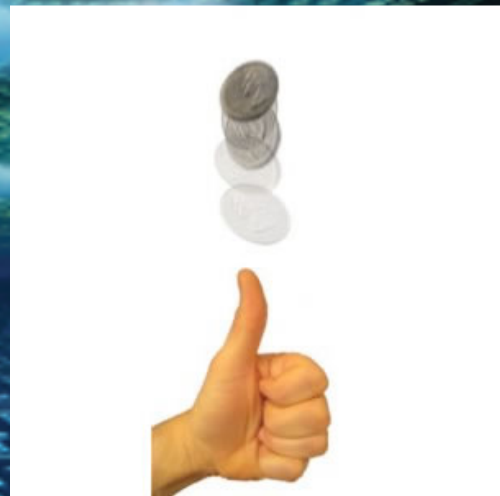
Superconducting Supercomputers and Quantum Computation

Hans Hilgenkamp
MESA+ Institute for Nanotechnology
University of Twente
Enschede, The Netherlands



KIT Karlsruhe Institute of Technology

September 13-15, 2017, Karlsruhe, Germany

European Cryogenics Days 2017 and
2nd International Workshop on Cooling Systems for HTS Applications

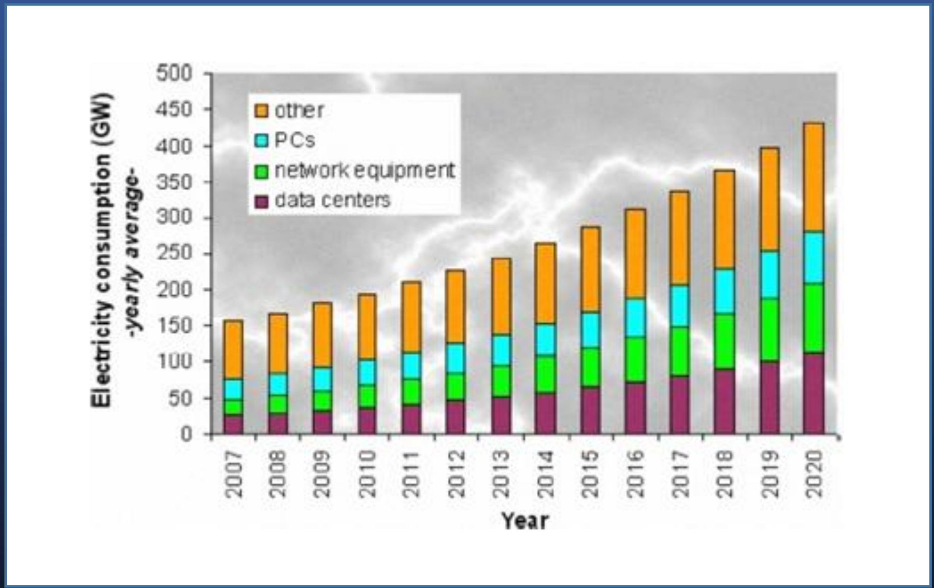
My intentions for this talk:

Convey in accessible words the interest and developments in novel computing technologies, with an emphasis on superconductivity.

This talk will not be a comprehensive review, nor a complete account for all the groups working on these topics or the latest news, and I will avoid all kinds of detail.

What is the problem?

1: Energy consumption becomes a major complication, also limiting speed of computation.

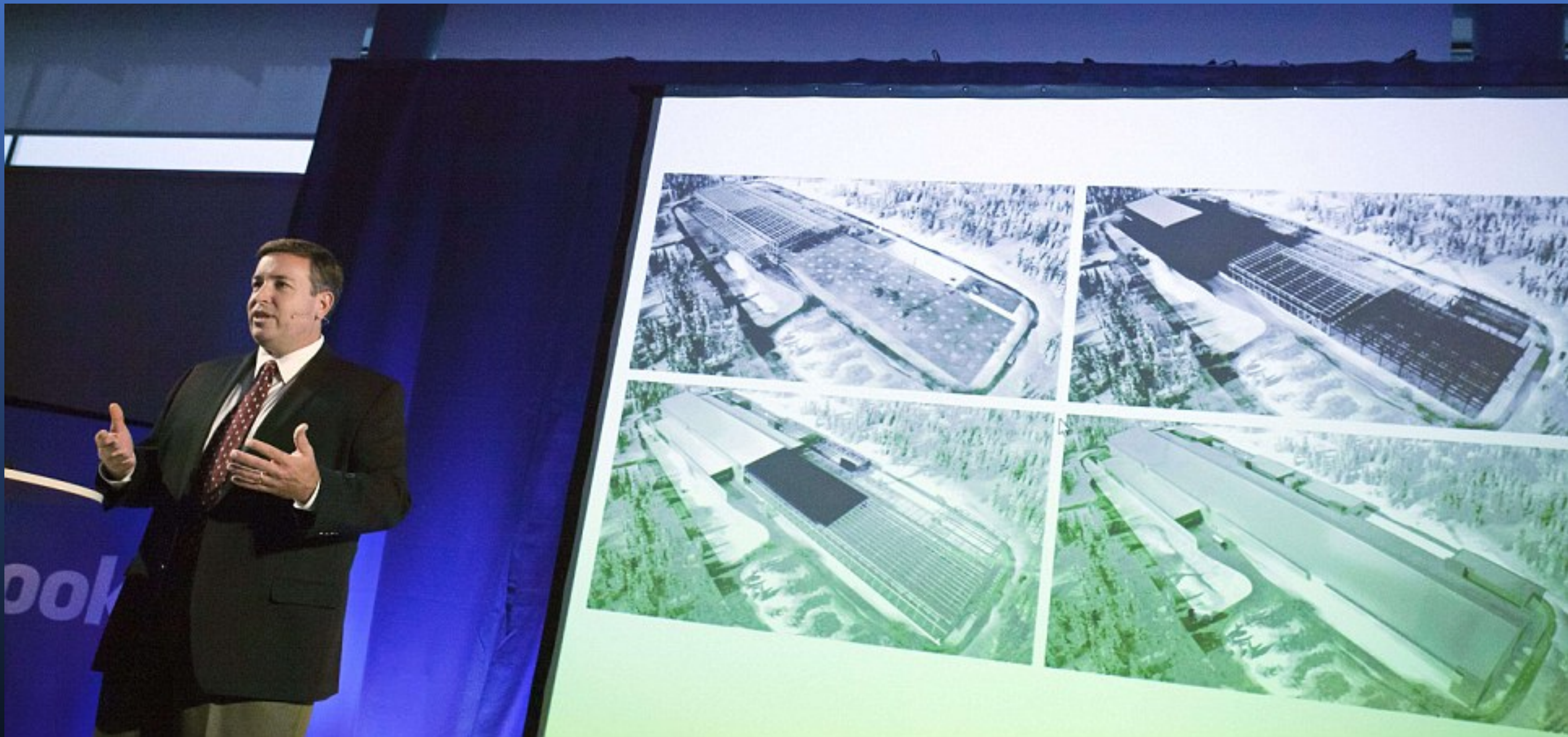


2: Current ‘Von Neumann’ computing paradigm has inherent limitations in cracking very complex problems.


THE INTERNET of
THINGS


Centralized/Cloud computing
-> Opportunities for cryogenic concepts

Google: Finland



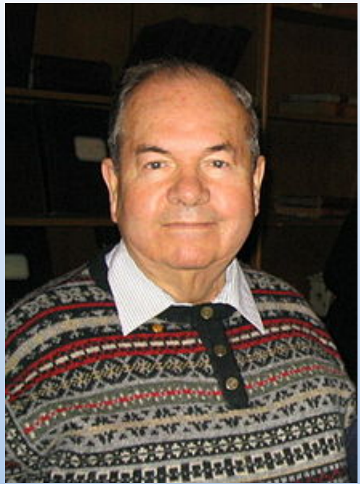
Facebook: Luleå (North-Sweden)
100 MW

Urgently needed: New materials and concepts for energy-efficient electronics:

Energy-efficient materials (e.g. 2D-materials)
Spintronics
Brain-inspired computing
→ Rapid single flux quantum (RSFQ) devices
..

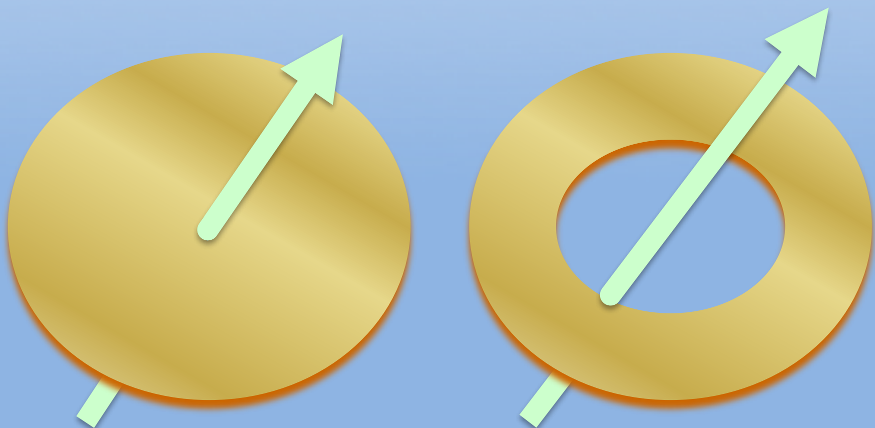
Highly desired: New computing paradigms to circumvent current limitations in computing:

Brain-inspired computing
→ Quantum Computation
..



Magnetic flux quanta as carriers of information

A.A. Abrikosov
(1928 – 2017)



THE DIRECT OBSERVATION OF INDIVIDUAL FLUX LINES IN TYPE II SUPERCONDUCTORS

U. ESSMANN and H. TRÄUBLE

Institut für Physik am Max-Planck-Institut für Metallforschung, Stuttgart and Institut für theoretische und angewandte Physik der Technischen Hochschule Stuttgart

Received 4 April 1967

Triangular flux line lattices have been observed by electron microscopy on Pb-4at% In and niobium specimens in the remanent state. These lattices contain various kinds of defects.

The Abrikosov solution [1] of the Ginsburg-Landau equations [2] for the mixed state of type II superconductors predicts a periodic arrangement of flux lines (flux line lattice) penetrating the specimen parallel to the applied field. Neutron diffraction studies [3,4] on niobium and nuclear magnetic resonance studies on vanadium [5] give evidence for the existence of a close packed arrangement of flux lines.

In this paper we present results on the flux line arrangement obtained by sirect observation of individual flux lines. As was shown in previous papers [6-8], the magnetic structures on the surfaces of ferromagnets and superconductors can be revealed with a resolution of about 500 Å or better by depositing small ferromagnetic particles on the specimen and observing the resulting patterns in the electron microscope by means of a replica technique.

We report here the magnetic structures of Pb-4at%In (κ = 1.35 at 1.1°K [8]) and niobium in the remanent state at 1.1°K based on observations on the end surfaces of well-annealed mono- or polycrystalline rods (4 mm diameter, 50 mm length) that had been magnetized parallel to the rod axis in a field of 3000 Oe. Parts of the surfaces exhibited a quite well defined triangular lattice of "points of exit" of the magnetic flux (fig. 1). In polycrystalline Pb-4at%In the lattice parameter (nearest neighbour separation) is a = 3500 Å. If each of the indivudual spots is as-

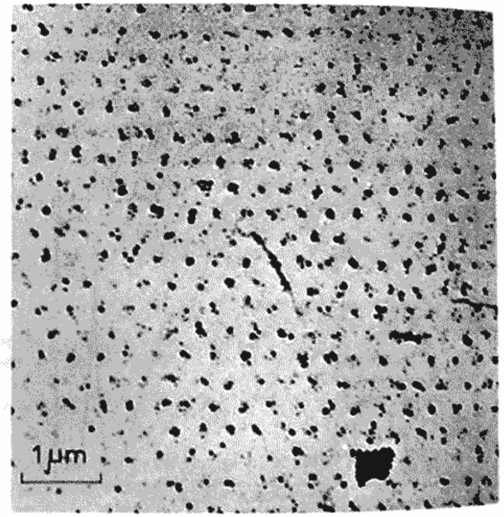
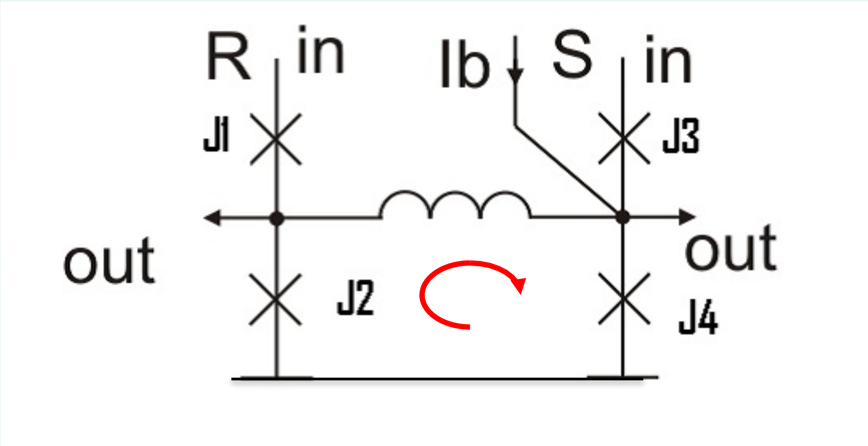
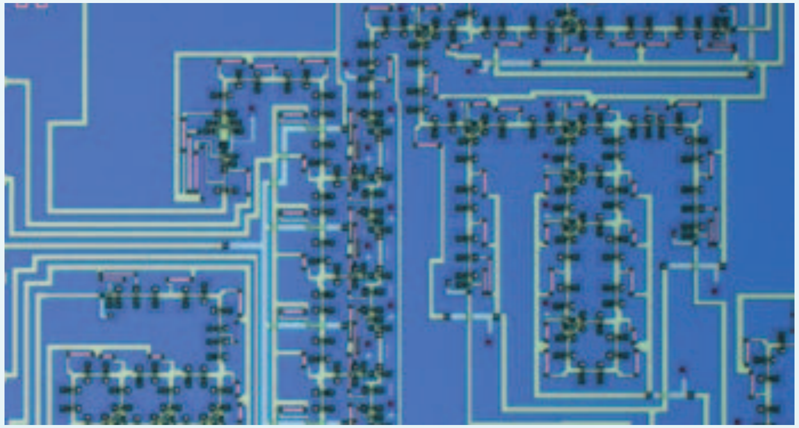


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Flux quantization is the basis for many superconducting electronics / sensing devices



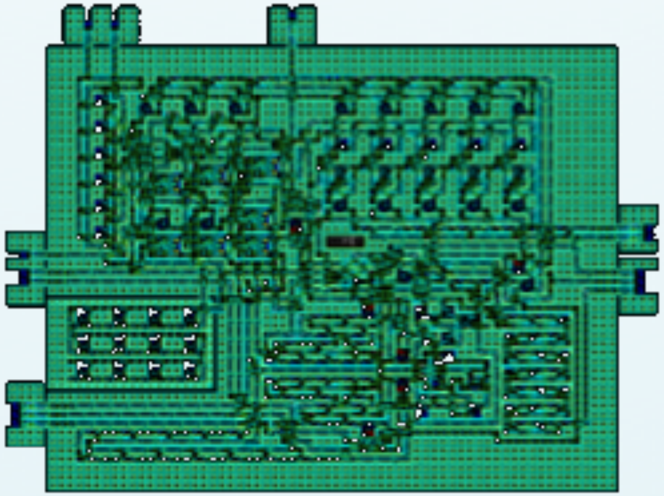
RSFQ Flip Flop
(adapted from S. Narayana & V. Semenov)



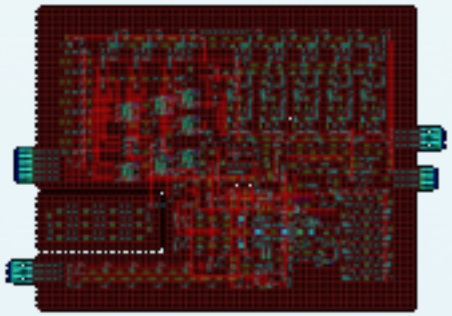
RSFQ Circuit
(Hypres)

Consumption of Microprocessor with Low-Voltage RSFQ Circuit

(from Prof. A. Fujimaki – Nagoya)



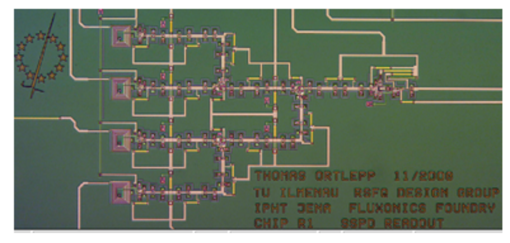
Multilayered PTLs introduced
JJ count: -23%, area: -50%



	CORE1α Prototype with Conventional RSFQ (2003) [1]	CORE1α with Low-Voltage RSFQ (2013) [2]
Technology	ISTEC 2.5-kA/cm^2 STP	AIST 10-kA/cm^2 ADP
Size, JJ Count	2.56 mm x 2.12 mm, 4999 JJs	1.38 mm x 1.71 mm, 3869 JJs
Bias Voltage	2.5 mV	**0.5 mV**
Power	1.6 mW	**0.23 mW**

SFQ examples

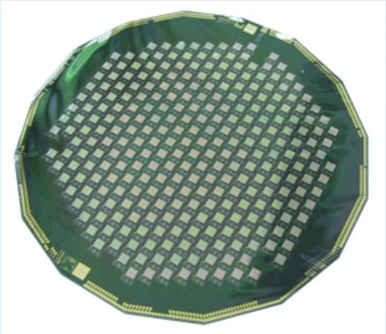
4 channel SNSPD
readout and multiplexer
circuit
15 JJ/channel



Photograph – T. Ortlepp,
Ilmenau University of
Technology, Germany

T. Ortlepp et al., Optics Express, 19 (2011) 18593

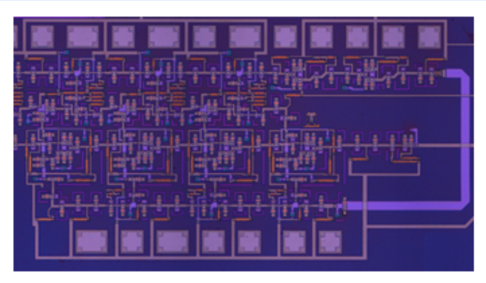
300 pixel TES array with
integrated SQUID
multiplexer for Atacama
Pathfinder experiment
(APEX) in Chili



Photograph – T. May
IPHT Jena, Germany

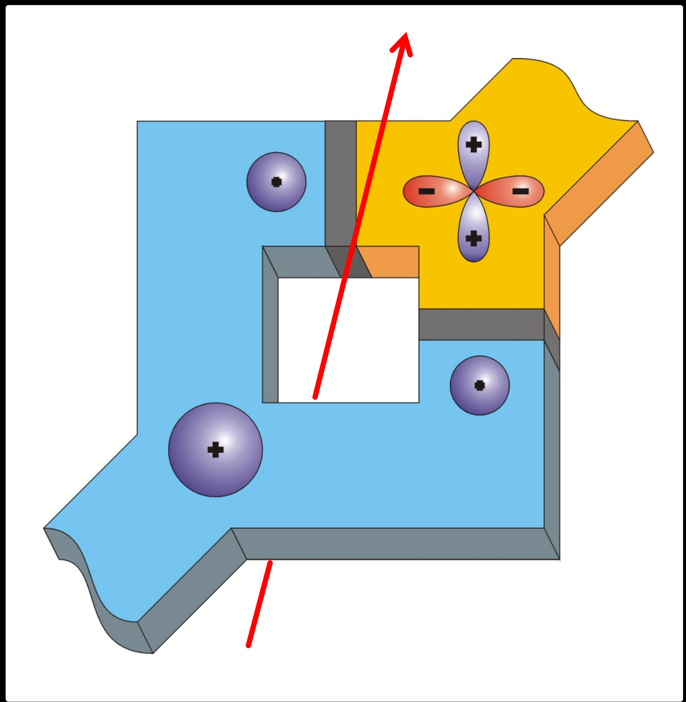
T. May et al. *Proceedings of SPIE 6949 (2008), 69490C*

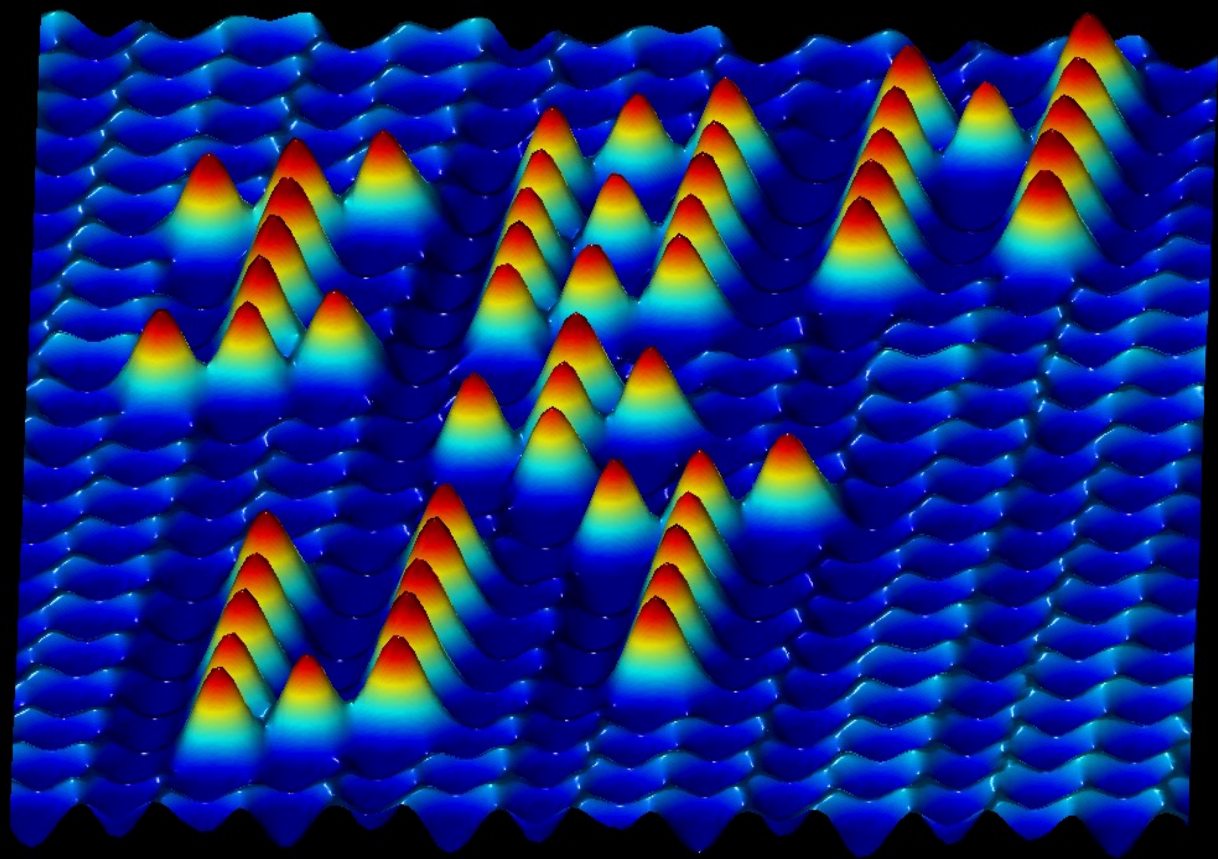
Digital magnetometer
decimation filter
4 GHz operation
360 JJs



Photograph – R. Stolz
IPHT Jena, Germany

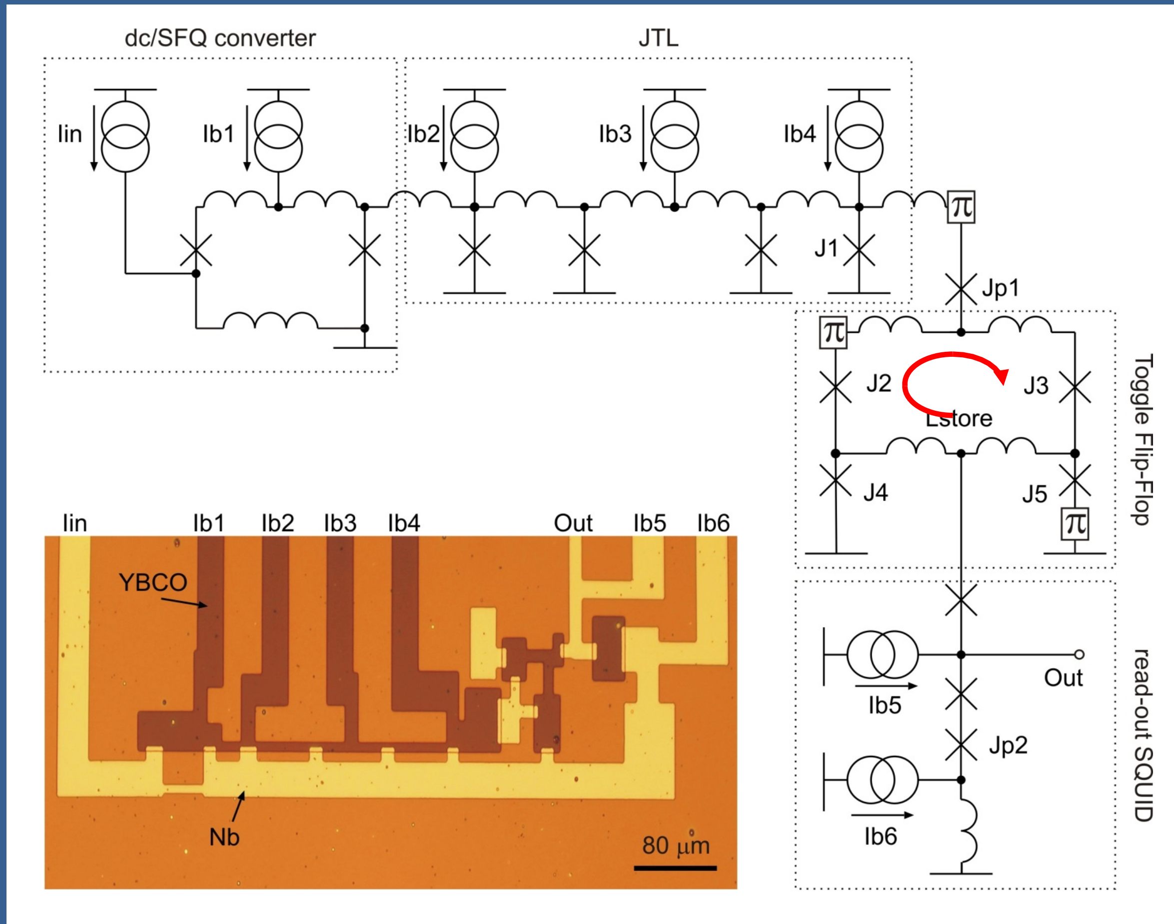
**J. Kunert at al.
IEEE TAS, 23, (2013)
1101707**





Hilgenkamp, Ariando, Smilde, Blank, Rijnders, Rogalla,
Kirtley & Tsuei, *Nature* 422, 50-53 (2003)

YBCO-Nb   RSFQ circuit



Ortlepp, Ariando, Mielke, Verwijs, Foo, Rogalla,
Uhlmann & Hilgenkamp, *Science* 312, 1495 (2006)

Status of RSFQ:

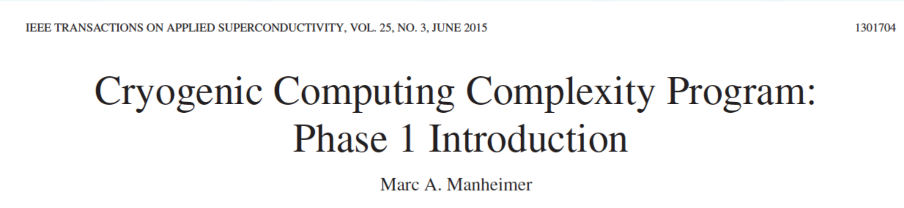
Proven concept for ultra-fast and energy-efficient information processing.
(approx. 1% of CMOS, clock frequencies of 10's of GHz feasible)

In use in specialty applications.

For VLSI, major steps need to be made in controllable high-J_c Josephson junction fabrication on the nanoscale and in development of cryogenic memory concepts.

Operation at 4.2K is foreseen (Nb as the superconductor of choice). Systems integration, wiring etc. are challenging, but should be solvable.

Major industrial-academic partnership programs in Japan and USA, but funding in EU is lagging behind.



IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 25, NO. 3, JUNE 2015 1301704

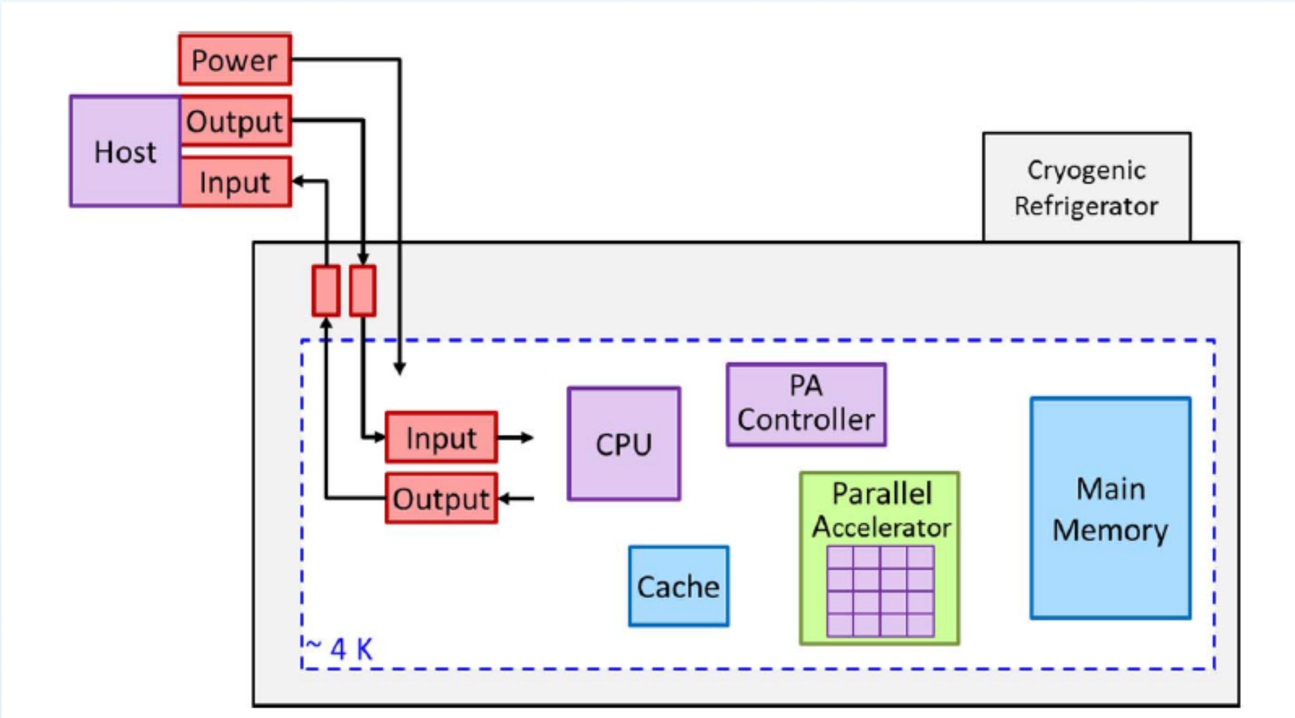
Cryogenic Computing Complexity Program: Phase 1 Introduction

Marc A. Manheimer

IARPA C3 Program

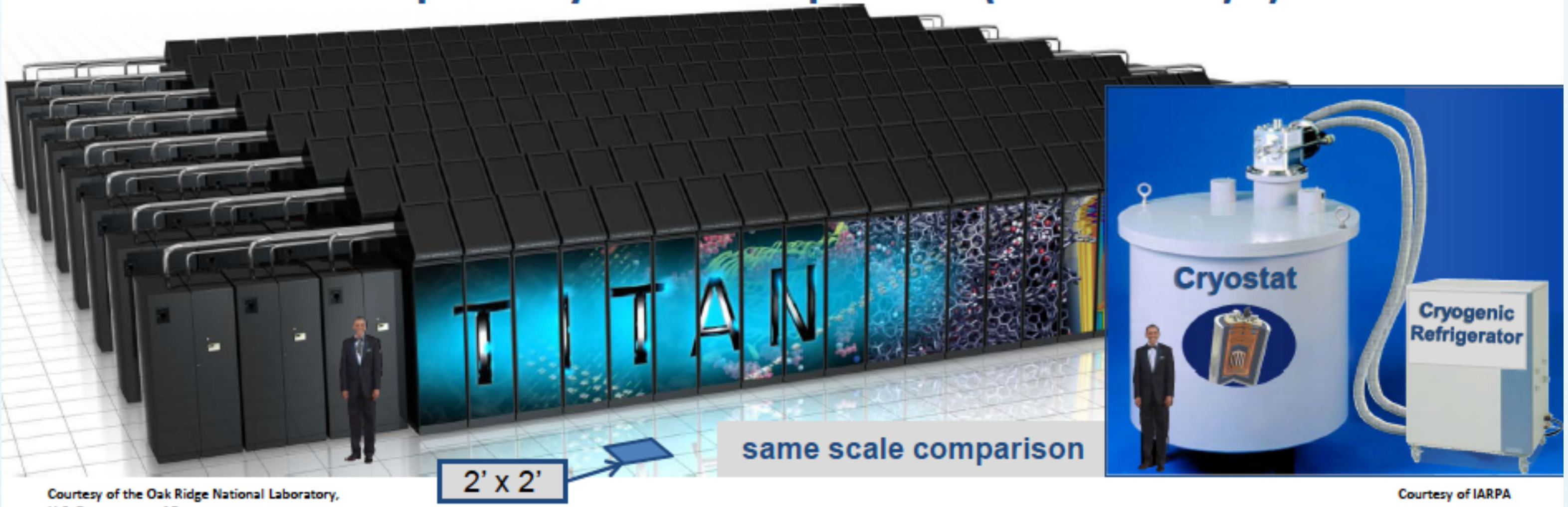
Goal; demonstrate a complete superconducting computer incl. processor and memory

3+2 years



Rationale: Towards exa-scale computer with reasonable energy requirements

Conceptual System Comparison (~20 PFLOP/s)



Courtesy of the Oak Ridge National Laboratory, U.S. Department of Energy

Courtesy of IARPA

	Titan at ORNL	Superconducting Supercomputer	
Performance	17.6 PFLOP/s (#2 in world*)	20 PFLOP/s	~1x
Memory	710 TB (0.04 B/FLOPS)	5 PB (0.25 B/FLOPS)	7x
Power	8,200 kW avg. (not included: cooling, storage memory)	80 kW total power (includes cooling)	0.01x
Space	4,350 ft^2 (404 m^2, not including cooling)	~200 ft^2 (19 m^2, includes cooling)	0.05x
Cooling	additional power, space and infrastructure required	All cooling shown	

* TOP500, 2015-11

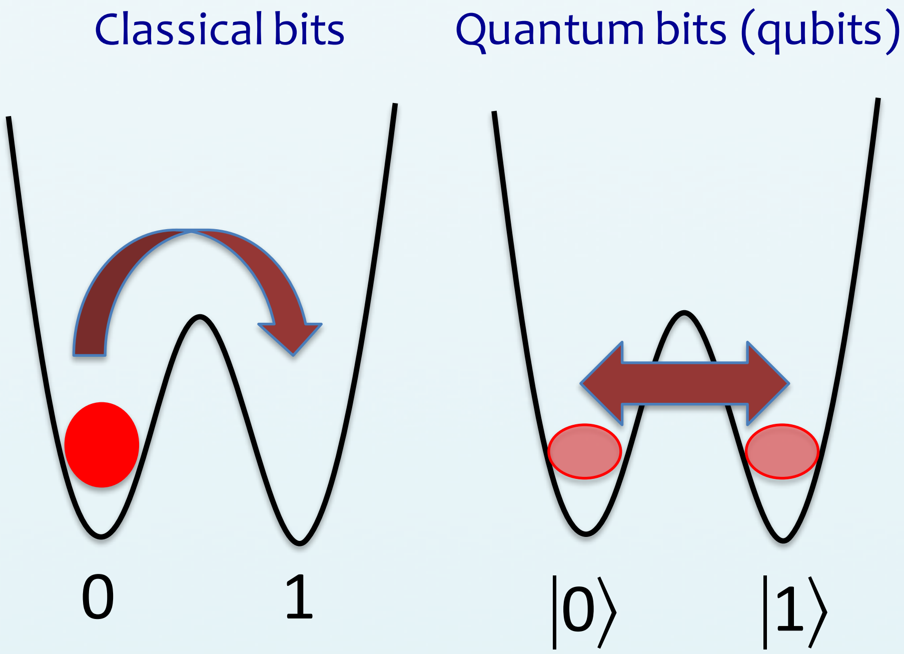
Urgently needed: New materials and concepts for energy-efficient electronics:

Energy-efficient materials (e.g. 2D-materials)
Spintronics
Brain-inspired computing
→ Rapid single flux quantum (RSFQ) devices
..

Highly desired: New computing paradigms to circumvent current limitations in computing:

Brain-inspired computing
→ Quantum Computation
..

Bits and qubits:



$\Psi = 0$ or

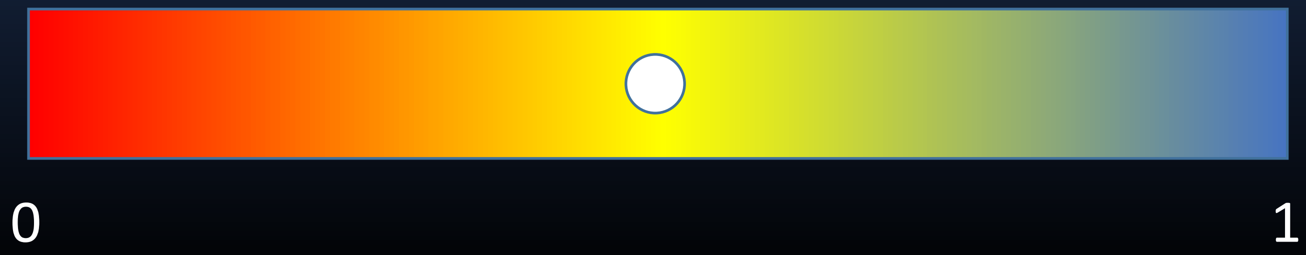
$\Psi = 1$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

with

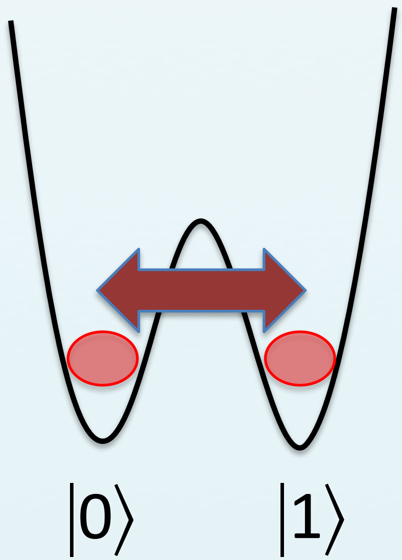
$$|\alpha|^2 + |\beta|^2 = 1$$

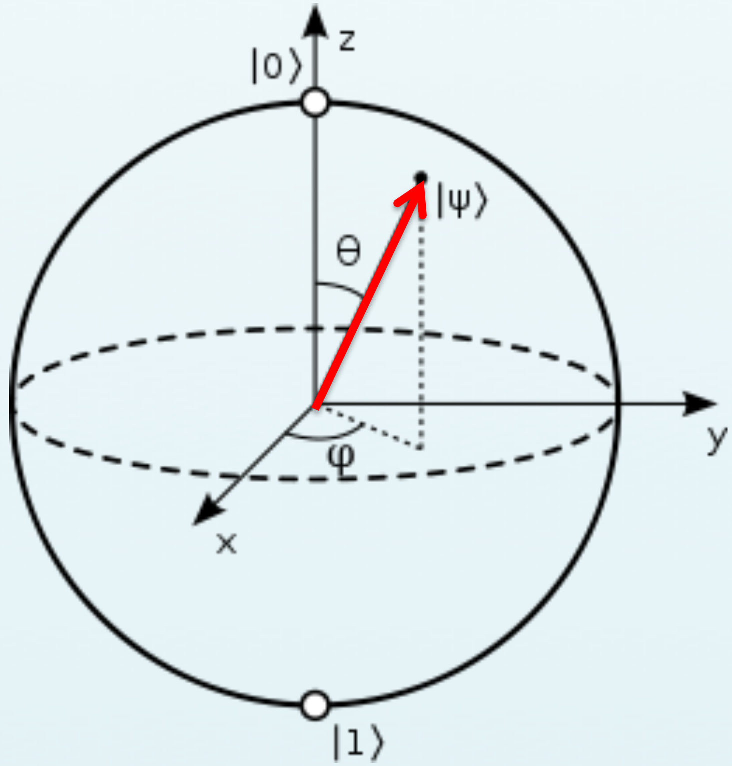
Probability



Two attributes: Probability and Phase -> 'Bloch sphere' representation

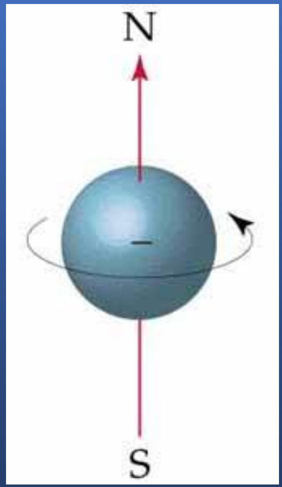
Quantum bits (qubits)

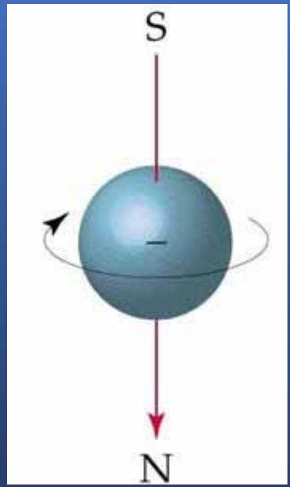




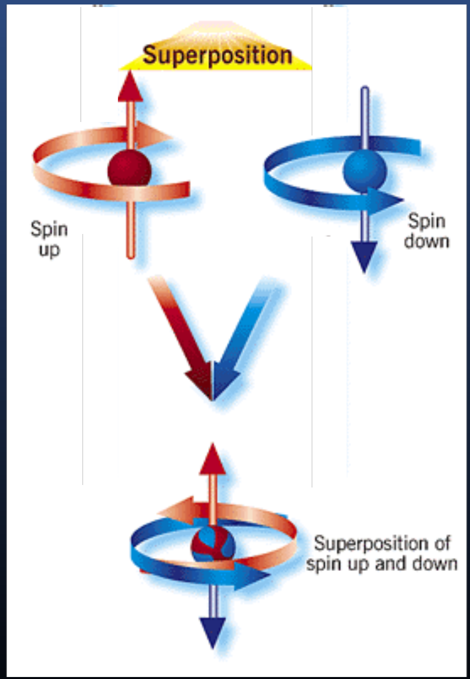
'Bloch sphere'

Electron spin

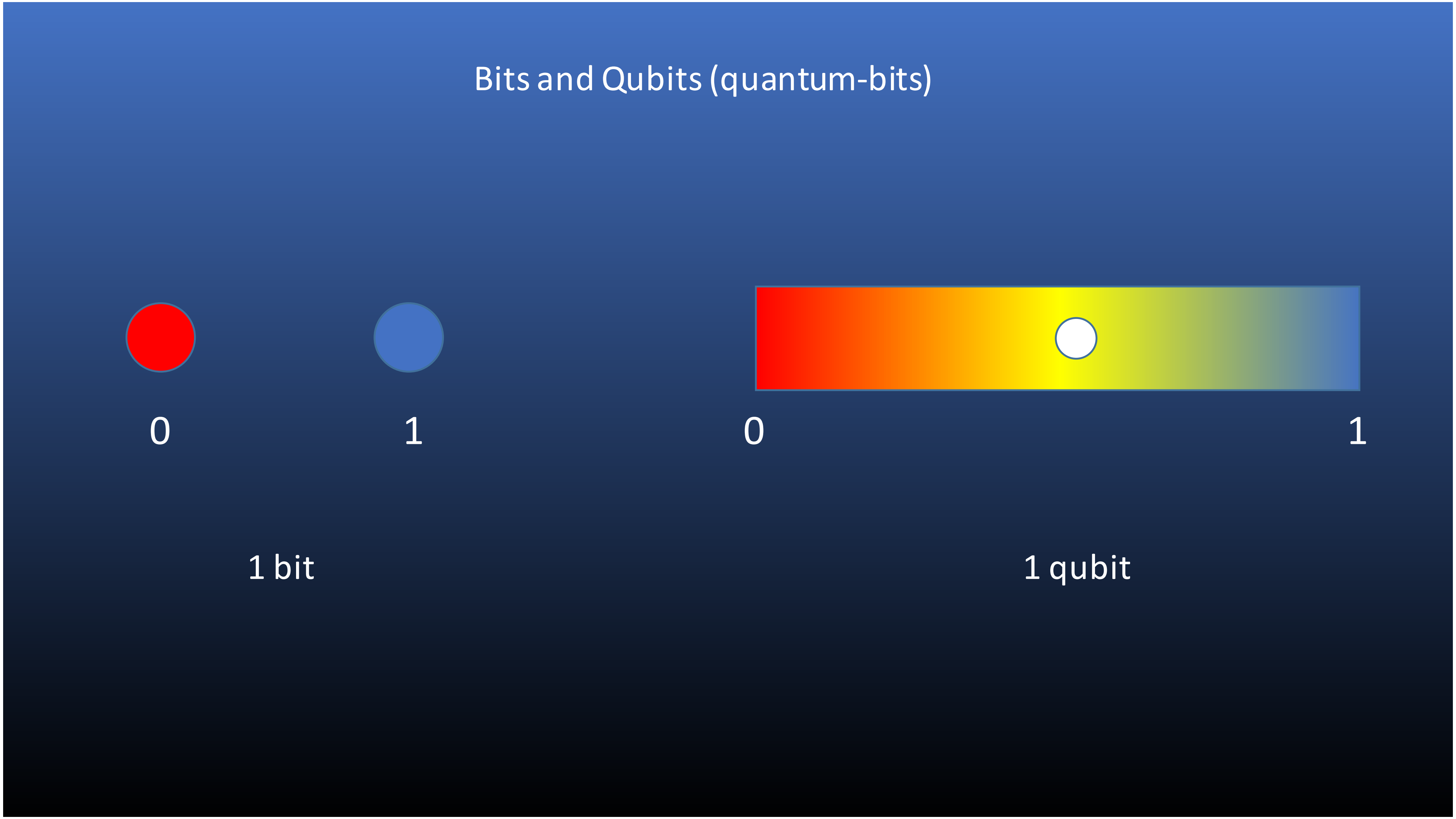


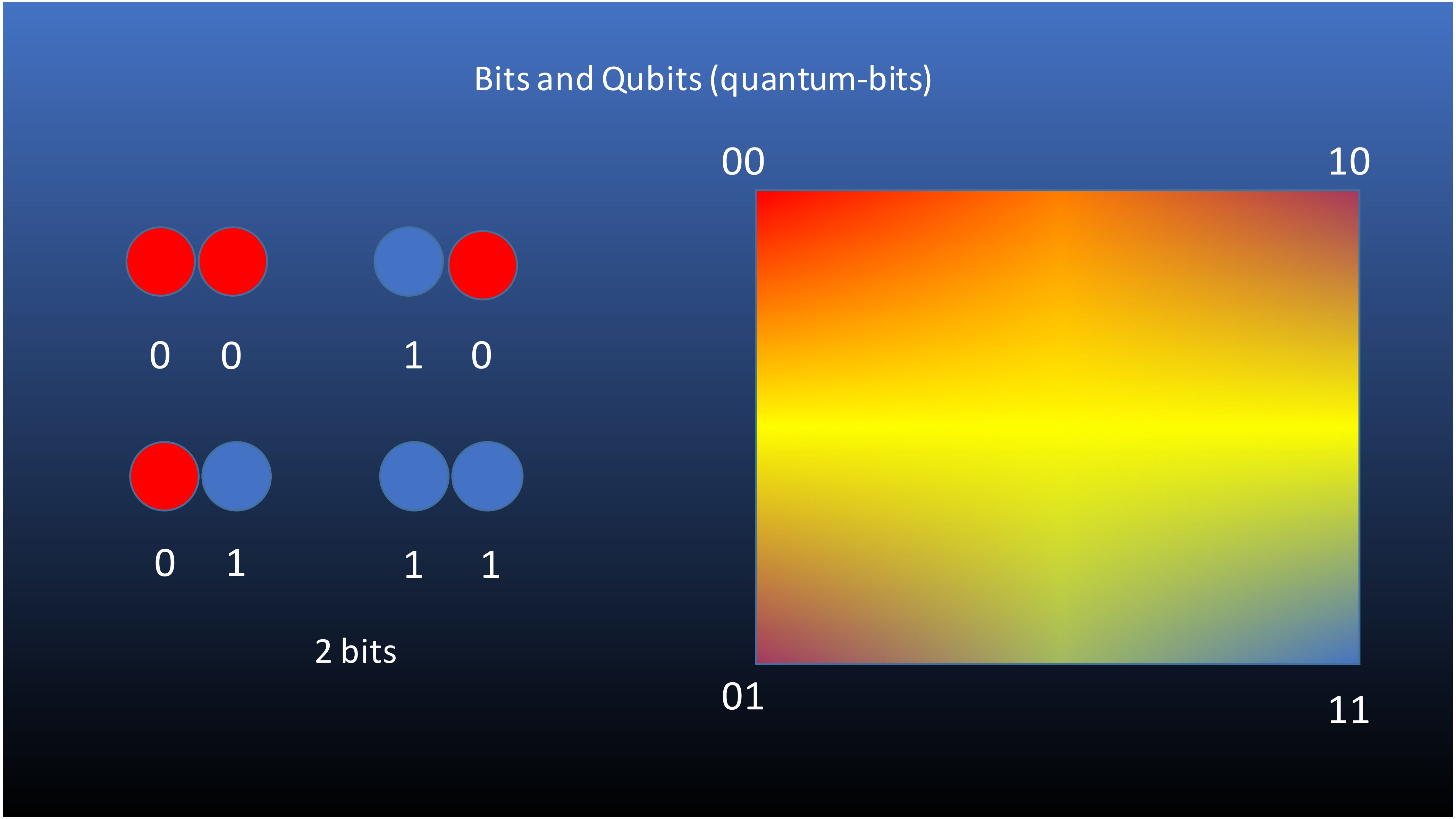


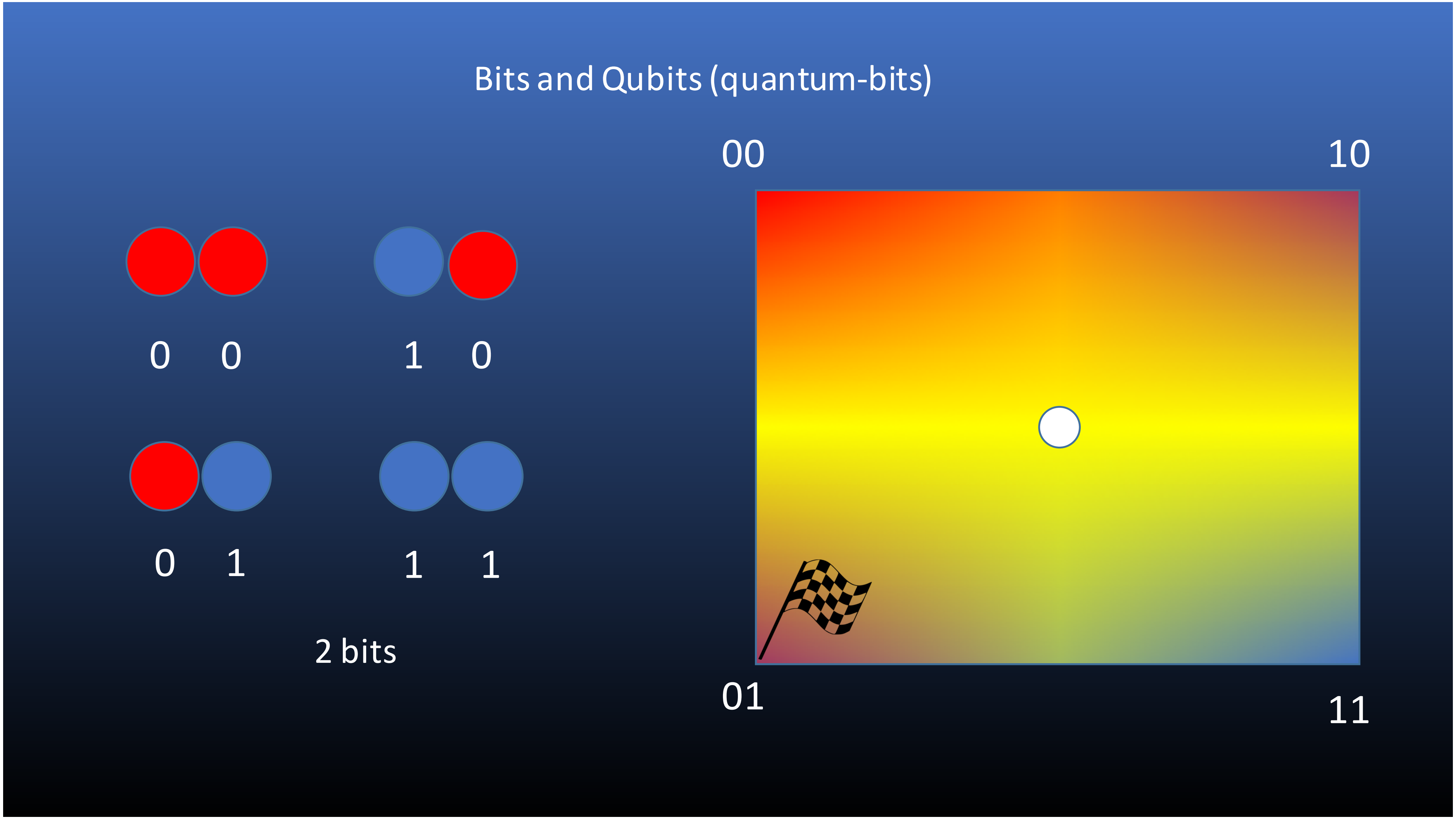
'Quantum Superposition'



Key-word: probability


Bits and Qubits (quantum-bits)
0
1
0
1
1 bit
1 qubit


Bits and Qubits (quantum-bits)
0 0
1 0
0 1
1 1
2 bits
00
10
01
11


Bits and Qubits (quantum-bits)
0 0
1 0
0 1
1 1
2 bits
00
10
01
11

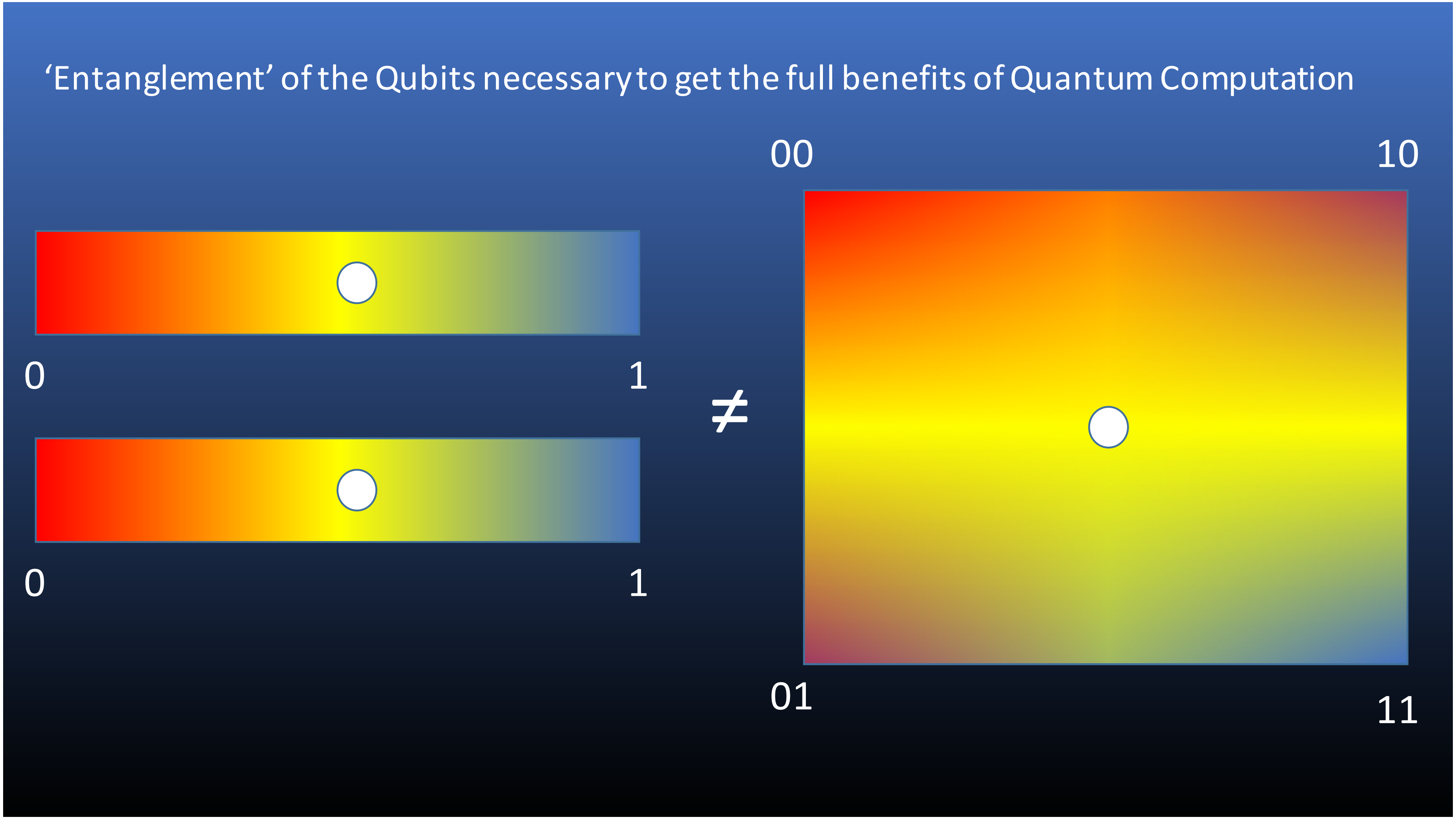
1 bit : 2 possibilities (0 and 1)

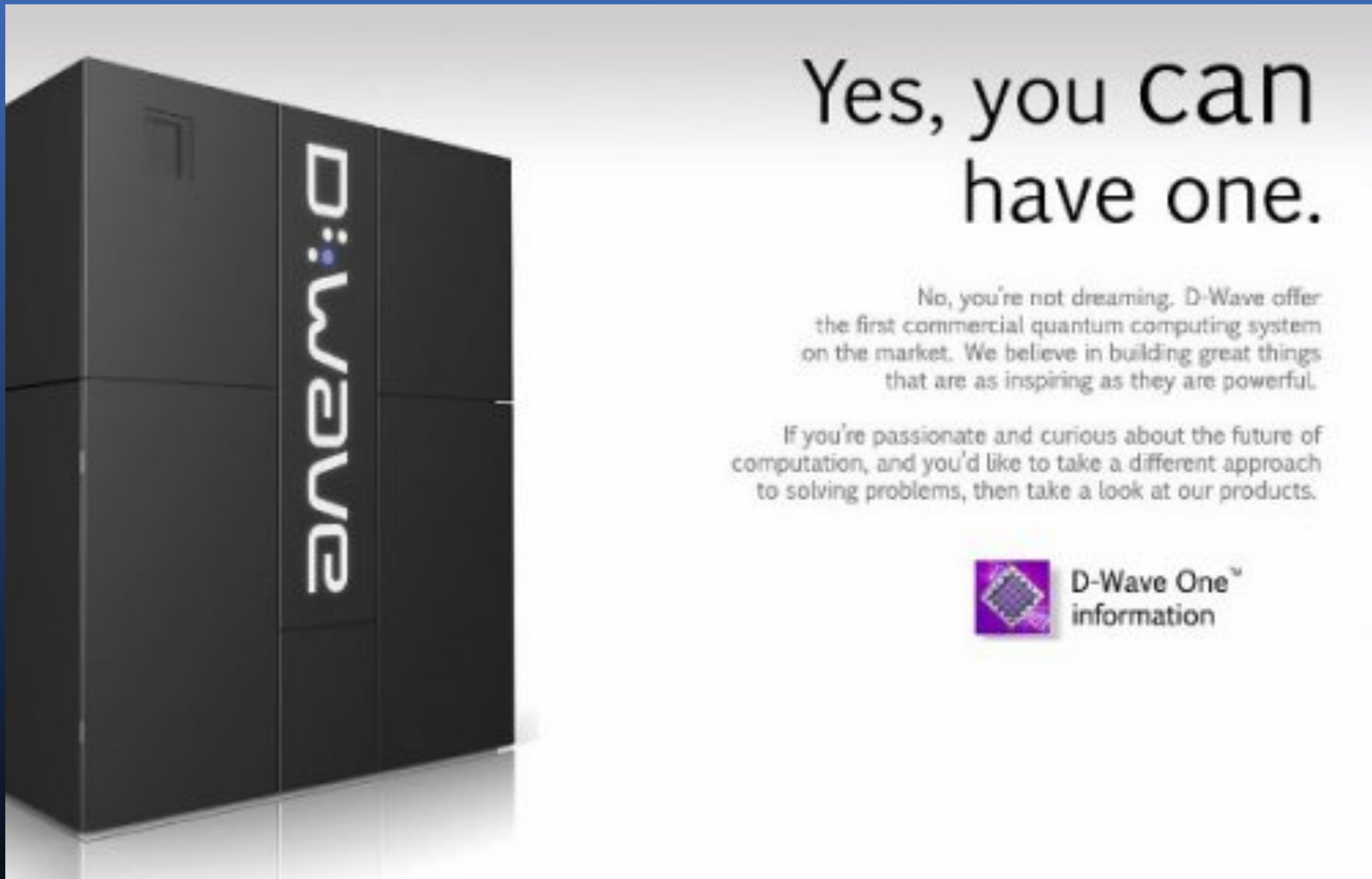
2 bits : 2x2 = 4 possibilities (00, 01, 10, 11)

3 bits : 2x2x2 = 8 possibilities (000, 001, 010, 011, 100, 101, 110, 111)

...

50 bits : 1.125.899.906.842.620 possibilities

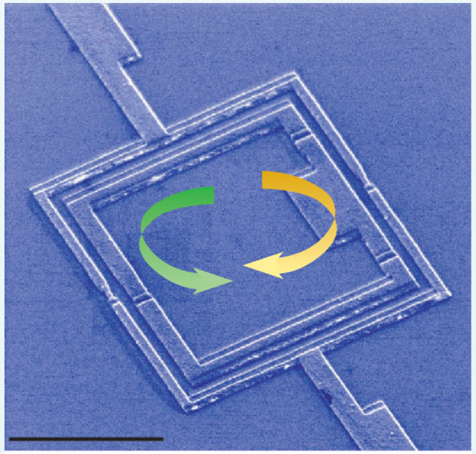

‘Entanglement’ of the Qubits necessary to get the full benefits of Quantum Computation
0
1
0
1
≠
00
10
01
11


D:wave
Yes, you can
have one.
No, you're not dreaming. D-Wave offer
the first commercial quantum computing system
on the market. We believe in building great things
that are as inspiring as they are powerful.
If you're passionate and curious about the future of
computation, and you'd like to take a different approach
to solving problems, then take a look at our products.
D-Wave One™
information

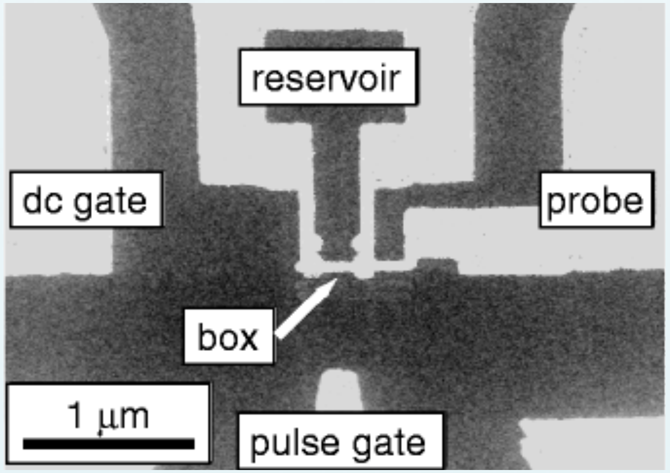
Superconducting qubits

Flux qubit

Charge qubit



J.E. Mooij *et al.*, *Science* 1999



Y. Nakamura *et al.*, *Nature* 1999

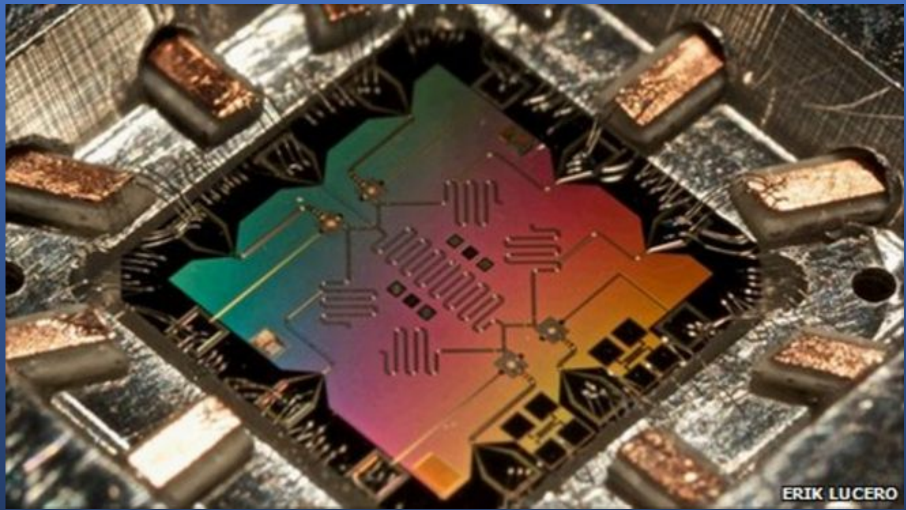
In addition:

Phase qubit
'cQED'
'Transmon'
'Quantronium'
'Fluxonium'
...

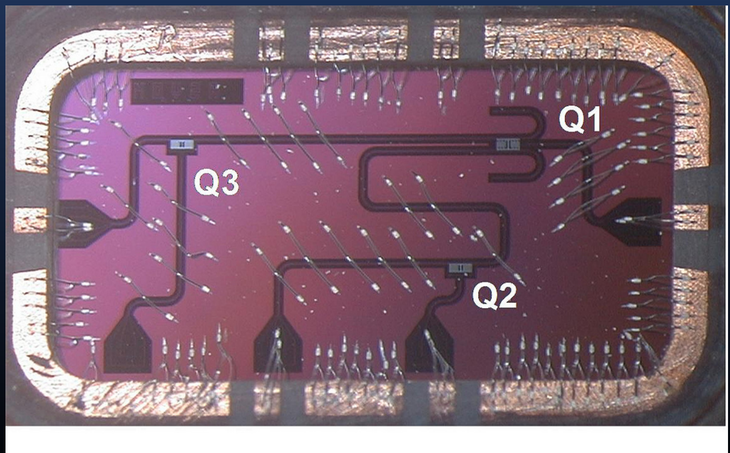
<u>Good reads:</u>

M.H. Devoret and R.J. Schoelkopf,
Science 339, 1169 (2013)

J. Clarke and F.K. Wilhelm,
Nature 453, 1031 (2008)



4 Qubit Chip (U.C. Santa Barbara)



M. Steffen et al. (IBM)
Phys. Rev. B 86, 100506 (2012)

Dilution refrigerator
(QUTECH - TU Delft)

Status of (Superconducting) Quantum Computation:

Potential to solve problems with many possible outcomes, that cannot be solved otherwise.

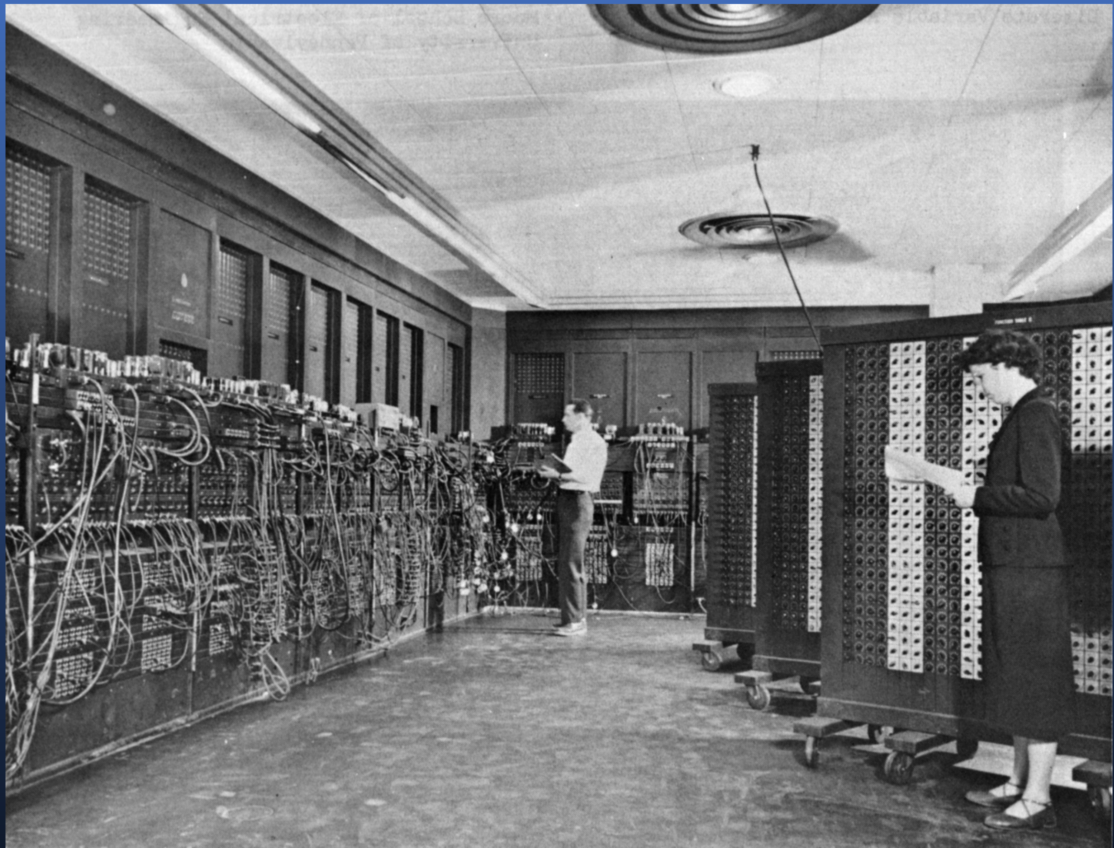
NB: Not a general purpose computer!

Qubits are being developed, and entanglement to the level of about 10 qubits is obtained.
Upscaling to the required 100, 1000 or more qubits is still an enormous step to take.

Operation at lowest possible temperatures (typically 10-15mK). Enormous challenges regarding e.g. wiring and control.

Room for new paradigms, such as topological quantum computation.

Great science and potential for spin off, but overclaims are too easily made with respect to (near-term) use of quantum computation.



‘ENIAC’ computer,
Univ. Philadelphia, 1955

IBM Watson, 2017