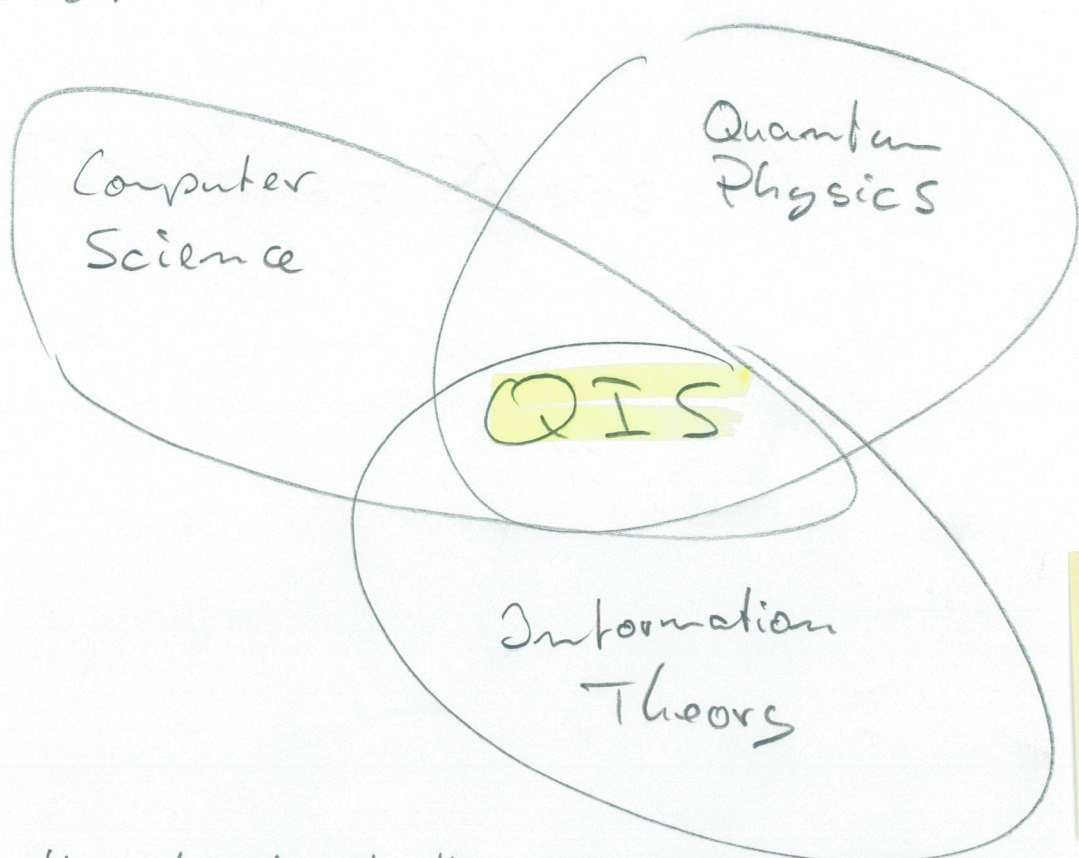


Brief historical background:

How did Quantum Information Science (QIS) develop?

QIS is an offspring of three different fields with their own development:

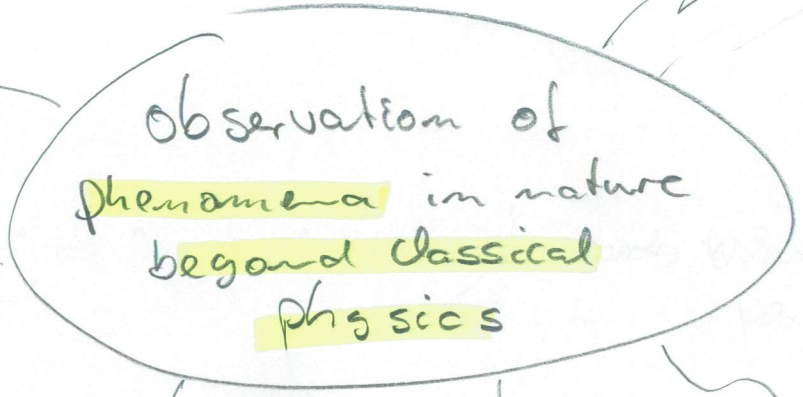


Will be discussed in physics colloquium on Thursday!

Let's briefly think about the development of these fields.

# Quantum Physics

Why was quantum mechanics developed at turn of 20<sup>th</sup> century?



## Matter waves:

- particle diffraction (e,  $\alpha$ , n, atoms, ...)

## tunnel effect:

- $\alpha$ -decay
- electronic tunnel junctions

## Statistics:

- bosons, fermions

## Quantization of electromagnetic radiation:

- photo effect (energy of photon  $h\nu$ )
- Compton effect (momentum of photon  $\frac{h\nu}{c}$ )
- black body radiation (Planck spectrum)

## Energy level quantization:

- discrete spectra of atoms (and other systems)
- stability of atoms

## Other phenomena:

- entanglement
- elementary particles
- structure of atoms and solids
- fission, fusion, superconductivity

In your opinion, which important experimental observations contributed most strongly to the development of quantum mechanics?



• Theory of quantum mechanics explains all of the mentioned phenomena and many more. (3)

In your opinion which concepts are the most important ones to understand these phenomena?

• It does so based only on a few postulates

① Complete description of the state of a physical system by a complex wave function (or equivalently by a vector in Hilbert space).

② the time evolution of any system is described by the Schrödinger equation

③ the measurement postulate governs the outcomes of measurements performed on quantum systems

④ composite quantum systems are completely described by tensor products of the component system states

these postulates are

- independent of the physical system under consideration
- largely successful in description of physical world
- but consequences are not always easy to understand

Interpretation of quantum mechanics:

- predictions of quantum mechanics often contradict classical intuition
- paradoxical situations may arise
  - e.g. Schrödinger's cat in superposition of dead and alive states
- consequences of measurement postulate are not trivial to understand
  - e.g. collapse of wave function

Quantum Information Science helps:

- formulates procedures and suggests experiments to better understand basic properties of quantum mechanical systems
- allows one to develop intuition for the predictions of quantum mechanics through experiments



# Developments in the field of quantum physics in the second half of 20th century and their importance for quantum information science.

## Collective quantum phenomena

- consider ensembles of quantum systems
- no control over or access to quantum state of individual particles

- e.g.:
- atoms: - spectroscopy in gas phase
  - solid state: - electronic band structure  
- superconductivity
  - light: - LASERS

VS.

## Single particle quantum phenomena

- isolate individual quantum systems
- control over quantum state and read-out of quantum state of individual particles

- e.g.:
- atoms: - ion traps  
- atom dipole traps
  - photons: - single photon sources & detectors  
- PDC, Cavities QED
  - charges: - single electron transistors
  - spins: - quantum dots
  - spins: - superconducting qubits

What would you think were important developments in Q.M. that have allowed the field of quantum information science to develop?

# Relevance of Single Particle Quantum Phenomena for Quantum Information Science

- QIS:
- requires control over single quantum systems
  - requires possibility to construct more complex systems (bottom up approach) from single particles

⇒ new insights into the nature of quantum physics driven by

- curiosity in new regimes of physics
- new experimental techniques and methods available



compare with other developments e.g. triggered by the advent of low temperatures.

- superconductivity (low  $T_c$ , high  $T_c$ )
- Hall effect (quantum & fractional)
- superfluidity

# State of the art of Quantum Computing

(7)

• many physical systems have been investigated:

- NMR
- ion traps
- charges & fluxes in supercond.
- charges & spins in semicond.
- neutral atoms
- NV centers

• level reached:

- factored  $15 = 3 \times 5$  (NMR)
- realized quantum byte (ions)
- several 10s to 100s of manipulations possible (ions, supercond.)
- algorithms realized (NMR, ions, s.c. qubits)

• the challenge:

- realize larger systems



# Computer Science Perspective

1936 Beginning of modern computer science

- Turing provides abstract definition of a programmable computer
- Universal Turing Machine: provides full description of any classical algorithmic information processing machine
- Church-Turing-Thesis (strong version): Any algorithmic process that can be executed on any hardware can be simulated efficiently on a Turing Machine.

↳ basis for theory of computer science

- John von Neumann defines components necessary for realizing a computer

1947 - Bardeen, Brattain, Shockley develop transistor at Bell Labs (USA)

Show slides on transistor and Moore's law!

⇒ Beginning of efficient and low cost realization of computers in electronic circuits



1947 - Now : Development of Computer hardware follows

(9)

## Moore's Law

Estimate how much longer Moore's law can continue?

What is the role of quantum mechanics?

"Doubling of number of transistors on a processor every two years at constant cost"

→ show slide -

⇒ amazing success of technology!

- BUT how much longer can Moore's Law continue to be valid?
- What are the consequences of continuing miniaturization?
- What to do in post Moore's Law era?

$$2 \log_2 650$$
$$= 18.5 \text{ years}$$

→ linear

$$2 \log_2 (650^2)$$
$$\Rightarrow 37 \text{ years}$$

# Quantum Computation

10

- a **new paradigm** of computing
- uses theory of quantum mechanics for performing computations
- has **speed (efficiency) advantage** that cannot be overcome by any conceived classical computing scheme
- quantum computers can be simulated on classical computers **BUT NOT EFFICIENTLY** (c.f. Strong Church-Turing Thesis)

efficient:

Computer running in time polynomial in the size of the problem

inefficient:

computer running in time super-polynomial (typically exponential) in the size of the problem

What could efficiently mean in the context of computation?



# Important Developments in the Theory of Quantum Computation

• 1985 Deutsch :

How many steps are required classically to solve Deutsch's problem?

- starts search for device to simulate efficiently any arbitrary physical (quantum) system
- seeks a challenge for strong Church-Turing-Thesis
- proposes to use device that is quantum mechanical
- presents first example algorithm now known as the Deutsch Algorithm

• 1994 Shor :

- develops algorithm that efficiently finds prime factors
- no efficient classical algorithm exists (no proof though)

• 1995 Grover :

- finds more efficient quantum algorithm to search in unstructured data bases

• 1982 Feynman :

- proposes to efficiently simulate physical quantum systems on computers based on the principles of quantum mechanics

# Other Algorithms?

(13)

(12)

- finding quantum algorithms is difficult
  - adverse to intuition based on classical world
- quantum algorithms need to be better than classical ones
  - Note: all classical algorithms can be run on a quantum computer (universality)
- it is not fully understood what makes a quantum computer more powerful than a classical one
  - superposition?
  - entanglement?
  - ↳ big challenge

Why could it be difficult to find good quantum algorithms?