# 1.0 Introduction to Quantum Systems for Information Technology

## 1.1 Motivation

What is quantum mechanics good for?

traditional historical perspective:

- beginning of 20th century:
  classical physics fails to explain phenomena observed in nature
  - stability of atoms
  - discrete spectra of light emitted by atoms
  - spectrum of black body radiation

- use quantum mechanics to explain phenomena occurring in nature
  - properties of microscopic systems (atoms, nuclei, electrons, elementary particles)
    - energy level quantization
    - tunneling
    - entanglement
    - ...
  - properties of macroscopic systems
    - superconductivity
    - electronic band structure of semiconductors
    - …

- quantum mechanics is a hugely successful theory ...

- … but its concepts are difficult to grasp
  - EPR paradox
  - entanglement
  - quantum measurement



**... Motivation**

- early on study of quantum information and quantum computation is motivated by desire to better understand quantum mechanics
  - relation between information and physics
    Rolf Landauer: information is physical
  - 80's: Can quantum mechanics be used to transmit information faster than light?
    No: shown in the context of the *no-cloning theorem.*

Efforts to try to make use of quantum mechanics:

- Quantum computation and quantum information is the study of information processing that can be accomplished with quantum mechanical systems.
  - it took a long time after the development of QM to invent this new field

quantum information processing is enabled by new technologies:

- 70's: develop complete control over single quantum systems
  - single atoms/ions/molecules
  - single photons
  - 90's: single electrons/spins/flux quanta in solid state
  - …
- explore new regimes of nature that only occur in single isolated quantum systems
- different from prior experiments in quantum phenomena in ensembles
  - superconductivity, collective quantum effect of $10^{23}$ electrons
    - no information over individual electrons
  - particle physics: analysis of constituents of matter
    - no control over individual particles

**… Motivation**

- now: control collections of individual quantum systems and their interactions
  - arrays of ions interacting electrically
  - arrays of atoms interacting in collisions
  - …
- demonstrate information processing with quantum systems
  - small systems have been realized (up to ten quantum objetcs)
  - larger systems remain a major physics and engineering challenge

Up to now we have discussed the physics perspective.

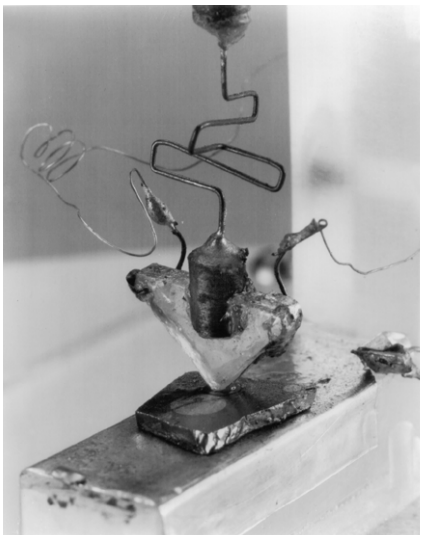
What about the **computer science** perspective?

- (1936) Turing machine
  - model for any realizable classical computer
  - But are there alternative computing schemes?
- realization of first electronic computers
  - 1947: the transistor is invented
  - great success up to now: Moore's Law (1965)



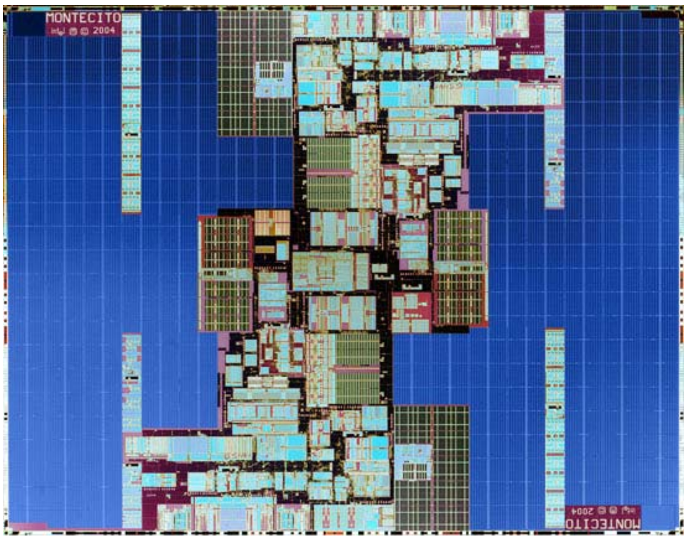
**Classical information processing** with electronic circuits

- first transistor at Bell Labs (1947) invented by John Bardeen, Walter Brittain, and Will Shockley



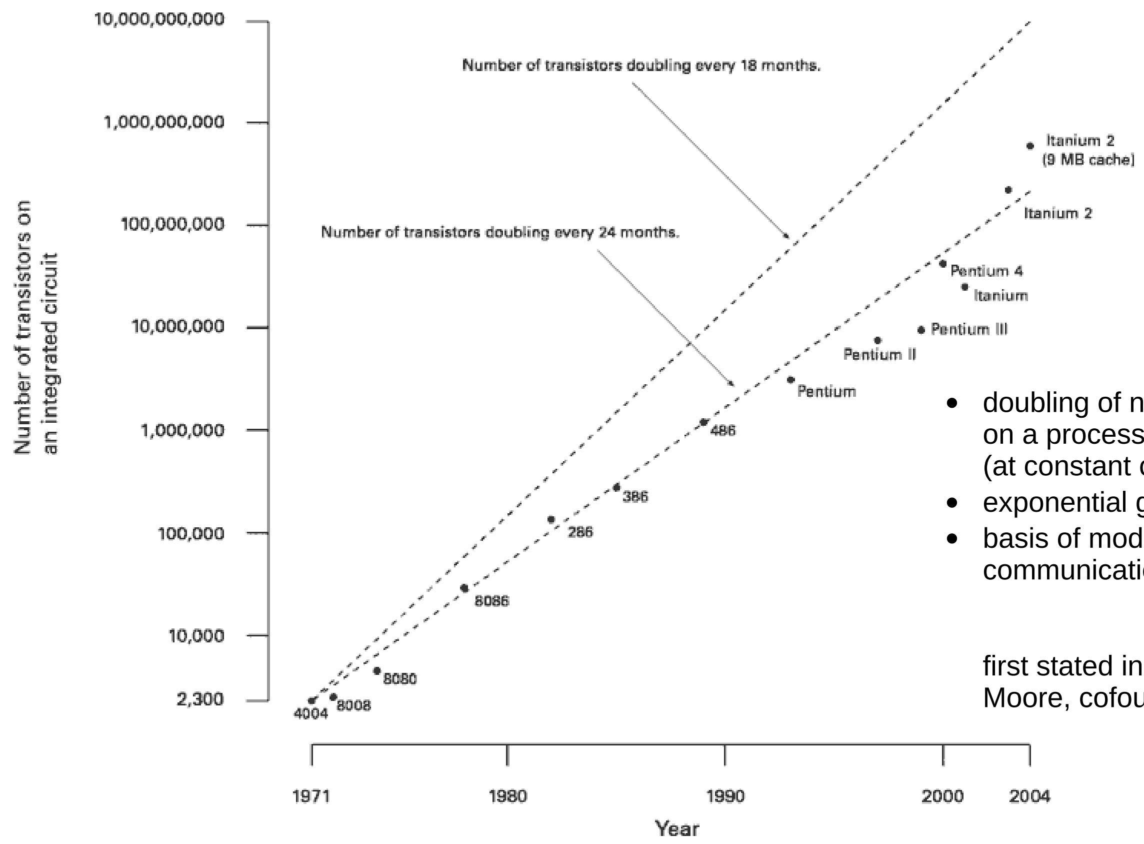
- 1 transistor
- size a few cm

- intel dual core processor (2006)




- 2.000.000.000 transistors
- smallest feature size 65 nm
- clock speed ~ 2 GHz
- power consumption 10 W
- 5 nW per transistor
- 2.5 $10^{-18}$J per transistor per cycle

## Moore's Law




- doubling of number of transistors on a processor every 24 months (at constant cost)
- exponential growth
- basis of modern information and communication based society

first stated in 1965 by Gordon E. Moore, cofounder of Intel



**… Motivation**

- What will happen when electronic circuit components reach atomic sizes?
  - Will quantum mechanics be a problem?
  - Or will it be an opportunity?

- Make use of quantum mechanics as an opportunity for novel approaches to computing.

- Quantum computing is a new paradigm in computer science.

*quantum information processing (QIP):*

- Deutsch (1985)
  - finds a simple algorithm that is more efficient on a quantum computer
  - searches for computation device that could efficiently simulate any physical system (incl. quantum systems)
    - a device based on quantum mechanics in itself

- Shor (1994)
  - develops an efficient algorithm to find prime factors of an integer
  - exponential speed-up in comparison to classical algorithm
  - important because encryptions schemes (RSA) are based on difficulty of problem

- Grover (1995)
  - searching in unstructured data bases (quadratic speed up)

- Feynman (1982)
  - simulate complex quantum systems
  - potentially the most interesting application

**… Motivation**

*state of the art:*

- difficult to realize and control even a small quantum computer
- BUT the concepts do work and have been demonstrated
  - prime factors of 15 = 3 * 5 have been calculated on a nuclear magnetic resonance (NMR) quantum computer
- ongoing research into realizing scalable hardware for a quantum computer
  - solid state systems
  - ions
- ongoing quest for quantum algorithms
  - difficult to find efficient quantum algorithms that are better than classical ones
  - any classical algorithm can be run on a quantum computer
  - develop of novel approaches to information processing that are enabled by quantum mechanics

*quantum communication (QC):*

- efficient encoding of information in photons
  - super dense coding (Bennett '92)
- unconditionally secure communication using individual photons
  - quantum cryptography (Bennett, Brassard '84)

*state of the art:*

- quantum cryptography is used in commercial applications for distributing keys in optical fiber networks [http://www.idquantique.com/]
- limited by loss of photons in optical fibers
- ongoing research into quantum repeaters to extend range



**1.2 Goals of Lecture:** **Quantum Systems for Information Technology**

- Introduction to Quantum Information Processing (QIP)
  - understand basic concepts
    - What are qubits?
    - What are their properties?
    - How to process information with quantum systems?
    - Which algorithms can a quantum computer execute efficiently?
  - get to know physical realizations
    - How to realize a quantum information processor?
    - Example: Superconducting Electronic Circuits
      - characterization of qubits
      - initialization, control and read-out of qubits
      - realization of quantum logic
    - gain general understanding of methods used to characterize physical realizations of quantum systems
  - learn how to evaluate the physical properties and prospects of different qubit implementations
    - atomic qubits
    - photonic qubits
    - spin qubits
    - semiconductor qubits
    - ...

## 1.3 Structure of Course: Quantum Systems for Information Technology

- Introduction to Quantum Information Processing (QIP)
  - basic concepts
    - qubits and their properties
    - single qubit control and measurement
    - multiple qubits
    - qubit/qubit interactions and logical operations
  - basic quantum algorithms
    - Deutsch-Josza
    - Teleportation
    - later: basic principles of factorization (Shor) and search algorithms (Grover)

- Quantum Systems for Information Processing
  - qubits based on superconducting quantum electronic circuits
    - realizations of qubits in electronic circuits
      - harmonic oscillators
      - types of superconducting qubits
      - qubit initialization
    - measurement of the qubit state
      - dispersive read-out
      - other types of state measurements
      - spectroscopy
    - qubit state control and basic time-resolved measurements
      - Rabi oscillations
      - Ramsey fringes
      - spin echo



## Structure: Quantum Systems for Information Technology

- Quantum Systems for Information Processing
  - qubits based on superconducting quantum electronic circuits (continued)
    - decoherence
      - sources of decoherence
      - reducing decoherence
    - quantum state tomography
      - single and two-qubit read-out
    - two-qubit interactions
      - realization of logic gates
    - summary

  - physical systems for QIP
    - atomic qubits
      - ions
      - neutral atoms
    - spin qubits
      - nuclear spins
      - electron spins
    - semiconductor quantum dots
      - electrostatic quantum dots
      - self-assembled systems
    - qubit/photon interactions
      - cavity quantum electrodynamics