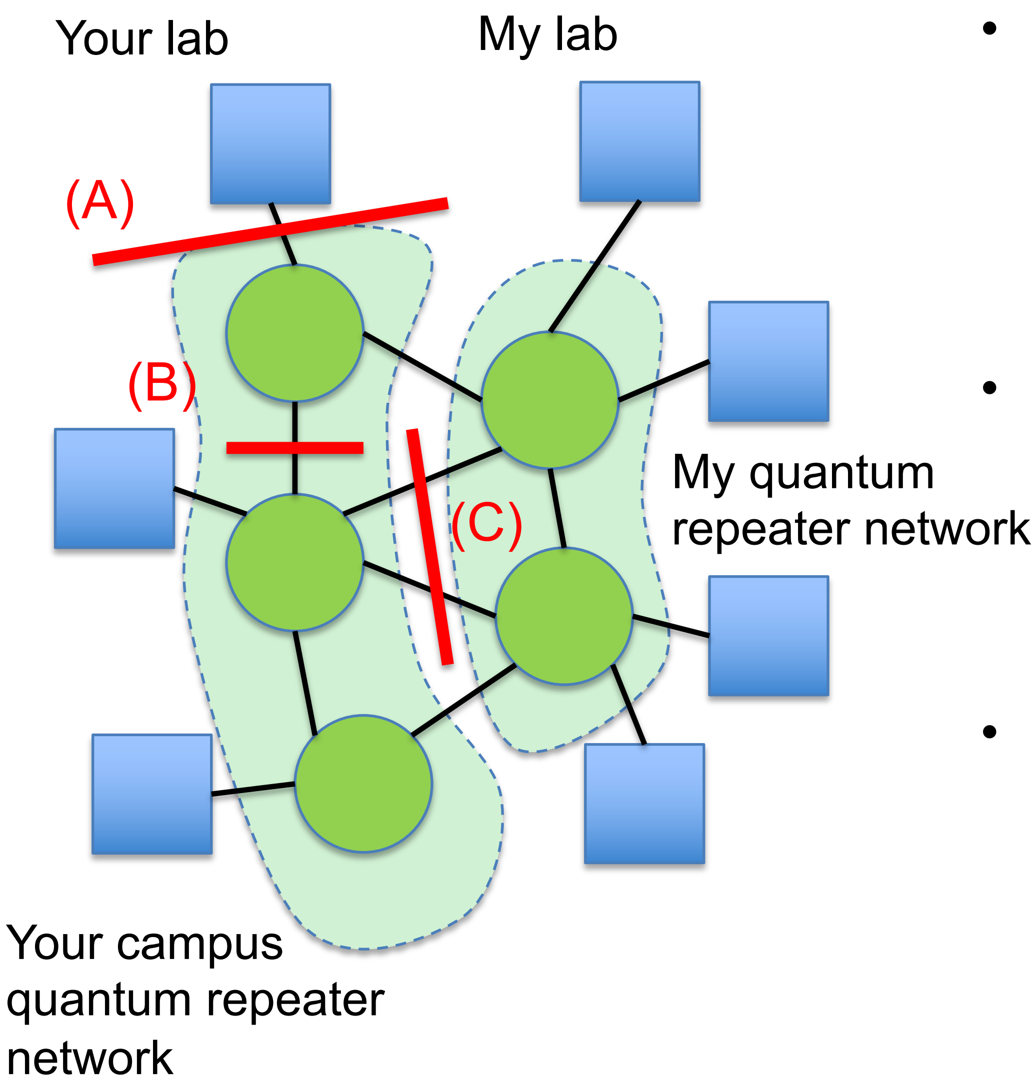

- **(A) Quantum computer to quantum repeater**
  - What wavelength(s)?
  - What teleportation protocols?
- **(B) Repeater to repeater within an AD**
  - Do not have to be identical to (A), but must provide compatible service
- **(C) AD to AD**
  - Will probably need to be compatible, even if each quantum repeater network is implemented differently

Protocols and protocol stacks

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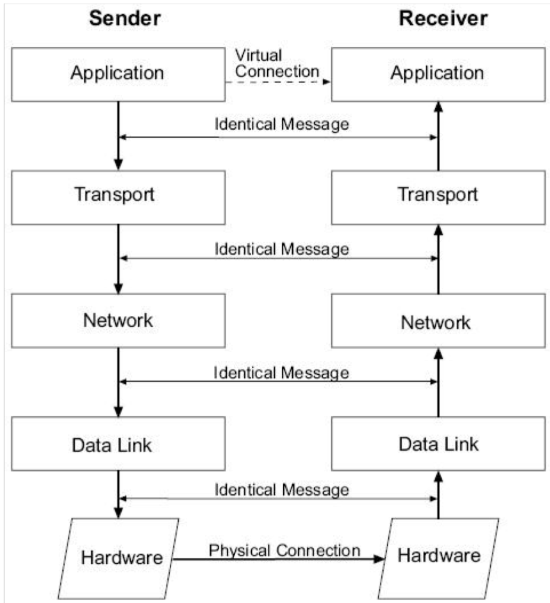
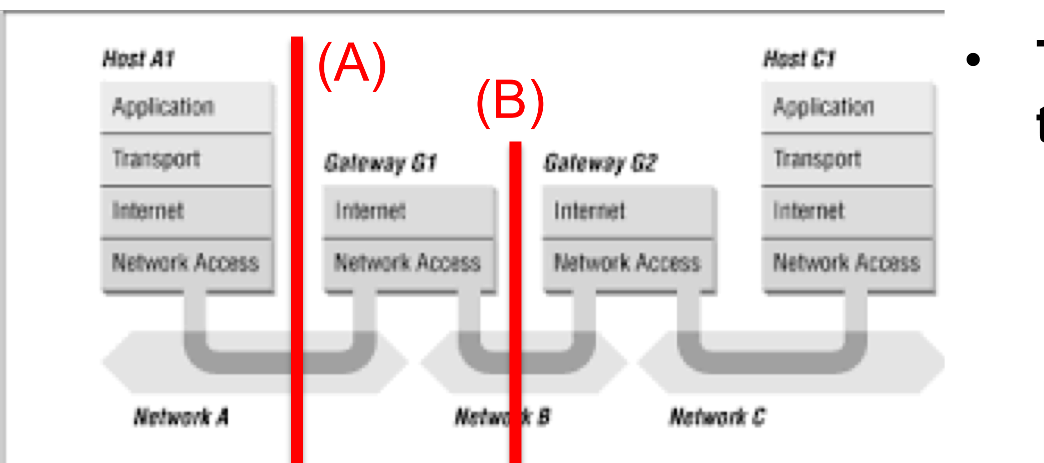
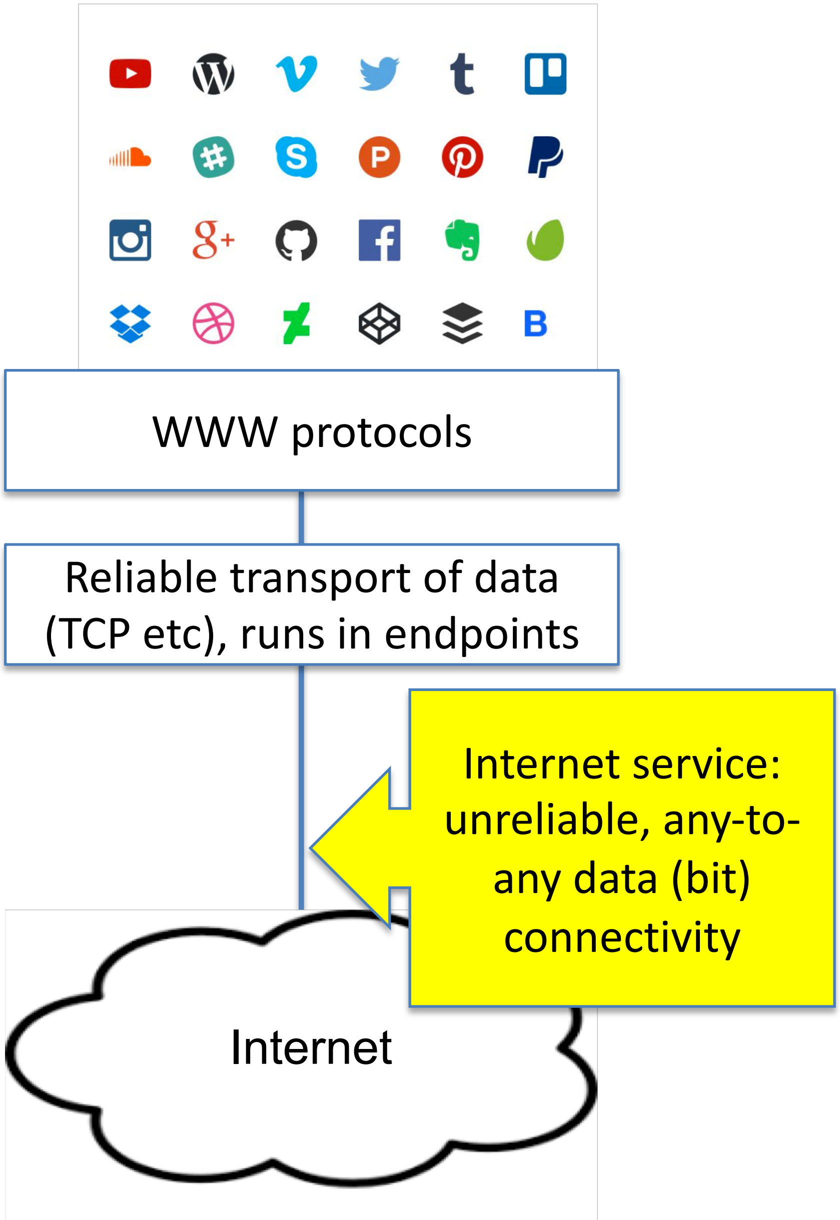


- **Protocol layers / stacks**
  - To manage complexity, protocols are "layered", where each layer provides a specific kind of functionality (service)
- **The bottom layer is physical**
  - Example: what wavelength on the optical fiber
- **The highest layers run "end to end" between endpoints**
  - Network gear only participates in the layers needed to provide basic connectivity



Networks provide ***services***



- **Optical network**
  - Optical path between device A and device B
- **Internet**
  - Unreliable, any-to-any data (bit) connectivity
- **Classic telephone network**
  - Voice calls
  - Fax
- **Cellphone network**
  - Voice calls
  - Texting
  - Internet

What services does a quantum network provide ?

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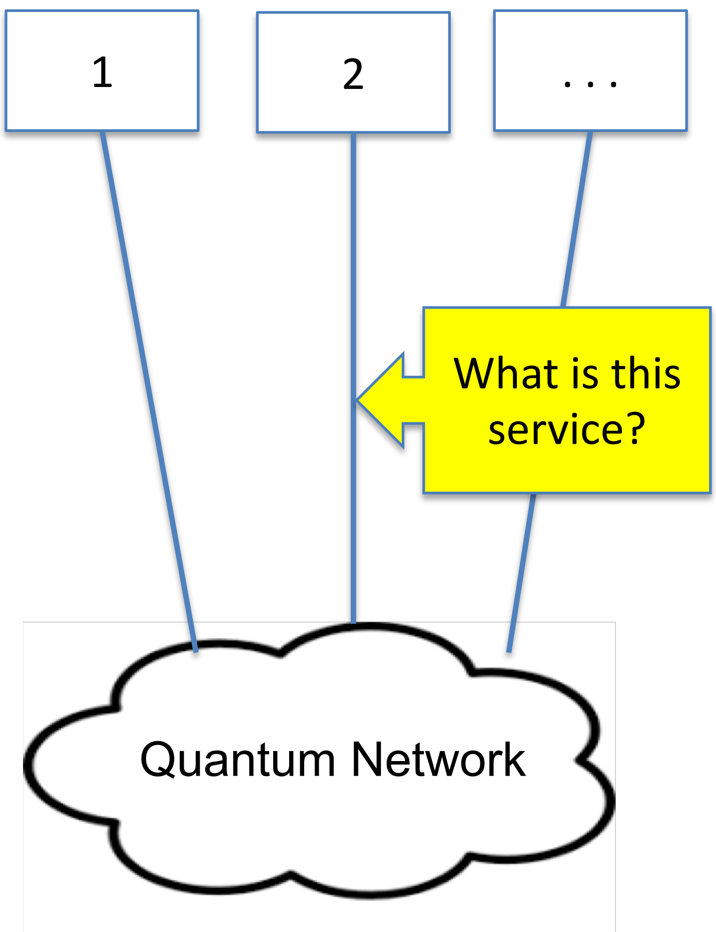
Quantum devices

(Are they all quantum computers?)



- Qubit teleportation ?
- Or simply amassing reservoirs of entanglement between devices ? (i.e. teleportation is an app)
- With what fidelity guarantees ?
- With what timing constraints ?
- Point-to-point, or permitting N-way entanglement ?
- Tailored for qubits, or servicing arbitrary quantum states ?
  - e.g. NOON states ?

Quantum repeater chains and their protocols

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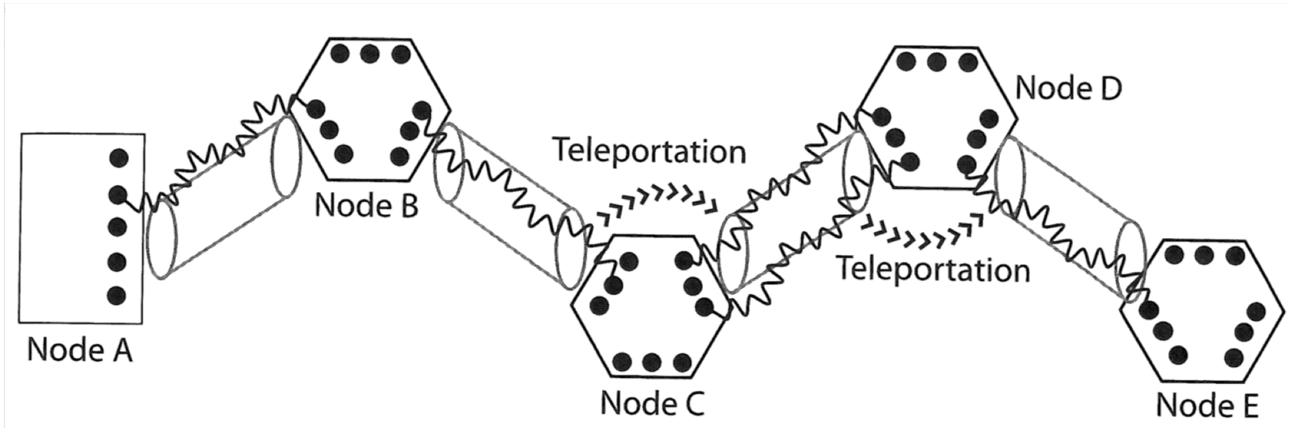
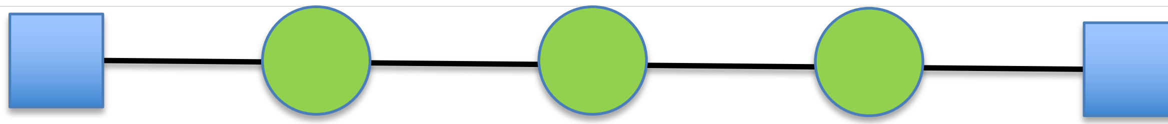
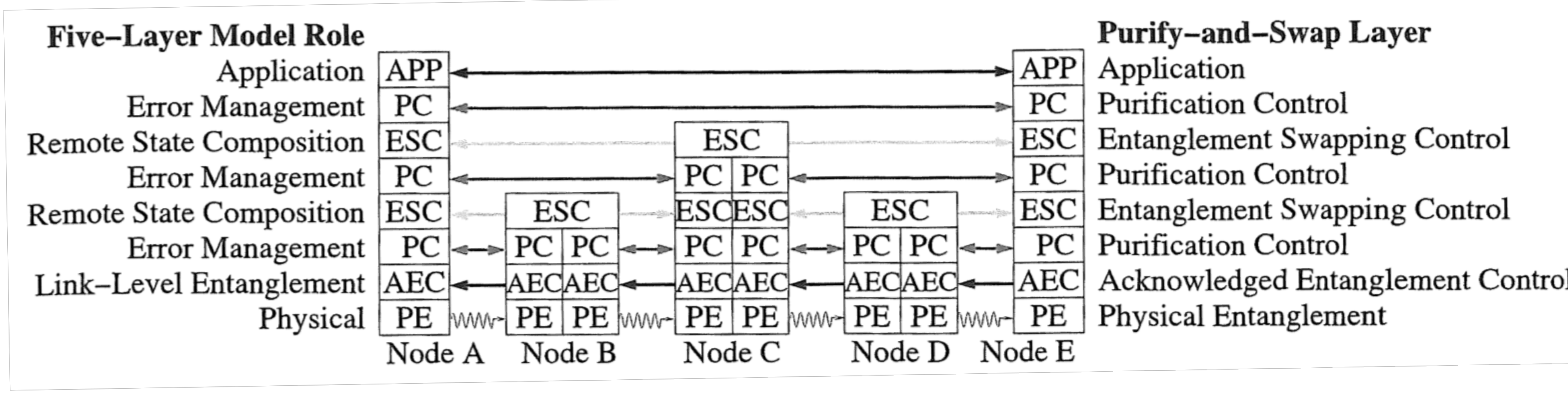




Corresponding protocol stack for Purify-and-Swap Quantum Repeaters



Both diagrams from "Quantum Networking," Rod Van Meter, page 205.

Protocols, time scales, and decoherence

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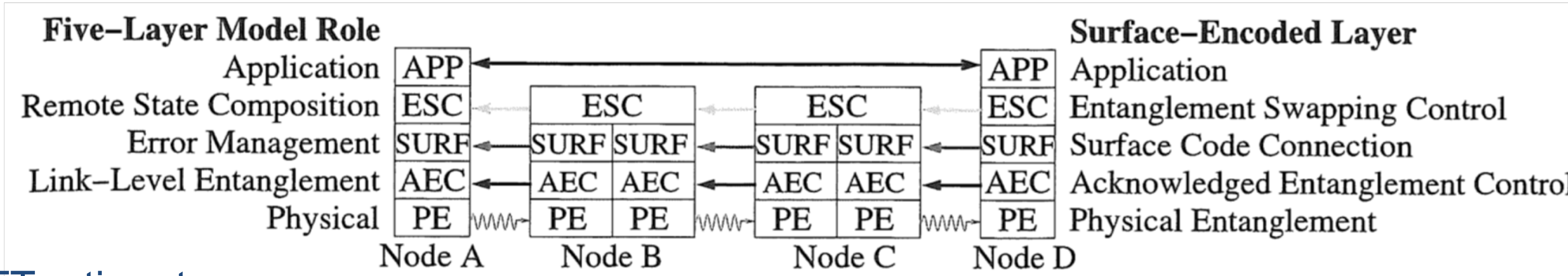

Figure 11.9. *The surface code repeater protocol stack*

RTT = time to hold qubit before using in QEC state

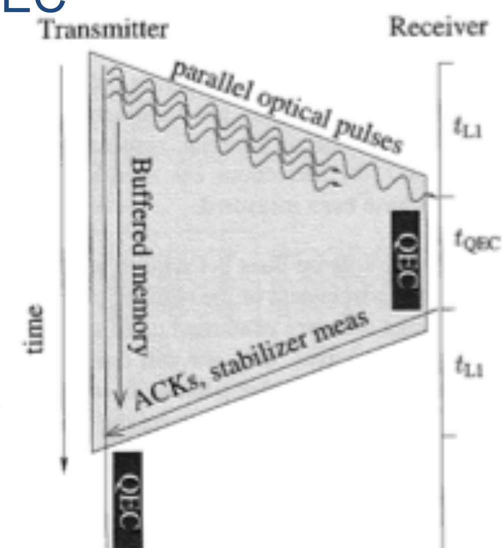

Figure 11.4. *The gray trapezoid represents round-trip processing on a single M → M link, including the buffering of memory at the sender, pending the entanglement success/failure acknowledgments*

RTT = time for completed teleportation

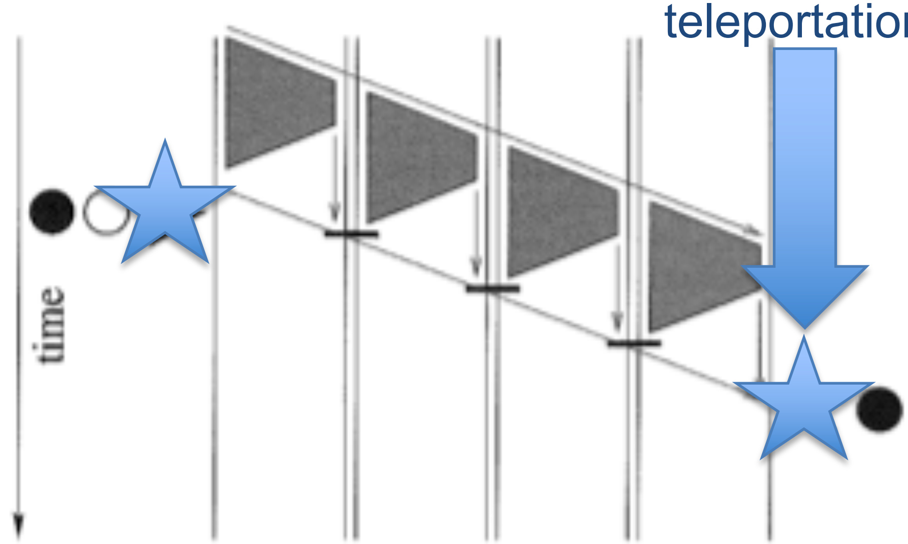

Figure 12.1. *Timing for forward propagation in quasi-asynchronous repeaters. Vertical arrows indicate necessary memory hold time waiting for BSM or final Pauli frame correction, and here sum to one end-to-end round-trip time*

Diagrams from "Quantum Networking," Rod Van Meter, page 226, 233, and 239.

Quantum repeater networks

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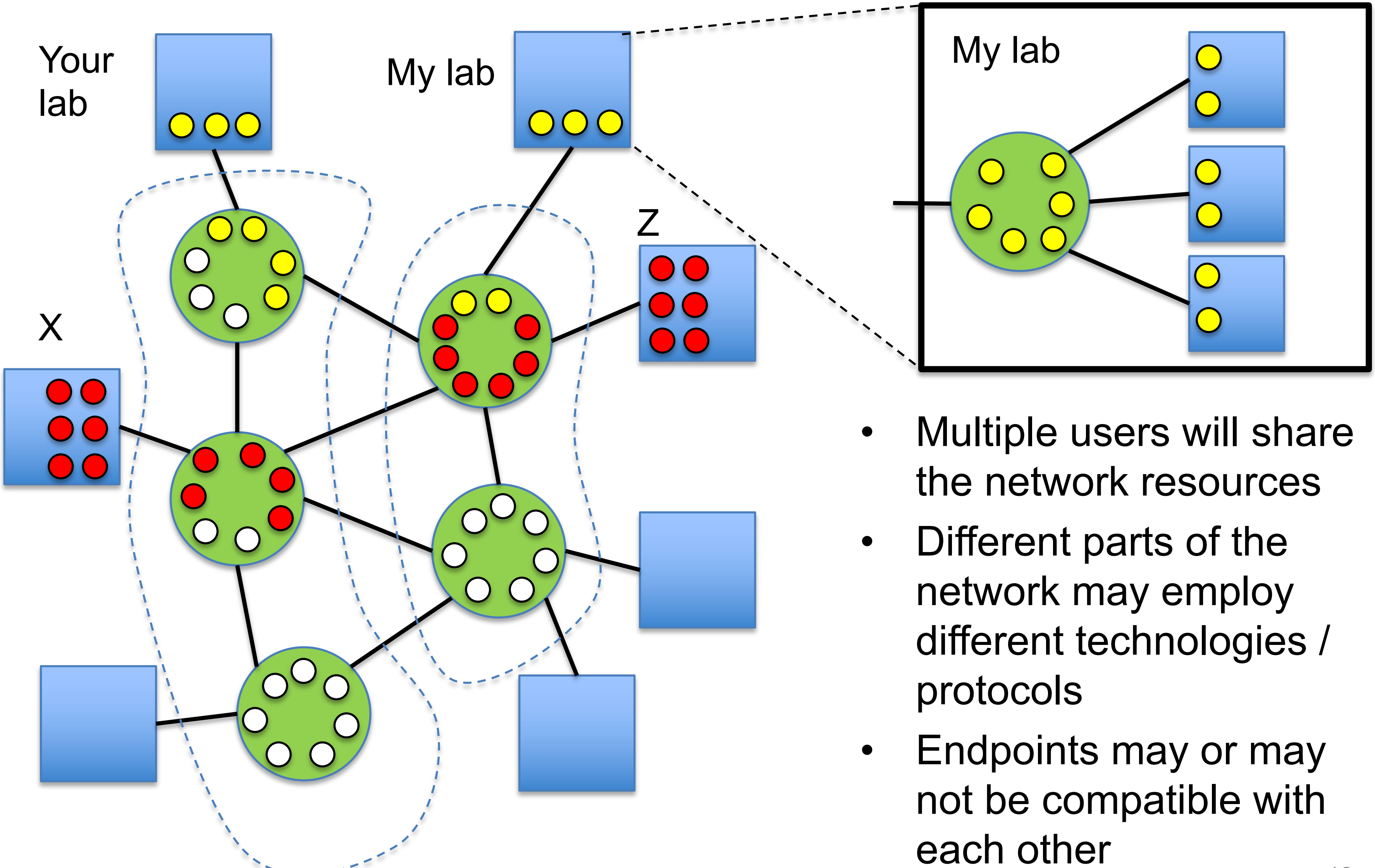

- Multiple users will share the network resources
- Different parts of the network may employ different technologies / protocols
- Endpoints may or may not be compatible with each other

Pairs used for You-Me path   Pairs used for X-Z path

All the classic networking tasks – but different

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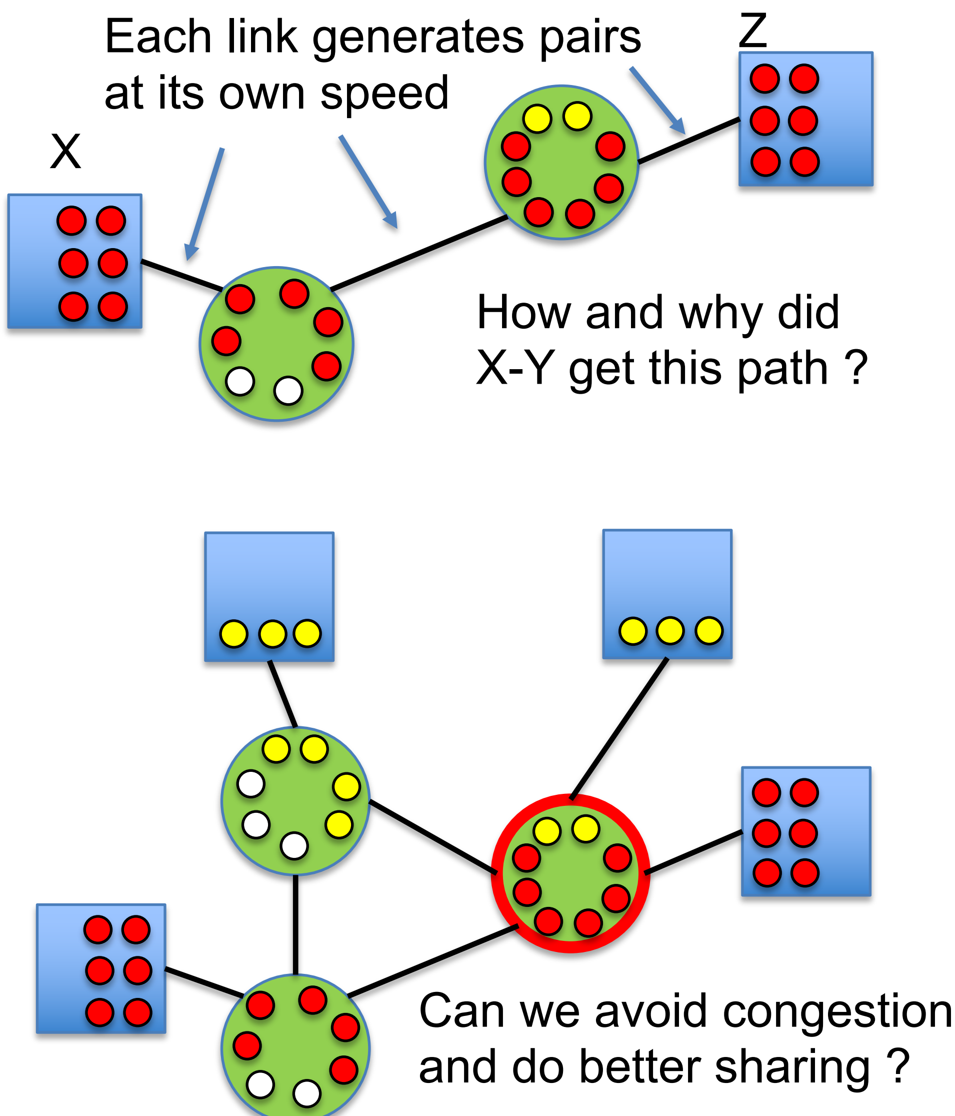

- **Finding and building paths through the network**
  - Routing, path setup, potentially multipath
  - Resource aware (how many free pairs along the way)
  - Link entanglement rates (perhaps hard to predict)
- **Resource contention and management**
  - Congestion avoidance
  - Fair sharing
- **Network management**
- **Etc etc etc**

Many novel challenges for quantum networks

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- **Physical-layer challenges** [not discussed in this talk]
  - E.g. transduction, fiber lambdas, etc.
- **Entanglement-distribution architectures**
  - Pioneering mechanisms & protocols have been outlined
  - There are probably many other approaches
  - What entanglement should be positioned *where*, within the network?
  - What about N-way entanglement ?
- **Services and layerings**
  - Exactly what services does the network offer ?
  - Grappling with (estimates of) link-specific entanglement rates
  - Is fidelity “one size fits all” or can it be requested ?
  - What kinds of layerings are “best” (flexible, efficient, …)
- **Many interesting challenges in resource management**
  - Inter-relationship of protocol timings, decoherence, etc.

A closing thought

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- This time, please don't ignore SECURITY

Thank you and . . .

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