The Next Project
— Moscow, Vladivostok, Osaka —

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

Moscow city

Atsushi Nakamura

May 19,2023

Osaka Castle

Subjects today

- What shall we do next ?

Participants

Zakharov
Bornyakov
Molochkov
Goy
Ragalyov
Kudrov

Hosaka
Nakamura

Any new
commers
are welcome

How about
Entanglement Entropy !

First let us study Entanglement

↑

Study of Quantum Field Theory

by Numerical Simulations

↓

on Quantum Computers

Content
I. Quantum Computer
II. Entanglement
III. What shall we do ?

Good paper

I thank Vitaly for introducing this paper to me.

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

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

Google

Klco, Calculation Nature Naturally

CLICK

I. Quantum Computer

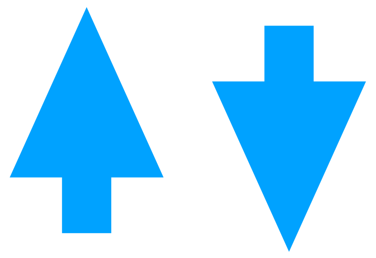
IBM

This is the Cooling device part.

D-wave

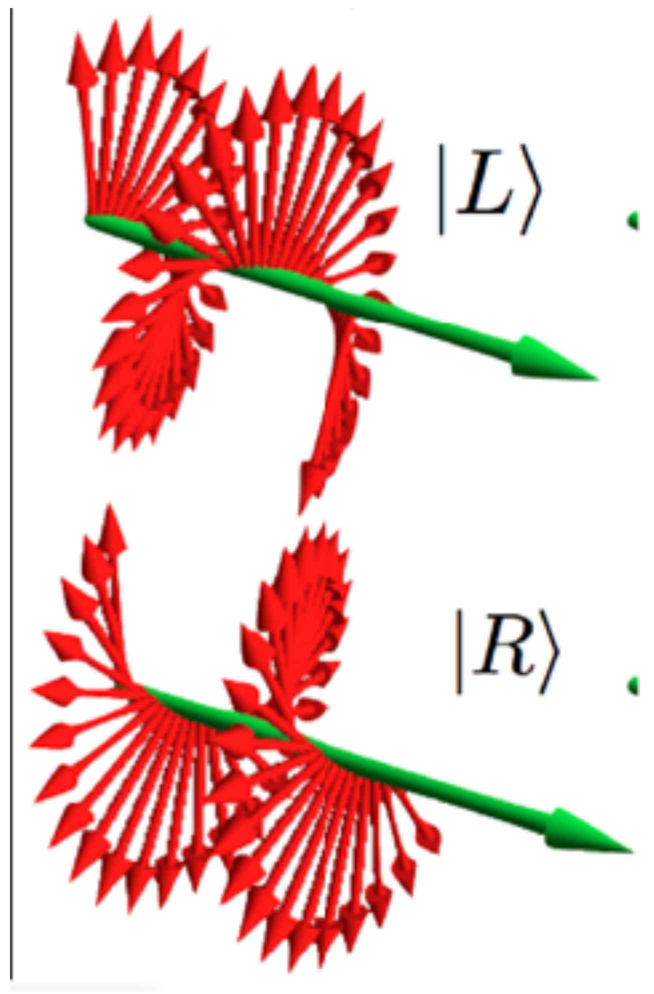
How to express |0> and |1>

1. Spin up and down



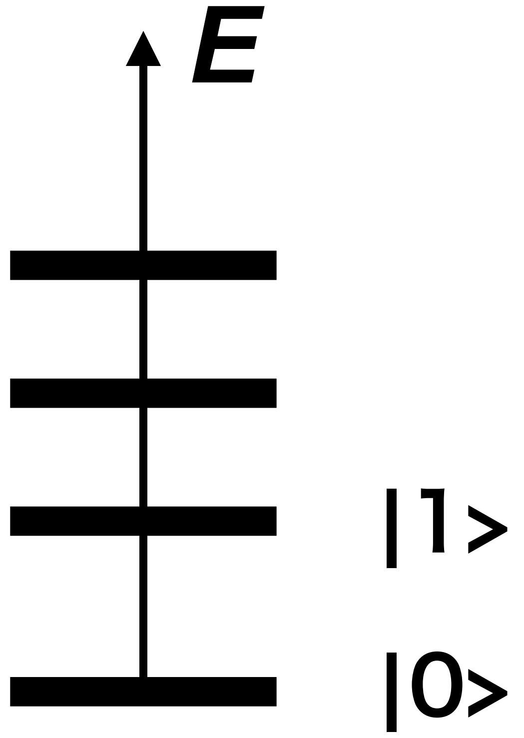
2. photon polarization

   (right and left circular polarization)



wiki-pedia

3. ground energy level and an excited level



4. etc

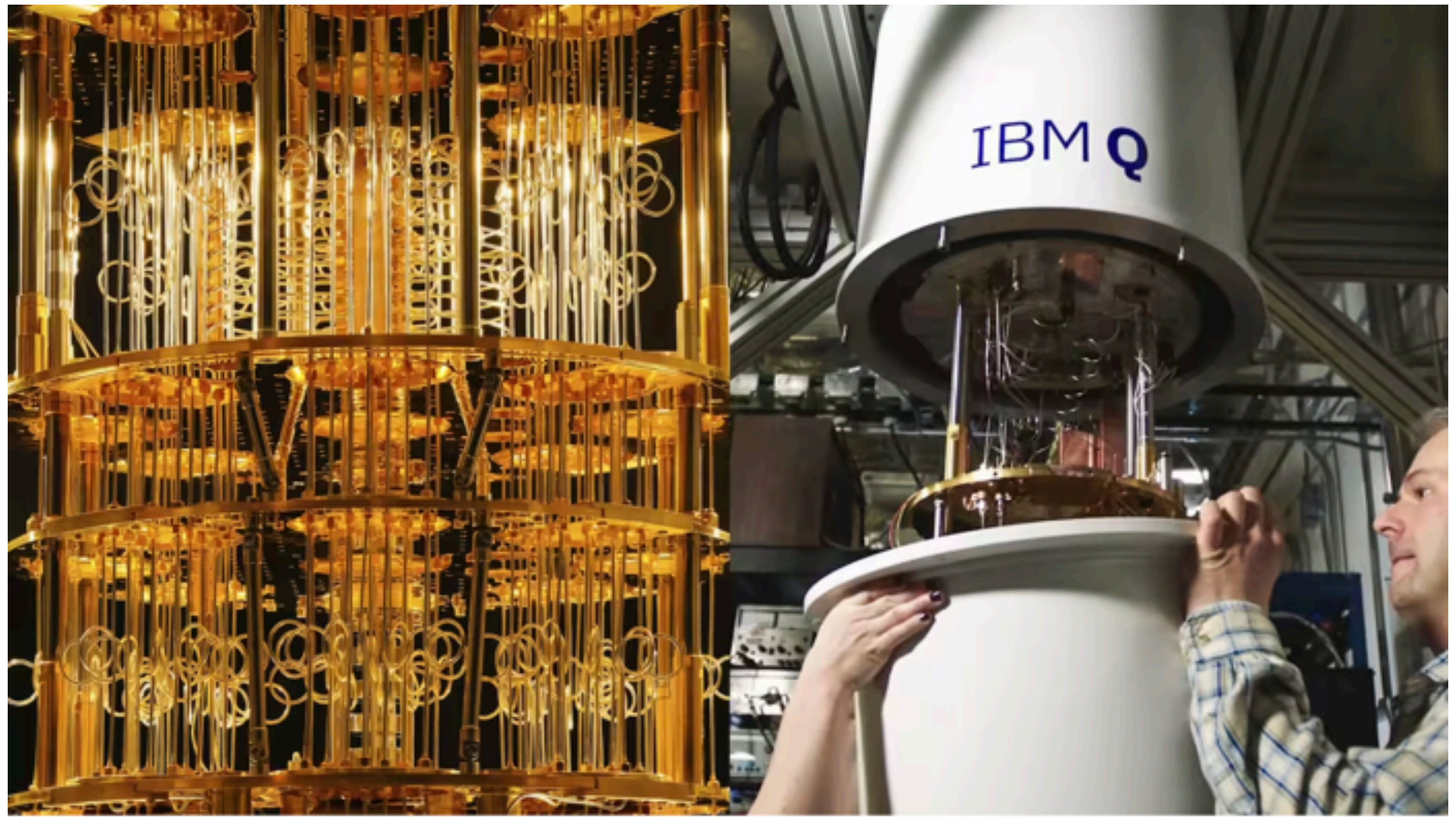
Two types of Quantum Computers

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

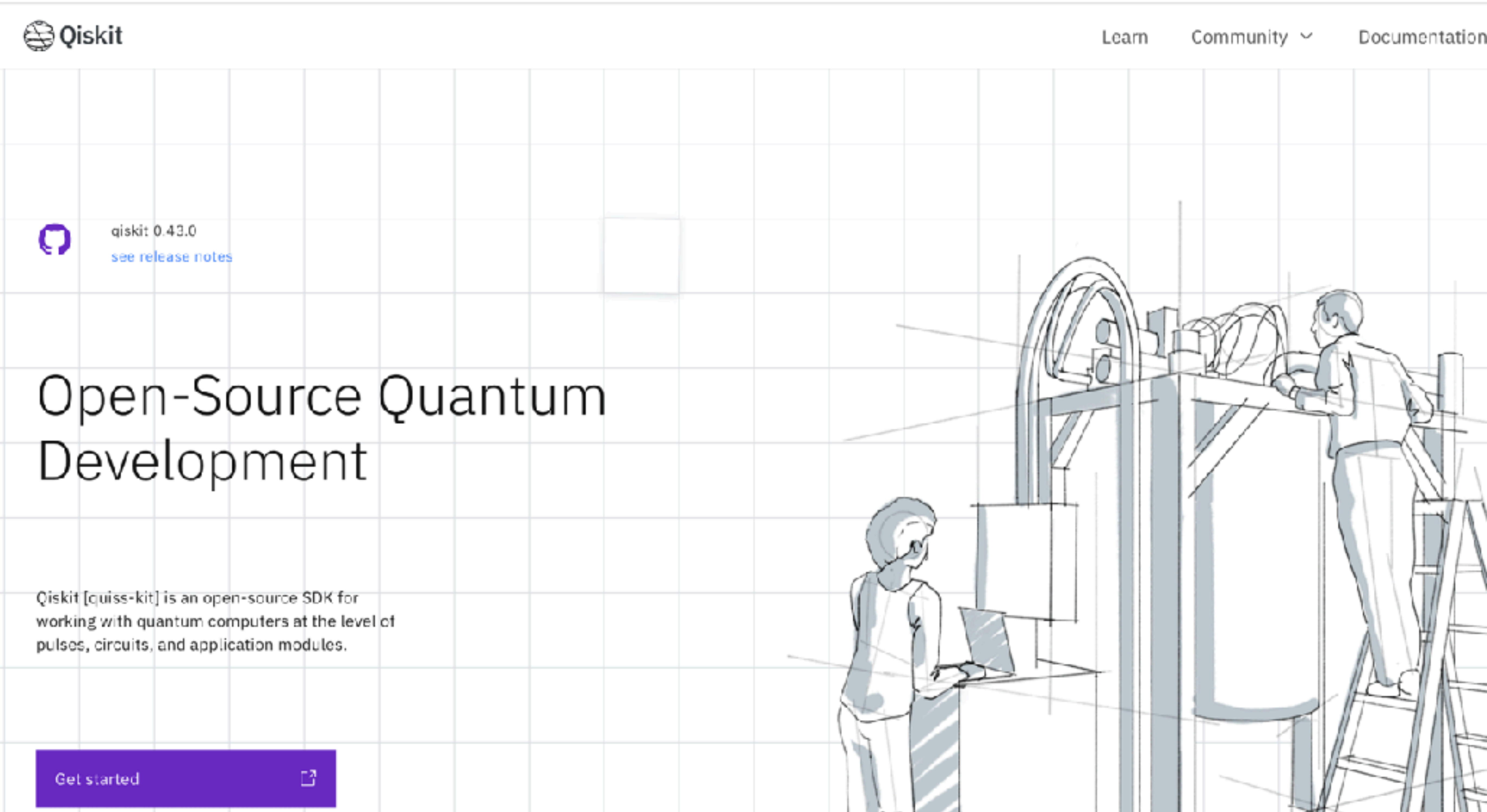


IBM Q

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

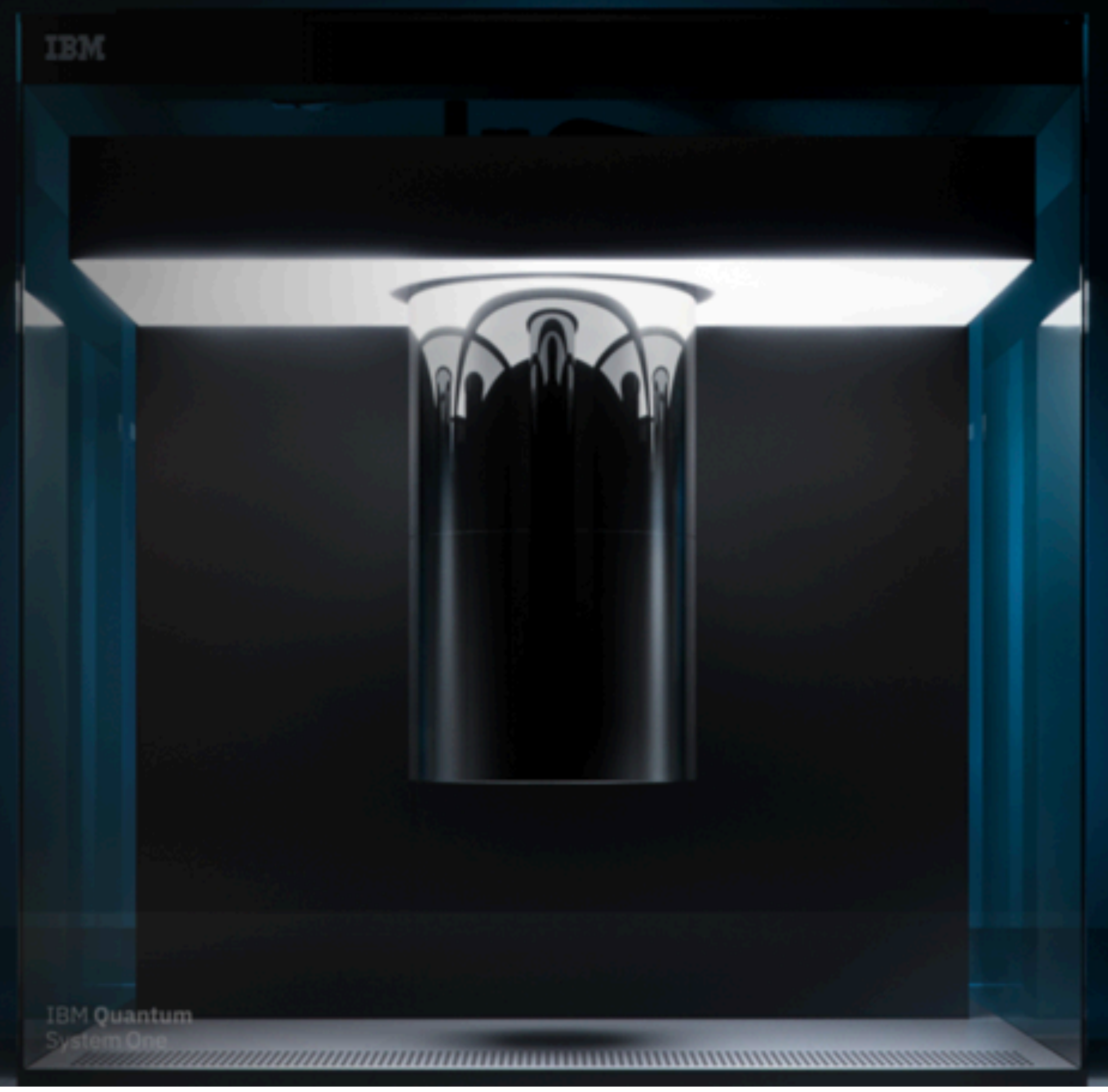
https://qiskit.org/

IBM Document worth reading



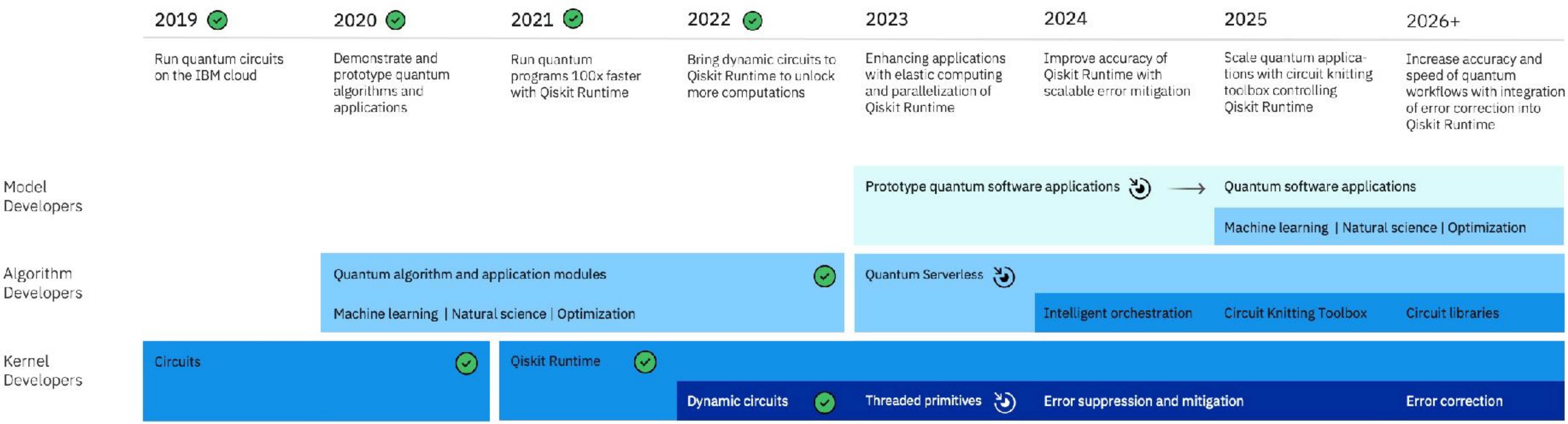
IBM Quantum systems

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



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.

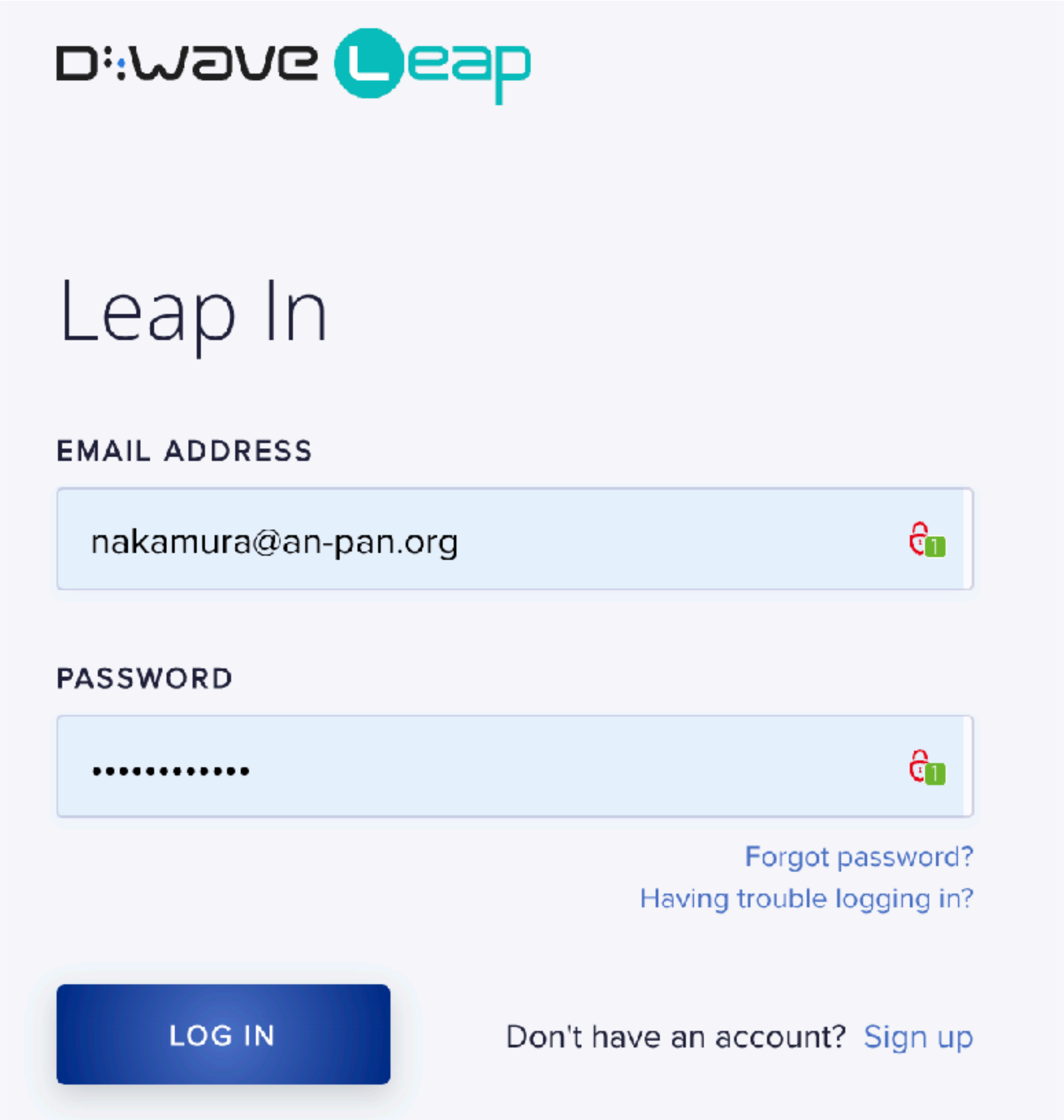
Solver Documentation

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

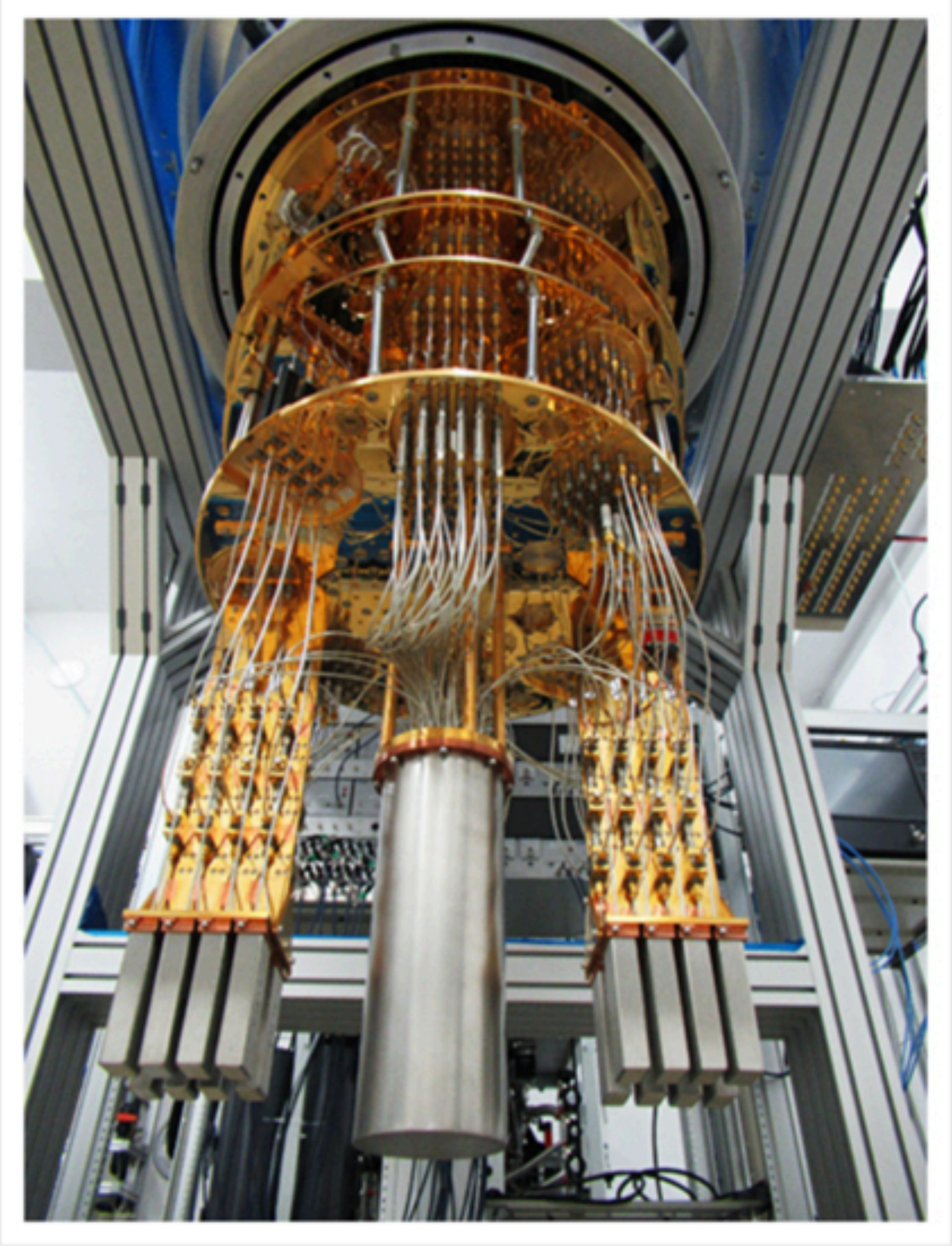


図5 64量子ビット超伝導量子コンピュータ用の希釈冷凍機内の配線

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

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

China

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

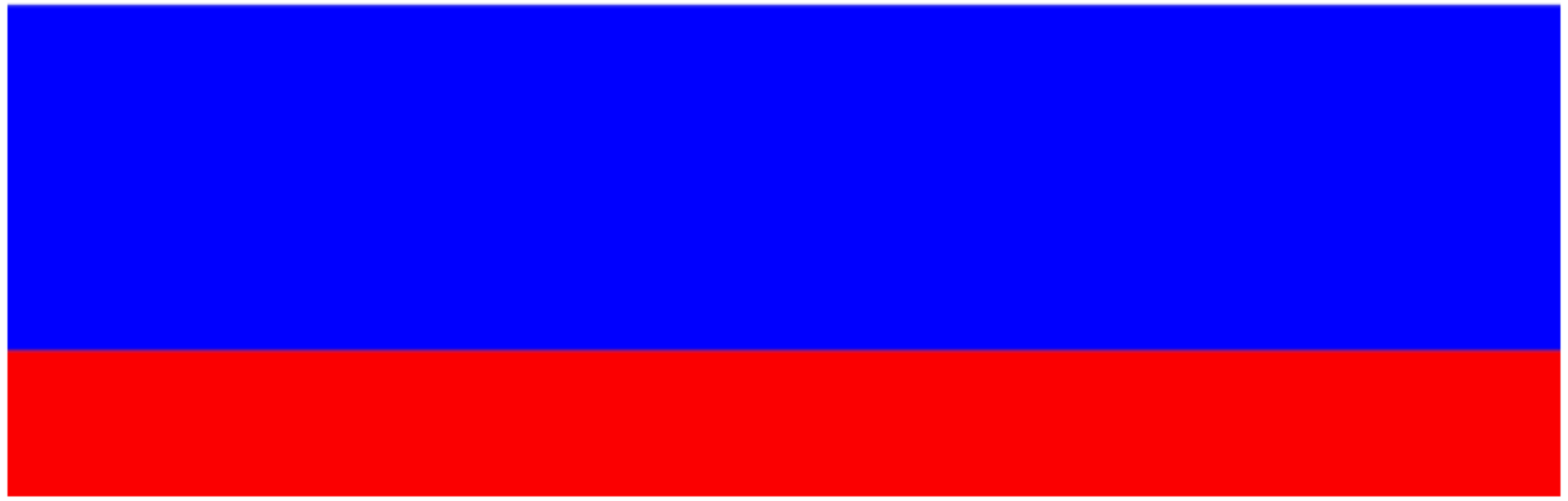
Baidu (China) announced their first quantum computer

Russia

INSIDE
QUANTUM TECHNOLOGY NEWS

News ⌄ Research ⌄ Podcast ⌄ Zones ⌄ Zurich Instruments Events ⌄ Abou

When and where ?



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.

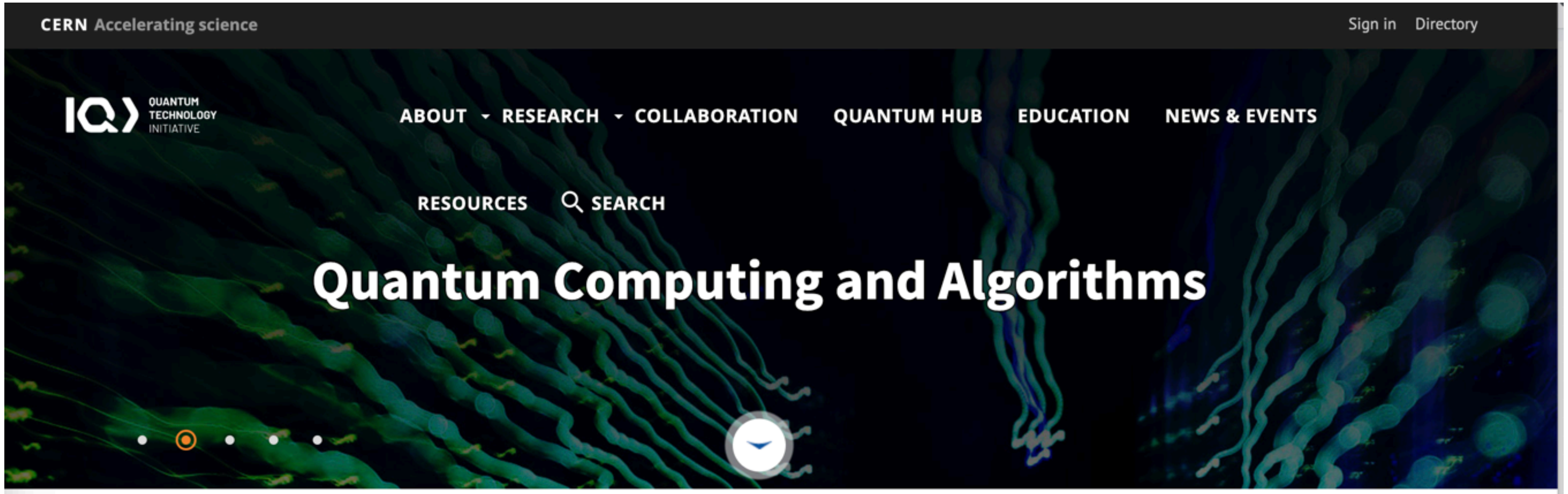
The report attributed the information to Rosatom, the Russian state atomic energy corporation, which has been coordinating an effort among researchers that began in 2019 with the aim to develop a quantum computer by 2024. The report said that scientists from the Russian Quantum

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

Witten discussed Entanglement 2018?

Zakharov group already 2009.

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*
[3] *Theoretical Research Division, Nishina Center, RIKEN, Wako 351-0198, Japan*
[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*
*E-mail: eitou@post.kek.jp, knagata@post.kek.jp, atsushi@rcnp.osaka-u.ac.jp, vzakharov@itep.ru

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 $\Lambda_{\mathrm{QCD}}^{-1}$ $\left(\sim T_c^{-1}\right)$ 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

Entanglement Entropy in Field Theories

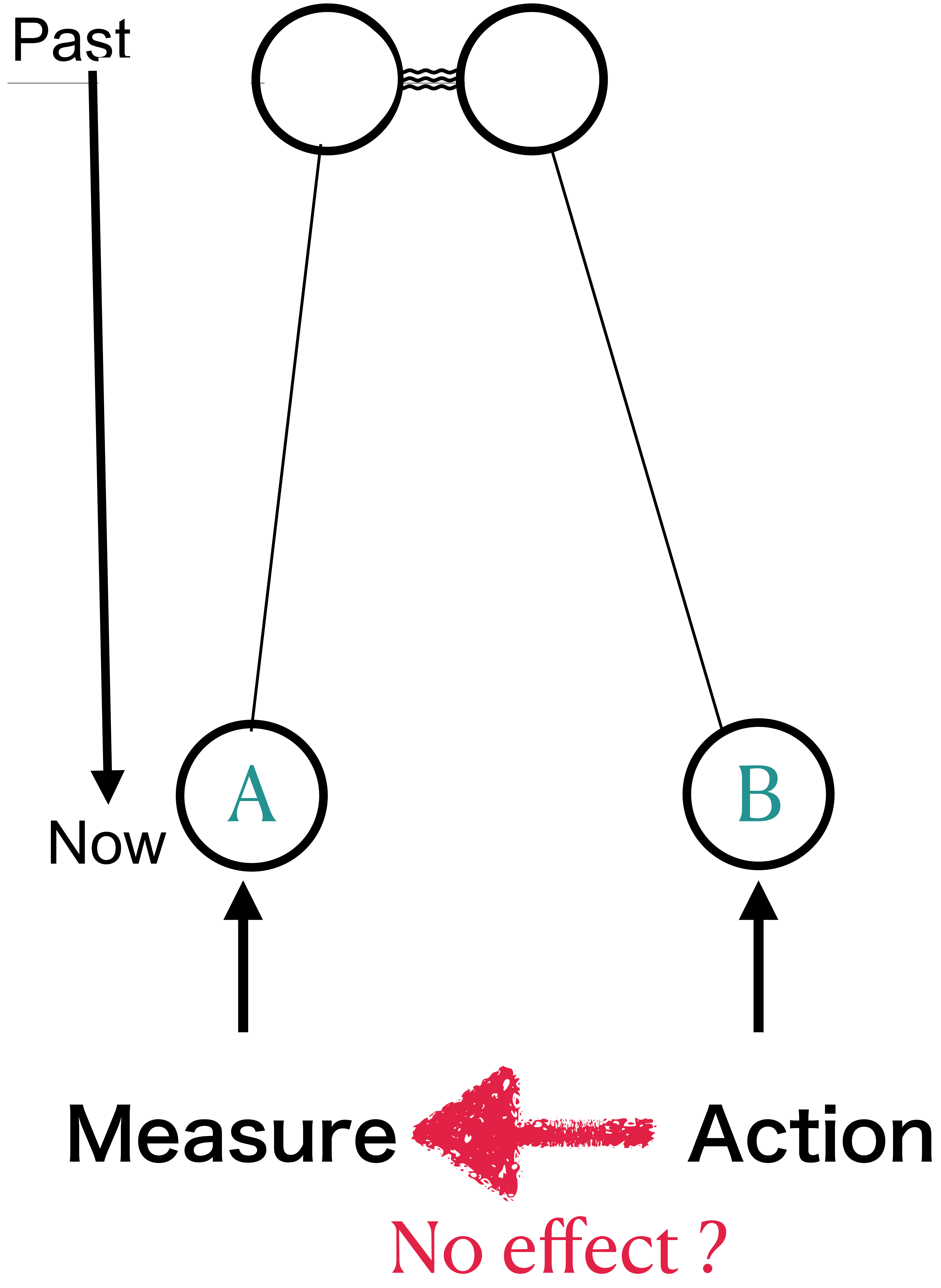
- Quantum entanglement
  - States which we cannot write as

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

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
  - States which we cannot write as

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even A and B are far from each other.

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

- 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)
  - Phys. Rev. Lett. 96 (2006) 181602
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  - SU(2) numerical simulation

III. What shall we do ?

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

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

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

Subjects not discussed today

- Quantum supremacy → **A1**
- Quantum Fourier Transform → **A2**
- Quantum Teleportation → **A3**
- Error-tolerable quantum computing → **A4**
- Quantum Random Numbers → **A5**
- Inside of the hardware

Appendix

- Quantum Supremacy
- Quantum Fourier transformation
- Quantum Teleportation
- Error-tolerable quantum computing
- Quantum Random numbers

A1. Quantum supremacy

- Speed of Computation

Quantum computer >> Ordinary computer

In 2015, Google and NASA reported that D-Wave quantum computer works 10^6 faster than a regular computer chip !

In 2019, Google publishes the quantum supremacy claim. Nature, vol. 574, no. 7779, Oct. 2019, pp. 461+

In 2020, University of Science and Technology of China (中国科学技術大学) announced they realized Quantum supremacy by 「九章」 (Jiuzhang). 九章2号 was announced (2020)

A2. Quantum Fourier Transform using Qiskit

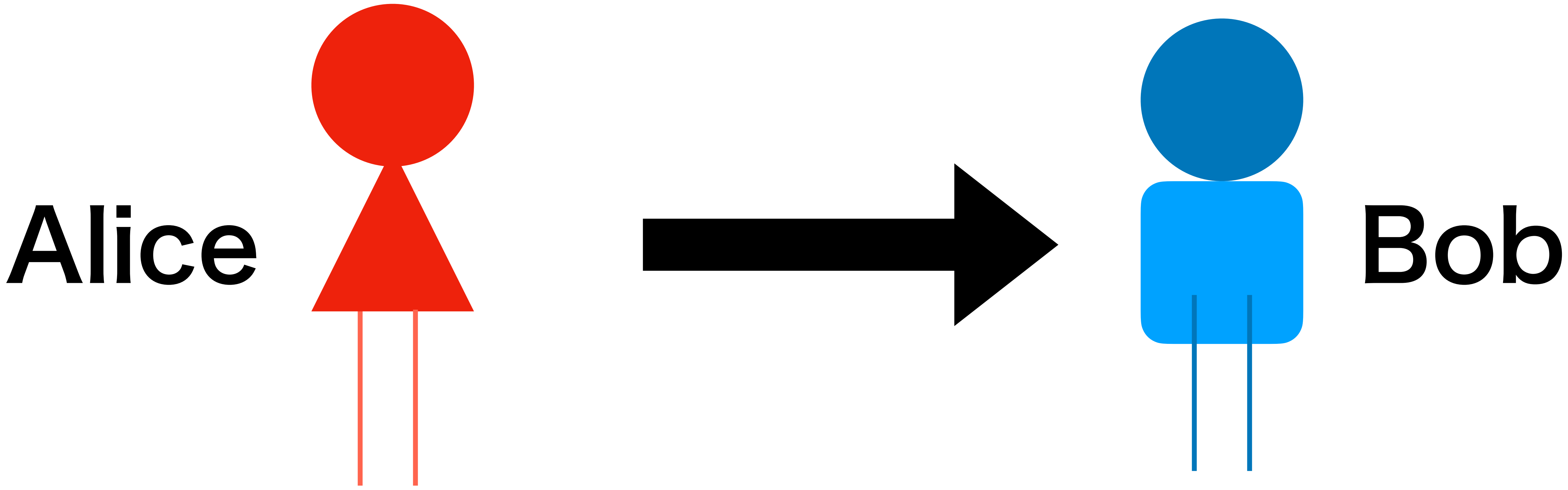
https://qiskit.org/textbook/ja/ch-algorithms/quantum-fourier-transform.html

What is Qiskit ?

Qiskit is an open-source software development kit (SDK) for working with quantum computers at the level of circuits, pulses, and algorithms.
Written in： Python (wiki-pedia)

From Fourier to Schroedinger

A3. Quantum Teleportation



Alice will transmit the state of a qubit, Q

Receiver

Alice's qubit

Bob's qubit

Assist qubit

1. Alice has a qubit, **Q** with state |Ψ>. Alice wishes to transmit the state Ψ > to Bob
2. Alice starts with two additional qubits, which we label R and S. S will be sent to Bob, and the other will stay with Alice.
3. Alice prepares an entangle state with qubits R and S.
4. Alice sends quibit S to Bob
5. Alice perform a measurement on her original qubit Q and half of R

A4. Error-tolerable quantum computing

- 1995, Shor et al shows that quantum error correction is possible, in spite of the no-cloning theorem.

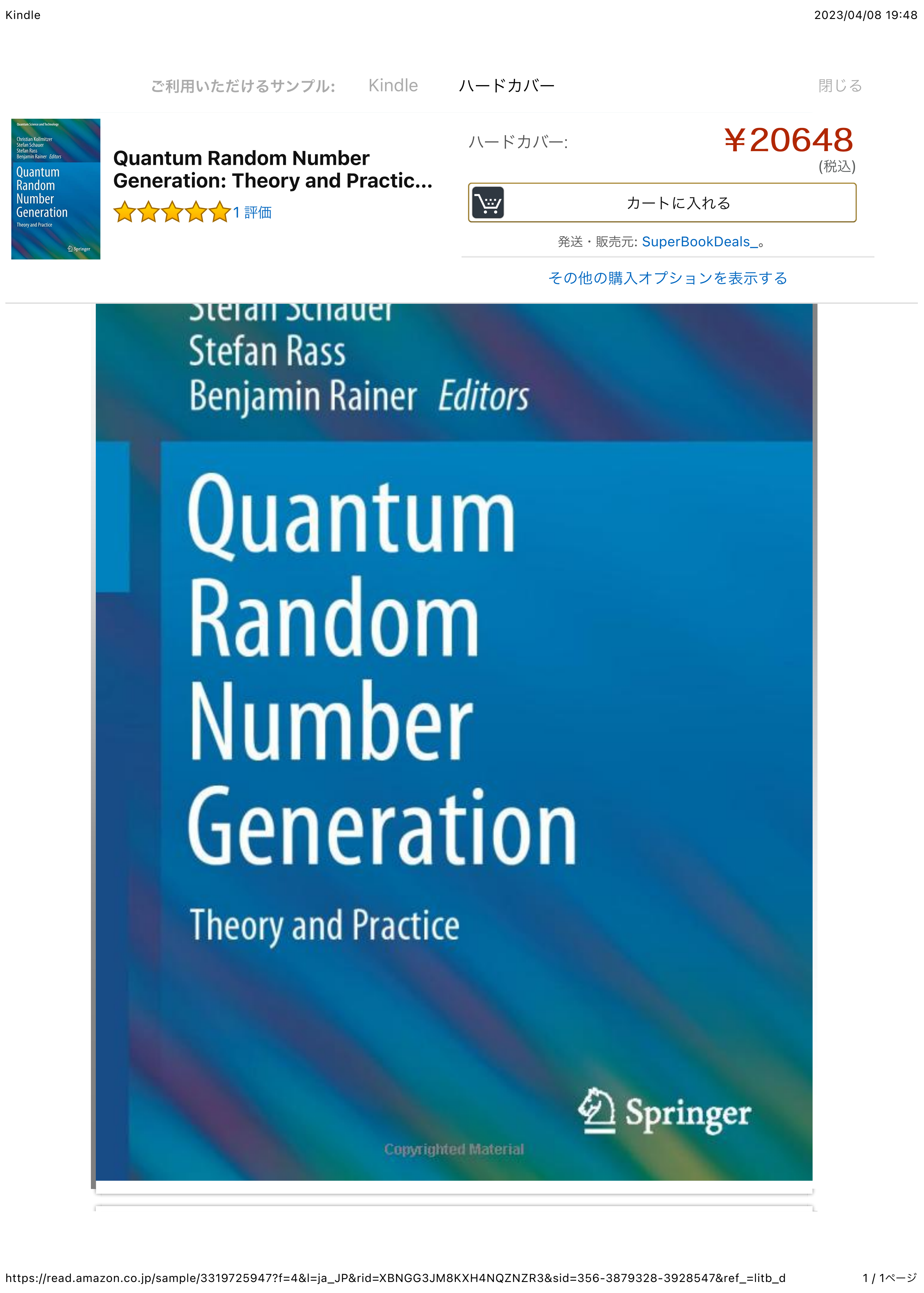
No-cloning theorem:

The theorem forbids the creation of identical copies of an arbitrary unknown quantum state.

W. Wootters and W. Zurek,
"A Single Quantum Cannot be Cloned" Nature 299: 802–803.
D. Dieks,
"Communication by EPR devices" Physics Letters A 92: 271

A5. Quantum Random Number Generators

- Important for Monte Carlo simulations
- But old pseudo-random number such as “Linear congruential method”, “Mersenne twister” are not enough ?
- If Quantum computers run very fast, we need lots of Random numbers …



A6.Comparison of R/D among Japan, US, Europe, China

from JST CRDS “R/D and industry trends”

stable →

developping ↗

	Japan	US	Europe	China
Hardware				
Basic research	◎ →	◎ →	◎ →	○ →
Application research	○ →	◎ →	◎ →	○ ↗
Software				
Basic research	○ →	◎ ↗	◎ ↗	○ ↗
Application research	○ →	◎ ↗	○ ↗	○ ↗

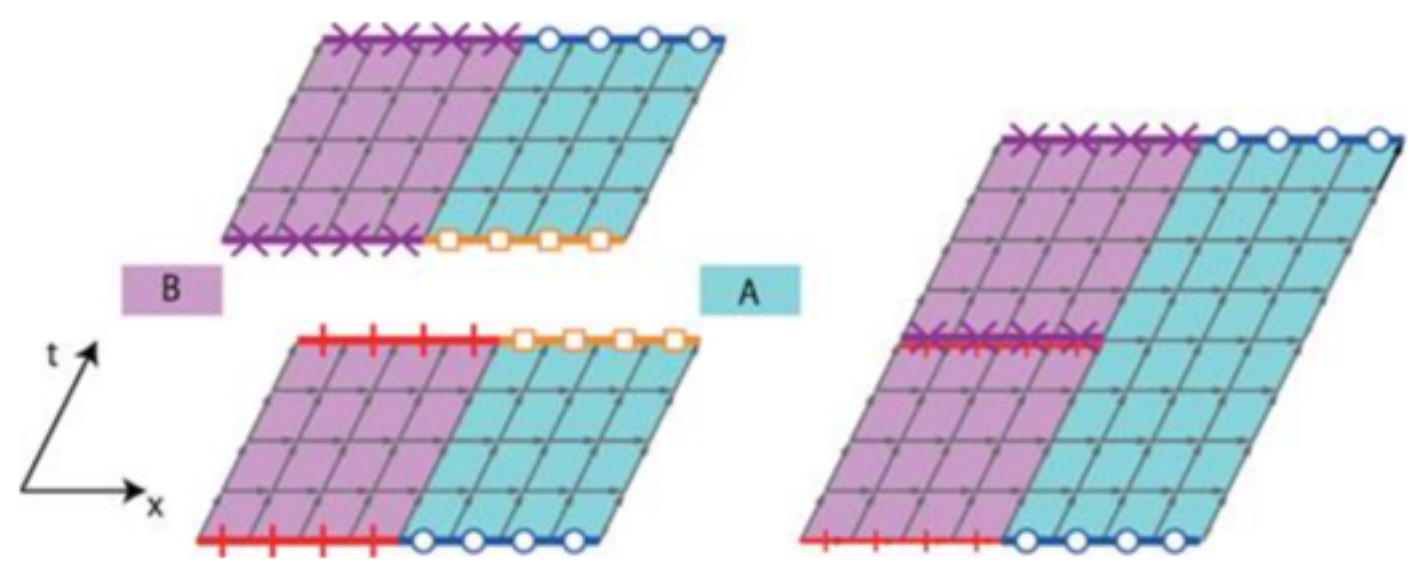
Entropy

Entropy is important quantity.

$$S_A = -\mathrm{Tr}\, \rho_A \ln \rho_A$$

But it is non-trivial to calculate it on the Lattice.

Fig. 1.



In the previous analysis, we got reasonable results.
But we suffered from large errors especially near the phase transition point.
Simulations with the renormalization-group improved action will improve this situation.

Quantum annealing

Developped by D-Wave Systems

1. Backgroud

- In 2013　IT consumed around 10 % of the world power generation

  Big IT companied construct their data-center at cool areas, for reducing power for the cooling

- Quantum anneaaling machines using the super-conductivity quantum bits is

  around 20kW:

  corresponding ca. 50 houses in Japan

  (in case of Super computer, K, around 300,000 houses)

What is Quantum Annealing
(D-Wave System Documentation documentation.pdf)

What is Quantum Annealing?

This section explains what quantum annealing is and how it works, and introduces the underlying quantum physics that governs its behavior. For more in-depth information on quantum annealing in D-Wave quantum computers, see QPU Solver Datasheet.

Applicable Problems

Quantum annealing processors naturally return low-energy solutions; some applications require the real minimum energy (optimization problems) and others require good low-energy samples (probabilistic sampling problems).

What is Quantum Annealing (contin.)

Intuitive explanation by D-Wave in youtube
https://youtu.be/zvfkXjzzYOo

D-Wave company page:

Big Difficulty of Quantum Computers

Quantum Computers will run much faster than super-computers.

But **Noise problem !**

Noise due to decoherence and other quantum noise

For the perfect coherence, the system should be perfectly isolated.	Noise from disturbances in Earth's magnetic field, local radiation from Wi-Fi or mobile phones, cosmic rays, and even the influence that neighboring qubits

Quantum error correction is inevitable, but not so easy.