Quantum Science with Superconducting Circuits

HS 2019

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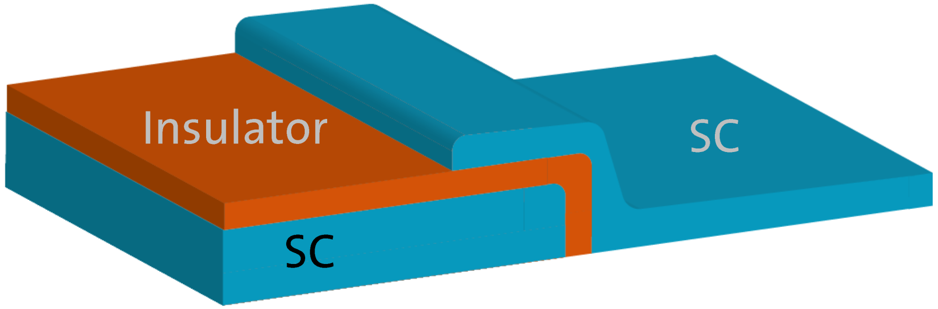
What is this lecture about?

Central Questions:

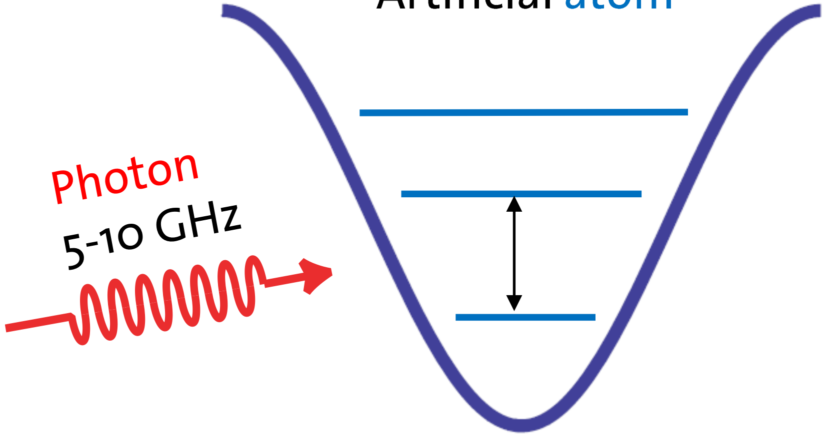
- What makes quantum physics a vibrant research topic a century after its theoretical foundation?
- How does one use quantum systems to store and process information?
- How do we build and operate physical systems for this purpose?
- What makes superconducting circuits one of today's most versatile experimental systems to study quantum information science?

Superconducting Circuits

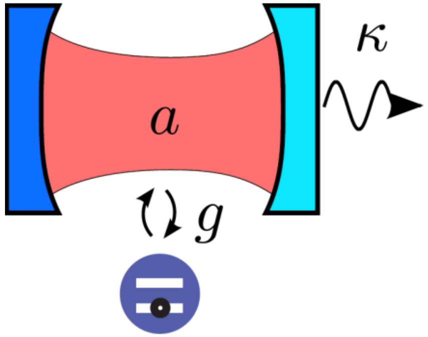
Josephson Junction



Electrical Circuit
=
Artificial atom



Circuit QED



Josephson effect

Josephson 1962
Rowell 1962

Macropscopic quantum tunneling

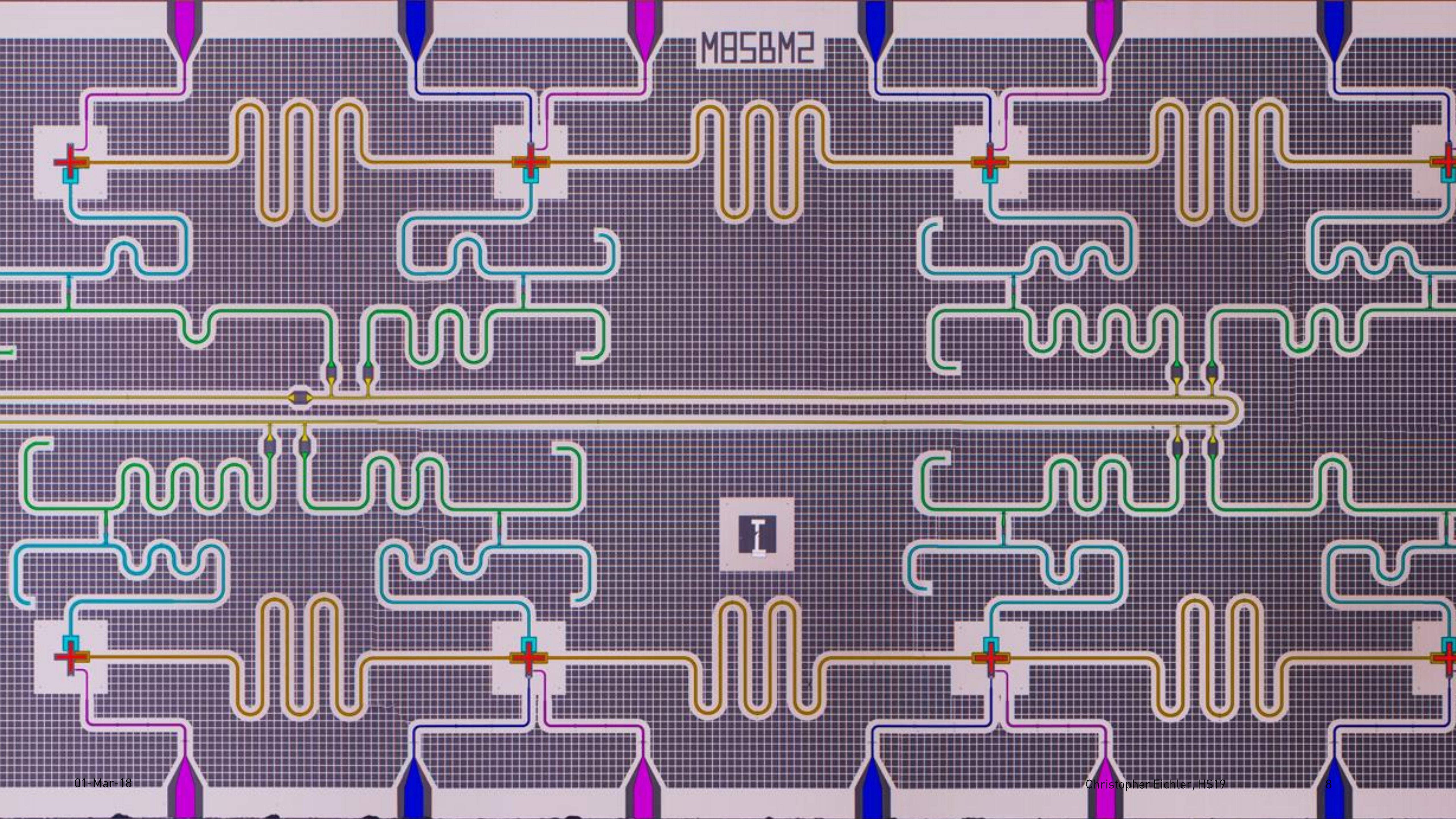
Devoret, Clark, Martinis 1985

Coherent oscillations

Nakamura, et al. 1999
Vion et al., 2002

Strong Light-matter coupling

Wallraff et al., 2004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Goals of the Lecture

- Understand the physical concepts underlying superconducting circuit experiments
  - Superconductivity and the Josephson effect
  - Quantization of electrical circuits
  - Design and fabrication of superconducting quantum devices
  - Control and measurement techniques
  - Experimental setup

- Understand how superconducting circuits are used …
  - … to address questions in basic science and quantum information processing
  - … to develop quantum computers, implement basic algorithms, and correct for errors

Skills and Competencies to be Developed

You ...

- ... know basic **requirements** and **concepts for performing quantum control experiments.**
- ... learn how to design, build and control quantum coherent devices based on superconducting circuits.
- ... gain practical skills in the modelling and simulation of quantum systems.
- ... develop ability to apply this knowledge in different physical implementations **not discussed in the lecture.**
- ... are able to **judge the state of the art** of quantum technology.
- ... are able to **critically evaluate prospects of practical use** of quantum physics for information processing.
- ... acquire a basis to decide if you want to **work in this field** of research.
- ... come up with your **own ideas** of how to do an interesting QIP project.

Tell us about yourself!

- Help us to adjust the lecture to your interests and needs.

- Who are you?
  - Introduce yourself.

  - Which degree program are you in? (**EduApp**)
    - 1 Physics
    - 2 Micro- and Nanosystems
    - 3 Electrical Engineering & Information Technology
    - 4 Mechanical Engineering
    - 5 PhD
    - 6 Others

  - Where did you complete your Bachelor degree? (**vote**)
    - At ETH Zurich or at another university?

Tell us about yourself!

- Do you attend (have you previously attended) classes on Quantum Physics (Exp/Theo) or Quantum Information (Exp/Theo)? (**EduApp**)
  - 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, del Rio, Home, Wallraff, Imamoglu)
  - 4 Quantum Information Theory (QIT)
  - 5 No prior courses (come and ask for advice)

- Do you have prior experience with programming in ... ? (**EduApp**)
  - 1 Python
  - 2 Mathematica
  - 3 Others or None

Reading

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

- Circuit QED: superconducting qubits coupled to microwave photons,
  S. M. Girvin Department of Physics, Yale University, New Haven, CT 06520, USA

- Additional reading material will be provided throughout the lecture and on moodle.

Exam & Credits

- Aural exam (20 minutes) during summer or winter exam session
- Exam dates as required by your program of study
- 6 credit points (KP) can be earned by successfully completing this class (individually counting as an elective course)
- Content of exam:
  - see goals of lecture
  - active contribution to lecture and exercise will be a bonus

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

- Christopher.Eichler@phys.ethz.ch
- www.qudev.ethz.ch (will be updated constantly)
- moodle: https://moodle-app2.let.ethz.ch/course/view.php?id=11511

1) Introduction to Quantum Information processing

1.1 Quantum Computing: Why interesting?

1.2 Quantum bit: One, two, many.

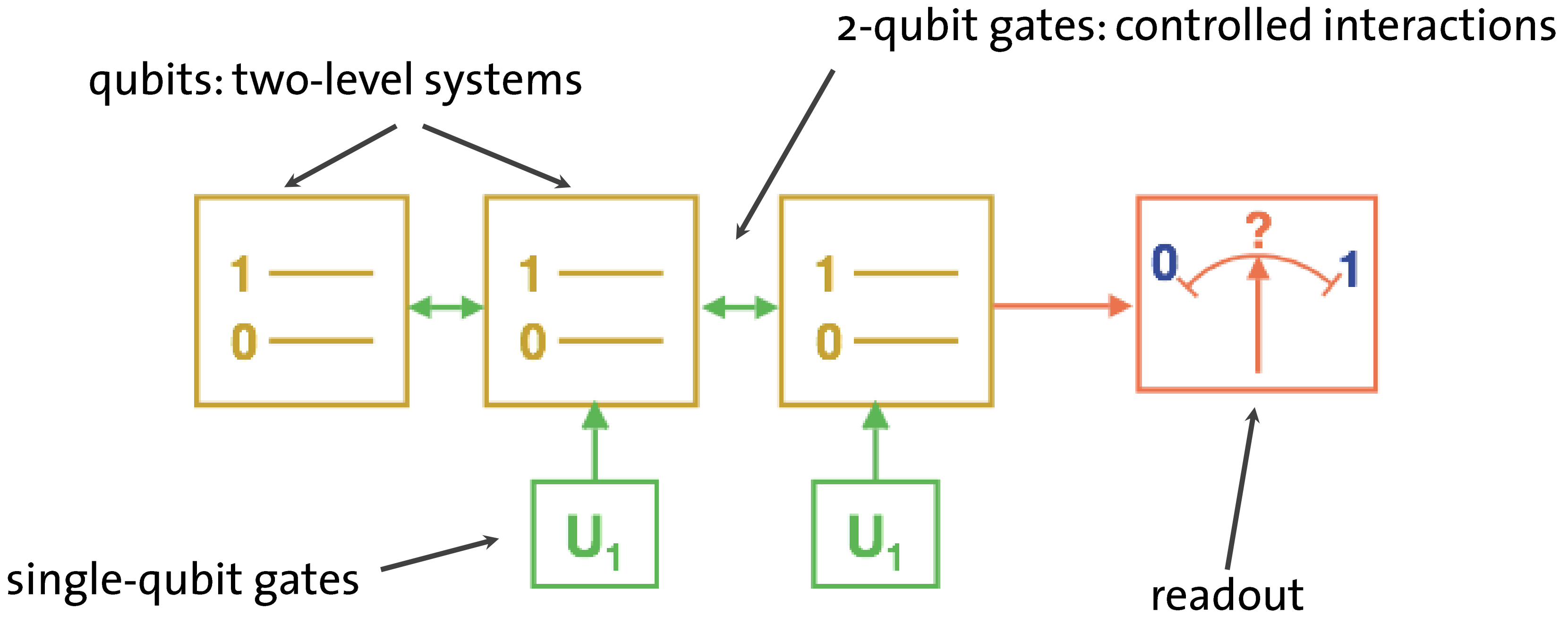
1.3 Quantum logics and quantum circuit model of quantum computing

1.4 Requirements for physical implementation of quantum computers

1.5 Physical realization of qubits

Discussion on the black board.

Components of a Generic Quantum Information Processor



The challenge:

Quantum information processing requires excellent qubits, excellent gates, excellent readout ...

Conflicting requirements: perfect isolation from environment while maintaining perfect addressability

M. Nielsen and I. Chuang, Quantum Computation and Quantum Information (Cambridge, 2000)

1.4 Requirements for physical implementation

Compare **DiVincenzo's criteria** (2000):

1) Scalable, physical realization of a qubit
2) Ability to initialize qubits in a fiducial state, e.g. the ground state
3) Coherence time needs to be much greater than the gate time
4) Need universal set of gates
5) Need high-fidelity measurement of qubits

And two more criteria related to the transmission of quantum information between different nodes of a network.

6) The ability to interconvert stationary and mobile (or flying) qubits.
7) The ability to faithfully transmit mobile qubits between specified locations.

David P. DiVincenzo, The Physical Implementation of Quantum Computation, arXiv:quant-ph/0002077 (2000)

Outlook

This week (lecture 1):

- Organization of the course
- Brief introduction to Quantum Information Science and Quantum Computing

Next week (lecture 2):

- Quantization of electrical circuits
  - First step: “Given an electrical circuit composed of inductors and capacitors, find the corresponding system Hamiltonian.”