The Next Project
— Moscow, Vladivostok, Osaka —

10:00 Moscow
16:00 Japan
17:00 Vladivostok

Moscow city

FEFU

Atsushi Nakamura

May 19, 2022

Osaka Castle

Subjects today

- What shall we do next ?

How about

Entanglement Entropy !

Participants

Zakharov
Bornyakov
Molochkov
Goy
Ragalyov
Kudrov

Hosaka
Nakamura

Any new commers are welcome

First let us study Entanglement

↑

Study of Quantum Field Theory

by Numerical Simulations

↓

on Quantum Computers

Content

Good paper

I thank Vitaly for introducing this paper to me.

Natalie Klco (U. Washington, Seattle (main)) (Oct 26, 2020)

Google

Klco, Calculation Nature Naturally

CLICK

Calculating Nature Naturally:
Toward Quantum Simulation of Quantum Fields

Natalie Klco

A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2020

I. Quantum Computer

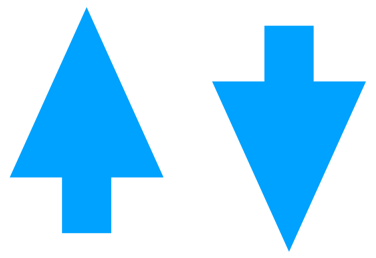
IBM

This is the Cooling device part.

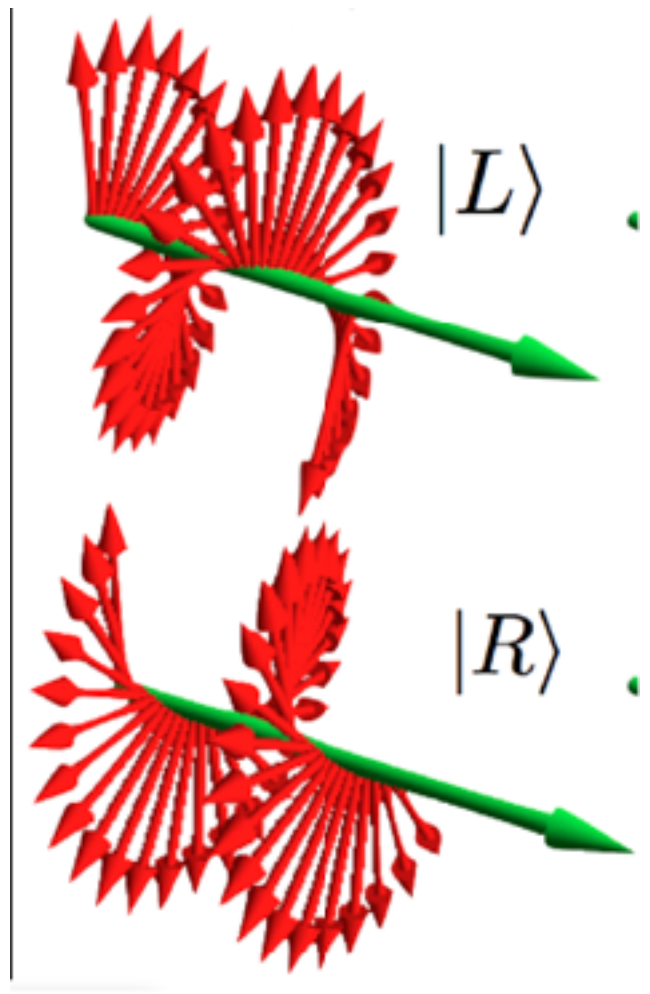
D-wave

How to express |0> and |1>

1. Spin up and down

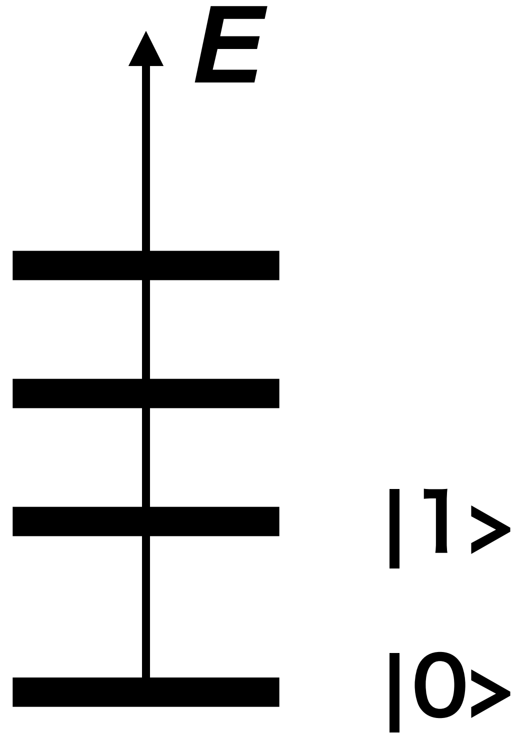


2. photon polarization
   (right and left circular polarization)



wiki-pedia

3. ground energy level and an excited level



4. etc

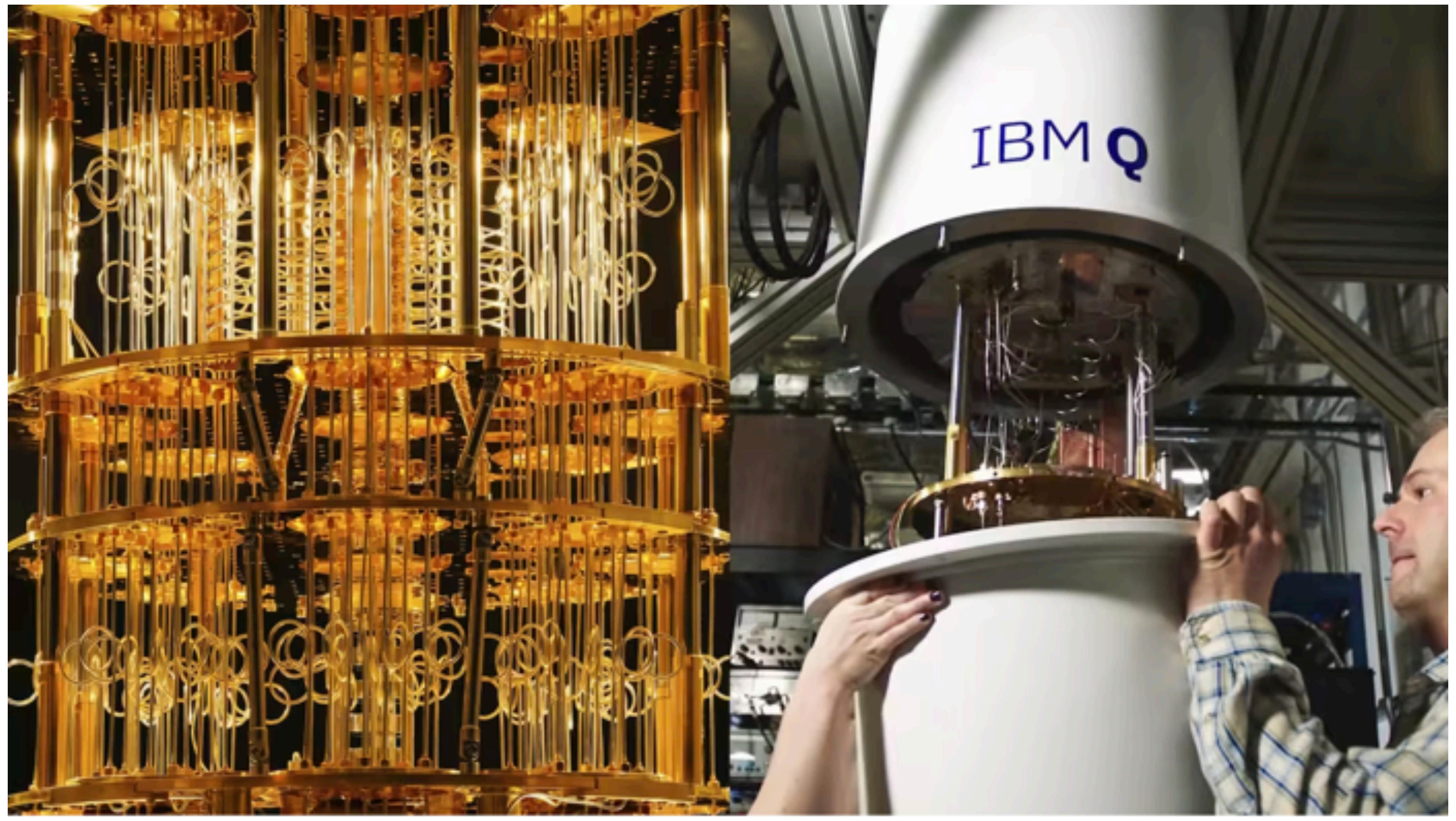
Two types of Quantum Computers

1. Gate-based quantum computer (IBM, for example)

2. Annealing type (D-wave for example)

They change to the gate method ?

Geordie Rose, the founder of D-Wave Systems

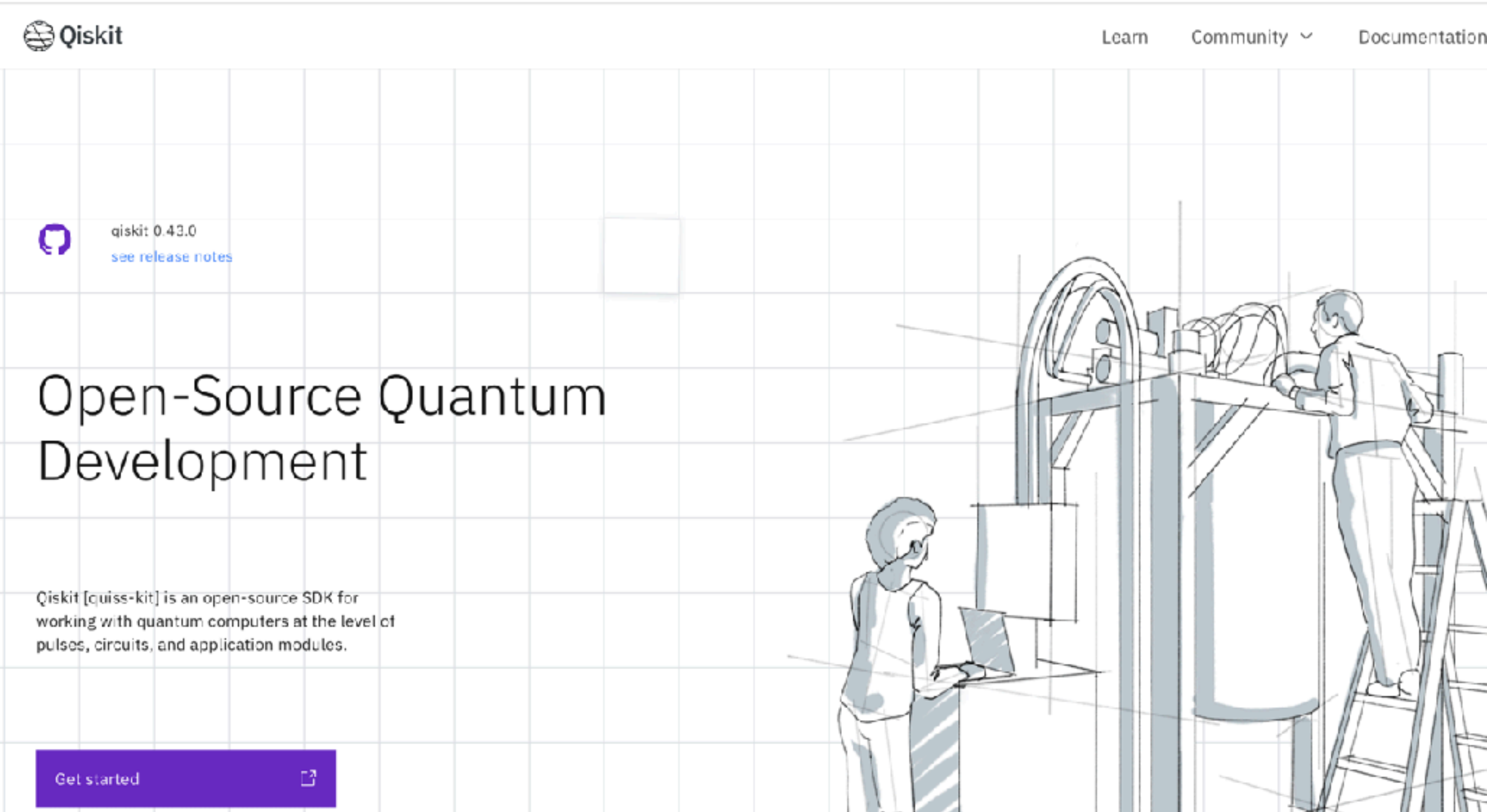


IBM Q

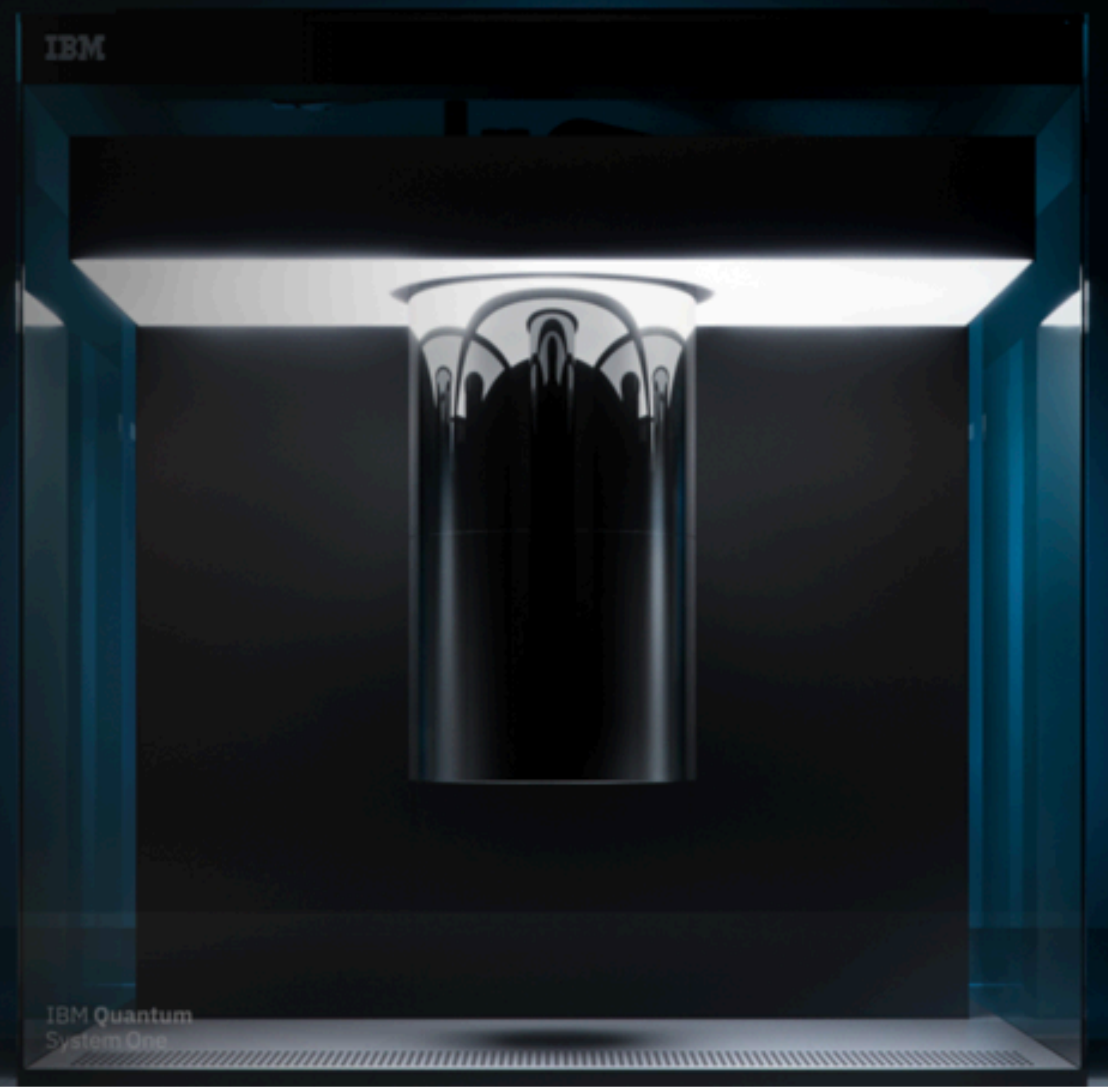
- [Documentation Home]
- [Quantum computing in a nutshell]
- [Getting started]
- [Introduction to Qiskit]
- [Tutorials]
- [API Reference]

https://qiskit.org/

IBM Document worth reading



IBM Quantum systems



IBM Quantum leads the world in quantum computing systems. We have over 20 systems worldwide, based on our iconic System One.

IBM Quantum Computing roadmap

IBM **Quantum**

2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023	2024	2025	2026+
Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime

Model Developers
- Prototype quantum software applications → Quantum software applications
  - Machine learning | Natural science | Optimization

Algorithm Developers
- Quantum algorithm and application modules ✓
  - Machine learning | Natural science | Optimization
- Quantum Serverless
  - Intelligent orchestration
  - Circuit Knitting Toolbox
  - Circuit libraries

Kernel Developers
- Circuits ✓
- Qiskit Runtime ✓
  - Dynamic circuits ✓
  - Threaded primitives
  - Error suppression and mitigation
  - Error correction

D-wave

https://docs.dwavesys.com/docs/latest/index.html

What is Leap ?

Look "Introduction to Leap" !

Introduction to Leap
…..
…..
Run demos and interactive coding examples in Resources.

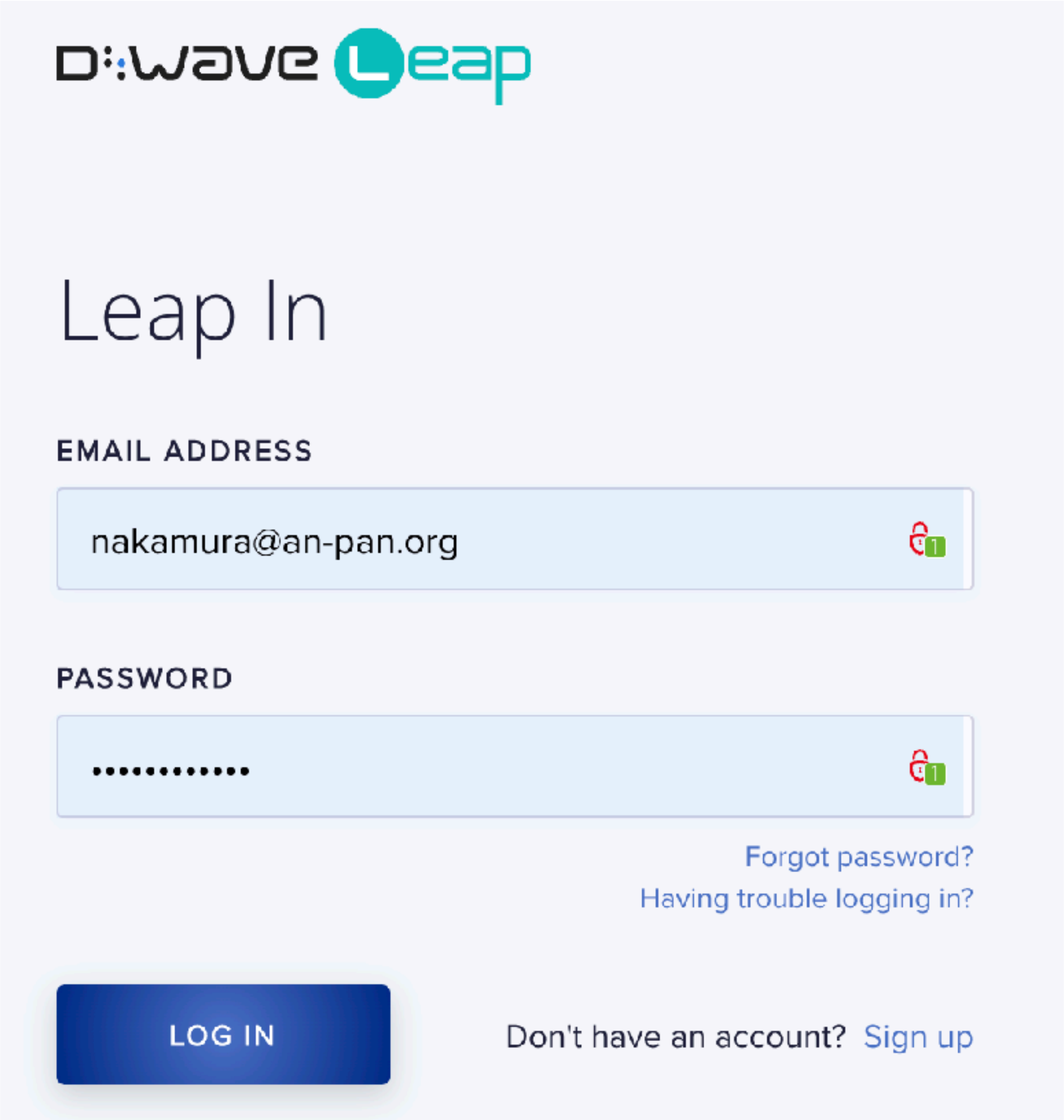
Solver Documentation

Leap Documentation

Useful Links

- Ocean software documentation and source code
- Getting Started with D-Wave Solvers guide
- Introduction to Leap
- Ocean documentation's concepts and glossary

D-wave (cont.)


D:wave Leap
Leap In
EMAIL ADDRESS
nakamura@an-pan.org
PASSWORD
Forgot password?
Having trouble logging in?
LOG IN
Don't have an account? Sign up

RIKEN Center for Quantum

The first made-in-Japan Quantum computer ?

announced on March 24, 2023

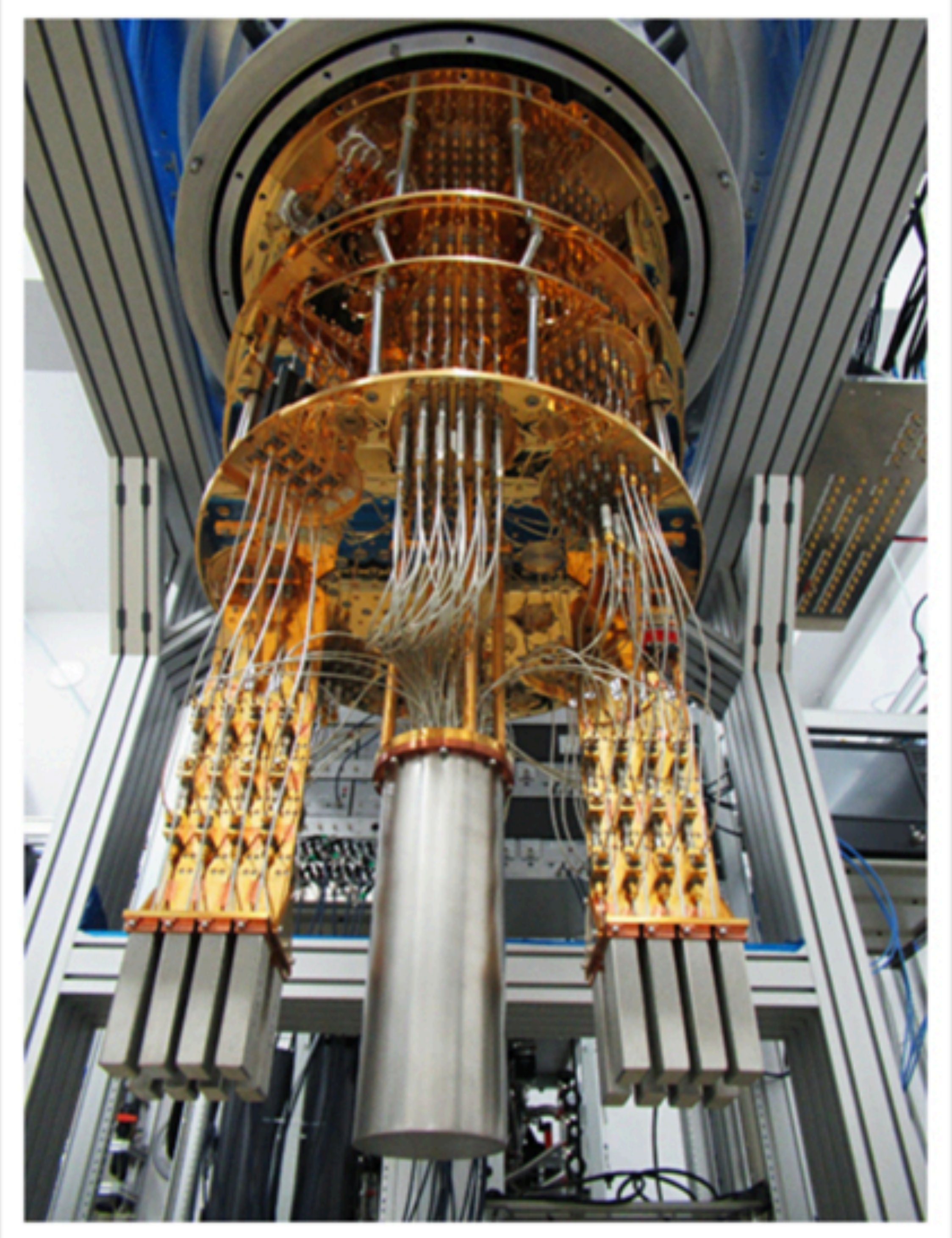


図5 64量子ビット超伝導量子コンピュータ用の希釈冷凍機内の配線

RIKEN Center for Quantum Computing

Semiconductor Quantum Information Device Research Team

Team Leader: Seigo Tarucha (D.Eng.)

Japanese Page

Research Summary | Main Research Fields | Related Research Fields | Keywords | Selected Publications | Related Links | Lab Members | Contact Information

Research Summary

We perform research and development to apply semiconductor electron (or hole) spins to quantum computing. Study on semiconductor quantum computing has been motivated by advantages of compatibility with existing semiconductor device integration technology and capability of high-temperature (> 1 Kelvin) operation. We demonstrate that coherent manipulation of semiconductor spin qubits in semiconductor nanostructures and superconducting nano-scale junctions is useful as elemental technology of information processing and develop relevant

Top

They use Spin-up.down for “|0> and |1>” ?.

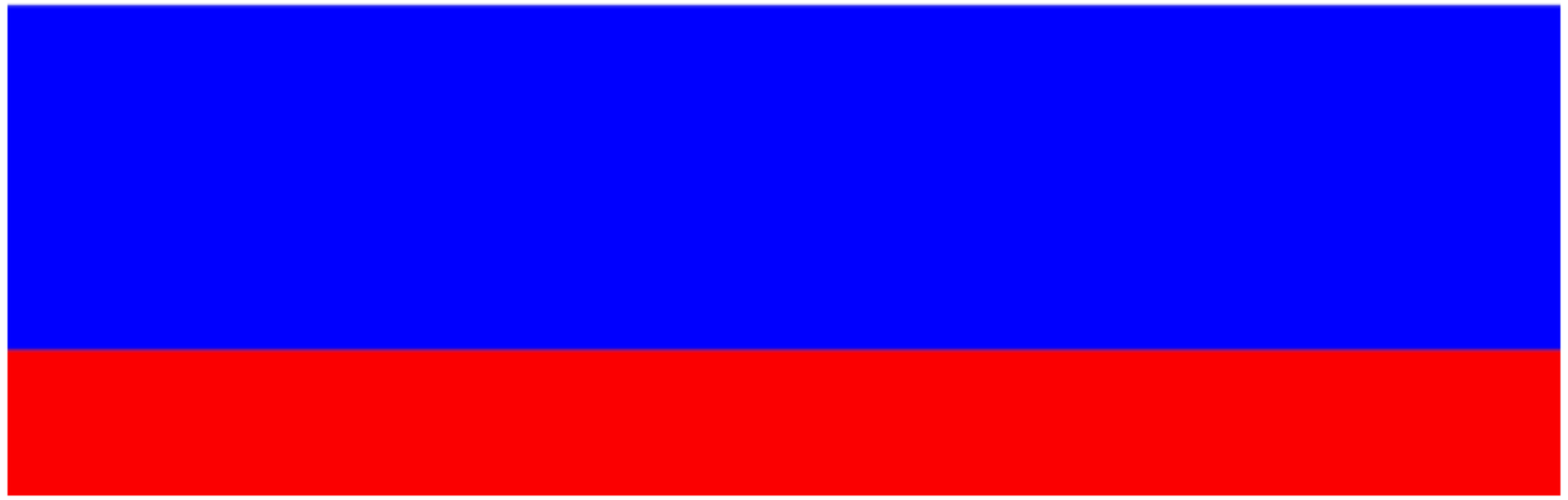
China

Baidu has released a superconducting quantum computer “Qian Shi”(乾始)

チエン?

Baidu (China) announced their first quantum computer

INSIDE
QUANTUM TECHNOLOGY **NEWS**



By Dan O'Shea posted 30 Dec 2021

Russian scientists have reached the latest milestone on the country's quantum computing roadmap, having developed a prototype 4-qubit ion quantum computer, the Russian news agency Interfax reported.

The report attributed the information to Rosatom, the Russian state atomic energy corporation, which has been coordinating an effort among researchers that began in 2019 with the aim to develop a quantum computer by 2024. The report said that scientists from the Russian Quantum Center and the P.N. Lebedev Physics Institute of the Russian Academy of Sciences unveiled the prototype.

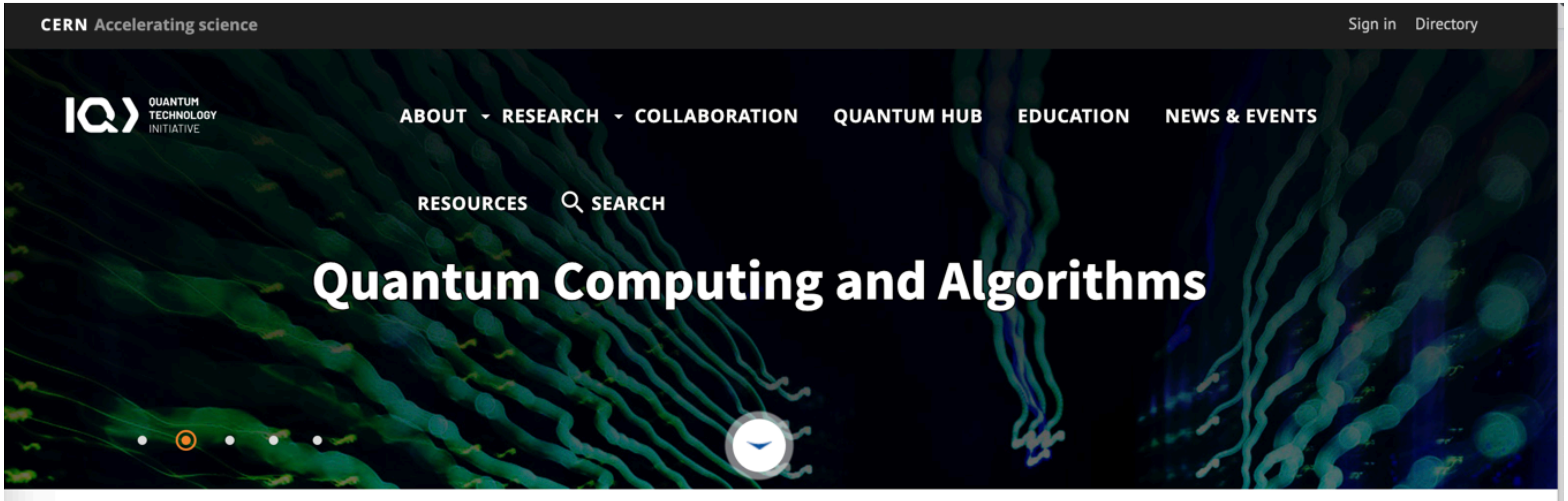
When and where ?

Russian scientists have reached the latest milestone on the country's quantum computing road map, having developed a prototype 4-qubit ion quantum computer.

Quantum Computing in CERN

Is there a real machine?

Can we use it?



Quantum technology is an emerging field of physics and engineering that has the potential to revolutionise science and society in the next five to ten years. Knowledge in this rapidly evolving field has advanced considerably, yet still, there are resources required that are not mainstream today.

CERN can be at the forefront of this revolution.

II. Entanglement

V. Chandrasekaran, R. Longo, G. Penington and E. Witten, JHEP 02, 082 (2023)

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limit in holography [24, 25], observations outside a black hole horizon were described by
an algebra of Type II∞  [26].
The entanglement entropy of a local region in quantum field theory is always ultraviolet
divergent, as discovered long ago [27, 28]. An abstract explanation of why this happens
is that the algebra of observables in a local region in quantum field theory is of Type III
[29], and there is no notion of entropy for a state of an algebra of Type III. By contrast,
for states of an algebra of Type II, it is possible to define an entropy, though in physica
l
terms this is a sort of renormalized entropy with a state-independent divergent constant
subtracted. Thus, at least for the black hole and de Sitter space, the fact that gravity
converts the algebra of observables from being of Type III to being of Type II gives an
abstract explanation of why the entropy of a region of spacetime is better-defined in the
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E. Witten, "Entanglement Properties of Quantum Field Theory," Rev. Mod. Phys. 90 (2018), 045003, arXiv:1803.04993.

Witten discussed Entanglement and Quantum Field Theories already 2018 !

Nakagawa, Nakamura, Motoki and Zakharov

Entanglement entropy of SU(3) Yang-Mills theory

PoS LAT2009:188,2009

arXiv:0911.2596 [hep-lat]

Itou, Nagata, Nakagawa, Nakamura and Zakharov

Prog. Theor. Exp. Phys. (2016) 061B01

PTEP Prog. Theor. Exp. Phys. **2016**, 061B01 (8 pages)
DOI: 10.1093/ptep/ptw050

Letter

Entanglement in four-dimensional SU(3) gauge theory

Etsuko Itou[1,*], Keitaro Nagata[1,*], Yoshiyuki Nakagawa[2], Atsushi Nakamura[3,4,5,*], and V. I. Zakharov[5,6,7,*]

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[2] *RIISE, Hiroshima University, Higashi-Hiroshima, Hiroshima, 739-8521, Japan*
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[4] *Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka, 567-0047, Japan*
[5] *School of Biomedicine, Far Eastern Federal University, Sukhanova 8, Vladivostok 690950, Russia*
[6] *ITEP, B. Cheremushkinskaya 25, Moscow, 117218 Russia*
[7] *Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, 141700 Russia*
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Received March 28, 2016; Accepted April 4, 2016; Published June 2, 2016

We investigate the quantum entanglement entropy for the four-dimensional Euclidean SU(3) gauge theory. We present the first non-perturbative calculation of the entropic c-function ($C(l)$) of SU(3) gauge theory in lattice Monte Carlo simulation using the replica method. For $0 \leqslant l \leqslant 0.7$ fm, where l is the length of the subspace, the entropic c-function is almost constant, indicating conformally invariant dynamics. The value of the constant agrees with that perturbatively obtained from free gluons, with 20% discrepancy. When l is close to the $\Lambda_{\mathrm{QCD}}^{-1}$ $(\sim T_c^{-1})$ scale, the entropic c-function decreases smoothly, and it is consistent with zero within error bars at $l \gtrsim 0.9$ fm.

Subject Index B01, B30

Witten discussed Entanglement 2018?

Zakharov group already 2009.

Entanglement Entropy in Field Theories

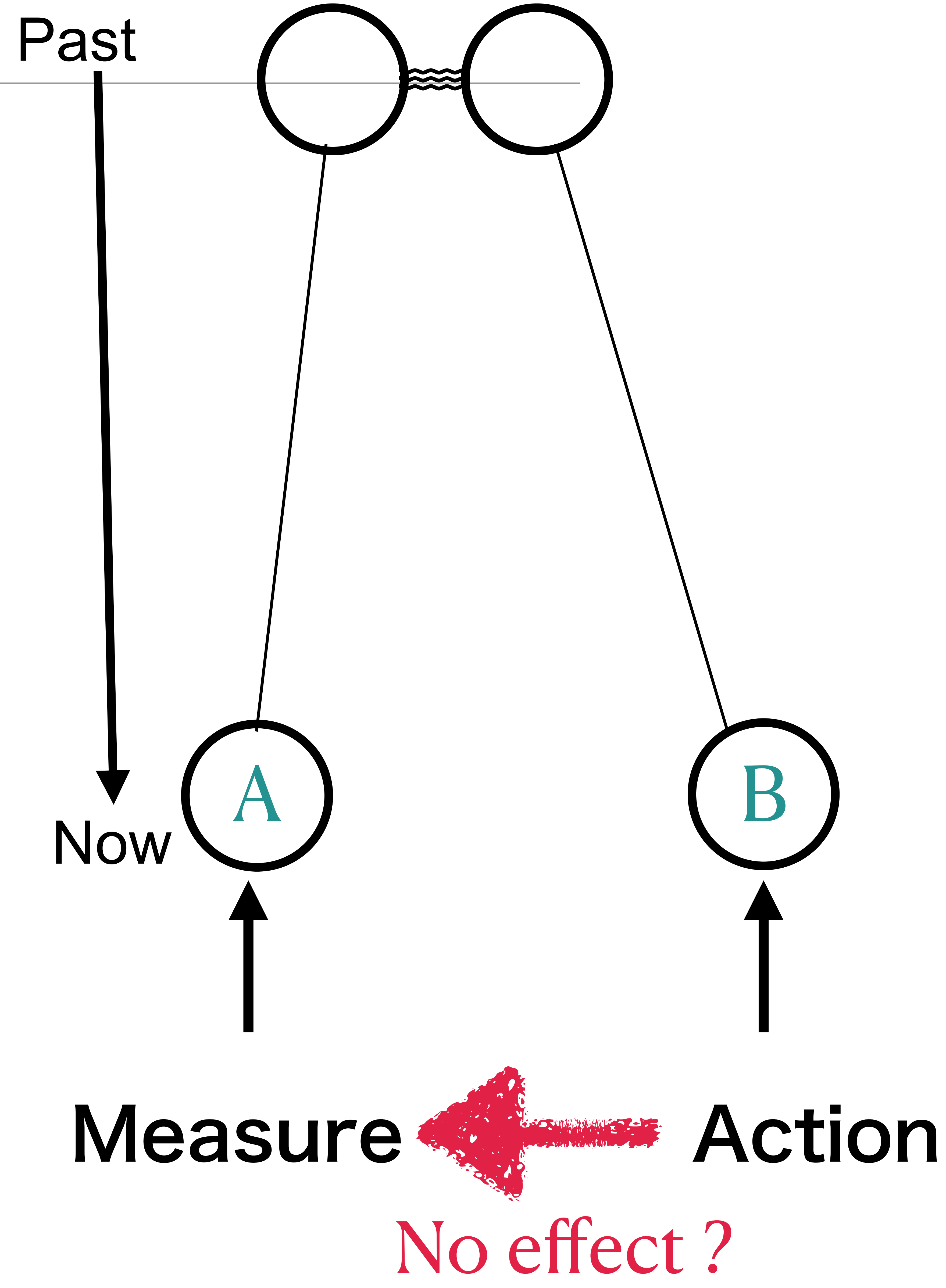
- Quantum entanglement
  - States which we cannot write as

$$|\psi\rangle = |\phi_A\rangle|\phi_B\rangle$$

even A and B are far from each other.

$$|\psi\rangle = \frac{|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle}{\sqrt{2}}$$

- Famous Example



- Quantum entanglement
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$$|\psi\rangle = \frac{|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle}{\sqrt{2}}$$

- Famous Example

References

- Ryu & Takayanagi
  - “Aspects of Holographic Entanglement Entropy”
  - JHEP0608:045,2006 (arXiv:hep-th/0605073)
  - Phys. Rev. Lett. 96 (2006) 181602
- Buividovich & Polikarpov
  - “Numerical study of entanglement entropy in SU(2) lattice gauge theory”
  - Nucl. Phys. B802 p458 (2008) arXiv:0802.4247
  - SU(2) numerical simulation

References

- Calabrese & Cardy
  - "Entanglement Entropy and Quantum Field Theory"
  - J. Stat. Mech. (2004) P06002 (arXiv:hep-th/0405152)
  - Entanglement Entropy can be expressed as a path-integral of regions with cuts.
- Ryu & Takayanagi
  - "Aspects of Holographic Entanglement Entropy"
  - JHEP0608:045,2006 (arXiv:hep-th/0605073)
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  - SU(2) numerical simulation

III. What shall we do ?

1. **<u>Numerical study of the Entanglement Entropy</u>**
   We have experience.
   Very interesting and valuable for studying Quantum Field Theories

2. **<u>Study of Hadrons at finite temperature and density</u>**
   Quantum computer is a good environment for this study
   This is valuable for NICA and J-PARC experiments.

3. **<u>Problem</u>**: At this moment, it is unclear whether we can get GPU time on any quantum computer.

Subjects not discussed today

- Quantum supremacy (量子超越性) ⟶ **A1**
- Quantum Fourier Transform ⟶ **A2**
- Quantum Teleportation ⟶ **A3**
- Error-tolerable quantum computing (誤り耐性量子計算) ⟶ **A4**
- Quantum Random Numbers ⟶ **A5**
- Inside of the hardware