Quantum communication and computation with simple ion traps

Jake Taylor (MIT)

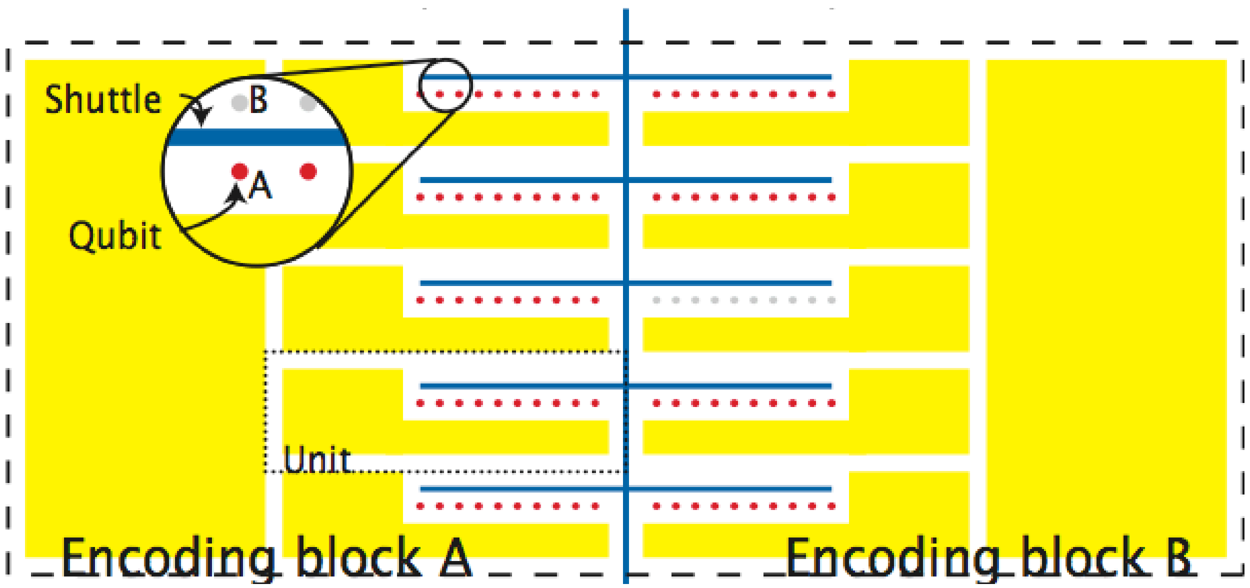
Massachusetts Institute of Technology

Motivation

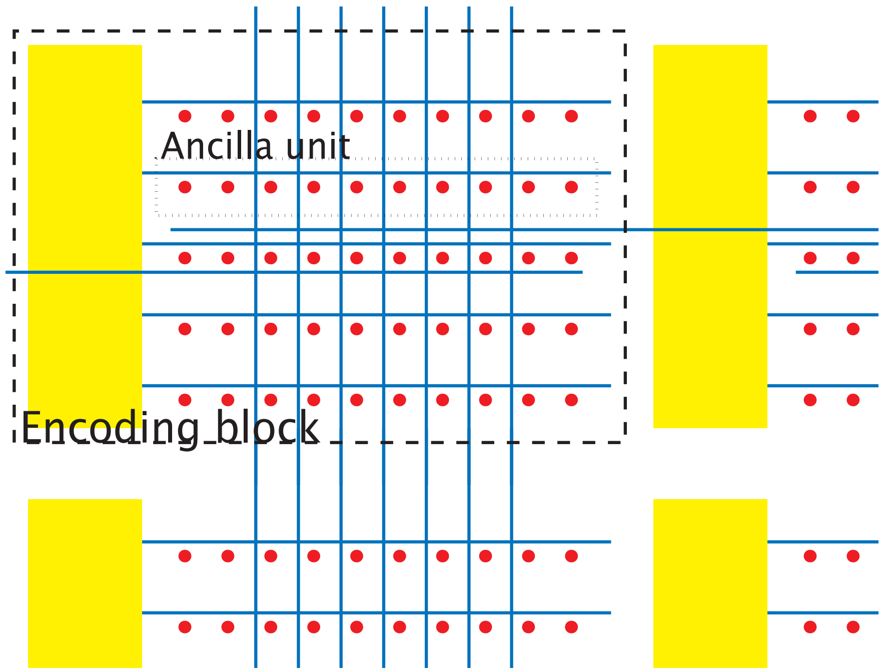
Historical	Atomic clocks
Technological	Precision measurement Quantum communication Quantum processors
Physical	New states of matter? Quantum simulation? Nano-scale science?

Architectures

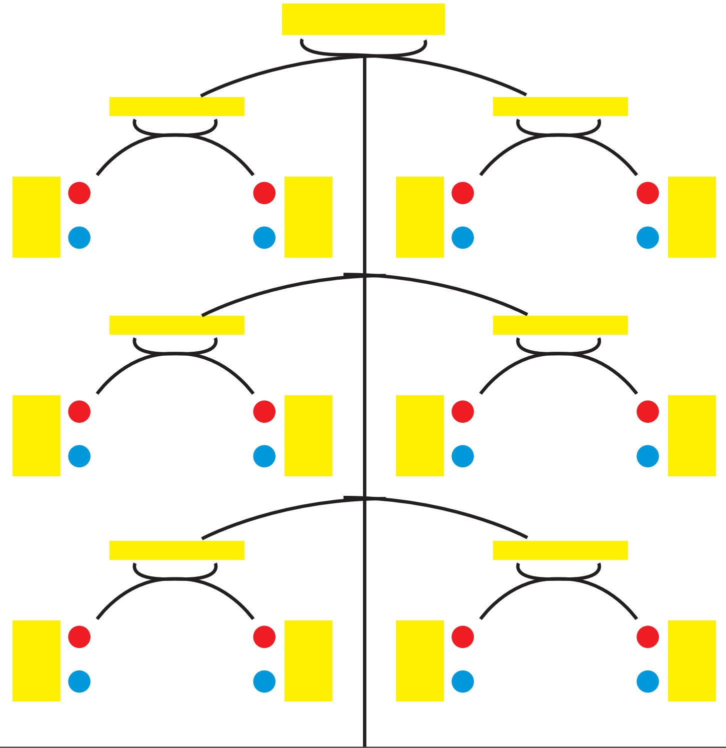
Qubit shuttle approach



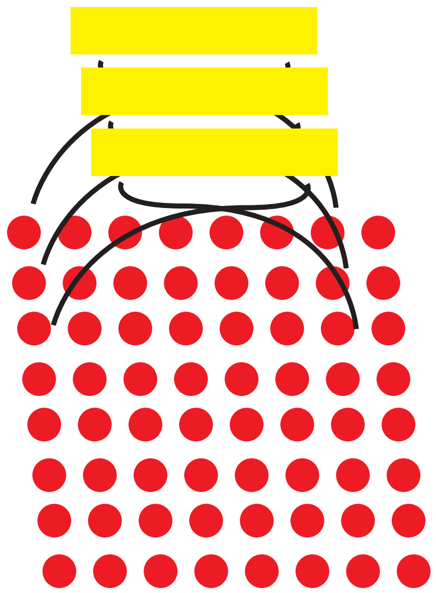
Resonator approach



Distributed computation



Crystal approach



Architectures

Qubit shuttle approach

Resonator approach

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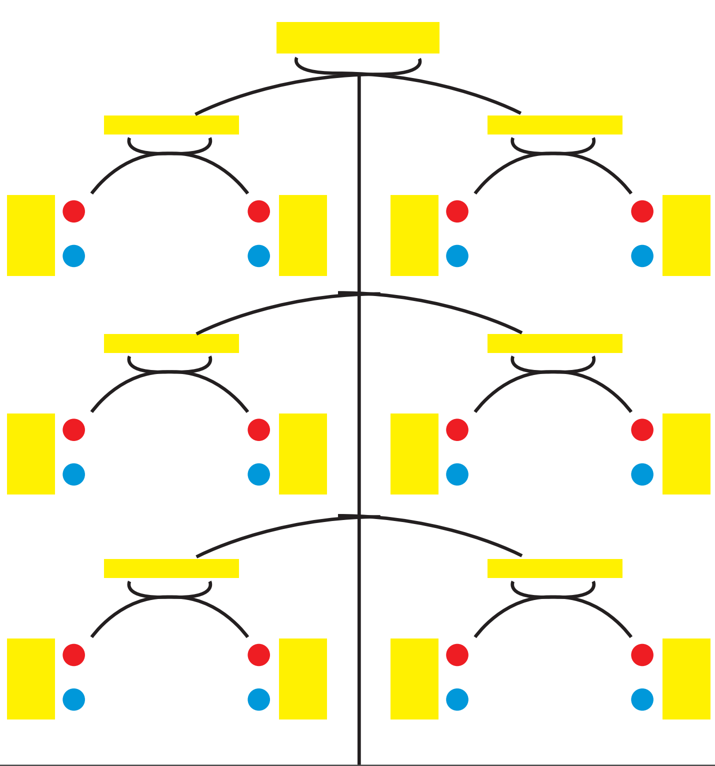

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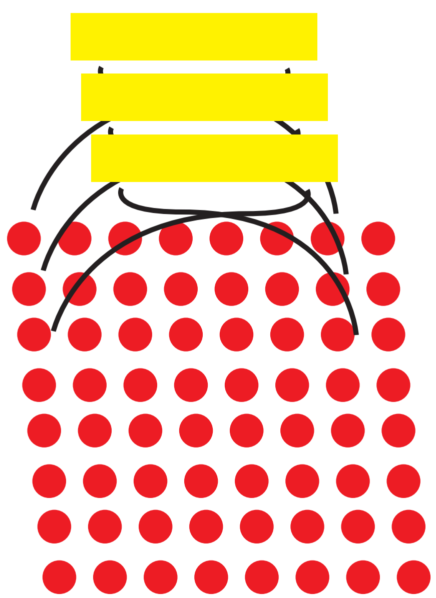
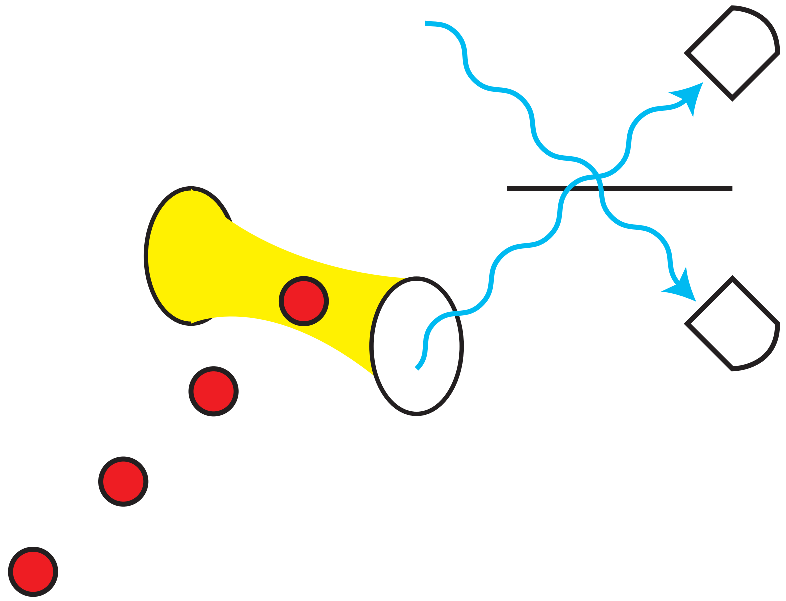


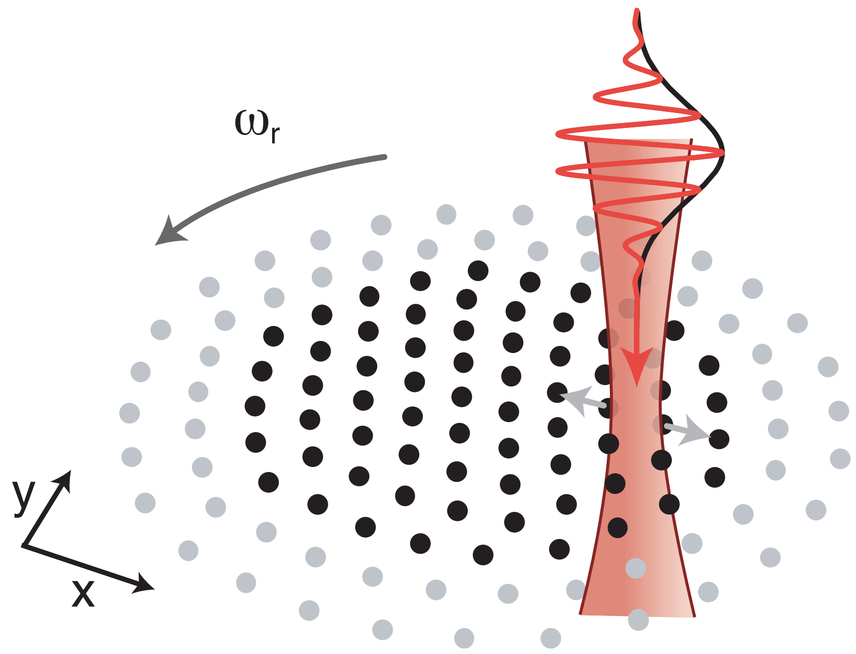
Focus of this talk

Quantum communication

Distributed computing



Wigner crystal-based quantum memory



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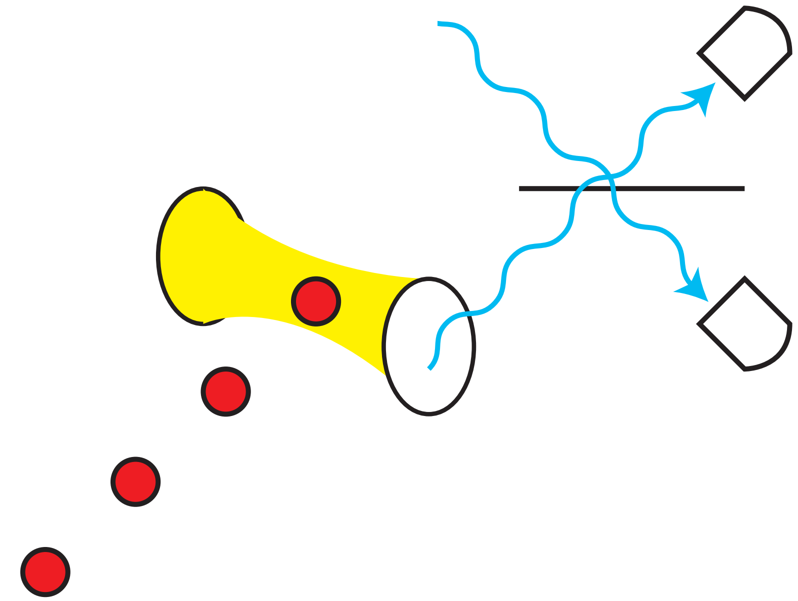

Distributed computing

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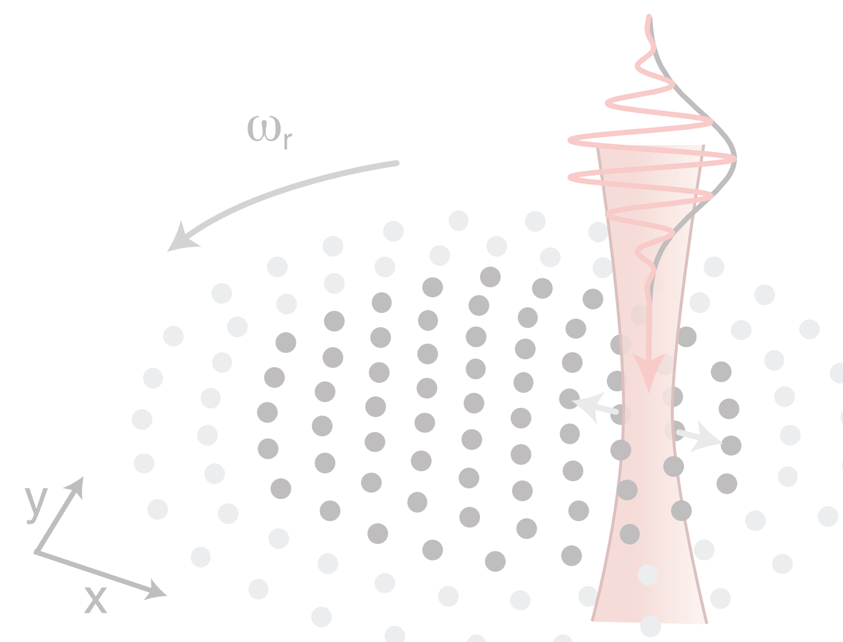
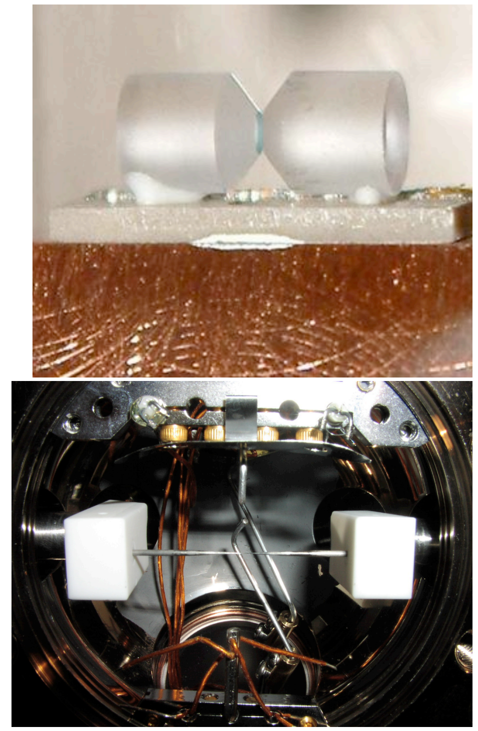


Small-scale devices

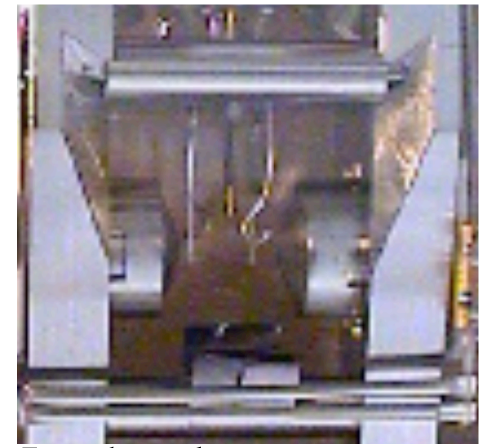
Linear Paul traps

+

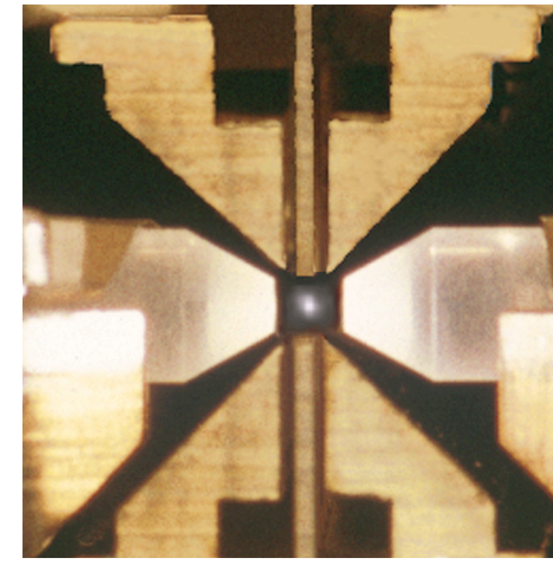
Photons



Georgia Tech / U Mich



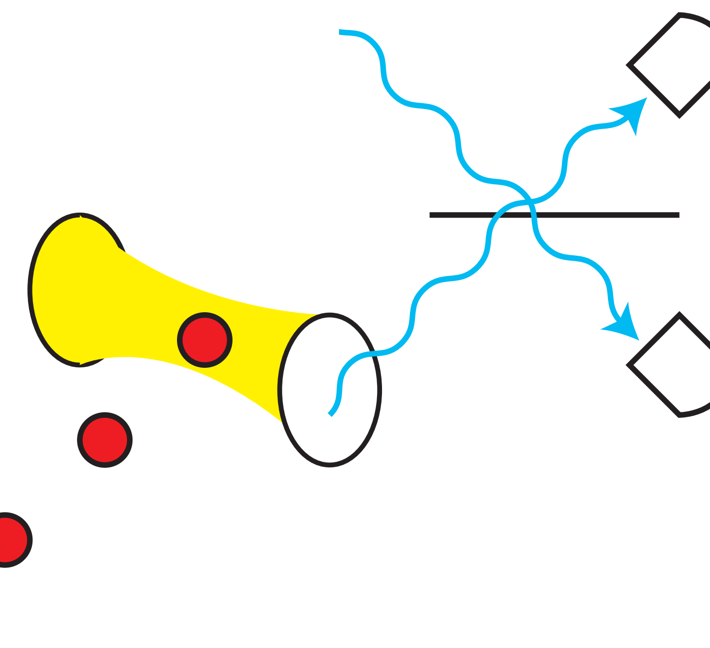
Innsbruck



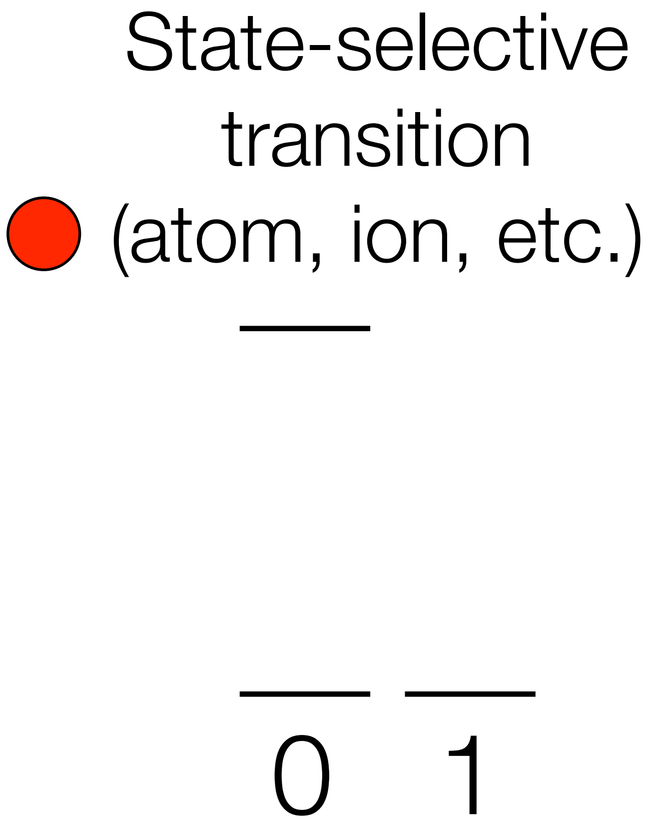
Sussex

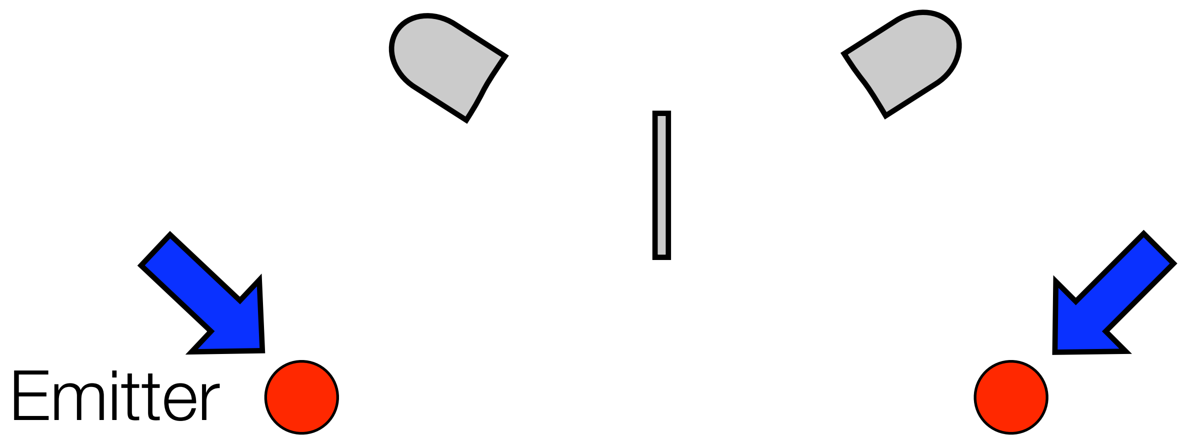
- good quantum memory
- good local operations
- photons allow quantum communication

Processor (Paul trap)



Using photons to build entanglement





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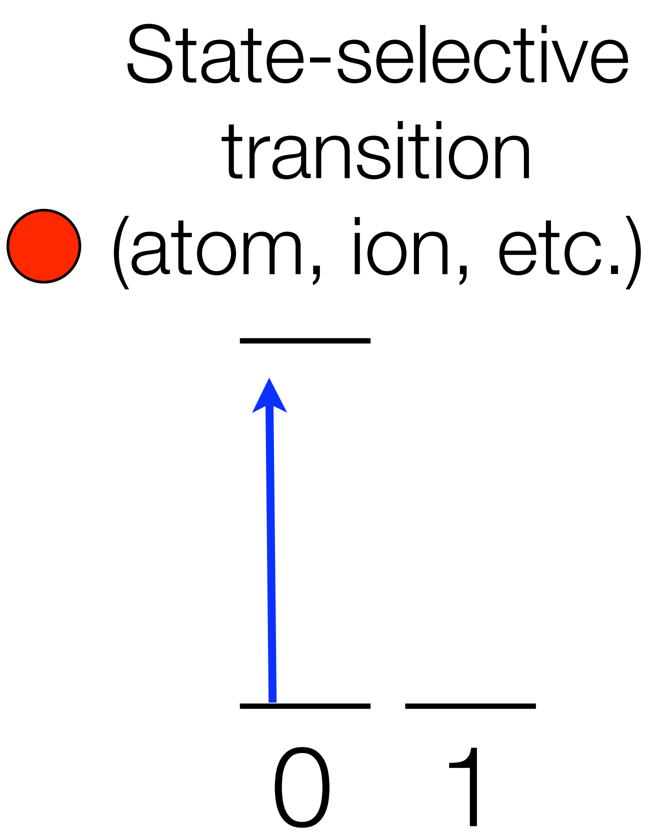

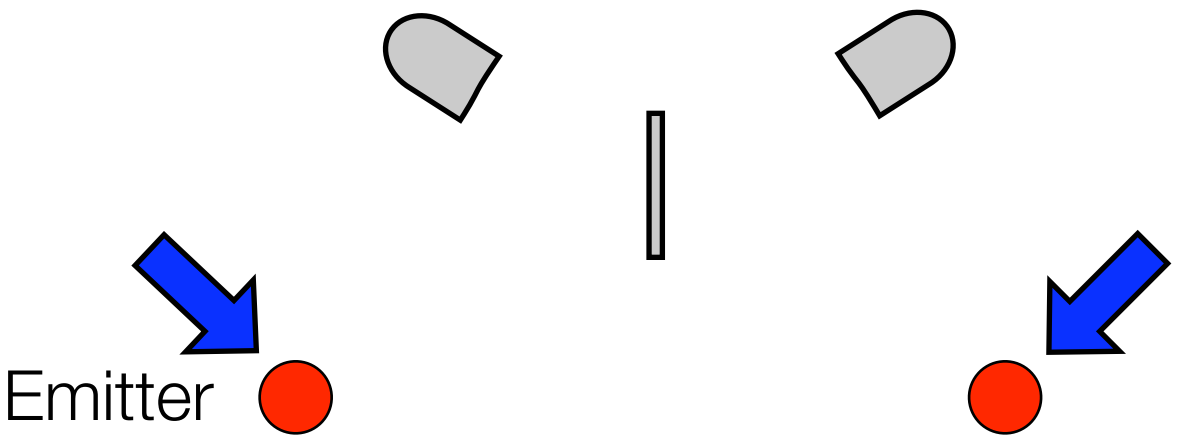

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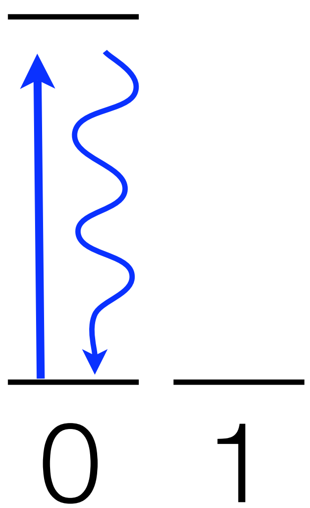

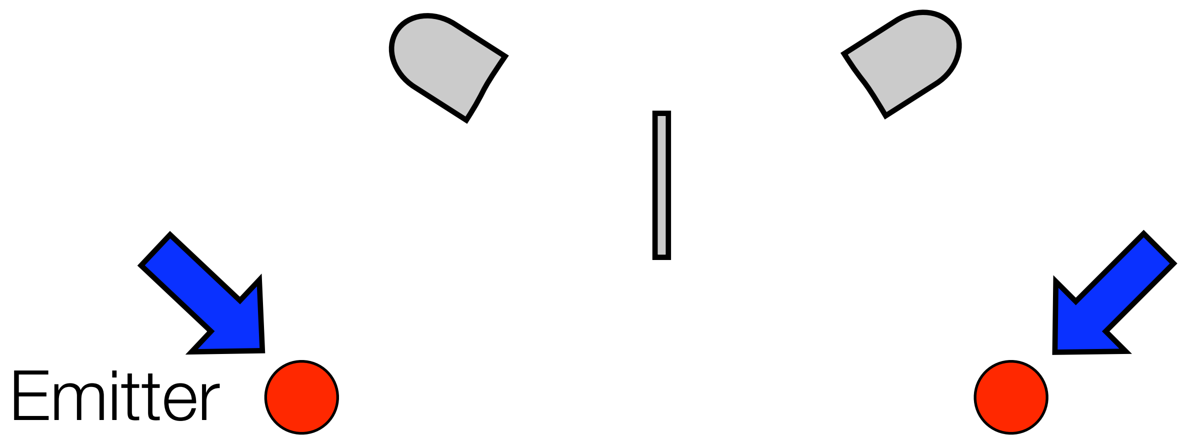

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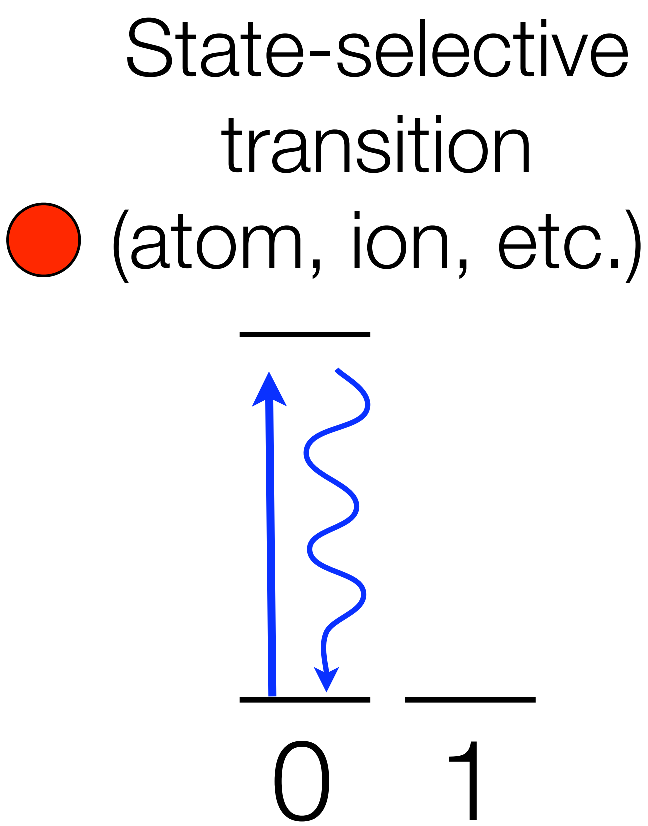

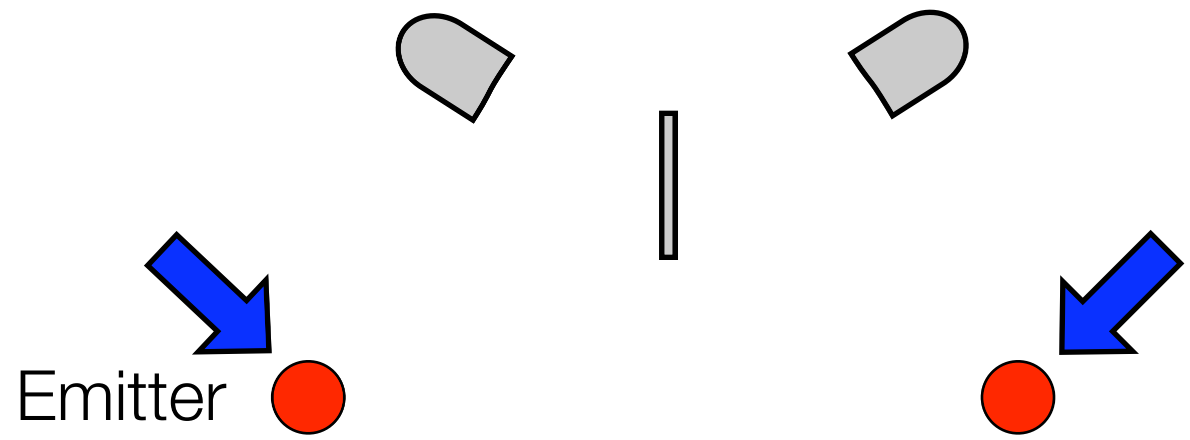

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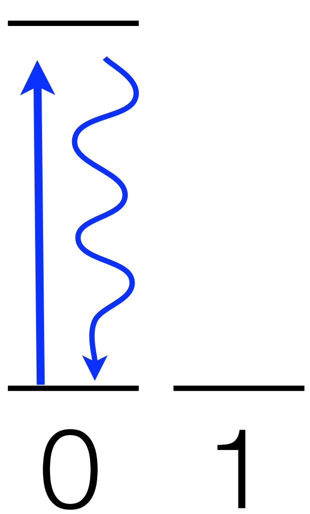

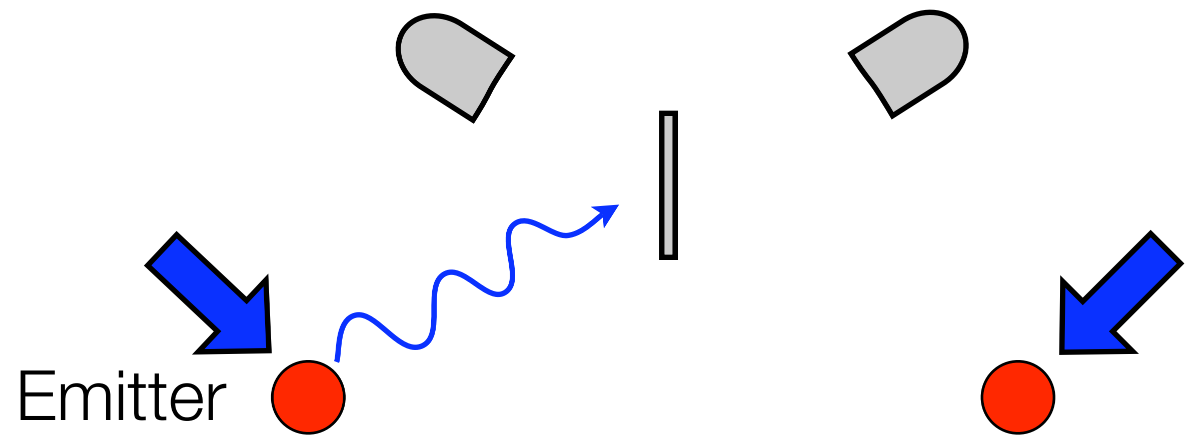

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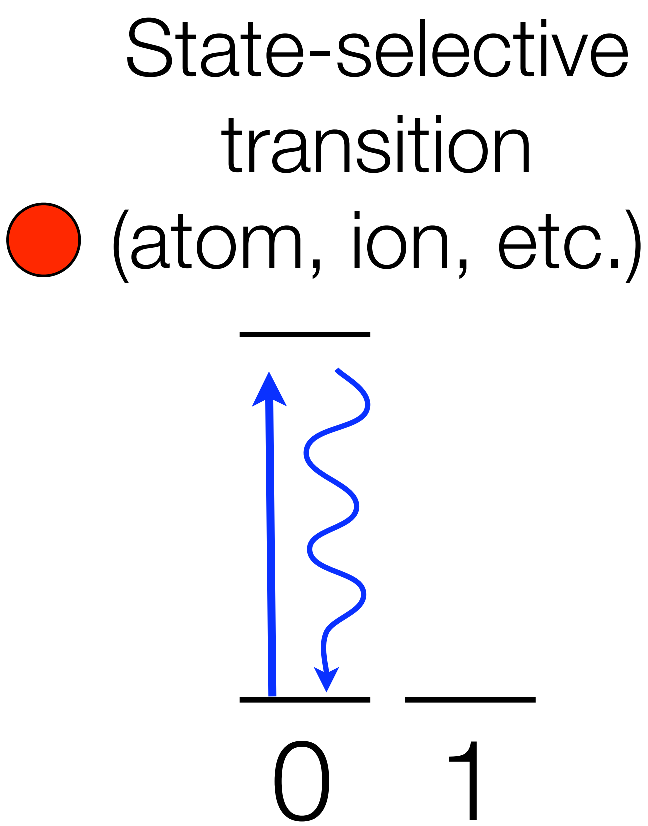

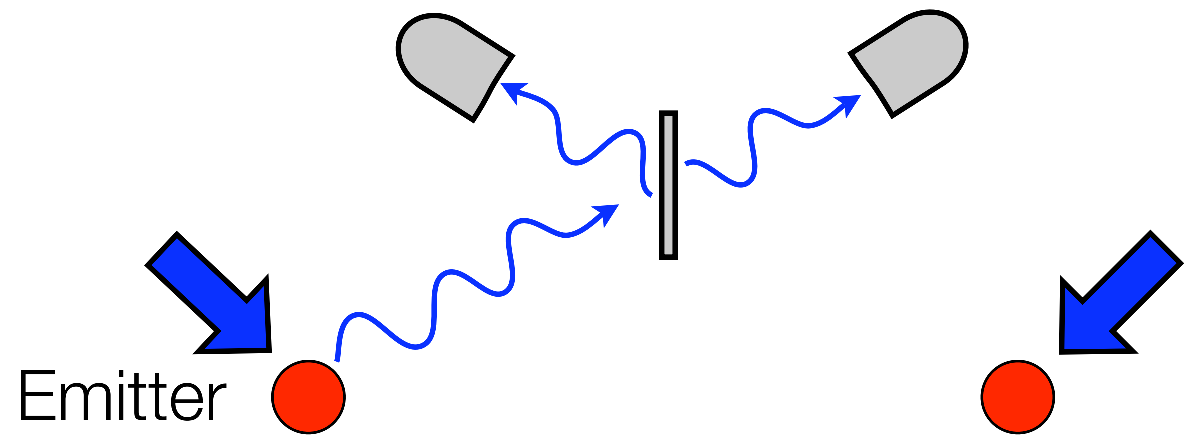

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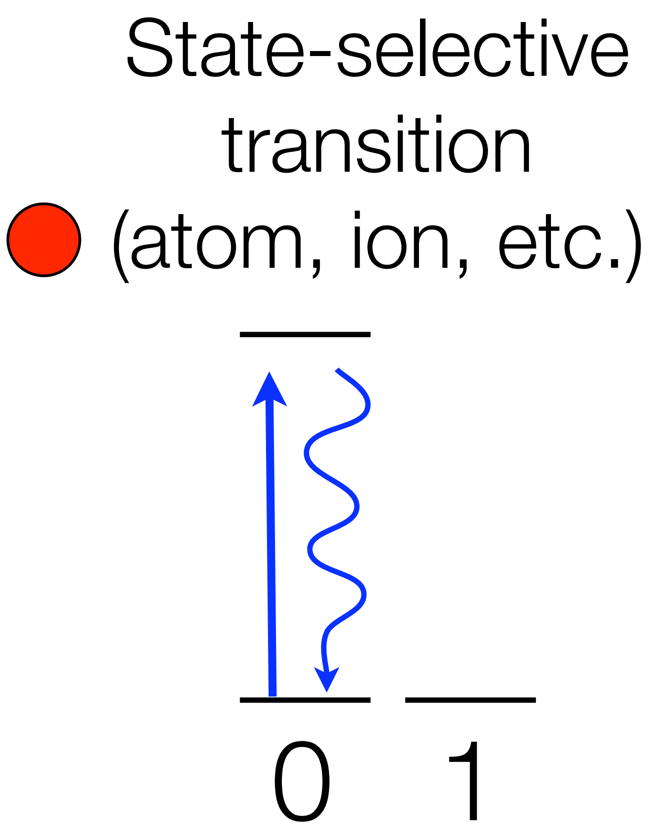

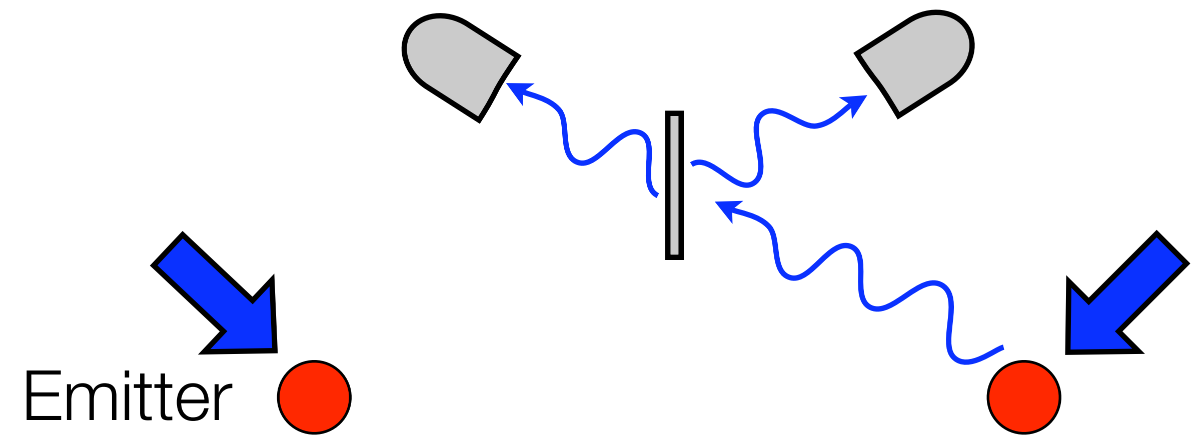

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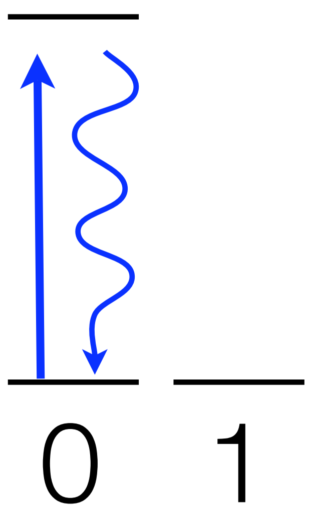

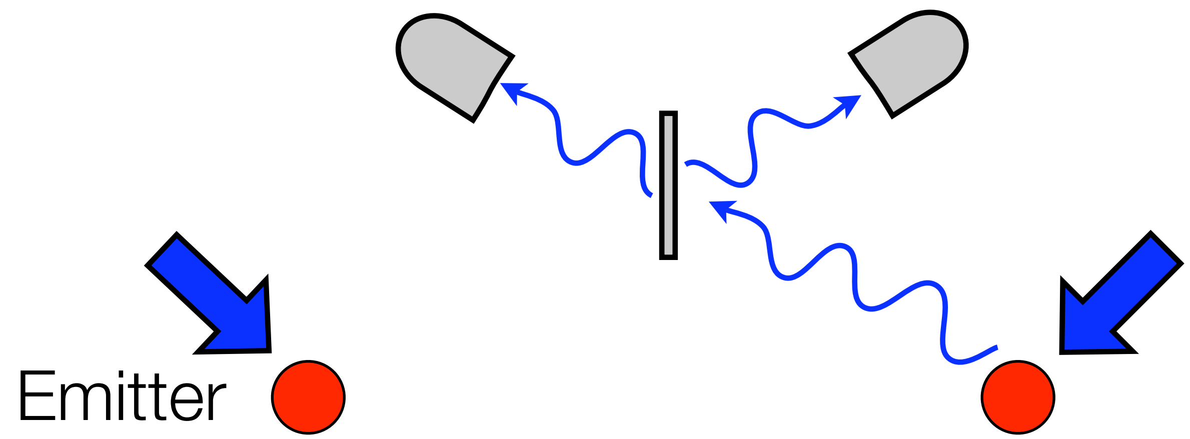

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- Single “click” with no which-path information
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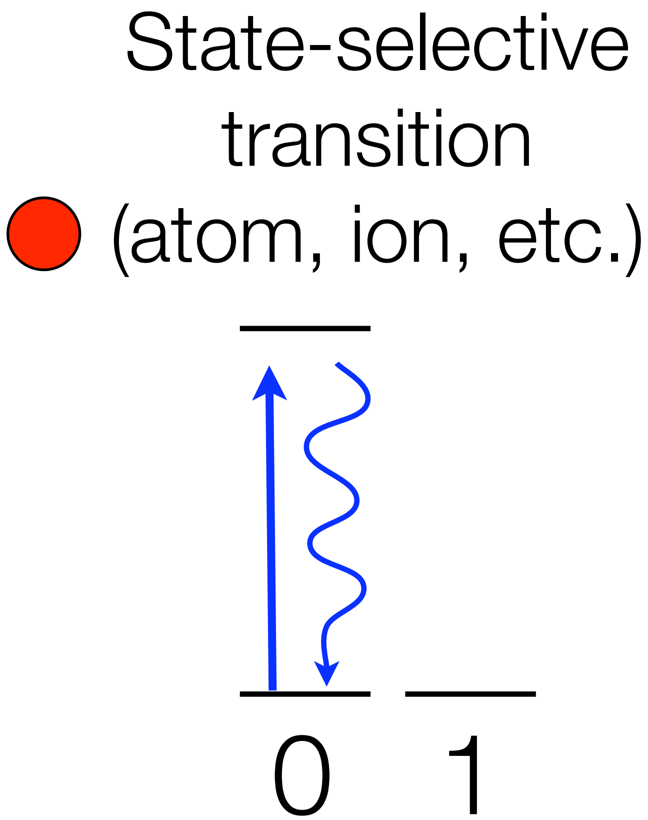

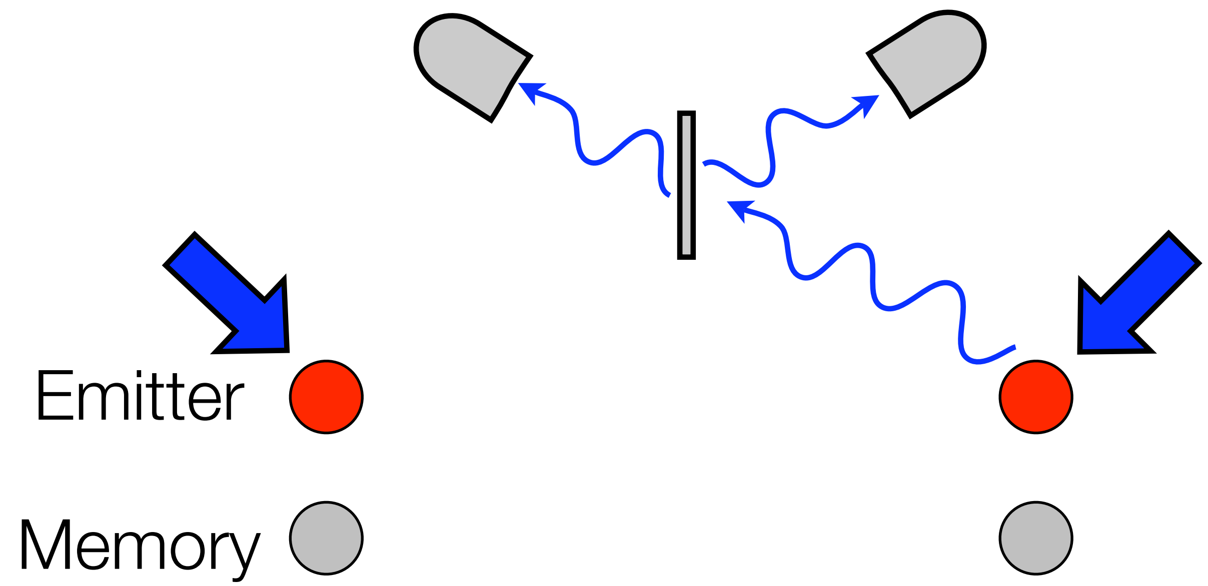

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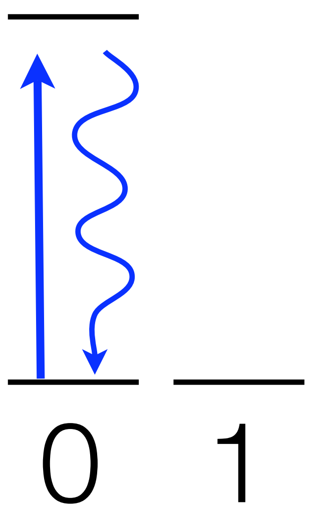

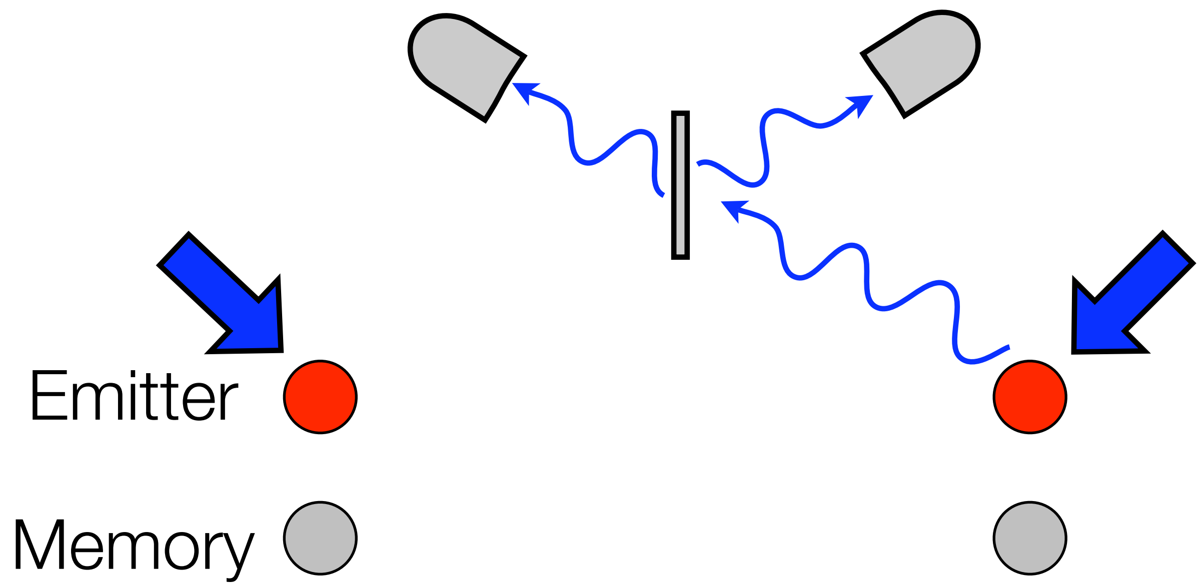

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Recent experiment! [Moehring et al., Nature (2007)]

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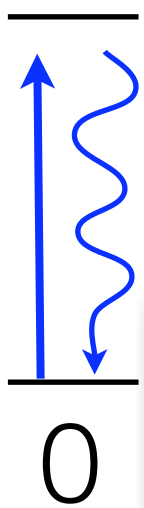

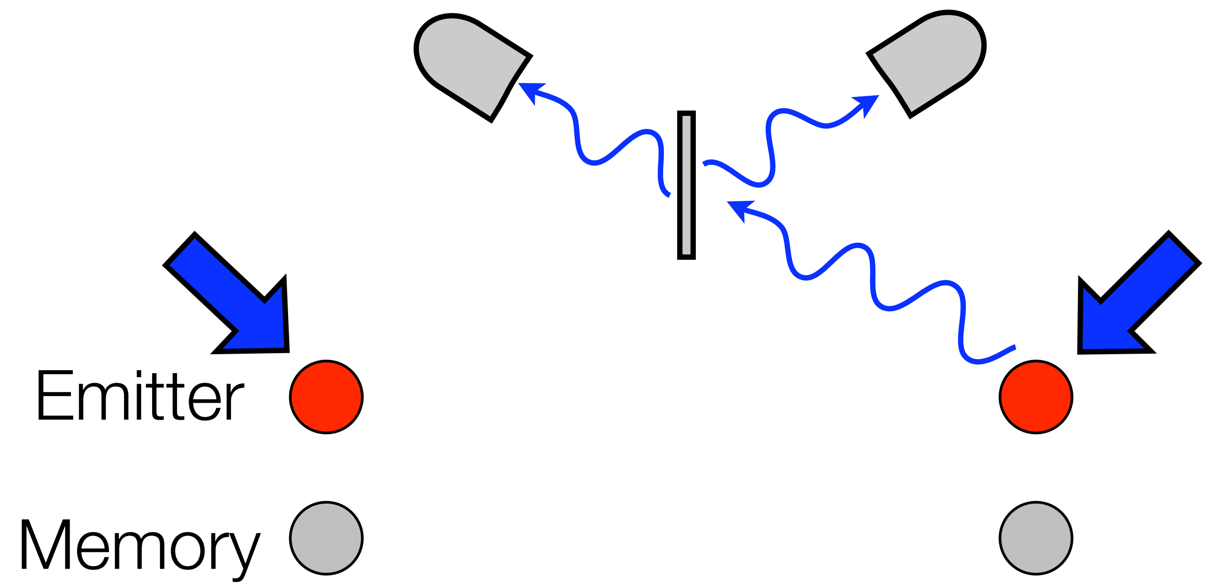

$) \rightarrow$

$\mathcal{O}(p)$

Q. Communication?

Attenuation problem (exponential with distance)

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

Quantum communication: quantum repeaters

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

- Goal: long range entanglement

- Problem: photon attenuation
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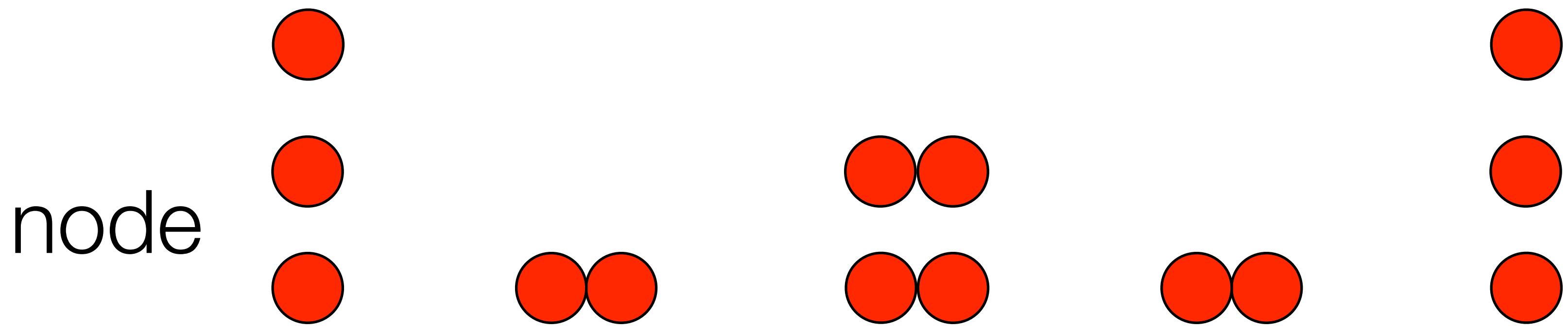

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer

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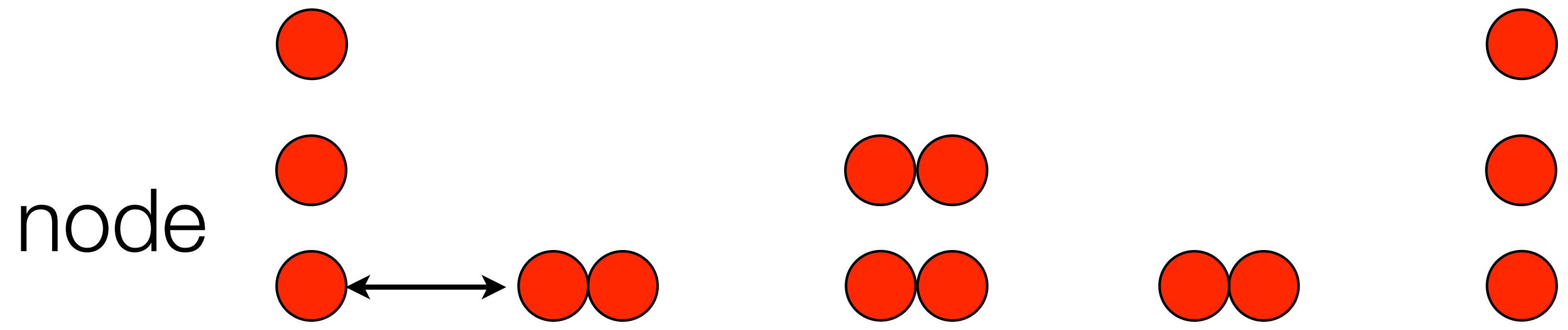

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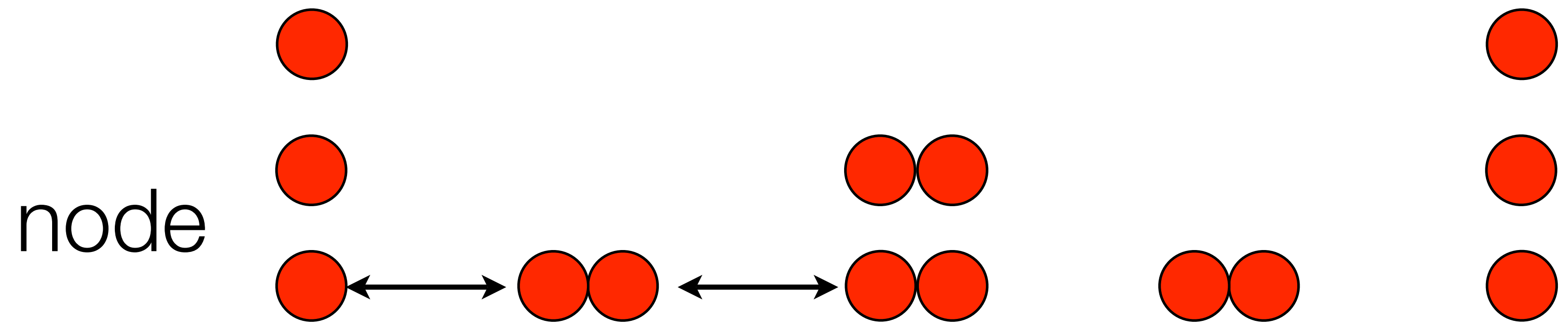

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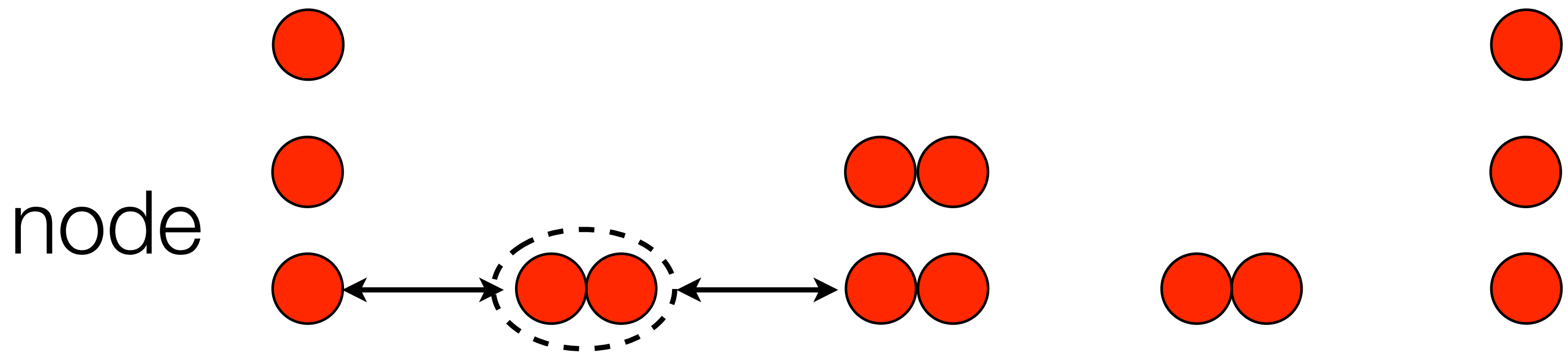

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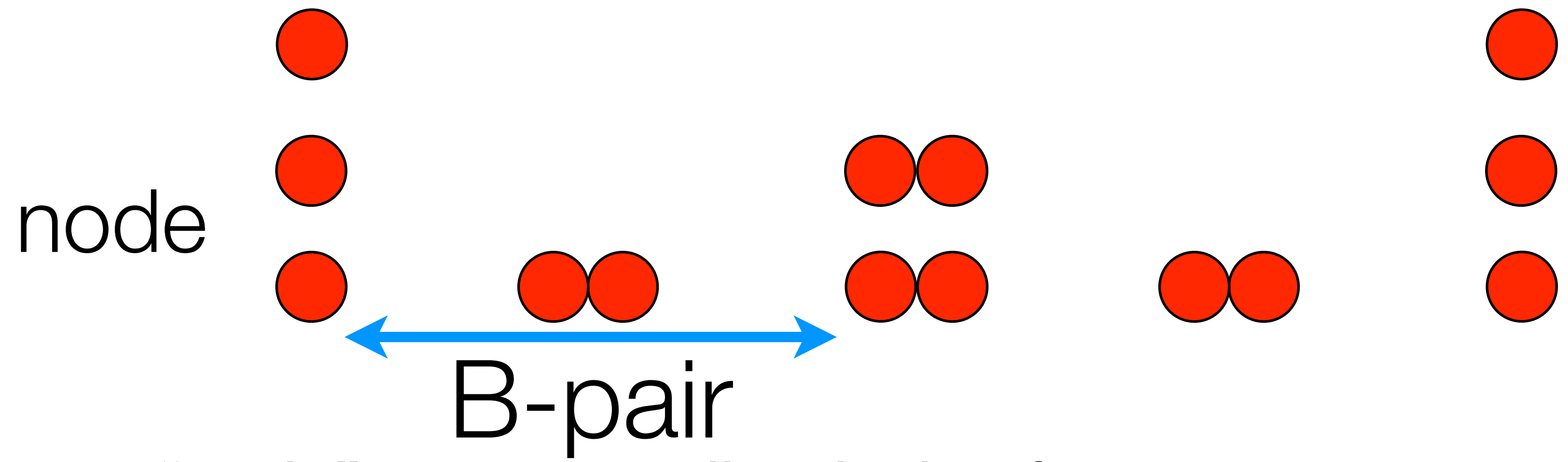

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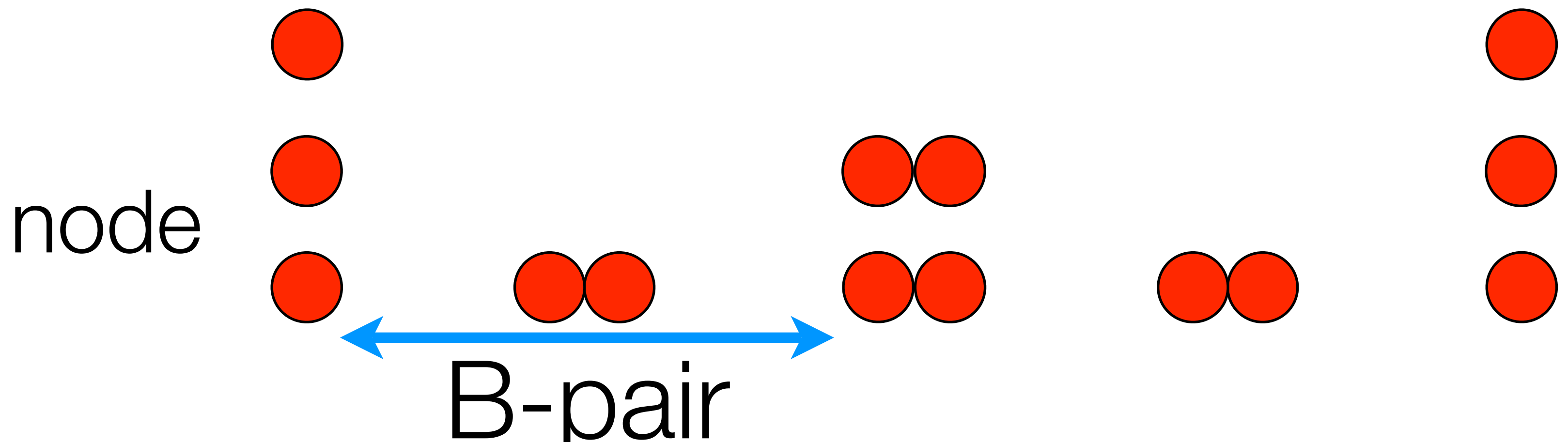

$t_1 \sim 2t_0/p_0$

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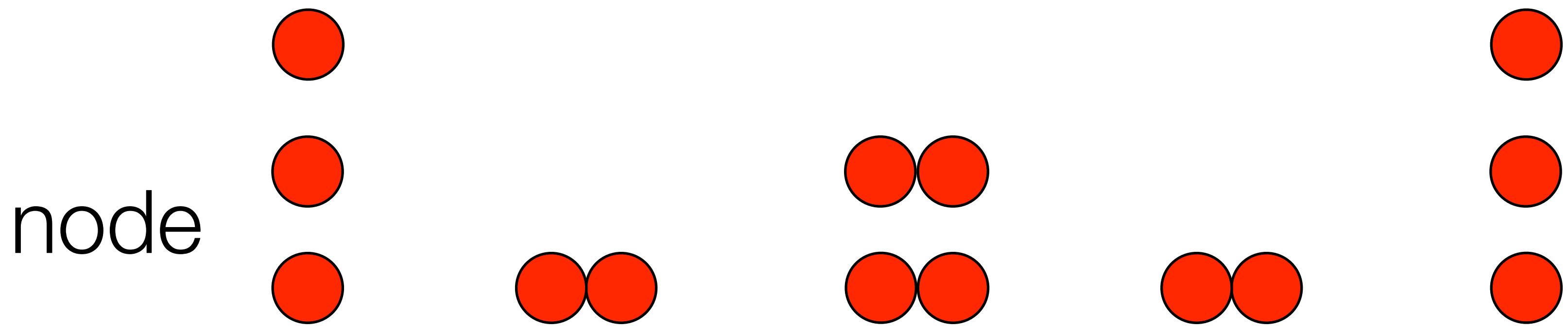

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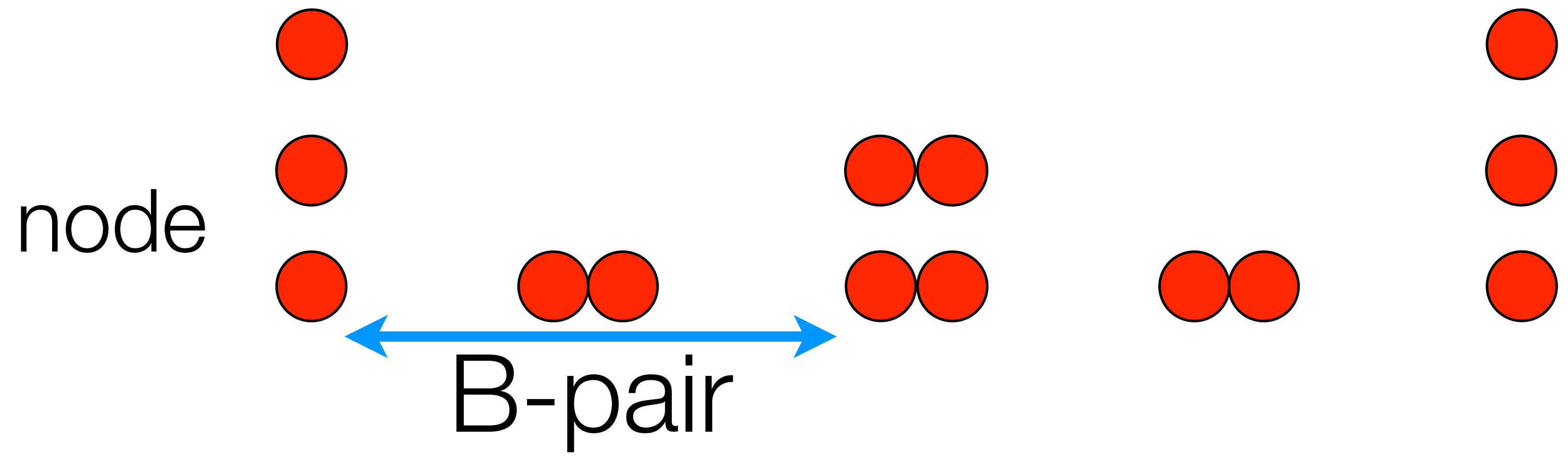

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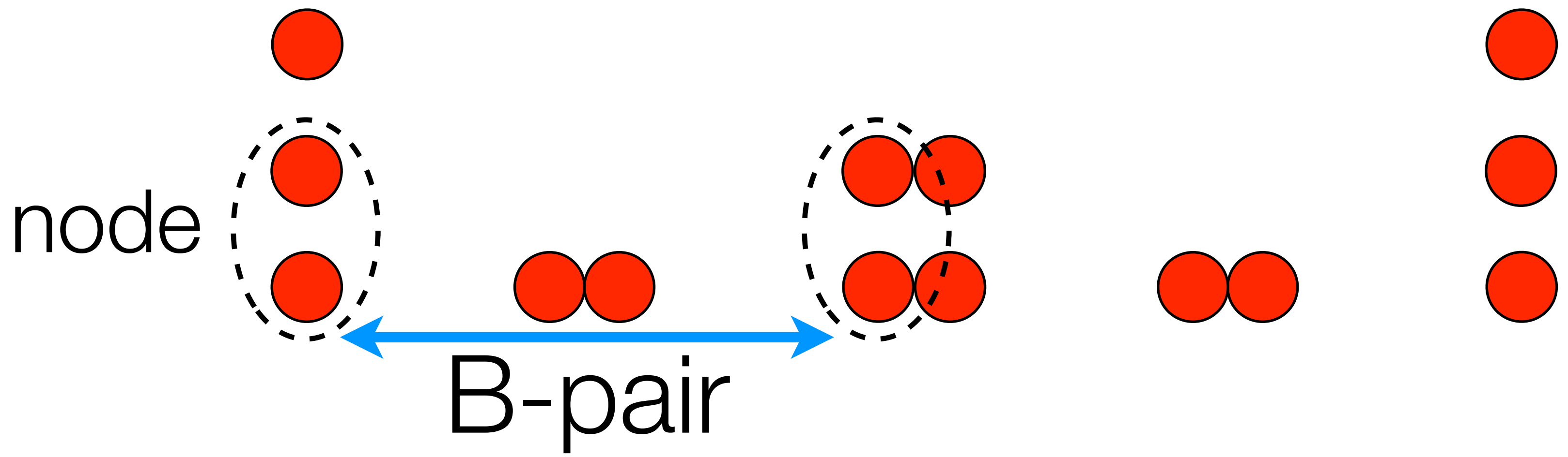

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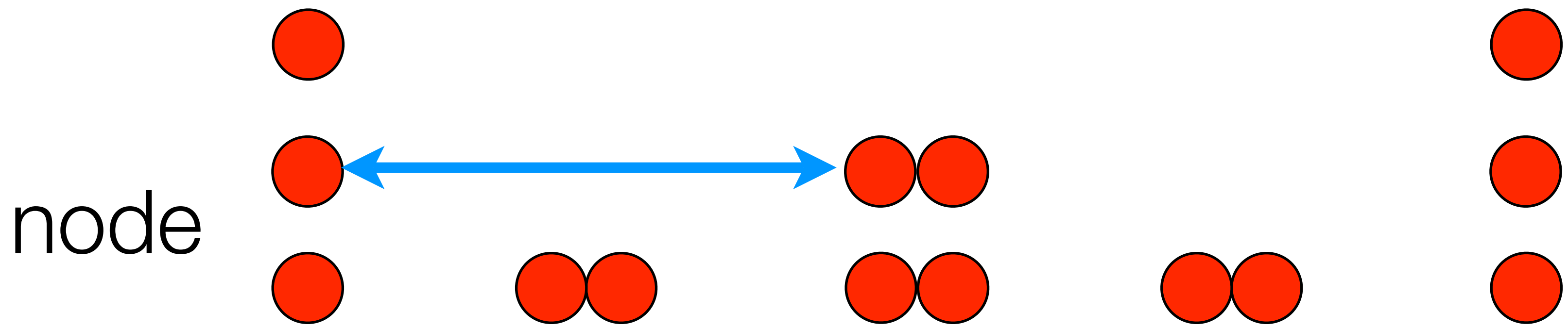

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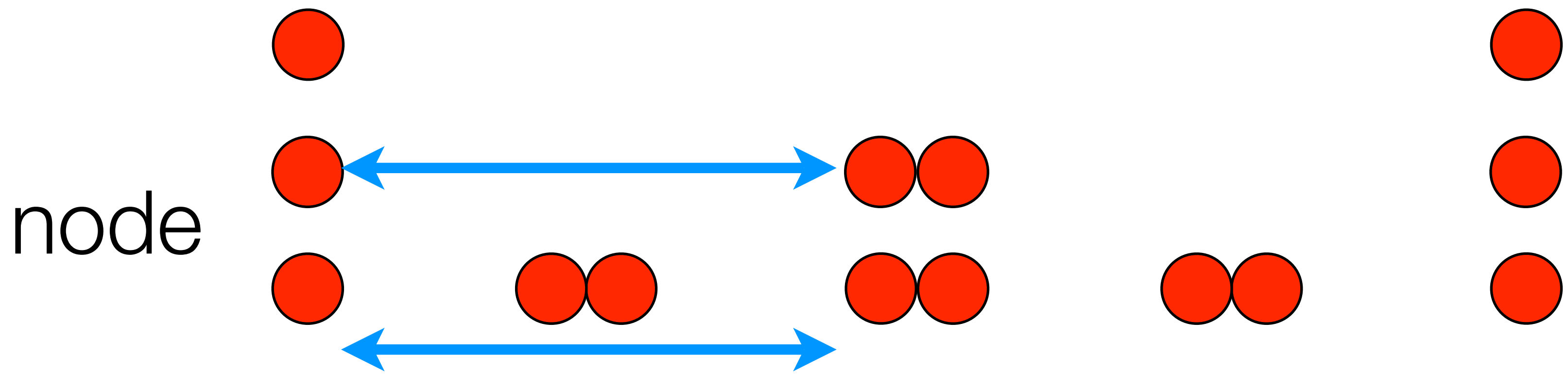

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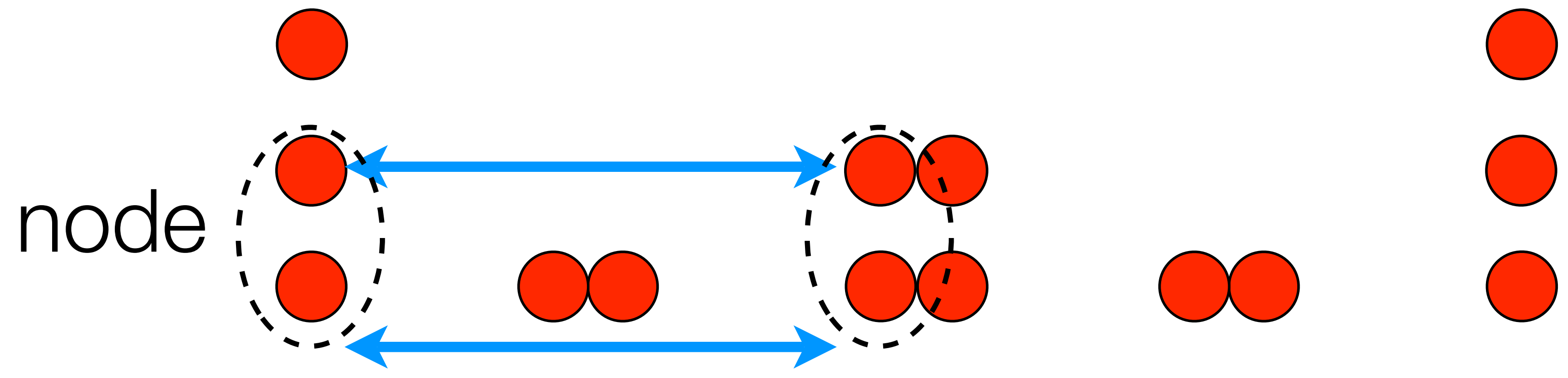

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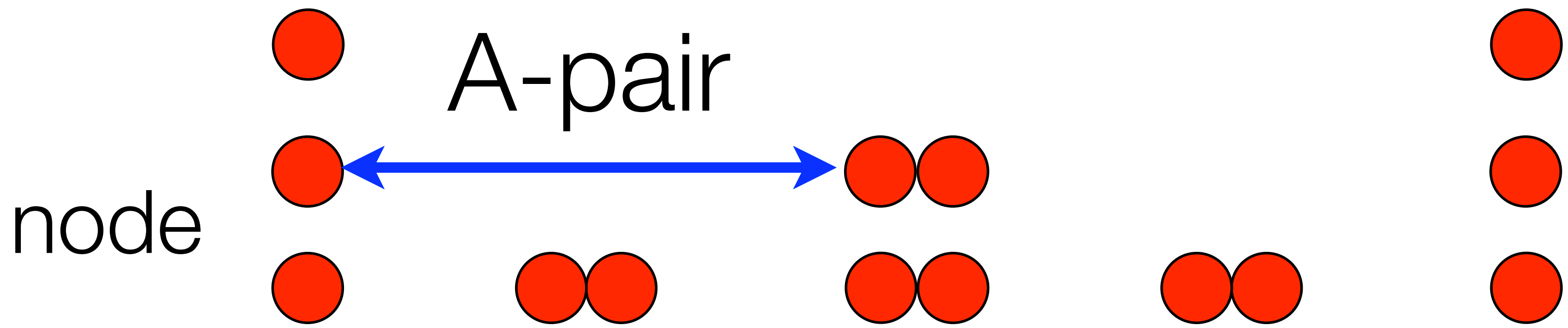

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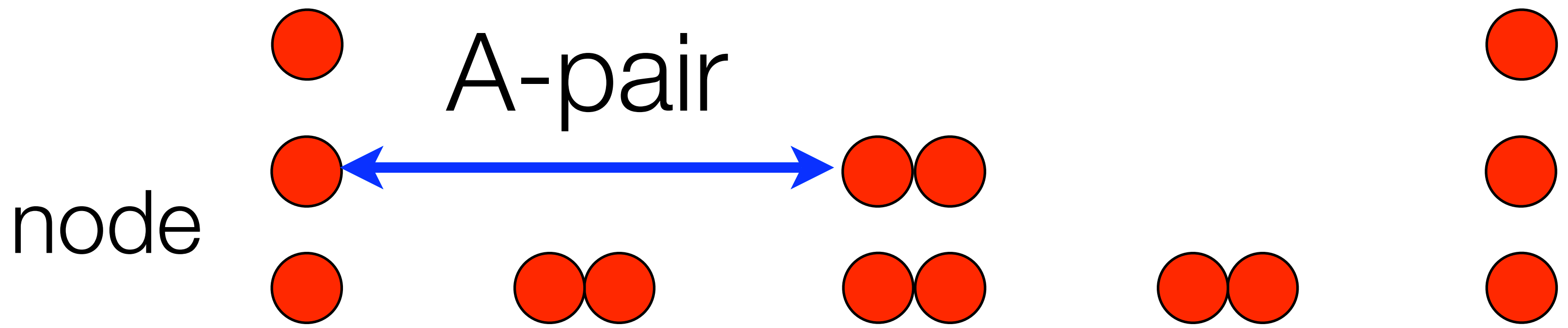

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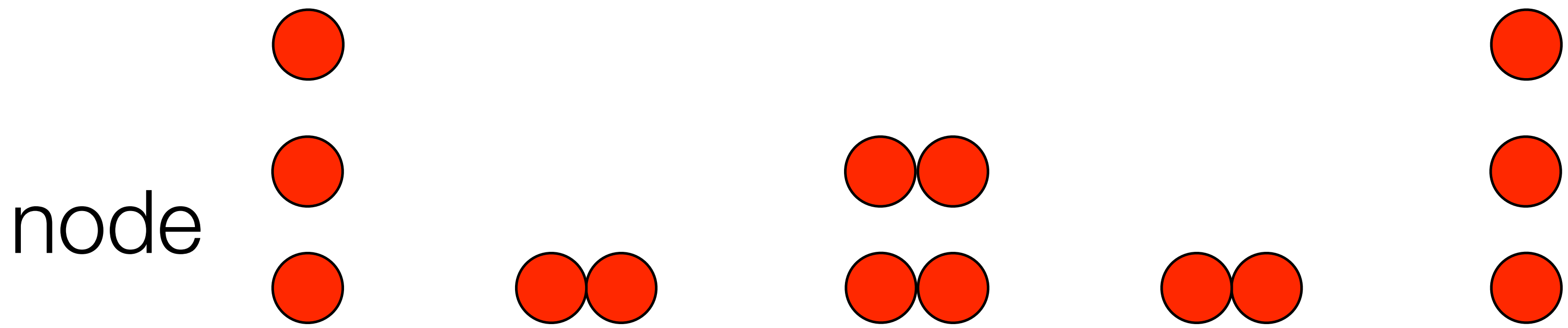

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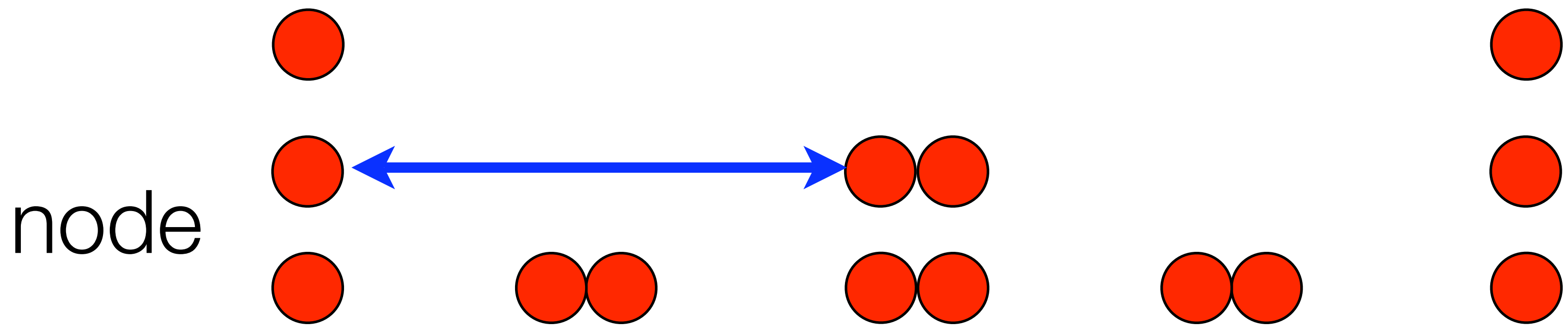

- Repeater “node”: a commodity device for quantum communication
- Repeater protocol: divide and conquer

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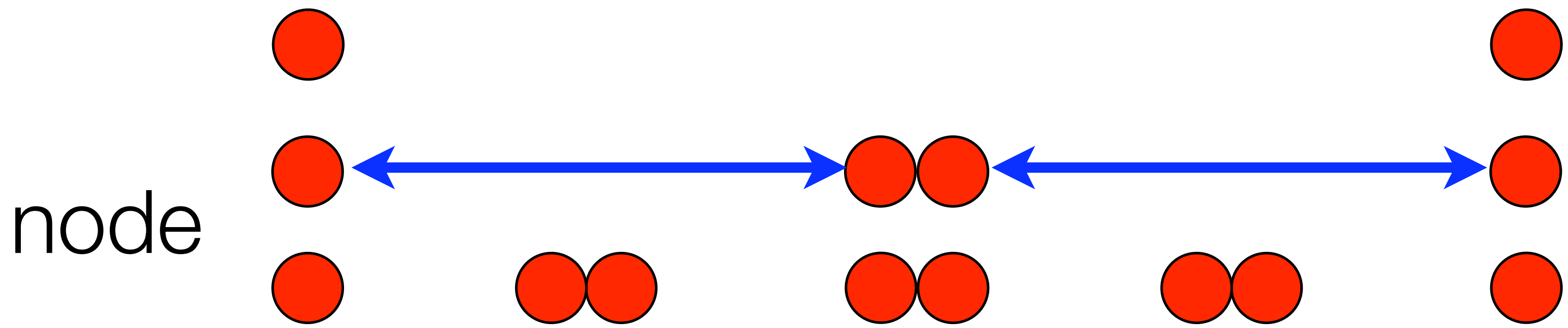

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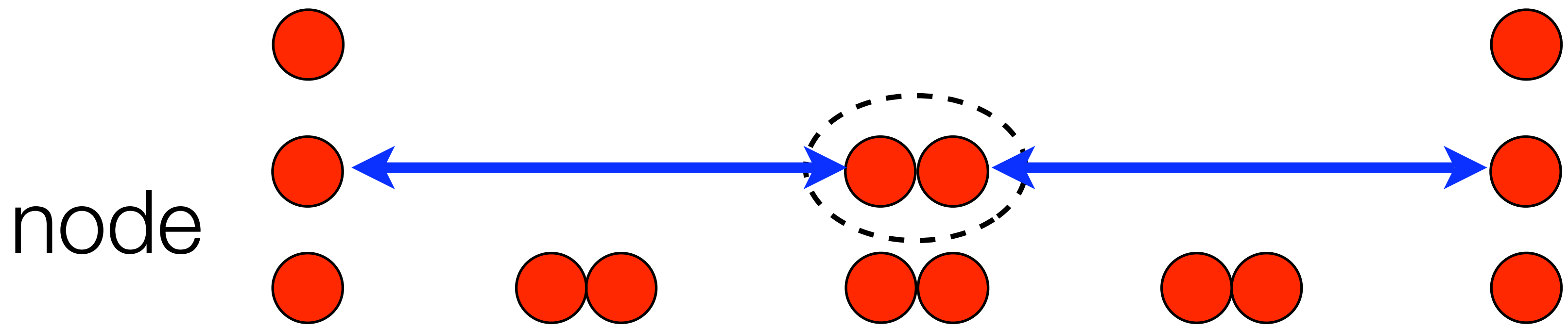

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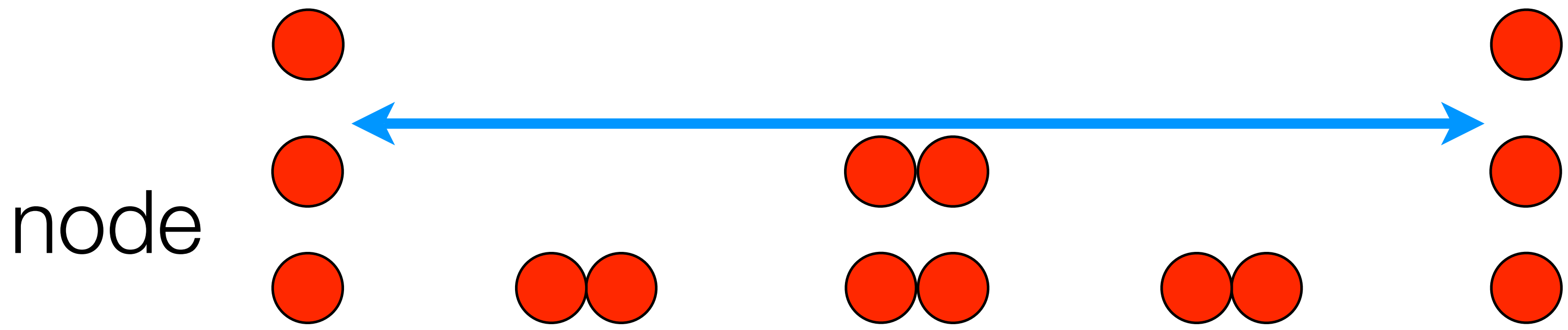

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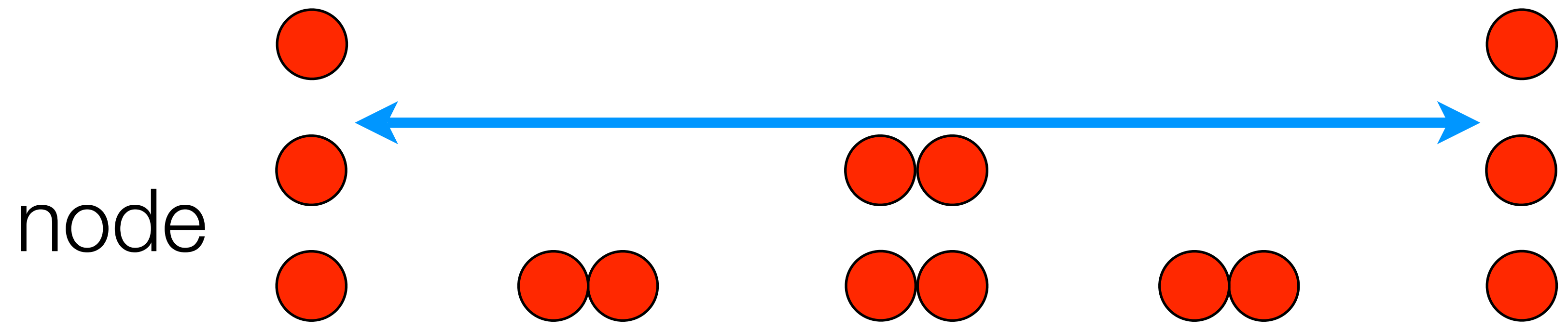

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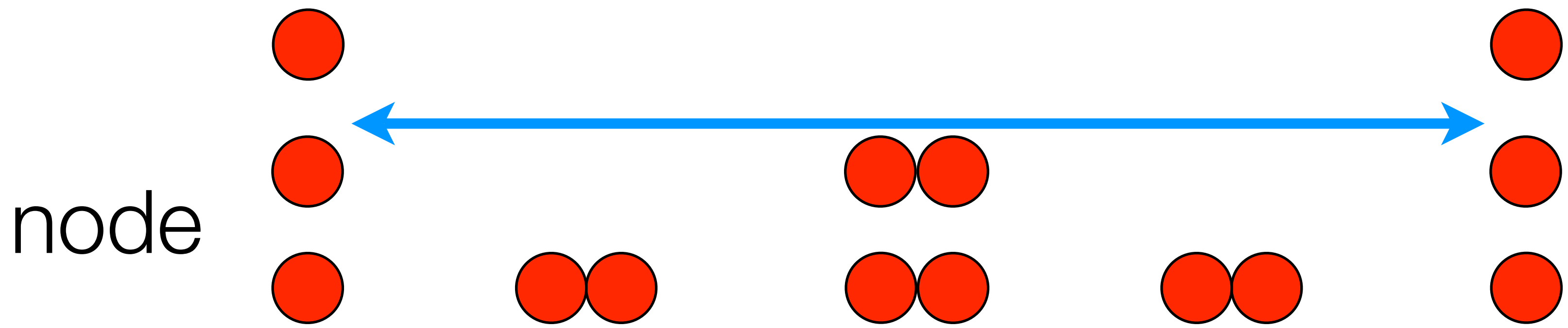

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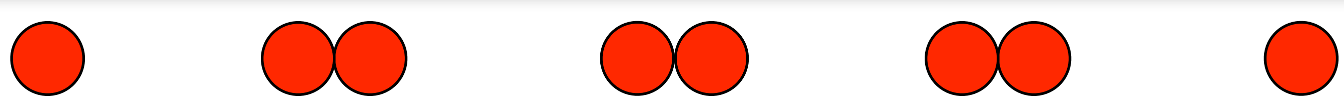
Linear Paul traps + cavities provide good implementation

node



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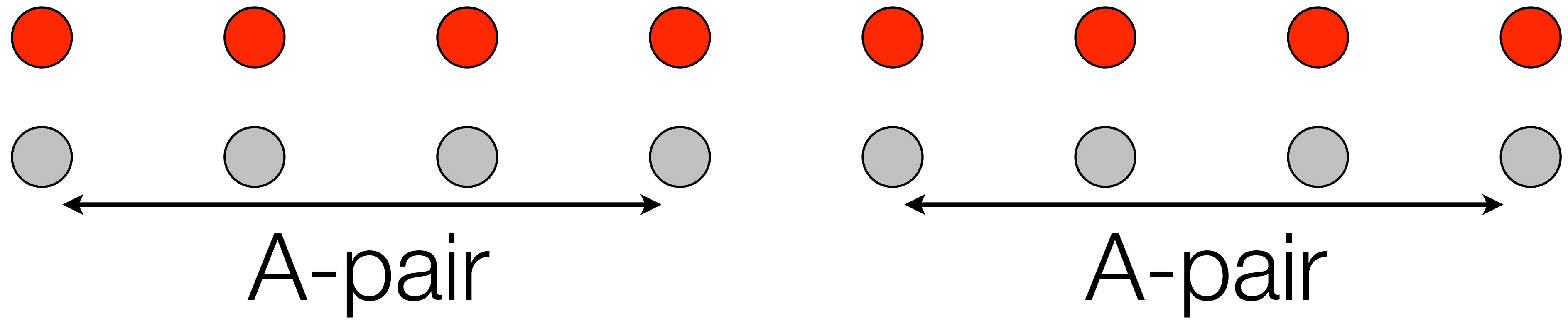

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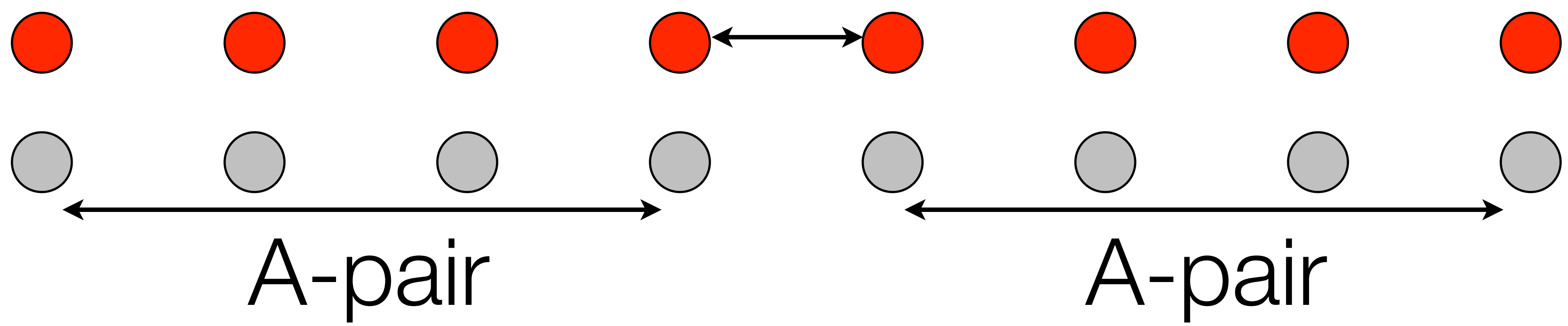

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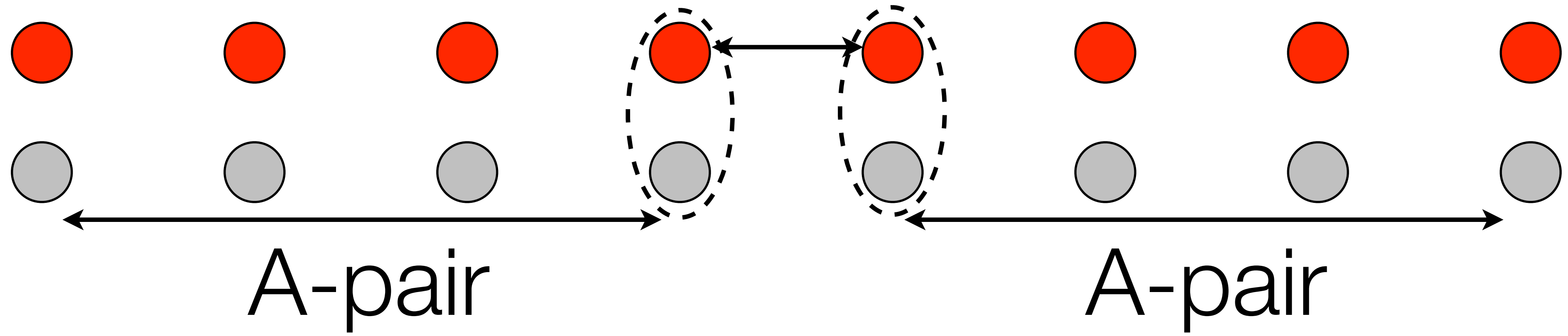

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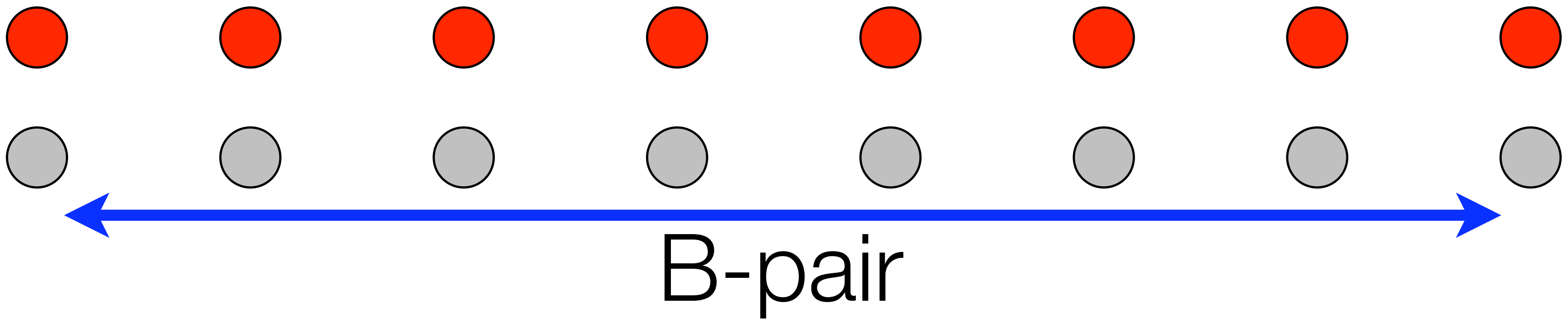

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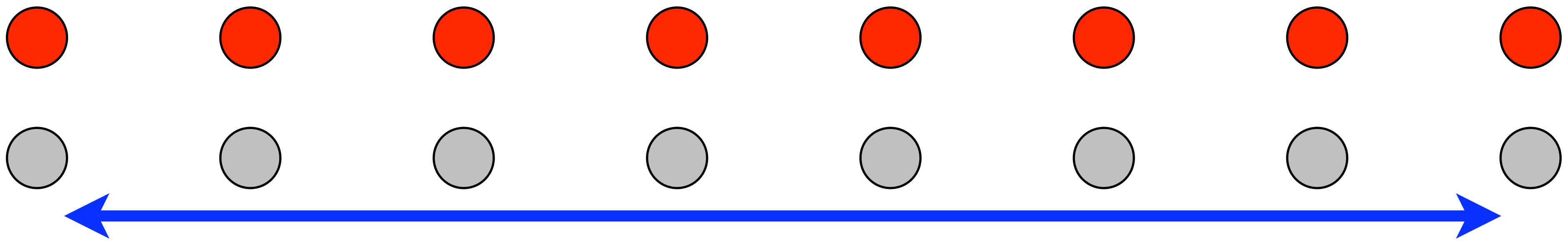

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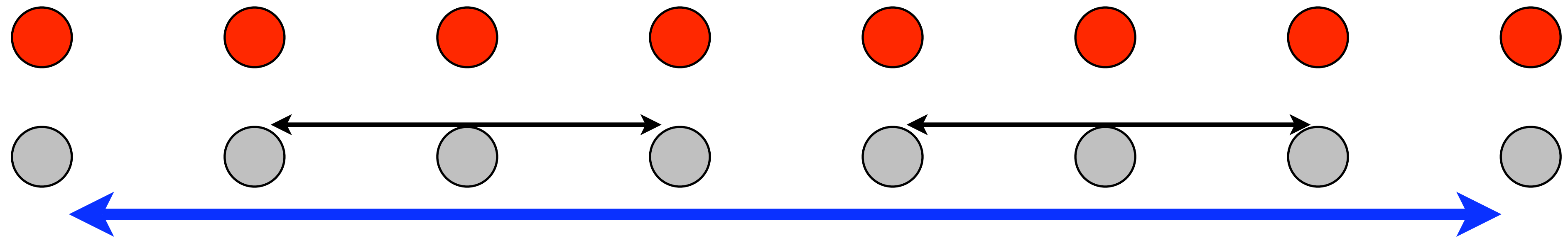

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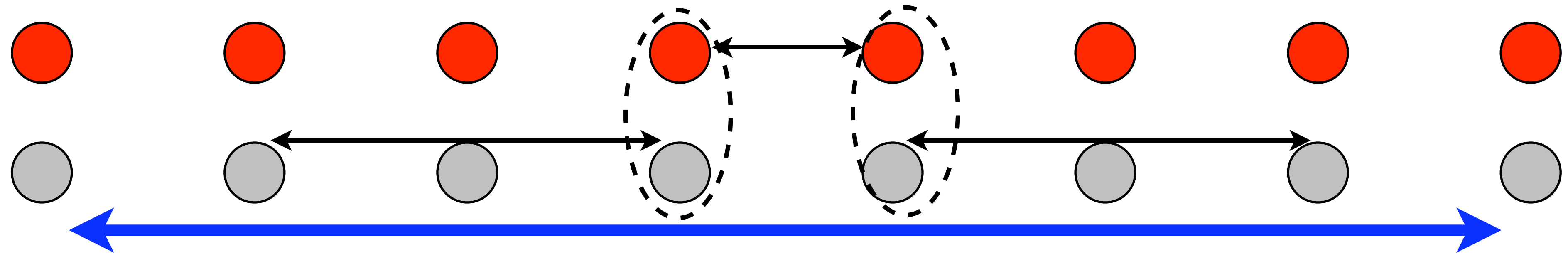

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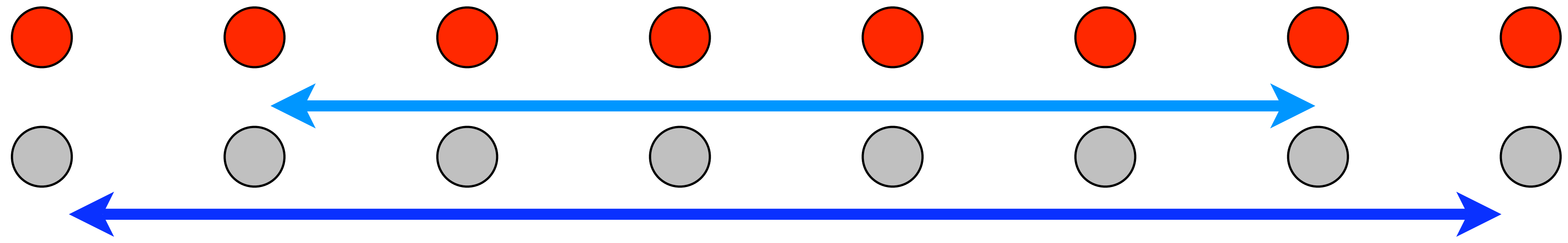

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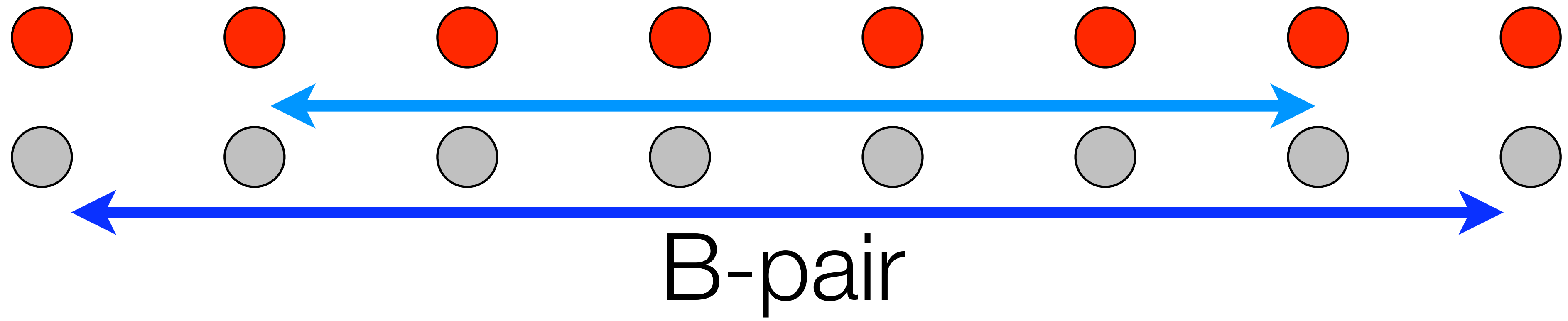

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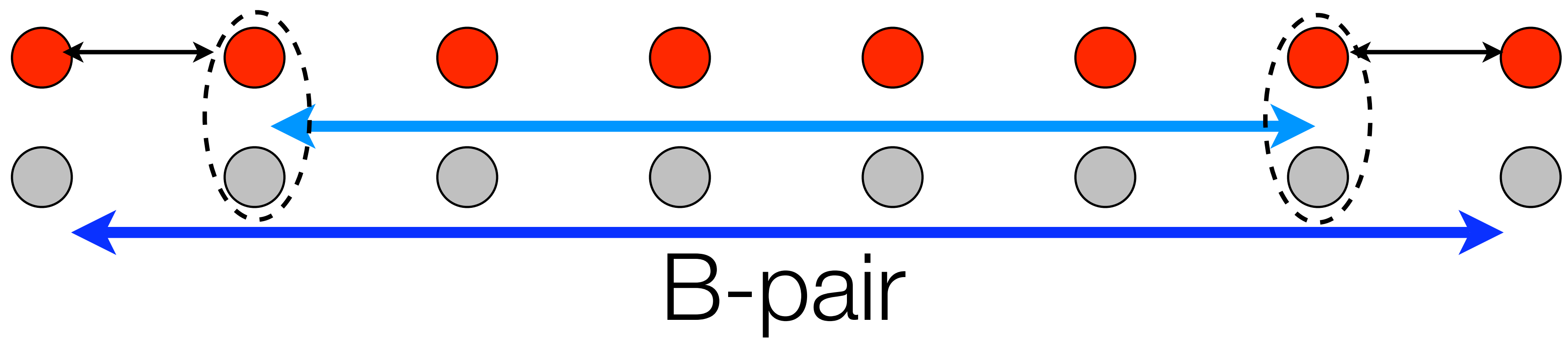

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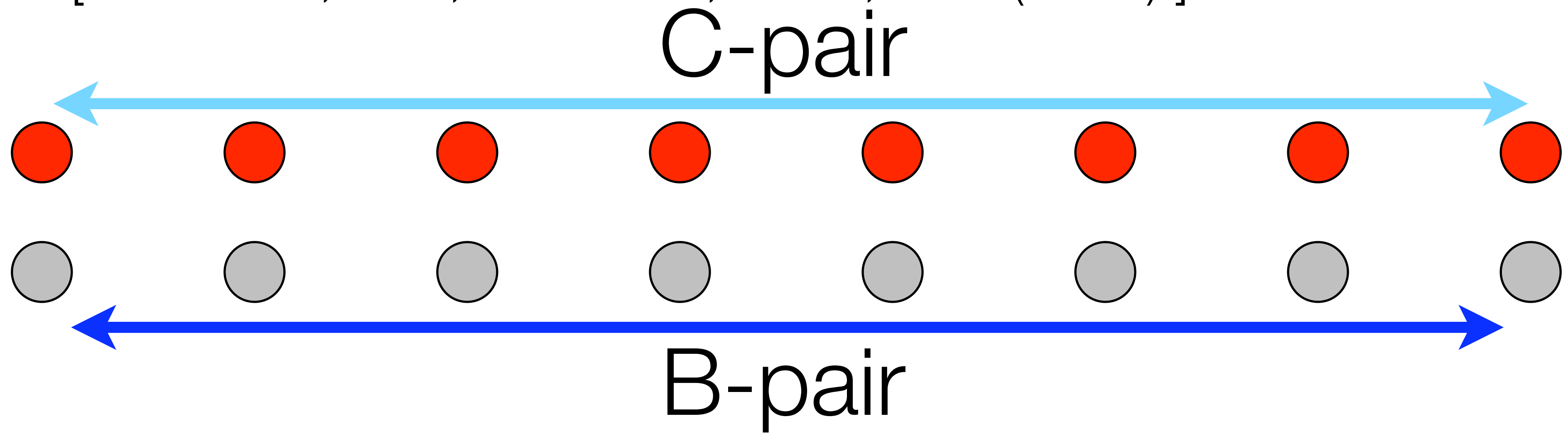

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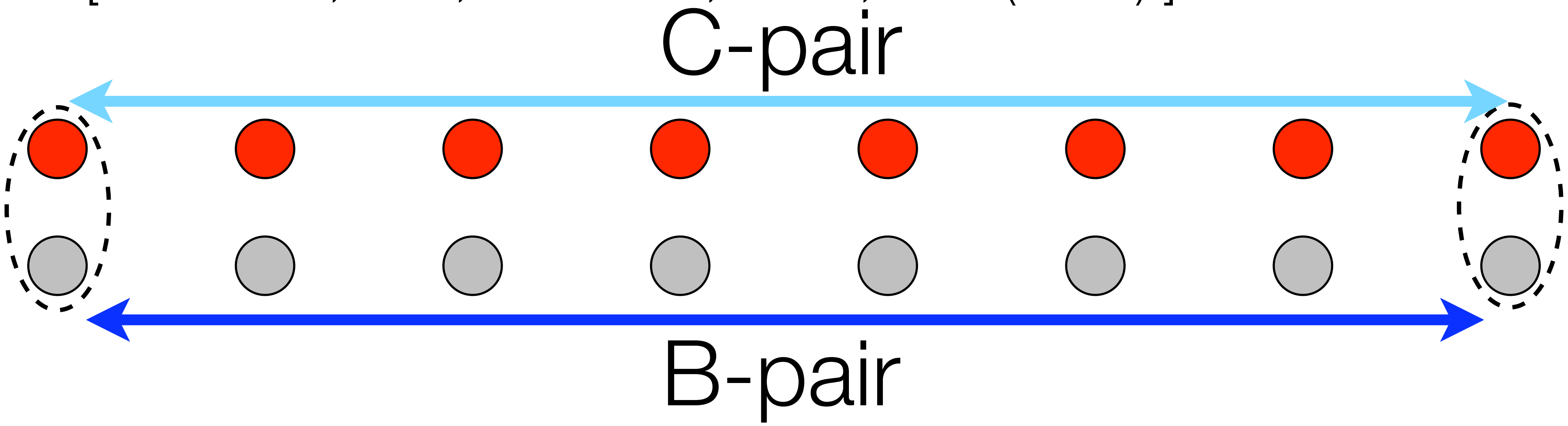

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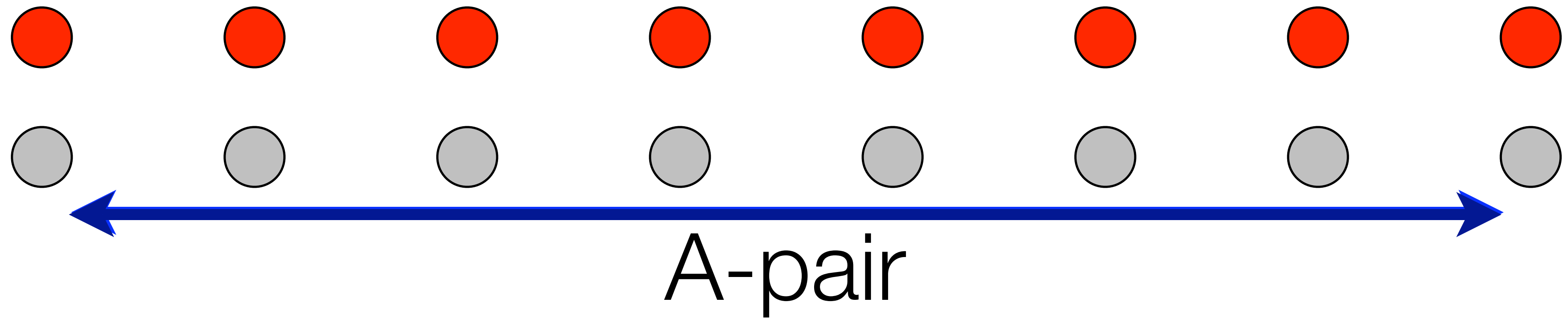

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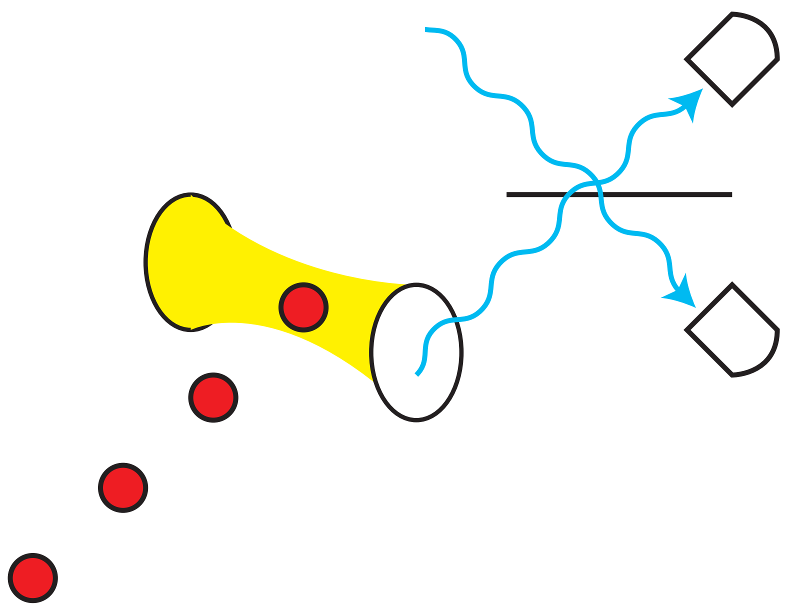
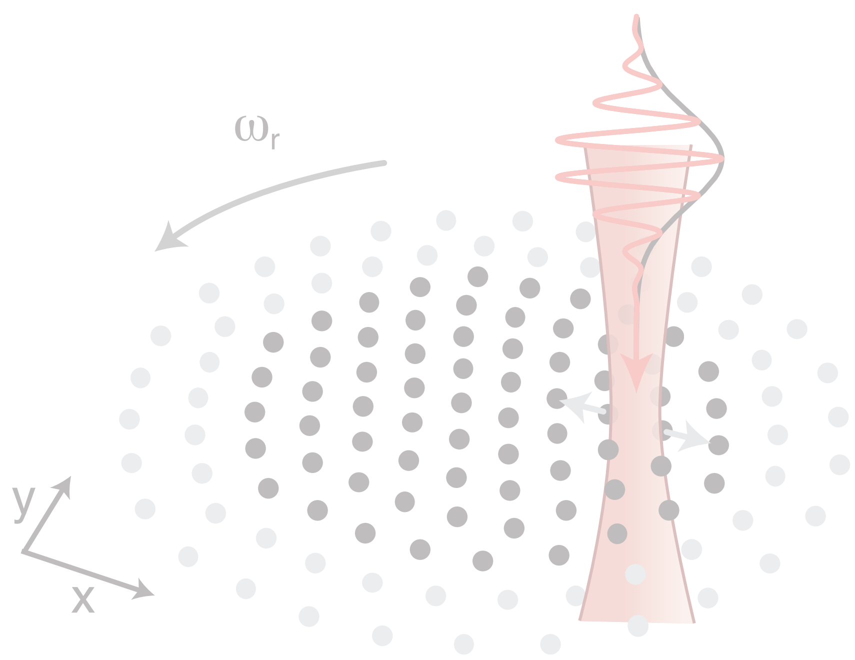
Focus of this talk

Quantum communication



Distributed computing

Wigner crystal-based quantum memory



Distributed computation

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

[image from Janis.com]

with L. Jiang, A. Sørensen, M. D. Lukin,
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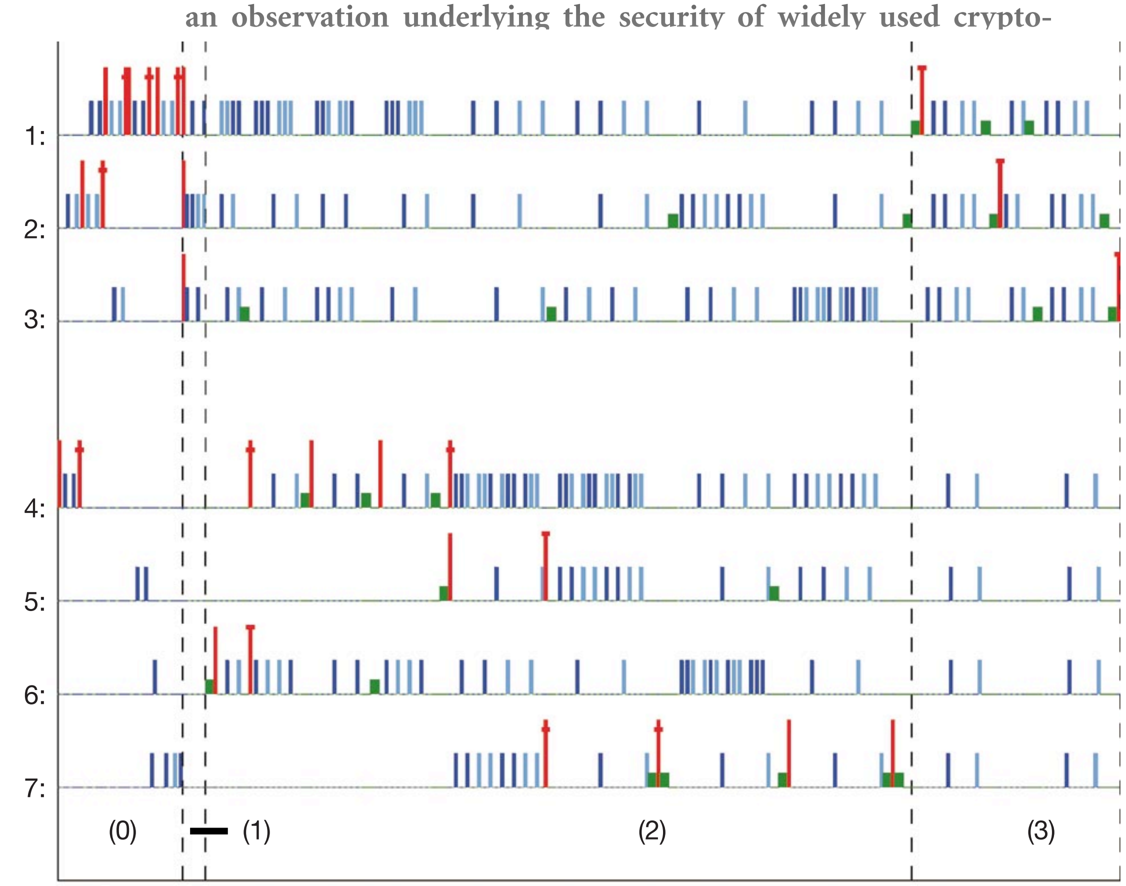
Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

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-



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

Distributed computation

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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

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

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Early ideas (monolithic architecture)

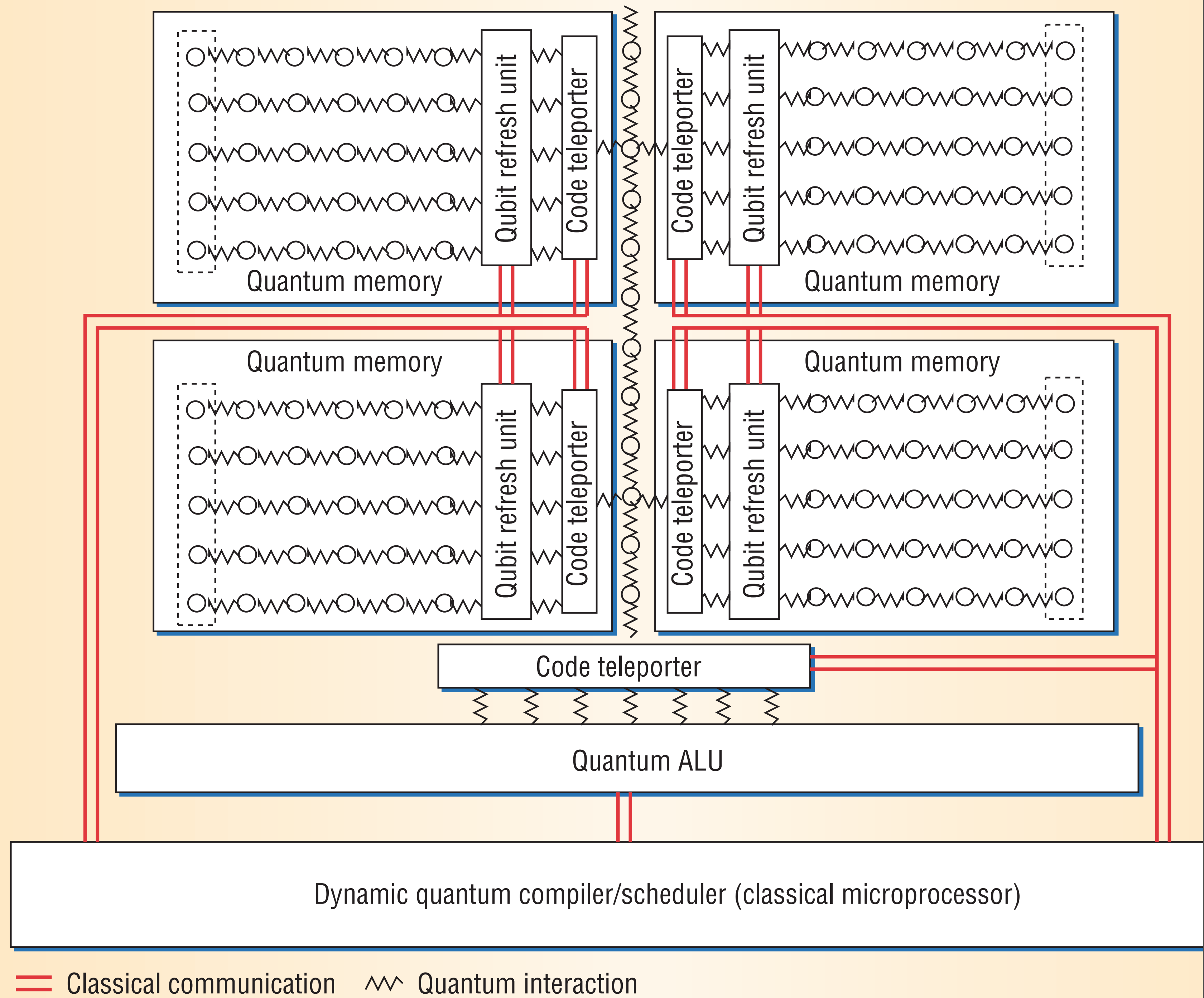
A Practical Architecture for Reliable Quantum Computers

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

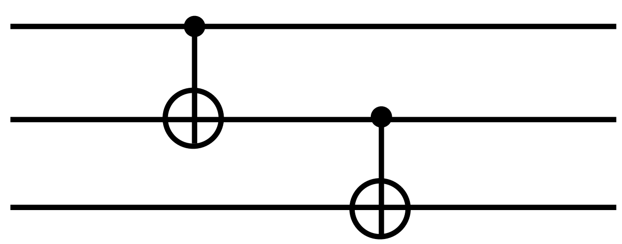
Isaac L. Chuang
Massachusetts Institute of Technology



[Oskin et al., IEEE 2002]

Deterministic distributed computation

desired (logical) circuit



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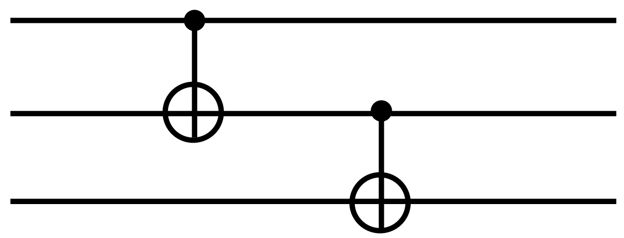

Idea:

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

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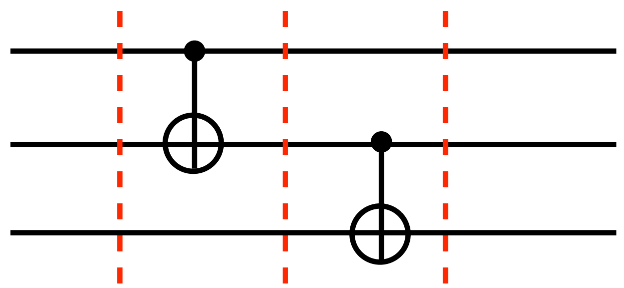

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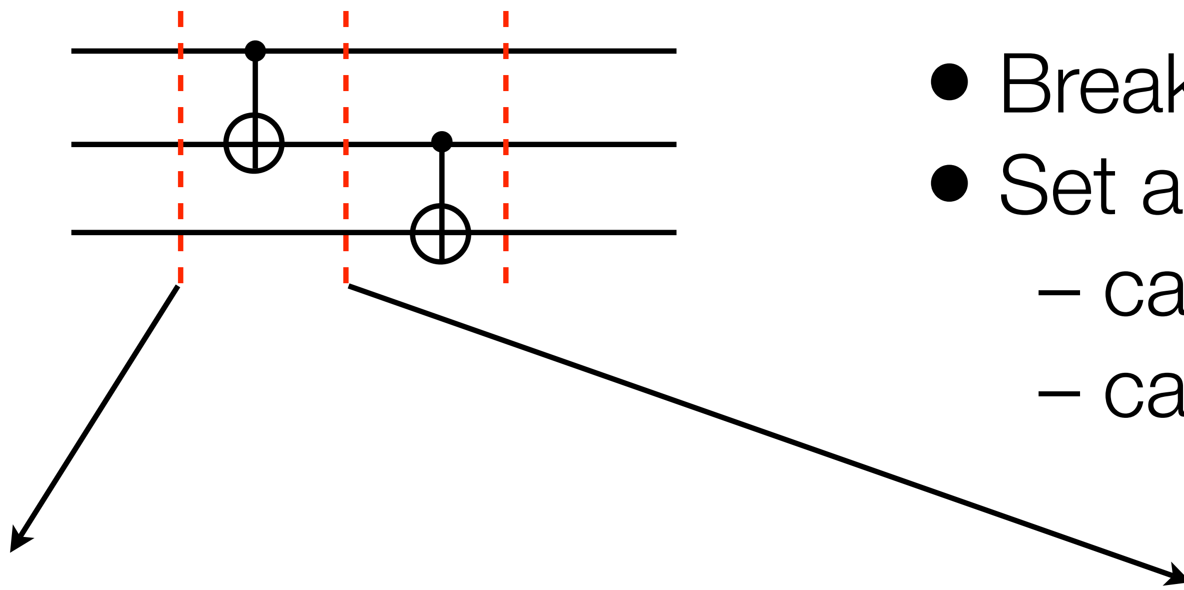

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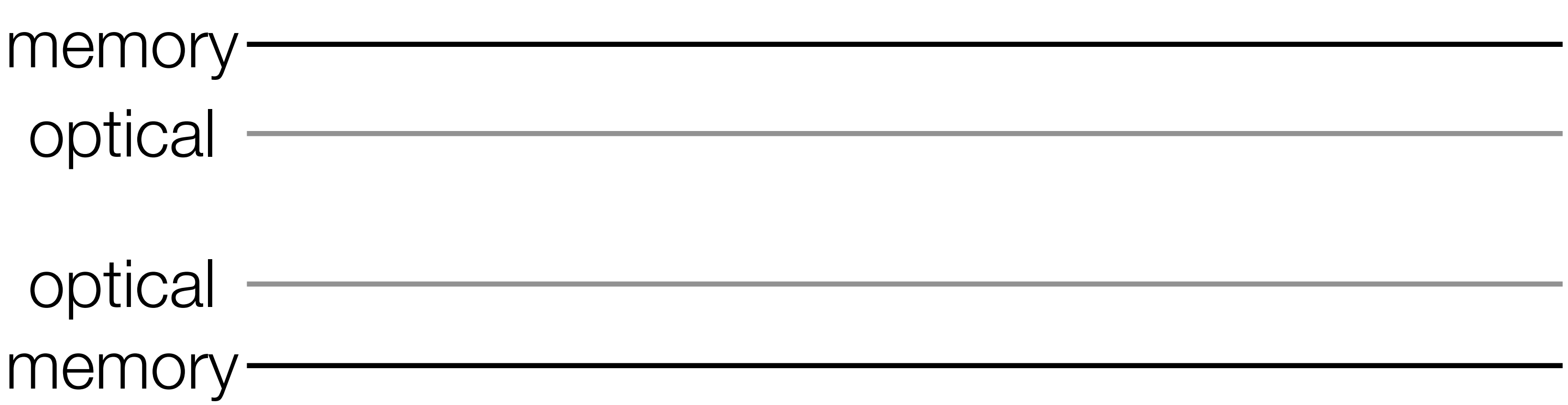

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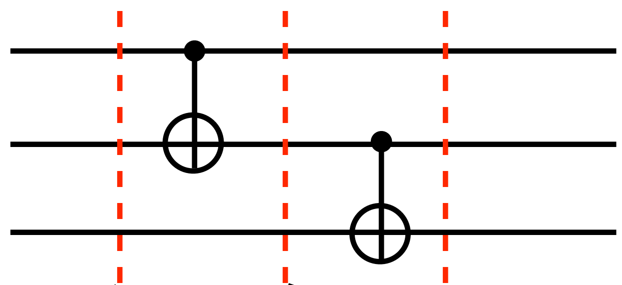

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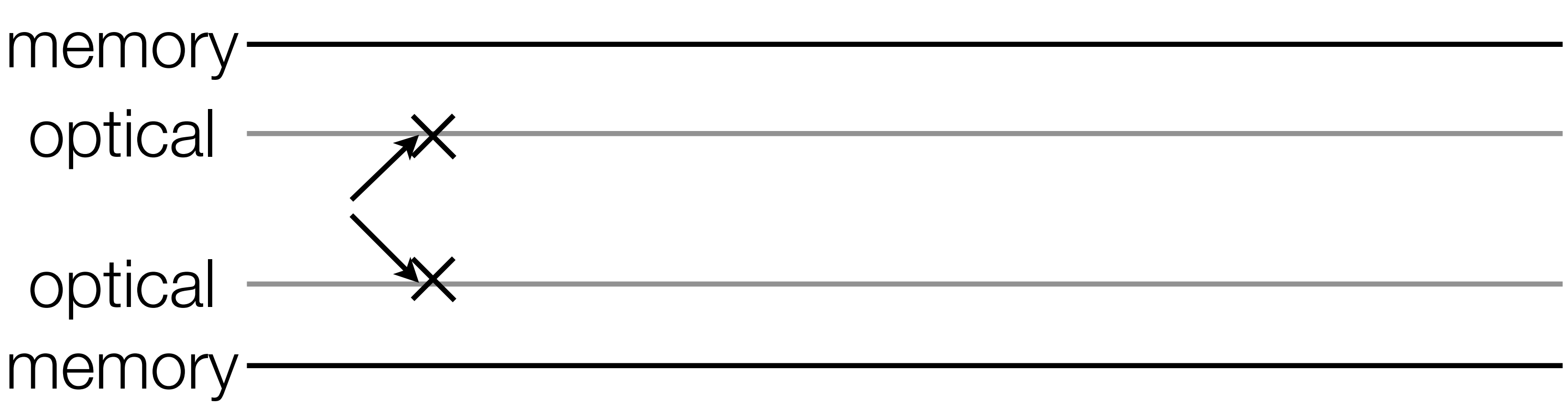

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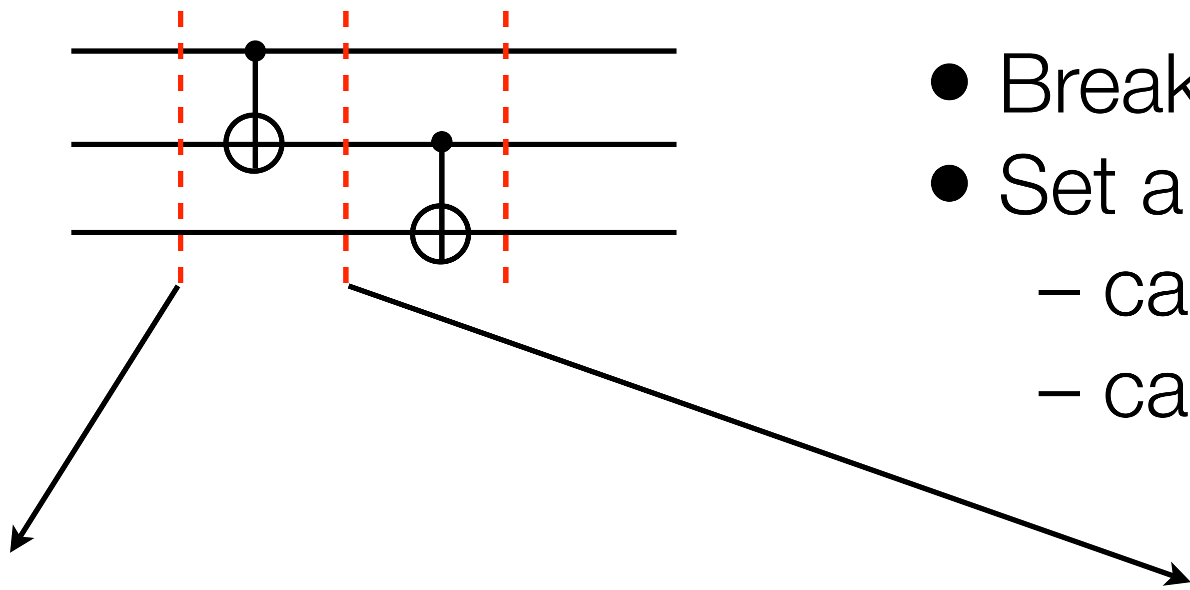

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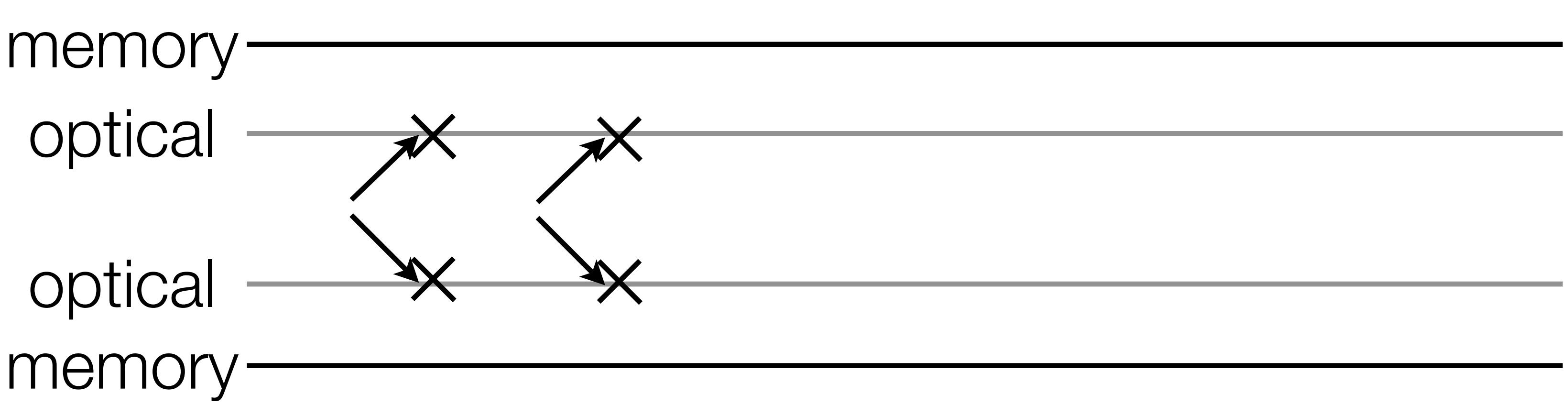

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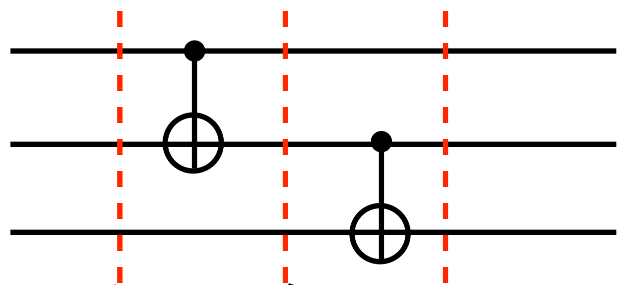

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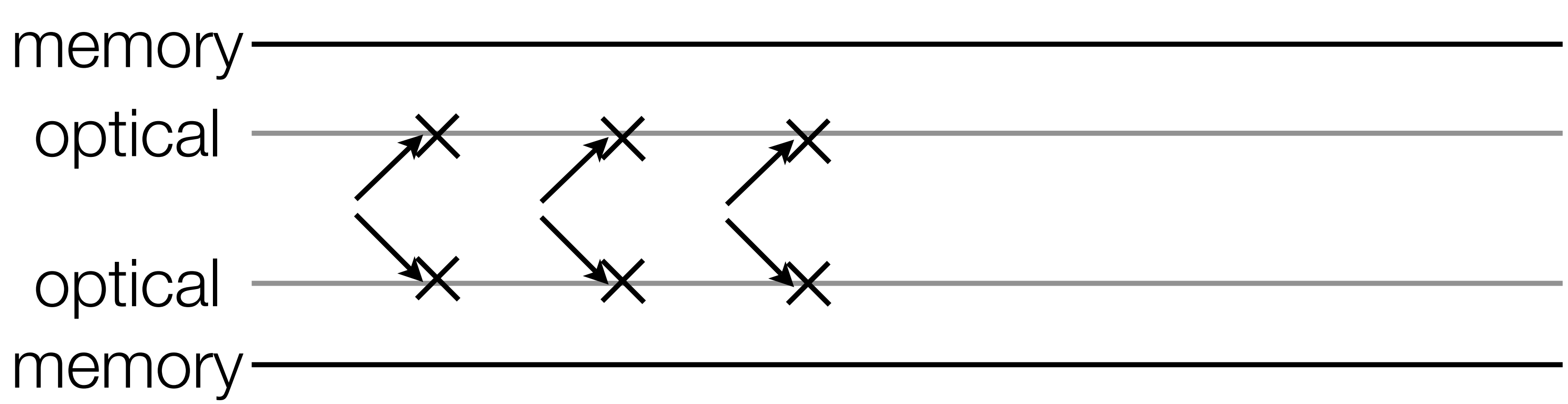

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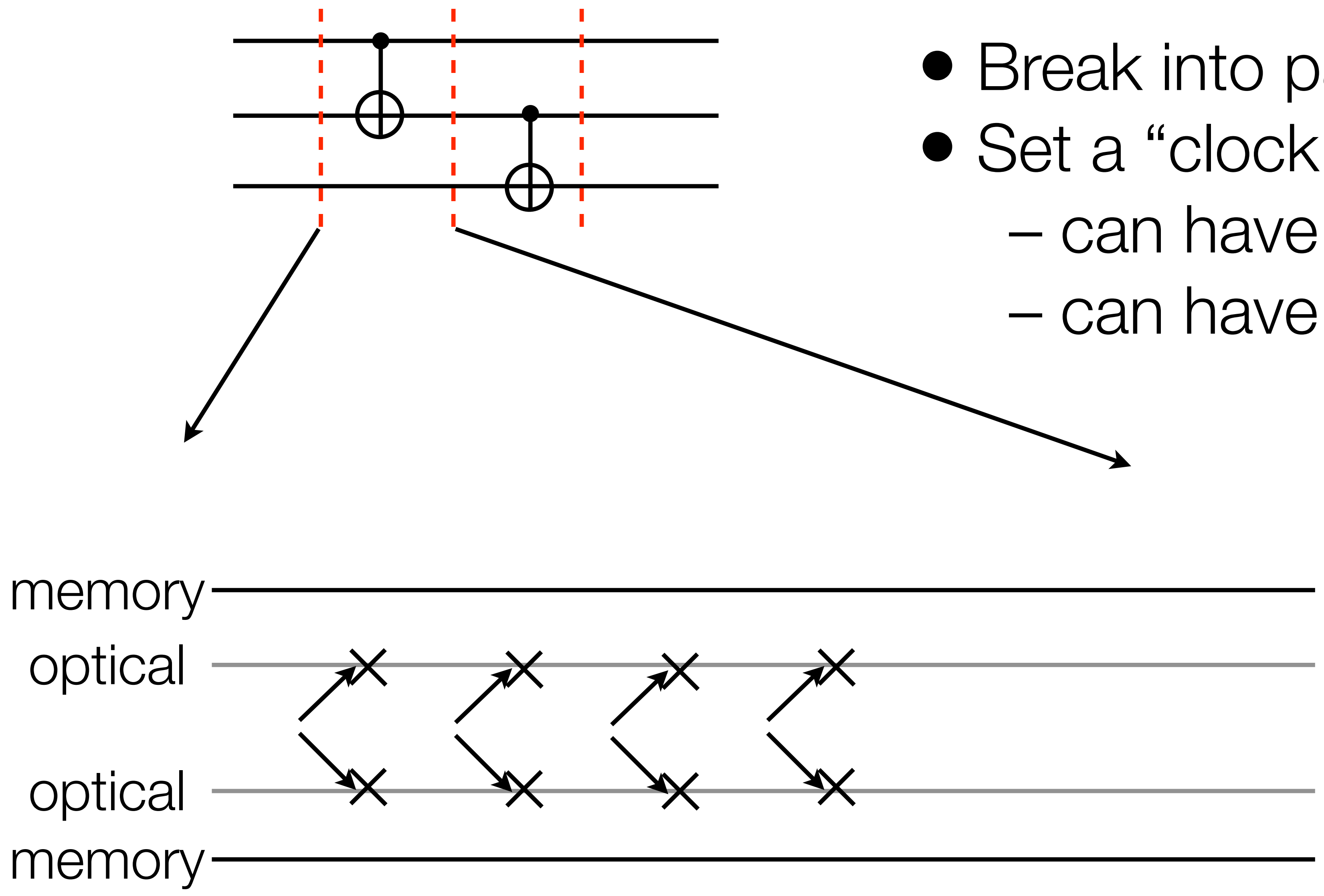

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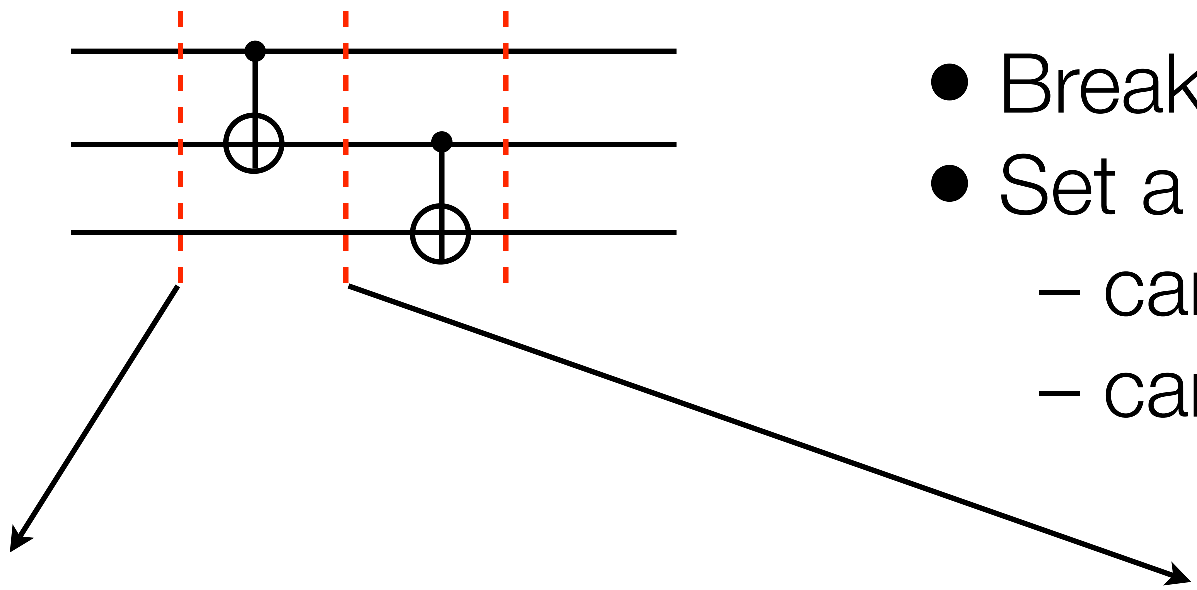

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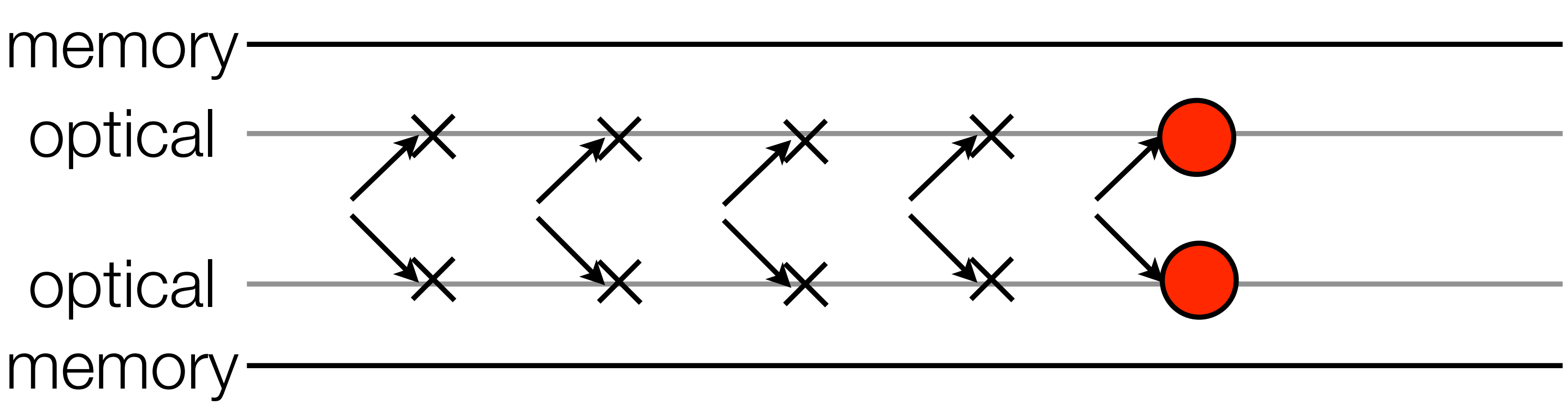

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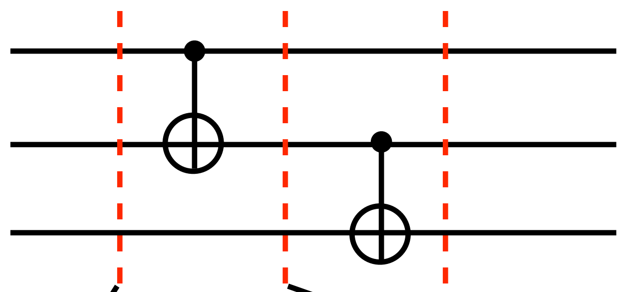

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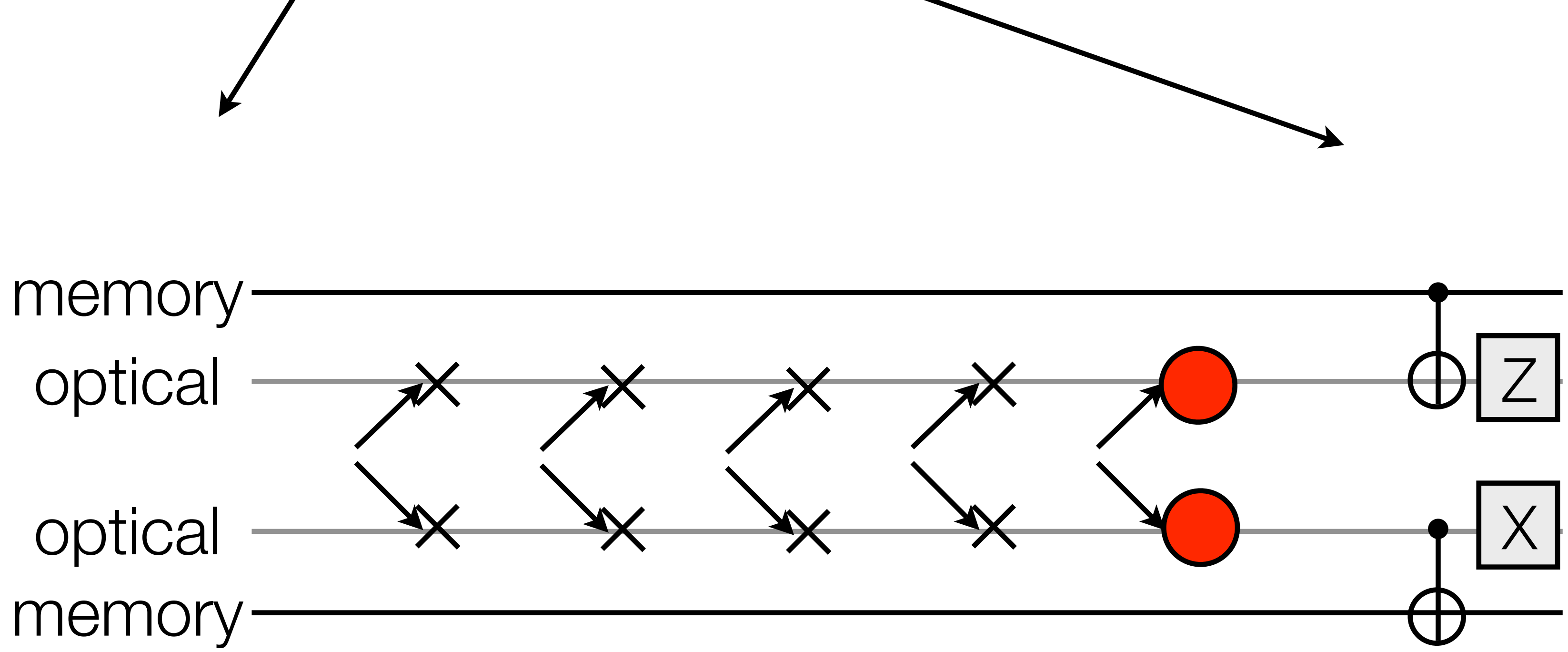

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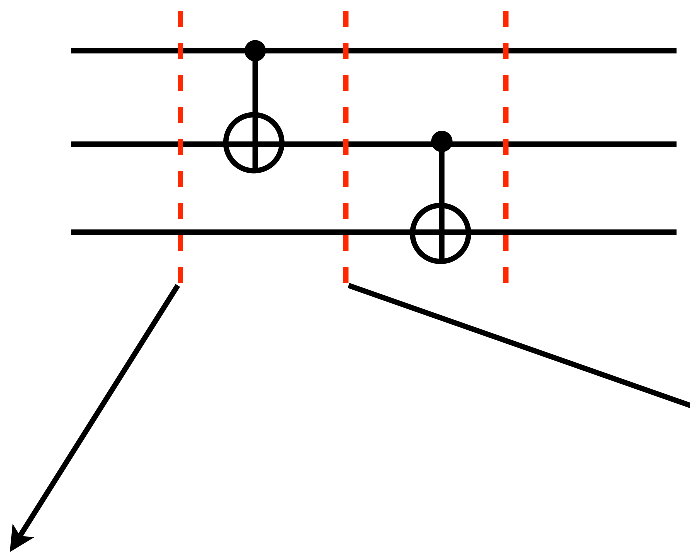

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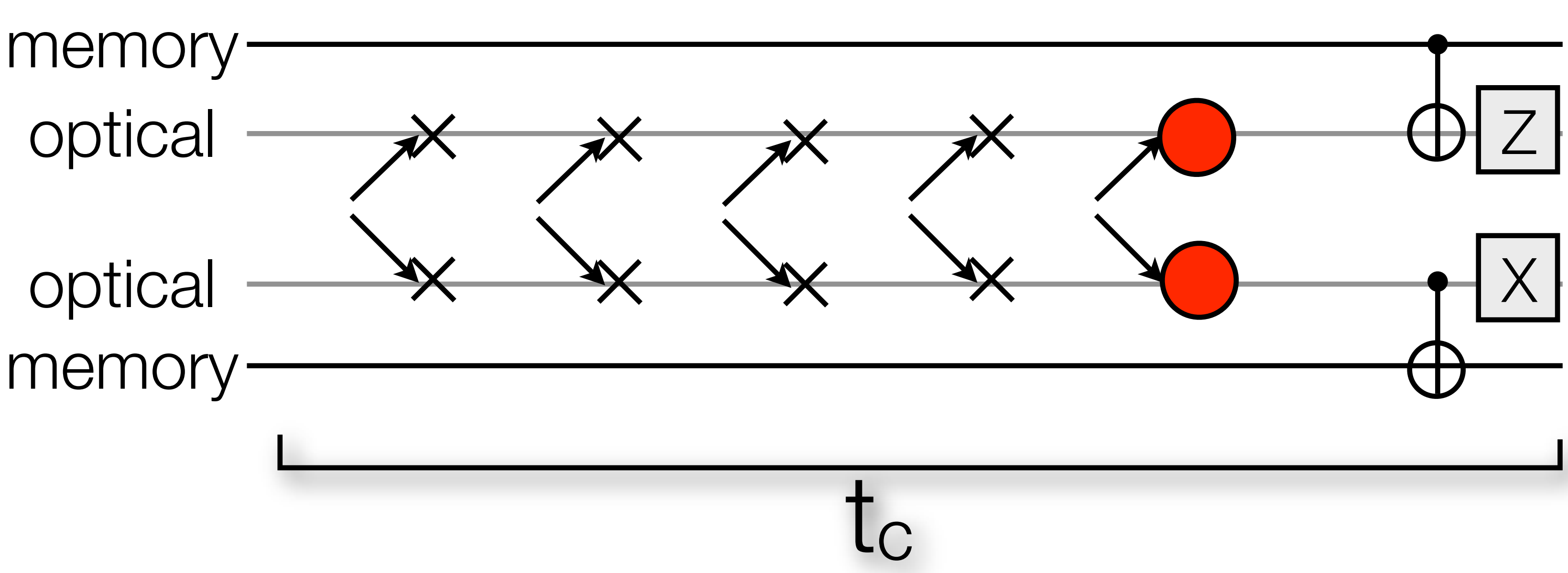

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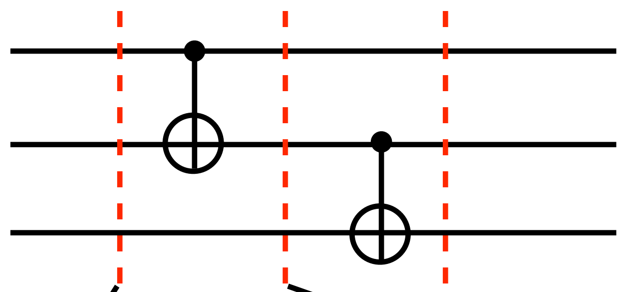

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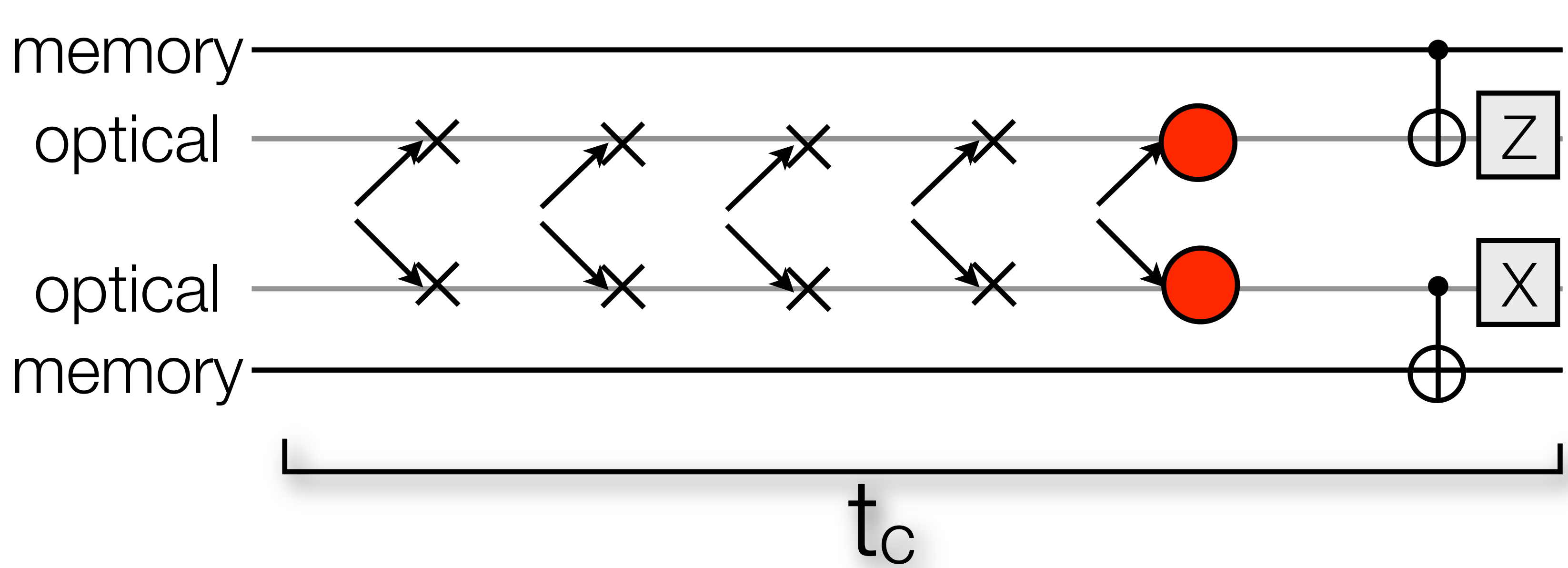


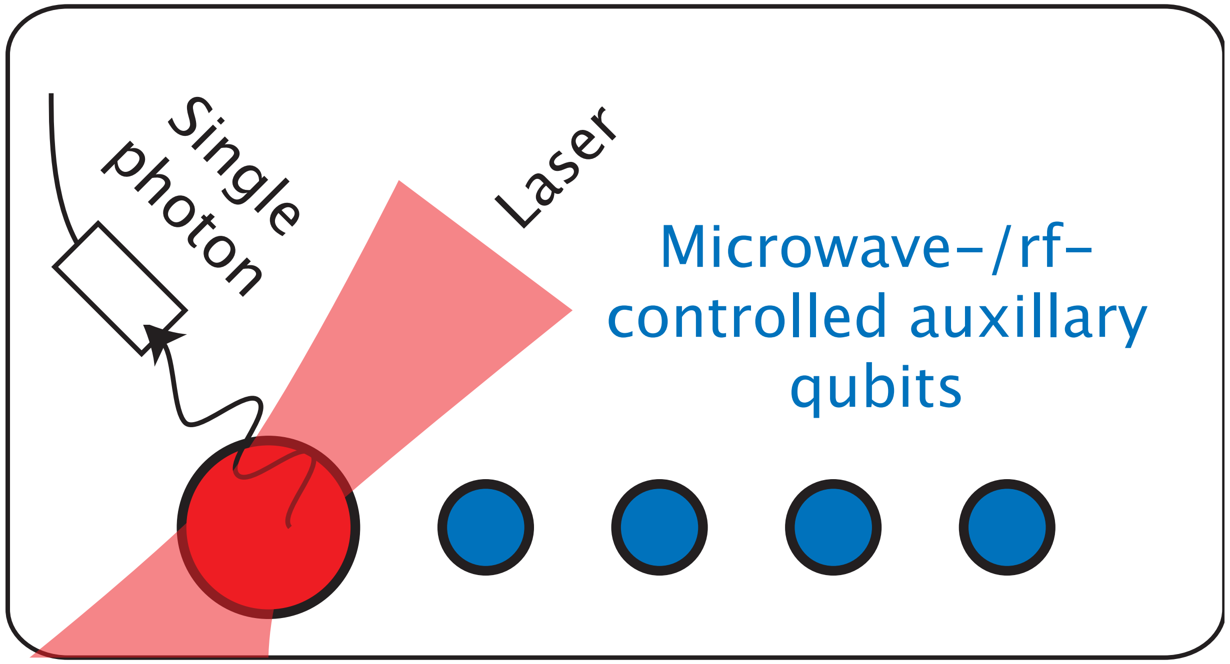
time/gate = t_c
error/gate = $N_{eff}\, p_L$

A minimal register

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]

A minimal register

Minimum requirements:

- "optical" qubit
  - entanglement generation
  - measurement / initialization
- "memory" qubit
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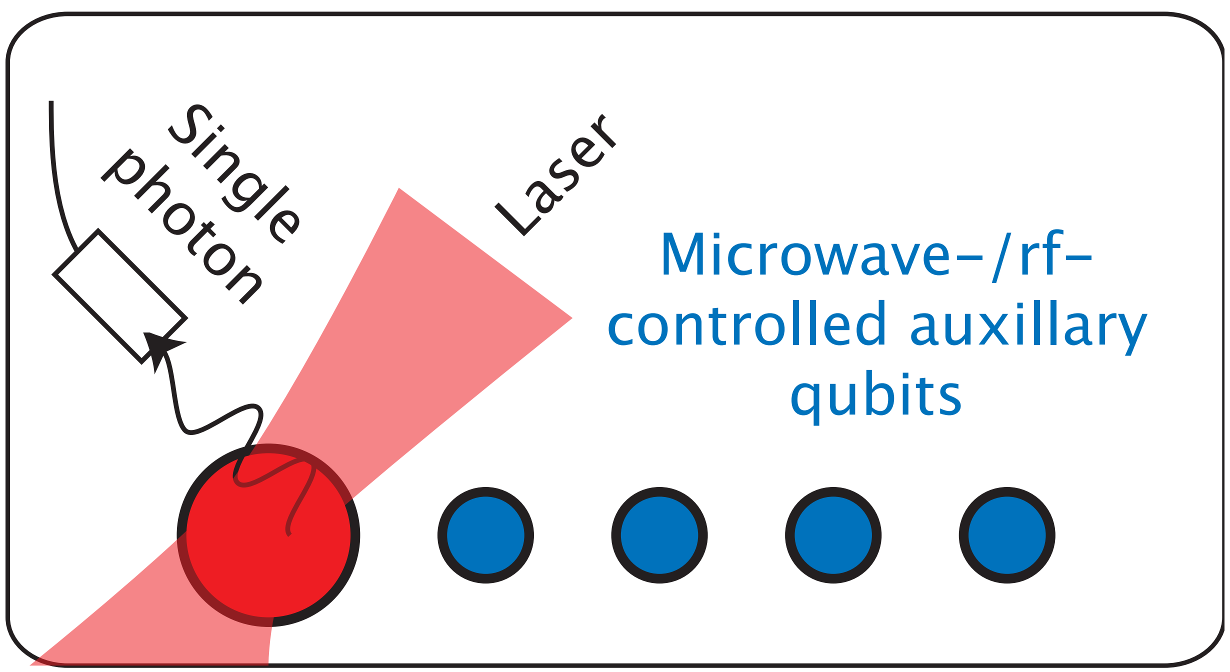

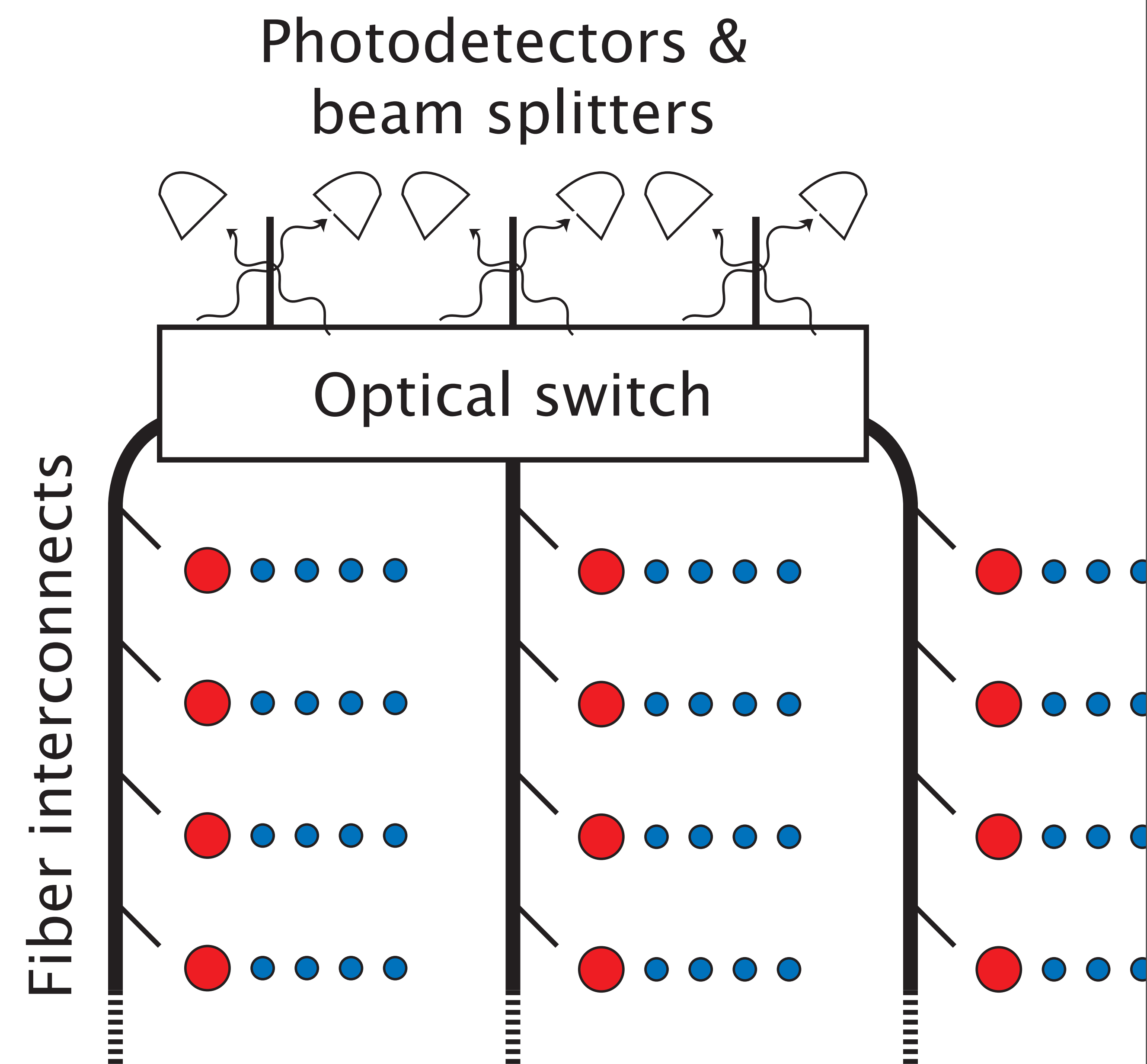

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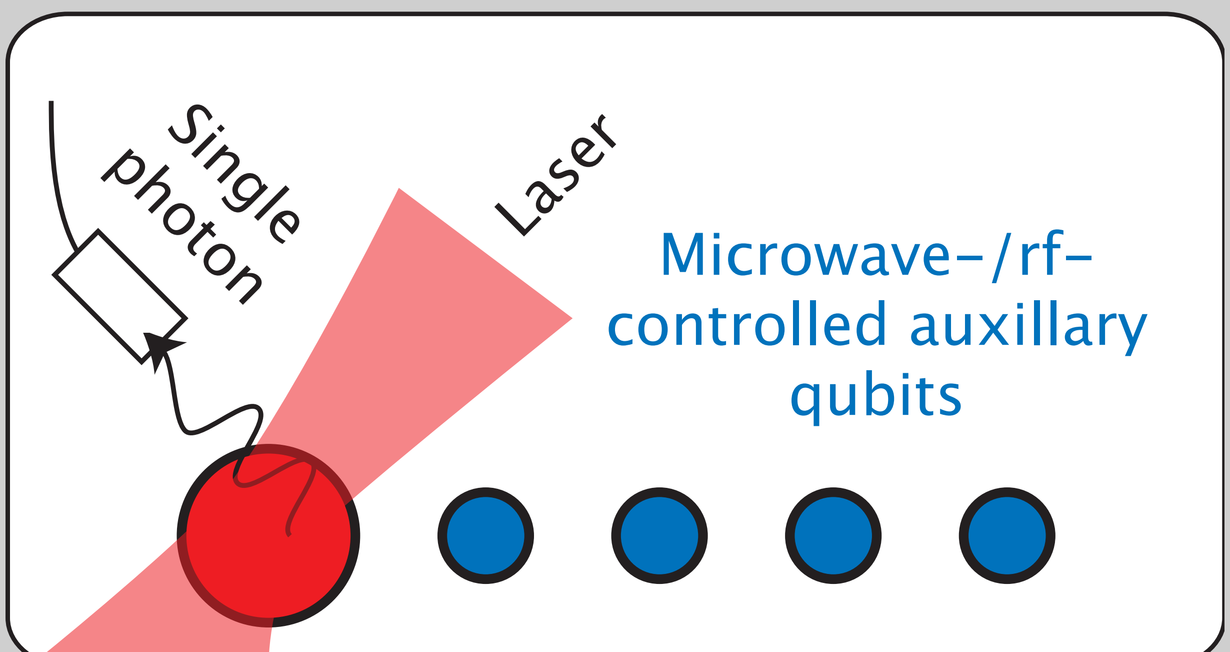
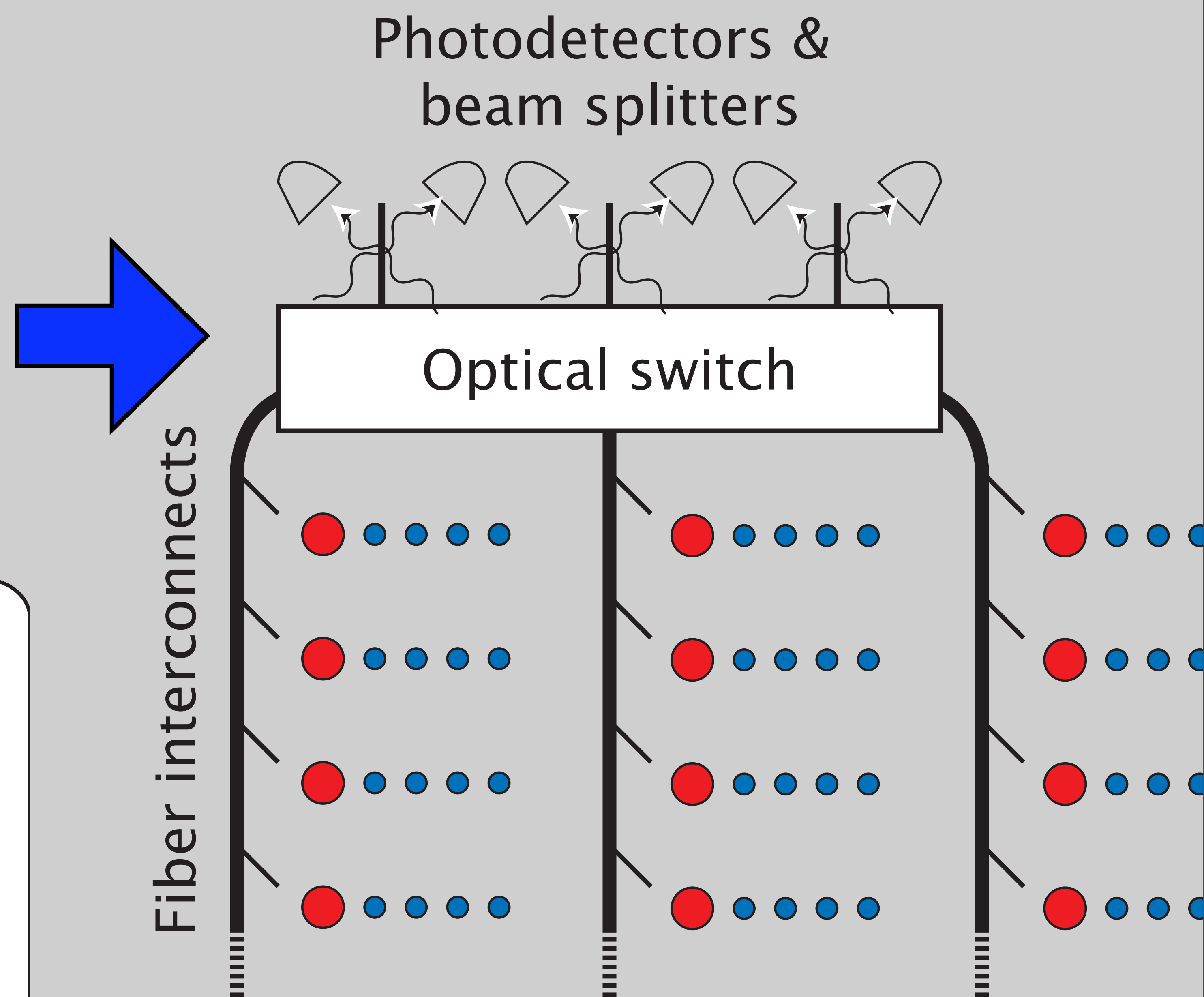
[early ideas: Dür & Briegel]

Small size ion "computer"

+

Optical interface





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Dealing with imperfections: 3 more spins

Robust measurement

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

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

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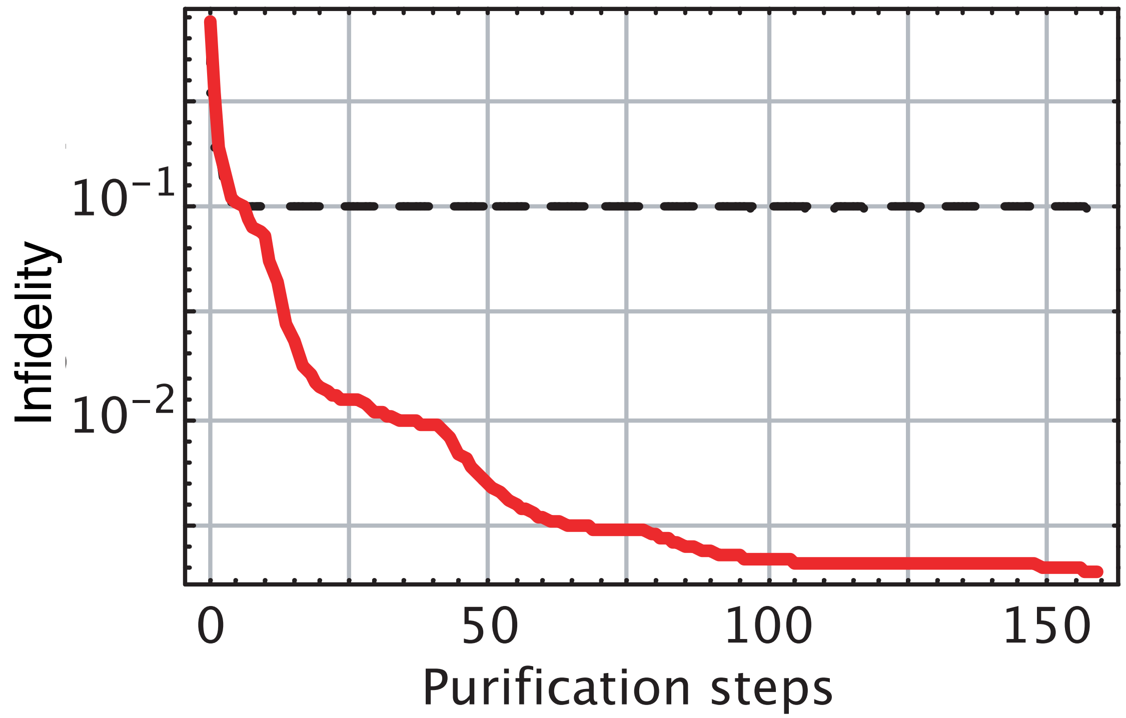
  (t_C ~100–1000 t_L)
- Initial F=0.9 gives final F>0.995
  (N_{eff} ~ 20)
- Good quantum memory *critical*



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

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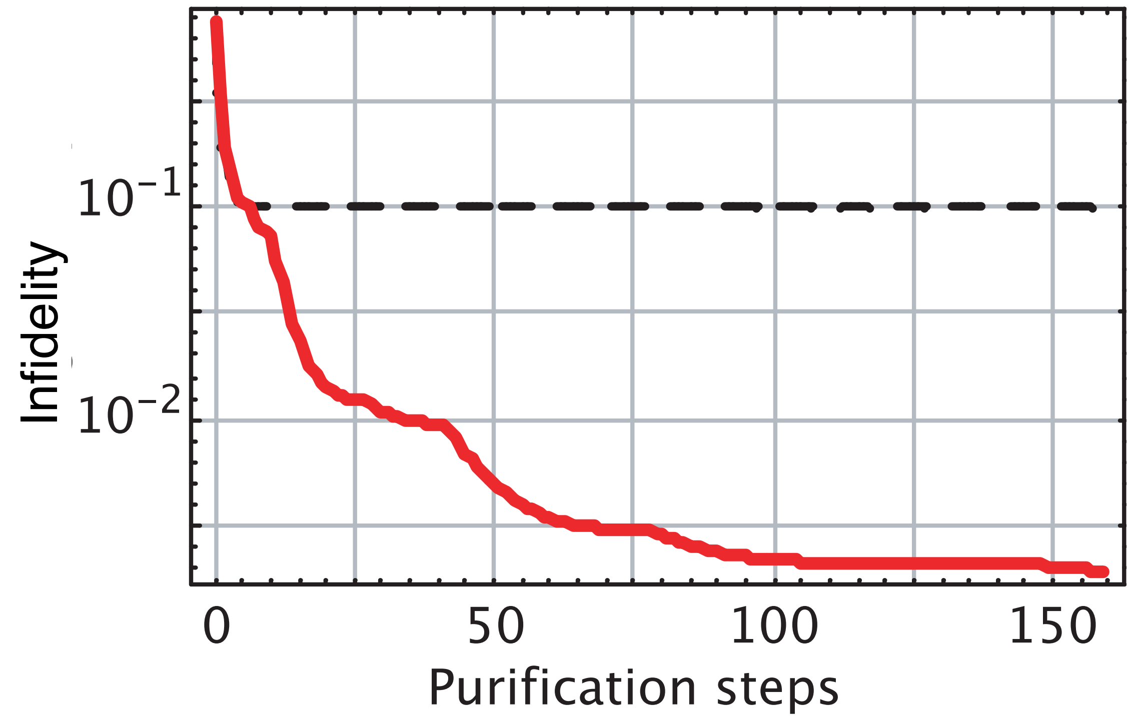

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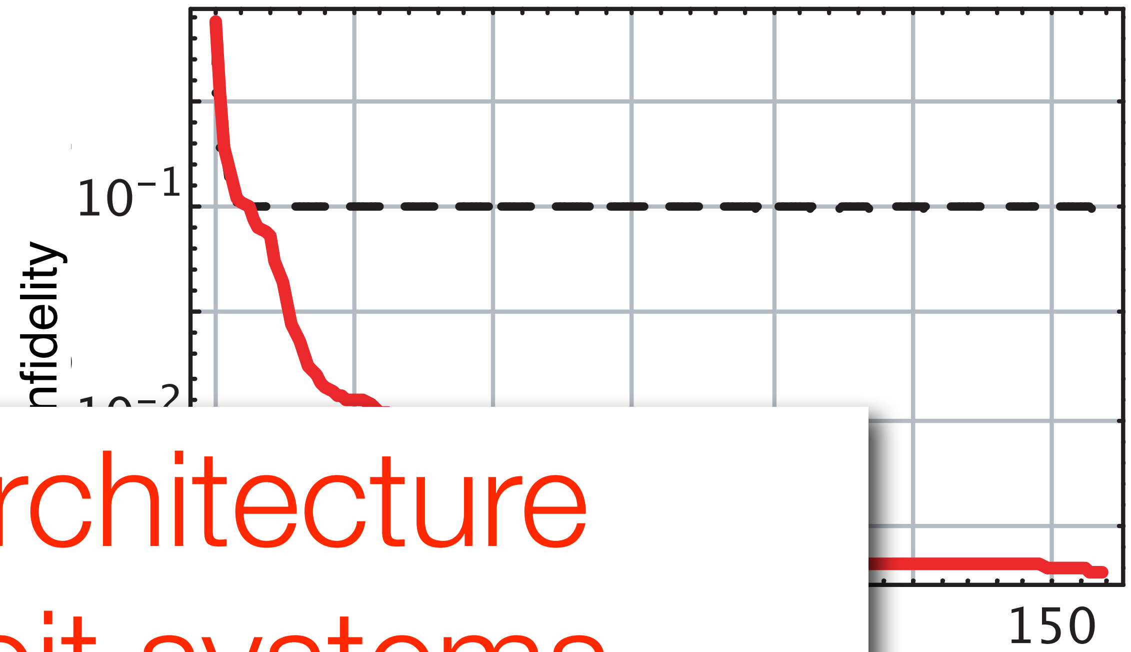
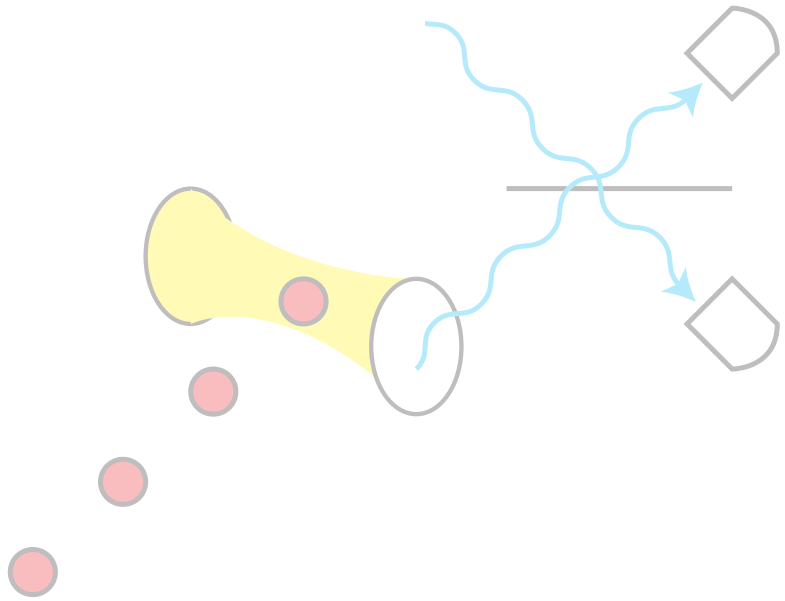


Scalable architecture
for few-qubit systems

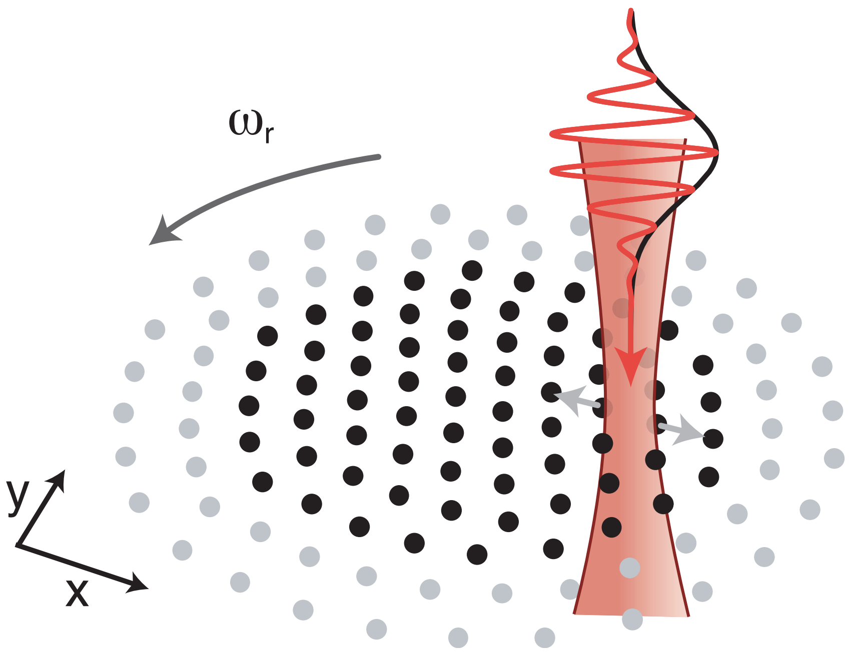
Focus of this talk

Quantum communication



Distributed computing

Wigner crystal-based quantum memory



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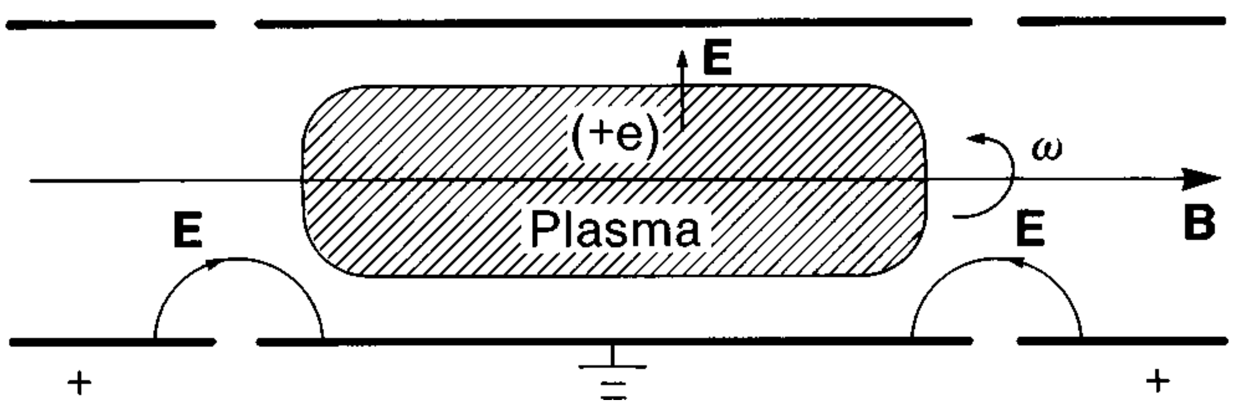
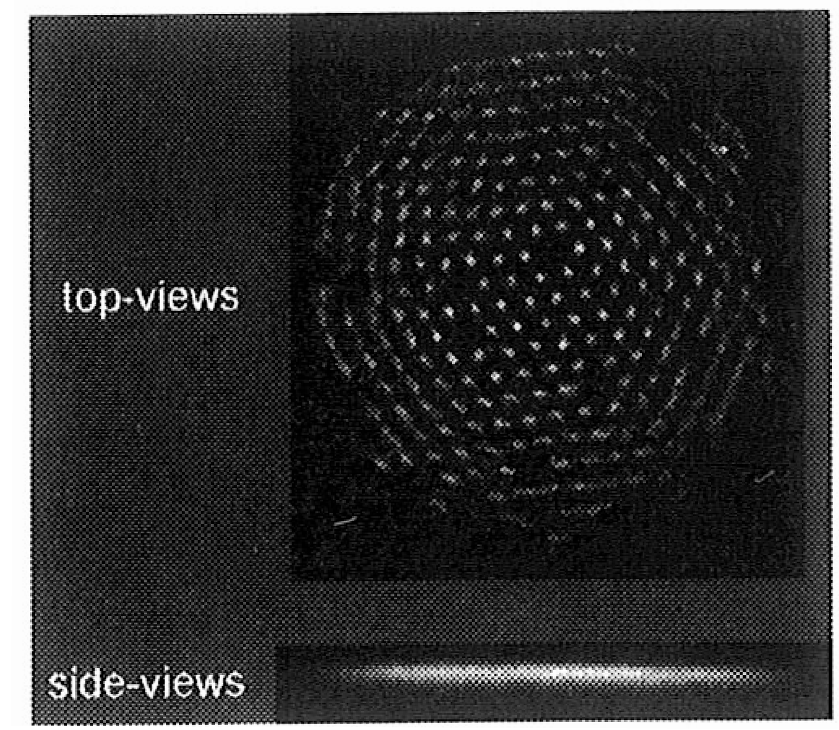


[Dubin & O'Neil, RMP (1999)]

Progress toward making spin squeezed states with ions in a Penning-Malmberg trap.

N. Shiga, W.M. Itano and J.J. Bollinger
National Institute of Standard and Technology,
325 Broadway, Boulder, CO 80305, USA
e-mail: *shiga@boulder.nist.gov*



[QCMC 2006]

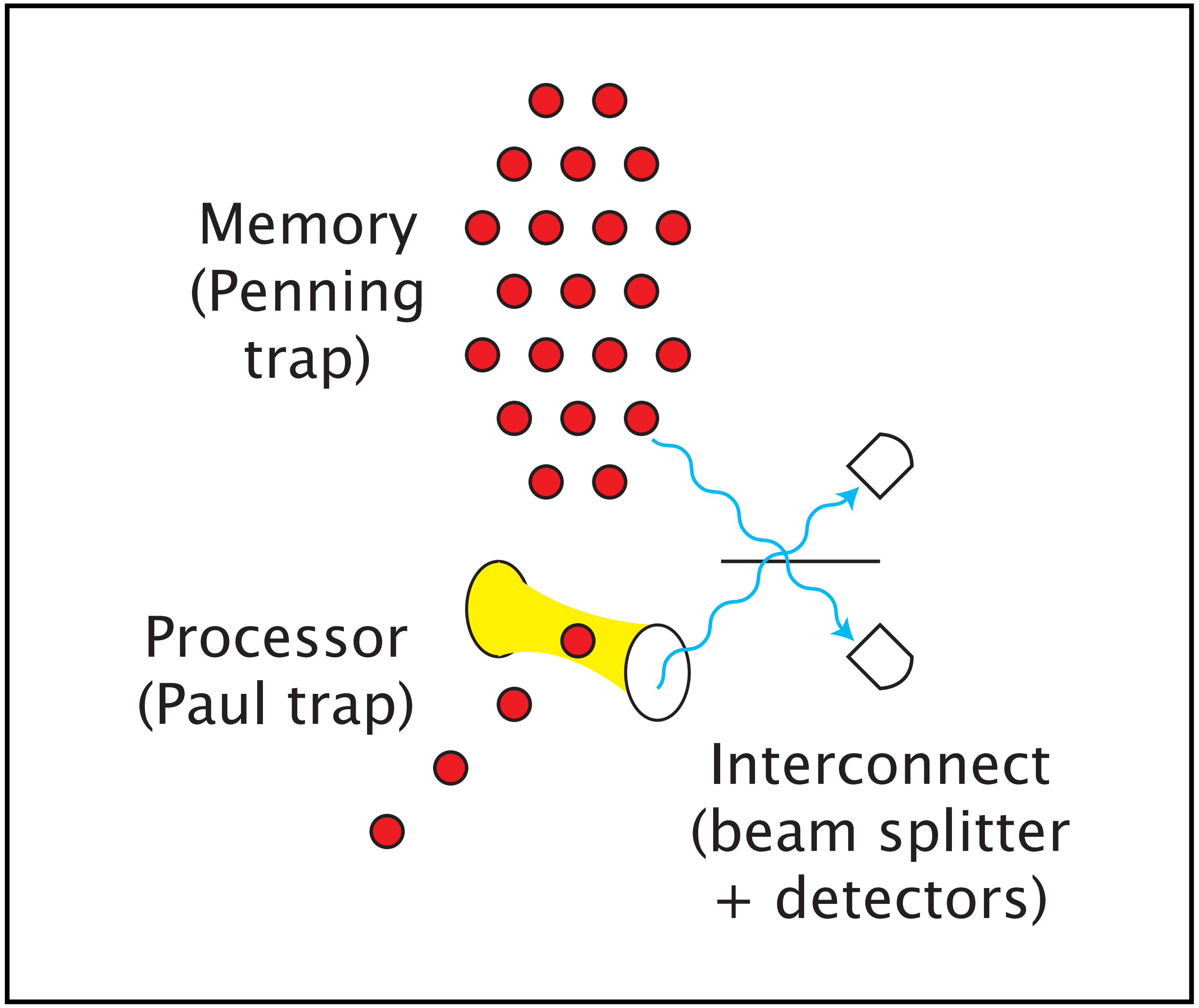
Advantages:

- many ions (good memory)
- self-organized, stable
- optically resolved sites

Problems:

- high temperature
- finite size
- low collection efficiency

Wigner crystal-based quantum memory



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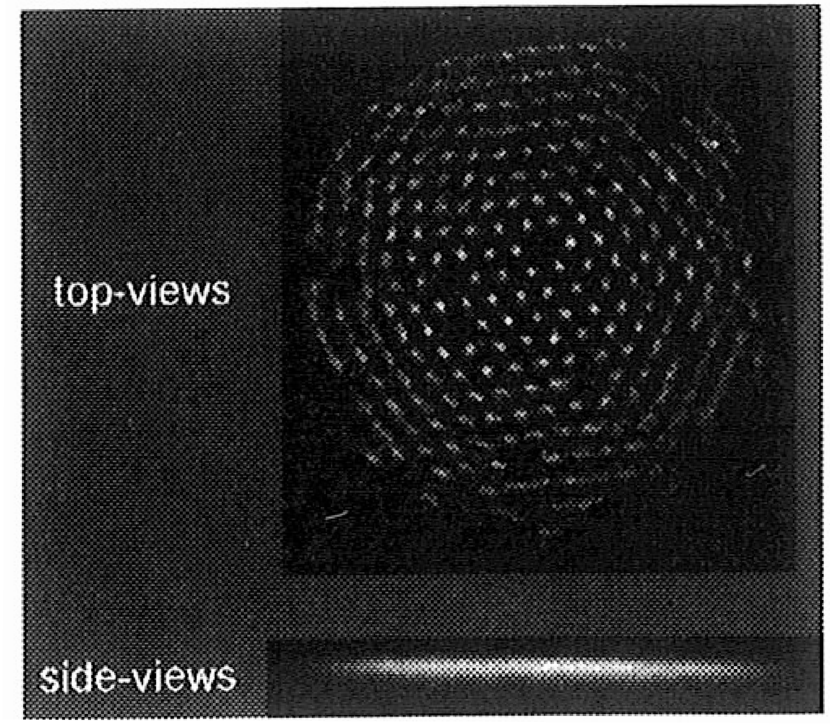

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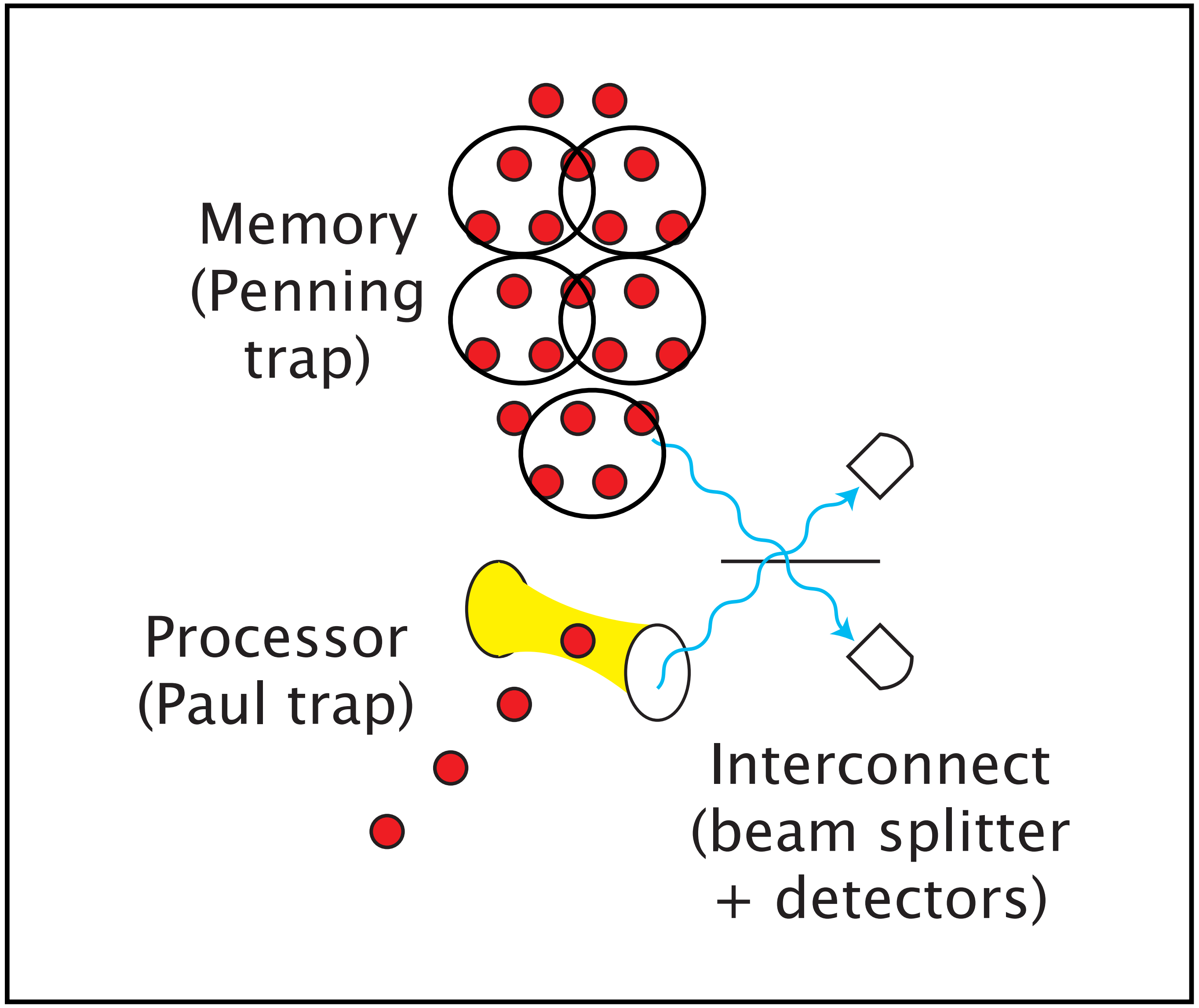

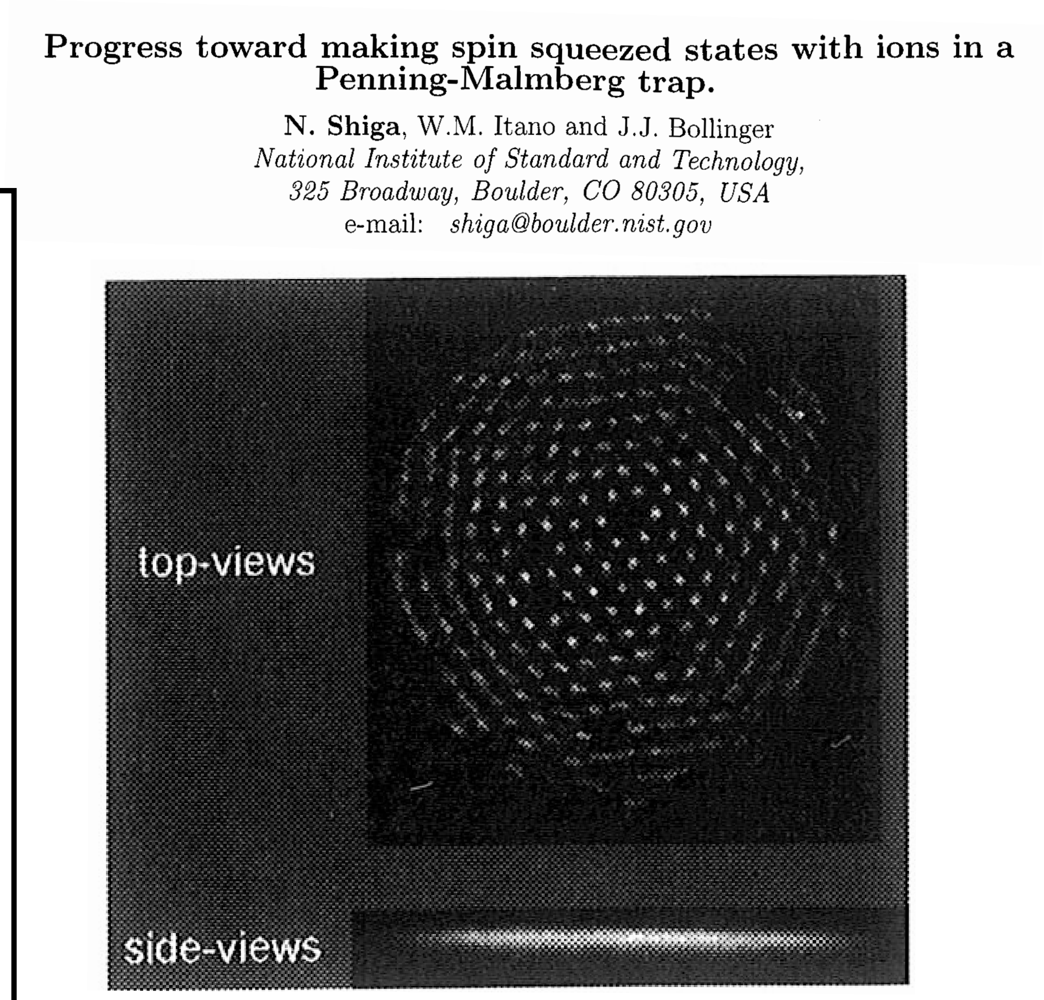

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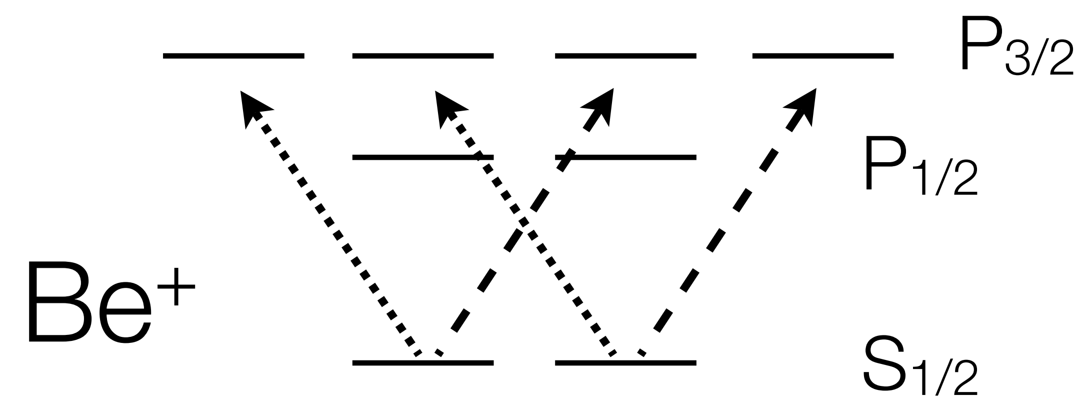
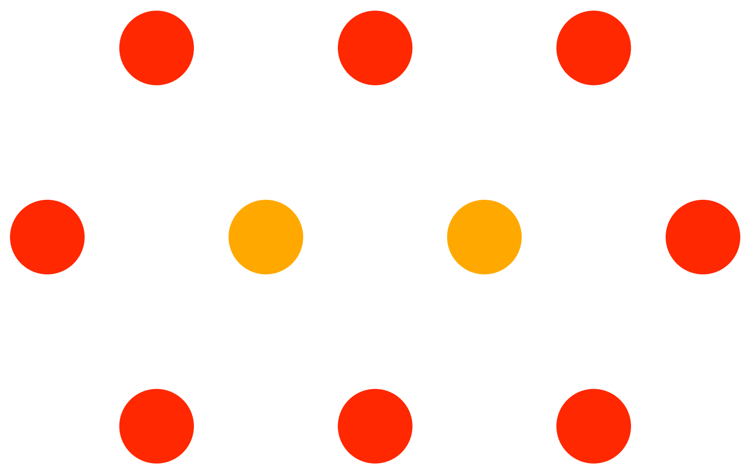
Quantum gates at high temperature

Push gates

- AC Stark shift -> effective potential
- Different internal states -> different potentials
- Control sign, strength



$$V = \sum_i (\vec{x}_i \cdot \vec{f}_i(t))\sigma_i^z$$



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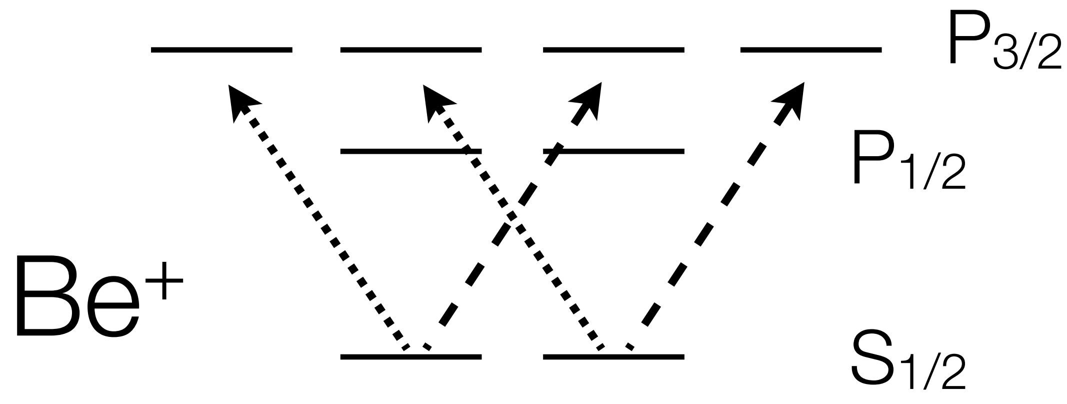

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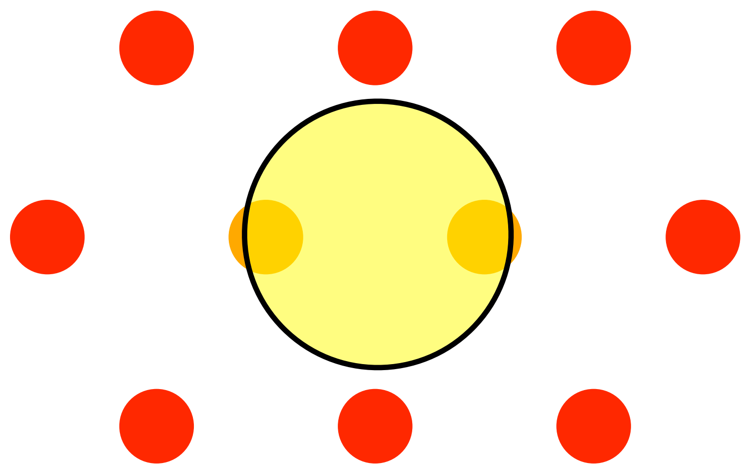

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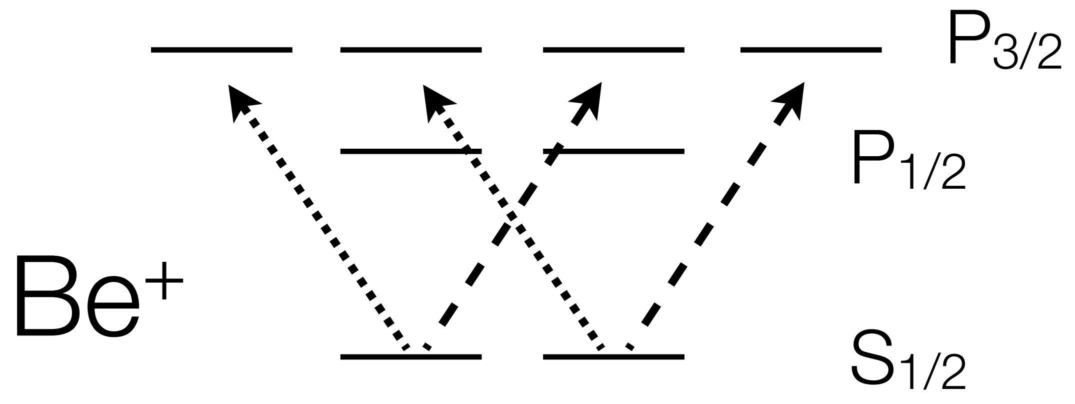

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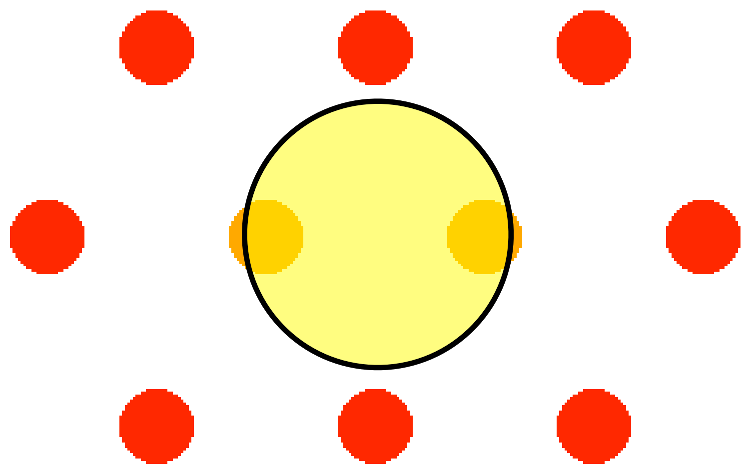

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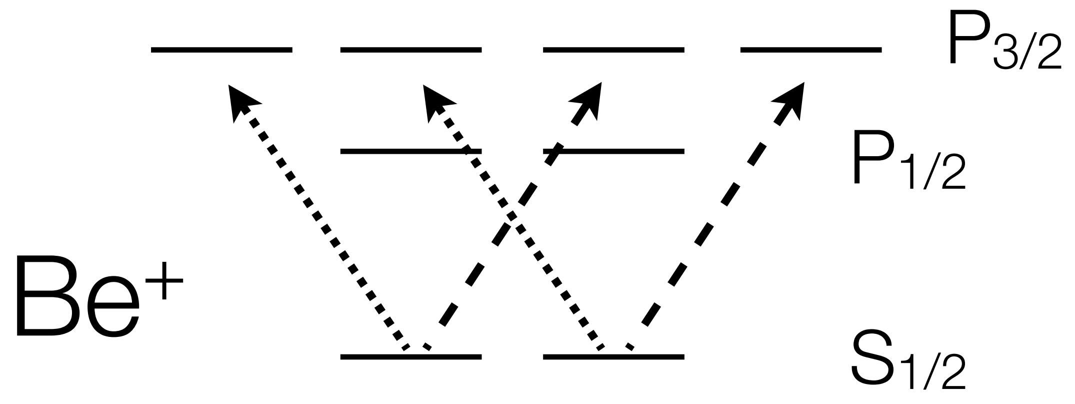

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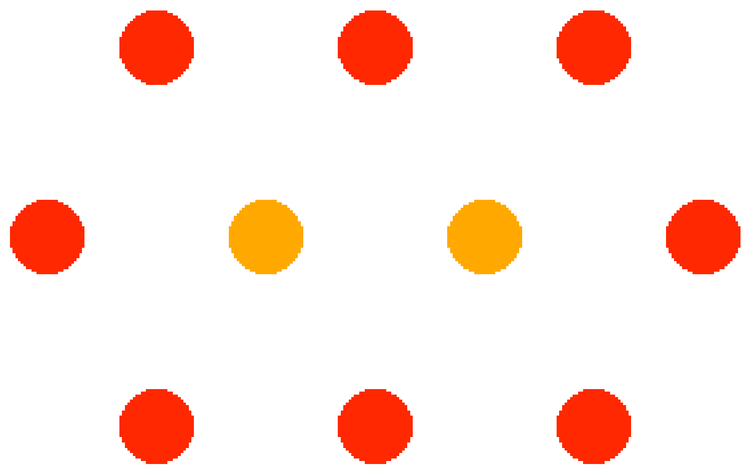

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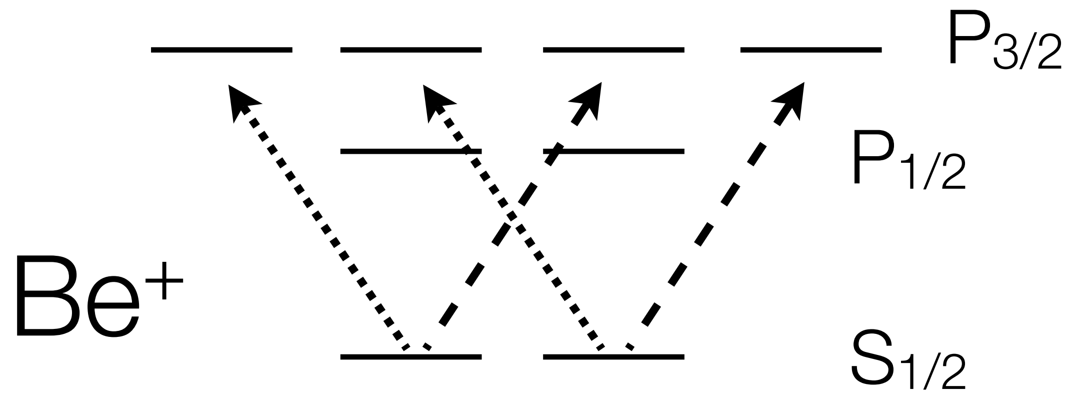

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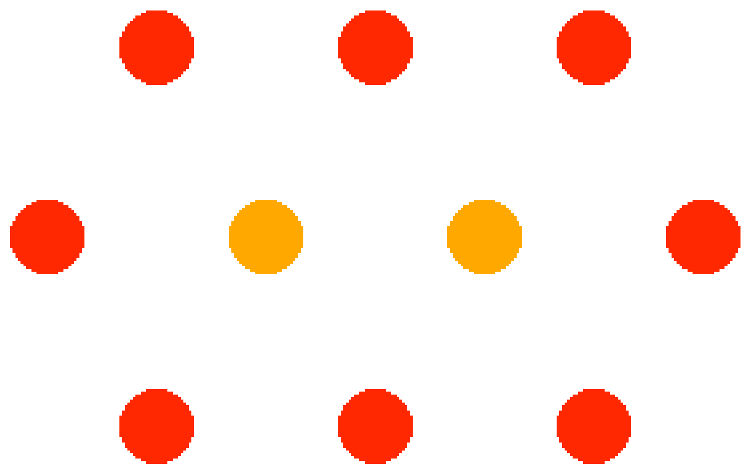


Coulomb interaction -> effective z-z interaction

Requirement: *slow* w.r.t. phonon modes (but, no gap!)

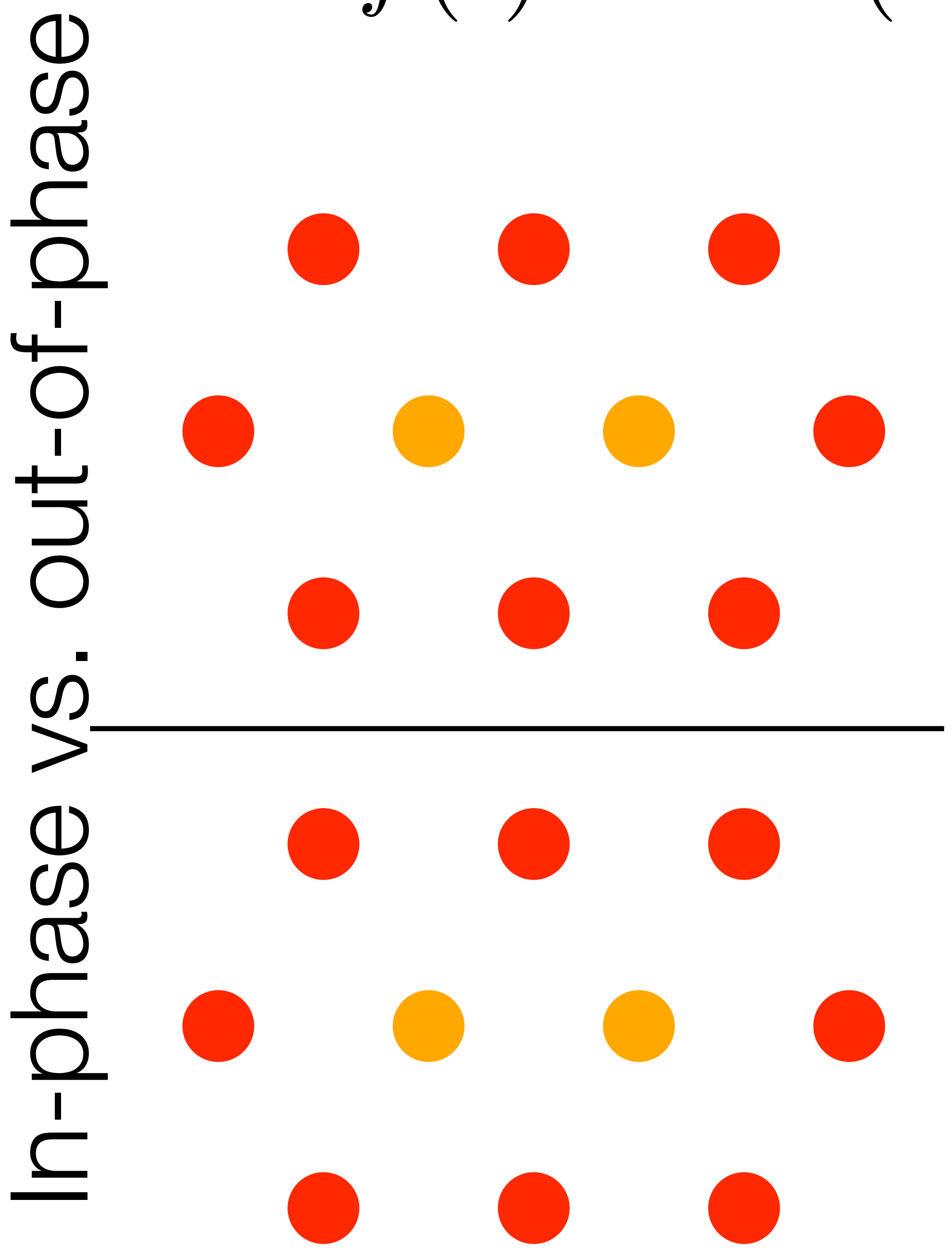
[Porras & Cirac, PRL 2006]

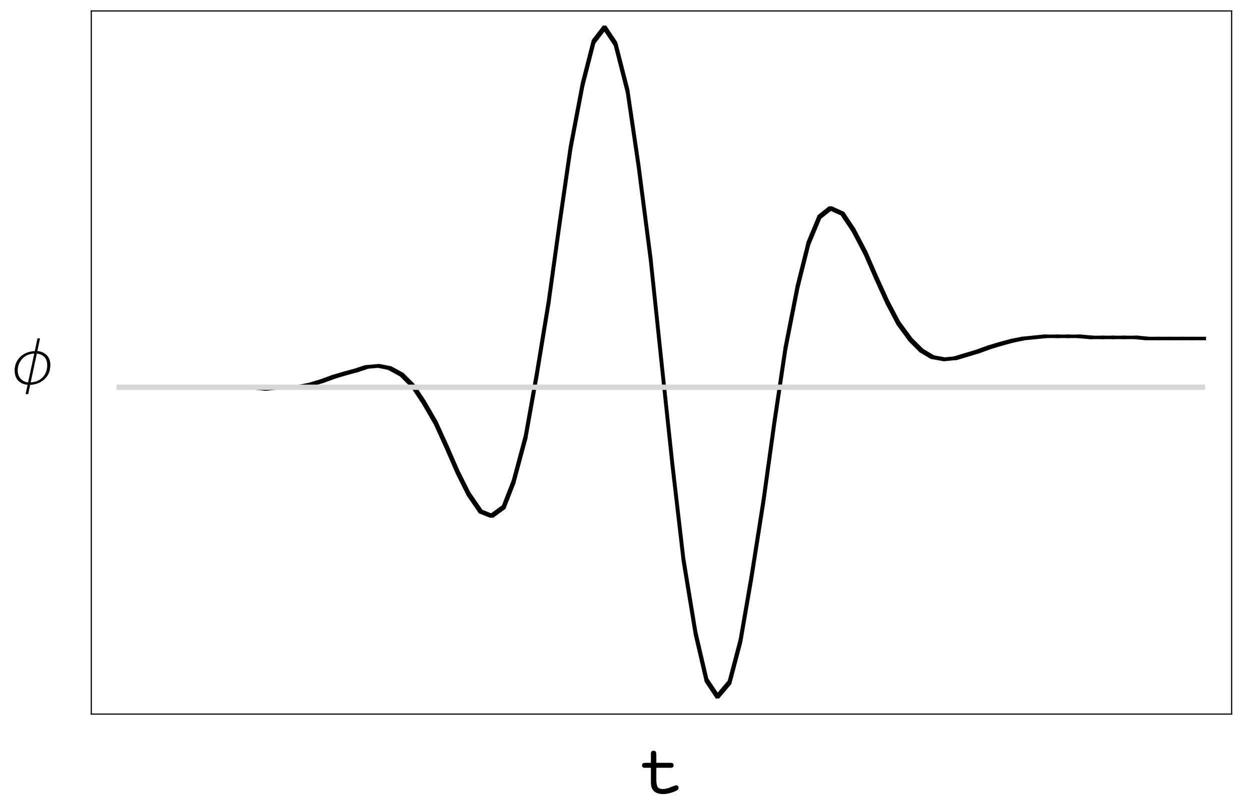
Fast carrier-modulated gate

Idea: modulate force *fast* w.r.t. phonons (fast-kick)

[García-Ripoll et al. PRL 2003]

$$f(t) \rightarrow \cos(\nu t) f(t)$$





[Taylor & Calarco (0706.1951)]

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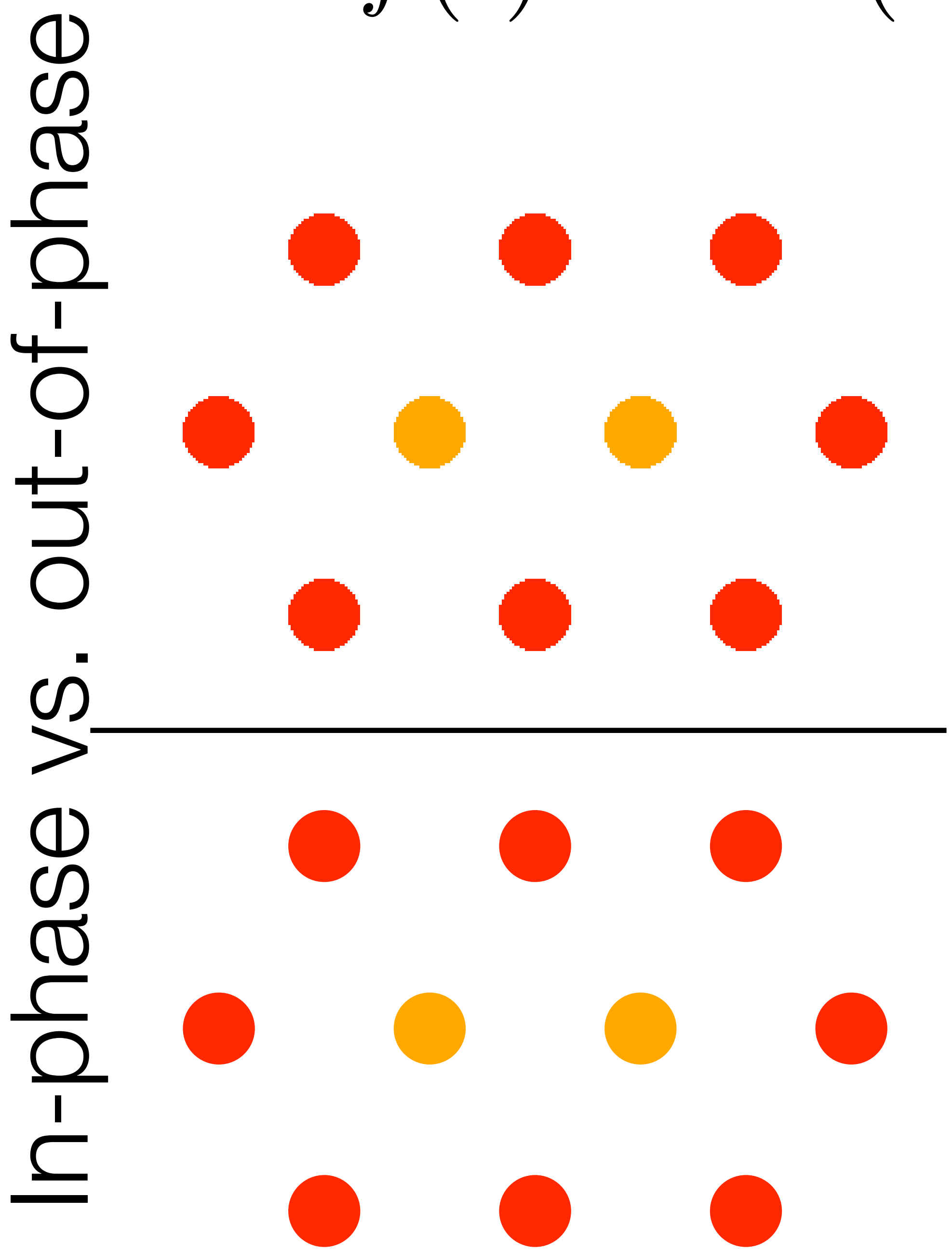

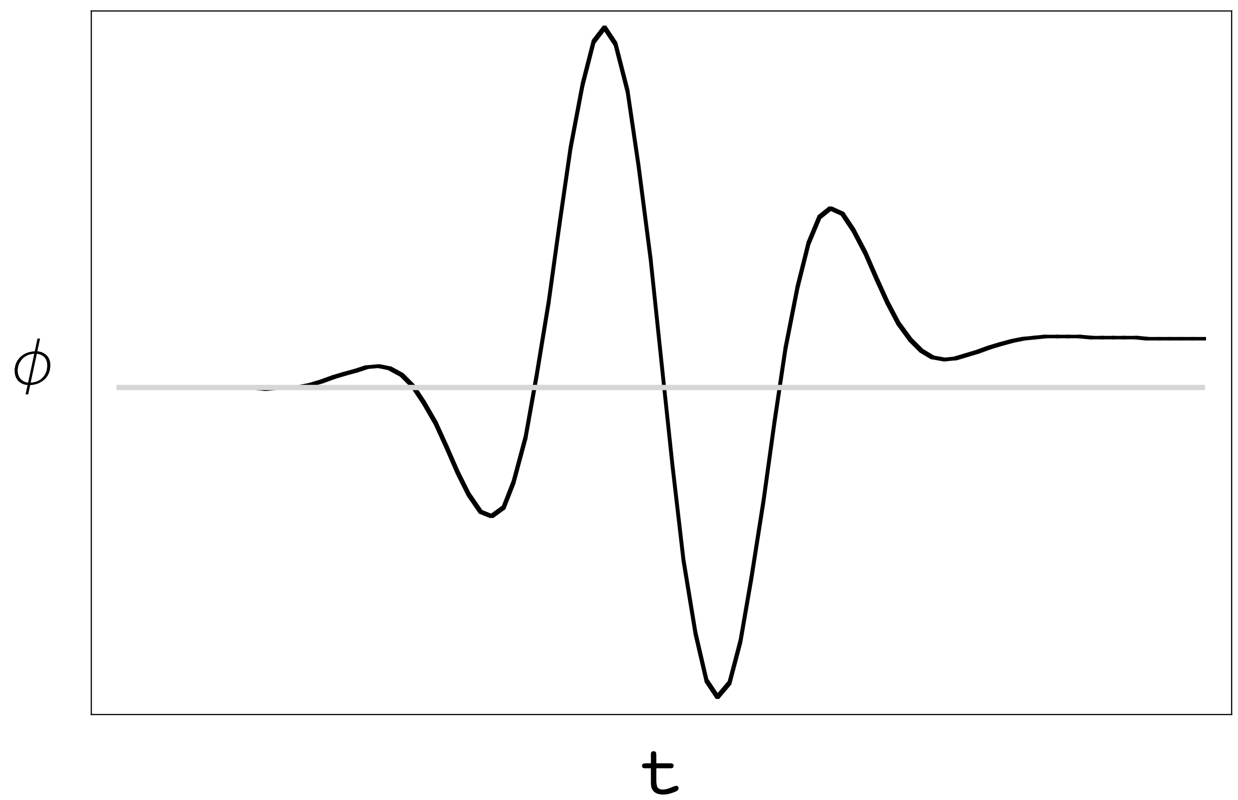

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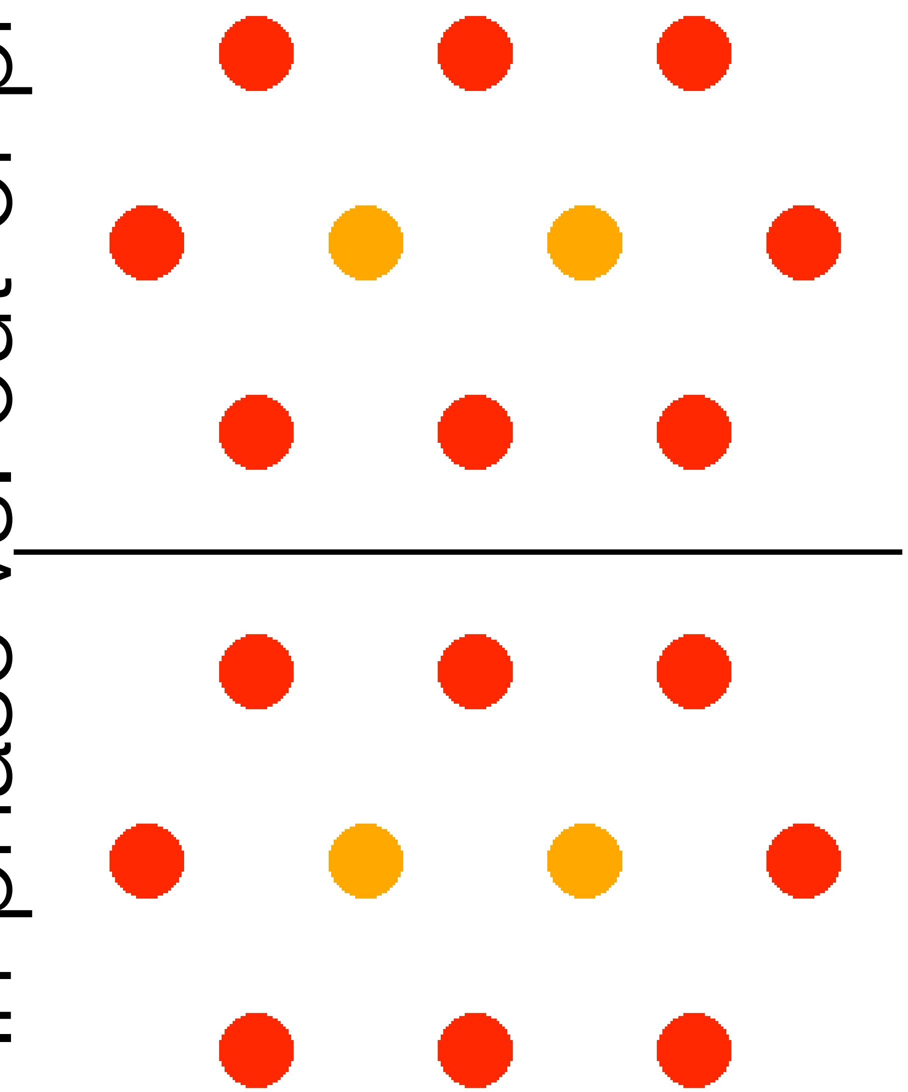
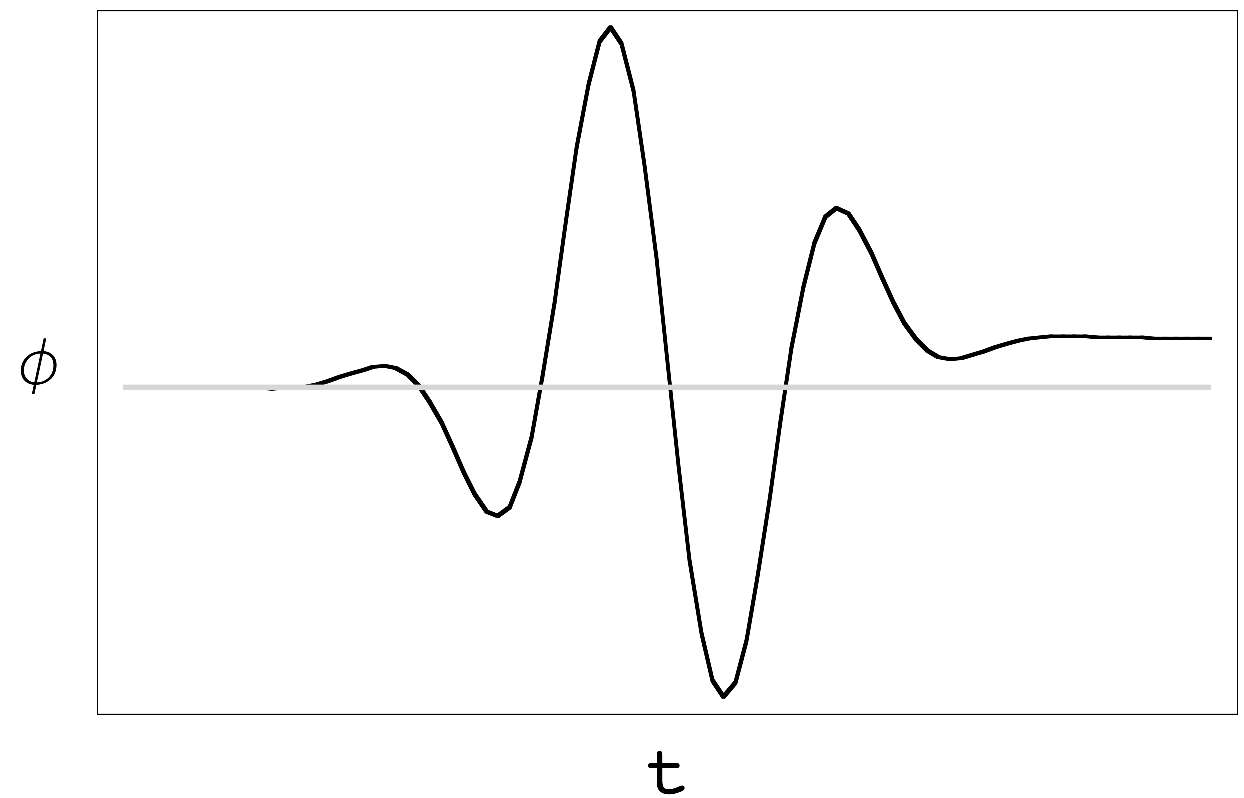
In-phase vs. out-of-phase





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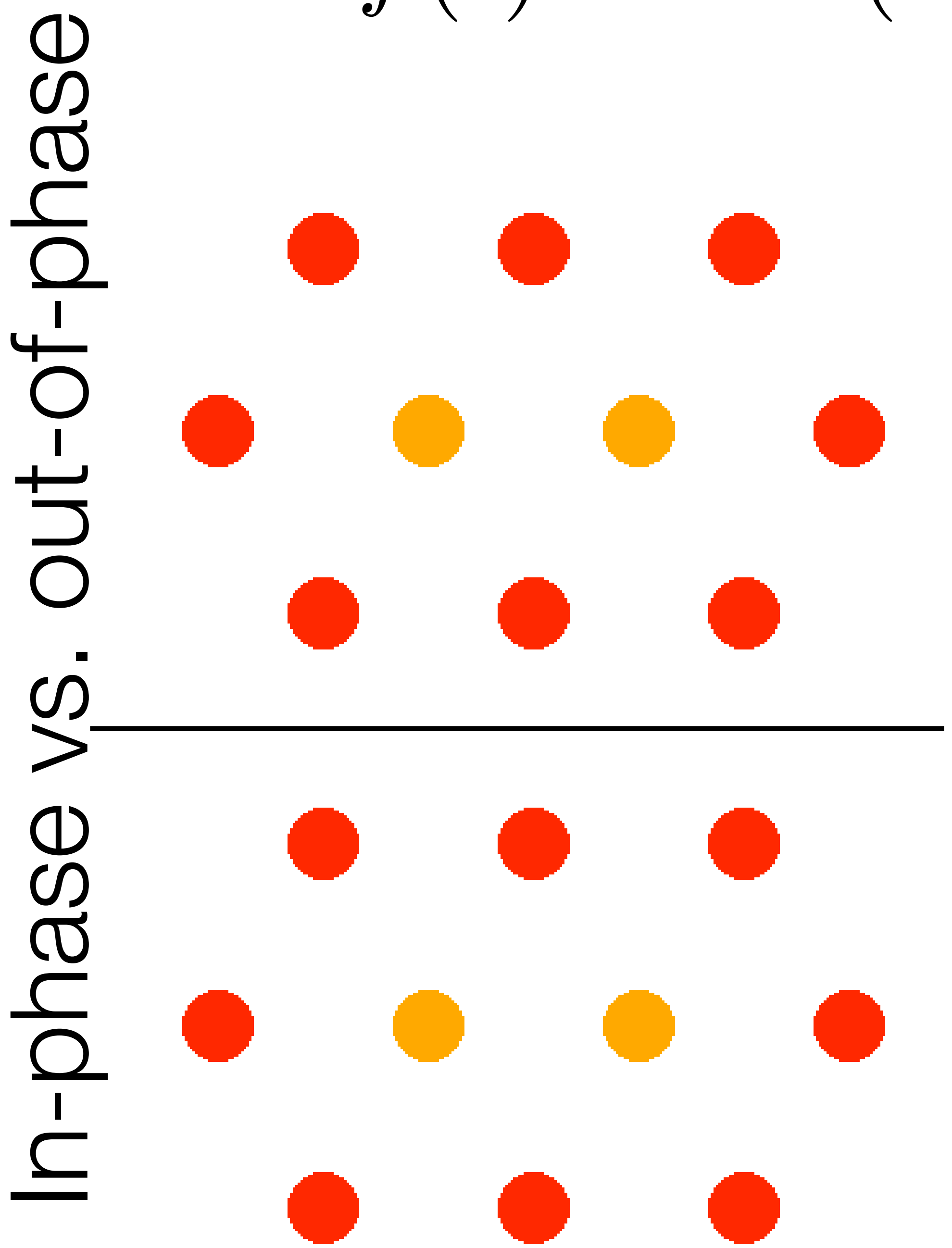

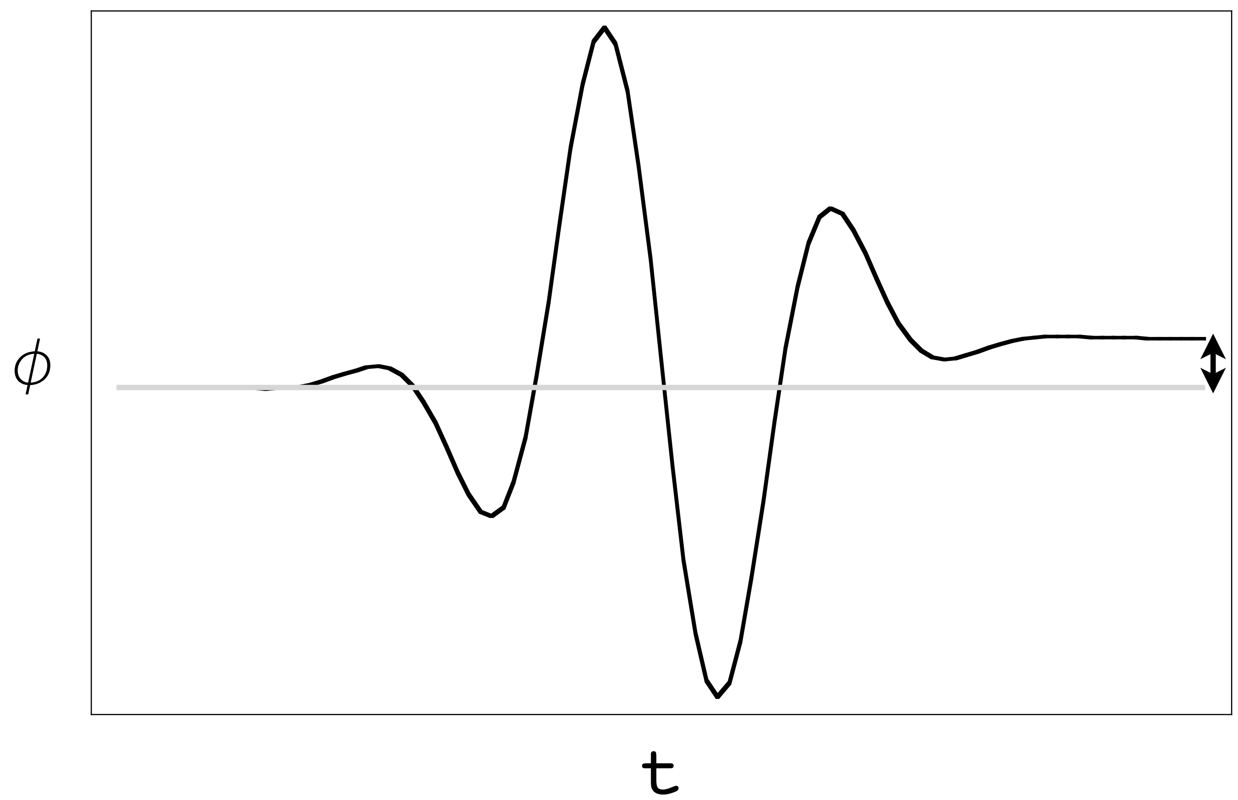

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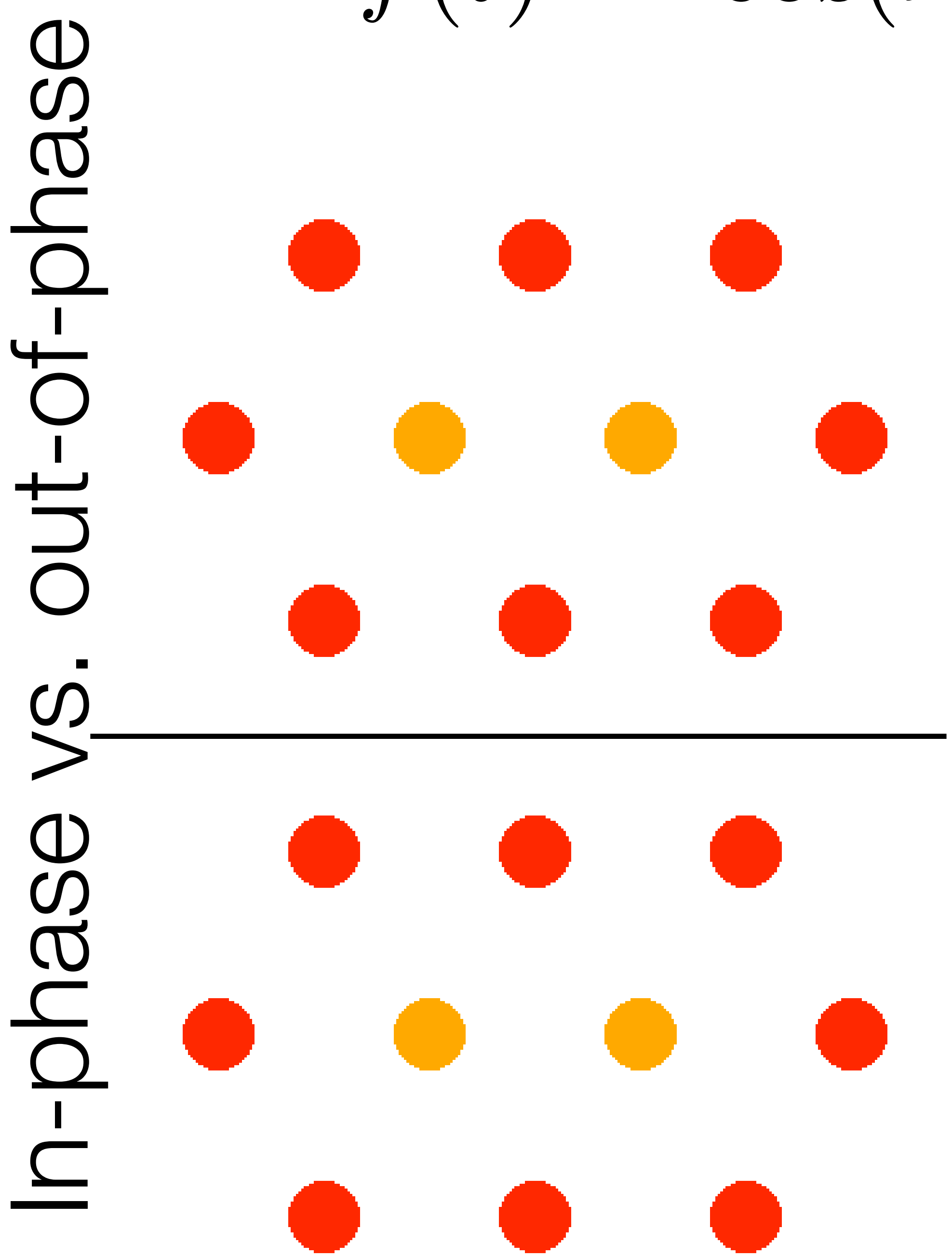
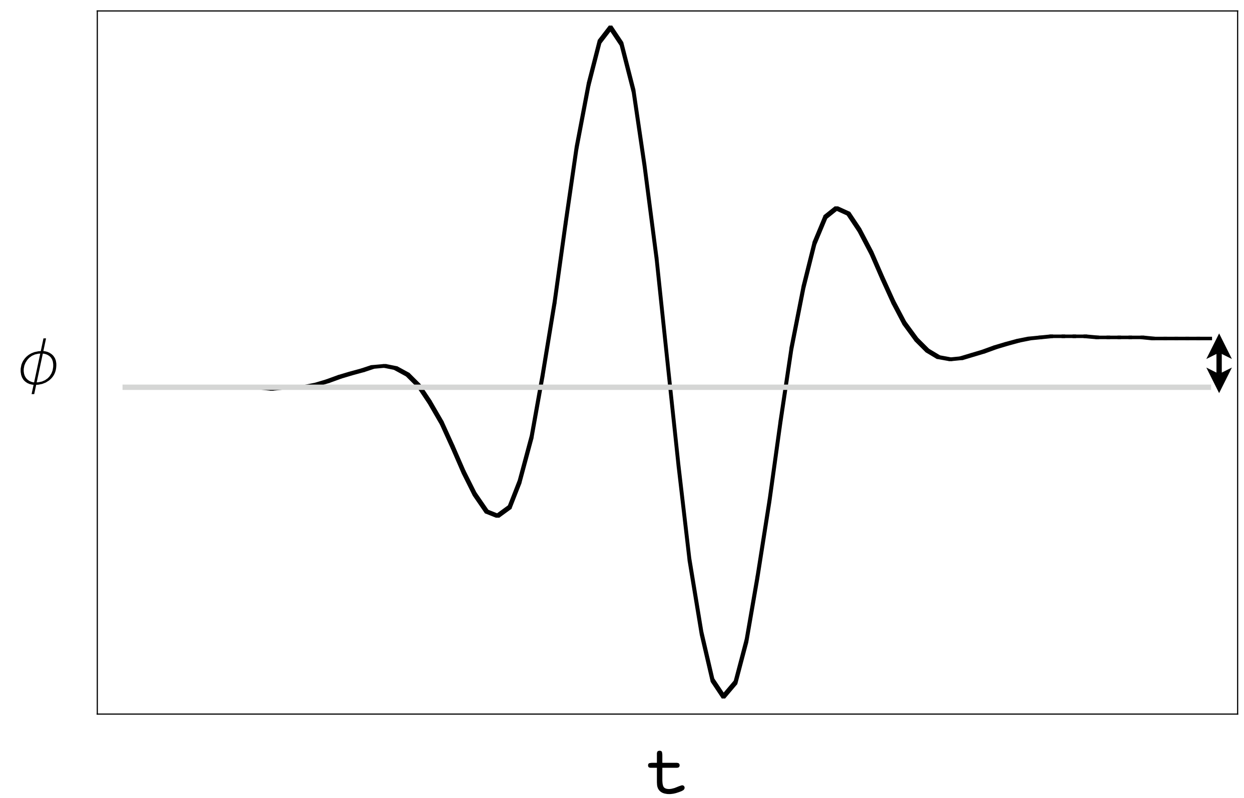
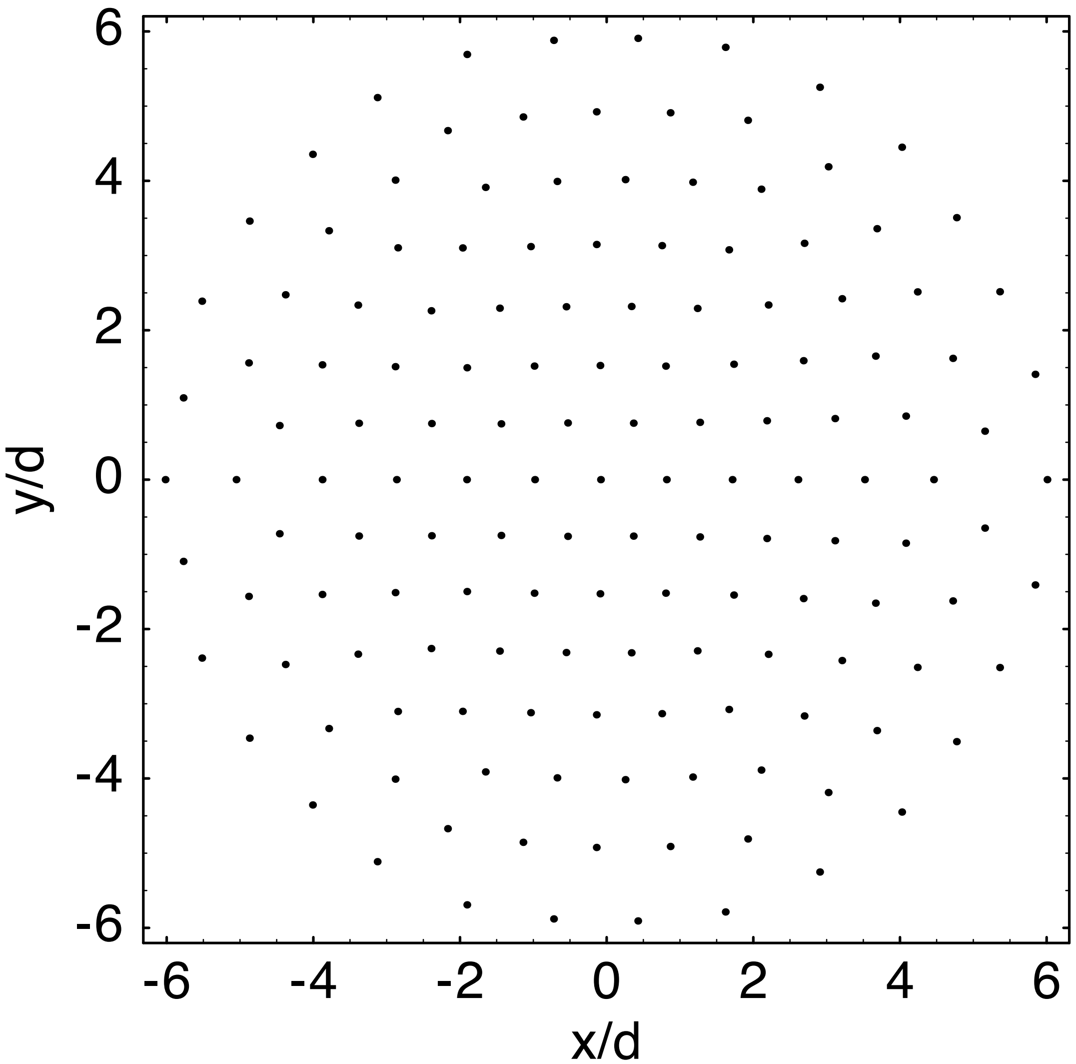


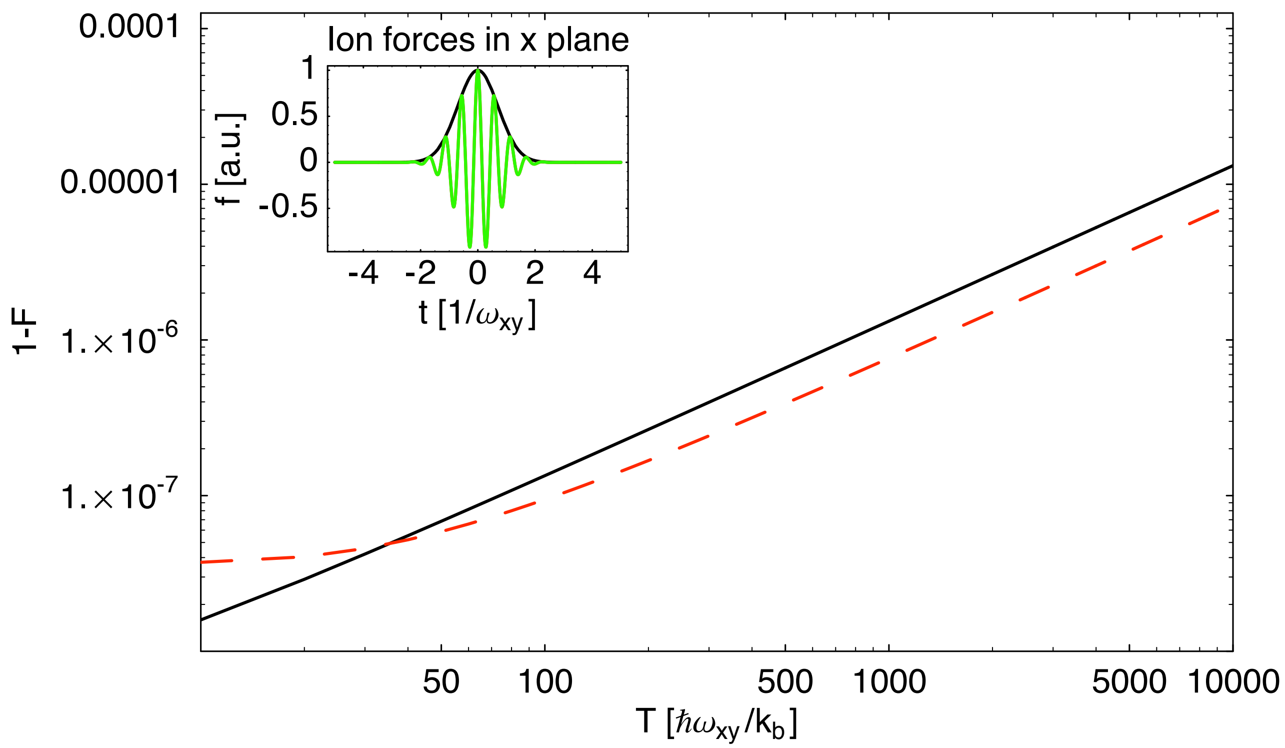


Over an oscillation,
no phonon evolution
(no heating, no entanglement)

[Taylor & Calarco (0706.1951)]

Numerical simulations of gates in 2D

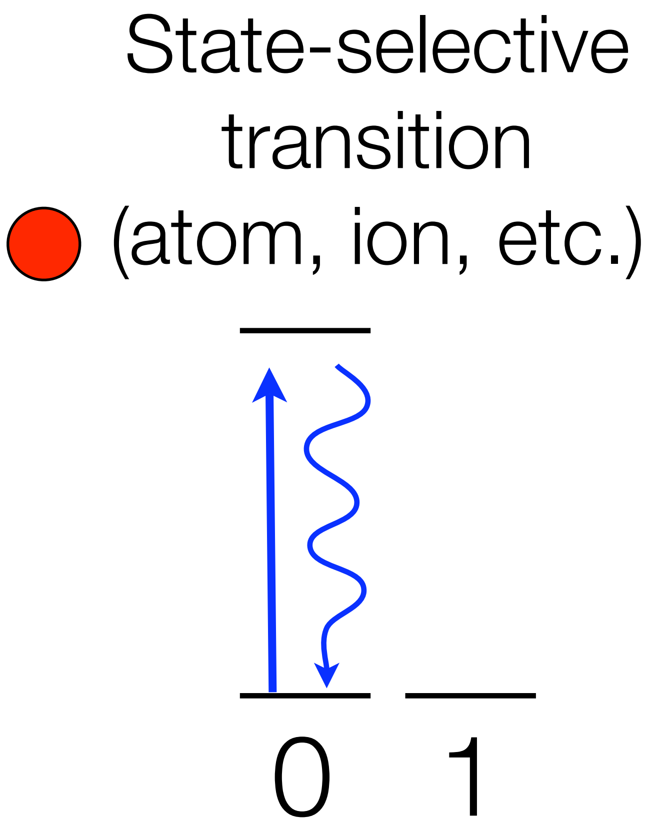




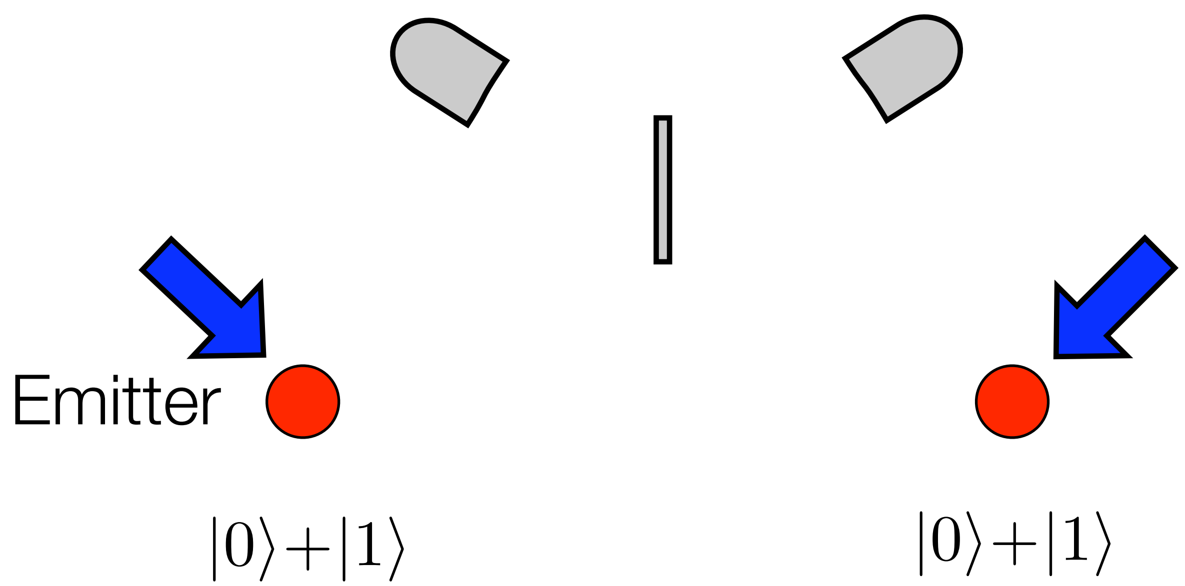
High fidelity at high temperatures
(also works in 3D)

[Taylor & Calarco (0706.1951)]

Asymmetric protocols for quantum register-based computation



Entanglement generation



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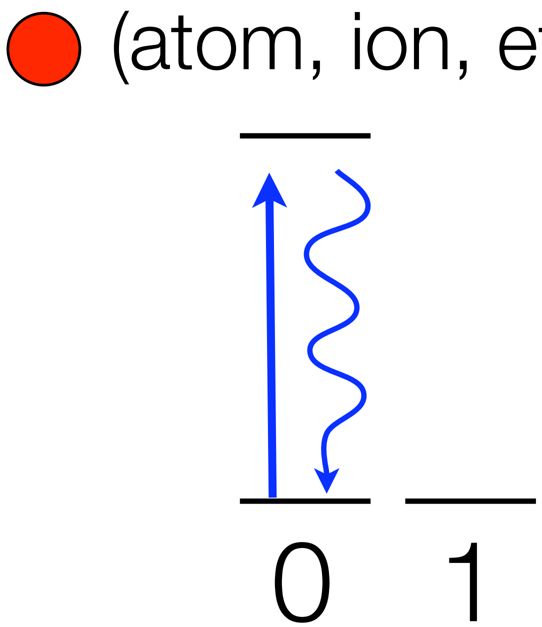
Asymmetric protocols for quantum register-based computation

State-selective transition

(atom, ion, etc.)



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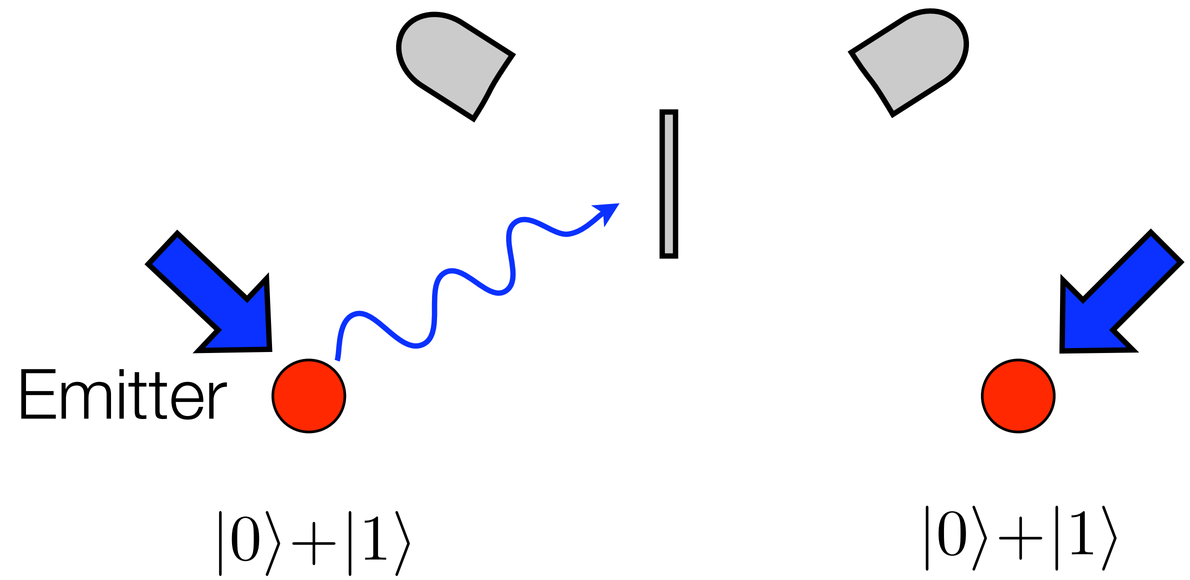

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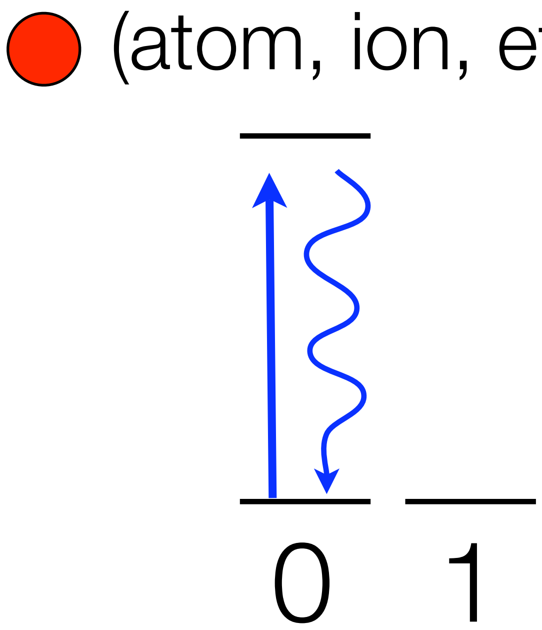

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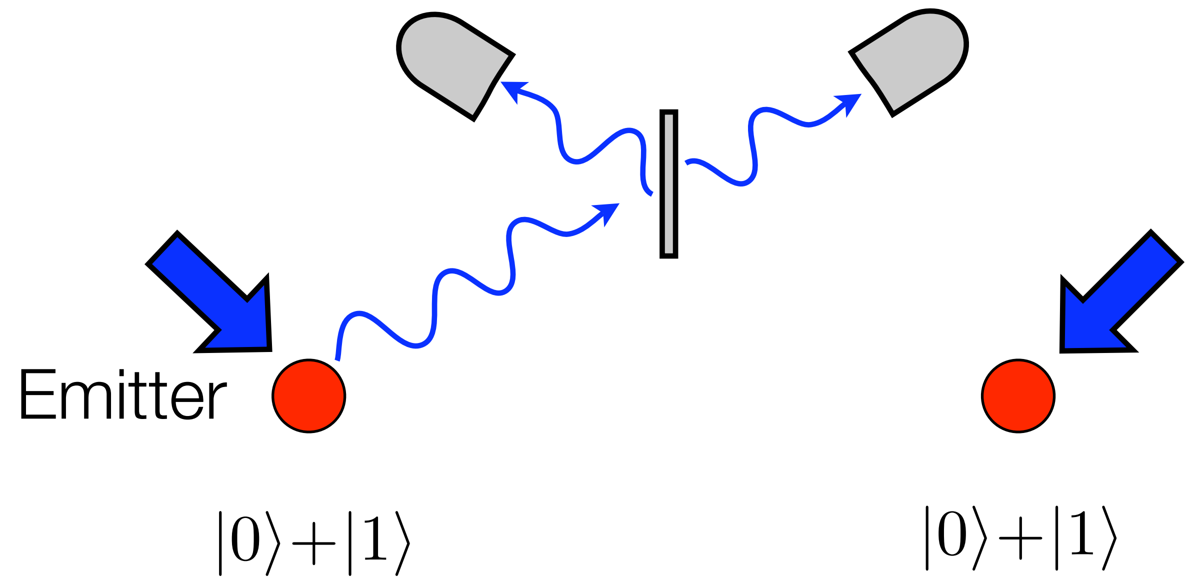

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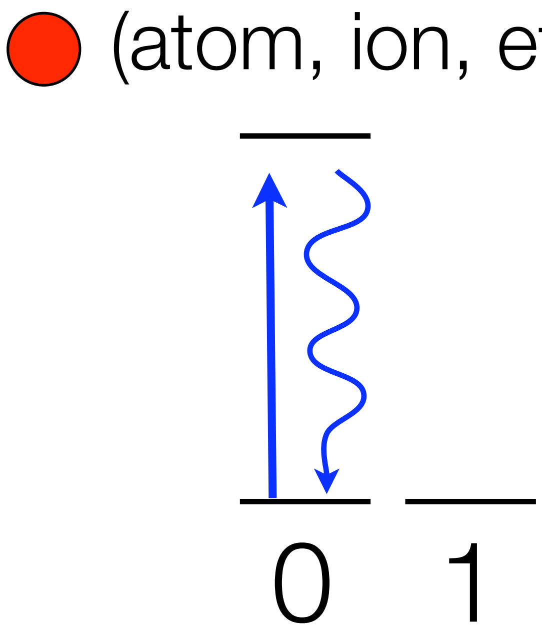

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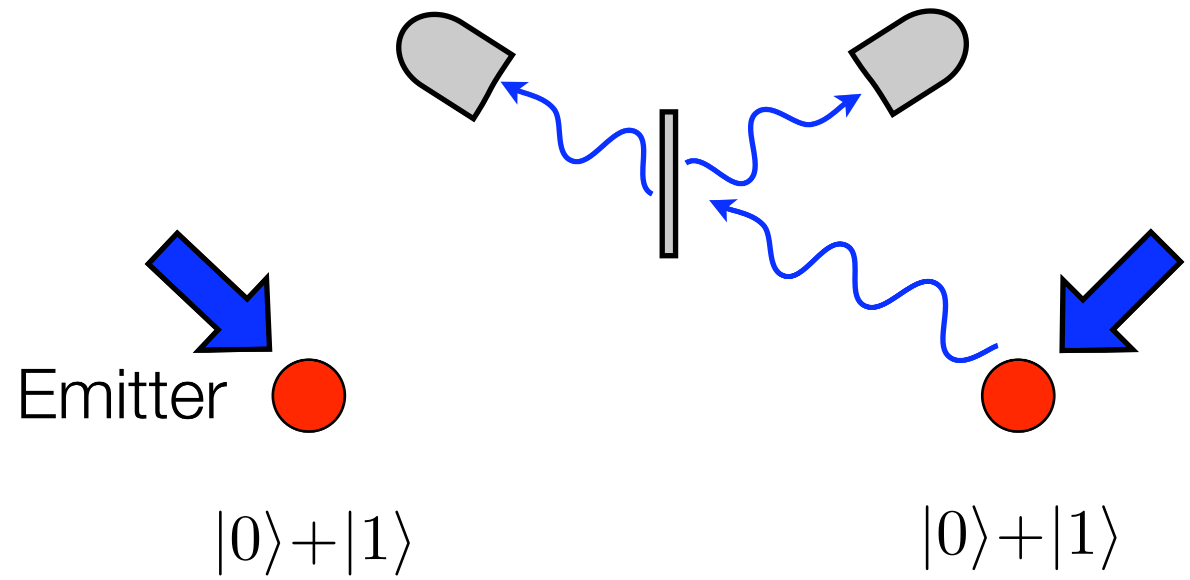

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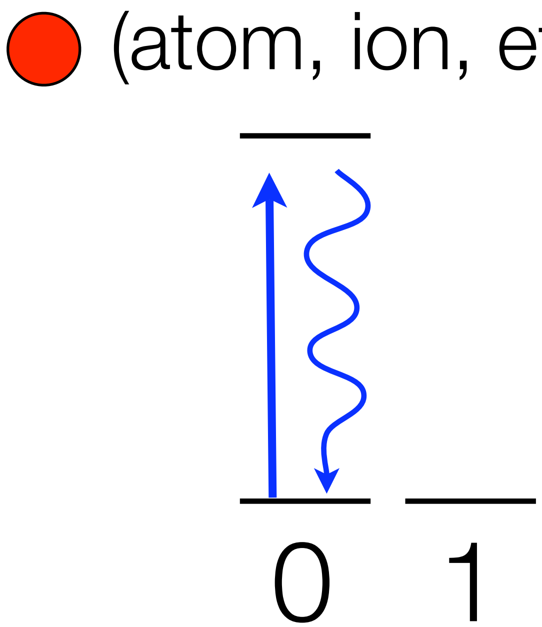

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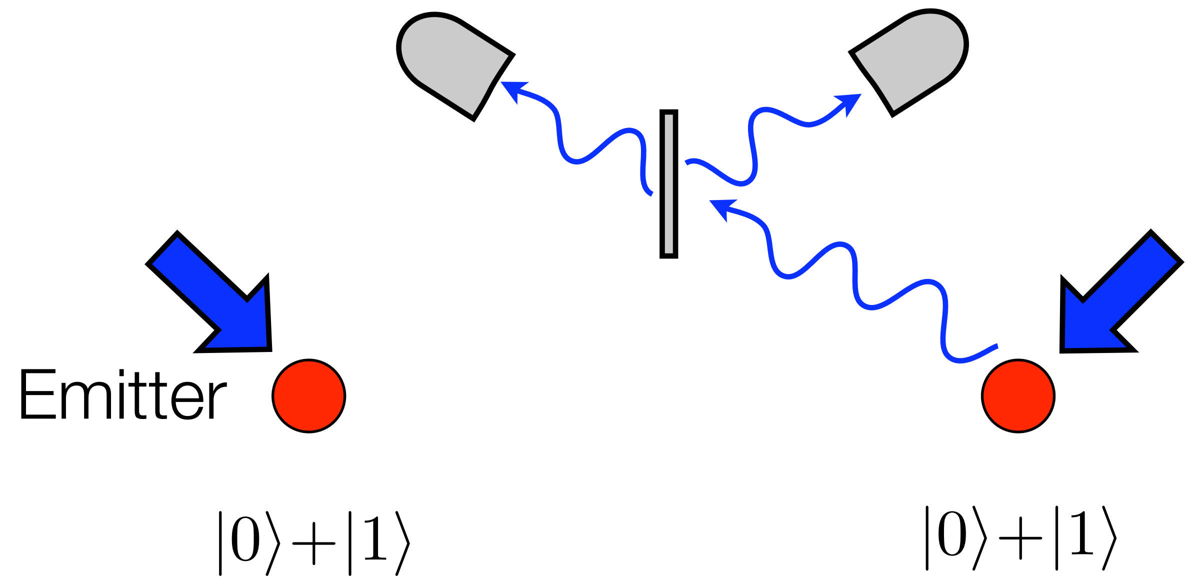

$$\eta' \left(\sqrt{\frac{\eta}{\eta'}}\,|01\rangle \pm |10\rangle\right)\left(\sqrt{\frac{\eta}{\eta'}}\,\langle 01| \pm \langle 10|\right) + O(\sqrt{\eta'})|11\rangle\langle 11|$$

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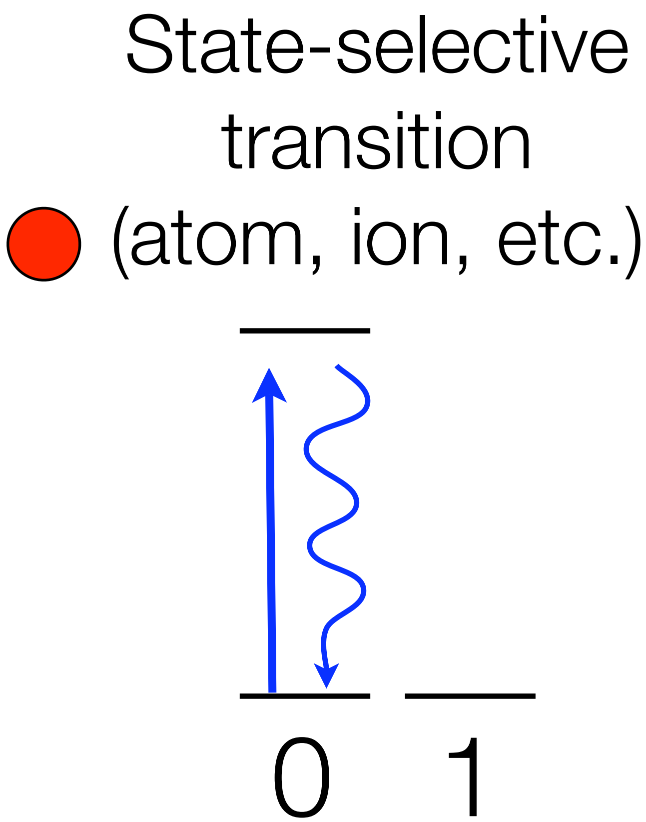

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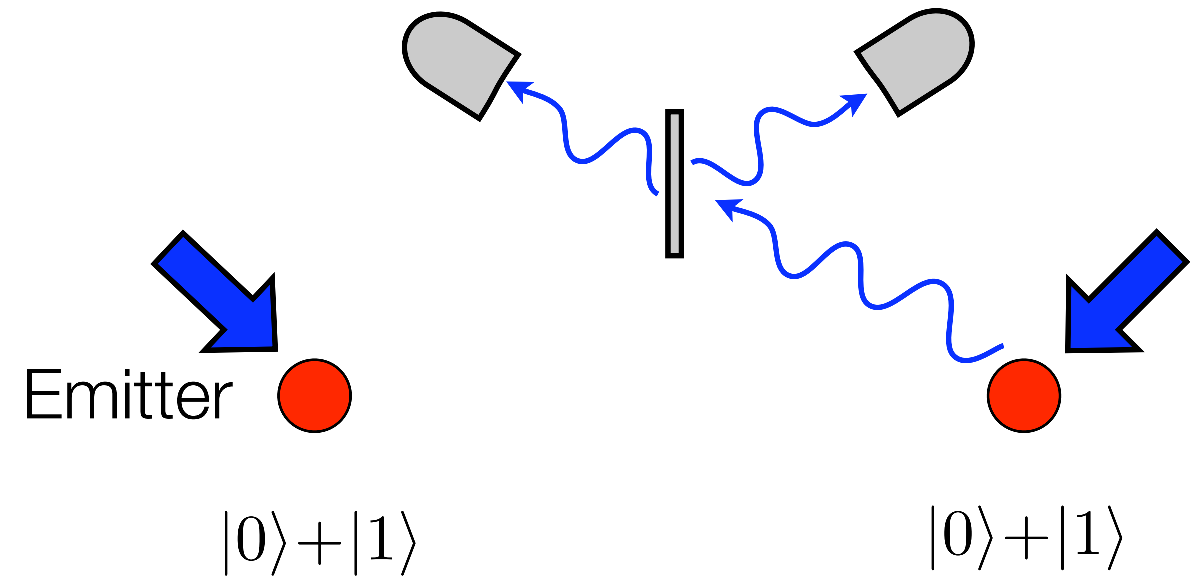

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Solution: flip bit, try again

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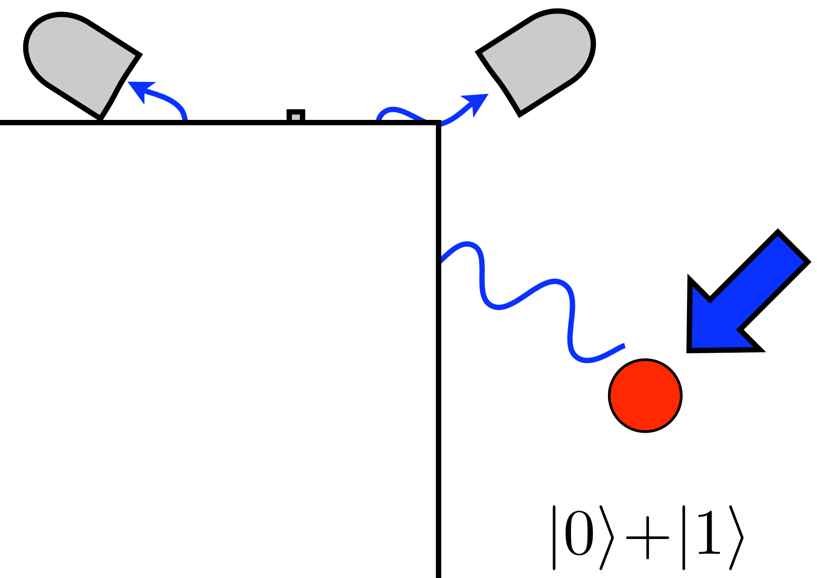

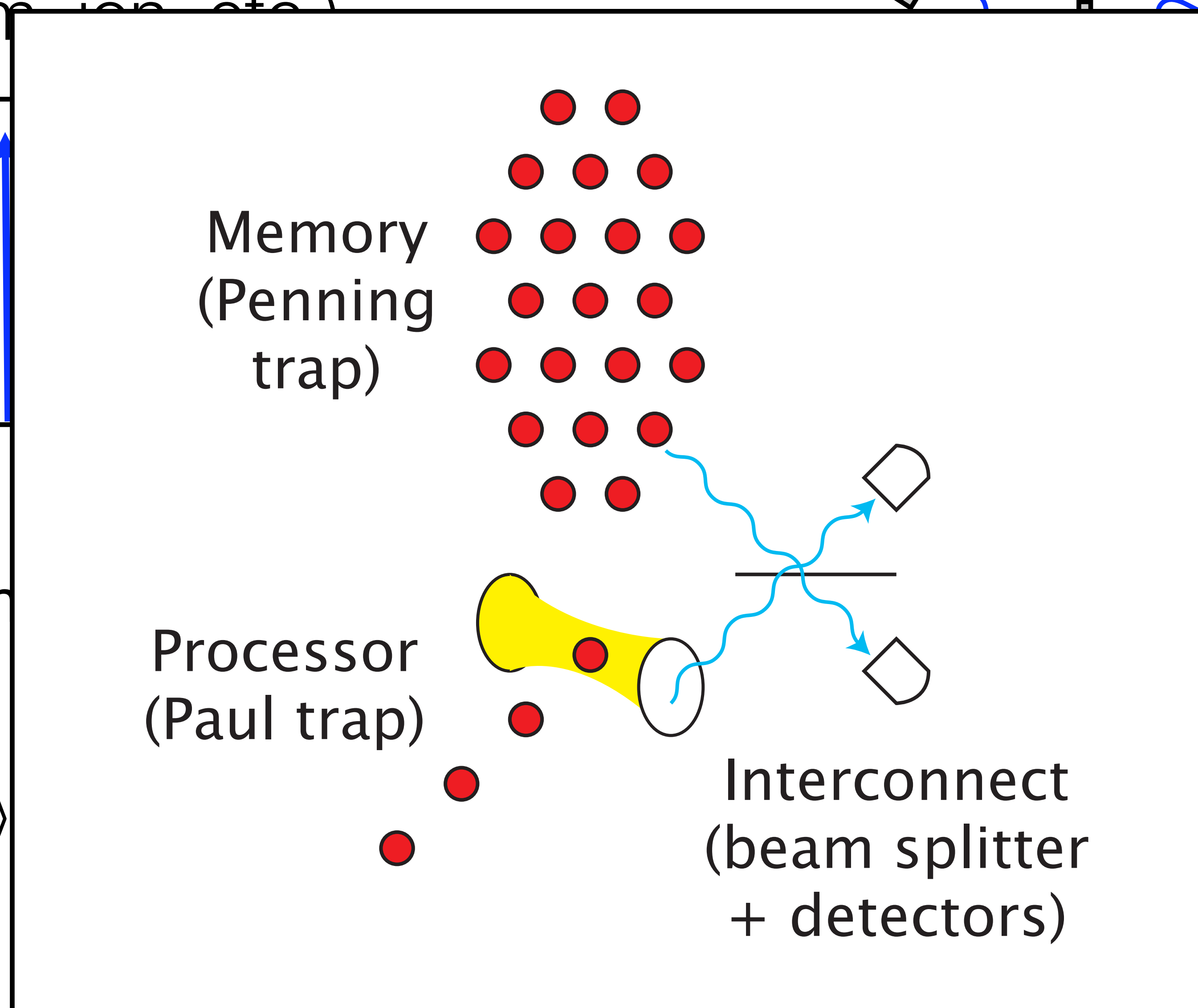

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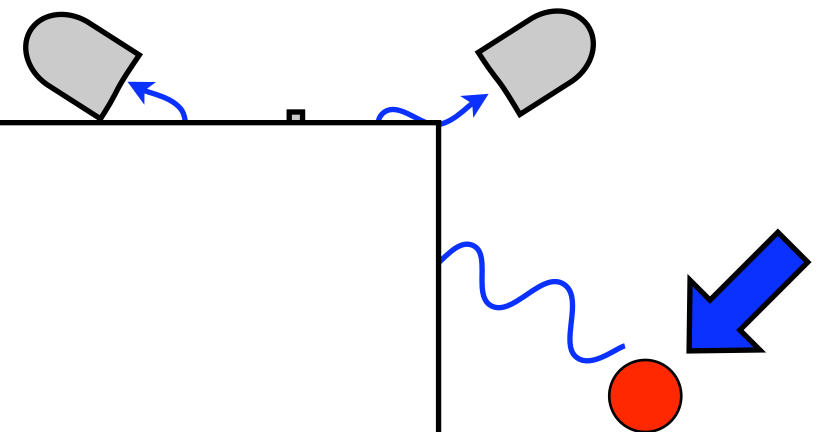
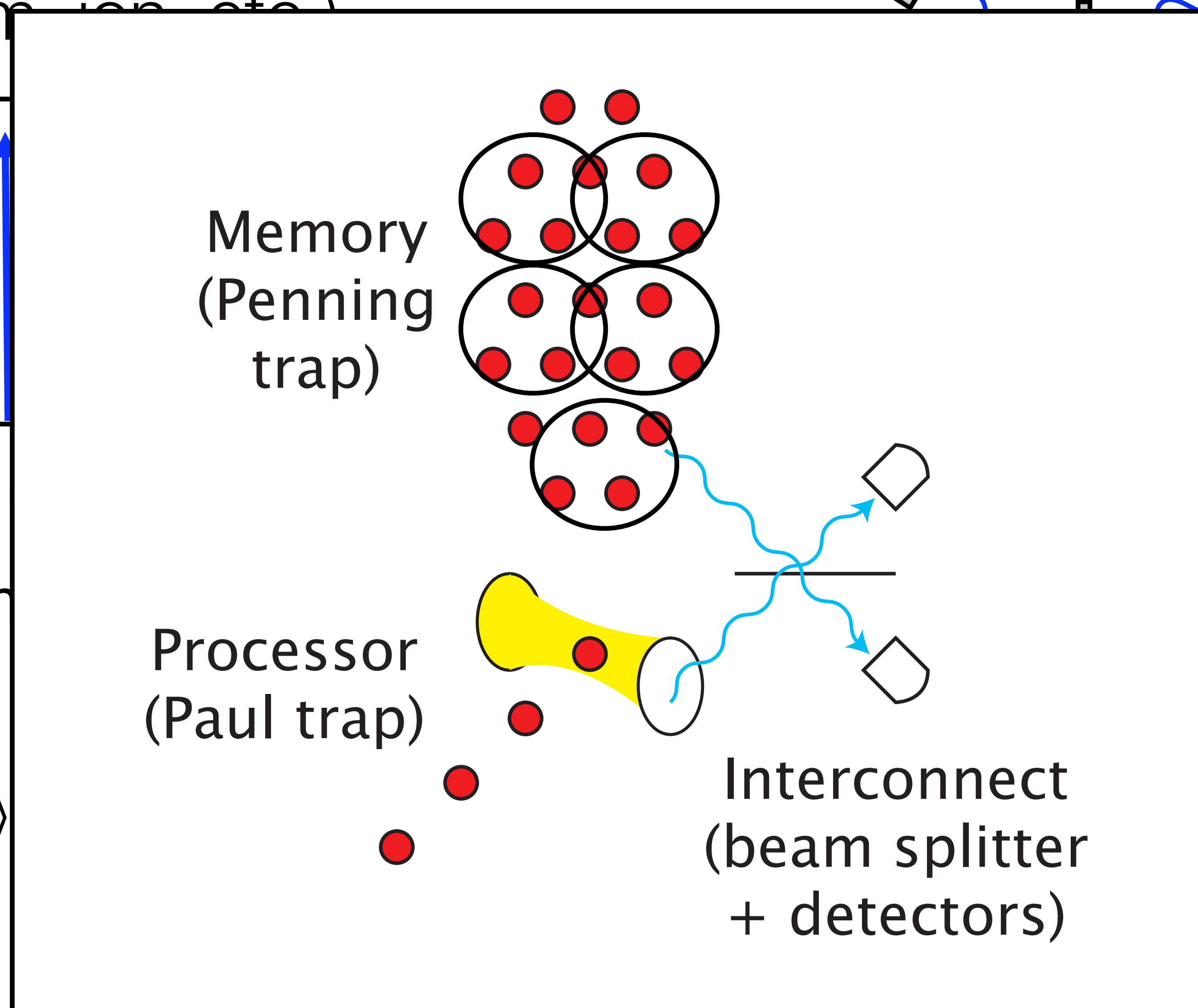
transition
(atom



$|0\rangle + |1\rangle$



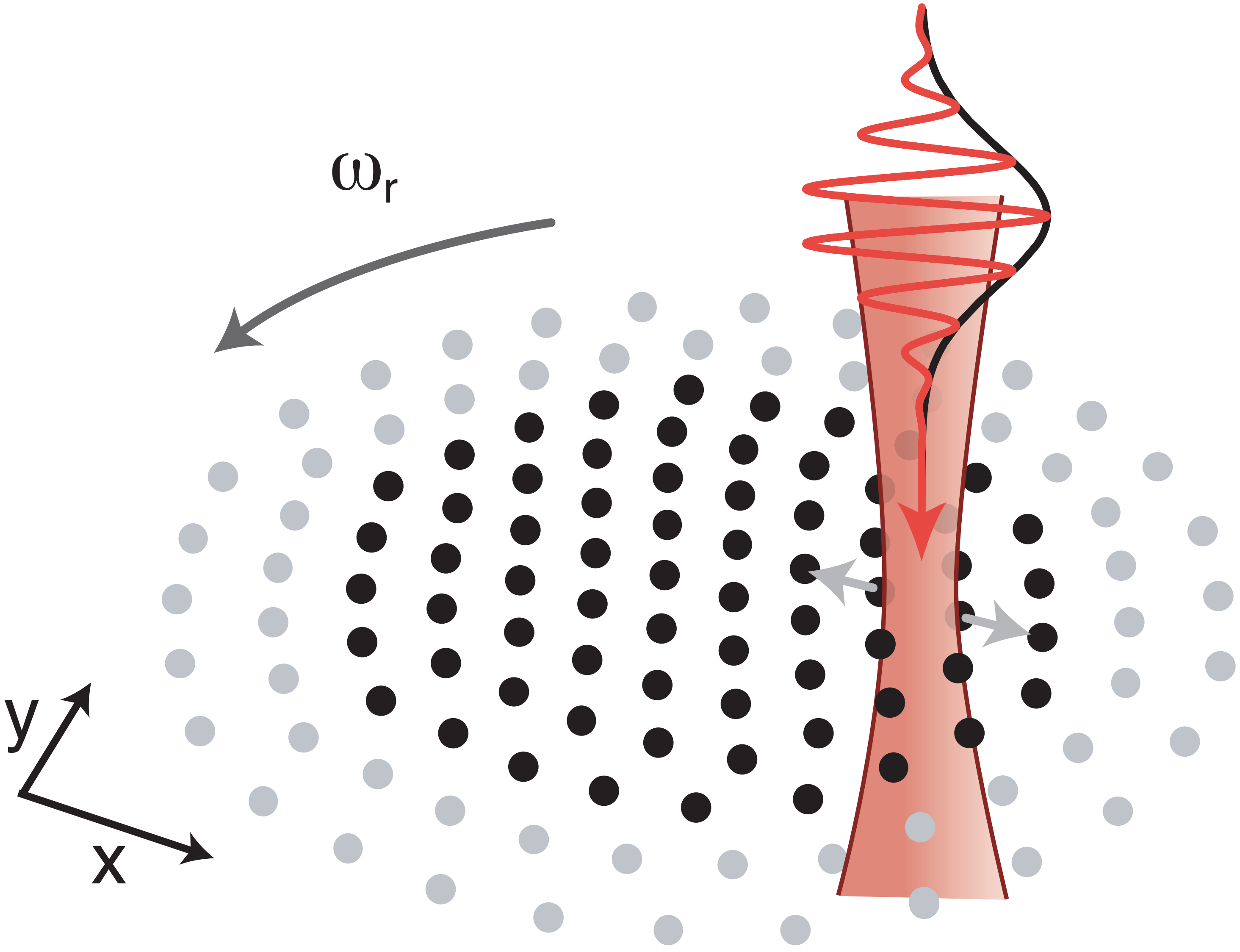
Entanglem

$\eta' \left(\sqrt{\frac{\eta}{\eta'}} \, |01\rangle \right.$ … $\left. \sqrt{\eta'} \right) |11\rangle\langle 11|$

Solution: flip bit, try again

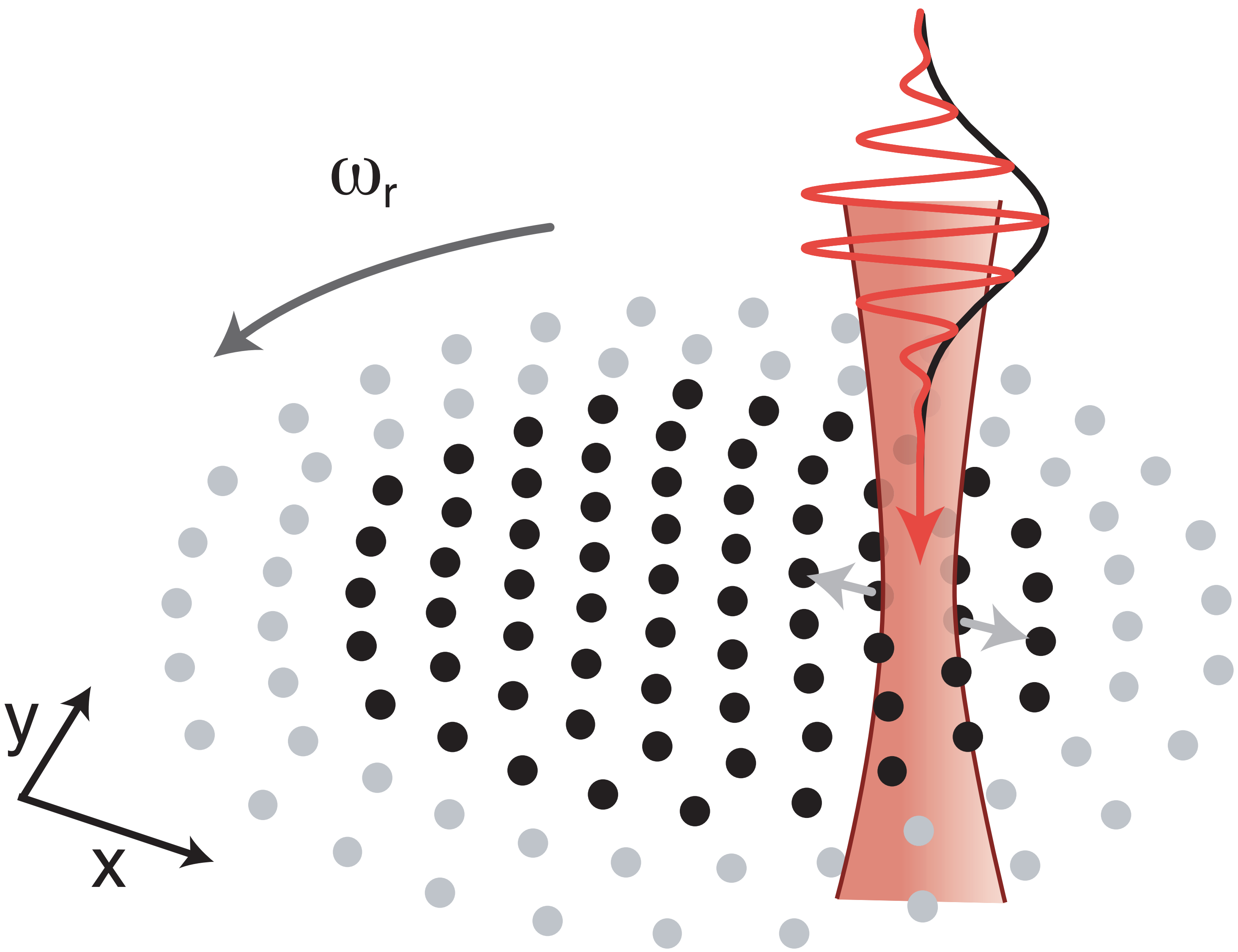
[Taylor & Calarco (0706.1951)]

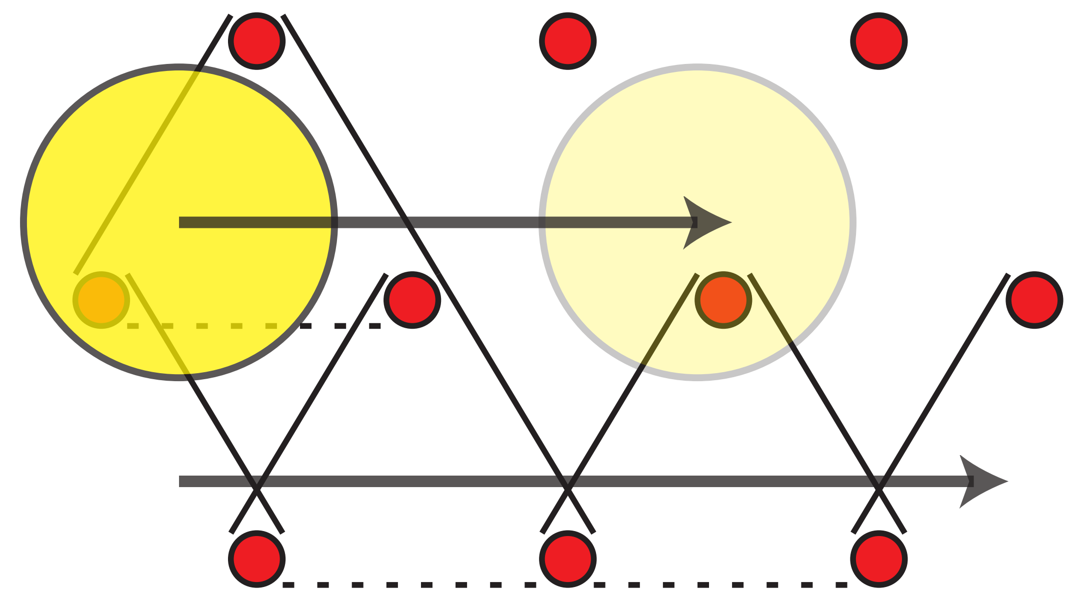
Outlook: cluster generation



[Taylor & Calarco (0706.1951)]

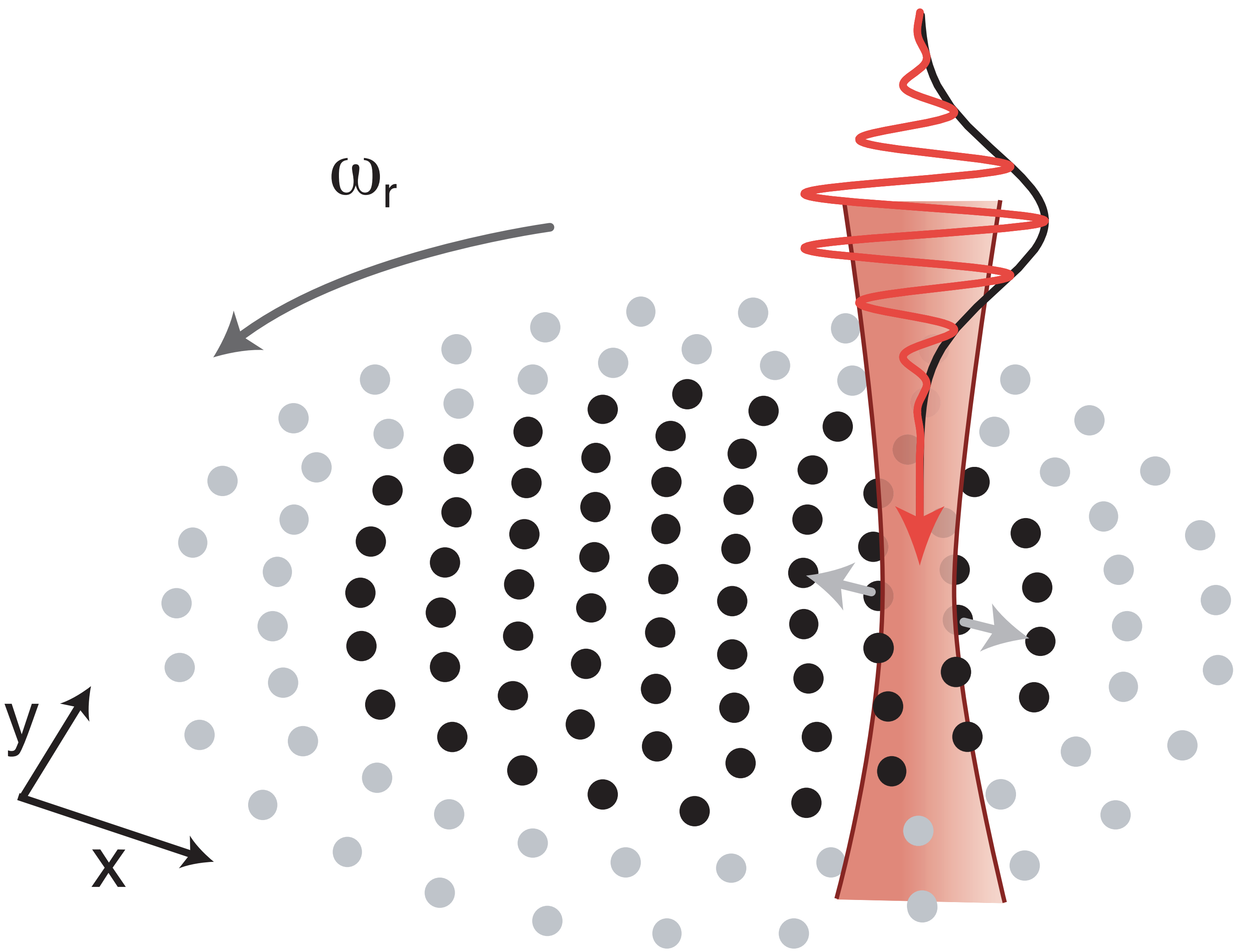
Outlook: cluster generation

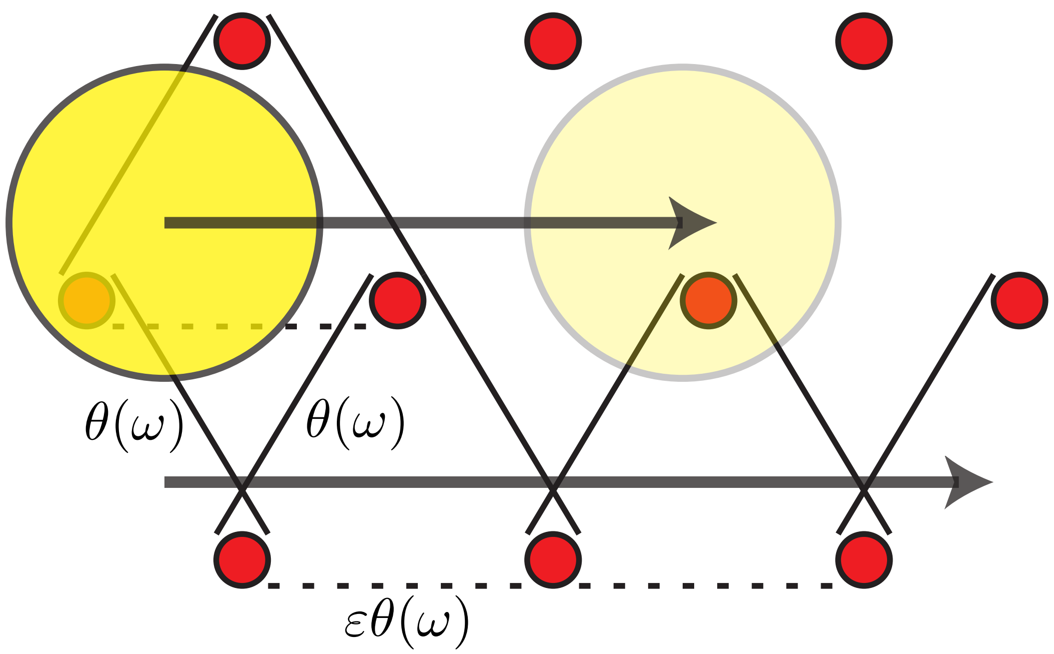




[Taylor & Calarco (0706.1951)]

Outlook: cluster generation

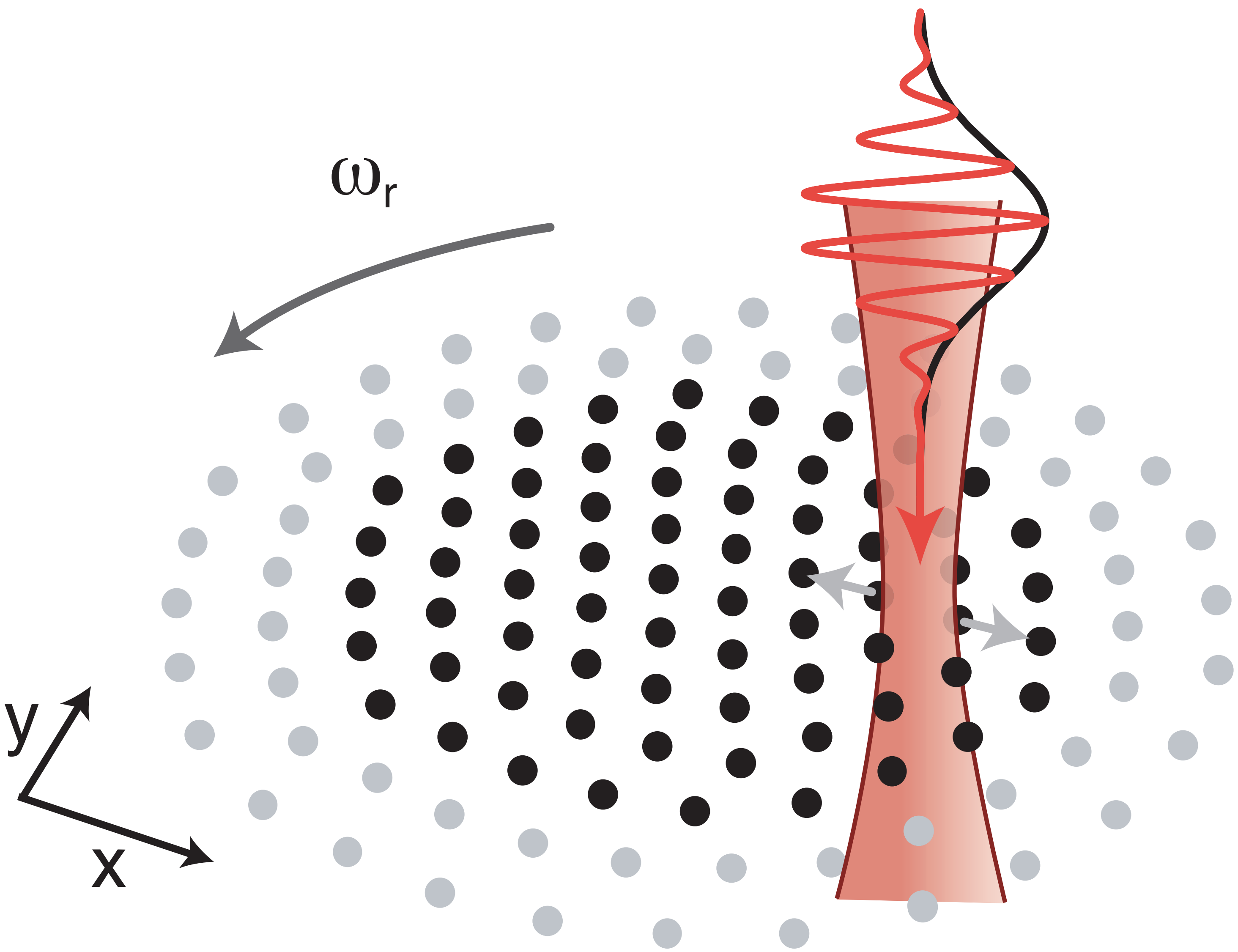


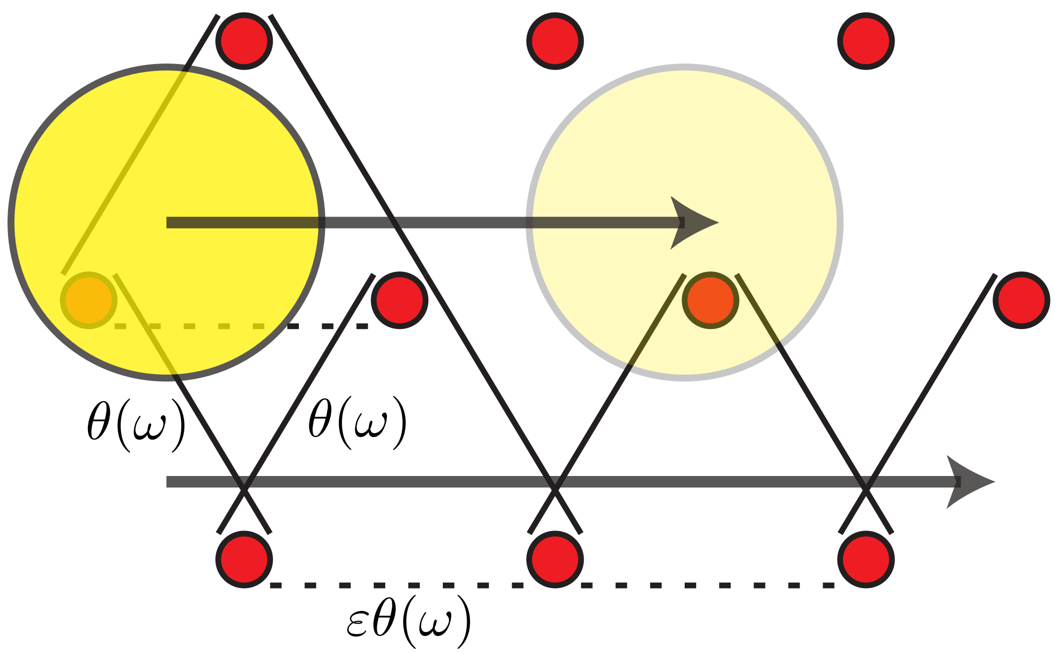


Idea: set spot size, sweep rate for links (—) vs (--)

[Taylor & Calarco (0706.1951)]

Outlook: cluster generation





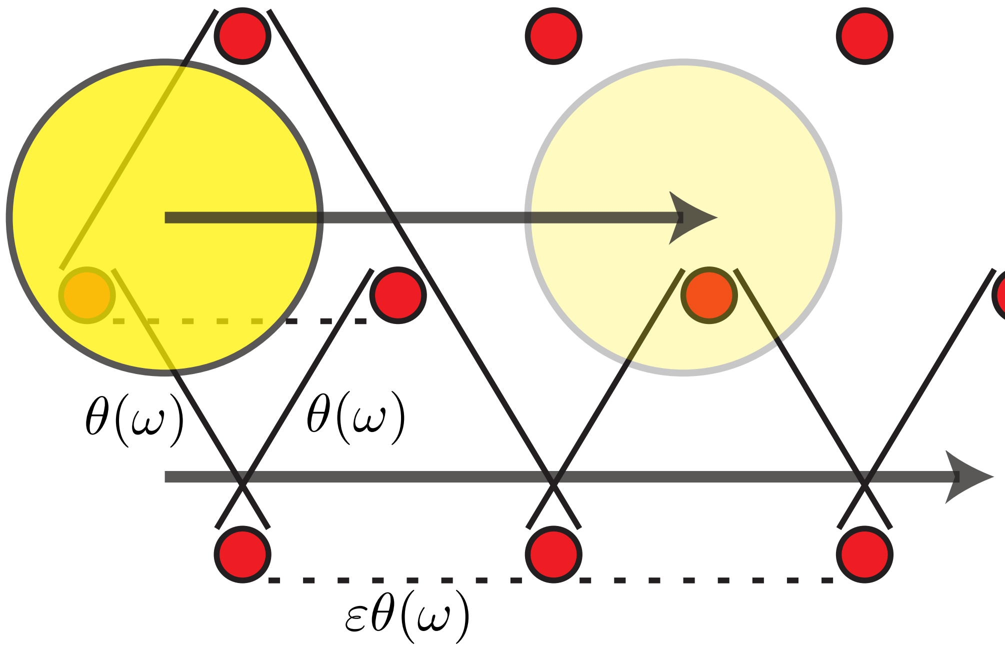
Idea: set spot size, sweep rate for links (—) vs (--)

Single laser can generate cluster in O(n) time

[Taylor & Calarco (0706.1951)]

Outlook: cluster generation

Idea: set spot size, sweep rate for links (—) vs (--)



$$\theta(\omega) = \frac{\Omega_0^4}{\omega^2\Delta^2}\frac{\alpha^4}{\rho^4}\frac{q^2}{\hbar\epsilon_0 v}\frac{e^{-1/(2\sigma^2)}}{\sqrt{8\pi}\sigma}\left(\frac{1}{\sigma^2}+\frac{1}{8}\right)$$

$$\varepsilon = e^{-3/(8\sigma^2)}(11-8\sigma^2)/(\sigma^2+8)$$

[Taylor & Calarco (0706.1951)]

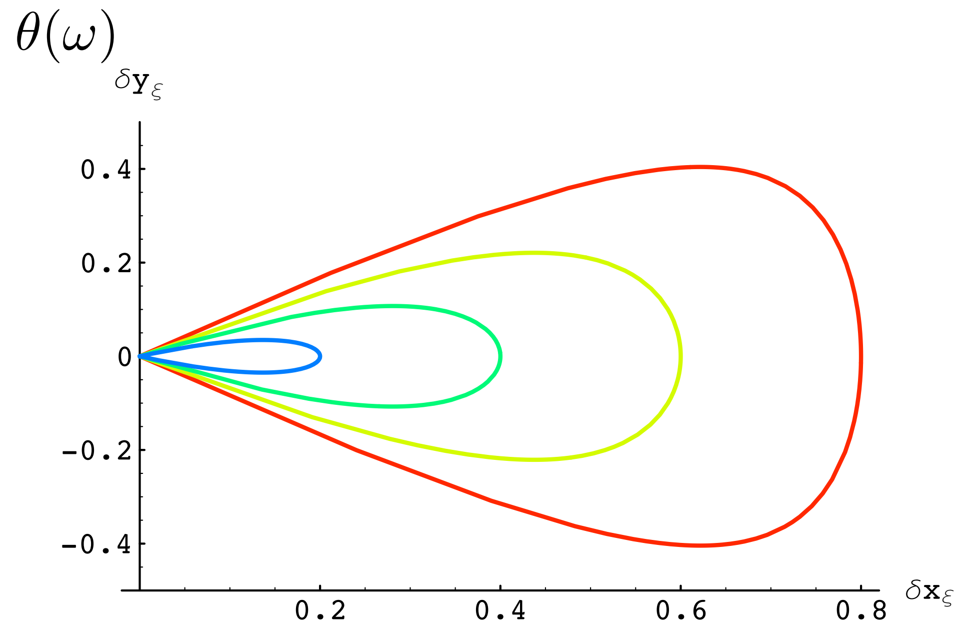
Outlook: cluster generation

Idea: set spot size, sweep rate for links (—) vs (--)

$$\theta(\omega) = \frac{\Omega_0^4}{\omega^2\Delta^2}\frac{\alpha^4}{\rho^4}\frac{q^2}{\hbar\epsilon_0 v} \ldots$$

$$\varepsilon = e^{-3/(8\sigma^2)}(11 - 8\sigma^2)/(\sigma^2 + 3)$$

Crystal rotation?
use time-dependent displacement



[Taylor & Calarco (0706.1951)]

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
- Other aspects:
  - Wigner crystals of ions as a quantum “hard drive”? (Many qubits per device)

Collaborators

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