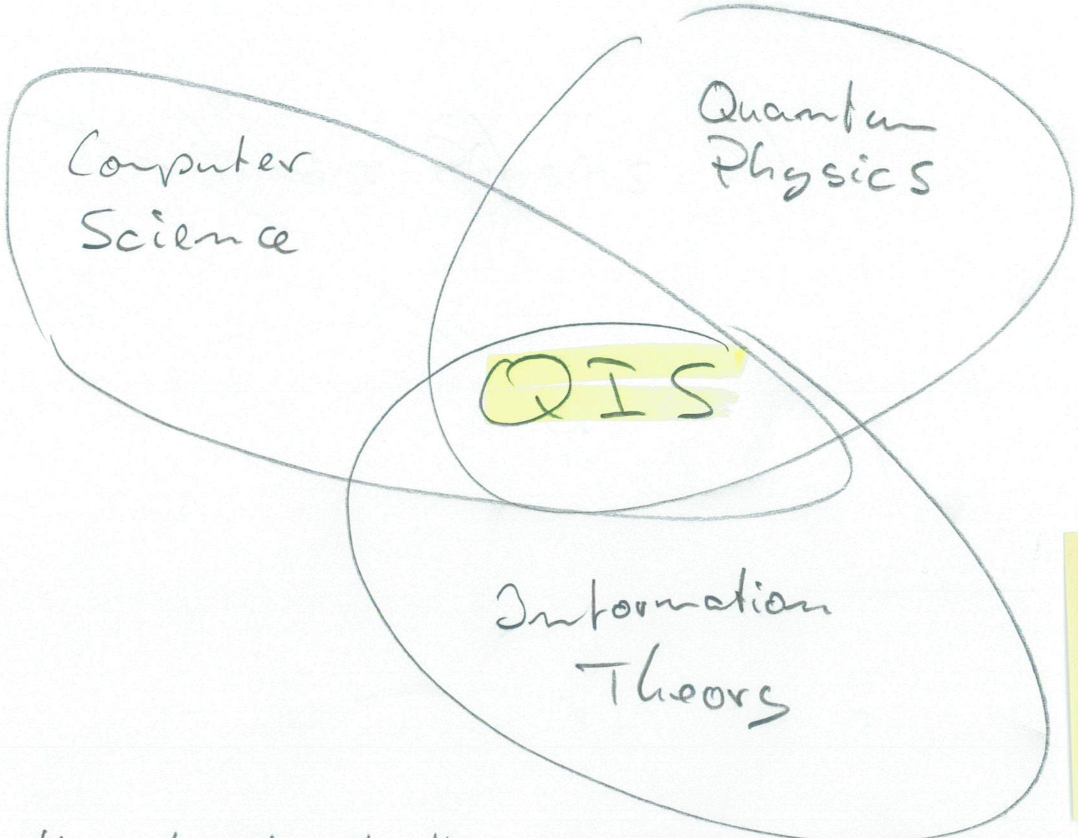
Brief historical background:

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 20th century?

**observation of phenomena in nature beyond classical physics**

## 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)

## matter waves:
- particle diffraction ($e^-$, $\alpha$, n, atoms, ...)

## tunnel effect:
- $\alpha$-decay
- electronic tunnel junctions

## energy level quantization:
- discrete spectra of atoms (and other systems)
- stability of atoms

## qu…tum statistics:
- …osons, fermions

## 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.

> 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
- hugely 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

# 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

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

| Collective quantum phenomena | vs. | Single particle quantum phenomena |
| --- | --- | --- |

**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

**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, Cavity QED

charges & spins: – single electron transistors
– quantum dots
– superconducting qubits

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

# State of the art of Quantum Computing

- 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)

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

Show slides on transistor and Moores law!

1947 – Now : Development of Computer Hardware follows

## Moore's Law

Estimate how much longer Moores law can continue?

What is the role of quantum mechanics?

$2 \log_2 650$

= 18.5 years

=> linear

$2 \log_2 (650^2)$

=> 37 years

"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?

# Quantum Computation

- 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)

What could efficiently mean in the context of computation?

**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

# Important Developments in the Theory of Quantum Computation



- **1985 Deutsch**:
  - 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

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

- **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 ?

- 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?