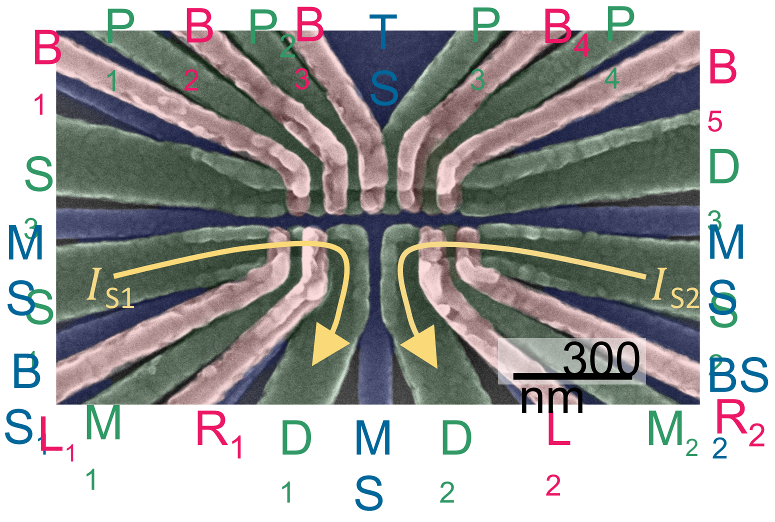
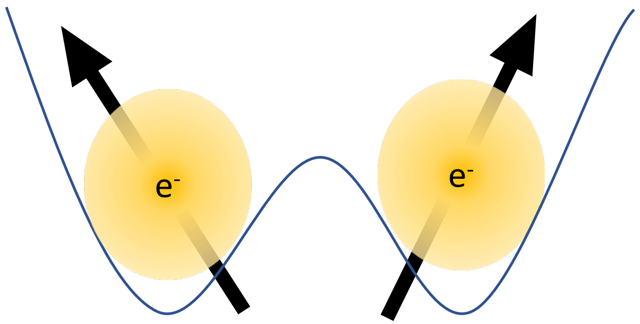




Engineering high-fidelity gates in silicon quantum processors

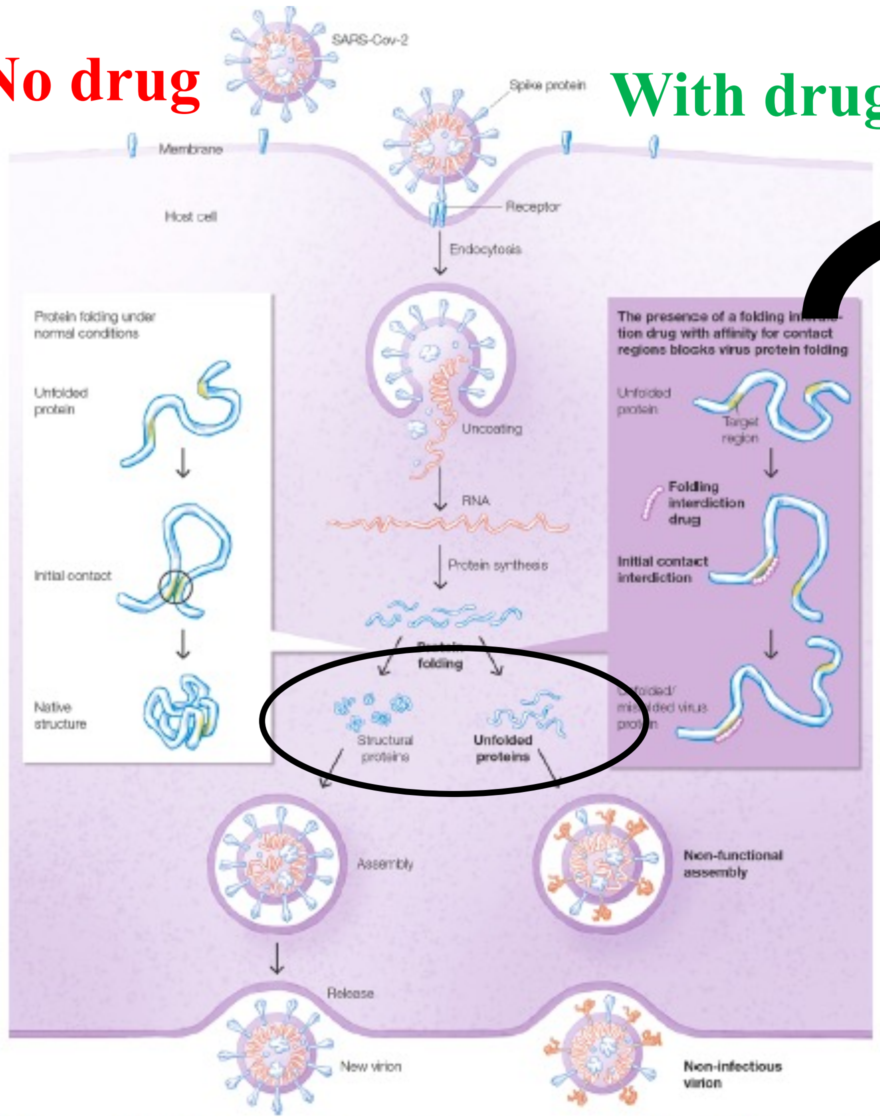
Nima Leclerc (nleclerc@seas.upenn.edu), PhD Student
Sigillito Lab

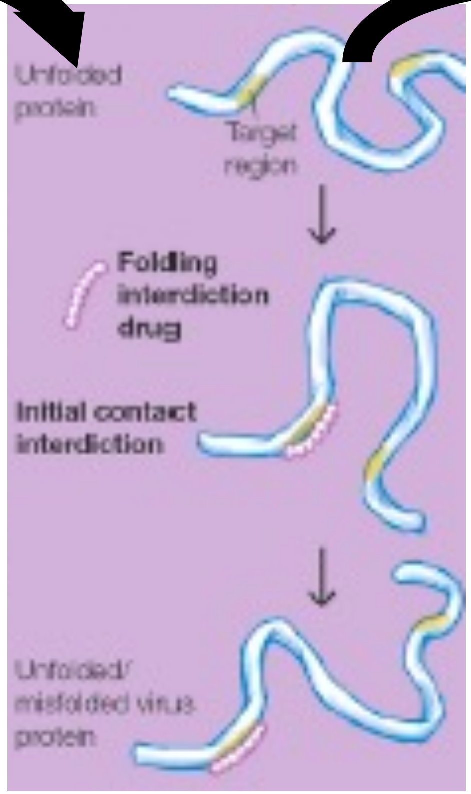
Electrical and Systems Engineering Colloquium, University of Pennsylvania

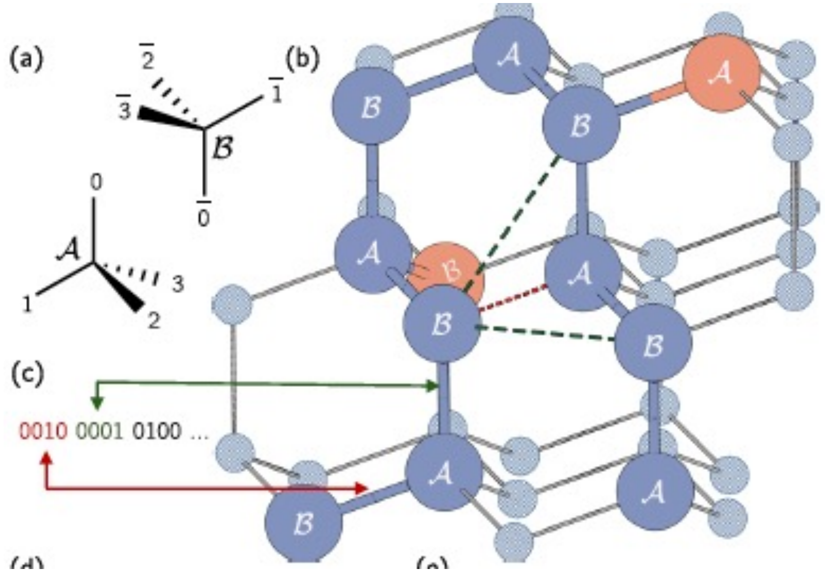
October 22, 2021

Therapeutic drug design for COVID-19

No drug **With drug**







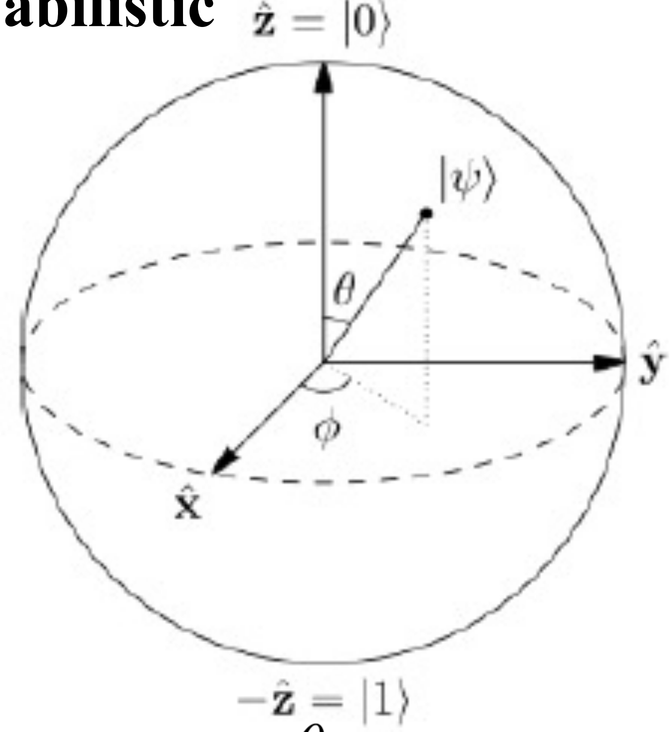
J. Phys. Chem. B 2020, 124, 8201−8208

npj Quantum Information 7.1 (2021): 1-5.

Increase computational space with different encodings

Bits = deterministic

Qubits = probabilistic



$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

c_1 c_2

c_1 c_2

➔ probabilities of being in |0> and |1> states.

Increase computational space combining multiple qubits

Classical

Bit 1

+

Bit 2

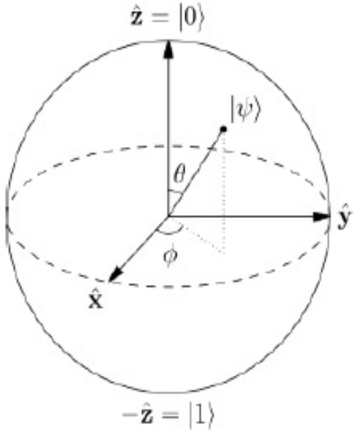
→

'1’ '1’

‘0’ ‘0’

2 computational states from 2 bits

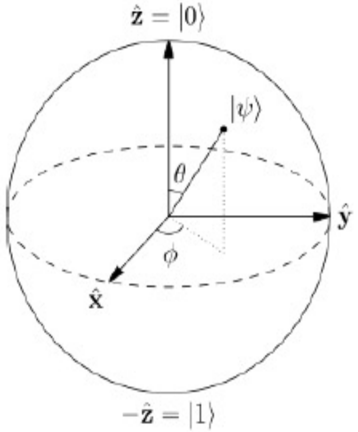
Quantum



Qubit 1

$|\psi\rangle_1$

$\otimes$



Qubit 2

$|\psi\rangle_2$

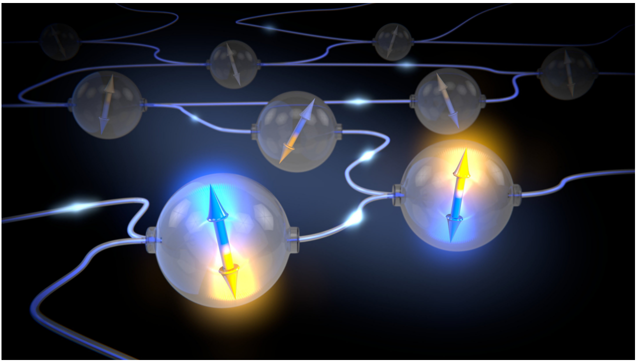
→

$$|\psi\rangle_1 \otimes |\psi\rangle_2 = (c_1^1|0\rangle_1 + c_2^1|1\rangle_1) \otimes (c_1^2|0\rangle_2 + c_2^1|1\rangle_2)$$

$$= c_1^1 c_1^2 |0\rangle_1|0\rangle_2 + c_1^1 c_2^2 |0\rangle_1|1\rangle_2 + c_2^1 c_1^2 |1\rangle_1|0\rangle_2 + c_2^1 c_2^2 |1\rangle_1|1\rangle_2$$

4 computational states from 2 qubit ➔ 4 states for each qubit pair

Encoding information in correlations



‘spooky action at a distance’ ➔ *entanglement*

$$|\psi\rangle_1 \otimes |\psi\rangle_2 = (c_1^1|0\rangle_1 + c_2^1|1\rangle_1) \otimes (c_1^2|0\rangle_2 + c_2^1|1\rangle_2)$$

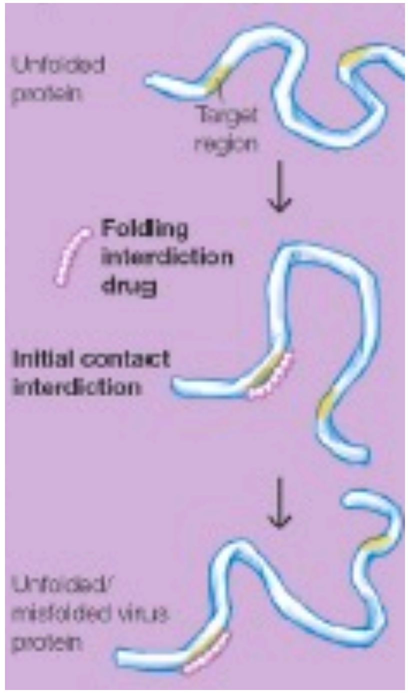
Information is stored in the correlation between states ➔ exponentially increased computational space

$$|\psi\rangle = (|0\rangle + |1\rangle)^{\otimes N}$$

N ➔ number of physical qubits

- $N = 30$ (IonQ machine) ➔ ~ 1 GB classical transistors
- $N = 50$ (Google machine) ➔ ~ 8,000 TB classical transistors
- $N = 800$ ➔ > number of atoms in the universe to encode information !!

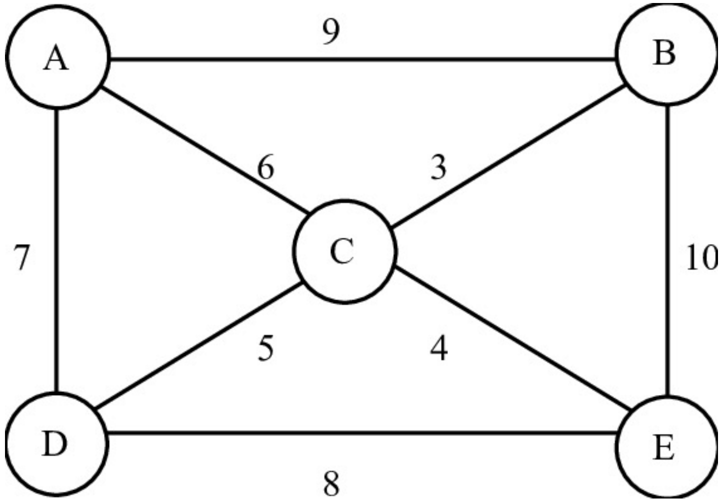
Entanglement encoding for drug design and other applications



Protein folding
Quantum simulation

Classical algorithm (HF): $\mathcal{O}(2^N)$

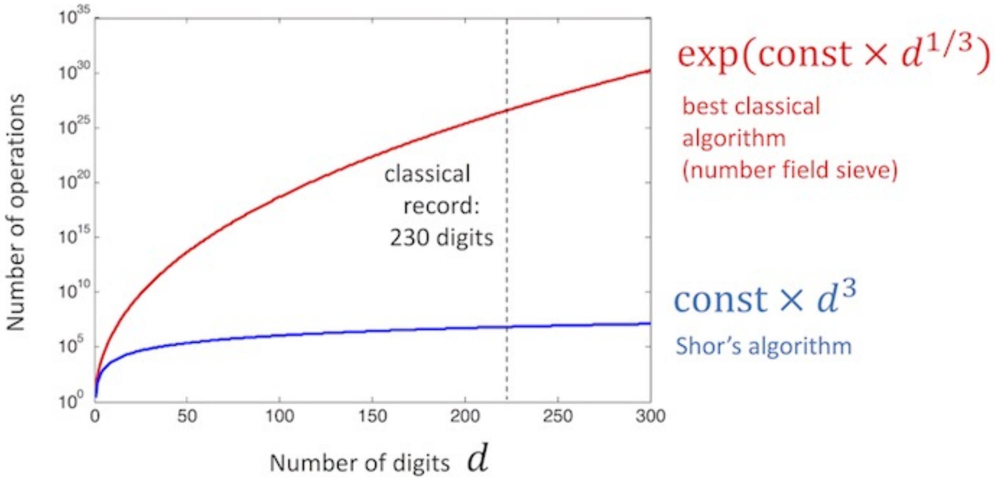
Quantum algorithm (VQE): $\mathcal{O}(N^3)$



Optimization
Search algorithms

Classical algorithm (MTZ): $\mathcal{O}(2^N)$

Quantum algorithm (Grover): $\mathcal{O}(\sqrt{N})$



Factoring
Quantum Fourier transform

Classical algorithm (NFS): $\mathcal{O}(2^N)$

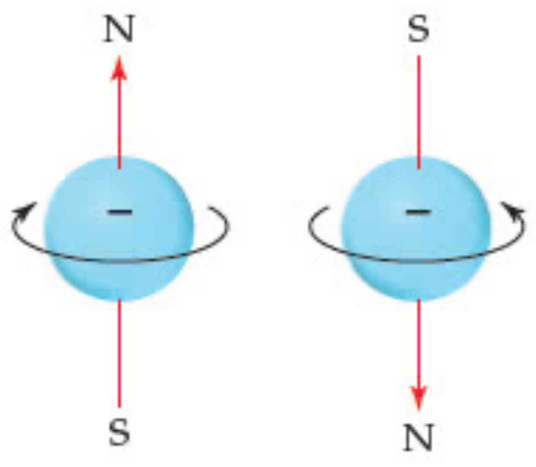
Quantum algorithm (Shor's):

$\mathcal{O}(\log N)$ or $\mathcal{O}(N^3)$

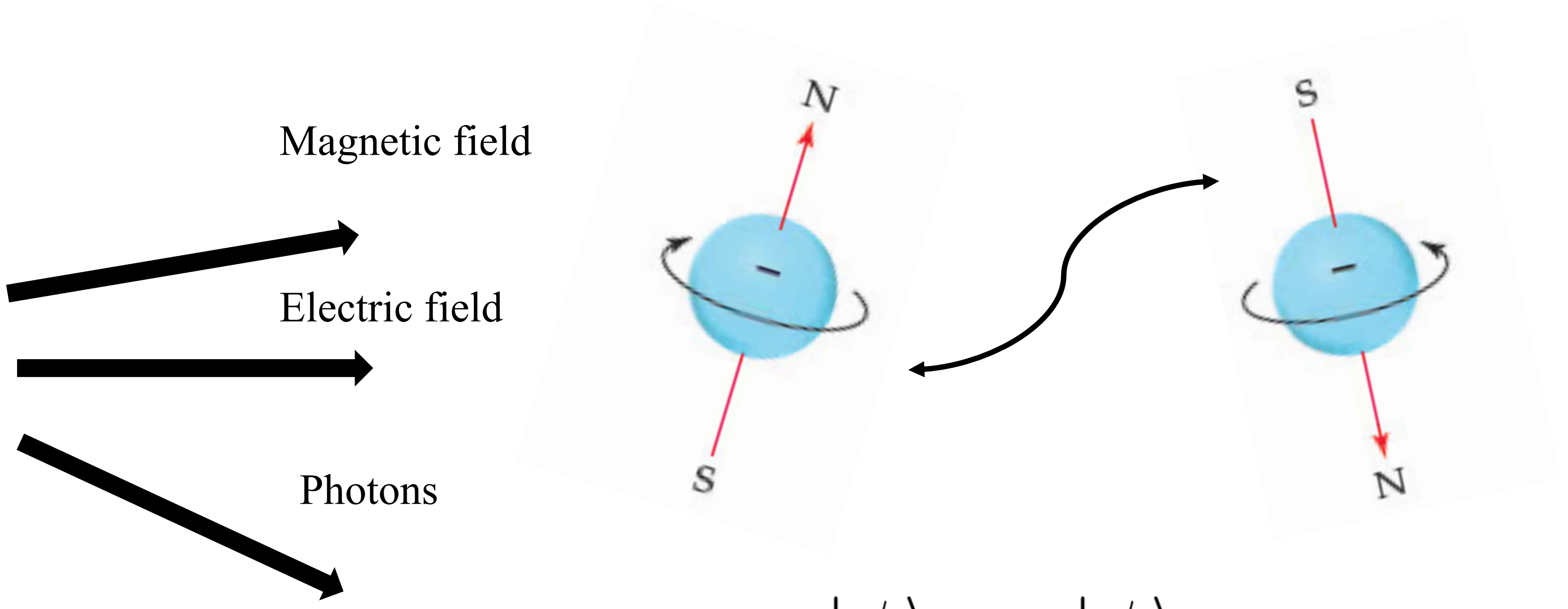
J. Phys. Chem. B 2020, 124, 8201−8208

https://quantum-computing.ibm.com/composer/docs/iqx/guide/shors-algorithm

Encoding quantum information in a physical system: small magnets

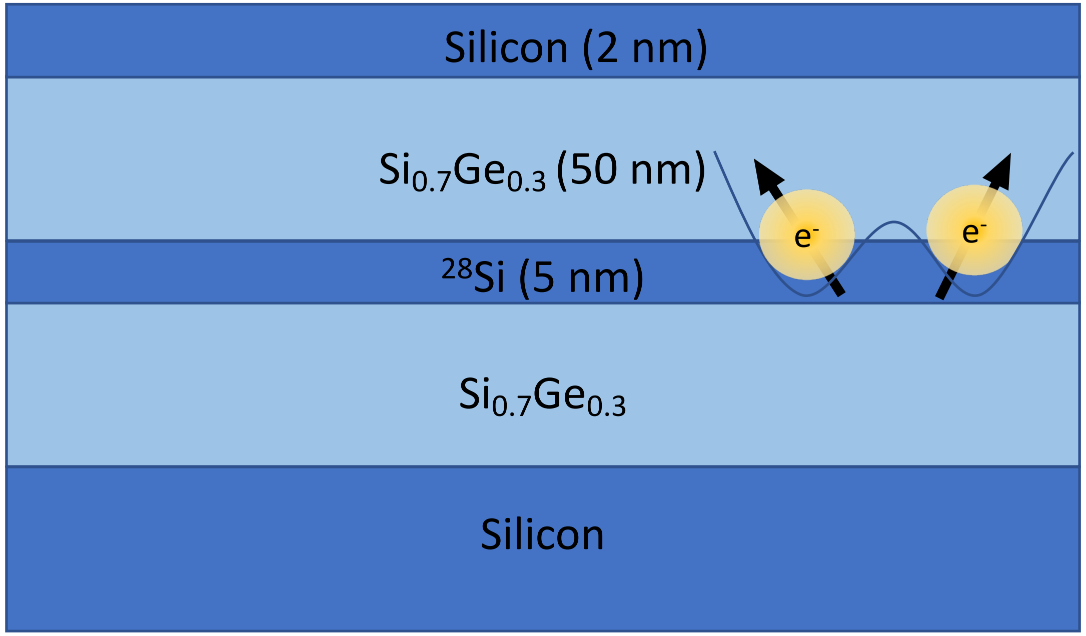


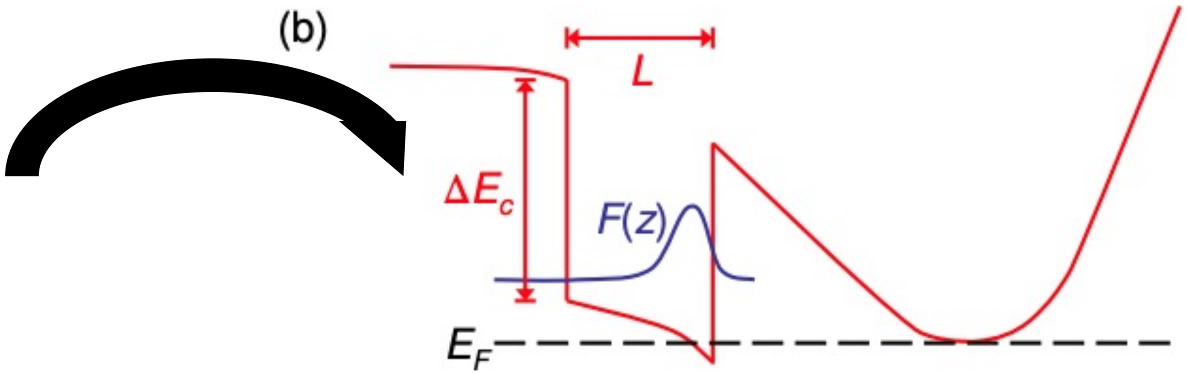
$$|\psi\rangle_1 = |\uparrow\rangle \; |\psi\rangle_2 = |\downarrow\rangle$$



$$|\psi\rangle_1 \otimes |\psi\rangle_2$$

Trapping single spins in semiconductors

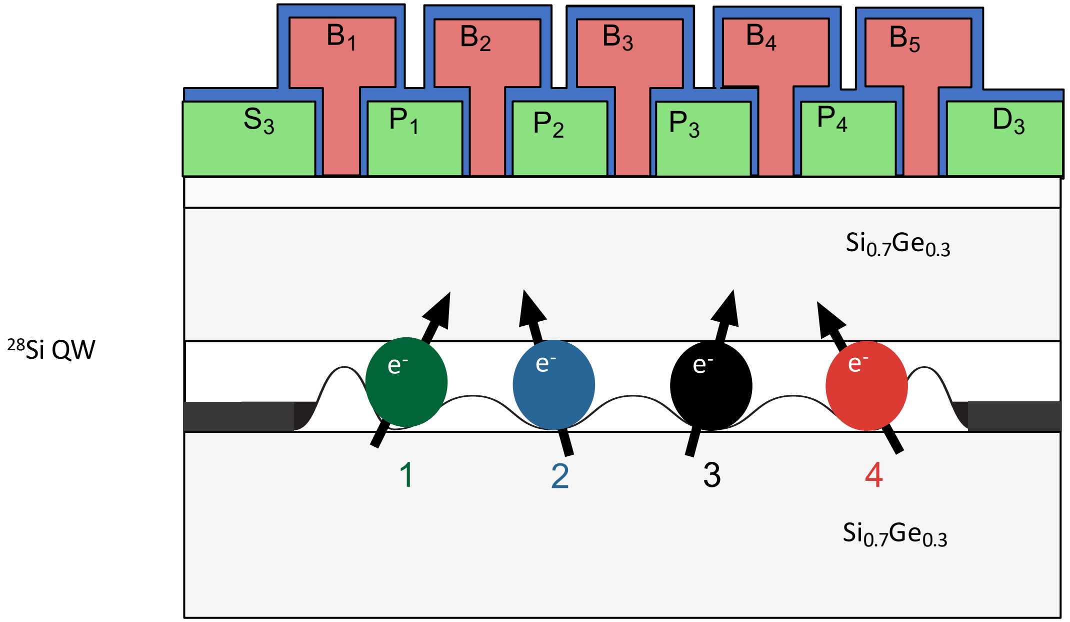


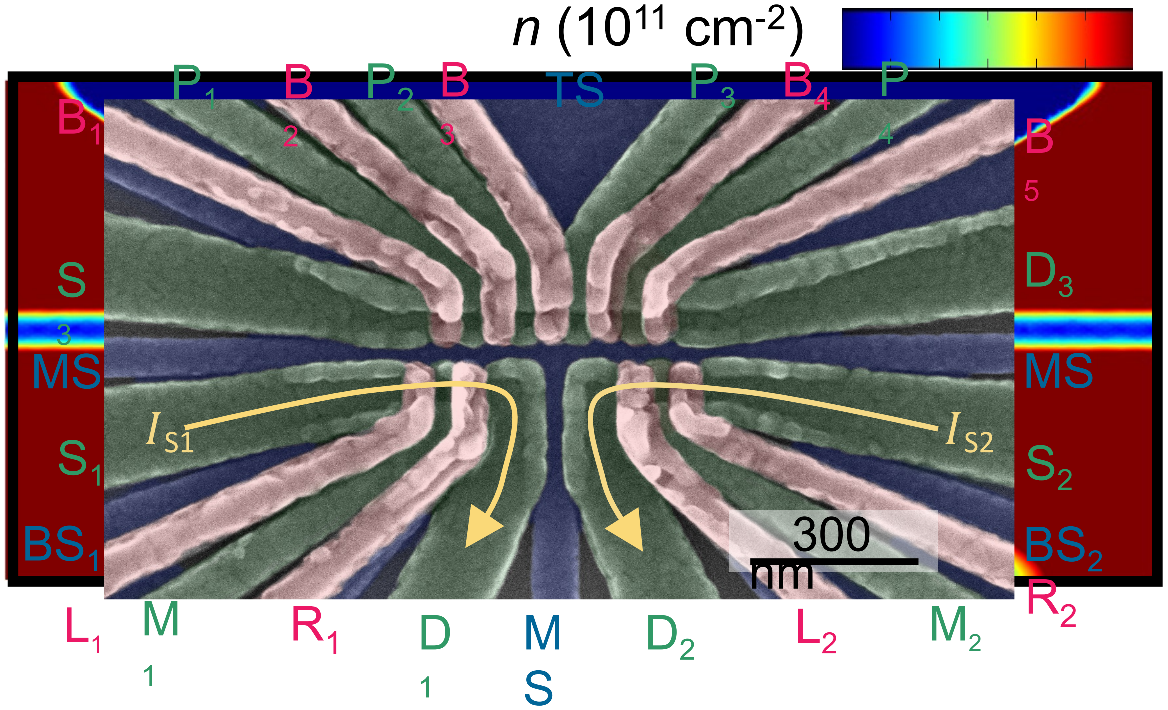


2D electron gas (2DEG)

Band diagram from: Friesen *et al*., PRB **75**, 115318 (2007)

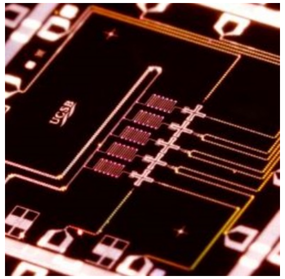
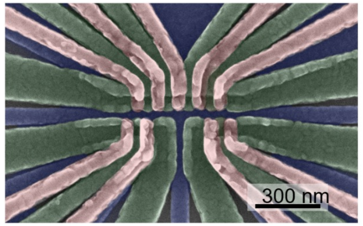
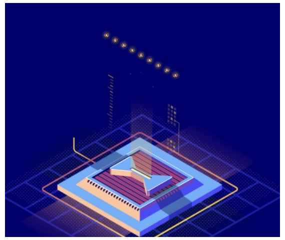
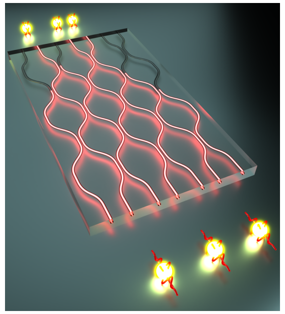
Trapping single spins in semiconductors





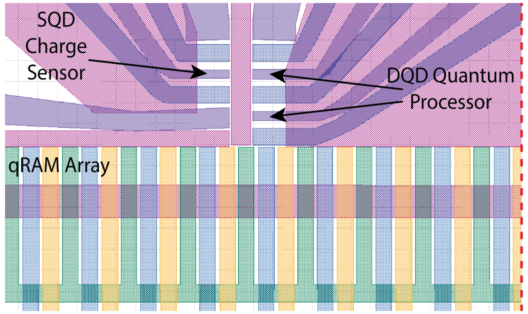
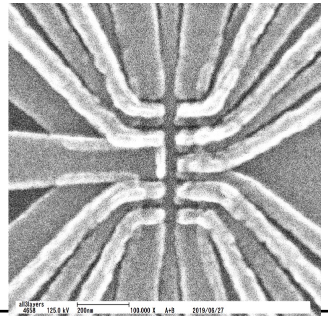
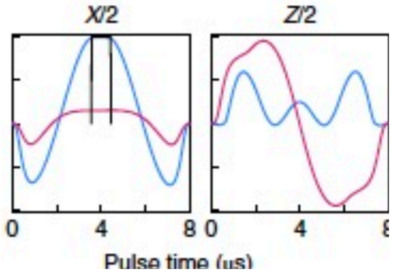
Voltage gates modify 2DEG potential ➔ trap electrons with high precision

A zoo of quantum computing architectures

Qubit	Superconducting	Silicon Spin Qubits	Ions/Atoms	Photons
				
Number Qubits Demonstrated	72 (Bristlecone) 53 (Sycamore) 50 IBM	4	32	~70
Gate Fidelities (2 QB)	99.9%	>99.5%	>99.9%	>99.5
One qubit gate fidelity	99.95%	>99.95%	>99.99%	>99.5
Challenges in qubit scalability	Qubit crosstalk dominates, decoherence, too big	Low 2-qubit fidelities, too many wires , too cold	Bulky vacuum systems, soft potential (weak interaction)	Cannot reliably produce photons, difficult to mediate interaction

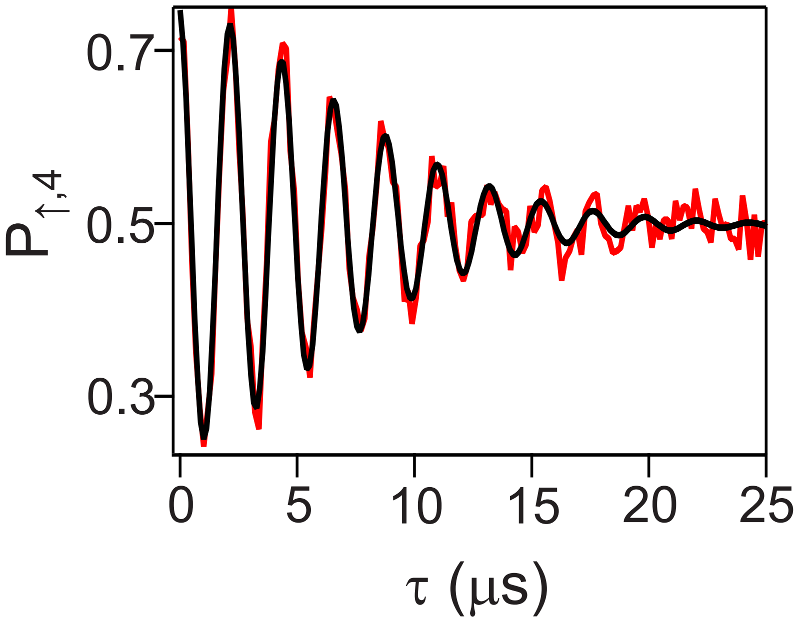
Images from: Martinis Group/Google, IonQ, PsiQuantum

Towards an intermediate scale silicon quantum computer

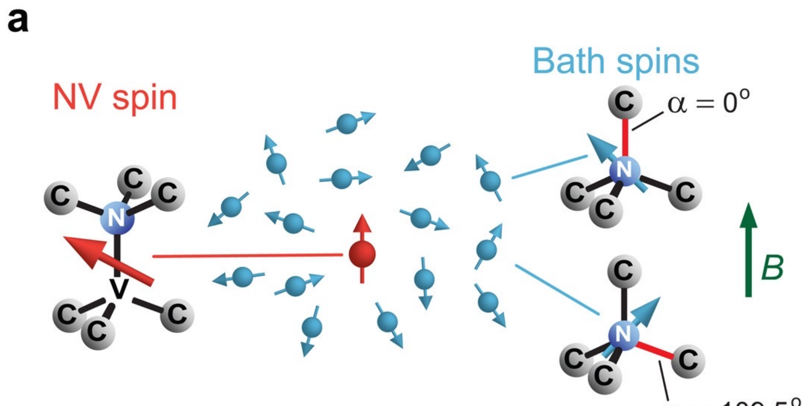
Challenges	Proposed solution
Low-connectivity - Spins limited to nearest-neighbor interactions - Difficult to form large cluster states	Quantum random access memory 
Complexity - Each qubit requires multiple wires connected to bond pads - Simultaneous voltage + MW control	Overlapping gate architecture ➔ all qubits share same barrier voltage 
Qubit infidelity -Decoherence induced ➔ spin-spin interactions lead to information loss - Noise induced ➔ charge noise leading to fluctuations in exchange interactions	Pulse engineering for noise induced infidelity. Res-Sqrt(SWAP) gates for decoherence induced. 

Infidelity in silicon spin-qubit systems: decoherence + noise

Decoherence



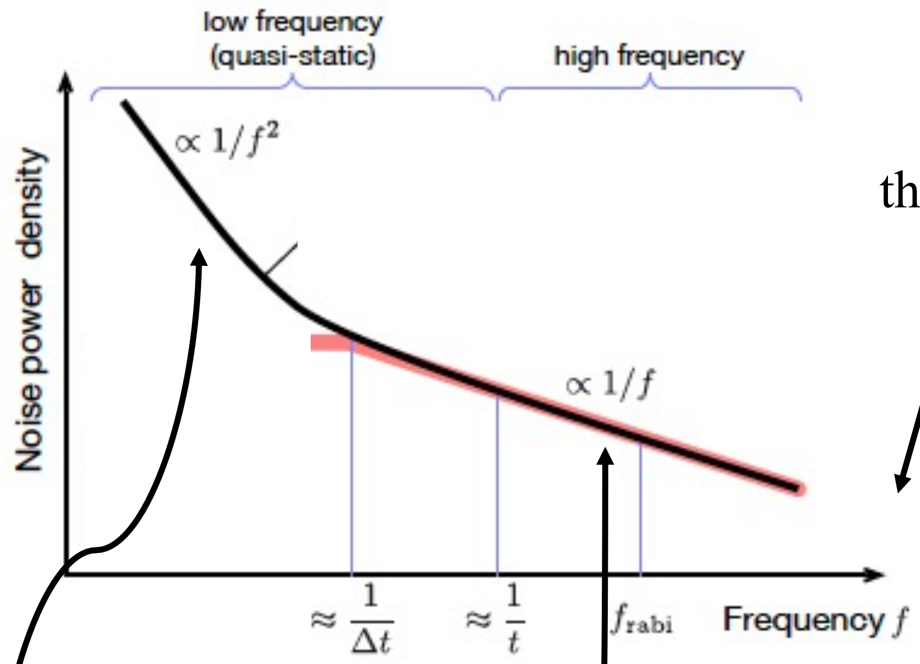
Sigillito *et al.*, Phys. Rev. Appl. **6**, 061006 (2019)



De Lange, Gijs, et al *Scientific reports* 2.1 (2012): 1-5.

Spins interacting with other spins! (hyperfine coupling)

Noise



thermal noise

fluctuating charges (δQ) ➔

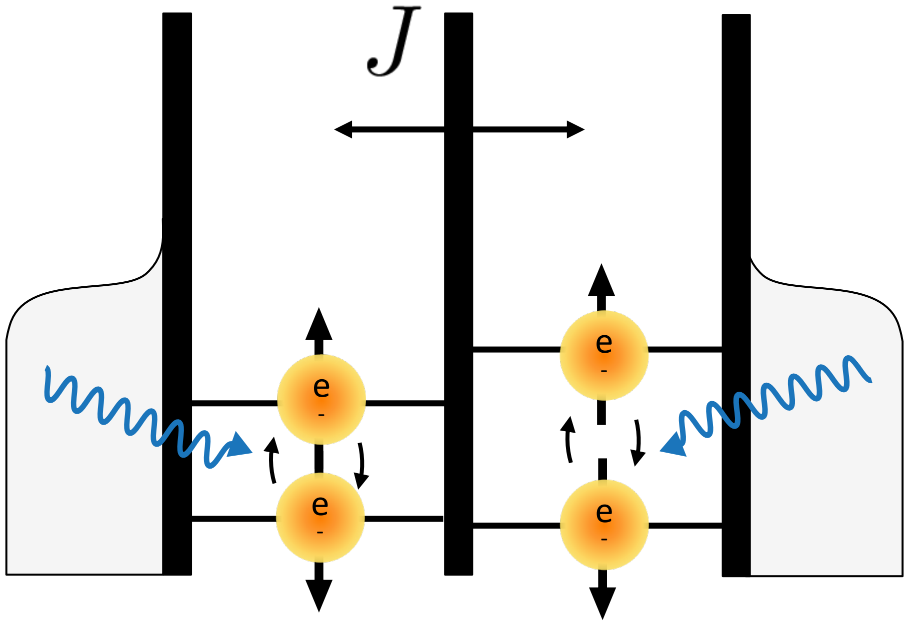
fluctuating exchange (δJ)

➔ fluctuating magnetic fields δB

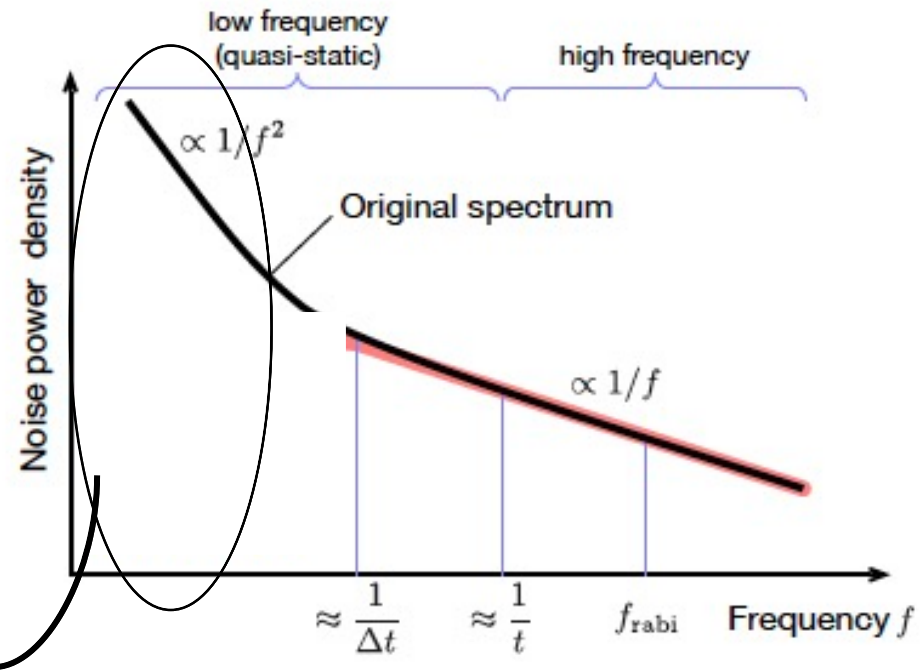
fluctuating surface magnetic fields δB

Nakajima, Takashi, et al. *Physical Review X* 10.1 (2020): 011060.

Charge noise induced infidelity



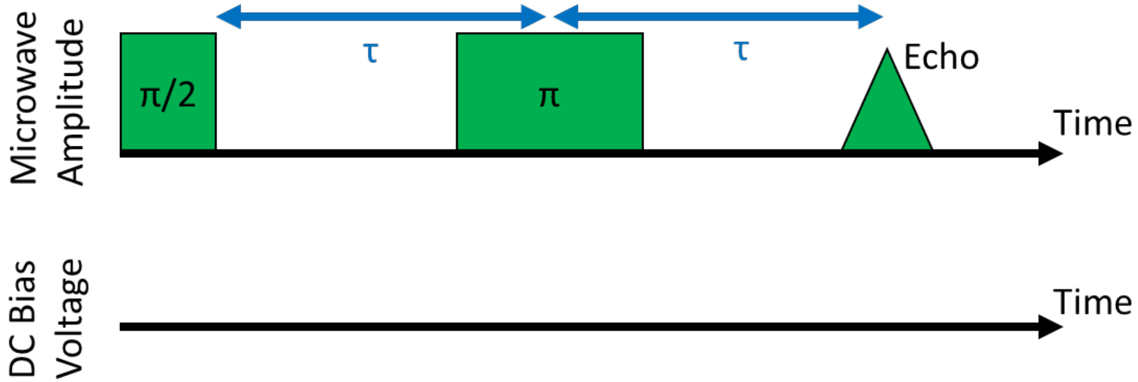
Left dot Right dot

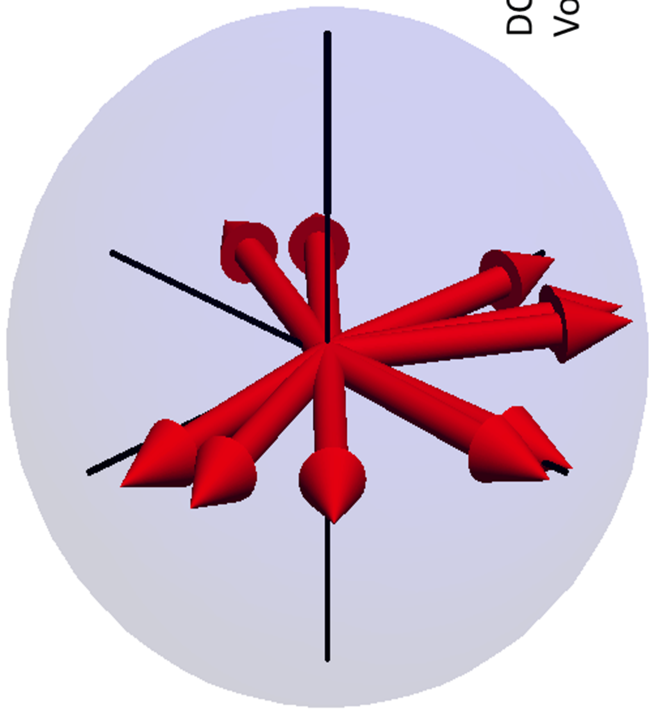


$$
\mathrm{H} = \begin{pmatrix} E_z & 0 & 0 & 0 \\ 0 & -(\delta E_z + J)/2 & J/2 & 0 \\ 0 & J/2 & (\delta E_z - J)/2 & 0 \\ 0 & 0 & 0 & -E_z \end{pmatrix}
$$

$$
J = J_0 + \delta J
$$

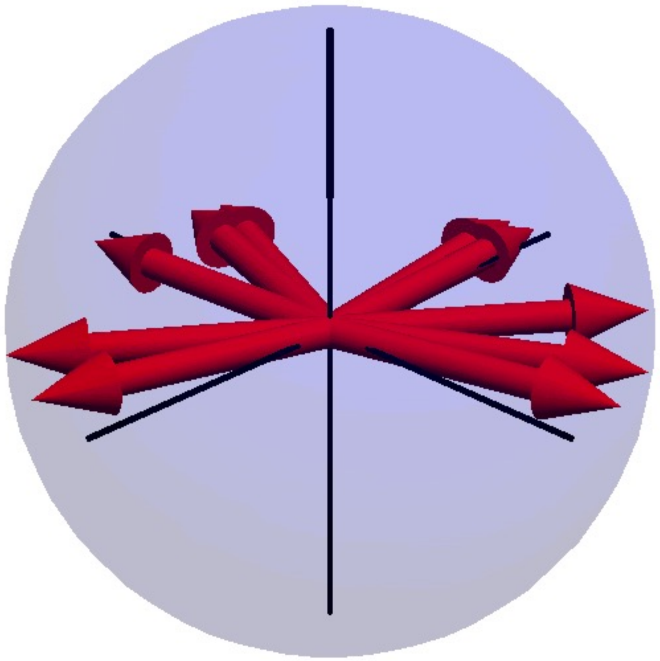
Charge noise induced infidelity (cont'd))





Unperturbed system

$\delta B = 0$



Charge noise present

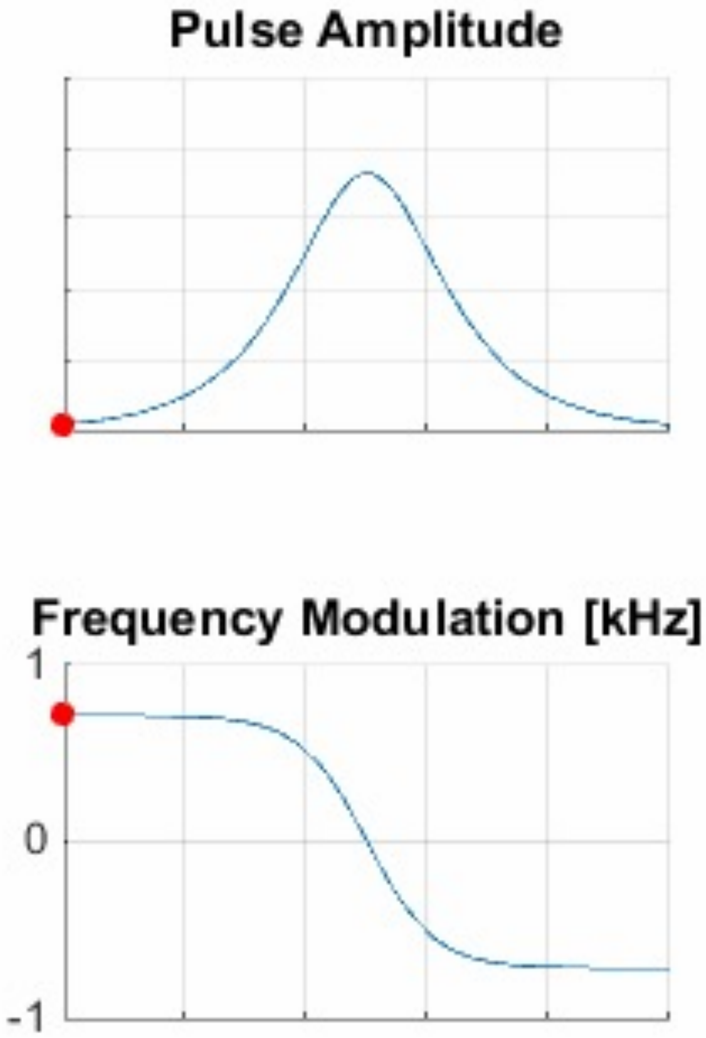
$\delta B \neq 0$

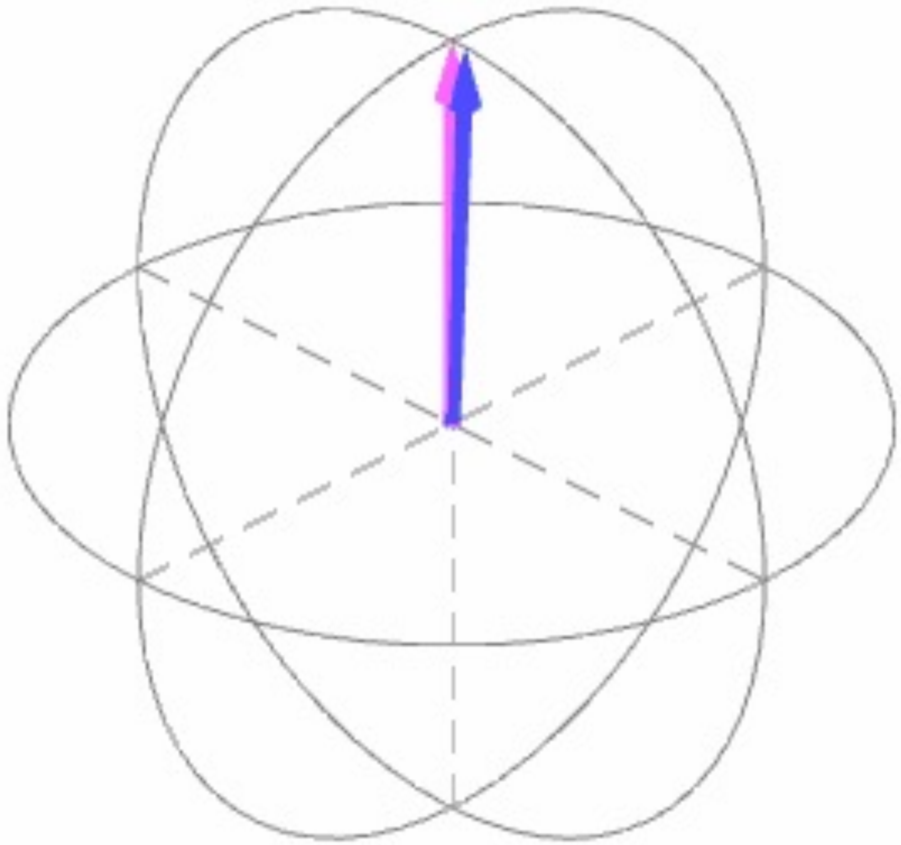
Controlling spins with microwaves

- Apply magnetic field orthogonal to *B*
- Needs to be resonant with spins rotating frame
- Microwave frequencies
- Axis of rotation = phase

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

Shaping pulses for noise robustness

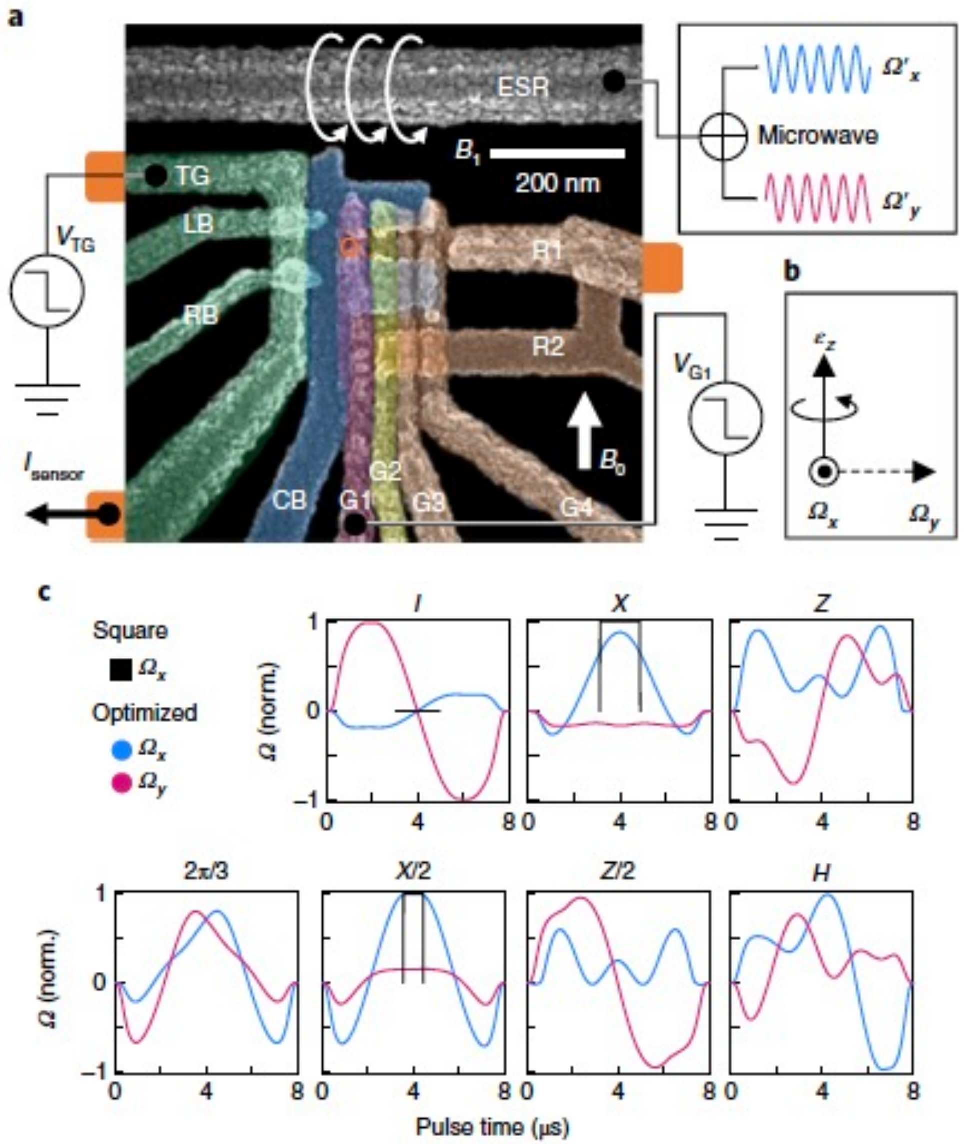




http://mriphysics.github.io/teaching-rf-pulses.html

Systematic pulse engineering for single qubit gates

Operator	Gate(s)		Matrix
Pauli-X (X)	X	⊕	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)			$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

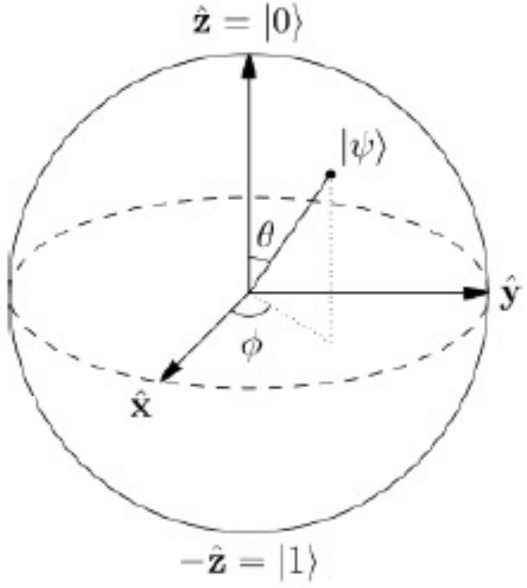


Yang, C. H., et al. (2019): 151-158.

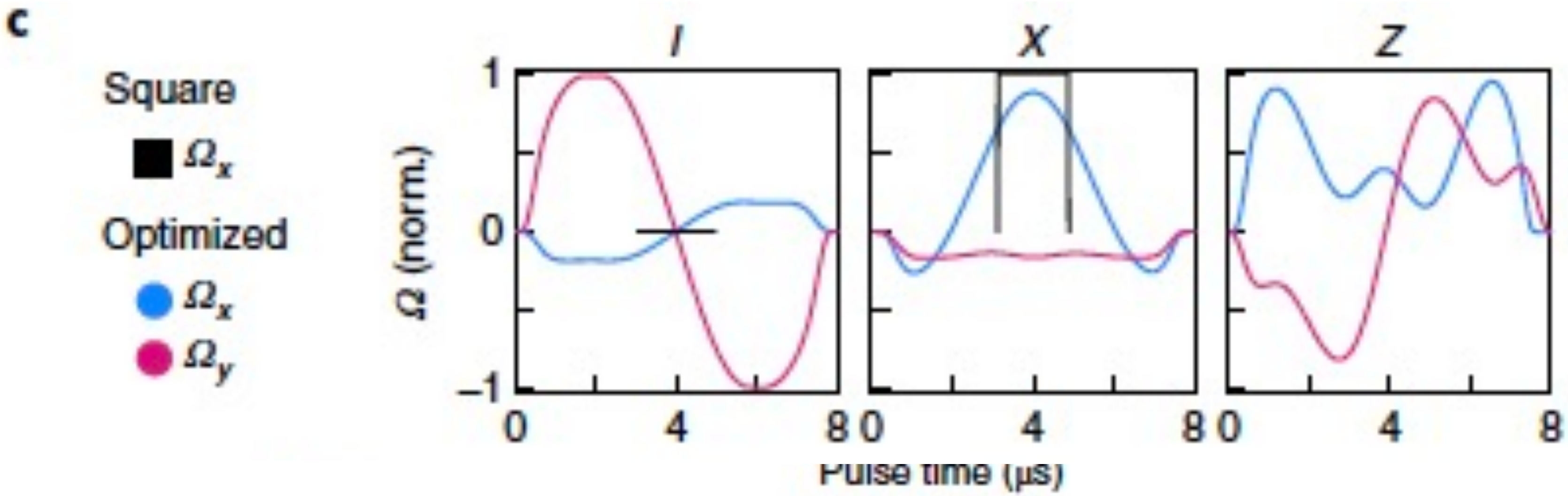
Pulse engineering protocol: gradient based optimization

$$\mathcal{H} = \Omega_{drift}\Omega_{ESR}(\Omega_x\sigma_x + \Omega_y\sigma_y) + (f_{ESR} + \epsilon_z)\sigma_z$$

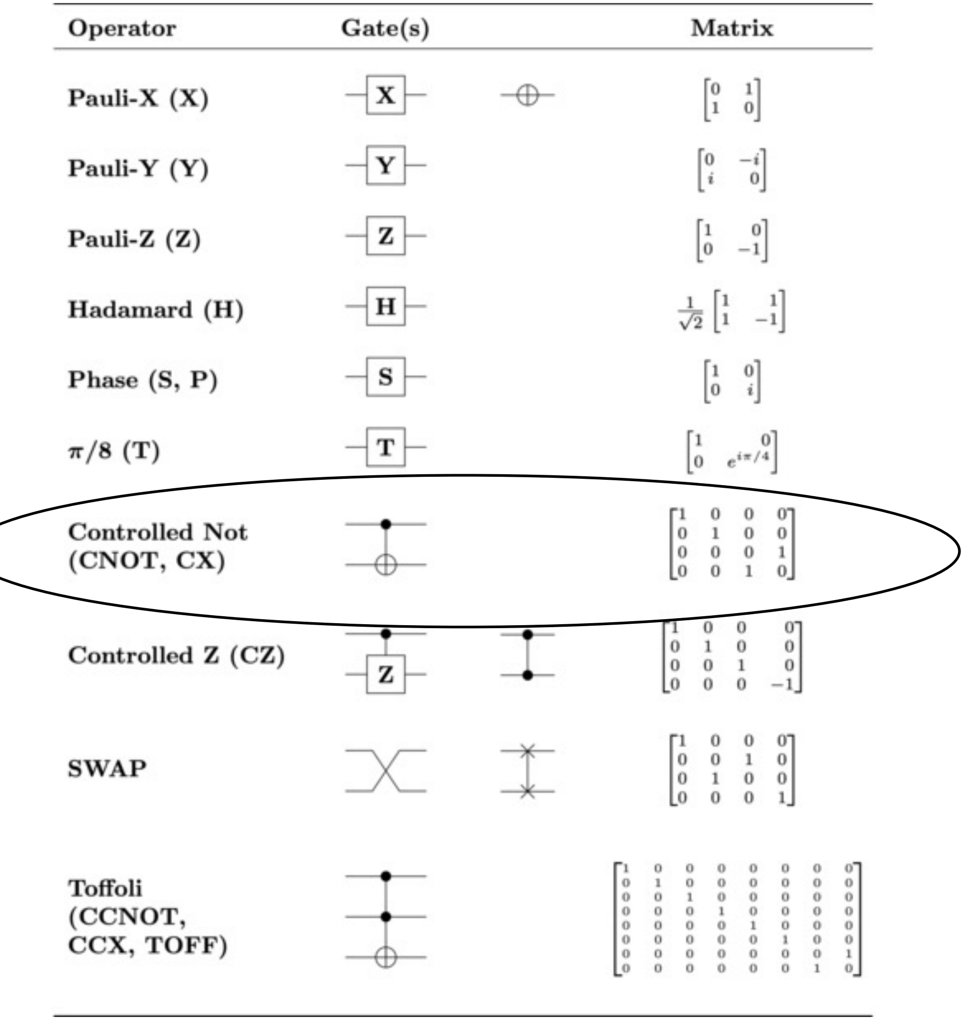
ϵ_z ➡ noise from phase flips



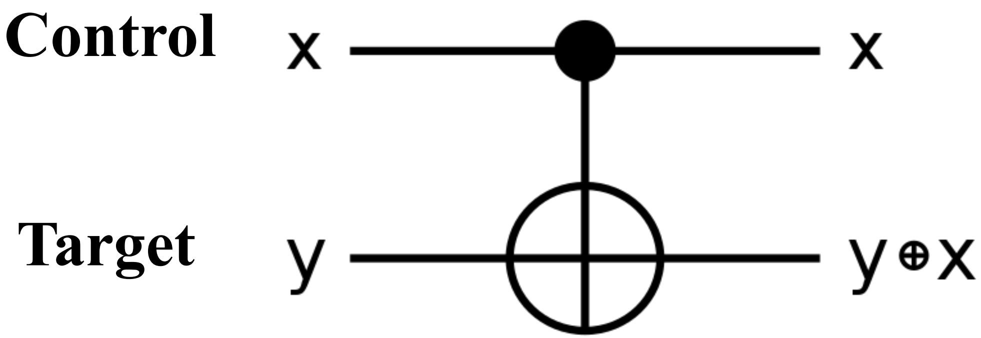
(1) Randomize ϵ_z
(2) Calculate $\frac{\delta\Psi}{\delta\Omega}$ for all Ω pointwise, with the current Hamiltonian H
(3) Update $\Omega \rightarrow \Omega + \eta\frac{\delta\Psi}{\delta\Omega}$
(4) Filter Ω for smoothness and bound condition $\Omega_{max}^2 \geq \Omega_x^2 + \Omega_y^2$



Extension to 2-qubit gates: CNOT gate



Operator	Gate(s)	Matrix
Pauli-X (X)	X	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	T	$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	Z	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&1 \\ 0&0&0&0&0&0&1&0 \end{bmatrix}$

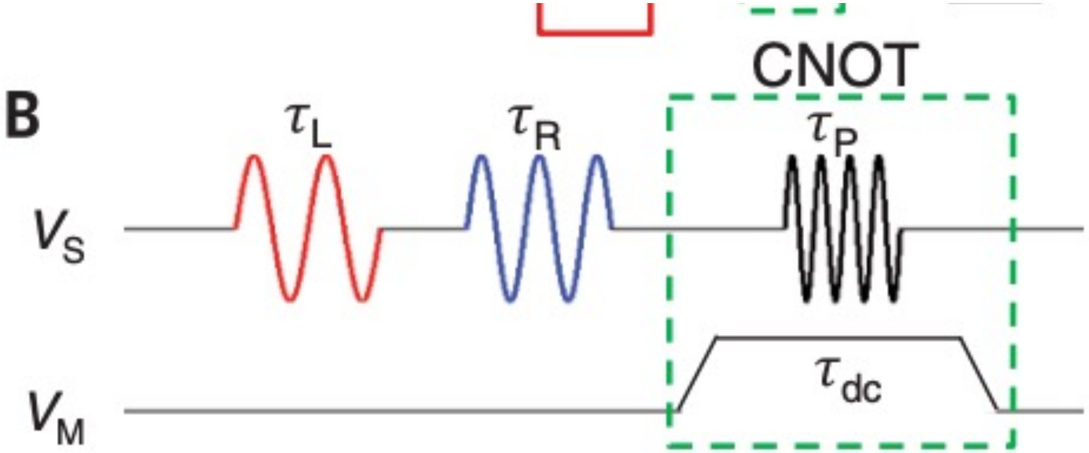


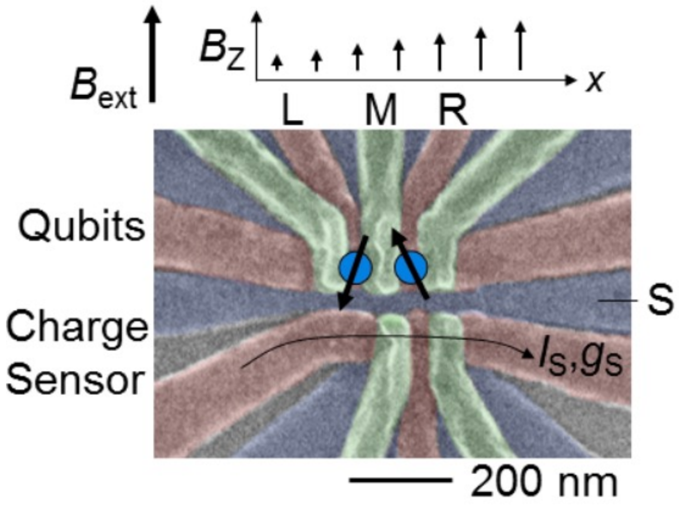
input		output	
x	y	x	y+x
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

If control = 1, flip target!

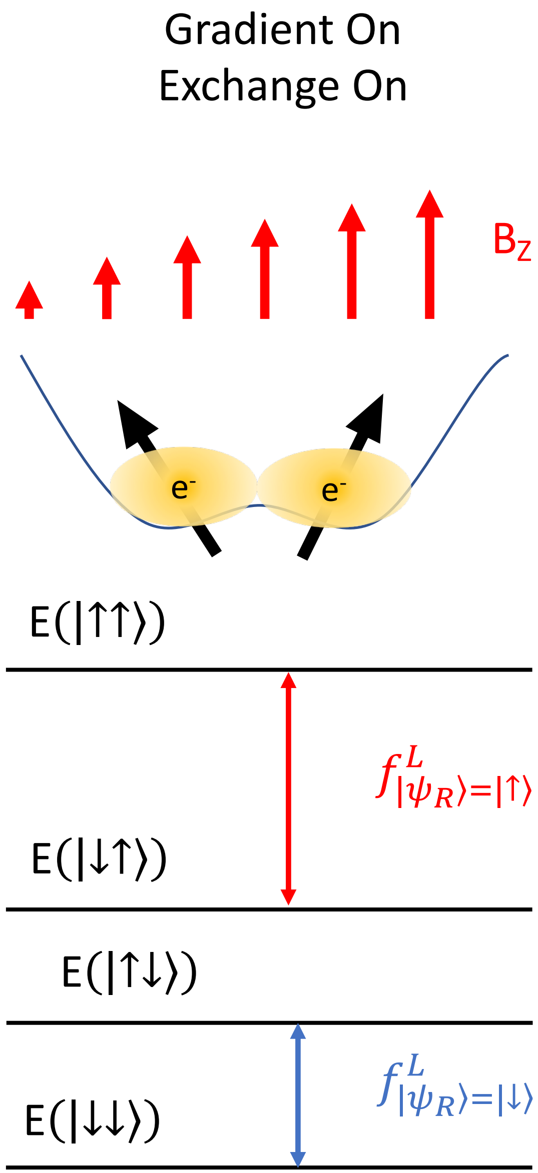
Pulse shaping for CNOT gate

$$\delta E_z >> J$$

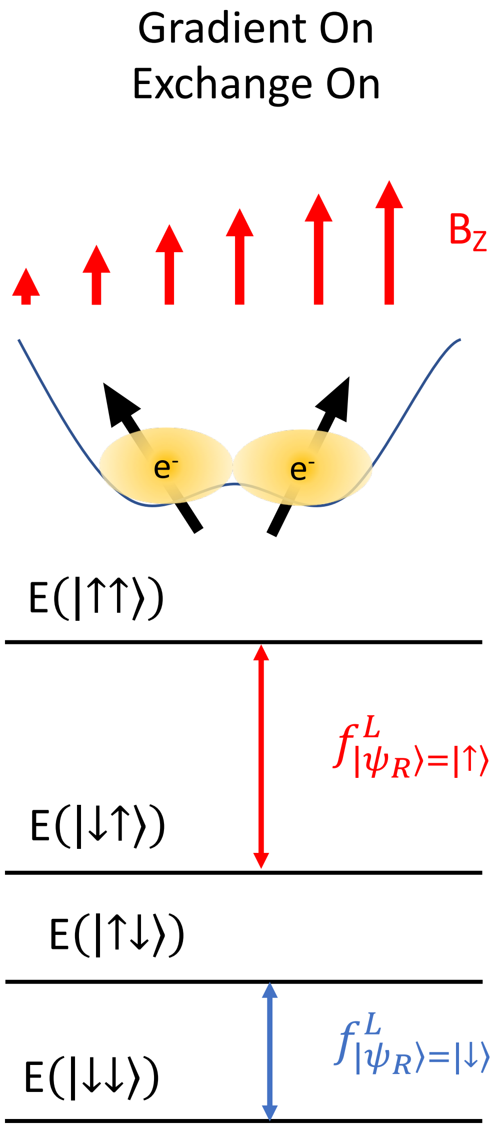


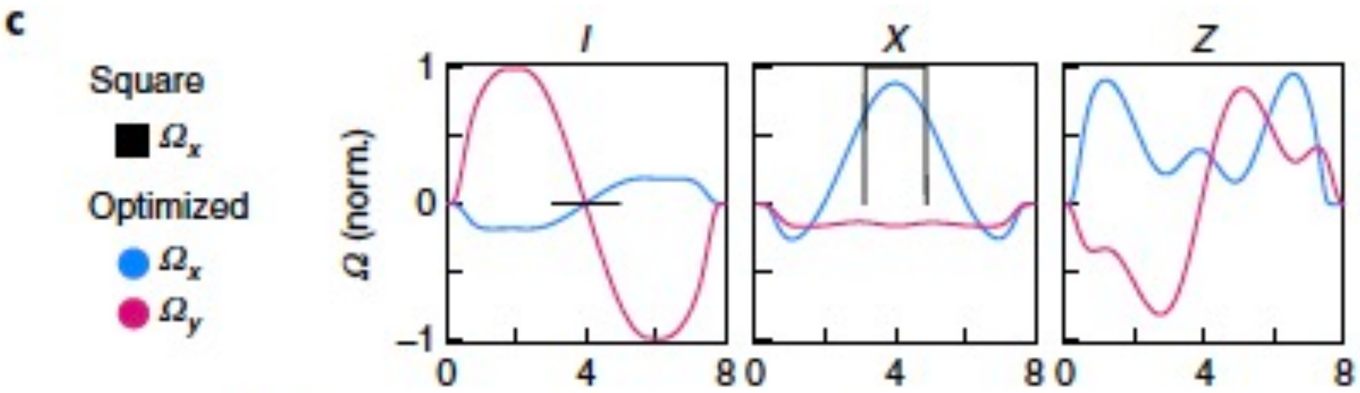


Zajac, AJS *et al.*, Science (2018)
Russ, AJS *et al.*, PRB (2018)



Pulse shaping for CNOT gate (cont'd)



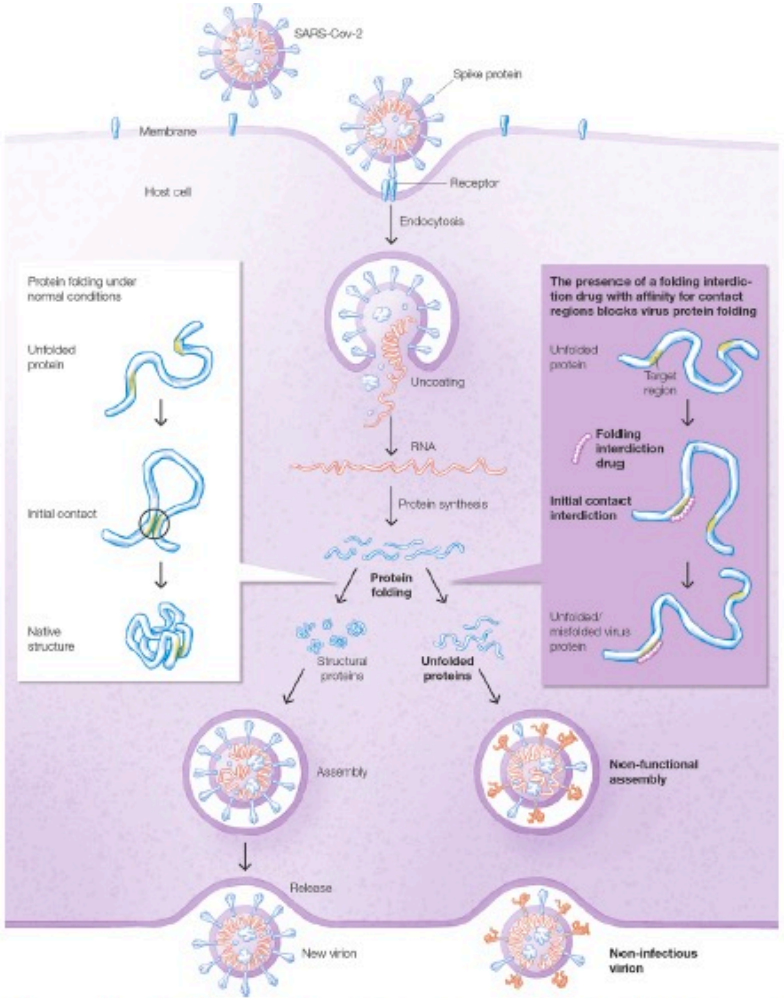


$$+$$

$$V_M \rightarrow J$$

Optimized res-CNOT gate as first 2-gate demonstration, many more to come!

Outlook: towards therapeutic drug design using quantum



$$\mathcal{O}(2^N) \longrightarrow \mathcal{O}(N^3) \text{ ??}$$

Will need hundreds of qubits!

Challenges	Proposed solution
Low-connectivity - Spins limited to nearest-neighbor interactions - Difficult to form large cluster states	Quantum random access memory
Complexity - Each qubit requires multiple wires connected to bond pads - Simultaneous voltage + MW control	Overlapping gate architecture ➔ all qubits share same barrier voltage
Qubit infidelity -Decoherence induced ➔ spin-spin interactions lead to information loss - Noise induced ➔ charge noise leading to fluctuations in exchange interactions	Pulse engineering for noise induced infidelity. Res-Sqrt(SWAP) gates for decoherence induced.

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