Networking Problems in Using Quantum Repeaters

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MAUI, 2009/4/16

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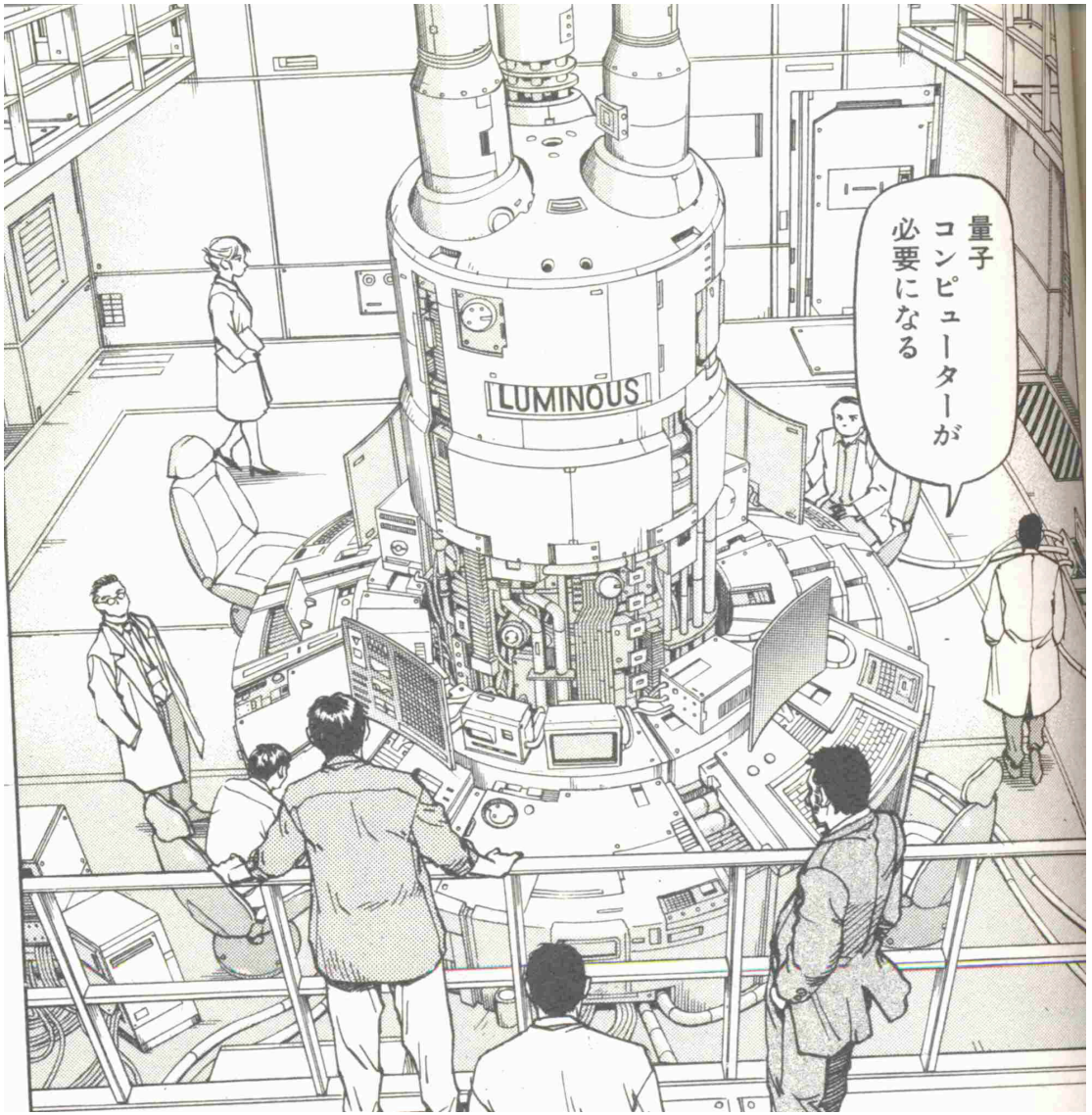
Assume a Quantum Computer Like This...



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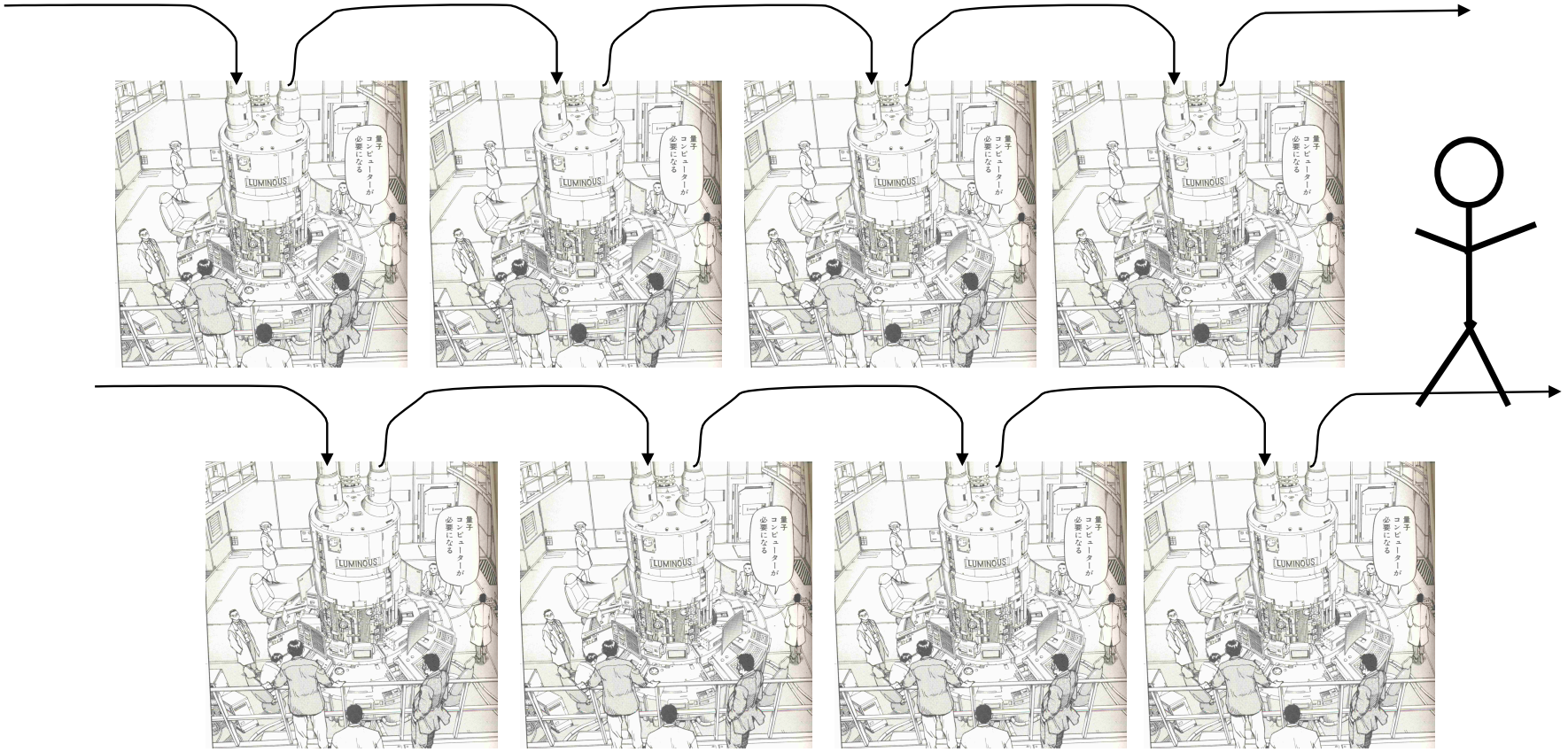
I want to Build a Distributed Quantum System Like This



Laboratory-sized quantum multicomputer or transcontinental network, either one!

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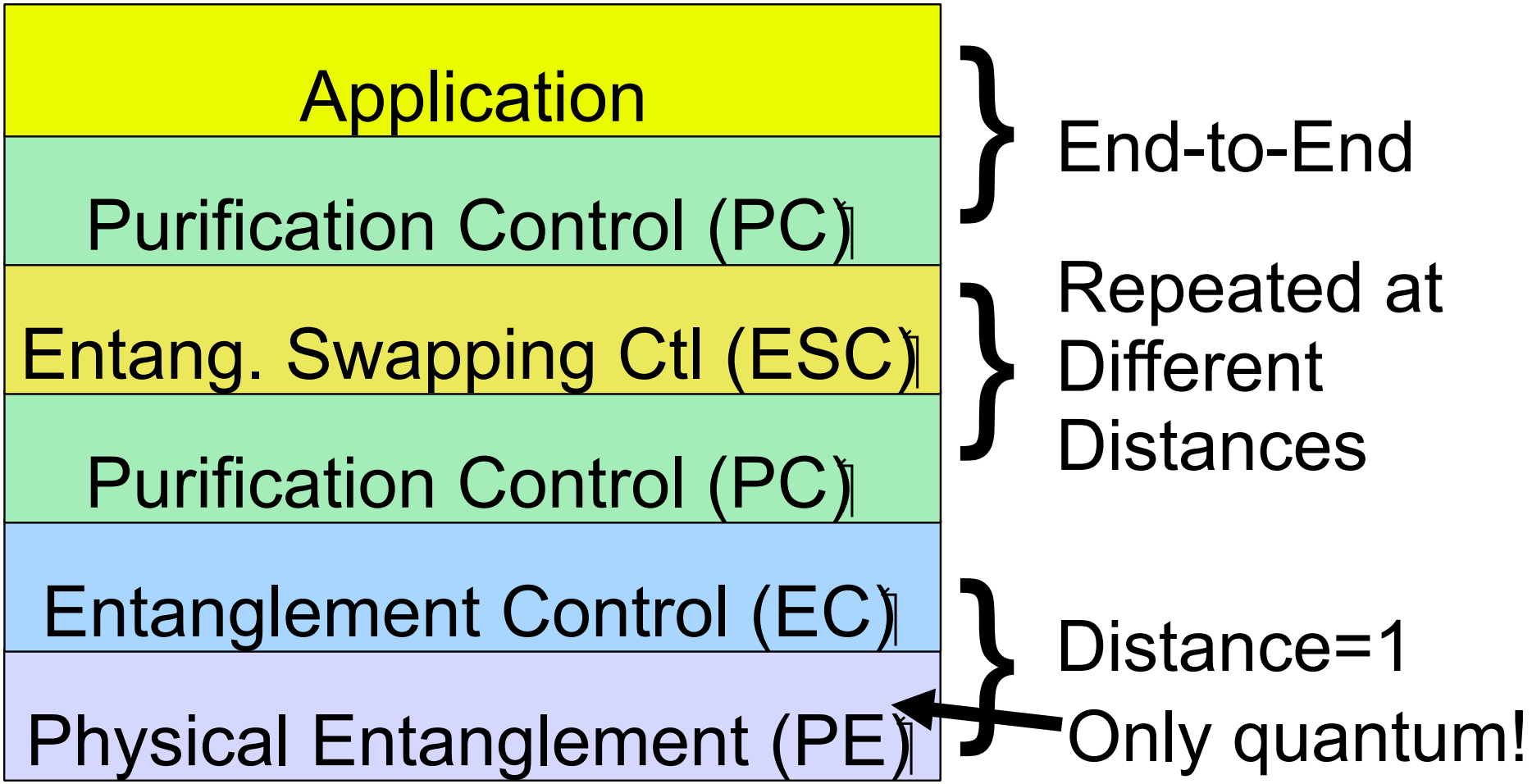
Repeater Protocol Stack



Van Meter *et al.*, IEEE/ACM Trans. on Networking, Aug. 2009 (to appear), quant-ph:0705.4128

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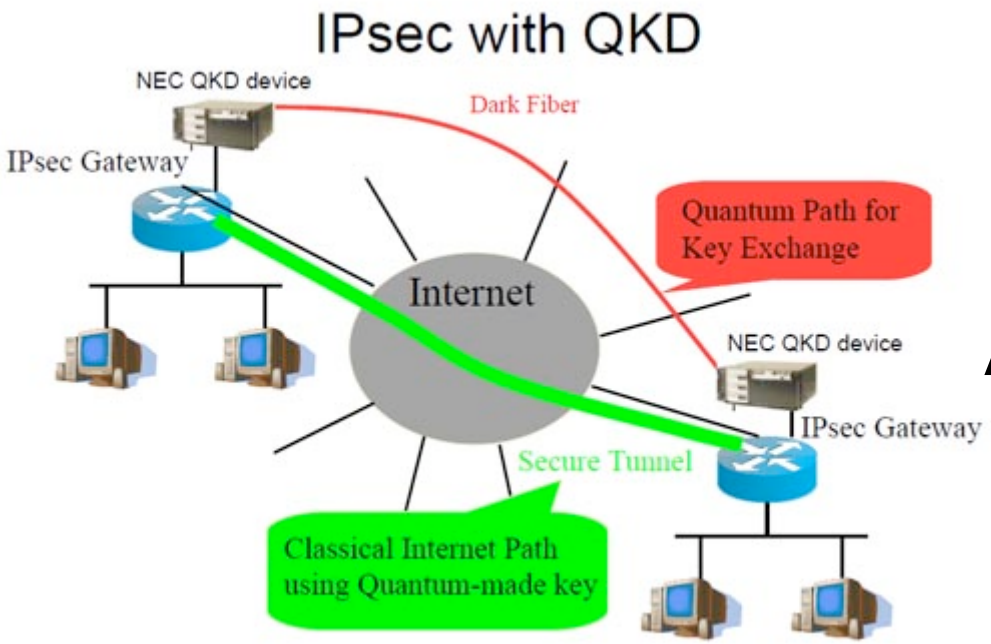
Outline

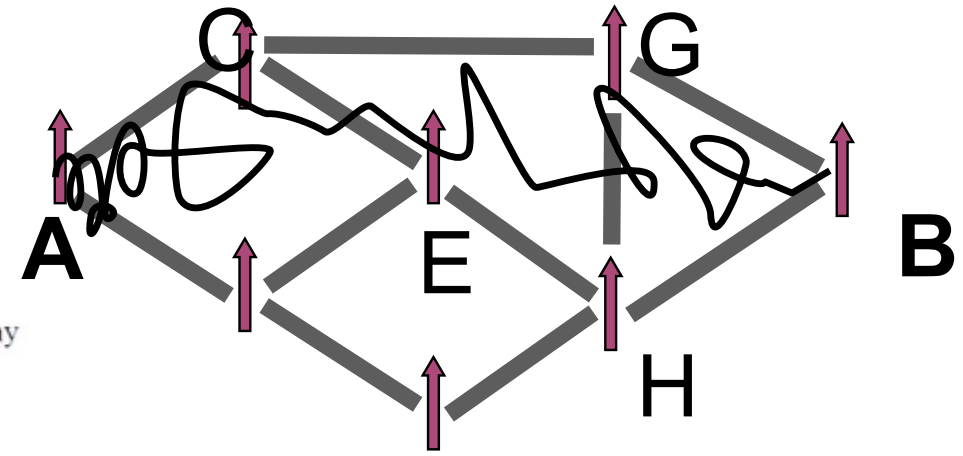
- Two types of quantum networks
- IPsec with QKD
  - IPsec with QKD
  - US & European efforts
  - Open problems & plans
- Repeaters
  - Basic concepts
  - Our recent results
  - Open problems & plans

Two Types of Quantum Networks

Unentangled Networks



Entangled Networks



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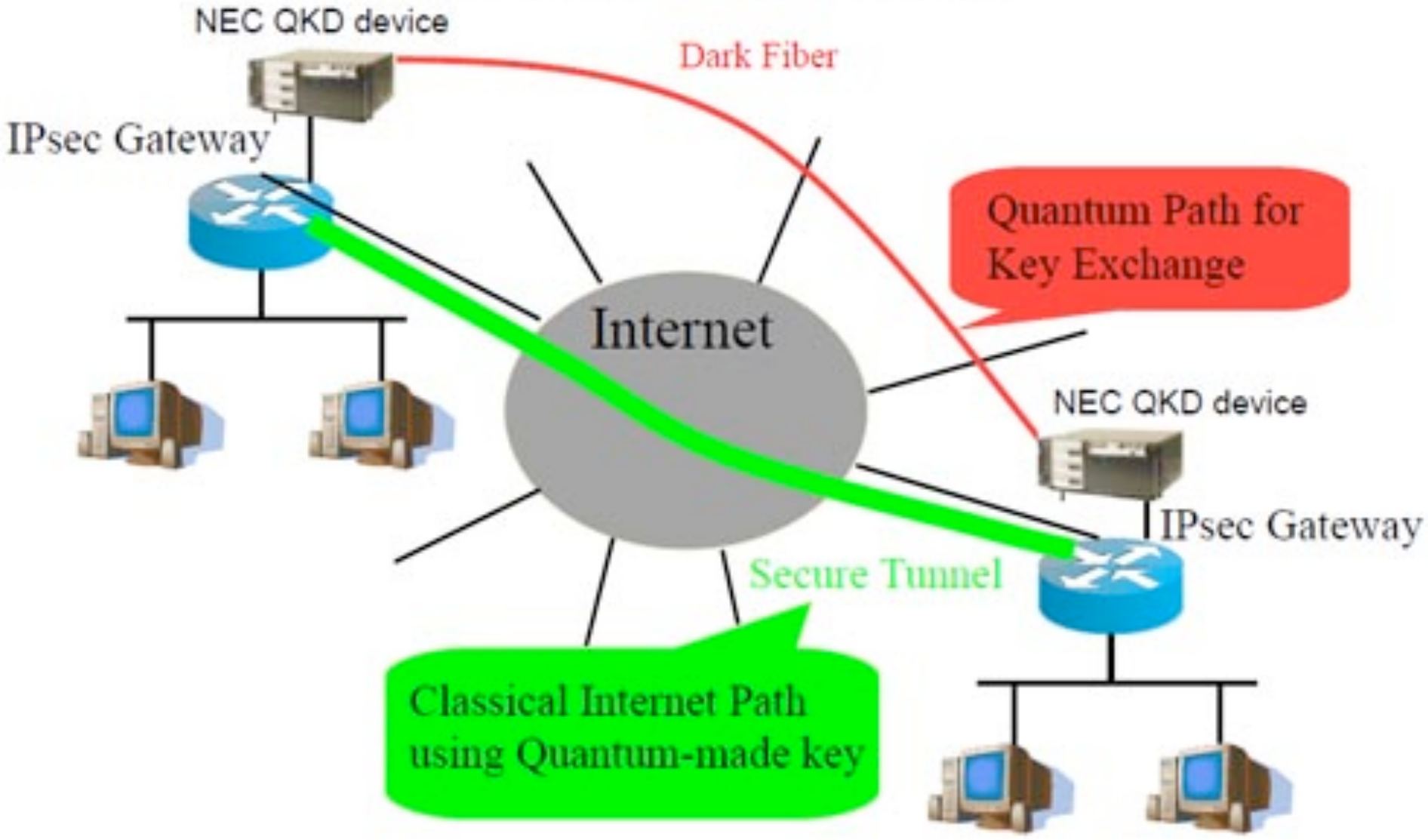
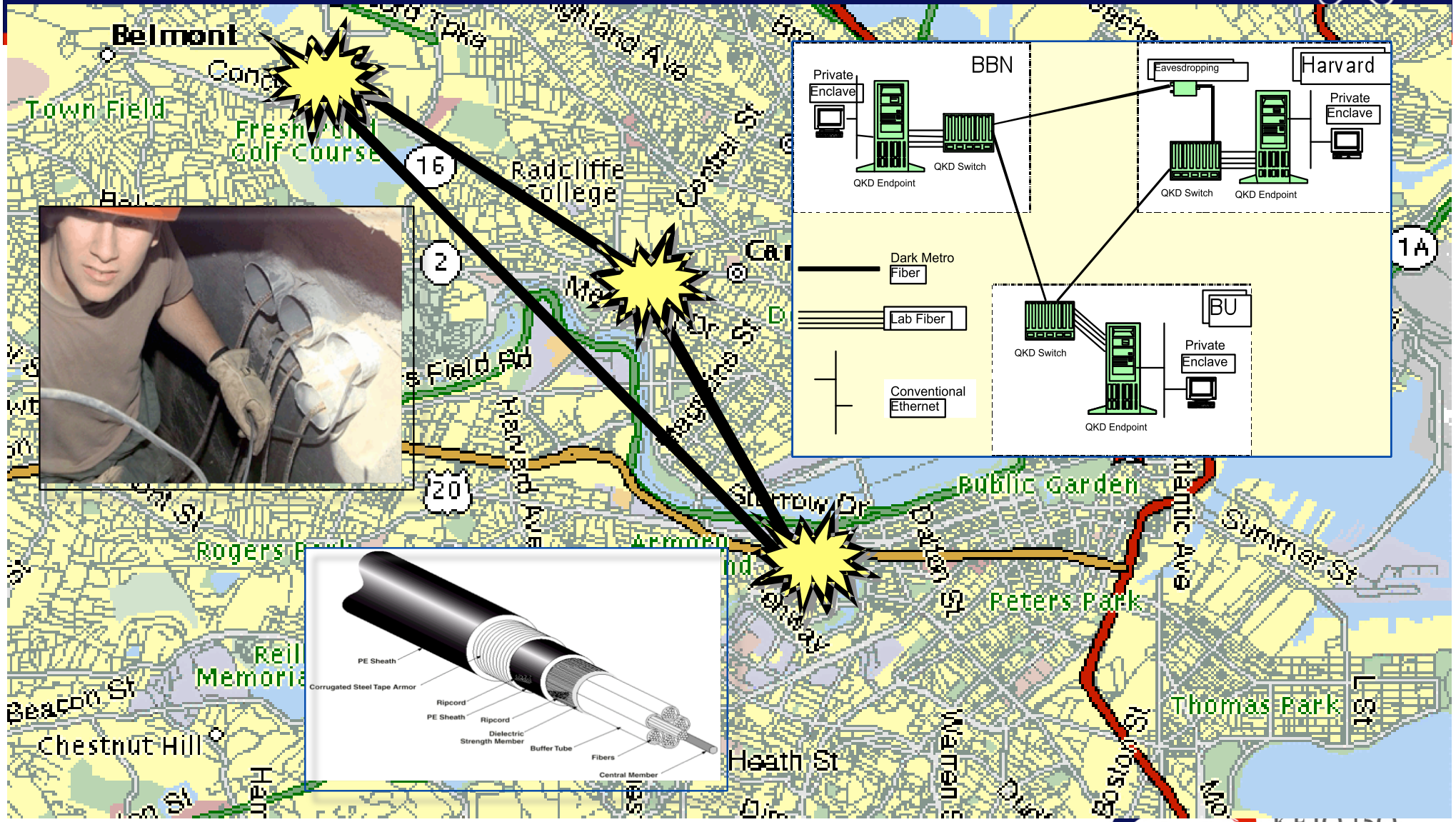
Quantum Key Distribution (QKD)

- Creates a *shared, random secret* between two nodes
- Uses physical effects to guarantee that key has not been observed
- Requires authenticated classical channel
- Limited to <150km per hop

IPsec with QKD



The DARPA Quantum Network



slide from Elliott, BBN

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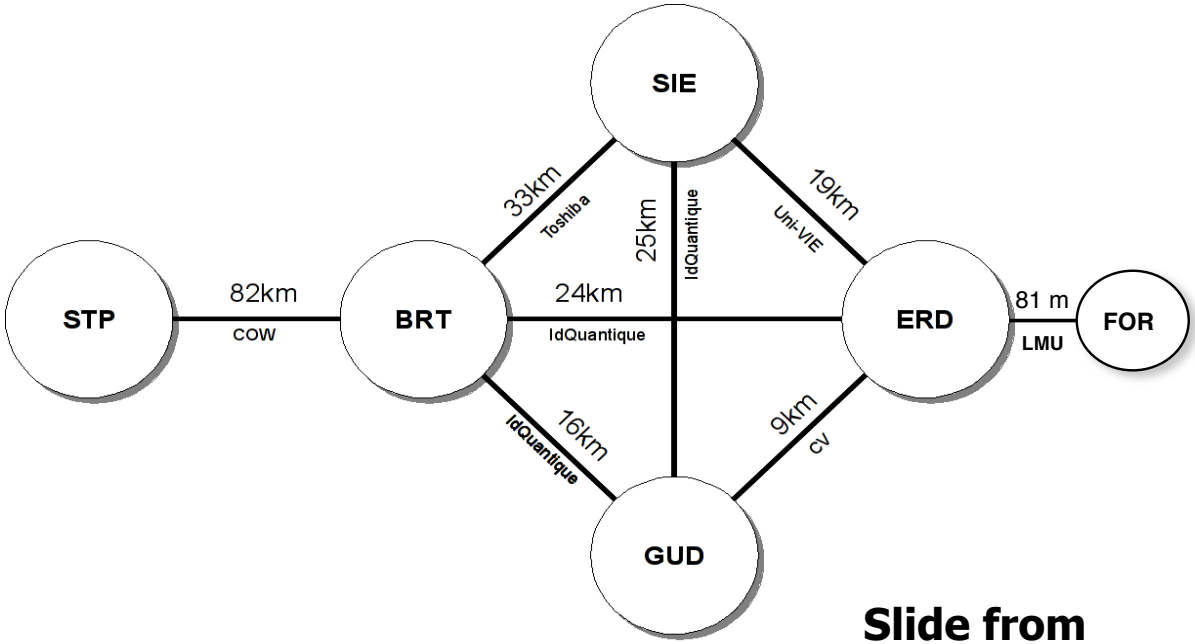
SECOQC Prototype – principle layout



Slide from M. Peev, 2008

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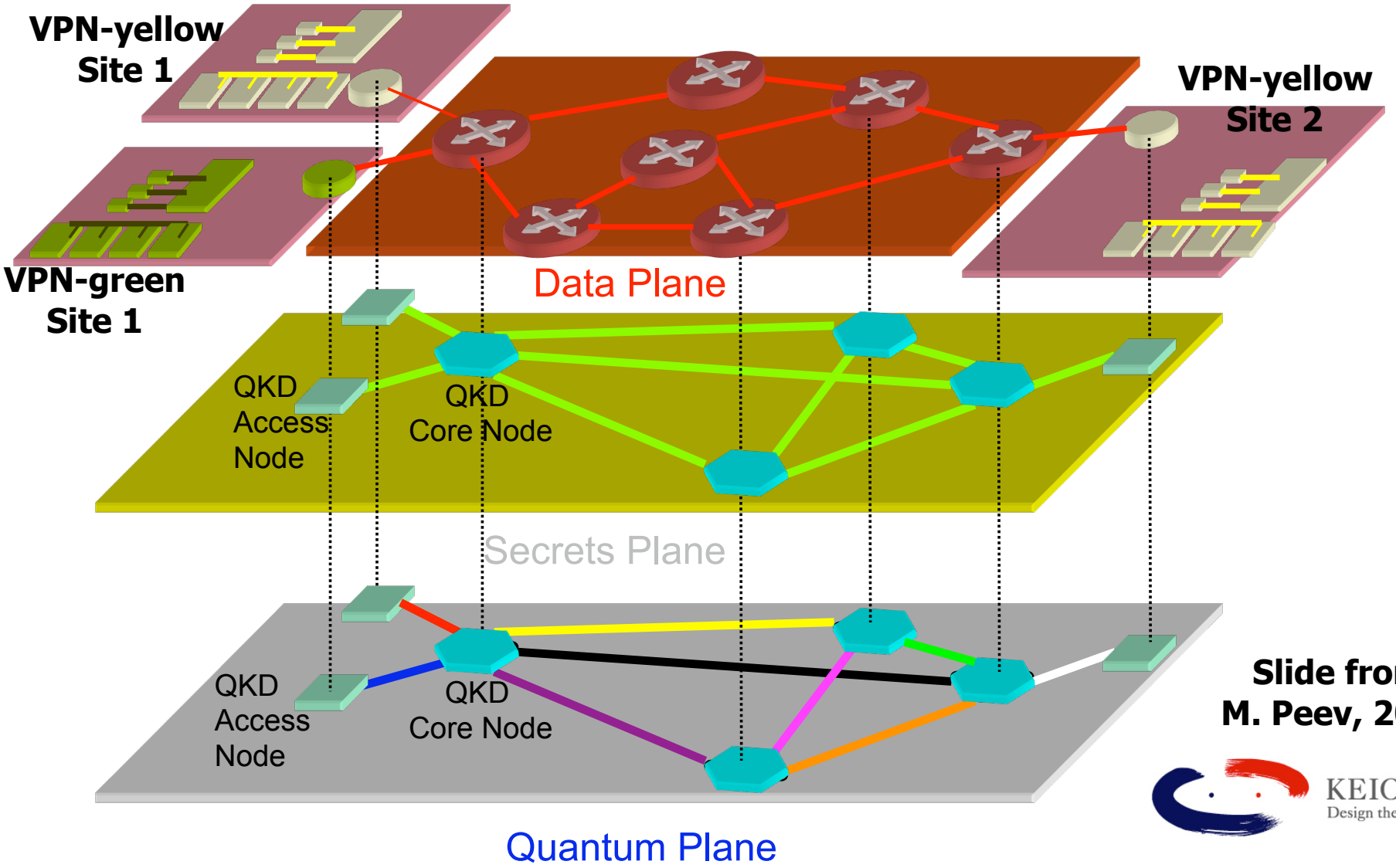
A Trusted repeater QKD-Network: Abstract Architecture (SECOQC, Europe)



Slide from M. Peev, 2008

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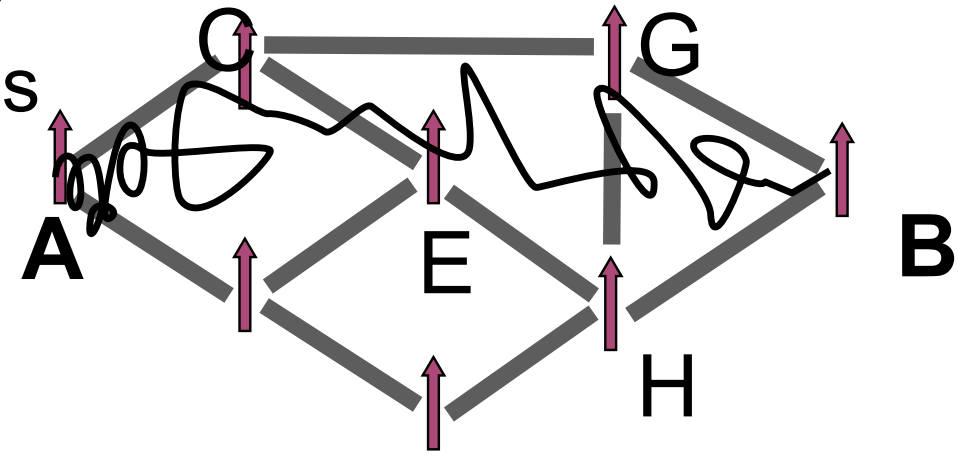
QKD with IPsec Plans

- Test over raw fiber, Yagami<->K2
- Use key for one-time pad
- Work w/ NEC, BBN & ITU to standardize
- Write experimental I-D on IKE changes
- Take to IETF in Hiroshima?

Outline

- Two types of quantum networks
- IPsec with QKD
  - IPsec with QKD
  - US & European efforts
  - Open problems & plans
- **Repeaters**
  - **Basic concepts**
  - **Our recent results**
  - **Open problems & plans**



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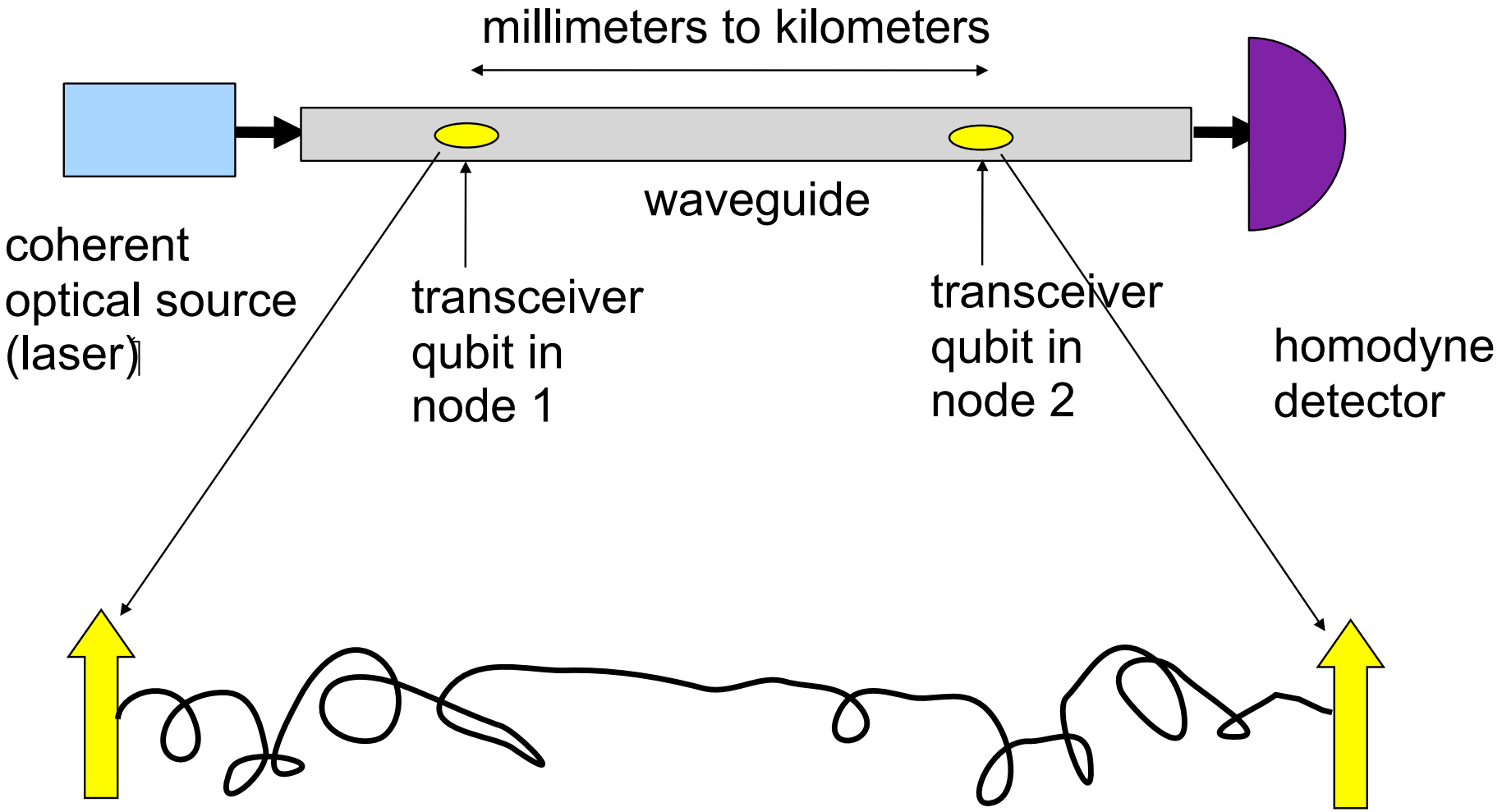
Network Link Technology (Qubus)



Munro, Nemoto, Spiller, New J. Phys. 7, 137 (2005)

Ladd et al., NJP 8, 184 (2006)

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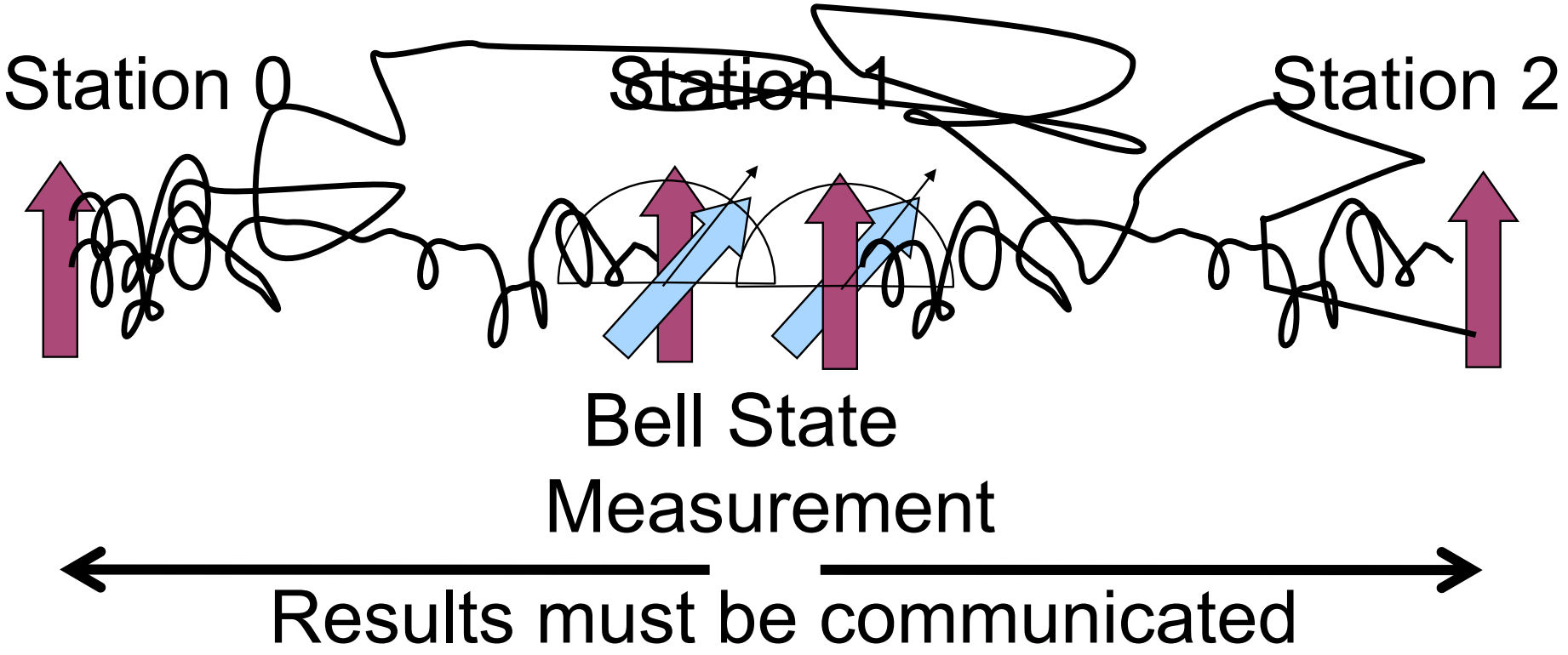
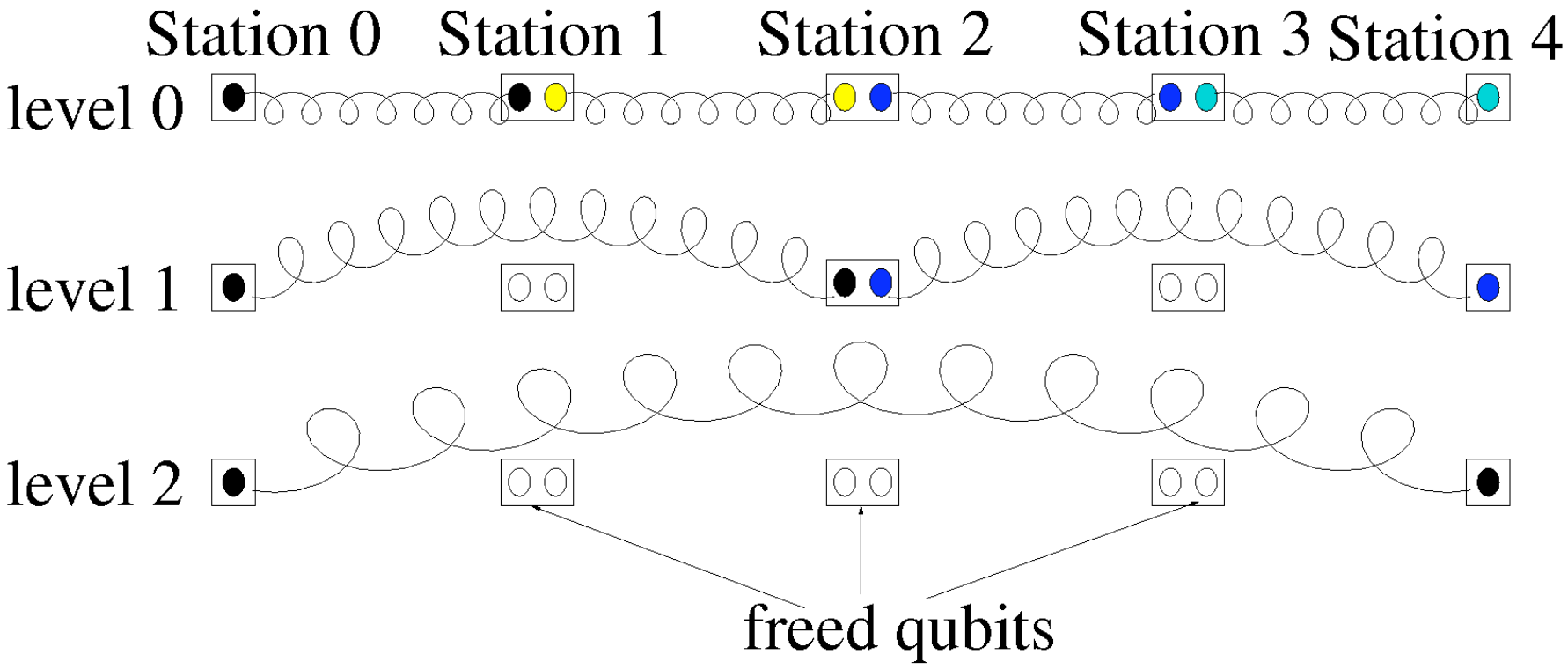
Quantum Repeater Operation: Entanglement Swapping



Fidelity decreases; you must *purify* afterwards

Nested Entanglement Swapping



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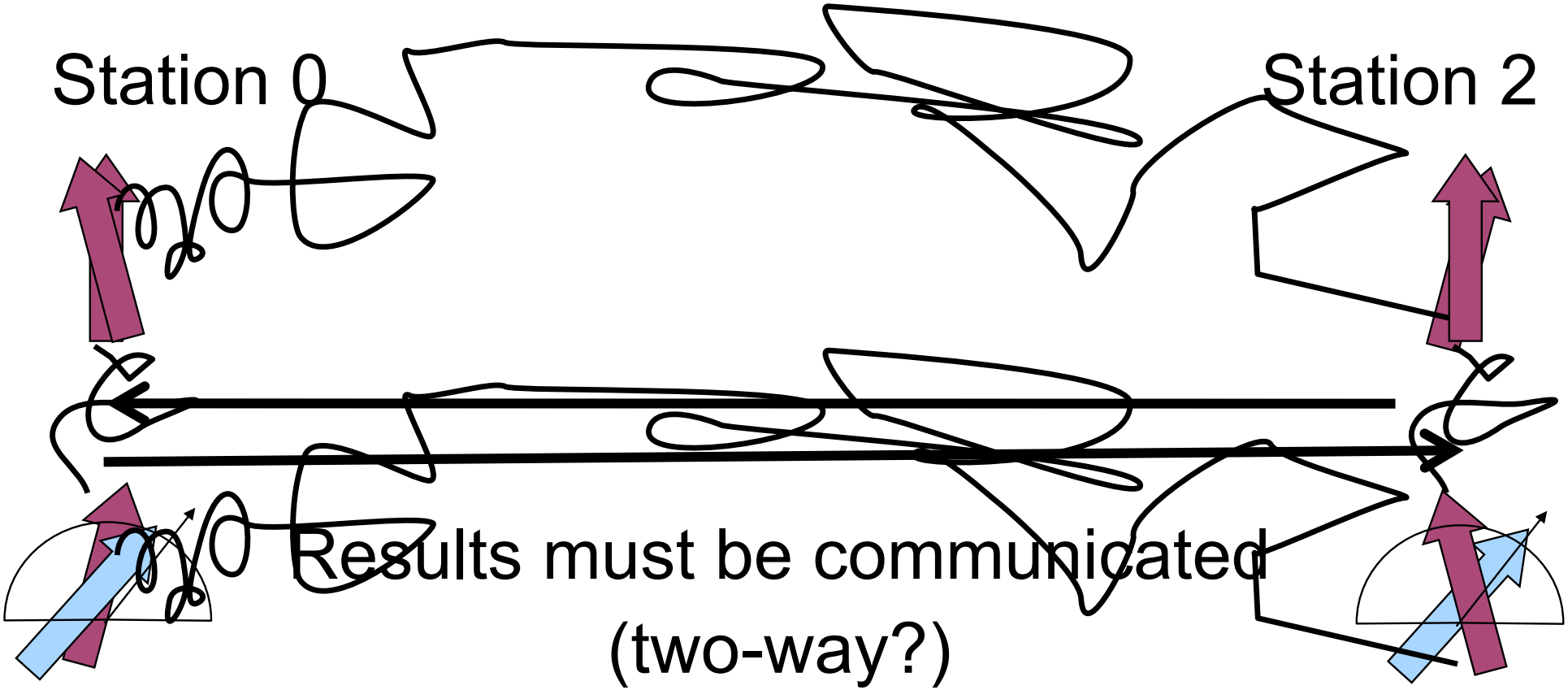
Purification



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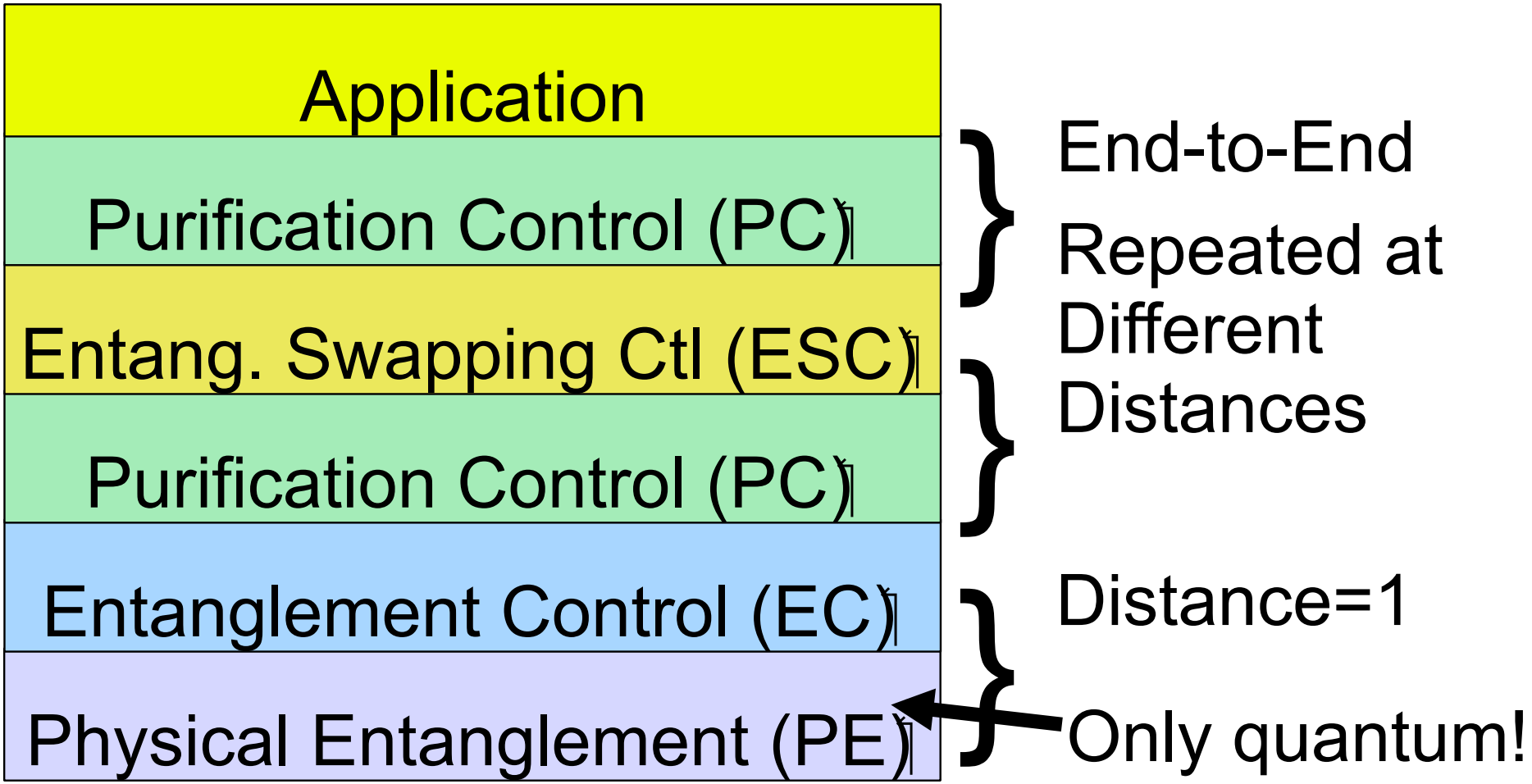
Repeater Protocol Stack



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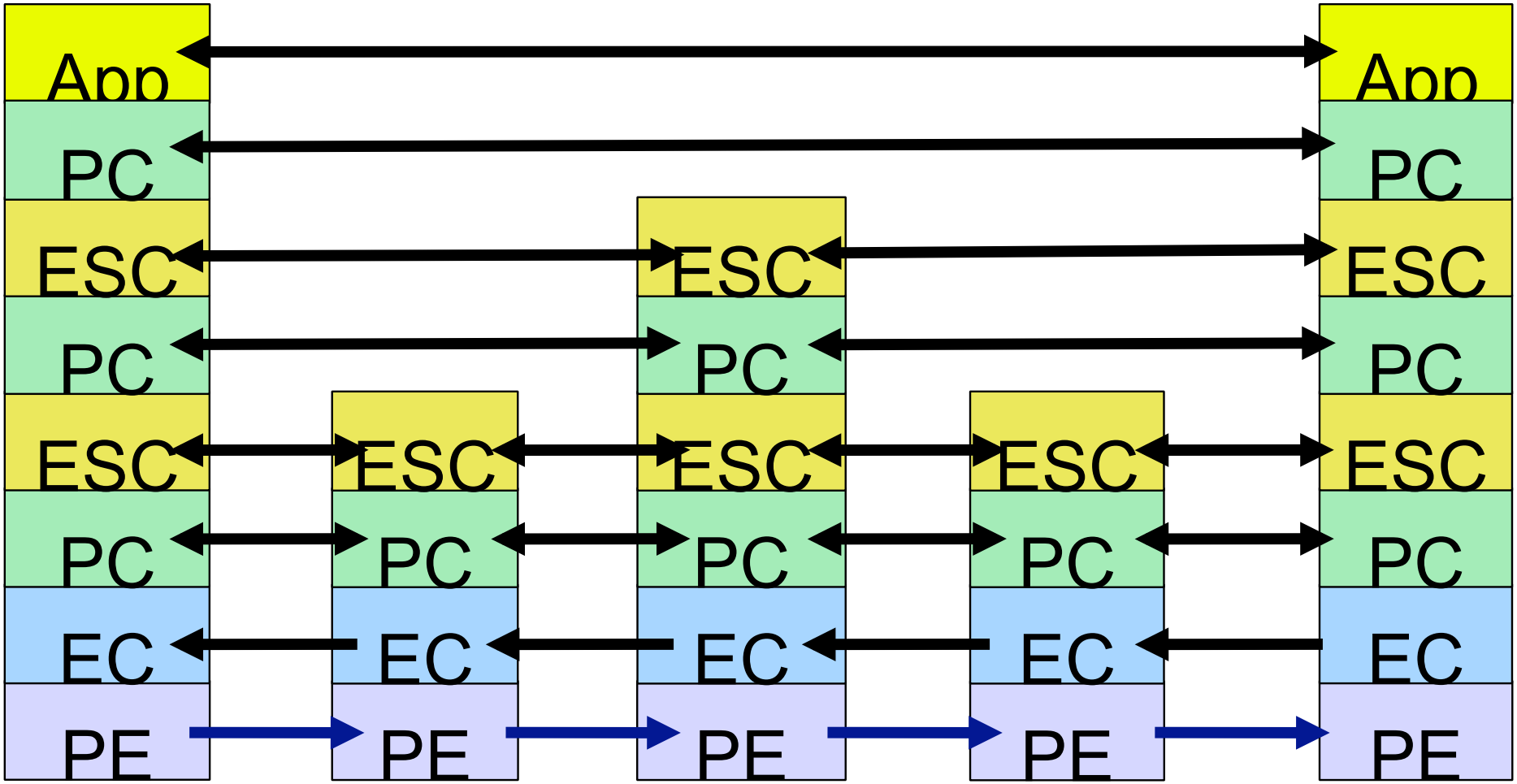
Four-Hop Protocol Interactions



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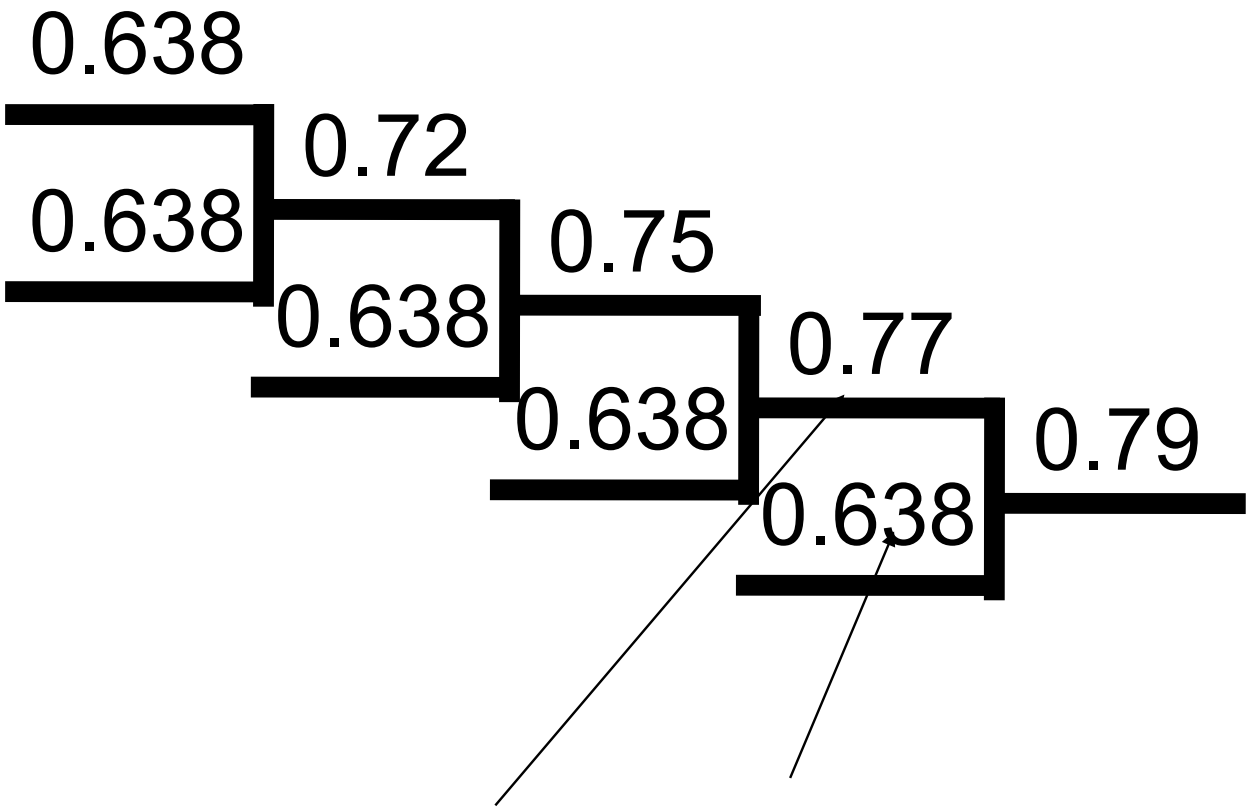
The Repeater's Jobs

Entanglement swapping & purification, which require:

- A little bit of quantum communication
- Quantum memory
- Local quantum operations (gates & measurements)
- Lots of decision making (both local and distributed)
- Lots of classical communication

Entanglement Pumping



Ineffective w/ large fidelity difference

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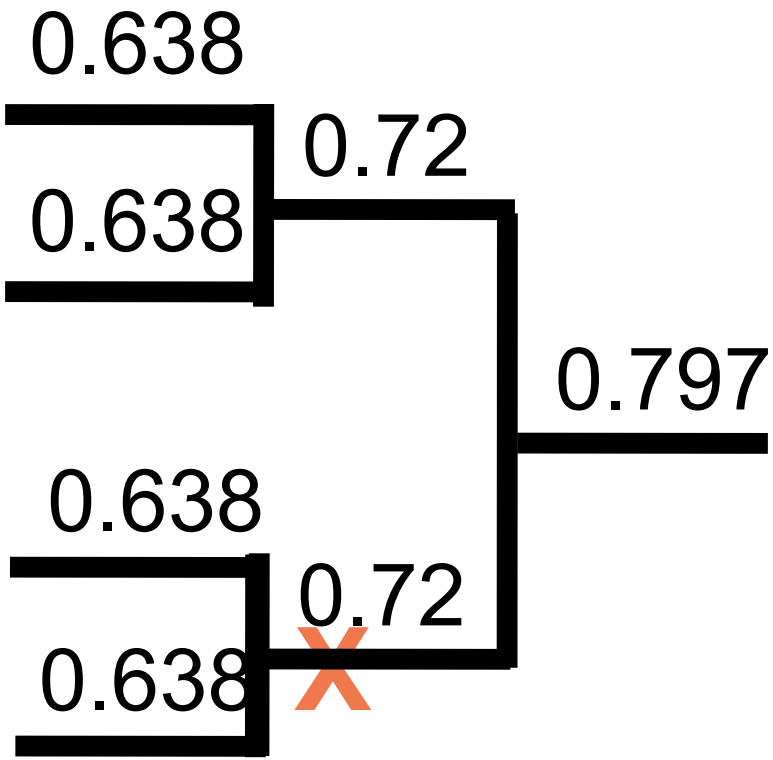
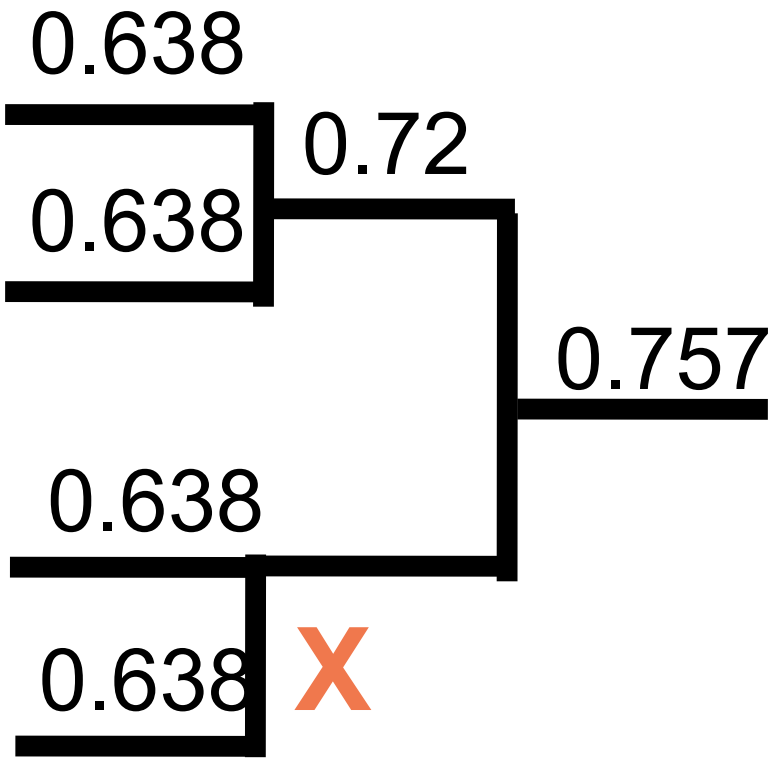
Symmetric Purification



Problems:
Exact matching can require long waits.
Not realistic when memory effects (decoherence) considered.
Can deadlock if resources are limited.

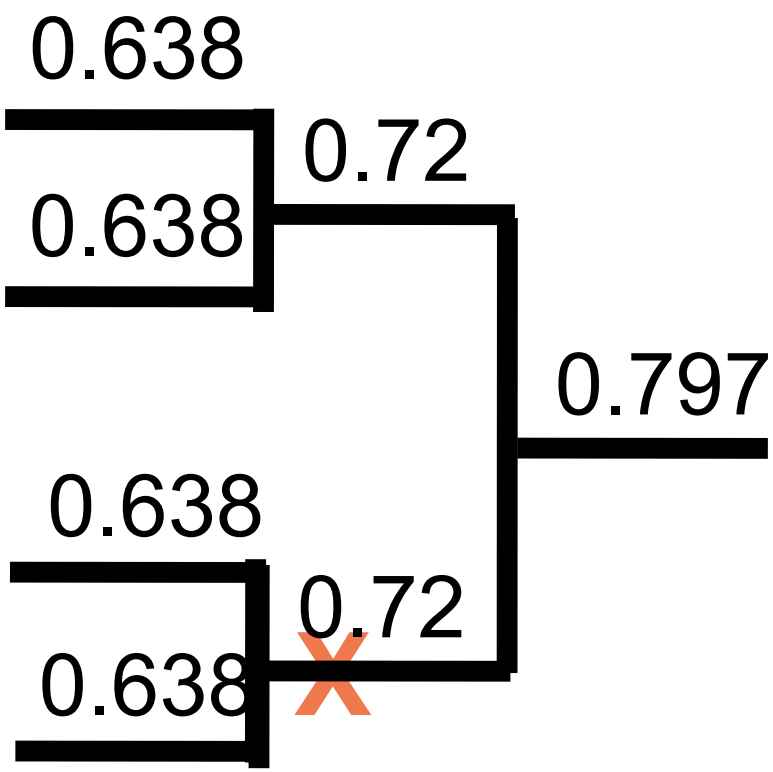
Greedy Purification



Doesn’t wait for anything, uses whatever’s available.

Works well w/ large number of qubits per repeater.

Banded Purification



Large gains in throughput.
Moderate # qubits (5-50).
Avoids deadlock.
Realistic memory model.
Simple to implement in real time (even in HW).
Probably not optimal, but probably close.

Divide fidelity space into multiple *bands*
e.g., above & below 0.70

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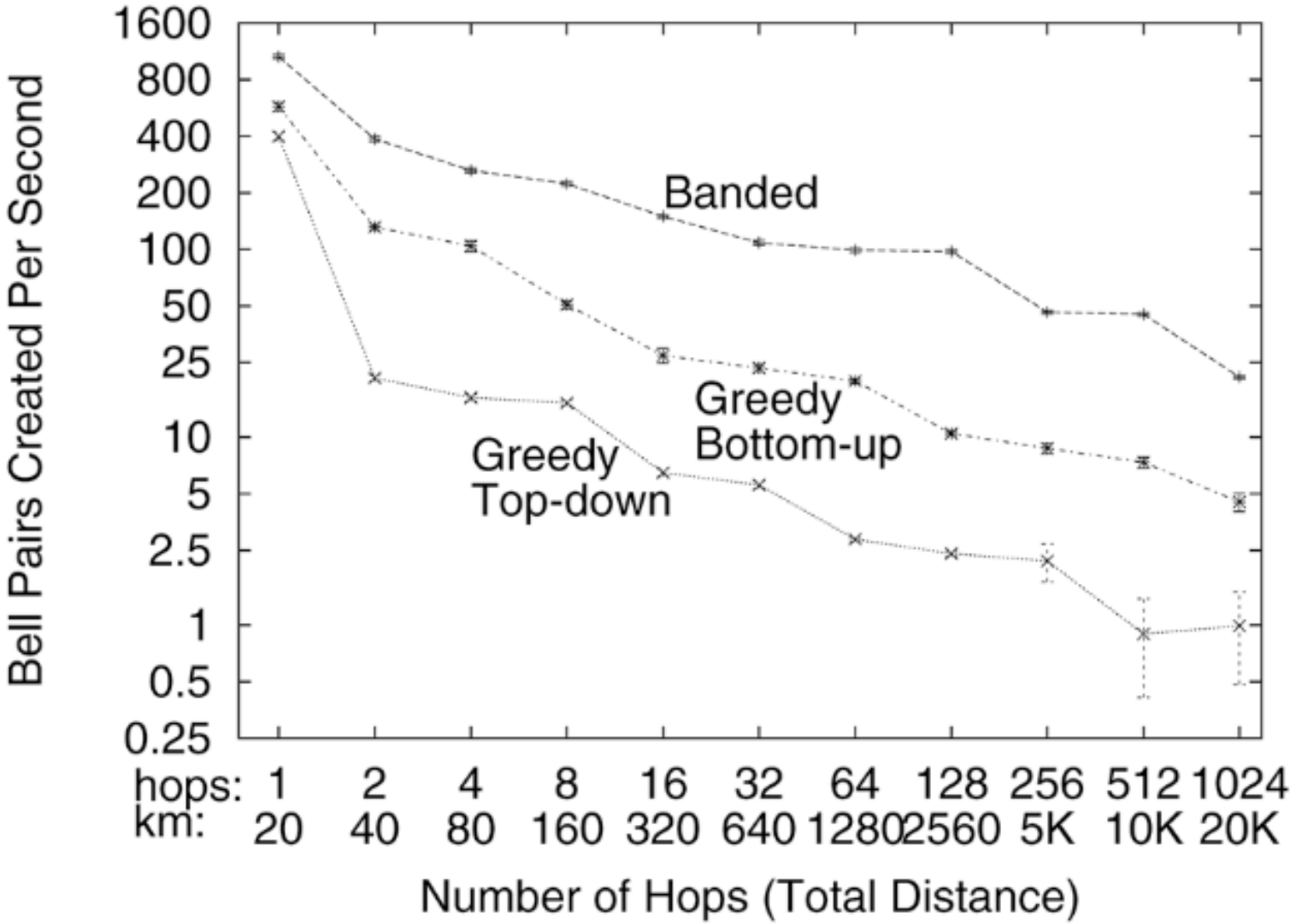
Banded Purification Performance



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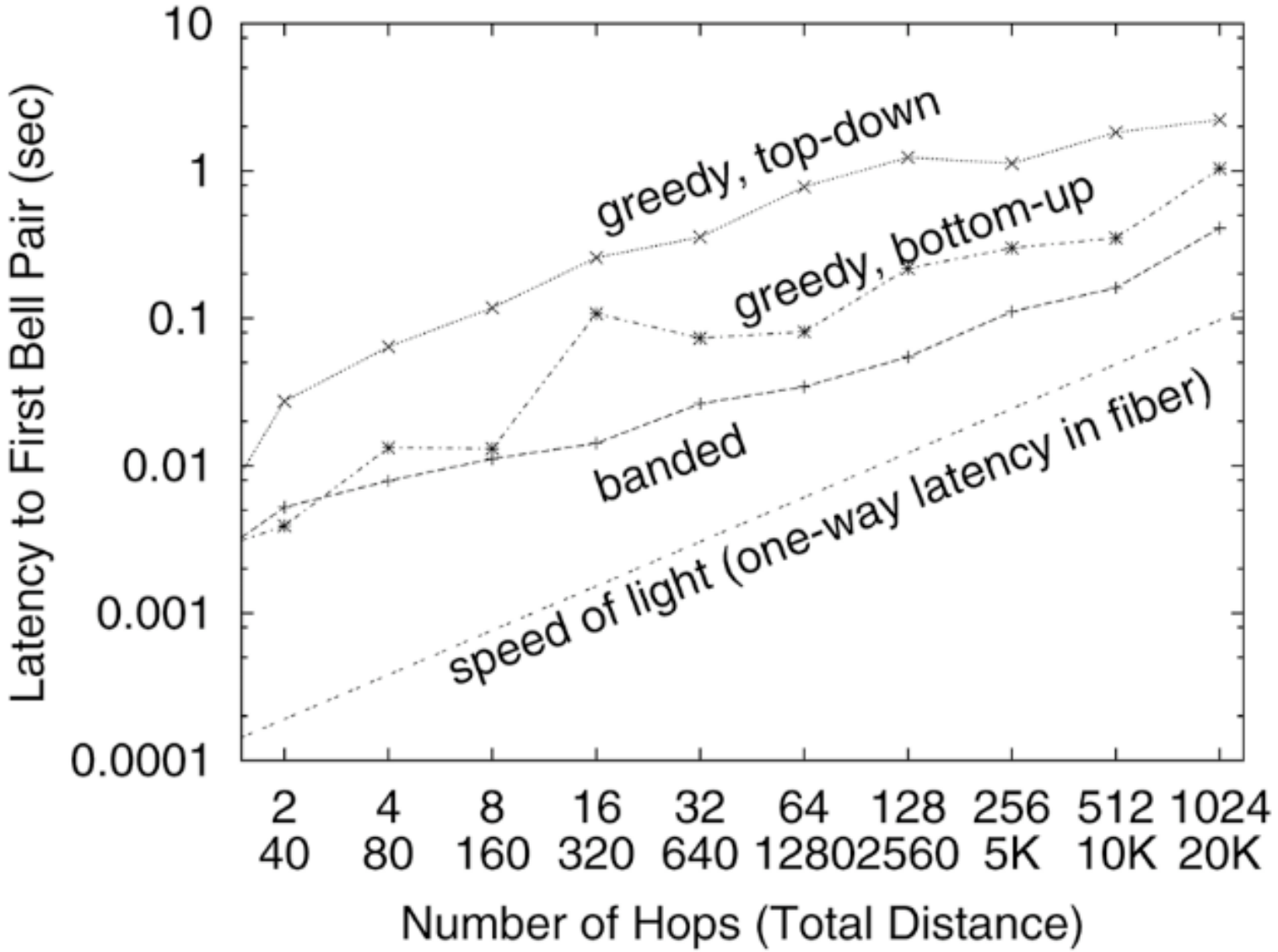
Banded Purification Latency



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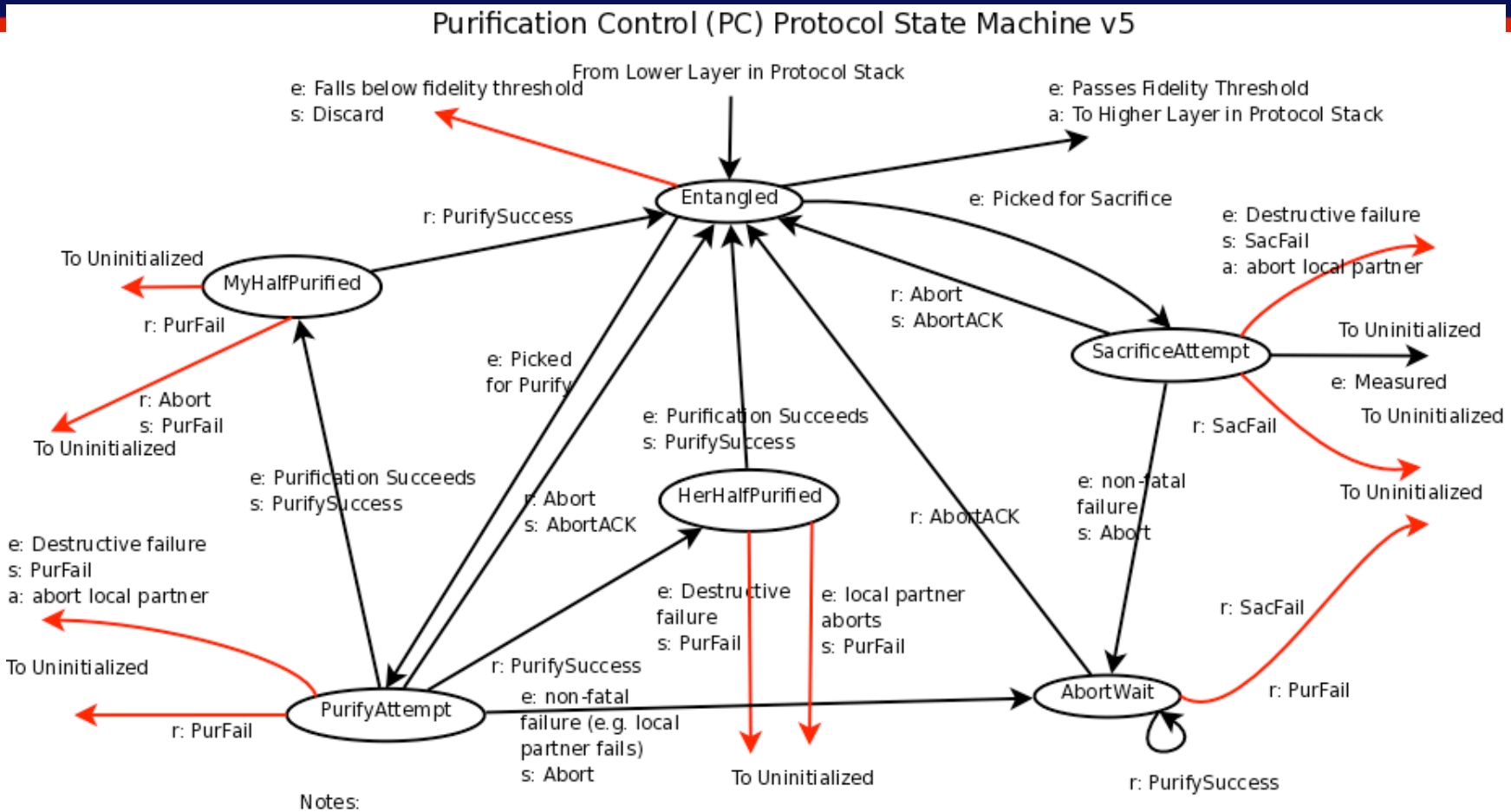
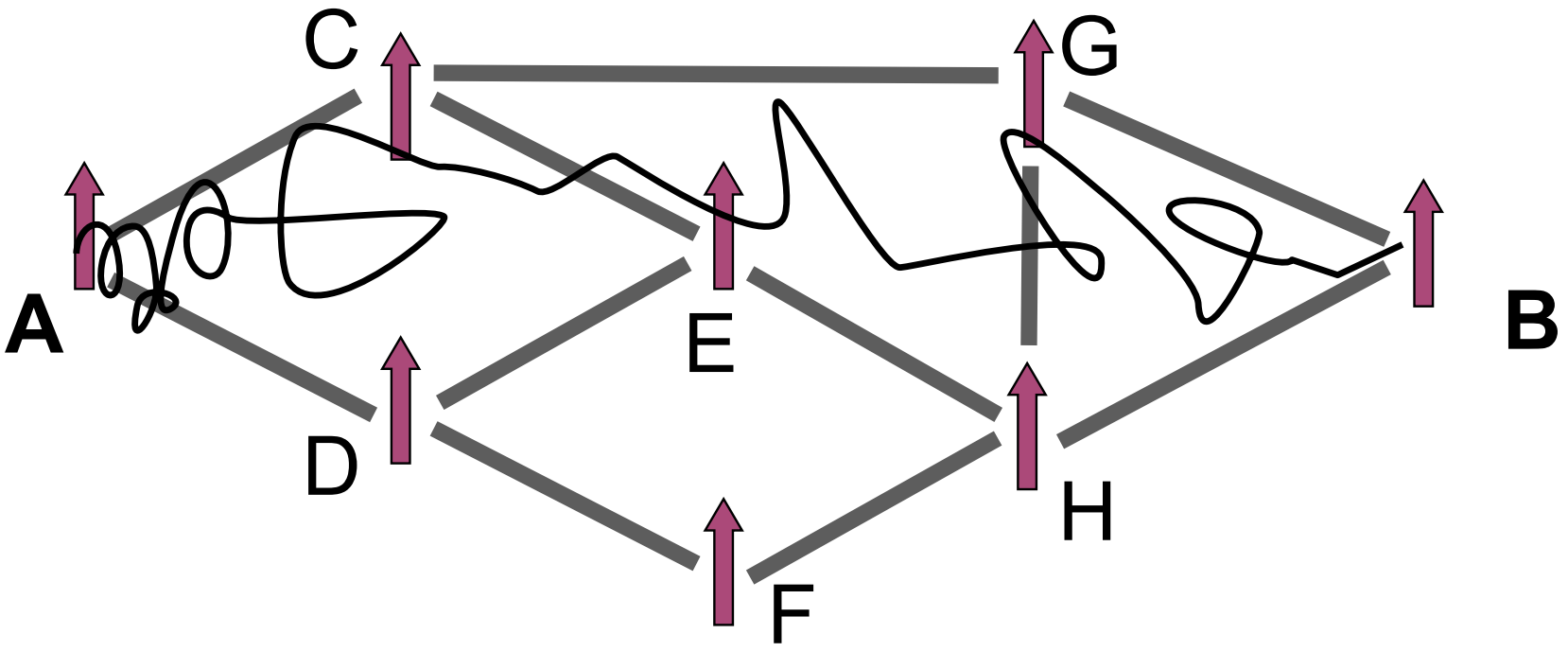
Protocol Design



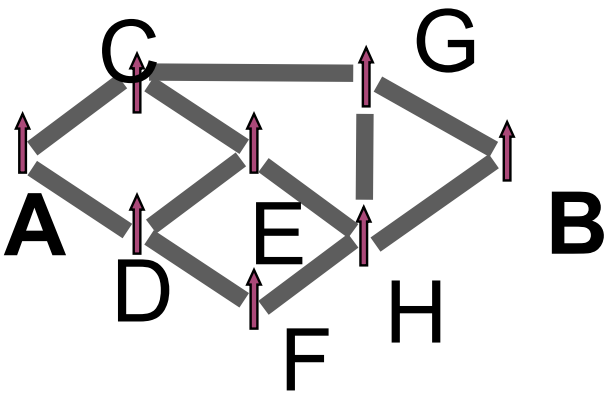
Routing



Simple: use Dijkstra's Shortest Path First.

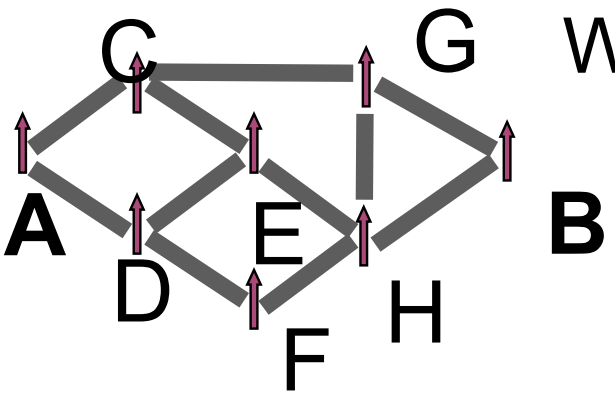
...but we don't yet know the cost metric.

A Different Meaning of "Which Path?"



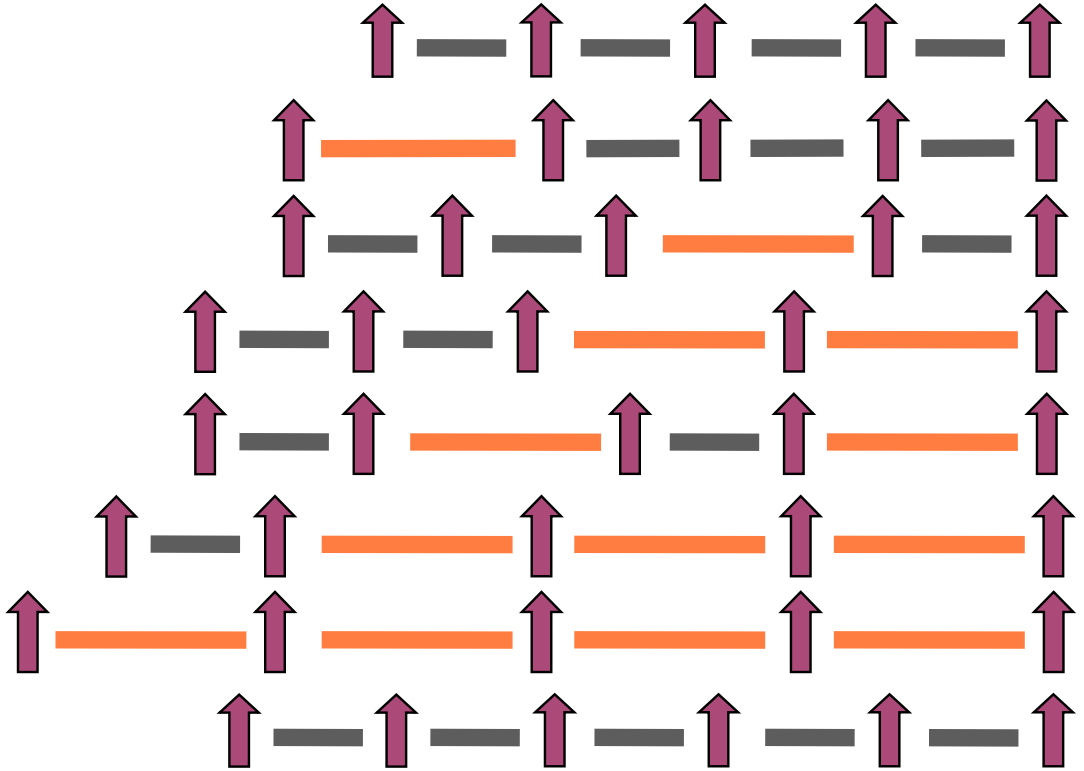
3 hops: ACGB
4 hops: ACGHB
ACEHB
ADEHB
ADFHB
5 hops: ACEHGB
ADEHGB
ADECGB
ADFHGB
6 hops: ACECGHB
7 hops: ADFHECGB
ACEDCHGB

But What is Distance?



What if hops are not homogeneous?

Are 2^n-1 hops,
2^n hops,
and 2^n+1 hops
significantly different?



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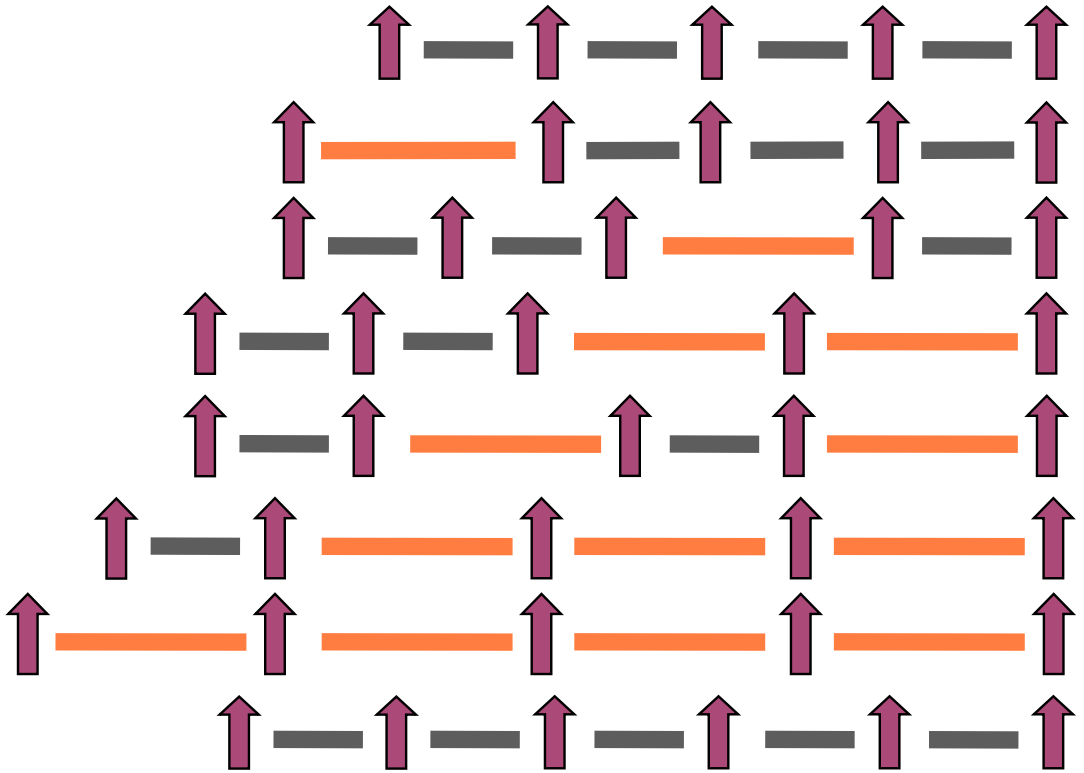
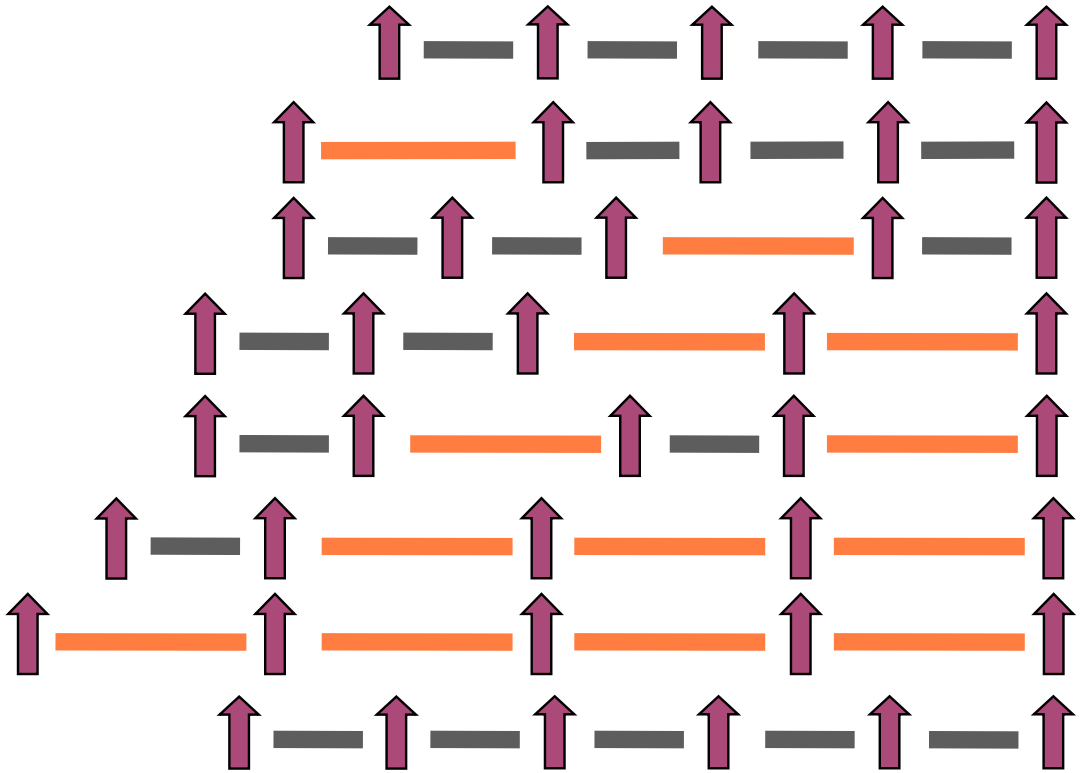
How Do We Order These?

- How does *number* of links matter?
- Does *number* of **weak** links matter?
- Does *position* of weak link matter?
- Is cost **additive?**
- At this logical level, is this technology-independent?



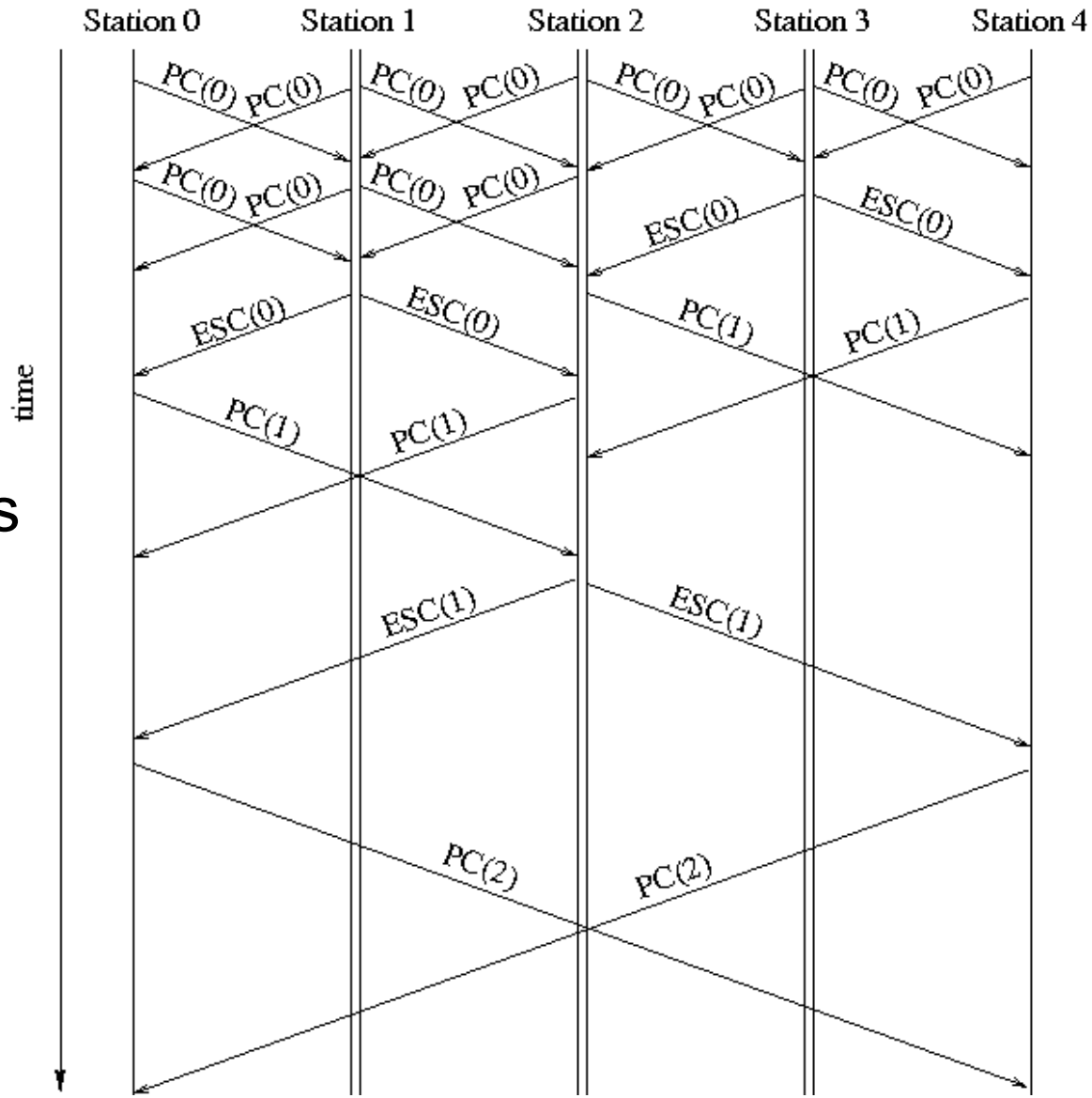
Other Problems

- Defining swap points
- Static or dynamic?
- Avoiding leapfrog
- Avoiding deadlock
- Minimizing waits for classical messages

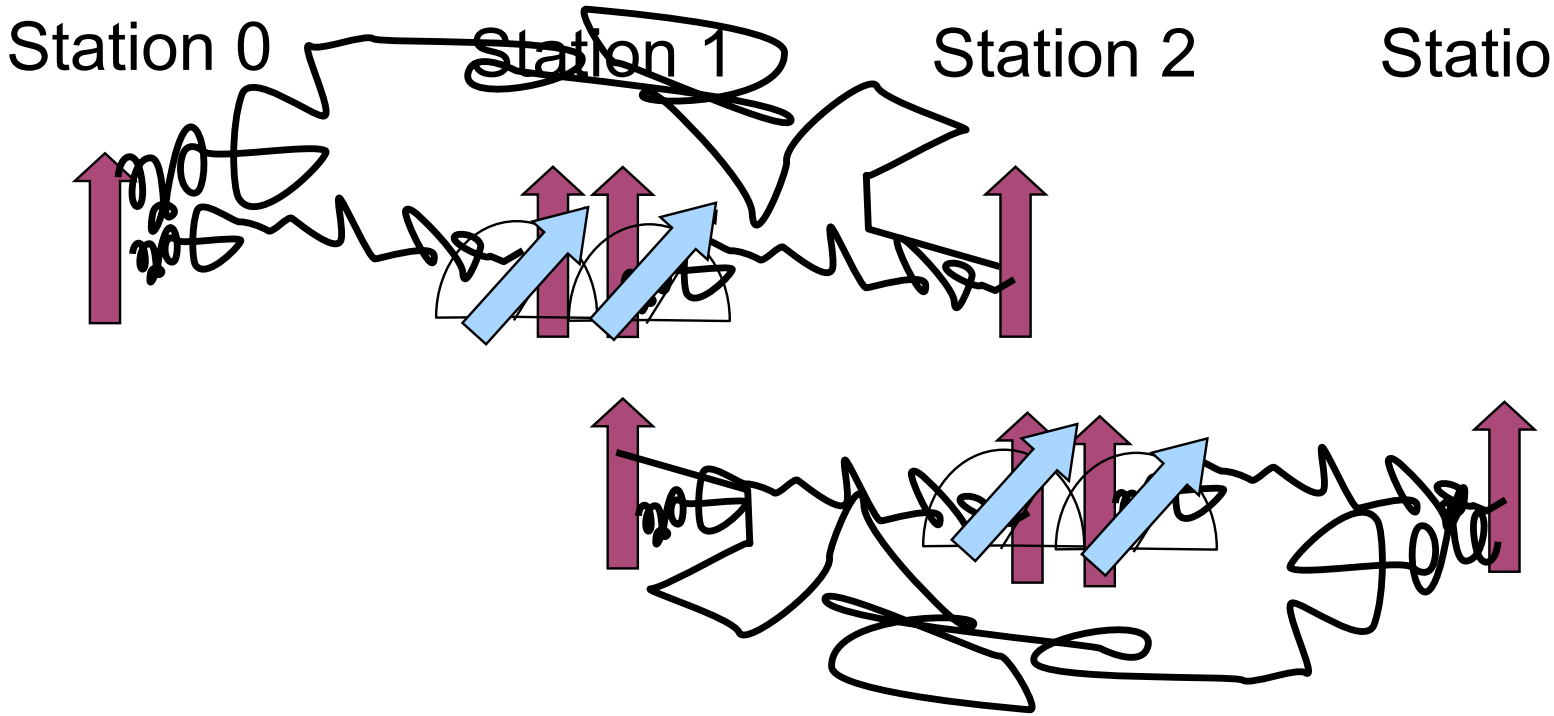


Other Problems

- Partial messaging sequence
- Can this be made more efficient?
- Due to memory degradation, gains will be better than linear



Leapfrog



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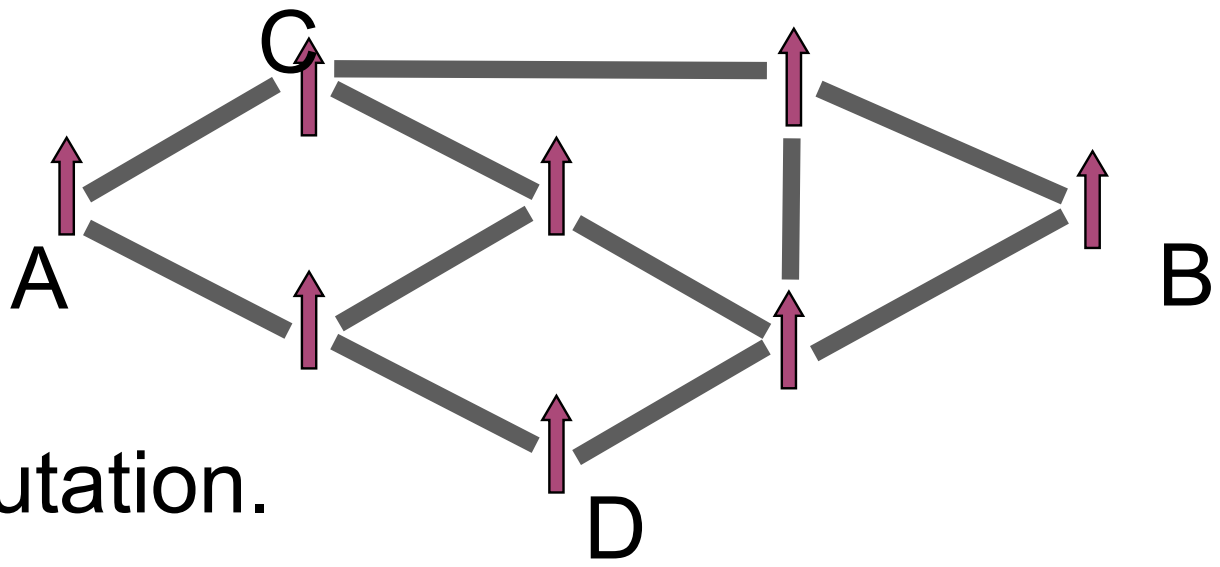
Resource Management (QoS?)

A<->B & C<->D want to talk.



Remember, it's a *distributed* computation.

Worse, fragile quantum memory means there is a *hard real time* component.

==>requires *circuit switching*???
(bottleneck likely is memory per node)

Open Repeater Problems

- Well, repeater HW doesn’t work yet...
  - Sims of “weak links” mostly functional
  - Establishing swapping points
  - More dynamic behavior
  - Non-power-of-two hops
  - Finish & publish protocol state machine

Open Complex Network Problems

- Coding partially done
  - Using graphviz file format
  - Routing not done
  - Workload generator needs work
  - QoS / resource allocation not implemented
- Visualization of networks
- Investigate graph states & quantum network coding
- More detailed workload definition

Milestones for JSPS

- Define a cost metric
  (figure out if it's additive!)
- Define a path selection algorithm
- Define test cases
- Simulate that set of test cases
- Extend to topologically complex networks
- Create static visualizations

Food for Thought

- When will first *Science* or *Nature* paper appear *using* a quantum computer, but not *about* the quantum computer?
- That is, when will a quantum computer ***do*** science, rather than ***be*** science?
- Answers from quantum researchers range from “less than five years” to “more than forty years”

Thanks

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AQUA: Advancing Quantum Architecture