Technische Hochschule Ingolstadt
Fakultät Informatik

Alain Aspect John Clauser Anton Zeilinger

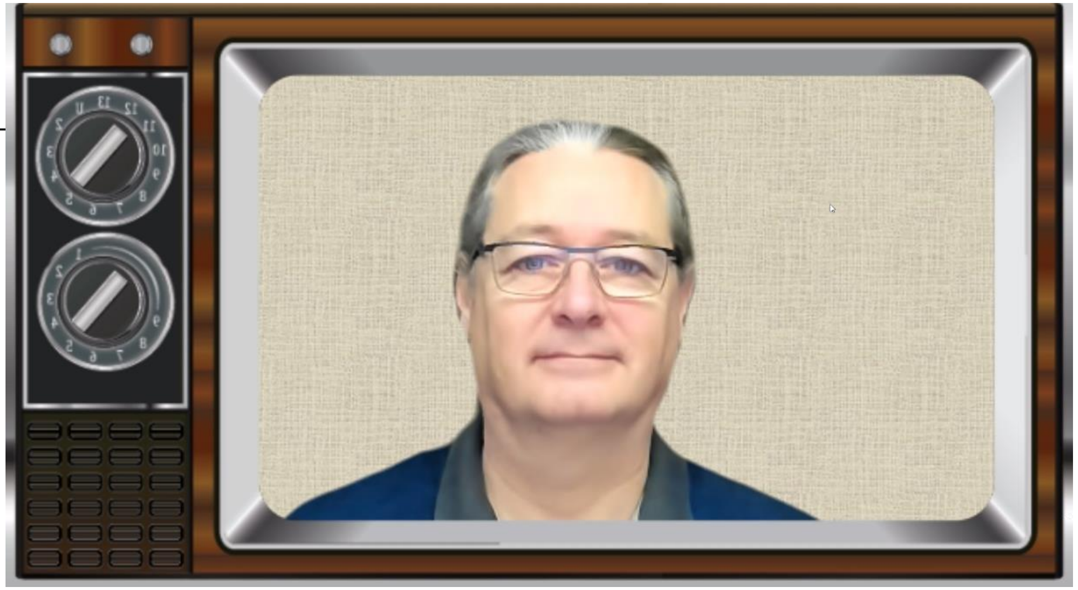
Quantum Computing and Quantum Information

Elective WS 2023/24

Prof. Dr. Ulrich Margull **11.10.2023**

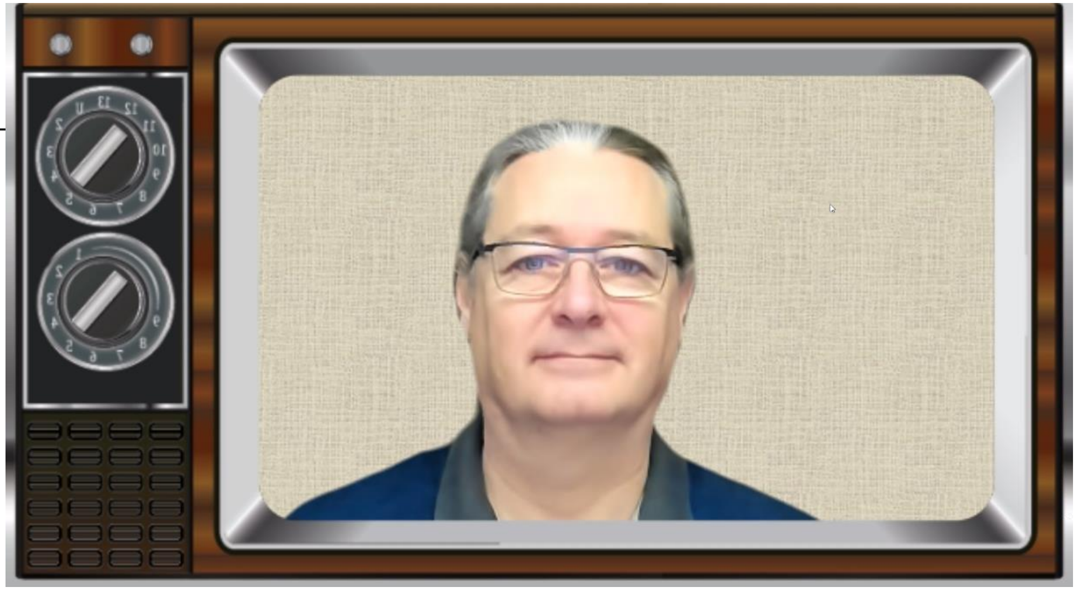
More on the Nobel prize: https://www.youtube.com/watch?v=O0sLYBeaaAM

Prof. Dr. Ulrich Margull



- 1996 PhD (Dr. rer. nat.) in Physics
- 1990 – 2012 IT Consulting
  - Design and Program of Embedded Systems
  - Software Architecture
  - Real-Time Streaming, Peer-To-Peer Communication
- Consulting in the Automotive Domain
  - Navigation systems (1999-2000, Siemens AT)
  - CarBody (2003-2004, SiemensVDO)
  - Powertrain (2004-2012, Continental Automotive), especially real-time architecture, performance validation and optimization, multicore
- 2005 – 2012 CEO & CTO at 1 mal 1 Software GmbH
- Since Oct. 2012
  - Professor for embedded systems @ Technische Hochschule Ingolstadt
  - Research activities: heterogeneous real-time systems, safety-critical software for automotive and avionics, intelligent battery systems
- Since Oct. 2019 dean of studies

Prof. Dr. Ulrich Margull



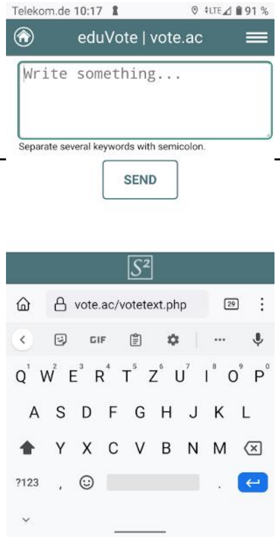
- Availabiltiy
  - Room Raum A103
  - Tel. 9348 - 4280
  - Email ulrich.margull@thi.de
- Office Hours
  - **Tuesday 11:35 – 12:20**
  - Please register for the office hour, either per Email or here: https://moodle.thi.de/moodle/course/view.php?id=1082
  - moodle course IC_QC_eng_1019, Password **Rigel**
    Link: https://moodle.thi.de/course/view.php?id=8231
  - Please use the forum for all questions about the lecture (content or organizational)

News, Announcements, Questions & Answers

This forum is used for news and organizational announcements, as well as for questions or remarks from your side. Please feel free to post here!

What is your study programme?

www.vote.ac
ID: Margull

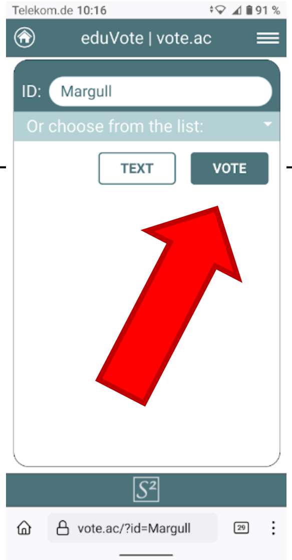


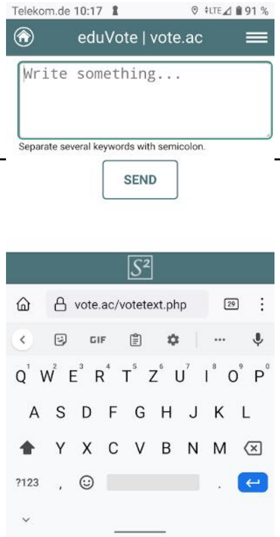
Please state your programme here.

Umfrage starten

ID =
Umfrage noch nicht gestartet

Why did you take this course?





www.vote.ac
ID: Margull

Please state your motivation here IN SHORT.

Umfrage starten

ID =
Umfrage noch nicht gestartet

DRUCK AUF BUNDESREGIERUNG

Wirtschaft und Wissenschaft fordern

tagesschau

Sendung verpasst?

ren

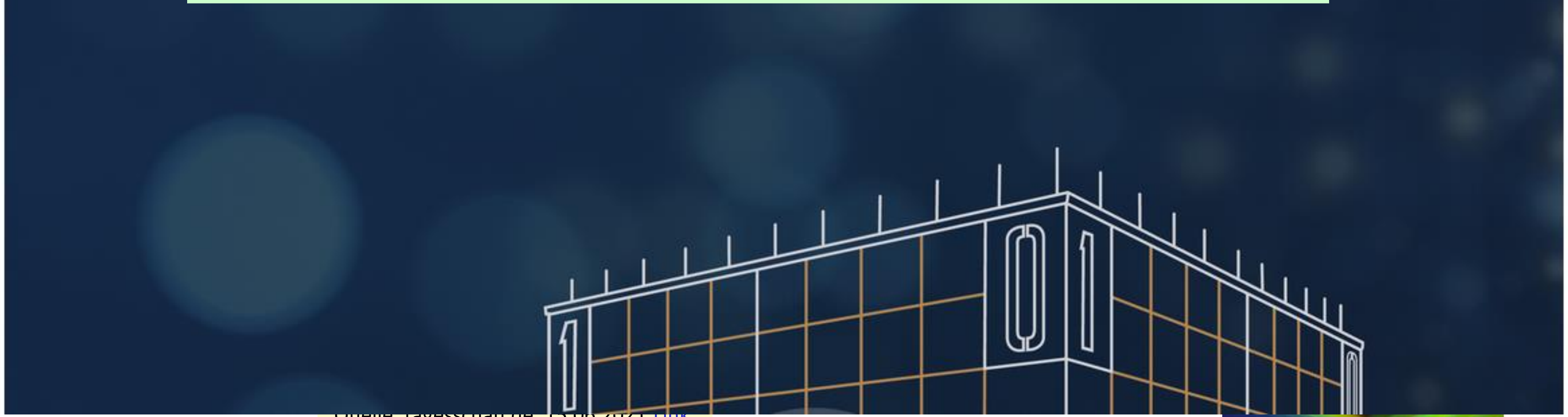
Wirtschaft

European quantum computer to come to Bavaria

Quantum computing for widespread use: Leibniz Supercomputing Centre's "Euro-Q-Exa" project convinces funding bodies in Bavaria, the German federal government and Europe; it focuses on using quantum processors as accelerators for supercomputers.

05.10.2022 | New

What‘s behing the hype about Quantum Computing?



Quelle: tagesschau.de, 15.06.2021 Link

Von Michael Herr, SWR

Ein großes Unternehmen mit Zugkraft fehlt Europa im Vergleich mit den USA bisher.

(Foto: Max Boenke)

Quelle: Handelsblatt, 13.01.2021 Link

23. Oktober 2019 Link

ORGANIZATIONAL STUFF

Goals of this class

After successful participation of this course, the students

- understand quantum information and are able to describe the difference between normal information and quantum information,
- understand principles of quantum circuits and are able to design simple circuits,
- are able to write simple programs that can be executed on a quantum computer (using IBM Qiskit environment)
- understand how quantum information can be transmitted,
- know how the principle of quantum key exchange and its advantages,
- understand the potential of quantum computing and are able to classify future evolvement of quantum computing

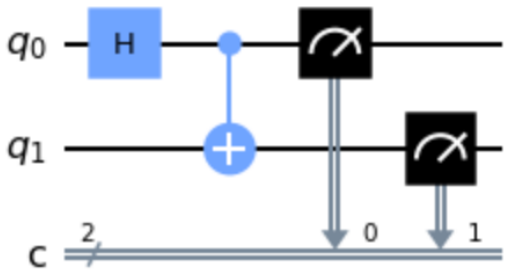
Content

- Qubit and qubit gates
- Multiple qubits (qubit registes) and complex gates
- Some Algorithms
  - Deutsch Algorithm
  - Deutsch-Joska
  - Grover
  - Shor
- Teleportation
- Cryptography
  - Classic Cryptography, e.g. RSA
  - Quantum Cryptography: BB84, u.a.
- Error Correction
- Quantum Hardware
- Adiabatic Quantum Computing

… and some basic math: complex numbers, vector spaces, matrices, scalar product, tensor product

Teaching methods

- Classical lectures with in-class exercises
- Homework
- Practical work using the IBM Qiskit environment




```
{'11': 498, '00': 502}
```

In [1]:
```
from qiskit import *
from qiskit.visualization import plot_histogram
import numpy as np
```

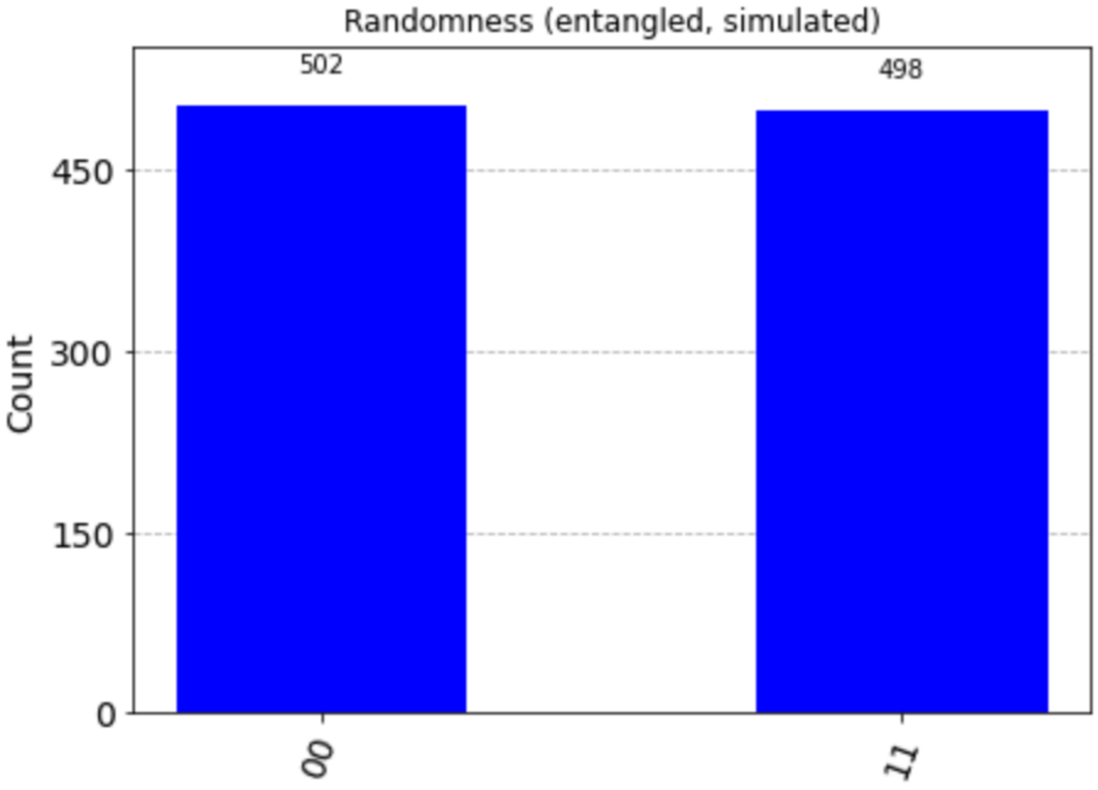
In [3]:
```
qc = QuantumCircuit(2, 2) # A quantum circuit with a single qu

# Apply hadamard
qc.h(0)
qc.cx(0,1)

# Finally, we extract the |0⟩/|1⟩ output of the qubit and encod
qc.measure(0,0)
#qc.h(0)
qc.measure(1,1)
qc.draw('mpl')

# We'll run the program on a simulator
backend = Aer.get_backend('aer_simulator')
job = backend.run(qc, shots=1000, memory=True)

display(qc.draw())
print(job.result().get_counts())
plot_histogram(job.result().get_counts(), color='blue', title="Randomness (entangled, simulated)")
```



Bonus Points for this Lecture

In this lecture, bonus points will be rewarded according the APO §25 (3) for the following educational performances:

- **0,5 bonus points** will be rewarded for the solution / work on a weekly homework. There are altogether 10 exercises, i.e. there will be a maximum of 5 bonus points that can be achieved. One bonus point corresponds to 1/100 of the total point in the written exam.
- Exercises will be published in the lecture
  - Each exercise consists of one or more subtasks
- Typically,
  - … a 10 days deadline for the exercise
  - … 50% of the subtasks must be correct to pass the task
  - … there might be further time constraints for the task, i.e. 1 hour for processing the exercises
  - … the exercise may not be repeated
- Some tasks might deviate from these general rules (read the instruction for each task).
- See also the document in Moodle: https://moodle.thi.de/mod/resource/view.php?id=370223

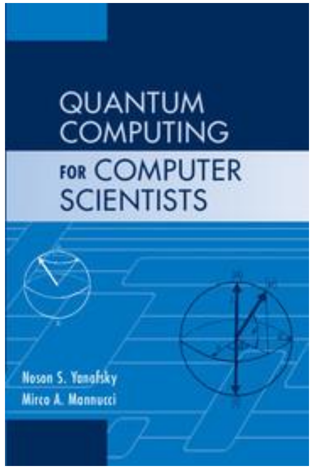
Exam

- Written Exam
- Duration: 90 minutes
- Content: Everything we did in class (lecture, black board, exercises..)
- Whats allowed to bring with in the exam?
  - non-programmable pocket calculator
  - one handwritten sheet of paper A4 ("cheat sheet")

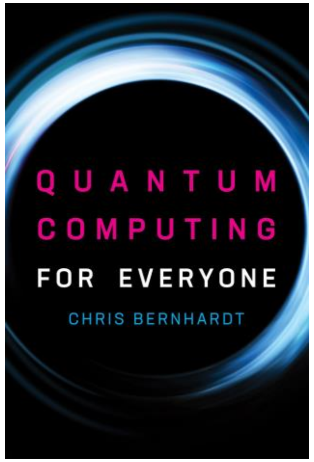
In preparation : electronic exam

Literatur

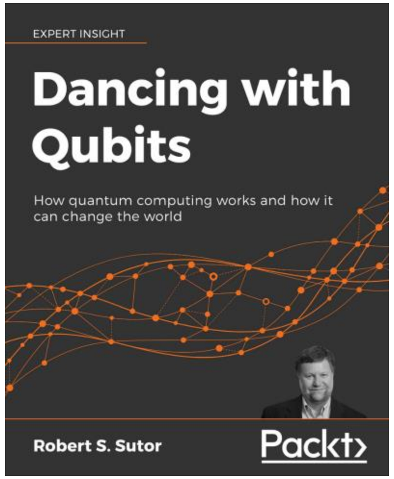
(1) YANOFSKY, N and M. MANNUCCI, 2008. Quantum Computing for Computer Scientists. 1. Auflage. ISBN 978-0-521-87996-5 (rather old, but I think a very good book for computer scientists).



(2) BERNARD, CHRIS, 2019. Quantum Computing for Everyone. ISBN 9780262039253 (short overview, not too detailed).

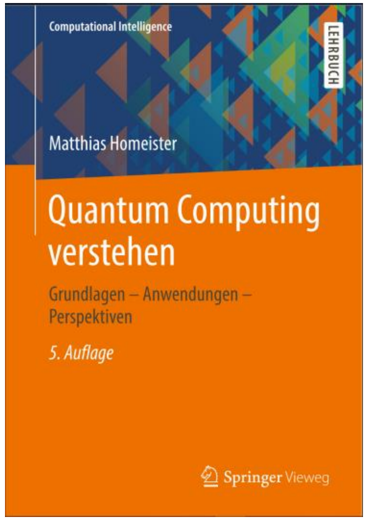


(3) Sutor, Robert S. *Dancing with Qubits: How quantum computing works and how it can change the world*. Packt Publishing Ltd, 2019.



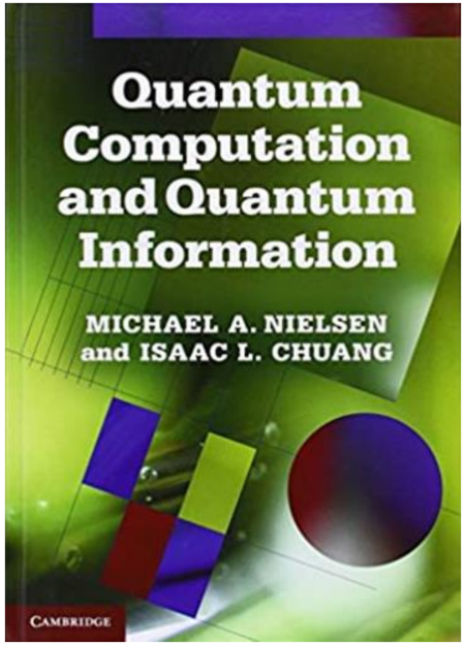
(4) ?? Many more books

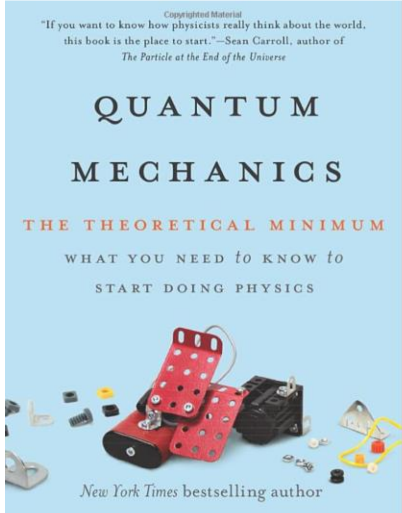
Some other helpful literature



Homeister, Quantum Computing verstehen, Springer, 2018. ISBN 978-3-658-22883-5
ISBN 978-3-658-22884-2 (eBook)
https://doi.org/10.1007/978-3-658-22884-2
Als E-Book in der Bibliothek erhältlich.

The bible of Quantum Computing:
NIELSEN, M. and I. CHANG, 2010. Quantum Computation and Quantum Information, Cambridge University Press. **(nothing for the faint-hearted, physics knowledge required)**

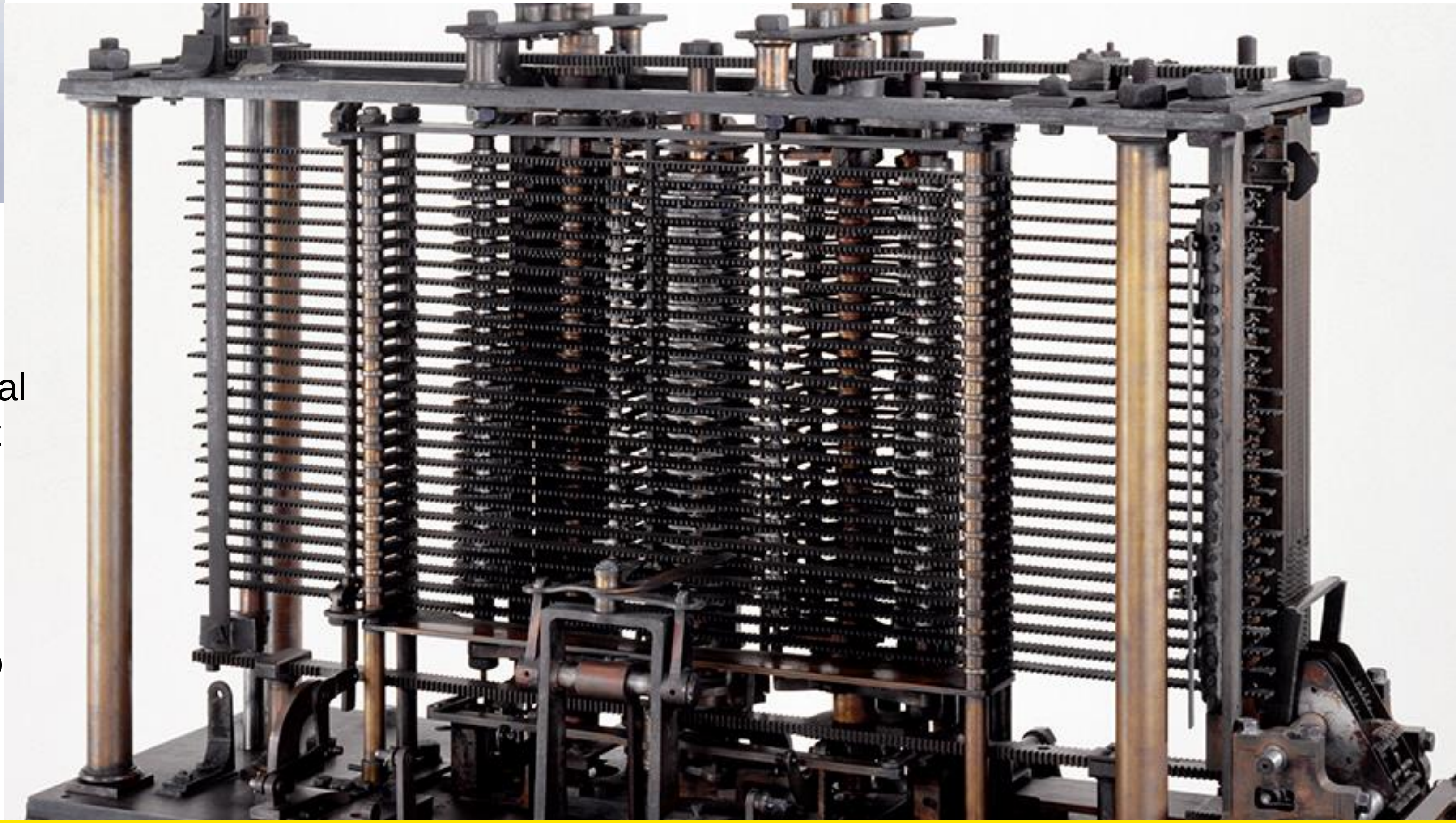




SUSSKIND, Leonard; FRIEDMAN, Art. Quantum mechanics: the theoretical minimum. Basic Books, 2014.

CONVENTIONAL COMPUTERS

Analytical Engine (concept, 19. Jahrhundert)

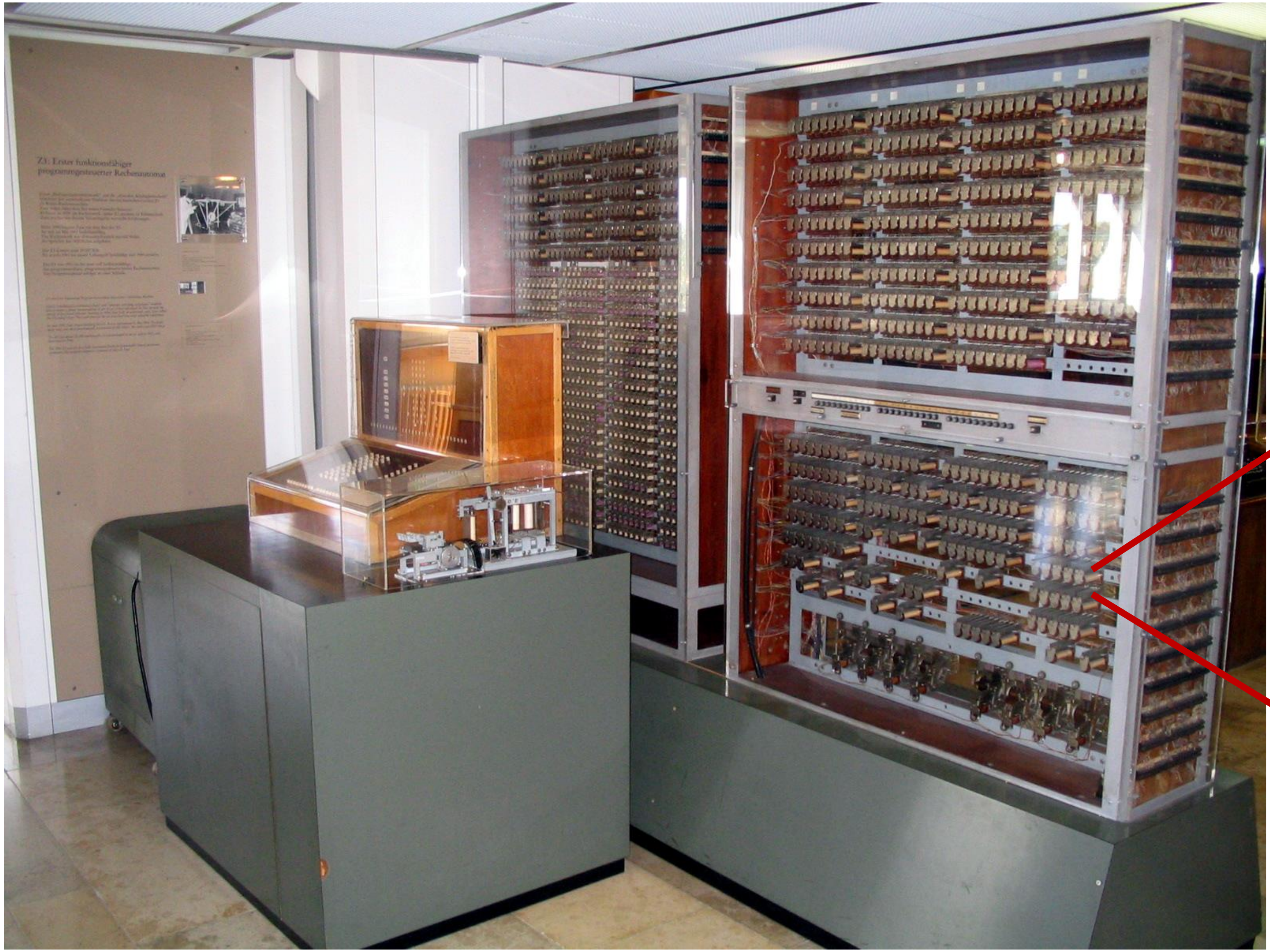


Charles Babbage entwickelte im 19.ten Jahrhundert das Konzept einer mechanischen, programmierbaren Analytical Machine. Obwohl sie nie gebaut wurde, gilt sie als funktionsfähig.

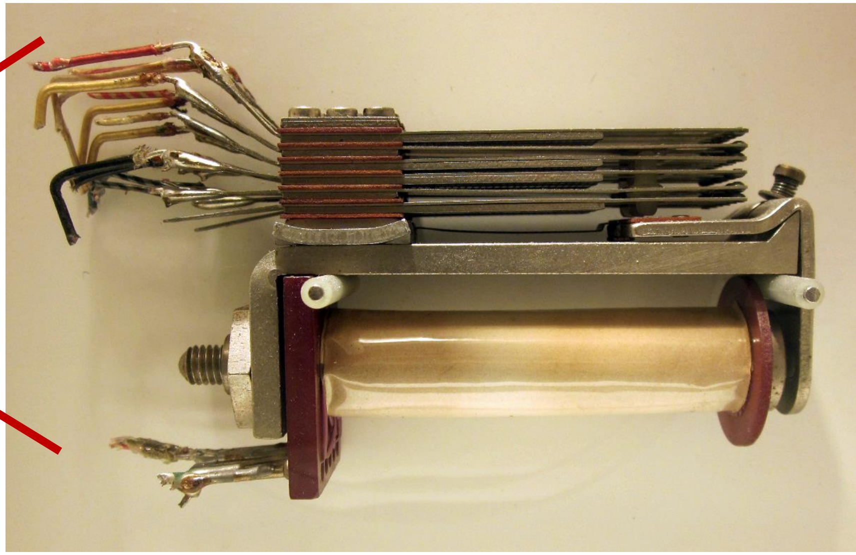
Ada Lovelace hat dazu einen Plan entwickelt, mit der die Bernoulli-Zahlen berechnet werden können, und gilt deshalb als erste Programmiererin.

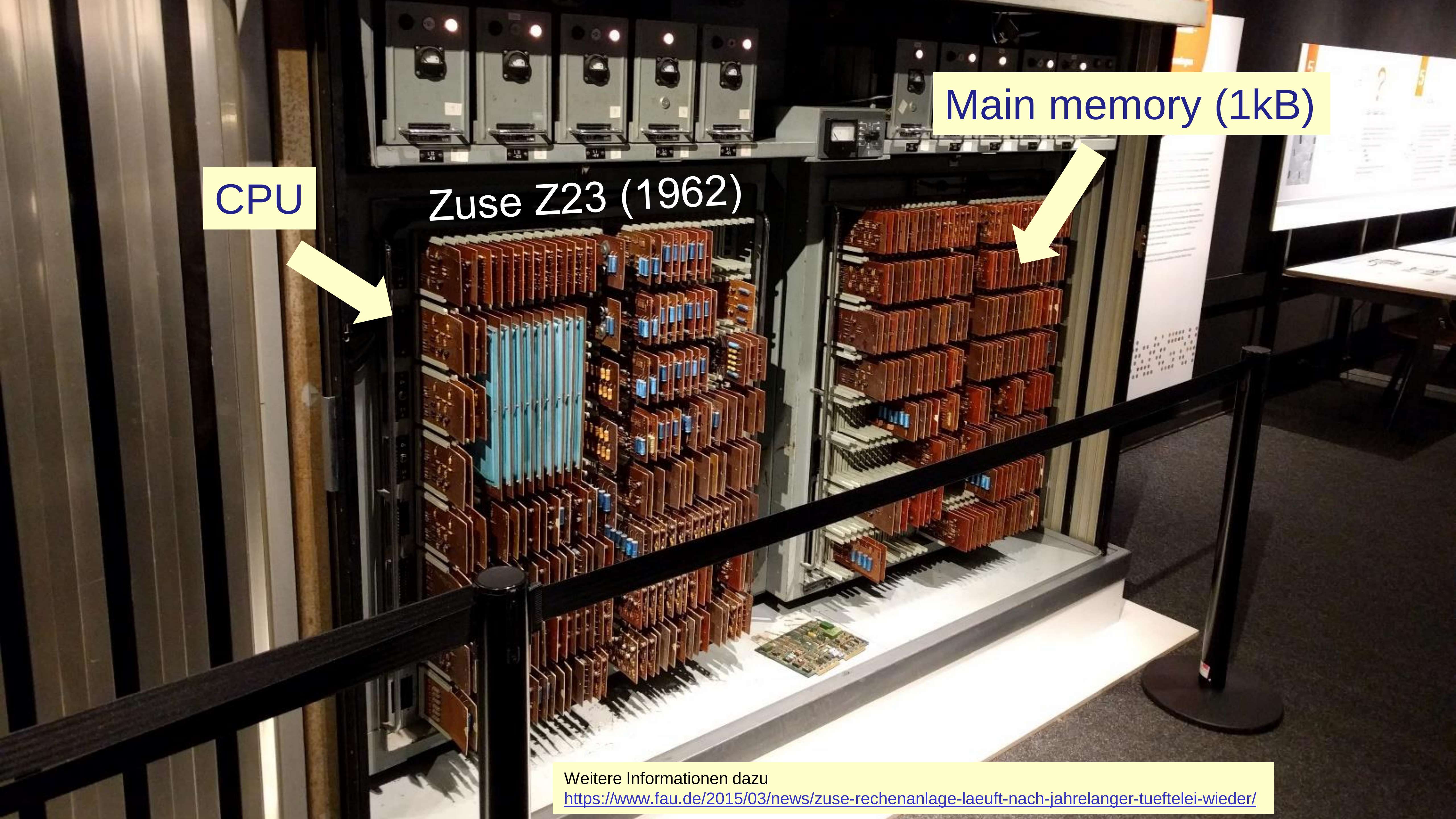
Quelle: Heinz Nixdorf Museumsforum, https://www.hnf.de/dauerausstellung/ausstellungsbereiche/galerie-der-pioniere/charles-babbage-1791-1871.html

Zuse Z3 (1941)



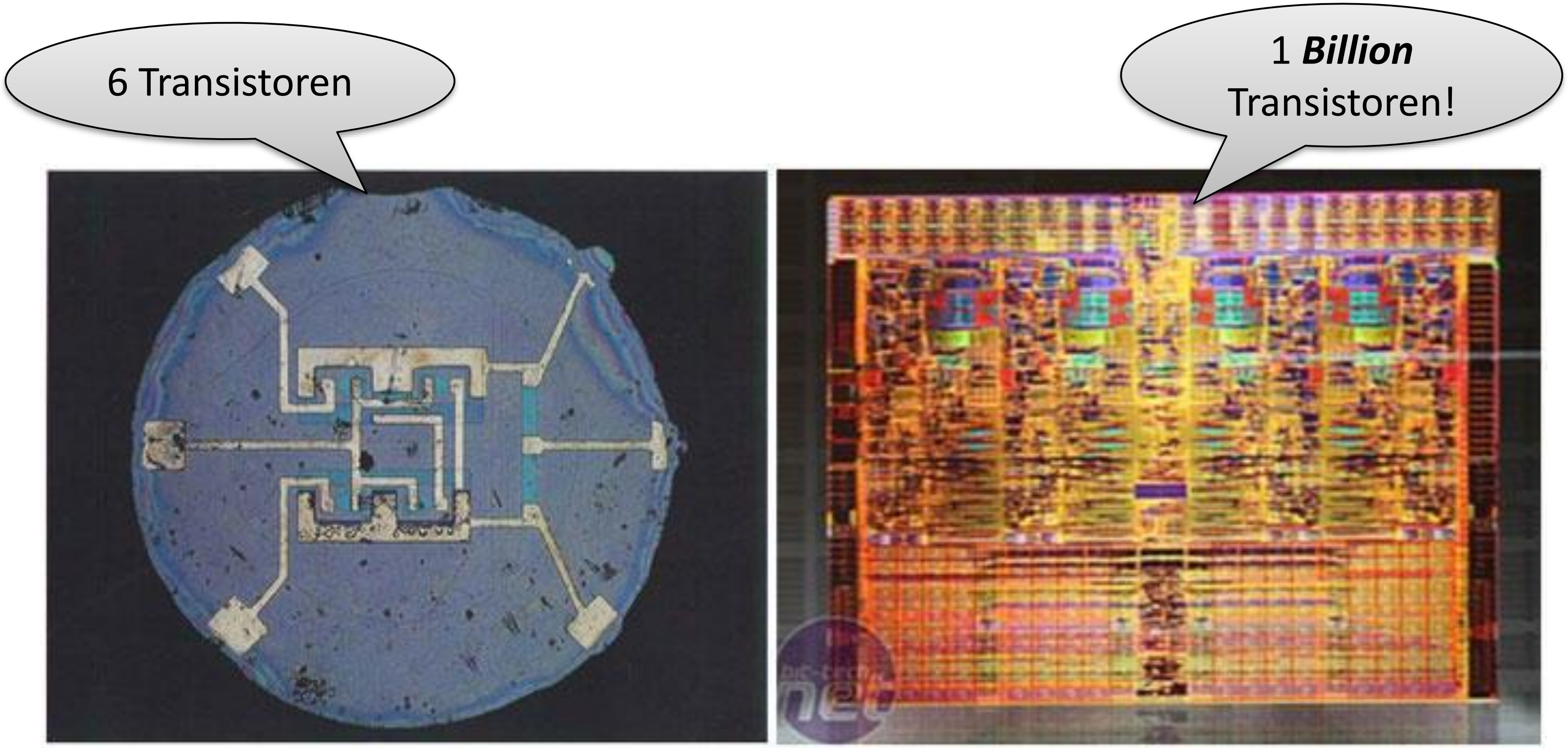
In 1941, **Konrad Zuse** built the Zuse Z3 calculator maschine. He used around 600 electro-mechanical relais for the calculator and about 1400 for the memory.





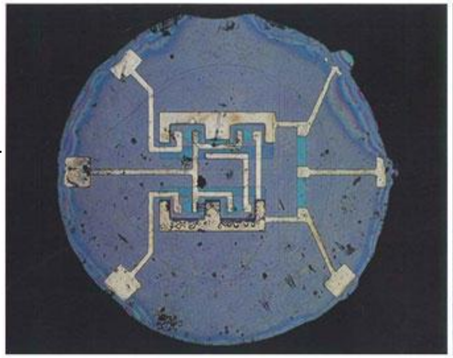
Weitere Informationen dazu
https://www.fau.de/2015/03/news/zuse-rechenanlage-laeuft-nach-jahrelanger-tueftelei-wieder/

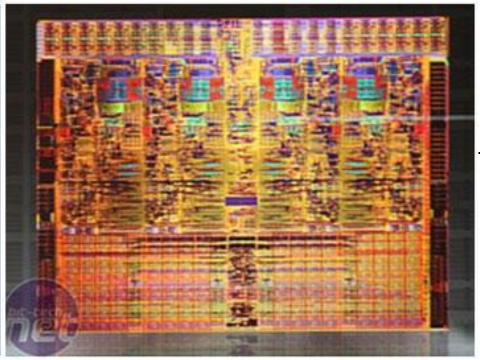
Recap: integrated circuits



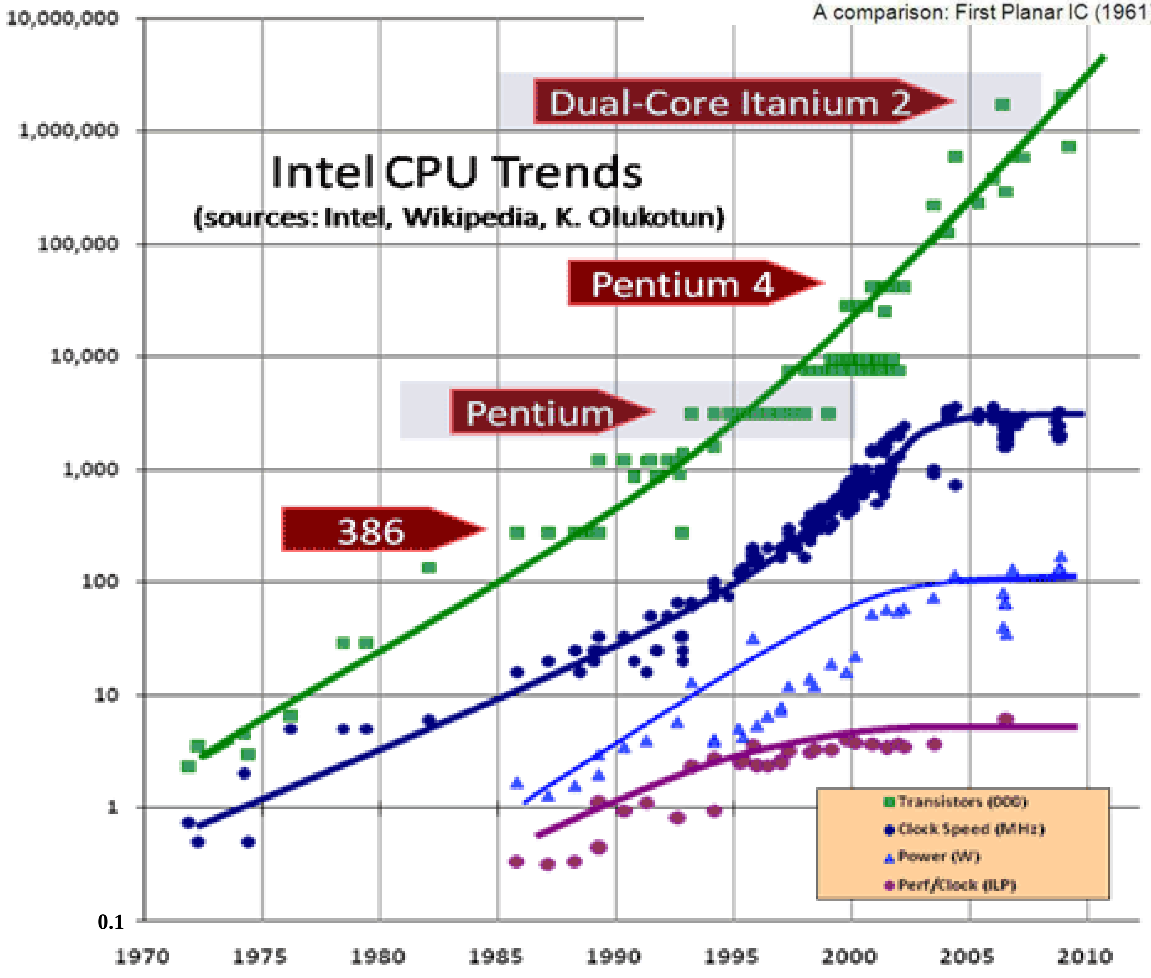
A comparison: First Planar IC (1961) and Intel Nehalem Quad Core Die

Evolving integrated circuits



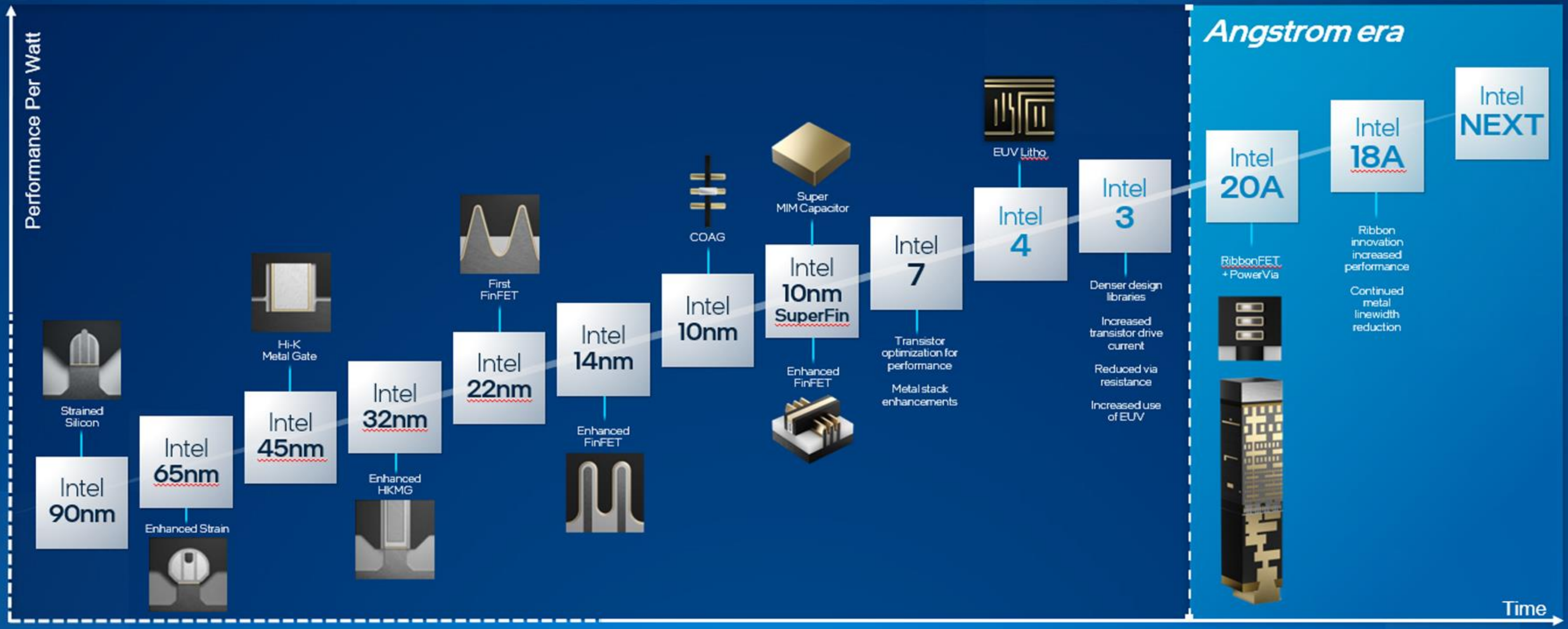


A comparison: First Planar IC (1961) and Intel Nehalem Quad Core Die



Quelle: http://www.engineersgarage.com/articles/vlsi-design-future

Intel Process Technology

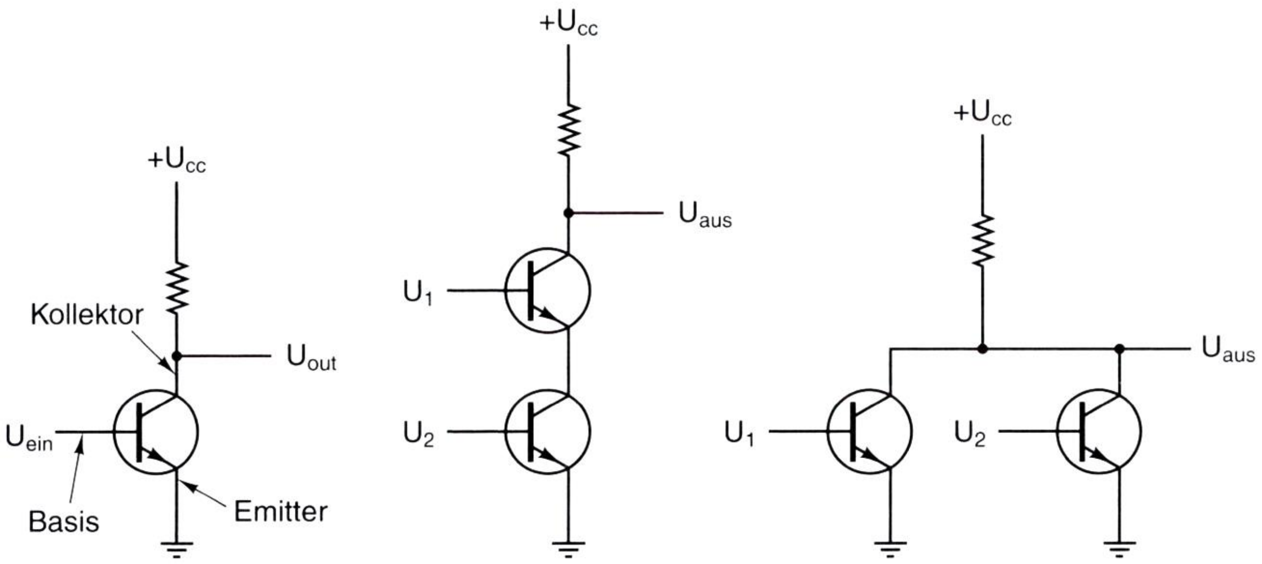


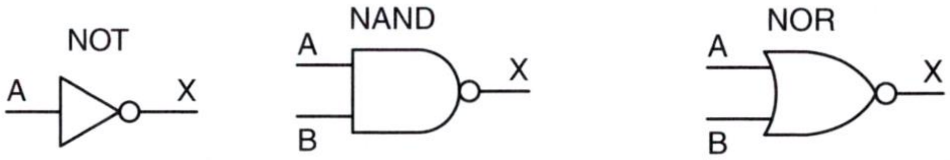
Every major transistor innovation in the past 20 years delivered by Intel and we are driving the next with RibbonFet & PowerVia

*Graphic is for illustrative purposes only and is not to scale

Quelle: 2022, https://www.intel.com/content/www/us/en/newsroom/resources/press-kit-accelerated-event-2021.html

Transistors and Gates





U_{ein}	U_{aus}
0 V	1,5 V
1,5 V	0 V

U_{cc} = 1,5 V

A	X
0	1
1	0

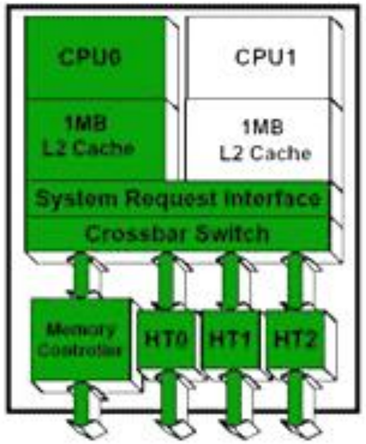
A	B	X
0	0	1
0	1	1
1	0	1
1	1	0

A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

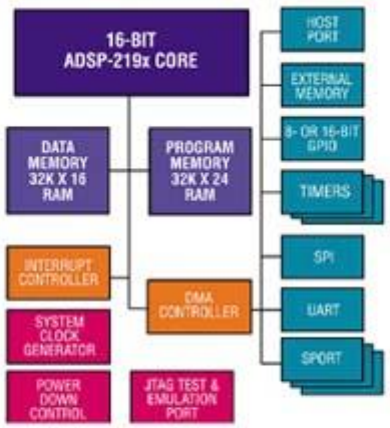
Quelle: Tanenbaum, Austin, „Rechnerarchitektur“, Pearson, 6te Auflage, 2014.

Classification of information processing unit

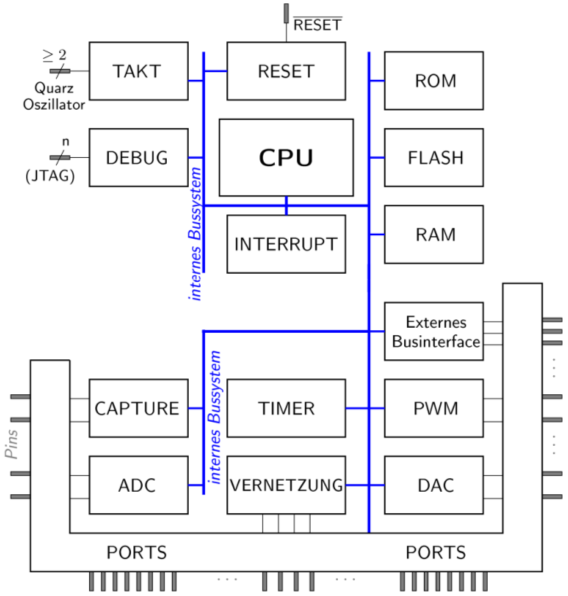
- Processor



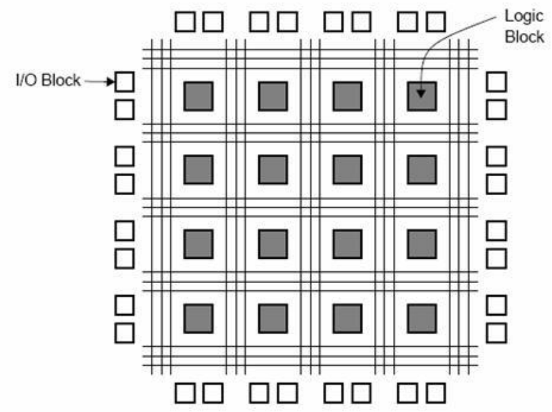
- Digital signal processor



- Microcontroller

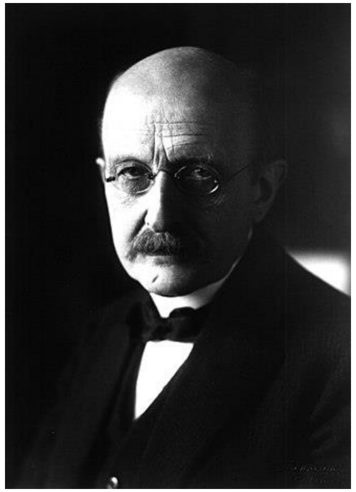


- ASIC / FPGA

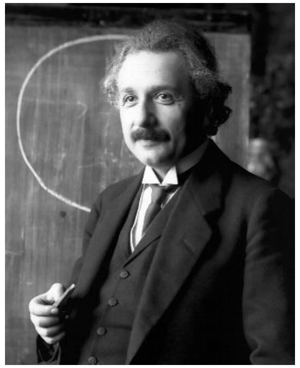



Magic World of
Quantum Mechanics
WRONG WAY
SOMEWHERE

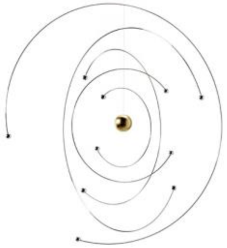
History of Quantum Mechanics



1900: ***Plank*** solves the “ultraviolet catastrophy” by introducing a quantization of the photon energy: $\Delta E = hf$

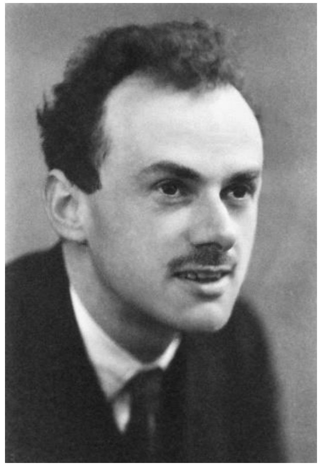


1905: ***Albert Einstein*** explains the photoelectric effect with **light particles (Photonen)**. Since in other experiments light behaves wave-like, the dualism wave – particle is established.



1913: Nils Bohr develops a model of the atom

1925: Matrix mechanics are created by ***Heisenberg***, Born, Jordan => this is the beginning of modern quantum mechanics



1927: discovery of the uncertainty relation by Heisenberg

1930: Paul ***Dirac*** introduces operator-theory and creates the Bra-Ket-Notation

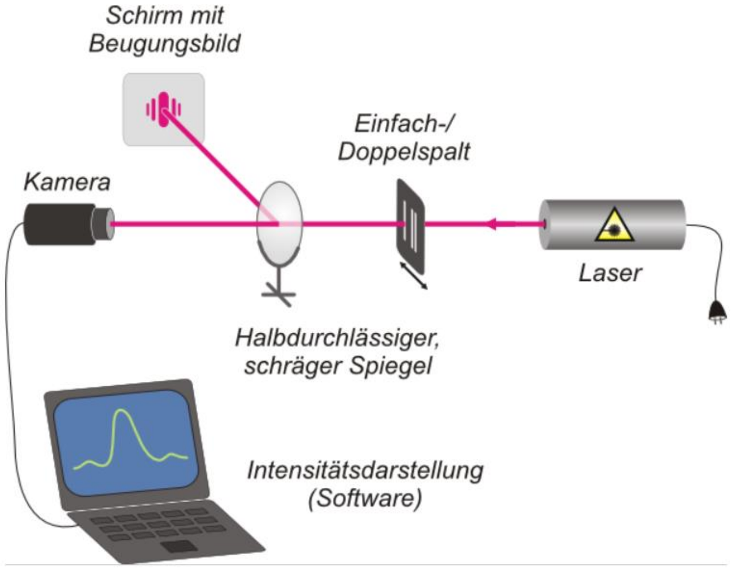
All photos: wikipedia.org

Fraction on a slit / double slit

- In the physical world in the 19th century, it was unclear whether light was a wave or a particle
  - The formulae for optics are based on wave-like nature of light and are successful to explain many aspects of light.

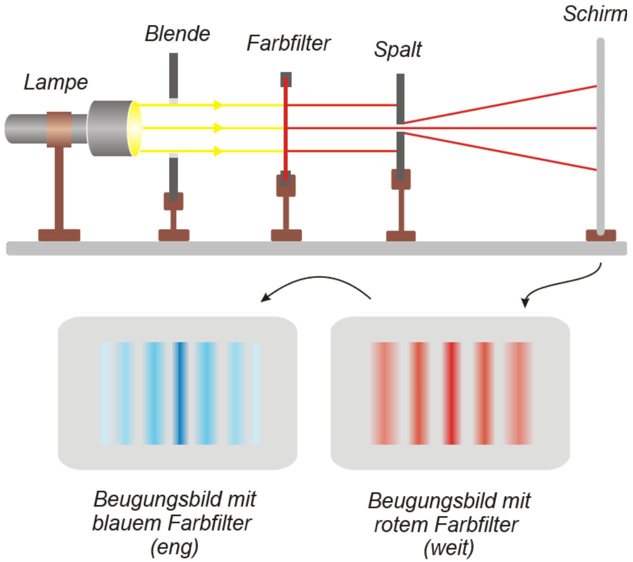
- Example: fraction on a slit

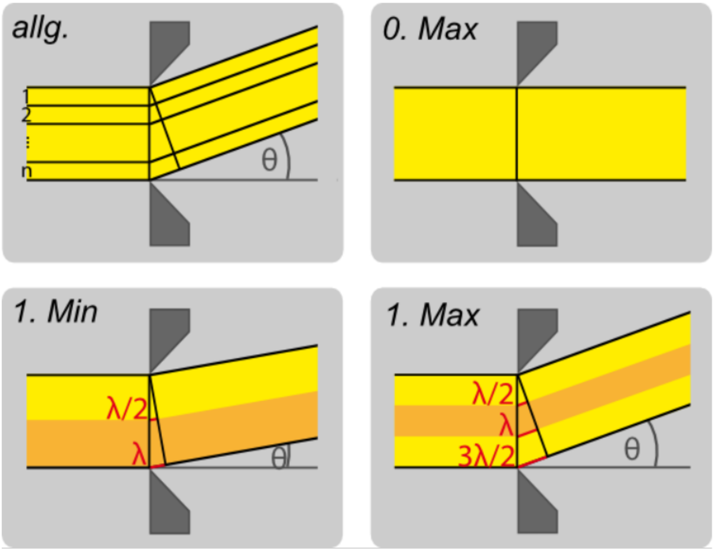
Link: https://lp.uni-goettingen.de/get/text/1531



Beugung am Einfach- und Doppelspalt

schließen oder Esc-Taste





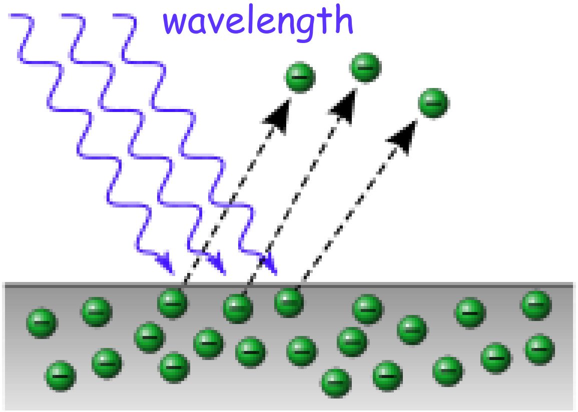
Schematisches Prinzip der Entstehung des Beugungsbildes am Einfachspalt

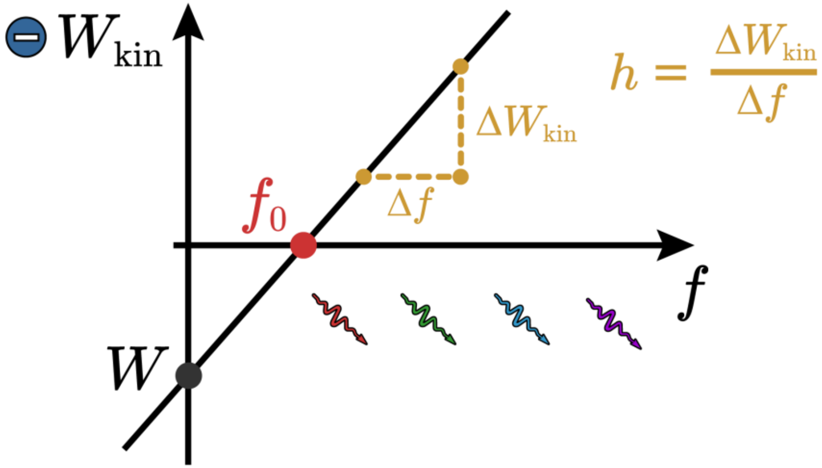
schließen oder Esc-Taste

- Fraction of water waves (on slit and double slit) can be seen here: https://www.youtube.com/watch?v=gzjdKjrgbmU

The photo-electric effect

- However, there are also experiments that show the particle nature of light.
- The most famous one is the photo-electric effect, where light hits a metal and sets free electrons. The effect depends on the color of light: while red light might not have any effect, blue light will set free the electrons. The energy of the free electrons depends on the color, too. The shorter the wave length of the light, the more energy do the electrons have.

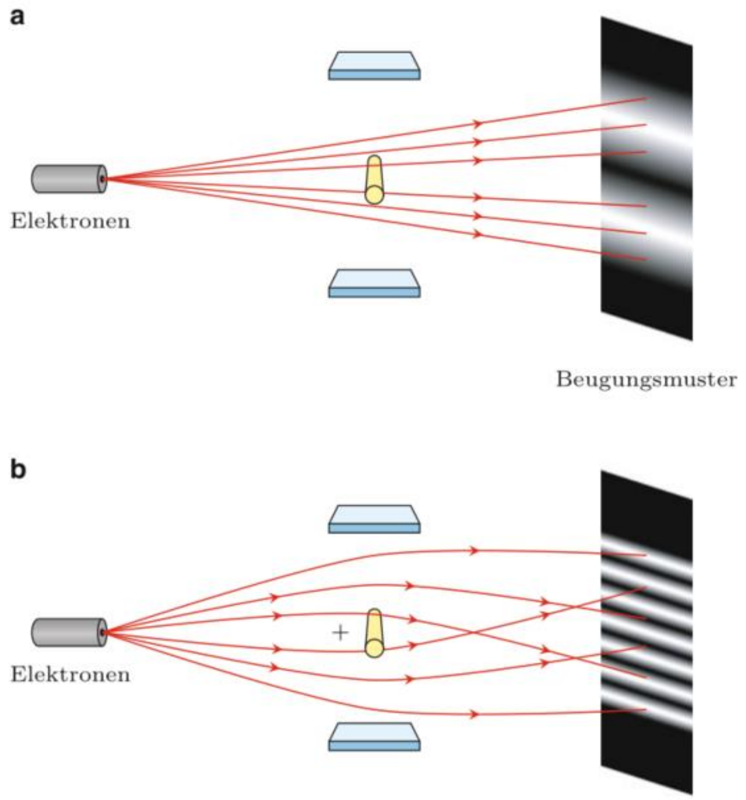




- See for example: https://www.youtube.com/watch?v=7fLFOgSVFJM

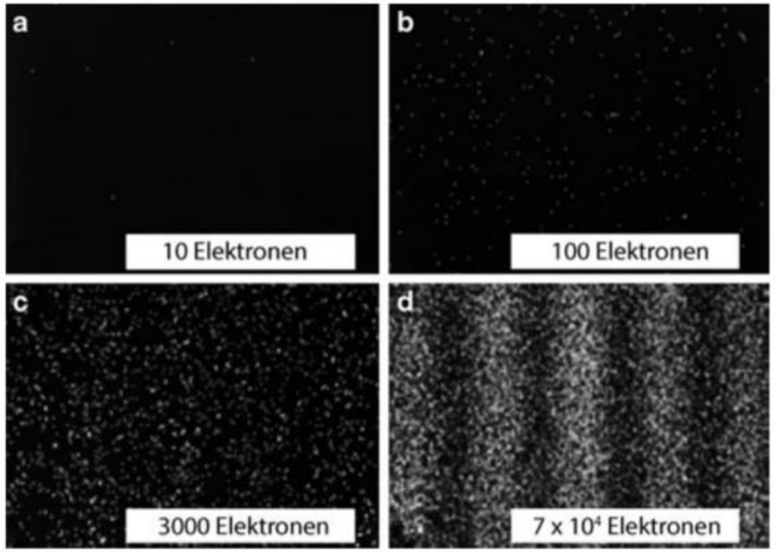
Wave/particle dualism of electrons

Wave



Electrons going thru a double slit experiment produce interference pattern on the monitor

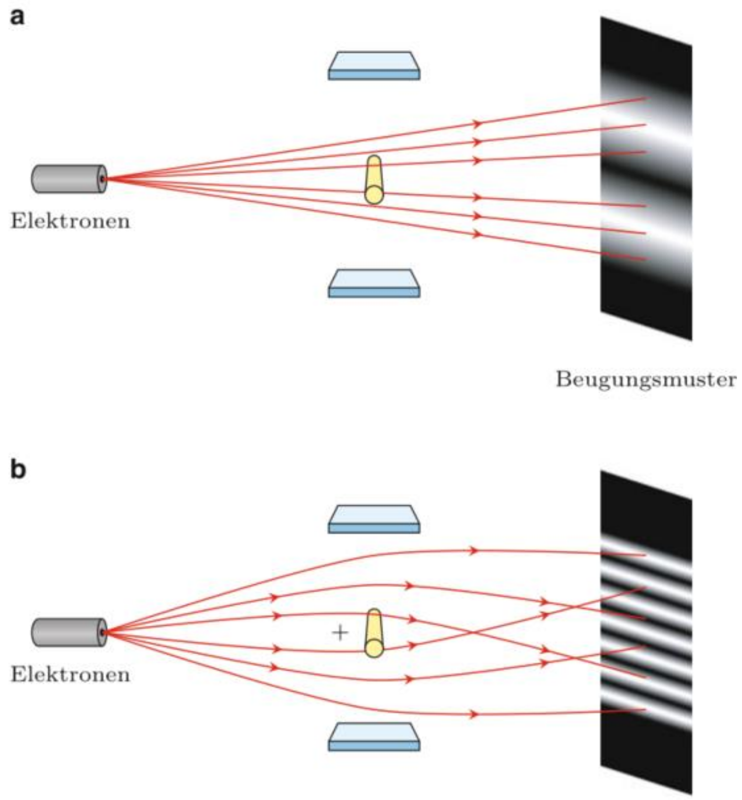
Particle



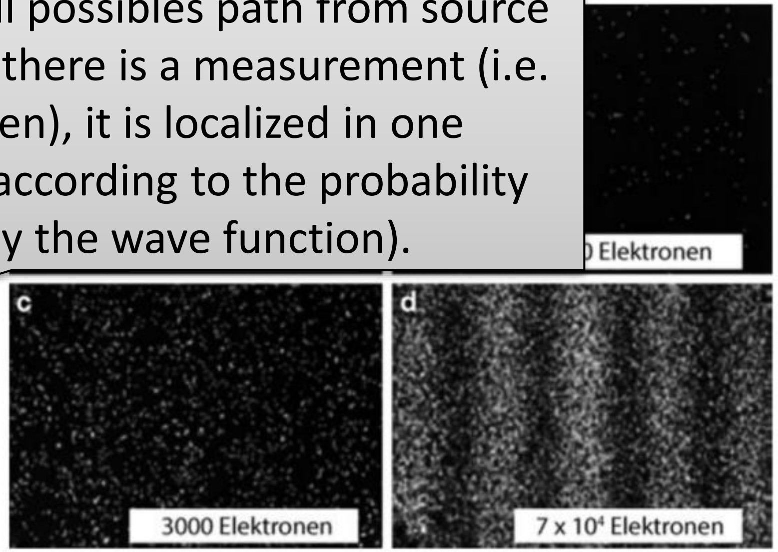
With a single electron source, only one electron is send thru the double slit at a time. Each electron produces a dot on the monitor. However, even in this setup an interference pattern is produced.
How does the electron interferes with itself?

Wave/particle dualism of electrons

Wave



Quantum mechanical interpretation: the electron does not have a defined location/path, but moves along all possibles path from source to monitor. Only if there is a measurement (i.e. it hits the screen), it is localized in one „random“ place (according to the probability described by the wave function).



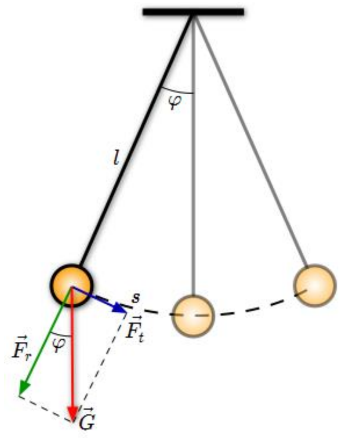
Electrons going thru a double slit experiment produce interference pattern on the monitor

With a single electron source, only one electron is send thru the double slit at a time. Each electron produces a dot on the monitor. However, even in this setup an interference pattern is produced.
How does the electron interferes with itself?

QUANTUM MECHANICS: THE SPIN

State of a classical system

- In physics, the state of a classical system is typically described by observable parameters. Once all parameter are known, we have complete knowledge about the system.
- Example: a pendulum
  - The state of a pendulum is completely described by the displacement and velocity. Once this is known, we can calculate the evolution of the system.
  - Speed and displacement can be measured without affecting the system.
- The **inner state** of a classical system can be determined by observation.

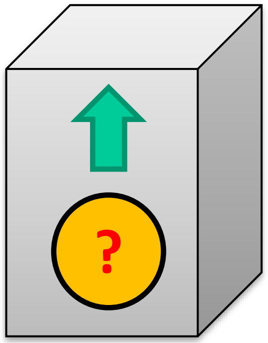


Classical vs. quantum mechanical system (Spin)

- Lets look at a very simple system: a coin
- Can be either head (K) or tail (Z)
- Or, in a more abstract description: let σ be the state of a system with two possible values +1 and -1.
- The system evolves step by step. Let σ_n be the state after n steps. If the state does not change in one step, we have

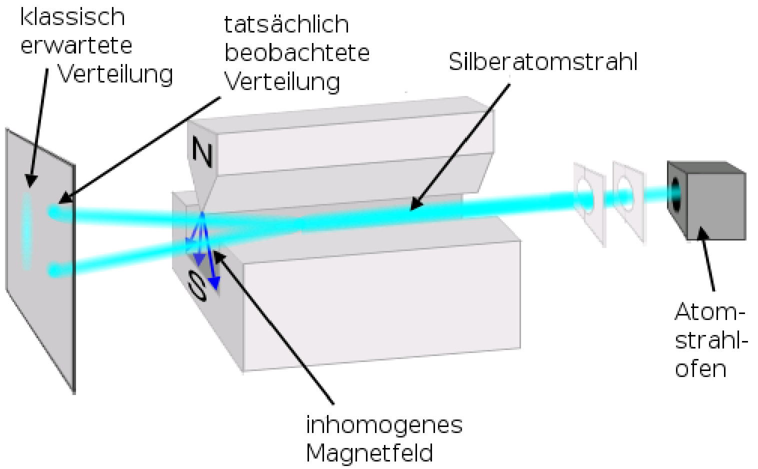
$$\sigma(n+1) = \sigma(n)$$

- In addition we assume that we use an apparatus **A** to "look" at the system, i.e. to measure it's state (more precise, we measure one observable). Lets assume that the apparatus has an orientation in space, noted by the green arrow.

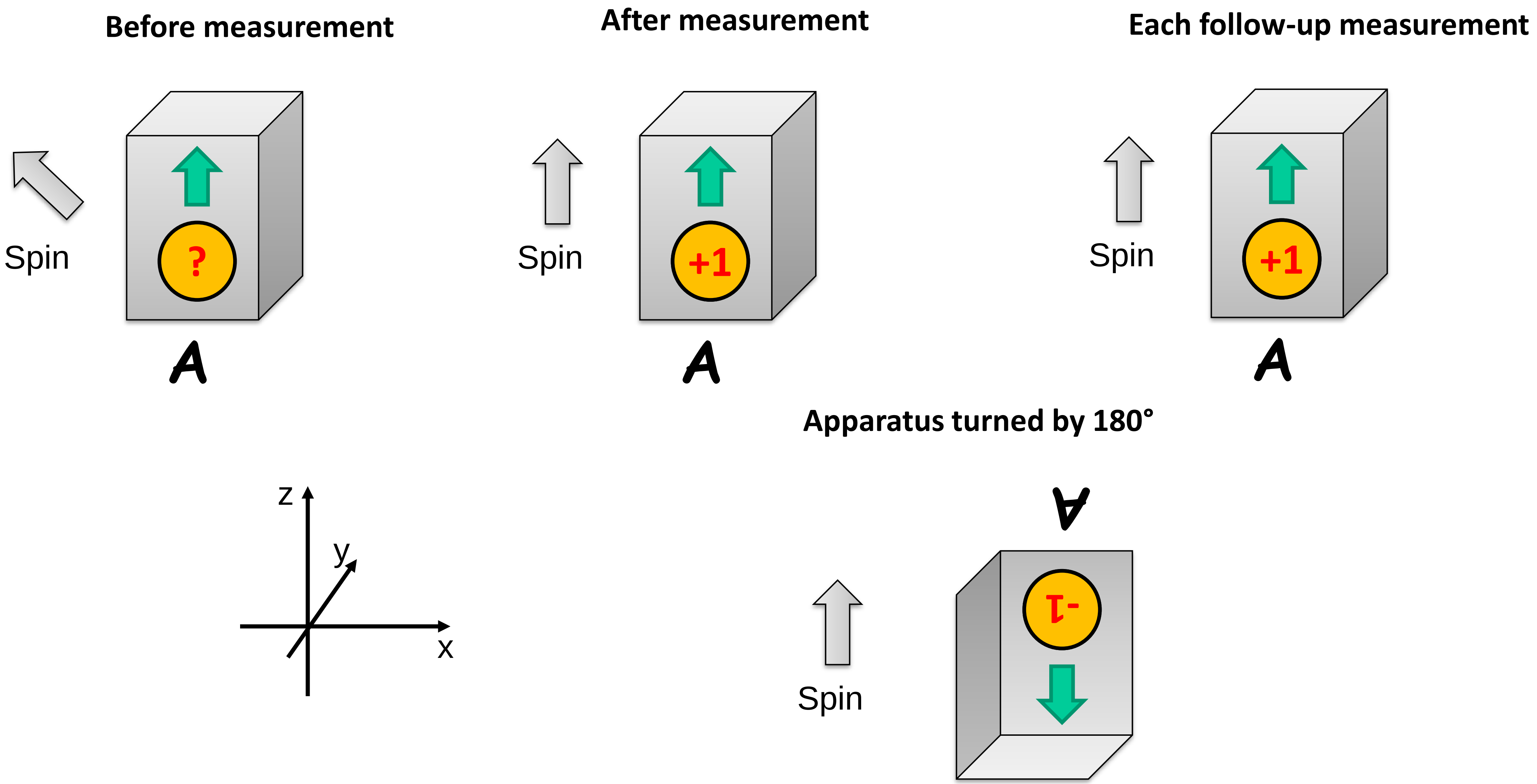


A

Stern-Gerlach-Versuch (1922)

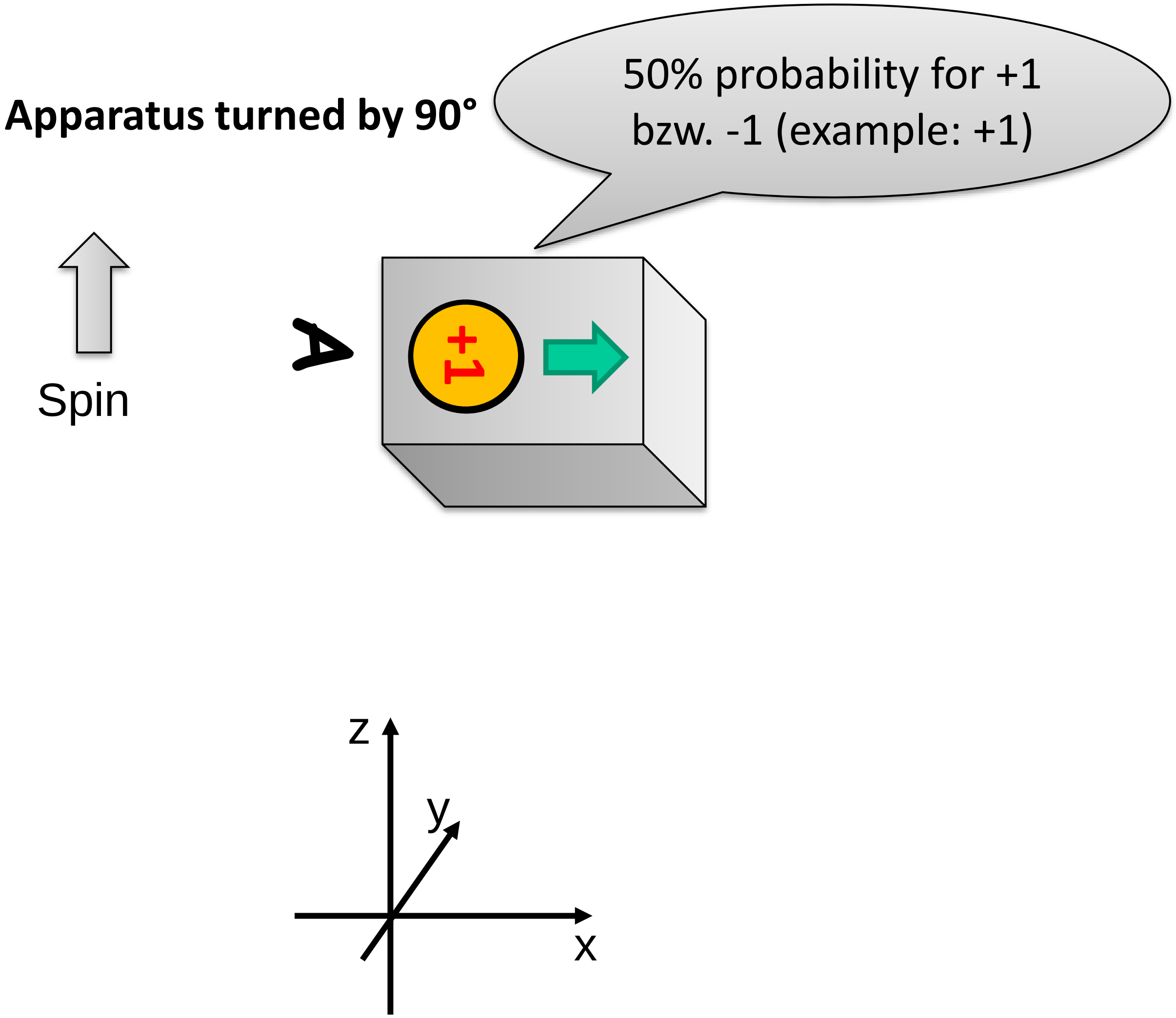


Spin

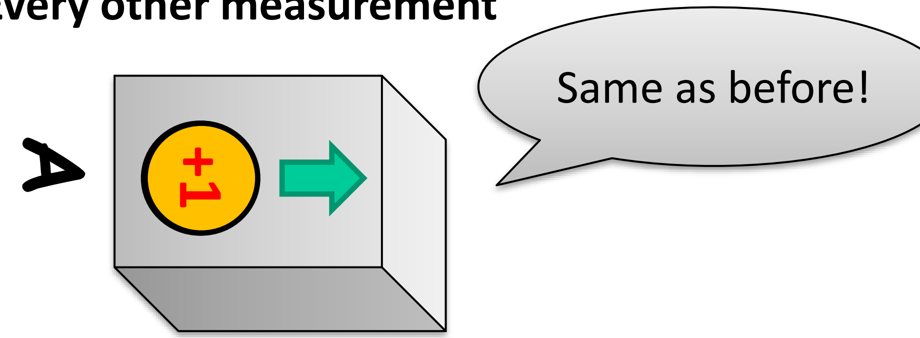

Before measurement
Spin
?
A
After measurement
Spin
+1
A
Each follow-up measurement
Spin
+1
A
Apparatus turned by 180°
A
-1
Spin
z
y
x

Spin

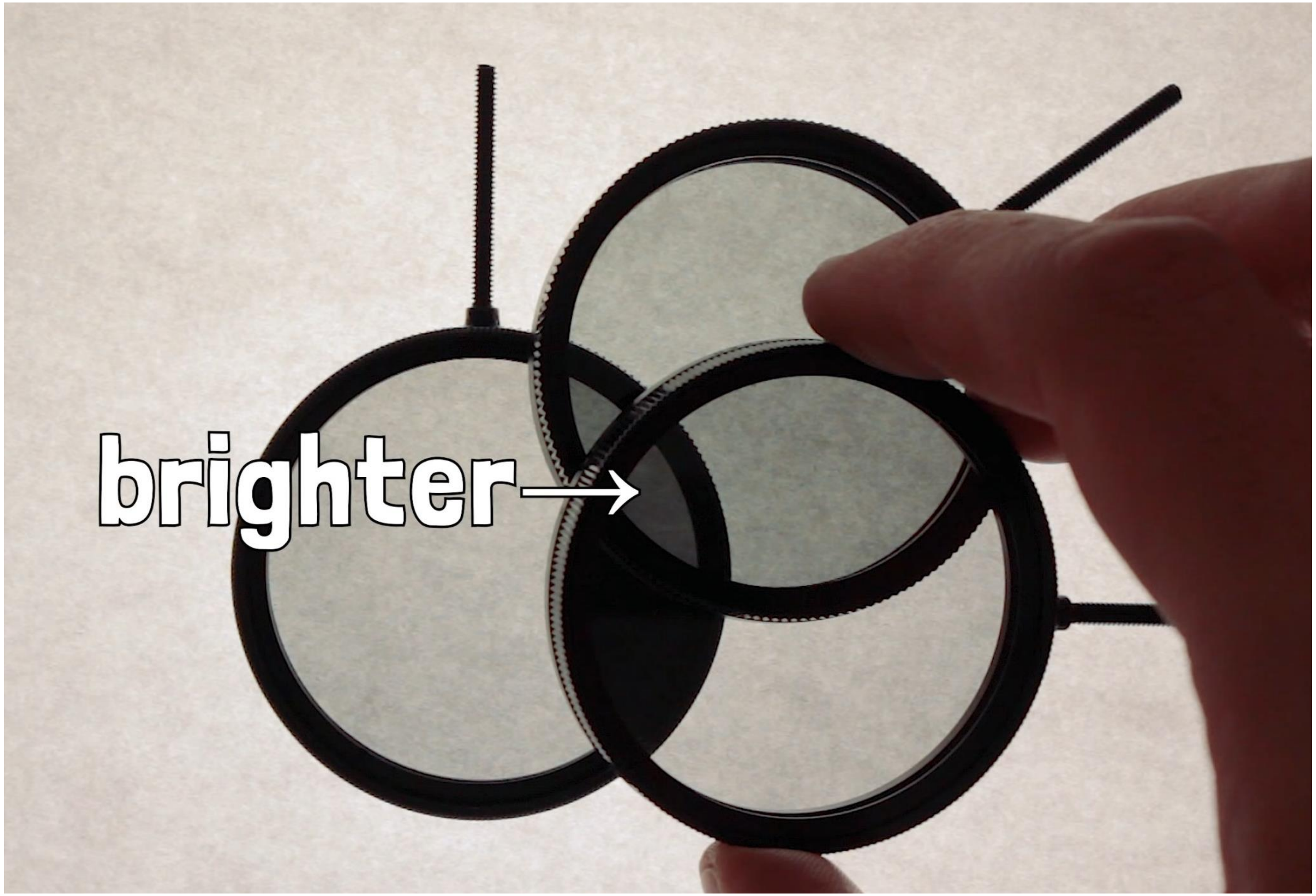
Apparatus turned by 90°



Every other measurement



Polarization of light



Quelle: 3brown1blue **Bell's Theorie: Das Quanten-Venn-Diagramm-Paradoxon**
https://www.youtube.com/watch?v=zcqZHYo7ONs