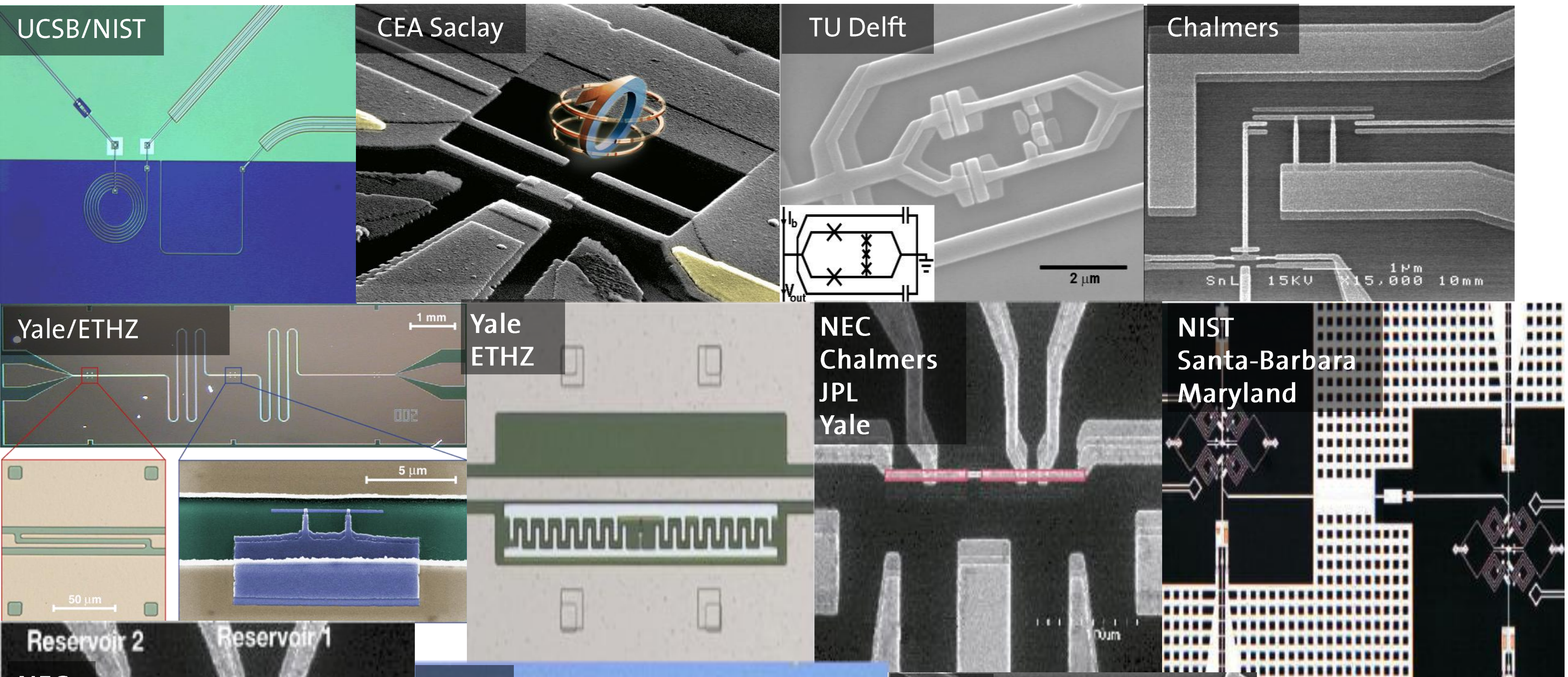
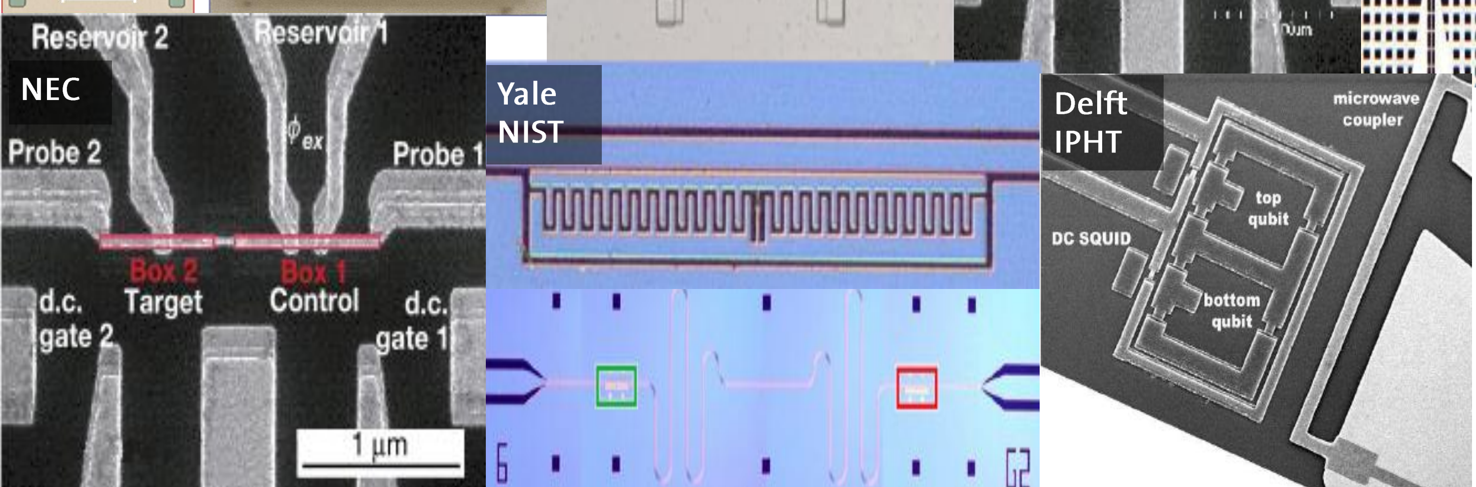
Building a Quantum Information Processor using Superconducting Circuits

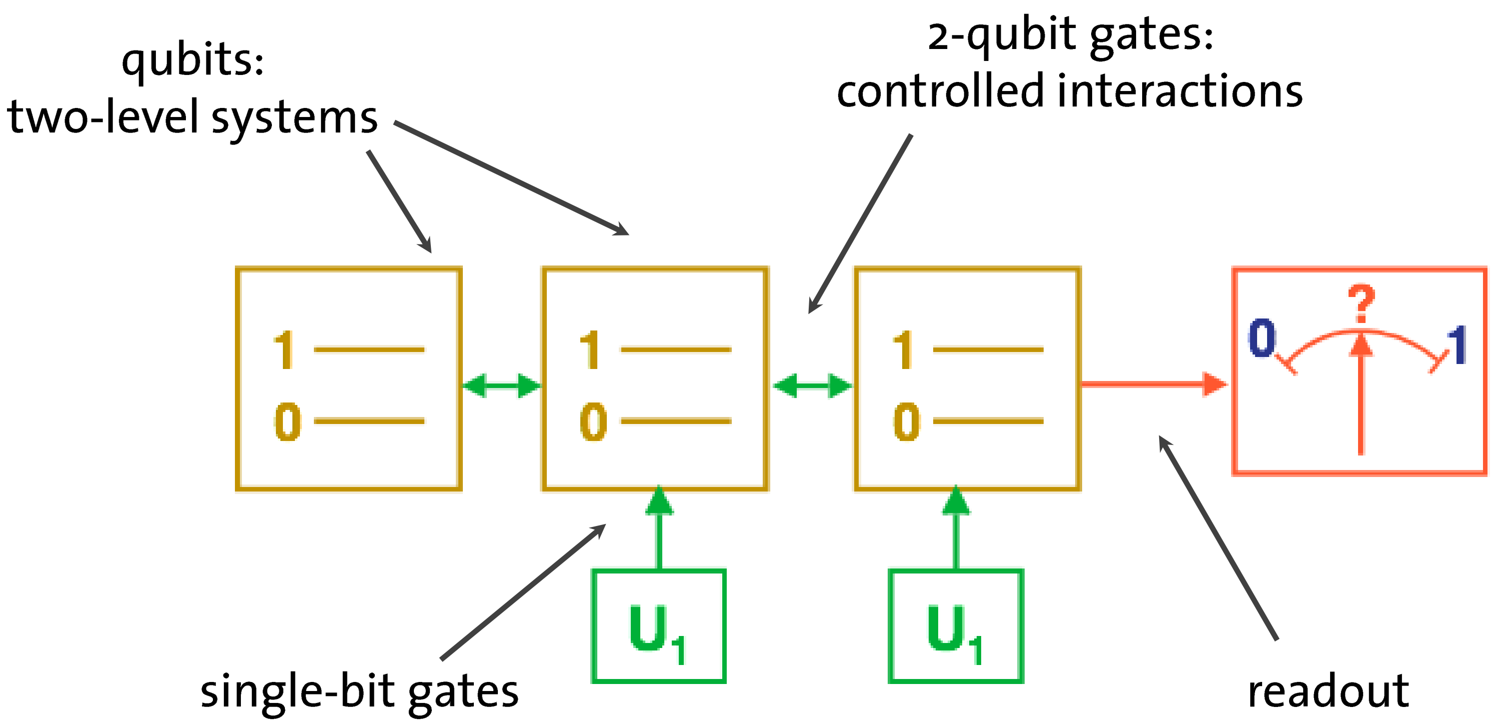




with material from NIST, UCSB, Berkeley, NEC, NTT, CEA Saclay, Yale and ETHZ

Generic Quantum Information Processor

The challenge:



- Quantum information processing requires excellent qubits, gates, ...
- Conflicting requirements: good isolation from environment while maintaining good addressability

M. Nielsen and I. Chuang,
Quantum Computation and Quantum Information (Cambridge, 2000)

The DiVincenzo Criteria

for Implementing a quantum computer in the standard (circuit approach) to quantum information processing (QIP):

#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.

plus two criteria requiring the possibility to transmit information:

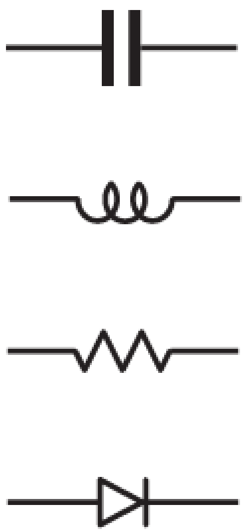
#6. The ability to interconvert stationary and mobile (or flying) qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

Topics

- realization of superconducting quantum electronic circuits
    - harmonic oscillators (photons)
    - non-harmonic oscillators (qubits)
- controlled qubit/photon interactions
    - cavity quantum electrodynamics with circuits
- qubit read-out
- single qubit control
- decoherence
- two-qubit interactions
    - generation of entanglement
    - realization of quantum algorithms

Conventional Electronic Circuits

basic circuit elements:

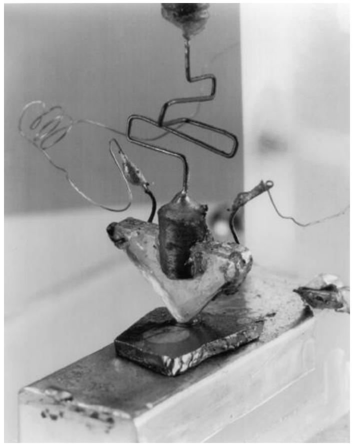


basis of modern information and communication technology

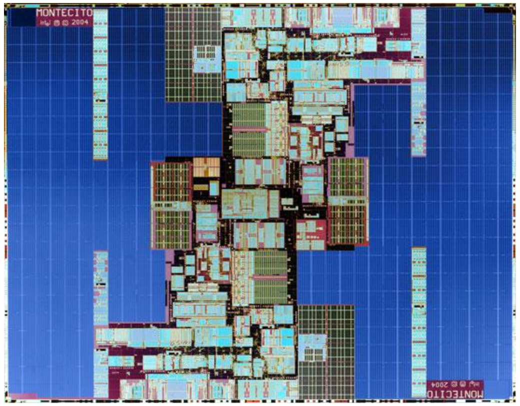
properties :

- classical physics
- no quantum mechanics
- no superposition principle
- no quantization of fields

first transistor at Bell Labs (1947)



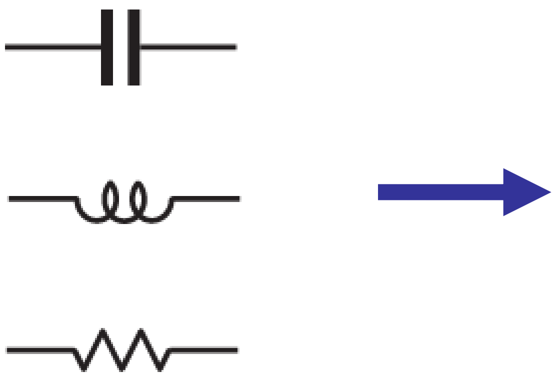
intel dual core processor (2006)



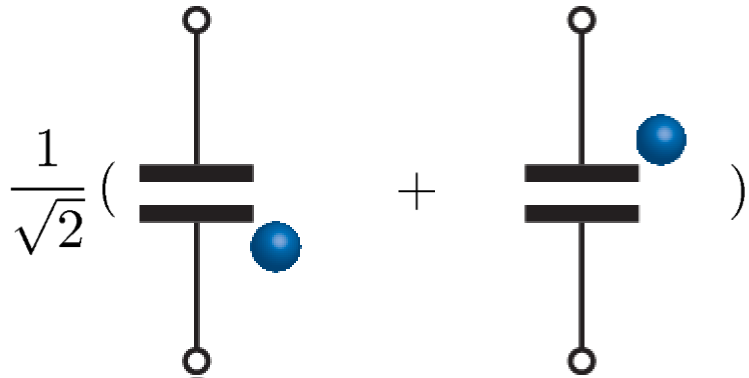
2.000.000.000 transistors
smallest feature size 65 nm
clock speed ~ 2 GHz
power consumption 10 W

Classical and Quantum Electronic Circuit Elements

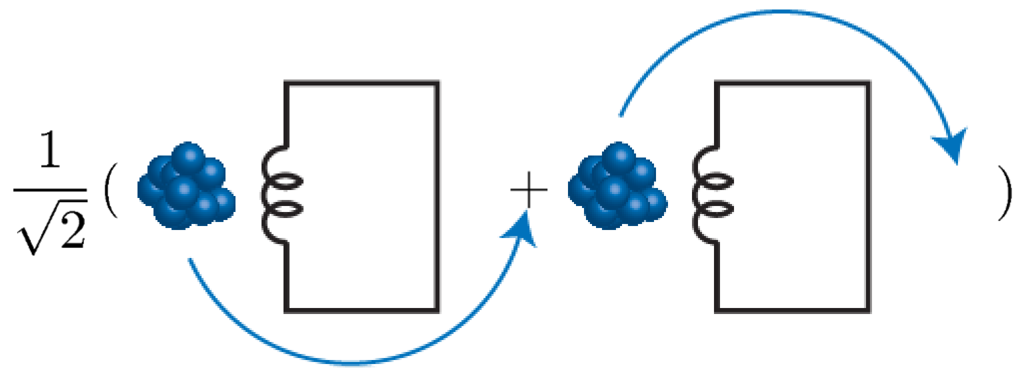
basic circuit elements:



charge on a capacitor:



current or magnetic flux in an inductor:

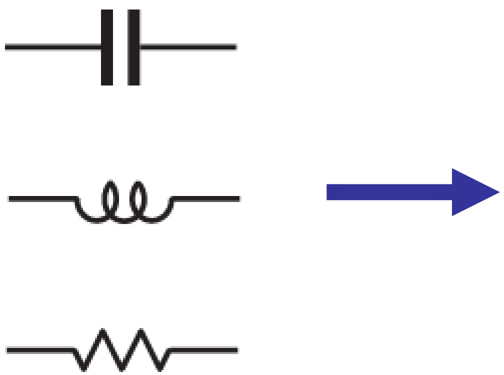


quantum superposition states:

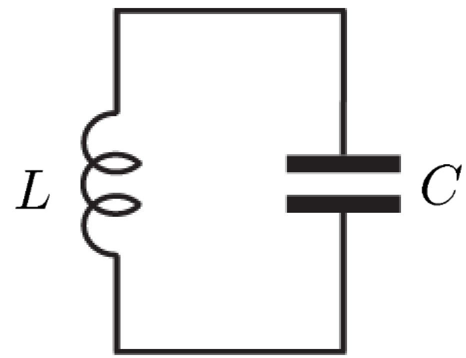
- charge q
- flux ϕ

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



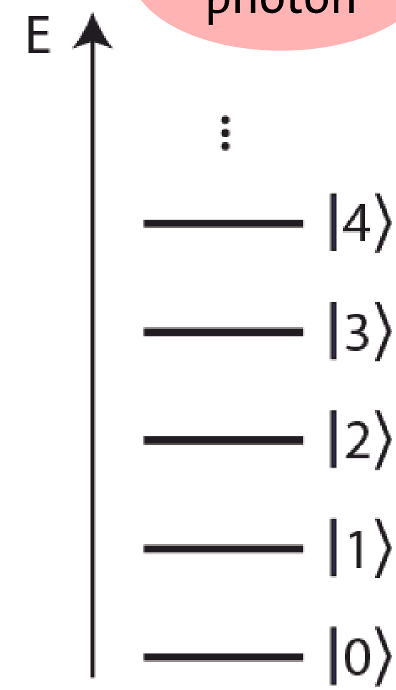
harmonic LC oscillator:



$$\omega = \frac{1}{\sqrt{LC}} \sim 5\,\mathrm{GHz}$$

energy:

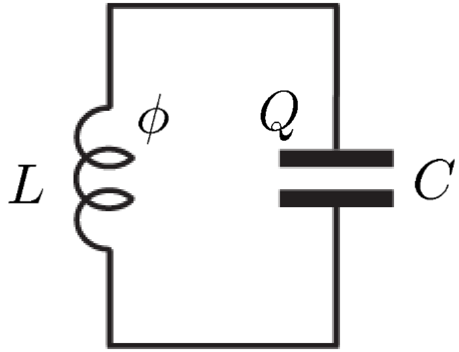
electronic photon



Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

Quantization of an Electronic Harmonic Oscillator

Harmonic LC oscillator:



$$Q = CV \quad \text{Charge on capacitor}$$

$$\phi = LI \quad \text{Flux in inductor}$$

$$V = -L\dot{I} = -\dot{\phi} \quad \text{Voltage across inductor}$$

Classical Hamiltonian:

$$H = \frac{CV^2}{2} + \frac{LI^2}{2} = \frac{Q^2}{2C} + \frac{\phi^2}{2L}$$

Conjugate variables:

$$\frac{\partial H}{\partial \phi} = \frac{\phi}{L} = I = \dot{Q}$$

$$\frac{\partial H}{\partial Q} = \frac{Q}{C} = V = -L\dot{I} = -\dot{\phi}$$

Hamilton operator:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{q}^2}{2C}$$

Flux and charge operator:

$$\hat{\phi} = \phi$$

$$\hat{Q} = -i\hbar \frac{\partial}{\partial \phi}$$

Commutation relation:

$$\left[\hat{\phi}, \hat{q}\right] = i\hbar$$

Creation and Annihilation Operators for Circuits

Hamilton operator of harmonic oscillator in second quantization:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \hbar\omega(\hat{a}^\dagger \hat{a} + 1/2)$$

$$\hat{a}^\dagger |n\rangle = \sqrt{n+1}\,|n+1\rangle$$ **Creation operator**

$$\hat{a} |n\rangle = \sqrt{n}\,|n-1\rangle$$ **Annihilation operator**

$$\hat{a}^\dagger \hat{a} |n\rangle = n\,|n\rangle$$ **Number operator**

$$\hat{Q} = \sqrt{\frac{\hbar}{2Z_C}}(\hat{a}^\dagger + \hat{a})$$ **Charge/voltage operator** $$\hat{V} = \frac{\hat{Q}}{C}$$

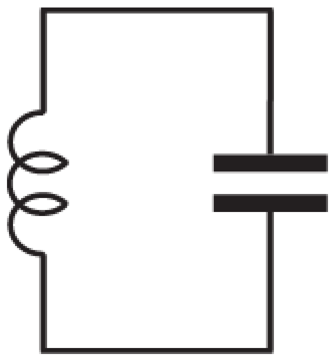
$$\hat{\phi} = i\sqrt{\frac{\hbar Z_C}{2}}(\hat{a}^\dagger - \hat{a})$$ **Flux/current operator** $$\hat{I} = \frac{\hat{\phi}}{L}$$

With characteristic impedance:

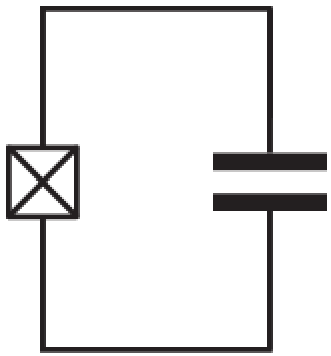
$$Z_C = \sqrt{\frac{L}{C}}$$

Linear vs. Nonlinear Superconducting Oscillators

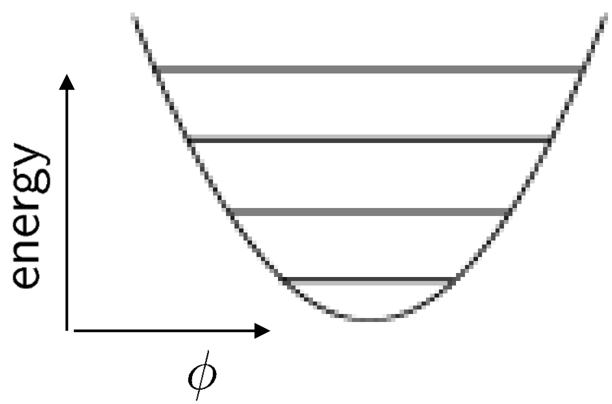
LC resonator:

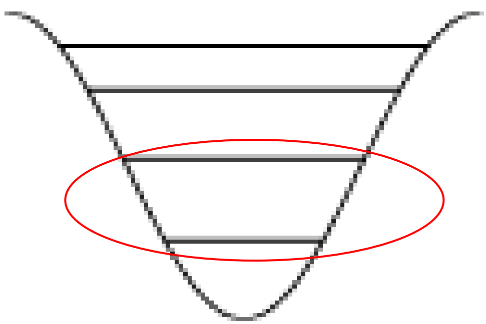


Josephson junction resonator:
Josephson junction = nonlinear inductor



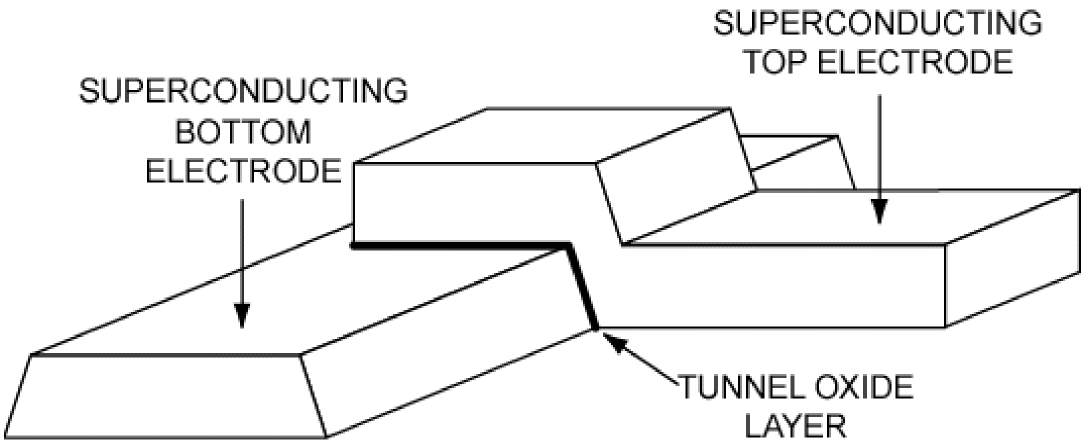
anharmonicity defines effective two-level system





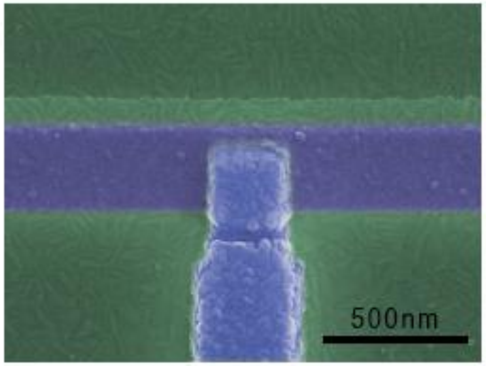
A Low-Loss Nonlinear Element

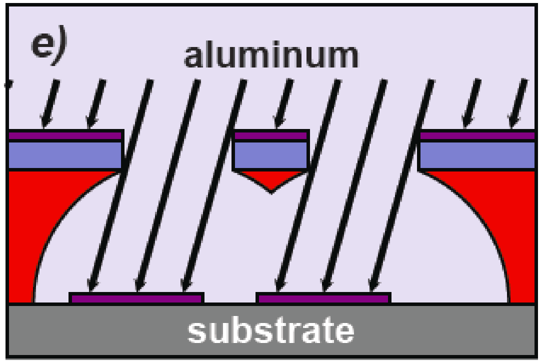
a (superconducting) Josephson junction:

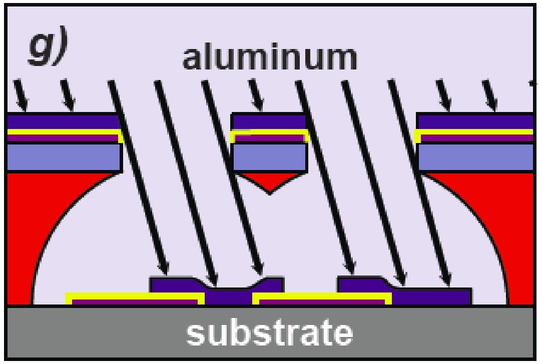


- superconductors: Nb, Al
- tunnel barrier: AlO_x

Josephson junction fabricated by shadow evaporation:



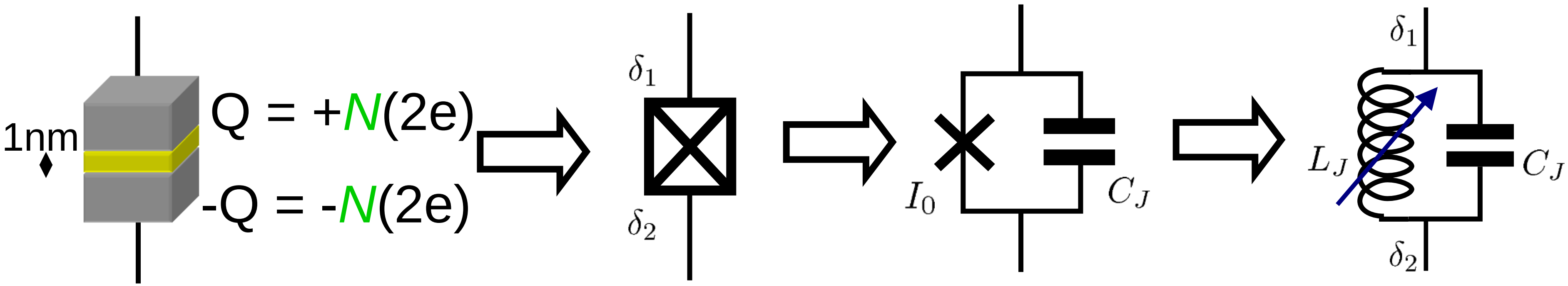




M. Tinkham, *Introduction to Superconductivity* (Krieger, Malabar, 1985).

Josephson Tunnel Junction

The only non-linear resonator with no dissipation (BCS, $k_B T<\Delta$)



Tunnel junction parameters:

- Critical current I_o
- Junction capacitance C_J
- Internal resistance R_J

Josephson relations:

$$I = I_0 \sin\delta$$

$$V = \frac{\phi_0}{2\pi}\dot{\delta}$$

Flux quantum:

$$\phi_0 = \frac{h}{2e}$$

Phase difference:

$$\delta = \delta_2 - \delta_1$$

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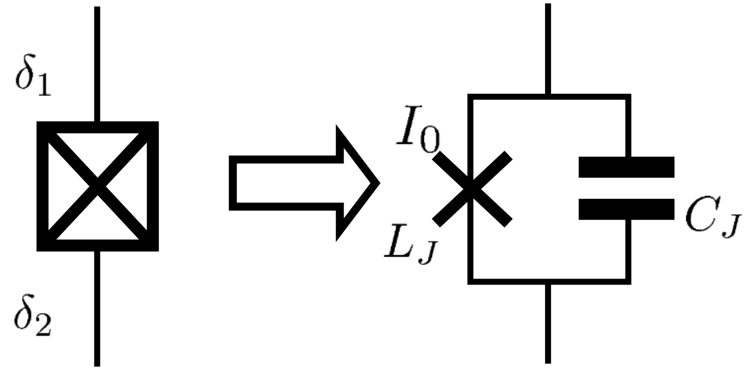
Swiss Federal Institute of Technology Zurich

derivation of Josephson effect, see e.g.: chap. 21 in R. A. Feynman: Quantum mechanics, The Feynman Lectures on Physics. Vol. 3 (Addison-Wesley, 1965)

The Josephson Junction as an ideal Non-Linear Inductor

a nonlinear inductor without dissipation



Josephson relations:

$$I = I_0 \sin\delta = I_0 \sin\left[2\pi\phi(t)/\phi_0\right]$$

$$V = \frac{\phi_0}{2\pi}\dot{\delta} = \dot{\phi}$$

nonlinear current/phase relation

gauge inv. phase difference:

$$\delta = \delta_2 - \delta_1 = 2\pi\phi(t)/\phi_0$$

specific Josephson inductance L_{J0}

Josephson inductance:

$$V = -L_J \dot{I} = \frac{\phi_0}{2\pi I_0}\frac{1}{\cos\delta}\dot{I}$$

specific Josephson energy E_{J0}

Josephson energy:

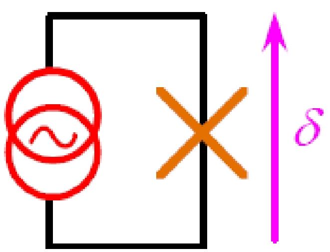
$$E_J = \int V I dt = \frac{I_0 \phi_0}{2\pi}\cos\delta$$

A Classification of Josephson Junction Based Qubits

How to make use in of Jospehson junctions in a qubit?

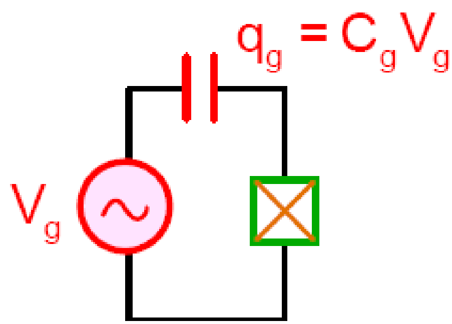
Common options of bias (control) circuits:

phase qubit



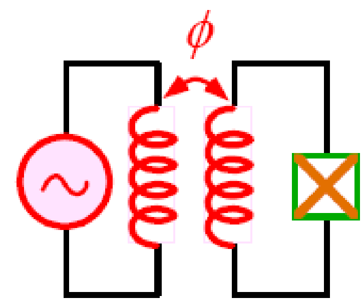
current bias

charge qubit
(Cooper Pair Box, Transmon)



charge bias

flux qubit



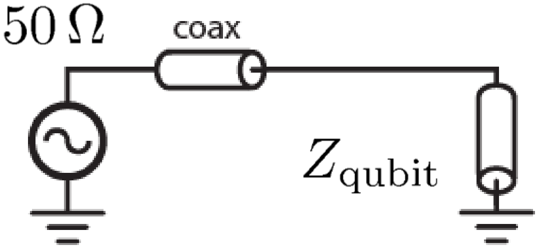
flux bias

How is the control circuit important?

Control of Coupling to Electromagnetic Environment

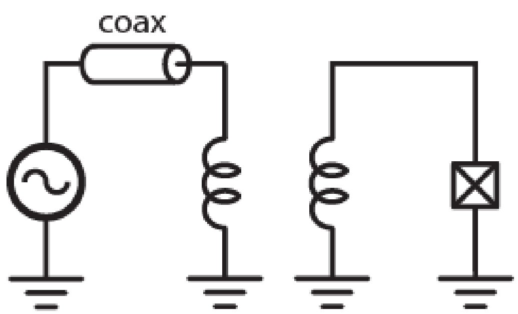
coupling to environment (bias wires):

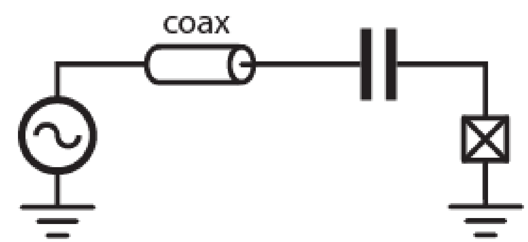
$Z_{\text{line}} \sim 50\,\Omega$



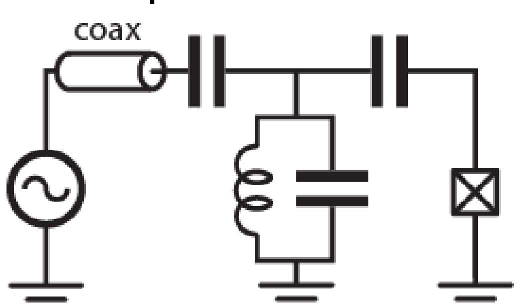
decoherence due to energy relaxation stimulated by the vacuum fluctuations of the environment (spontaneous emission)

Decoupling schemes using non-resonant impedance transformers ...



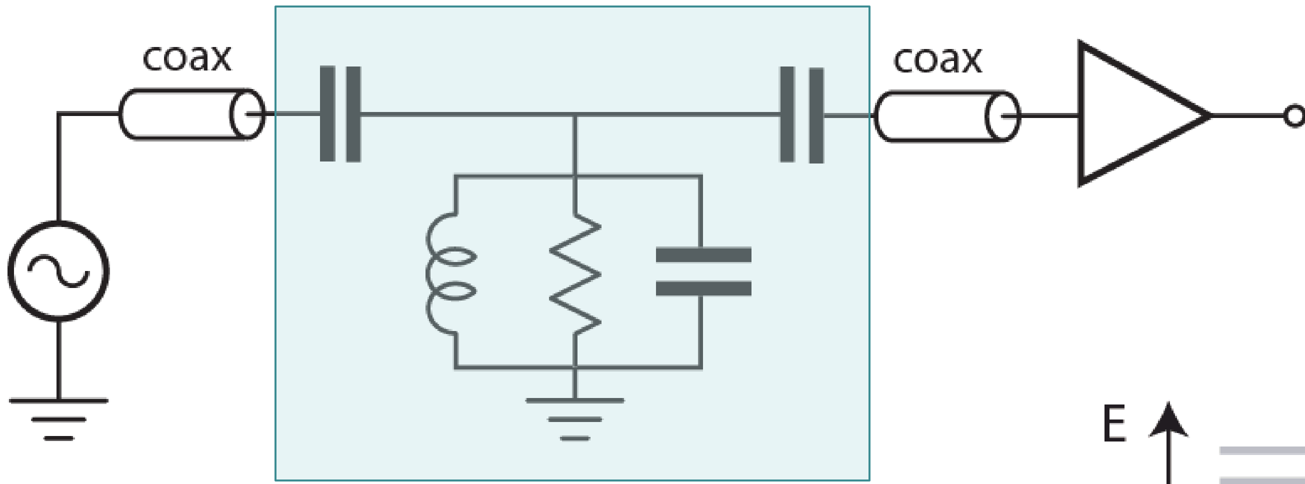


... or resonant impedance transformers

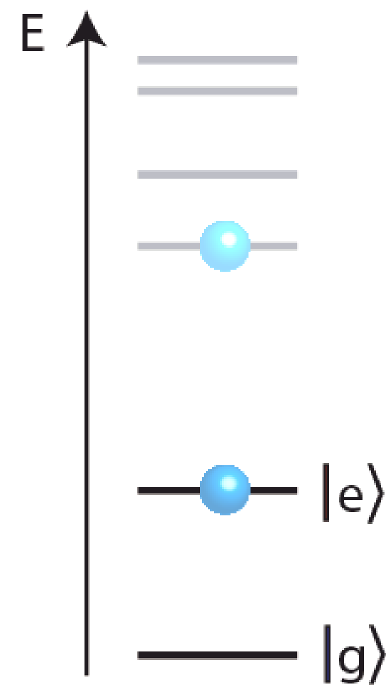


control spontaneous emission by circuit design

How to Operate Circuits Quantum Mechanically?



$T \sim 0.01\,\mathrm{K}$



recipe:

- avoid dissipation
- work at low temperatures
- isolate quantum circuit from environment

Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)