Lecture 2, March 2, 2017

Last week:

- Introduction to topics of lecture
  - Algorithms
  - Physical Systems
- The development of Quantum Information Science
  - Quantum physics perspective
  - Computer science perspective

Further reading: Nielsen & Chuang

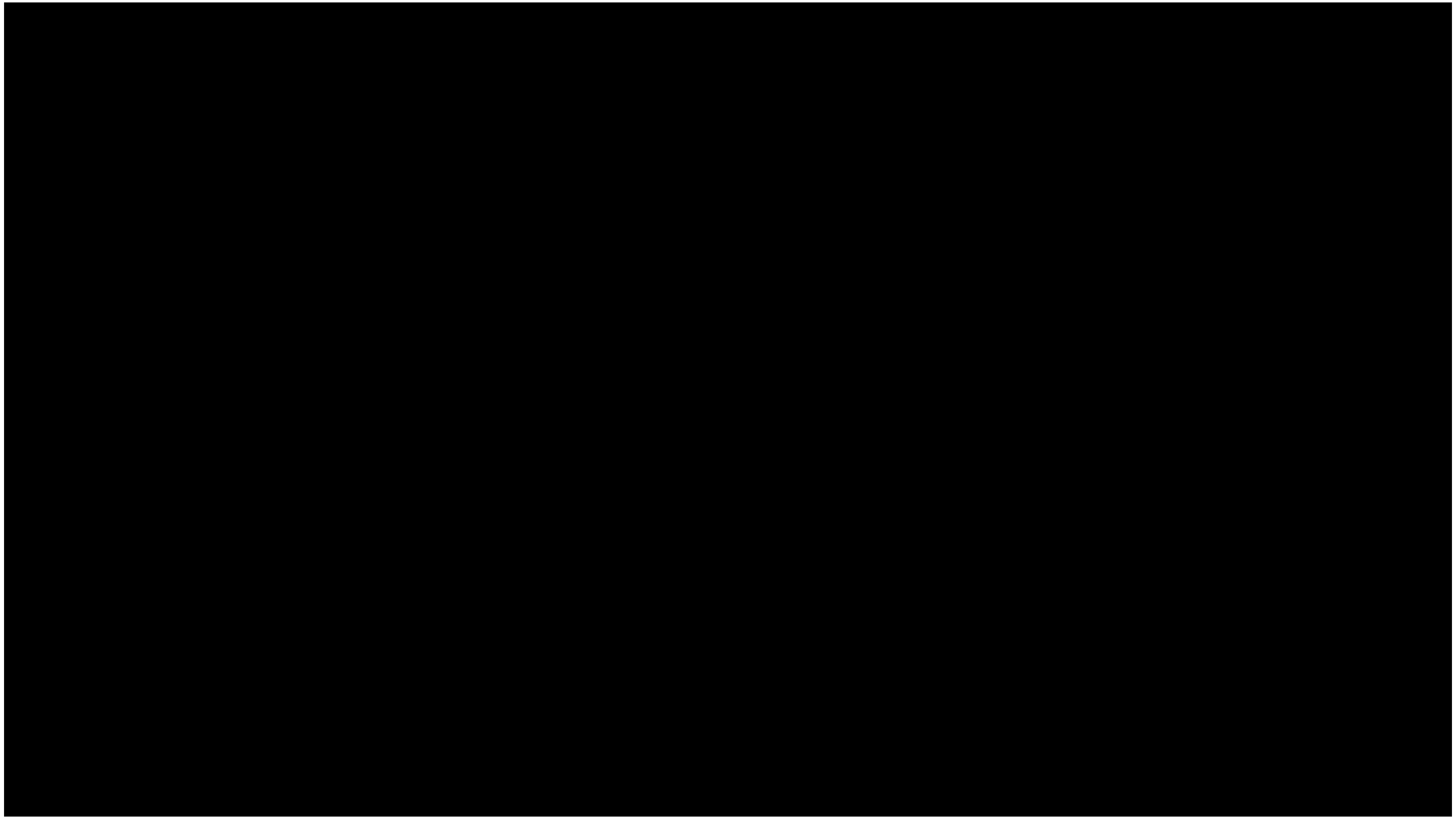
Please take a seat
in the front center part of the lecture hall
if you do not mind.

This week:

- Components of a quantum computer
  - The DiVincenzo criteria
  - Quantum bits
- Building a quantum computer from electronic circuits
  - Quantum electronic harmonic oscillators
    - Quantum description of electronic circuits
    - The role of loss
  - Quantum bits: non-linear oscillators
    - The Josephson effect
    - The Cooper pair box qubit

Classical Bits, their Physical Representation and Manipulation

Discussion on the black board.

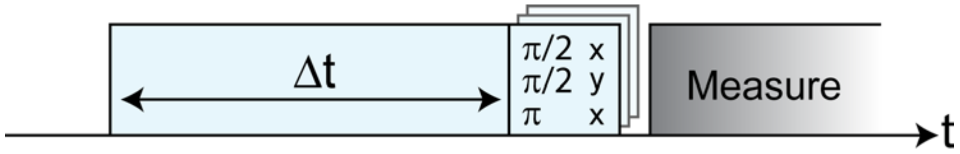


Quantum Bits

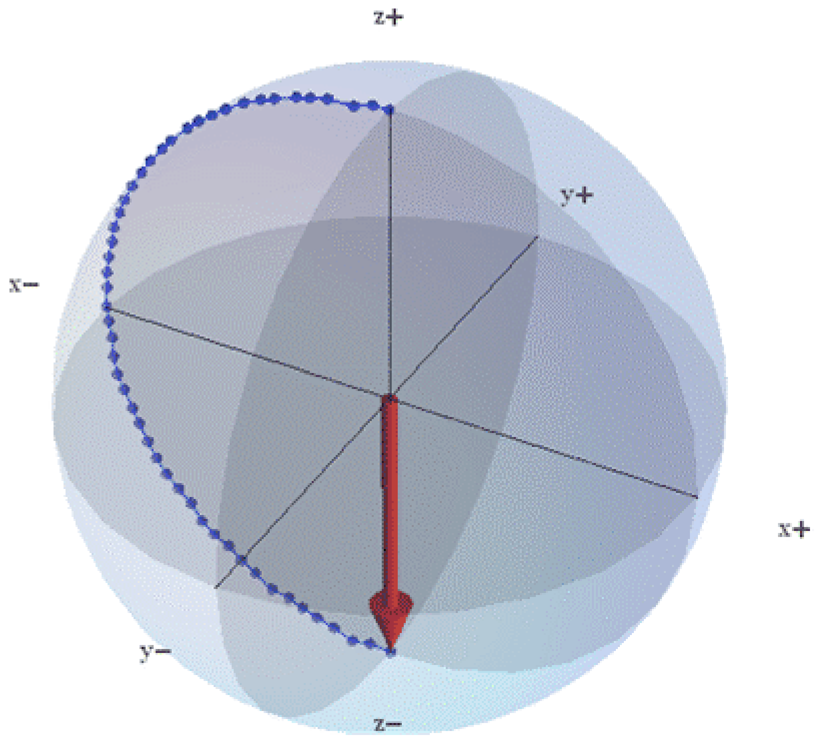
Discussion of qubits on the black board.

The Bloch Sphere and Rotations of the Qubit State Vector

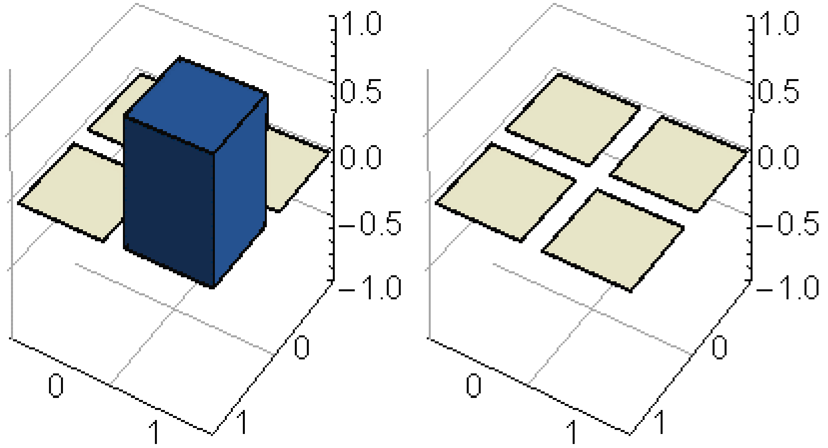
Pulse sequence for qubit rotation and readout:

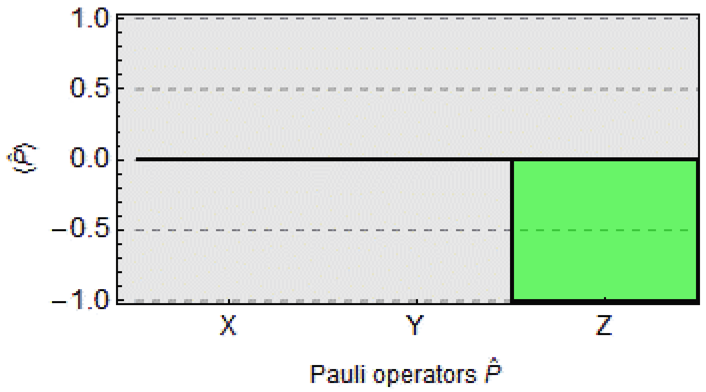


experimental state vector on the Bloch sphere:



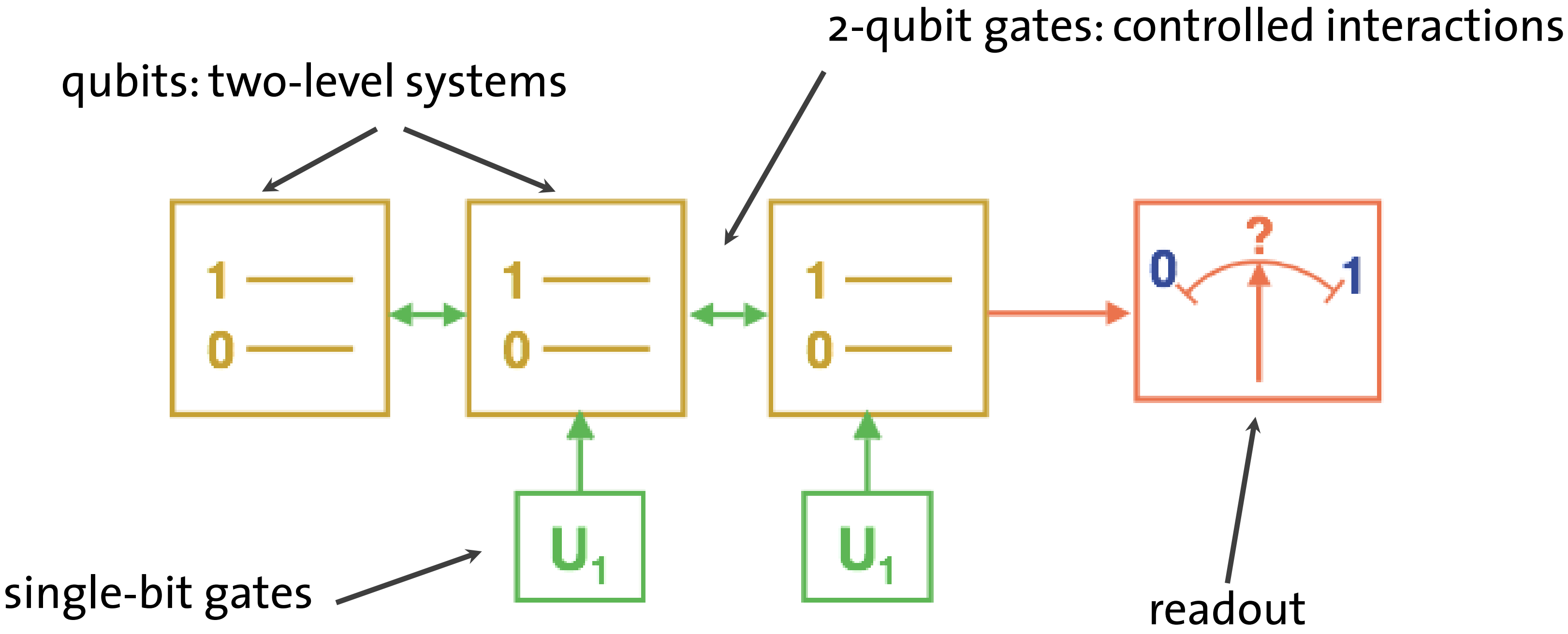
experimental density matrix and Pauli set:





Discussion in next exercise class

Components of a Generic Quantum Information Processor



The challenge:

Quantum information processing requires excellent qubits, excellent gates, excellent readout ...

Conflicting requirements: perfect isolation from environment while maintaining perfect 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):

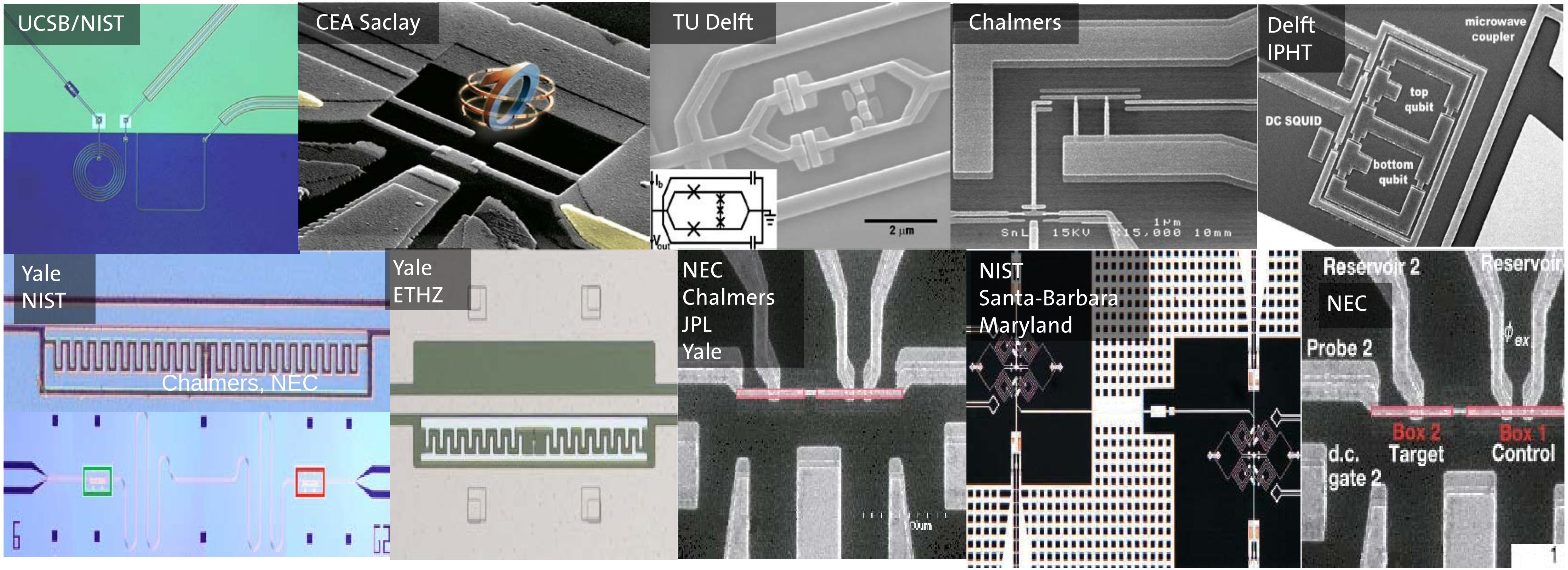
#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.

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 mobile qubits between specified locations.

David P. DiVincenzo, The Physical Implementation of Quantum Computation, *arXiv:quant-ph/0002077* (2000)

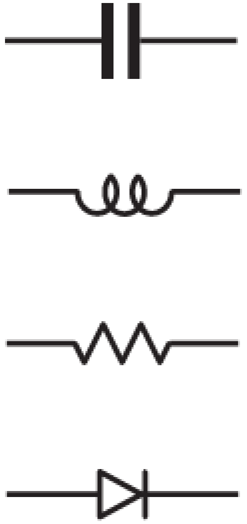
Building a Quantum Processor with Superconducting Circuits



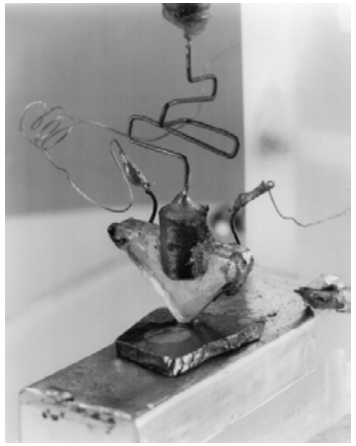
with material from NIST, UCSB, Berkeley, NEC, NTT, CEA Saclay, Yale and ETHZ

Conventional Electronic Circuits

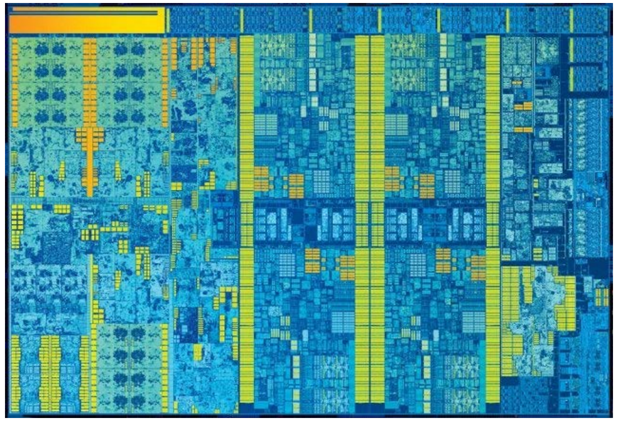
basic circuit elements:



basis of modern information and communication technology



first transistor at Bell Labs (1947)



Intel Core i7-6700K Processor

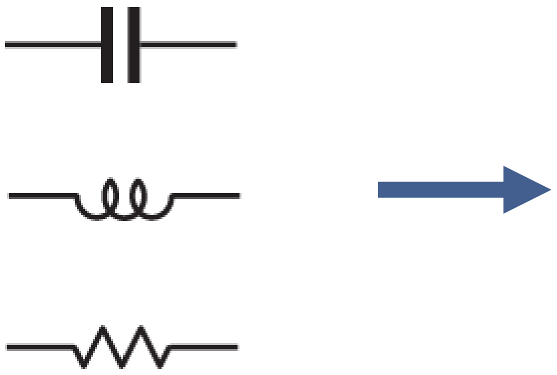
smallest feature size 14 nm
clock speed ~ 4.2 GHz
> 3. 10^9 transistors
power consumption > 10 W

properties :

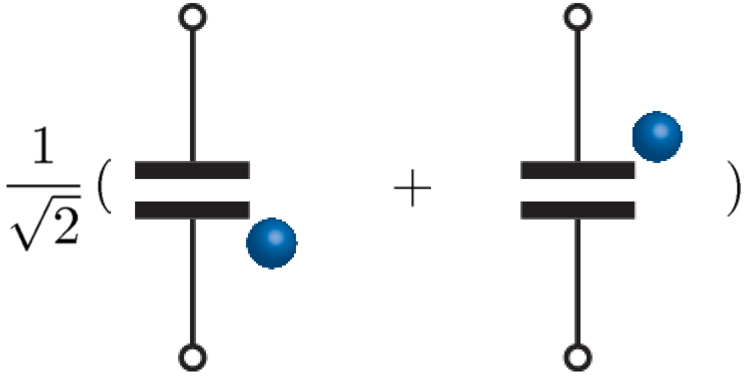
- classical physics
- no quantum mechanics
- no superposition principle
- no quantization of fields

Classical and Quantum Electronic Circuit Elements

basic circuit elements:



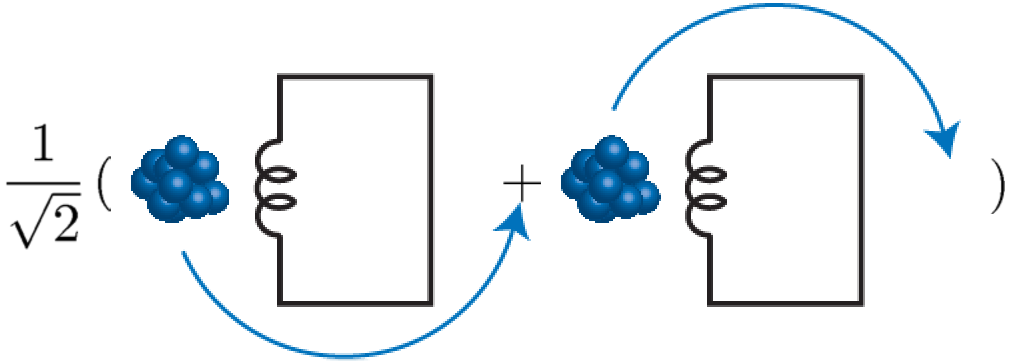
charge on a capacitor:



quantum superposition states of:

- charge Q
- flux ϕ

current or magnetic flux in an inductor:



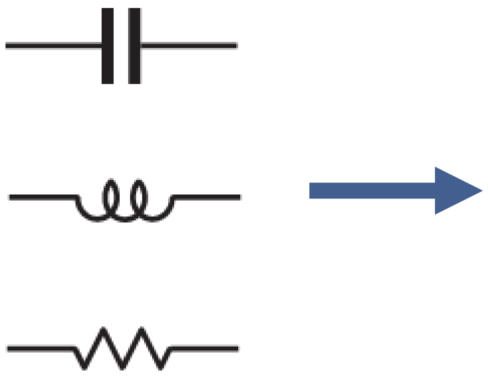
Q,ϕ are conjugate variables

quantum uncertainty relation $\Delta\phi\Delta Q > h$

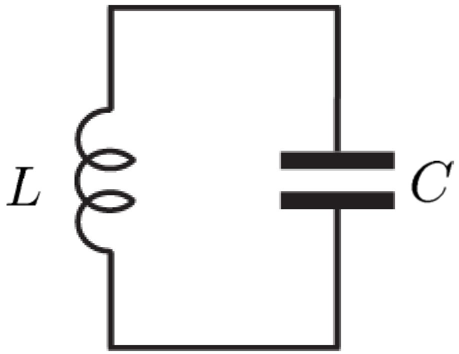
Constructing Linear Quantum Electronic Circuits

electronic photon

basic circuit elements:



harmonic LC oscillator:

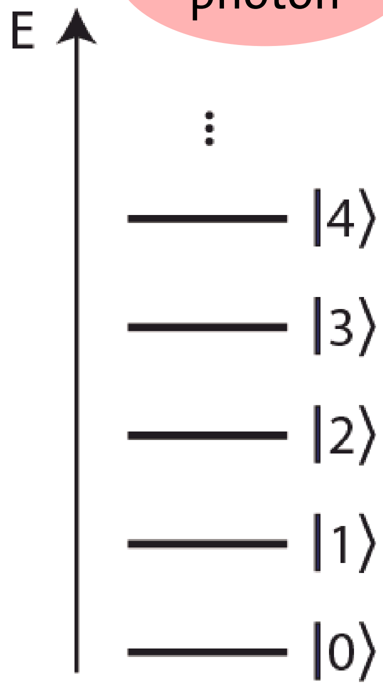


$$\omega = \frac{1}{\sqrt{LC}} \sim 5\,\mathrm{GHz}$$

typical inductor: L = 1 nH
wire in vacuum L ~ 1 nH/mm

typical capacitor: C = 1 pF
size 10 x 10 μm² and
dielectric AlOx (ε = 10) of
10 nm thickness: C ~ 1 pF

energy:



classical physics:

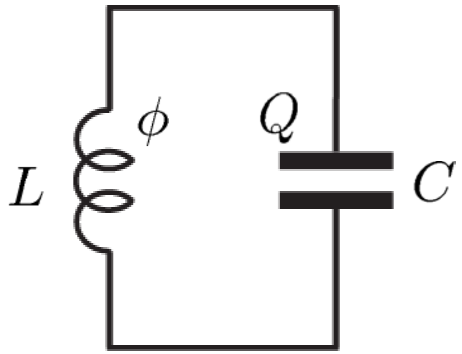
$$H = \frac{\phi^2}{2L} + \frac{Q^2}{2C}$$

quantum mechanics:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2}) \qquad \left[\hat{\phi}, \hat{Q}\right] = i\hbar$$

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

Quantization of an Electronic Harmonic LC Oscillator



$$\begin{aligned} Q &= CV \\ \phi &= LI \\ V &= -L\dot{I} = -\dot{\phi} \end{aligned}$$

Charge on capacitor

Flux in inductor

Voltage across inductor

Classical Hamiltonian:

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

Conjugate variables:

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

Hamilton operator:

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

Flux and charge operator:

$$\begin{aligned} \hat{\phi} &= \phi \\ \hat{Q} &= -i\hbar\frac{\partial}{\partial \phi} \end{aligned}$$

Commutation relation:

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