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
  - entanglement
  - quantum measurement
  - EPR paradox

... 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

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- 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.

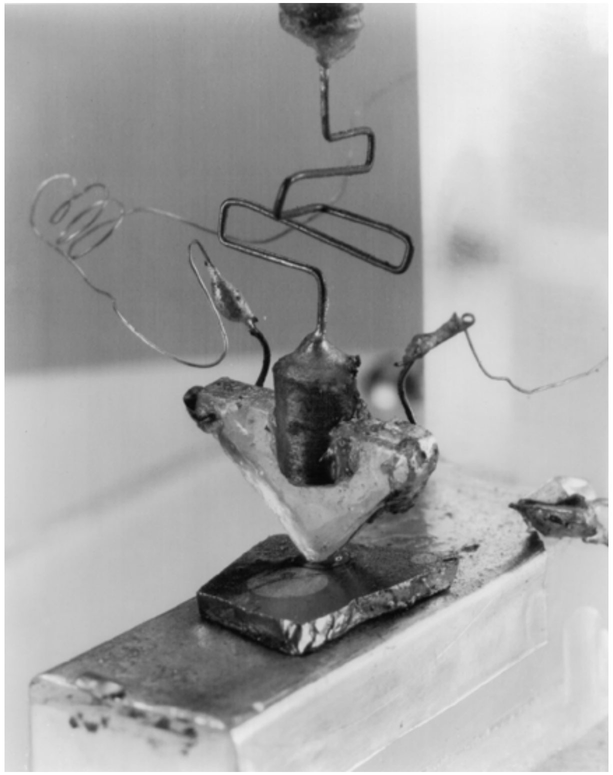
What about the **computer science** perspective?

- (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)

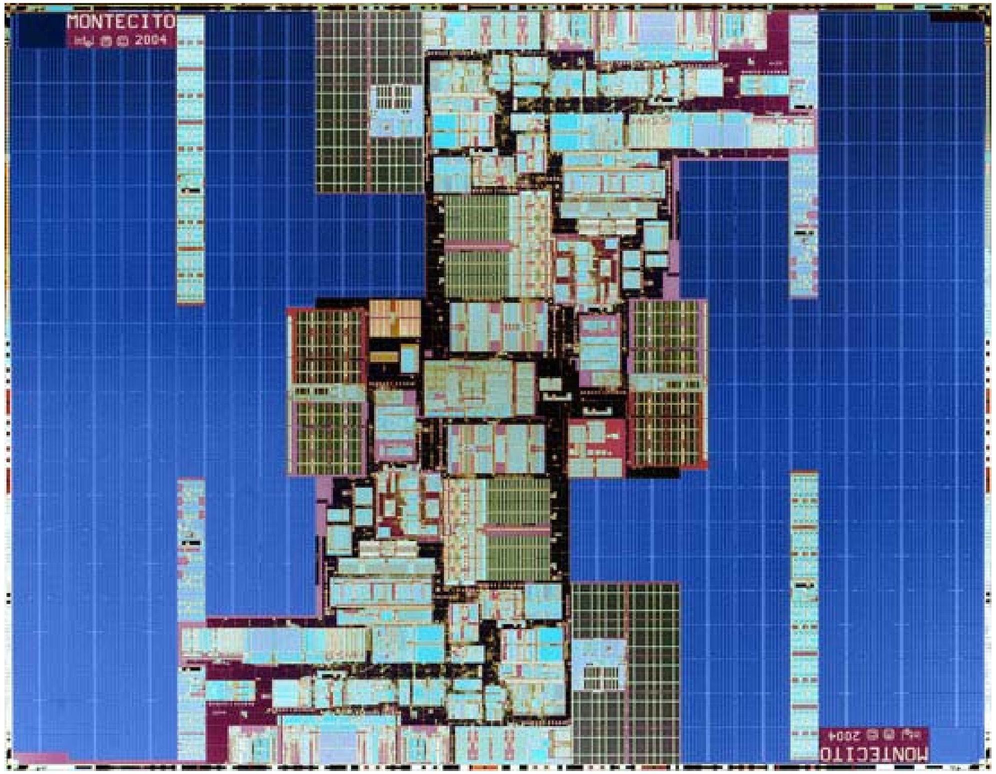
Classical information processing with electronic circuits

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



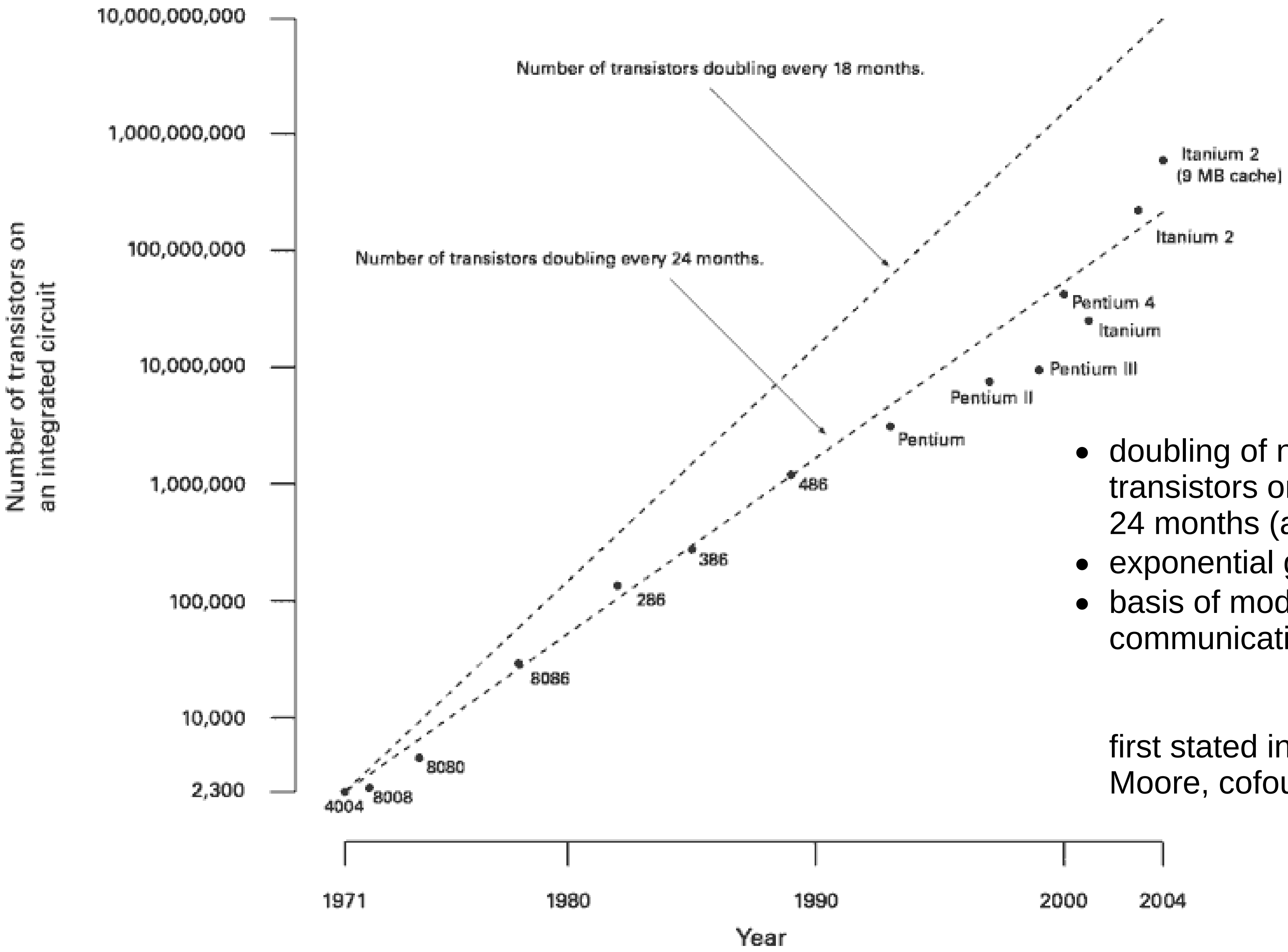
- 1 transistor
- size a few cm

- 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 encryption 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
      - improving coherence
    - 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