Lecture 26, 15 Dec 2020

$$H|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

$$|\psi(t)\rangle = e^{-iHt/\hbar}|\psi(0)\rangle$$

$$\hbar \approx 10^{-34}\ kg\,m^2/s = 10^{-34}\ J\cdot s$$

$$\sim 6.6\cdot 10^{-15}\ eV\cdot s$$

vis light $\sim \omega \sim 10^{15}\ s^{-1}$

dipole moment

mag field

$$\mathcal{H} = (\text{kinetic terms}) + \vec{\mu}_B B$$

$$e^{(\ \ ) - i\vec{\mu}_B\vec{B}t_0}$$

$$e^{i\frac{\theta}{2}\sigma_z}$$

phase

Unitary operators

Quantum Physics

[Submitted on 11 Dec 2020 (v1), last revised 14 Dec 2020 (this version, v2)]

Saving superconducting quantum processors from qubit decay and correlated errors generated by gamma and cosmic rays

John M. Martinis

Error-corrected quantum computers can only work if errors are small and uncorrelated. Here I show how cosmic rays or stray background radiation affects superconducting qubits by modeling the phonon to electron/quasiparticle down-conversion physics. For present designs, the model predicts about 57\% of the radiation energy breaks Cooper pairs into quasiparticles, which then vigorously suppress the qubit energy relaxation time ($T_1 \sim 160$ ns) over a large area (cm) and for a long time (ms). Such large and correlated decay kills error correction. Using this quantitative model, I show how this energy can be channeled away from the qubit so that this error mechanism can be reduced by many orders of magnitude. I also comment on how this affects other solid-state qubits.

Quantum computers have intrinsic errors, so algorithms can be natively run with typically only a few hundred to thousand logic operations [3, 4]. In order to run the most powerful and useful algorithms, say with millions to billions of logic gates, errors must be reduced to a parts per million or billion range, or lower. Fortunately, this is possible using quantum error correction, where the qubit state is distributed to many physical qubits in a way similar to classical error correction, so that errors in the physical qubit states can be selectively measured, decoded and corrected. For example, surface code error correction encodes a protected "logical" state with about 1000 physical qubits [5, 6]. As long as physical errors are small, about 0.1%, and occur randomly and independently among these 1000 qubits, then the logical error can be less than 0.1 part per billion [7]. However, if errors are large or correlated, bunching together either in time or across the chip in space, then error decoding fails. With a logical error, the memory of the quantum computer is lost and the algorithm fails.

This paper explains how cosmic rays and background gamma ray radiation are pulsed energy sources that produce large and correlated errors in superconducting qubits. Cosmic rays naturally occur from high energy particles impinging from space to the atmosphere, where they are converted into muon particles that deeply penetrate all matter on the surface of the earth. When the muons traverse the quantum chip, they deposit a large amount of energy in the substrate of the quantum processor, on average 460 keV [8], which then briefly "heats" the chip. Gamma rays from natural background sources have a somewhat larger rate and can deposit even greater energy, up to about 1 MeV [8]. Experiments on low-

Using a quantitative model for the generation of quasiparticles and their decay, I show that one can reliably redesign the quantum processor by channeling the phonon energy away from the qubits. The most important change is using thick films of a normal metal or low-gap superconductor to channel energy away from qubits. This redesign should reduce the initial quasiparticle density by a factor of 100, usefully larger than for a previous detector experiment with thin films [11]. This work is also complementary to a recent paper that describes well the radiation physics and the effects of breaking electron-hole pairs in the silicon crystal as part of the down-conversion process [8]; such charge offsets should not be an issue with large transmon qubits [18].

Quantum Physics

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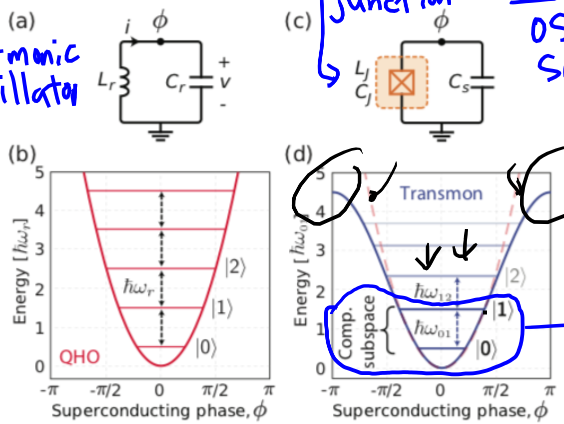
A Quantum Engineer's Guide to Superconducting Qubits

Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, William D. Oliver

The aim of this review is to provide quantum engineers with an introductory guide to the central concepts and challenges in the rapidly accelerating field of superconducting quantum circuits. Over the past twenty years, the field has matured from a predominantly basic research endeavor to one that increasingly explores the engineering of larger-scale superconducting quantum systems. Here, we review several foundational elements -- qubit design, noise properties, qubit control, and readout techniques -- developed during this period, bridging fundamental concepts in circuit quantum electrodynamics (cQED) and contemporary, state-of-the-art applications in gate-model quantum computation.

LC circuit = harmonic oscillator

Josephson junction ⇒ anharmonic oscillator, so $\omega_{12} \neq \omega_{01}$



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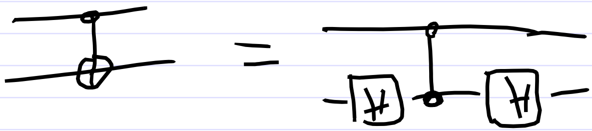
2-state quantum system = qubit

FIG. 1. **(a)** Circuit for a parallel LC-oscillator (quantum harmonic oscillator, QHO), with inductance L in parallel with capacitance, C. The superconducting phase on the island is denoted ϕ, referencing ground as zero. **(b)** Energy potential for the QHO, where energy levels are equidistantly spaced $\hbar\omega_r$ apart. **(c)** Josephson qubit circuit, where the nonlinear inductance L_J (represented with the Josephson-subcircuit in the dashed orange box) is shunted by a capacitance, C_s. **(d)** The Josephson inductance reshapes the quadratic energy potential (dashed red) into sinusoidal (solid blue), which yields non-equidistant energy levels. This allows us to isolate the two lowest energy levels $|0\rangle$ and $|1\rangle$, forming a computational subspace with an energy separation $\hbar\omega_{01}$, which is different than $\hbar\omega_{12}$.

What about CNOT?

Mermin App H

$$C^z = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -1 \end{pmatrix}$$



$$C_{10} = H_0 C^z H_0$$

$$C^z = \frac{1}{2}\left(1 + Z_0 + Z_1 - Z_0 Z_1\right)$$

$(C^z)^2 = 1$ so $e^{iC^z\theta} = \cos\theta\, \mathbb{1} + iC^z \sin\theta$

$\theta = \pi/2$

$$\Rightarrow C^z = -i e^{i\pi/2\, C^z} = e^{-i\pi/4}\, e^{i\frac{\pi}{4}(1 + Z_0 + Z_1 - Z_0 Z_1)}$$

$\vec{\mu}_B \vec{B} t_0$

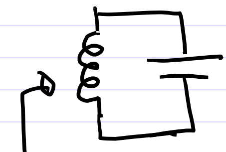
mag field on spin

two-spin coupling

but unrealistic:

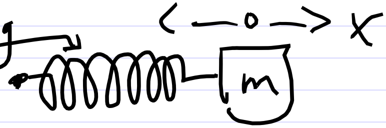
i) anisotropic, only z-component of spin

ii) coupling of mag field to single spins has exactly same strength as two-spin coupling



K.E. P.E.

$$\frac{1}{2}CV^2 + \frac{1}{2}LI^2$$



like mechanical oscillator

$$\mathcal{H} = p^2/2m + \frac{1}{2} m\omega^2 x^2$$

Quantize $= \hbar\omega\left(a^\dagger a + \frac{1}{2}\right)$

where
$$a = \sqrt{\frac{m\omega}{2\hbar}}\left(x + \frac{i}{m\omega}p\right)$$

$[x, p] = i\hbar$ (implies $\Delta x \Delta p \gtrsim \hbar$)

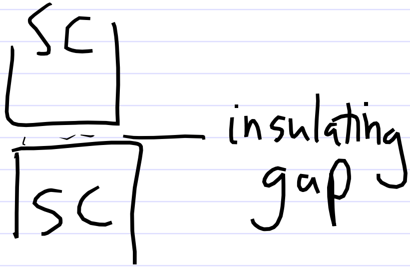
$\Rightarrow [a, a^\dagger] = 1$

algebra describes equally spaced levels starting from $|0\rangle$ with $a|0\rangle = 0$, then $|n\rangle \propto (a^\dagger)^n |0\rangle$ has $a^\dagger a|n\rangle = n|n\rangle$, and $E_n = \hbar\omega\left(n + \frac{1}{2}\right)$

$\Delta x \Delta p \gtrsim \hbar$ $\quad \omega = 1/\sqrt{LC}$

$\Delta E \Delta t \gtrsim \hbar$

J.J.



$$\Phi = LI$$

$$\frac{1}{2}LI^2 = \frac{\Phi^2}{2L} \longrightarrow -\frac{1}{L}\cos\Phi$$

$$I = I_c \sin\varphi \longleftarrow \text{non-linear}$$

leading order: $\left(a^\dagger a + \frac{1}{2}\right) - \lambda\left(a^\dagger + a\right)^4$

"transmon" $\quad C_s >> C_J$

potential term $\propto \cos\Phi$ dominates

Now change gap to a loop:

DC squid. $\Rightarrow$ apply magnetic field, changes ω

Couple them?

1 qubit gates become difficult, require two frequencies and for n qubits would require 2^n frequencies to execute 1-qubit gates.

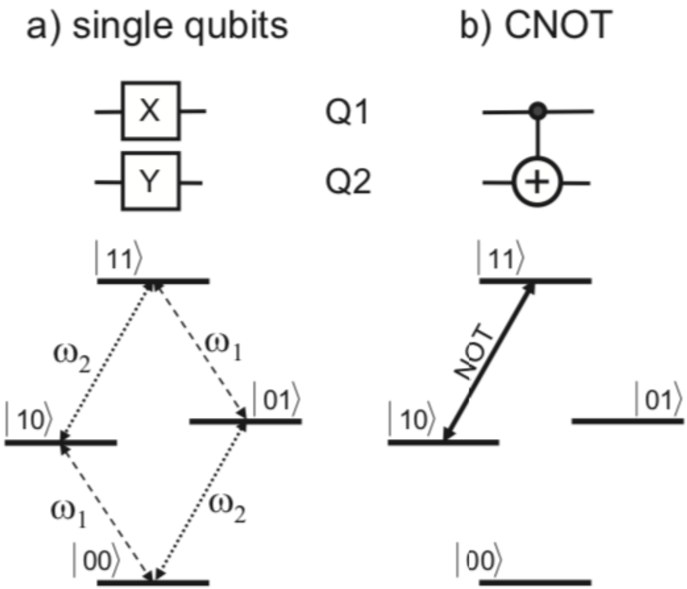


FIG. 1: Single and CNOT logic gates, in the transition picture, for two uncoupled qubits. Plotted is the qubit energy (vertical) for the four possible states. (a) Here, the transition frequency ω_1 for the first qubit (dashed lines) is the same for the pair of transitions $|00\rangle \leftrightarrow |10\rangle$ and $|01\rangle \leftrightarrow |11\rangle$. There is a similar pair (dotted lines) at frequency ω_2 for the second qubit. (b) The CNOT logic gate must swap only the states $|10\rangle$ and $|11\rangle$, which cannot be accomplished because of the degeneracy with the transition frequency $|00\rangle \leftrightarrow |01\rangle$.

Solution: turn couplings on and off

$$\mathcal{H} \sim \begin{pmatrix} \omega_1 & g \\ g & \omega_2 \end{pmatrix}$$

two qubits with off-diagonal coupling g

eigenvalue equation $(\lambda-\omega_1)(\lambda-\omega_2)-g^2=0$ has solutions

$$\lambda_{1,2} = \frac{\omega_1+\omega_2}{2} \pm \sqrt{\Delta^2/4+g^2}$$

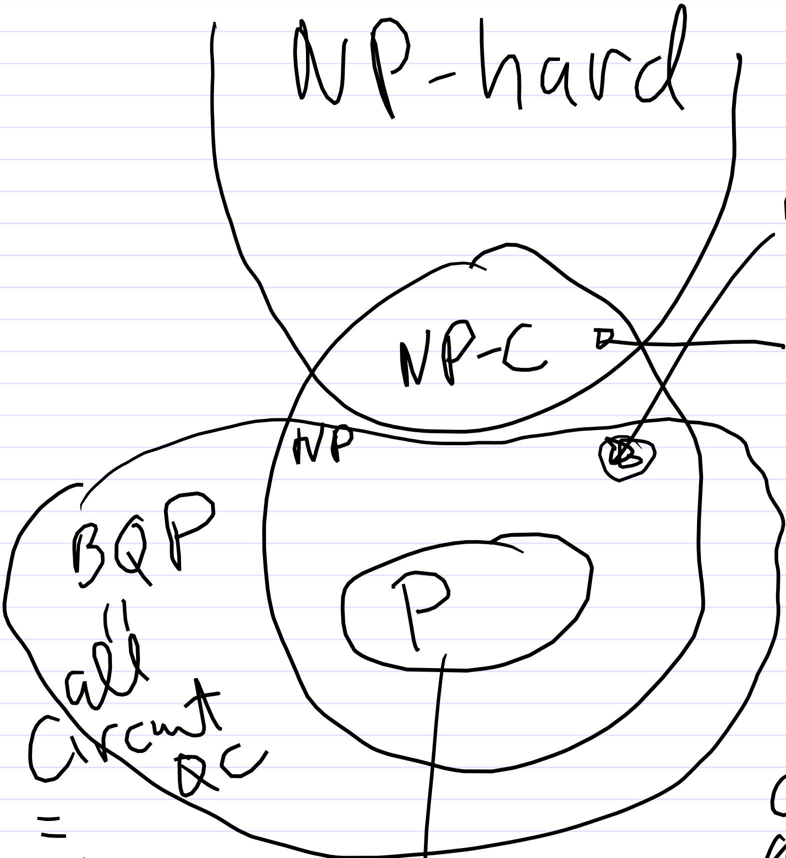
where $\Delta = \omega_1 - \omega_2$

Coupling on: tune $\omega_1=\omega_2=\omega$ then $\begin{cases} \lambda_1 = \omega+g \\ \lambda_2 = \omega-g \end{cases}$

Coupling "off": tune $\Delta \gg g$ $\begin{cases} \lambda_1 \approx \omega_1 + g^2/\Delta \\ \lambda_2 \approx \omega_2 - g^2/\Delta \end{cases}$

$$\text{off}/\text{on} \propto \frac{g^2/\Delta}{g} = g/\Delta = \frac{30\,\text{Mhz}}{300\,\text{Mhz}} = 1/10$$

in practice



GI, factoring

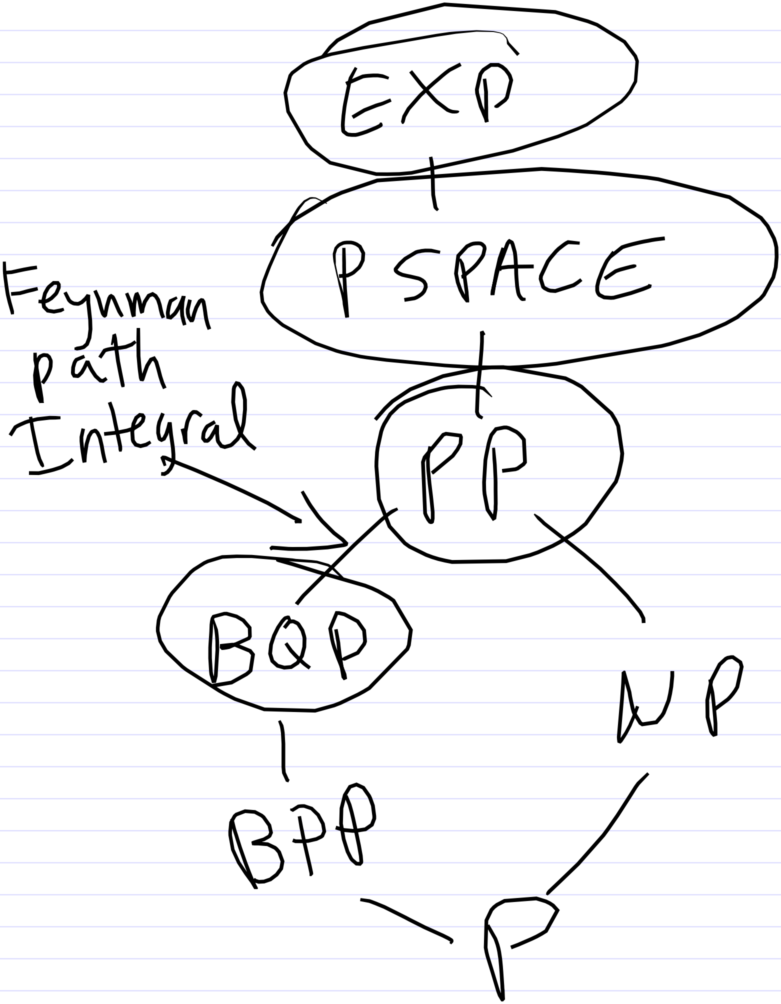
Solve any one of these, solves all...:
Hamitonian path
TSP
Knapsack
packing
comb. opt.
graph coloring
3-SAT

$x_0 \vee x_1 \vee \bar{x}_2$
$\bar{x}_5 \vee x_8 \vee x_9$
...

= "Bounded Quantum polynomial"

graph connectivity
primality testing
Matrix determinant
linear programming
Dykstra for shortest path
Marriage Problem, ...

(e.g. Levenstein distance)



(assumes

$P \neq NP$)

End
of
Lec 26