Minimum resource approaches to quantum communication and computation

Jake Taylor (jmtaylor@mit.edu)

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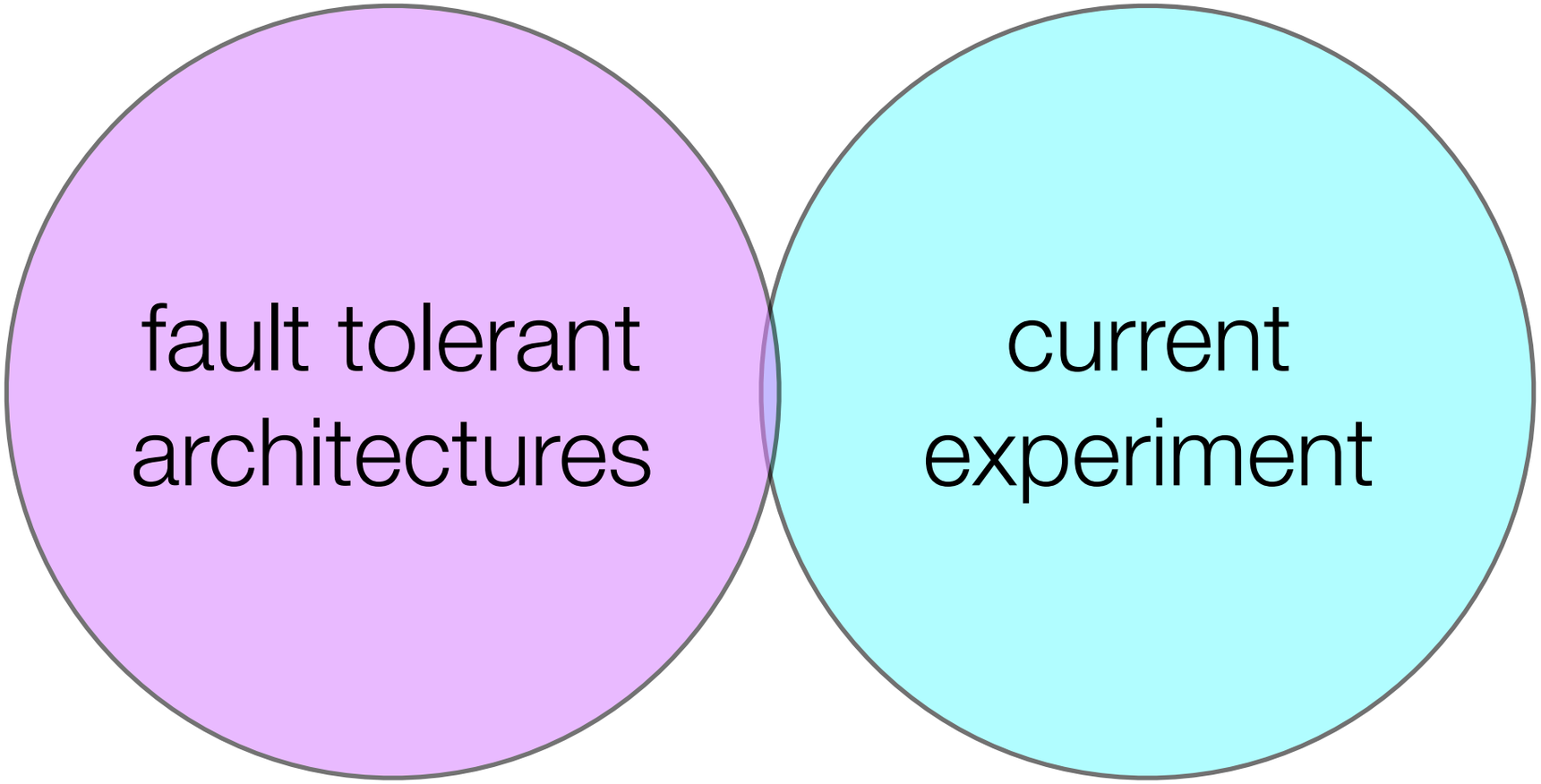
QEC 2007 @ USC

Massachusetts Institute of Technology

In principle...
Fault tolerant
thresholds reachable

In practice...
Experiments indicate
a hard systems problem



In principle...
Fault tolerant
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Premise: there exists an *evolutionary* path to large scale computation

fault tolerant architectures

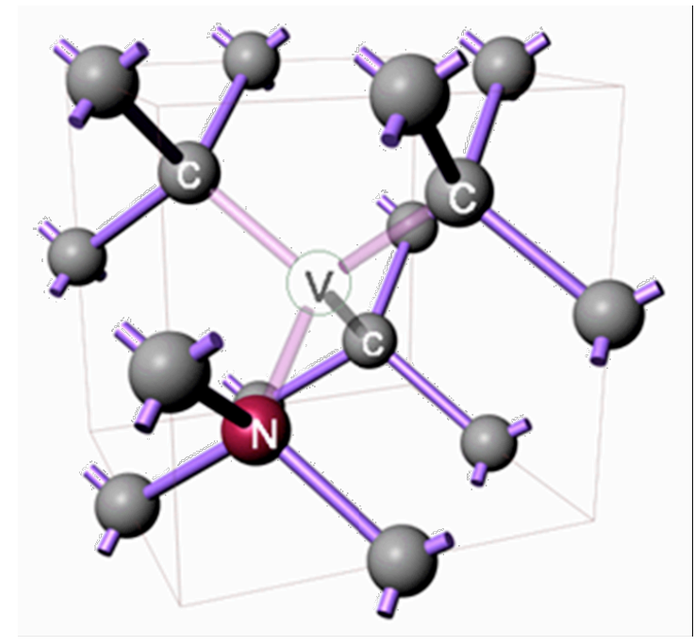
current experiment

Along the way:

- long-distance entanglement
- macroscopic quantum states
- new phases of matter

Current small-scale devices

- good quantum memory
- good local operations
- hard to scale to many qubits



NV centers in diamond

Georgia Tech / U Mich

Innsbruck

Sussex

Linear Paul traps

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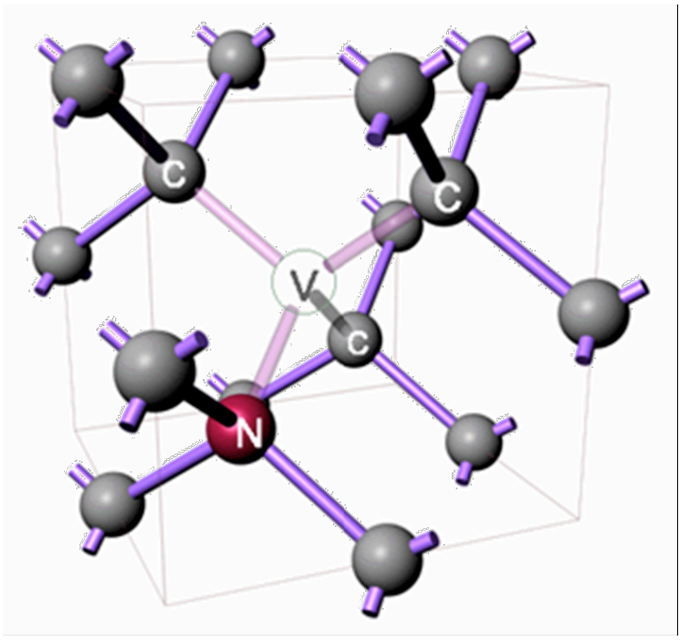

centers in
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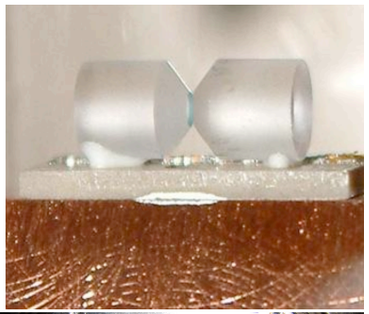
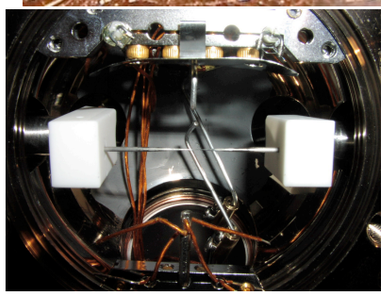
Immediate application: quantum communication





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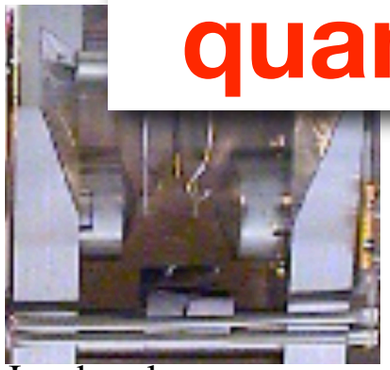

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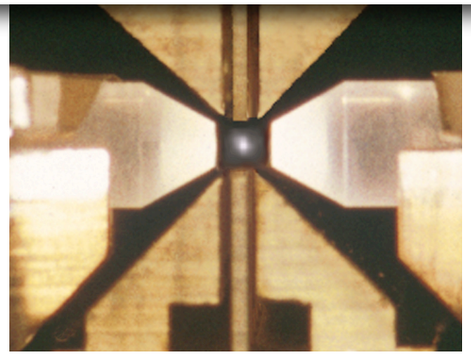

Sussex

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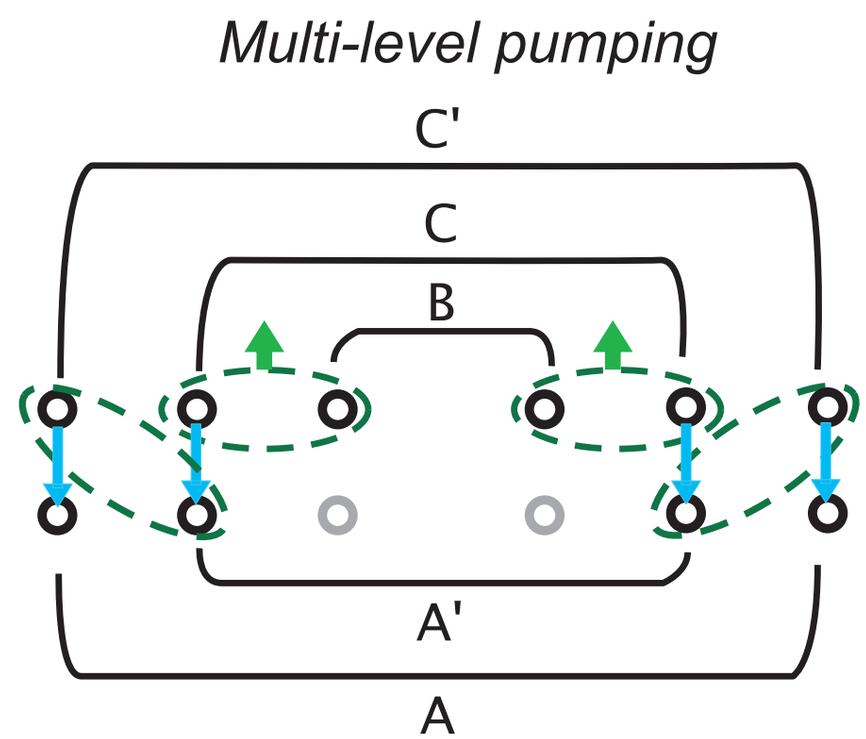
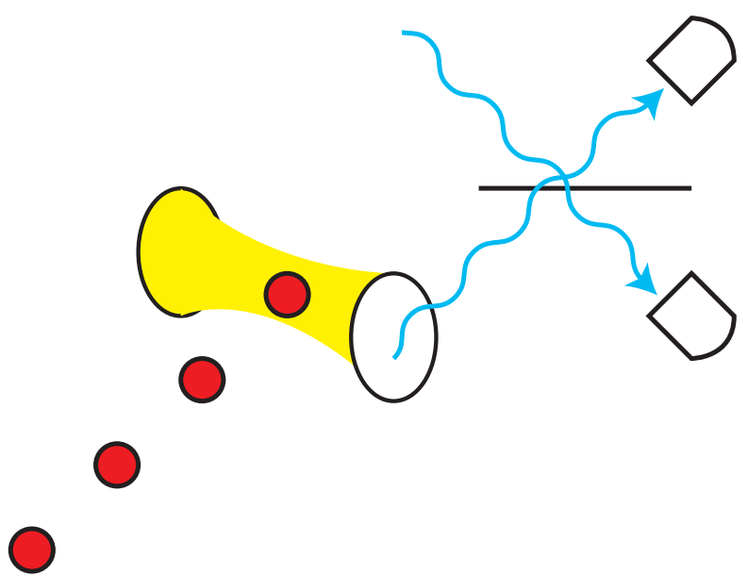
Focus of this talk

Optimizing quantum communication





Minimal resource distributed computing

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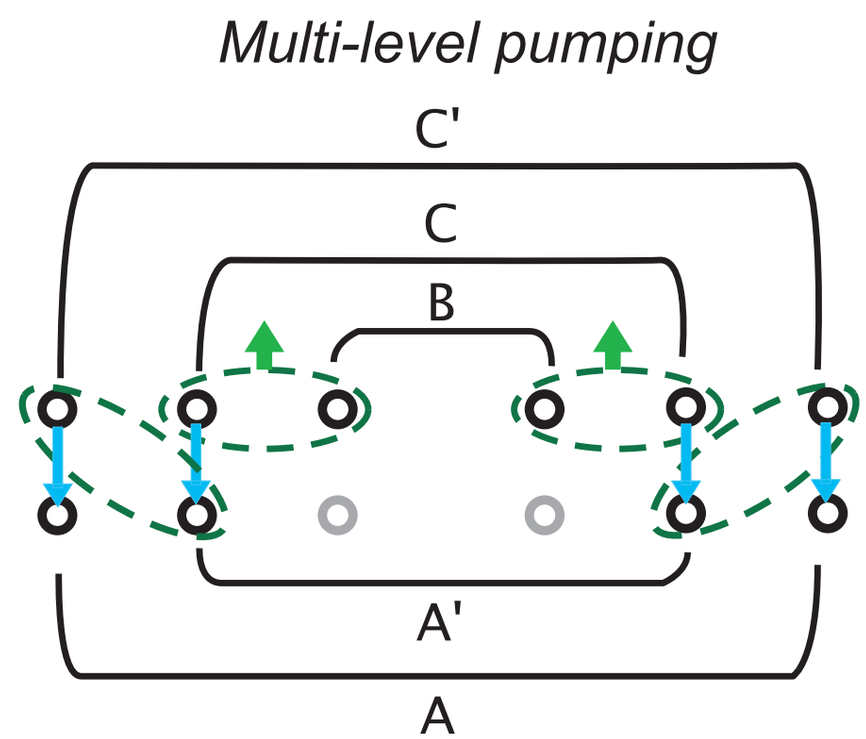
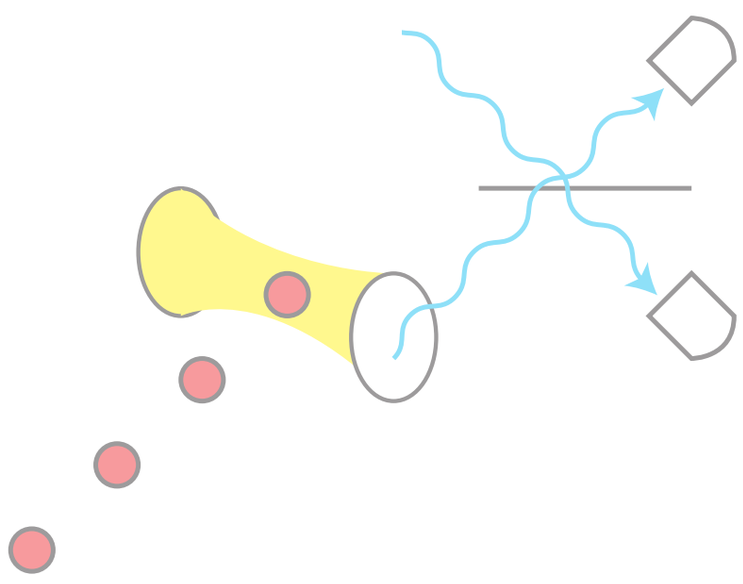
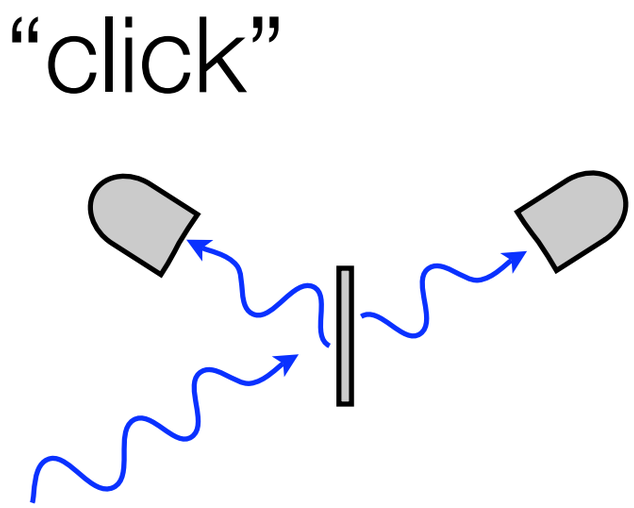




Minimal resource distributed computing

Photons, linear optics, and Bell states



incoming photons

$$\hat{a}_L \quad \rightarrow \hat{a}_L + \hat{a}_R$$

$$\hat{a}_R \quad \rightarrow \hat{a}_L - \hat{a}_R$$

- Beamsplitter rotates between modes
- Fock states mapped to entangled state

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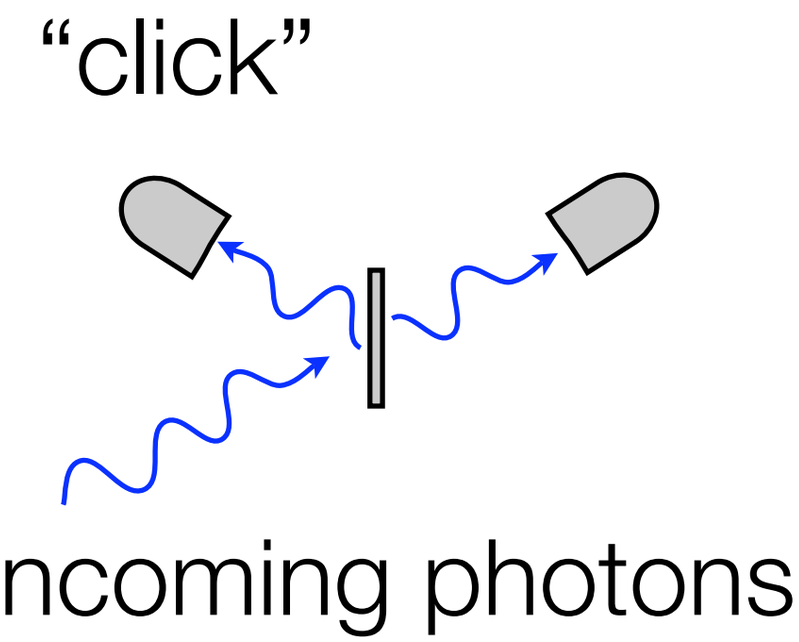

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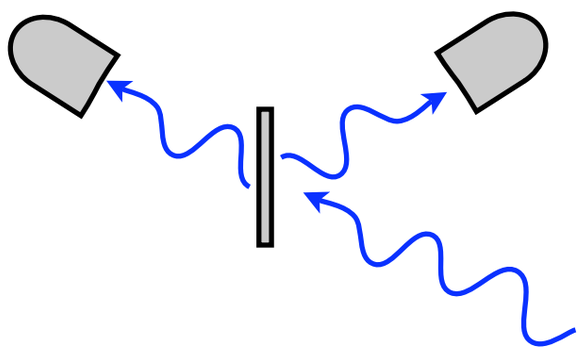
"left"–"right" entanglement

$$\hat{a}_L^\dagger|\mathrm{vac}\rangle \rightarrow \frac{1}{\sqrt{2}}(\hat{a}_L^\dagger + \hat{a}_R^\dagger)|\mathrm{vac}\rangle$$

$$\left(\; |10\rangle \rightarrow |10\rangle + |01\rangle \; \right)$$

Photons, linear optics, and Bell states

"click"



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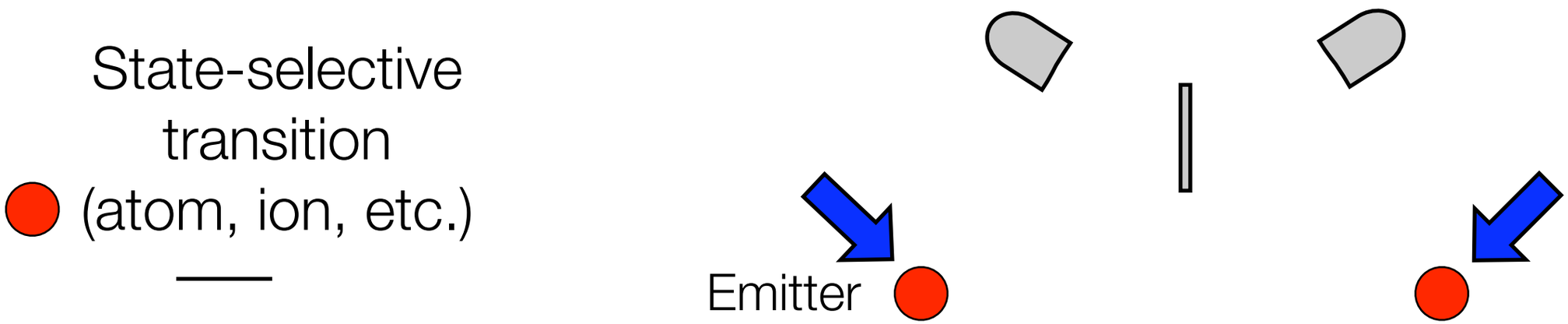
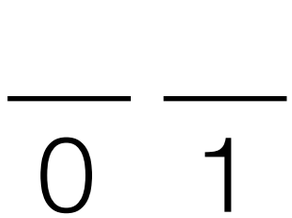
Using photons to build entanglement





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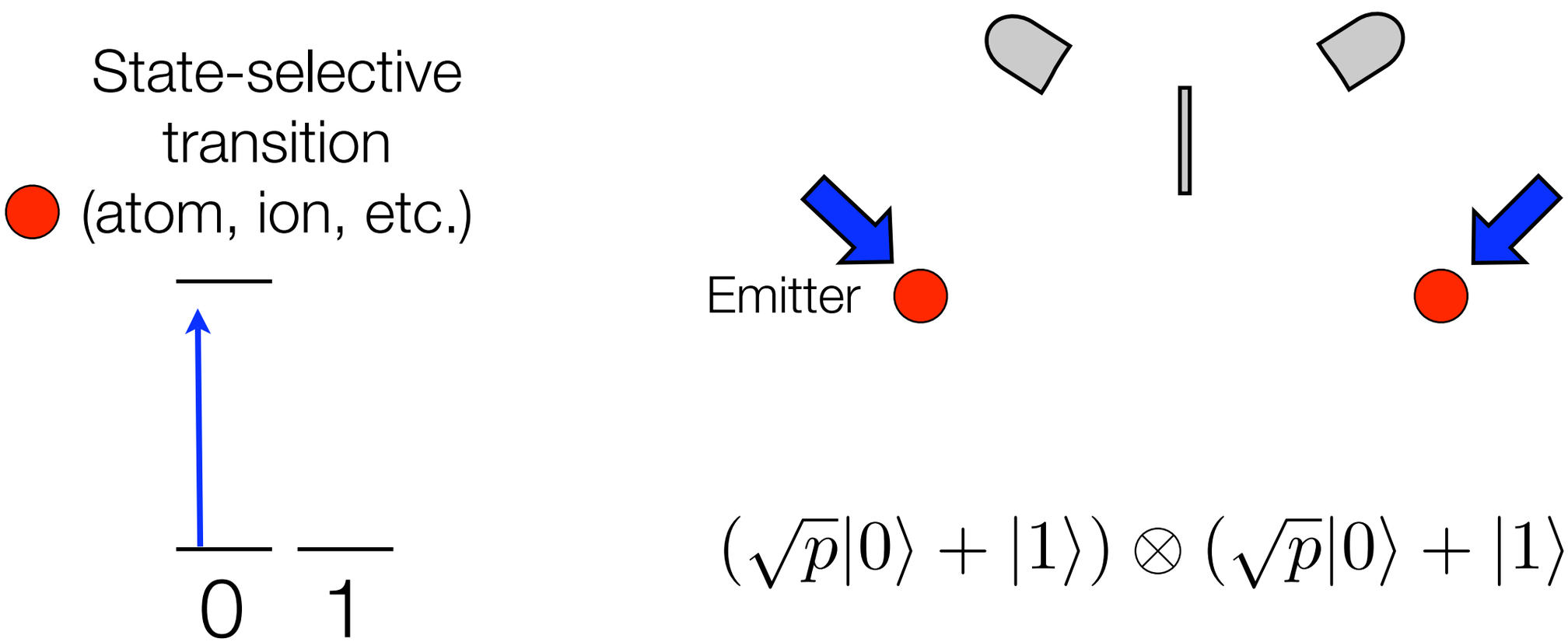

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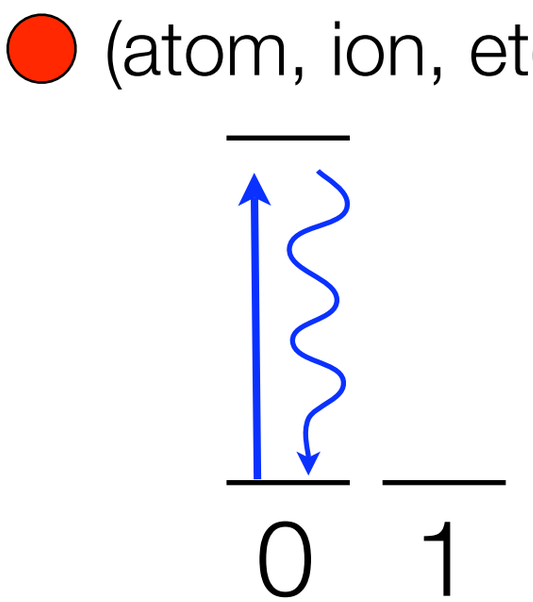

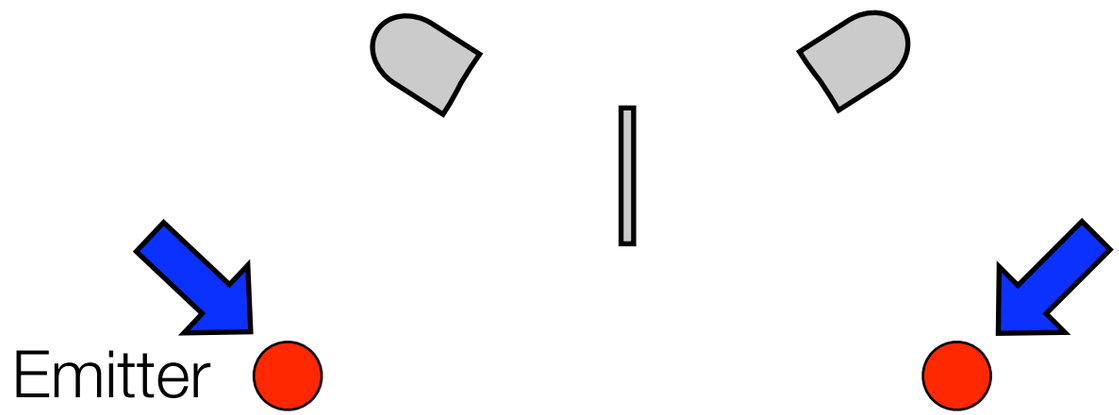

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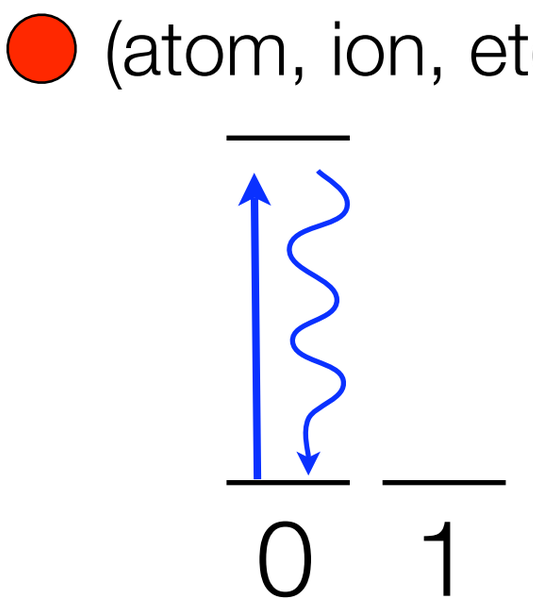

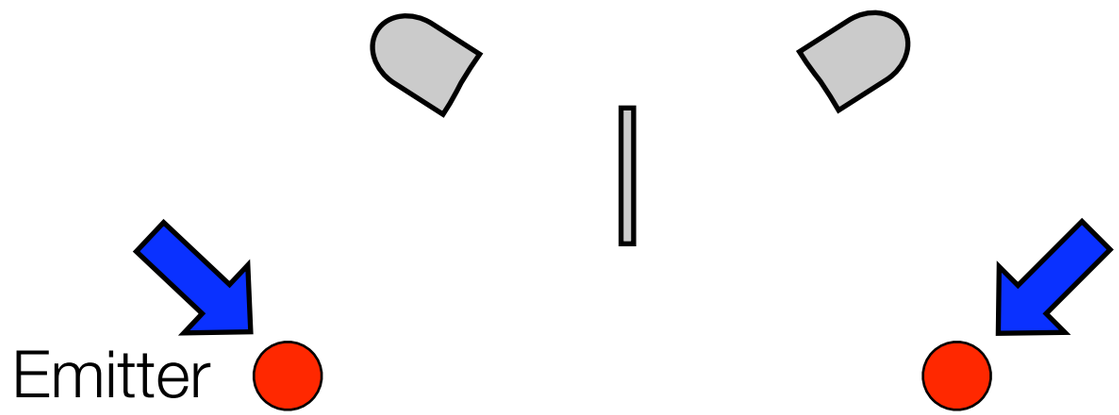

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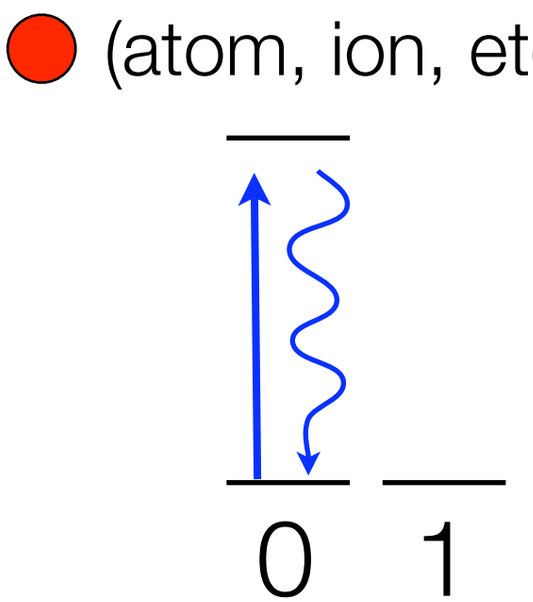

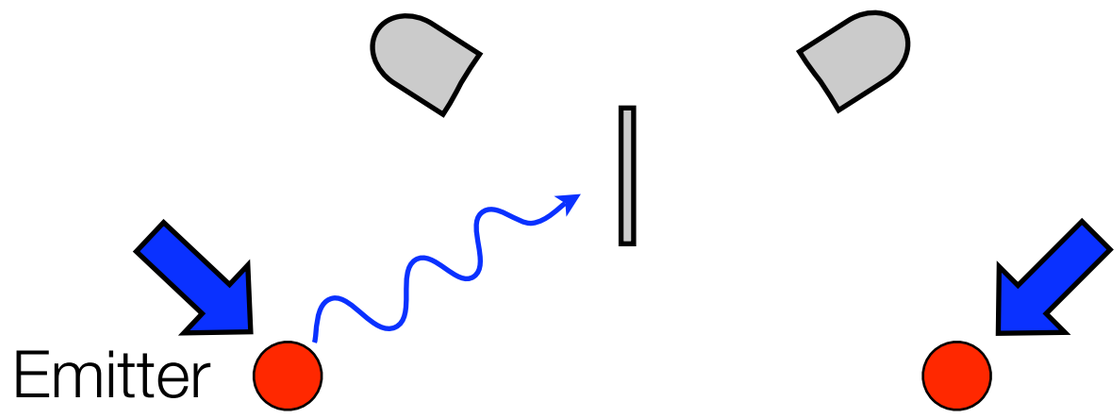

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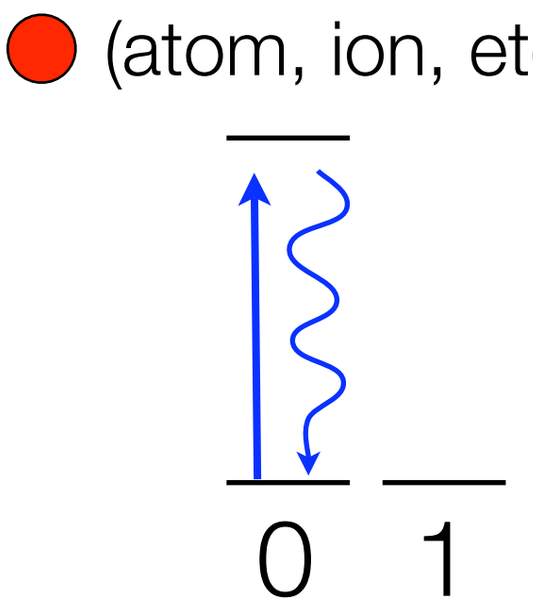

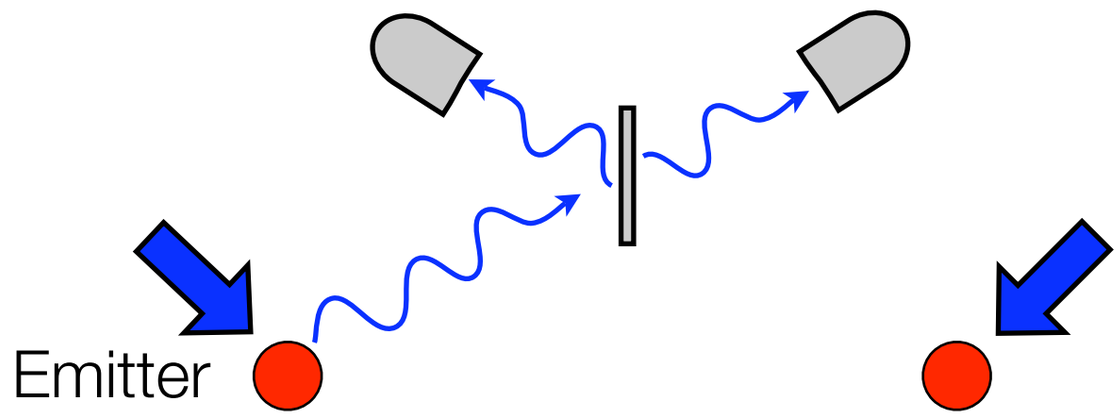

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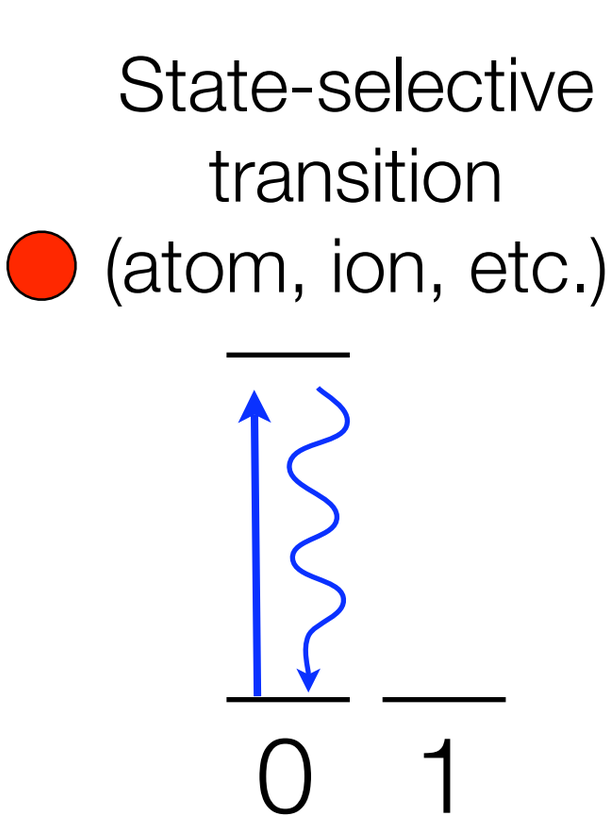

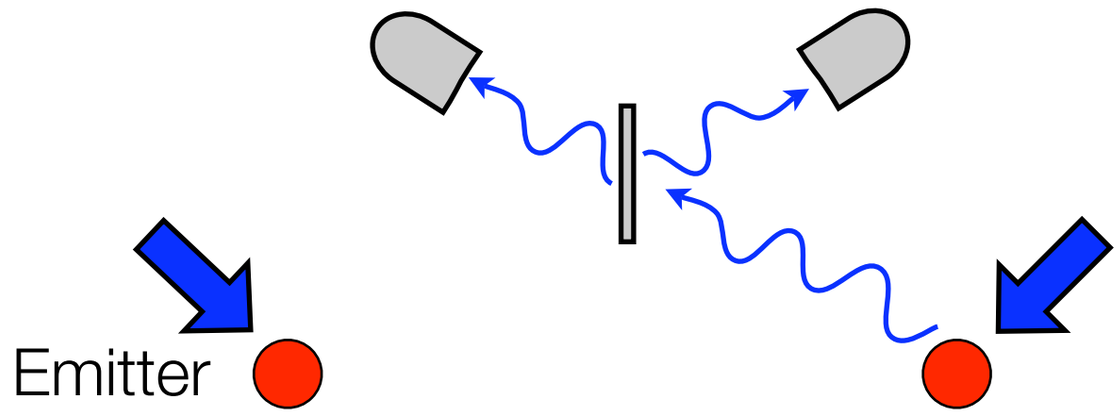

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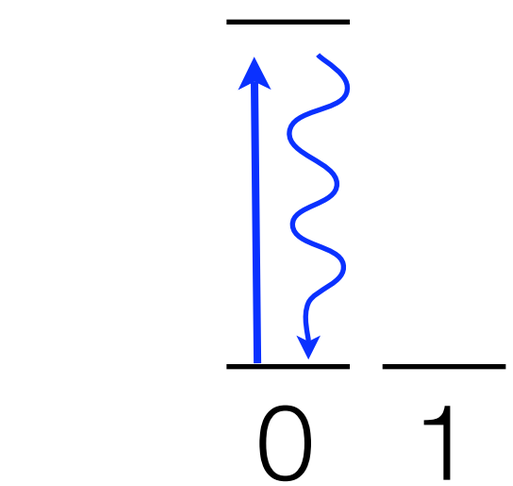
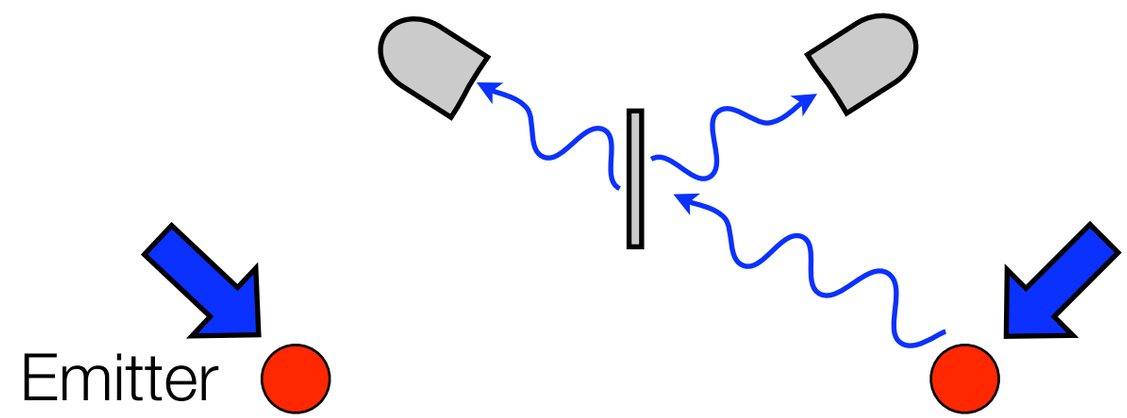
State-selective transition (atom, ion, etc.)





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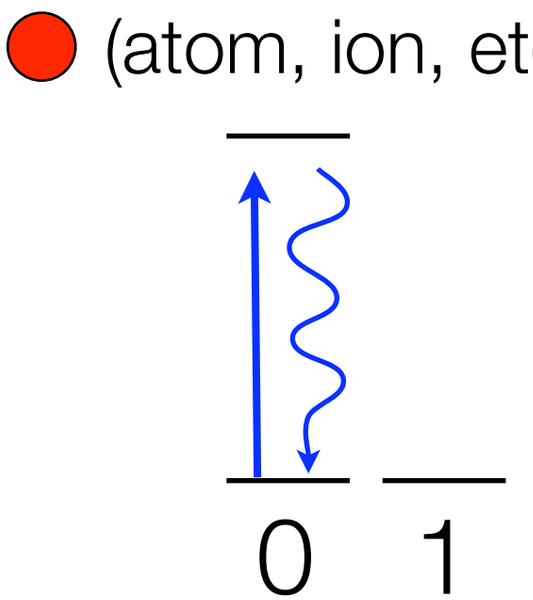

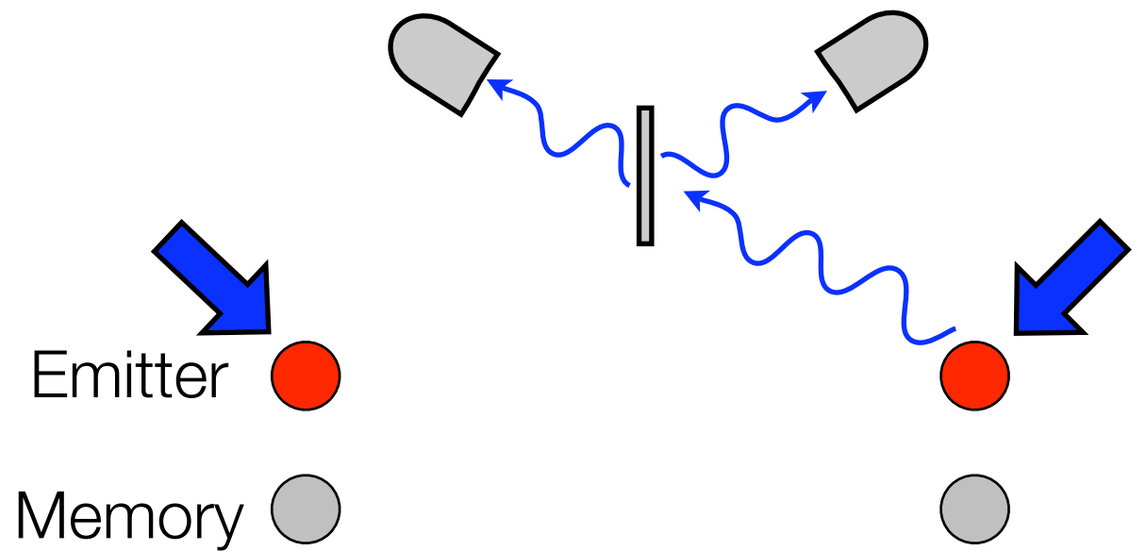

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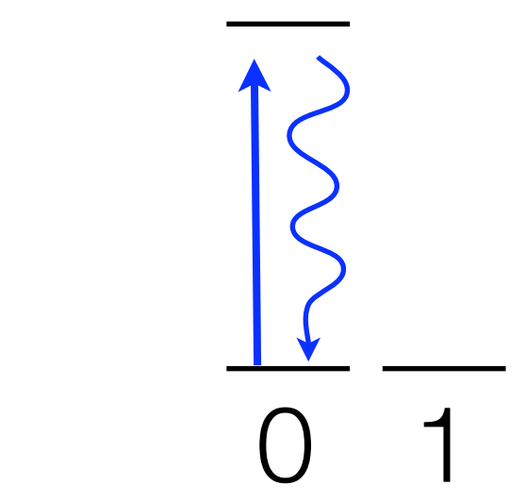

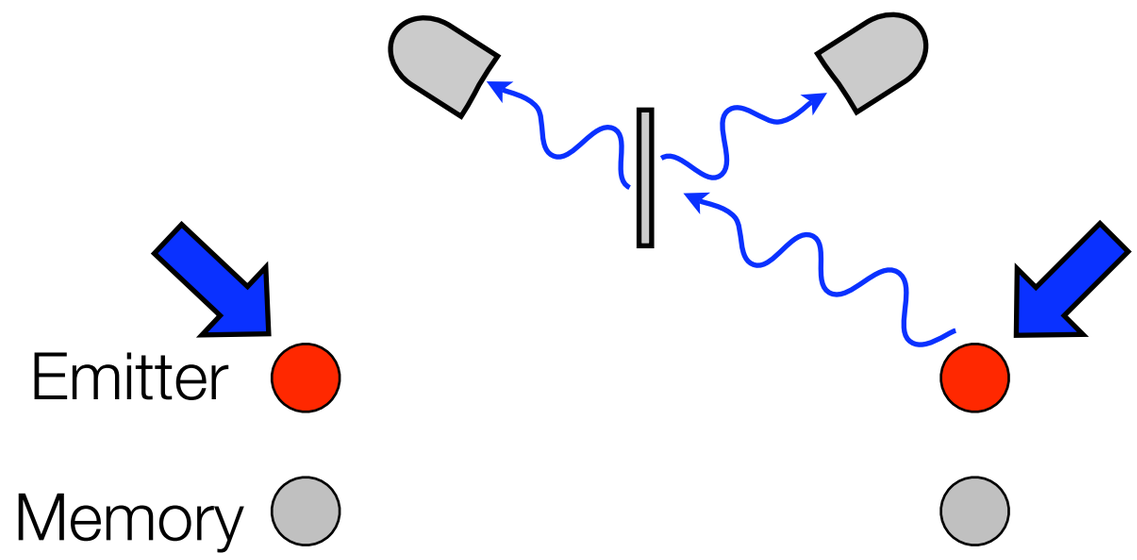

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Recent experiment! [Moehring et al., Nature (2007)]

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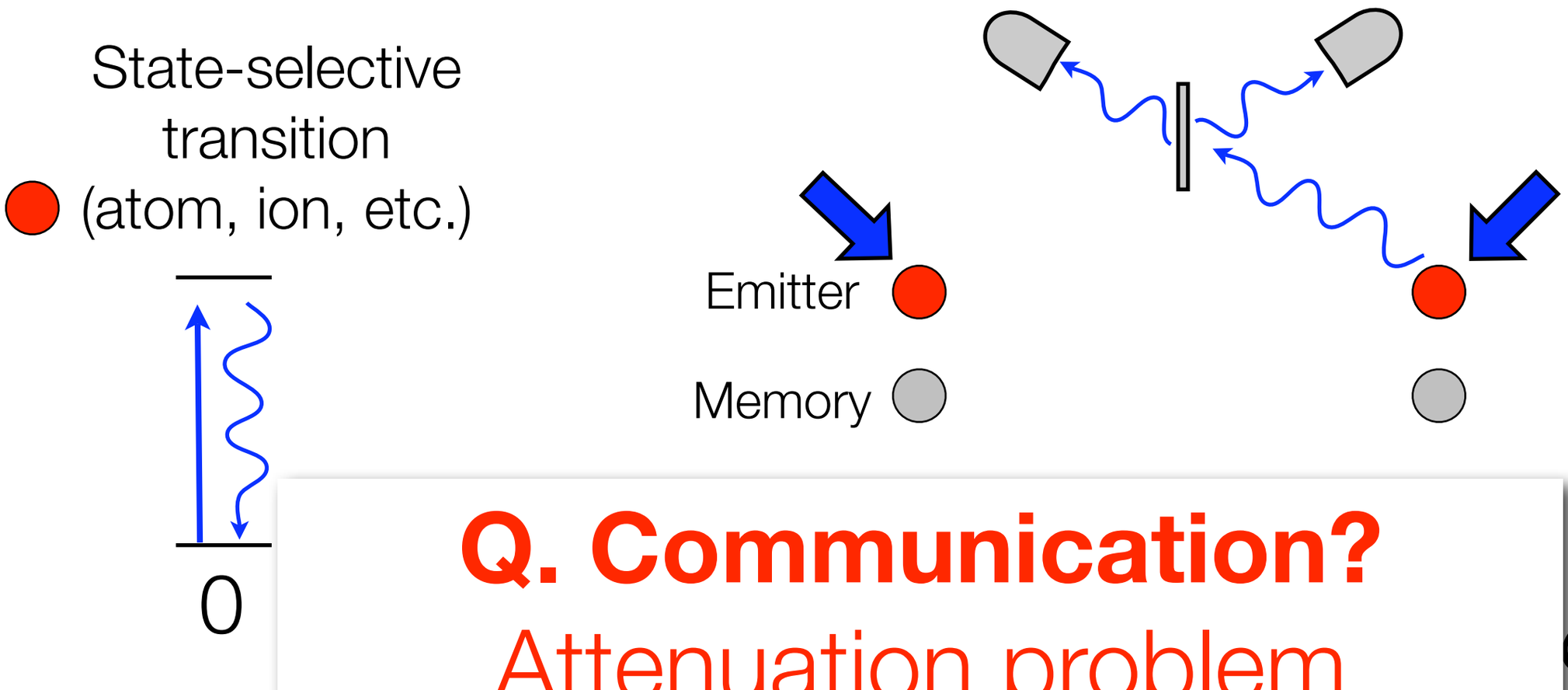

Q. Communication?

Attenuation problem
(exponential with distance)

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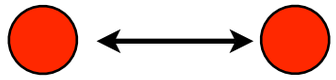
Quantum repeaters

[early ideas: Briegel, Dür, Cirac, Zoller; Bennett, Ekert]

- Goal: long range entanglement



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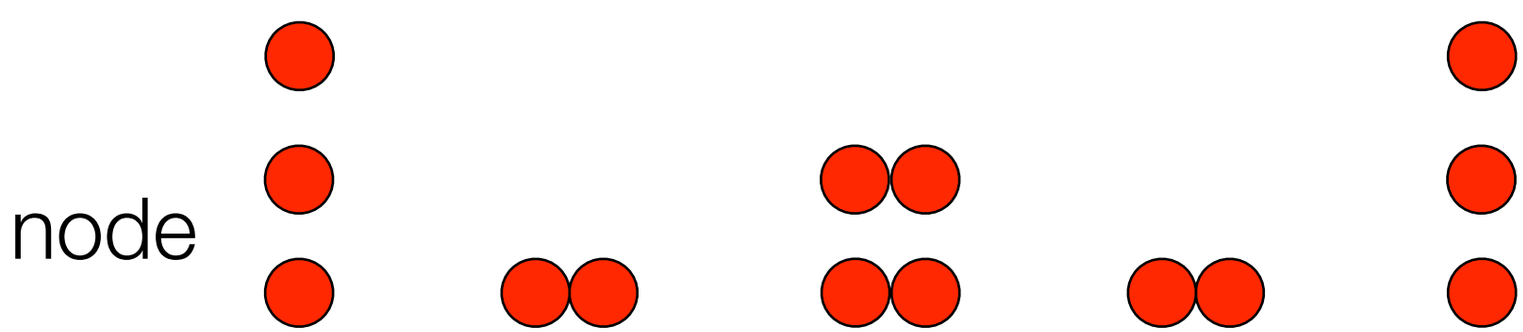

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer

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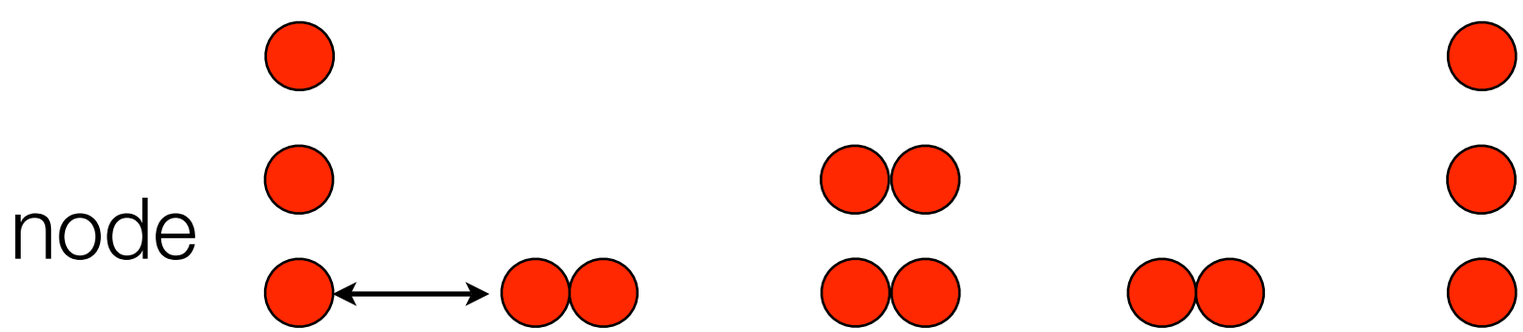

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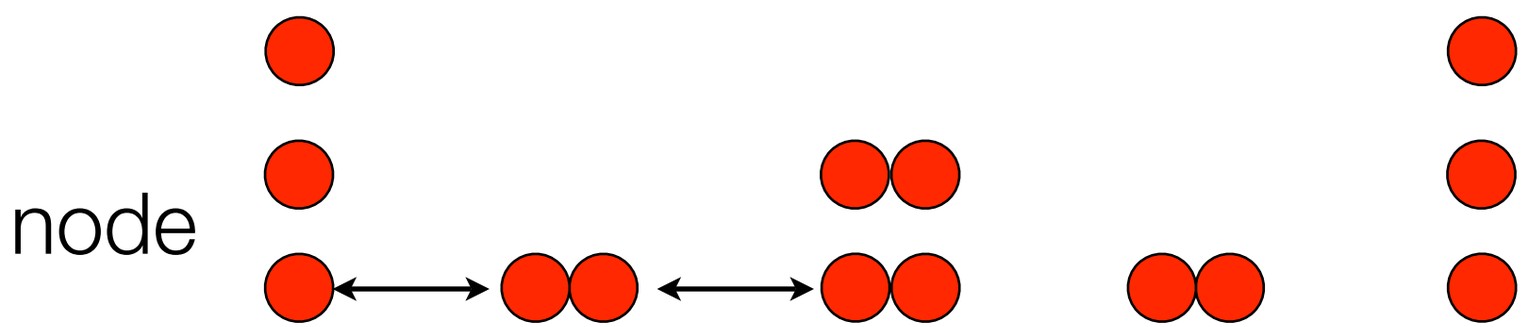

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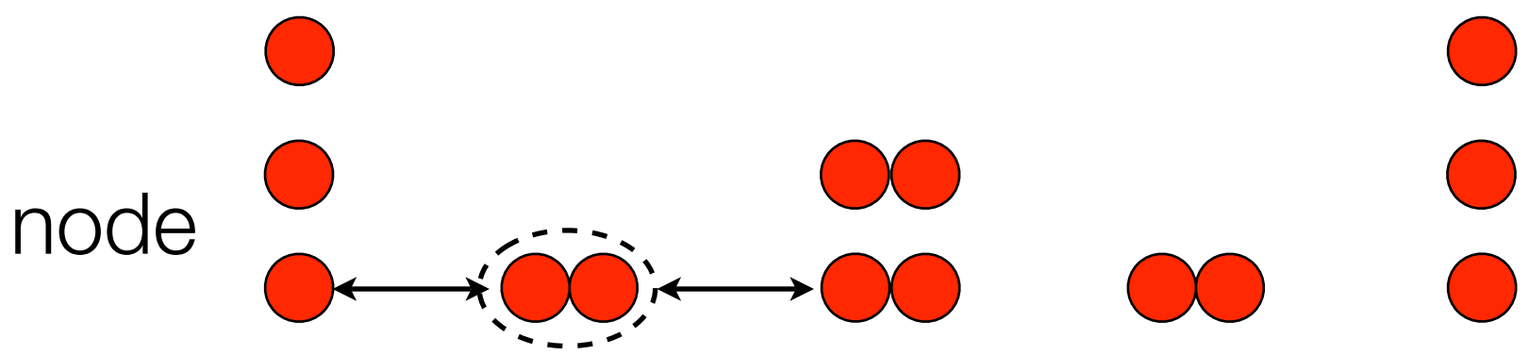

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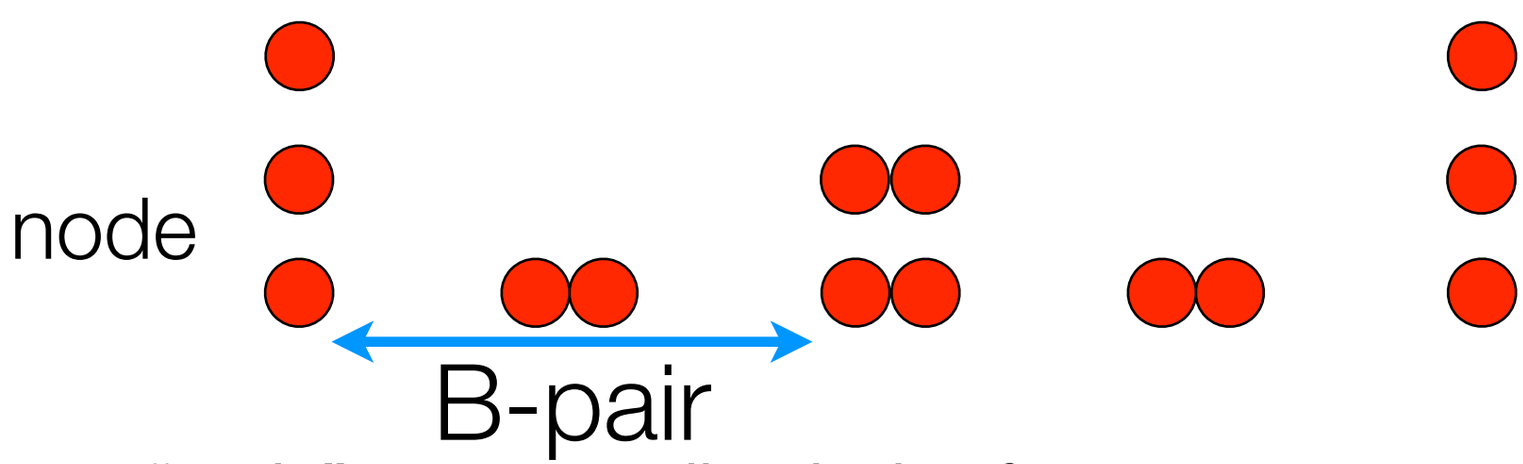

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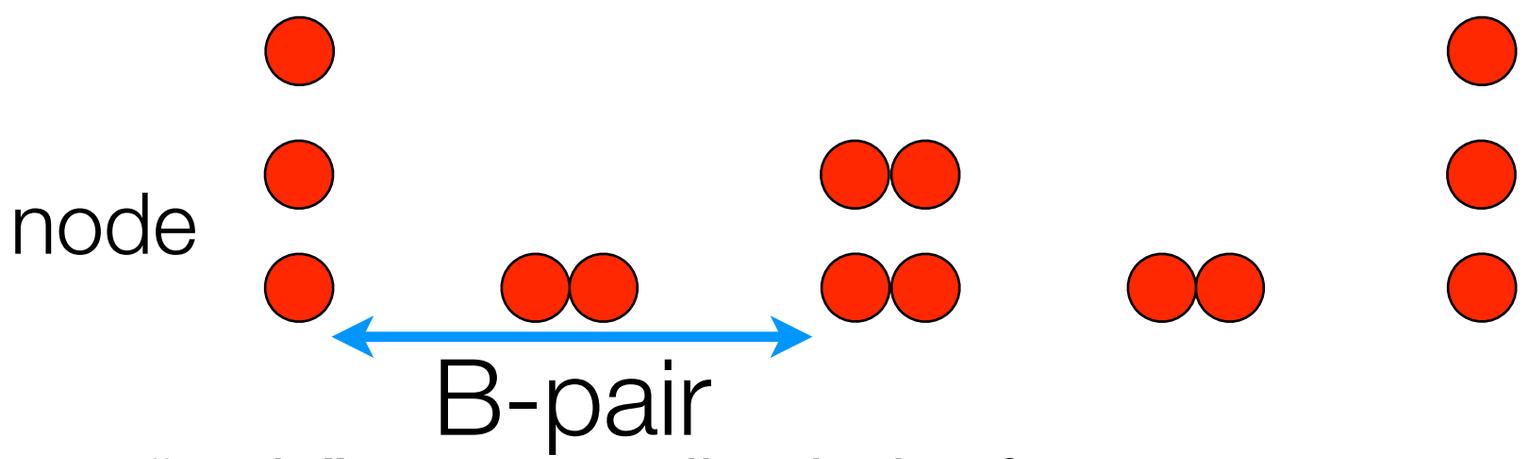

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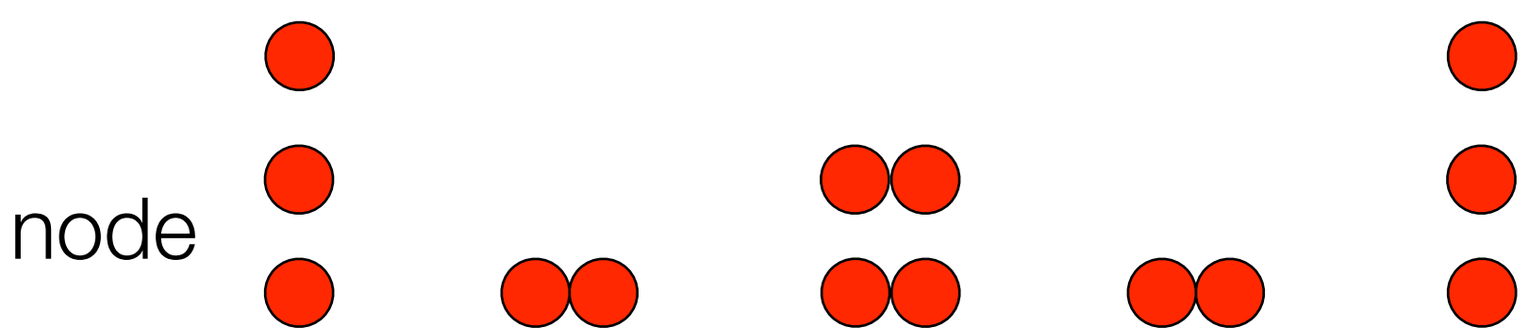

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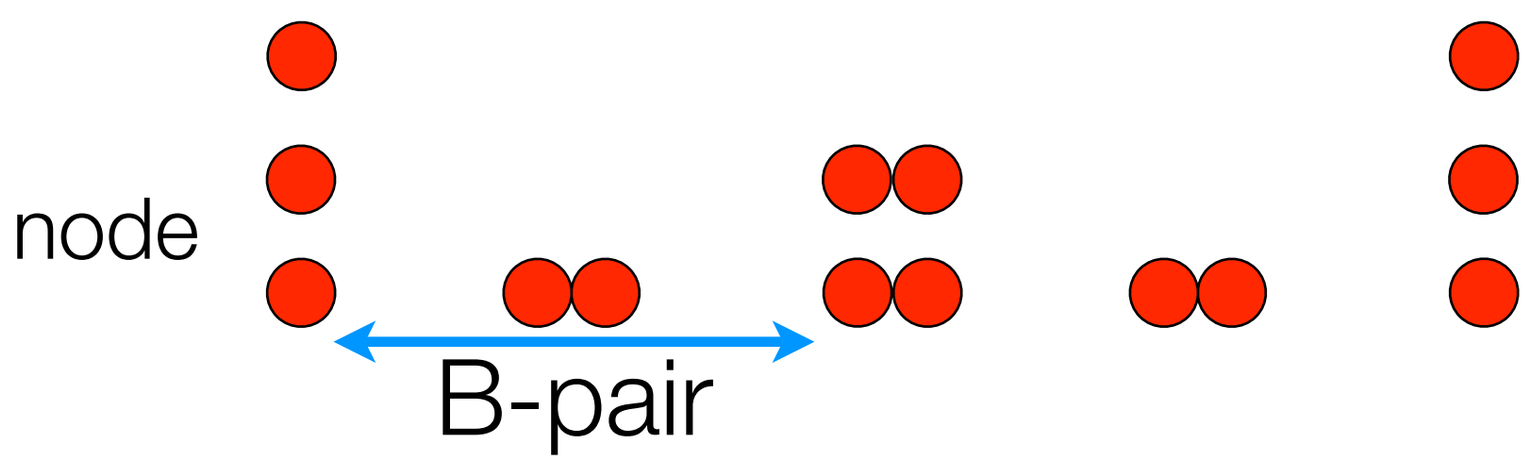

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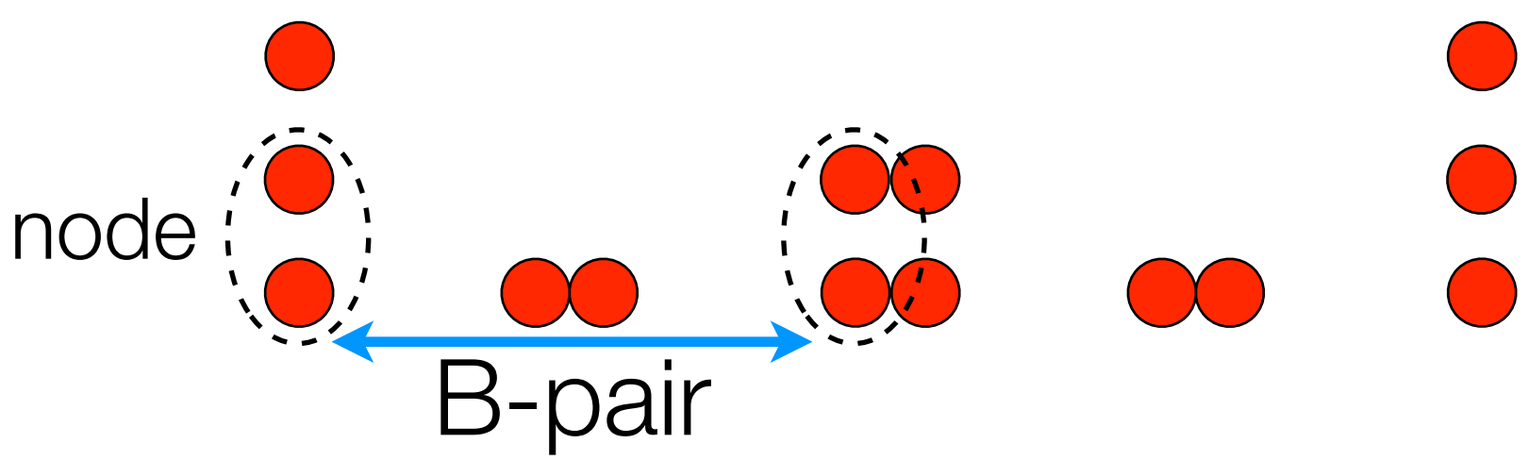

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- Repeater protocol: divide and conquer

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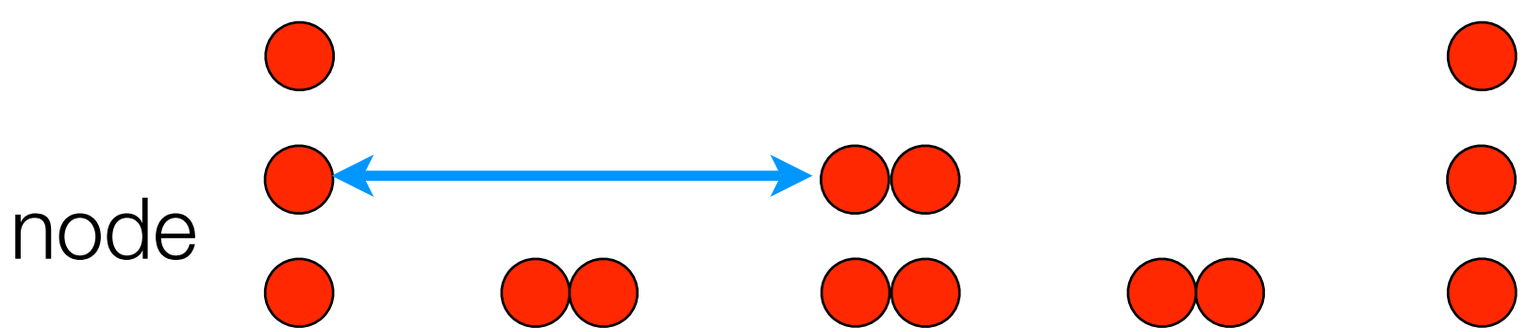

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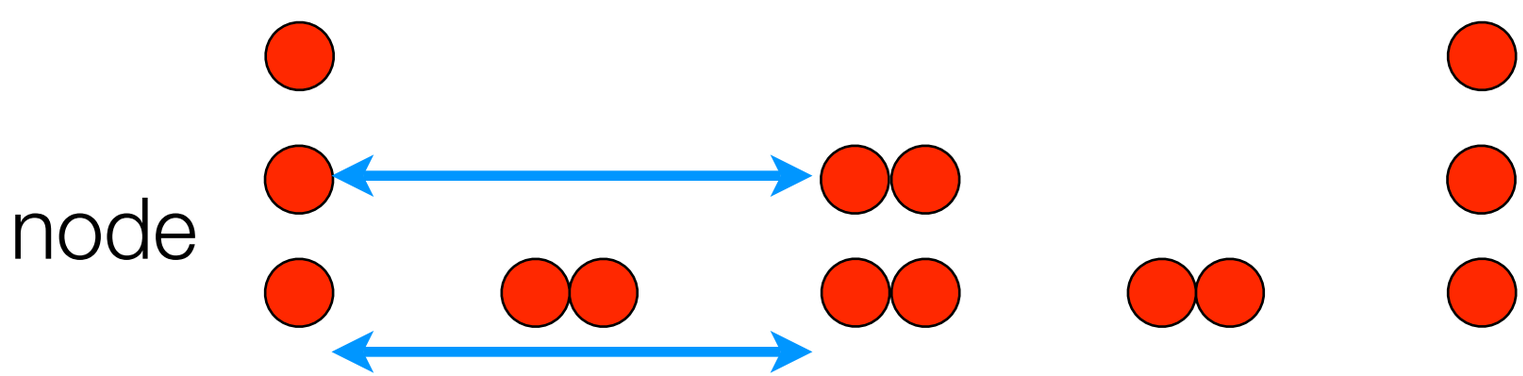

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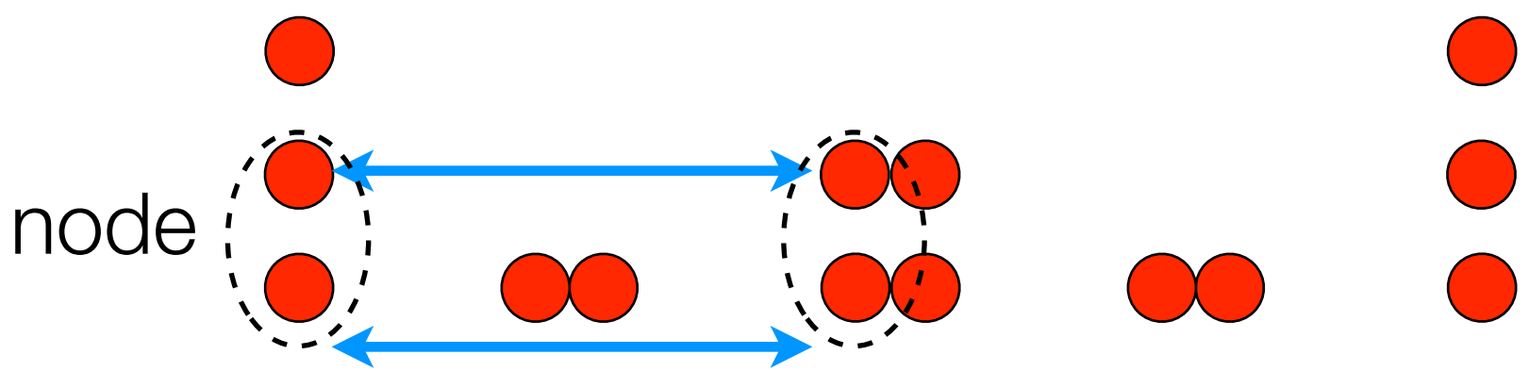

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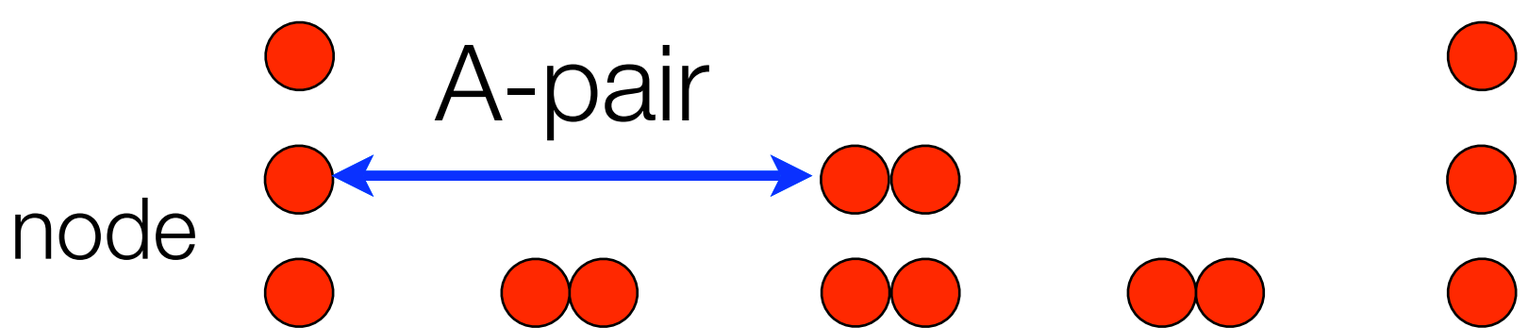

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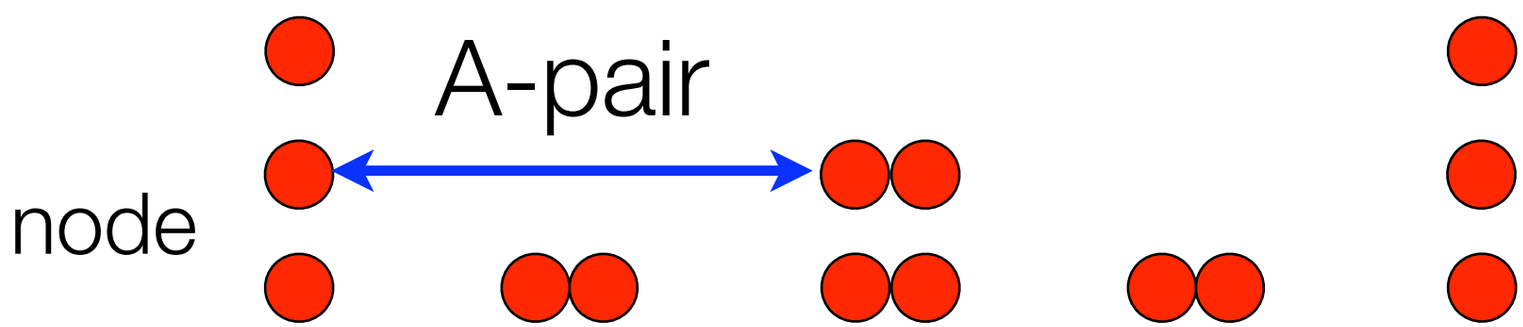

$t_1' \sim t_1(2/p_1')$

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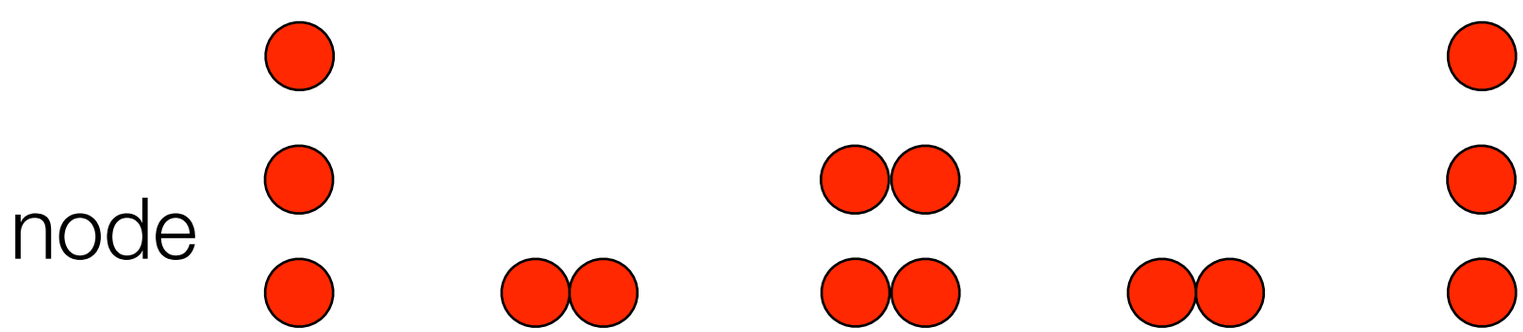

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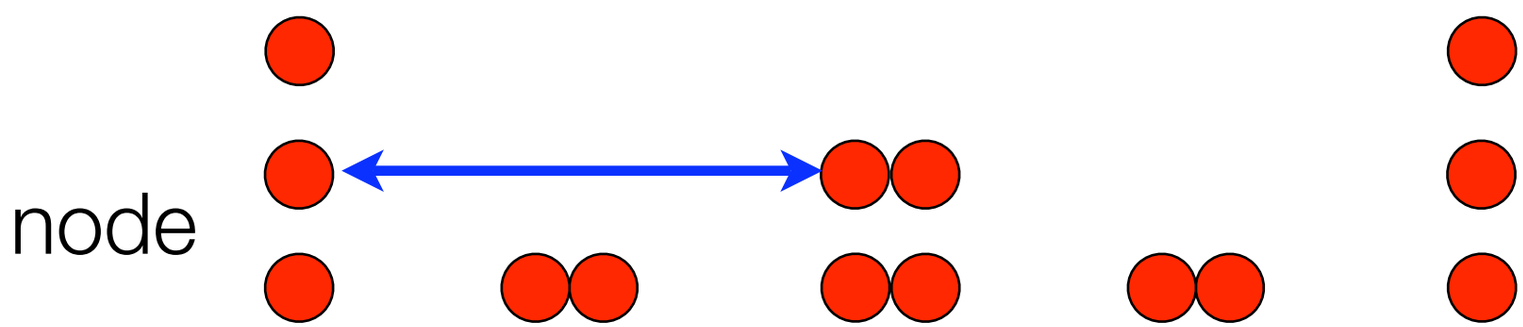

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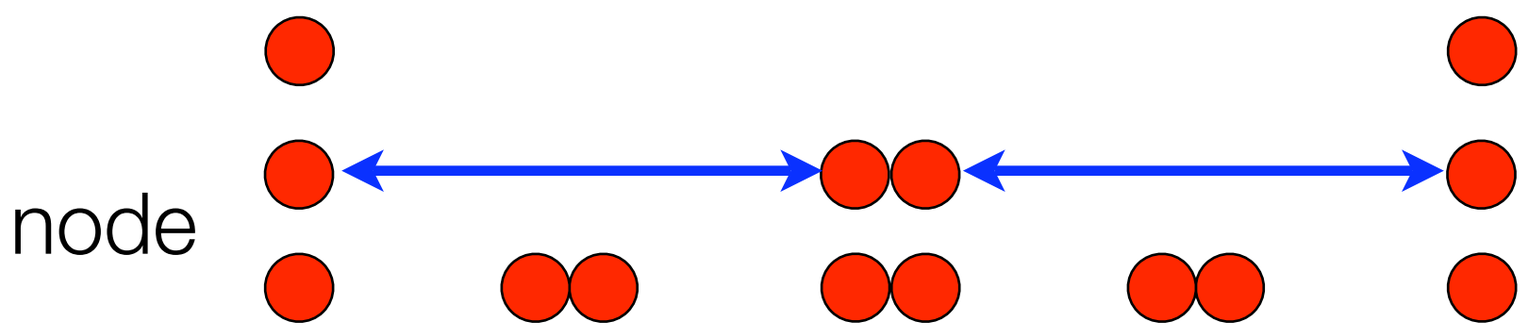

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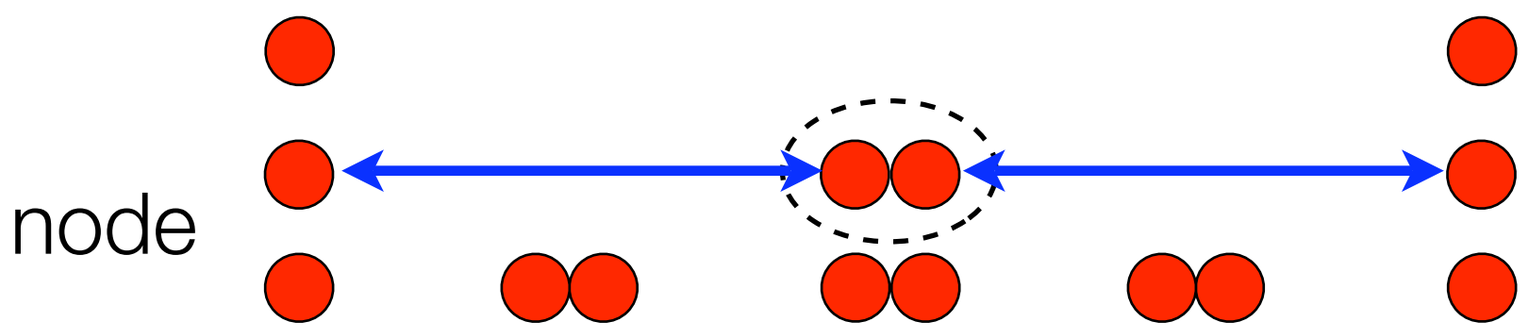

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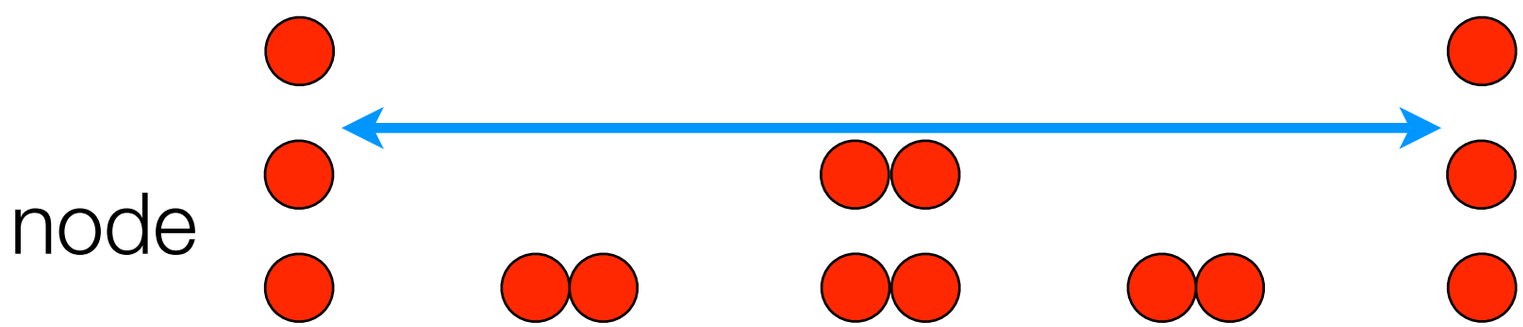

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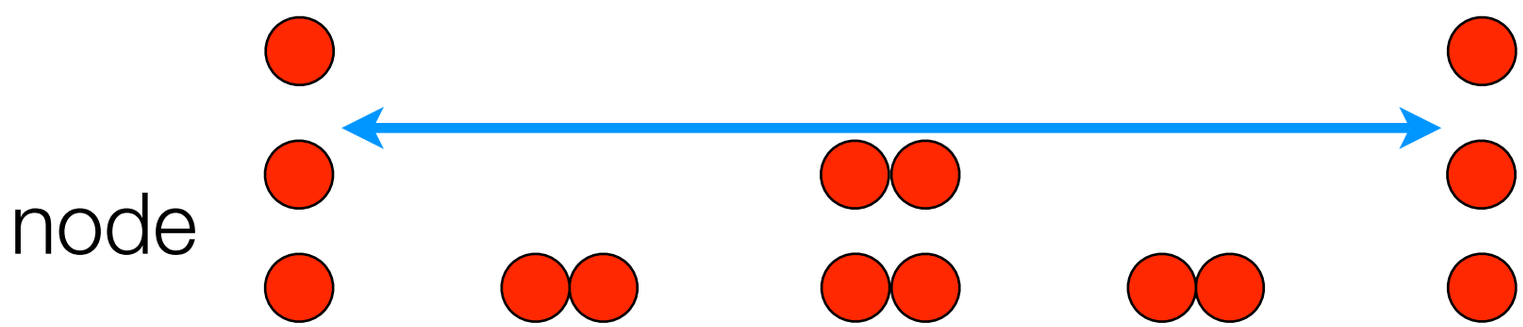

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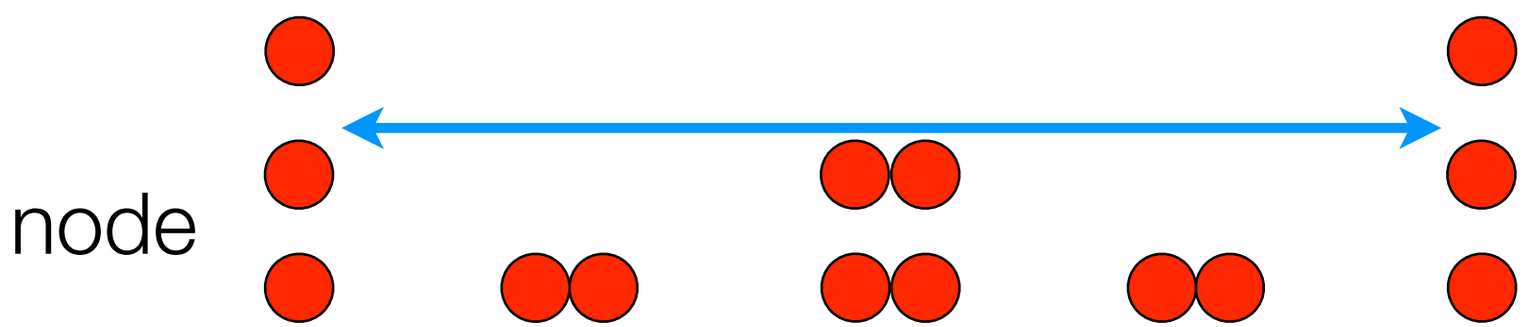

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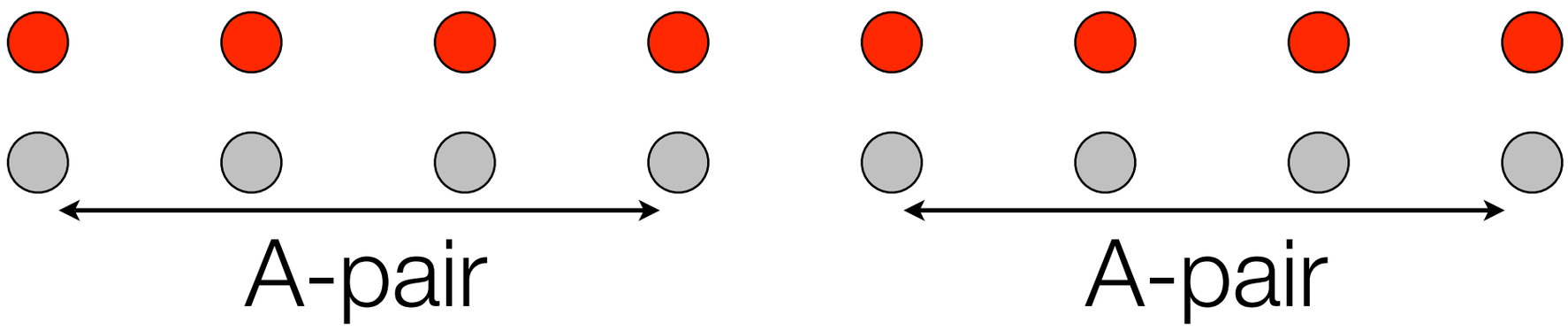

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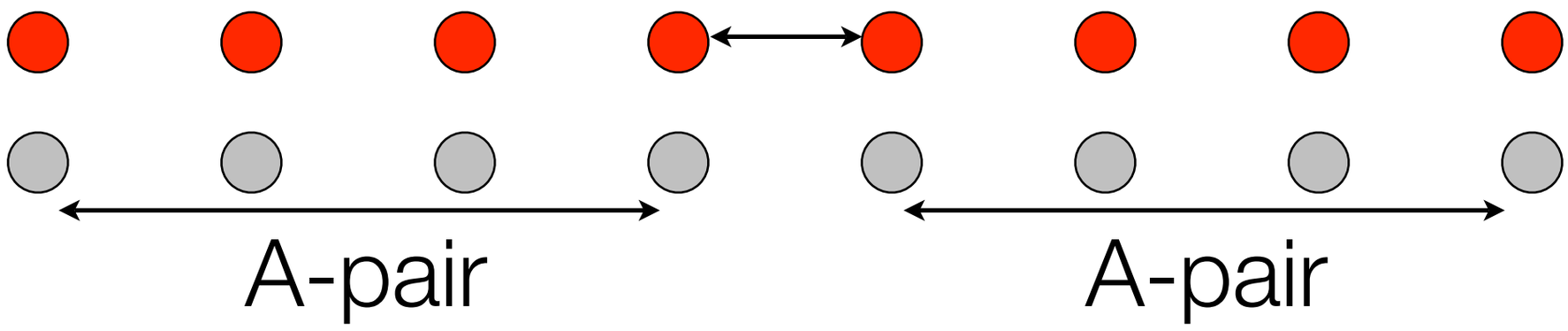

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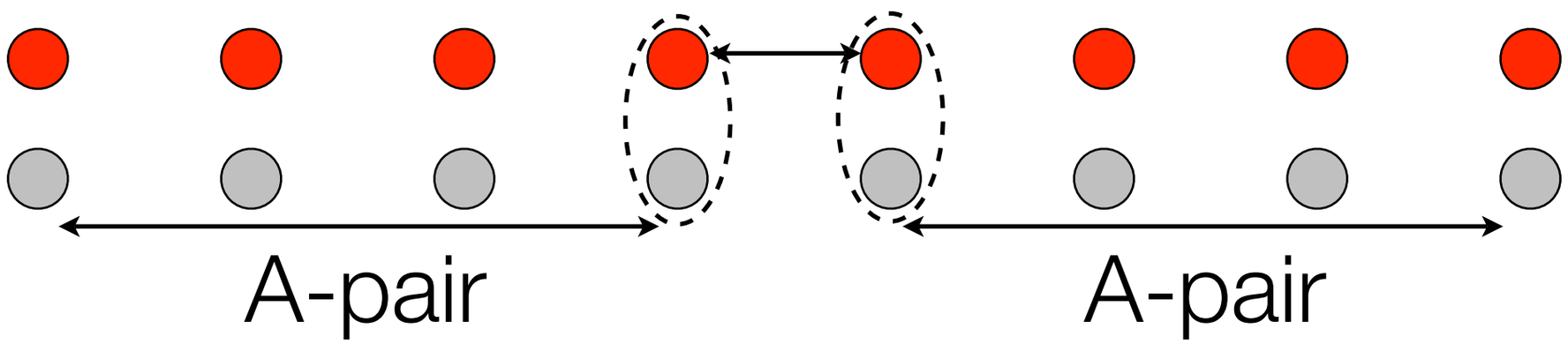

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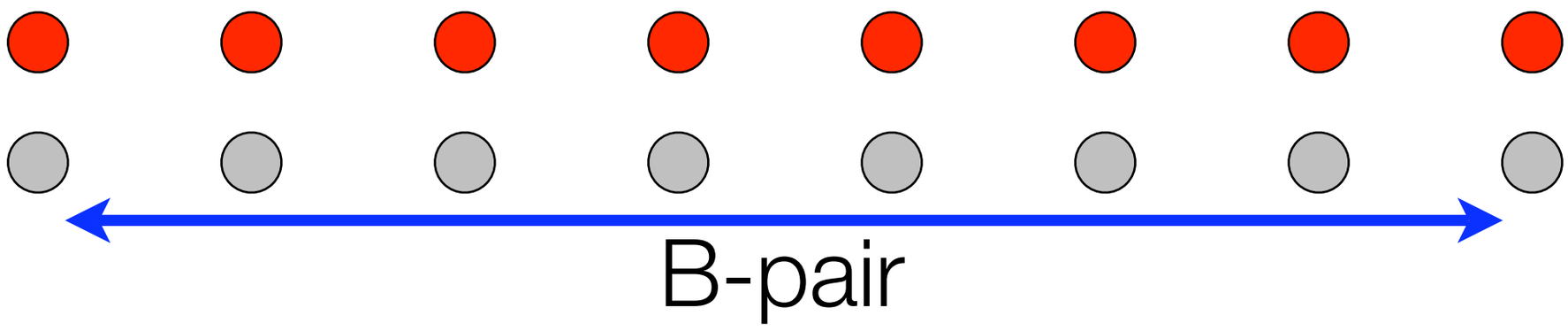

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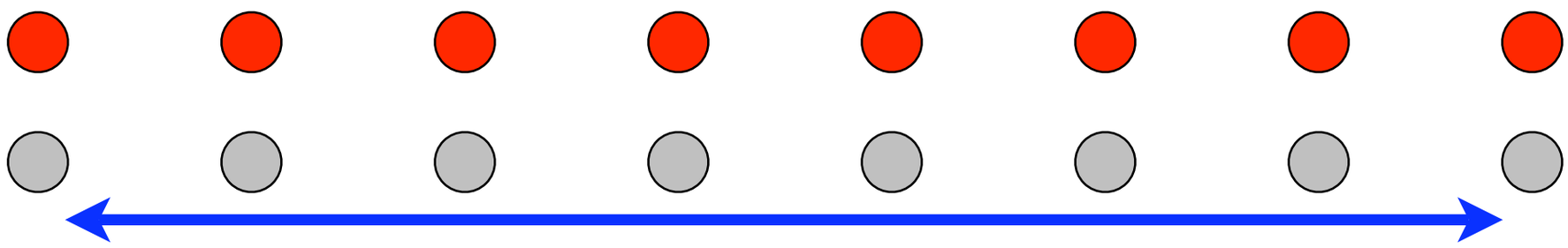

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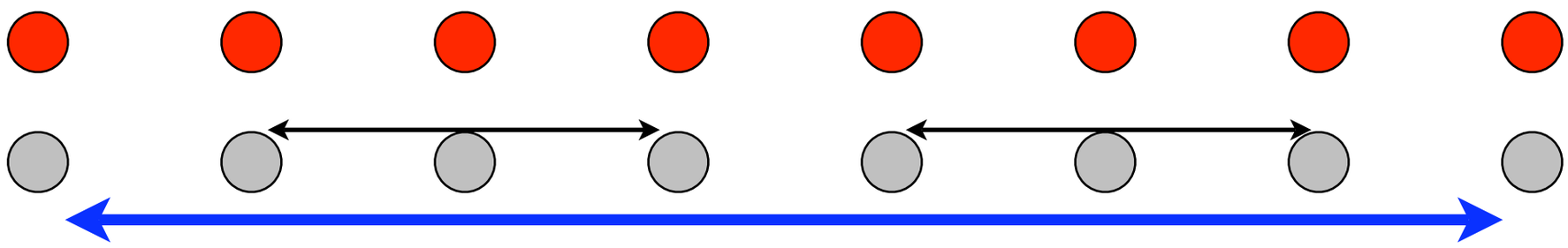

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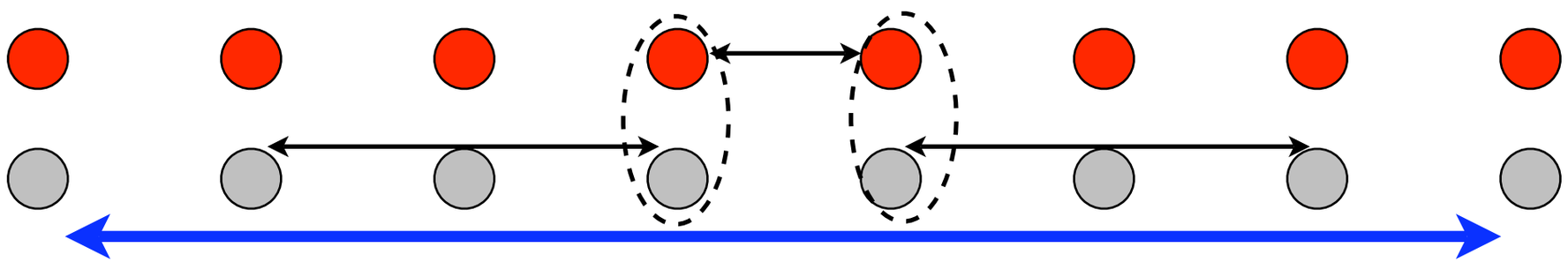

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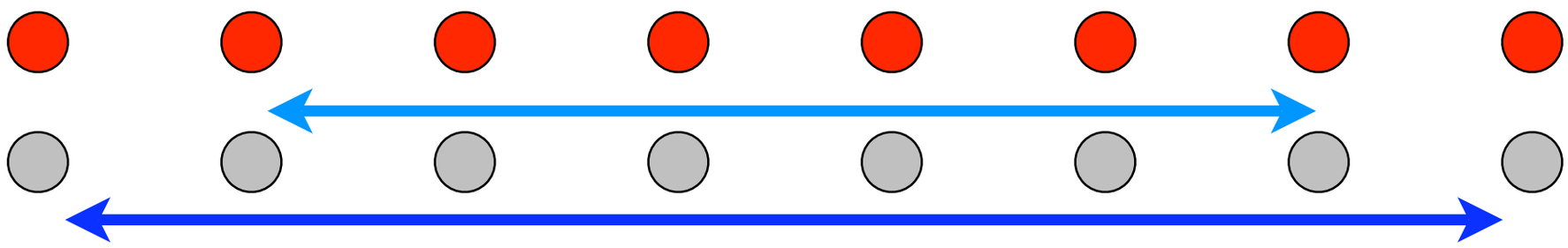

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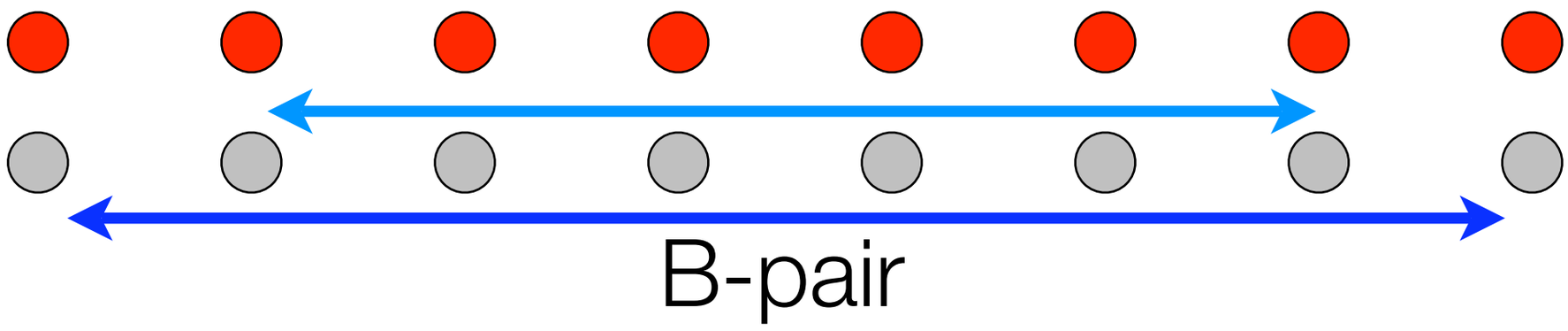

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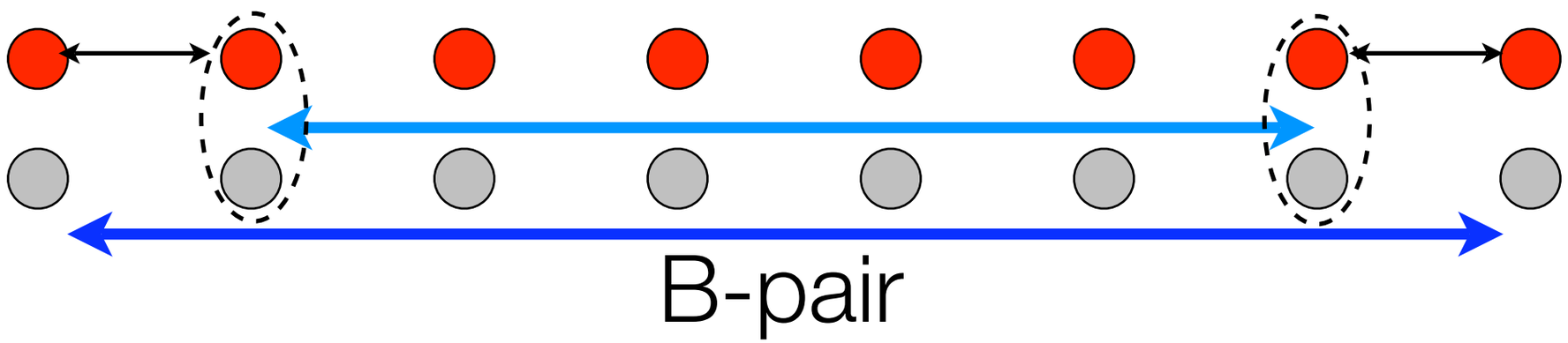

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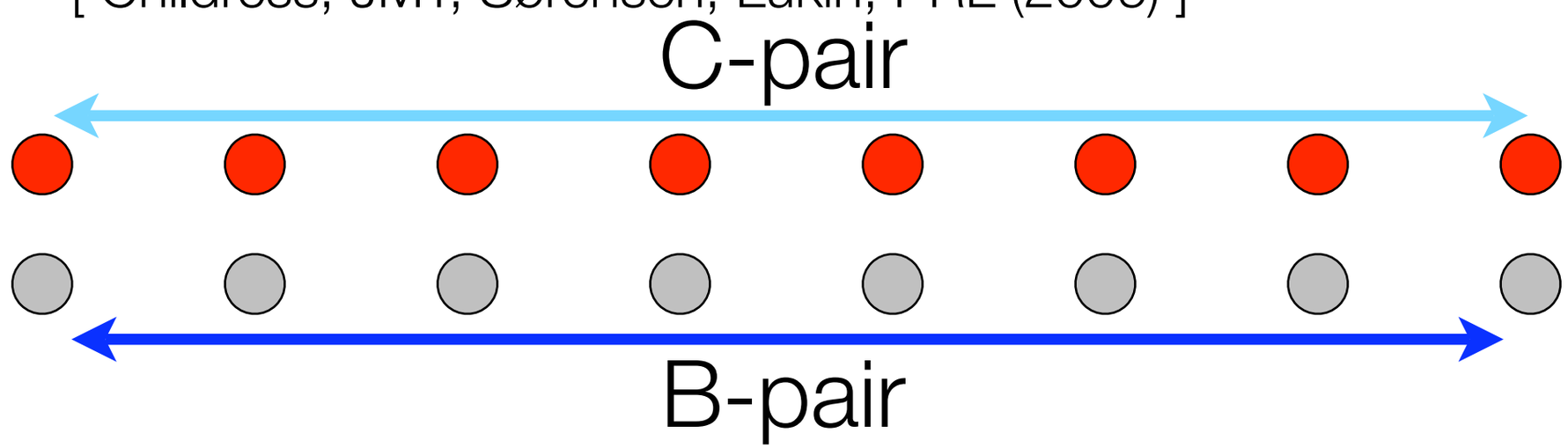

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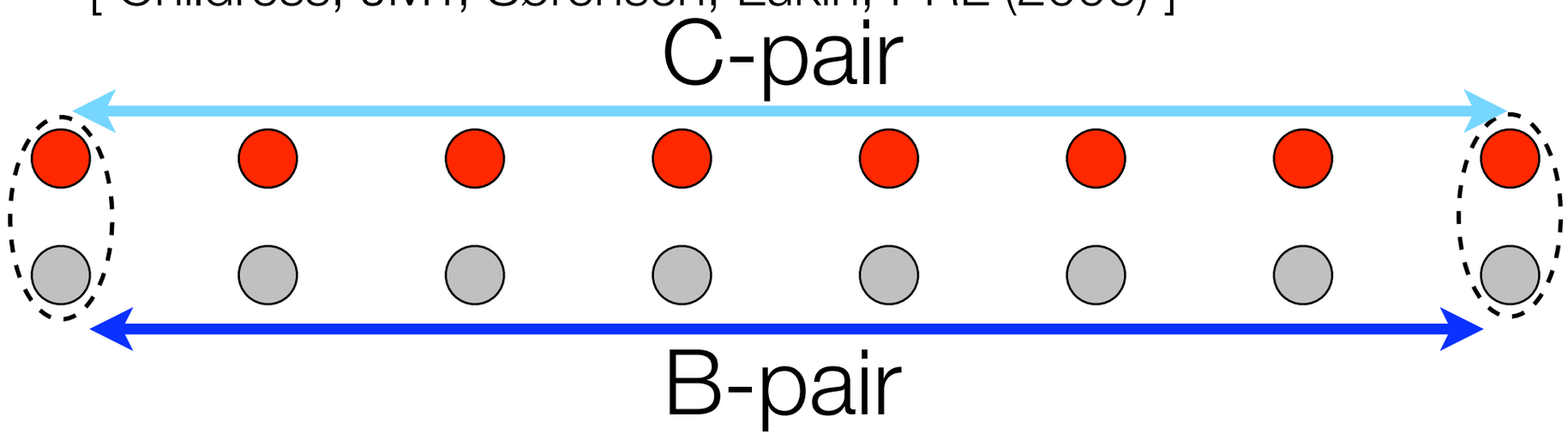

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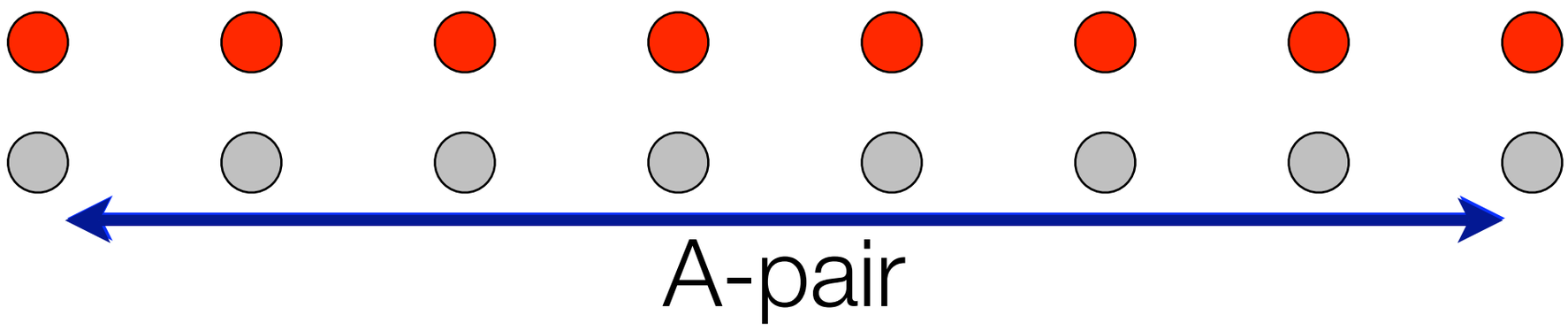

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Two qubit, commodity devices sufficient

A-pair

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  Given: a distance D and fidelity F
  Want: entangled pair with f>F in *minimum time*
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- Challenge: exponential space of sub-optimal solutions

  Choices:
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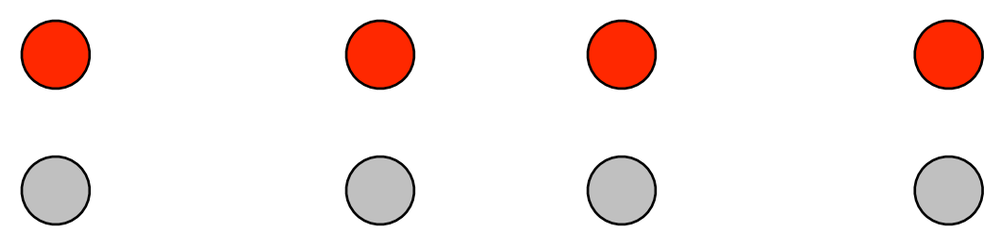

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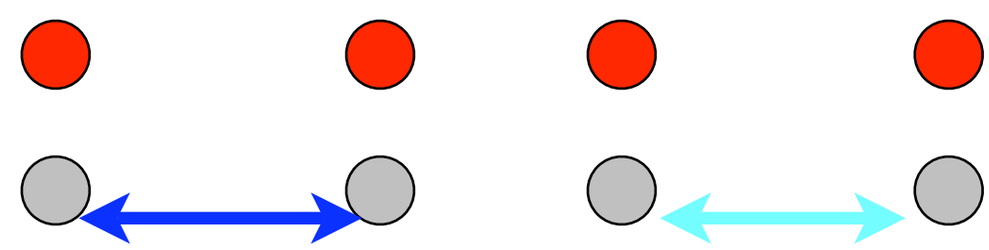

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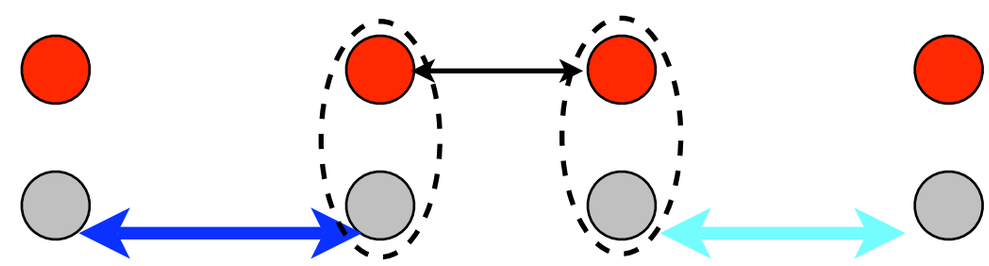

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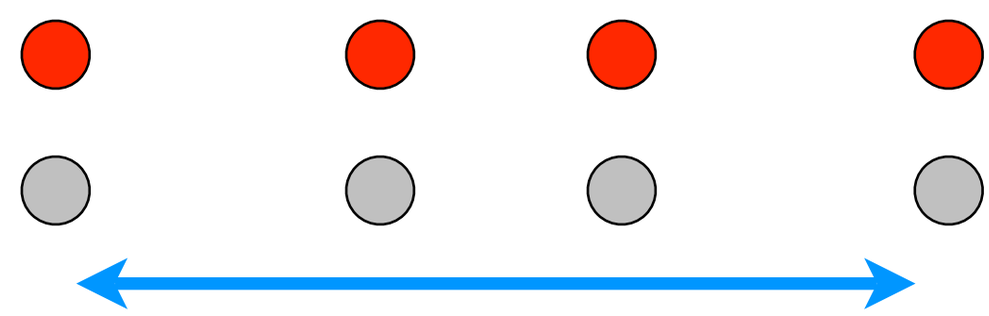

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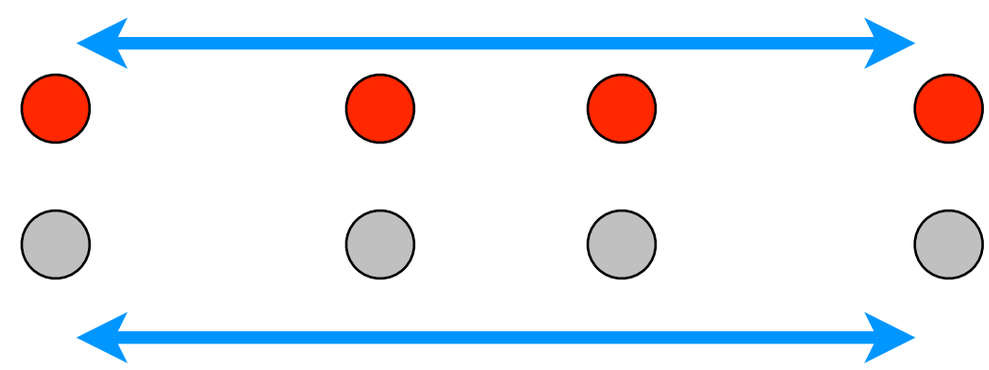

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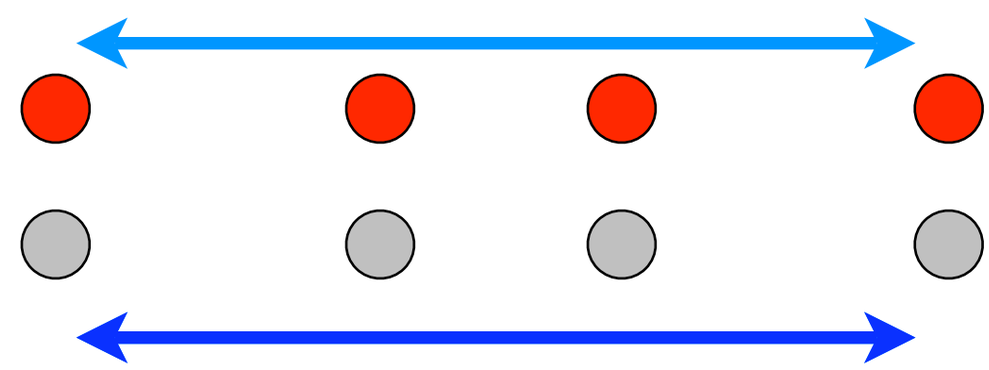

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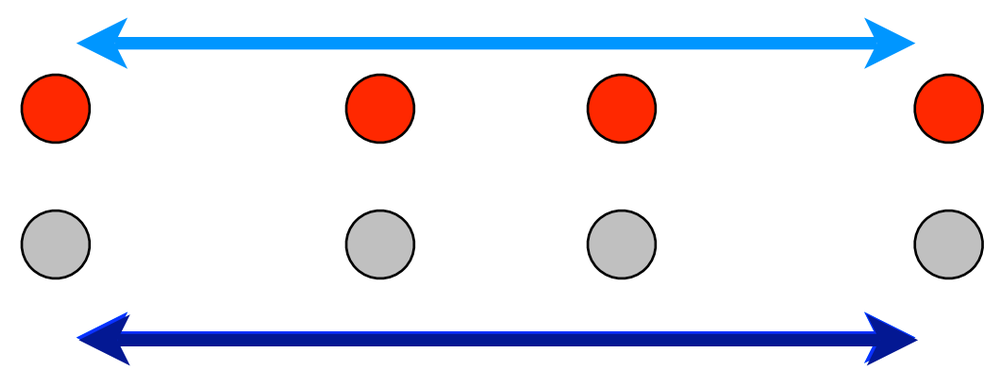

Optimization

- Choice in implementation

  Fixed: local operation fidelity, photon attenuation length, qubits-per-node

  Vary: purification steps, intermediate fidelity, node distances

- Approach: algorithmic search

d=D/2 solutions
F=0.98
F=0.96
...

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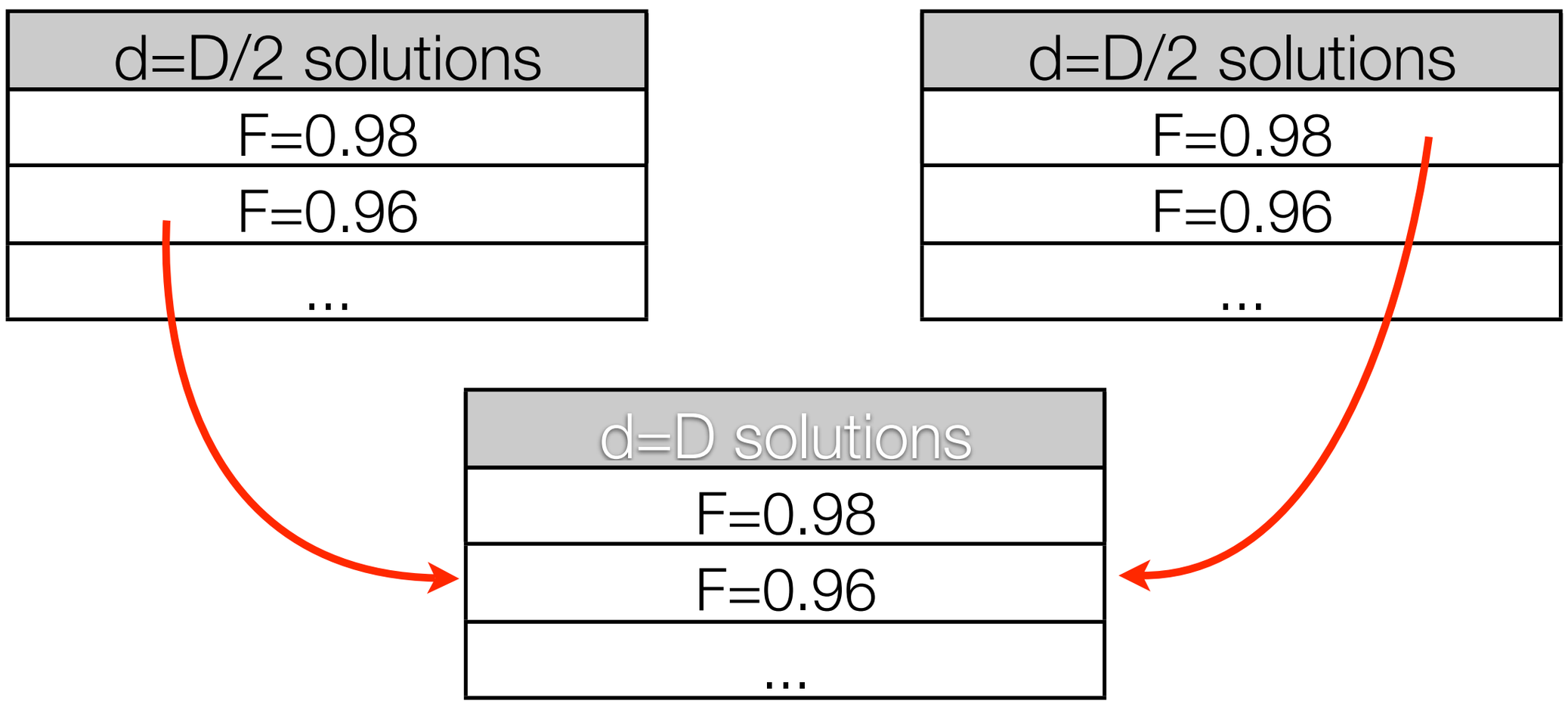

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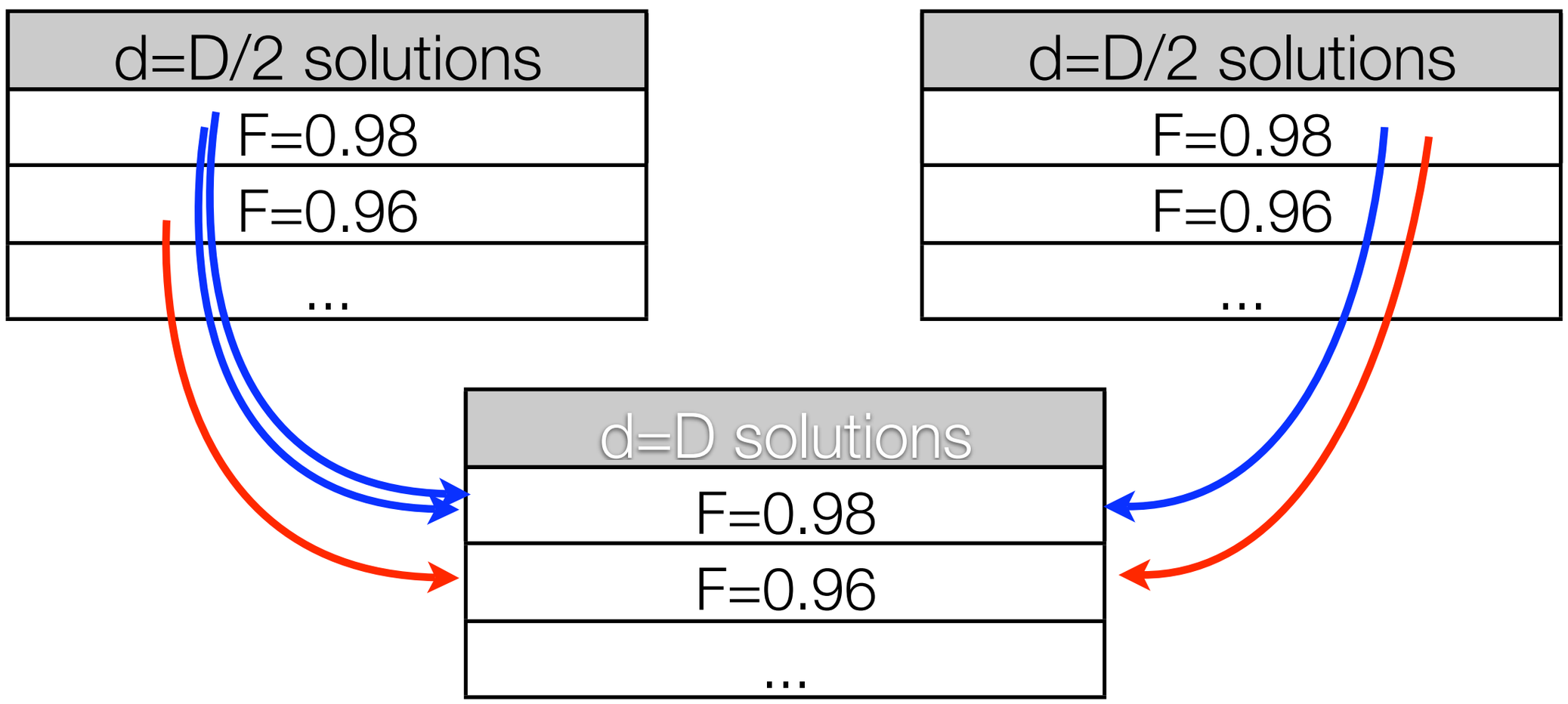


Example case: D=11

Original

```
A3 *-------------------------------------------------------*
C  o-------------------------------------------------------o
     B  *-----------------------------------------*
     A3 *------------------* A3 *------------------*
     C  o------------------o C  o------------------o
          B  *---------*          B  *---------*
               A3 *----*               A3 *----*
     B  *------------------* B  *------------------*
     A3 *----* A3 *---------* A3 *----* A3 *---------*
               C  o---------o          C  o---------o
               B  *---------*          B  *---------*
                    A3 *----*               A3 *----*
B  *-------------------------------------------------------*
A3 *-----------------------* A3 *-----------------------*
C  o-----------------------o C  o-----------------------o
     B  *-------------*          B  *-------------*
     A3 *----* A3 *----*          A3 *----* A3 *----*
B  *-----------------------* B  *-----------------------*
A3 *---------* A3 *---------* A3 *---------* A3 *---------*
C  o---------o C  o---------o C  o---------o C  o---------o
B  *---------* B  *---------* B  *---------* B  *---------*
     A3 *----*      A3 *----*      A3 *----*      A3 *----*
```

Example case: D=11

Original

```
A3 *-------------------------------------------------------*
C  o-------------------------------------------------------o
     B  *-----------------------------------------*
     A3 *------------------* A3 *------------------*
     C  o------------------o C  o------------------o
          B  *---------*          B  *---------*
               A3 *----*               A3 *----*
     B  *------------------* B  *------------------*
     A3 *----* A3 *---------* A3 *----* A3 *---------*
               C  o---------o          C  o---------o
               B  *---------*          B  *---------*
                    A3 *----*               A3 *----*
B  *-------------------------------------------------------*
A3 *-----------------------* A3 *-----------------------*
C  o-----------------------o C  o-----------------------o
     B  *-------------*          B  *-------------*
     A3 *----* A3 *----*          A3 *----* A3 *----*
B  *-----------------------* B  *-----------------------*
A3 *---------* A3 *---------* A3 *---------* A3 *---------*
C  o---------o C  o---------o C  o---------o C  o---------o
B  *---------* B  *---------* B  *---------* B  *---------*
     A3 *----*      A3 *----*      A3 *----*      A3 *----*
```

Optimized

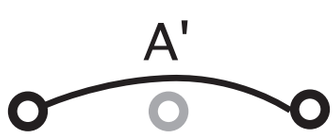
```
A2 *-------------------------------------------------------*
C  o-------------------------------------------------------o
     A1 *-----------------------------------------*
     C  o-----------------------------------------o
          A0 *-------------------------------*
          B  *-------------------------------*
          A1 *-------------* A1 *-------------*
          C  o-------------o C  o-------------o
               A1 *----*           A1 *----*
          B  *-------------* B  *-------------*
          A2 *----* A2 *----* A2 *----* A2 *----*
     B  *-----------------------------------------*
     A3 *-------------* A1 *-----------------------*
     C  o-------------o C  o-----------------------o
          A1 *----*           A1 *-------------*
     B  *-------------*       C  o-------------o
     A1 *----* A1 *----*            A1 *----*
                                 B  *-------------*
                                 A1 *----* A1 *----*
                            B  *-----------------------*
                            A0 *----* A1 *-------------*
                                      C  o-------------o
                                           A1 *----*
                                      B  *-------------*
                                      A1 *----* A1 *----*
B  *-------------------------------------------------------*
A1 *-----------------------* A1 *-----------------------*
C  o-----------------------o C  o-----------------------o
     A1 *-------------*          A1 *-------------*
     C  o-------------o          C  o-------------o
          A1 *----*                   A1 *----*
     B  *-------------*          B  *-------------*
     A1 *----* A1 *----*          A1 *----* A1 *----*
B  *-----------------------* B  *-----------------------*
A0 *----* A1 *-------------* A0 *----* A1 *-------------*
          C  o-------------o          C  o-------------o
               A1 *----*                   A1 *----*
          B  *-------------*          B  *-------------*
          A2 *----* A2 *----*          A2 *----* A2 *----*
```

Inductive optimization

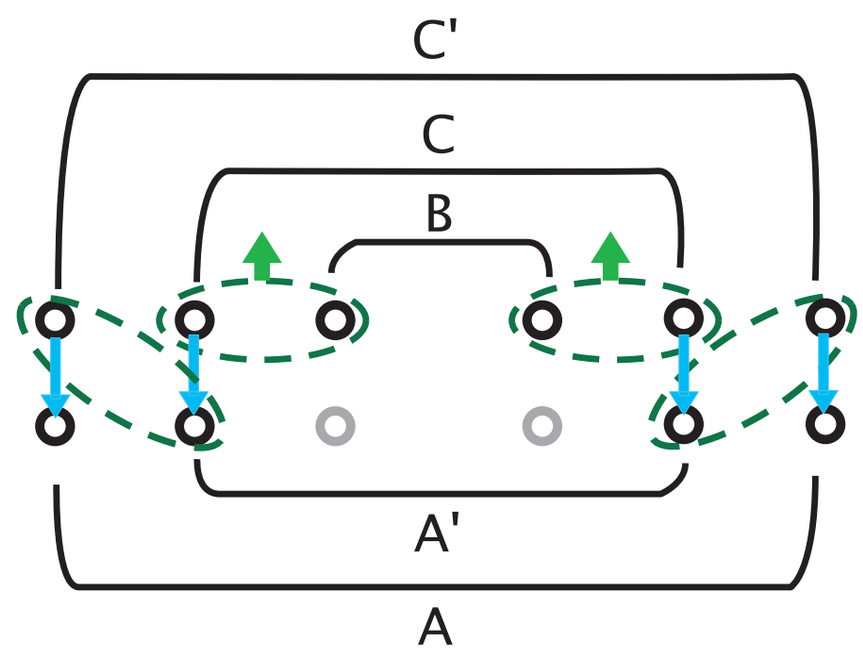
- Dynamic programming:
  given (approximate) optimal solutions for distances d<D and parameter ranges (e.g., F = [0.8,1]), find (approximate) optimal approach for distance D

- Some non-obvious improvements:
  node skipping
  multi-level pumping

Node skipping



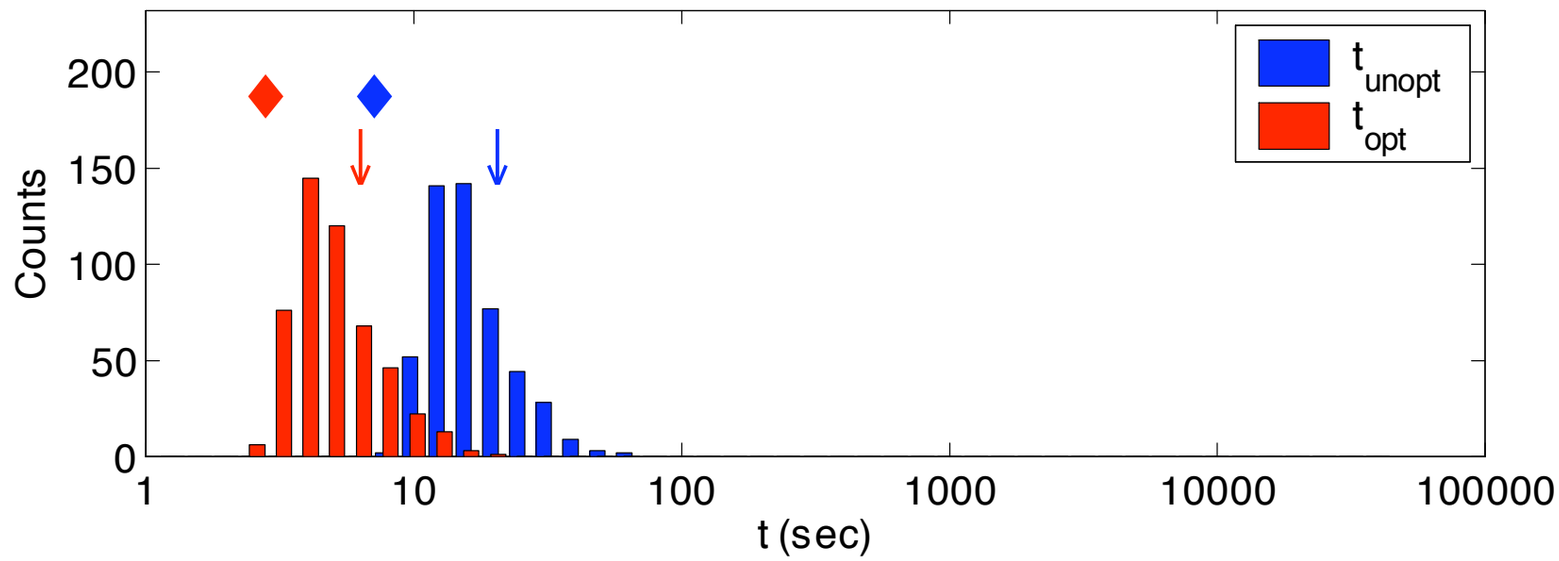
Multi-level pumping



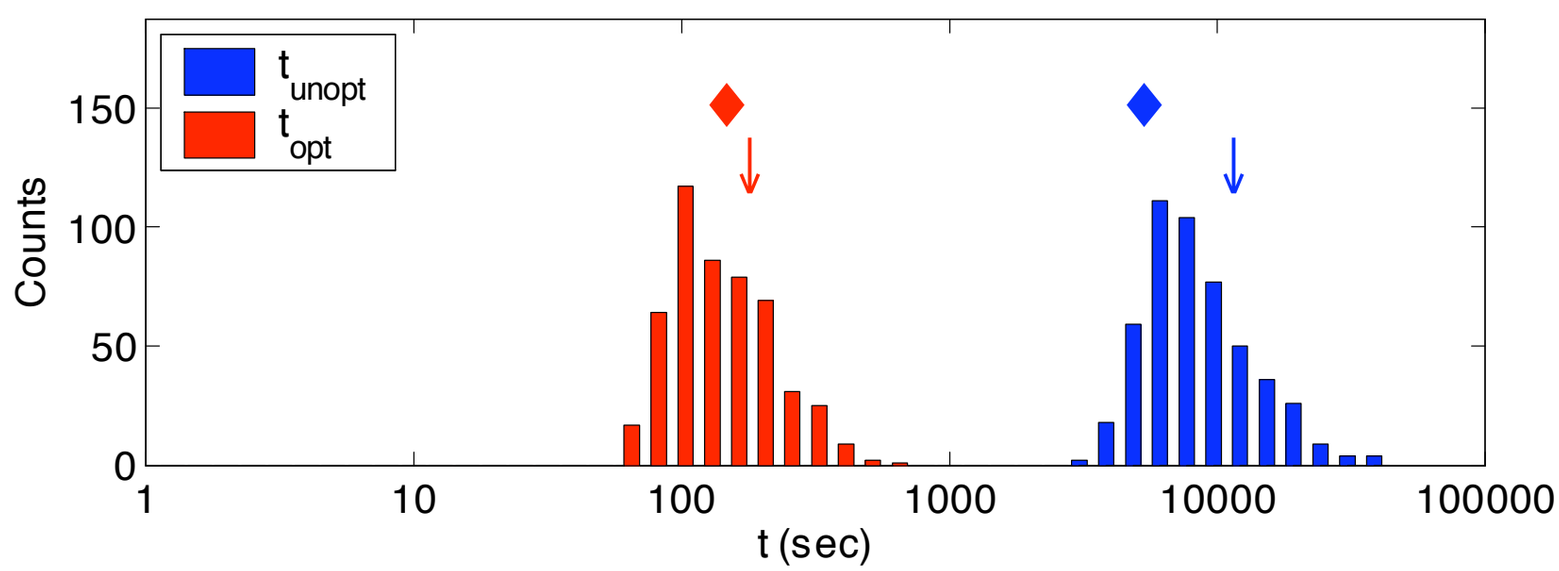
Monte Carlo simulations

Final pair fidelity F=0.97, distance = 1280 km

Briegel-Dür-Cirac-Zoller



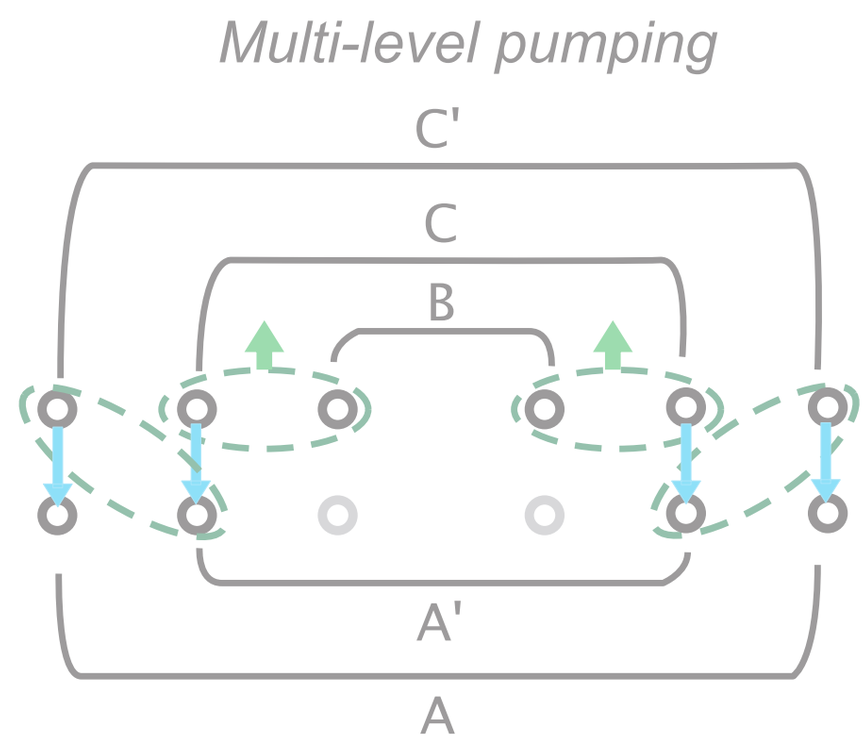
Childress-Taylor-Sørensen-Lukin

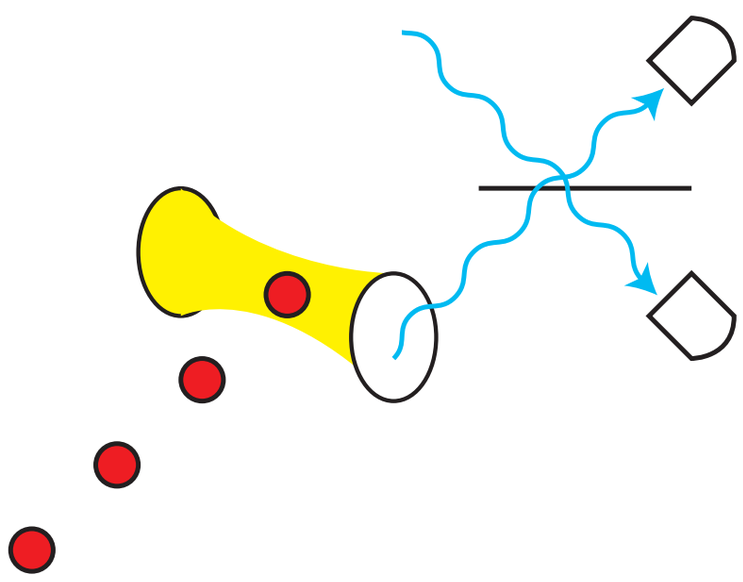


[Jiang, Taylor, Khaneja, Lukin, in progress]

Focus of this talk

Optimizing quantum communication





Minimal resource distributed computing

Distributed computation

- Problem: apparatus for many qubits?
  - limited coupling strengths in a NMR molecule (frequency selectivity)
  - quantum control in limited space

[see talks by R. Van Meter, D. Cory]

[image from Janis.com]

with L. Jiang, A. Sørensen, M. D. Lukin,
[Harvard, Copenhagen]

Distributed computation

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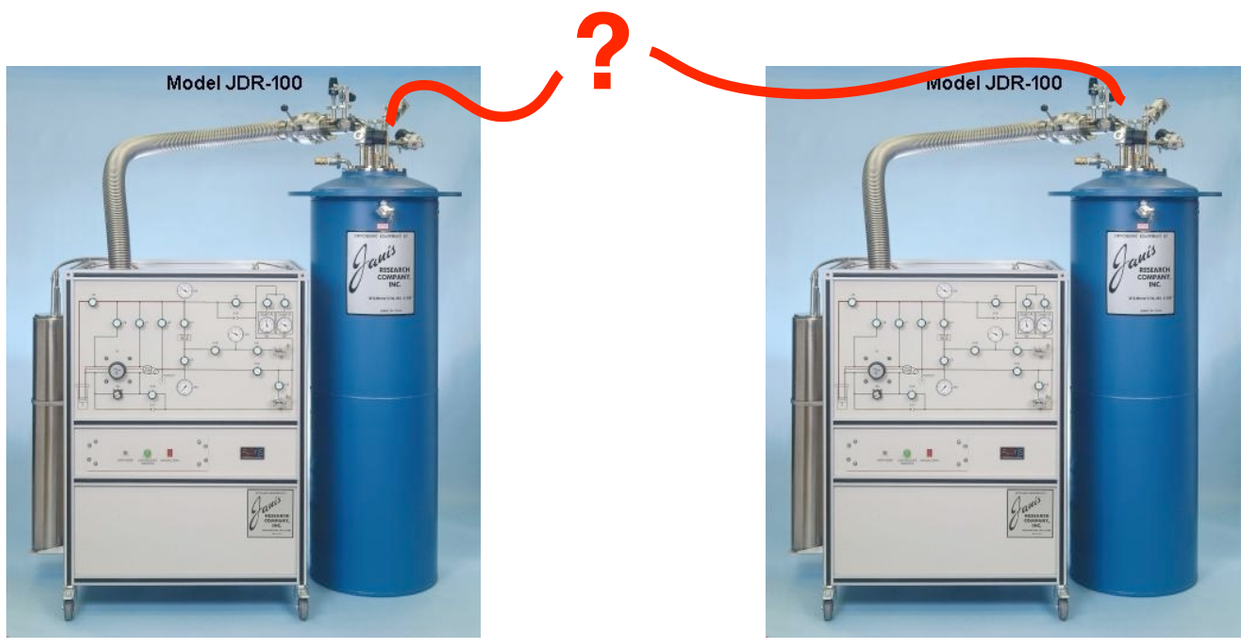


[image from Janis.com]

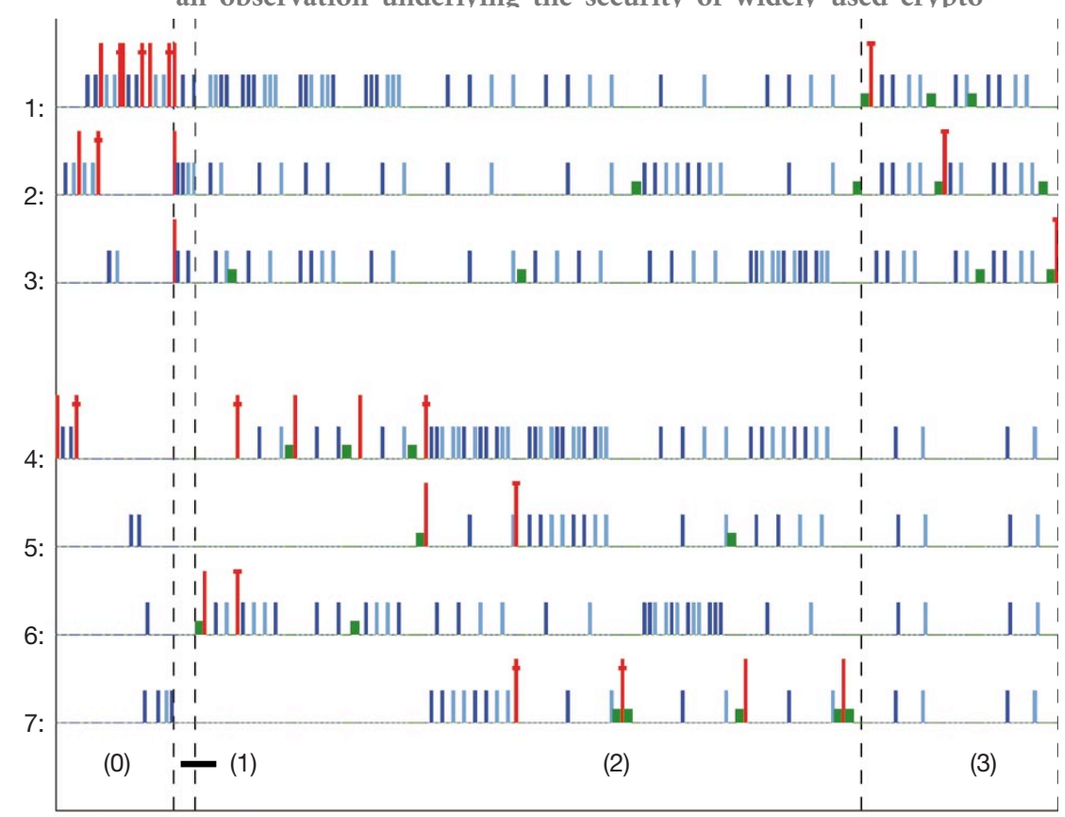
with L. Jiang, A. Sørensen, M. D. Lukin,
[Harvard, Copenhagen]

Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

Lieven M. K. Vandersypen*†, Matthias Steffen*†, Gregory Breyta*, Costantino S. Yannoni*, Mark H. Sherwood* & Isaac L. Chuang*†

** IBM Almaden Research Center, San Jose, California 95120, USA*
† Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA

The number of steps any classical computer requires in order to find the prime factors of an *l*-digit integer *N* increases exponentially with *l*, at least using algorithms known at present[1]. Factoring large integers is therefore conjectured to be intractable classically, an observation underlying the security of widely used crypto-



Distributed computation

- Problem: apparatus for many qubits?
  - limited coupling strengths in a NMR molecule (frequency s
  - quantum co

[see talks by R.

Approach: build a
Quantum Register

Use quantum communication between registers
- noisy, failure prone, still OK

Have good local operation of a given register

Use many local operations to improve (faulty) inter-register operations

with L. Jiang, A. Sørensen, M. D. Lukin,
[Harvard, Copenhagen]

Early ideas (monolithic architecture)

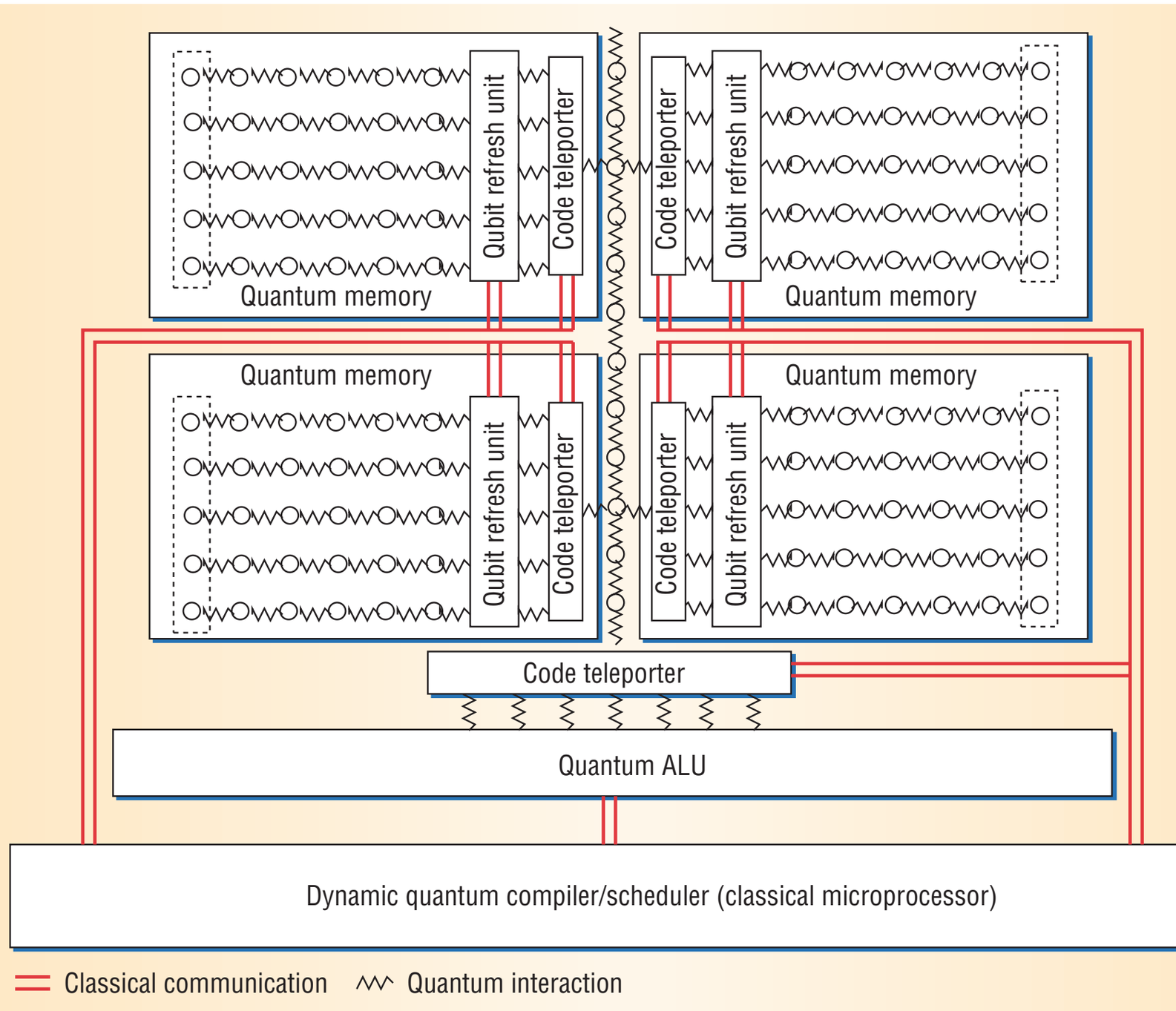
A Practical Architecture for Reliable Quantum Computers

Quantum computation has advanced to the point where solutions can help close the gap between emerging qua and real-world computing requirements.

Mark Oskin
University of Washington

Frederic T. Chong
University of California, Davis

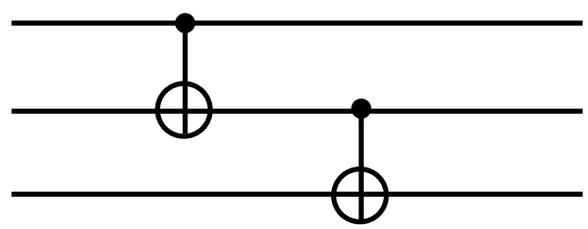
Isaac L. Chuang
Massachusetts Institute of Technology



[Oskin et al., IEEE 2002]

Deterministic distributed computation

desired (logical) circuit



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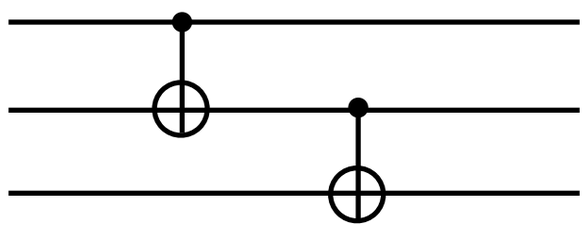

Idea:

- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors

Deterministic distributed computation

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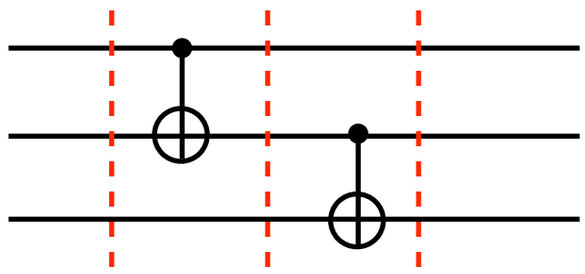

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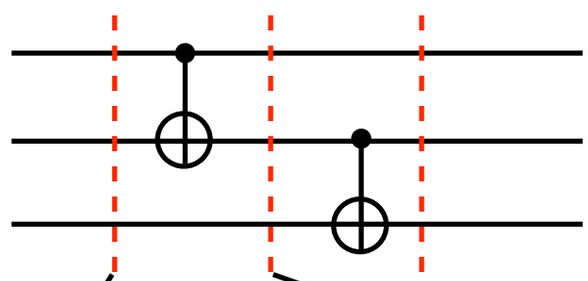

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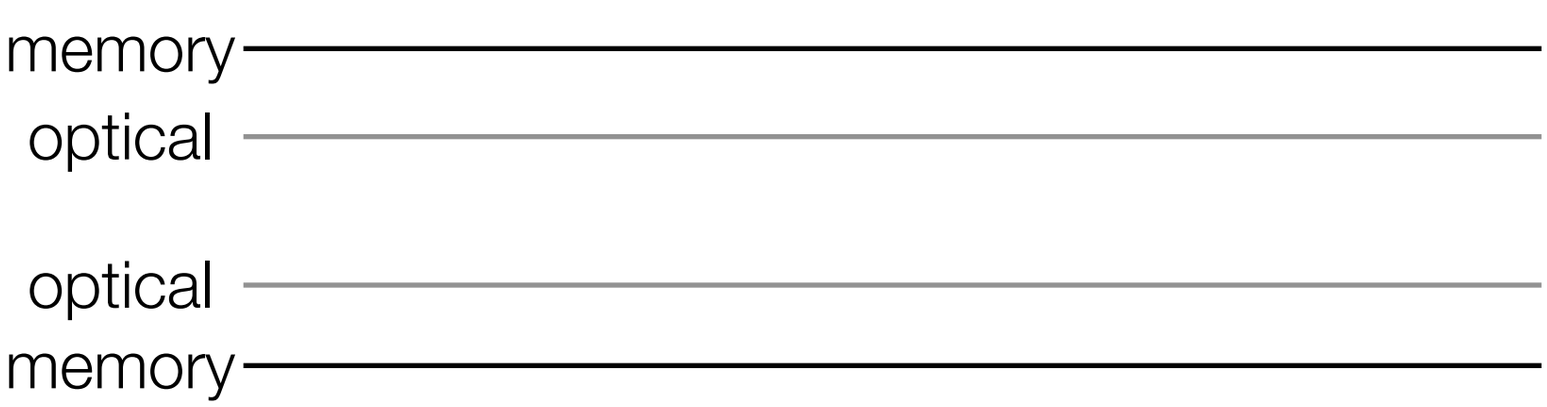

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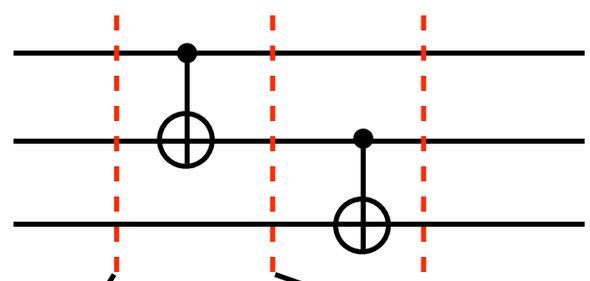

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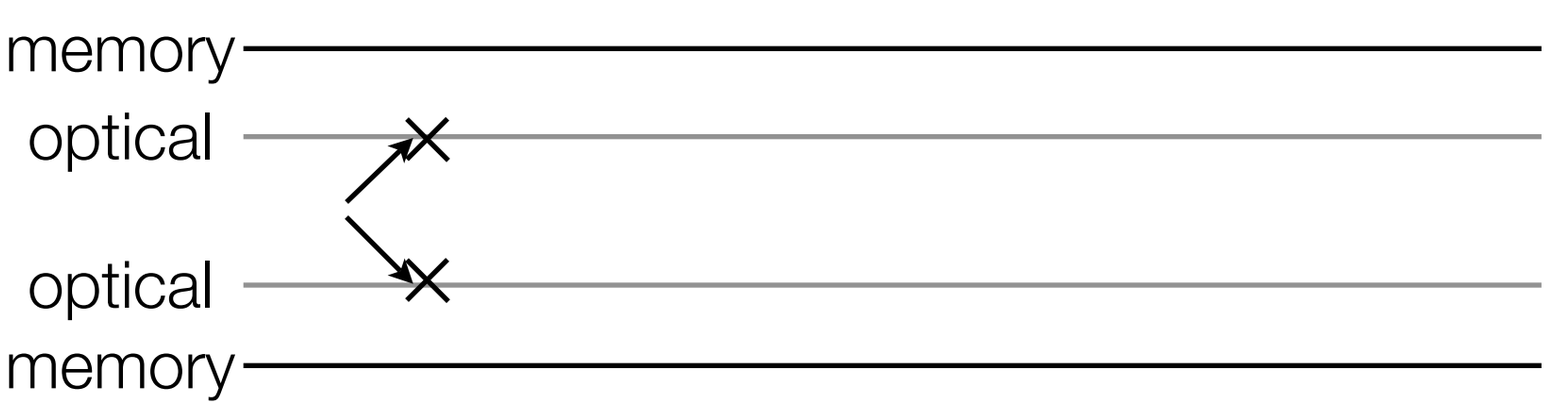

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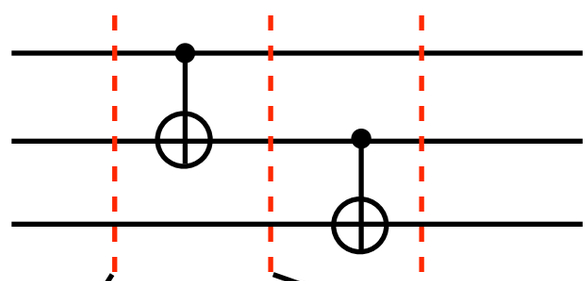

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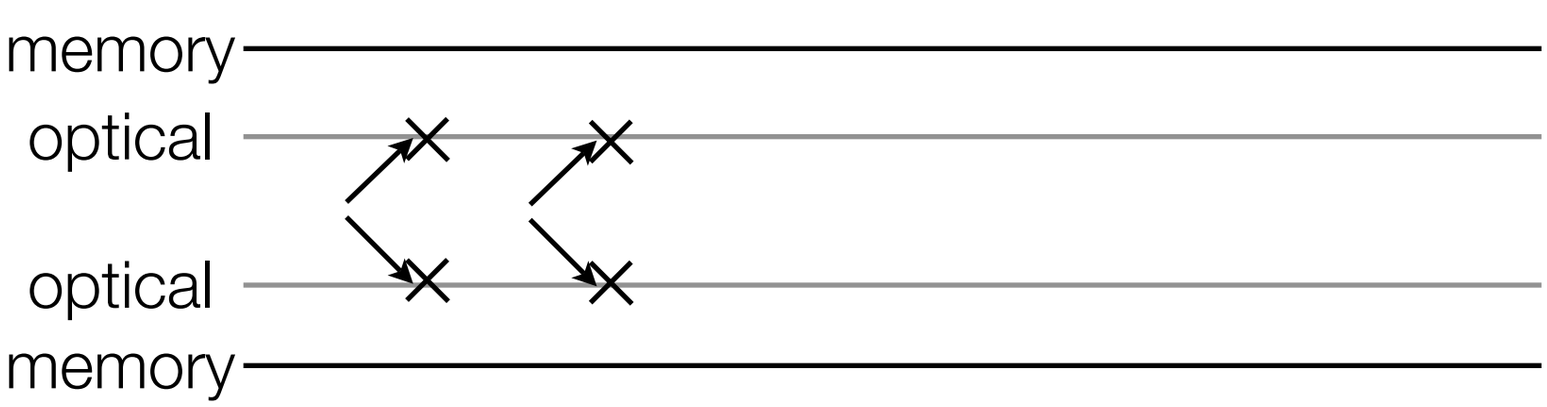

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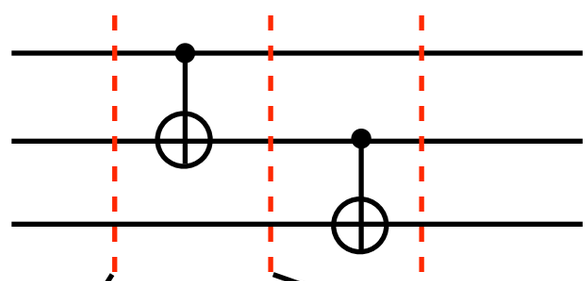

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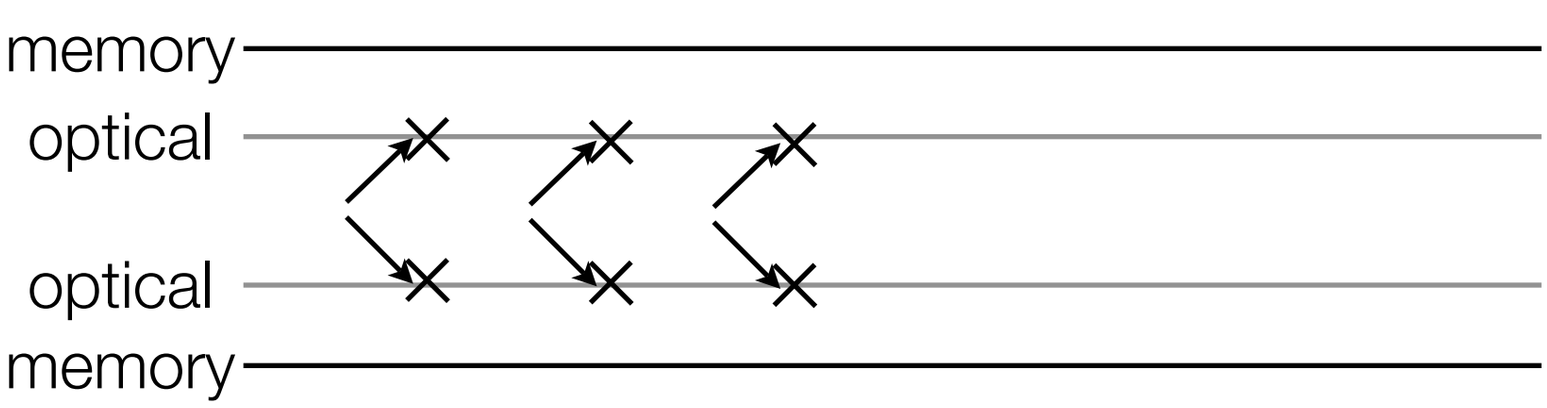

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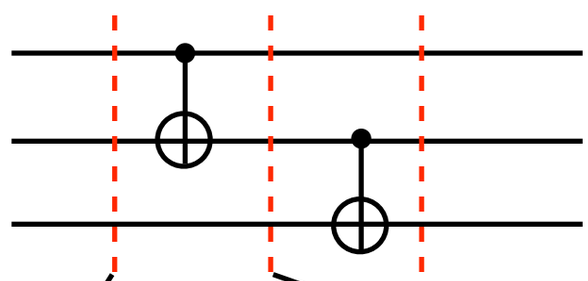

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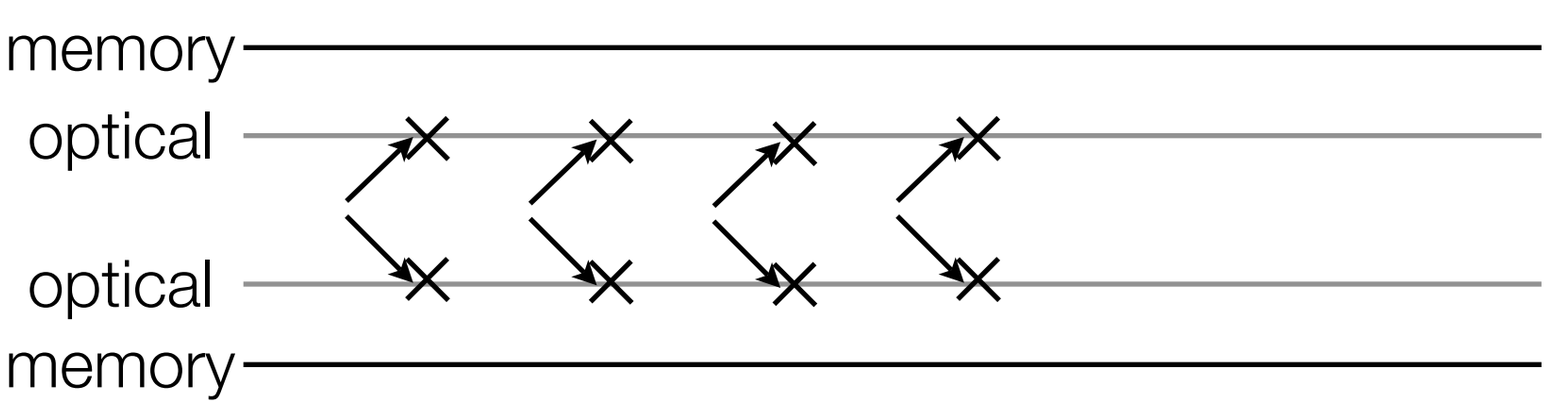

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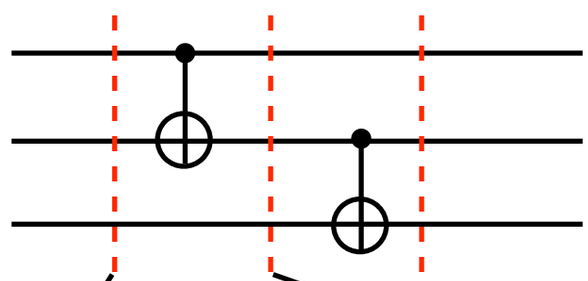

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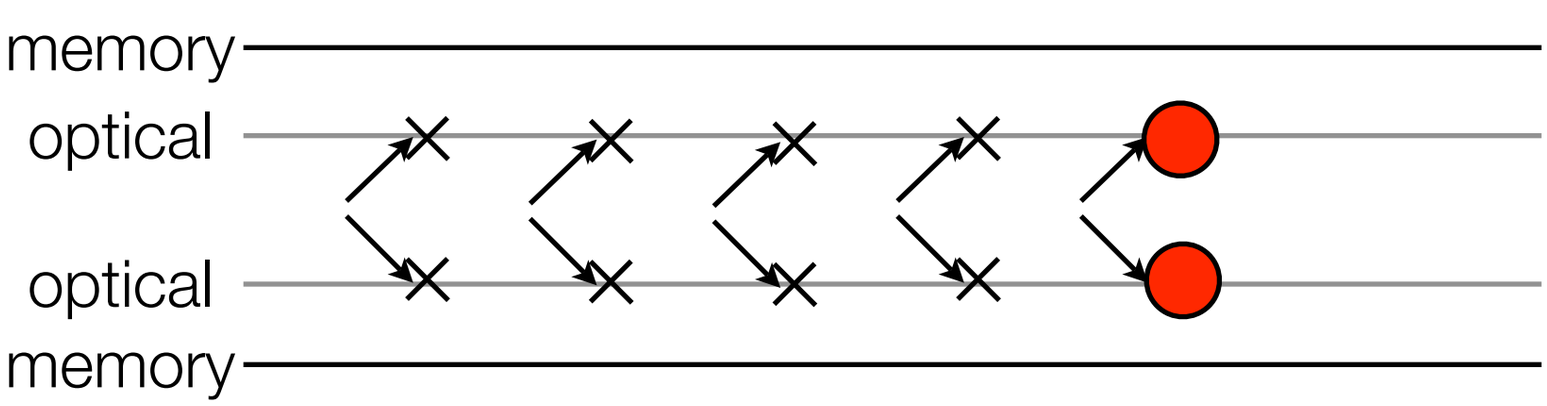

Deterministic distributed computation

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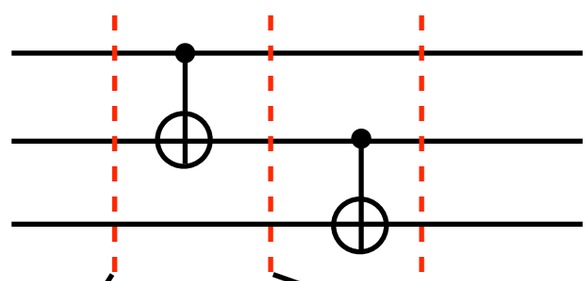

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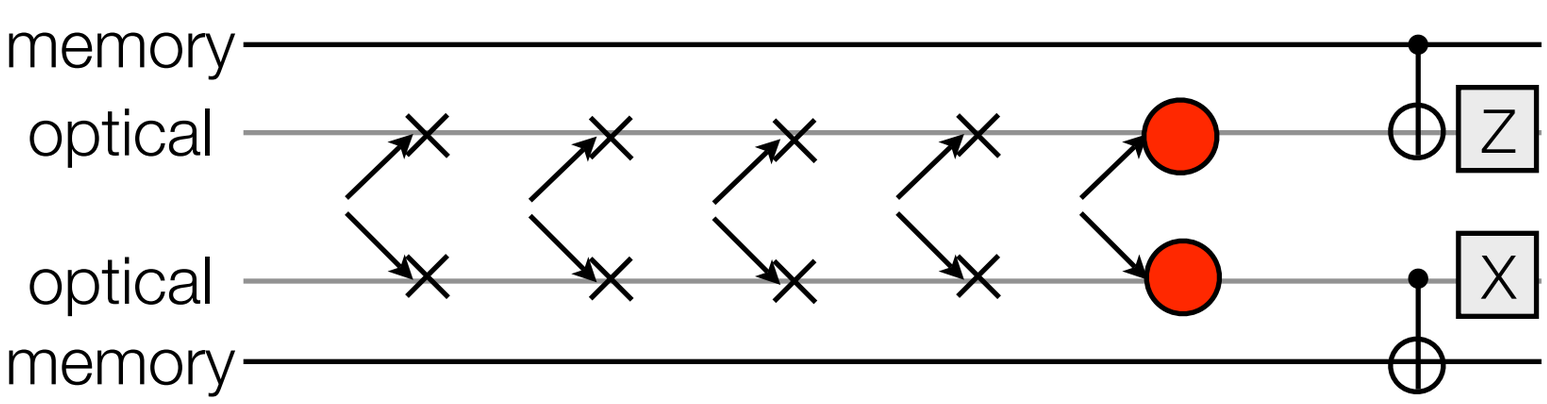

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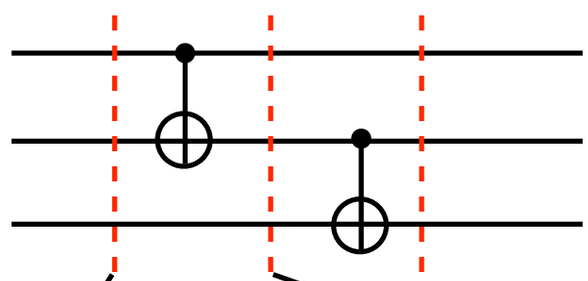

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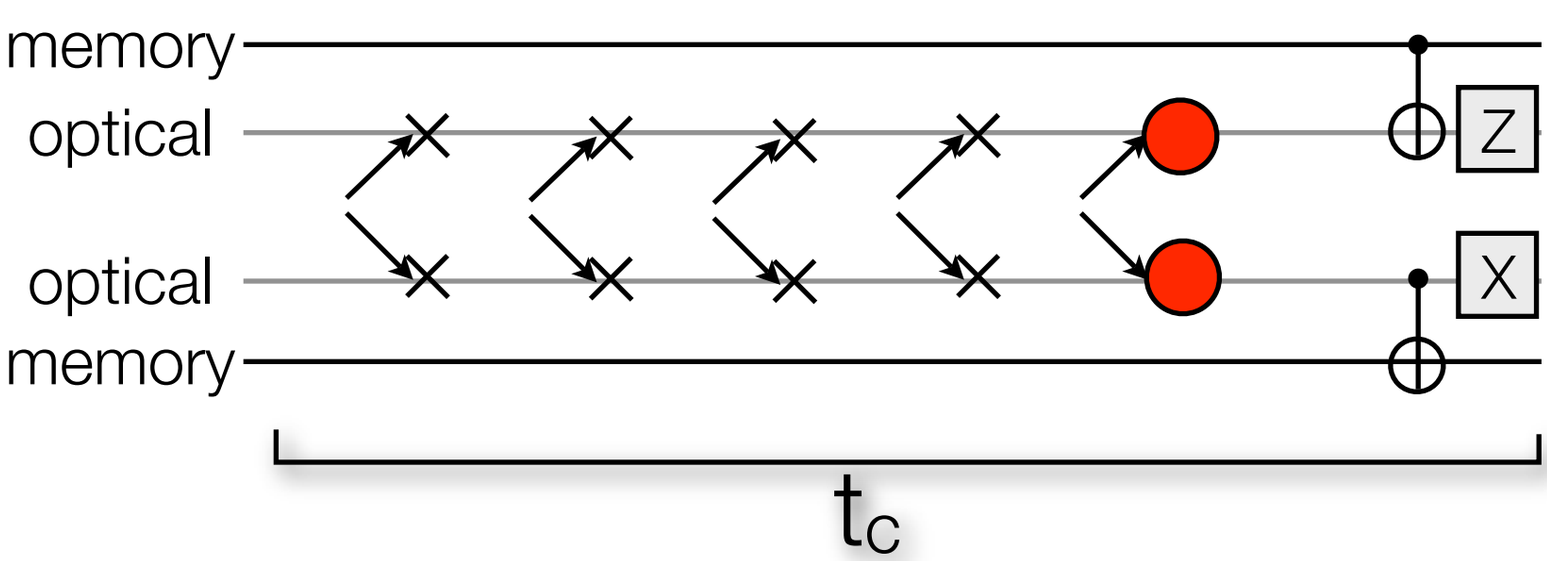

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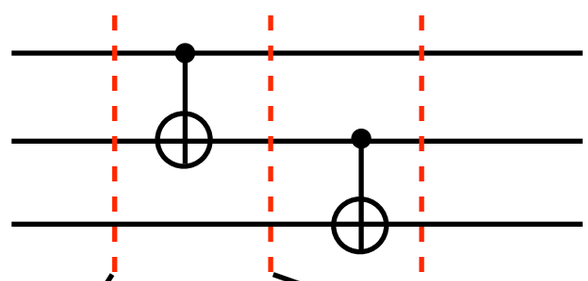

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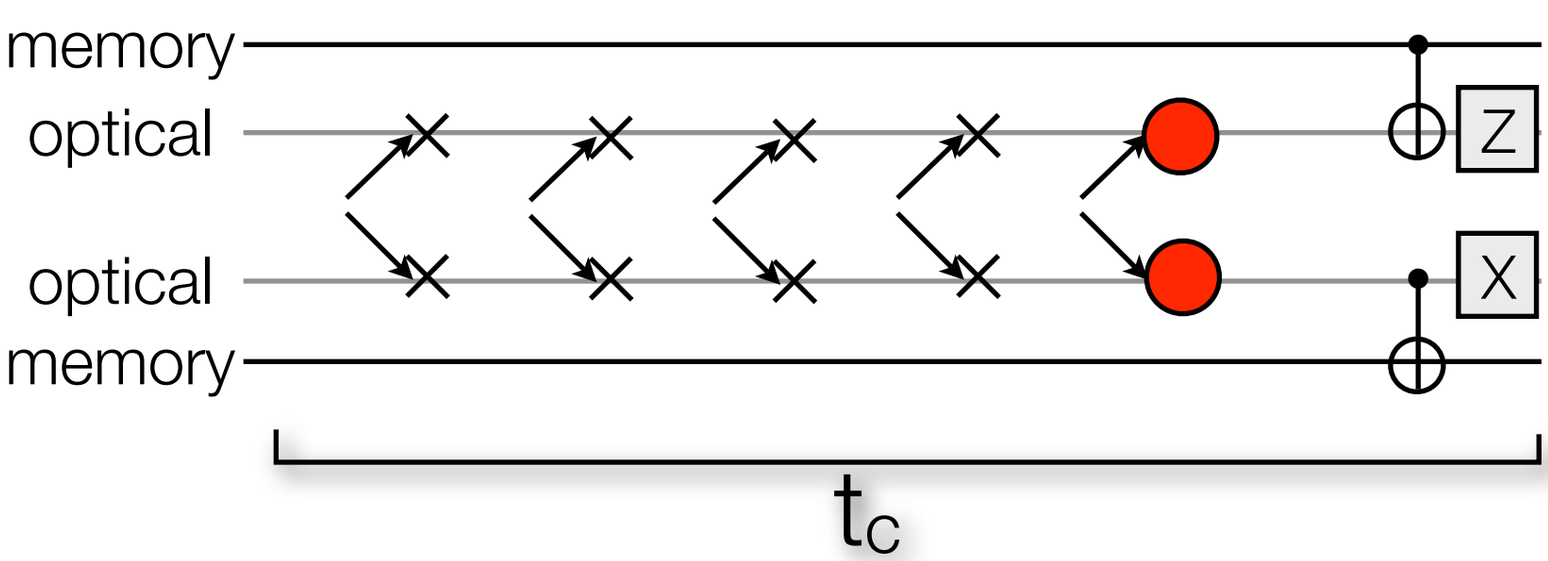


time/gate = t_c

error/gate = $N_{eff}\, p_L$

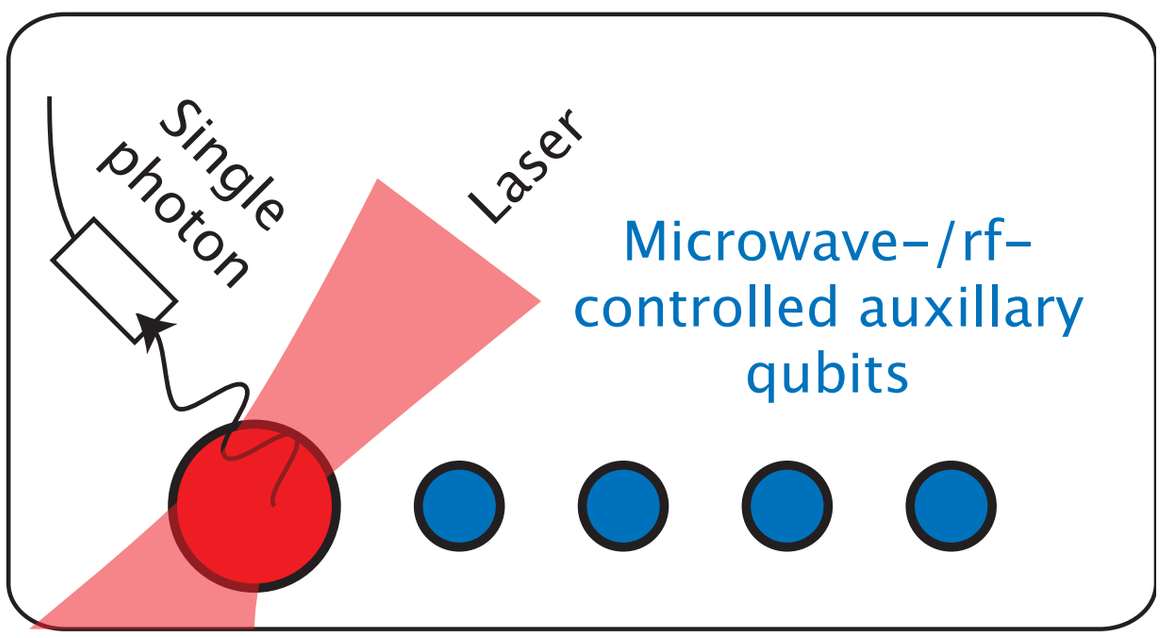
A minimal register

[see talk by T. Ladd]

Minimum requirements:

- “optical” qubit
  - entanglement generation
  - measurement / initialization
- “memory” qubit
- very good local control
- reasonable optical interface

  [early ideas: Dür & Briegel]



[Jiang et al. quant-ph/0703029,
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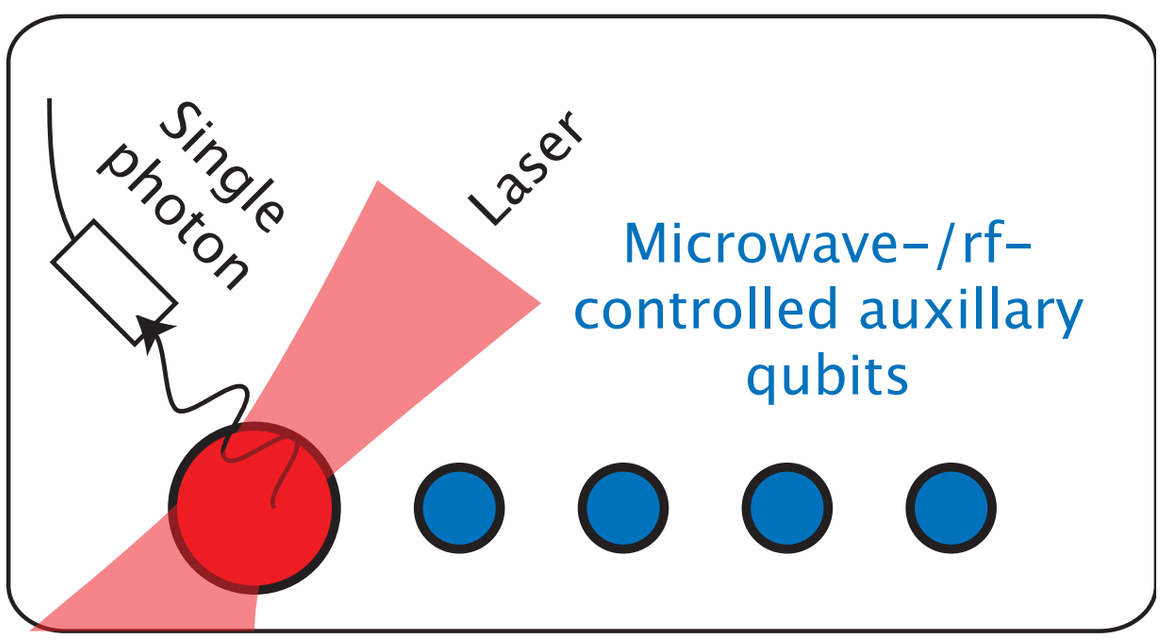

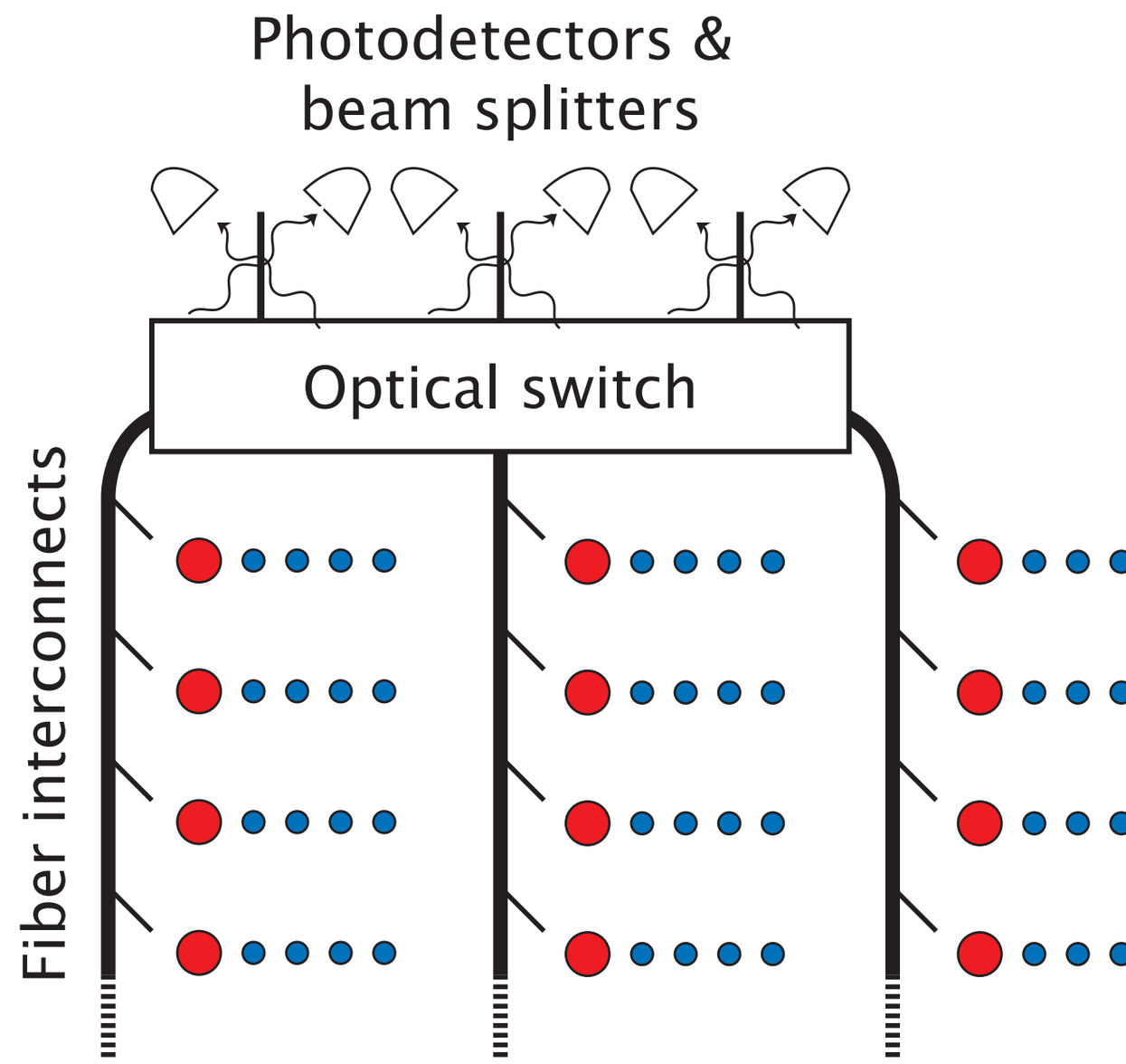

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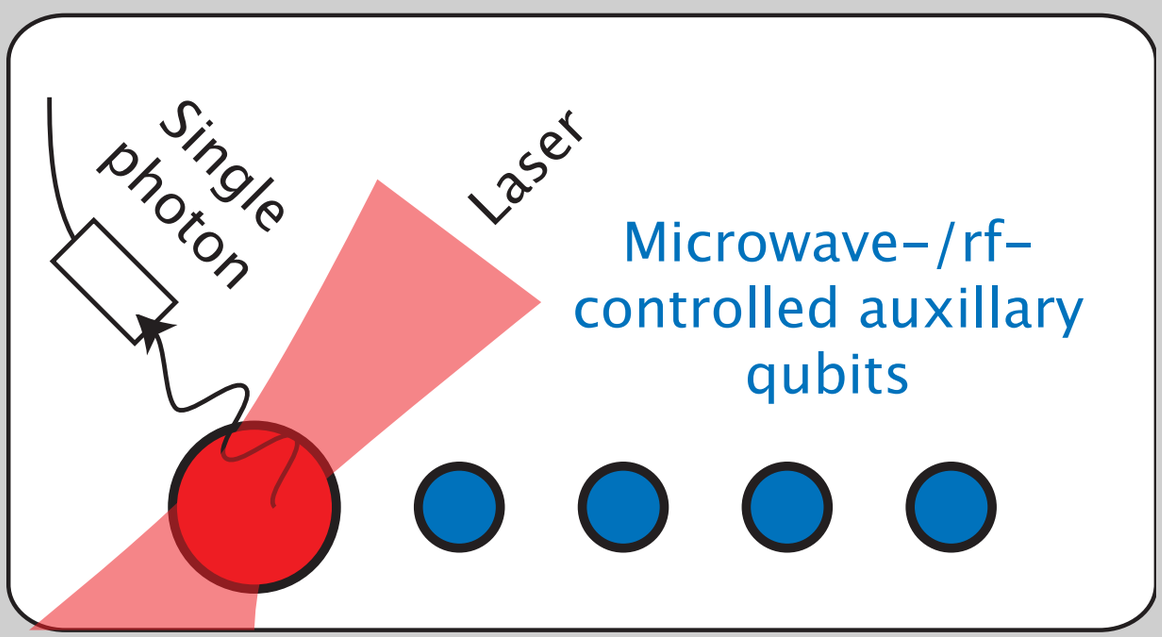
- reasonable optical interface

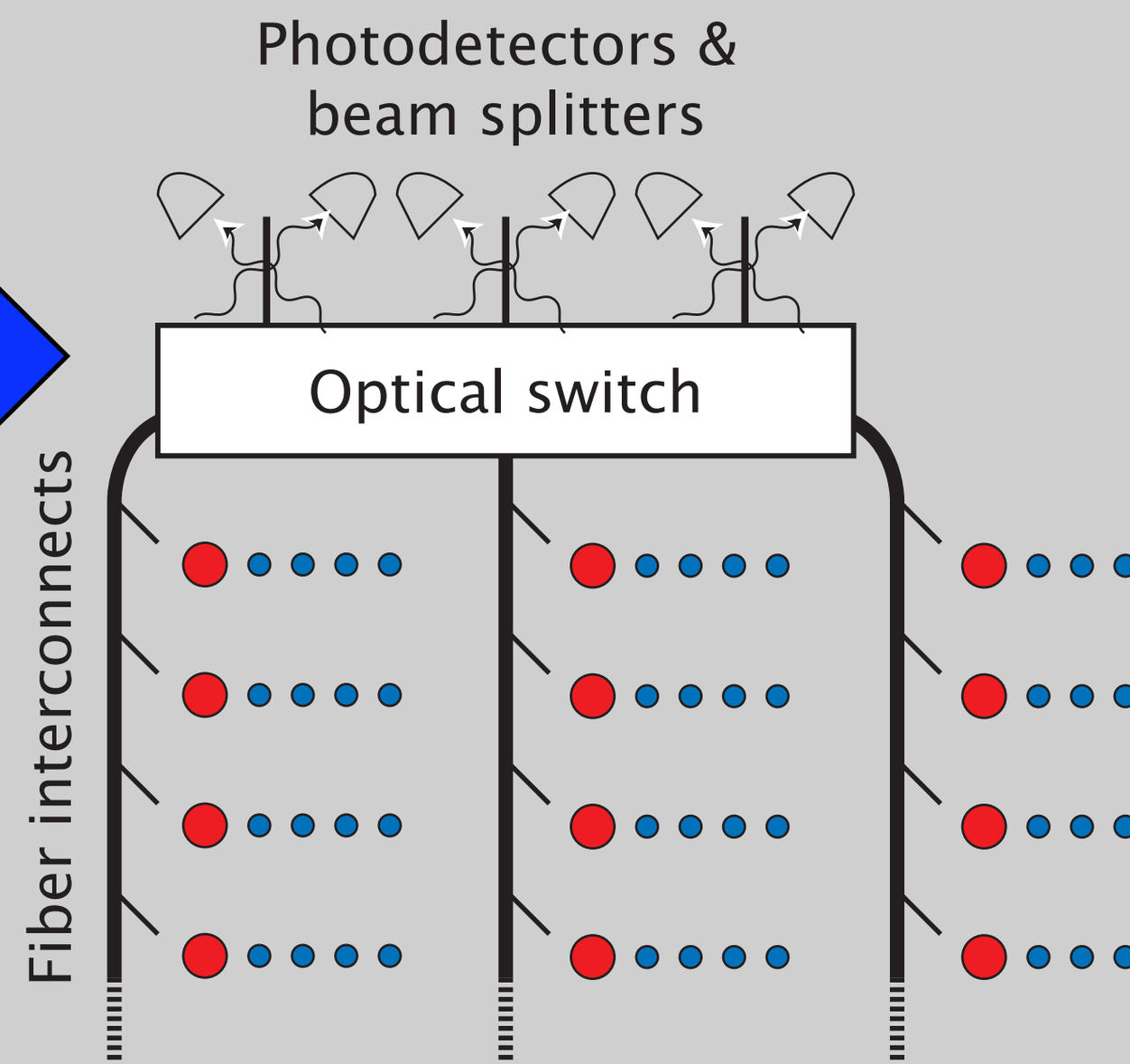
[early ideas: Dür & Briegel]

Small size ion "computer"

+

Optical interface





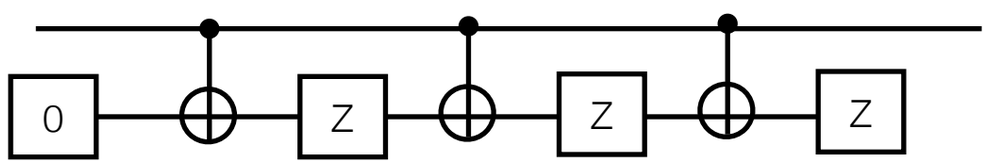
[Jiang et al. quant-ph/0703029, Jiang et al., PRA (2007)]

Dealing with imperfections: 3 more spins

Robust measurement

- imperfect initialization, measurement (p_I,p_M ~ 5%)
- near-perfect local operation (p_L ~ 0.01%)

Bit verification



[see talk by Wineland]

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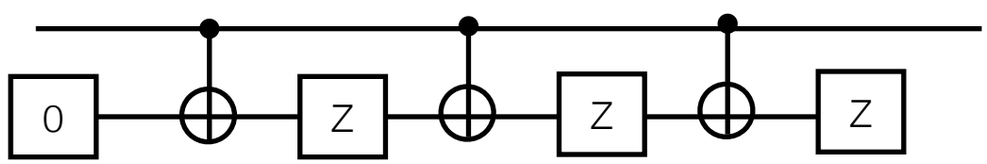

Take majority vote of 2*m*+1 measurements

$$\tilde{\varepsilon}_M \approx \binom{2m+1}{m+1} (p_I + p_M)^{m+1} + (2m+1)\, p_L$$

$$\tilde{t}_M = (2m+1)\,(t_I + t_L + t_M)$$

[see talk by Wineland]

Dealing with imperfections: 3 more spins

Robust measurement

- imperfect initialization, measurement (p_I,p_M ~ 5%)
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$$\tilde{\varepsilon}_M \approx \begin{pmatrix} 2m+1 \\ m+1 \end{pmatrix} (p_I + p_M)^{m+1} + (2m+1)\, p_L$$

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Dealing with imperfections: 3 more spins

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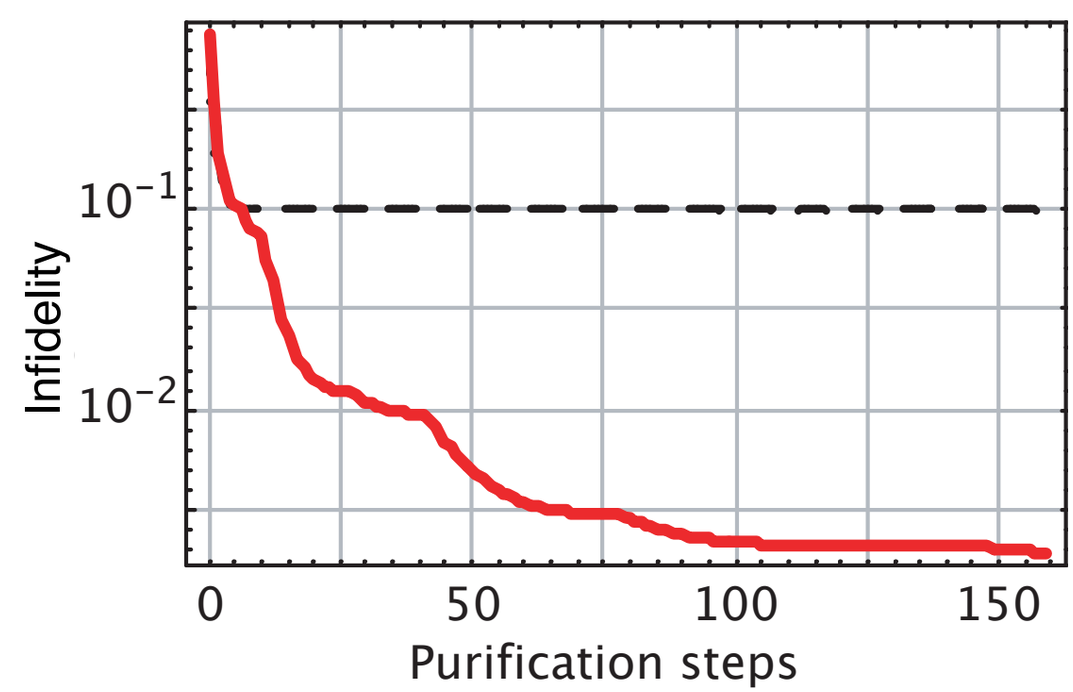
Robust entanglement generation

- Large time overhead (t_C ~100–1000 t_L)
- Initial F=0.9 gives final F>0.995 (N_{eff} ~ 20)
- Good quantum memory *critical*



Dealing with imperfections: 3 more spins

Robust measurement

- imperfect initialization, measurement (p_I,p_M ~ 5%)
- near-perfect local operation (p_L ~ 0.01%)

$$\tilde{\varepsilon}_M \approx \binom{2m+1}{m+1} (p_I + p_M)^{r}$$

$$\tilde{t}_M = (2m+1)\,(t_I + t_L + t_M$$

Further improvements:
better collection efficiency via optical cavities (Purcell effect)
— improves both speed and fidelity

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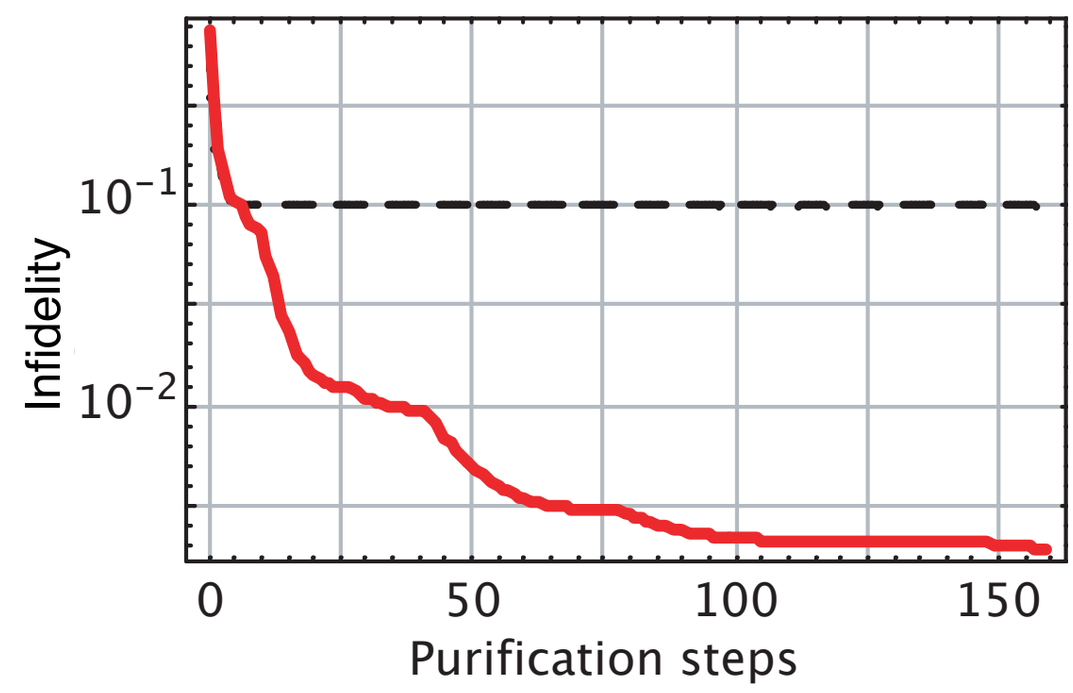

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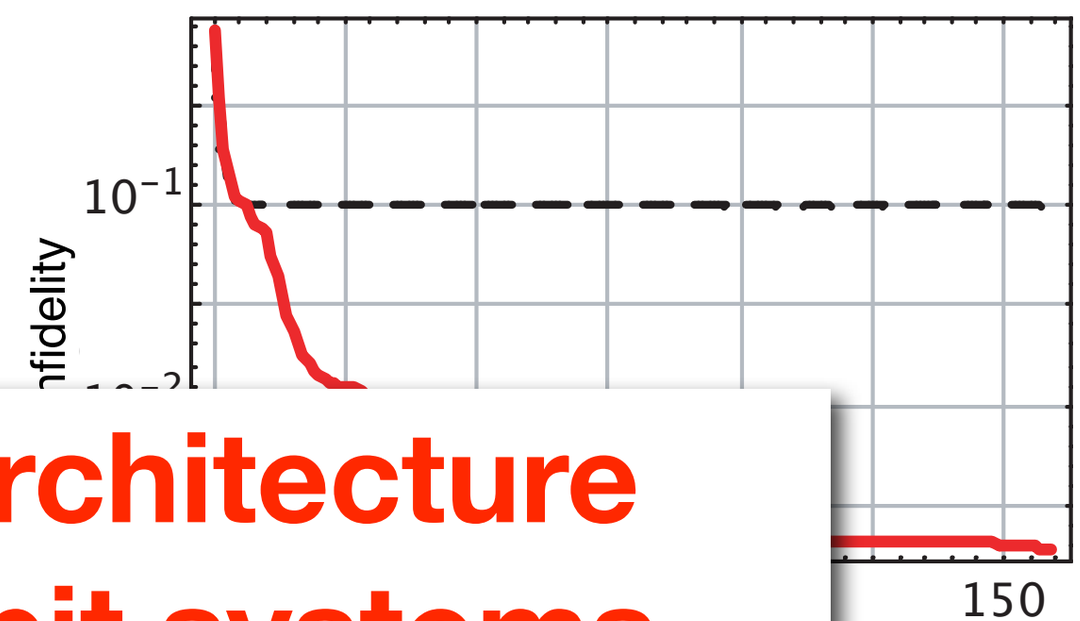
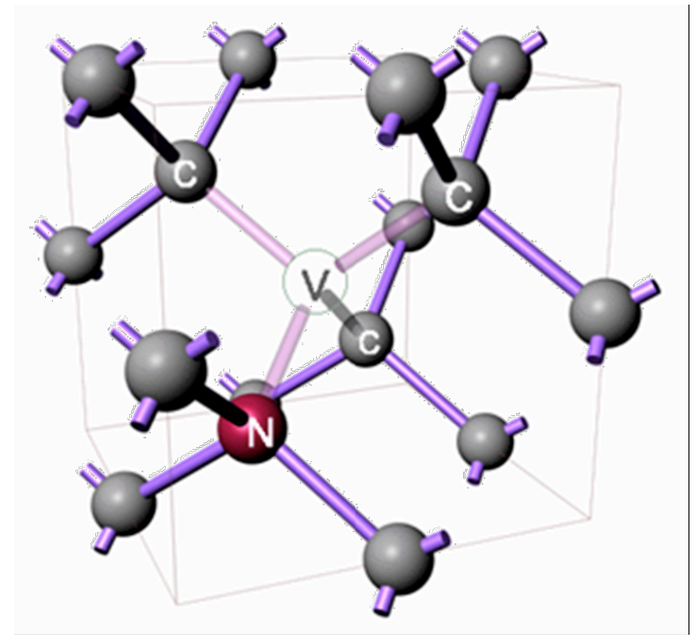
- Good c



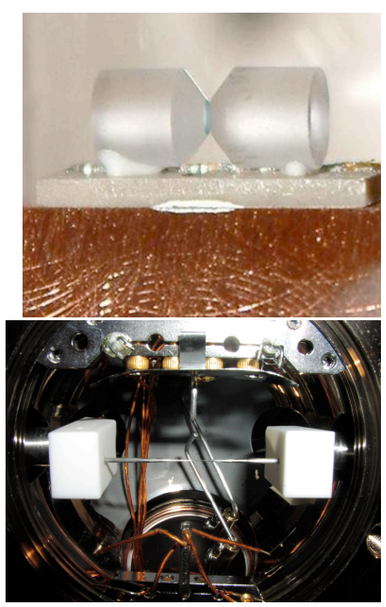
Scalable architecture for few-qubit systems

Implementation: small-scale devices

- good quantum memory
- good local operations
- photons allow quantum communication



NV centers in diamond



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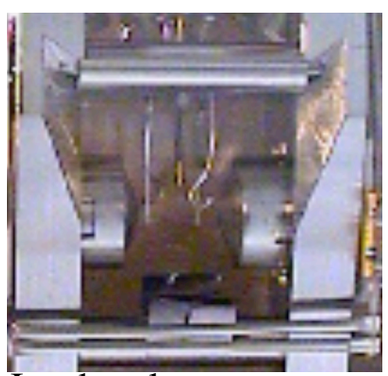
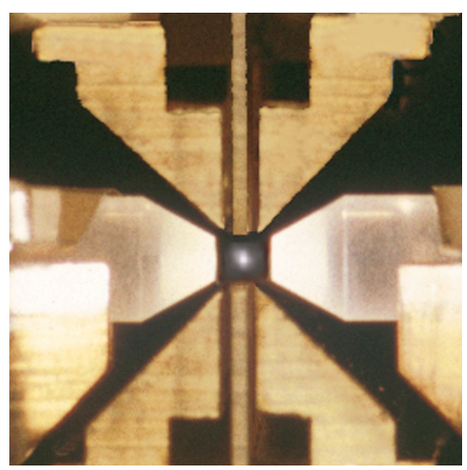


Innsbruck



Sussex

Linear Paul traps

Implementation: small-scale devices

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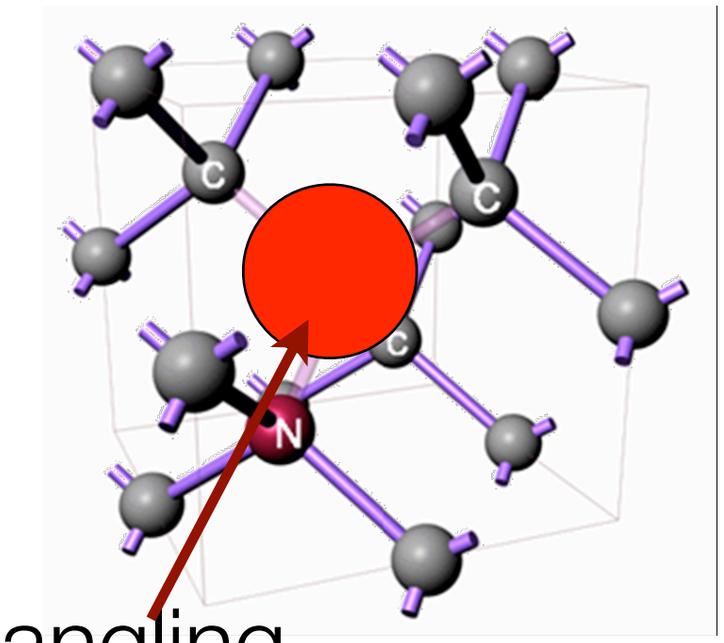
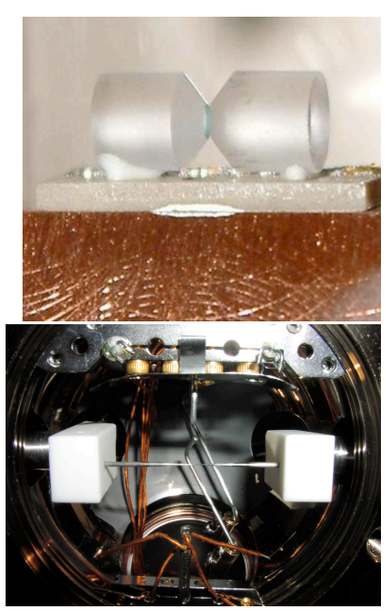


Entangling (optical) qubit

NV centers in diamond



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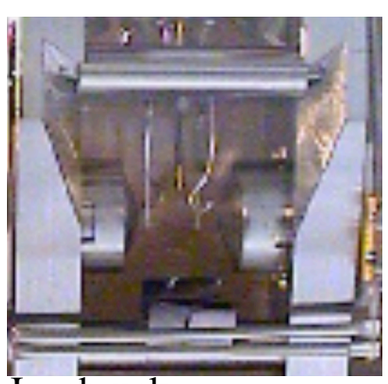

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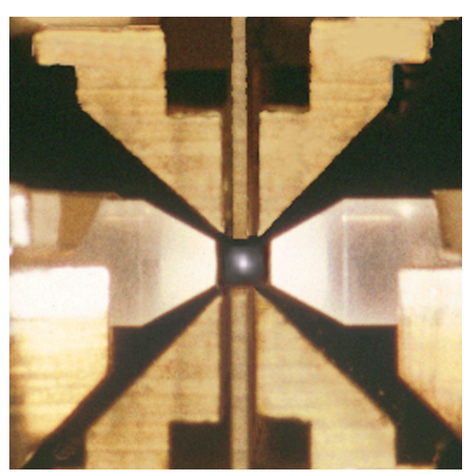

Sussex

Linear Paul traps

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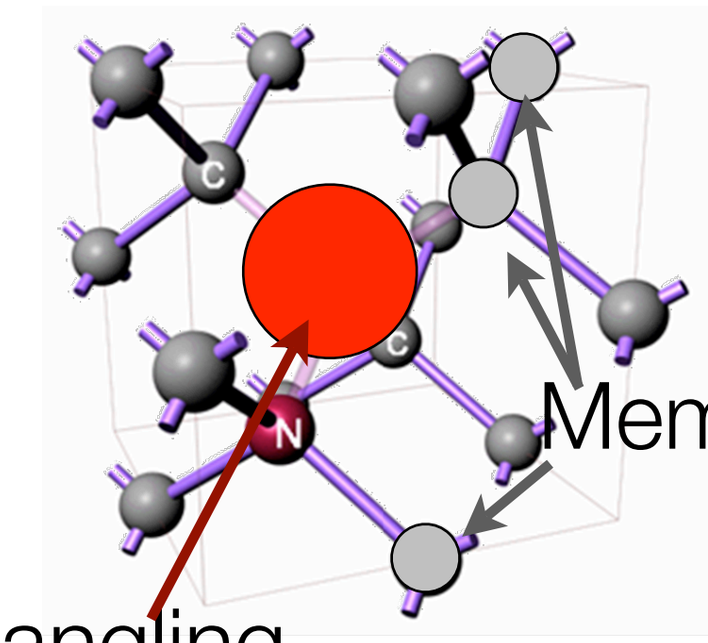

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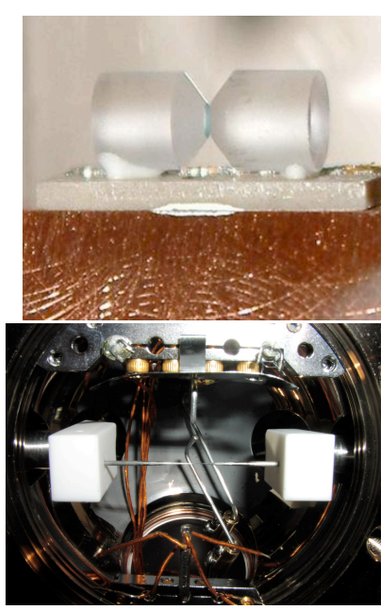

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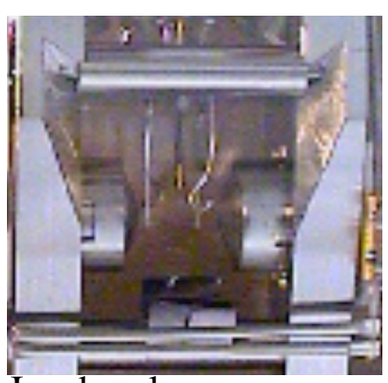

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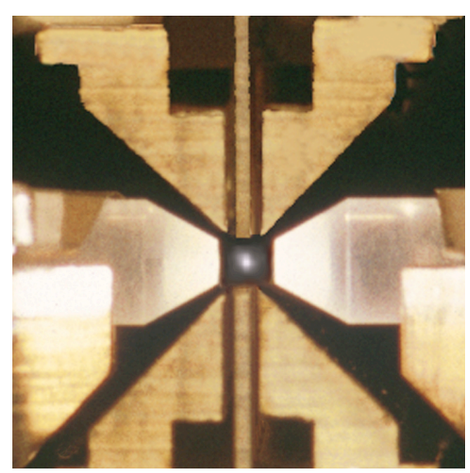

Sussex

Linear Paul traps

Outlook

- Commodity good: cheap, interchangeable, ubiquitous
- Finite size control problem *per register*.
  - GRAPE pulses [Khaneja et al.], feedback & filtering, composite pulses, etc.
- Optical or other “distributed qubit” interconnect system can be faulty (<50% errors after post-selection sufficient; for <10%, only 5 qubits needed)
- Implementations:
  - NEED: few coupled, controllable qubits with very good quantum memory; optical (or phononic, or qubit-bus) interconnection possible
- Improvements
  - Better code choices for distributed computing? High-Q cavities for higher fidelity entanglement generation? Cluster-state approach?

Collaborators

$$$: Pappalardo, ARO, DARPA-QIST, NSF, ...

Quantum registers

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Quantum repeaters

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N. Khaneja (Harvard)
L. I. Childress (Bates)
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M. D. Lukin (Harvard)