Lecture

Quantum Information Processing II: Implementations

spring term (FS) 2017

Please take a seat
in the front center part of the lecture hall
if you do not mind.

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

What is this lecture about?

Introduction to experimental realizations of systems for quantum information processing (QIP)

Questions:

- How can one use quantum physics to process and communicate information more efficiently than using classical physics only?
  ► QIP I: Concepts

- How does one design, build and operate physical systems for this purpose?
  ► QIP II: Implementations

Is it really interesting?

Even fashion models talk about it!

You do not believe it?

Watch this!

Goals of the Lecture

- generally understand how quantum physics is used for
  - quantum information processing
  - quantum communication
  - quantum simulation
  - quantum sensing
- know basic implementations of important quantum algorithms
  - Deutsch-Josza Algorithm
  - searching in a database (Grover algorithm)

Concept Question

You are searching for a specific element in an unsorted database with N entries (e.g. the phone numbers in a regular phone book). How many entries do you have to look at (on average) until you have found the item you were searching for?

1. N^2
2. N Log(N)
3. N
4. N/2
5. Sqrt(N)
6. 1

Goals of the Lecture

- generally understand how quantum physics is used for
  - quantum information processing
  - quantum communication
  - quantum simulation
  - quantum sensing
- know basic implementations of important quantum algorithms
  - Deutsch-Josza Algorithm
  - searching in a database (Grover algorithm)
  - prime number factorization (Shor algorithm)
  - simulating quantum systems (Feynman)
- to be able to explain basic protocols for quantum communication
  - efficient information transfer (quantum dense coding)
  - transfer of unknown quantum information (teleportation)
  - secure communication (quantum cryptography)

Goals of the Lecture (continued)

- convey basic concepts of QIP
  - representation of information in qu(antum)bits
  - manipulation and read-out of information stored in qubits
- discuss physical systems used for QIP
  - including photons, atoms, spins, solid state quantum systems
  - know characteristic energy scales and operating conditions
  - know criteria to evaluate suitability of physical systems for QIP
- explore basic experimental techniques to realize and characterize quantum systems
  - realization of quantum devices
  - experimental setups and systems
  - general measurement and characterization techniques

Skills and Competencies to be Developed

- You
  - are able to apply quantum mechanics in different physical contexts relevant for QIP: atomic physics, solid state physics, optical physics, nuclear physics
  - know basic concepts for performing QIP experiments in different physical systems
  - can use your knowledge of QIP concepts to understand research in areas not discussed in the lecture
  - are able to judge the state of the art and relative progress in different technologies for QIP
  - are able to critically evaluate prospects of practical use of quantum physics for information processing and other quantum technologies
  - acquire a basis to decide if you want to work in this field of research
  - come up with your own idea of how to do an interesting QIP project

These skills seem to be quite relevant, even in talk shows.

Watch Conan O'Brien and Jim Carrey on the 'Late Night' show.

Tell us about yourself!

- Who are you?
  - Introduce yourself.
  - Which degree program are you in?
    - **1** Physics
    - **2** Micro- and Nanosystems
    - **3** Electrical Engineering & Information Technology
    - **4** Mechanical Engineering
    - **5** PhD
    - **6** Others
  - Where did you do you Bachelor?
    - **1** ETH Zurich
    - **2** Elsewhere (Where?)

Tell us about yourself!

- Who are you?
  - Do you attend (have you previously attended) classes on Quantum Physics (Exp/Theo) or Quantum Information (Exp/Theo)?
    - **1** Introduction to Quantum Physics (e.g. @ ETH: Physics III, …)
    - **2** Theoretical Quantum Physics (e.g. @ ETH : QM 1, QM 2, …)
    - **3** Quantum Information Processing (e.g. @ ETH : Renner, Home)
    - **4** Quantum Information Theory (QIT)
    - **5** No prior courses (come and ask for advice)
  - Do you attend (or plan attending) this terms class (FS 17) **Quantum Information Processing I: Concepts** by Jonathan Home?
    - **4** Yes
    - **3** No

Basic Structure of QSIT course

Part I: Introduction to Quantum Information Processing (QIP)

- basic concepts: qubits, gate operations, measurement
- circuit model of quantum computation

Part II: Superconducting Quantum Electronic Circuits for QIP

- qubit realizations, characterization, coherence
- physical realization of qubit control, qubit/qubit interactions and read-out
- interfacing qubits and photons: cavity quantum electrodynamics
- realizations of algorithms and protocols

Part III: Survey of Physical Implementations for QIP

- photons in linear optics
- ions and neutral cold atoms
- Electronic and nuclear spins in semiconductor quantum dots, NV centers and molecules

Student Presentations

- Topics: experimental implementations of quantum information processing
- Goal: present key features of implementation and judge its relevance/prospects
- Material: books, research papers and review articles
- Preparation: teams of three (maybe two) students,
  ~ 10 slots for teams available in each exercise class
- Coaching and support by TAs
- Duration: presentation + discussion (30+15 minutes)
- Presentation: blackboard, transparencies, PowerPoint …
- feedback on both content and presentation of your talk

Exercise Classes

- part I (week 1 - 2)
  - regular exercise session led by TAs
- part II (week 3 - 13)
  - student presentations
- teaching assistants:
  - Christian Kraglund Andersen (chanders@phys.ethz.ch)
  - Christopher Eichler (eichlerc@phys.ethz.ch)
  - Sebastian Krinner (skrinner@phys.ethz.ch)

Reading

- Quantum computation and quantum information
  Michael A. Nielsen & Isaac L. Chuang
  Cambridge : Cambridge University Press, 2000
  676 S.
  ISBN 0-521-63235-8

- additional reading material will be provided throughout the lecture and on the web page: www.qudev.ethz.ch

Credit Requirements

- active contribution to lectures and exercises
- prepare and present a high quality talk on one of the physical implementations of quantum information processing

Exam & Credits

- aural exam (20 mins) during summer or winter exam session
- exam dates as required by your program of study
- 5 credit points (KP) can be earned by successfully completing this QIP II class (individually counting as an elective course)
- 10 credit points (KP) can be earned by successfully completing both QIP I and QIP II (together counting as a core course)
- content of exam:
  - see goals of lecture
  - good presentation and active contribution to lecture will be a bonus

Time and Place

- Lecture: Thursday (11-13), 10:45 – 12:30, HCI G 3
- Exercises: Monday (17-18), 16:45 – 17:30, HCI E 8
HIL E 10.1
HPV G 5
- Selection of exercise room (and TA) through Moodle platform by the end of this week

Registration & Contact Information

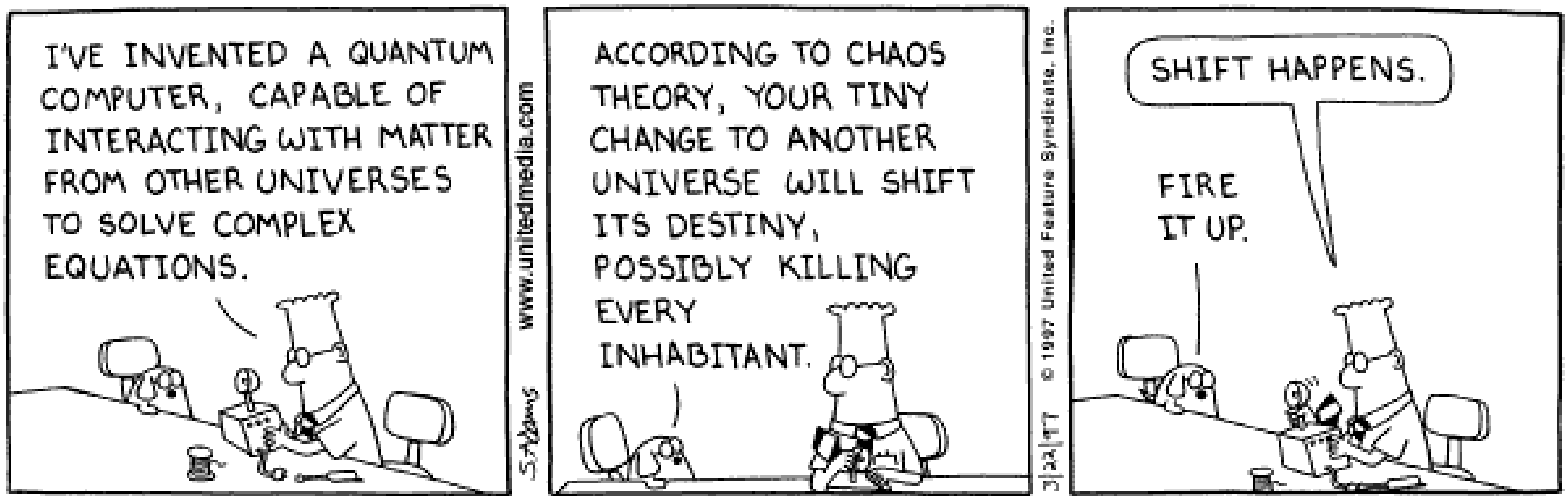
Your registration and contact information

- please register online for the class
- in this way we are able contact you
- you will get automatic access to the material on the moodle platform

Our contact information

- qipii@phys.etzh.ch
- www.qudev.ethz.ch (will be updated constantly)
- moodle: https://moodle-app2.let.ethz.ch/course/view.php?id=3151

Let's get started!



The first transistor

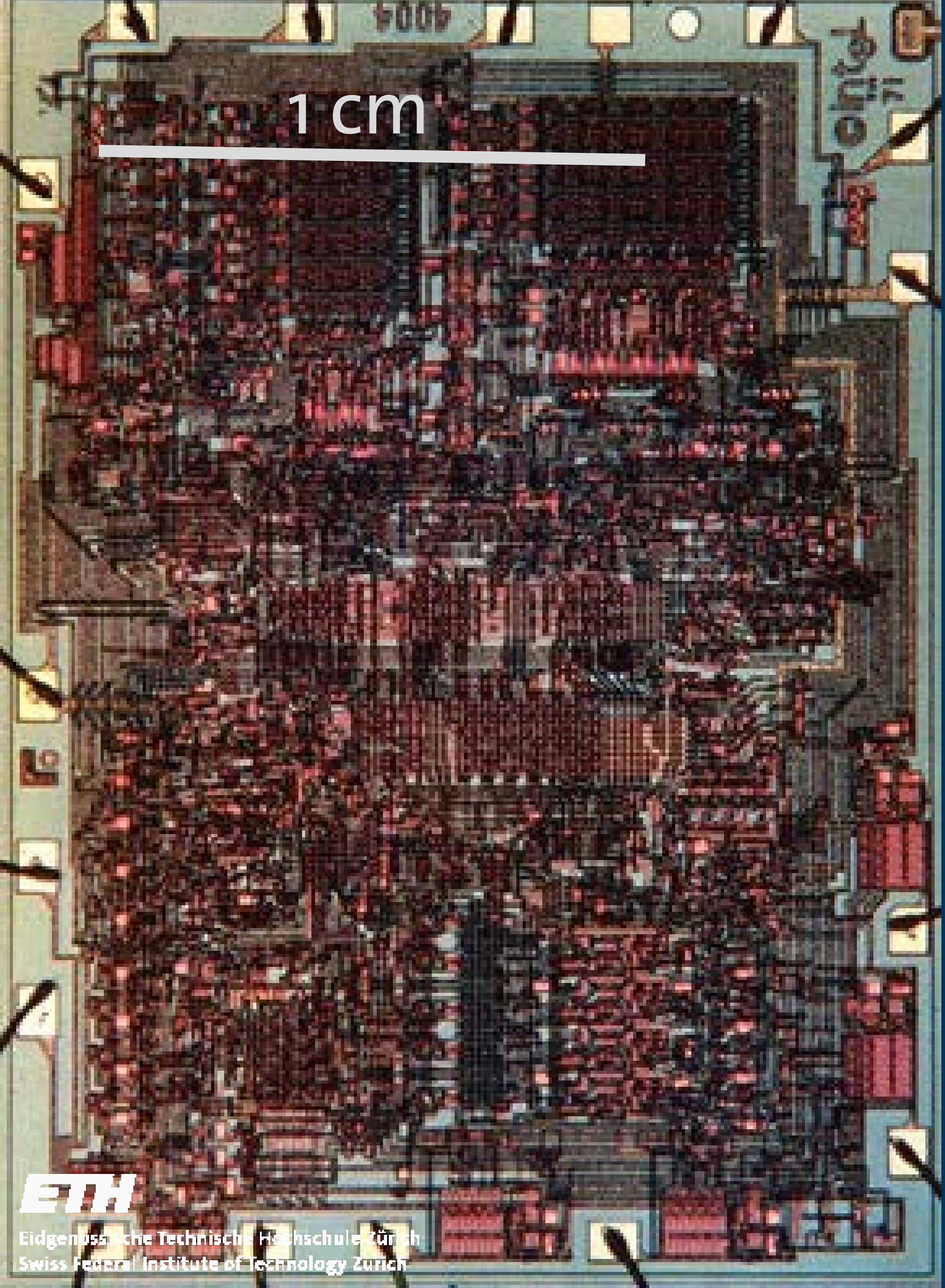
developed at Bell Labs 1947 by John Bardeen, Walter Brattain and William Shockley.

Nobel prize in physics, 1956

material:
- semiconductor

clock rate:
- 1 Hz

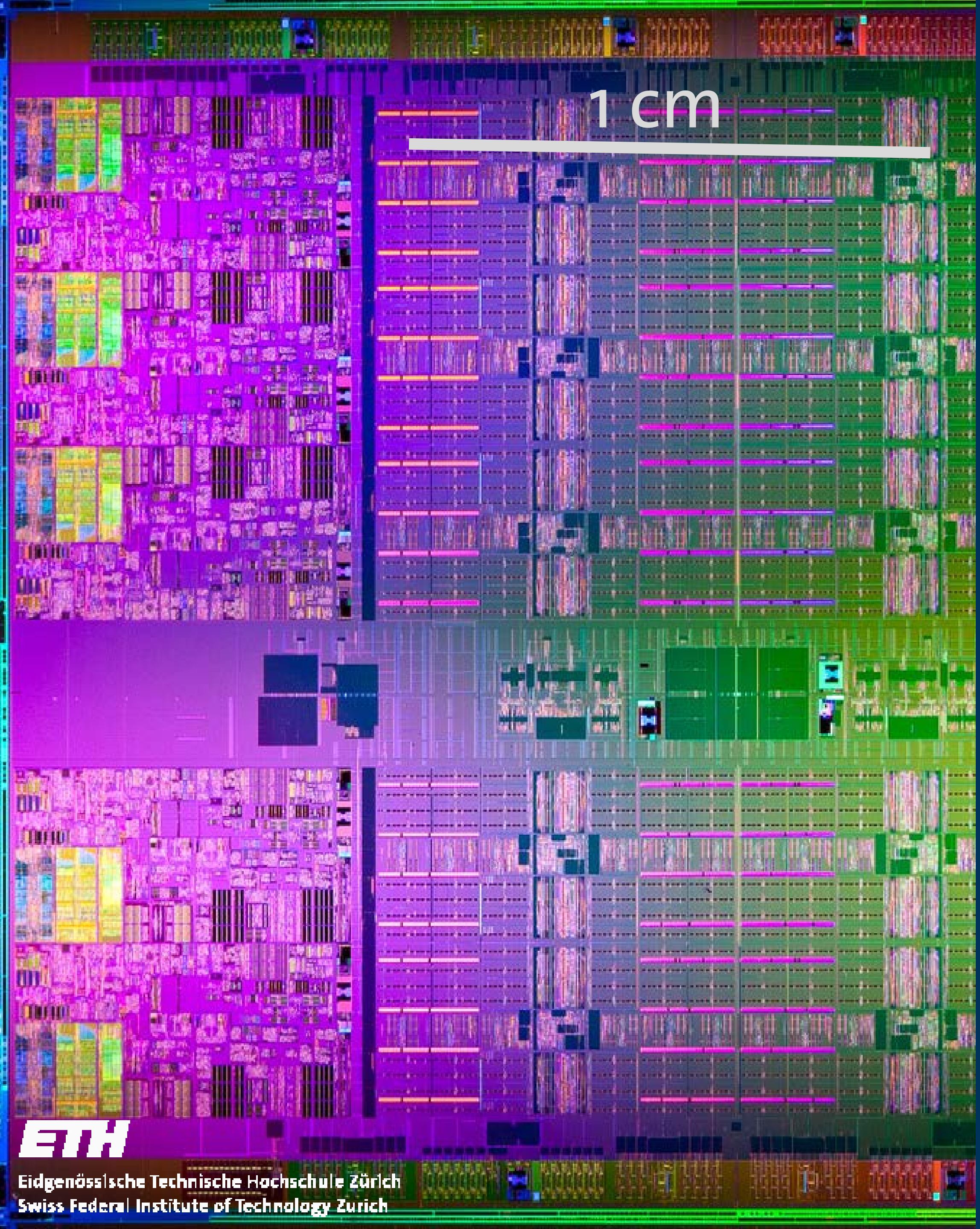
dimensions:
- 1 cm



First Intel Processor

Intel 4004, 1971

- 2000 transistors
- 60 kHz
- 10.000 nm = 0,001 cm



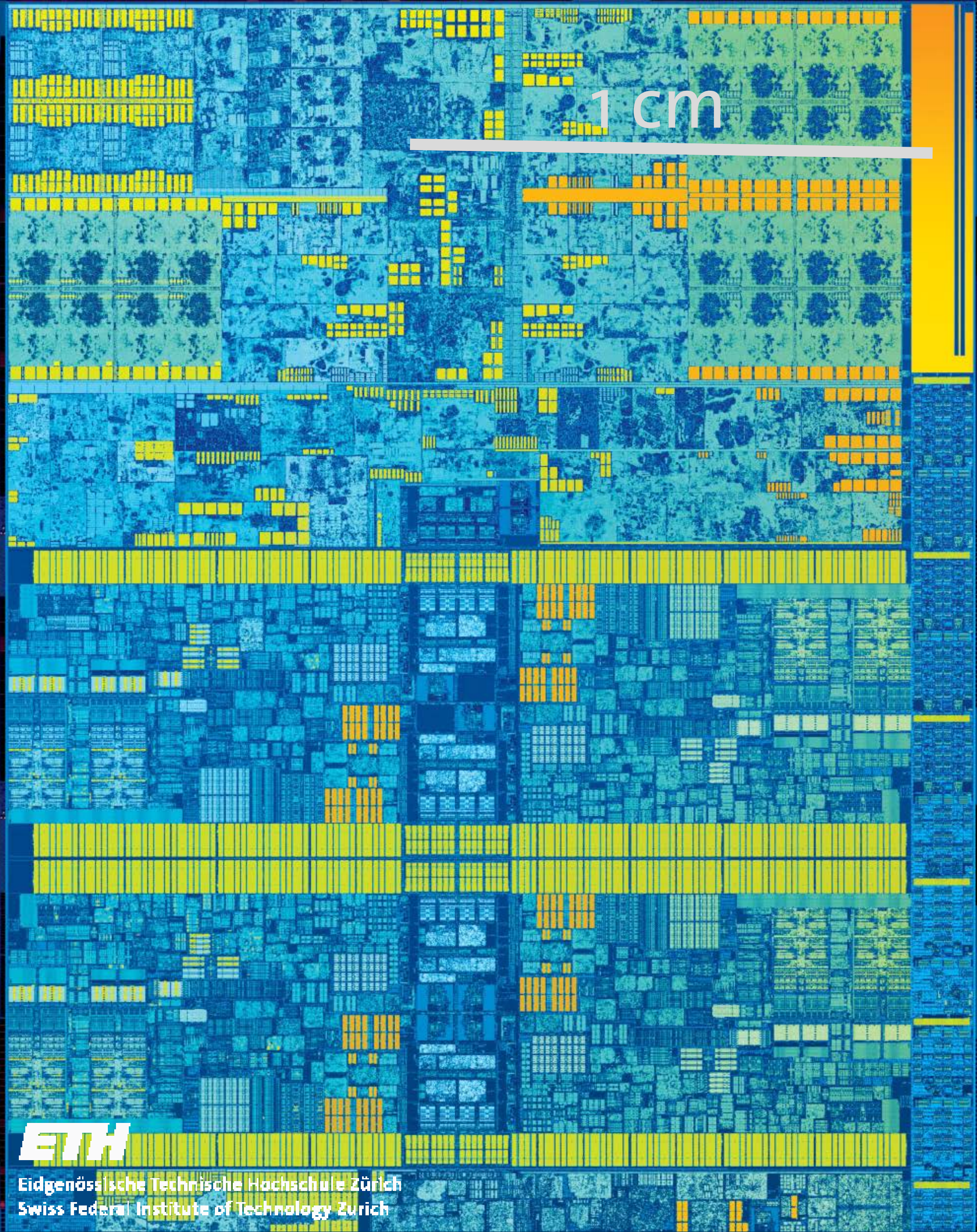
A few years ago

Intel Xeon, 2011

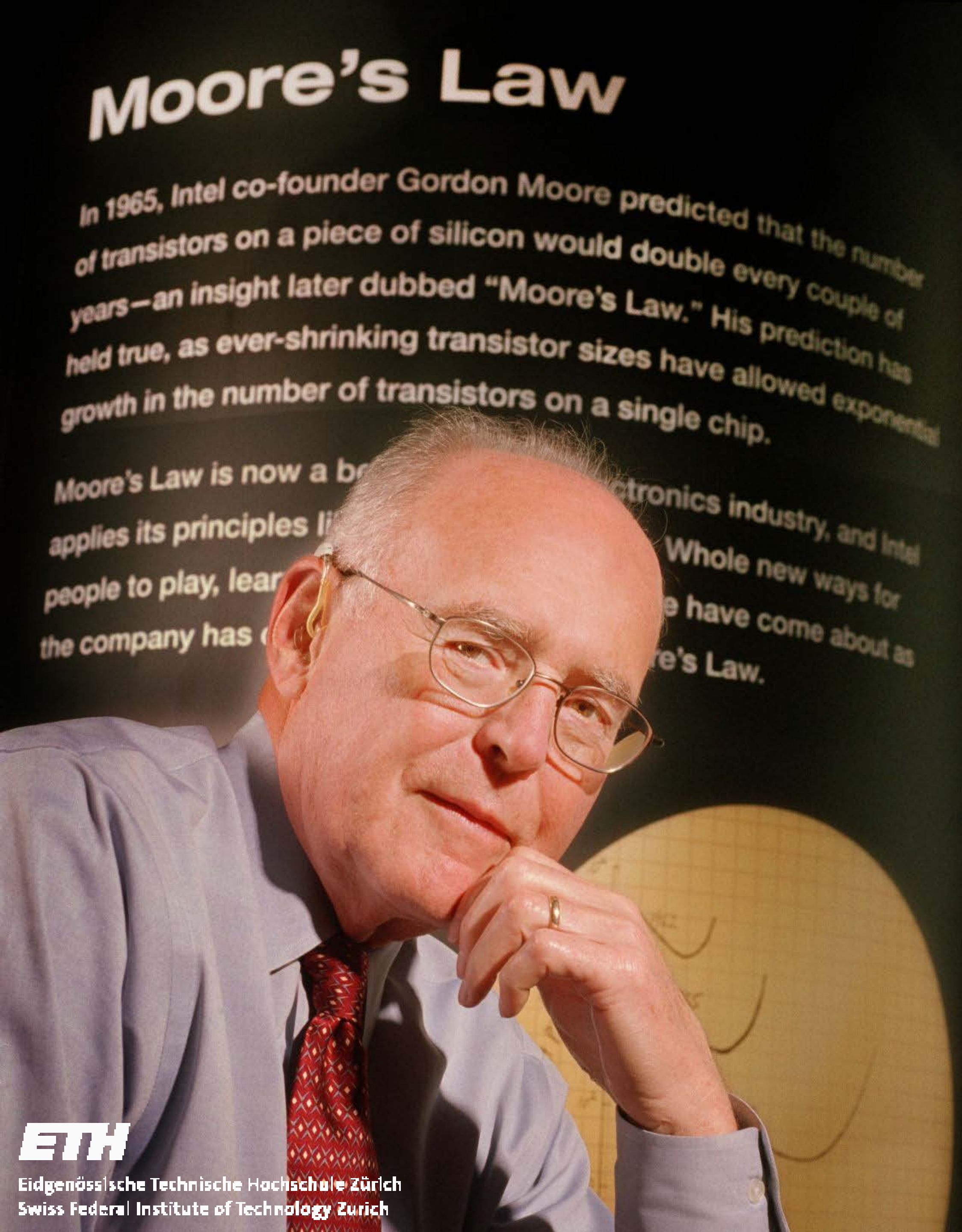
- 3 Billion Transistors
- 3 GHz
- 32 nm = 0.0000032 cm

Todays Processors

Intel Skylake, 2015
6th Gen Intel Core (80662)



- ~ 6 Billion Transistors
- 4 GHz
- 14 nm = 0.0000014 cm



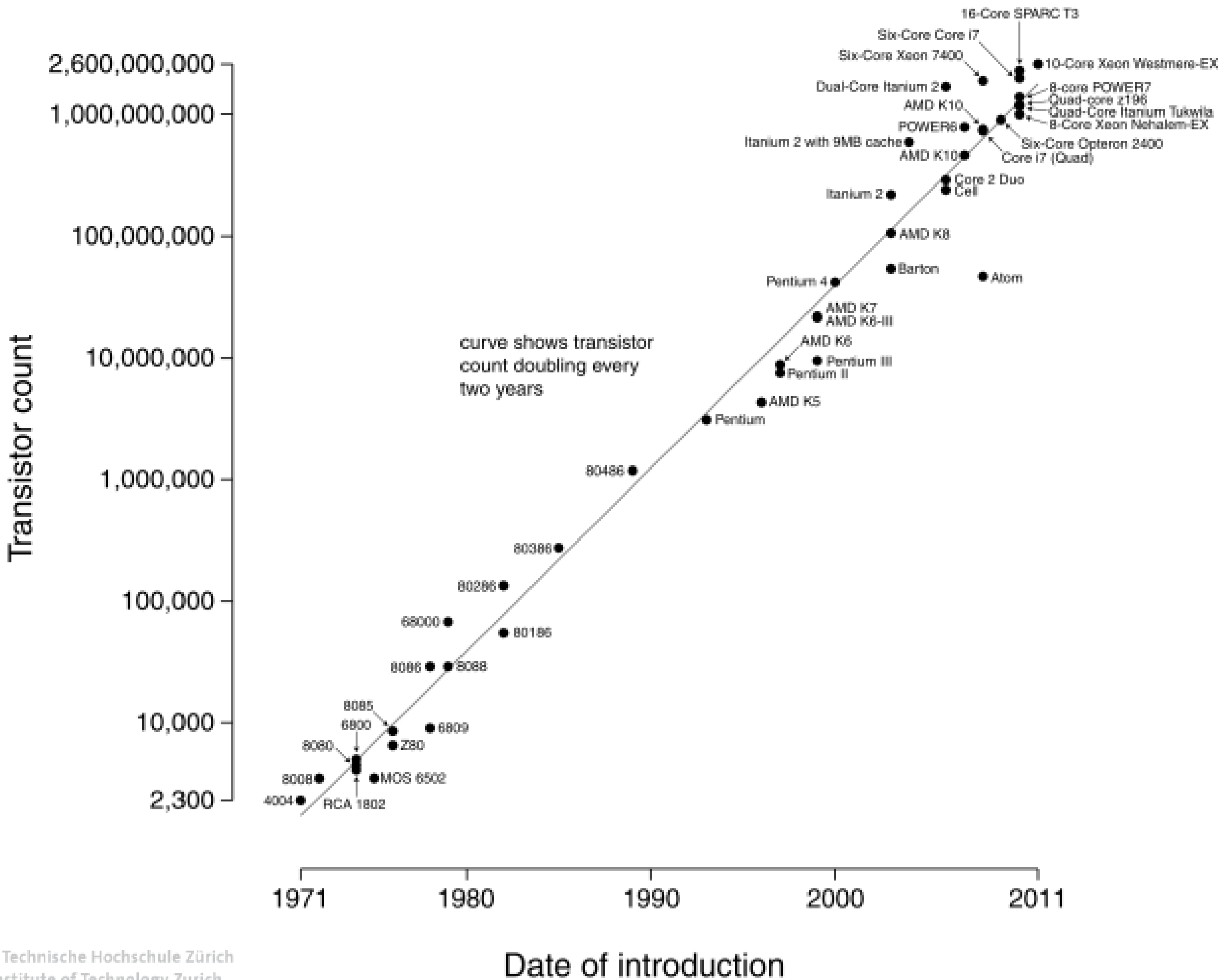
The Development

"The number of transistors on a piece of silicon will double every couple of years."

Gordon E. Moore, 1965
Co-founder of Intel

Is valid since more than 40 years!

Microprocessor Transistor Counts 1971-2011 & Moore's Law



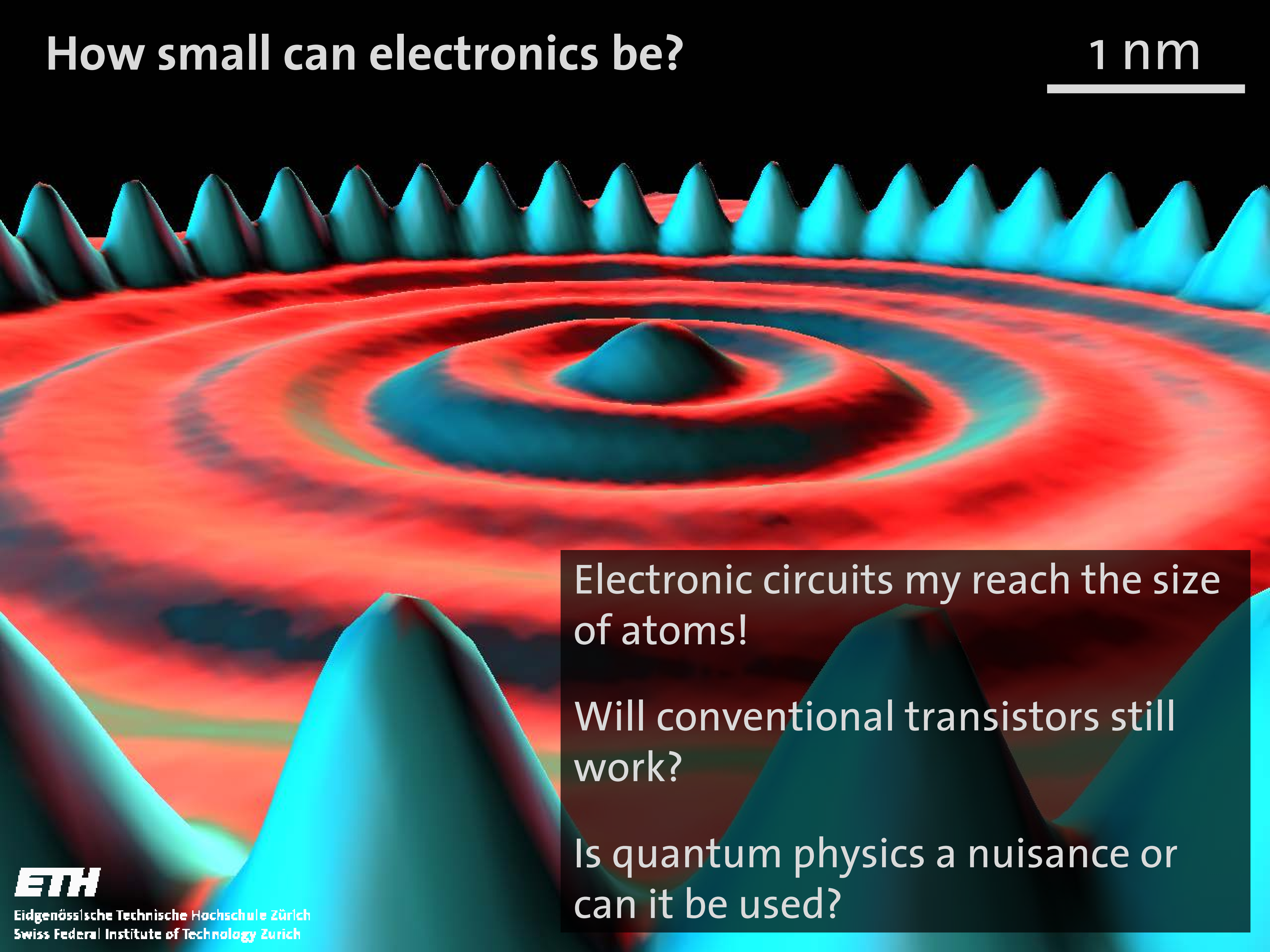
Will information technology develop in the same way in the next 40 years?

Are there limits to the current technology?

Can we overcome these limitations?

What will future computing technology look like?

How small can electronics be?



Electronic circuits my reach the size of atoms!

Will conventional transistors still work?

Is quantum physics a nuisance or can it be used?