Quantum Routing and Beyond with Superconducting Resonators

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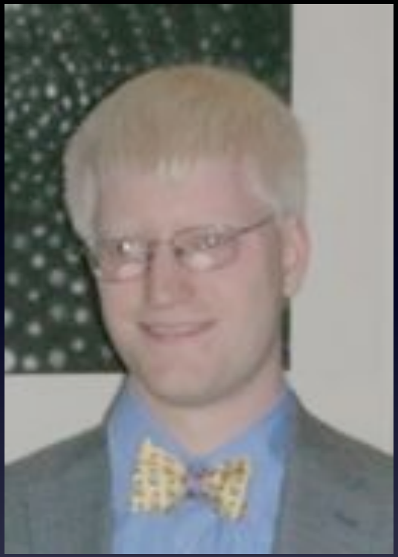
Funding: NSF, Research Corporation

Collaborators

Kurt Jacobs, UMass Boston

Ray Simmonds, NIST Boulder

Collaborators



Chris Chudzicki
'10, MIT

Kurt Jacobs, UMass
Boston

Ray Simmonds,
NIST Boulder

Outline

- **Superconducting Qubits and Resonators**
- **Quantum Routing on Networks**
  - Perfect State Transfer on Hypercube Networks
  - Parallel State Transfer and Efficient Quantum Routing

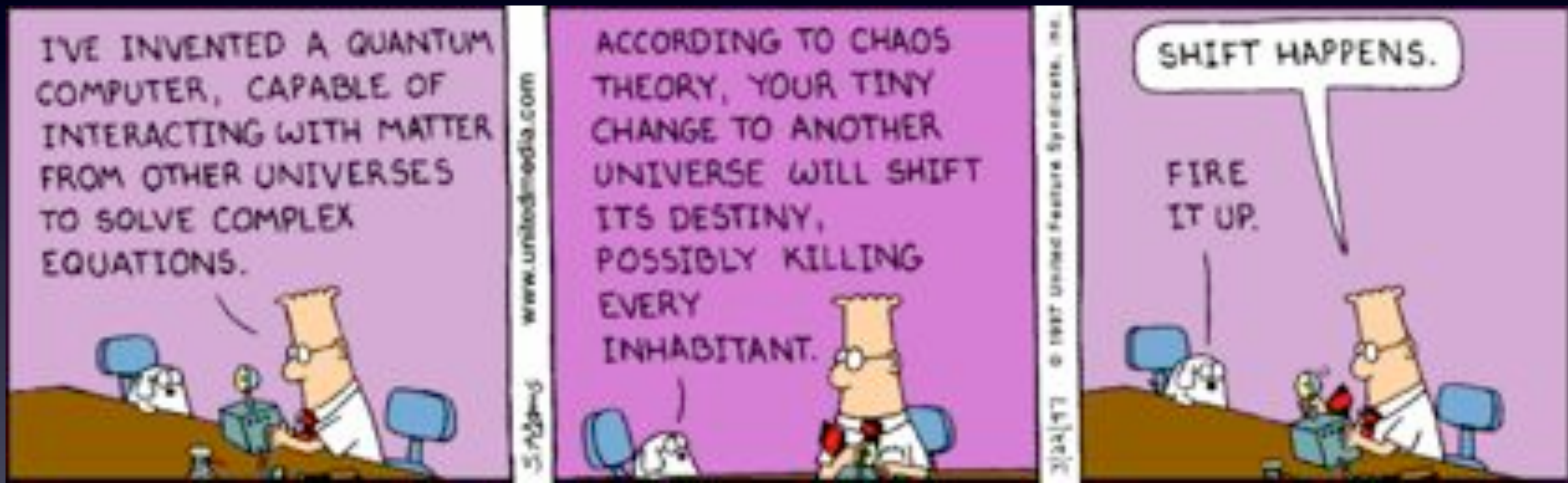
C. Chudzicki ’10 + FWS, Phys. Rev. Lett. **105**, 260501 (2010)

- **Quantum Computing with Superconducting Resonators**
  - Entangled ‘NOON’ States
  - Multi-level quantum logic

FWS, K Jacobs, and RW Simmonds, Phys. Rev. Lett. **105**, 050501 (2010)
FWS + K Jacobs, in preparation

Quantum Computing

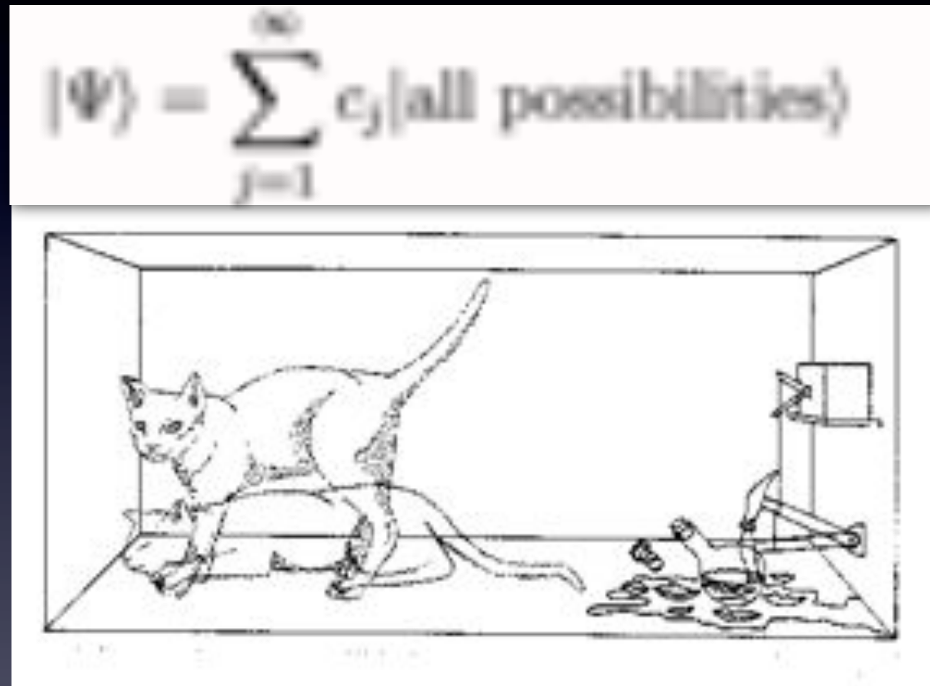
Executive Summary



Quantum Computing

Extended Abstract

Quantum Computer:
A hypothetical device which uses the intrinsic weirdness of the universe (?multiverse?) to speed up computational tasks.



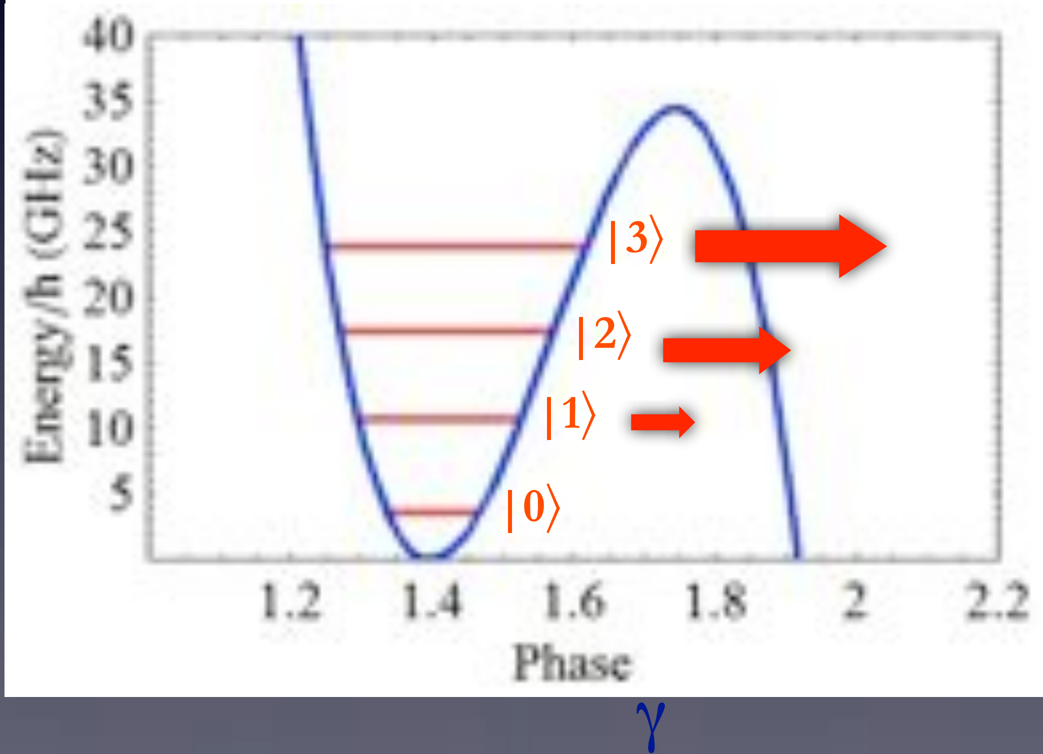
Quantum Algorithms:
Factoring, Search, Simulation (+ a few more)

Quantum Bit: A bit (binary digit) that can be in a superposition of both 0 and 1

Phase Qubit

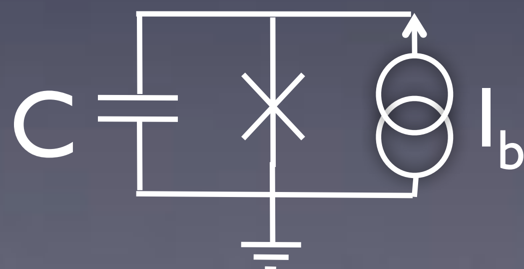
Artificial Atom, Controlled by Wires!

$$-\frac{\hbar^2}{2C(\Phi_0/2\pi)^2}\frac{d^2\Psi}{d\gamma^2}-\frac{\Phi_0}{2\pi}(I_c\cos\gamma+I_b\gamma)\Psi=E\Psi$$



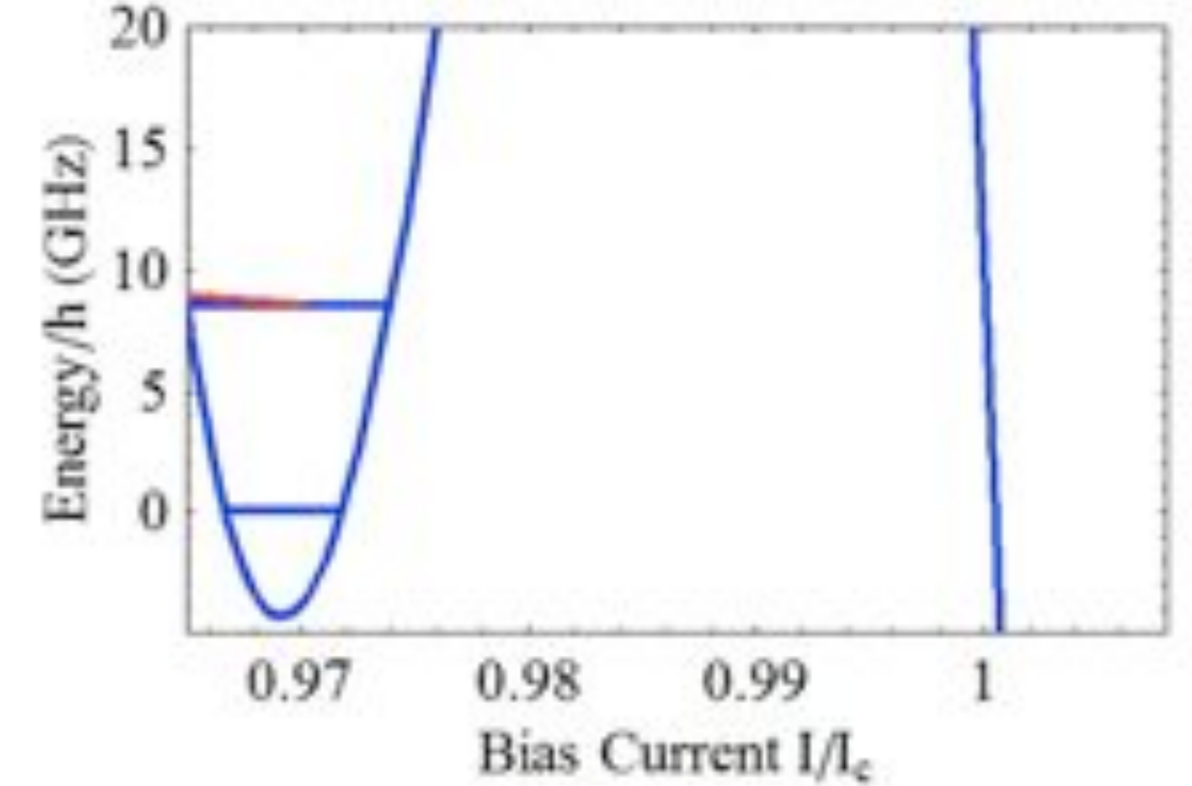
Josephson Junction

AC Circuits:
Capacitor, Inductor + JJunction



Tunable Oscillator

$$-\frac{\hbar^2}{2C\left(\Phi_0/2\pi\right)^2}\frac{d^2\Psi}{d\gamma^2}-\frac{\Phi_0}{2\pi}\left(I_c\cos\gamma+I_b\gamma\right)\Psi=E\Psi$$



Sweep of bias current allows experimental control of energy levels.

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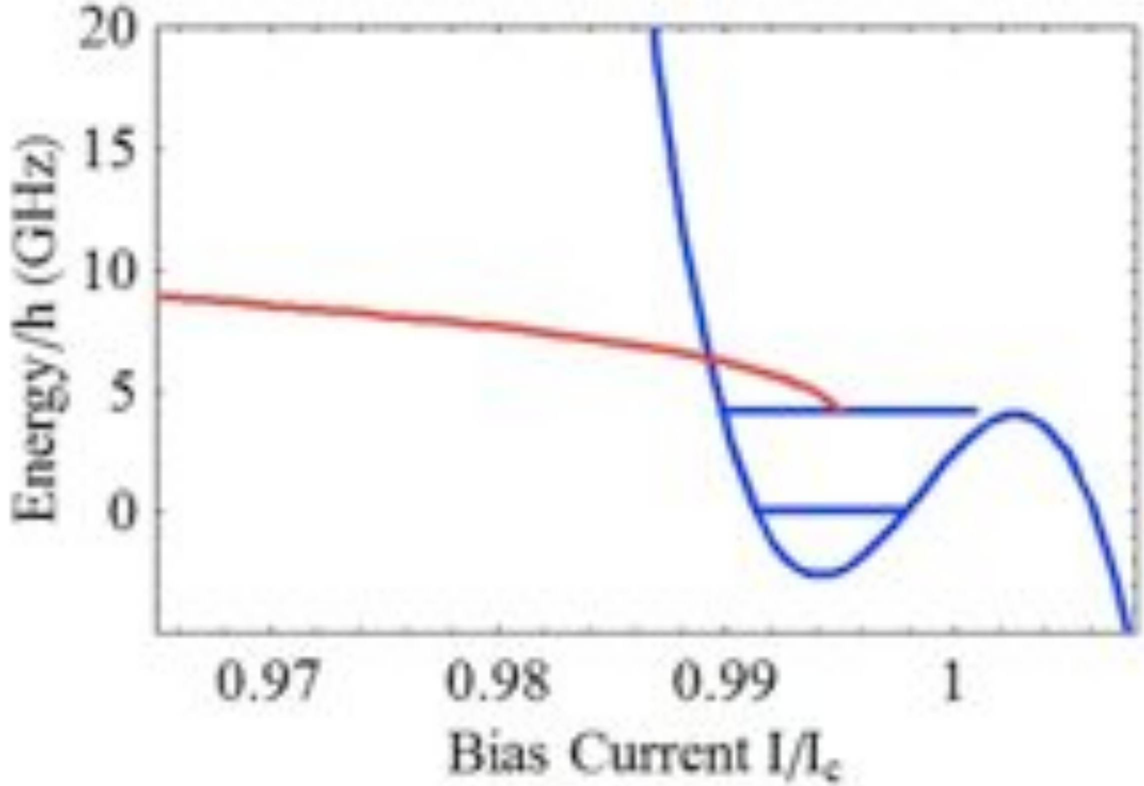

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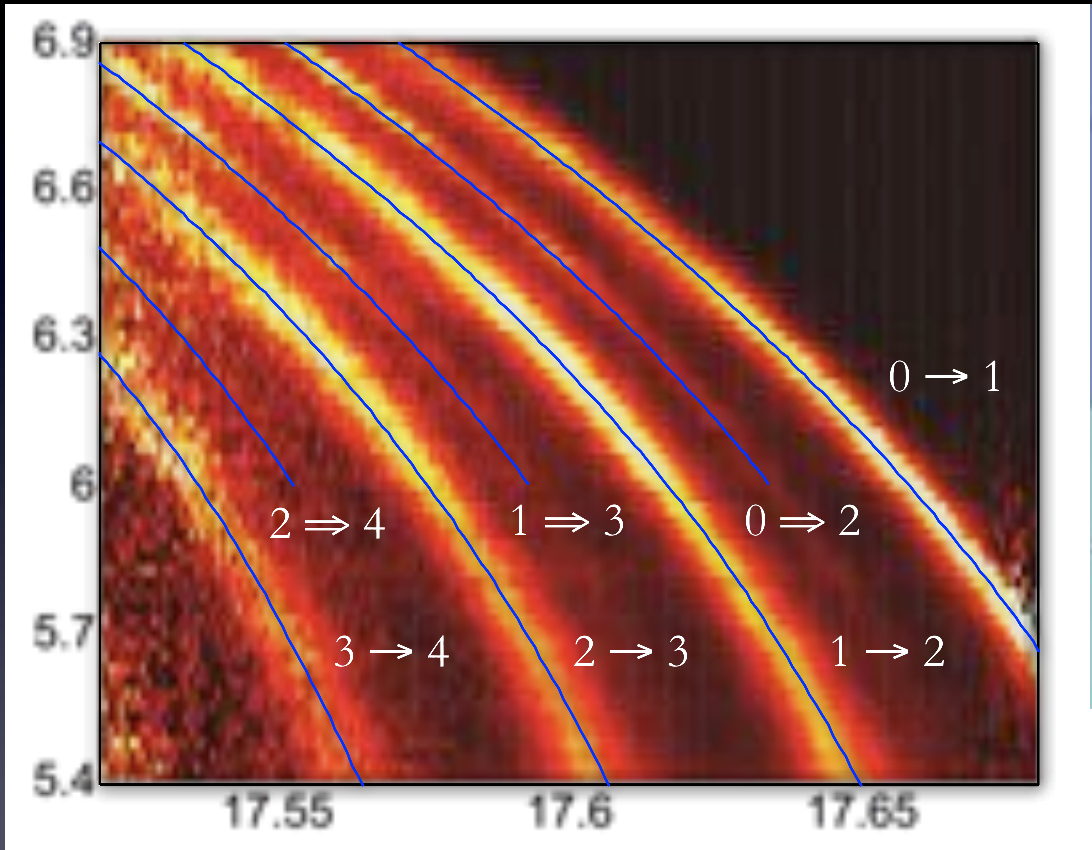
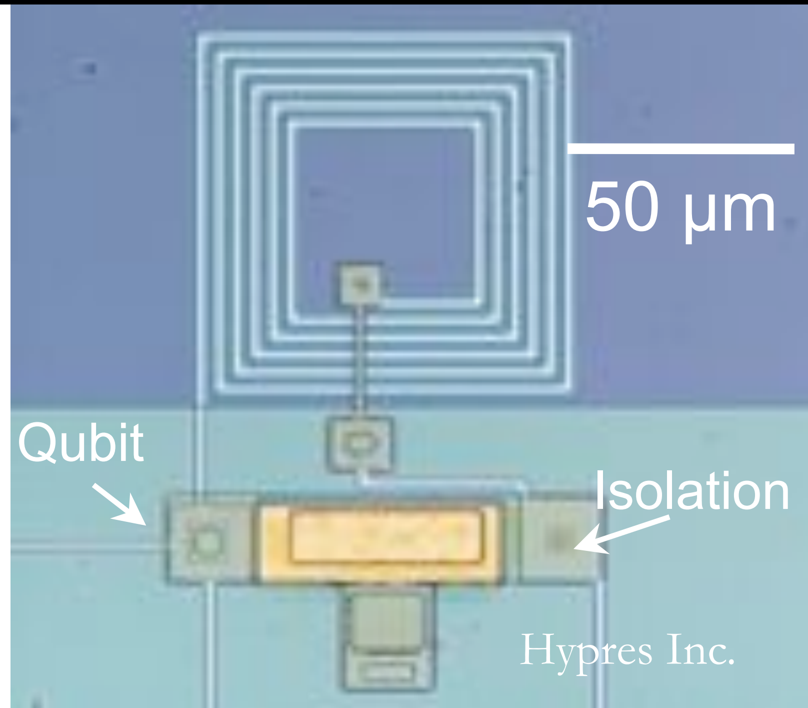
Phase Qubit Spectroscopy



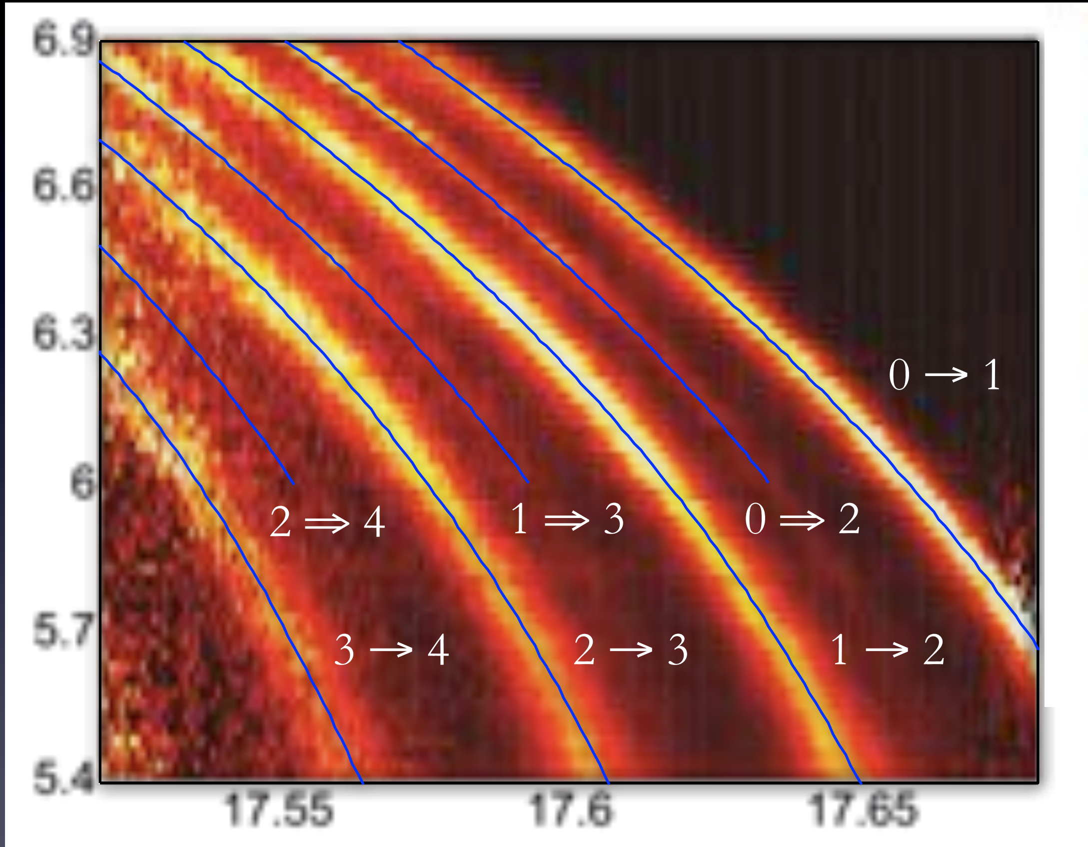


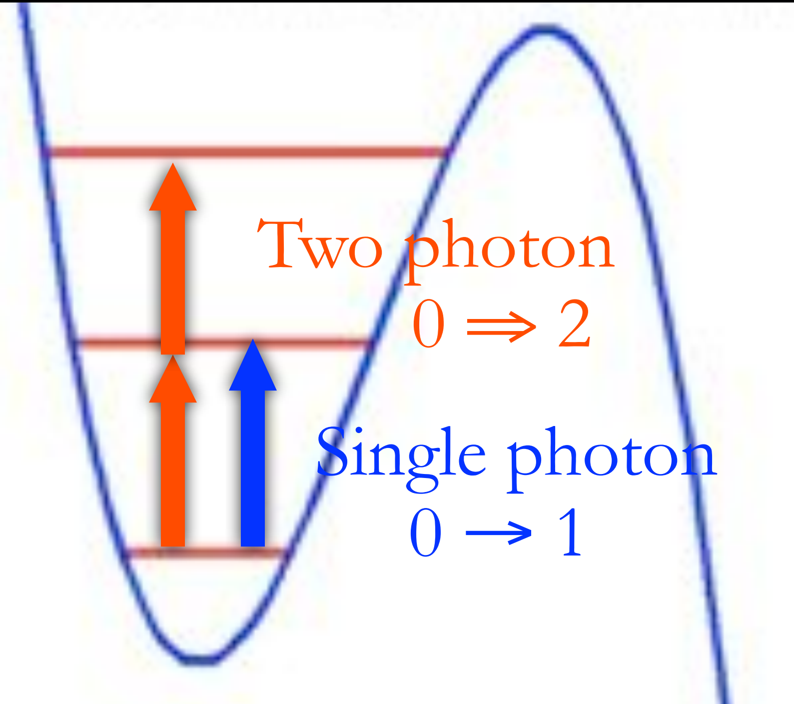
Sudeep Dutta et al. (Univ. Maryland)

Each microwave transition is an excitation of the junction with an increased tunneling rate. Bright indicates a large number of tunneling events, dark a small number of events.

Phase Qubit Spectroscopy

f (GHz)





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I (μ A)

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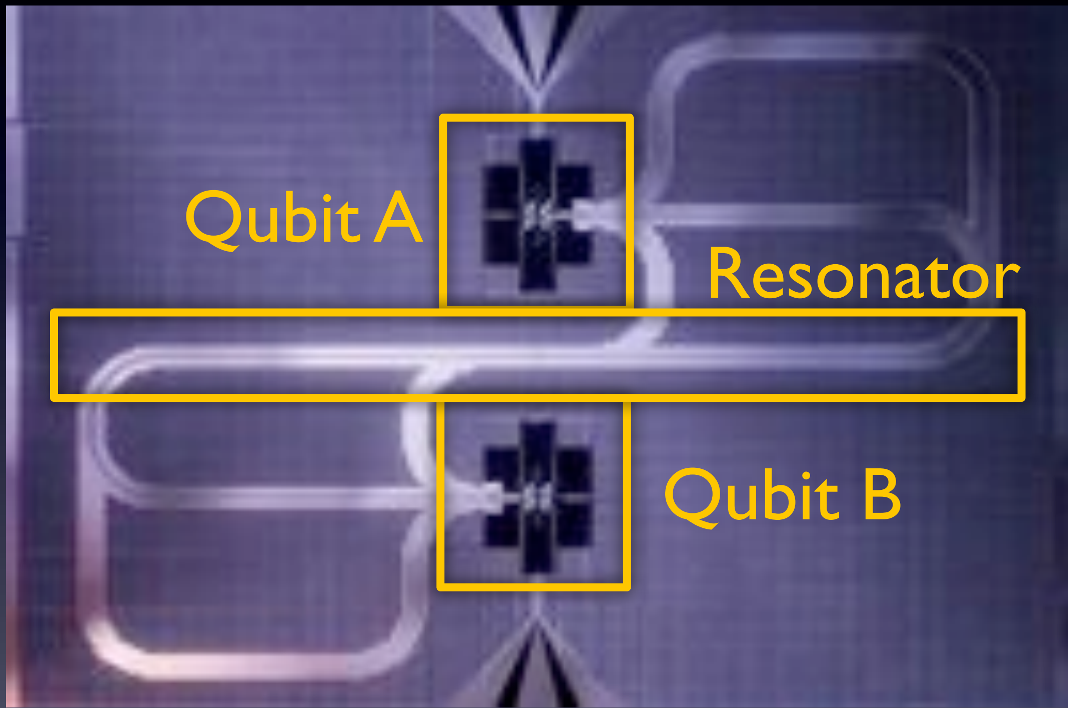
Coupling Qubits by Cavities



"Coherent quantum state storage and transfer between two phase qubits via a resonant cavity", M. Sillanpaa, J. I. Park, and R. W. Simmonds, *Nature* **449**, 438 (2007)

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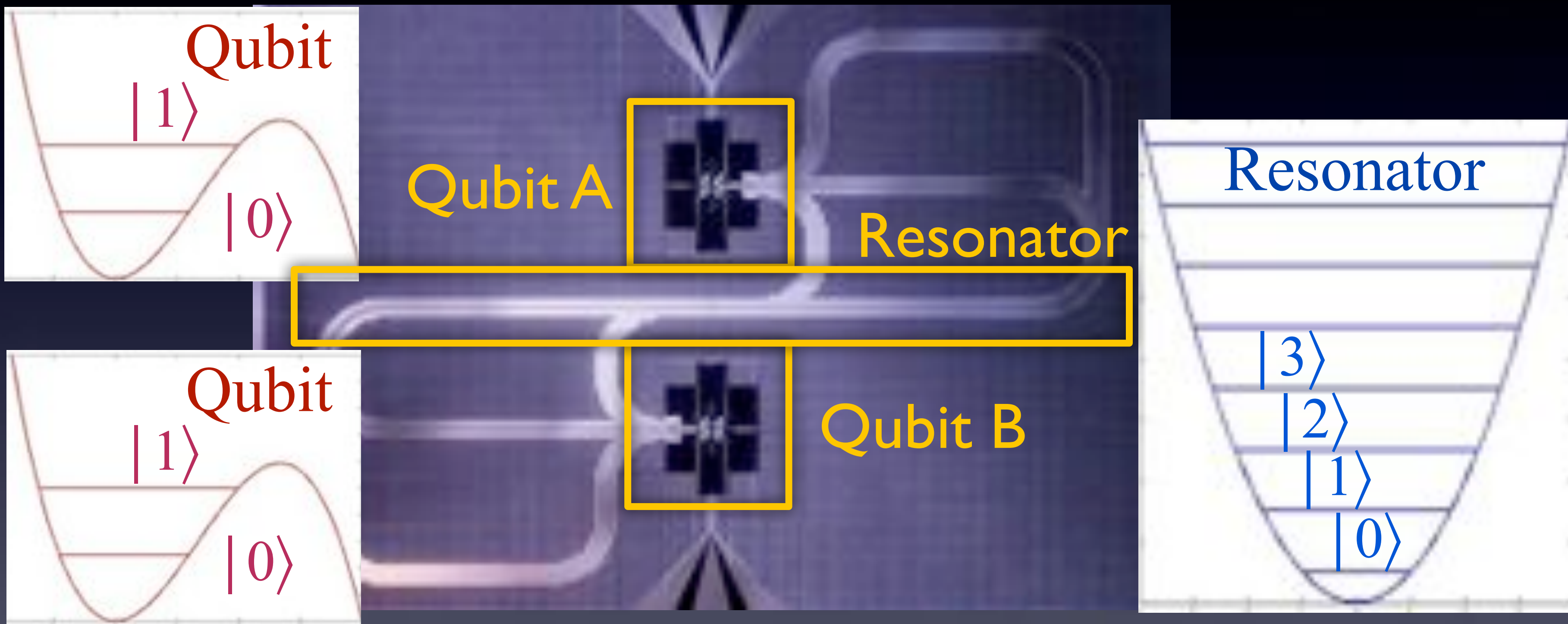

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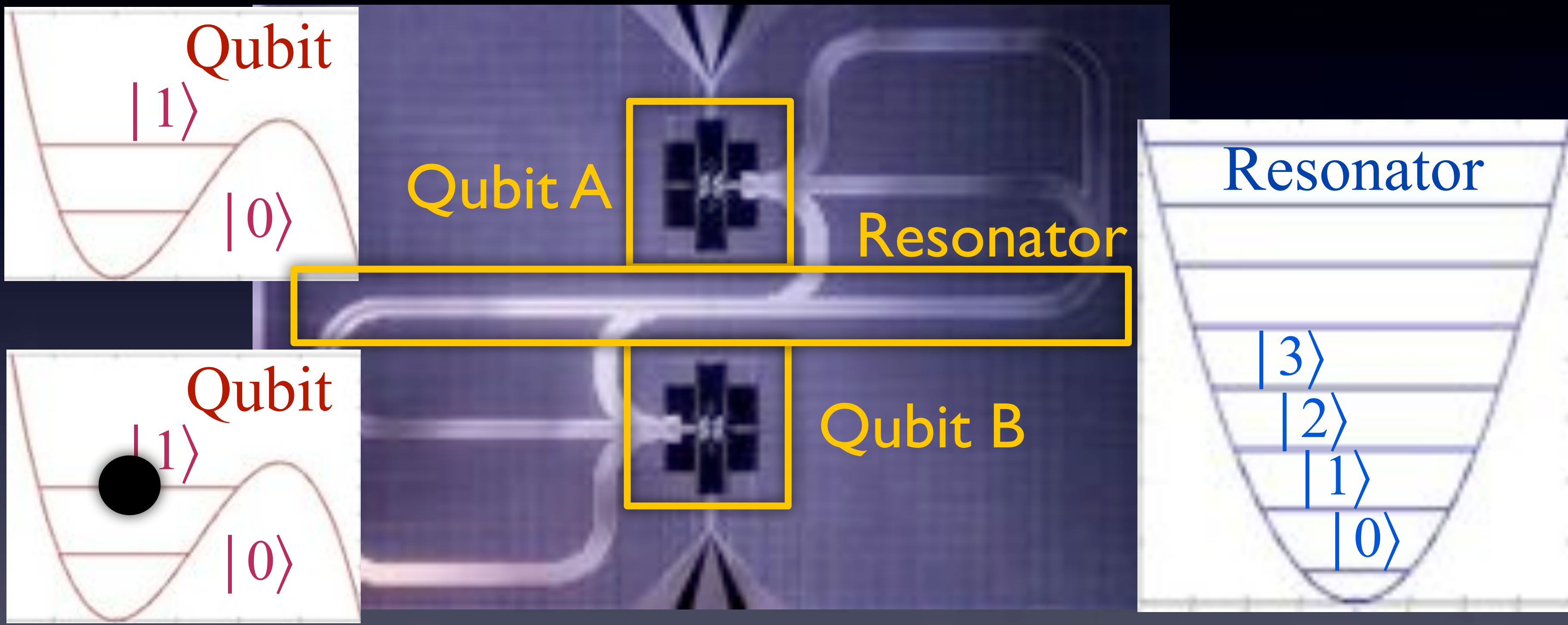

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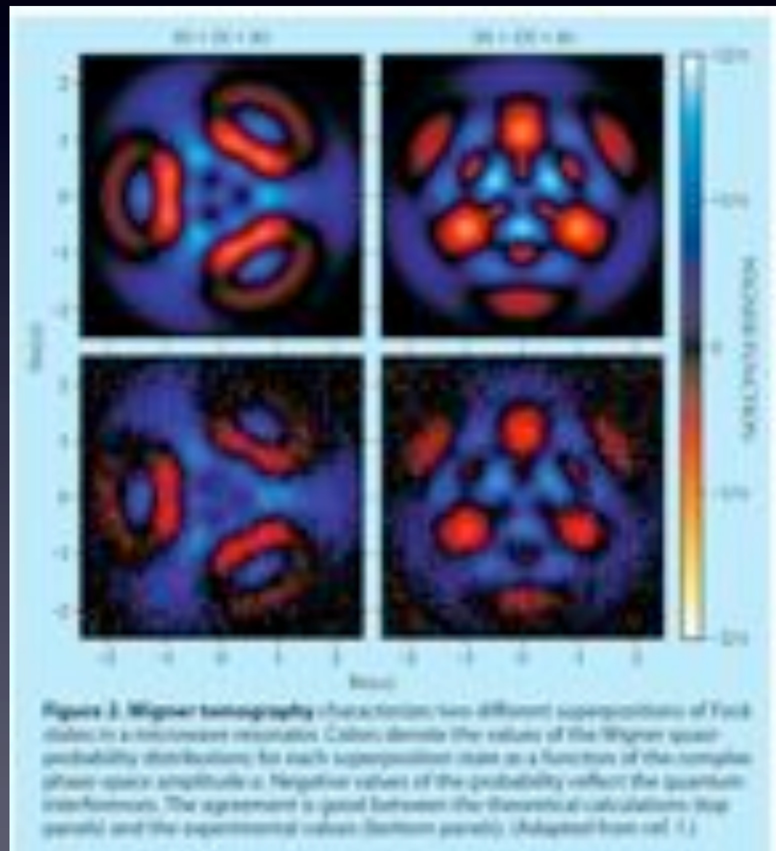
Arbitrary Control of a Superconducting Resonator



- Martinis Group, UC Santa Barbara (2008)

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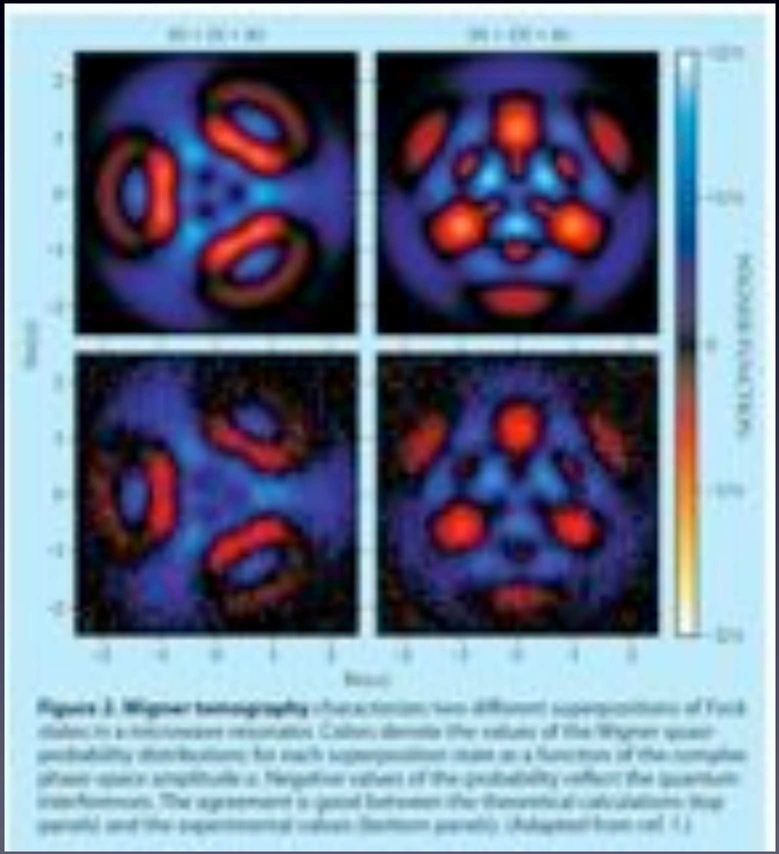

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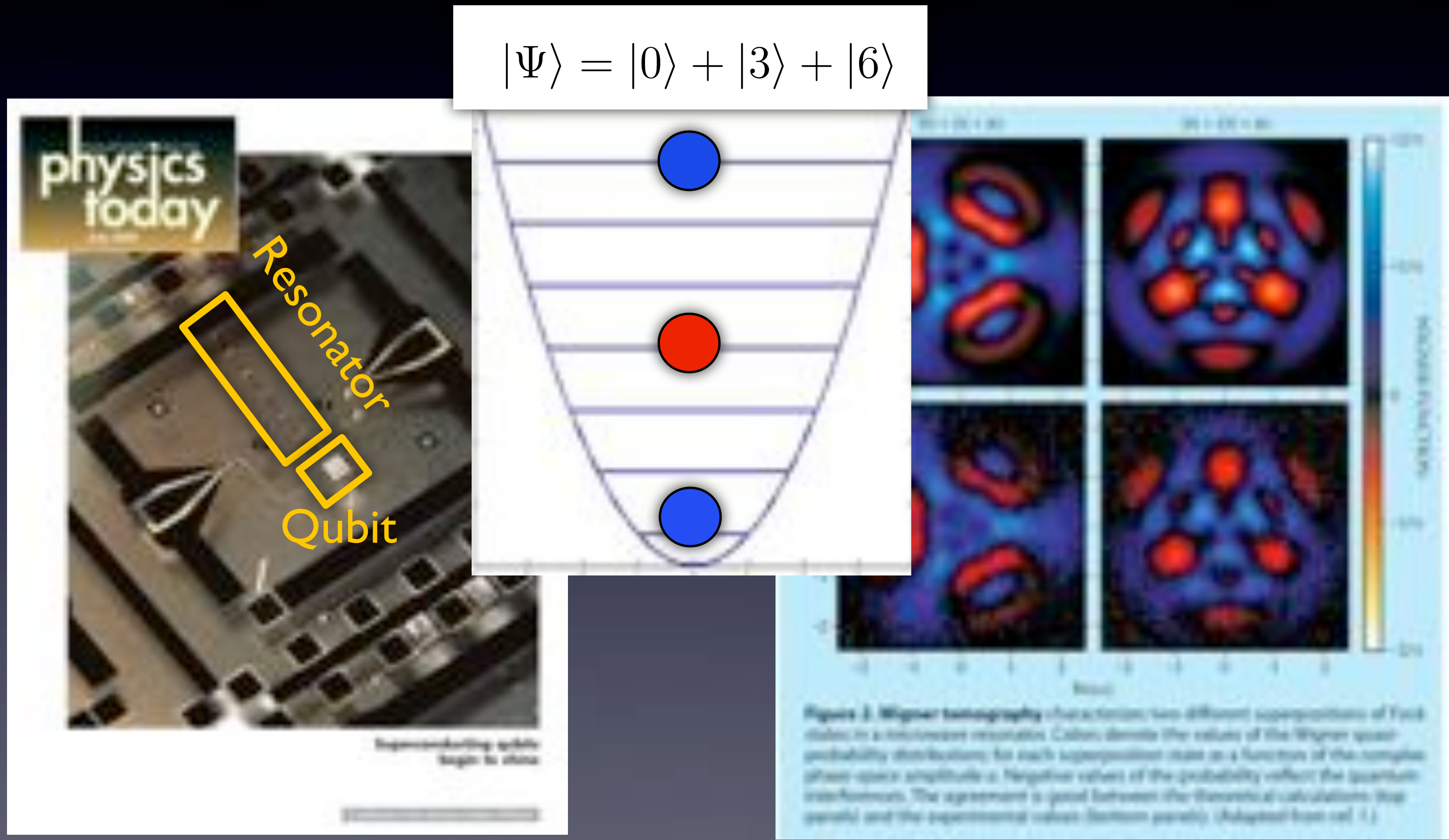

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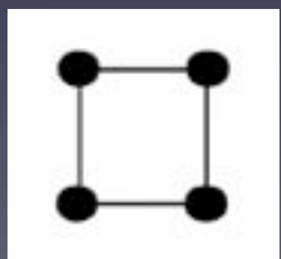
- **Quantum Routing on Networks**
- **Perfect State Transfer on Hypercube Networks**
- **Parallel State Transfer and Efficient Quantum Routing**
- **Quantum Computing with Superconducting Resonators**

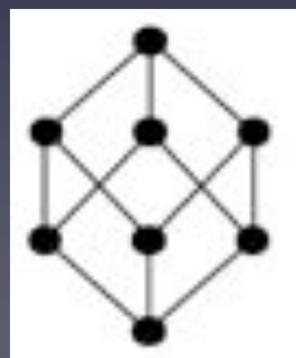
Quantum Networks

- Quantum computers require ***many qubits*** that can quickly communicate with each other.
- A possible solution is to couple qubits (or oscillators) as a ***hypercube network.*** (each node represents a qubit, coupled to some other qubits)
- These networks could be implemented using superconducting qubits!

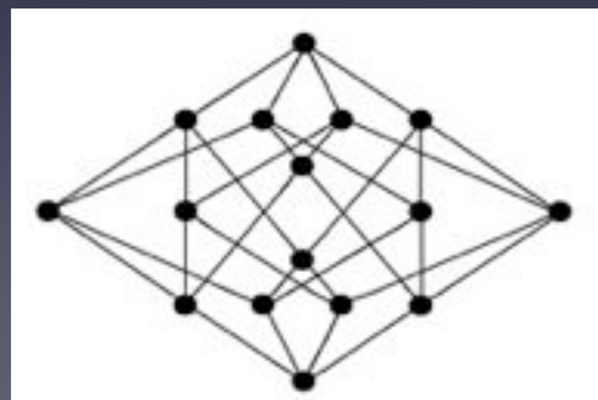
d = 1



d = 2



d = 3



d = 4

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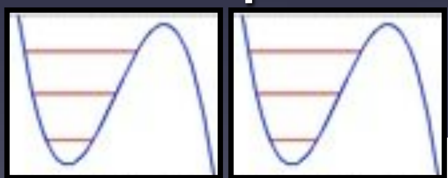
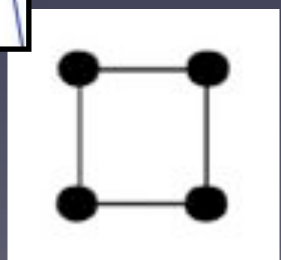


d = 1



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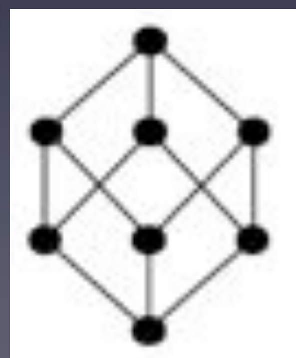

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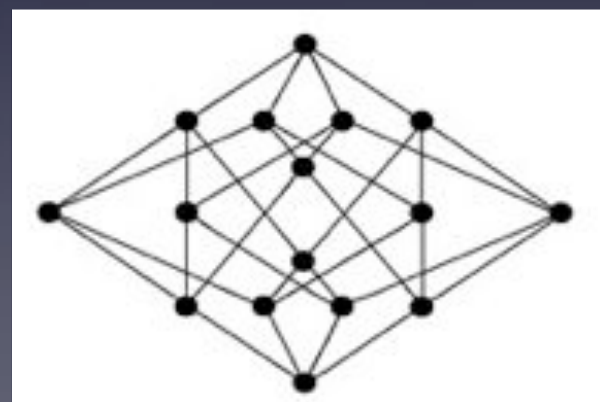

d = 4

Quantum Routing: Schematic

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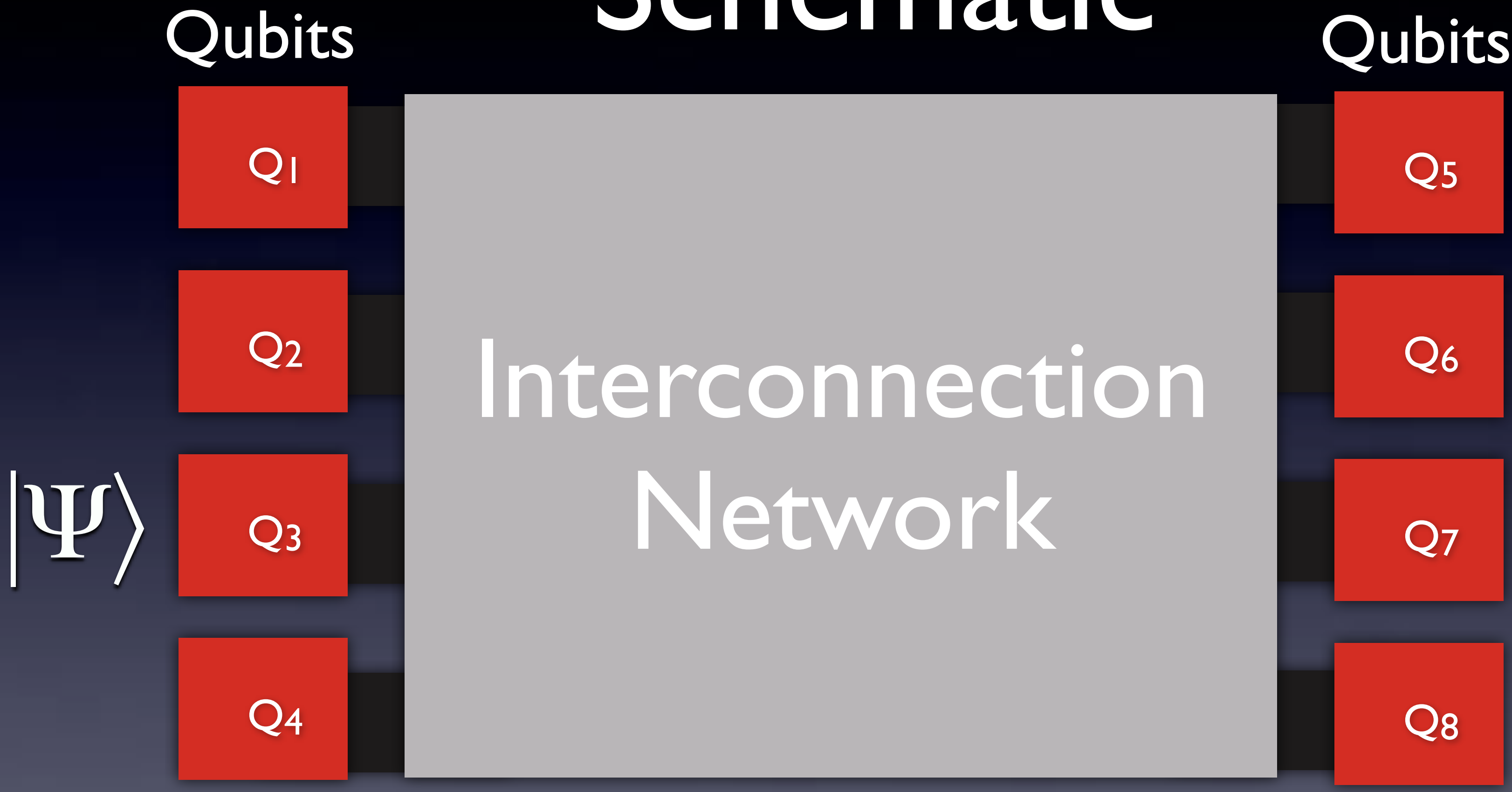

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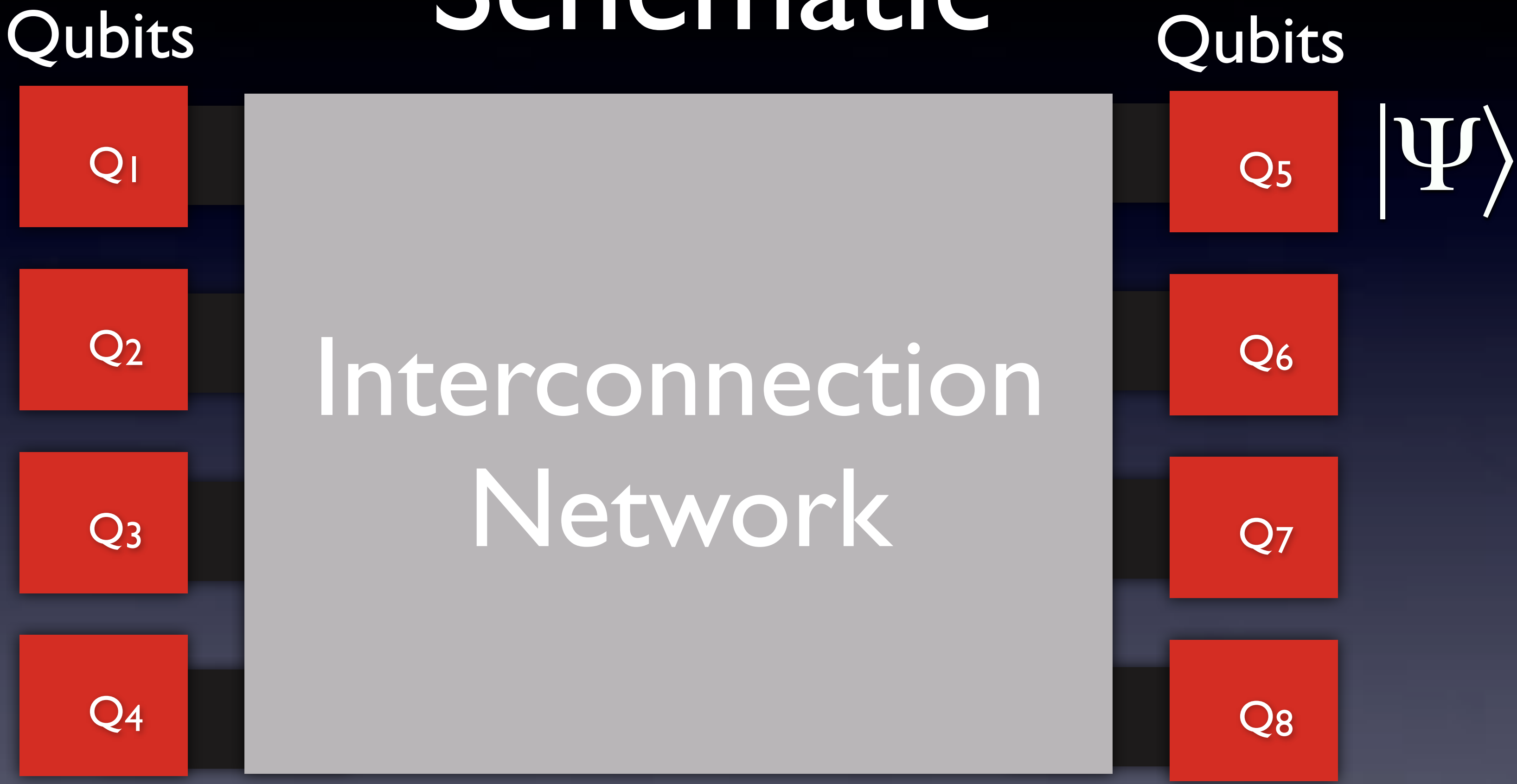

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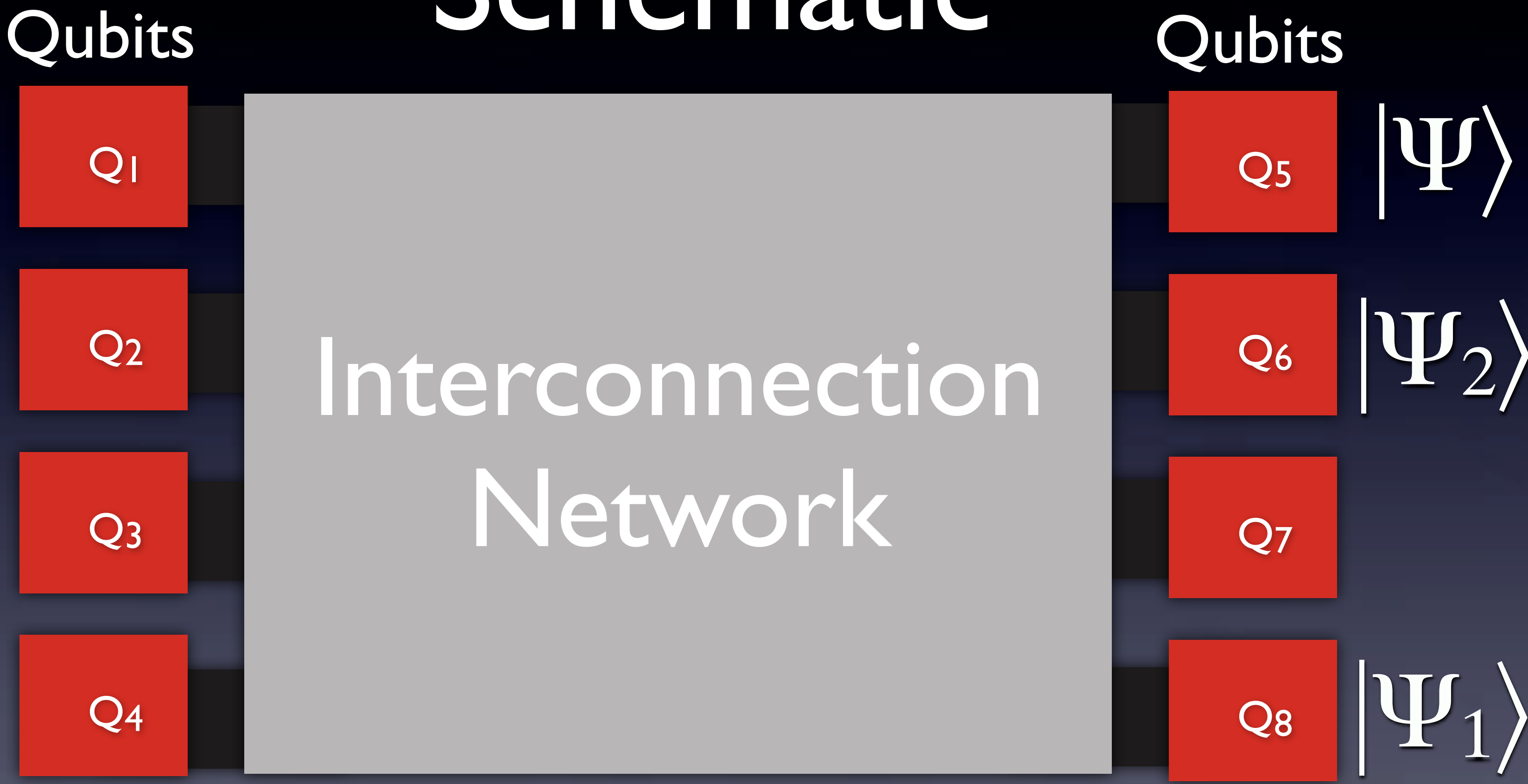

Quantum Routing

- **Goal:** Use a network of elements (qubits or resonators) to transfer quantum information.
- **Programmable**---send information between any two nodes.
- **Parallel**---information between different pairs of nodes can be sent at the same time.
- Ideally suited for **entanglement distribution** between distinct registers for **teleportation**, error detection, ancilla preparation, and other steps toward fault tolerance.

Entanglement⇒Teleportation

- Discovered by Bennett, Brassed, Crepeau, Jozsa, Peres, Wootters
- Very useful for quantum computers!

Very Unlikely

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Very Unlikely

but who knows?

Why Hypercubes?

- Transfer of a single quantum state is governed by a matrix differential equation:

$$i\frac{d\Psi}{dt} = \omega A \Psi$$

- ω is a frequency
- A is the adjacency matrix of the network (graph)
  - A_{jk} = 1 if nodes j and k are connected
  - A_{jk} = 0 if nodes j and k are not connected
- Two nodes: (pair):

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \quad A_{\text{pair}} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Quantum State Transfer

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

$$A_{\text{pair}} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\Psi(t) = \exp(-i\omega A_{\text{pair}} t)\Psi(0)$$

$$\exp(-i\omega A_{\text{pair}} t) = \begin{pmatrix} \cos(\omega t) & -i\sin(\omega t) \\ -i\sin(\omega t) & \cos(\omega t) \end{pmatrix}$$

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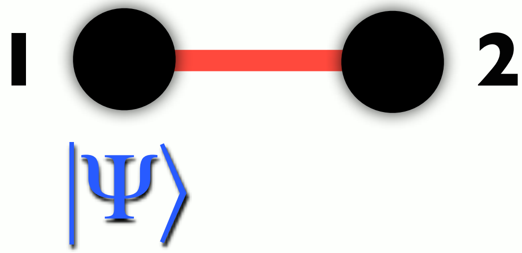

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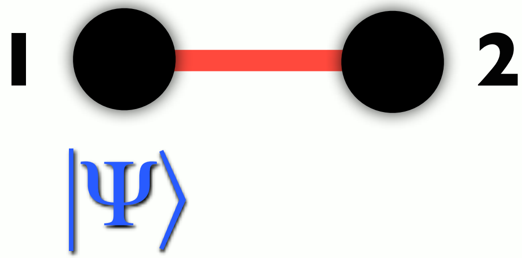

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Quantum State Transfer

Quantum state oscillates (swaps) between 1 and 2

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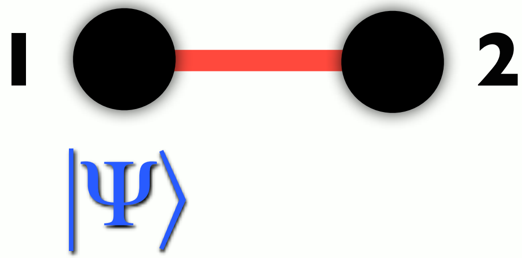

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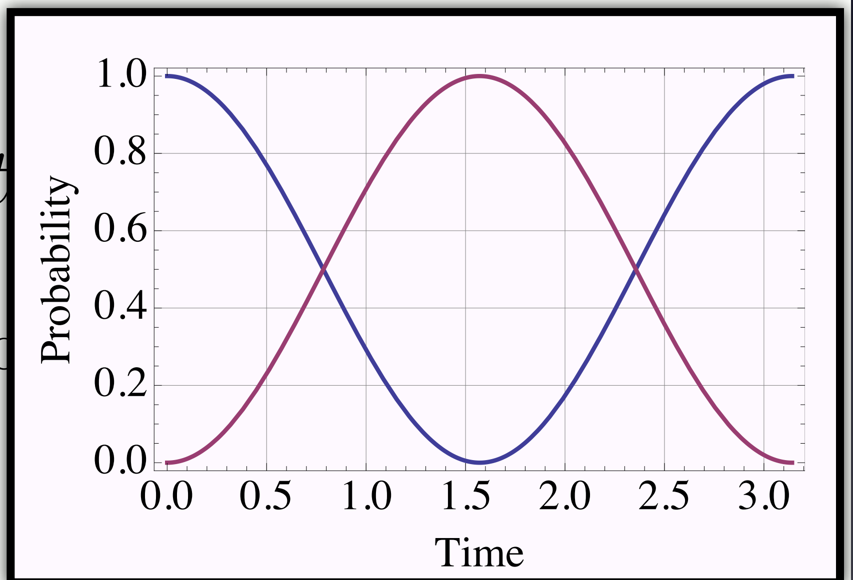
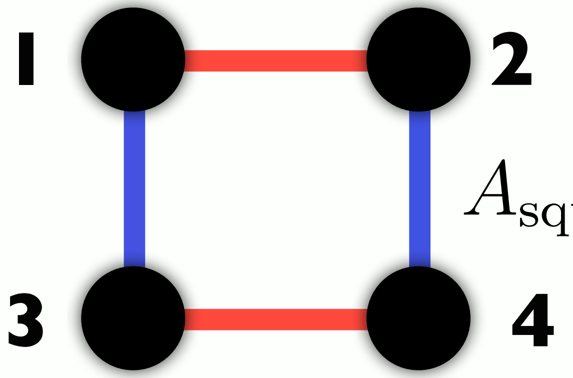


Why Hypercubes ??

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$



$$A_{\text{square}} = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$$\exp(-i\omega A_{\text{square}} t) = \begin{pmatrix} c & -is & 0 & 0 \\ -is & c & 0 & 0 \\ 0 & 0 & c & -is \\ 0 & 0 & -is & c \end{pmatrix} \times \begin{pmatrix} c & 0 & -is & 0 \\ 0 & c & 0 & -is \\ -is & 0 & c & 0 \\ 0 & -is & 0 & c \end{pmatrix} \tag{7}$$

$$s = \sin(\omega t) \quad c = \cos(\omega t)$$

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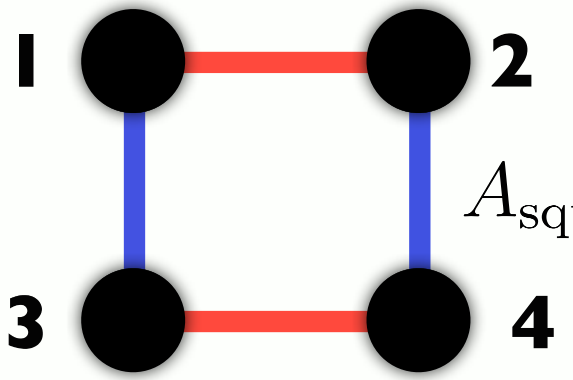

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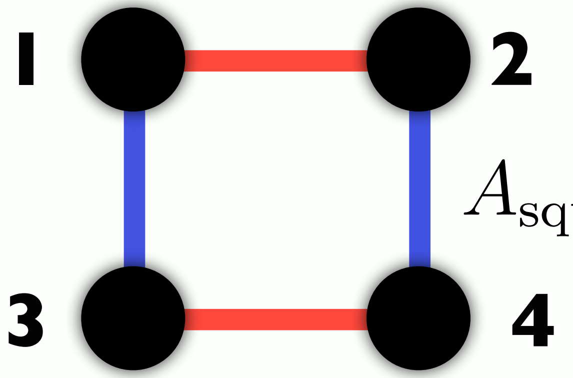

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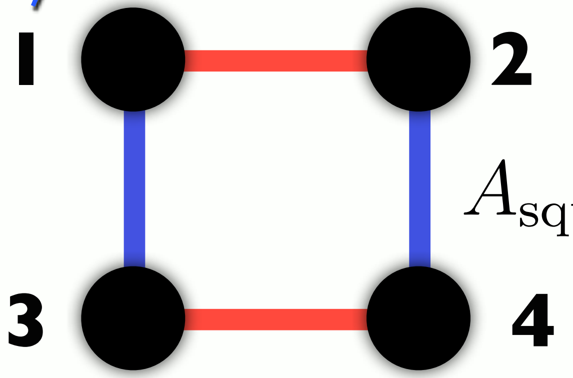

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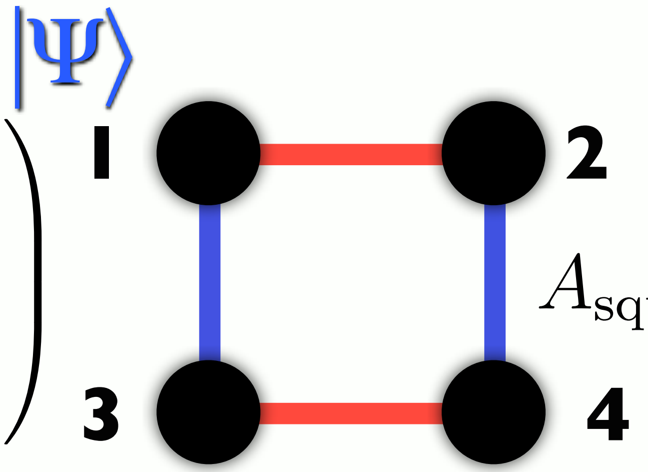

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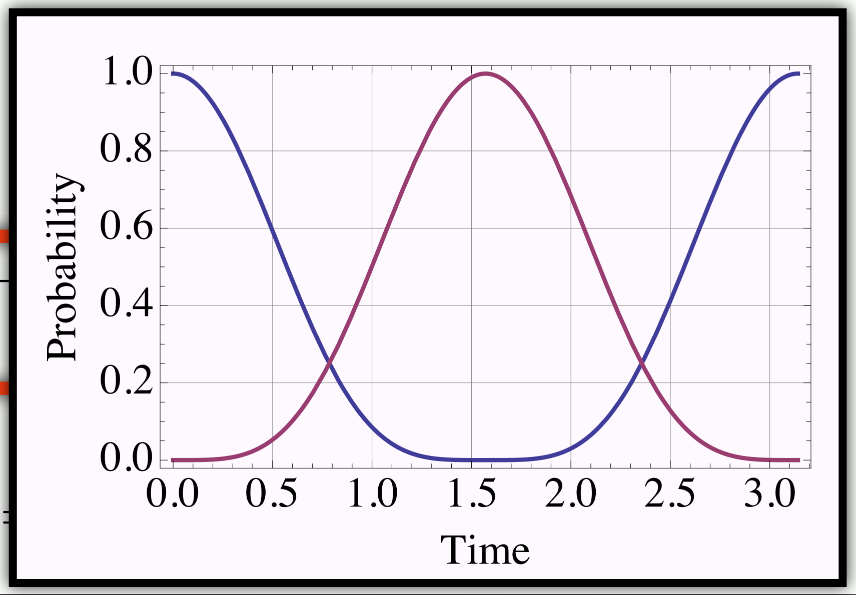

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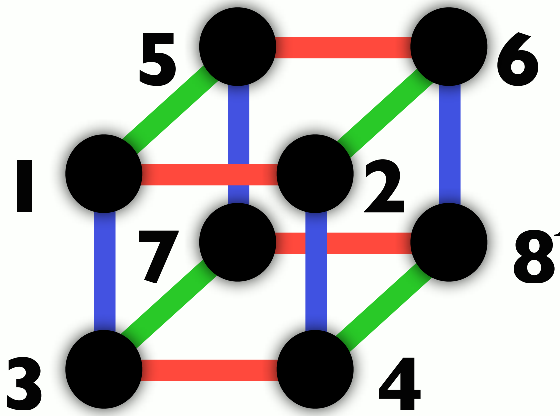

$$A_{\rm cube} = \begin{pmatrix} 0&1&1&0&1&0&0&0 \\ 1&0&0&1&0&1&0&0 \\ 1&0&0&1&0&0&1&0 \\ 0&1&1&0&0&0&0&1 \\ 1&0&0&0&0&1&1&0 \\ 0&1&0&0&1&0&0&1 \\ 0&0&1&0&1&0&0&1 \\ 0&0&0&1&0&1&1&0 \end{pmatrix}$$

$$\exp(-i\omega A_{\rm cube} t) = \begin{pmatrix} c&-is&0&0&0&0&0&0 \\ -is&c&0&0&0&0&0&0 \\ 0&0&c&-is&0&0&0&0 \\ 0&0&-is&c&0&0&0&0 \\ 0&0&0&0&c&-is&0&0 \\ 0&0&0&0&-is&c&0&0 \\ 0&0&0&0&0&0&c&-is \\ 0&0&0&0&0&0&-is&c \end{pmatrix} \begin{pmatrix} c&0&-is&0&0&0&0&0 \\ 0&c&0&-is&0&0&0&0 \\ -is&0&c&0&0&0&0&0 \\ 0&-is&0&c&0&0&0&0 \\ 0&0&0&0&c&0&-is&0 \\ 0&0&0&0&0&c&0&-is \\ 0&0&0&0&-is&0&c&0 \\ 0&0&0&0&0&-is&0&c \end{pmatrix} \begin{pmatrix} c&0&0&0&-is&0&0&0 \\ 0&c&0&0&0&-is&0&0 \\ 0&0&c&0&0&0&-is&0 \\ 0&0&0&c&0&0&0&-is \\ -is&0&0&0&c&0&0&0 \\ 0&-is&0&0&0&c&0&0 \\ 0&0&-is&0&0&0&c&0 \\ 0&0&0&-is&0&0&0&c \end{pmatrix}$$

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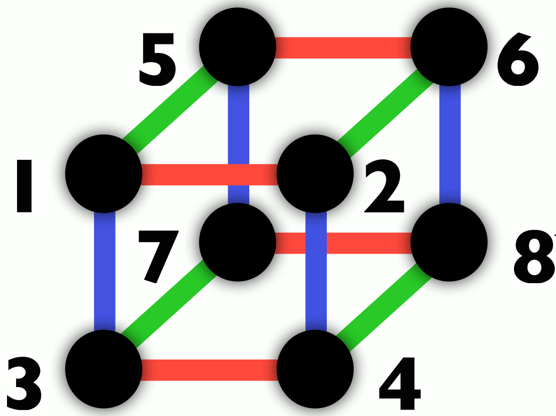
$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \\ \psi_5 \\ \psi_6 \\ \psi_7 \\ \psi_8 \end{pmatrix}$$

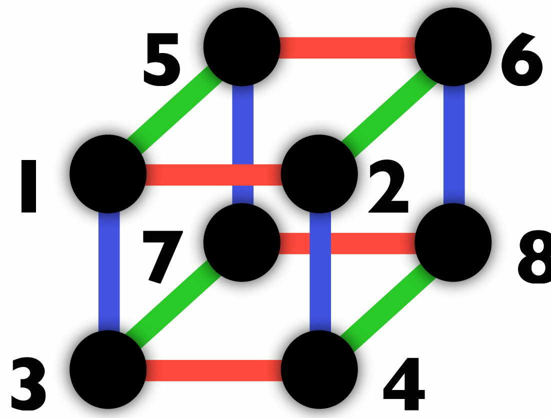


$$A_{\text{cube}} = \begin{pmatrix} 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{pmatrix}$$

$$\exp(-i\omega A_{\text{cube}} t) = \begin{pmatrix} c & -is & 0 & 0 & 0 & 0 & 0 & 0 \\ -is & c & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & c & -is & 0 & 0 & 0 & 0 \\ 0 & 0 & -is & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & -is & 0 & 0 \\ 0 & 0 & 0 & 0 & -is & c & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & c & -is \\ 0 & 0 & 0 & 0 & 0 & 0 & -is & c \end{pmatrix} \begin{pmatrix} c & 0 & -is & 0 & 0 & 0 & 0 & 0 \\ 0 & c & 0 & -is & 0 & 0 & 0 & 0 \\ -is & 0 & c & 0 & 0 & 0 & 0 & 0 \\ 0 & -is & 0 & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & 0 & -is & 0 \\ 0 & 0 & 0 & 0 & 0 & c & 0 & -is \\ 0 & 0 & 0 & 0 & -is & 0 & c & 0 \\ 0 & 0 & 0 & 0 & 0 & -is & 0 & c \end{pmatrix} \begin{pmatrix} c & 0 & 0 & 0 & -is & 0 & 0 & 0 \\ 0 & c & 0 & 0 & 0 & -is & 0 & 0 \\ 0 & 0 & c & 0 & 0 & 0 & -is & 0 \\ 0 & 0 & 0 & c & 0 & 0 & 0 & -is \\ -is & 0 & 0 & 0 & c & 0 & 0 & 0 \\ 0 & -is & 0 & 0 & 0 & c & 0 & 0 \\ 0 & 0 & -is & 0 & 0 & 0 & c & 0 \\ 0 & 0 & 0 & -is & 0 & 0 & 0 & c \end{pmatrix}$$

Why Hypercubes ???

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \\ \psi_5 \\ \psi_6 \\ \psi_7 \\ \psi_8 \end{pmatrix}$$



$$A_{\text{cube}} = \begin{pmatrix} 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{pmatrix}$$

"Simple" matrices for each direction!

$$\exp(-i\omega A_{\text{cube}} t) = \begin{pmatrix} c & -is & 0 & 0 & 0 & 0 & 0 & 0 \\ -is & c & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & c & -is & 0 & 0 & 0 & 0 \\ 0 & 0 & -is & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & -is & 0 & 0 \\ 0 & 0 & 0 & 0 & -is & c & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & c & -is \\ 0 & 0 & 0 & 0 & 0 & 0 & -is & c \end{pmatrix} \begin{pmatrix} c & 0 & -is & 0 & 0 & 0 & 0 & 0 \\ 0 & c & 0 & -is & 0 & 0 & 0 & 0 \\ -is & 0 & c & 0 & 0 & 0 & 0 & 0 \\ 0 & -is & 0 & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & 0 & -is & 0 \\ 0 & 0 & 0 & 0 & 0 & c & 0 & -is \\ 0 & 0 & 0 & 0 & -is & 0 & c & 0 \\ 0 & 0 & 0 & 0 & 0 & -is & 0 & c \end{pmatrix} \begin{pmatrix} c & 0 & 0 & 0 & -is & 0 & 0 & 0 \\ 0 & c & 0 & 0 & 0 & -is & 0 & 0 \\ 0 & 0 & c & 0 & 0 & 0 & -is & 0 \\ 0 & 0 & 0 & c & 0 & 0 & 0 & -is \\ -is & 0 & 0 & 0 & c & 0 & 0 & 0 \\ 0 & -is & 0 & 0 & 0 & c & 0 & 0 \\ 0 & 0 & -is & 0 & 0 & 0 & c & 0 \\ 0 & 0 & 0 & -is & 0 & 0 & 0 & c \end{pmatrix}$$

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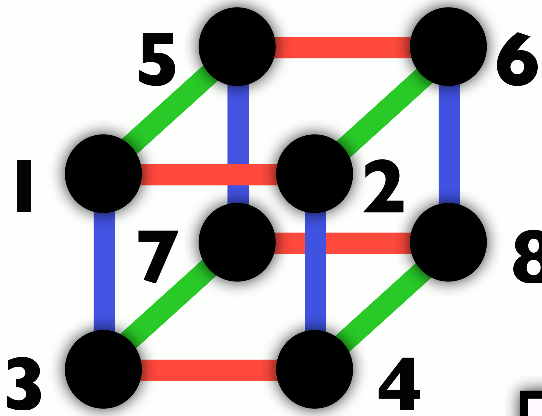
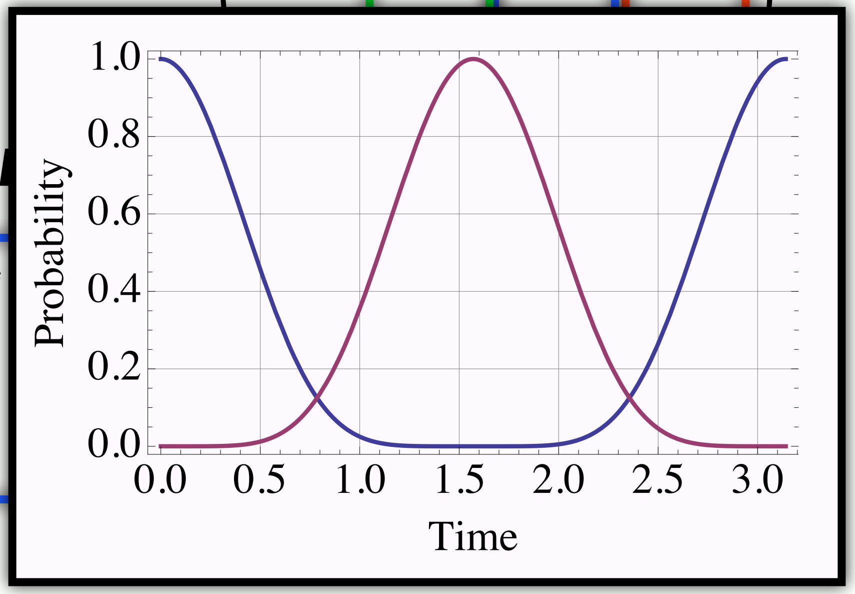


$$A_{\text{cube}} = \begin{pmatrix} 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \end{pmatrix}$$

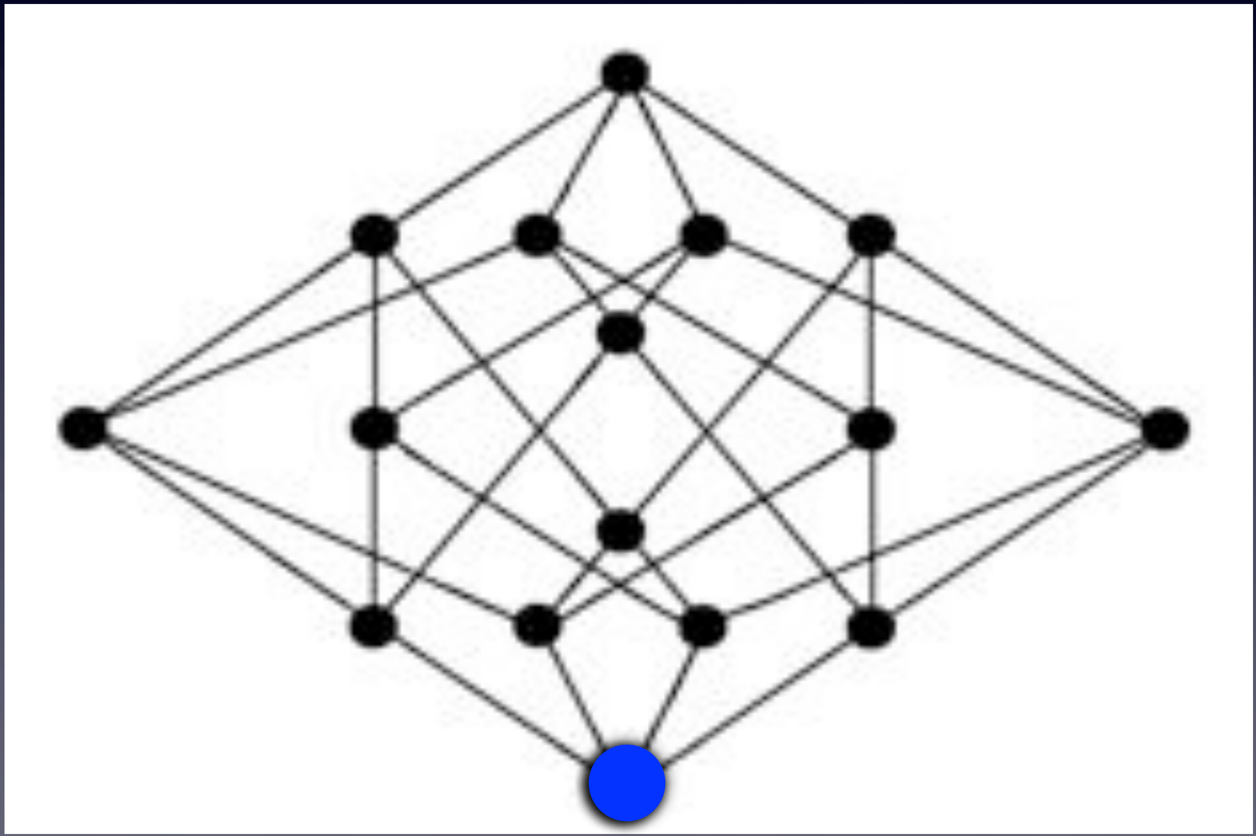
“Simple” matrices fo

$$\exp(-i\omega A_{\text{cube}} t) = \begin{pmatrix} c & -is & 0 & 0 & 0 & 0 & 0 & 0 \\ -is & c & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & c & -is & 0 & 0 & 0 & 0 \\ 0 & 0 & -is & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & -is & 0 & 0 \\ 0 & 0 & 0 & 0 & -is & c & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & c & -is \\ 0 & 0 & 0 & 0 & 0 & 0 & -is & c \end{pmatrix} \begin{pmatrix} c & 0 & -is \\ 0 & c & 0 \\ -is & 0 & c \\ 0 & -is & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



Hypercube State Transfer

- Each node represents a qubit. Quantum states travel along **all paths simultaneously** in superposition with **full constructive interference,** yielding **perfect state transfer.**



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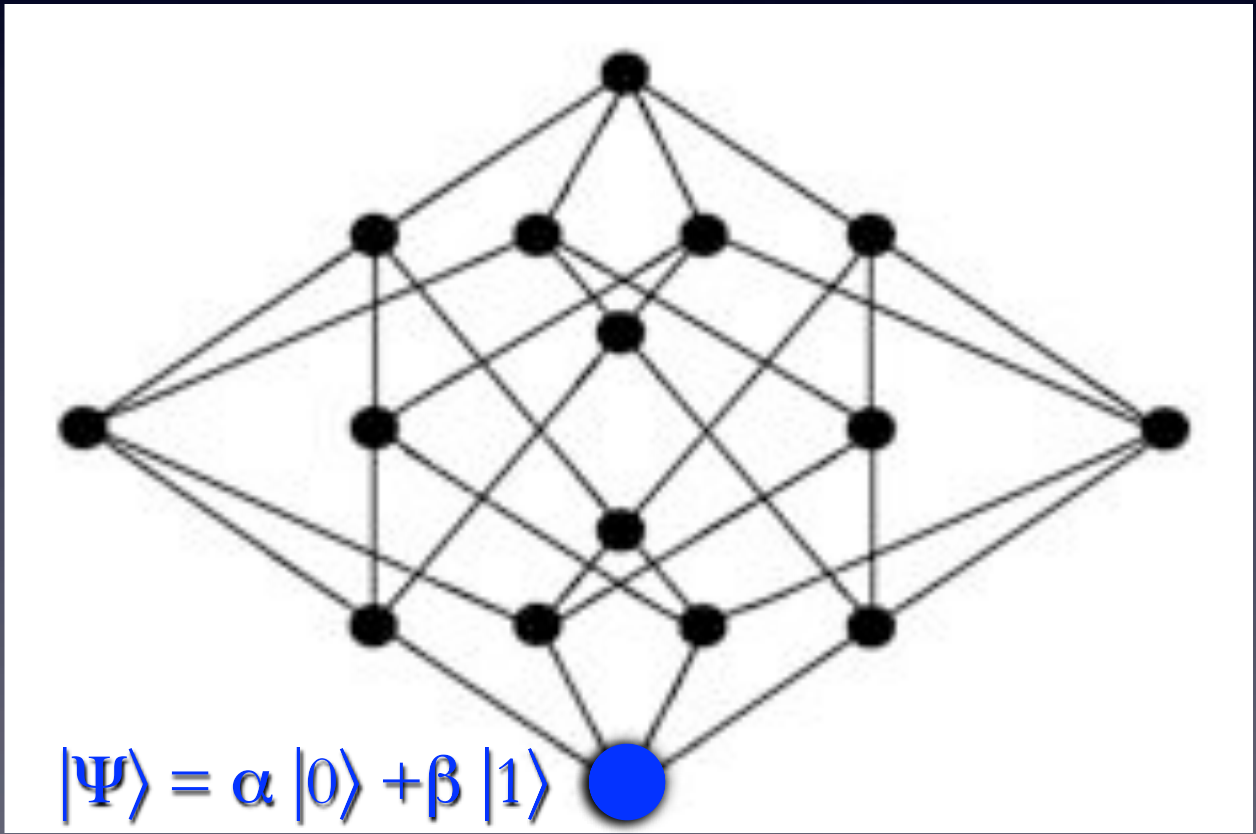

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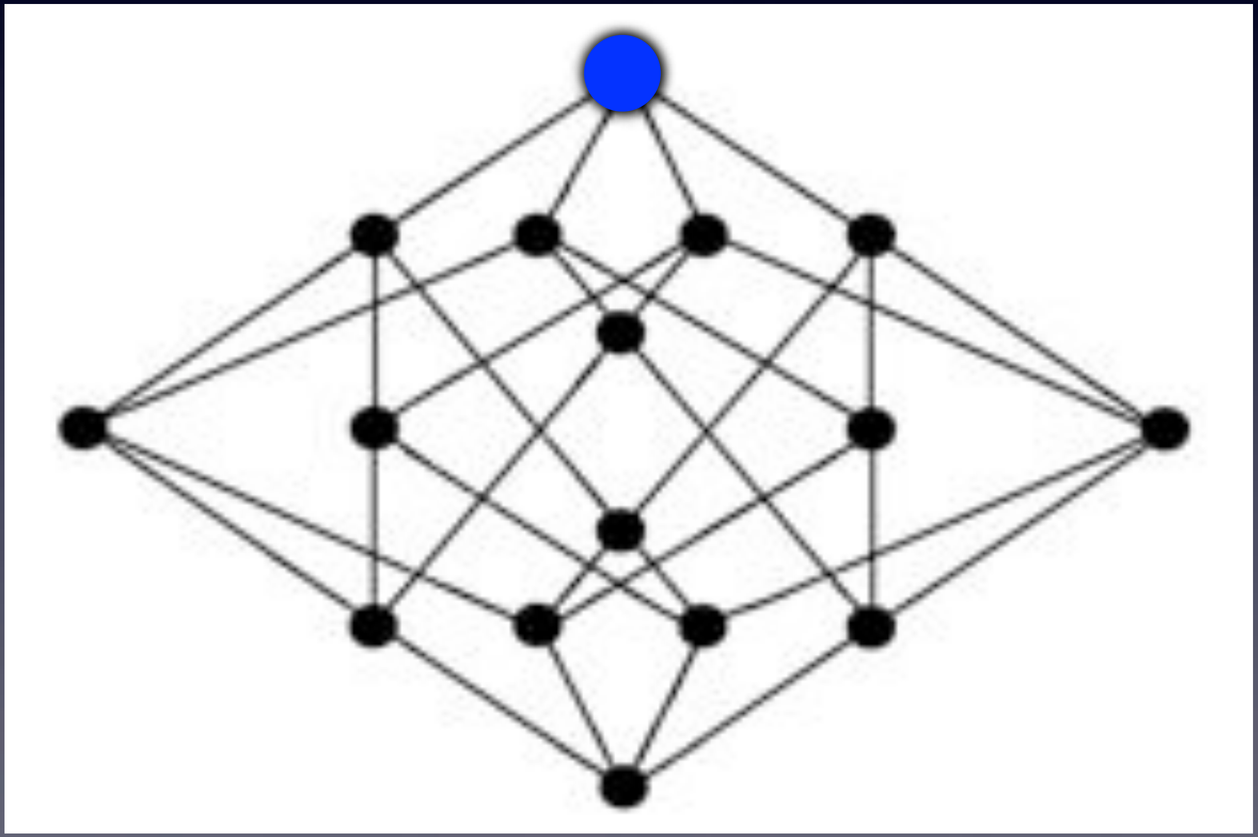

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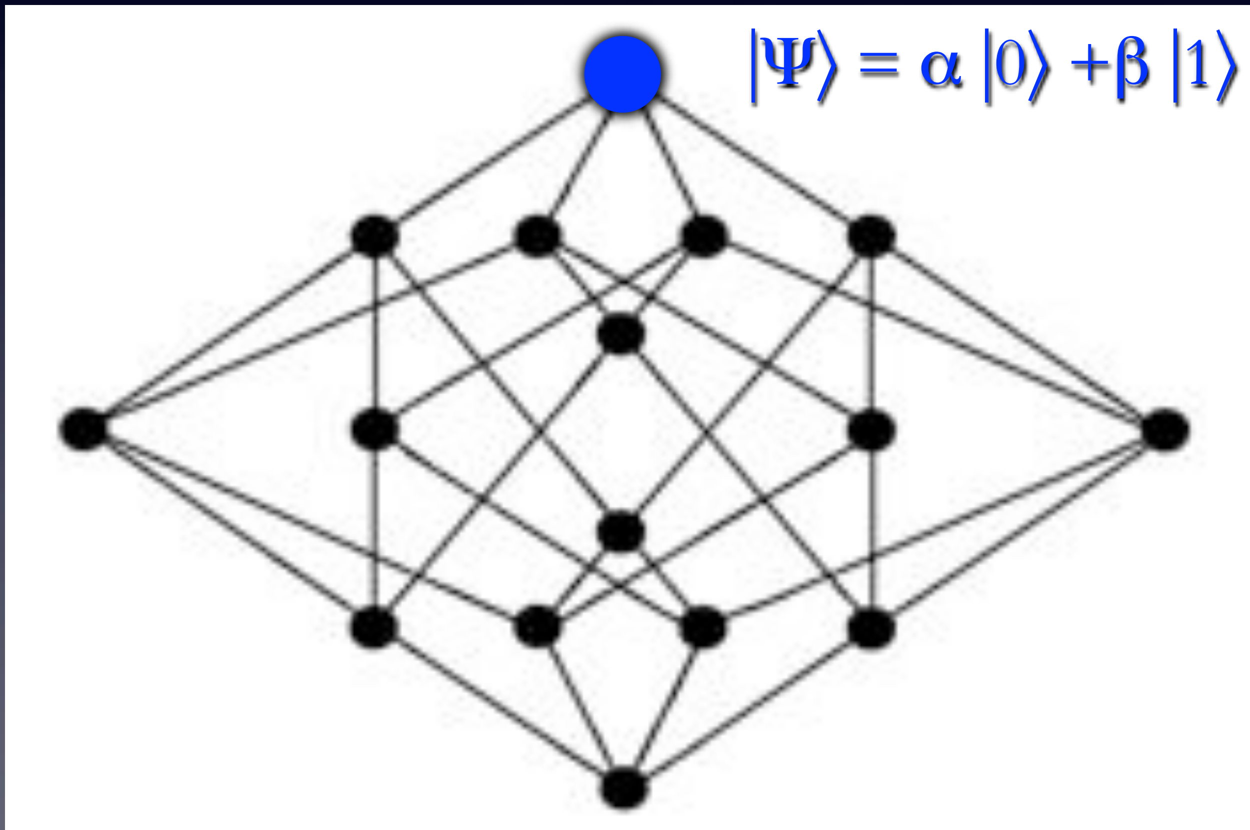


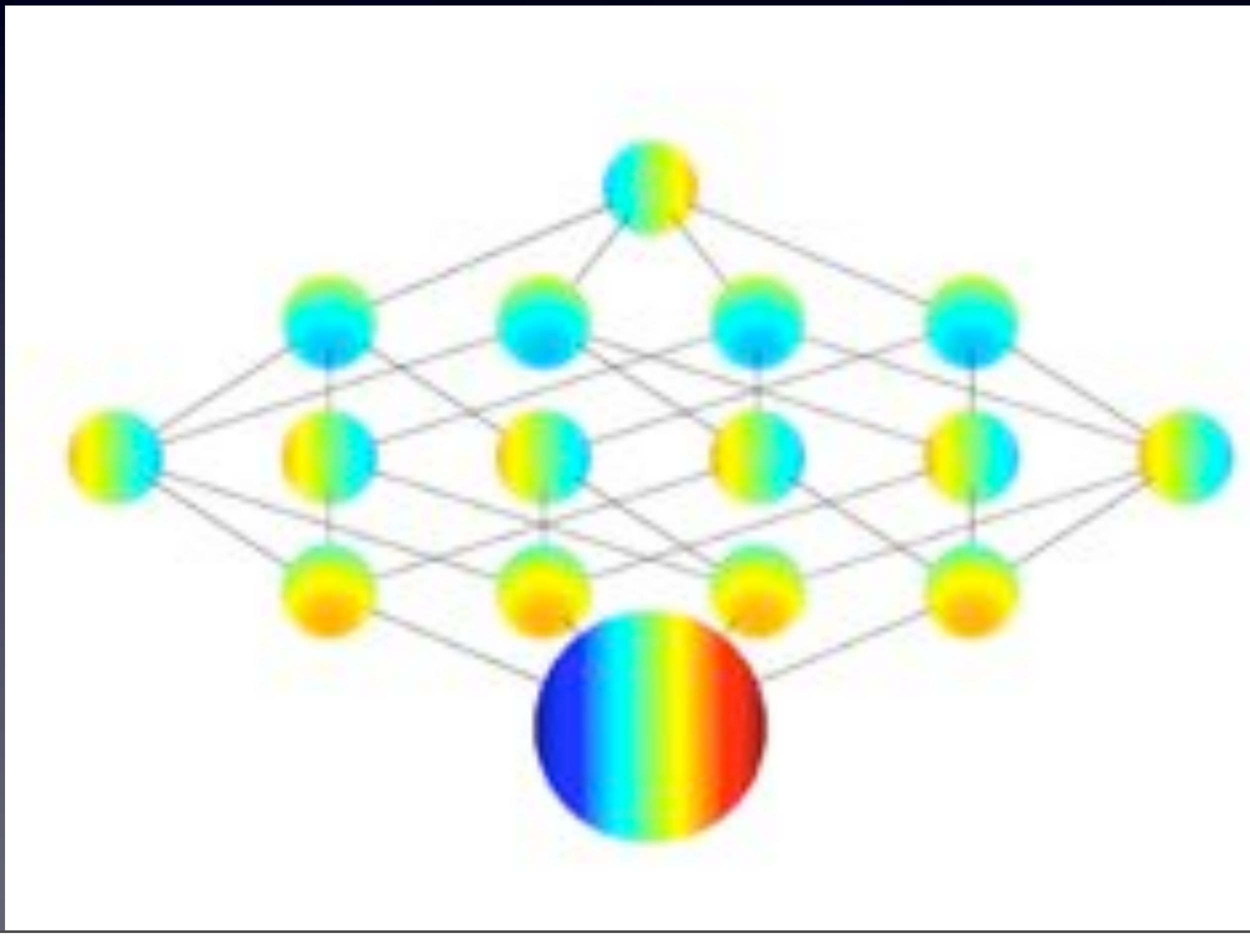
Exact Calculation

with Qiao Zhang '13

$\Psi = |\Psi| e^{i\theta}$

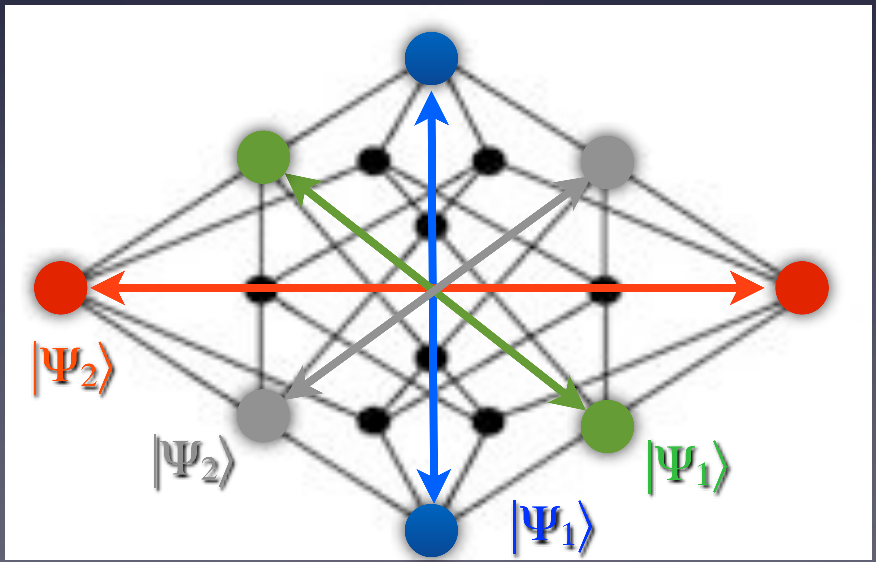
Size of Sphere ~ $|\Psi|$

Orientation of Sphere ~ θ



Parallel State Transfer

- Transmit multiple quantum states at the same time!
- Use Oscillator Networks:
  Each node has an infinite number of states!
- **Calculation** not as simple, but still **exactly solvable.**



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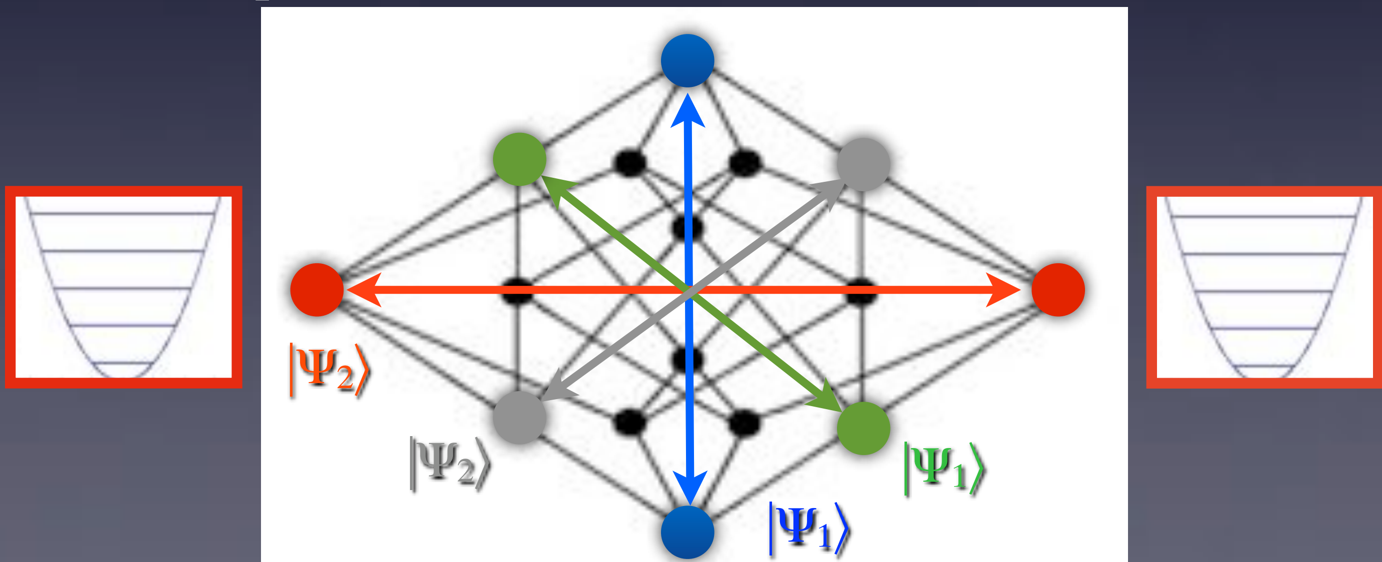
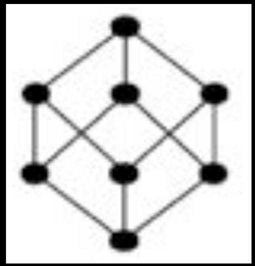
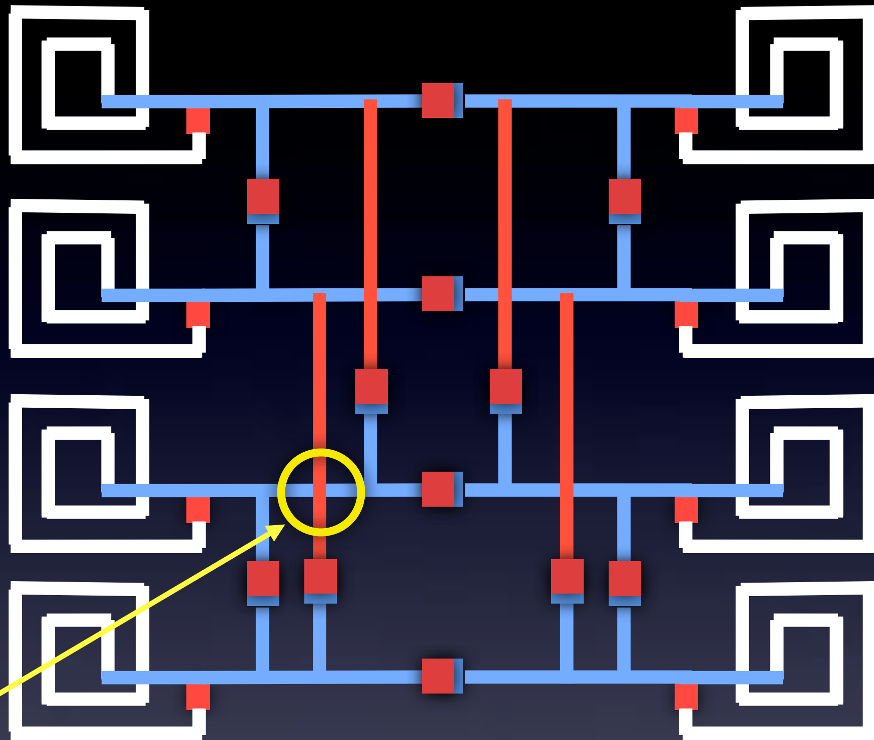
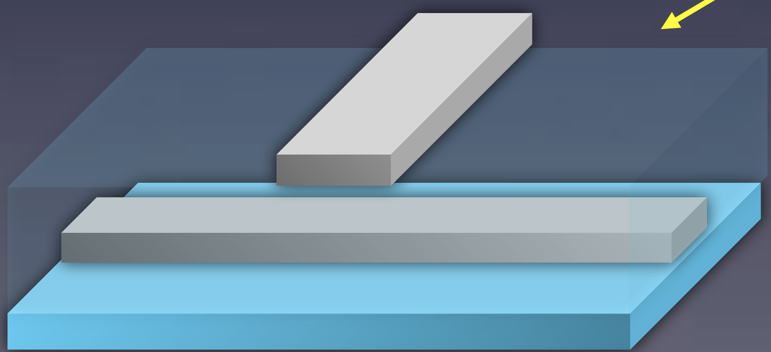




Phase Qubit Cube 1 2 3

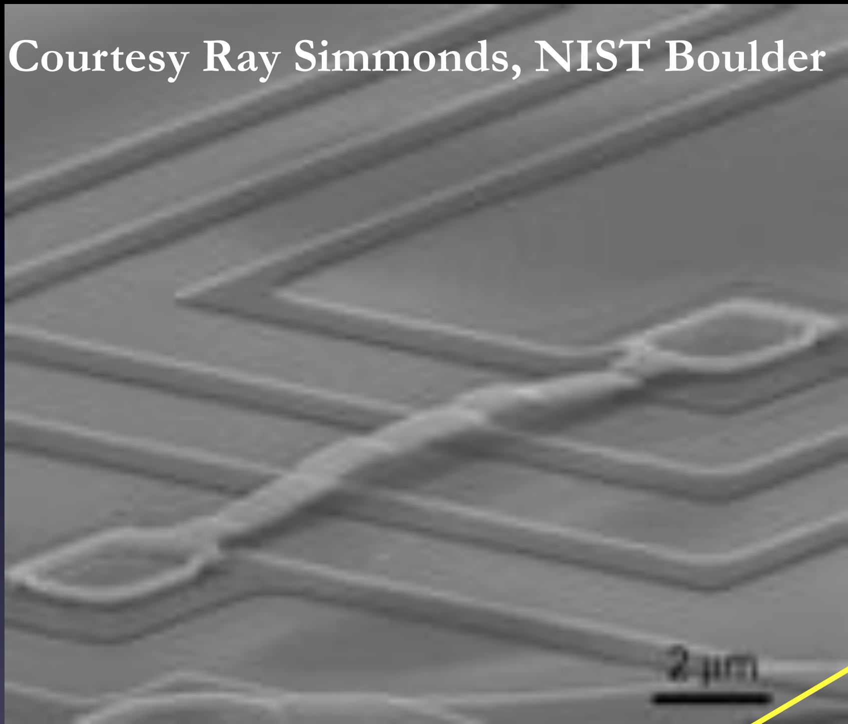


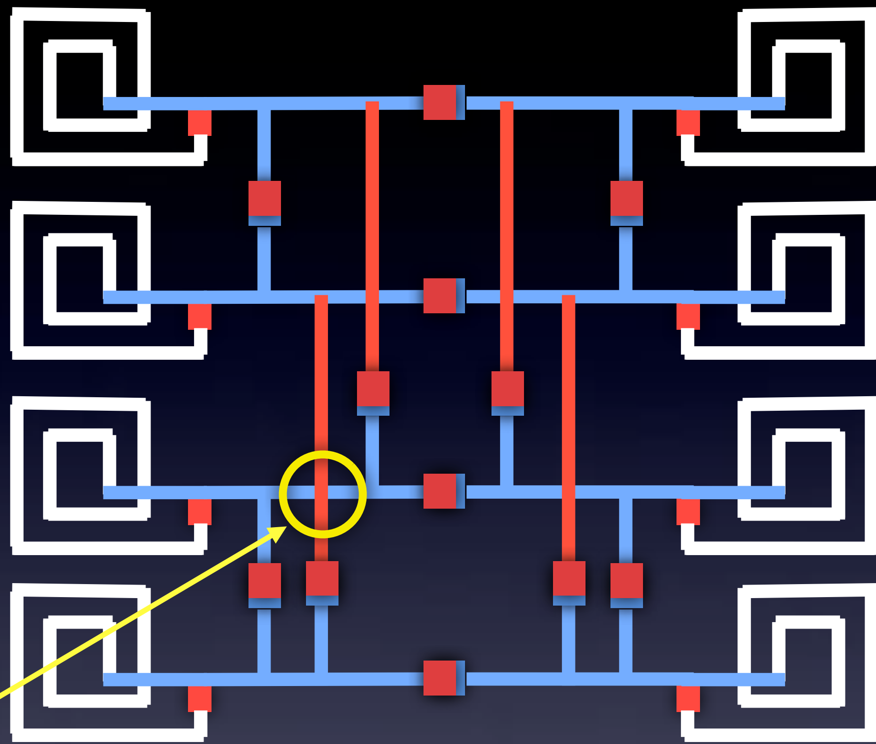
- *Circuits do not need to be simple two-dimensional layouts.*
- *Multi-layer interconnects allow many crossovers and complex couplings.*

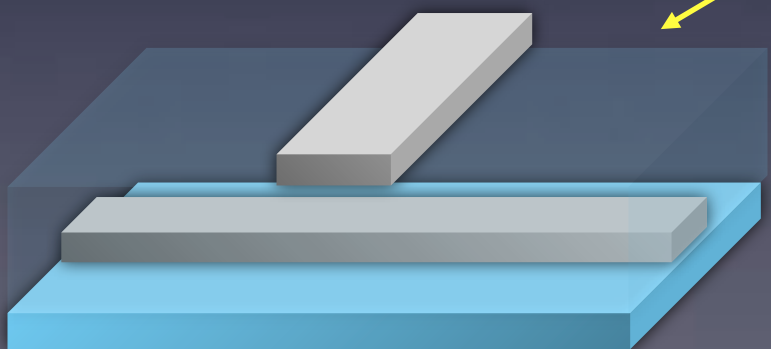


Fabrication Process of Planarized Multi-Layer Nb Integrated Circuits

Phase Qubit Cube 1 2 3







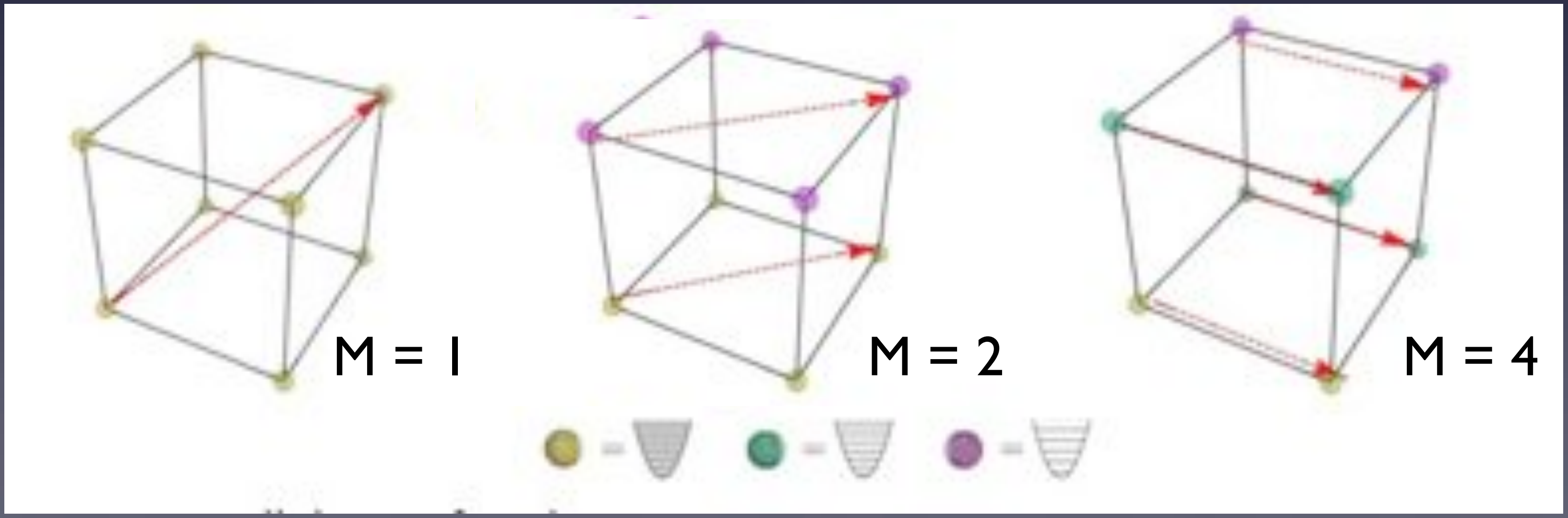

Fabrication Process of Planarized Multi-Layer Nb Integrated Circuits

Outline

- ~~Superconducting Qubits and Resonators~~
- ~~Quantum Routing on Networks~~
- ~~Perfect State Transfer on Hypercube Networks~~
- **Parallel State Transfer and Efficient Quantum Routing**
- **Quantum Computing with Superconducting Resonators**

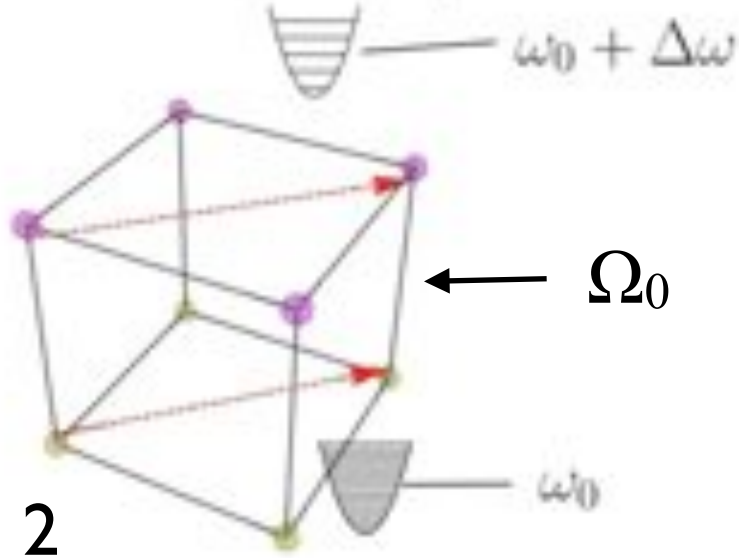
Chris Chudzicki's Senior Thesis

- Study tunable resonators: exactly solvable!
- Split cube into M subcubes by resonator frequencies. ***(Matrices are still simple!)***
- Send quantum states in parallel.

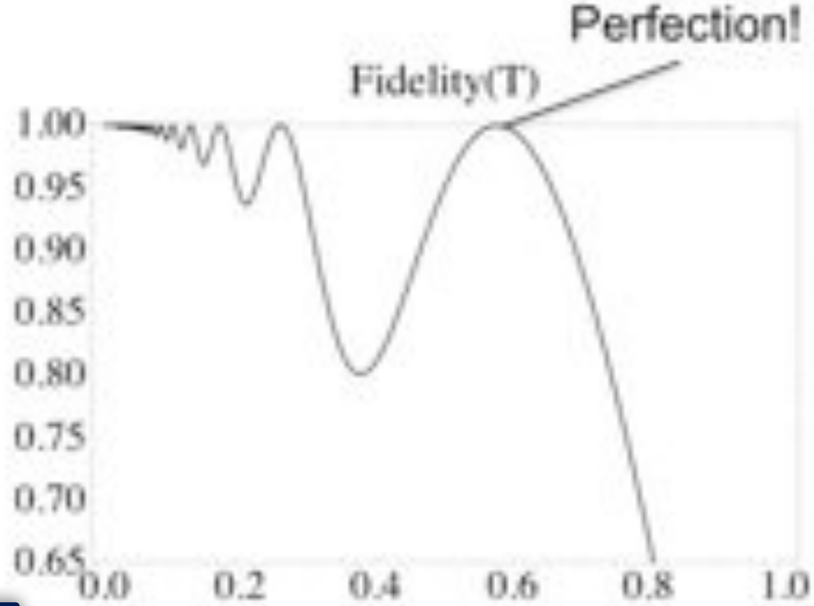


Parallel Transfer Fidelity

Fidelity = Probability of successfully transmitting a quantum state



M = 2



$$F(T) \gtrsim 1 - \frac{3}{2} \log_2(M)\, \eta^2 \sin^2 \xi_T$$

$$\eta = 2\Omega_0 / \Delta\omega$$

Detuning parameter

$$\xi_T = \frac{\pi}{2}\sqrt{1+\eta^{-2}}$$

M = # of parallel "messages"

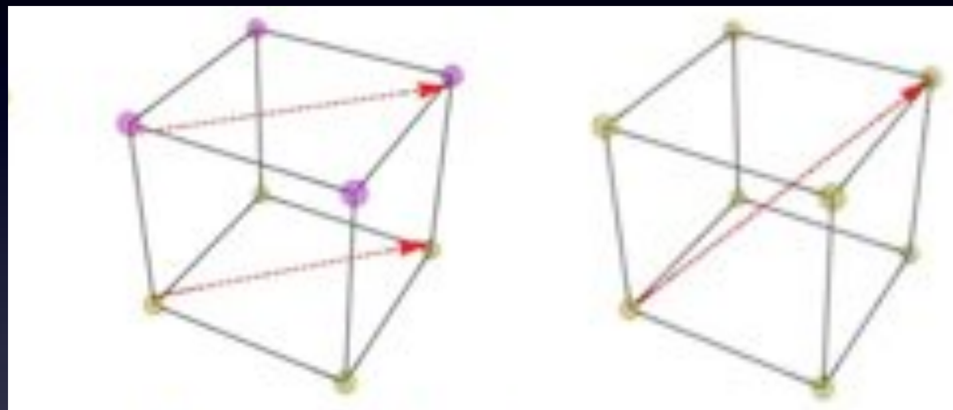
Efficient Quantum Routing

Method to Characterize the Efficiency of Quantum Routing by Parallel State Transfer

- **Goal** = Distribute entanglement between every pair of nodes ($N = 2^d$ total nodes for a hypercube network)
- Use **parallel state transfer**, sending states on each subcube
- Tune oscillators in a fixed frequency range **(finite bandwidth)**
- **Qubit-Compatible Scheme** = one state on each subcube
- **Massively Parallel Scheme** = multiple states on each subcube
- **Efficiency = Entanglement Distrubution Rate**

Qubit-Compatible Scheme

One state per subcube



$N = 2^d$ nodes total

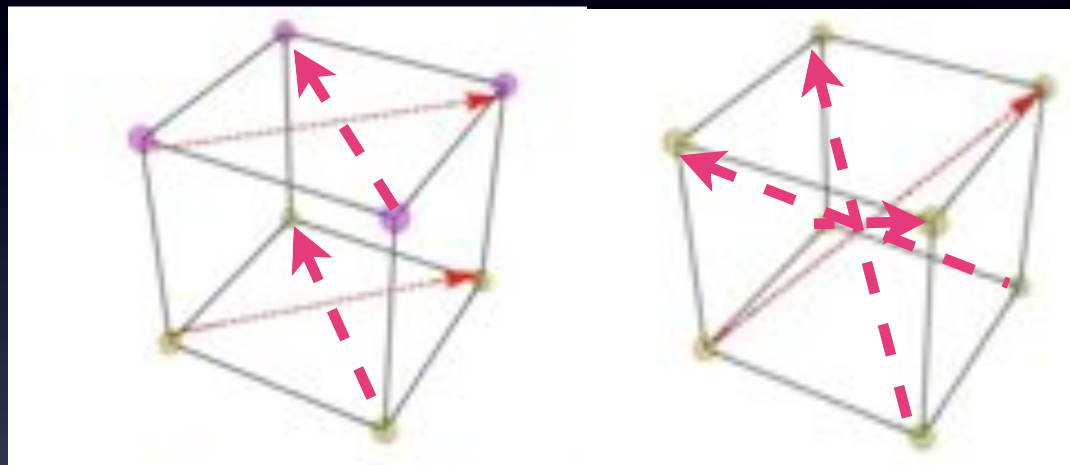
Rate scales as:

$$\mathcal{R}^{(QC)} \approx \frac{1}{T} N^{0.415}\left(1 - \frac{3}{4}\frac{\Omega_0^2}{(\omega_{\max} - \omega_{\min})^2} d^2(d+3)\right),$$

Rate calculation includes full set of "messages," weighted by their fidelities.

Massively Parallel Scheme

Multiple states per subcube



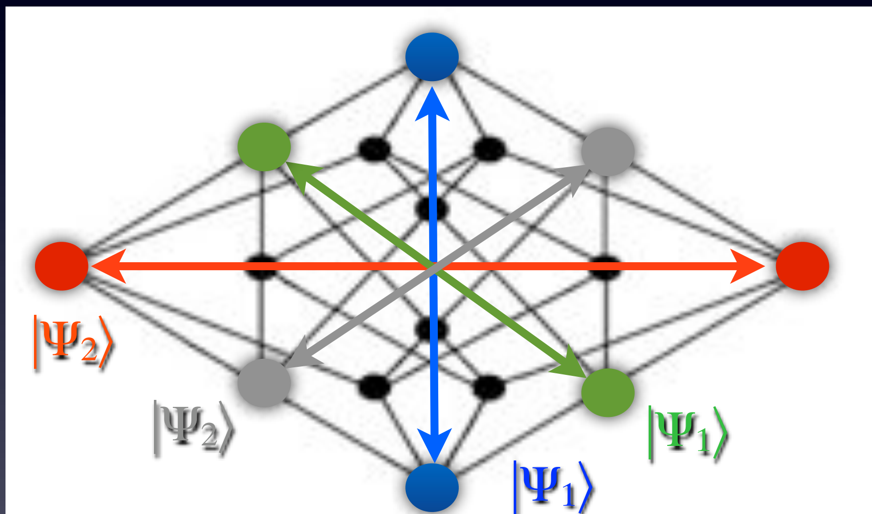
$N = 2^d$ nodes total

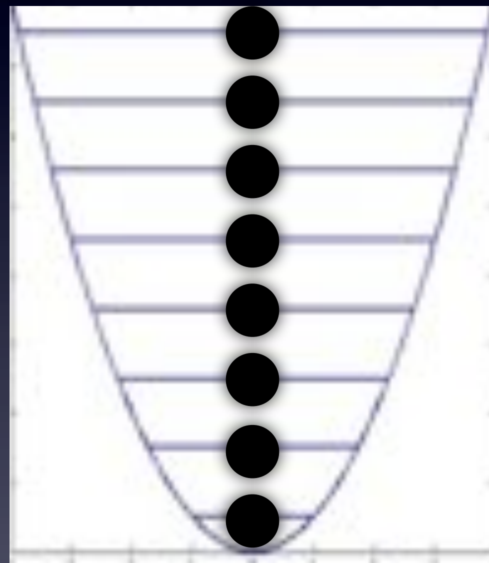
Rate scales as:

$$\mathcal{R}^{(\mathrm{MP})} \approx \frac{1}{T} N \left(1 - \frac{3}{4} \frac{\Omega_0^2}{(\omega_{\max} - \omega_{\min})^2} d^2 (d+3) \right).$$

Massively Parallel Distribution

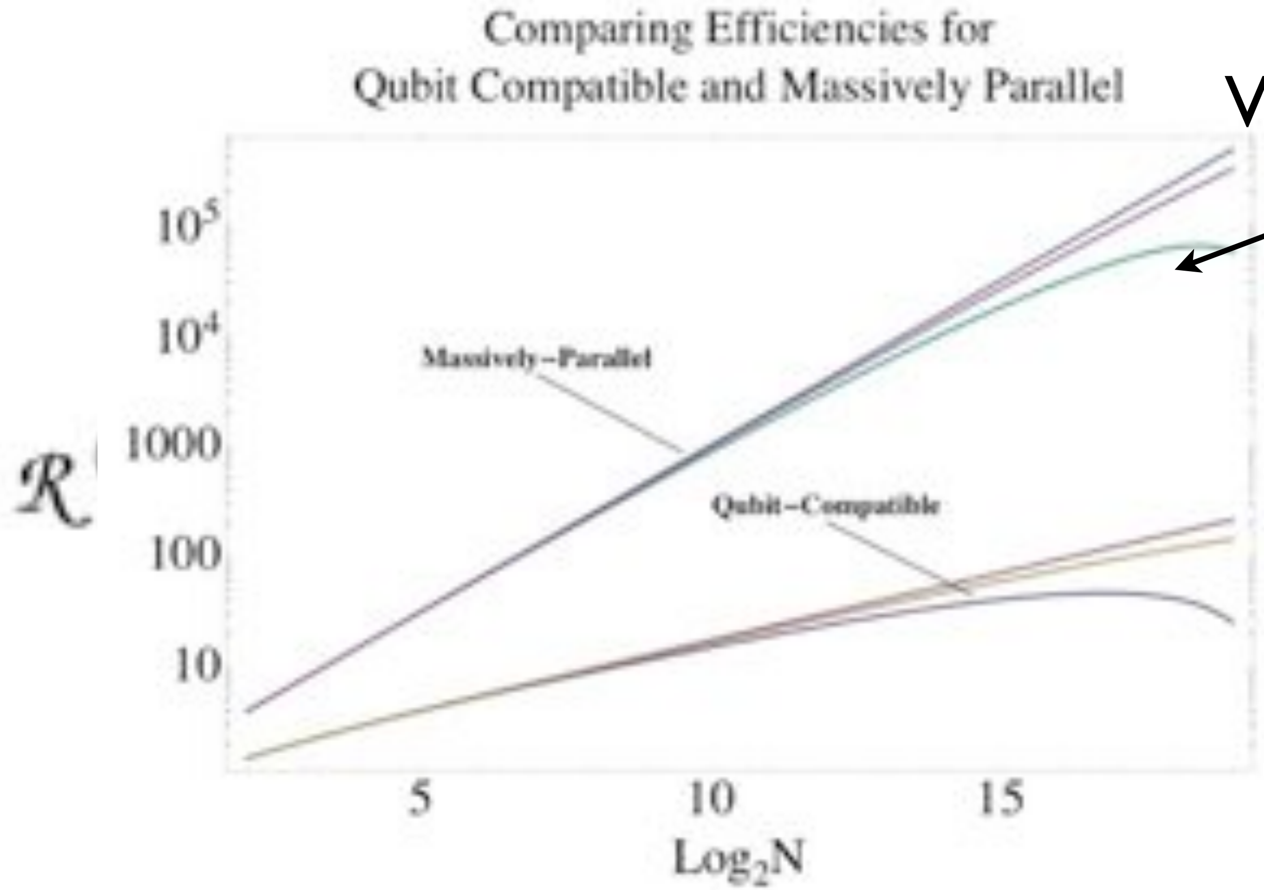
- Send oscillators' states between all corners simultaneously!





- Genuine Quantum Property!
- ***Excitations are noninteracting bosons: multiple photons just pass through each other.***

Massively Parallel Rate



Various Bandwidths

$\mathcal{R}^{(QC)} \propto N^{0.415}$

$\mathcal{R}^{(MP)} \propto N$

(N registers)

Entanglement Distribution using Oscillator Networks is both optimally efficient and robust!

Apker Award

Apker Finalists Meet in Washington

Photo by Shelly Johnston

Each year, APS selects two recipients of the Apker Award for outstanding research by an undergraduate. To determine the recipients, a number of finalists are chosen, and then interviewed by the selection committee. This year, the seven finalists met with the committee in Washington on September 3. They are, left to right: Chia Wei Hsu (Wesleyan University); Martin Blood-Forsythe (Haverford College); Erik Petigura (UC, Berkeley); Benjamin Good (Swarthmore College); Patrick Gallagher (Stanford University); William Throwe (MIT); and Christopher Chudzicki (Williams College). The recipients will be announced on the APS website and in a later issue of APS News.

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Beyond State Transfer

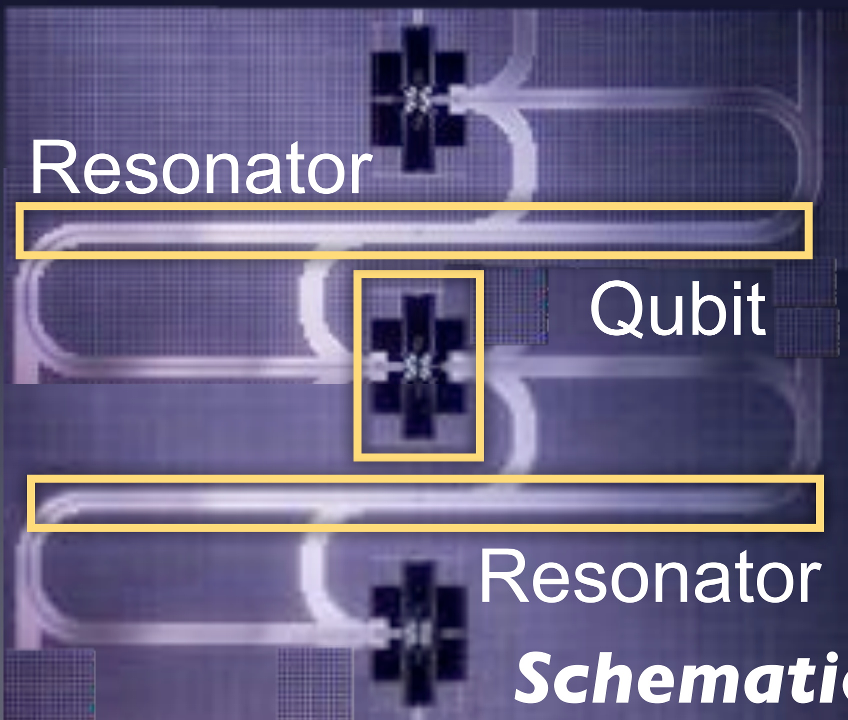
- **Superconducting resonators** could be used for quantum logic.
- Instead of qubits, these would be qudits (digits with arbitrary base)
- Resonators are significantly easier to fabricate and of higher quality than qubits!
- Results so far:
  - **Entangling Two Superconducting Resonators**
  - **Using Resonator as Multi-qubit Memory**
  - **Quantum Logic Using Resonator States**

Entangling Oscillators

FWS, K Jacobs, and RW Simmonds,
Phys. Rev. Lett. **105**, 050501 (2010)

Quantum Algorithm to generate highly non-classical "NOON" states:

$$|\Psi_{NOON}\rangle = |N,0\rangle + |0,N\rangle$$



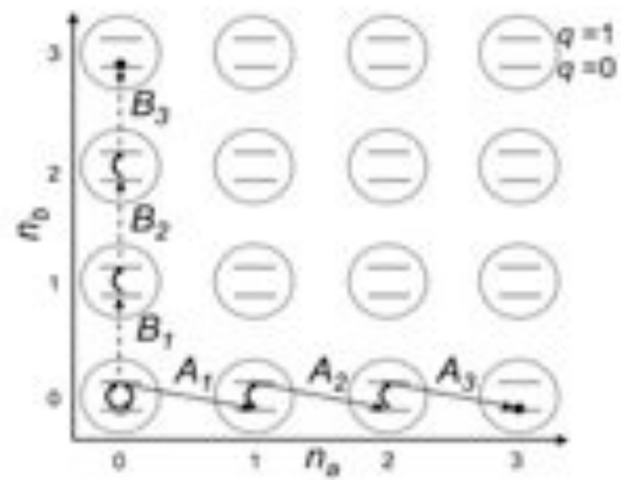


TABLE I: NOON State Synthesis Procedure

Step	Parameters	State
$R_{a,1}$	$\Omega t_{ge,1} = \pi/2, \omega_q = \omega_a$	$\|0,0,0\rangle - i\|1,0,0\rangle$
A_1	$g_a t_{a,1} = \pi$	$\|0,0,0\rangle - \|0,1,0\rangle$
$R_{a,2}$	$\Omega t_{ge,2} = \pi, \omega_q = \omega_1$	$\|0,0,0\rangle + i\|1,1,0\rangle$
A_2	$g_a t_{a,2} = \pi/\sqrt{2}$	$\|0,0,0\rangle + \|0,2,0\rangle$
$R_{a,3}$	$\Omega t_{ge,3} = \pi, \omega_q = \omega_2$	$\|0,0,0\rangle - i\|1,2,0\rangle$
A_3	$g_a t_{a,3} = \pi/\sqrt{3}$	$\|0,0,0\rangle - \|0,3,0\rangle$
$R_{b,1}$	$\Omega t_{gb,1} = \pi, \omega_q = \omega_b$	$-i\|1,0,0\rangle - \|0,3,0\rangle$
B_1	$g_b t_{b,1} = \pi$	$-\|0,0,1\rangle - \|0,3,0\rangle$
$R_{b,2}$	$\Omega t_{gb,2} = \pi, \omega_q = \omega_{-1}$	$i\|1,0,1\rangle - \|0,3,0\rangle$
B_2	$g_b t_{b,2} = \pi/\sqrt{2}$	$\|0,0,2\rangle - \|0,3,0\rangle$
$R_{b,3}$	$\Omega t_{gb,3} = \pi, \omega_q = \omega_{-2}$	$-i\|1,0,2\rangle - \|0,3,0\rangle$
B_3	$g_b t_{b,3} = \pi/\sqrt{3}$	$-\|0,0,3\rangle - \|0,3,0\rangle$

Experimental Results

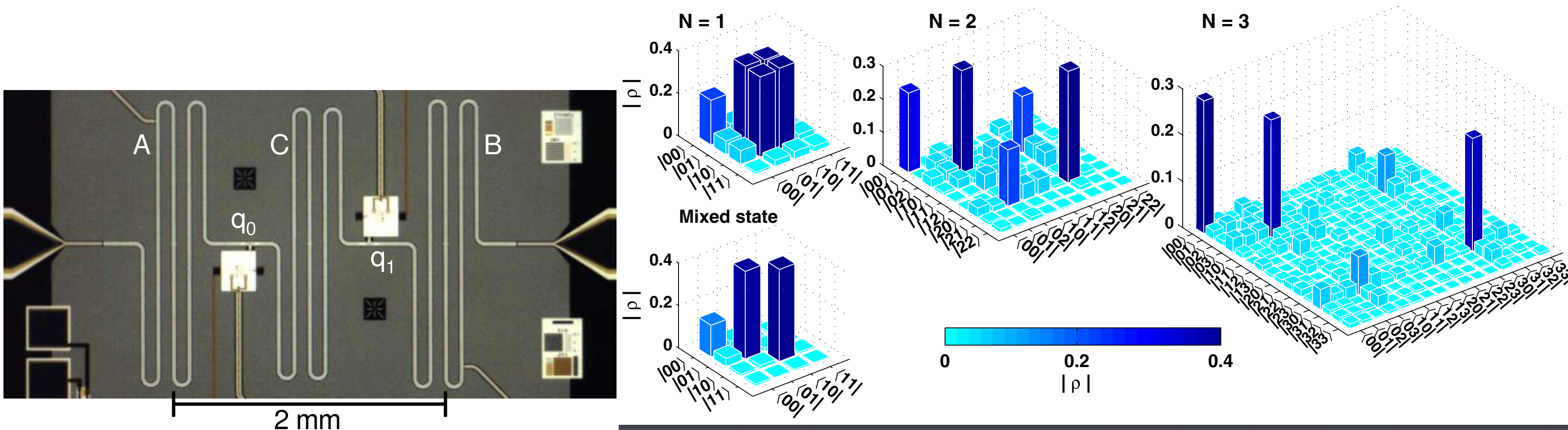
PRL **106,** 060401 (2011)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending
11 FEBRUARY 2011

Deterministic Entanglement of Photons in Two Superconducting Microwave Resonators

H. Wang,[1,2] Matteo Mariantoni,[1] Radoslaw C. Bialczak,[1] M. Lenander,[1] Erik Lucero,[1] M. Neeley,[1] A. D. O'Connell,[1] D. Sank,[1] M. Weides,[1] J. Wenner,[1] T. Yamamoto,[1,3] Y. Yin,[1] J. Zhao,[1] John M. Martinis,[1] and A. N. Cleland[1,*]

[1]*Department of Physics, University of California, Santa Barbara, California 93106, USA*
[2]*Department of Physics and Zhejiang California International NanoSystems Institute, Zhejiang University, Hangzhou 310027, China*
[3]*Green Innovation Research Laboratories, NEC Corporation, Tsukuba, Ibaraki 305-8501, Japan*

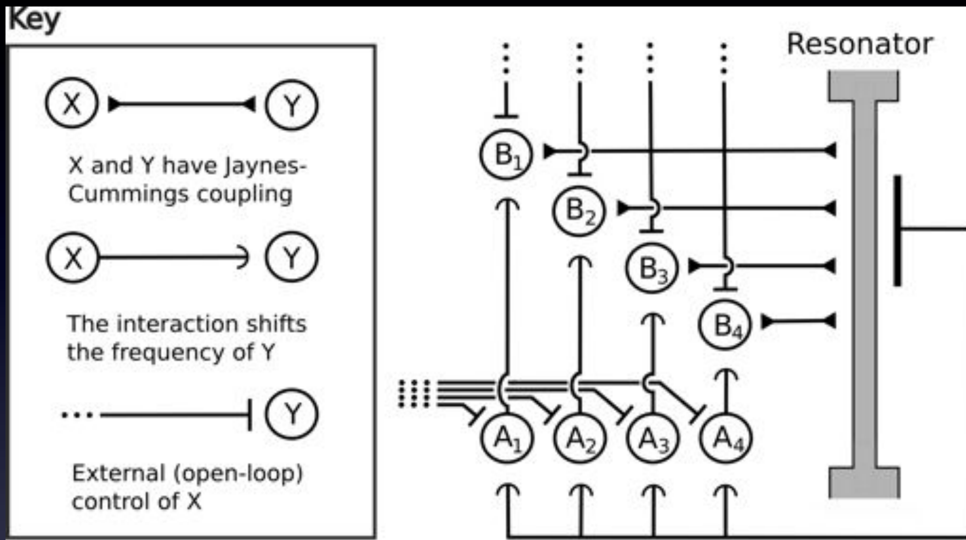
(Received 9 November 2010; published 7 February 2011)

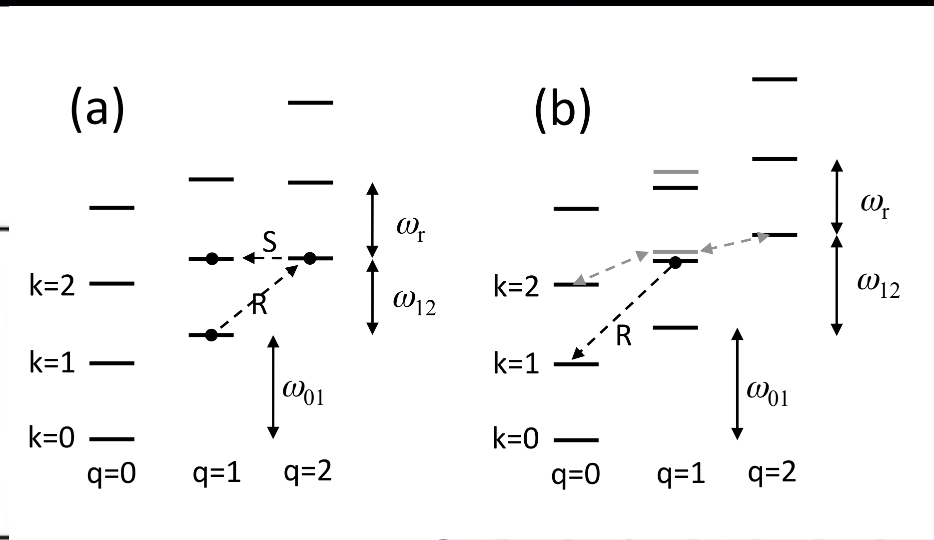


- Martinis Group, UC Santa Barbara

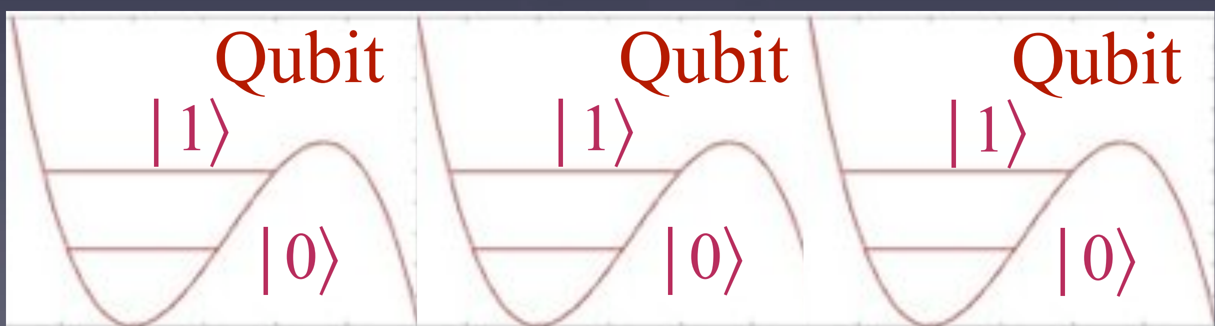
Multi-Qubit Memory

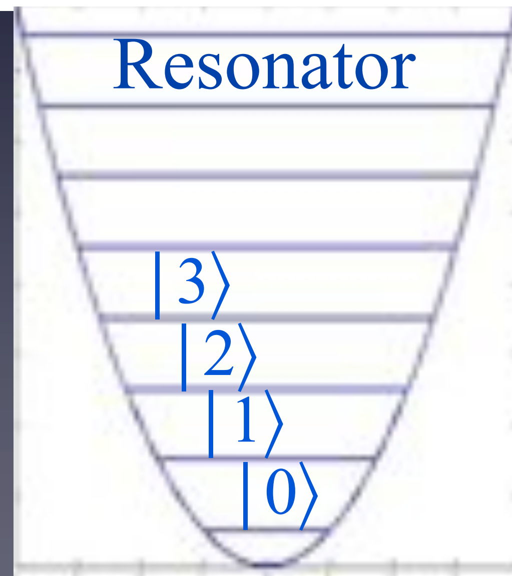
FWS and K Jacobs, in preparation





Swap Multiple Qubits into a Resonator





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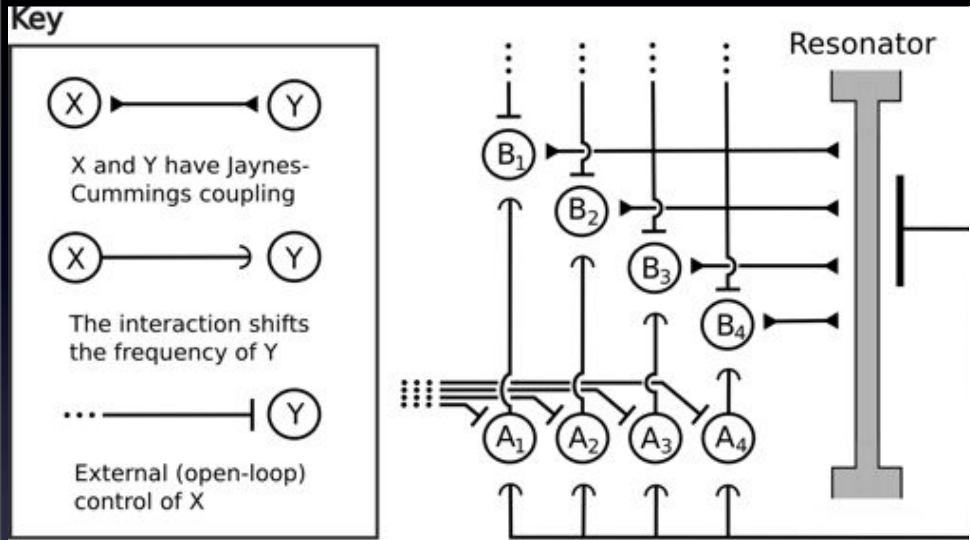
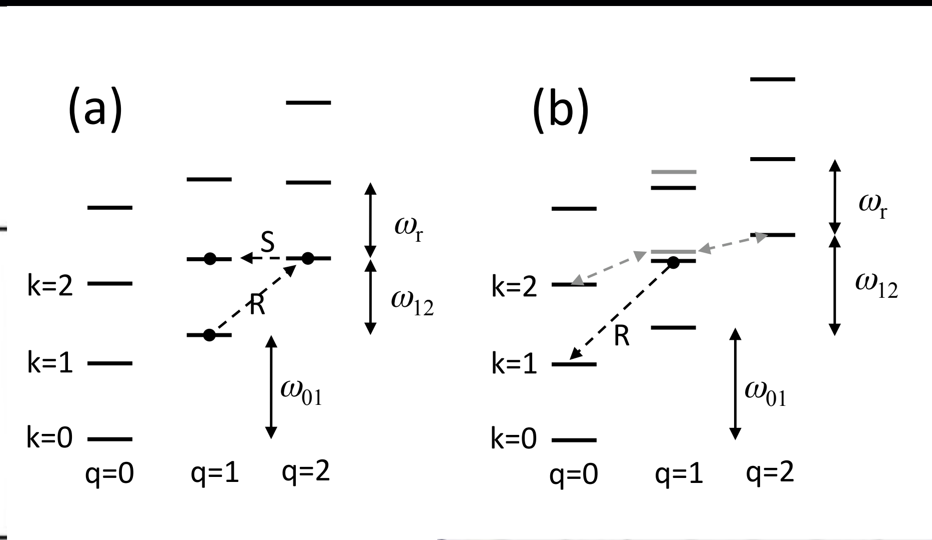
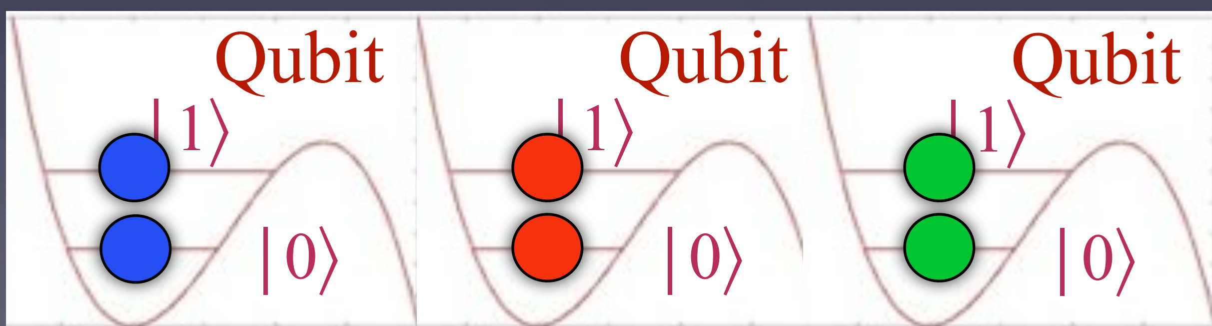
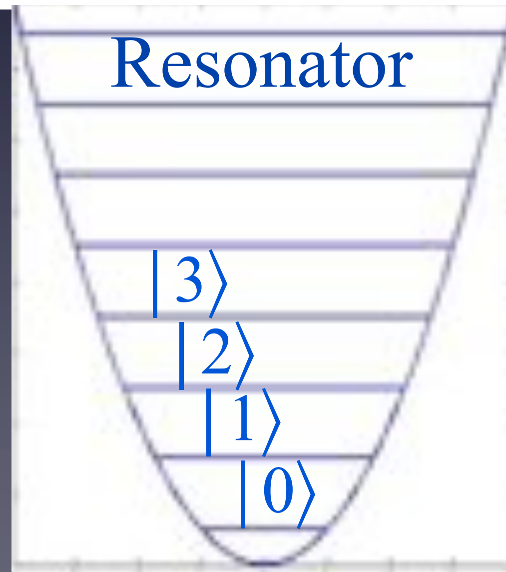
FWS and K Jacobs, in preparation





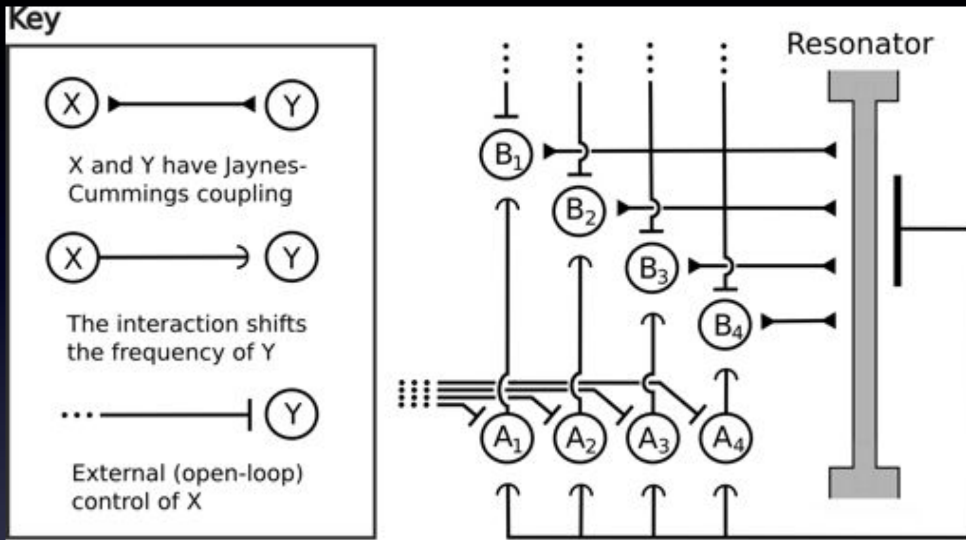
Swap Multiple Qubits into a Resonator

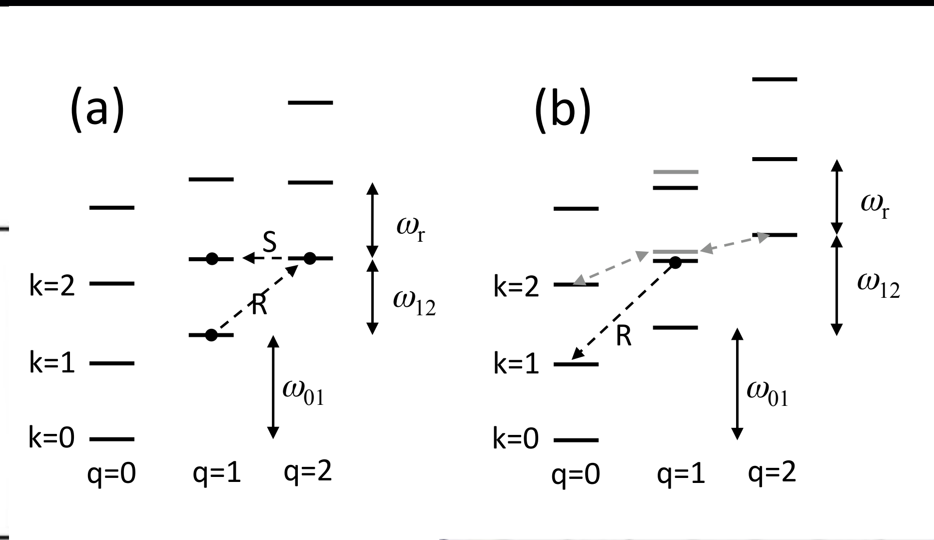




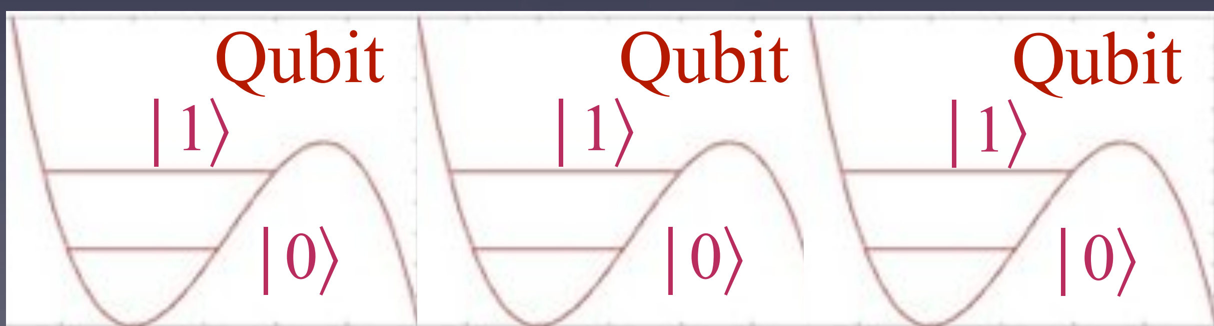
Multi-Qubit Memory

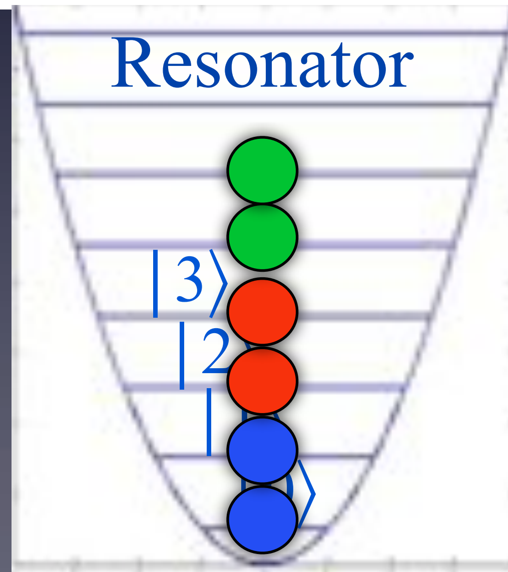
FWS and K Jacobs, in preparation





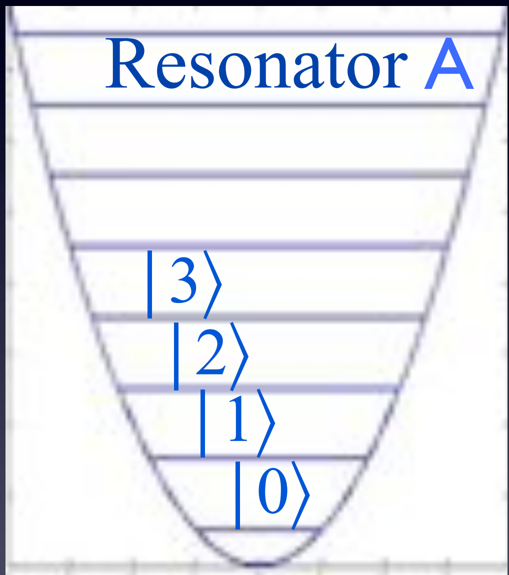
Swap Multiple Qubits into a Resonator

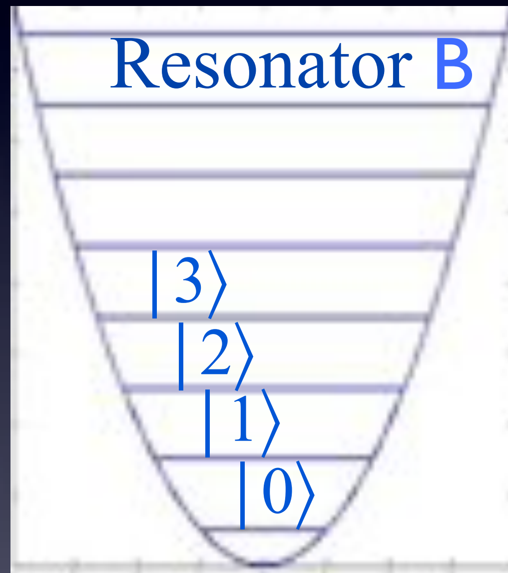




Quantum Logic

FWS and K Jacobs, in preparation

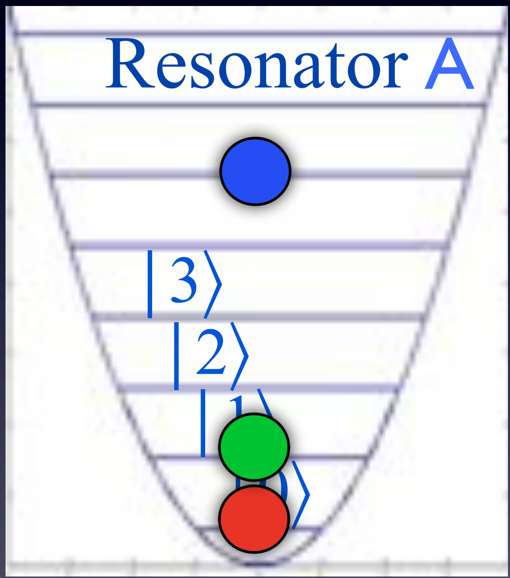


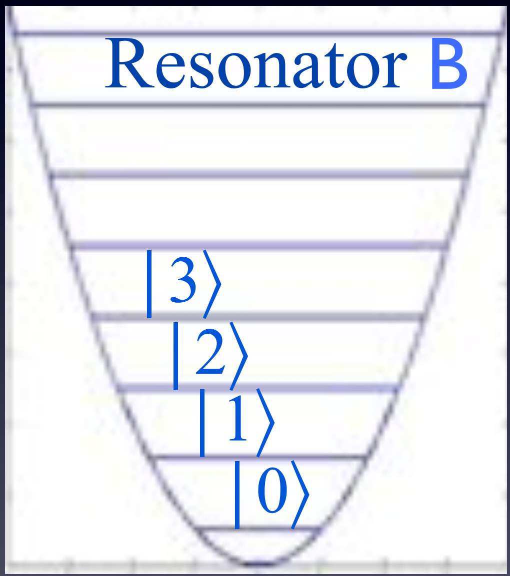


Same methods can be used to
Generate Arbitrary Transformations between Resonators

Quantum Logic

FWS and K Jacobs, in preparation

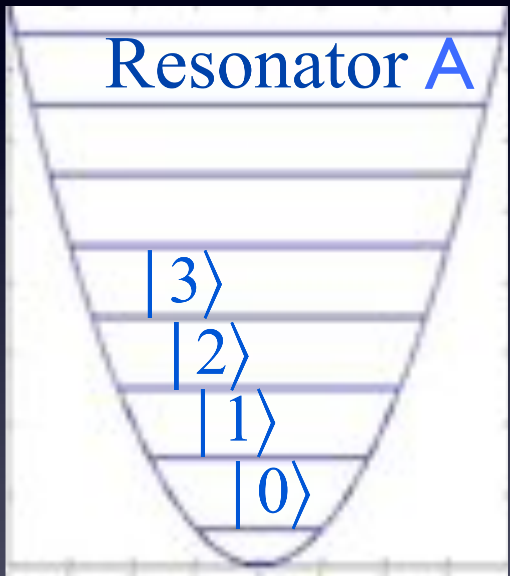


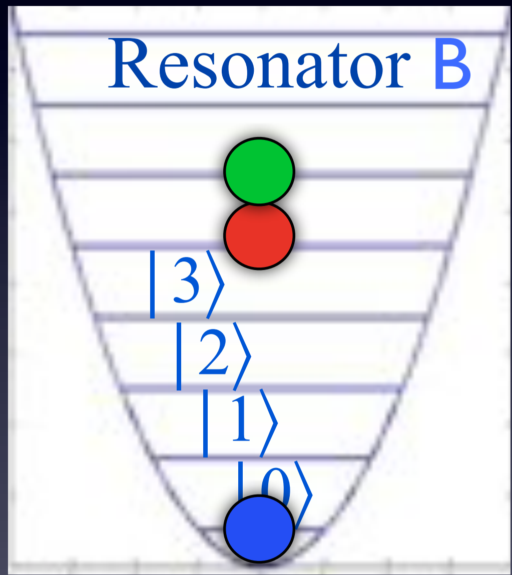


Same methods can be used to Generate Arbitrary Transformations between Resonators

Quantum Logic

FWS and K Jacobs, in preparation





Same methods can be used to
Generate Arbitrary Transformations between Resonators

Conclusions

- Superconducting Circuits are an exciting testbed for quantum processes (state transfer) and other algorithms.
- Superconducting resonators are really interesting---let's use them!
- Quantum Routing is both optimal and robust for certain networks of oscillators
- Entangled Resonator States Demonstrated!
- Quantum State Synthesis and Logic Gates on the way---stay tuned!