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Quantum Networks
NSF Engineering Research Center

Principles of Quantum Networks

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Outline

- Introduction
- Fundamentals of Quantum Communications
- Classical vs. Quantum Networks
- Scheduling in Quantum Repeater Chains
- Quantum Network Routing
- Connectionless Quantum Networks
- Quantum Network Management and Tomography
- Summary

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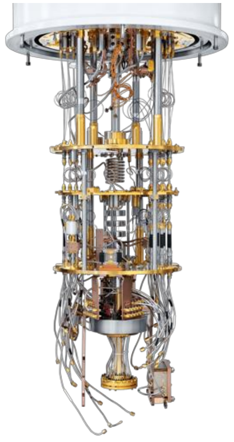
Introduction

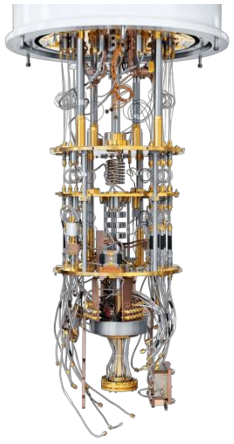
Purpose

Alice



$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

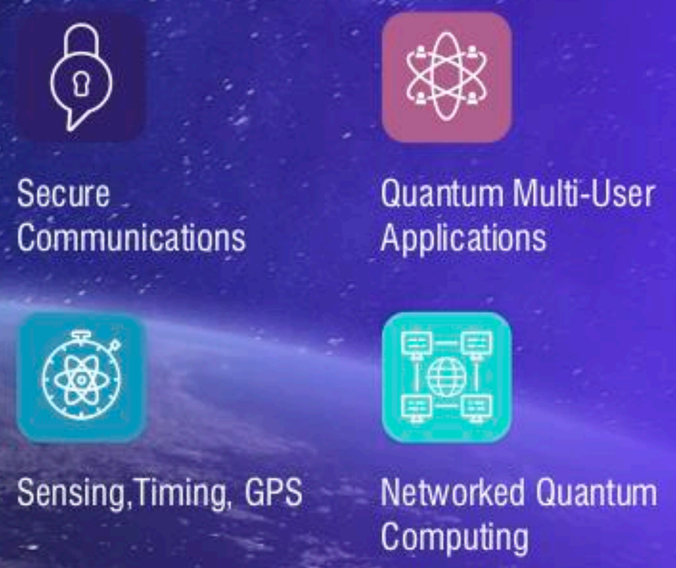
Bob

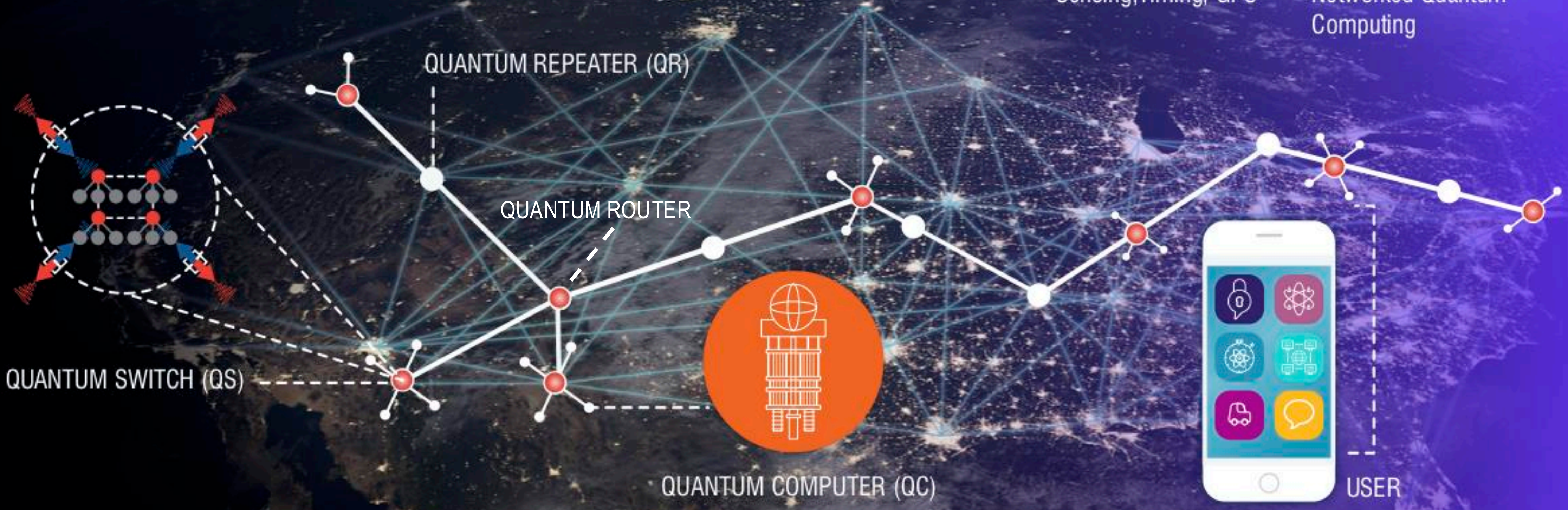


$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

The Quantum Internet

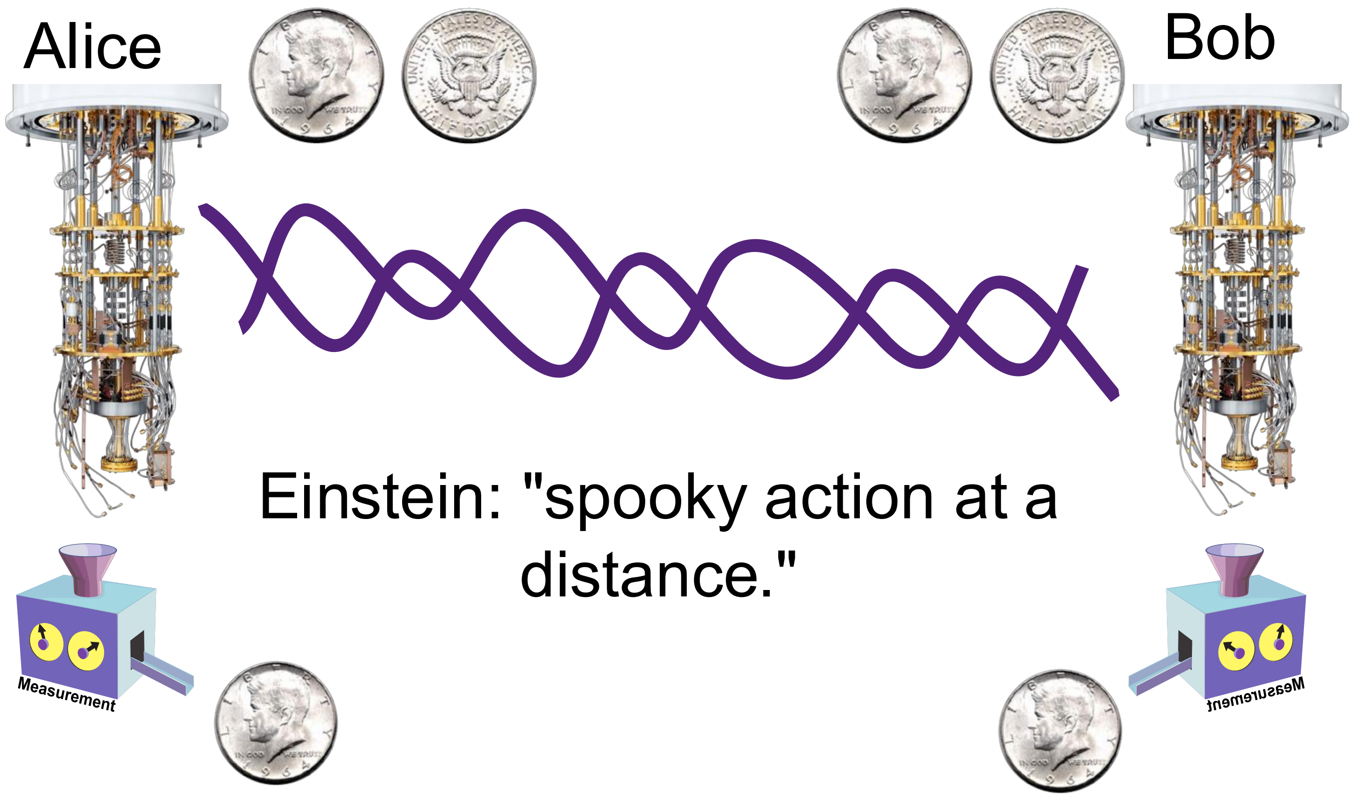
Vision: Quantum network enabling full quantum connectivity between multiple user groups.





Key ingredient

Quantum entanglement, *aka Bell state*, between pair of remote quantum processors



Bell state: $\frac{|0_A 0_B\rangle + |1_A 1_B\rangle}{\sqrt{2}}$

Nobel prize, Physics, 2022: A. Aspect, F. Clauser, A. Zeilinger

https://pubs.acs.org/doi/10.1021/cen-10036-scicon3

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Why Quantum Internet?

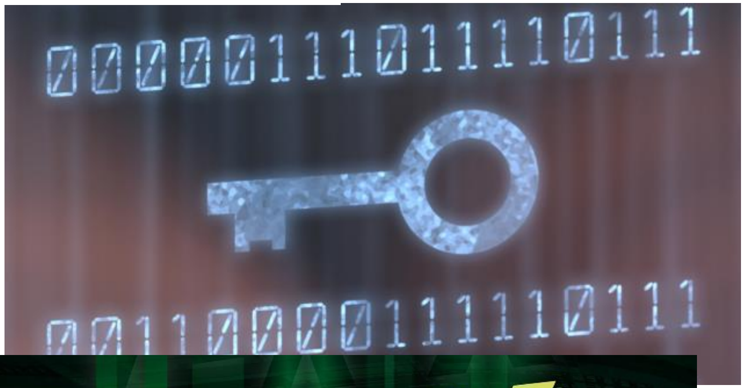
Cryptography, security – quantum key distribution (QKD)

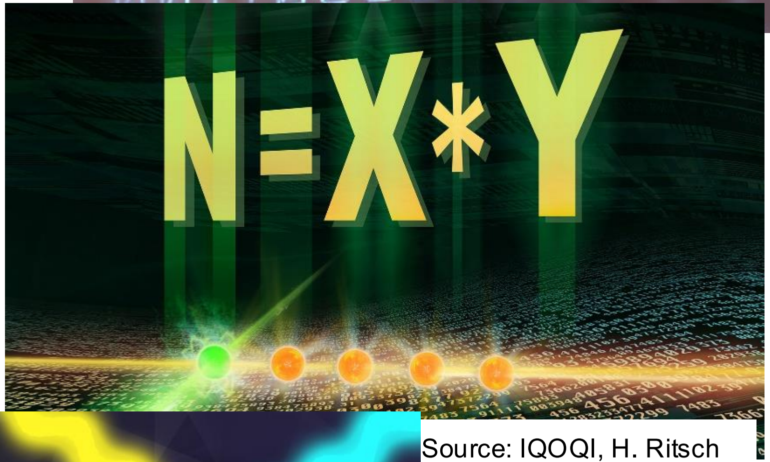
Distributed quantum computing – breaking web security, solving hard problems

High resolution sensing – exploring the universe

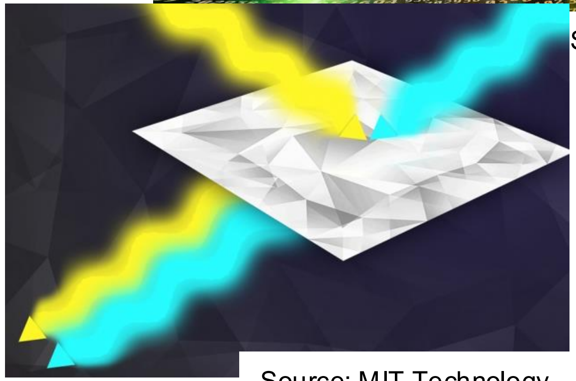
Quantum Teleportation – transmission of quantum information

Source: Physics World





Source: IQOQI, H. Ritsch



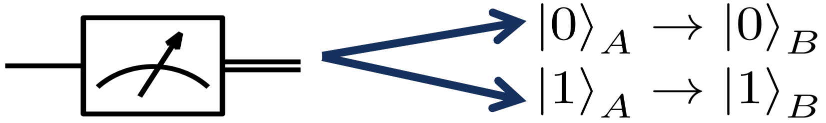
Source: MIT Technology

Bell state

- Bell state

$$\frac{|0_A 0_B\rangle + |1_A 1_B\rangle}{\sqrt{2}}$$

- Measuring Alice's qubit yields 0,1
  - if 0, measuring Bob's qubit yields 0
  - if 1, measuring Bob's qubit yields 1
  - can generate shared randomness across distances



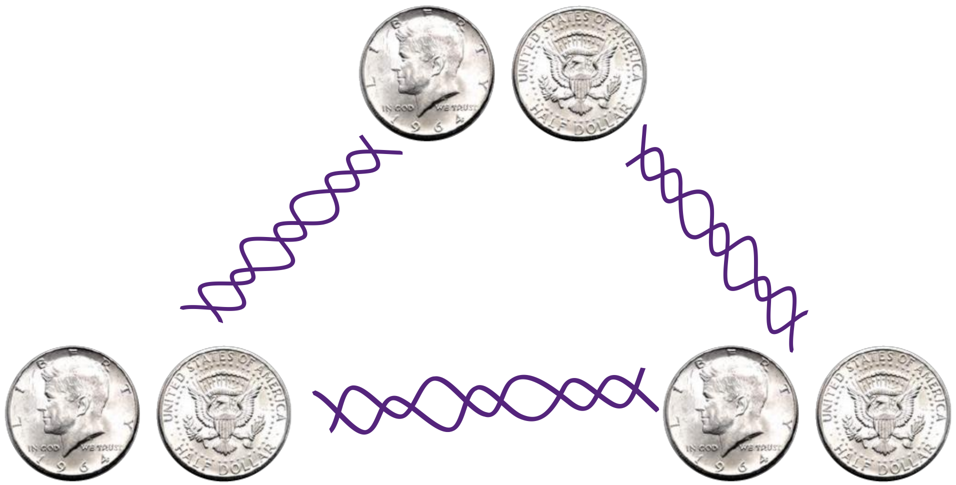
- Key ingredient of quantum teleportation, QKD, and many other applications

Multipartite extension of Bell state

Greenberger–Horne–Zeilinger (GHZ) state

- n-partite GHZ state $$|GHZ\rangle = \frac{|00\cdots0\rangle+|11\cdots1\rangle}{\sqrt{2}}$$

- used in multiparty QKD, secret sharing, quantum sensing, …



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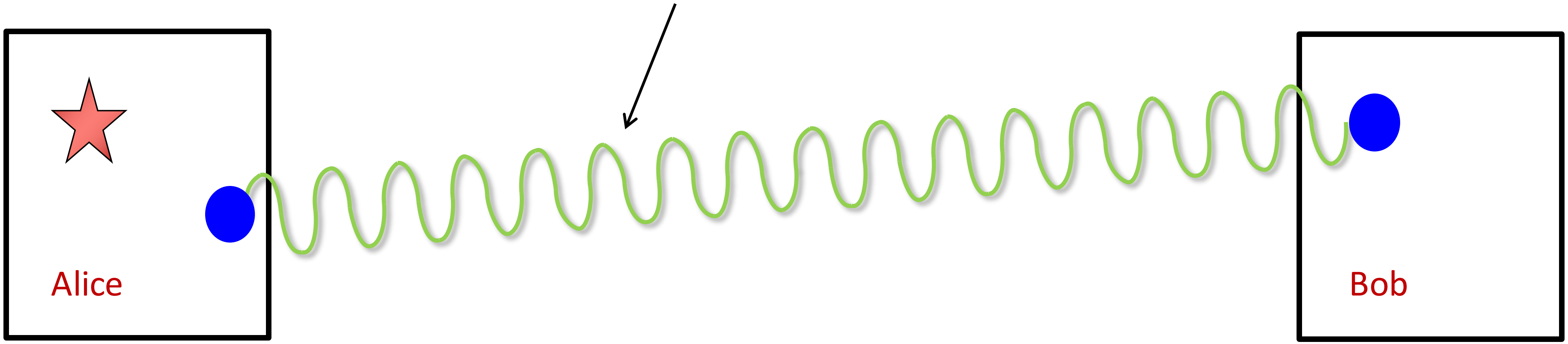
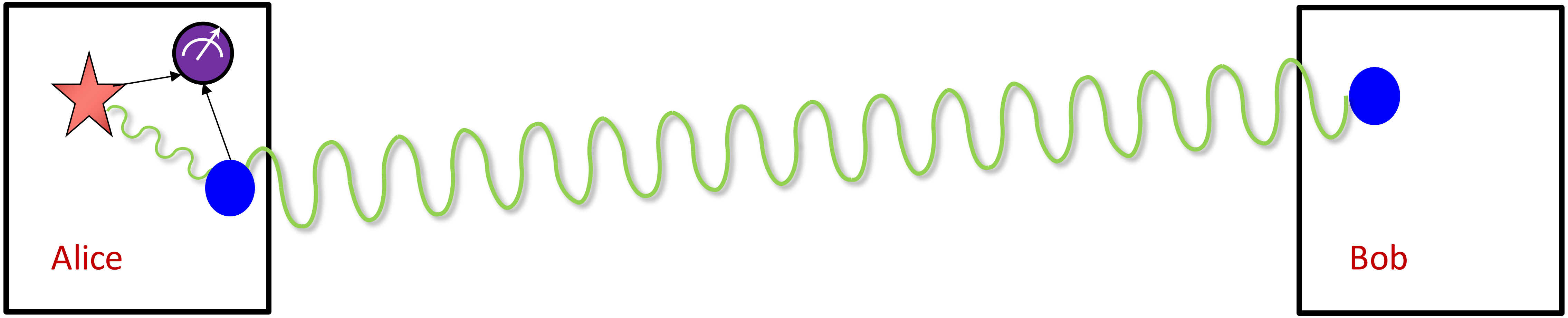
Quantum Teleportation

end-to-end entanglement $\frac{|0_A 0_B\rangle + |1_A 1_B\rangle}{\sqrt{2}}$



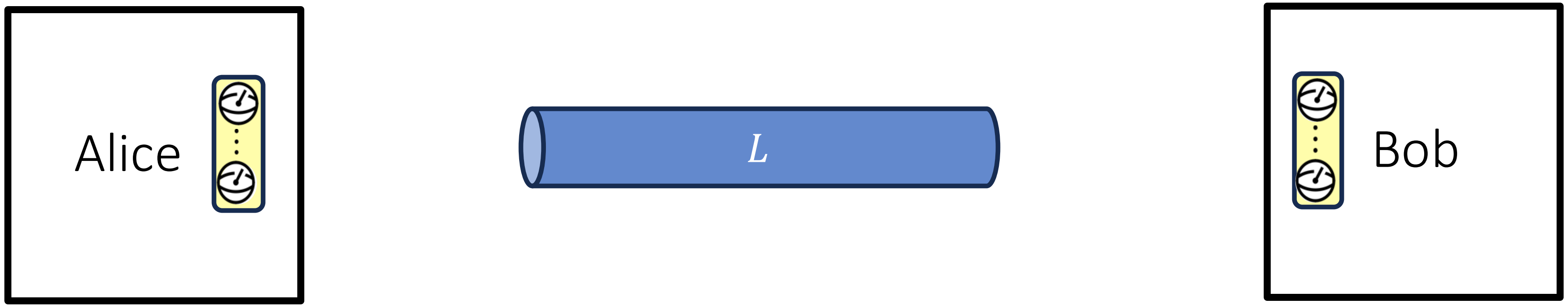
Teleportation



Teleportation

Fundamentals of Quantum Communications

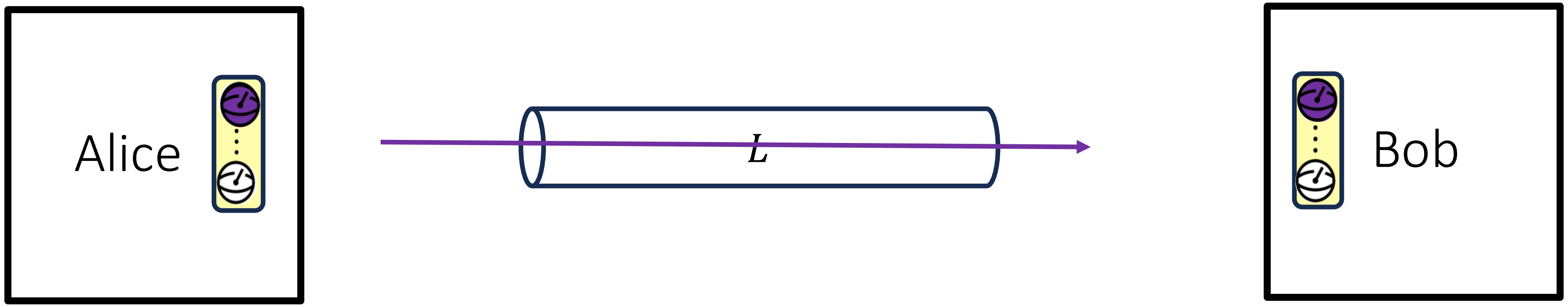
Quantum comms over link



- Nodes have qubits (memories)
- Photons are quantum information carriers
- Fiber/free space link connects nodes

Quantum comms over link

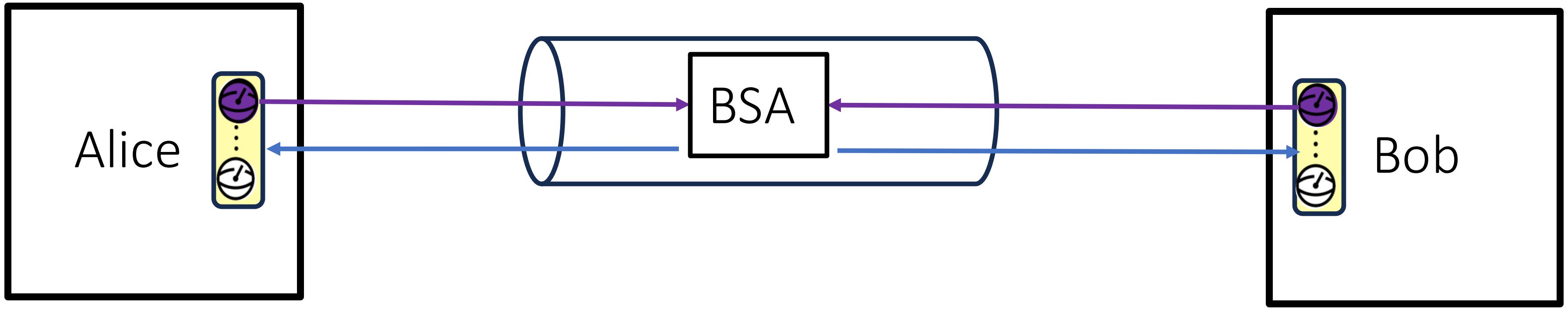
One-way communication



- Alice prepare qubit in state $|\psi\rangle$
- State transduced from memory to photon
- Photon sent to Bob through channel
- State $|\psi\rangle$ loaded in Bob's memory qubit

Quantum comms over link

Two-way communication



- Alice/Bob generate photon-memory Bell pair
- Photons traverse and meet at Bell state analyzer
- Measurement results sent back to Alice and Bob
- Bell state shared between Alice and Bob
- Additional operations herald state $\frac{|00\rangle+|11\rangle}{\sqrt{2}}$

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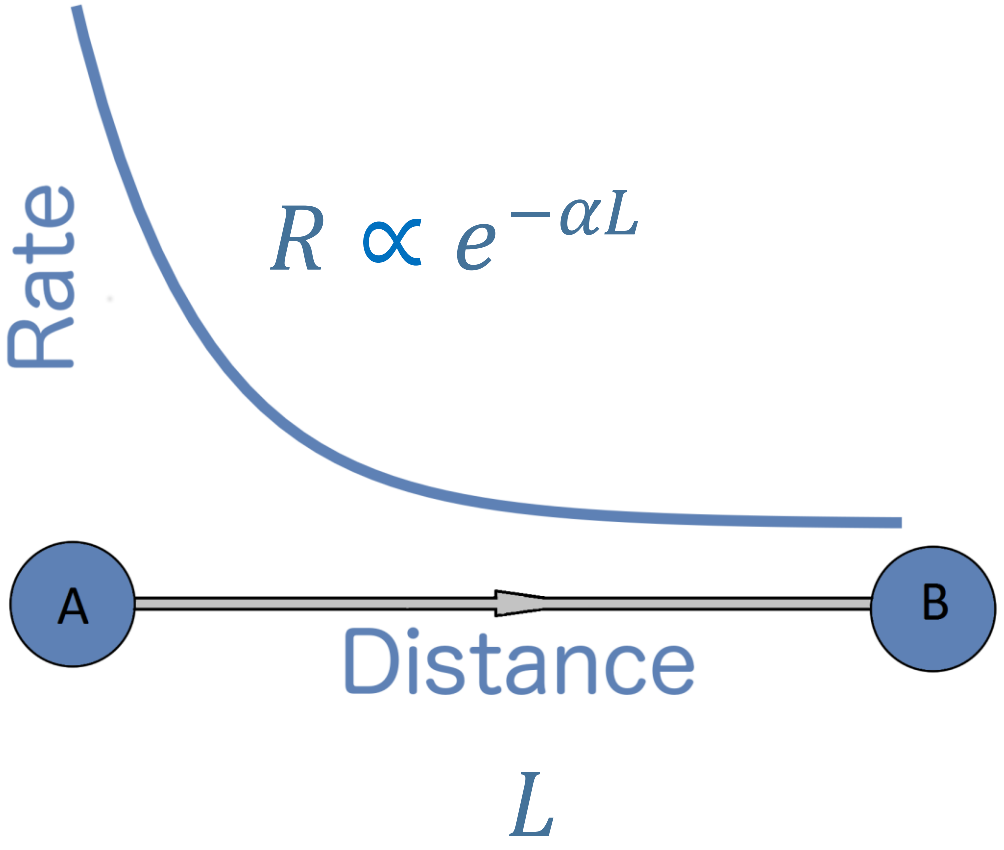
Why are quantum communications so hard?

Loss and noise!!!

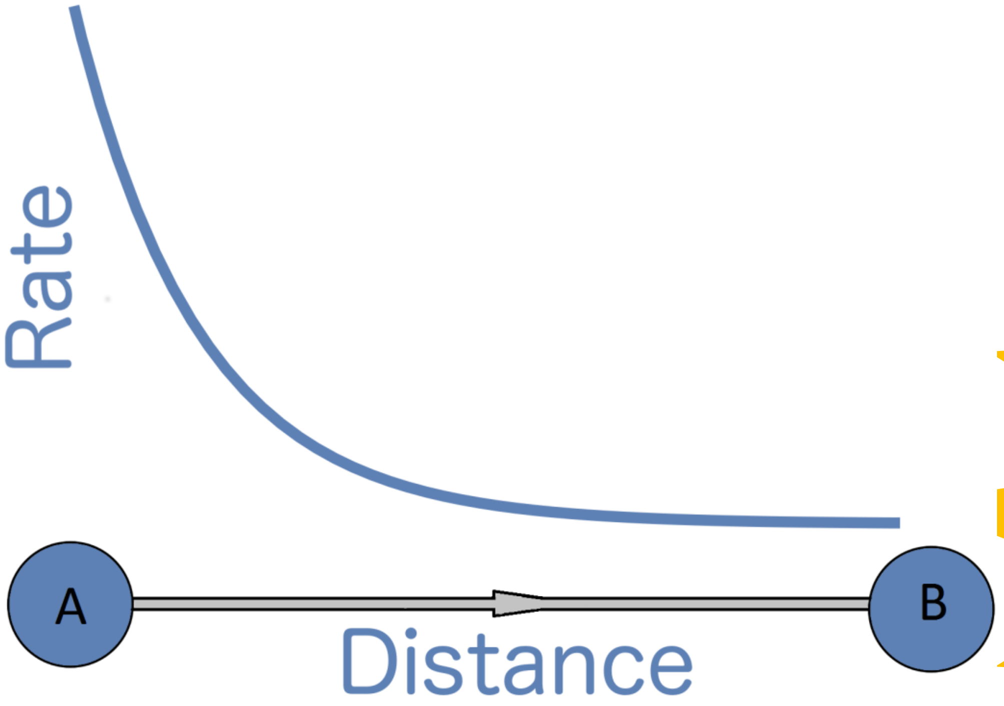
Why are quantum communications so hard?



Rate decays exponentially with distance

Can we amplify signal?

Why is it so hard?



Rate decays exponentially with distance

No cloning theorem!
Quantum signals cannot be copied

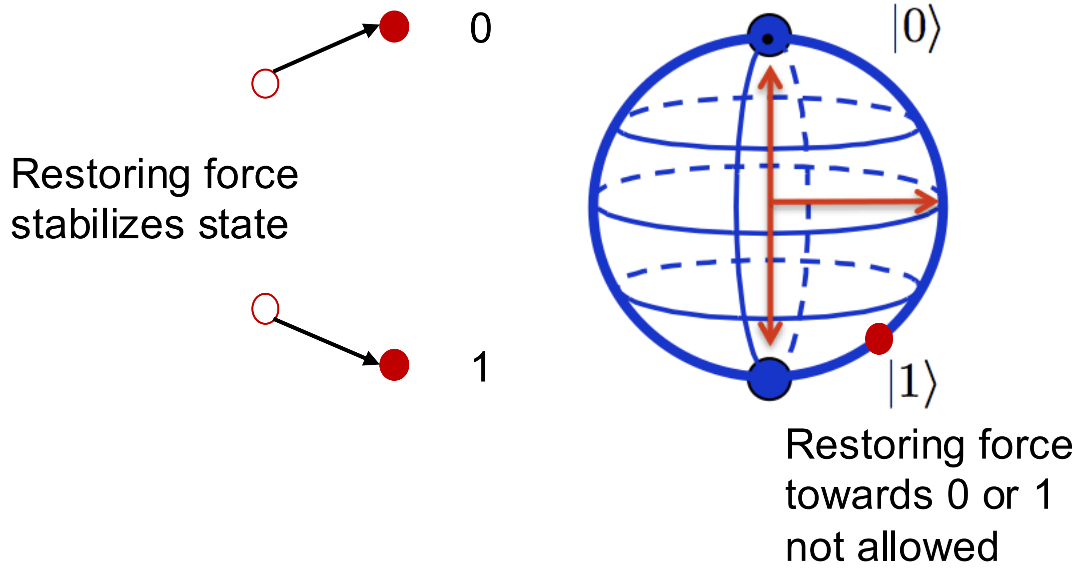
Poll Question

How does the generation rate of EPR pairs decay with distance in direct transmission through fiber?

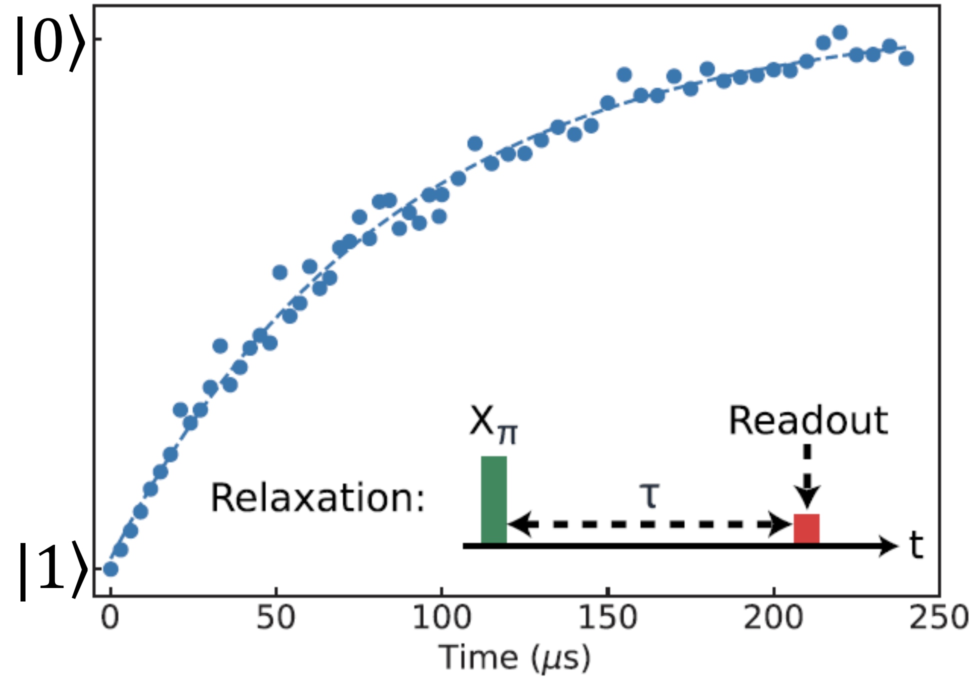
A. Polynomial decrease
B. Constant decrease
C. Exponential decrease
D. Depends on fiber technology used
E. I don't know

Why are quantum communications so hard?

- Qubits not self protected against smallest perturbation

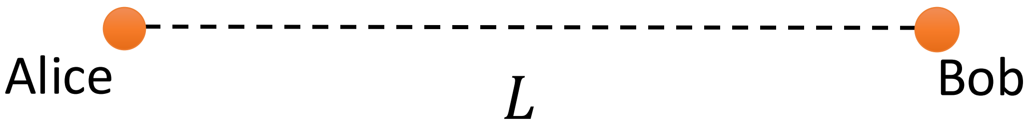


- Qubits have limited coherence times



P. Krantz, etal, Appl. Phys. Rev. 6, 021318 (2019)

Noise in quantum states



- Noise introduced thru comms
- States decohere, Bell states decohere twice!
- Noisy gates and memory operations

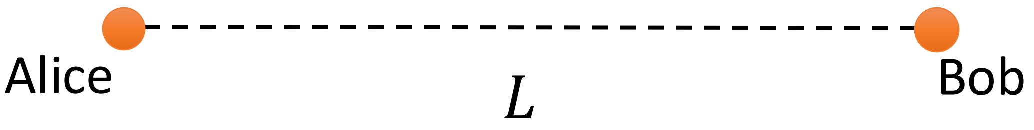
	One-way	Two-way
Expected	$\vert\psi\rangle$	$\frac{\vert 00\rangle + \vert 11\rangle}{\sqrt{2}}$
Obtained	1-qubit state ρ	2-qubit state ρ

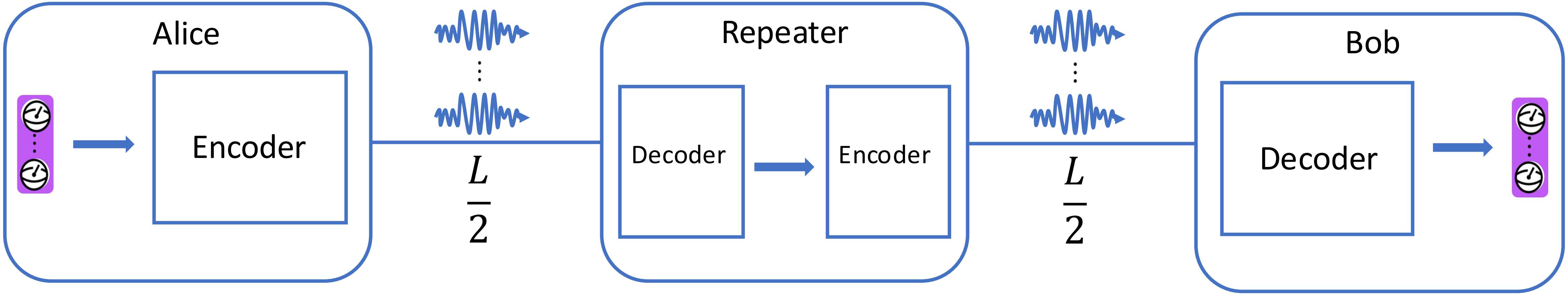
Fidelity: measure of closeness between two quantum states

Fidelity of direct transmission is between ρ and $|\psi\rangle$

Entanglement fidelity is fidelity between ρ and $\frac{|00\rangle+|11\rangle}{\sqrt{2}}$

One-way quantum repeaters





Protect information with Quantum Error Correction (QEC)

State recovered if sufficient photons survive

High-probability of delivering logical state, p depends on encoding

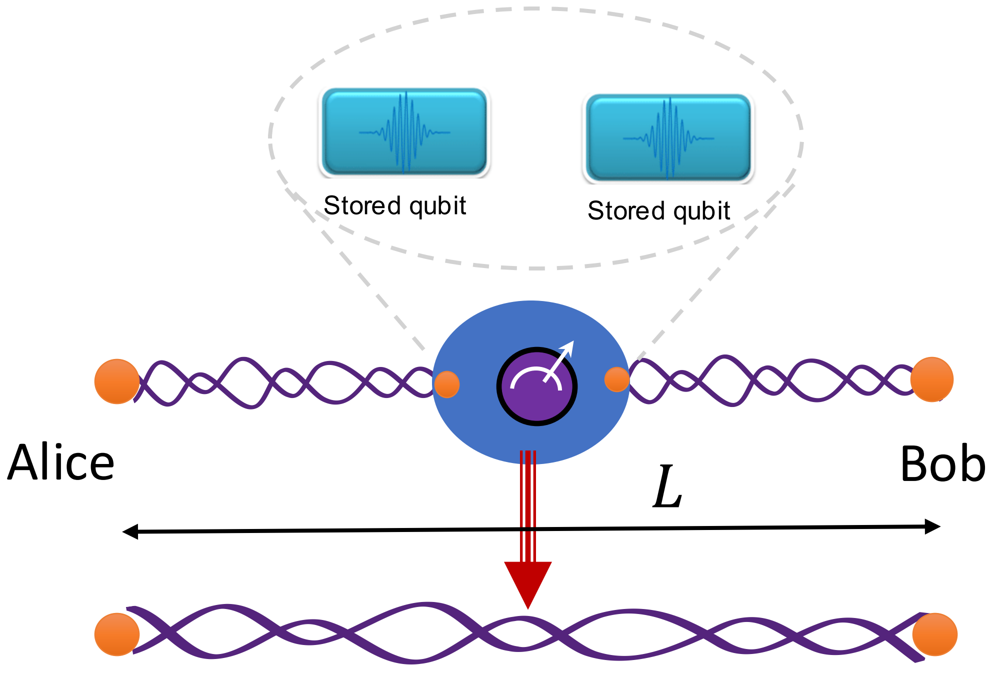
Repeater may not need quantum memories

Two-way quantum repeaters

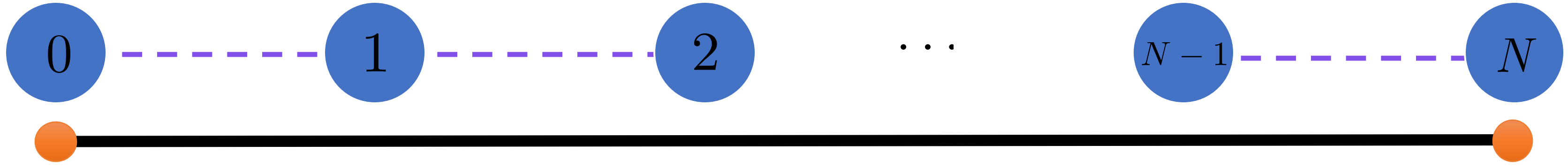
Quantum memories to store entanglement

Phase I: generate link level entanglement (Bell states)

Phase II: measurement propagates entanglements to ends



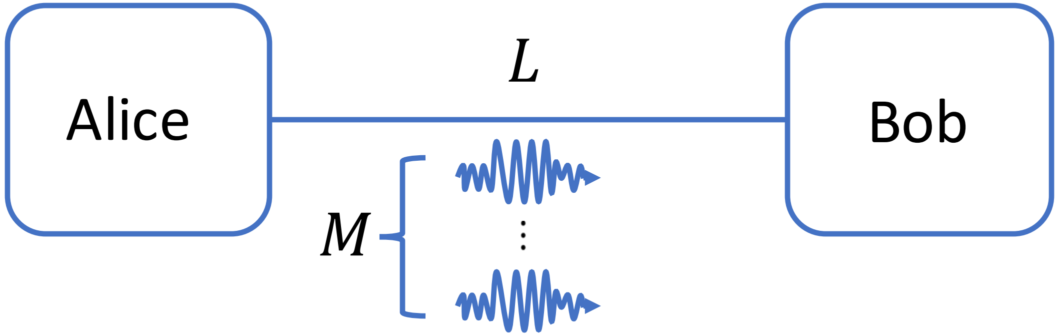
$$R = e^{-\alpha L/2}$$



$$R \propto e^{-\alpha L/N}$$

Multiplexing

What if we do parallel attempts?

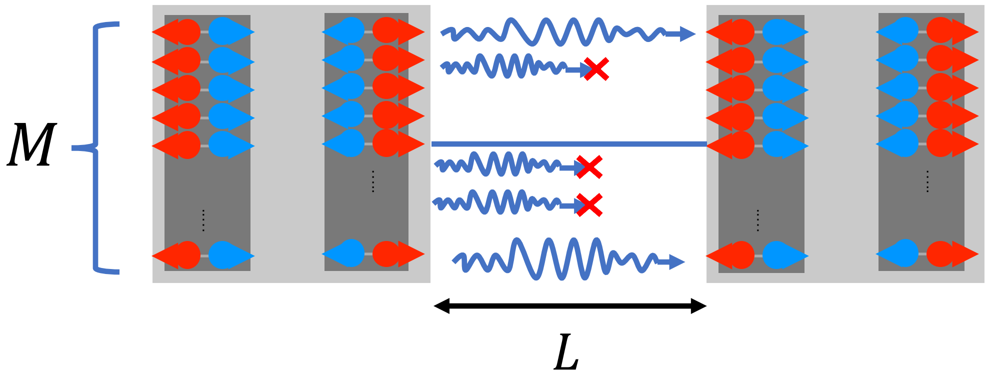


One-way repeaters utilize multiple photons!

QEC is like “quantum multiplexing!”

Use multiple entangled qubits (photons)!

In two-way repeaters



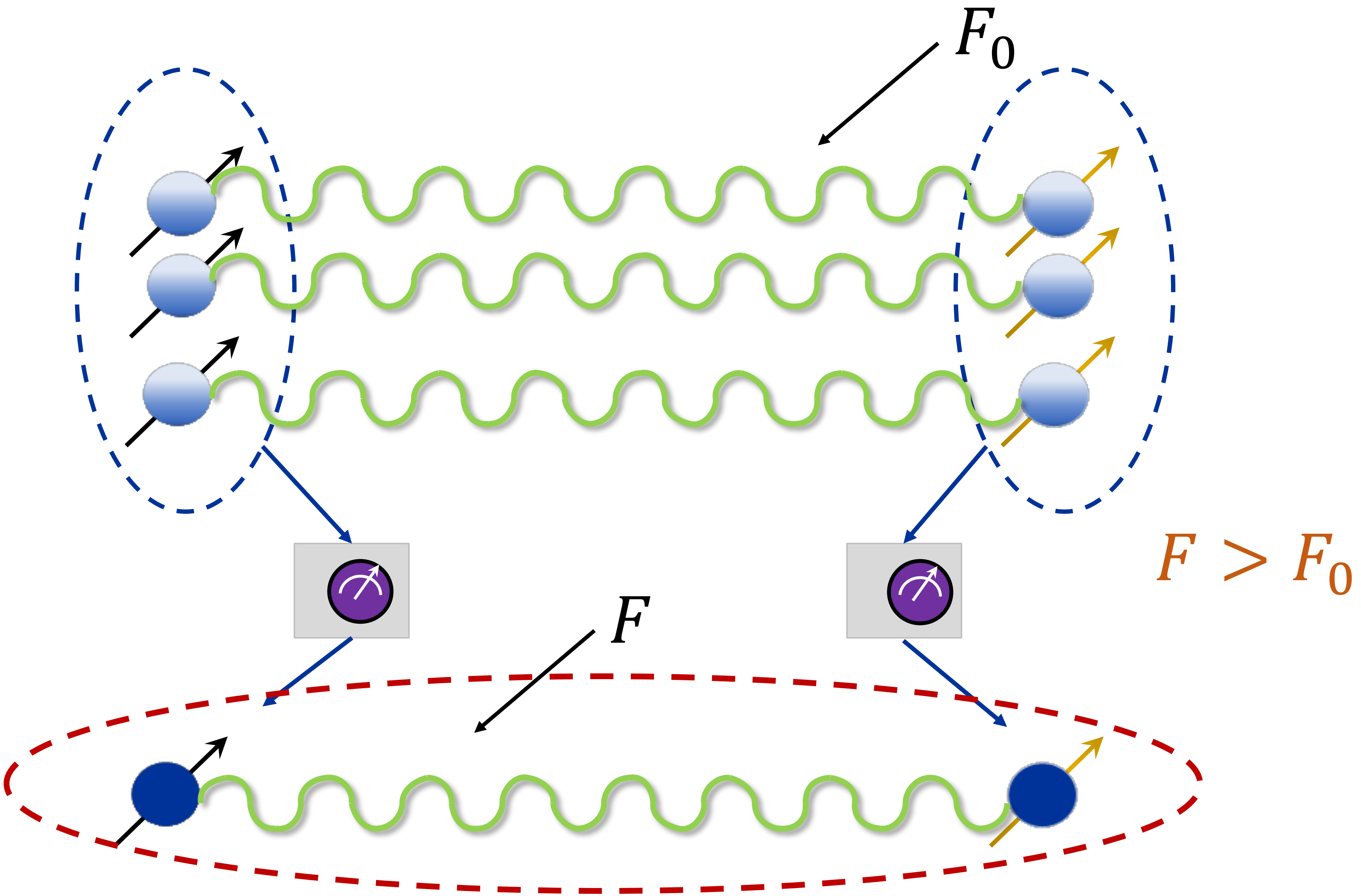
Probability that at least one survive?

$$\Pr[K = 1] = 1 - (1 - p)^M$$

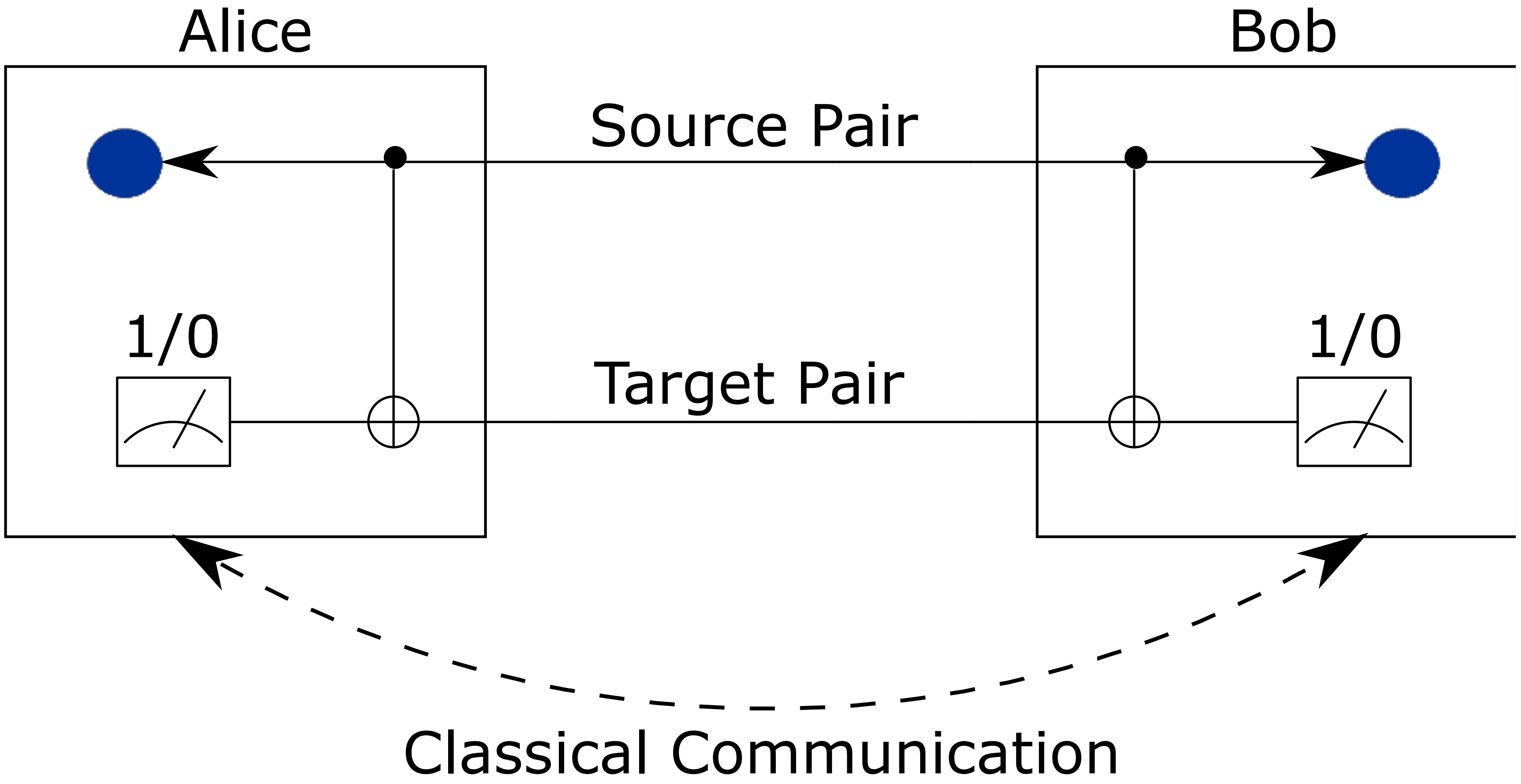
Probability that k survive?

$$\Pr[K = k] = \binom{M}{k} p^k (1 - p)^{M-k}$$

Entanglement distillation



Entanglement distillation



Probabilistically convert multiple noisy entangled pairs into single strongly entangled pair!

Phys. Rev. Lett. **76**, 722 (1996)

QoS metric

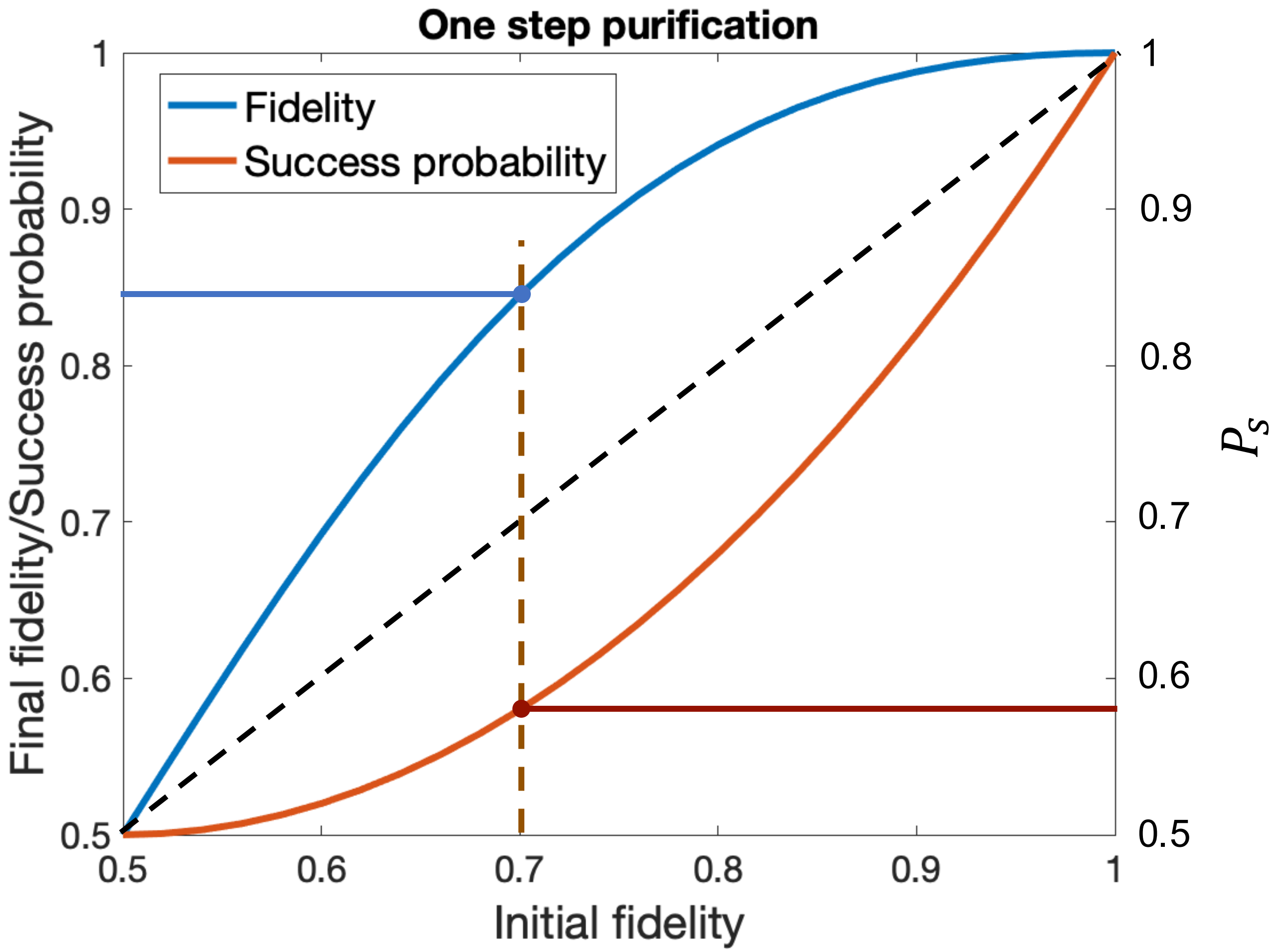
Fidelity: measure of closeness of entanglement to perfection

0 — 1

complete fidelity

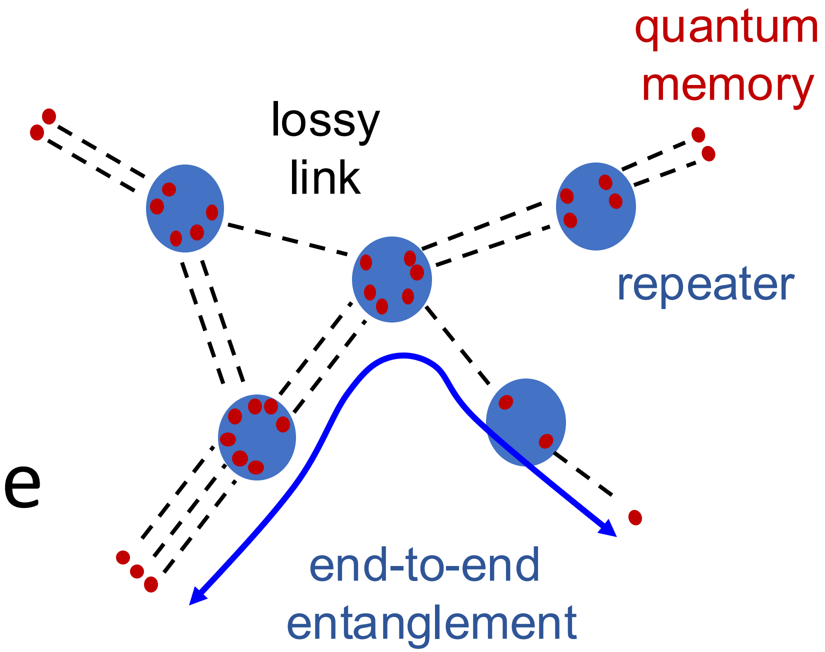
← decreasing fidelity

Distillation step succeeds with probability P_s



Quantum Networks

- Quantum switches with memories connected via lossy links
- Links generate entanglement / used to transmit quantum info. directly
- Switches concatenate (measure) to realize end-to-end entanglement between end nodes / decode-encode and forward quantum info



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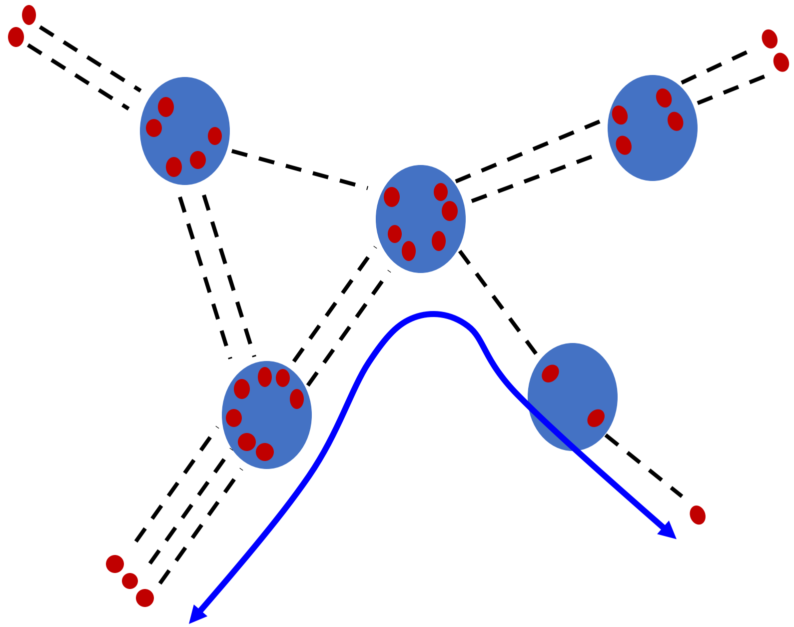
Quantum networking challenges

- Service to provide
  - entanglement distribution
  - direct quantum information transfer
- Noise!
- Who to serve
  - performance & resource allocation



- Network management
  - measurement & tomography
- Data, control plane design

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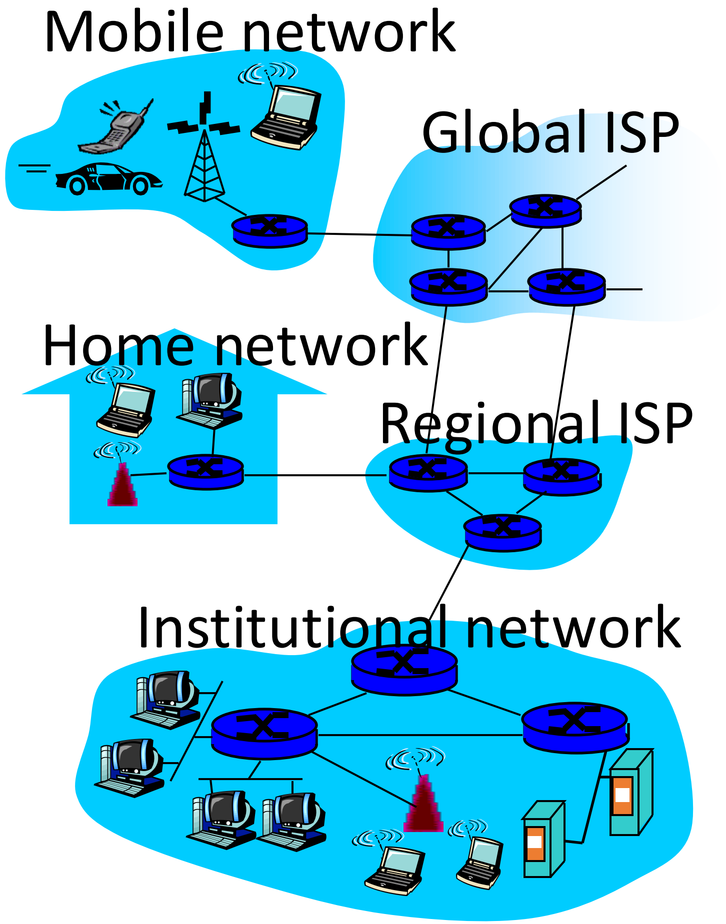
Classical vs. Quantum Networks

Outline

- Internet overview
- Network services, routing
- Switch/router design

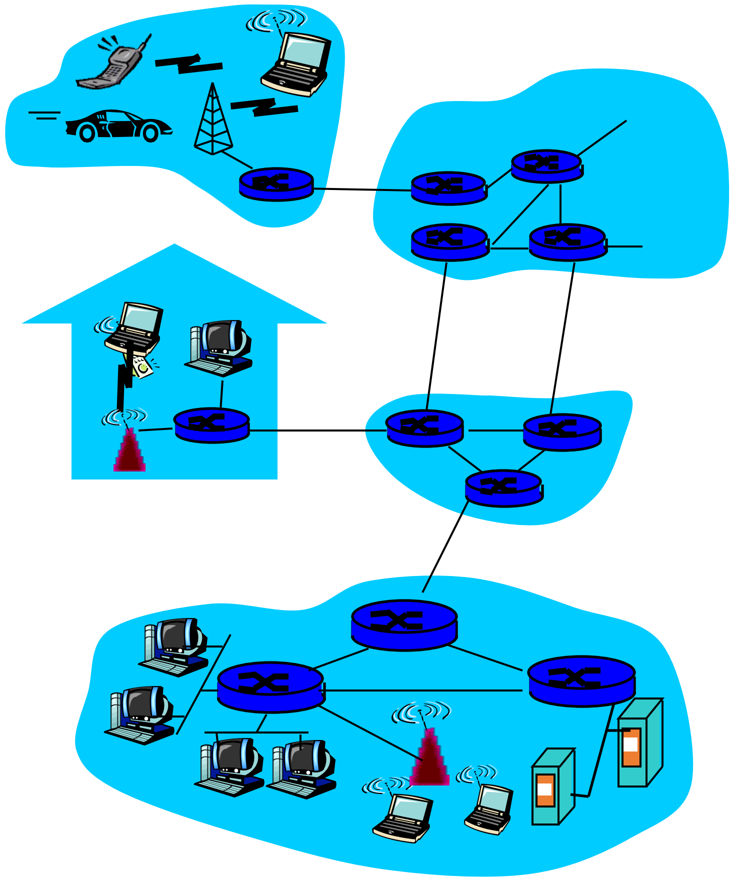
What's the Internet: "nuts and bolts" view

- *Internet:* "network of networks"
  - loosely hierarchical
  - public Internet versus private intranet
- *Protocols:* control sending, receiving of messages
  - e.g., TCP, IP, HTTP, RTMP, Ethernet, WiFi
- Internet standards
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force
  - IRTF: Internet Research Task Force
  - QIRG: Quantum Internet Research Group



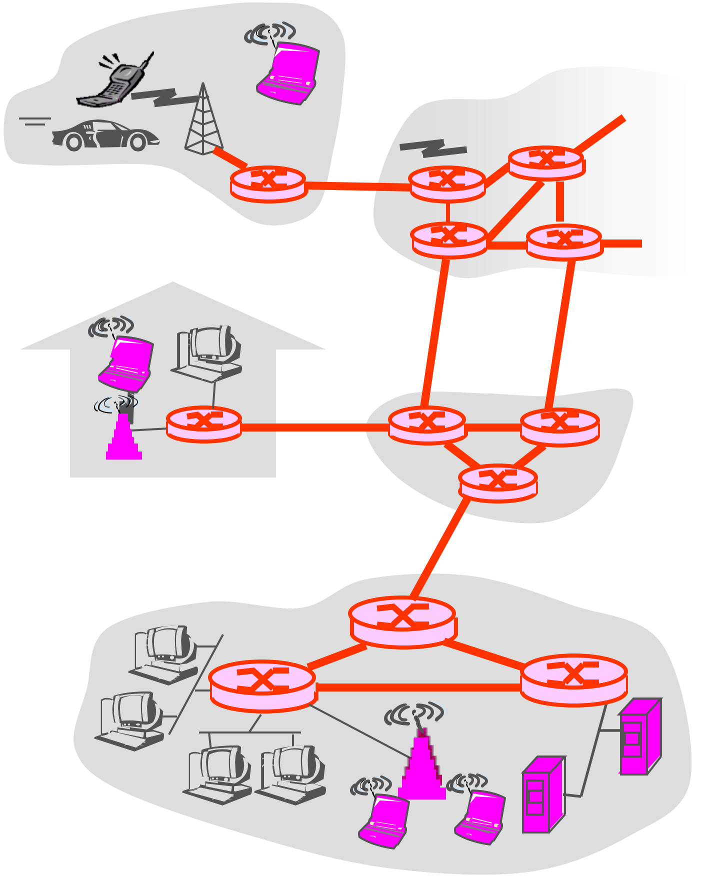
A closer look at network structure

- Network edge: applications and hosts
- Network core:
  - routers
  - network of networks
- Access networks
  - wired
  - wireless



The network core

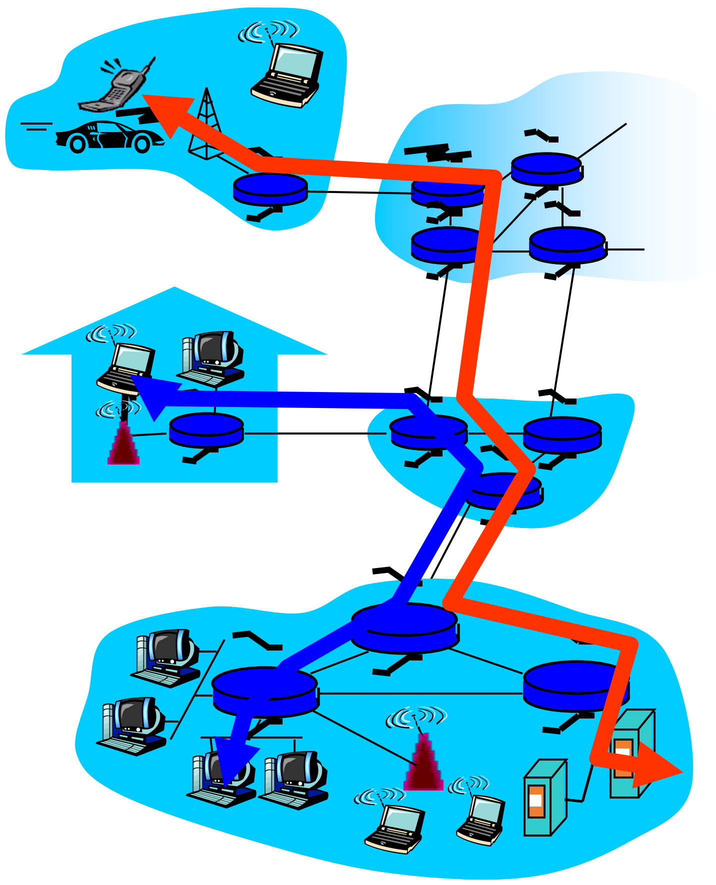
- Mesh of interconnected routers
- Fundamental question: how is data transferred through net?
  - circuit switching: dedicated circuit per call: telephone net
  - packet-switching: data sent thru net in discrete "chunks"



Network core: Circuit switching

End-end resources reserved for "call"

- Link bandwidth, switch capacity
- Dedicated resources: no sharing
- Circuit-like (guaranteed) performance
- Call setup required



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Network core: Packet switching

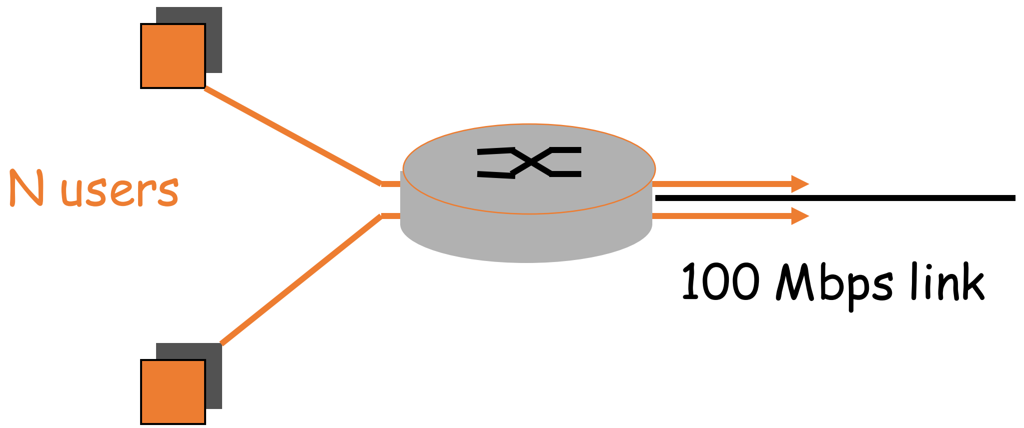
Each end-end data stream divided into *packets*

- User A, B packets *share* network resources
- Each packet uses full link bandwidth
- Resources used *as needed*

- Resource contention
- Aggregate resource demand can exceed amount available
- Congestion: packets queue, wait to use link
- Store and forward: packets move one hop at a time
  - transmit over link
  - wait turn at next link

Packet switching versus circuit switching

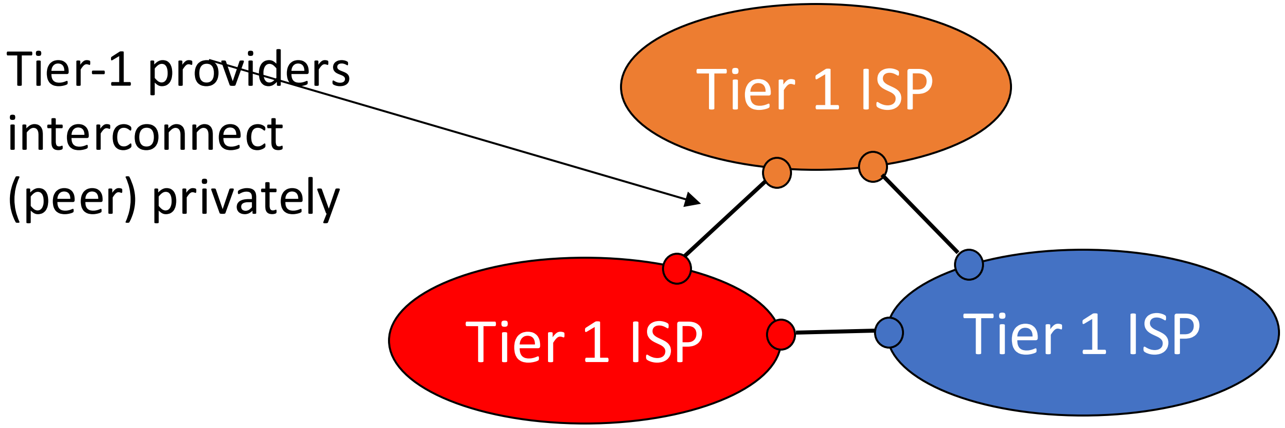
- 100 Mb/s link
- each user:
  - 10 Mb/s when “active”
  - active 10% of time
- Circuit-switching:
  - 10 users
- Packet switching:
  - with 35 users, probability > 10 active less than .0004



Packet switching allows more users to use network!

Internet structure: network of networks

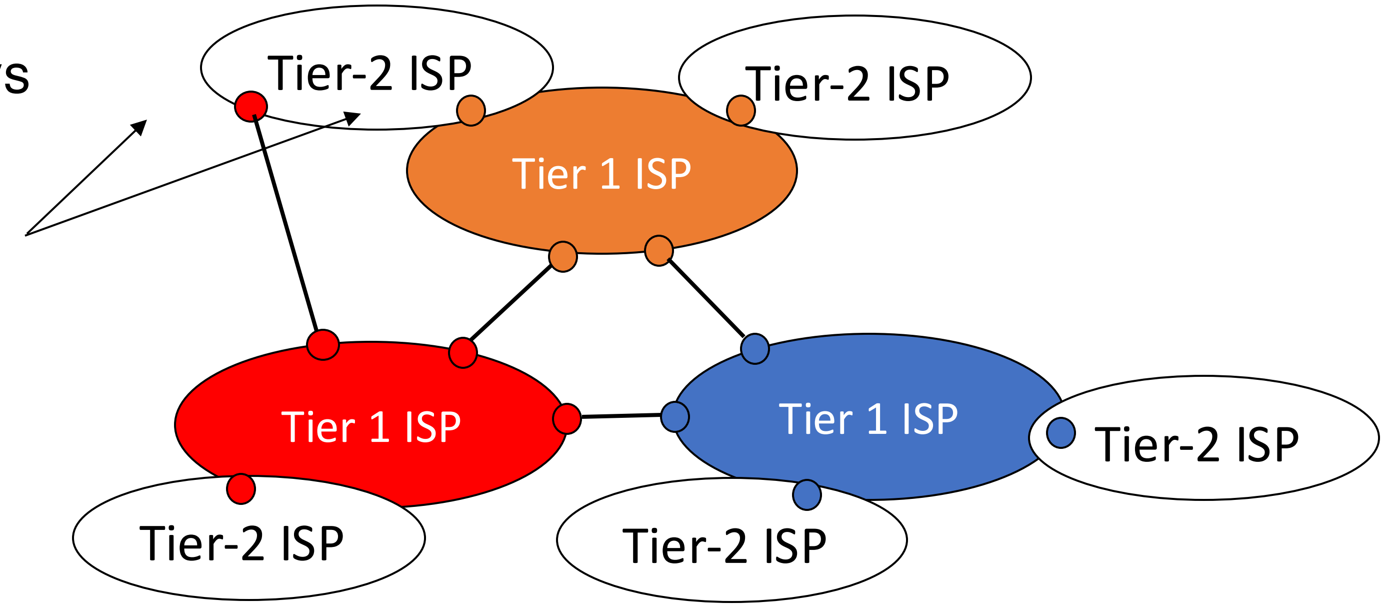
- Roughly hierarchical
- At center: "tier-1" ISPs (e.g., Verizon, Sprint, AT&T, Level 3), national/international coverage
  - treat each other as equals



Internet structure: network of networks

- "Tier-2" ISPs: smaller (often regional) ISPs
  - connect to one or more tier-1 ISPs, possibly other tier-2 ISPs

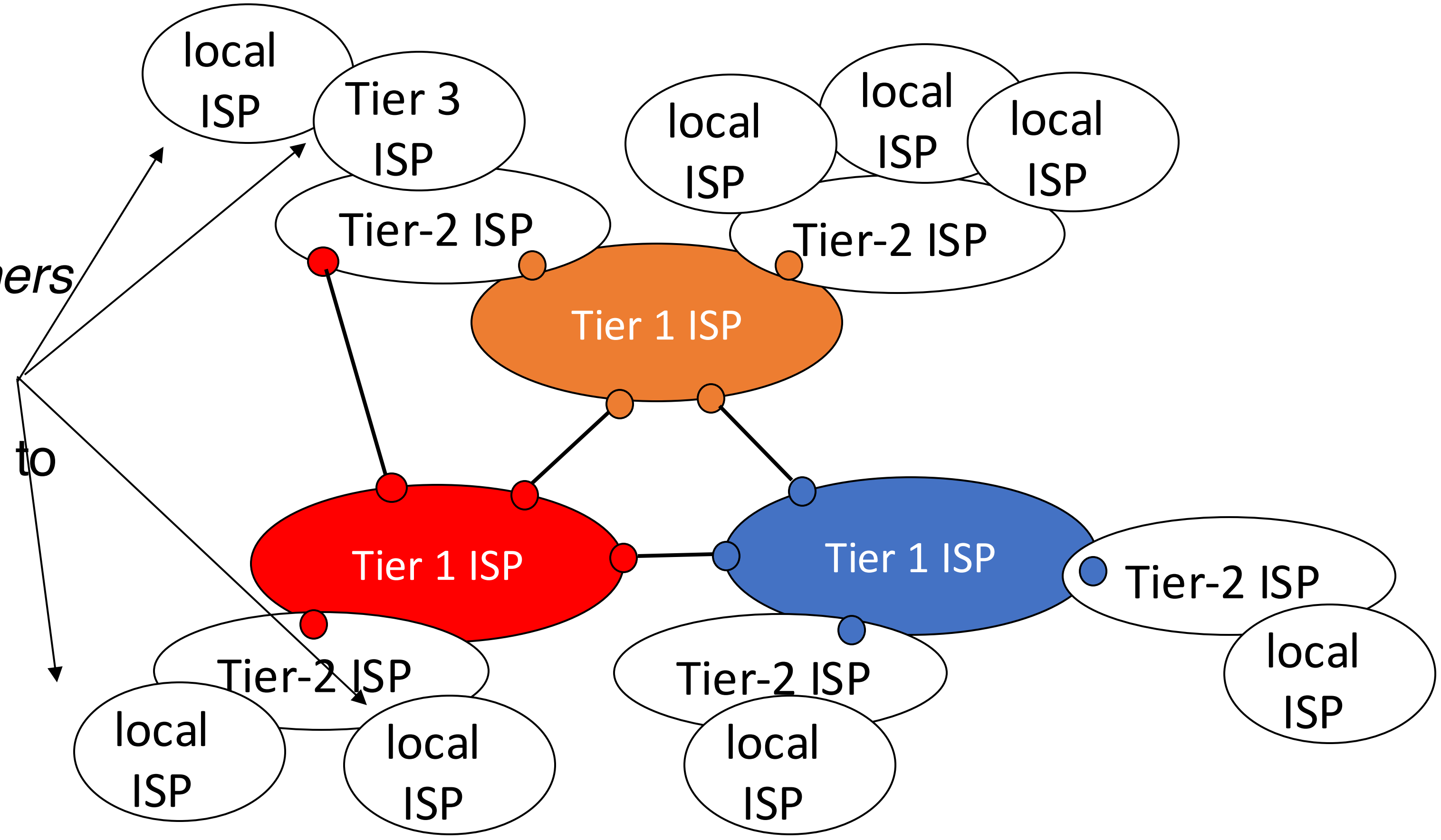
- tier-2 ISP pays tier-1 ISP for connectivity to rest of Internet
- tier-2 ISP is *customer* of tier-1 provider



Internet structure: network of networks

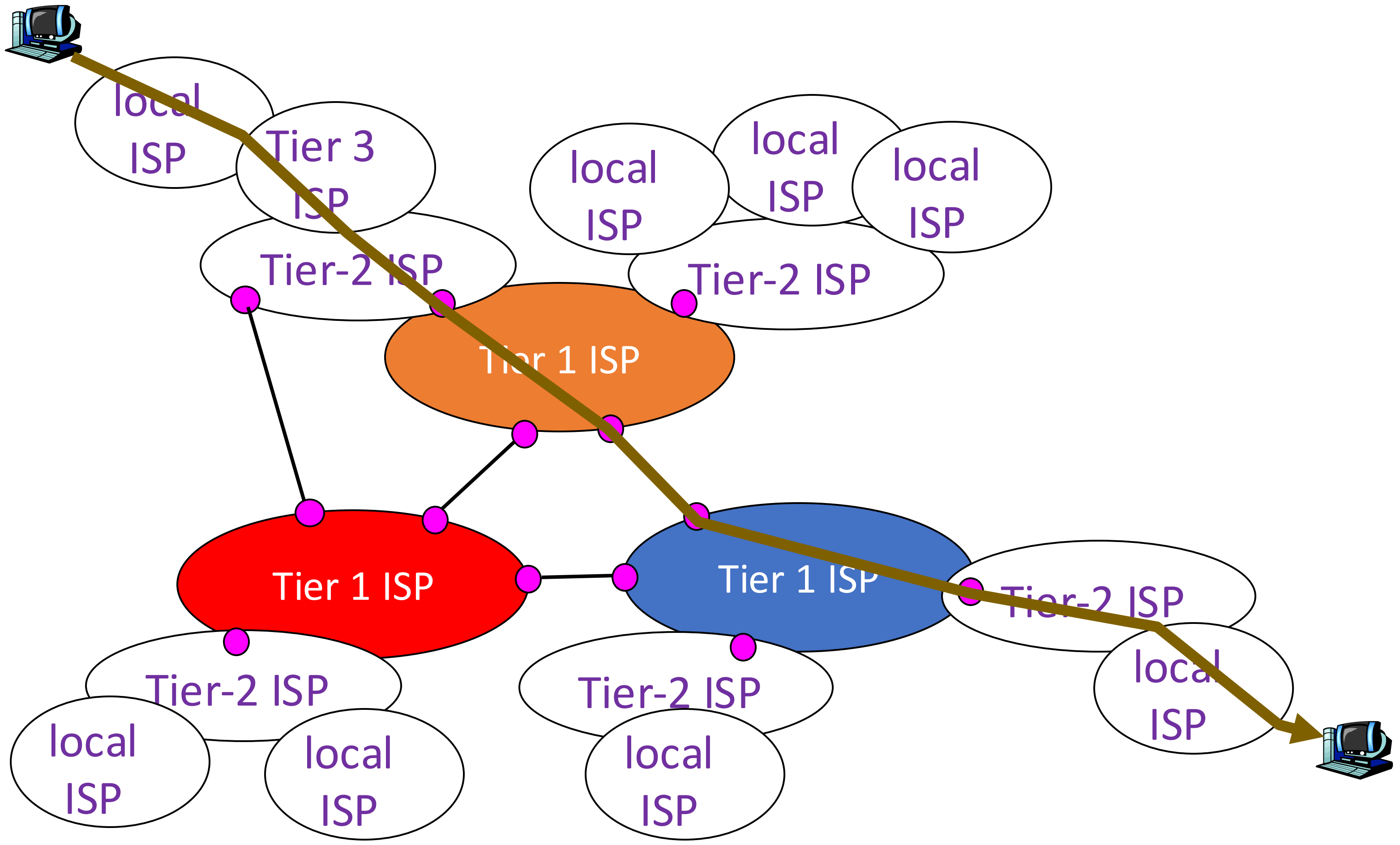
- “Tier-3” ISPs and local ISPs
  - last hop (“access”) network (closest to end systems)

Local and tier- 3 ISPs are *customers* of higher tier ISPs connecting them to rest of Internet



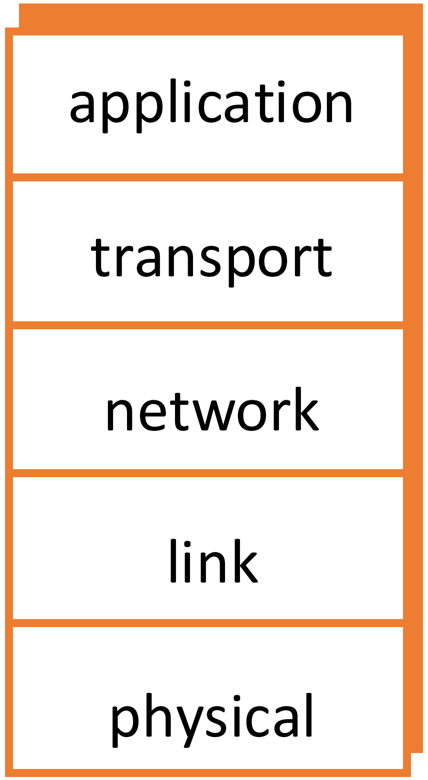
Internet structure: network of networks

- a packet passes through many networks!



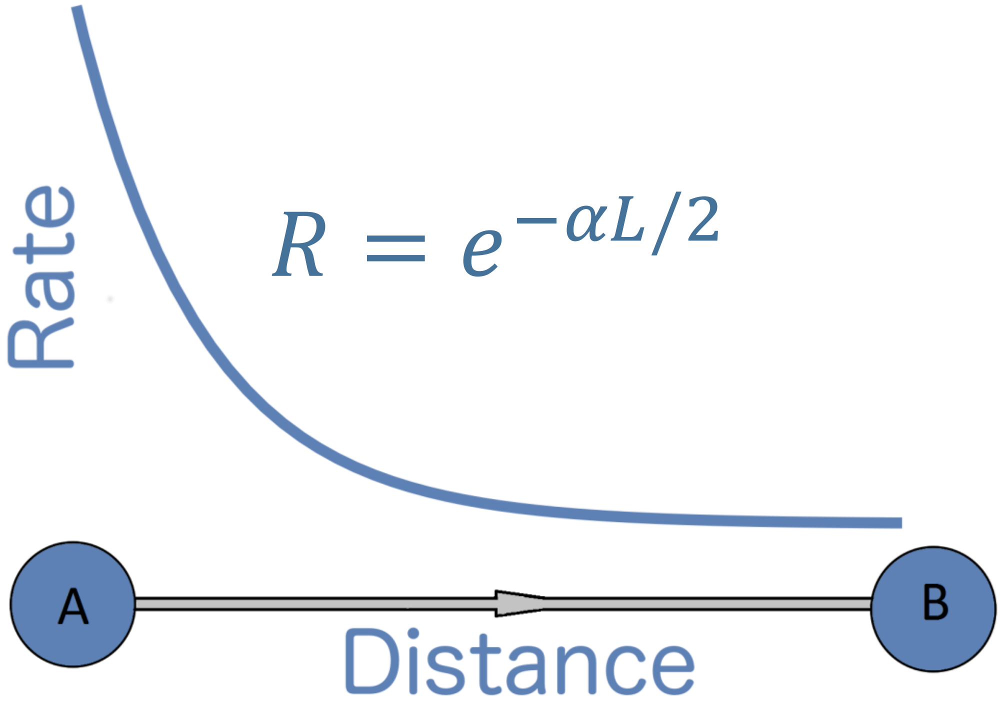
Internet protocol stack

- Application: supporting network applications
  - scp, smtp, https
- Transport: host-host data transfer
  - tcp, udp
- Network: routing of packets from source to destination
  - ip, routing protocols
- Link: data transfer between neighboring network elements
  - ppp, ethernet
- Physical: bits “on the wire”



Quantum Networks

Why is quantum communications so hard?



Rate decays exponentially with distance

No cloning theorem precludes copy and amplification

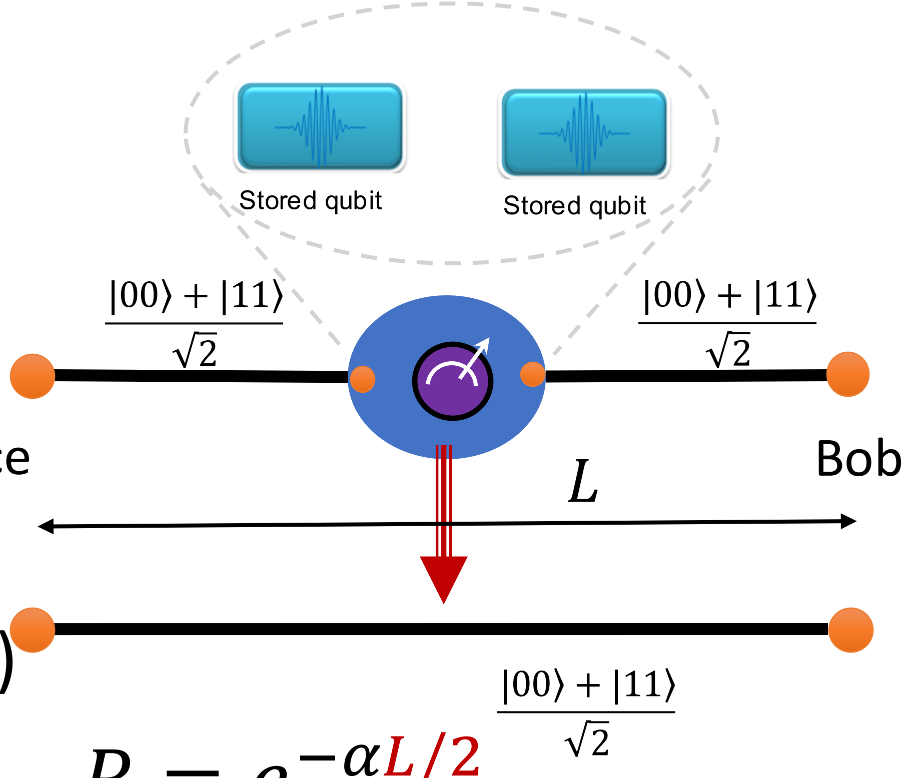
Quantum repeaters

Quantum memories to store qubits

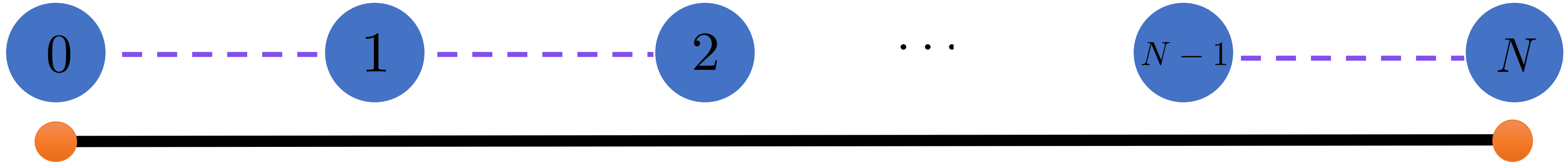
Phase I: generate link Bell states (entanglement)

Phase II: propagate entanglements

entanglement swap (Bell state measurement)

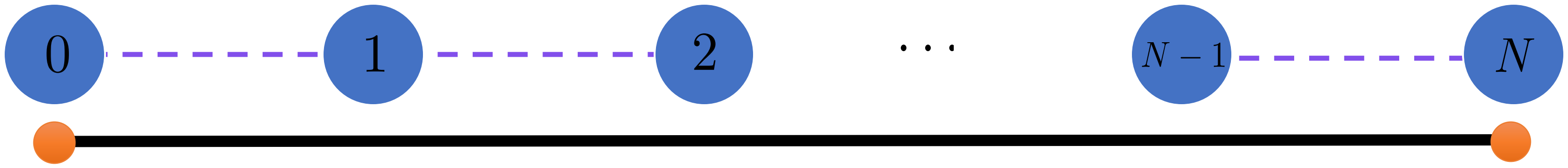


$$R = e^{-\alpha L/2}$$



$$R \propto e^{-\alpha L/N}$$

Repeater chain



- Infinite memory ⇒ distance independent entanglement rate

$$R \propto e^{-\alpha L/N}$$

- Finite (one) memory ⇒ exponential decay in entanglement rate as function of L

$$R \propto e^{-\alpha L}$$

Quantum Internet

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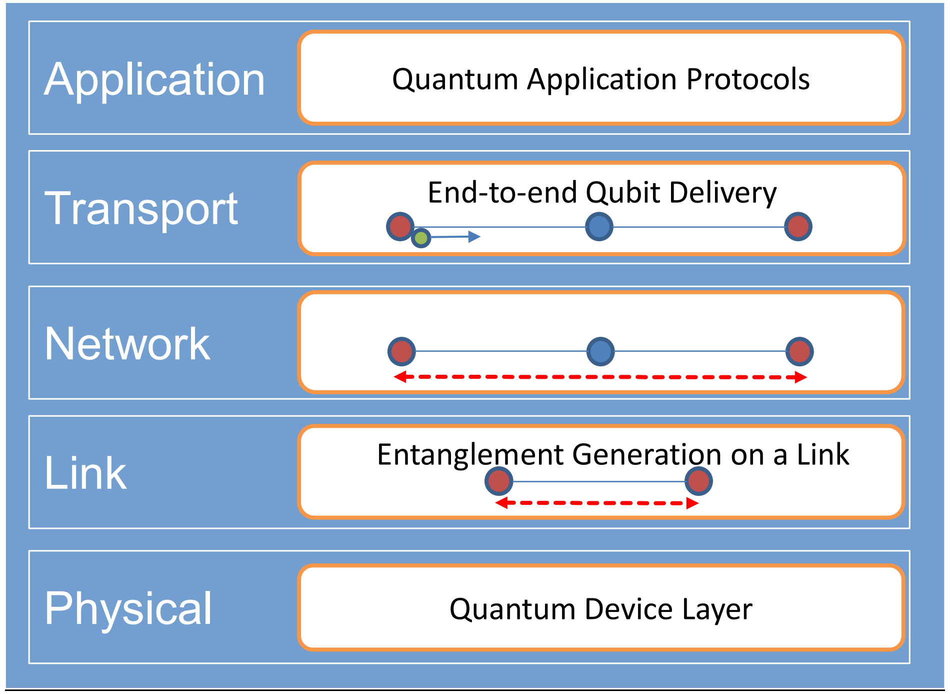
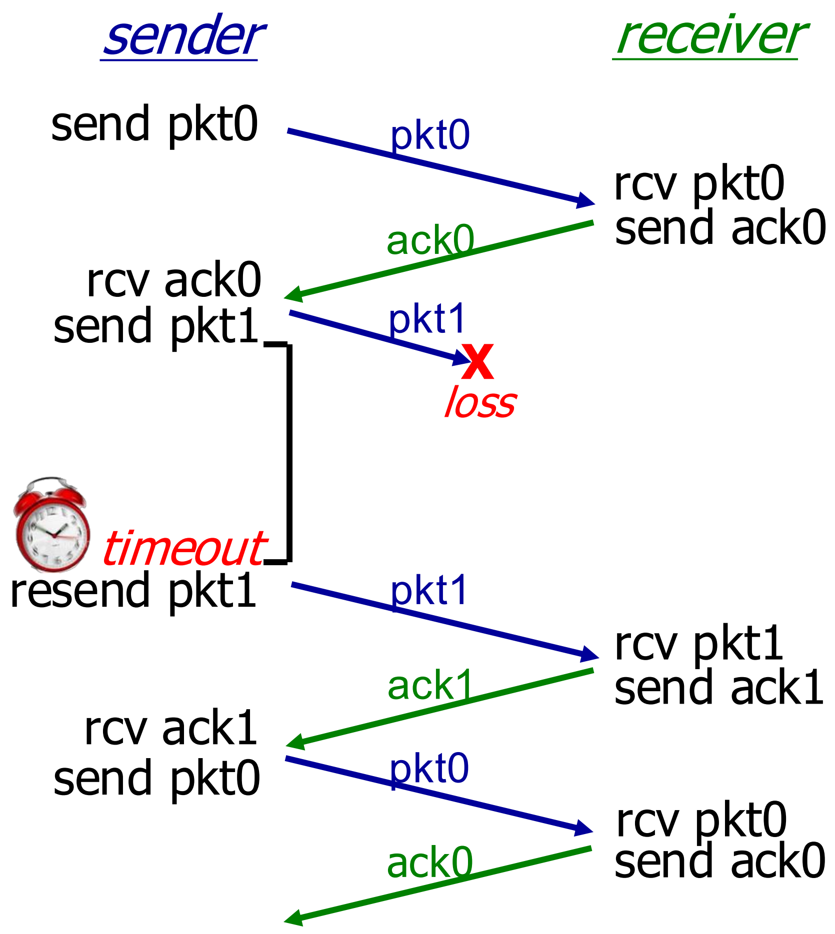
- Application: supporting network applications
- Transport: host-host quantum data transfer
  - qtcp, qudp
- Network: entanglement generation between end nodes
  - qip, path selection protocols
- Link: link-level entanglement generation
- Physical: photons "on the wire"



Stephanie Wehner et al.

Reliable communications (classical)

- Error models:
  - bit flips, erasures
  - *dropped packets*
- Recovery schemes
  - error detection/correction codes
  - packet retransmission
    - *relies on cloning!*



Reliable communications (quantum)

- Errors (non-exhaustive):
  - Models: Pauli channels, erasures, amplitude damping,…
  - Gate noise
  - Memory decoherence
  - Transduction
  - Loss in optical components
  - Collection efficiency
  - Probabilistic operations

- Recovery schemes
  - Quantum error correction (one-way)
  - Distillation
  - Data retransmission (one-way)
    - *Source must regenerate!*
  - Attempt until succeed (two-way)
    - *Two-way retransmission*

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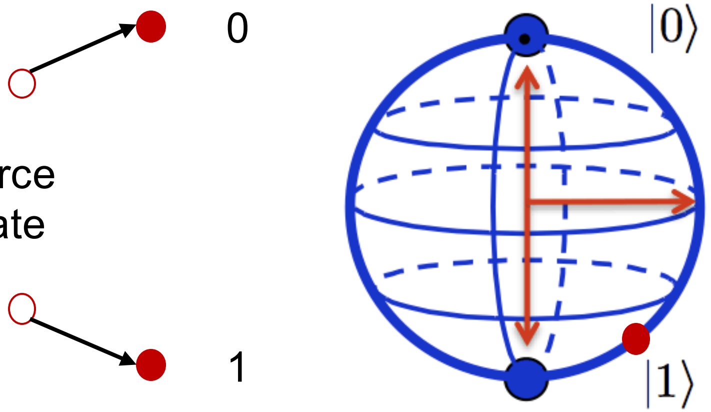
Quantum challenge

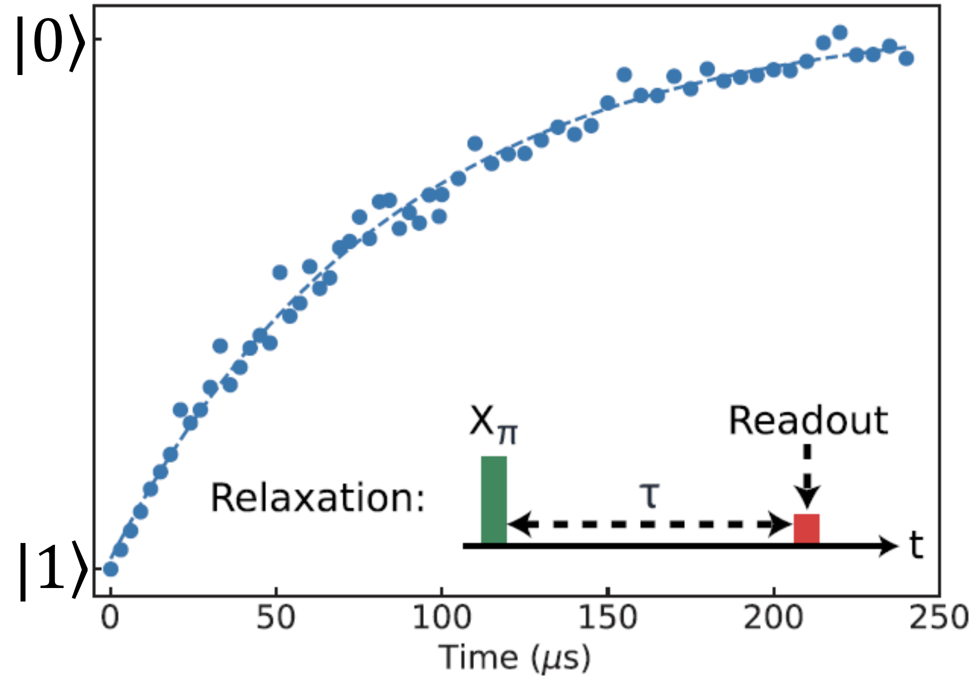
- Qubits not self protected against smallest perturbation



Restoring force stabilizes state

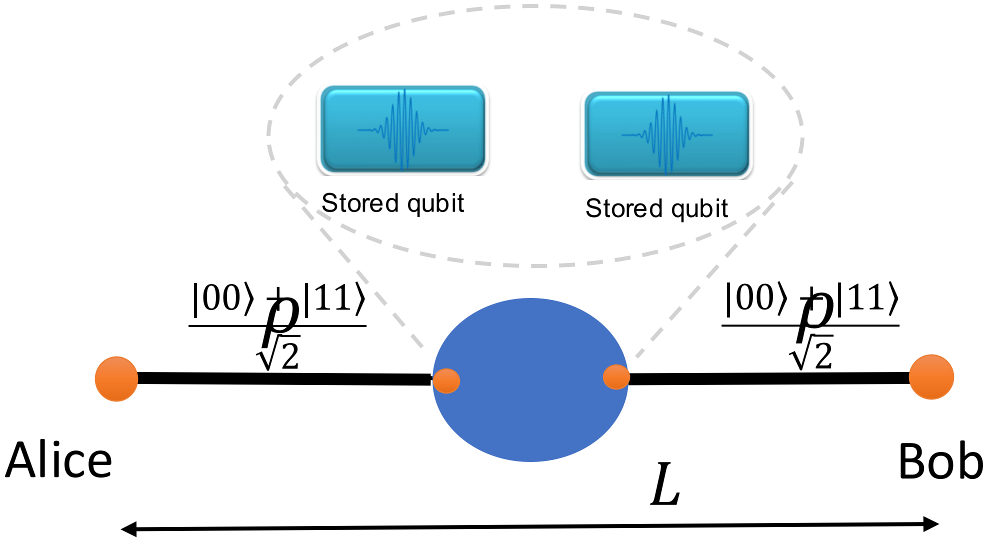
Restoring force towards 0 or 1 not allowed

- Qubits have limited coherence times



P. Krantz, etal, Appl. Phys. Rev. 6, 021318 (2019)

Imperfect Entangled States



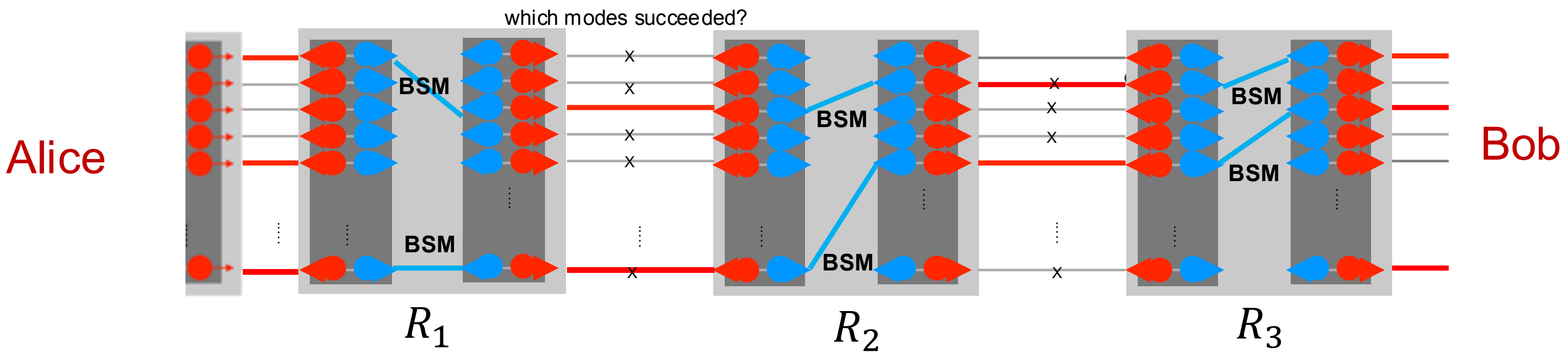
- Noise introduced thru comms
- Bell states decohere

Fidelity: measure of closeness between two quantum states

Entanglement fidelity is fidelity between ρ and $\frac{|00\rangle+|11\rangle}{\sqrt{2}}$

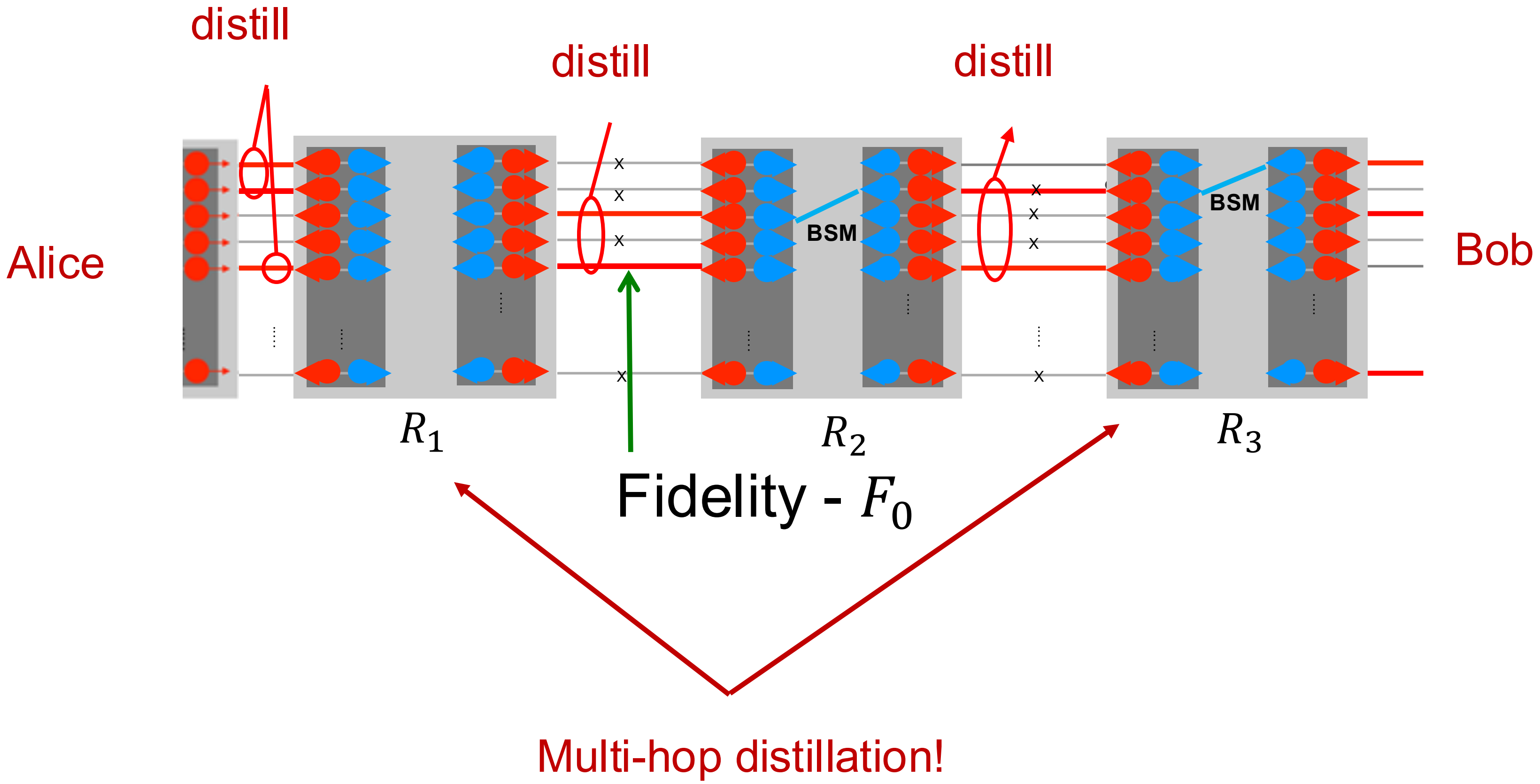
Multiplexed linear repeater network

- Parallel attempts performed at each link

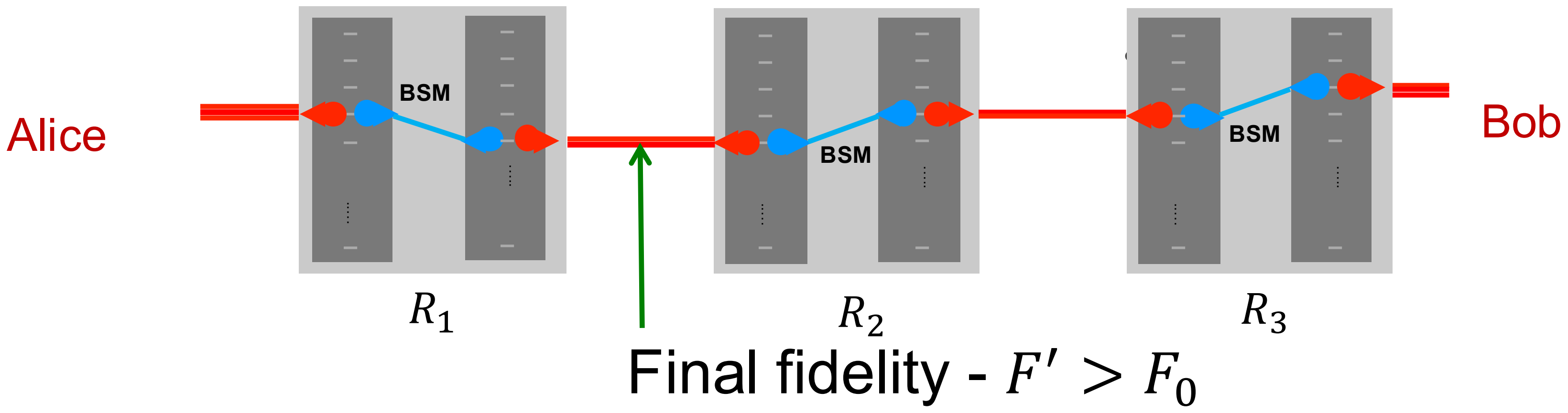


- Multiplexing increases rate
- Provides opportunity for distillation

Distillation



Distillation



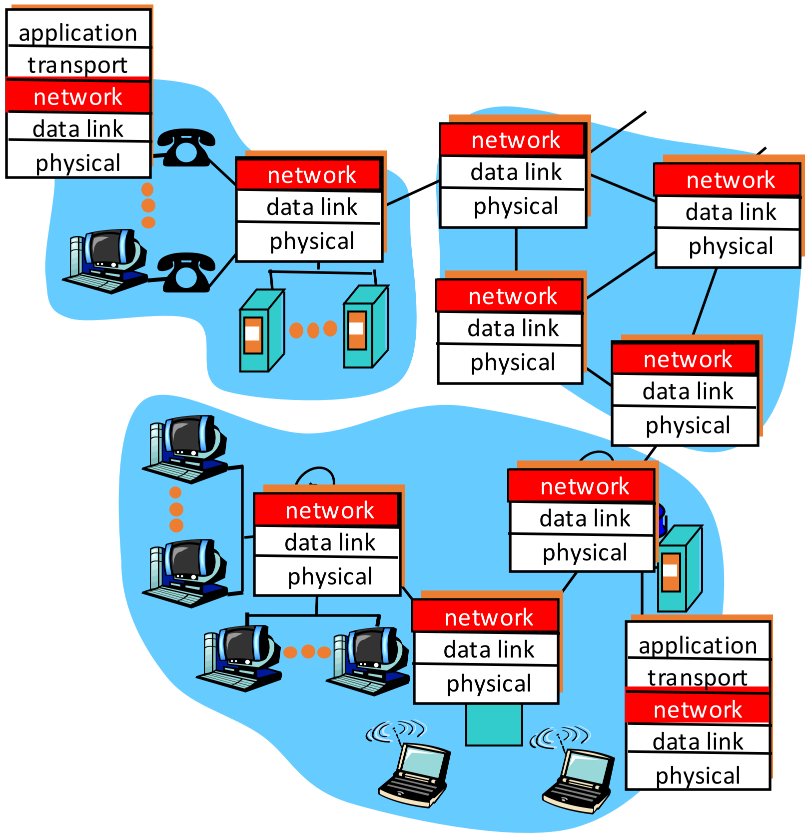
- Determine when and how much to distill
- Whether to distill across single or multiple links
- Possibly with minimum e2e fidelity constraint

Network layer functions

- Transport packet from sending to receiving hosts
- Network layer protocols in *every* host, router

Three important functions:

- *Path selection:* route taken by packets from source to destination (routing algorithms)
- *Switching:* move packets from router's input to appropriate router output
- *Call setup:* some network architectures require router call setup along path before data flows



Network service model

CRUCIAL question!

Q: What *service model* for "channel" transporting packets from sender to receiver?

service abstraction

- guaranteed bandwidth?
- preservation of inter-packet timing (no jitter)?
- loss-free delivery?
- in-order delivery?
- congestion feedback to sender?

The most important abstraction provided by network layer:

virtual circuit or datagram?

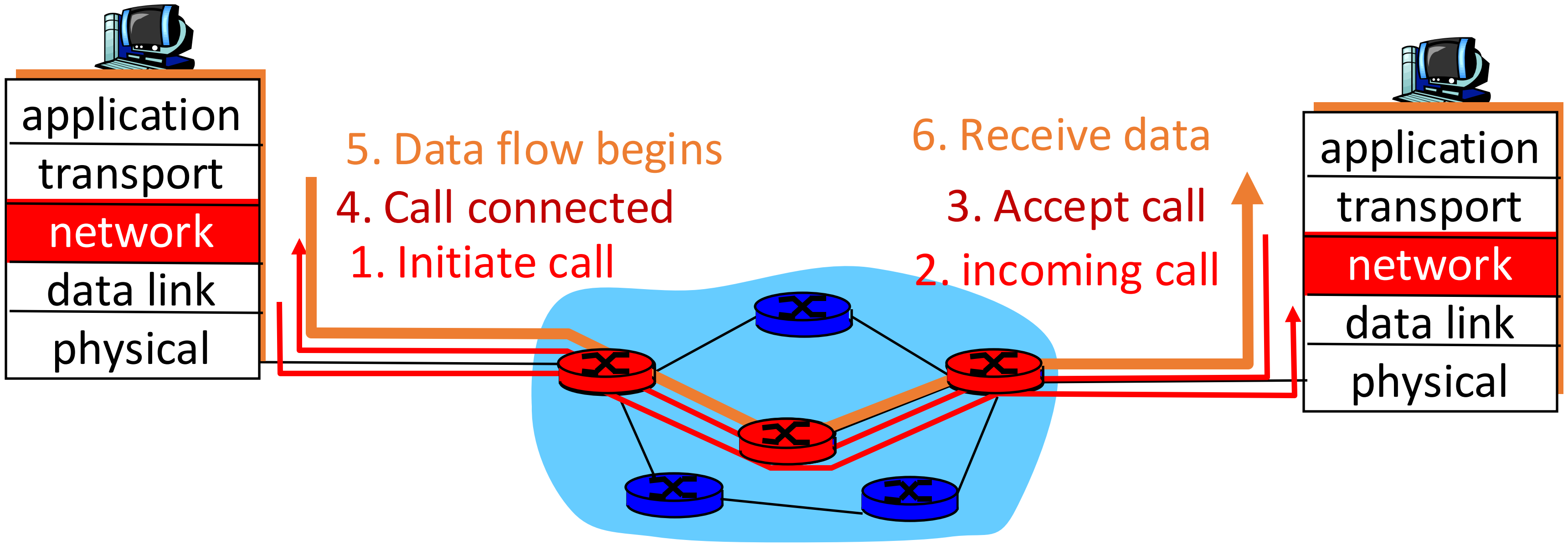
Virtual circuits

"source-to-dest path behaves like telephone circuit"

- performance-wise
- network actions along source-to-dest path

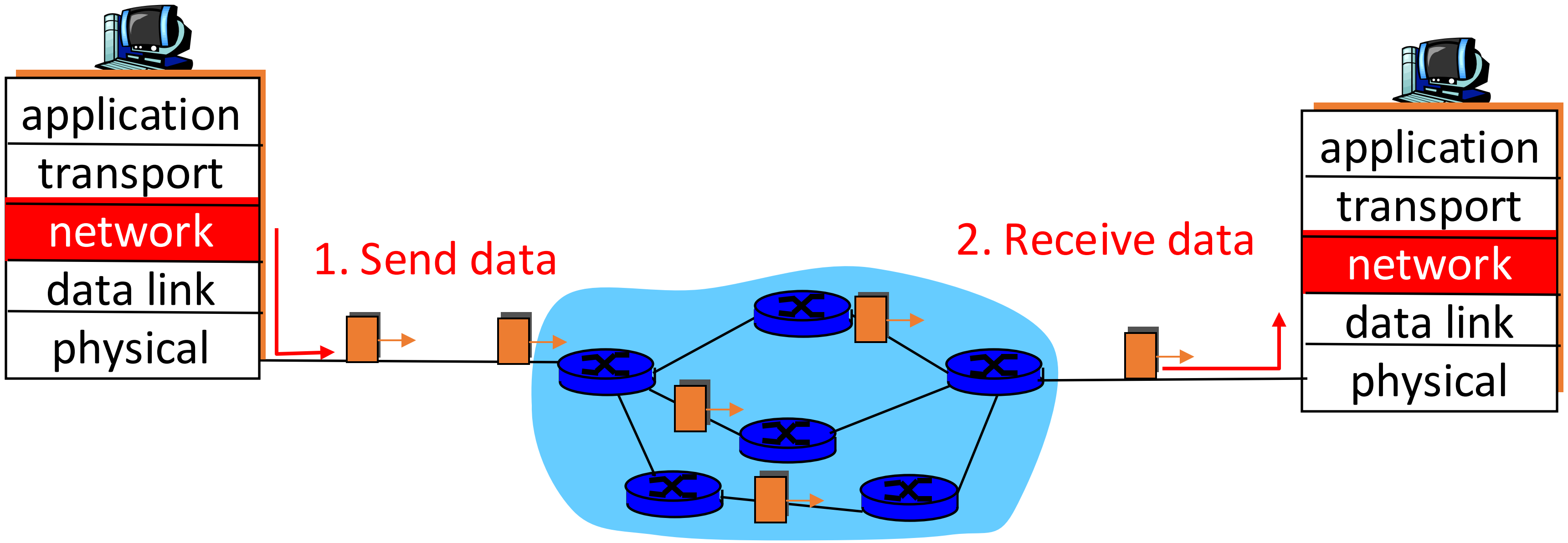
- Call setup, teardown for each call *before* data can flow
- Each packet carries VC identifier (not destination host ID)
- *Every* router on source-dest path maintains "state" for each passing connection
  - transport-layer connection only involved two end systems
- Link, router resources (bandwidth, buffers) may be *allocated* to VC
  - to get circuit-like performance

Virtual circuits in practice



Datagram network: The Internet model

- No call setup at network layer
- Routers: no state about end-to-end connections
  - no network-level concept of “connection”
- Packets typically routed using destination host ID
  - packets between same source-dest pair may take different paths



Quantum network service model

CRUCIAL question!

Q: What *service model* for "quantum channel" between end nodes?

service abstraction

- guaranteed rate?
- latency guarantee?
- minimum fidelity guarantee?

The most important abstraction provided by network layer:

entanglement generation

or

quantum information transmission

? ? ?

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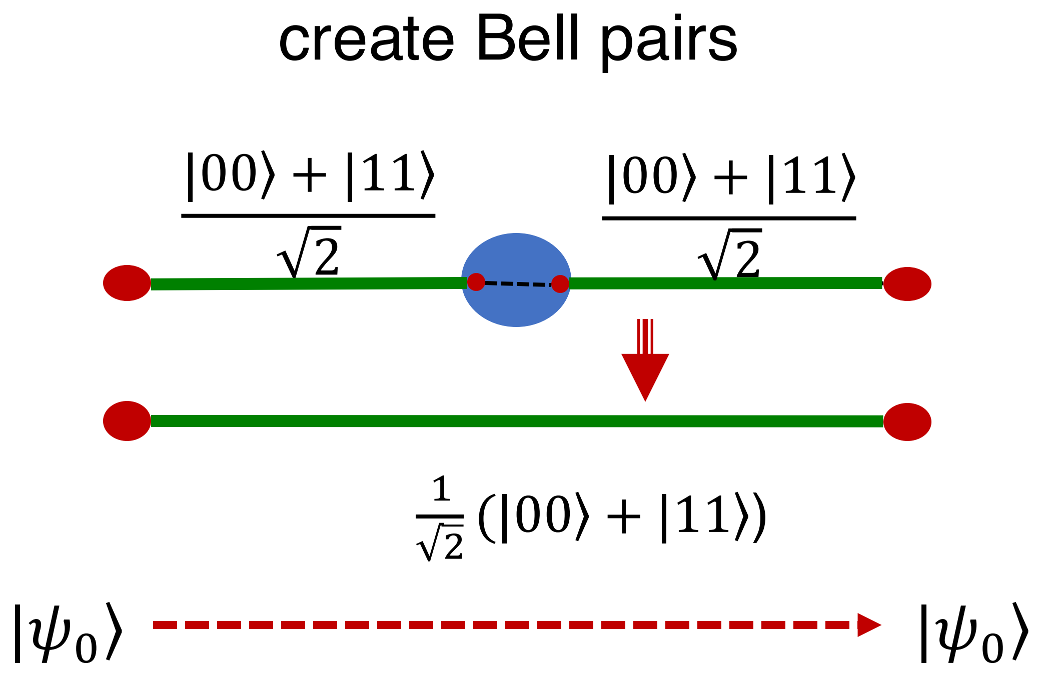
Entanglement distribution

(Two-way network architecture)

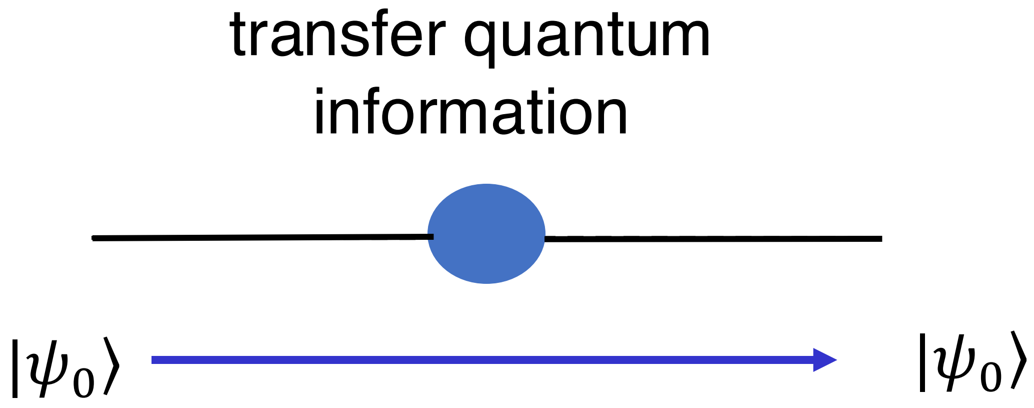
- Creation/distribution of Bell pairs (entanglement)
- Use teleportation to transfer quantum information
- Relies heavily on distillation to handle noise
- Requires exchange of classical information for correction



Quantum information transfer

(One-way network architecture)

- Transfer quantum information directly
- Note resemblance to classical network
- Relies heavily on Quantum Error Correction (QEC)
- Does not require exchange of classical info



Note: services are interchangeable

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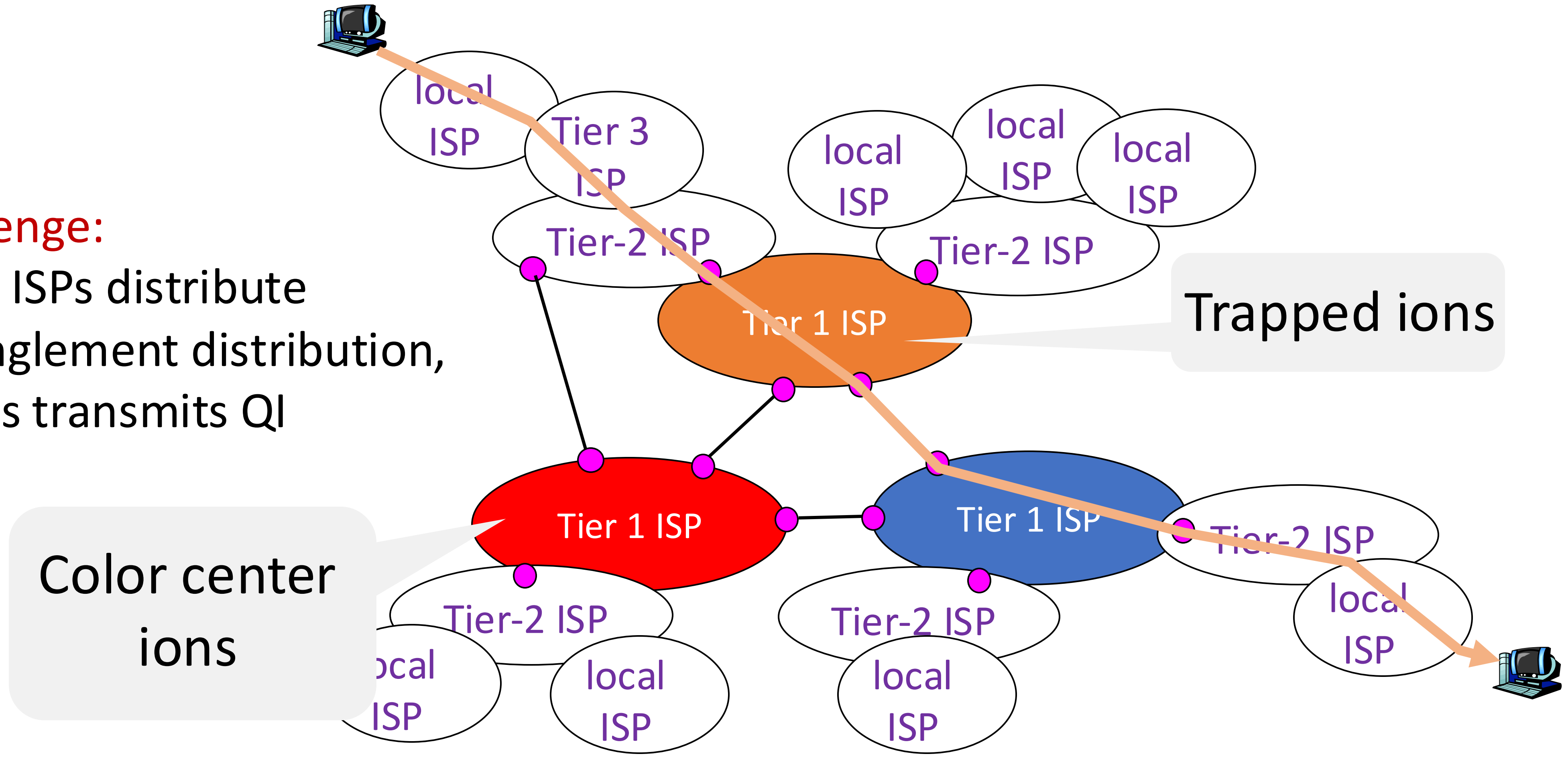
Quantum Internet

- Quantum information can pass through many networks!
- e2e entanglement over many networks



Challenge:
some ISPs distribute entanglement distribution, others transmits QI

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One way vs. Two way

Two way

Pros:

- Distillation simpler than QEC
- Bell pairs fungible ⇒
  - high rates
  - pre-shared entanglement
- Tolerates noisy gates

Cons:

- Increased latency due to classical comms
- High memory requirement

One way

Pros:

- No classical comms ⇒ low latency
- Low memory requirement
- Allows for pre-sharing entanglement

Cons:

- QEC very challenging, requires high quality gates
  - 100 physical qubits per logical qubit?
- Requires many high quality gates
- May require more q-repeaters

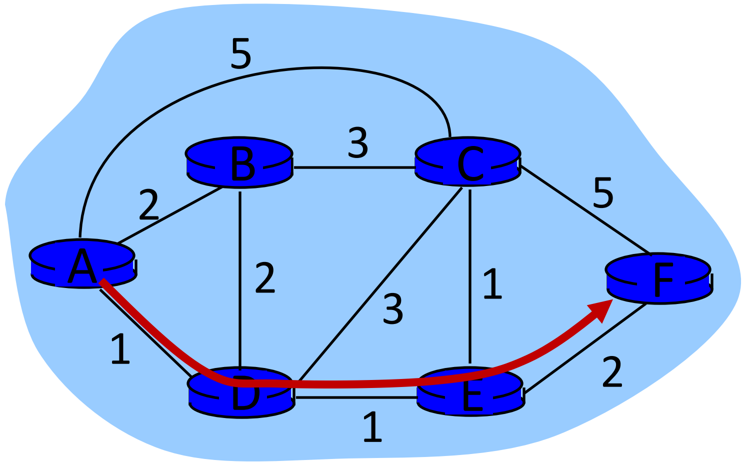
Muralidharan, Sreraman, et al. "Optimal architectures for long distance quantum communication." *Scientific reports* 6.1 (2016): 20463.

Mantri, Prateek, Kenneth Goodenough, and Don Towsley. "Comparing One-and Two-way Quantum Repeater Architectures." *arXiv preprint arXiv:2409.06152* (2024).

Classical routing

Routing protocol

Goal: determine "good" path (sequence of routers) thru network from source to dest.



Graph abstraction for routing algorithms:

- graph nodes are routers
- graph edges are physical links
  - link cost: delay, $ cost, or congestion level

"good" path:

- typically means minimum cost path
- other def's possible
- Dijkstra algorithm

Routing algorithm classification

Q: global or decentralized information?

global:

- central controller has complete topology, link cost info

Decentralized:

- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- "distance vector" algorithms

Q: static or dynamic?

static:

- routes change slowly over time

Dynamic:

- routes change more quickly
  - periodic update
  - in response to link cost changes

Current approach

- (Logical) central controller with complete topology, link cost info
- Includes policy constraints
  - e.g., party A cannot use link set $\mathcal{L}$
- Calculation of backup paths
- Diversity for load balancing

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Quantum routing

Static algorithms:

- shortest paths with link costs:
  - link entanglement rate, $1/R_l$
  - link fidelity, F_l
  - and others

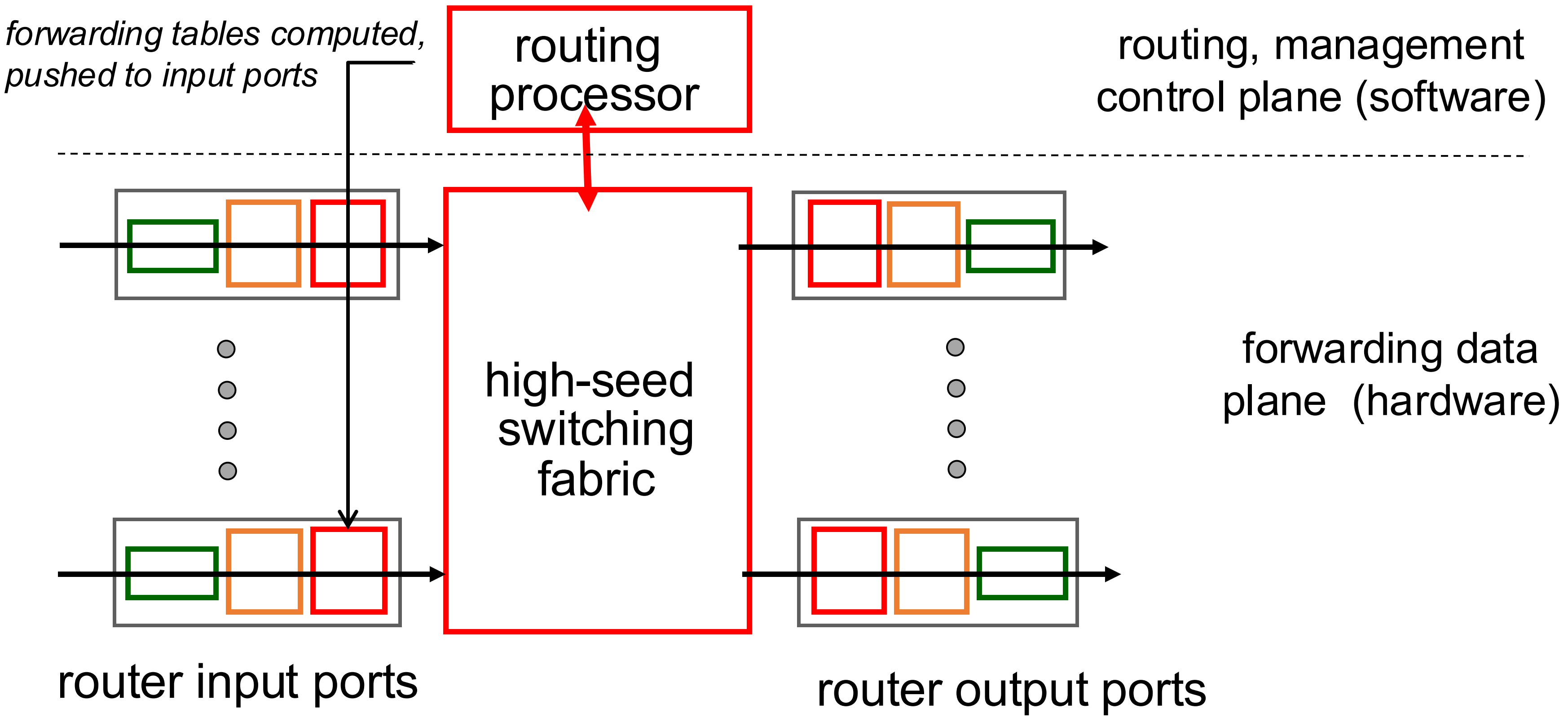
Dynamic algorithms:

- each node chooses neighbors to connect based on local state information

Classical router architecture overview

two key router functions:

- run routing algorithms/protocol
- *forwarding* packets from incoming to outgoing link



Questions

- capacity of router?
- scheduling policies that achieve capacity? that reduce switching fabric complexity?
  - matching algorithms
  - max weight policies
  - lightweight randomized algorithms

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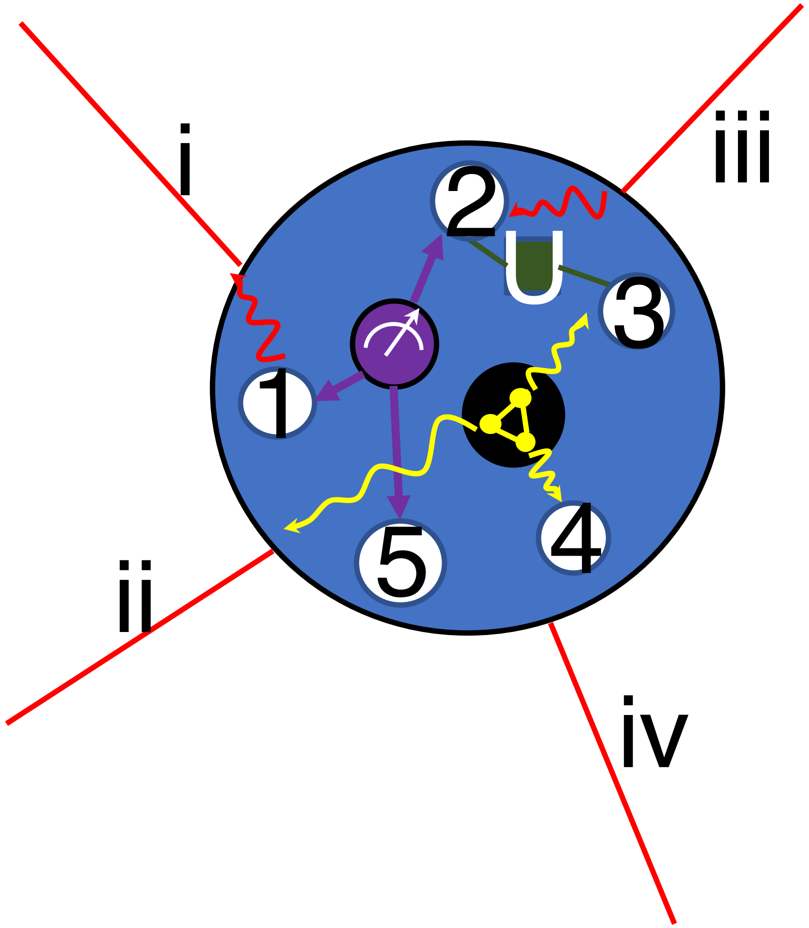
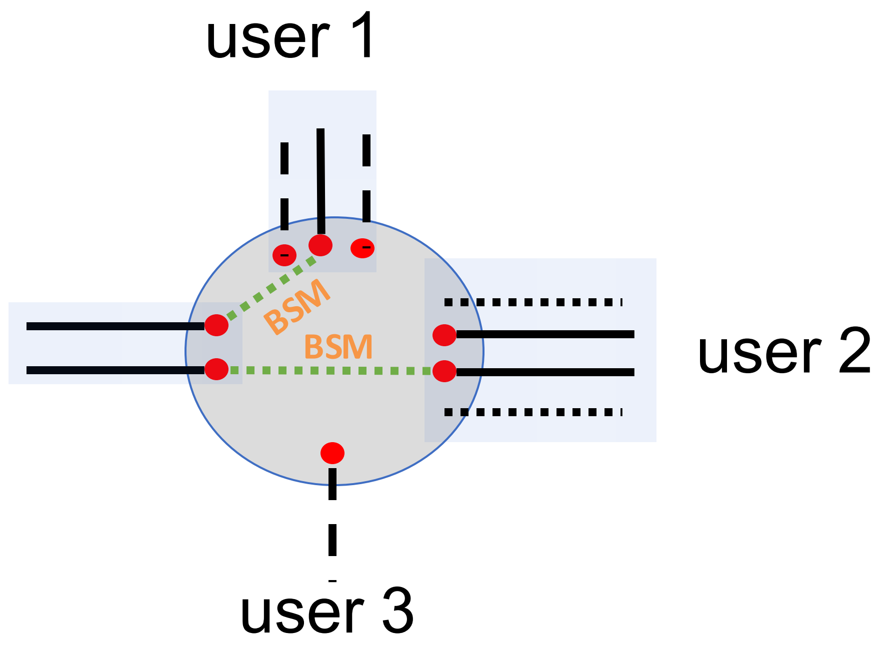
Two-way Quantum switch

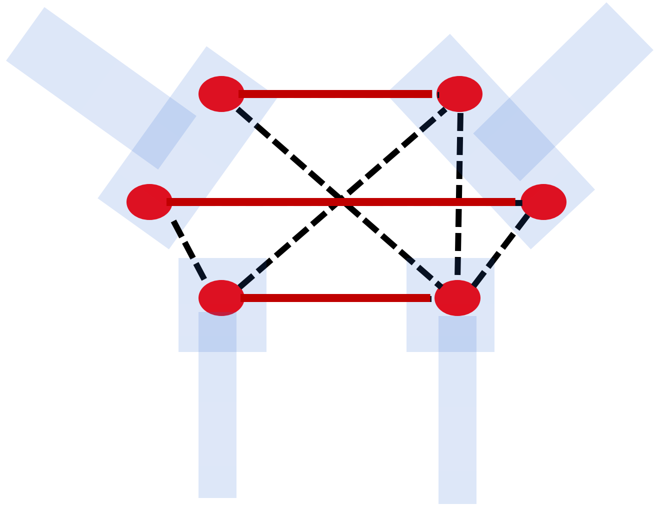
- Quantum memories: loading and readout
- Multi-qubit quantum measurements
- Quantum logic across qubits held in QMs
- Multi-photon entanglement sources
- Classical processing and communications



Quantum switch

- User pairs generate requests for Bell pairs
- Phase 1: links randomly generate Bell pairs
- Phase 2: given outstanding requests, switch selects Bell pairs to measure
    - equivalent to selecting eligible matching in a graph among memories
- Outcomes of BSM matchings form set of end-to-end entanglements between pairs of end nodes





Challenges

- switch design, switching fabric
  - teleportation fabric?
- network capacity, network resource allocation
  - global vs local vs no state information
  - timescale of state information

$\Rightarrow$ (virtual) circuit switching?

- memory decoherence, gate errors?
- quality of information – fidelity
  - fidelity degrades over time $\Rightarrow$ youngest qubit first (YQF), deadline scheduling?

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Summary

- entanglement distribution service very different from quantum information transfer service

- quantum networking introduces new problems

  … and old problems with new wrinkles

  - resource allocation, path selection, switch & entanglement scheduling
  - delivery of QoS in very noisy environment

Scheduling in repeater chains

Focus on two-way

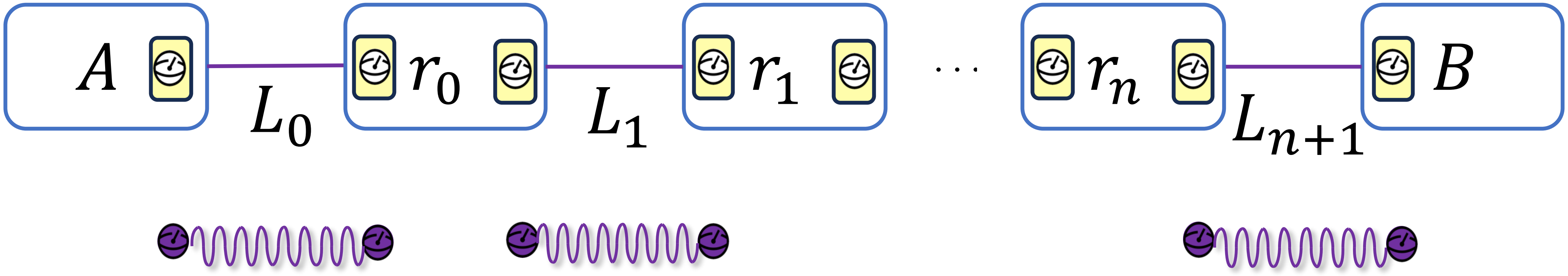
Distribution over a chain

How to generate entanglement between end-nodes?

When to generate link-level entanglement?

When to perform entanglement swapping?

Swaps commute



Assume all LLEG succeeded

BSMs commute with each other

Any swapping ordering distributes e2e entanglement!

Swap can be performed in parallel!

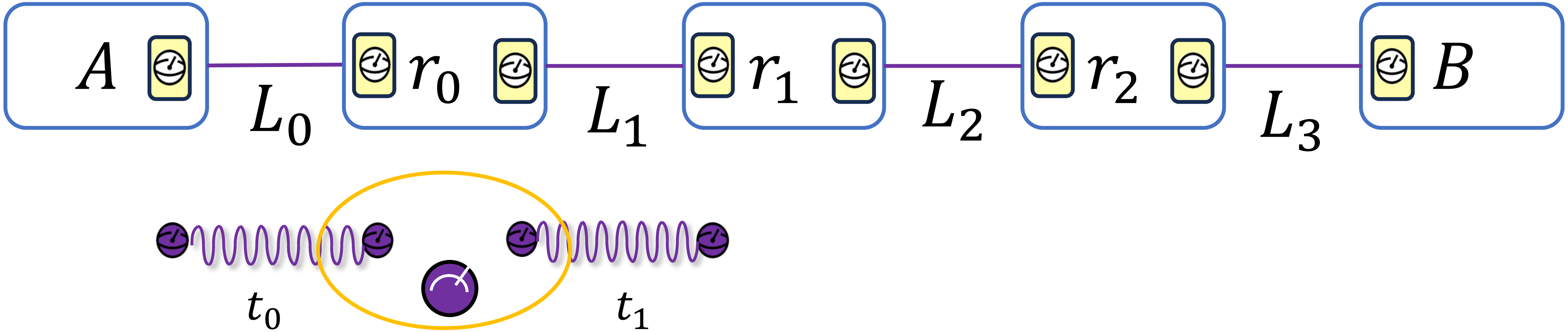
Swap order has profound impacts for performance, architecture and protocol design!

SWAP Policies

1. Sequential Swap
2. Swap As Soon As Possible (ASAP)
3. Nested swap

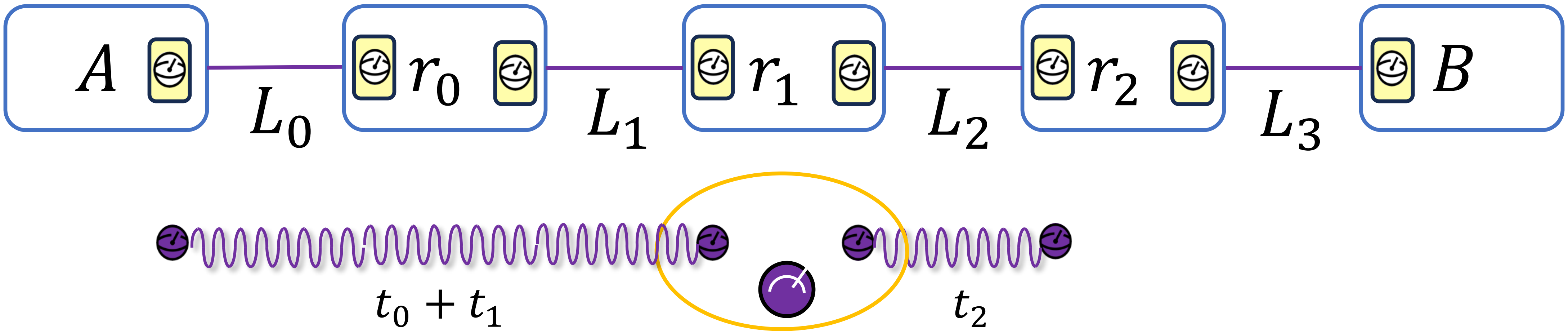
Assume deterministic swaps

Sequential Swap



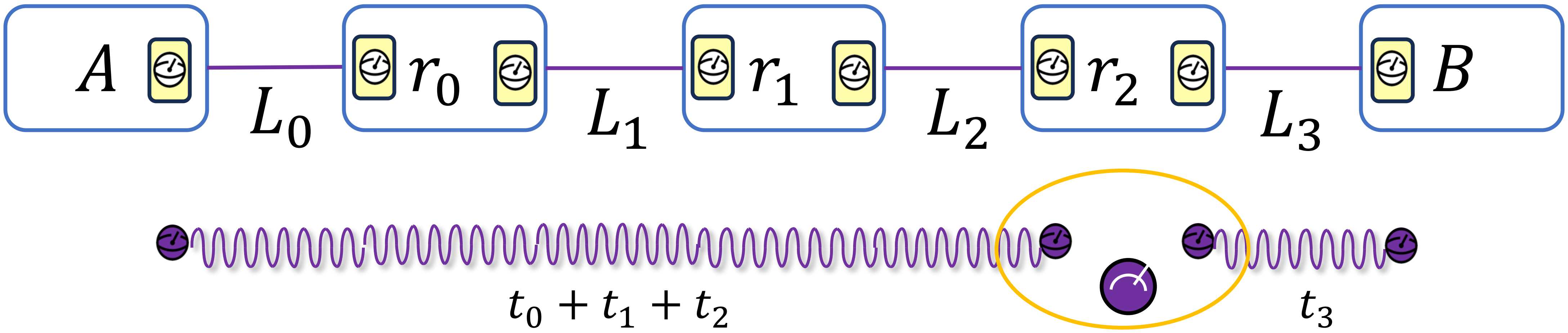
1. A starts LLEG r_0
2. Once succeeded, r_0 starts LLEG with r_1
3. BSM performed in r_0

Sequential Swap



1. A starts LLEG r_0
2. Once succeeded, r_0 starts LLEG with r_1
3. BSM performed in r_0
4. r_i repeats the process until B reached

Sequential Swap



1. A starts LLEG r_0
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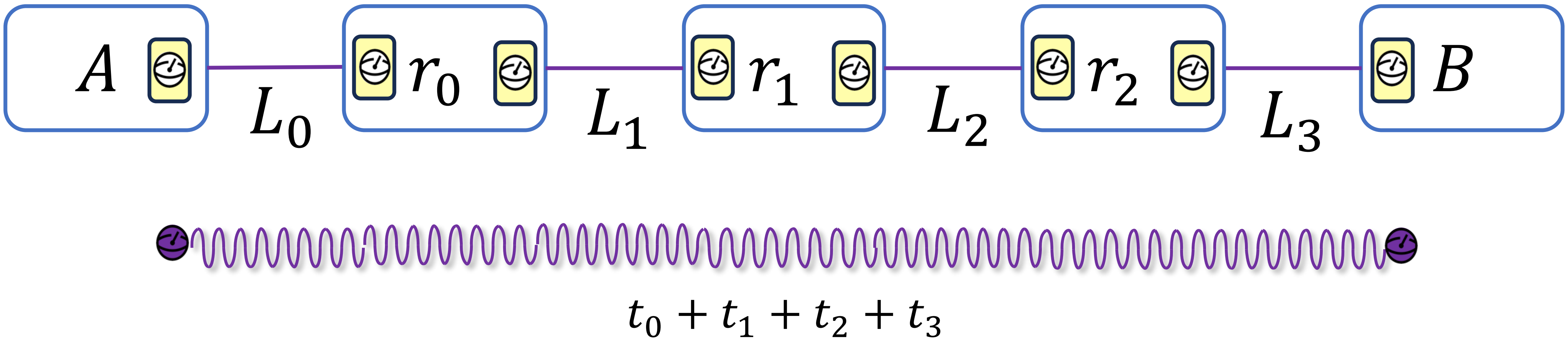
Sequential Swap



1. A starts LLEG r_0
2. Once succeeded, r_0 starts LLEG with r_1
3. BSM performed in r_0
4. r_i repeats the process until B reached
5. Latency is $O(n)$ where n is number of repeaters

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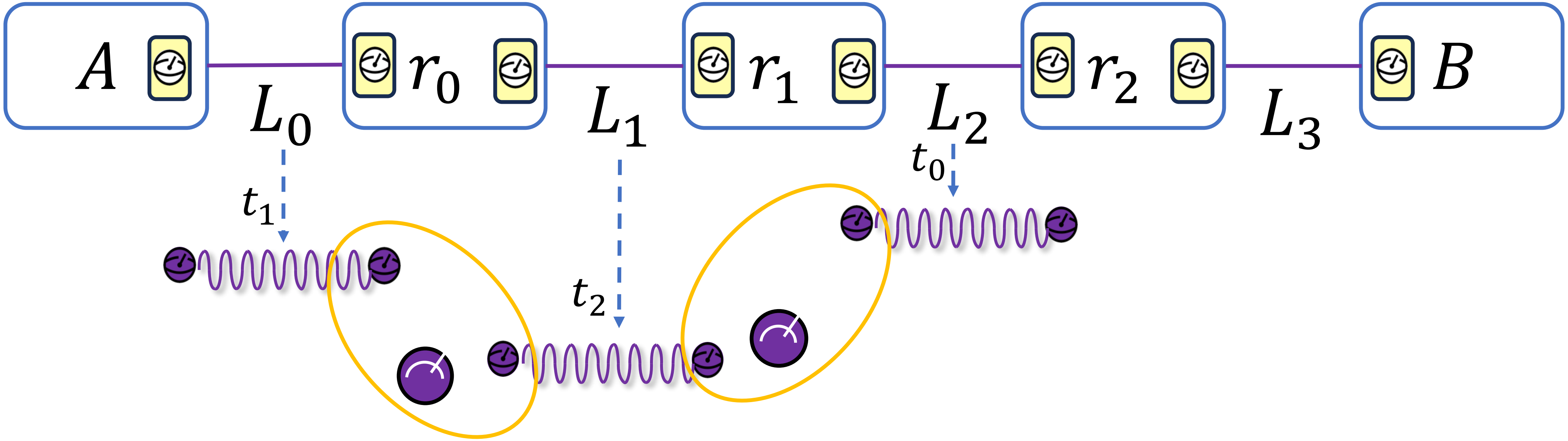
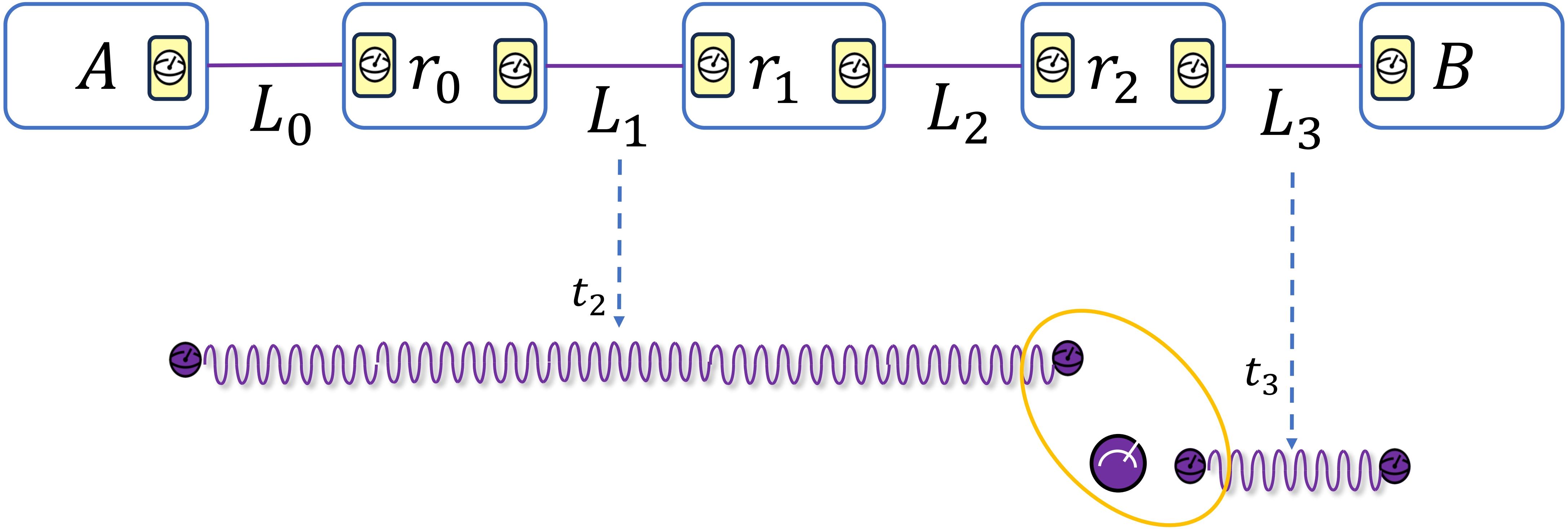
Swap ASAP



$t_2 \geq t_1 \geq t_0$

1. LLEG starts simultaneous on every link
2. Perform swap as soon as two links available
3. Stop when all repeaters swap

Swap ASAP



1. LLEG starts simultaneous on every link
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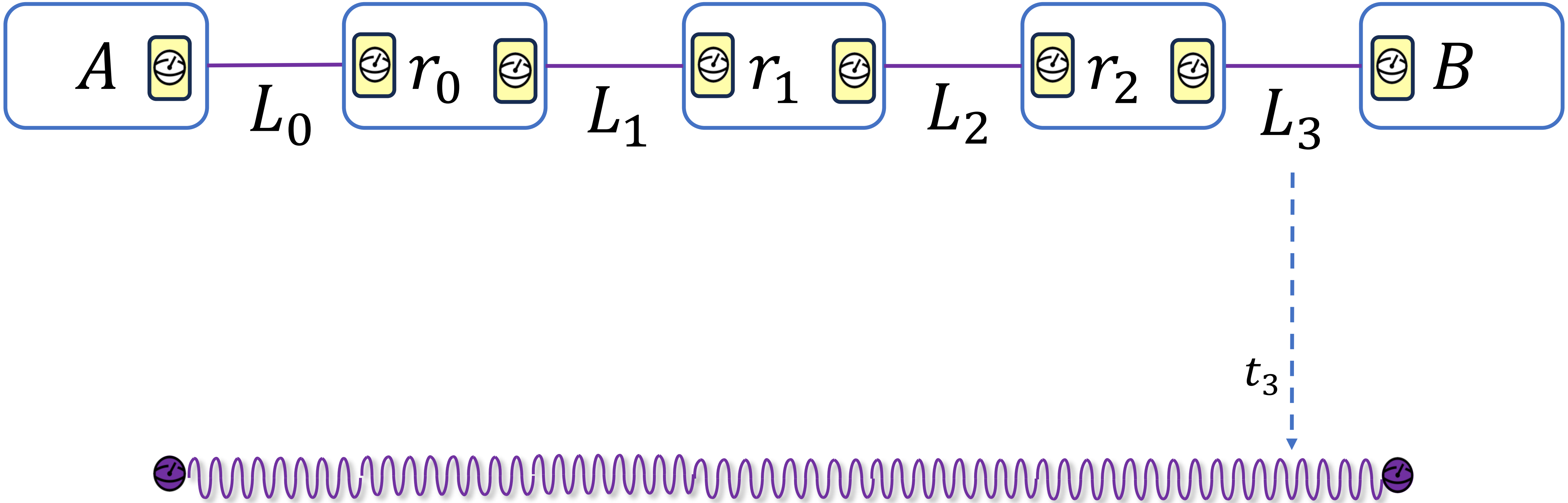
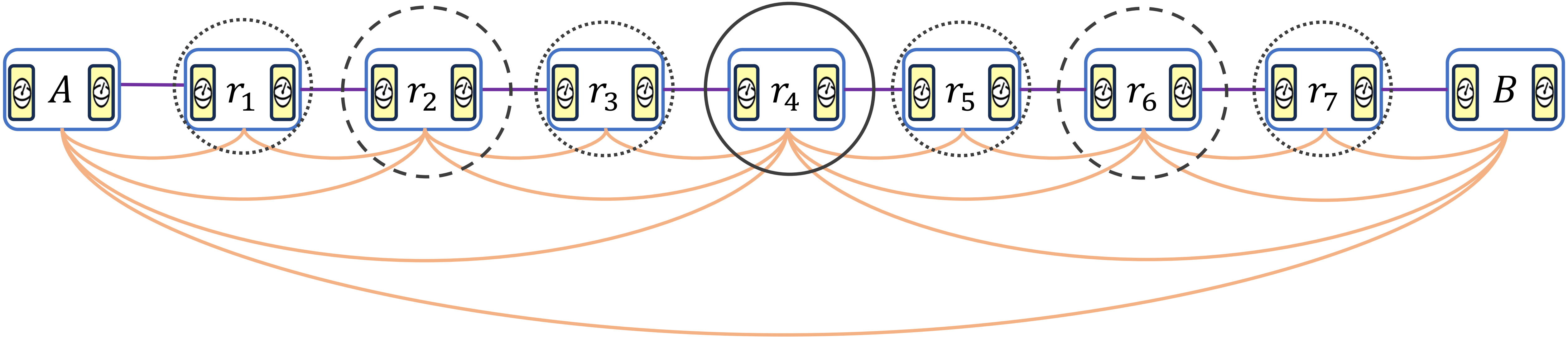
3. Stop when all repeaters swap

Swap ASAP

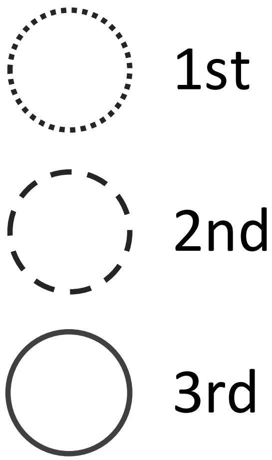


1. LLEG starts simultaneous on every link
2. Perform swap as soon as two links available
3. Latency is $O(\log n)$, n is number of repeaters

Nested Swaps



1. Attempt LLEG in parallel for all links
2. Find repeater at midpoint
3. Swap when both long range links have been created
4. Repeat process until possible



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Analysis

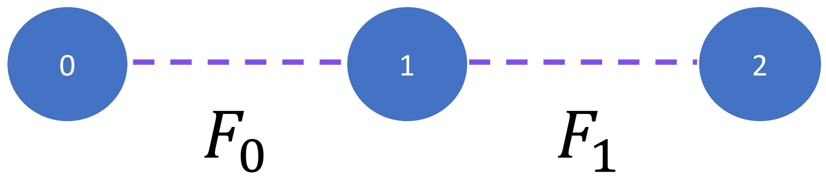
- Swap schedules have different performance
- If swap probability q, decay rate changes drastically
- Sequential simpler to implement, follow classical nets
- ASAP and Nested may require additional control

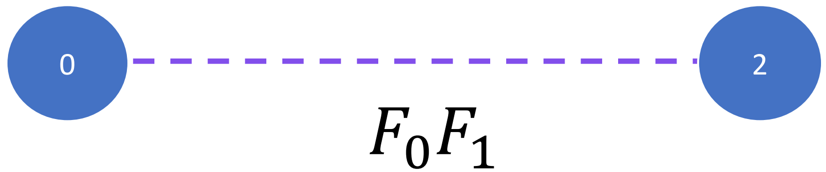
	Sequential	ASAP	Nested
Probability scaling with n	q^n	q^n	$q^{\log(n)}$
# of Bell pairs decohering	1	multiple	multiple
Latency	$O(n)$	$O(\log(n))$	$O(\log(n))$

Distribution and Noise

What happens with imperfect entanglement?

Assume that noise is depolarizing (worst case scenario)





Noise accumulates exponentially!

Distillation also requires scheduling!

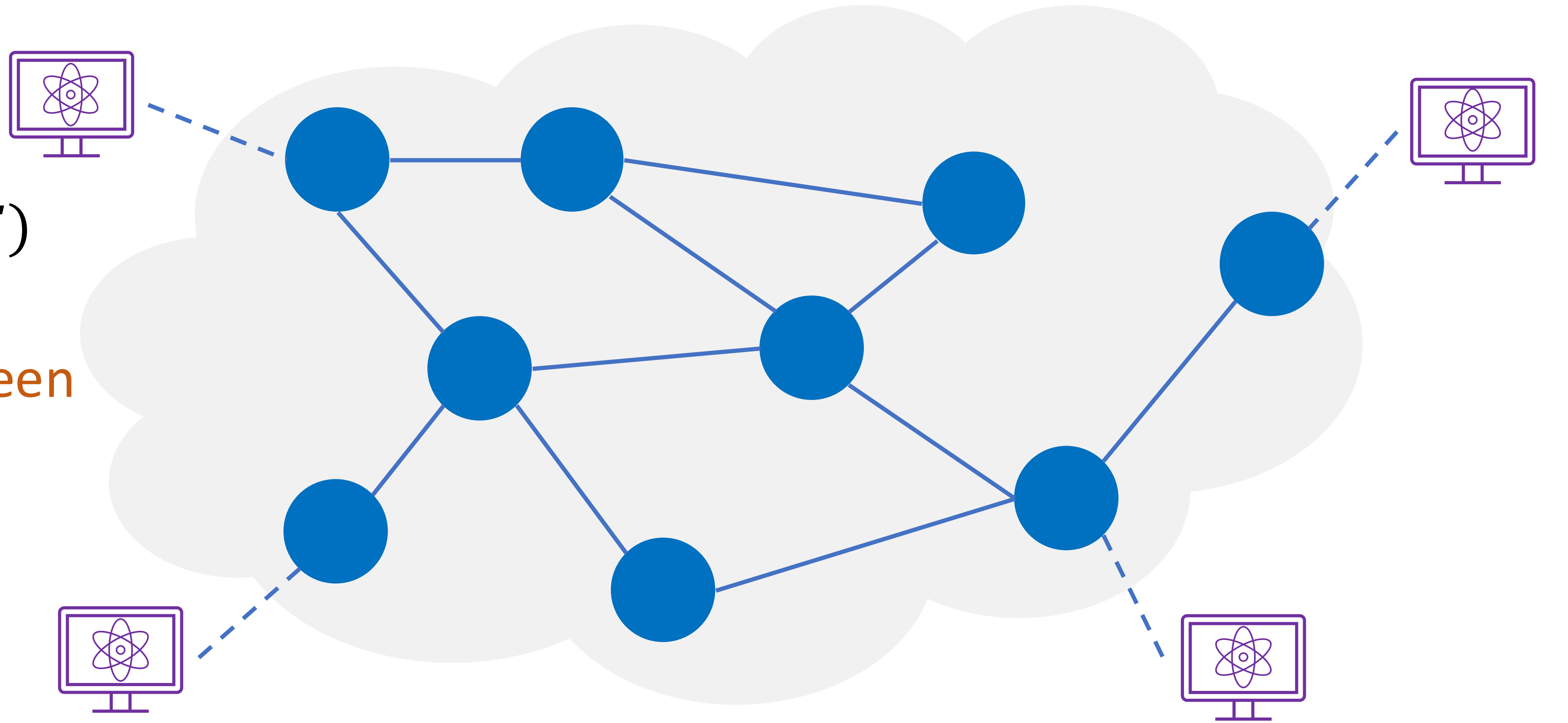
Different distillation schedules exhibit different performance!

Quantum Network Routing

The Routing Problem

Given $G = (V, E)$

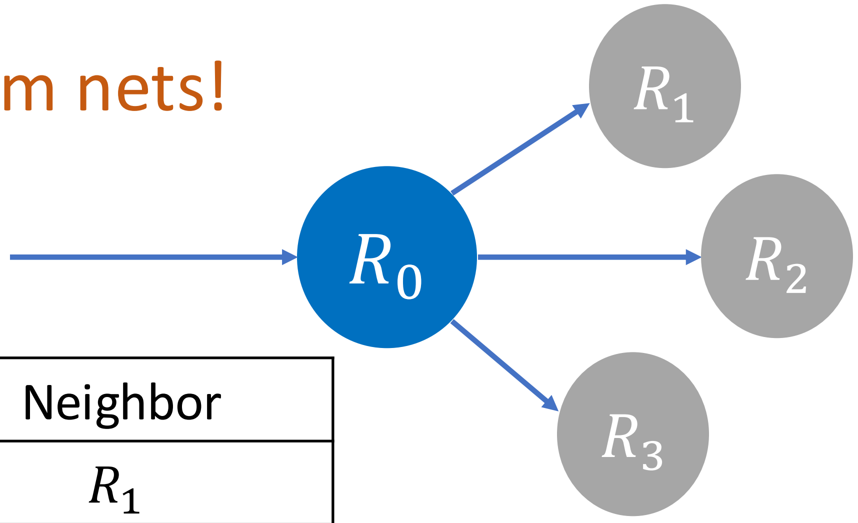
Find path between any nodes!



How is it solved in classical?

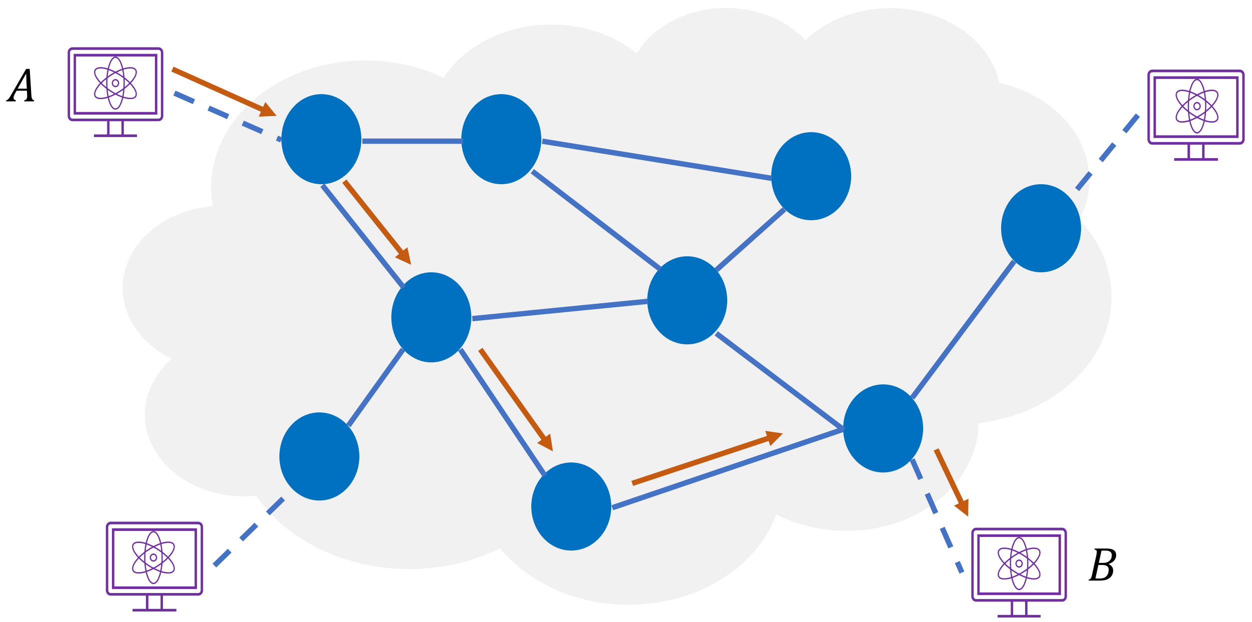
- Answer depends if circuit/packet switching
- For simplicity, focus on find paths
- Assume centralized controller knows topology
- Run shortest path algorithm
- Routers maintain tables with forwarding information

Works for one-way quantum nets!



Address / Flow ID	Neighbor
A	R_1
B	R_2

Do two-way networks differ?



A and B want to gen entanglement

Controller finds path $\mathcal{P}$

Distribute entanglement with favorite scheduling policy

Repeat until success

Methods work, although how much time its required?

Circuit switching / packet switching?

- Caveat: links are channels, not entanglement
- Connecting end-nodes requires LLE
- Process is probabilistic

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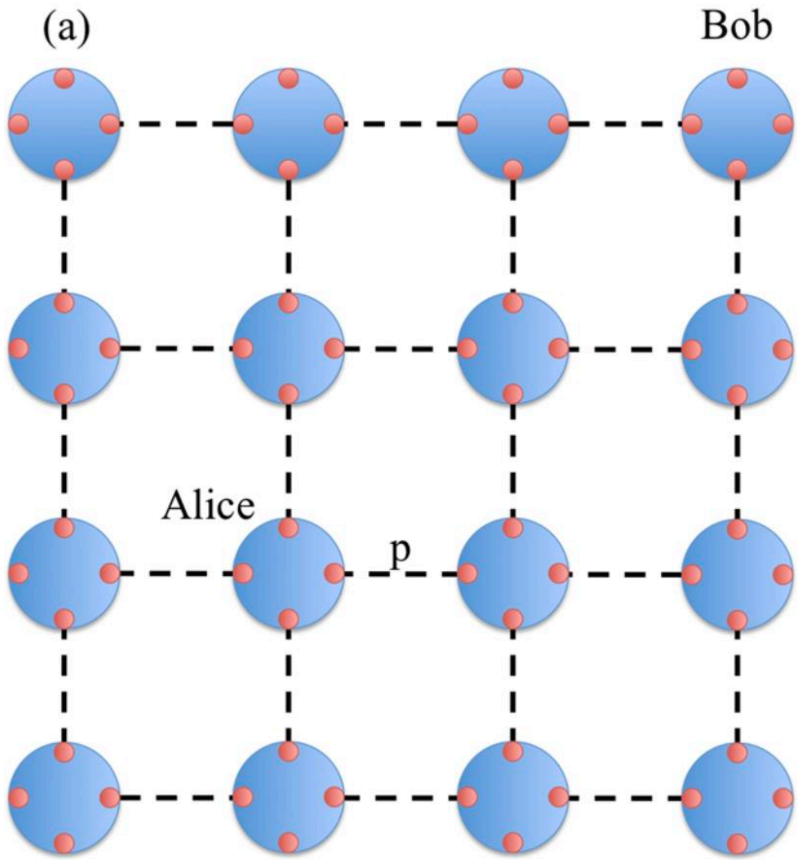
Back-of-the-Envelope Analysis

- Assume 2-phase time-slotted model (LLEG and swap)
- If memories only last for 1 slot -> rate decays exponentially with distance
- If probabilistic swaps -> only nested allows for non-exponential decay
- Precise scaling depends on multiplexing, coherence times, attempt frequency…

In classical, time scales linearly with distance / rate is constant

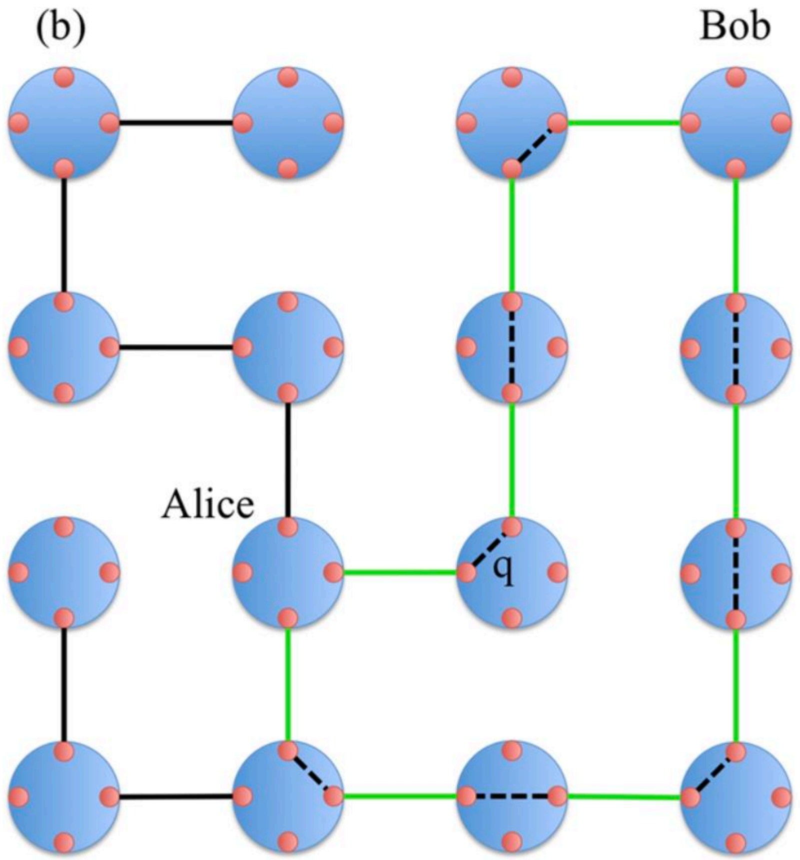
A different paradigm



Pant, Mihir, et al. "Routing entanglement in the quantum internet." *npj Quantum Information* 5.1 (2019): 25.

- Slotted time: 1 slot allows LLEG and swap
- Continuous LLEG attempts
- One qubit per link per router
- Swap succeeds with prob. q
- Memory holds states for 1 slot
- Route with successful entanglement through multiple paths!

Routing Decisions



Find set of edge-disjoint paths between Alice and Bob

Perform swaps according to paths (1-to-1 mapping between edges and qubits)

Success probability is $\sum_{l \in \mathcal{P}} p_l$ given $\mathcal{P}$

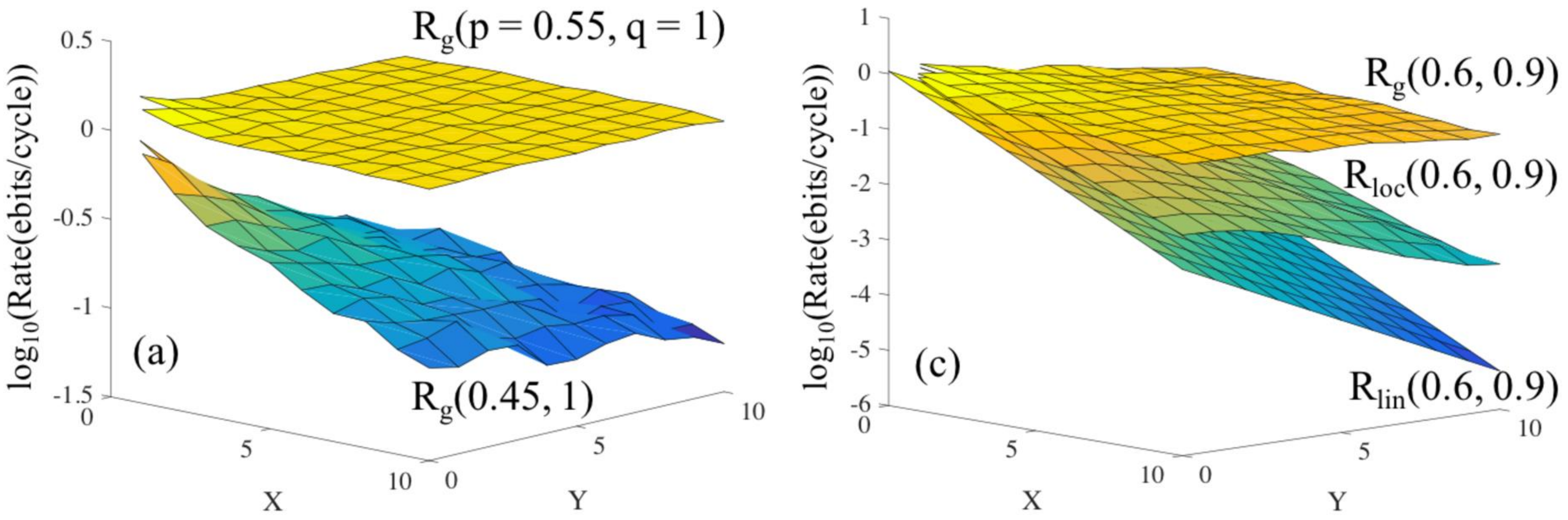
$$p_l \propto q^{|l|}$$

Requires global knowledge on LLEG, although local information can be used!

Analysis

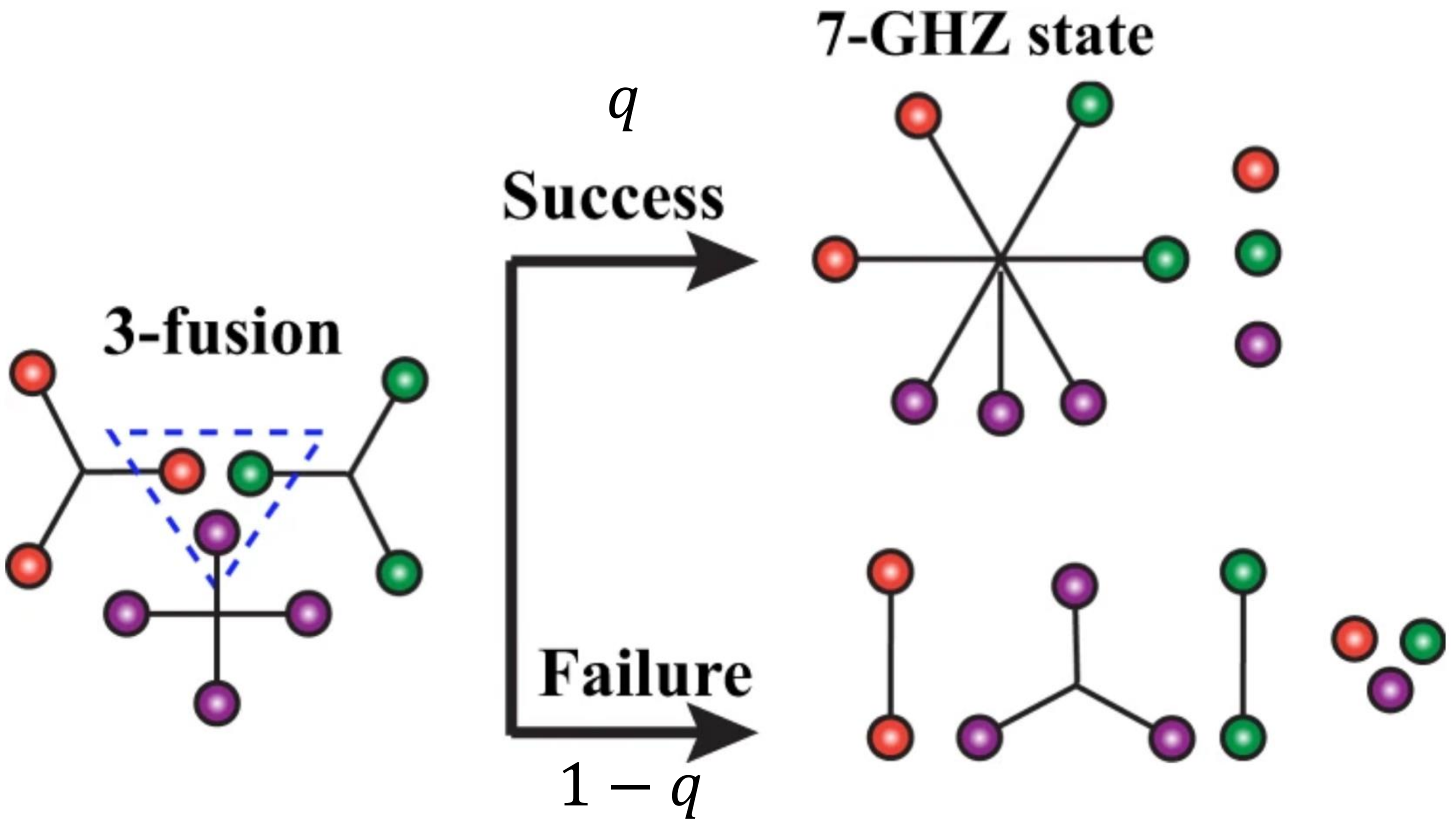
- Performance (rate) analyzed using percolation theory
- When $q = 1, p > p_{thresh}$ yields distance independent rates
- When $q < 1$, rate decays exponentially with distance
- Intuition: utilize all network resources available to serve user pair!

Distance-independent rate with $q < 1$?

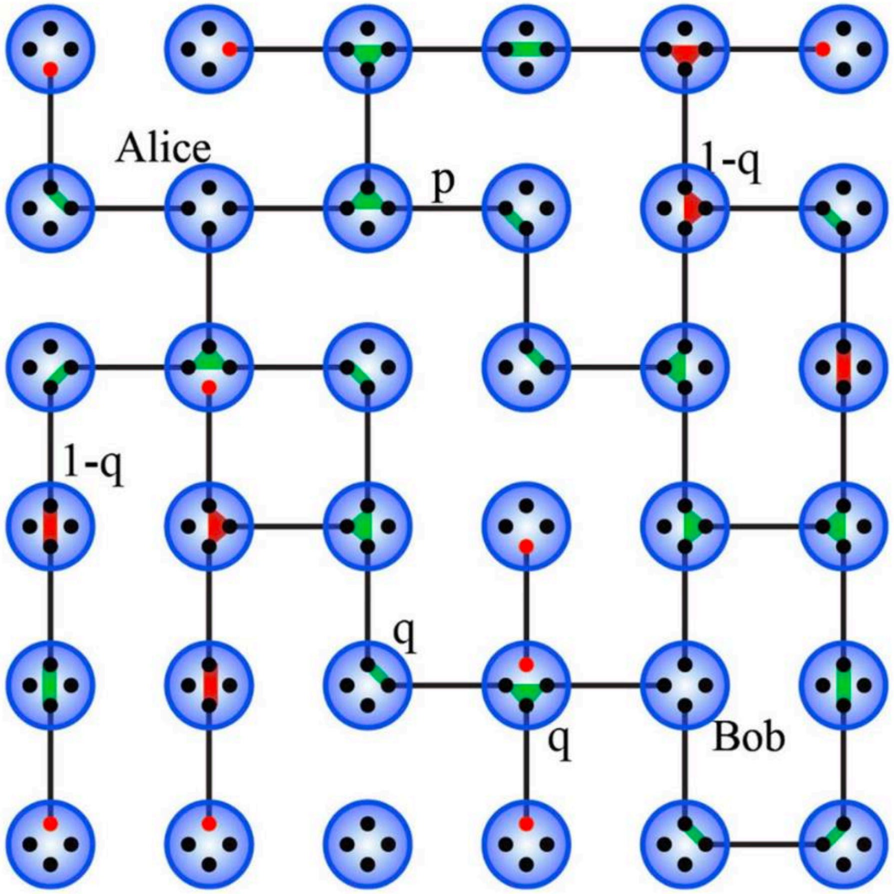


GHZ Fusions

- N-qubit GHZ states "generalizes" Bell pairs
- Entanglement swapping becomes GHZ fusion



Routing with GHZ



All nodes besides Alice and Bob perform GHZ fusions

Approach resembles broadcast

If p and q sufficiently large, percolation!
Distance independent rate even when $q < 1$

Problem deals with probabilistic generation, although not resilient to noise!

Different protocols obtained depending on how fusions are performed!

Connectionless Architecture for 2-way Quantum Networks

A connectionless Qnet architecture

- little or no flow state at switches/repeaters
- each entanglement request potentially handled separately

- swap ASAP
- nested swapping

} requires path-level synchronization (connection state)

- sequential swapping
  - link resources given to flow only when request needs them
  - only requires link-level synchronization

Analogous to datagram service in classical Internet

Pros

- simplifies synchronization; link by link classical comms
- amenable to analytics (understandability, management)
- allows deployment of classical Internet protocols
  - Q-TCP
  - destination-based routing
  - multicast ↔ multipartite state distribution

Bacciottini, soon to appear on arxiv

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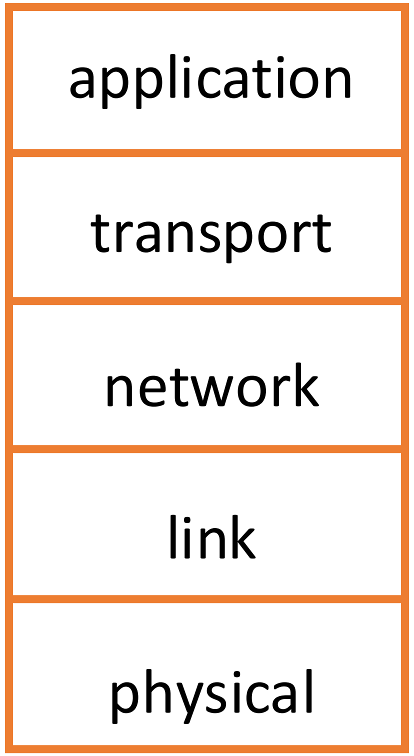
Connectionless Architecture

- Packet switching – Store and Forward
- TCP/IP network stack
- Statistical multiplexing enables multiple users
- Fundamental for Internet performance



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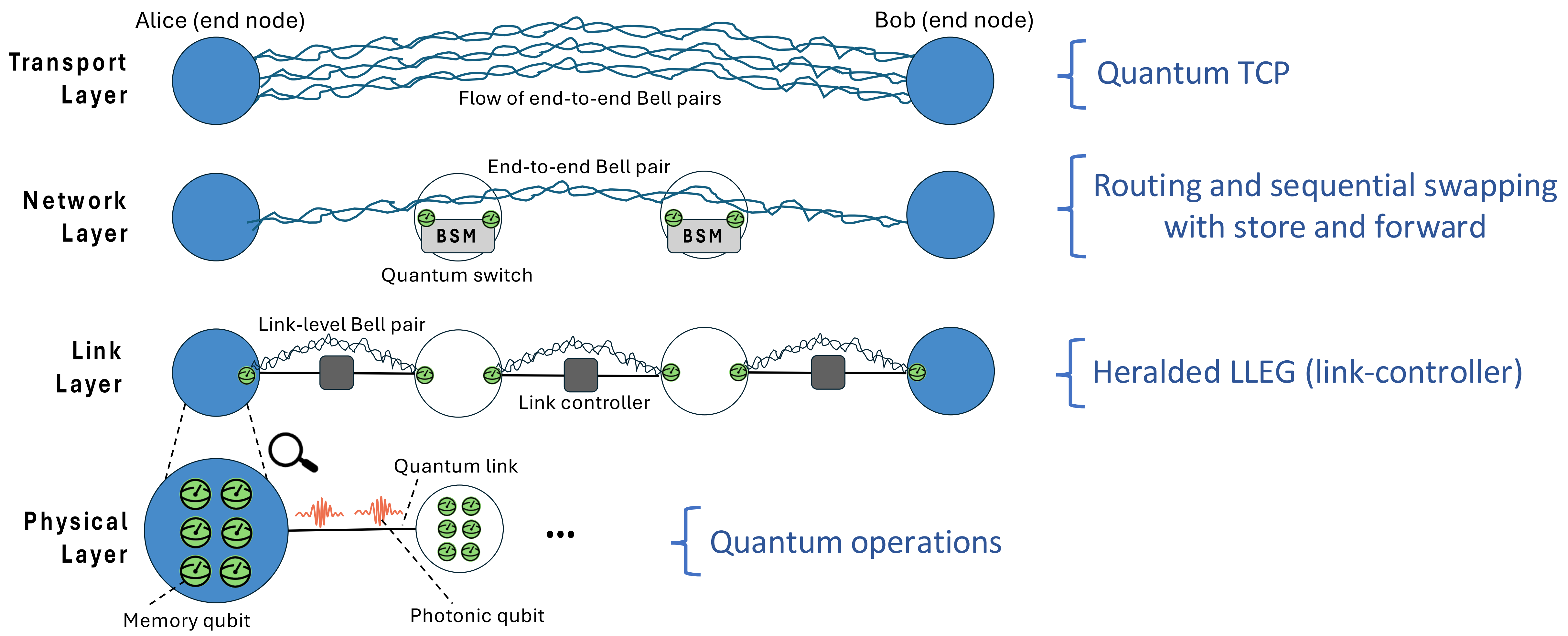
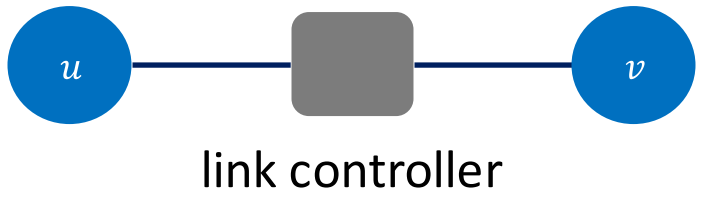
Architecture

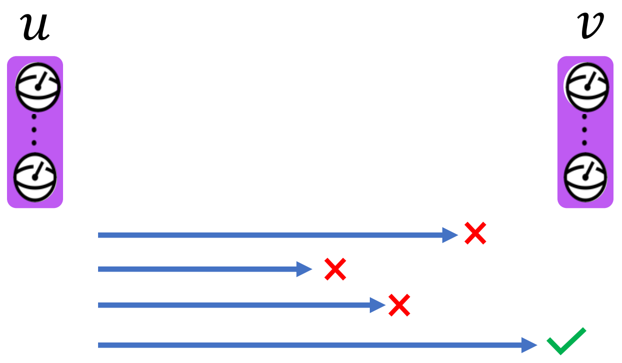


Link Layer

- Heralded LLEG (multiplexed)
- Nodes requests entanglement from controller
- Controller orchestrates generation
- Entanglement indexed by request ID and link-level label
- Can accommodate purification!

Link-layer generated entangled links for network layer to consume!!!

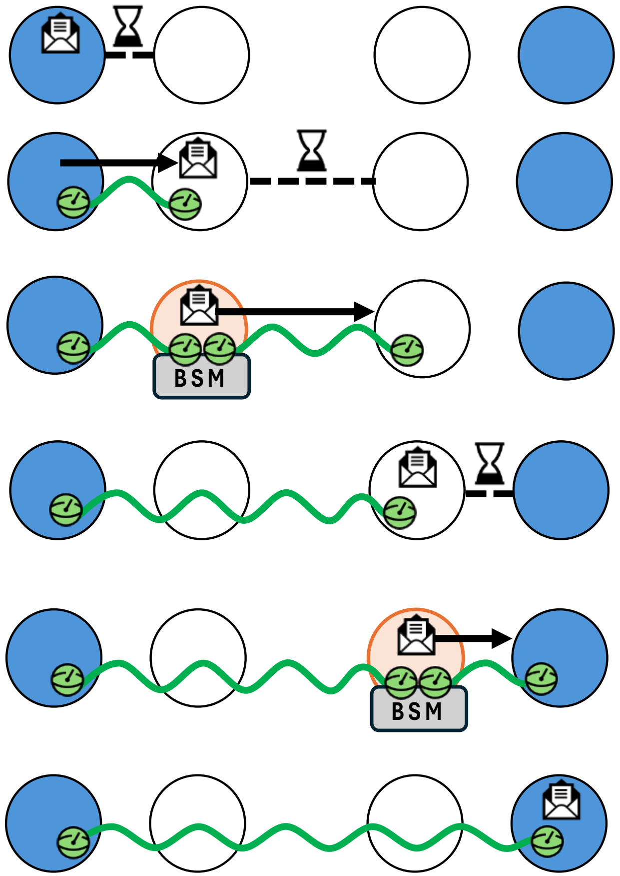




Entangled state $(ID, label)$ generated for u

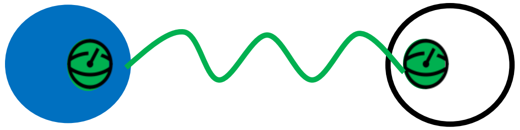
Network Layer

- Forward Bell states like packets via sequential entanglement swapping
- Quantum datagram
- No resource reservation
- Best-effort service
- Supports different schedules for link-level entanglement consumption



Quantum Datagram

Classical data



Quantum data

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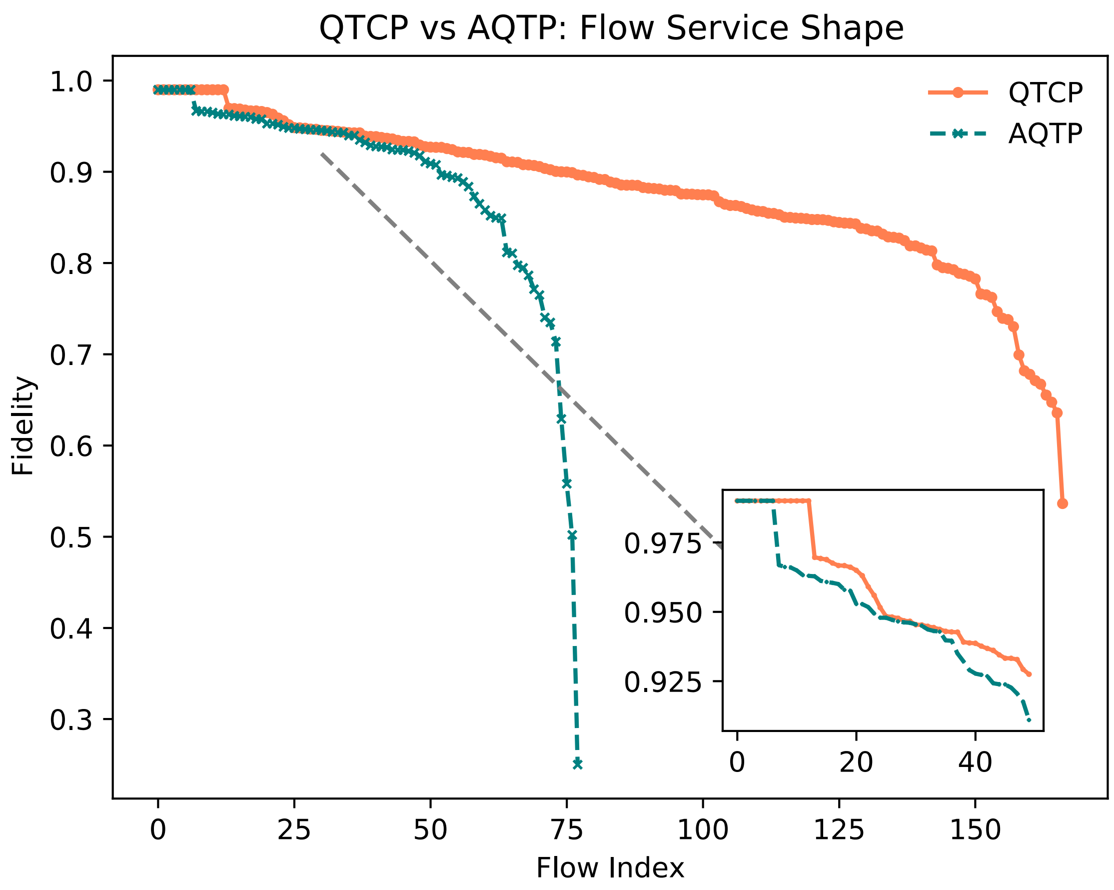
Transport Layer: QTCP

- TCP-like: opening handshake, data flow, closing handshake
- Ack's for delivered q-datagrams
- Control E2E q-datagram rate (congestion control, AIMD)
- Active queue management reduces time states decohere



Poll Question

What are the benefits of a connectionless quantum network architecture? Select all that apply.

A. Requires minimal synchronization
B. Reduces total amount of required classical communication.
C. Permits borrowing ideas from classical Internet for application to quantum Internet
D. Provides distance independent entanglement rates
E. I don’t know

Answer

What are the benefits of a connectionless quantum network architecture? Select all that apply.

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Quantum Network Tomography

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Outline

NETWORK MANAGEMENT AND TOMOGRAPHY OVERVIEW

CLASSICAL NETWORK TOMOGRAPHY

QUANTUM NETWORK TOMOGRAPHY (QNT)

CHARACTERIZING STAR NETWORKS

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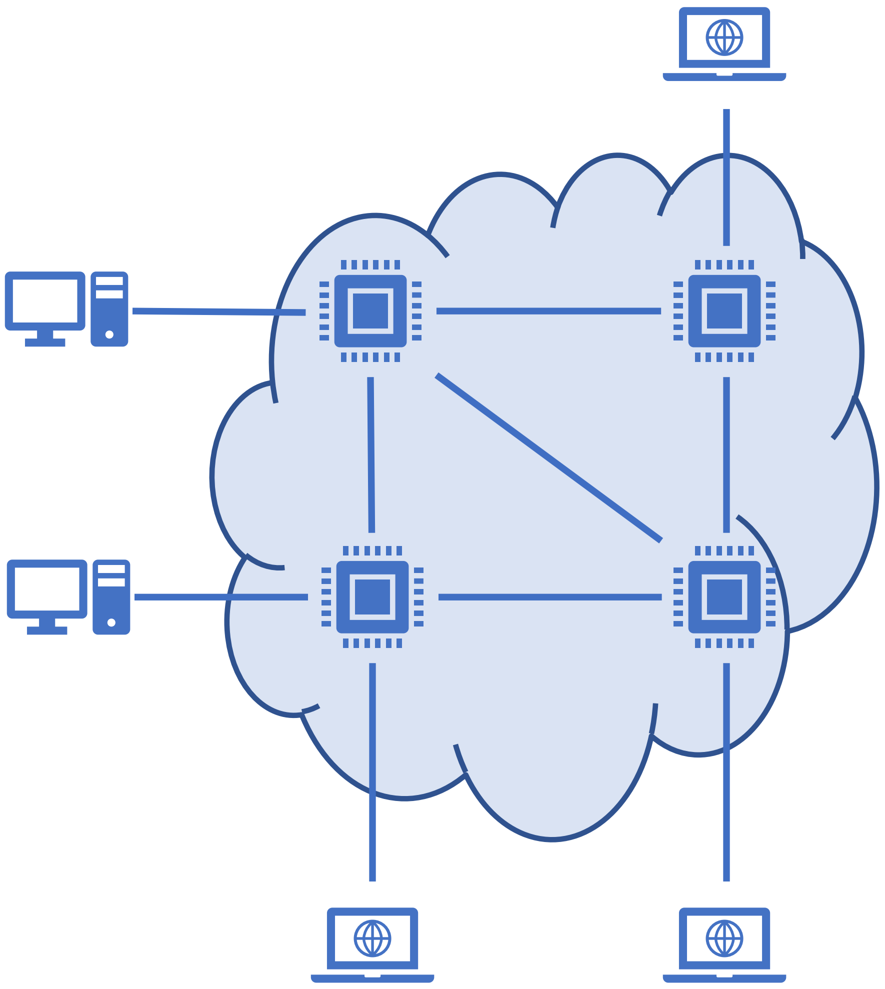
Network management

- Network component data collection
- Information to aid decision making
- Fault-detection for hardware / software
- Determine traffic patterns



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Network tomography

Goal

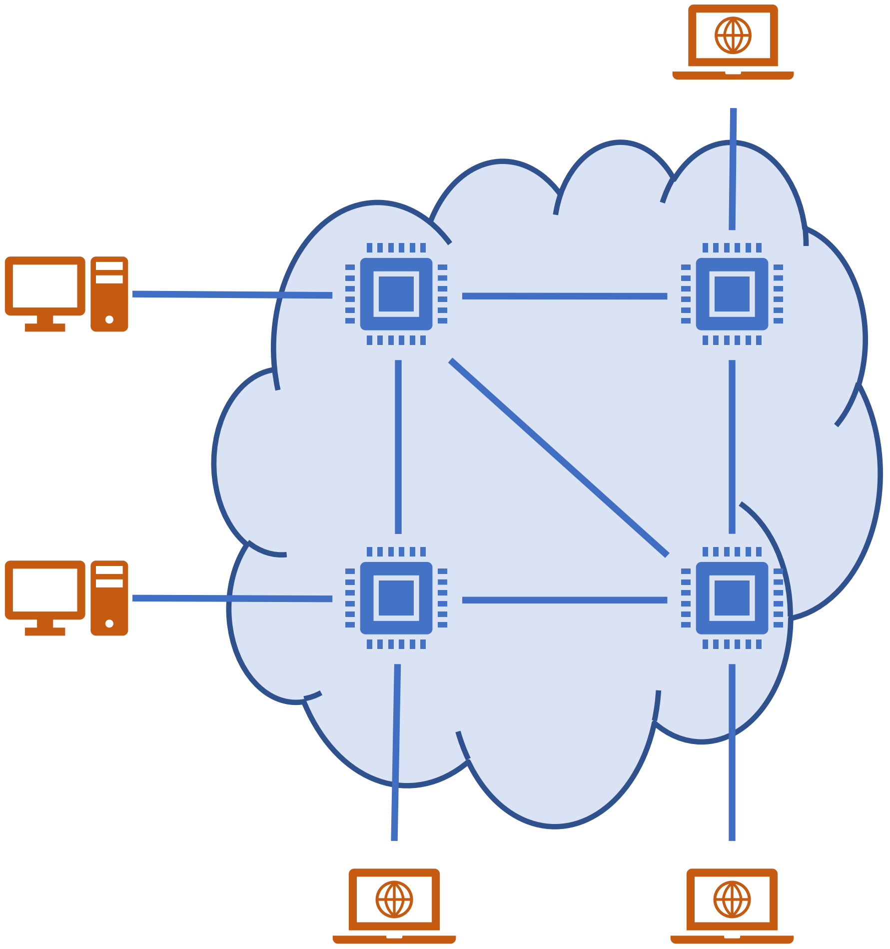
Infer internal behavior in network from external nodes

In practice

Estimate error parameters for internal components from end-to-end measures

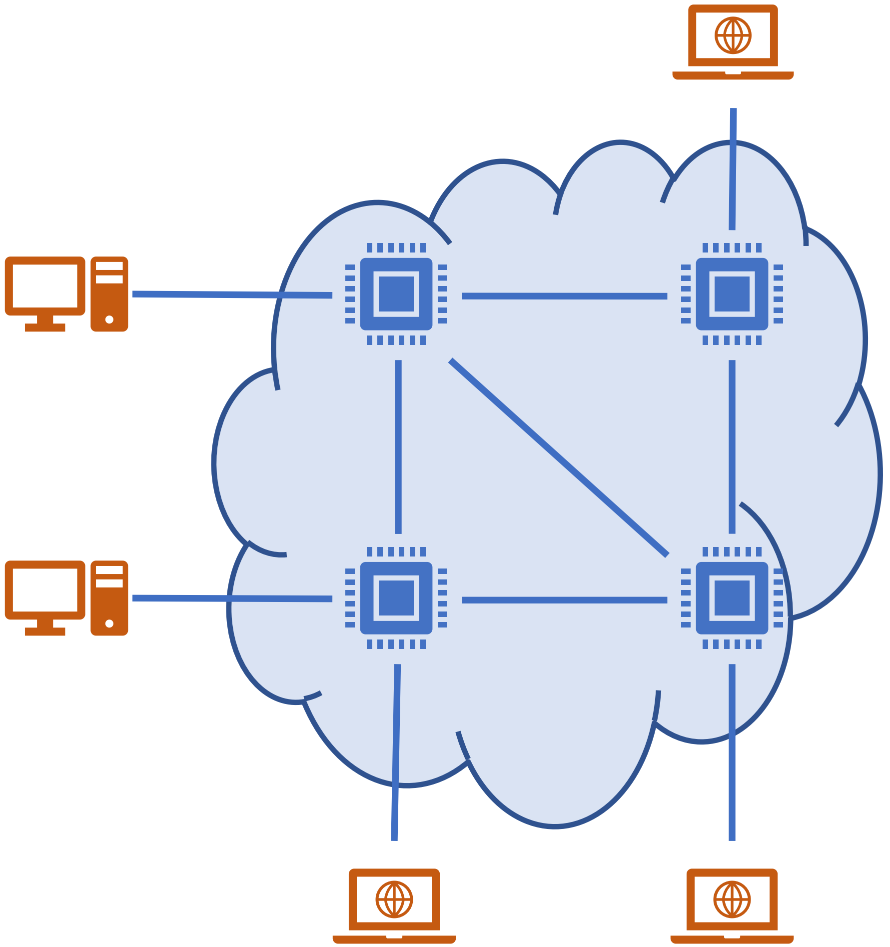
Identifiability

Obtain one value for parameters given a set of observations



Why end-to-end?

- No participation by network needed
  - Measurement probes regular packets
- No administrative access needed
- Inference across multiple domains
  - No cooperation required
  - Monitor service level agreements
- Reconfigurable applications
  - Video, audio, reliable multicast



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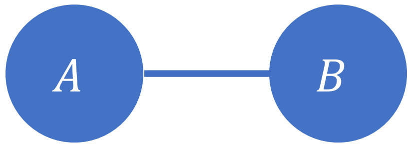
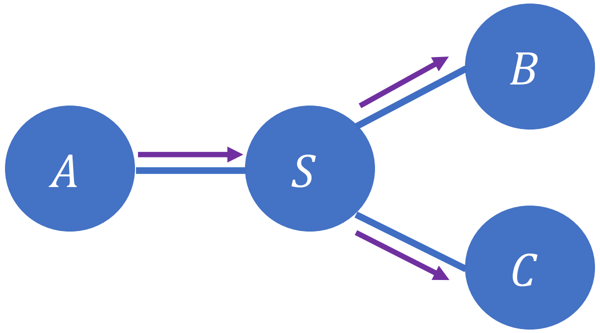
Definitions

Link-level metrics



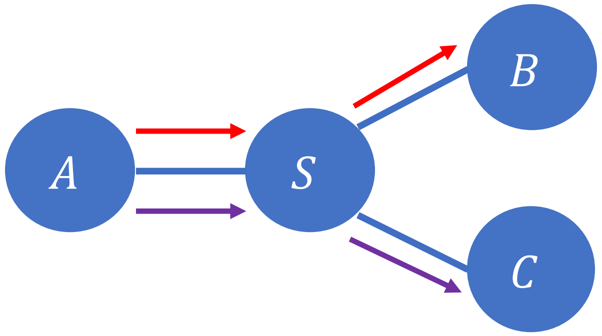
E.g: delay, loss, bit-flip rate

Multicast communication



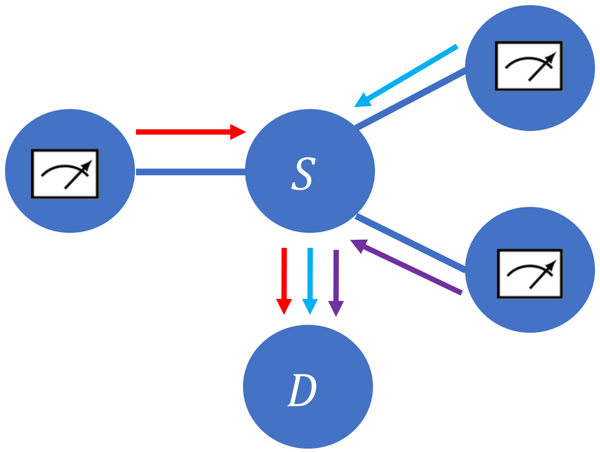
One-to-many

Unicast communication



One-to-one

Estimation



Data sent to fusion center

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Unicast Tomography

Assumptions

- Links are symmetric
- Additive metrics

Results

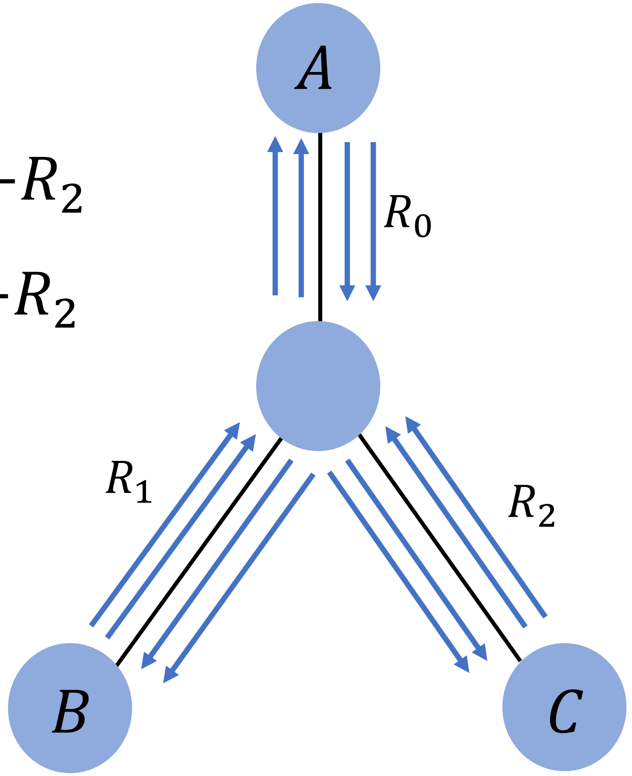
- Linear independence! (identifiable)
- True for general trees
- Can infer some link delays within general graph
- Measurements over cycles

Routing Matrix

$$R_{AB} = R_0 + R_1$$

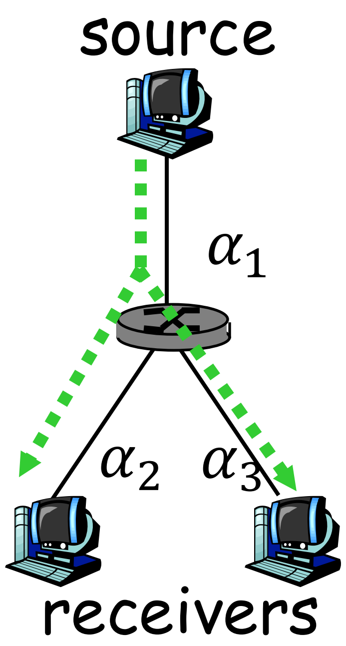
$$R_{AC} = R_0 + \quad + R_2$$

$$R_{BC} = \quad R_1 + R_2$$



Multicast Tomography

- Multicast probes
  - copies made *as needed* within network
  - Communication through trees
- Receivers observe correlated performance
- *Exploit* correlation to get link behavior
  - Loss rates
  - Delays



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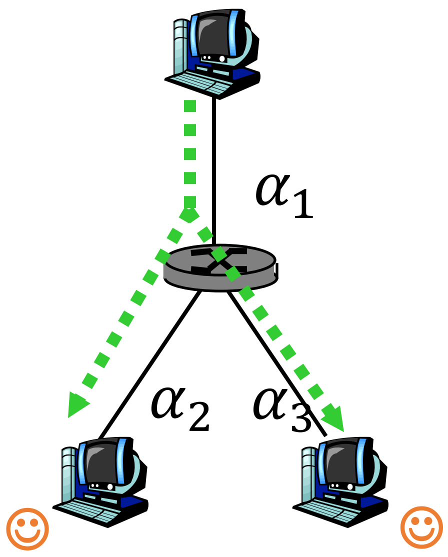

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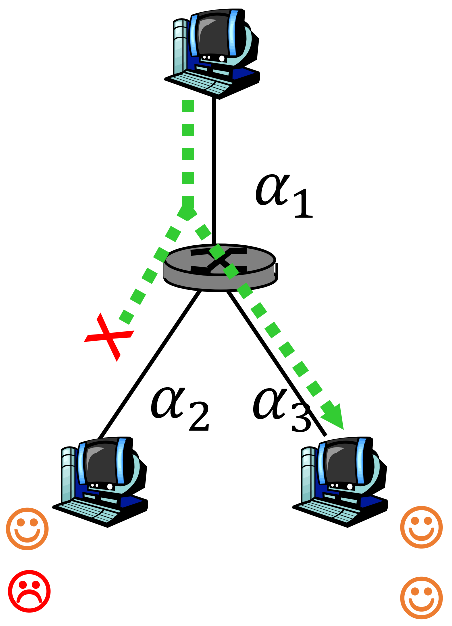

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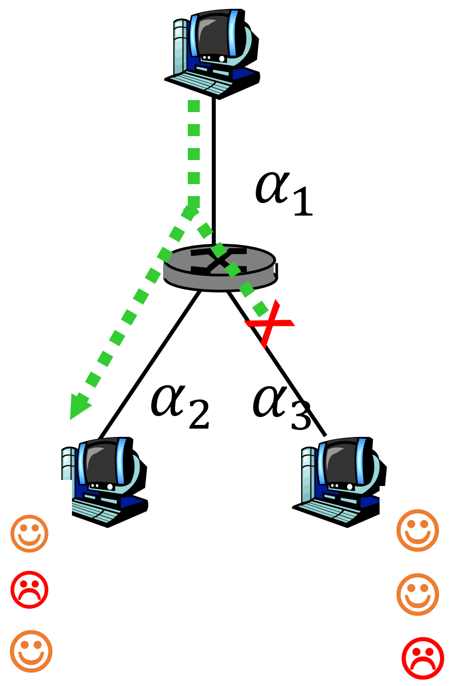

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Multicast Tomography

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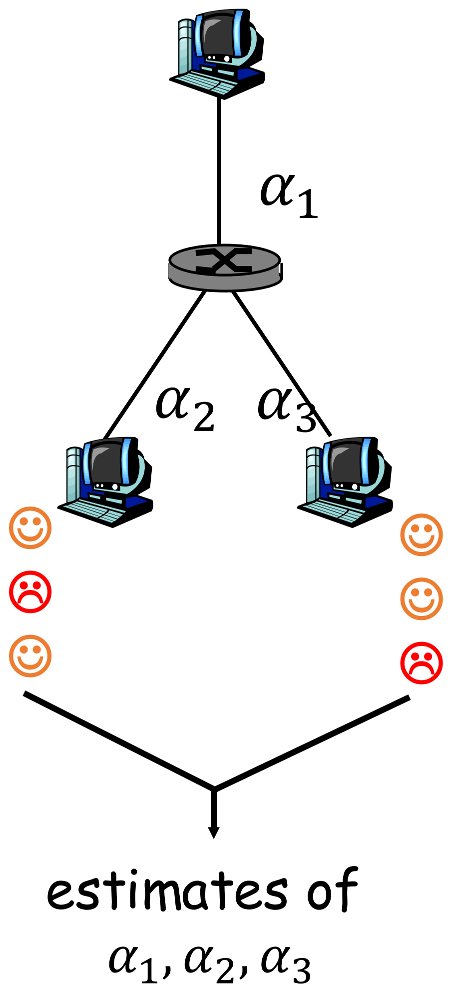
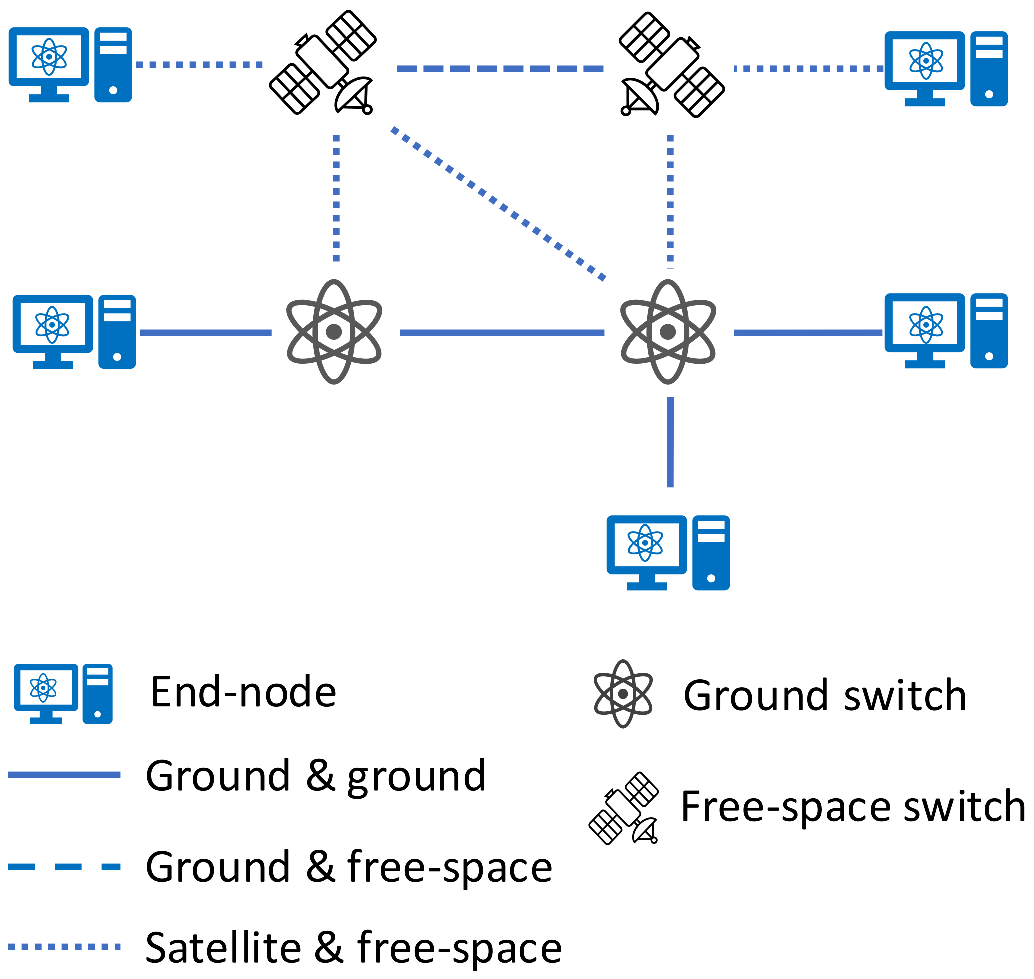


Quantum Network Tomography



How to characterize links with end-to-end measurements?

End-nodes

- Perform quantum circuits
- Request network state distribution
- Specify circuits for intermediate nodes

Intermediate nodes

- Receive requests for circuits
- Ancilla qubits
- No measurements for estimation

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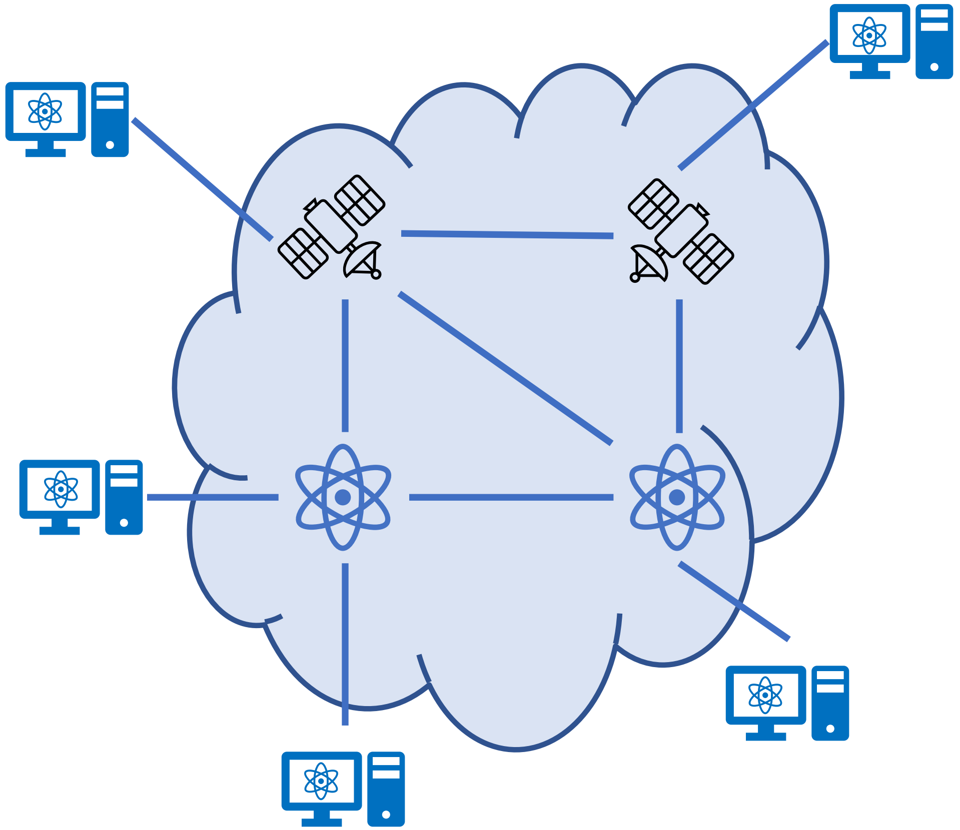
Motivation

- Inhomogeneous quantum hardware
- Hybrid communication media
- Network management
    - Faulty network hardware identification
    - Improved decision-making in resource utilization
    - Noise-informed quantum error correction
- Quality assurance
- Reconfigurable applications



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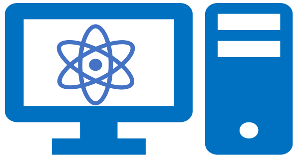
From Classical to Quantum

Classical	Quantum
Link-level metrics	Quantum channel parameters
Probes	State Distribution
Unicast	Bipartite state distribution
Multicast	Multipartite state distribution
End-to-end measurements	Measurements in end-nodes

Operational Assumptions

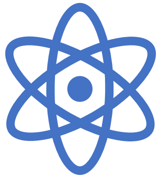
End-nodes V_E

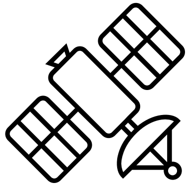
- Perform quantum circuits
- Request network state distribution
- Specify circuits for intermediate nodes



Intermediate nodes V_I

- Receive requests for circuits
- Ancilla qubits
- No measurements for estimation





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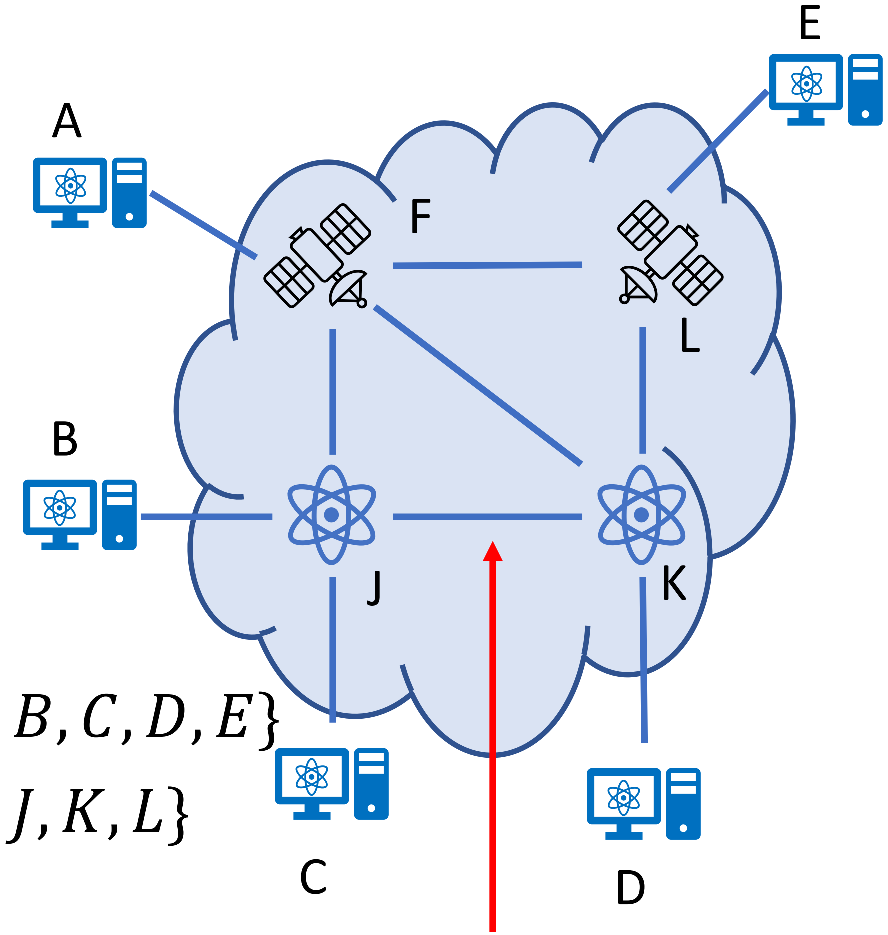
Quantum Network Model

- Network is graph $G = (V, E)$
  - V : quantum processors
  - E : fiber optics, free space channels
- End and intermediate nodes
- Links: single-qubit quantum channels
- One-way quantum transmission

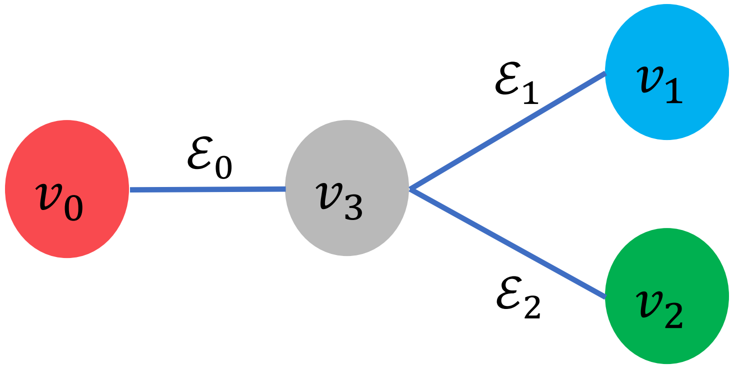


$$V_E = \{A, B, C, D, E\}$$
$$V_I = \{F, J, K, L\}$$

$$\mathcal{E}_e(\rho) = \sum_k \theta_{ek} \sigma_{ek} \rho \sigma_{ek}$$

Goal: estimate θ from E2E measurements!

Characterizing bit-flip stars

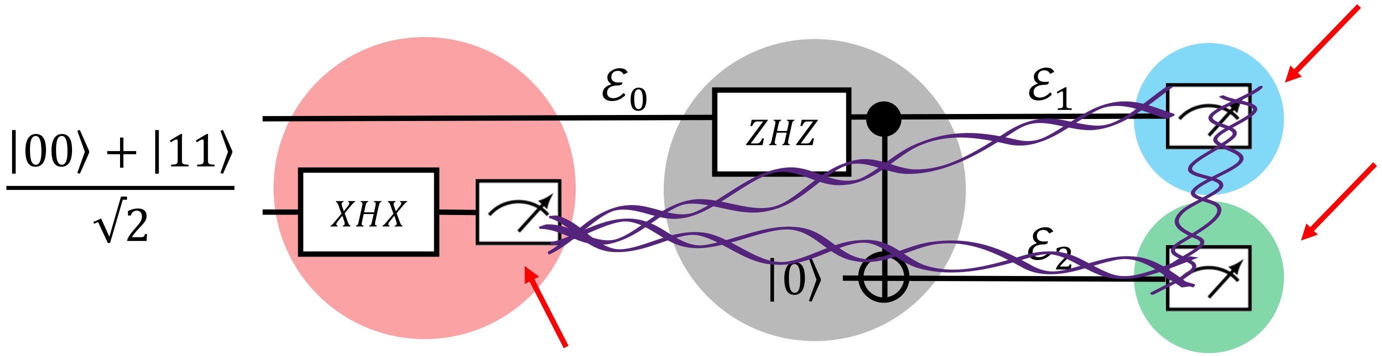


$$\mathcal{E}_e = \theta_e \rho + (1 - \theta_e) X \rho X$$

$|0\rangle \rightarrow |1\rangle$ with prob. θ_e

$|1\rangle \rightarrow |0\rangle$ with prob. θ_e

Probe: Independent Encoding

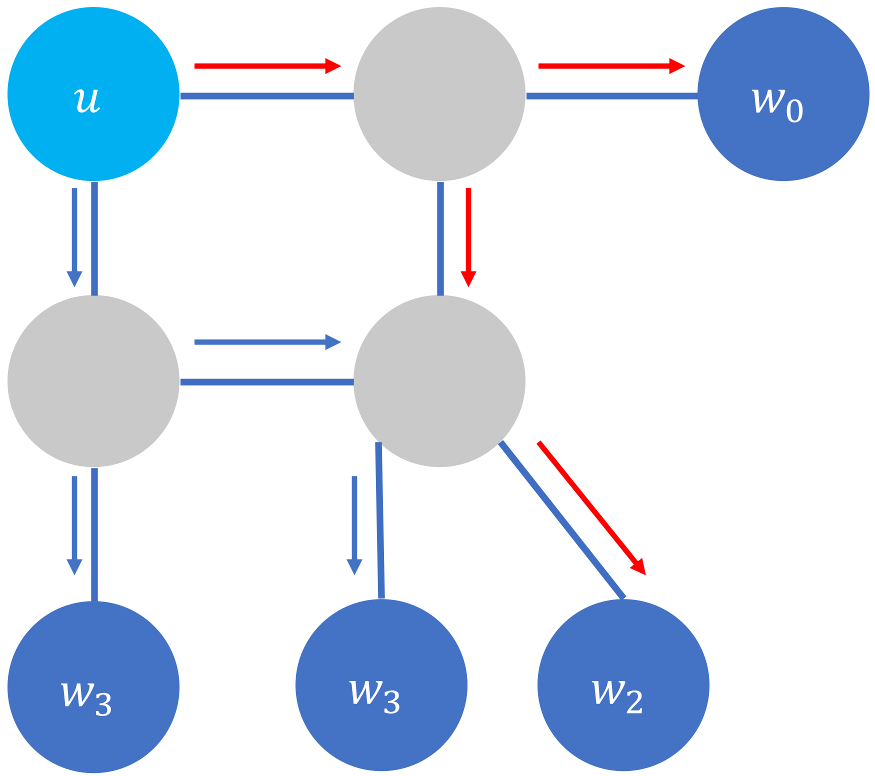


GHZ measurement implement with pre-shared entanglement

Probability of measuring $|1\rangle$ in v_i is θ_i!

Characterizing more complex networks

- State preparation for stars generalizes to rooted trees of G
- Characterize links in tree
- Characterize graphs through tree covering
- Compatible with one-way, two-way architectures



Active area of research!

Challenges

- What are the optimal estimation strategies for stars?
- How to generalize estimators for arbitrary trees?
- How to partition network in trees for estimation?
- How do bipartite and multipartite compare?
- Under which conditions entanglement provides advantage?
- Under which conditions are trees identifiable?
- How to generalize efficient estimators for Pauli channels?

Recap

- Fundamentals of quantum communications
- Classical and Quantum Networks
- Scheduling in repeater chains
- Routing in quantum networks
- Connectionless quantum networks
- Quantum network tomography

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Thank you!