Quantum Computers for Nuclear/Particle Physicists

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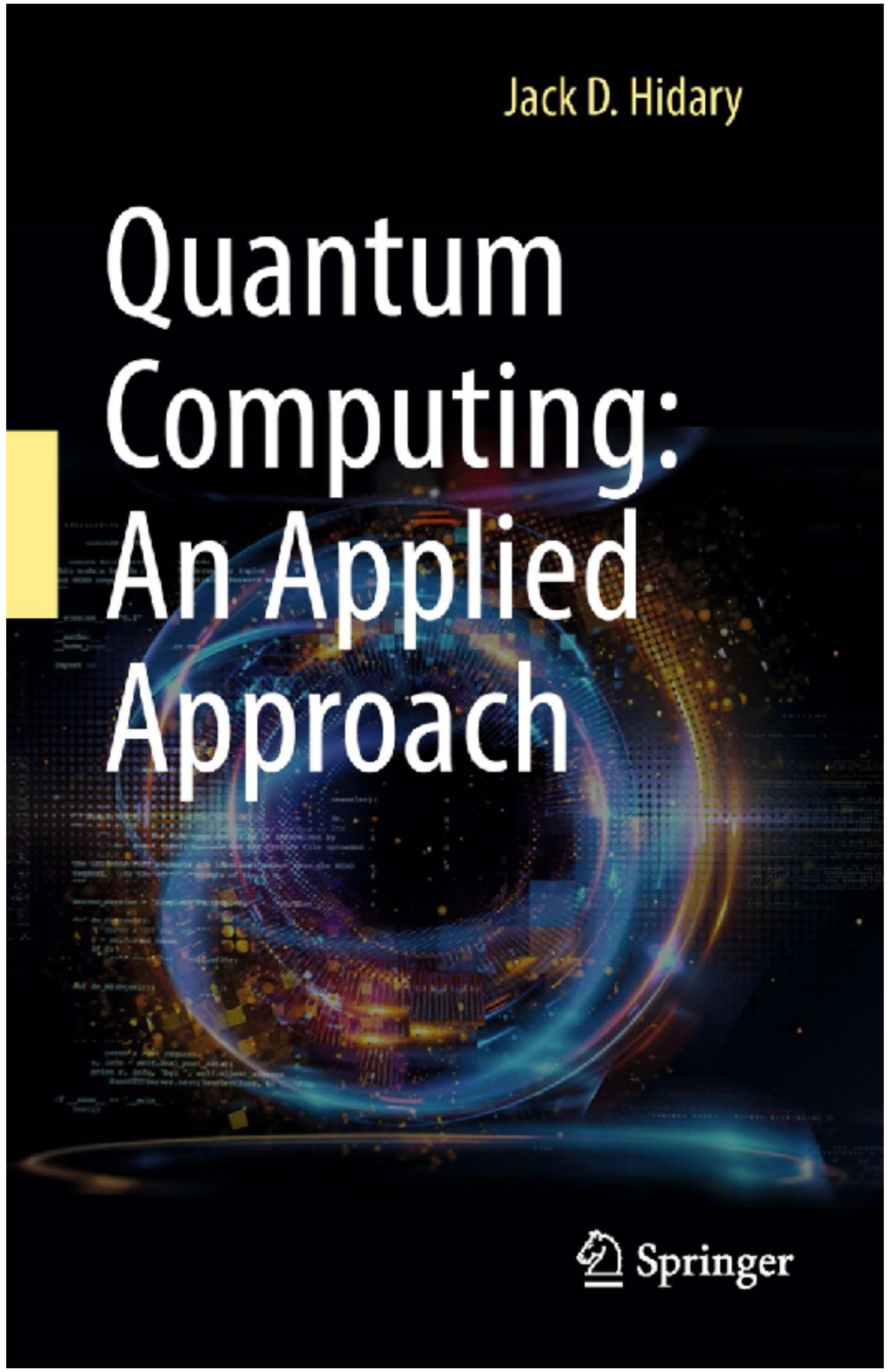
in collaboration with
Taizo Sasaki

May, 2023

Contents of a recent book, "Quantum Computing: An Applied Approach" J.D. Hidary

- I Foundation
  - 1. Superposition, Entanglement and Reversibility
  - 2. A Brief History of Quantum Computing
  - 3. Qubits, Operators and Measurement
  - 4. Complexity Theory
- II Hardware and Applications
  - 5. Building a Quantum Computer
  - 6. Development Libraries for Quantum Computer Programming
  - 7. Teleportation, Superdense Coding and Bell's Inequality
  - 8. The Canon: Code Walkthroughs

$26.49



Contents of a recent book, “Quantum Computing: An Applied Approach” (cont.)

- 9.Quantum Computing Methods
- 10. Applications and Quantum Supremacy
- III Toolkit
  - 11. Mathematical Tools for Quantum Computing I
    (Linear Algebra, Complex Numbers and the Inner Product, Matrix, Outer product and Tensor produ
    Set Theory, Linear Transformation, Vector space, Linear Independence)
  - 12. Mathematical Tools for Quantum Computing II
    (Linear Transformations as Matices, Matirces as Operators, Eigenvectors and Eigenvalues, Inner Products, Hermitian Operators, Unitary operators, Dirac Sum and Tensor product, Hilbert Space, Qubit as a Hilbert Space
  - 13. Mathematial Tools for Quantum Computing III
    (Boolean Functions, Logarithms and Exponentials, Euler’s Formula
  - 14. Dirac Notation
  - 15. Table of Quantum Operators and Core Circuits

Oh, any physics department student knows these !

So, we can skip these,
and we attack the essential points now.

Table of Contents

References

Many physicists !

- R.P.Feynman, *J. Theor Phys* **21**, 467–488 (1982)

  Feynman Lectures On Computation (Frontiers in Physics) (2000),
  1984 & 86, Feynman gave a course on computation at the CalTech

  “Nature isn’t classical and if you wan’t to make a simulation of nature, you’d better make it quantum mechanical”

References

One-night Cramming ?

一夜漬け？

References (cont.)

- Committee on Technical Assessment of the Feasibility and Implications of Quantum Computing, Ed. E.Grumbling and M.Horowitz、2020

  "Quantum Computing: Progress and Prospects"

- Course by Andrew Ng
  https://www.coursera.org/specializations/deep-learning?

- Learn Quantum Computing with Python and IBM Quantum Experience, A hands-on introduction to quantum computing and writing your own quantum programs with Python, 2020

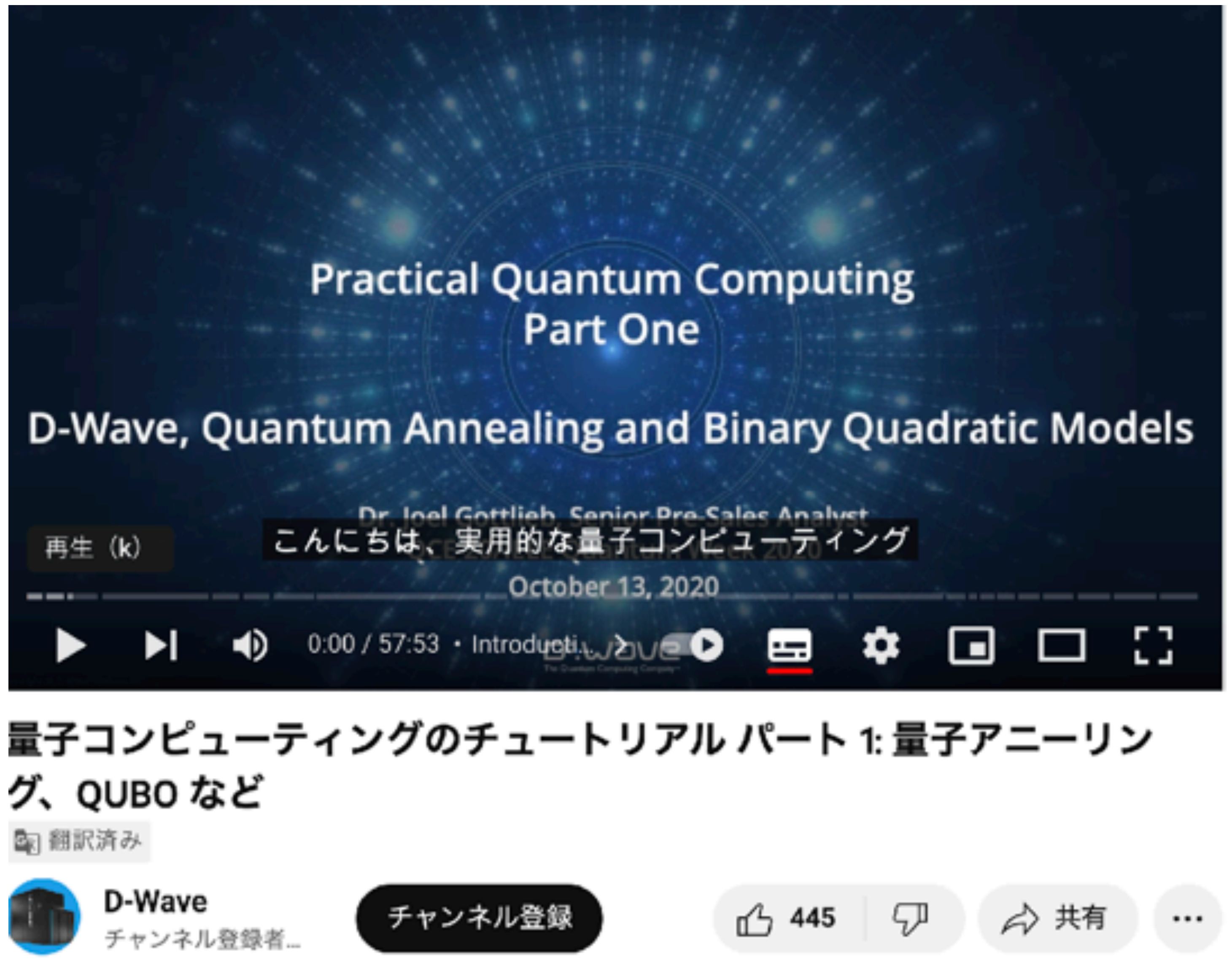
- Quantum Computing in Practice with Qiskit and IBM Quantum Experience, H.Norlen, 2020

References (cont.)

- “Dancing with Qubits
  How quantum computing works and
  how it can change the world”,
  R. S. Sutor (2019)

- D-Wave documents
  https://dwavejapan.com/

- Many tutorials in Youtube.



1. Quantum Computers - Overview -

- 1980 Paul. A. Benioff (young physicist at Argonne National Lab)

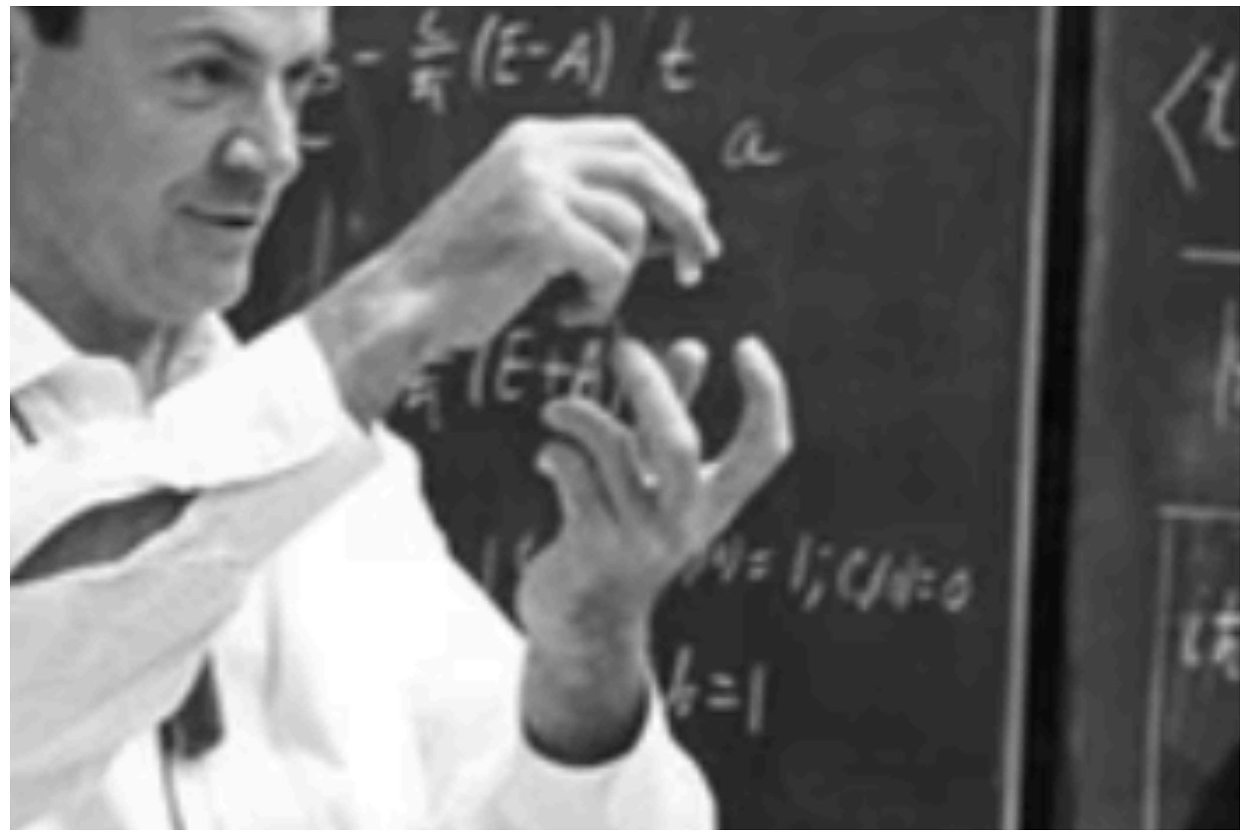
  “The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines”, J. of Statistical Physics 22(5):563, 1980

  Quantum Computer can run without energy consumption.

- 1982 R.P.Feynman

  ⭐“Simulating physics with computers”

  J. Theor Phys **21**, 467–488 (1982).11,086 citations



Feynman at CalTech

- 1985 D. Deutsch (British physicist at the University of Oxford)

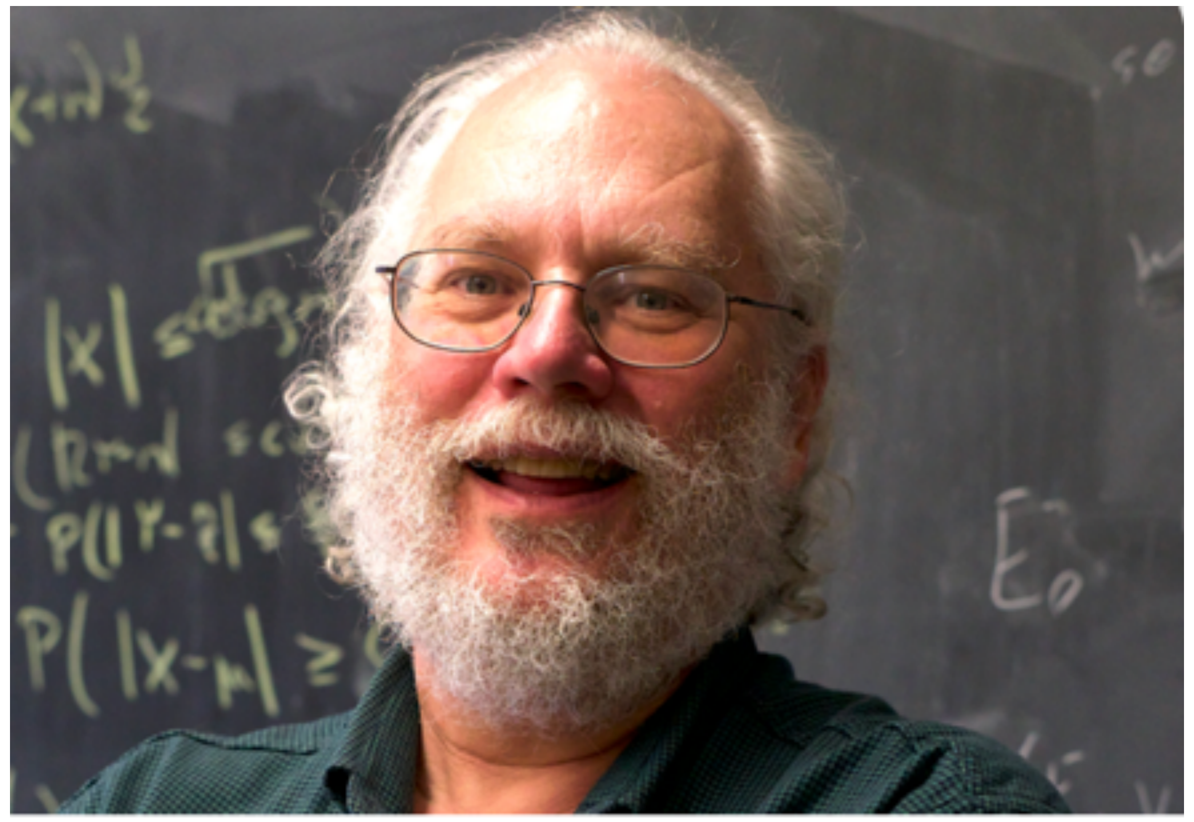
  Quantum Turing machine

- 1989 D. Deutsch, Quantum circuit, Proc. R. Soc. Lond. A**439** 553–558

Why the factoring is important ?

RSA (Rivest–Shamir–Adleman) public-key cryptosytem uses factorization

- 1992 D. Deutsch and R.Jozsa,
  ☆"Rapid solution of problems by quantum computation"
  Proc. R. Soc. Lond. A**439** 553–558 3,627 citations
- 1993 E. Bernstein and U. Vazirani
- 1994 P. W. Shor (American mathematician)
  ☆"Algorithms for quantum computation: discrete logarithms and factoring" $24 = 2^3 \times 3$, $90 = 2 \times 3^2 \times 5$, ….

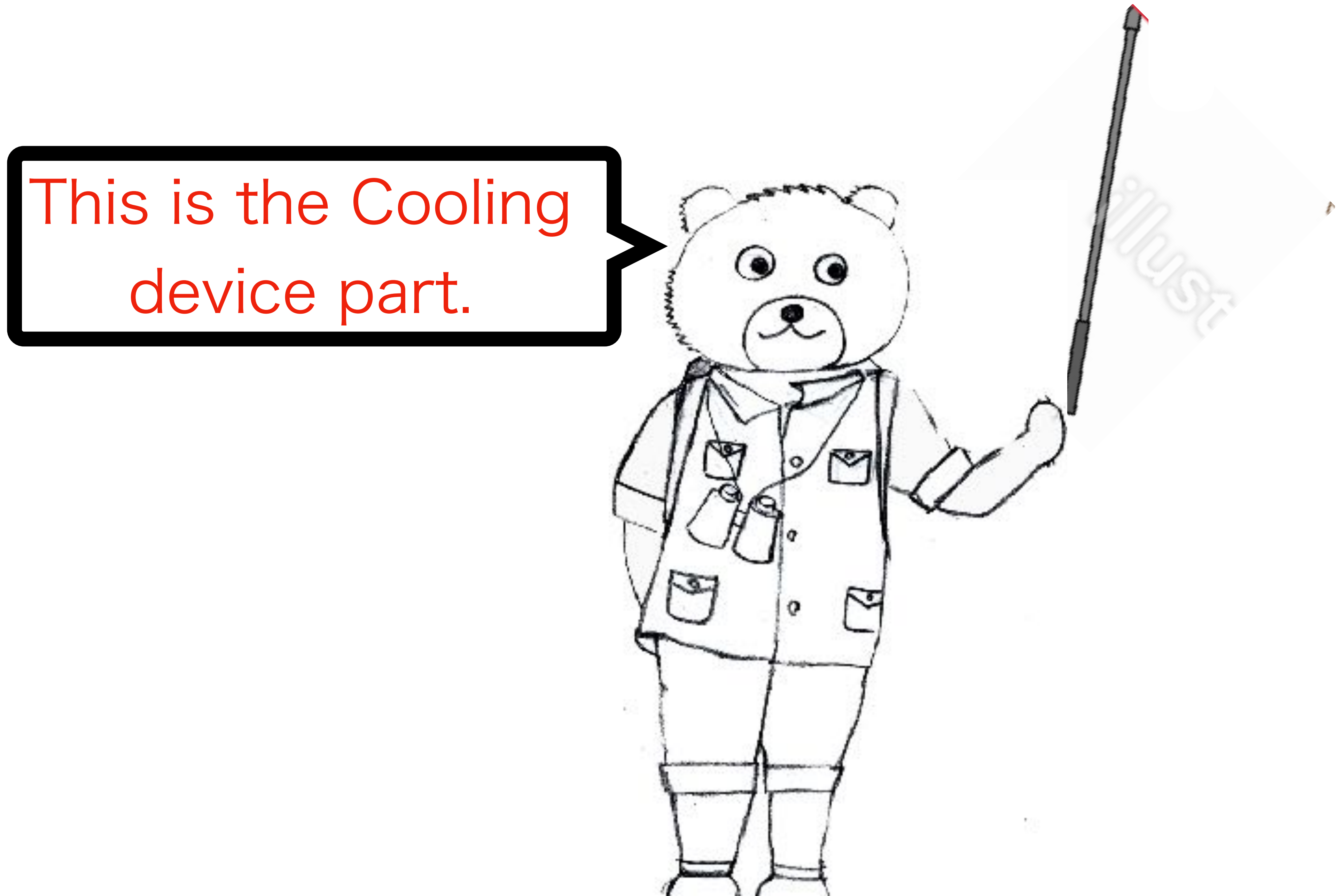


Shor

Store now, decrypt later !

Oh, I can crack crypt-systems!
I will collect public keys, and I will buy Quantum Computers.

IBM



D-wave

RIKEN Center for
Quantum Computing

The first made-in-Japan
Quantum computer ?

announced on March 24, 2023

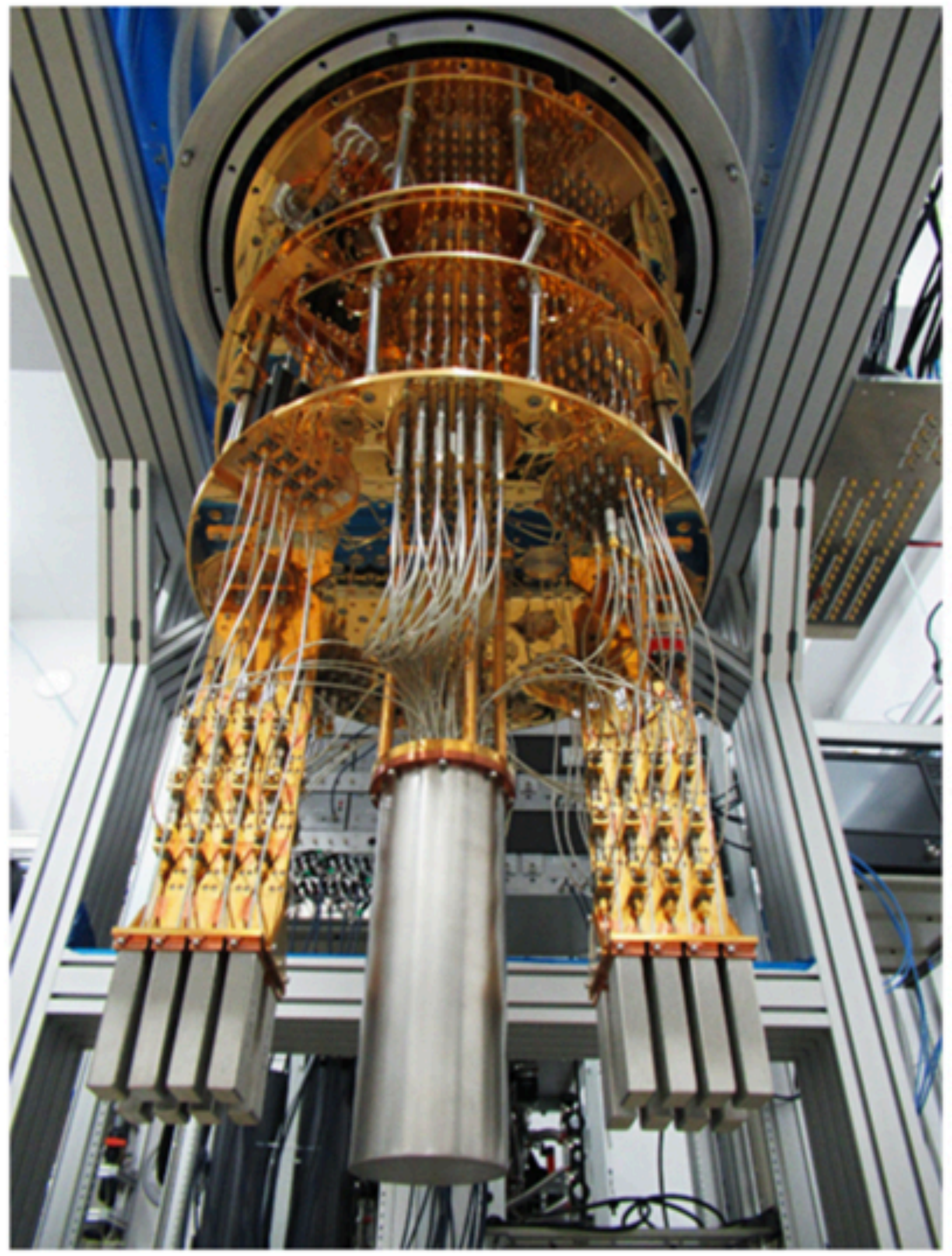


図5 64量子ビット超伝導量子コンピュータ用の希釈冷凍機内の配線

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

チエン?

Baidu (China) announced their
first quantum computer

Where are Quantum Computers in Japan

- IBM-UTokyo lab. Hongo Campus
- Fujitsu and Toshiba proceed Quantum computer studies.
- Several companies might have in-house.
- Gemini-mini by SpinQ, China, (深圳市)
  シンセン
  (1180,000Yen, 118万円)

1. Slower than human-being !
2. Japanese agency sold them
   (The first shipment was sold out !)

▶ 「Gemini Mini」の特徴

メンテナンスフリー：

室温で動作し、安定した性能を発揮

運用にあたりメンテナンスや追加コストが発生しない

豊富

複

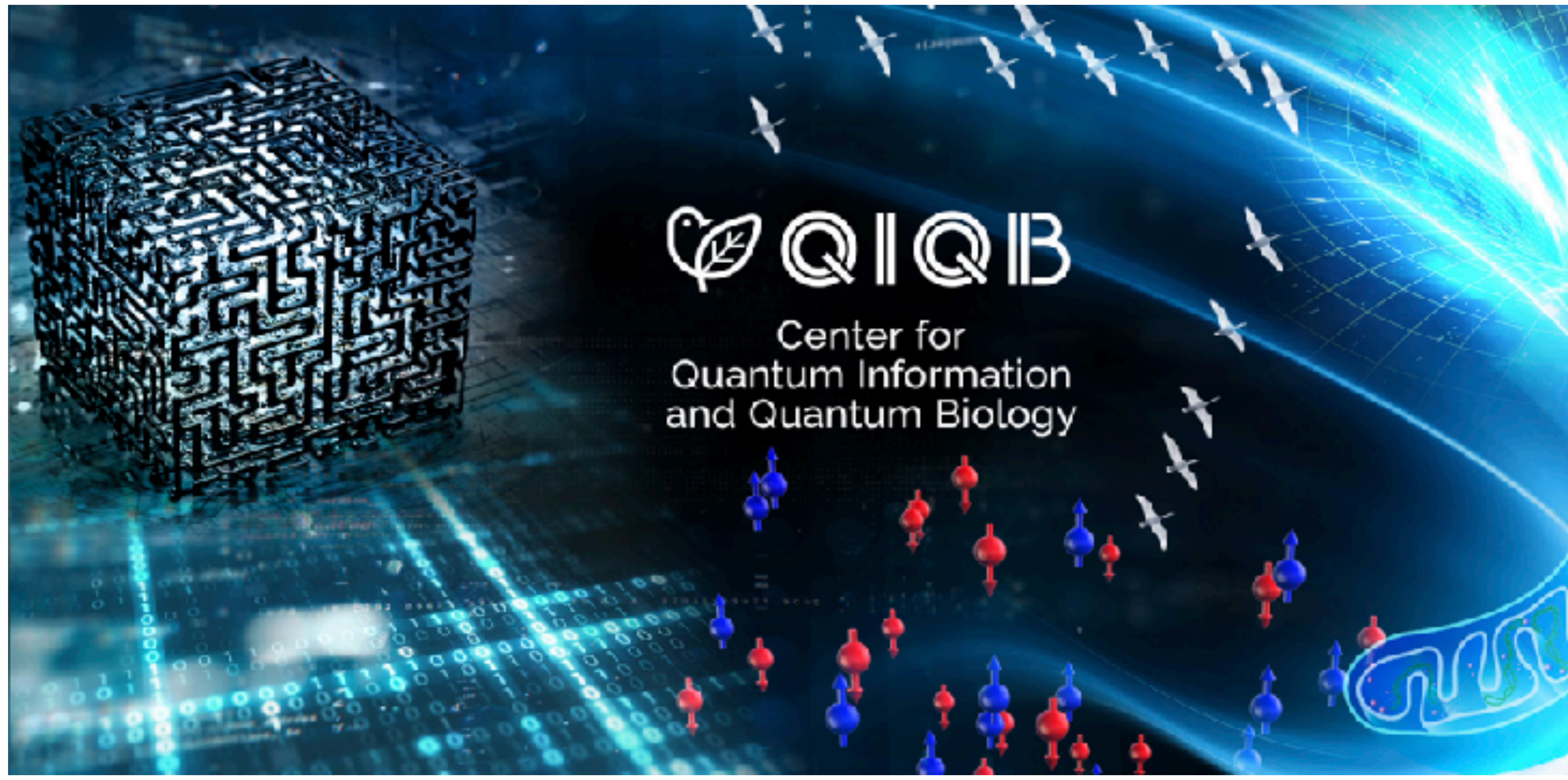
2

8

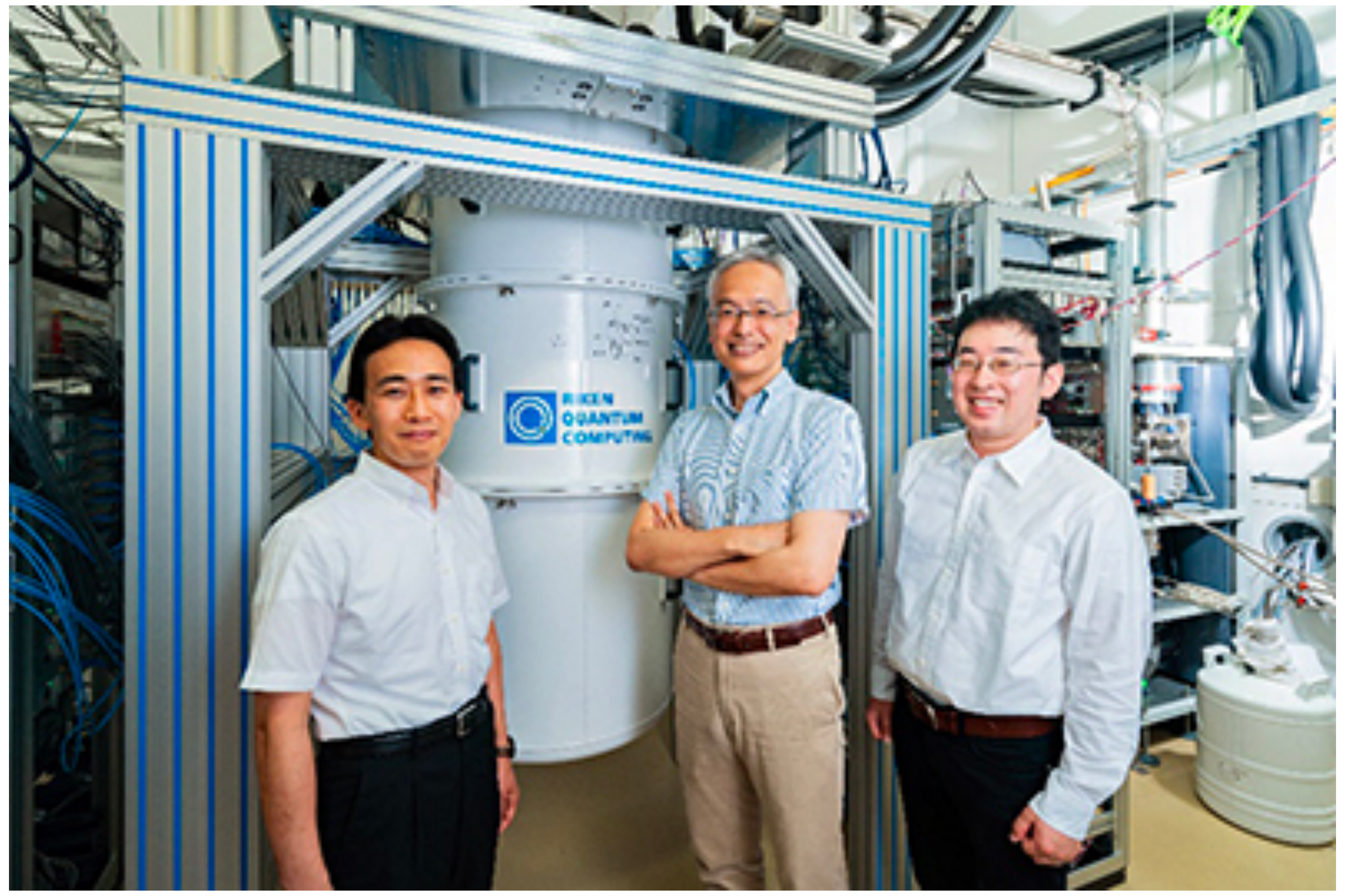
Where are Quantum Computers in Japan(2)

Japan

- Osaka university
  QIQB (Center for Quantum Information and Quantum Biology)



- RIKEN
  RQC (RIKEN Center for Quantum Computing)



- IBM-University of Tokyo Laboratory

NEC

Quantum Computer developed by NEC
(Quantum Annealing method) (Mock-up)
https://www.nikkei.com/article/DGXZQOUC235X10T20C22A6000000/

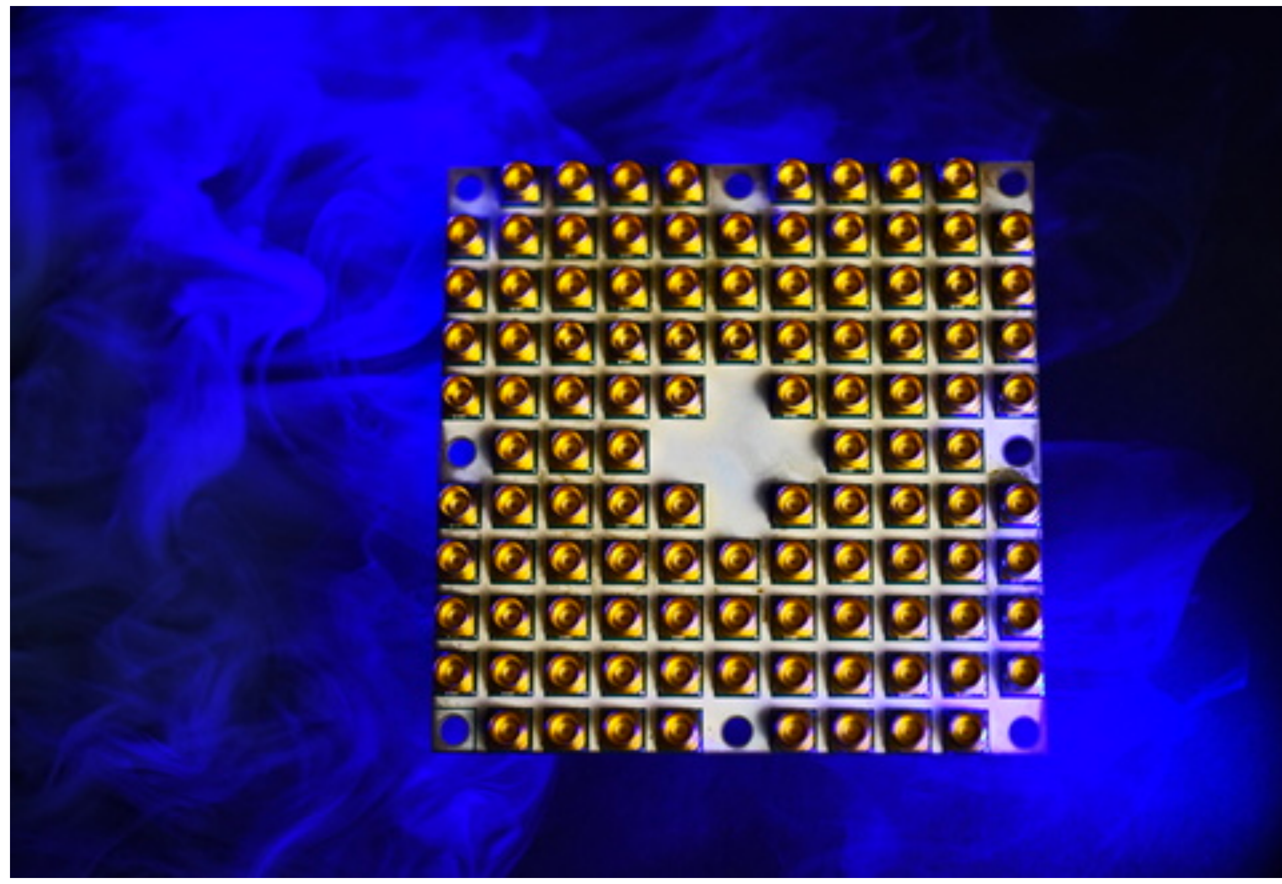
Fujitsu

Quantum Annealer

Where are Quantum Computers in the World (1)

US

- BNL Co-Design Center for Quantum Advantage (C2QA), now only design?
- IBM, Argonne National Laboratory (building?)
- Tangle Lake (Intel chip for Quantum Computers ?)

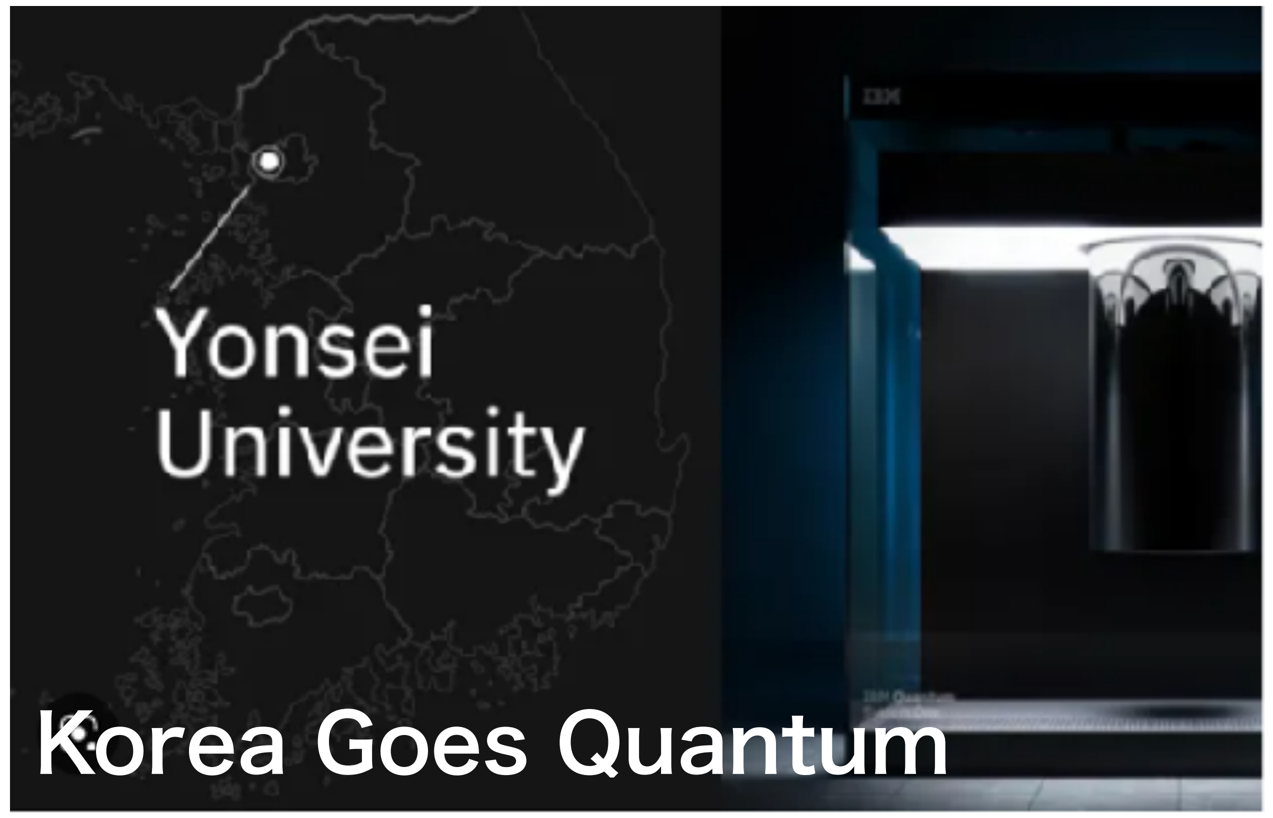


49 quantum bit Intel chip

Tangle Lake in Alaska

Where are Quantum Computers in the World (2)

- Canada
  - D-Wave
- Korea
  - Quantum Information Institute@Yonsei University (with IBM)



Korea Goes Quantum: IBM Collaborates With Yonsei University To Deploy Quantum System One In Korea — Quantum...

Yonsei University unveil collaboration to bring IBM Quantum System One to Korea - CIO Tech Asia

Where are Quantum Computers in the World (3)

- Russia

Quantum Science and Technology

PERSPECTIVE • OPEN ACCESS

Quantum technologies in Russia

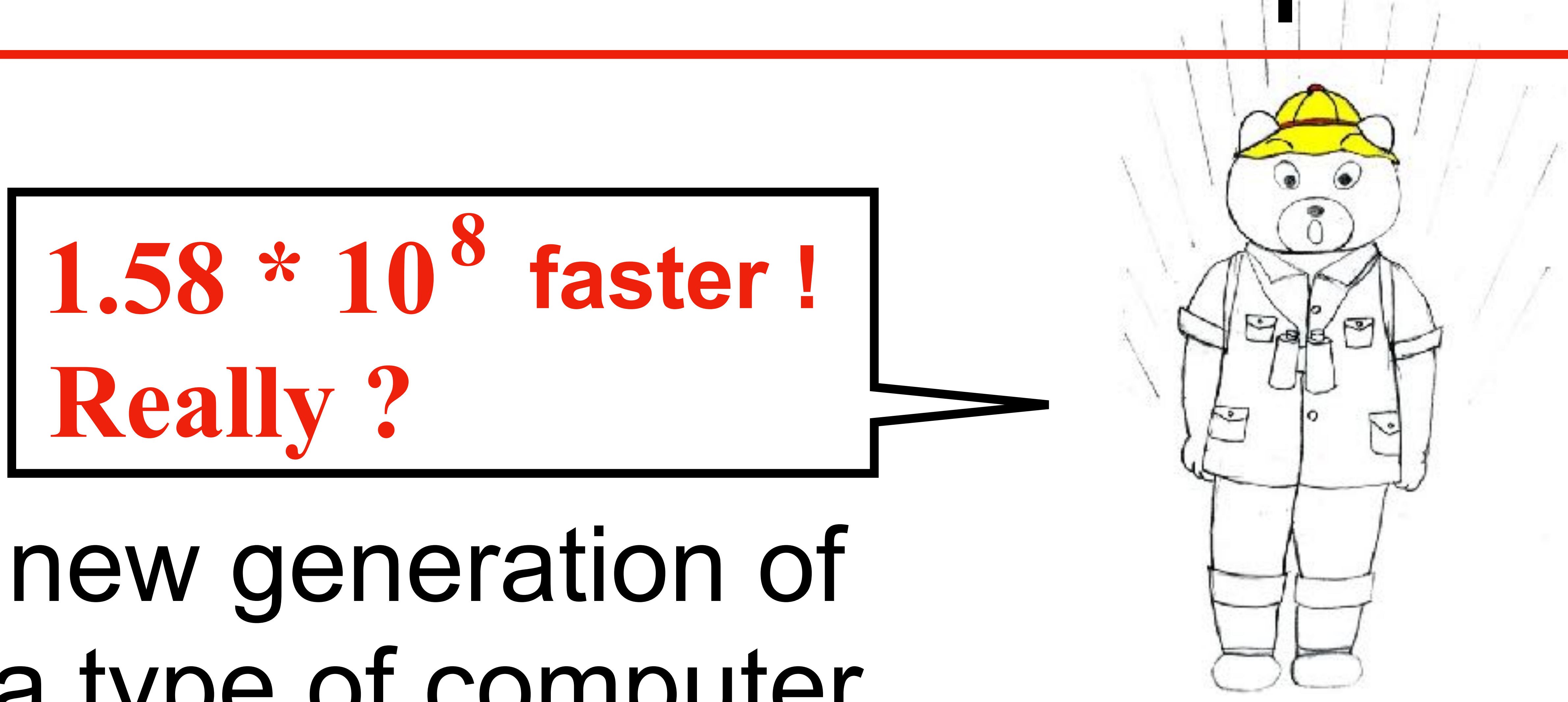
To cite this article: A K Fedorov *et al* 2019 *Quantum Sci. Technol.* 4 040501

View the article online for updates and enhancements.

You may also like

- Roadmap on quantum nanotechnologies
  Arne Laucht, Frank Hohls, Niels Ubbelohde et al.
- Democratization of quantum technologies
  Zeki C Seskir, Steven Umbrello, Christopher Coenen et al.
- Quantum Fisher information matrix and multiparameter estimation
  Jing Liu, Haidong Yuan, Xiao-Ming Lu et al.

Calculation Speed of Quantum Computer



- Quantum computing is a new generation of technology that involves a type of computer 158 million times faster than the most sophisticated supercomputer we have in the world today.
  https://www.livescience.com/quantum-computing
  By Mark Smith published March 18, 2022

2.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 ?

3. Quantum computers

What is Quantum computer ?

Wiki-pedia

History
Quantum information processing
Communication
Algorithms
Engineering
Theory
Toggle Theory subsection
See also
Notes
References
Further reading

WIKIPEDIA
The Free Encyclopedia

Quantum computing

(Redirected from Quantum computer)

IBM Q System One, a quantum computer with 20 superconducting qubits[1]

A **quantum computer** is a computer that exploits quantum mechanical phenomena. At small scales, physical matter exhibits properties of both particles and waves, and quantum computing leverages this behavior using specialized hardware. Classical physics cannot explain the operation of these quantum devices, and a scalable quantum computer could perform some calculations exponentially faster than any modern "classical" computer. In particular, a large-scale quantum computer could break widely used encryption schemes and aid physicists in performing physical simulations; however, the current state of the art is still largely experimental and impractical.

The basic unit of information in quantum computing is the qubit, similar to the bit in traditional digital electronics. Unlike a classical bit, a qubit can exist in a superposition of its two "basis" states, which loosely means that it is in both states simultaneously. When measuring a qubit, the result is a probabilistic output of a classical bit. If a quantum computer manipulates the qubit in a particular way, wave interference effects can amplify the desired measurement results. The design of quantum algorithms involves creating procedures that allow a quantum computer to perform calculations efficiently.

Physically engineering high-quality qubits has proven challenging. If a physical qubit is not sufficiently isolated from its environment, it suffers from quantum decoherence, introducing noise into calculations. National governments have invested heavily in experimental research that aims to develop scalable qubits with longer coherence times and lower error rates. Two of the most promising technologies are superconductors (which isolate an electrical current by eliminating electrical resistance) and ion traps (which confine a single atomic particle using electromagnetic fields).

Any computational problem that can be solved by a classical computer can also be solved by a quantum computer.[2] Conversely, any problem that can be solved by a quantum computer can also be solved by a classical computer, at least in principle given enough time. In other words, quantum computers obey the Church–Turing thesis. This means that while quantum computers provide no additional advantages over classical computers in terms of computability, quantum algorithms for certain problems have significantly lower time complexities than corresponding known classical algorithms. Notably, quantum computers are believed to be able to solve certain problems quickly that no classical computer could solve in any *feasible* amount of time—a feat known as "quantum supremacy." The study of the computational complexity of problems with respect to quantum computers is known as quantum complexity theory.

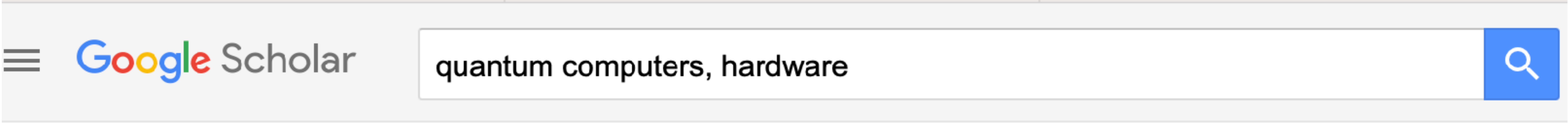
History

For many years, the fields of quantum mechanics and computer science formed distinct academic communities.[3] Modern quantum theory developed in the 1920s to explain the wave–particle

Hardware

- Superconductivity method
- Ion-Trap method (Ion Q etc)
- Many others

RCNP can make it !



35,900 articles !

NISQ era

Often, I see the word NISQ.
What does it mean?
How do I pronounce ?

- Until the full-spec Quantum Computer come,
NISQ (Noisy Intermediate-Scale Quantum Computer)
（ノイズがある中規模の量子コンピュータ）
plays role.

Quantum computers (cont.)

- Quantum bit (Q-bit)
- States: $|\psi> = \alpha|0> + \beta|1>$
- Entanglement （もつれ）
- Superposition

Entanglement

Entanglement Entropy in Yang-Mills theory: towards a simple model

E. Itou,[1,2] A. Nakamura,[3,4,5] and V.I. Zakharov[6,4,7,*]

[1] *Department of Mathematics and Physics, Kochi University, 2-5-1 Akebono-cho, Kochi 780-8520, Japan*
[2] *Research Center for Nuclear Physics, Osaka University, Osaka, 567-0 047, Japan*
[3] *Research Center for Nuclear Physics, Osaka University, Osaka, 567-0047, Japan*
[4] *School of Biomedicine, Far-East Federal University, Vladivostok, Russia*
[5] *Nishina Center, RIKEN, Wako 351-0198, Japan*
[6] *ITEP, B. Cheremushkinskaya 25, Moscow, 117218 Russia*
[7] *Moscow Inst Phys & Technol, Dolgoprudny, Moscow Region, 141700 Russia.*

We comment on theoretical implications of recent measurements of entanglement entropy in SU(3) Yang-Mills theory. We argue that the data represent a clean evidence against the Hagedorn mechanism of the deconfining phase transition. Holographic models, on the other hand, naturally accommodate alternative mechanisms of the phase transition. Next, we (approximately) relate correlation lengths revealed in measurements of the entanglement entropy and near (and above) the deconfining phase transition. This prediction of holography seems to be in reasonable agreement with the data.

INTRODUCTION

Dynamics of phase transitions is one of the most

such as existence of a finite correlation length.

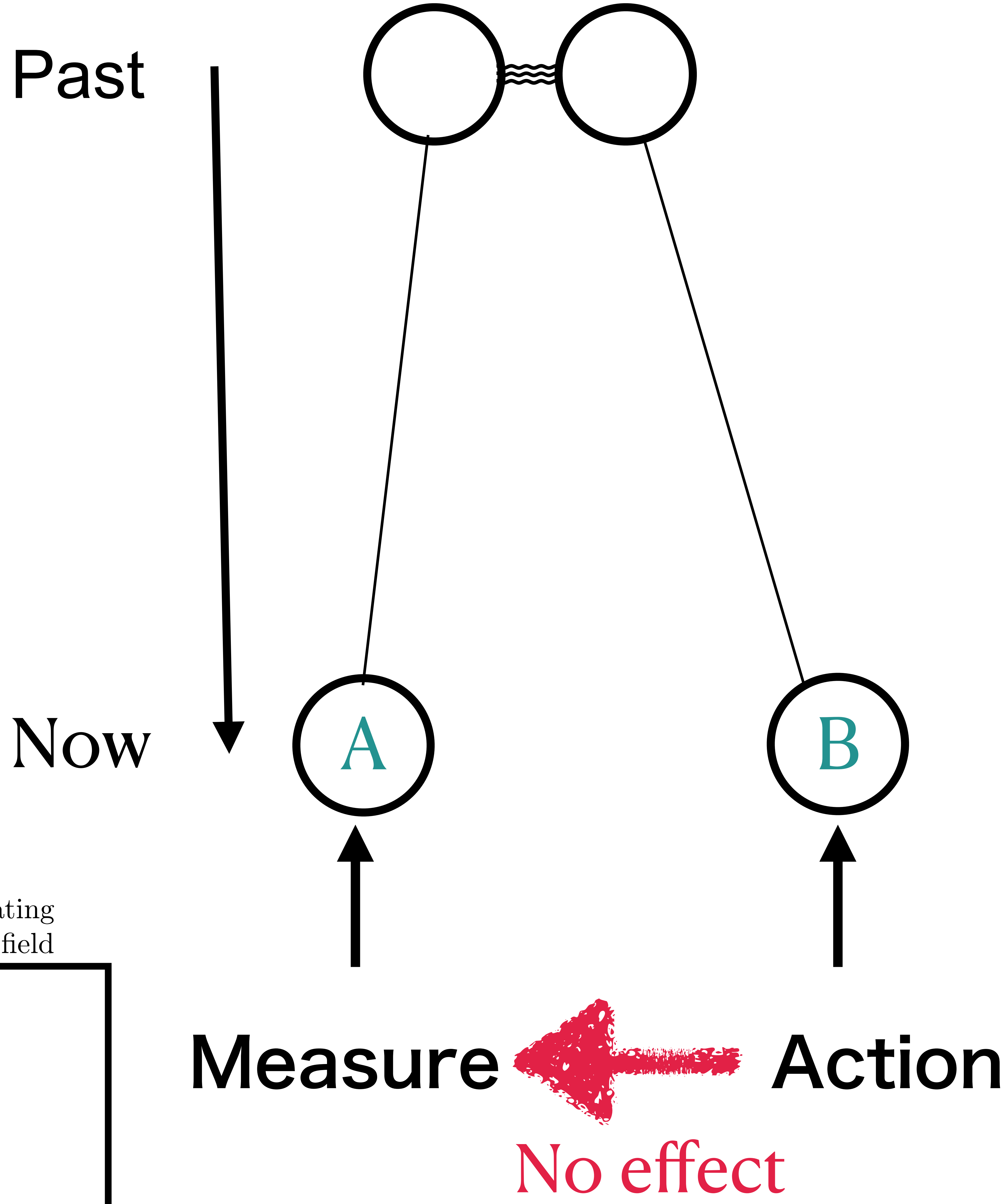
Moreover, a geometric approach to evaluating entanglement entropy in relativistic quantum field

suggests a unified geometric approach to theory of

Entanglement

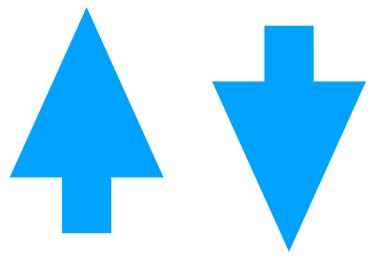
States which we cannot write

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



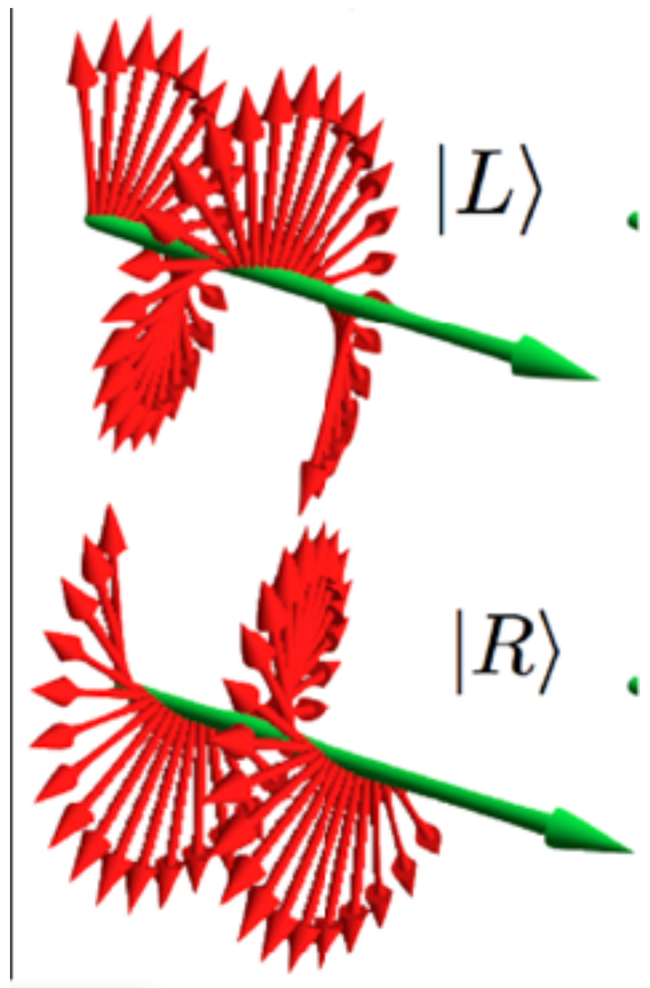
How to express |0> and |1>

1. Spin up and down



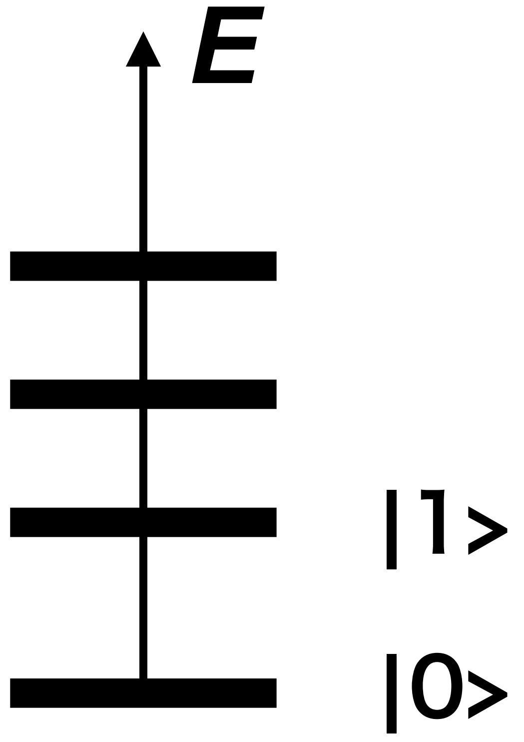
2. photon polarization

   (right and left circular polarization)



wiki-pedia

3. ground energy level and an excited level



4. etc

4. Quantum Algorithms

- Coppersmith (1994)
  - Quantum Fourier Transform
- Shor (1994)
  - Finding the prime factors
- Grover (1996)
  - Database search
- Simon (1994,1997)
  - One can determine the periodicity of a function exponentially faster on a quantum computer compared with a classical computer.
    (Simon's algorithm is the first example of an exponential speedup over the best known classical algorithm by using a quantum computer.)

Simon wrote a story:
The paper was rejected at a theoretical computer science conference (STOC 1993), Peter Shor on the program committee for that conference realized the value of the paper. but could not persuade the committee to accept the paper.
He submitted his paper to the next major theoretical computer science conference (FOCS 1993) in parallel with resubmitted paper by Simon.
Shor proposed, if only his paper was accepted, but not Simon's, he merged two papers.
At the end, both were accepted and got each credit.

5. Applications

- Quantum Teleportation
- Data search
- Decryption (暗号解読！)

6. Bleak future of Japan?

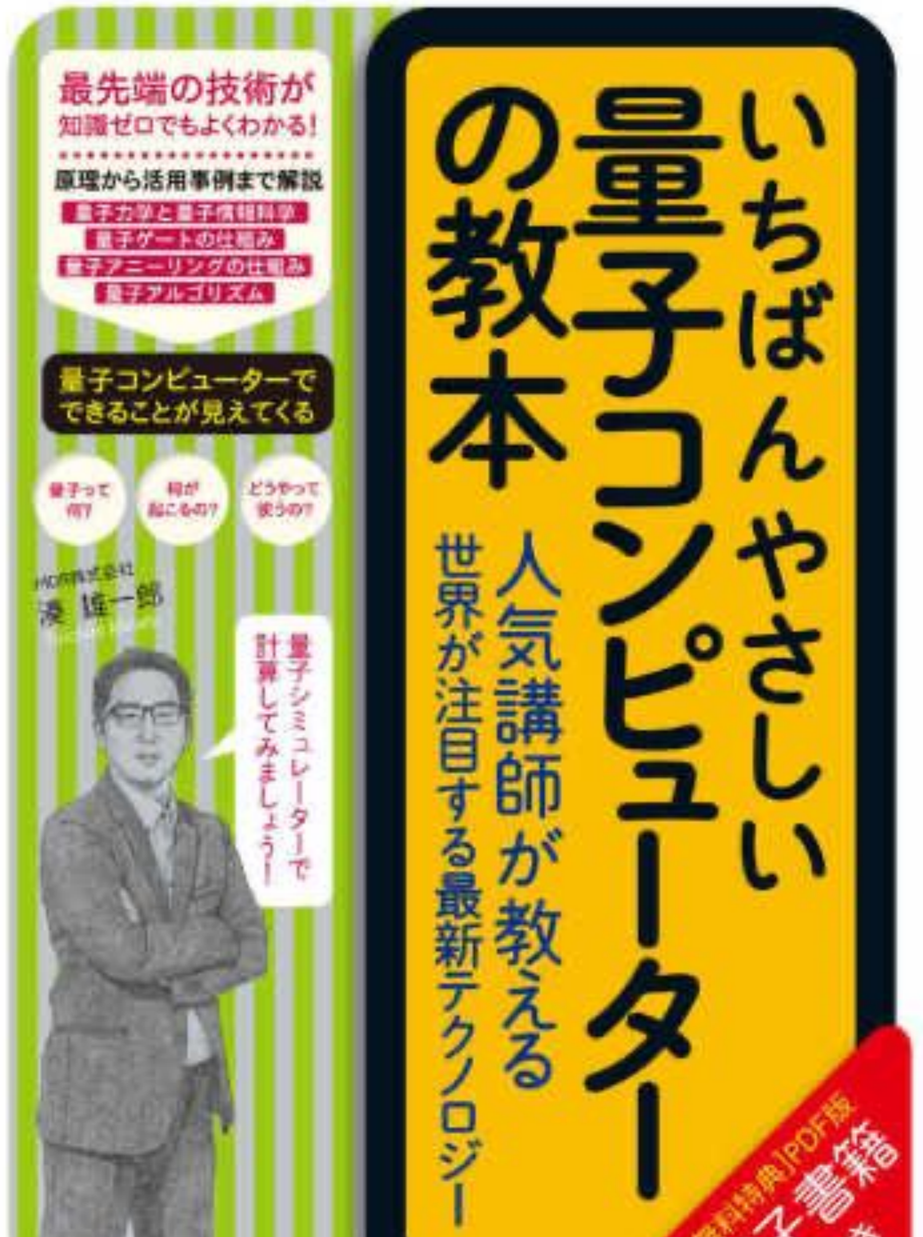
暗雲が

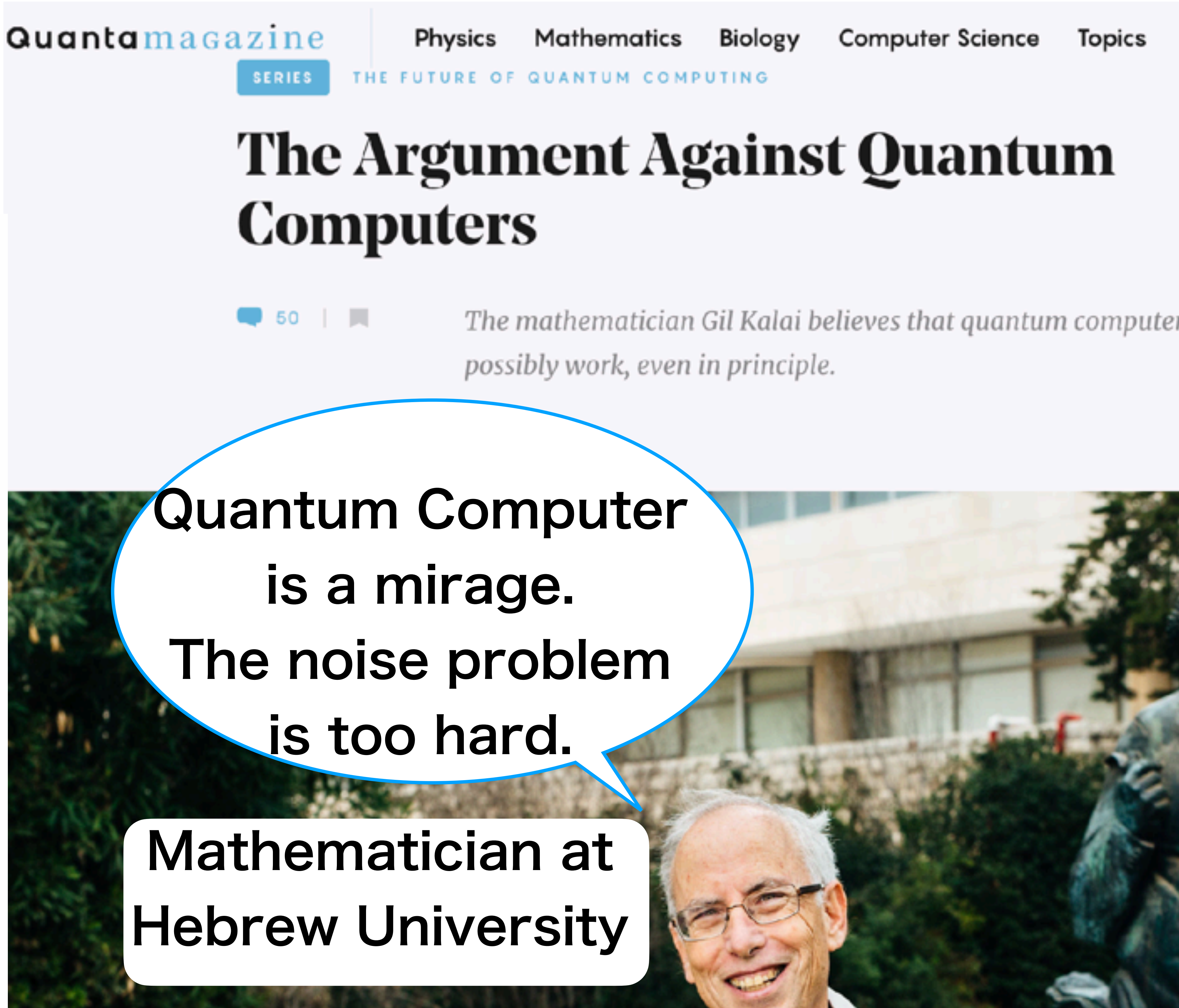
blueqat社、超伝導量子ビットの開発から撤退のお知らせ。シリコン量子ビットの研究は一部継続。

「量子ビットを動かすことはできたが、動作する時間は非常に短いものだった」実用に耐えるレベルまでもっていくには長い年月が必要となった。その過程で、予算規模で勝る米中勢に追い抜かれてしまった

NEC: 2020年 筑波研究所は閉鎖

ブルーキャット社
社長





Quantum Computer is a mirage.
The noise problem is too hard.

Mathematician at Hebrew University

7. Big Difficulty

Noise problem !

Quantum error correction is inevitable,
but not so easy.

8. What we plan to do

1. To use Quantum Computer for lattice QCD simulations.

2. Application to football trajectories (supervised by Prof. Asai)
   Because Quantum Computers run so fast, before a kicked ball reaches the goal, the calculation is over !

3. Fluid-Dynamics of Wind instrument
   Fluid-Dynamics is clasical, but it requires huge computational power.

Sasaki’s flute

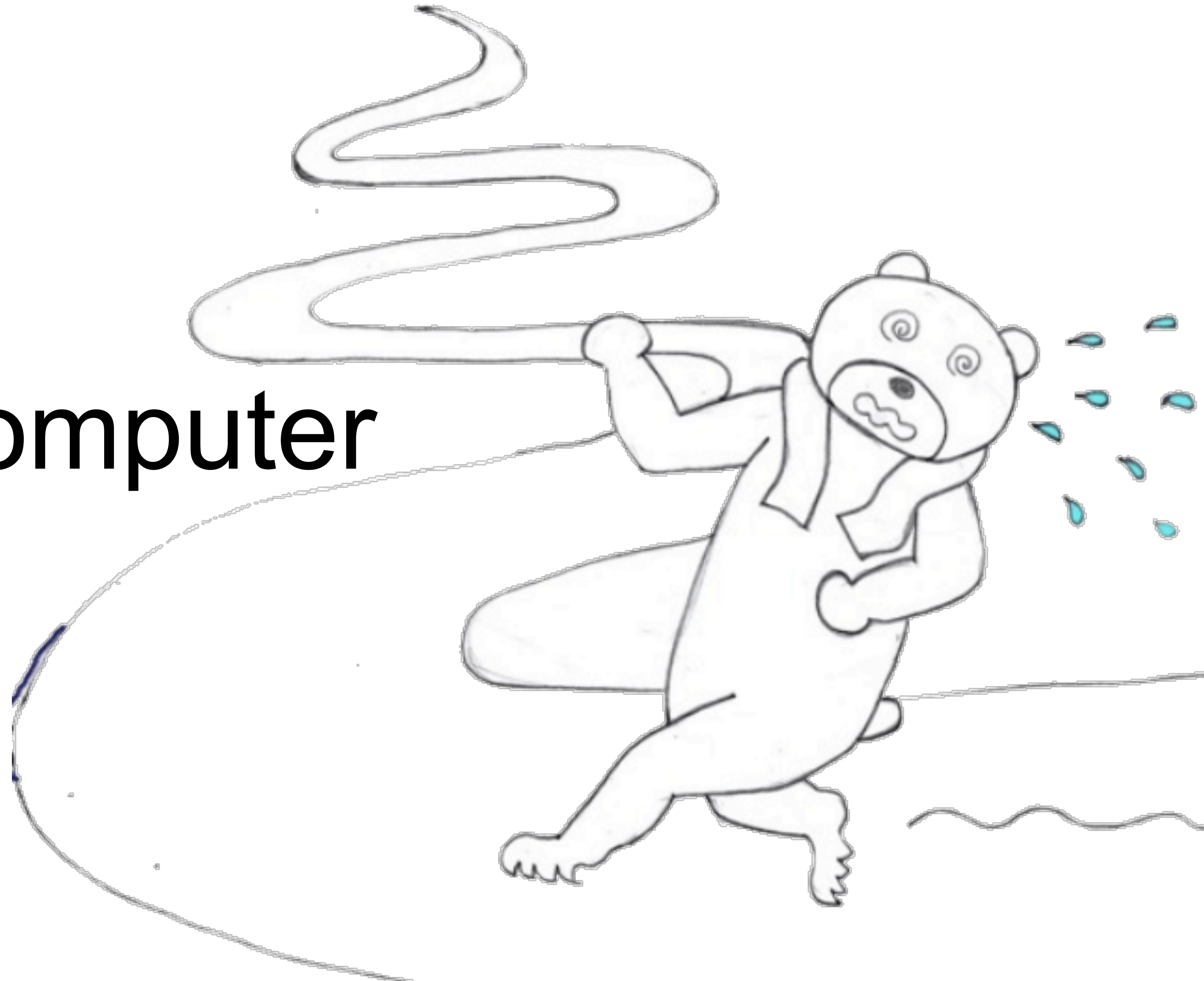
Summary

Good news:

- Quantum physics is our daily tool.
  Therefore,
  we can easily start quantum computer research.

Bad news:

- At this moment,
  (1) it is unclear whether the quantum computer has promising future or not.
  (2) not so easy to try a real machine.



I have a dream:

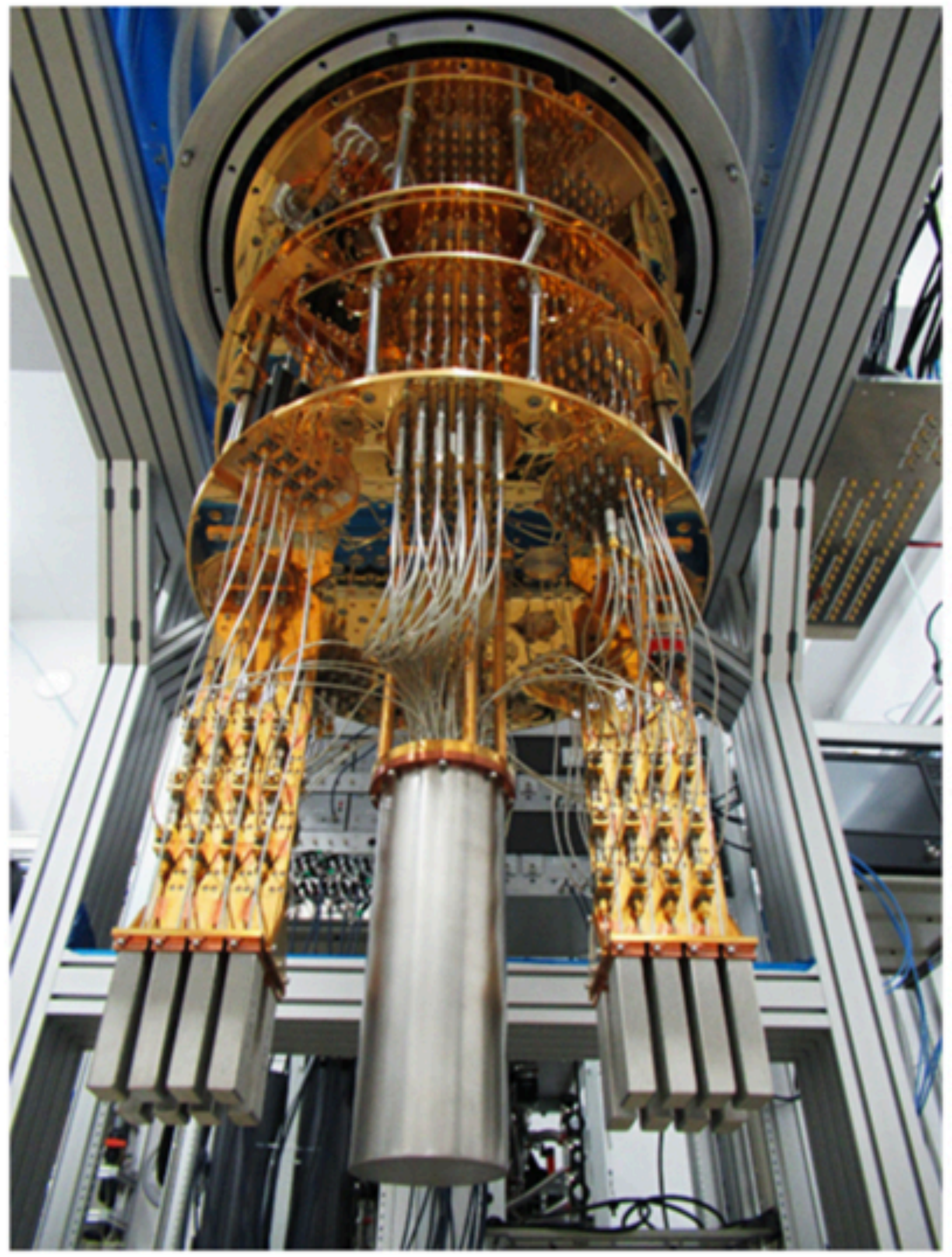


図5 64量子ビット超伝導量子コンピュータ用の希釈冷凍機内の配線

I use Quantum Computer
in lattice QCD simulations.
or
Write down all lattice QCD code
for Quantum Computer !

I hope RCNP introduces a Quantum Computer !
Surely, RCNP high energy group can build
a house maid one.

How to use Quantum Computer in High-Energy Physics

Molecular Dynamics
in Lattice QCD,
which requires
the computer resource.

Great Sword !

But what is your Target ?

Or it is a fun
to write all QCD code
on Quantum Computer.

Important subjects not discussed today

- Quantum supremacy (量子超越性) → **A1**
- Entanglement Entropy → **A2**
- Quantum Fourier Transform → **A3**
- Quantum Teleportation → **A4**
- Error-tolerable quantum computing (誤り耐性量子計算) → **A5**
- Quantum Random Numbers → **A6**
- Inside of the hardware

Backup Slides

A1. Quantum supremacy
A2. Entanglement Entropy in Field Theories
A3. Quantum Fourier Transform using Qiskit
A4. Quantum Teleportation
A5. Error-Tolerable quantum computing
A6. Quantum Random Number Generators

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」 (Jiu zhang). 九章2号 was announced (2020)

Photo by Kaori Nakamura

A2.Entanglement Entropy in Field Theories

量子コンピュータと何の関係があるの？

- 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

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
- 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

Why Interesting

- Information for studying the vacuum of field theories
  - So far ⇒ Correlation functions
  - Entanglement Entropy may be a new Probe
    - Interesting to study SU(3), U(1), scalar
    - Entanglement Entropy may show characteristic feature at Critical Point
    - What happens at finite temperature and density phase transition ?
      - Entanglement Entropy measures the Degrees of Freedom.

        QCD: confinement $O(1)$, Deconfinement $O(N_c^2)$

And many interesting works

- Gravity, Black hole
  - e.g., Ryu-Takayanagi, 2006
  - Tensor Network, MERA (Multi-scale Entanglement Renormalization Ansatz)
- Condensed Matter Physics
  - e.g., Ogawa, Takayanagi, Ugajin - JHEP, 2012
- etc etc

A3. Quantum Fourier Transform using Qiskit

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

目からうろこの

フーリエ変換

フーリエからシュレーディンガーまで

池田 直

What is Qiskit？ https://ja.wikipedia.org/wiki/Qiskit

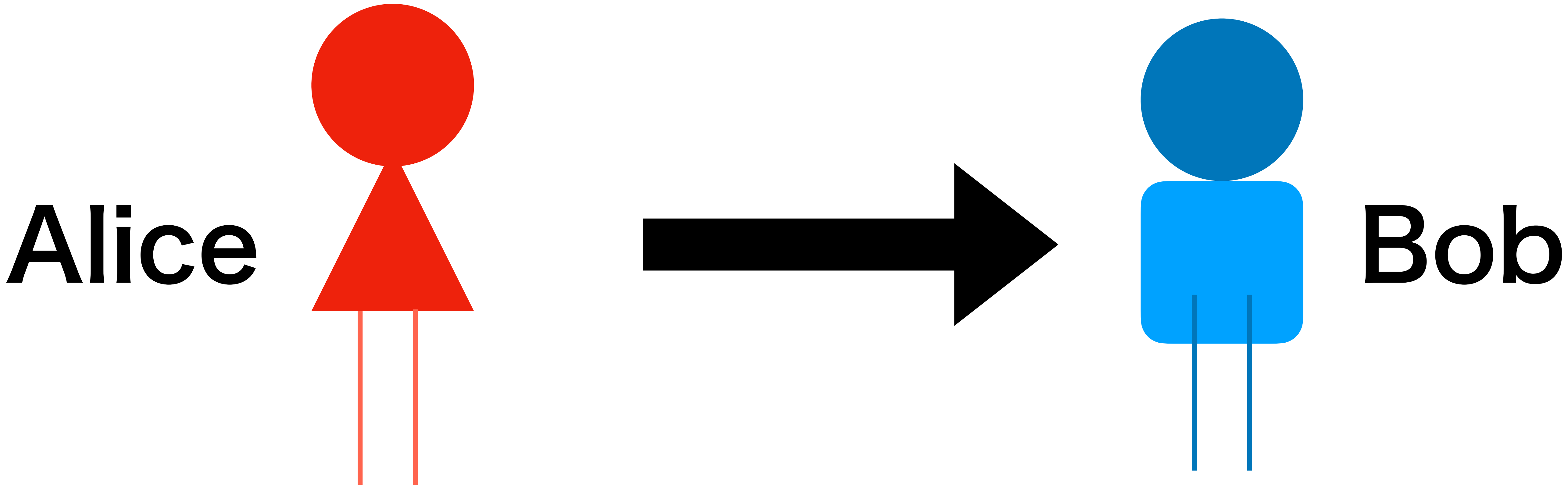
量子フーリエ変換

このチュートリアルでは、量子フーリエ変換（QFT）の紹介と、回路の導出、Qiskitを使用した実装を紹介します。実装においては、シミュレーターと5量子ビットデバイスでQFTを実行する方法を示します。

目次

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

A4. 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 qubit S to Bob ?
5. Alice perform a measurement on her original qubit Q and half of R

A5. Error-tolerable quantum computing (誤り耐性量子計算)

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

No-cloning theorem: (量子複製不可能定理)

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

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

from JST CRDS “R/D and industry trends”

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

A7. 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 …