NMR-Style Quantum Gates for Superconducting Artificial Molecules

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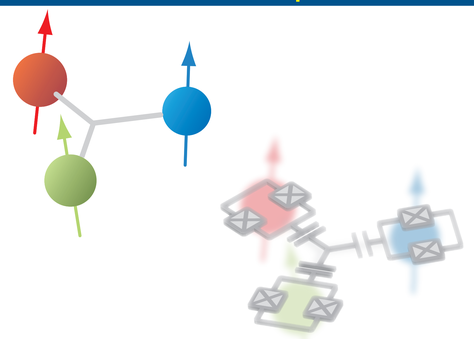
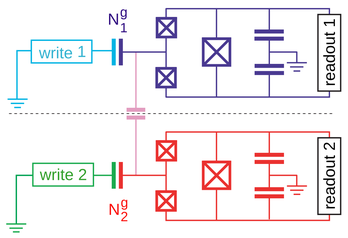
Concept



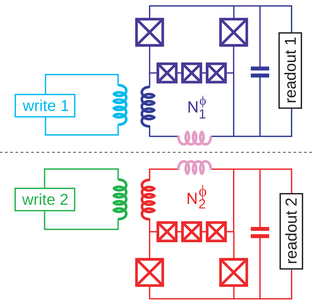
FLICFORQ: Fixed LInear Coupling between Fixed Off-Resonant Qubits

Two-Qubit Circuits

"charge" qubits with
on-chip capacitive coupling

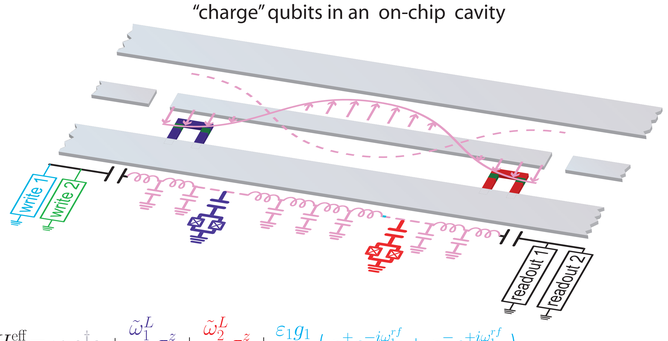


"flux" qubits with
on-chip inductive coupling



$$H^{\text{eff}} = \frac{\omega_1^L}{2}\sigma_1^z + \frac{\omega_2^L}{2}\sigma_2^z + \frac{\omega_1^R}{2}\cos(\omega_1^{rf}\, t + \phi_1)\sigma_1^x + \frac{\omega_2^R}{2}\cos(\omega_2^{rf}\, t + \phi_2)\sigma_2^x + \frac{\omega^{xx}}{2}\sigma_1^x\sigma_2^x$$

"charge" qubits in an on-chip cavity

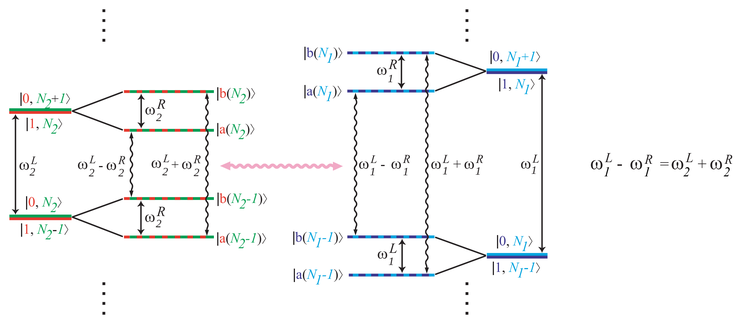


$$H^{\text{eff}} = \omega_r a^\dagger a + \frac{\tilde{\omega}_1^L}{2}\sigma_1^z + \frac{\tilde{\omega}_2^L}{2}\sigma_2^z + \frac{\varepsilon_1 g_1}{\Delta_1}\left(\sigma_1^+ e^{-i\omega_1^{rf}} + \sigma_1^- e^{+i\omega_1^{rf}}\right)$$

$$+ \frac{\varepsilon_2 g_2}{\Delta_2}\left(\sigma_2^+ e^{-i\omega_2^{rf}} + \sigma_2^- e^{+i\omega_2^{rf}}\right) + \frac{g_1 g_2(\Delta_1+\Delta_2)}{2\Delta_1\Delta_2}\left(\sigma_1^+\sigma_2^- + \sigma_1^-\sigma_2^+\right)$$

RF Pulses Generate Entanglement

Quantum Optics Picture: Qubits "Dressed" by RF Photons



$$\omega_J^L - \omega_J^R = \omega_2^L + \omega_2^R$$

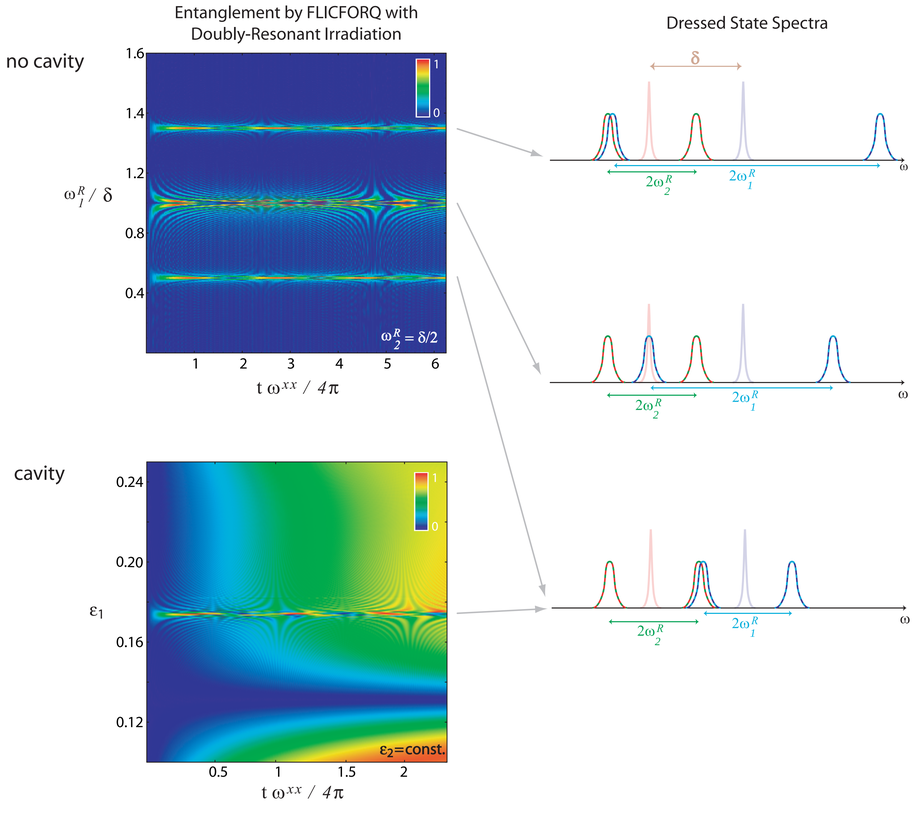
Coupling reactance allows qubits to exchange photons of energy $\omega_J^L - \omega_J^R = \omega_2^L + \omega_2^R$

NMR Picture: Treat RF Fields Classically in Rotating Frame

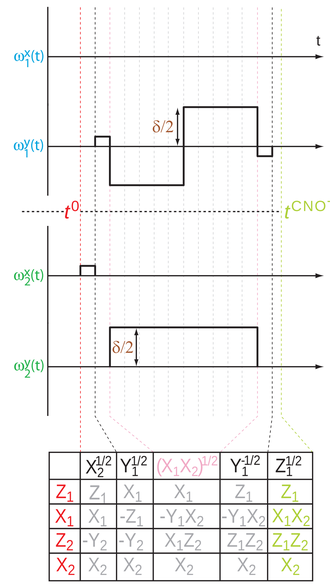
$$H_{R'} = \frac{\omega^{xx}}{16}\left(\sigma_1^y\sigma_2^y - \sigma_1^z\sigma_2^z\right)\cos(\phi_1 - \phi_2) + \left(\sigma_1^z\sigma_2^y + \sigma_1^y\sigma_2^z\right)\sin(\phi_1 - \phi_2)$$

in quadruply rotating frame for $\omega_1^R = \omega_2^R = \delta/2$

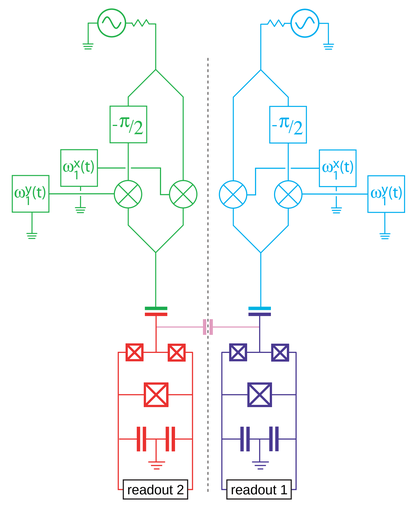
Numerical Simulations of Two-Qubit Systems



Experimental Protocol for CNOT Gate



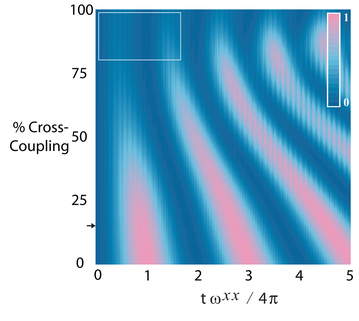
	$X_2^{1/2}$	$Y_1^{1/2}$	$(X_1X_2)^{1/2}$	$Y_1^{1/2}$	$Z_1^{1/2}$
Z_1	Z_1	X_1	X_1	Z_1	Z_1
X_1	X_1	$-Z_1$	$-Y_1X_2$	$-Y_1X_2$	X_1X_2
Z_2	$-Y_2$	$-Y_2$	X_1Z_2	Z_1Z_2	Z_1Z_2
X_2	X_2	X_2	X_2	X_2	X_2



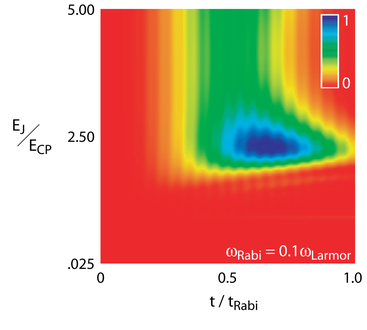
Sources of Gate Error

- Leakage to higher energy states
- Signal cross-coupling
- Imperfect pulses (finite rise time, amplitude/phase instability)
- Presence of fixed coupling

Entanglement by DRI/FLICFORQ
with Signal Cross-Coupling



Leakage Probability for Charge
Qubit Under Strong Driving



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