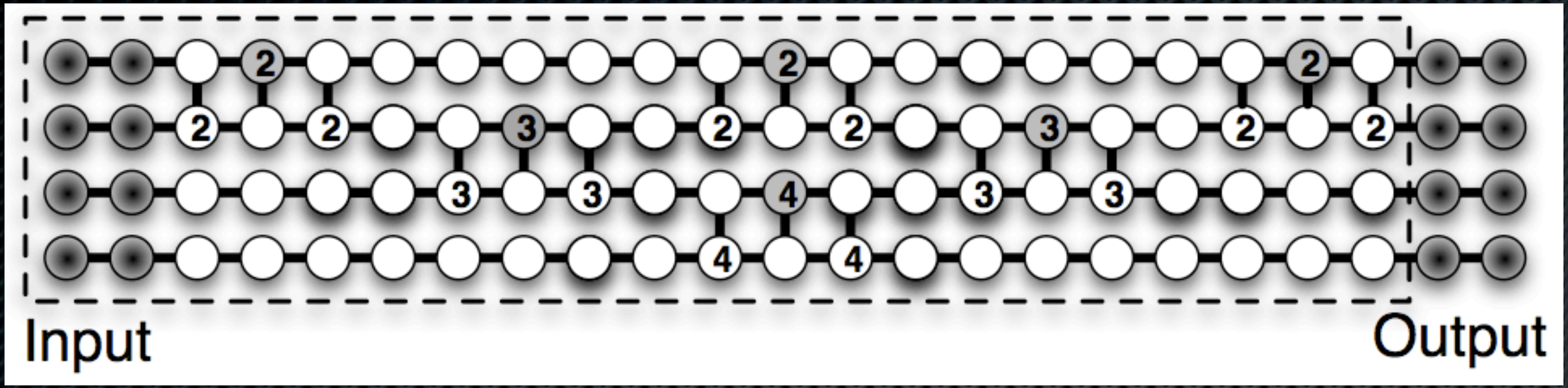

Adiabatic Quantum Transistors

Dave Bacon, Gregory Crosswhite

University of Washington

&

Steve Flammia

Perimeter Institute

Workshop on Quantum Algorithms, Computational Models and Foundations of Quantum Mechanics

UBC, Vancouver, 23 July 2010

A zoo of quantum computational models

Measurement-based

Topological

Circuit model

Holonomic

Adiabatic

A zoo of quantum computational models

Which one (if any!) will lead to an actual quantum computer?

easurement-based

This talk: try to combine aspects of all of these models to devise a new architecture for quantum computing

Adiabatic

A review of the zoo

- Adiabatic evolution offers robustness to timing and control errors that exist in the circuit model
- Errors are suppressed by the spectral gap
- It is unknown if it is fault tolerant (without additional assumptions) and lack of modularity makes it difficult to analyze theoretically

Adiabatic

A review of the zoo

- Holonomic QC is also **robust** to timing errors, and some (fewer) types of control errors
- Can be made **fault tolerant** Oreshkov Brun Lidar, PRL 2009

- Typically requires simultaneous control of **multiple parameters** to achieve non-trivial geometric phases

Holonomic

A review of the zoo

Topological

- Topological quantum phases are insensitive to local perturbations

  Bravyi Hastings Michalakis 2010

- Naturally long-lived quantum memory

- Sensitive to finite temperature, and still requires active error correction. Also, initialization is difficult.

A review of the zoo

Measurement-based

Topological

- Very minimal requirements: only local measurements, which every scheme uses anyway
- Simple initial states (relatively speaking) can be used as the entangled resources.

Holonomic

- There is absolutely nothing disadvantageous about measurement-based QC

A review of the zoo

- Circuit model provides the most natural language for programming quantum computers and designing quantum algorithms

Circuit model

- Direct implementation involves pulsed gates and a huge amount of control... very challenging, to say the least.

Adiabatic teleportation

single qubit

Bell pair

$|\psi\rangle$ $|\Phi\rangle$

This is a ground state of $H_i = -X_2 X_3 - Z_2 Z_3$

(could also use the exchange interaction)

Bacon STF, PRL 2009

Related: Oreshkov Brun Lidar, PRL 2009; Oreshkov, PRL 2009

Adiabatic teleportation

$|\Phi\rangle$ $|\psi\rangle$

This is a ground state of $H_f = -X_1 X_2 - Z_1 Z_2$

Adiabatic teleportation

$|\psi\rangle$

$$H(t) = (1-t)H_i + tH_f$$

Adiabatic teleportation

$$H(t) = (1-t)H_i + tH_f$$

Adiabatic teleportation

$$H(t) = (1-t)H_i + tH_f$$

$$\mathcal{T}\exp\left(-i\int_0^T \mathrm{d}\tau H(\tau)\right)$$

Adiabatic teleportation

$$H(t) = (1 - t)H_i + tH_f$$

Adiabatic teleportation

$$H(t) = (1-t)H_i + tH_f$$

Notice that the ground space is stabilized by XXX and ZZZ for all t.

Adiabatic teleportation

$$|\psi\rangle$$

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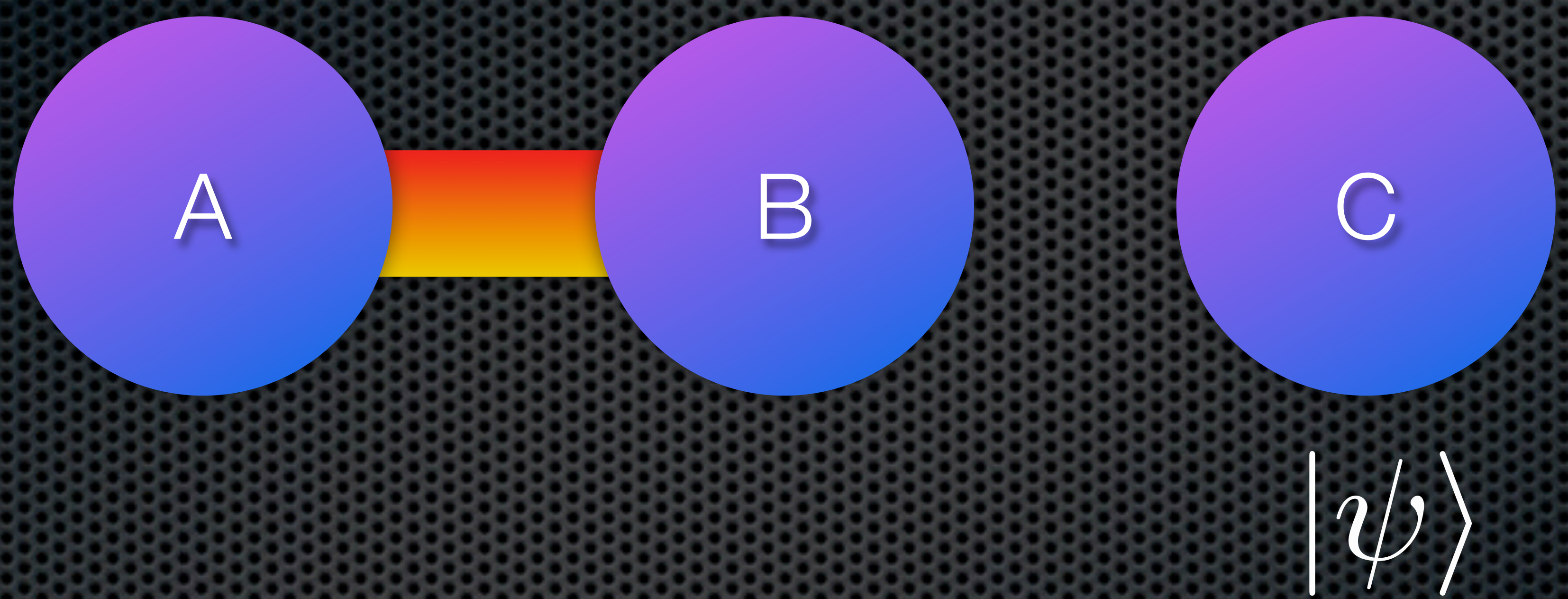
Notice that the ground space is stabilized by XXX and ZZZ for all t.

Adiabatic teleportation



The adiabatic evolution acts like a post-selected teleportation!

Notice that the ground space is stabilized by XXX and ZZZ for all t.

Adiabatic *gate* teleportation

$|\psi\rangle$

$$U_3 H(t) U_3^\dagger = (1-t) U_3 H_i U_3^\dagger + t H_f$$

Gottesman Chuang 1999

Adiabatic *gate* teleportation

$$U_3 H(t) U_3^\dagger = (1-t) U_3 H_i U_3^\dagger + t H_f$$

Gottesman Chuang 1999

Adiabatic *gate* teleportation

$$U_3|\psi\rangle$$

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Gottesman Chuang 1999

Adiabatic *gate* teleportation

$$U_3|\psi\rangle$$

$$U_3 H(t) U_3^\dagger = (1-t) U_3 H_i U_3^\dagger + t H_f$$

Now the adiabatic evolution *teleports* the unitary onto the qubit.

Gottesman Chuang 1999

Universality

$U_a|\psi\rangle$

Universality

$U_b U_a |\psi\rangle$

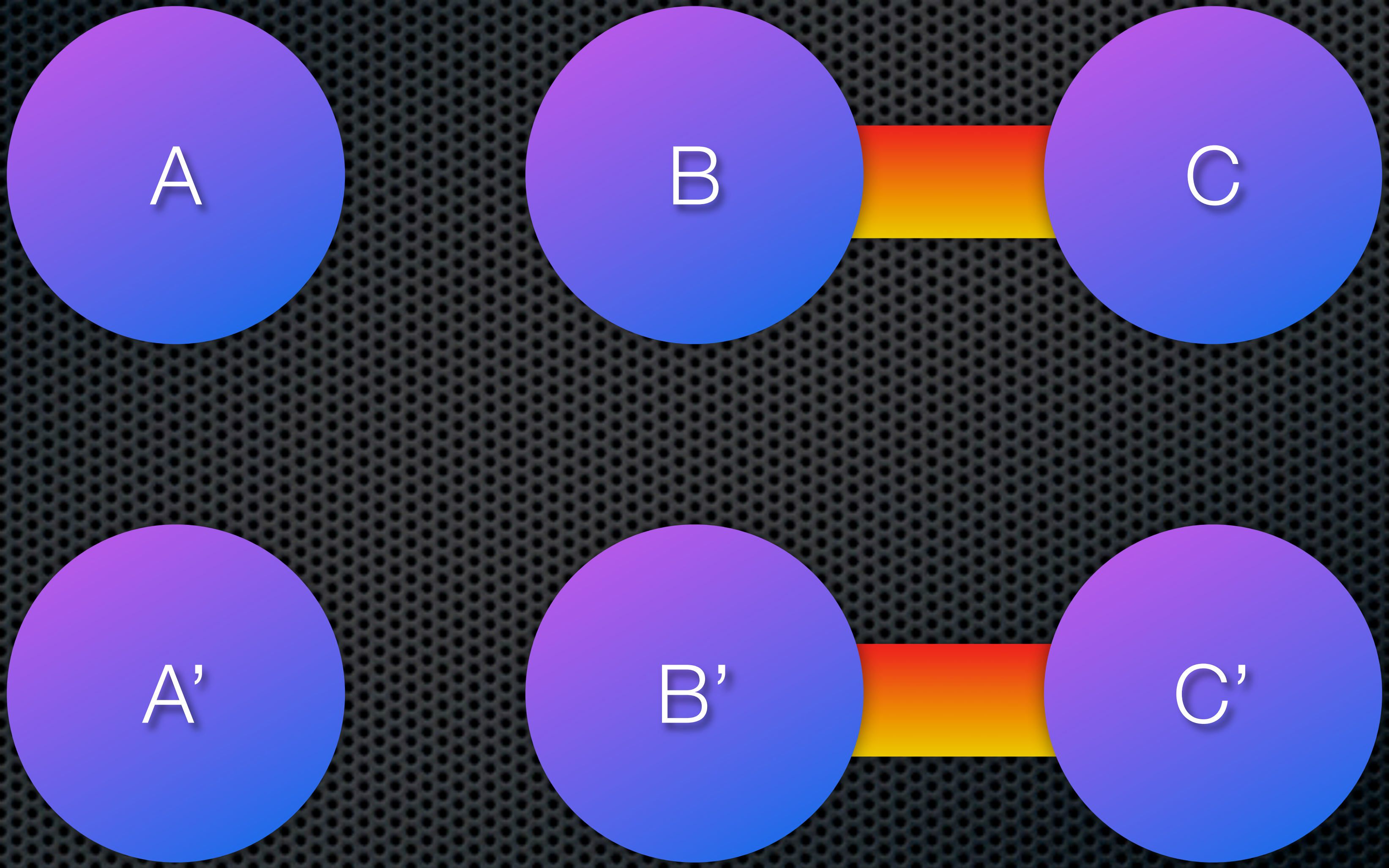
Universality

$$U_b U_a |\psi\rangle$$

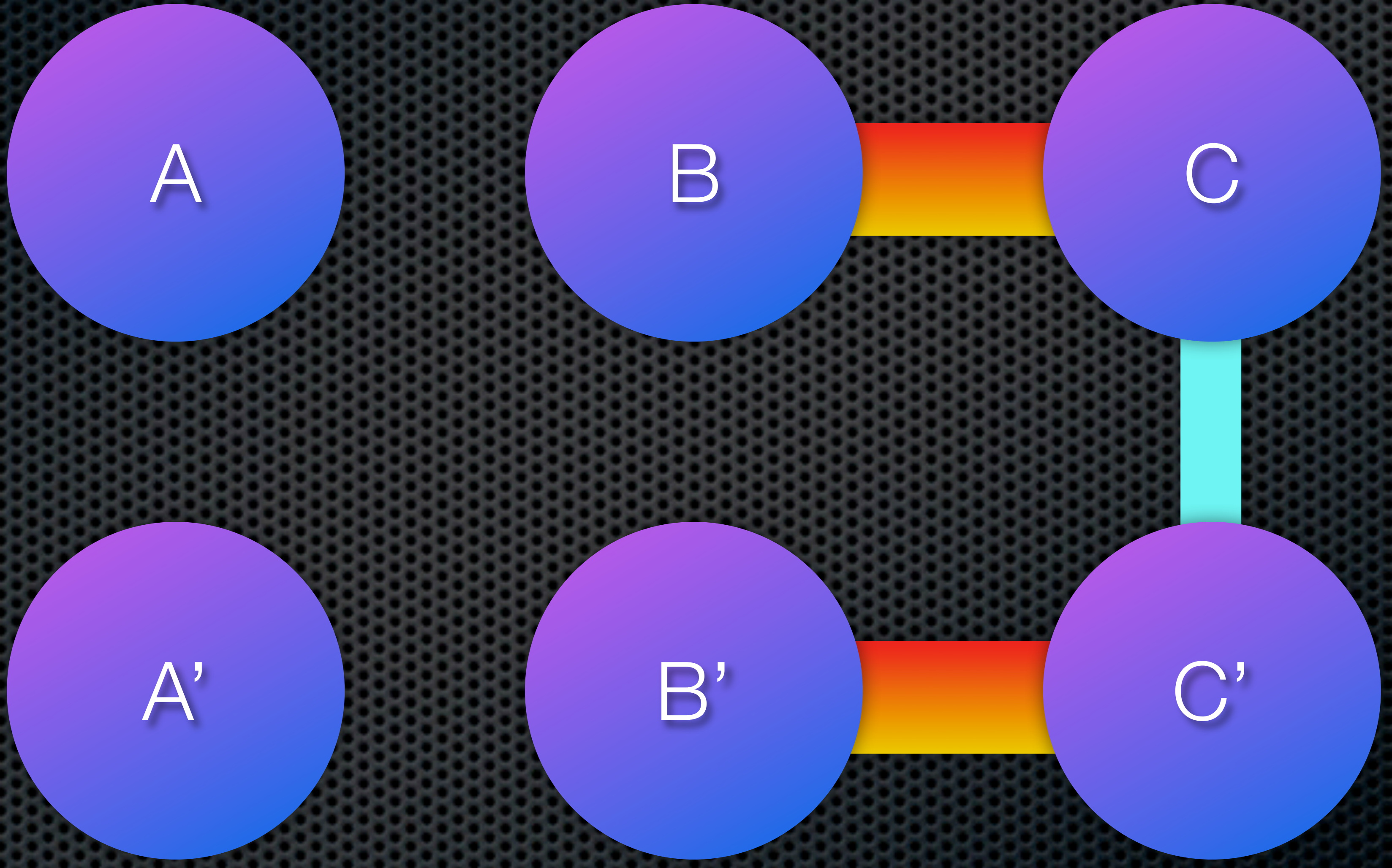
Etc...

but what about two qubit gates?

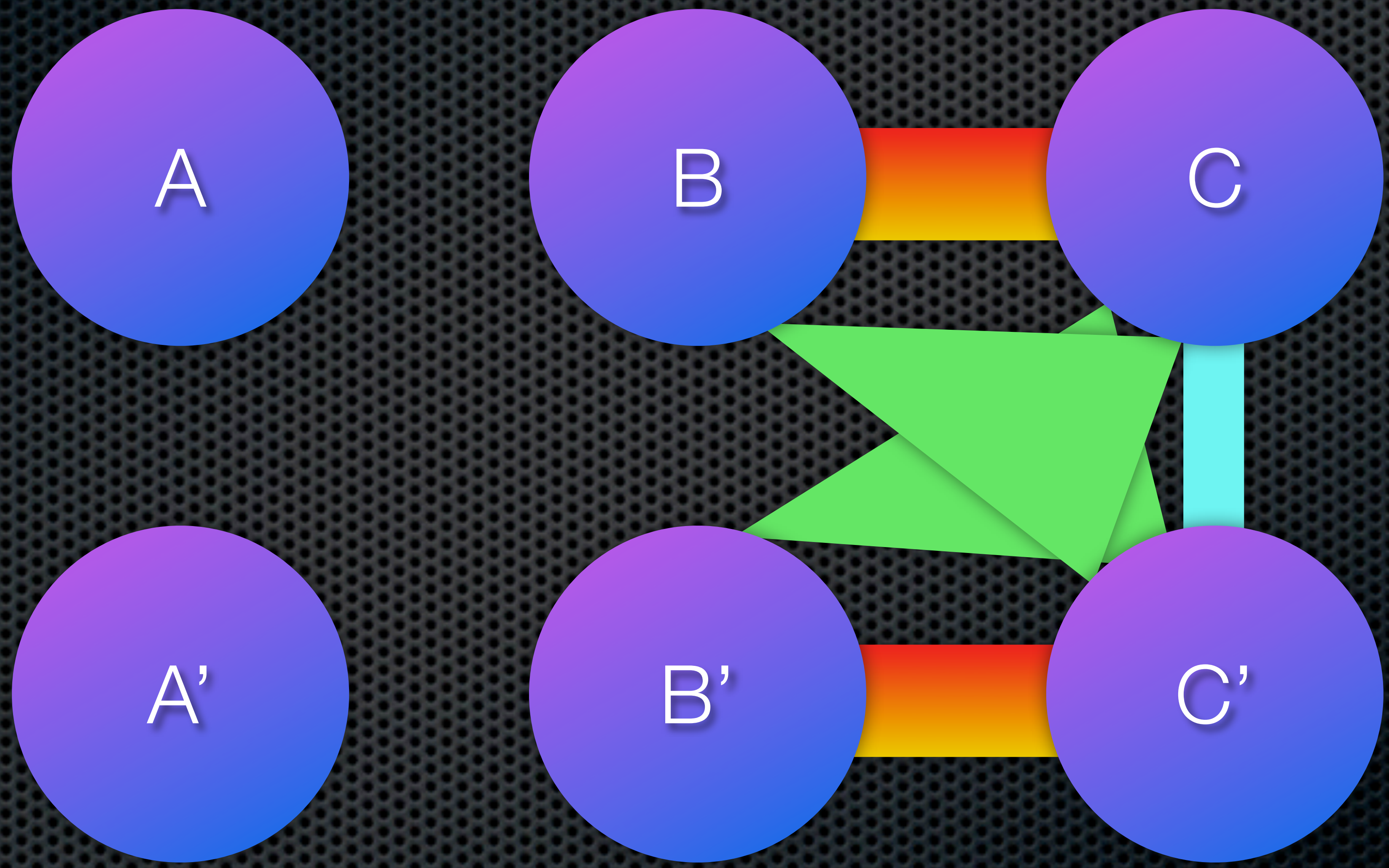
Universality



Universality

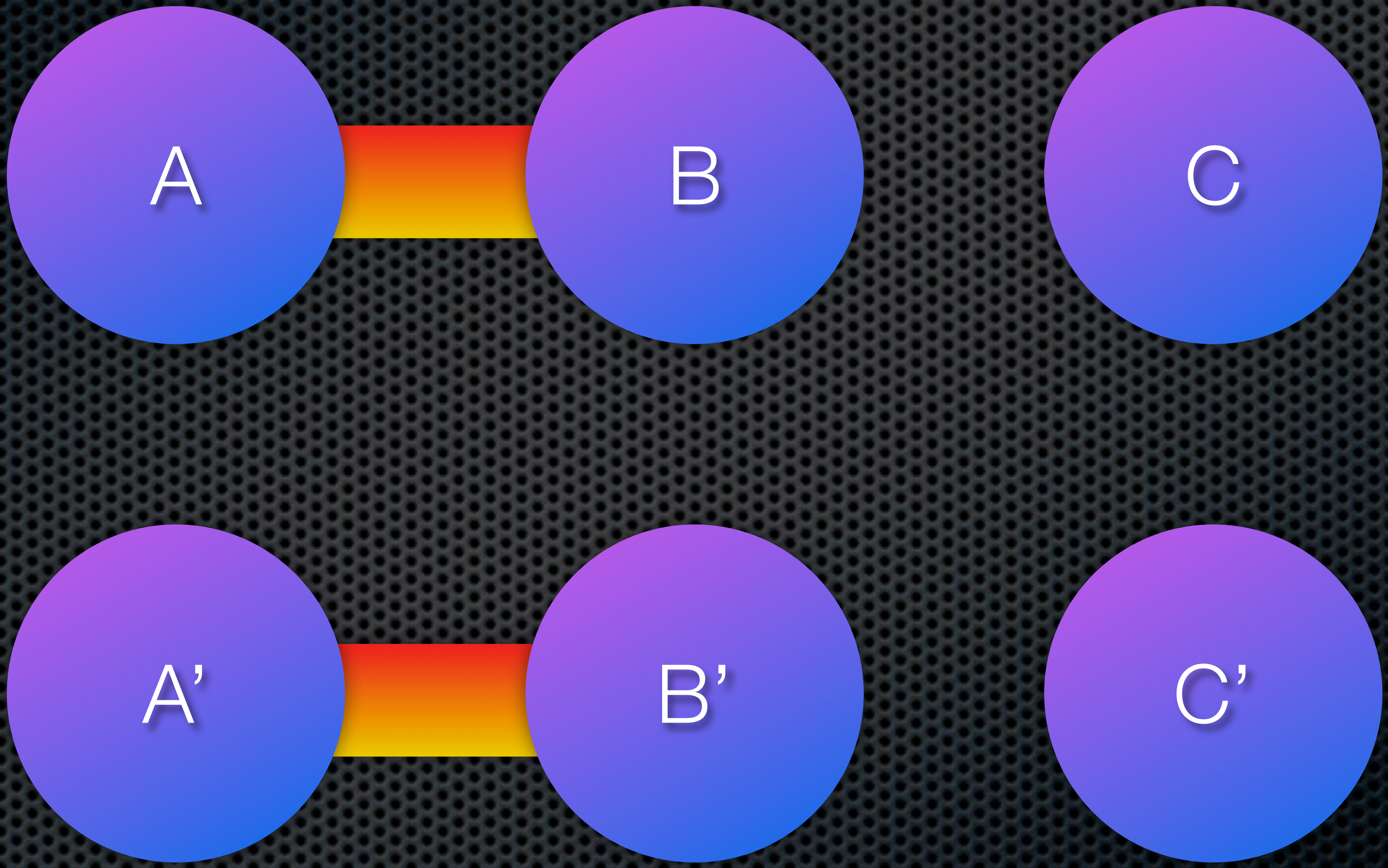


Universality



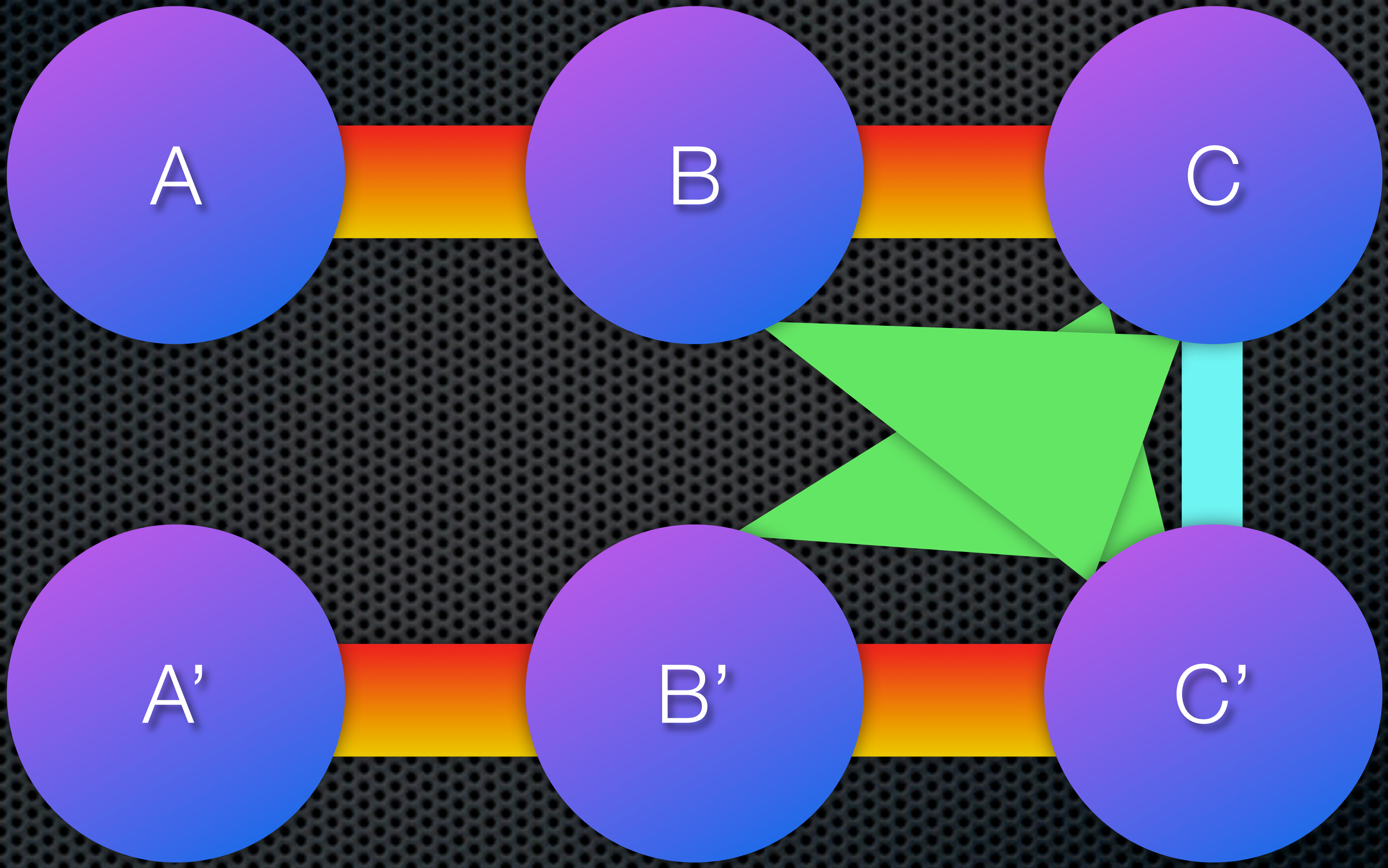
Two-qubit gates introduce 3-body terms...

Universality



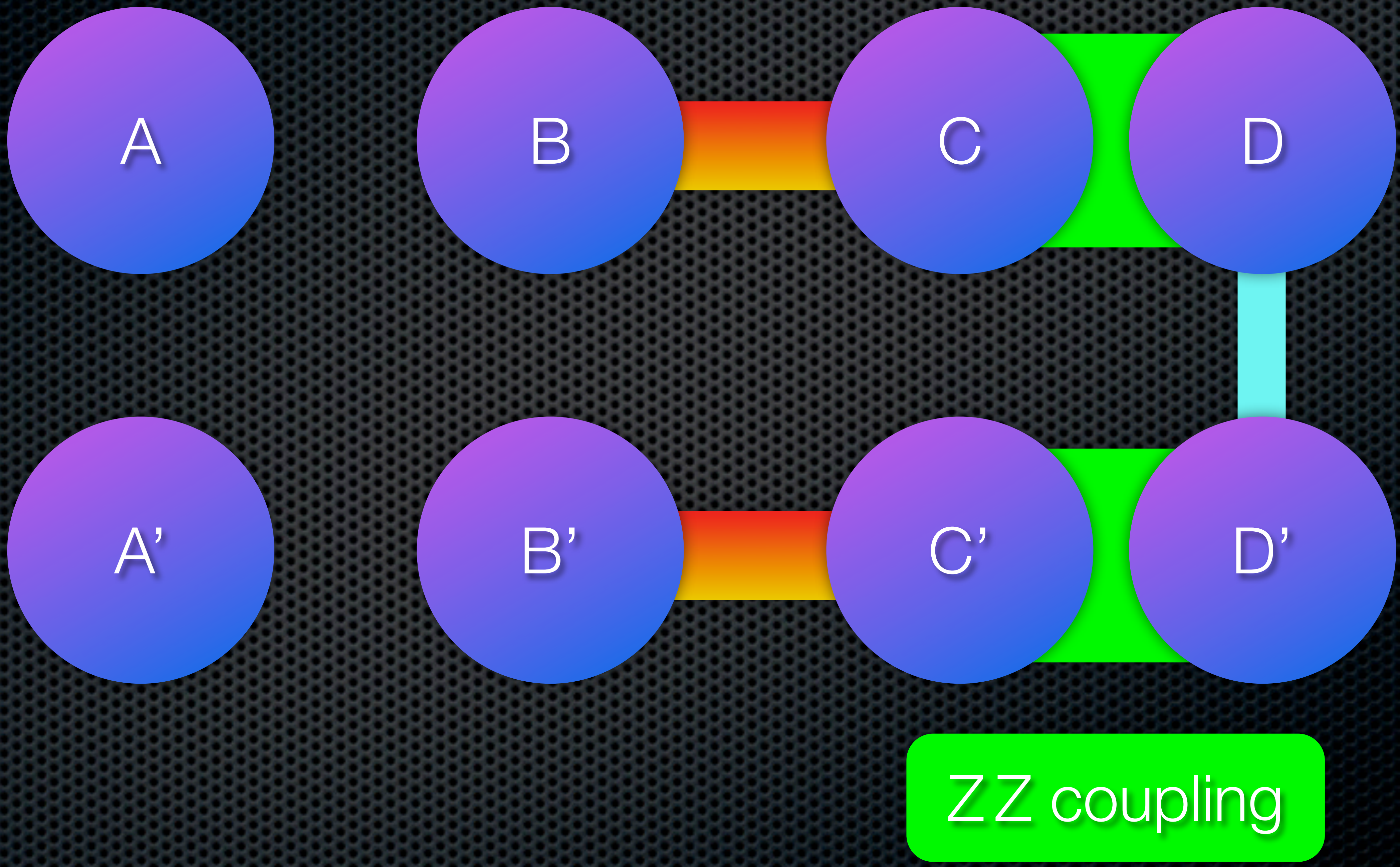
Two-qubit gates introduce 3-body terms...

Universality



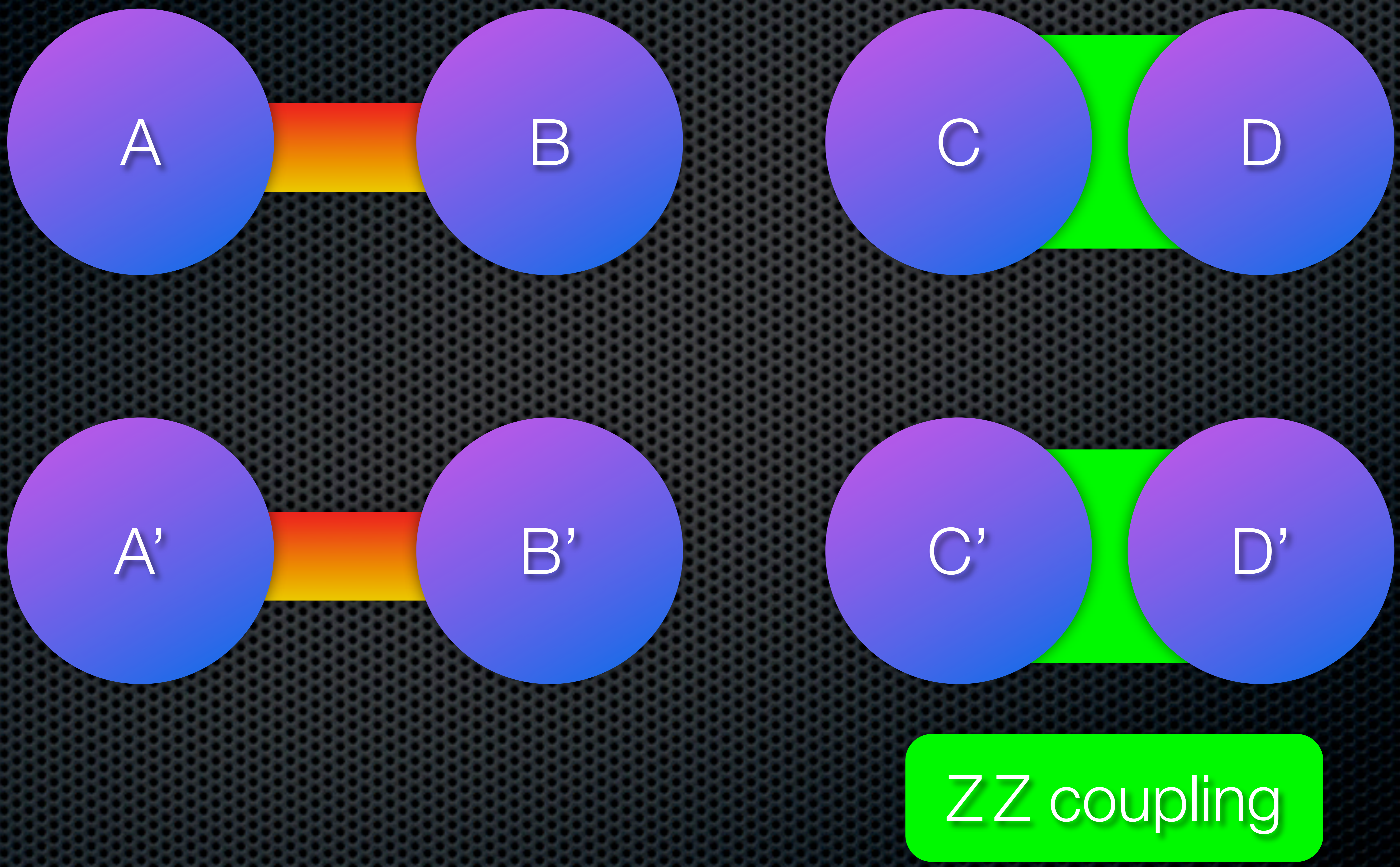
Two-qubit gates introduce 3-body terms...
to get rid of them, use perturbation gadgets.

Universal, 2-body



Our perturbation gadgets: Bartlett & Rudolph 2006

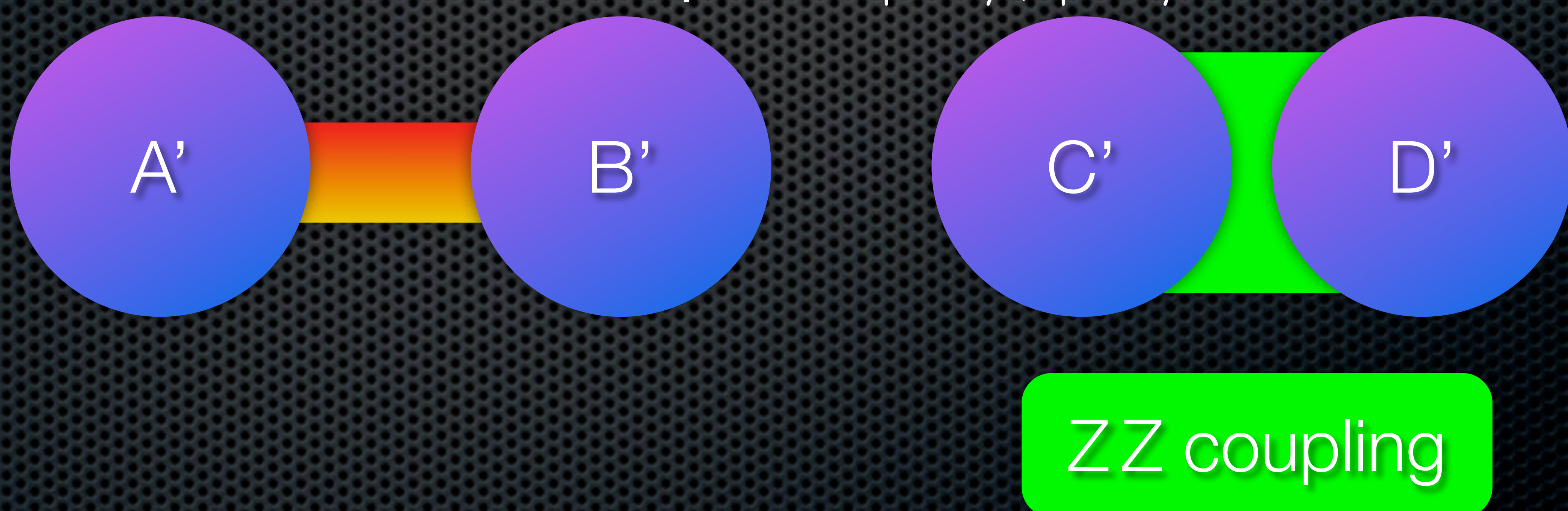
Universal, 2-body



Our perturbation gadgets: Bartlett & Rudolph 2006

Universal, 2-body

Qubit encoded in subspace $|00\rangle, |11\rangle$



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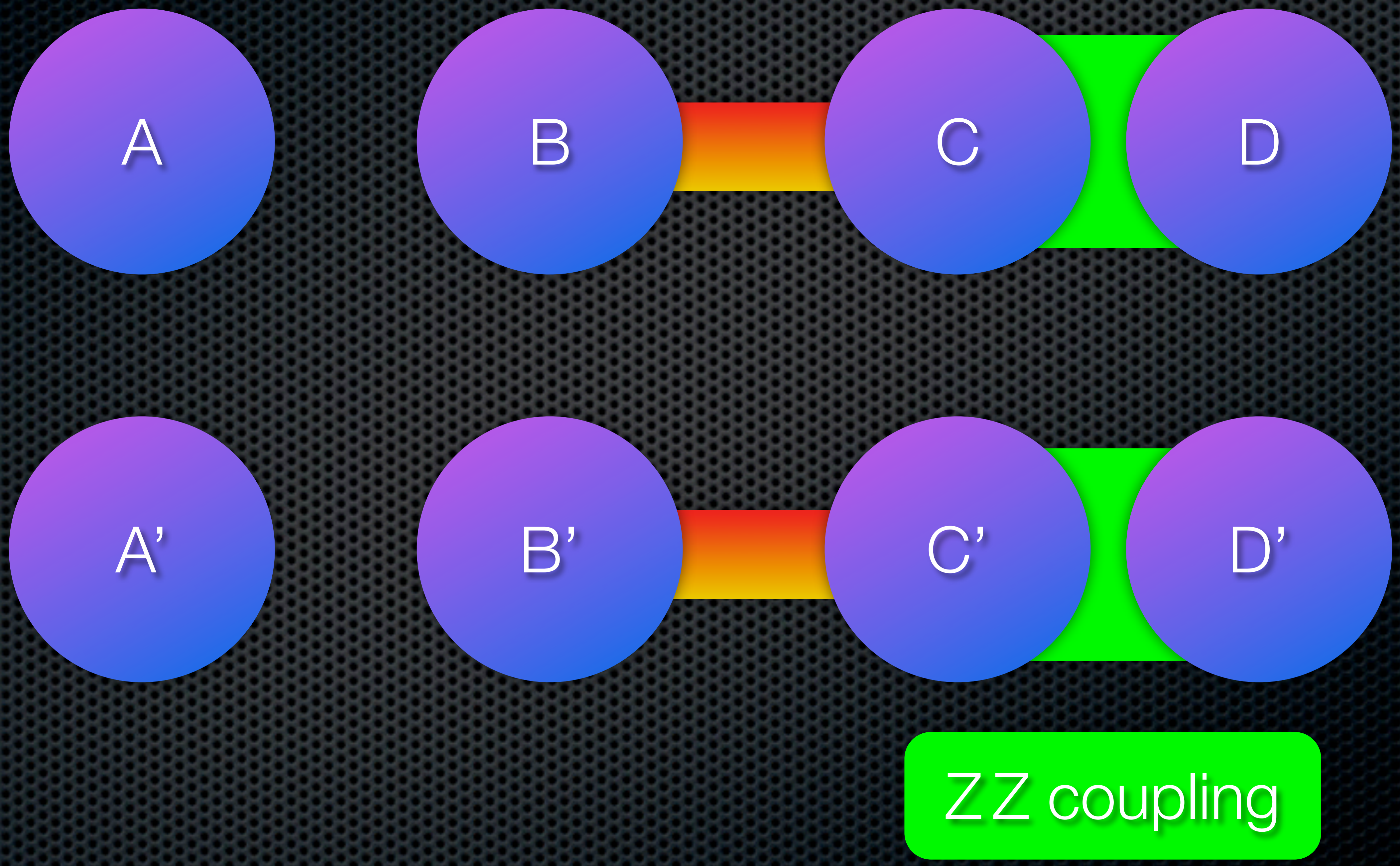

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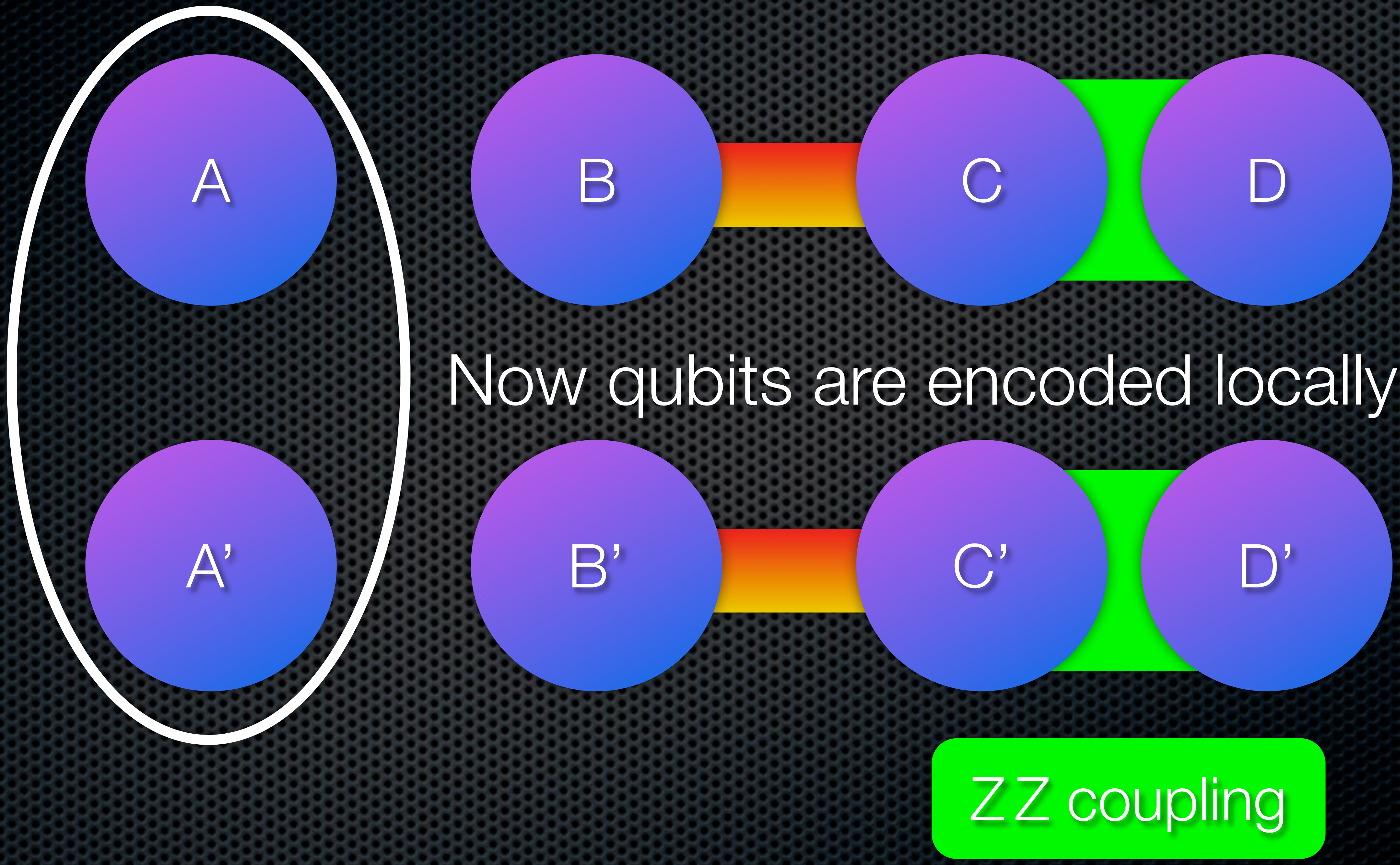

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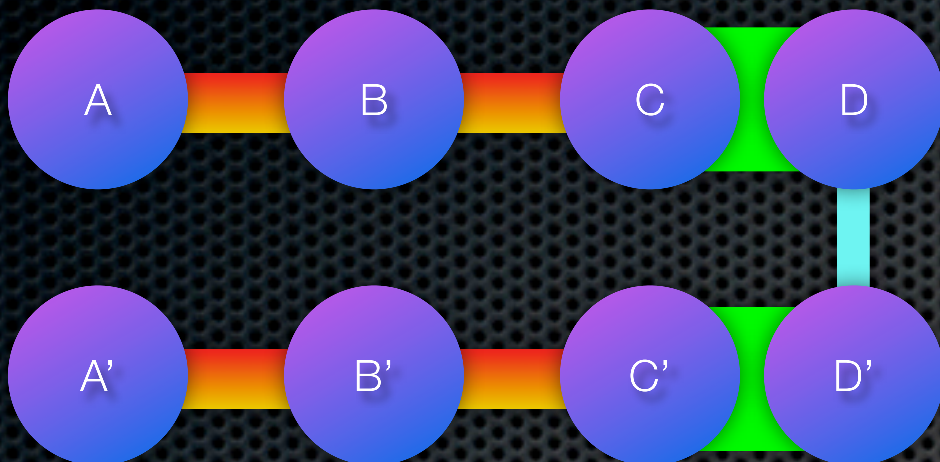
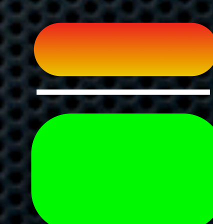


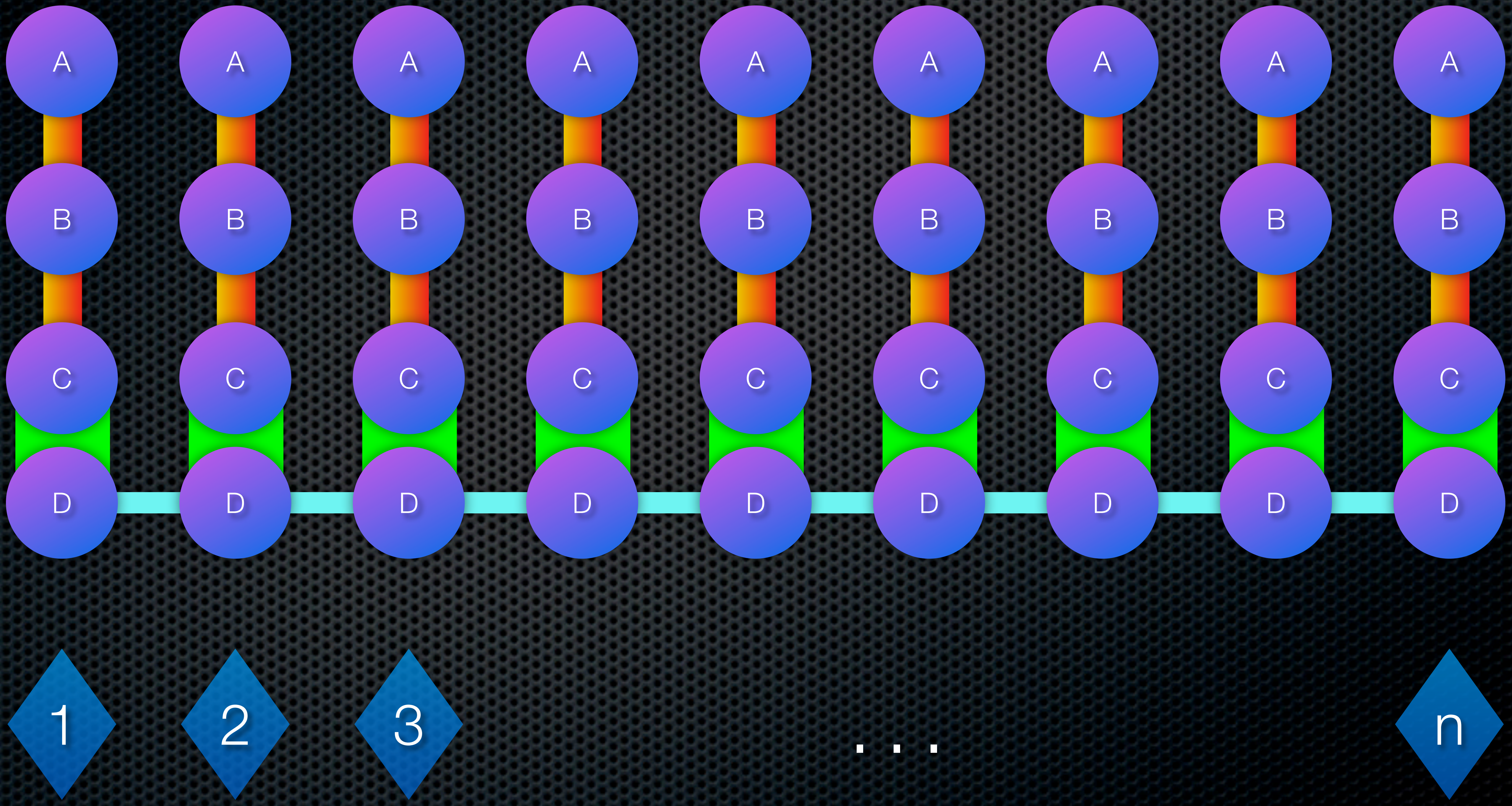
Gate fidelity $= 1 - \Theta(\lambda^2)$

Gap $= \Theta(\lambda)$

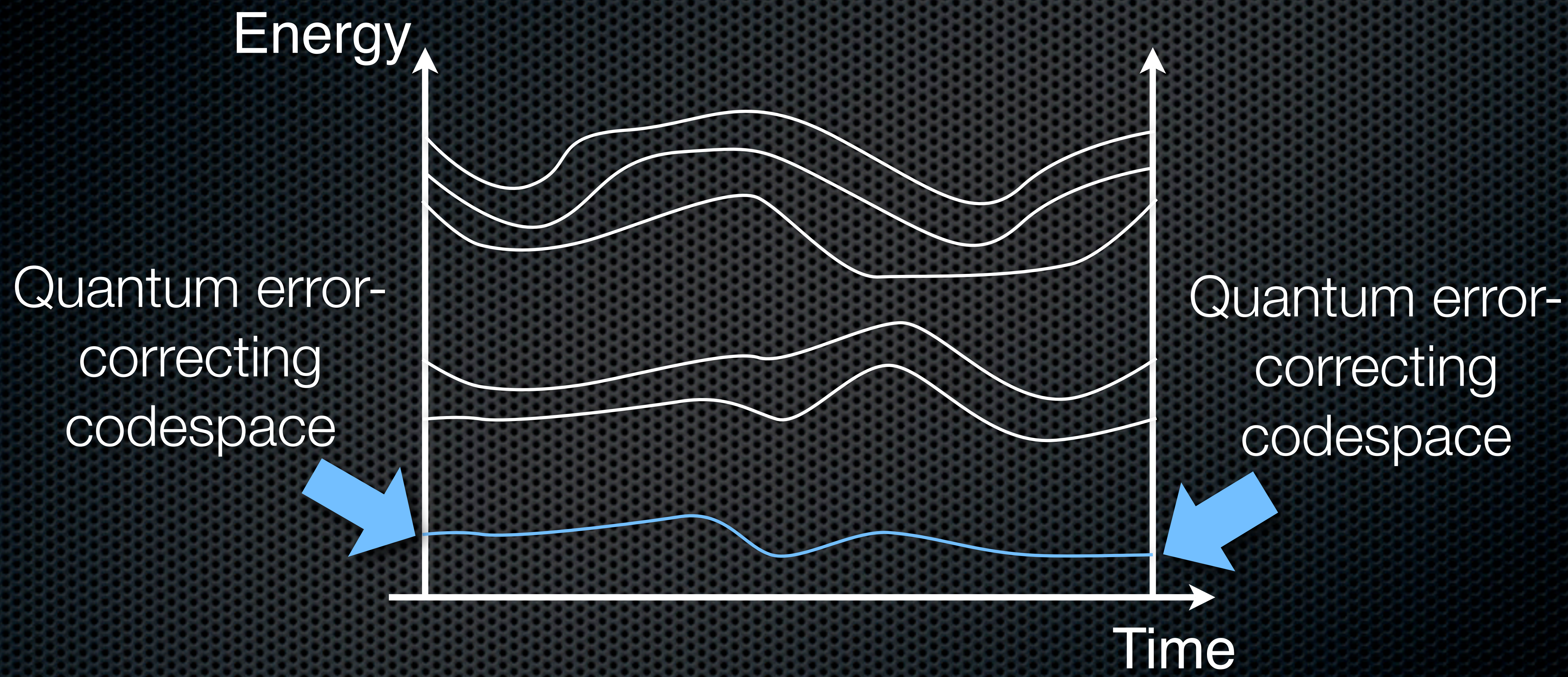
Ratio of energy scales $= \lambda =$ 

Our perturbation gadgets: Bartlett & Rudolph 2006

1-d architecture



Adiabatic Code Deformation



Must be degenerate throughout the entire evolution;
any splittings are errors that need to be coded for and corrected.

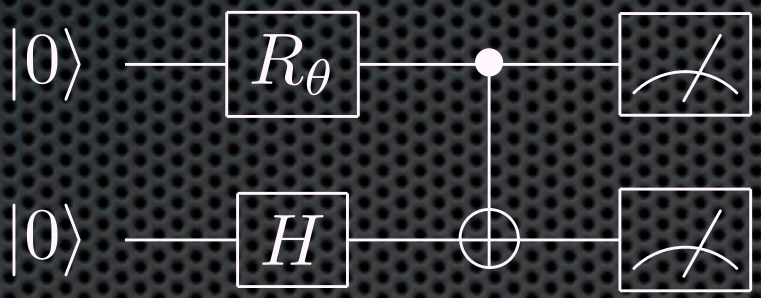
Bombin Delgado, J. Phys. A 2009

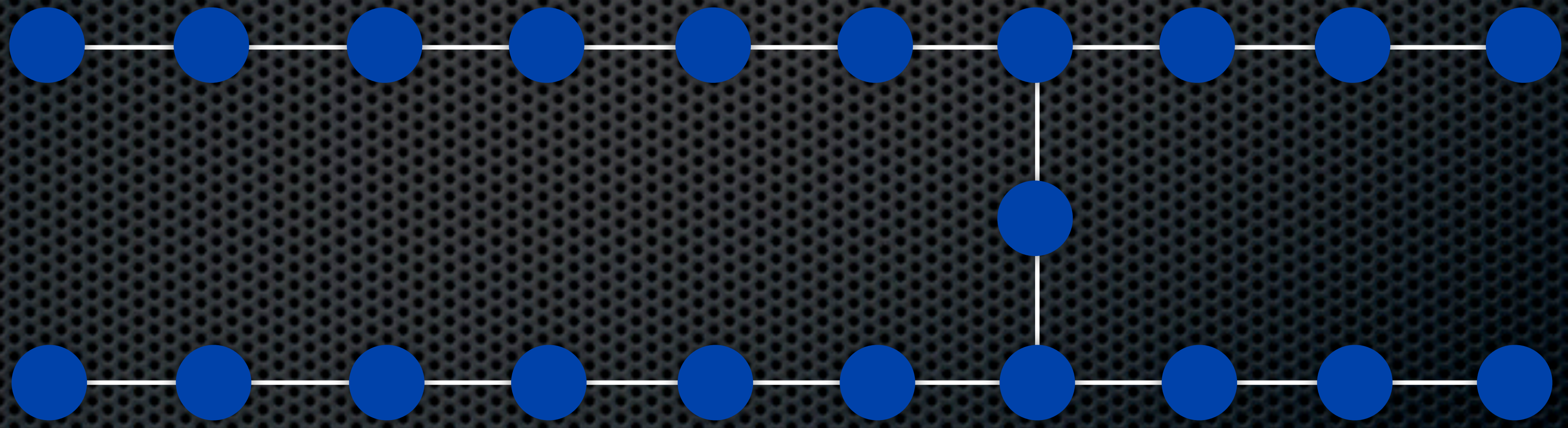
"Open-loop" holonomy, Kult Aberg Sjoqvist, PRA 2006

Why is this interesting?

- Adiabatic holonomic evolution offers robustness to timing and control errors that exist in the circuit model
- Excitations are suppressed by the constant gap
- "Ground state" errors can be corrected via coding
- It is modular, and hence as easy to program as the circuit model
- Uses only control between subsystems, not levels
- Gates are prepared offline, leading to fewer errors
- It leads to more results of interest to theorists...

One Way QC

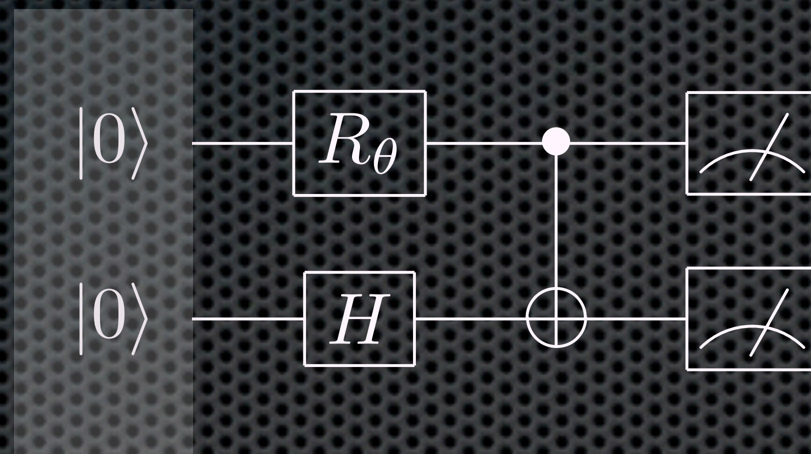


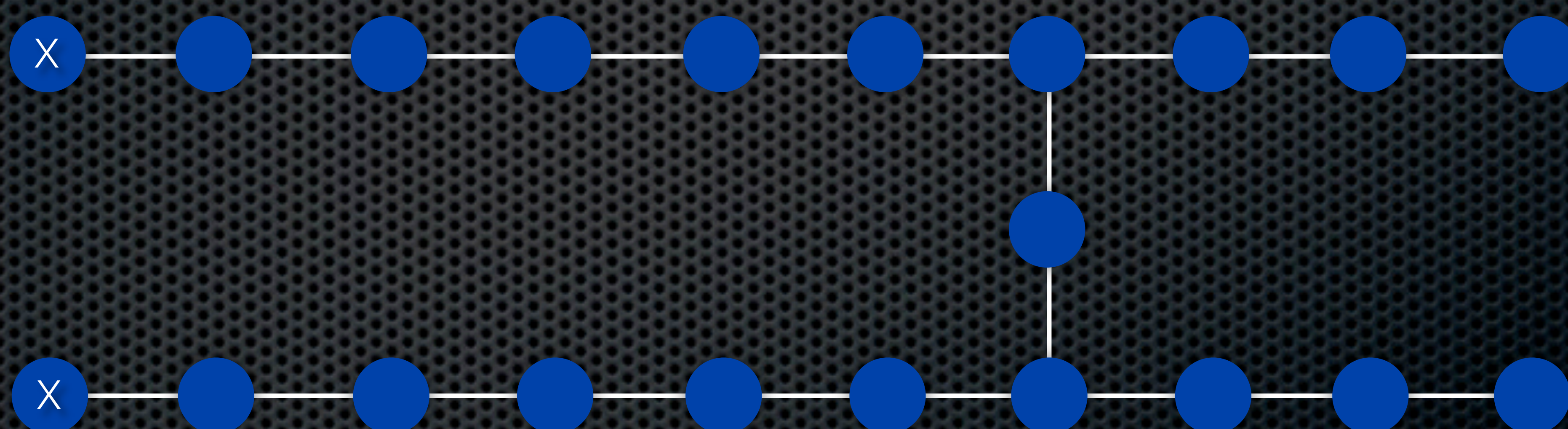


Create Entangled State

Raussendorf Briegel, PRL 2001

One Way QC

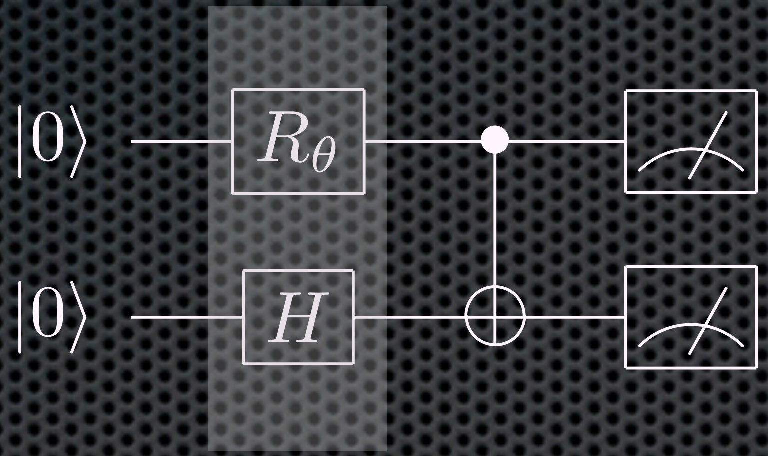


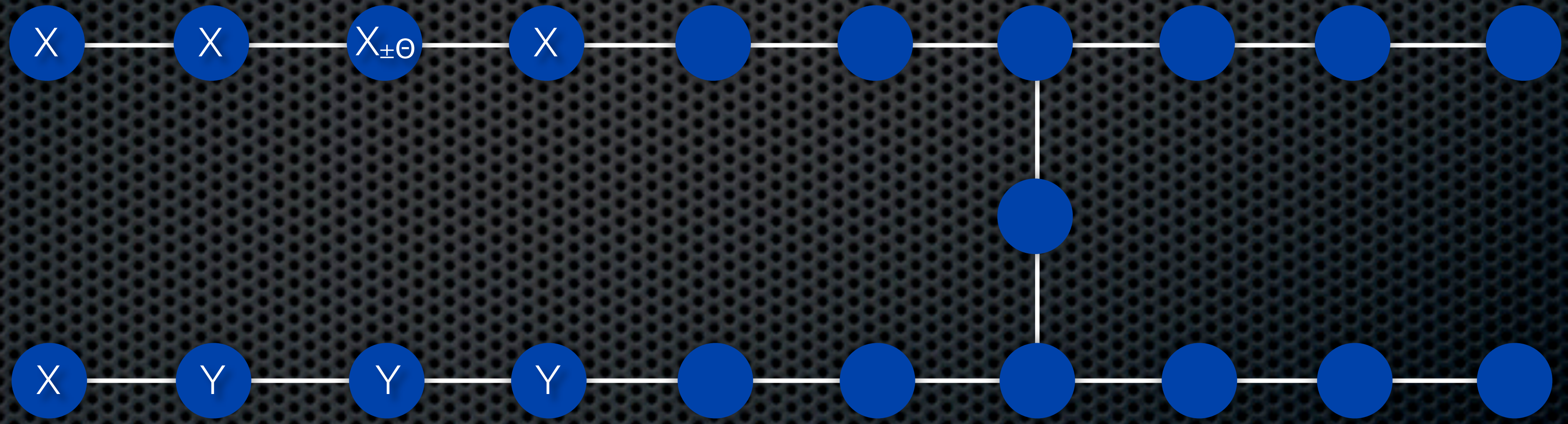


Adaptively measure to enact circuit

Raussendorf Briegel, PRL 2001

One Way QC





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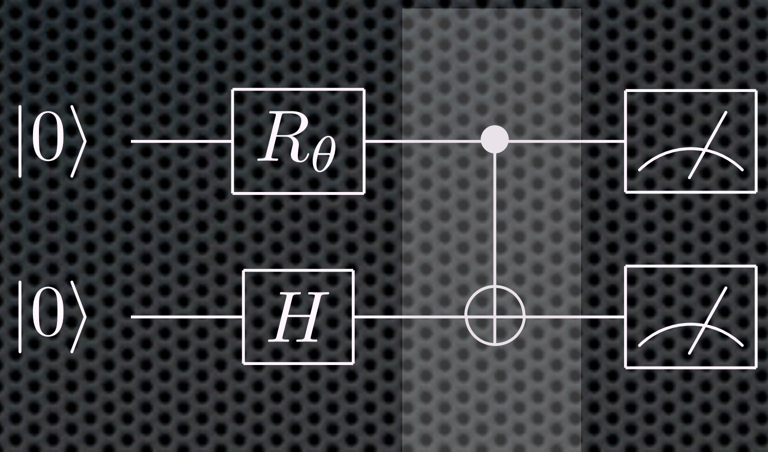

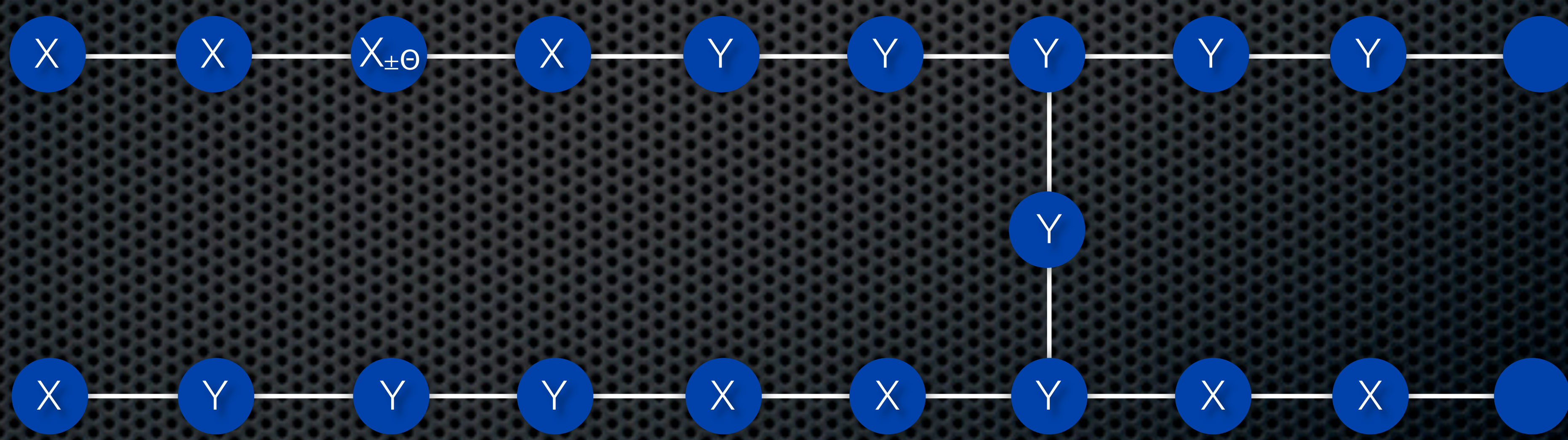

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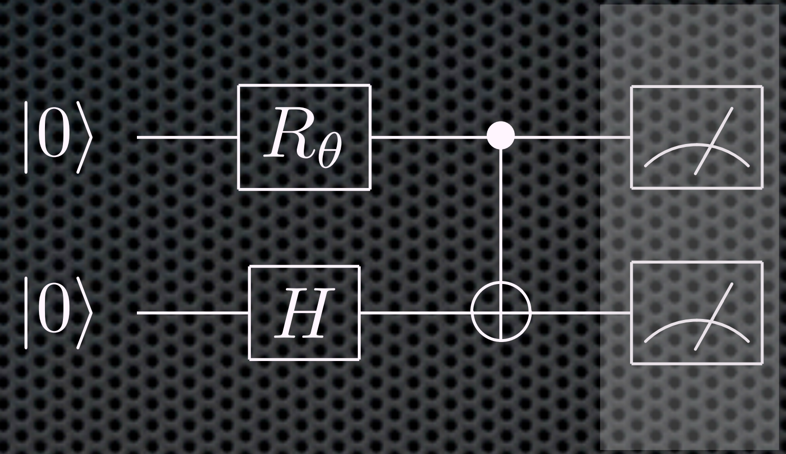
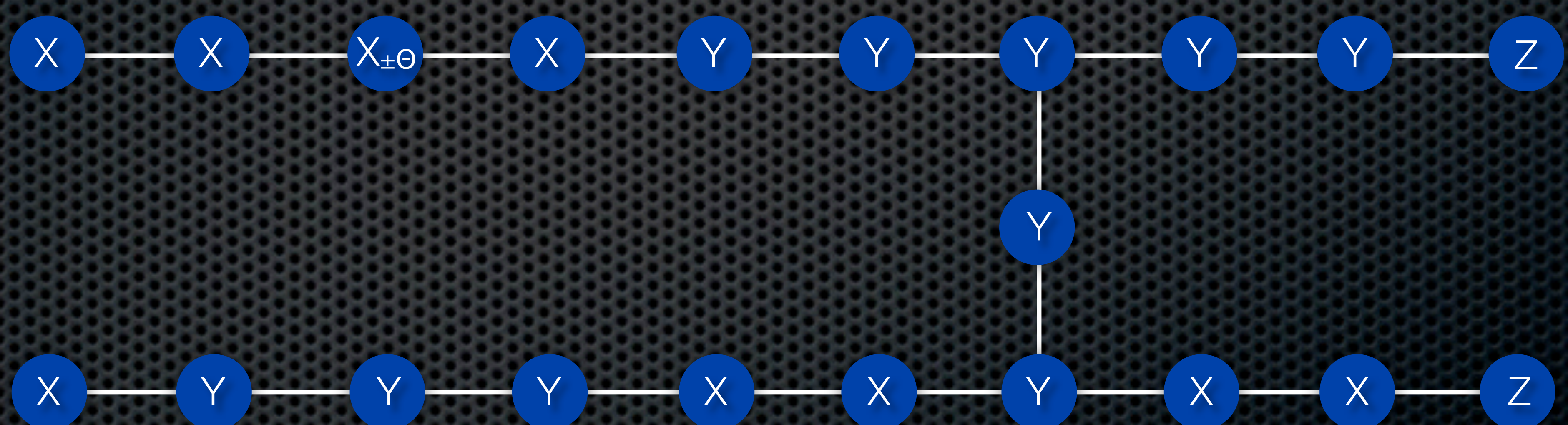
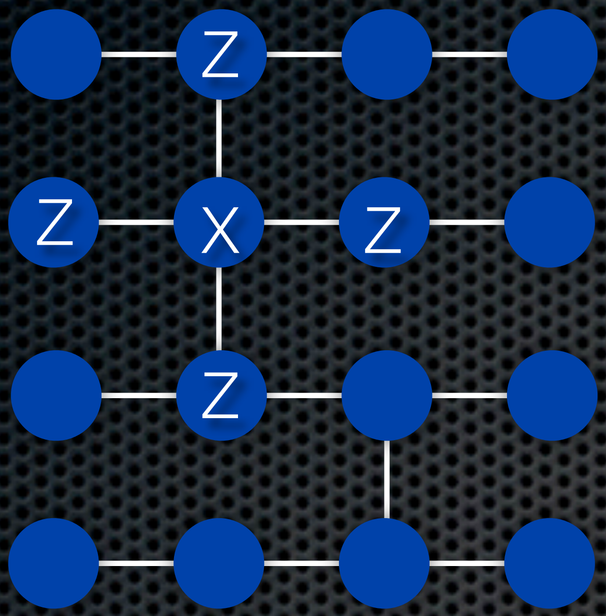




Adaptively measure to enact circuit

Raussendorf Briegel, PRL 2001

Cluster State Hamiltonian



$$S_v = X_v \prod_{w \text{ adjacent to } v} Z_w$$

Cluster state is ground state of $H_C = -\Delta \sum_v S_v$

Again, it's possible to use gadgets to make only 2-qubit interactions

Bartlett Rudolph, PRA 2006

Adiabatic One-way QC

$$S_j = Z_{j-1} X_j Z_{j+1}$$

$$H = -Z_{n-1} X_n - \sum_{j=2}^{n-1} S_j$$

Suppose we prepare $|+\rangle$ on the first physical qubit

Turn on -X fields and turn off cluster state coupling

Bacon Flammia, arXiv:0912.2098

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Bacon Flammia, arXiv:0912.2098

Adiabatic One-way QC

$H^n|+\rangle$

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Turn on -X fields and turn off cluster state coupling

Rotating the X fields in X-Y plane to make it universal

Bacon Flammia, arXiv:0912.2098

Adiabatic One-way QC

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Suppose we prepare $|+\rangle$ on the first physical qubit

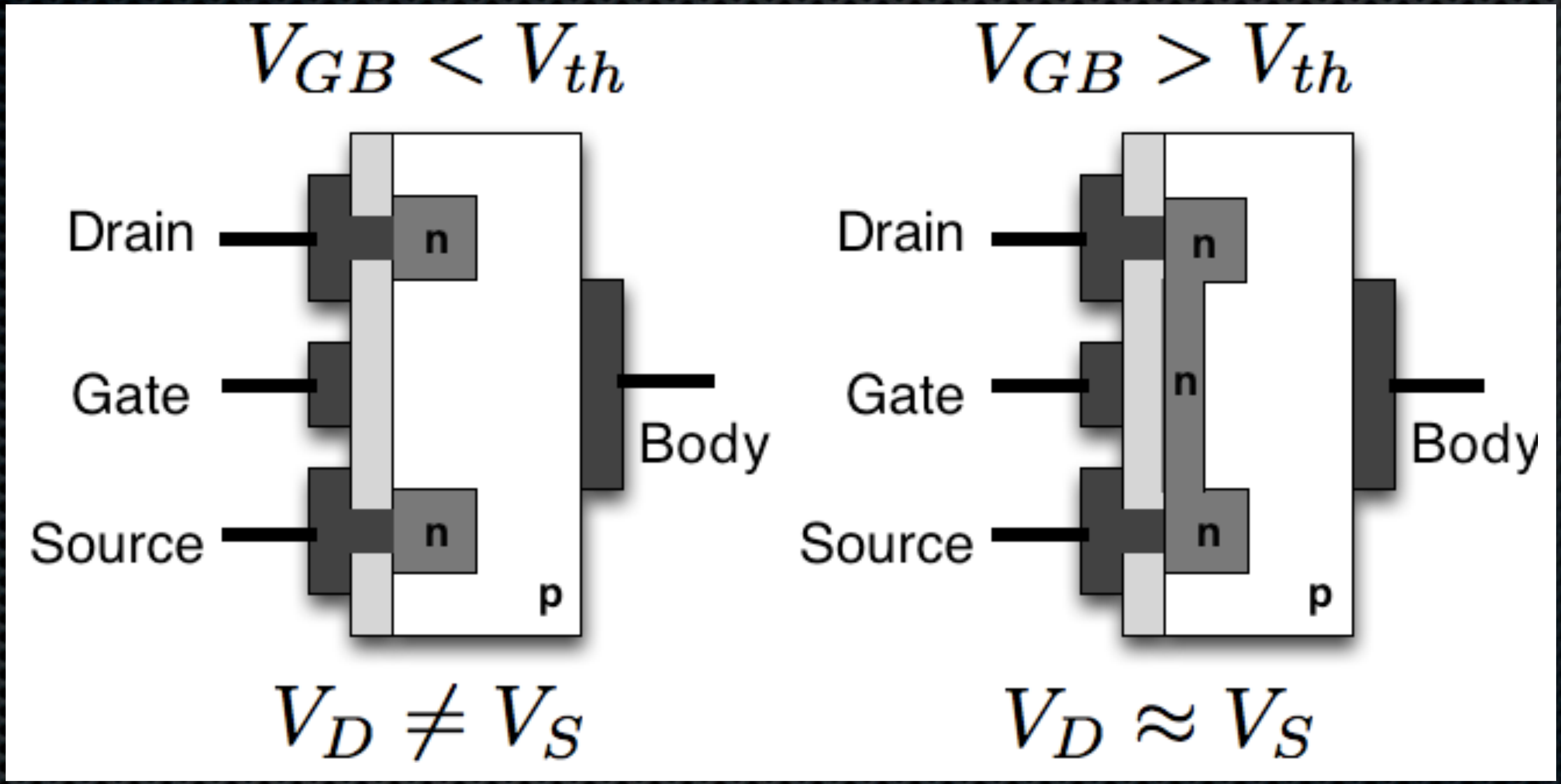
Turn on -X fields and turn off cluster state coupling

Rotating the X fields in X-Y plane to make it universal

The gap is still constant

Bacon Flammia, arXiv:0912.2098

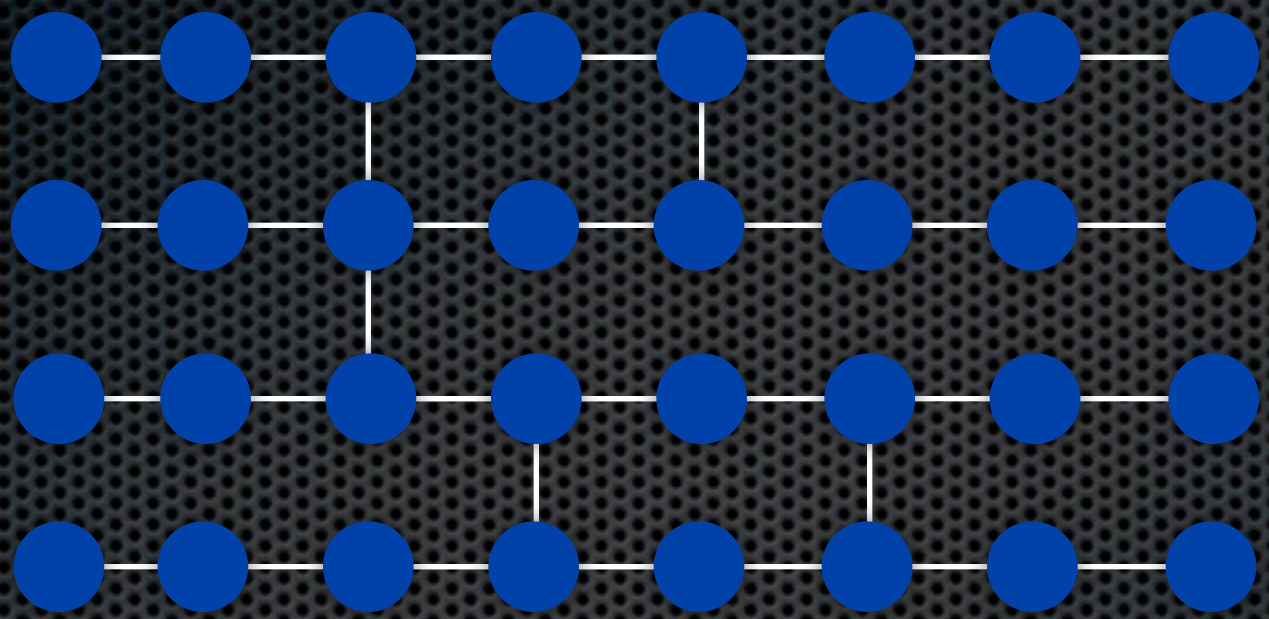
Classical Transistors



An “identity gate”

Problem: quantum information cannot be cloned

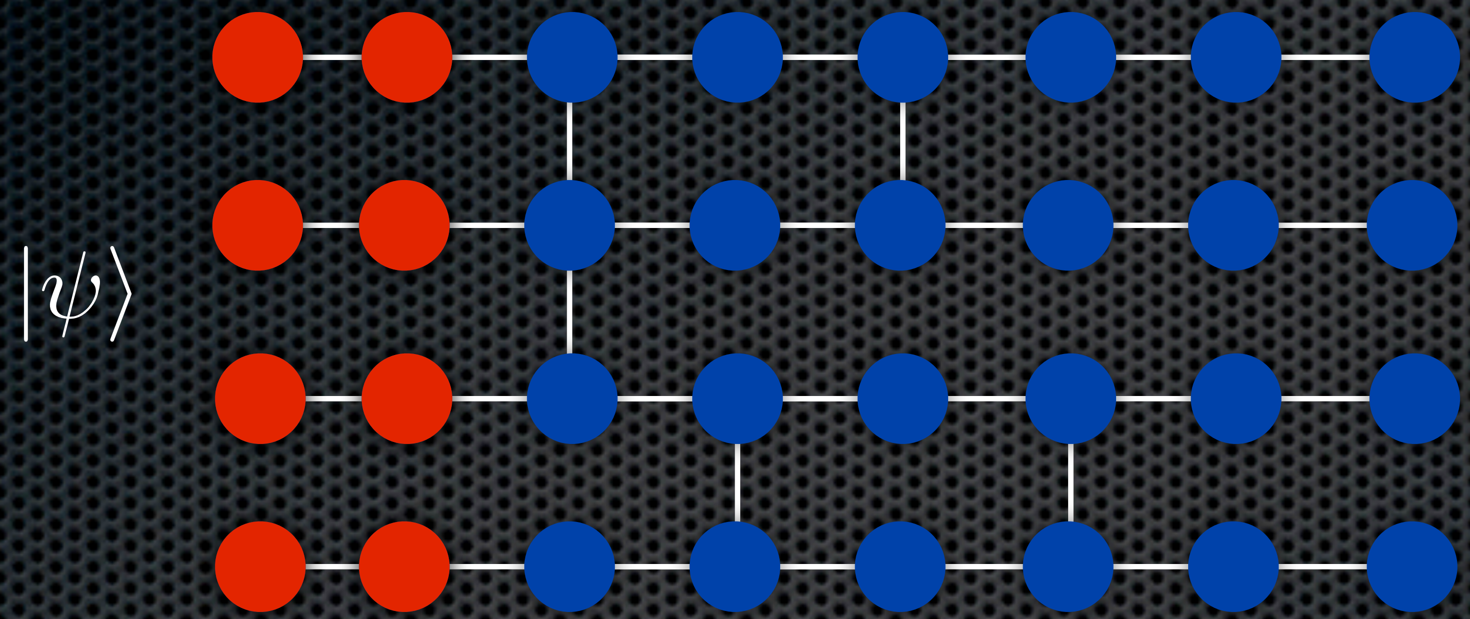
Quantum Transistors?



1. Many-body system in its ground state

Bacon Crosswhite Flammia, in preparation

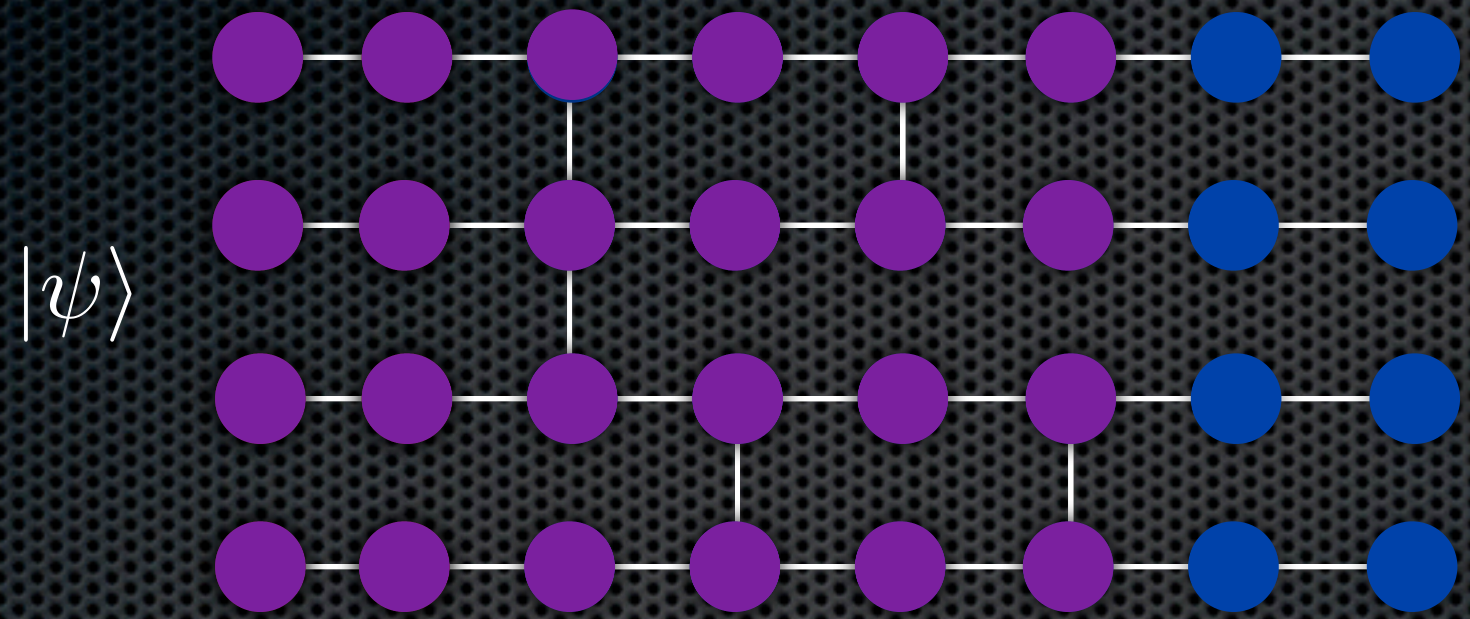
Quantum Transistors?



1. Many-body system in its ground state
2. Qubits localized on one side of the device

Bacon Crosswhite Flammia, in preparation

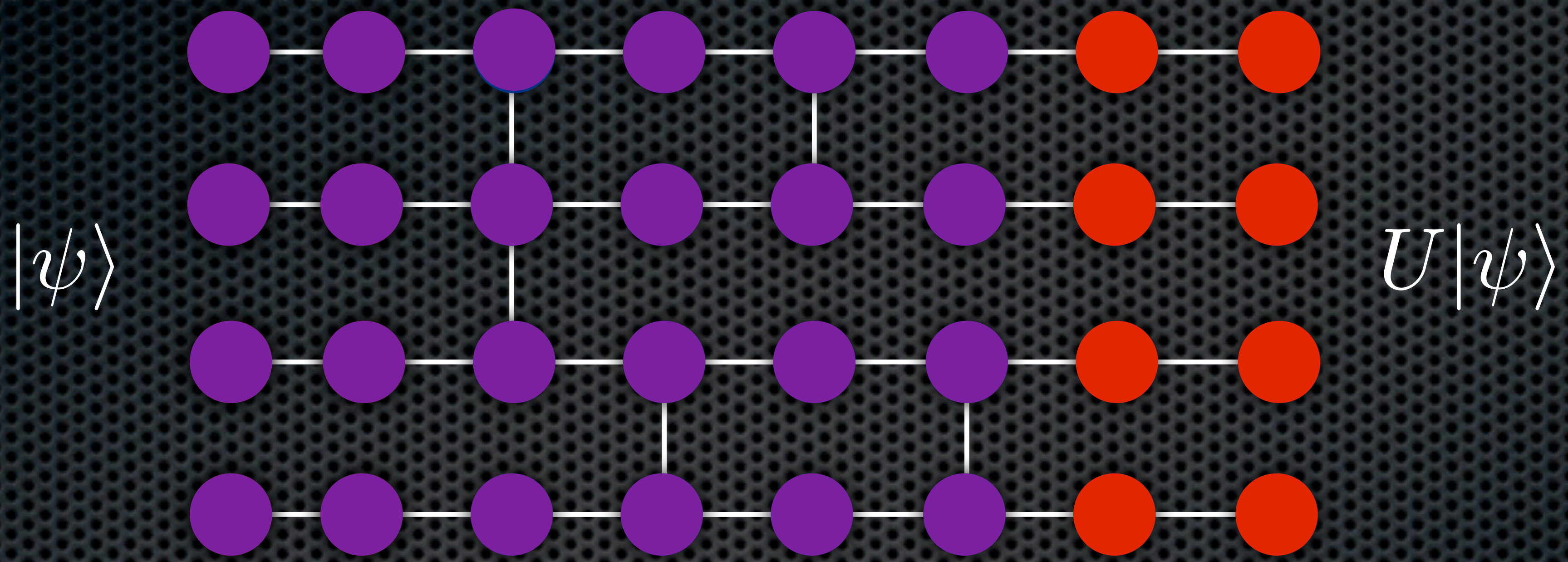
Quantum Transistors?



1. Many-body system in its ground state
2. Qubits localized on one side of the device
3. Apply a strong 1-qubit external field to device

Bacon Crosswhite Flammia, in preparation

Quantum Transistors?



1. Many-body system in its ground state
2. Qubits localized on one side of the device
3. Apply a strong 1-qubit external field to device
4. Qubits now localized on other side of device with a quantum circuit applied to the qubits

Bacon Crosswhite Flammia, in preparation

Adiabatic Quantum Transistors

What if we turn on the fields all at once?

Adiabatic Quantum Transistors

$$H(t) = (1-t)H_C + tH_X$$

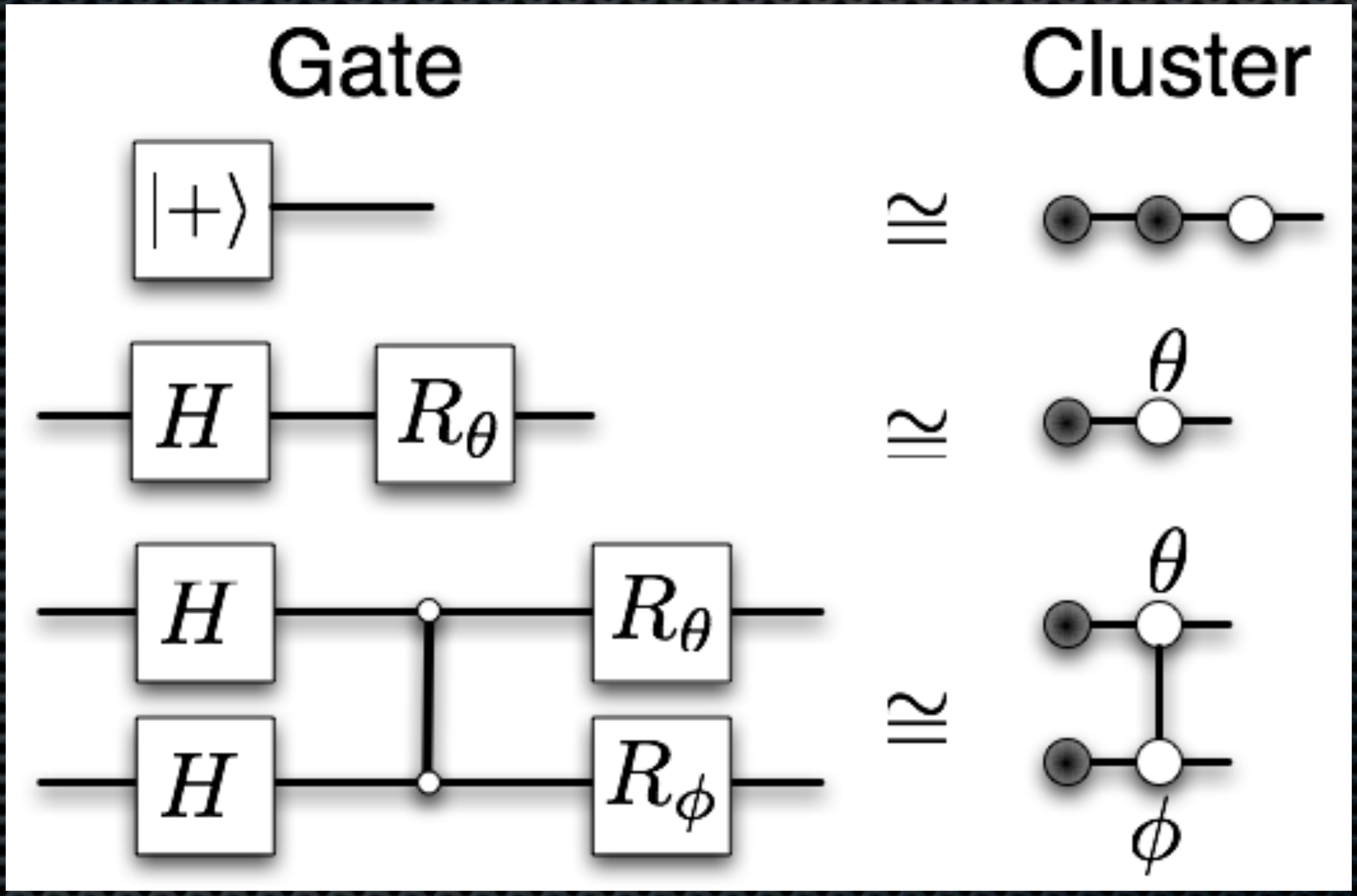
This is the transverse-field Ising model (with funny BCs)

The gap is $= \Theta(1/n)$

In analogy with transistors:

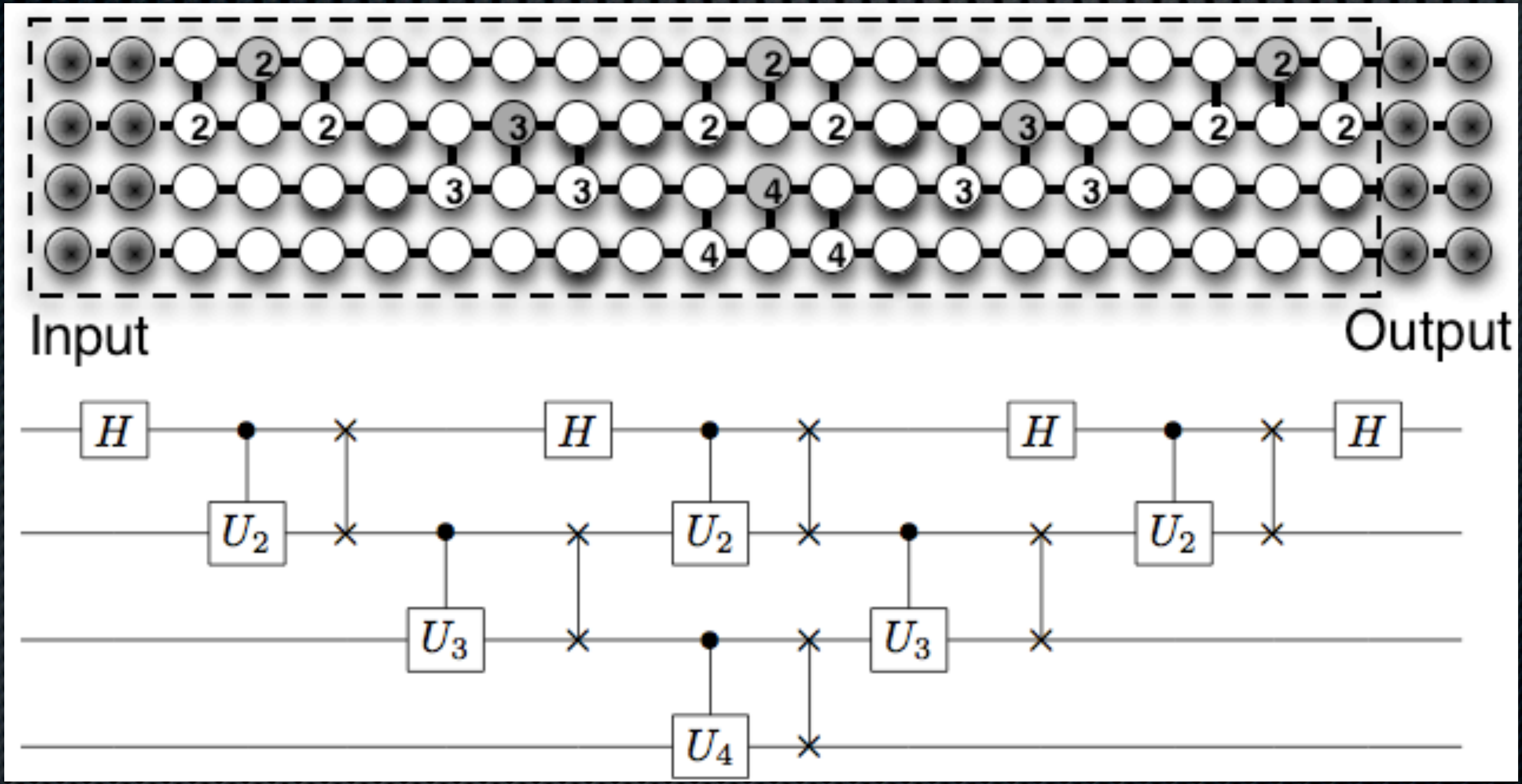
An applied field induces a quantum phase transition between an insulating and a “quantum logic” phase.

Quantum Transistor Dictionary



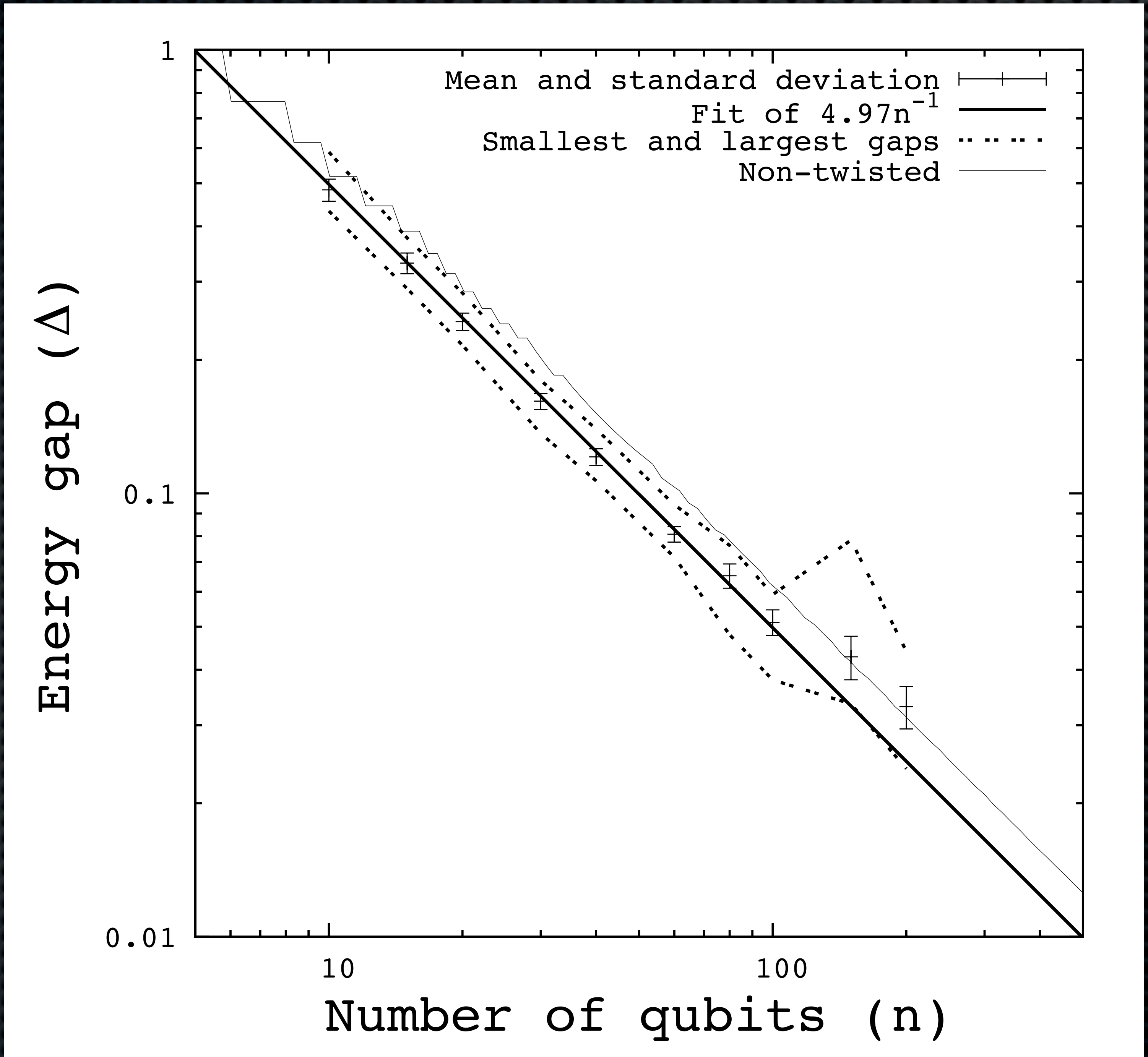
$$R(\theta) = \exp(-i\theta Z/2)$$

Example



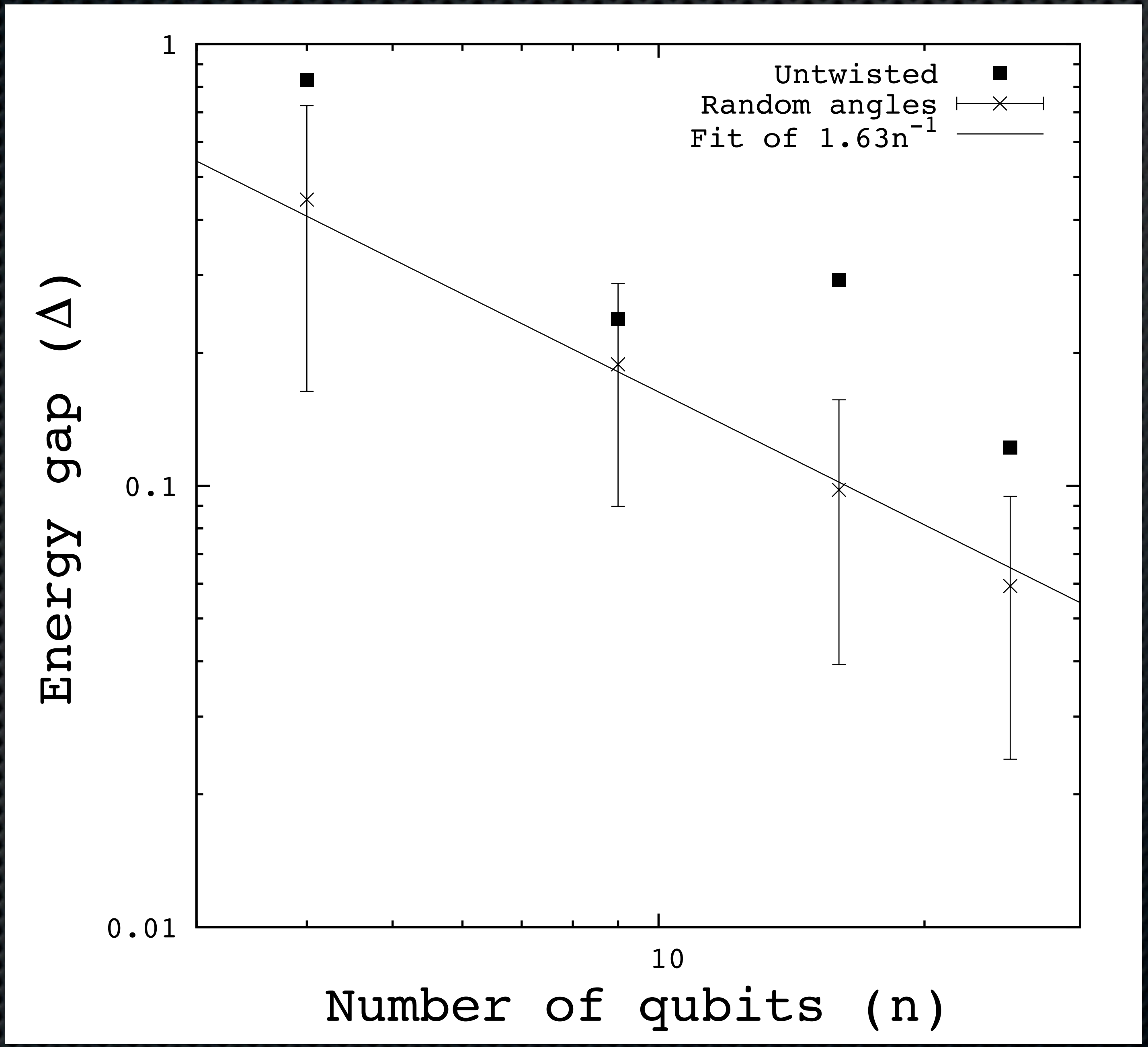
How slowly must we turn on the external field in order for the device to successfully quantum compute?

Gap Scaling: 1D Numerics



Gap for 1D circuit with random angle rotations...

Gap Scaling: 2D Numerics

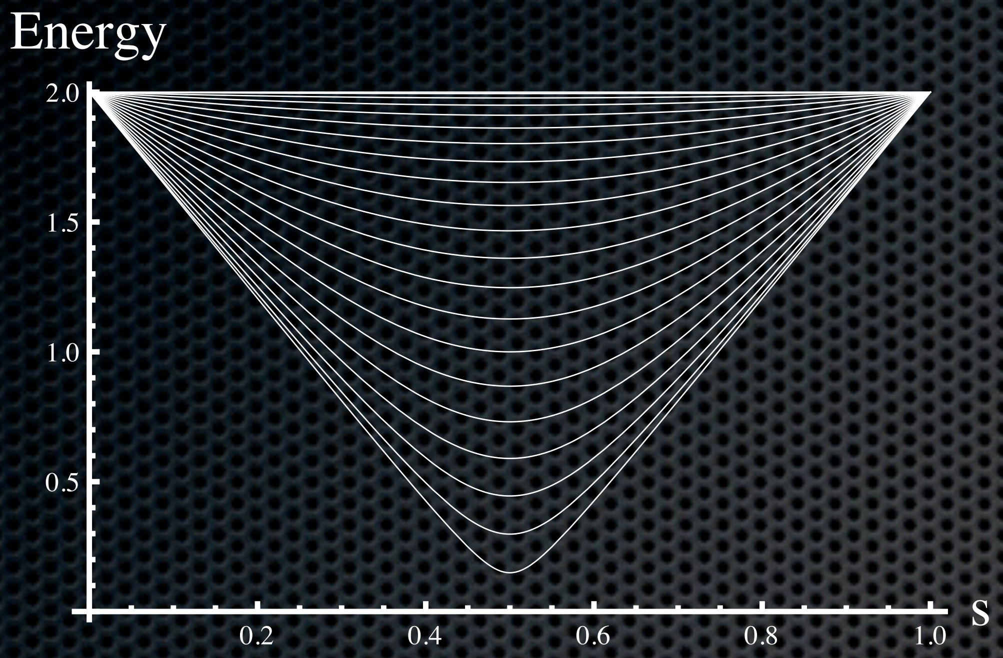


Gap for 2D circuit with random angle rotations

Gap Scaling Summary

- How slowly must we turn on the external field in order for the device to successfully quantum compute?
  - In 1D with no twists, we have rigorously proven the gap is inverse polynomial in the circuit size
  - In 1D with twists, we have extremely strong evidence of polynomial scaling in the circuit size
  - For the 2D case with twists, we have some evidence of polynomial scaling in the size of circuit
- We have not yet simulated the case with gadgets.

Fault-Tolerance



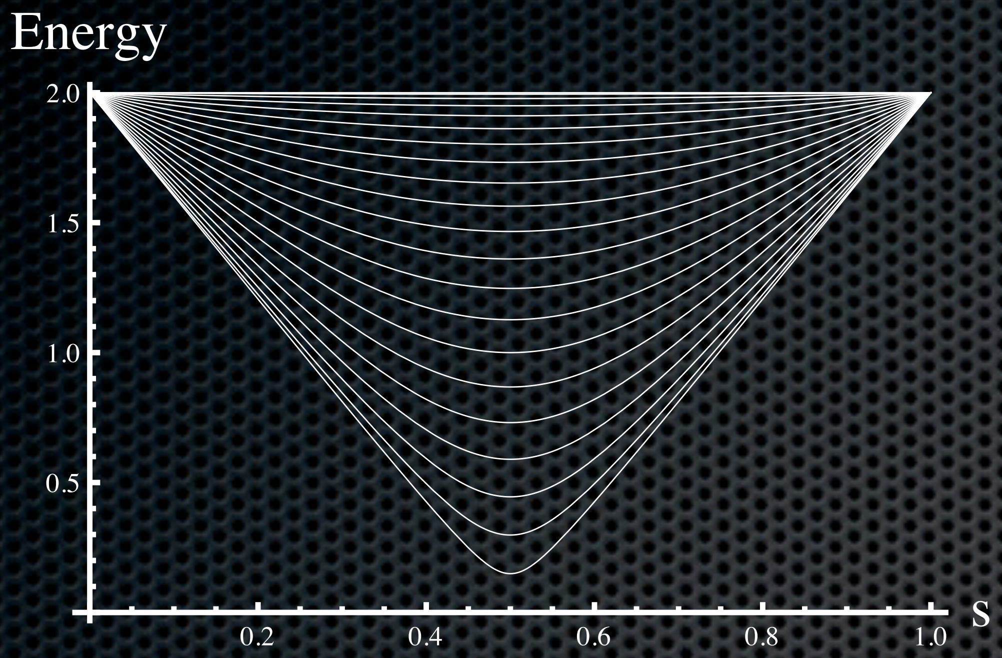
1D untwisted Hamiltonian decouples into two 1D Ising chains with a transverse field.

Two types of errors:

- Those that change energy
- Those within the degeneracy
- Includes system-bath couplings and Hamiltonian perturbations

- Assume the excitations obey detailed balance and are suppressed by a Boltzmann factor.
- Adiabatic evolution preserves eigenstates, so excitations can be (mathematically) dragged back to the beginning.
- Straightforward stabilizer arguments shows that these are correctible local and independent Pauli errors

Fault-Tolerance



1D untwisted Hamiltonian decouples into two 1D Ising chains with a transverse field.

Two types of errors:

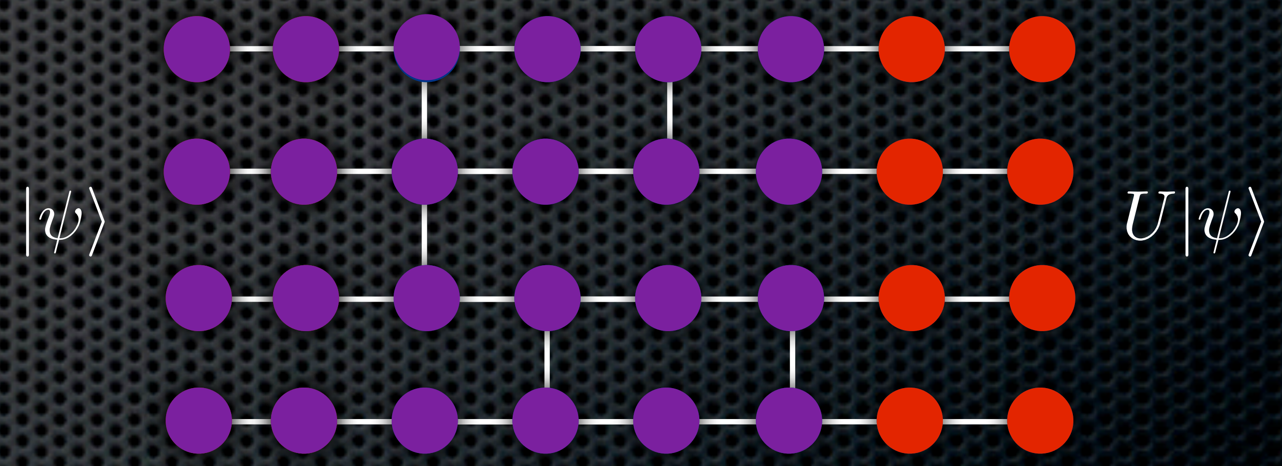
- Those that change energy
- Those within the degeneracy
- Includes system-bath couplings and Hamiltonian perturbations

- Quantum info is susceptible to decoherence near the beginning and end, but in the middle string-like stabilizer operators give us topological protection from local errors.
- We can reschedule the adiabatic evolution so that we only spend a constant amount of time in the bad regime, and these errors are local and independent there.

Conclusion

Adiabatic Gate Teleportation

can be combined with cluster states



to build robust adiabatic quantum logic elements