
TOHOKU UNIVERSITY
T-STARS
SUPERPOSITIONED TALENTS
AND ARTISTIC RESONANCE STATION

Quantum annealing and its application to real world

Graduate School of Information Sciences, Tohoku University
Institute for Innovative Research, Tokyo Institute of Technology
Sigma-i Co. Ltd.
Masayuki Ohzeki

Quantum annealing

Combinatorial Optimization Problem

- ✓ **Discrete variables**
- ✓ Cost function to be minimized(maximized) and with various constraints
- ✓ **Many applications exist in industry**
- ✓ **However it often takes exponentially long time to solve them (NP-hard)**

Quantum Annealing

- ✓ **A method to solve combinatorial optimization problem**
- ✓ The cost function is written as **quadratic unconstrained binary optimization**

$$E(\mathbf{x}) = \sum_{i,j} Q_{ij} x_i x_j \rightarrow H_0(\boldsymbol{\sigma}^z) = \sum_{i,j} J_{ij} \sigma_i \sigma_j + \sum_i h_i \sigma_i$$

Physical Realization

- ✓ **Quantum superposition** would search the ground state **from all the configurations**.

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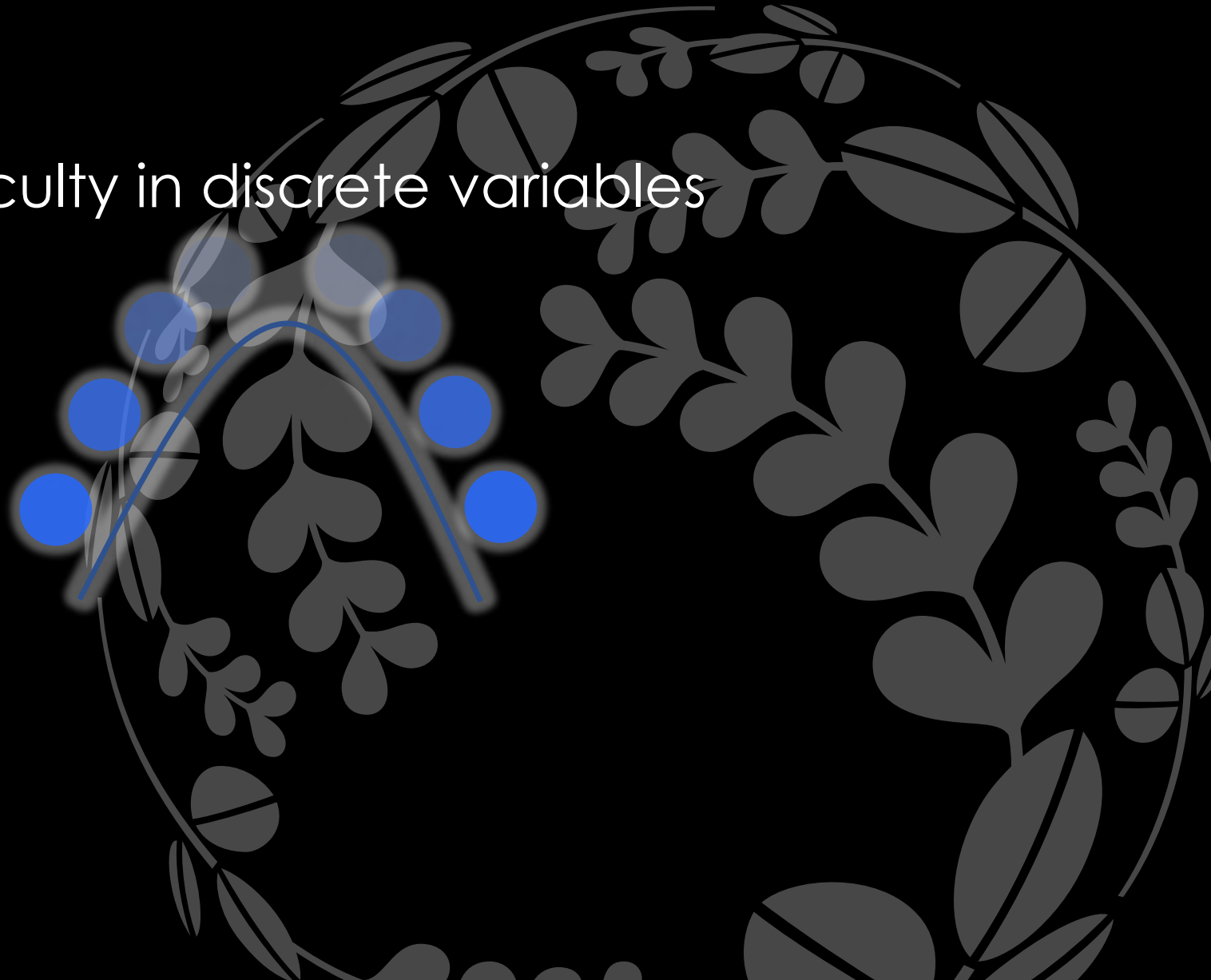
Quantum annealing

Difficulty in discrete variables



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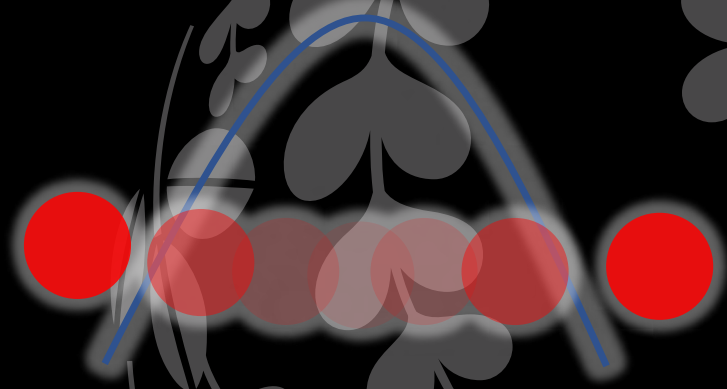
Quantum annealing

Penetrate wall of potential energy



By use of tunneling effect

Search ground state
while escaping from local minimum?
---- Quantum annealing

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Quantum annealing

T. Kadowaki and H. Nishimori: Phys. Rev. E, 58, 5355 (1998)

Proposal of quantum annealing(1998)

- ✓ As a pure science but now in industry in some sense
- ✓ D-Wave Systems Inc. realized and commercialized

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Quantum annealing

T. Kadowaki and H. Nishimori: Phys. Rev. E, 58, 5355 (1998)

2048 quantum bits

Computational time **20μs**

Power **20fW** +20kW

Since 2017 we use cloud service

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5640 quantum bits

Computational time **20μs**

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A hybrid system

Solve optimization problems
with a **million** variables

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Our laboratory

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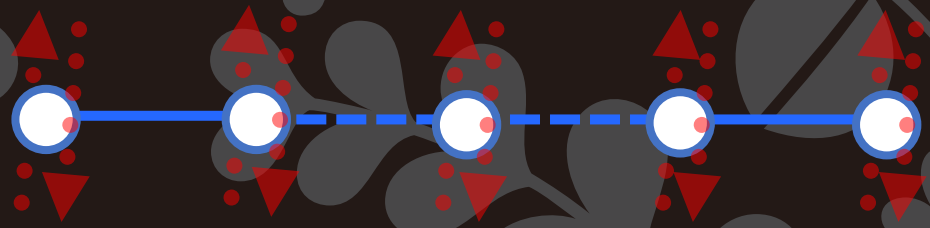
Outline

✓Formulate optimization in terms of “Ising model”

✓Introduce quantum fluctuation as a transverse field



Potential energy

Kinetic energy

Points

- ✓ Assurance: quantum adiabatic condition
- ✓ NP-hardness remains even by use of quantum mechanics
- ✓ Quantum annealing is a generic solver

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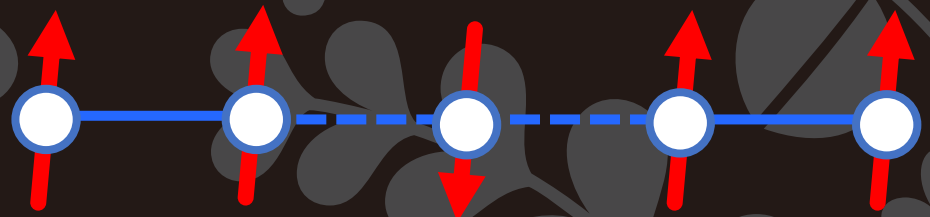

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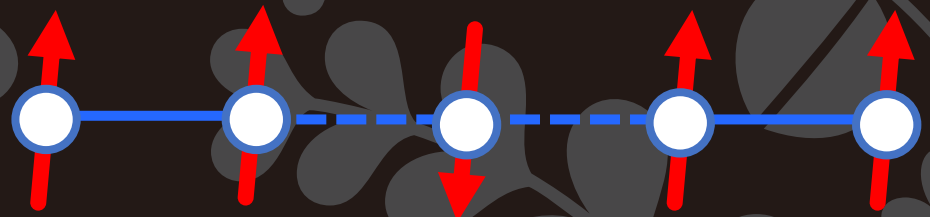

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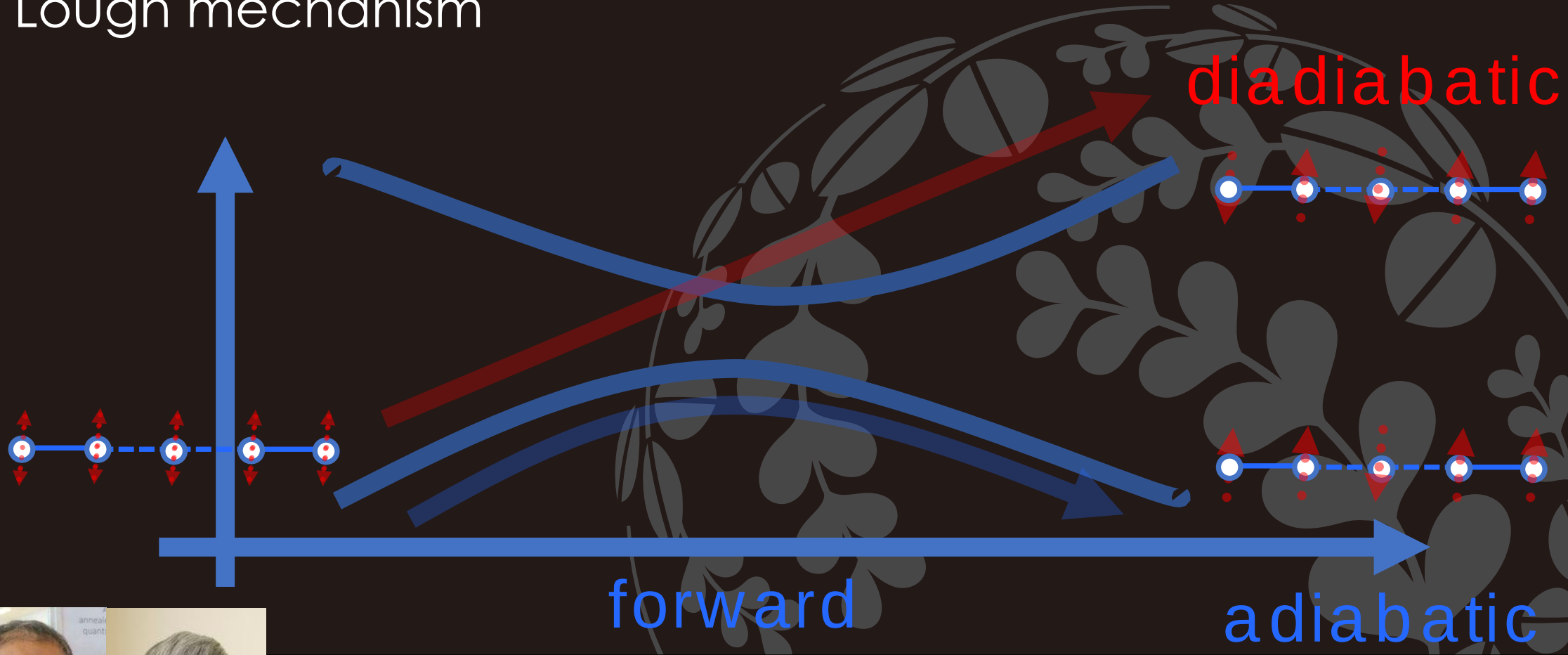
Lough mechanism



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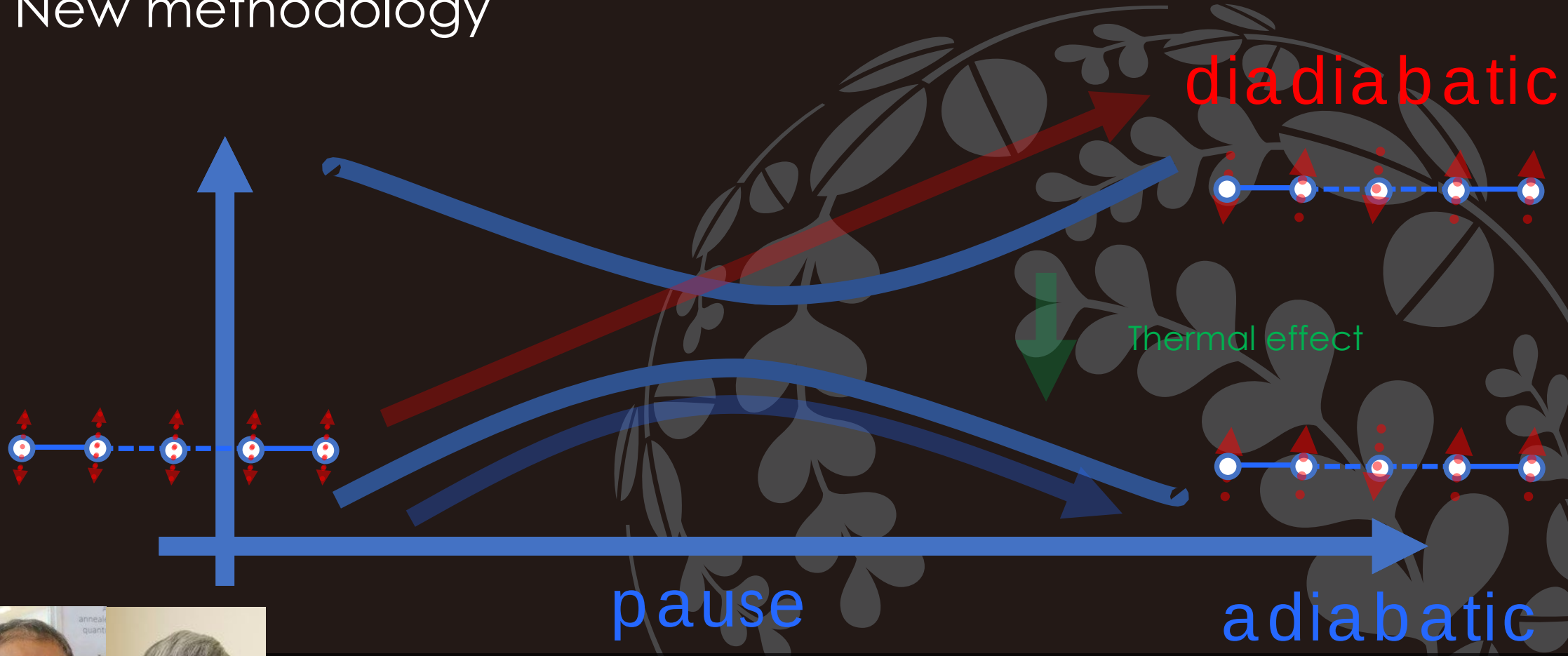
New methodology



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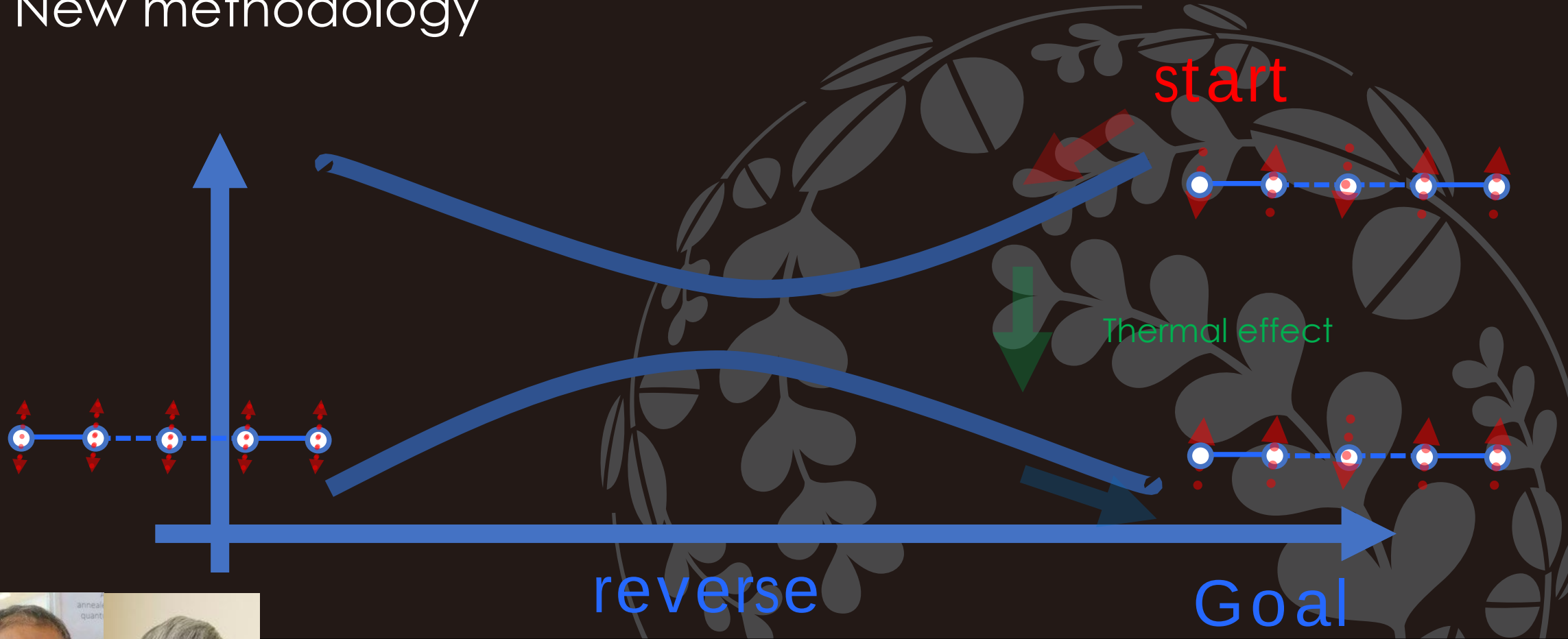

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Quantum annealing

D-Wave: The first commercial “quantum computer”

Many institutes and companies implement

“Lockheed Martin”, “NASA and Google”, “Los Alamos”, “OakRidge”, etc

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JUL 1, 2019

Sigma-i and D-Wave Announce Largest-Ever Quantum Cloud-Access Contract

Sigma-i
Integrate your ideas, our eyes and

Collaboration combines deep quantum expertise with powerful quar

Tokyo, Japan (July 2, 2019) – Sigma-i Co., Ltd., a company forn
quantum computing technologies, and D-Wave Systems Inc., the le
systems, software and services, today announced the companies ha
quantum cloud contract. Sigma-i will offer quantum consulting services and access to the D-Wave

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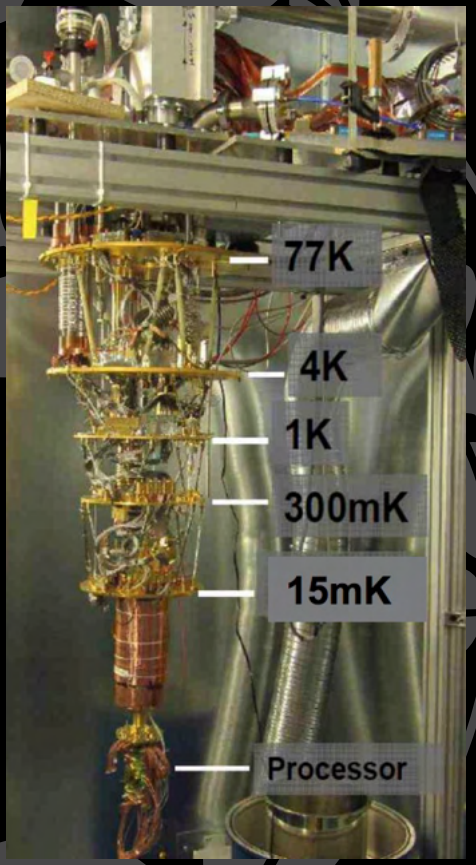

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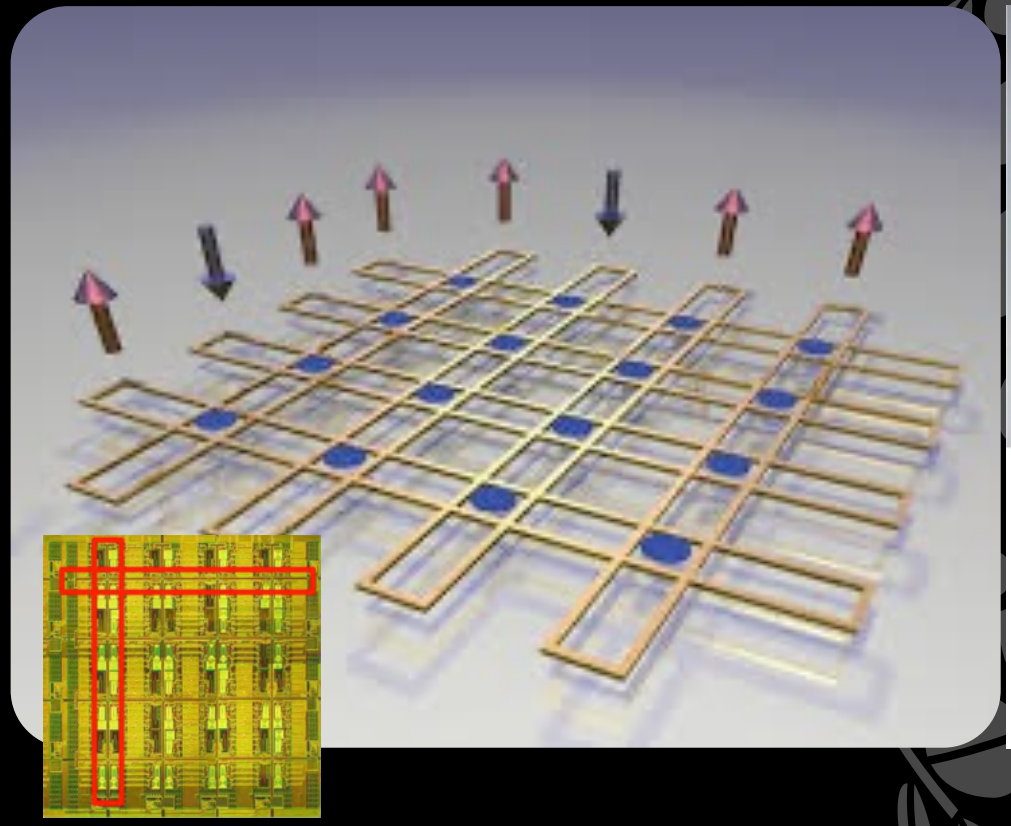

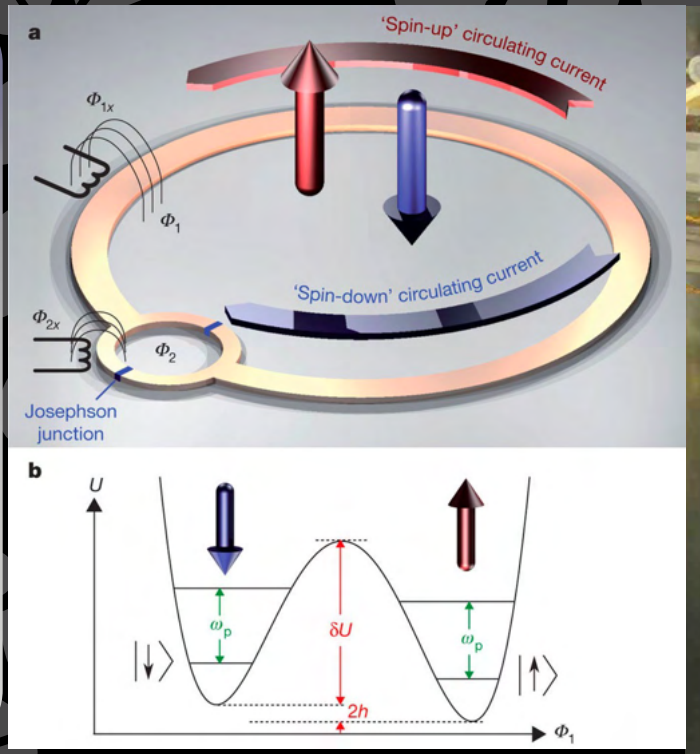

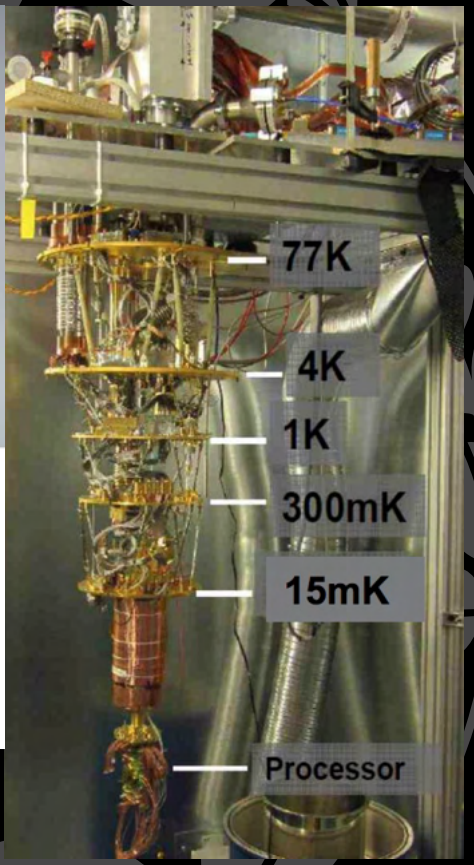

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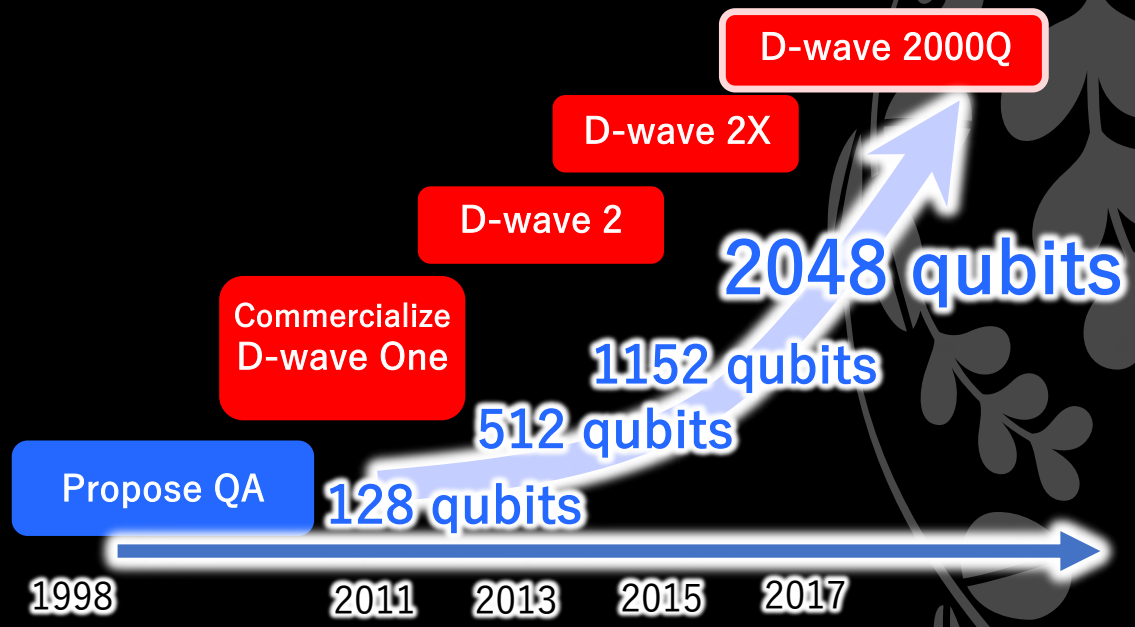
Quantum annealing

D-Wave: The first commercial “quantum computer”

Many institutes and companies implement

“Lockheed Martin”, “NASA and Google”, “Los Alamos”, “OakRidge”, etc

With 5000+ qubits



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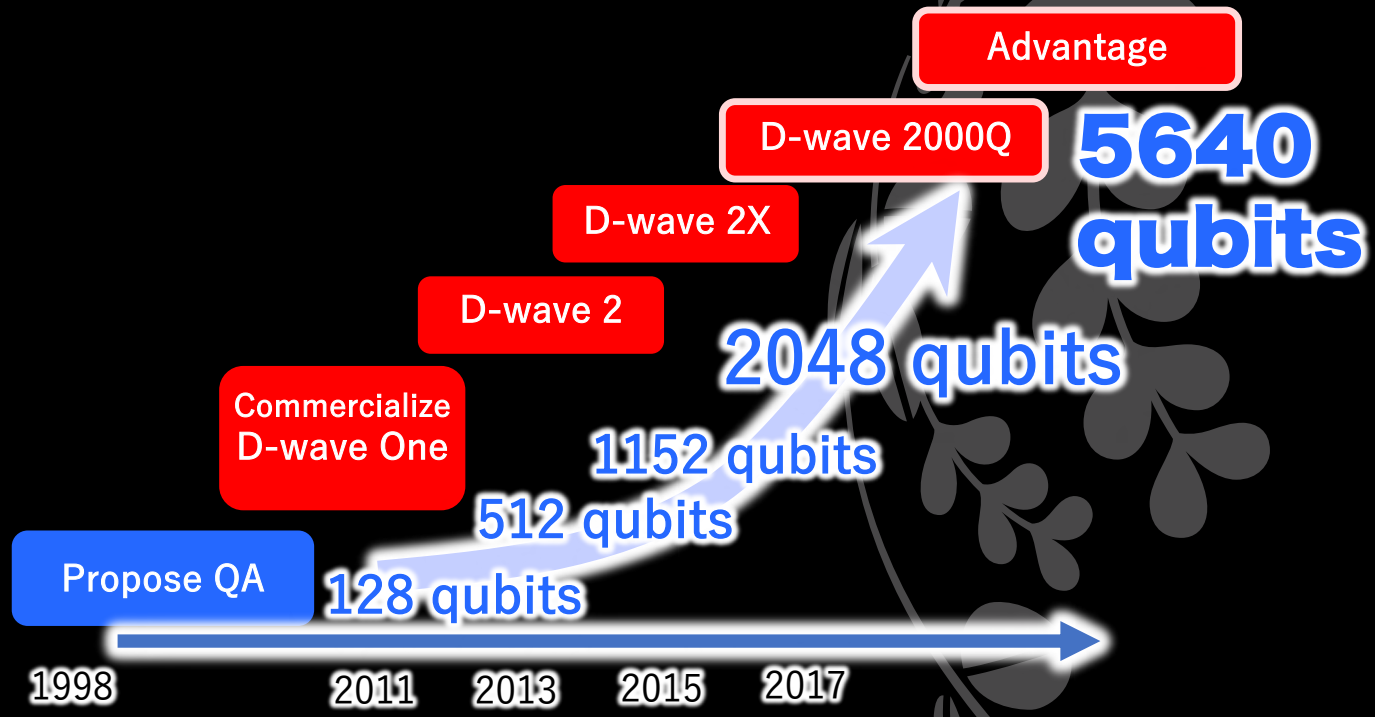

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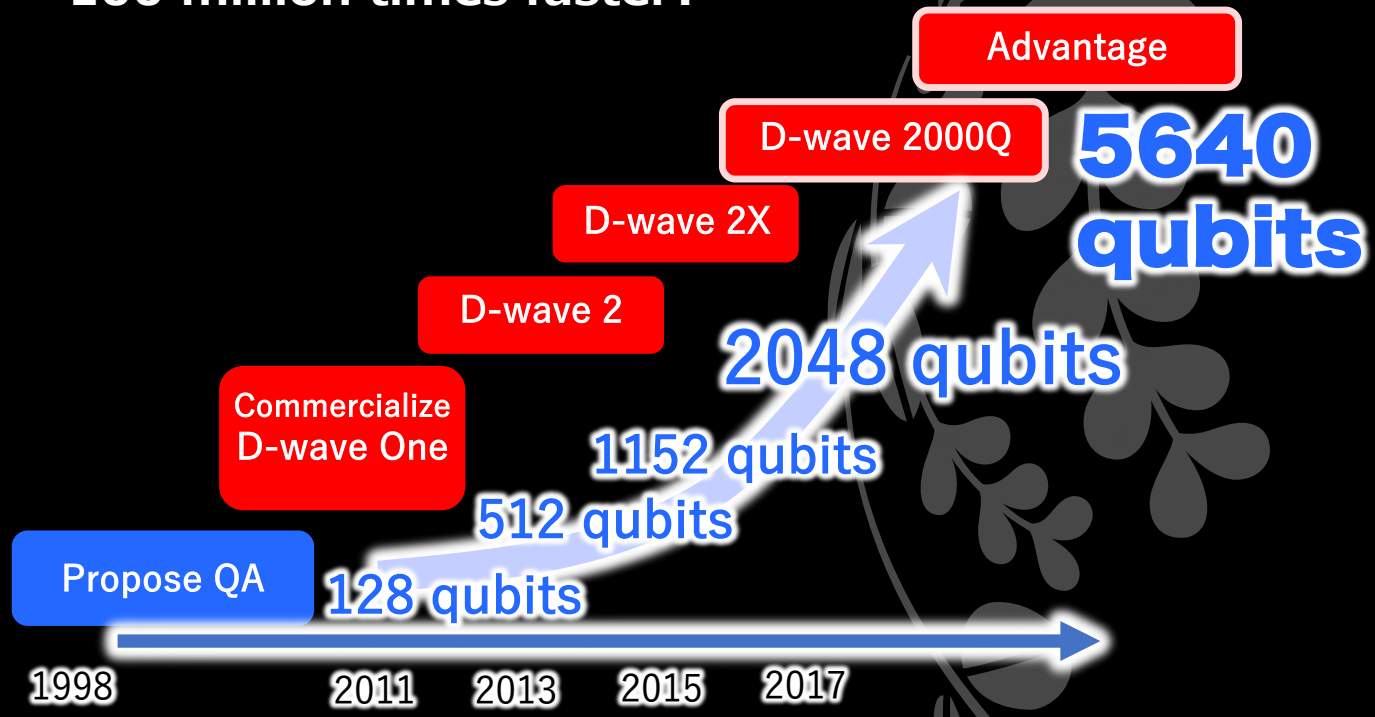
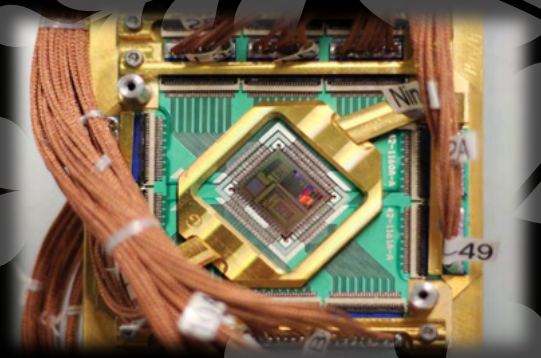
Quantum annealing

D-Wave: The first commercial “quantum computer”

- Many institutes and companies implement
  “Lockheed Martin”, “NASA and Google”, “Los Alamos”, “OakRidge”, etc
- With 5000+ qubits
- Extremely low temperature
- Extremely low power consumption
- **100 million times faster?**





20fW
(quantum processing unit)

20kW
(dilution refrigerator)

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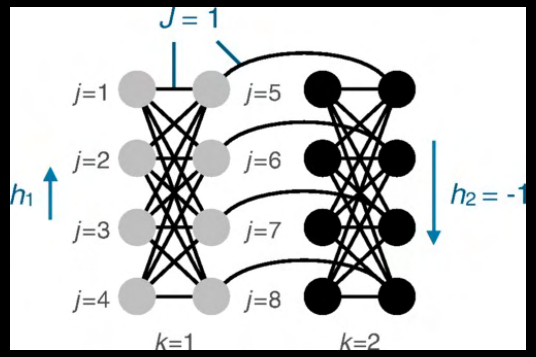
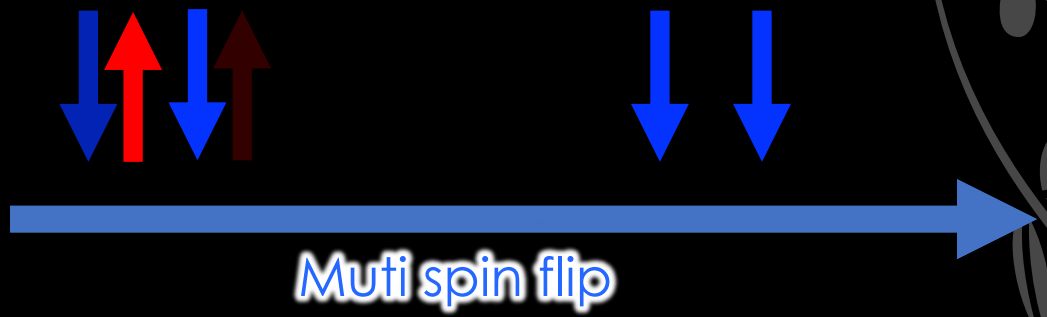
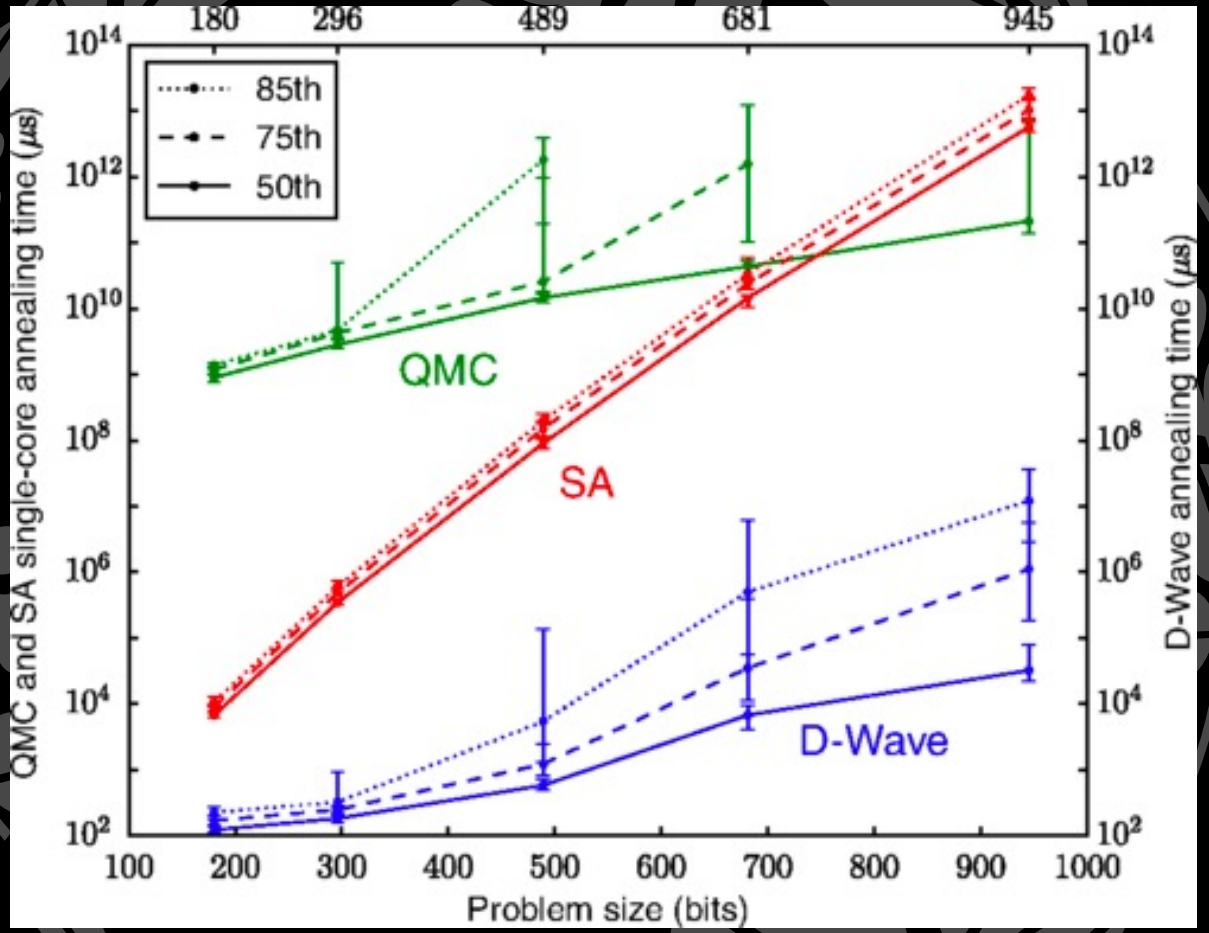




Vasil S. Denchev et. Al. Phys. Rev. X **6**, 031015



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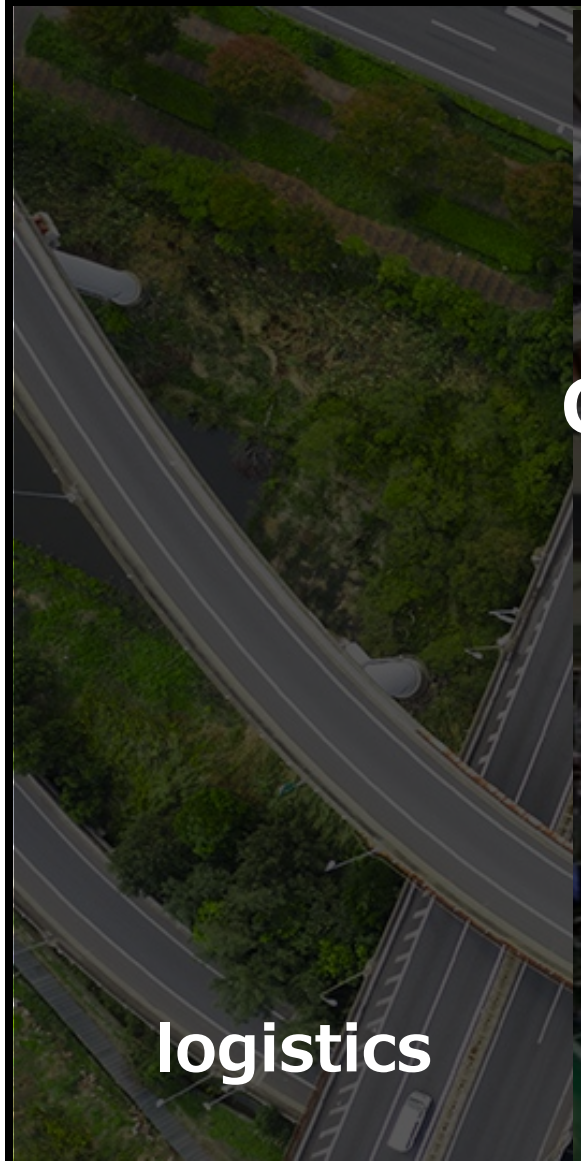
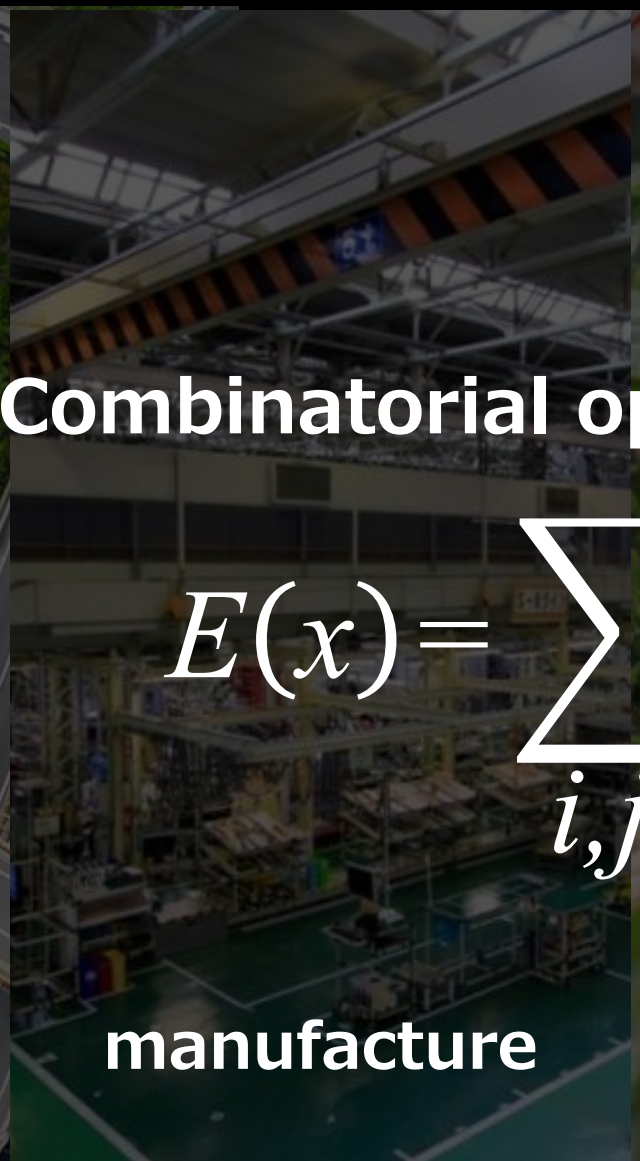
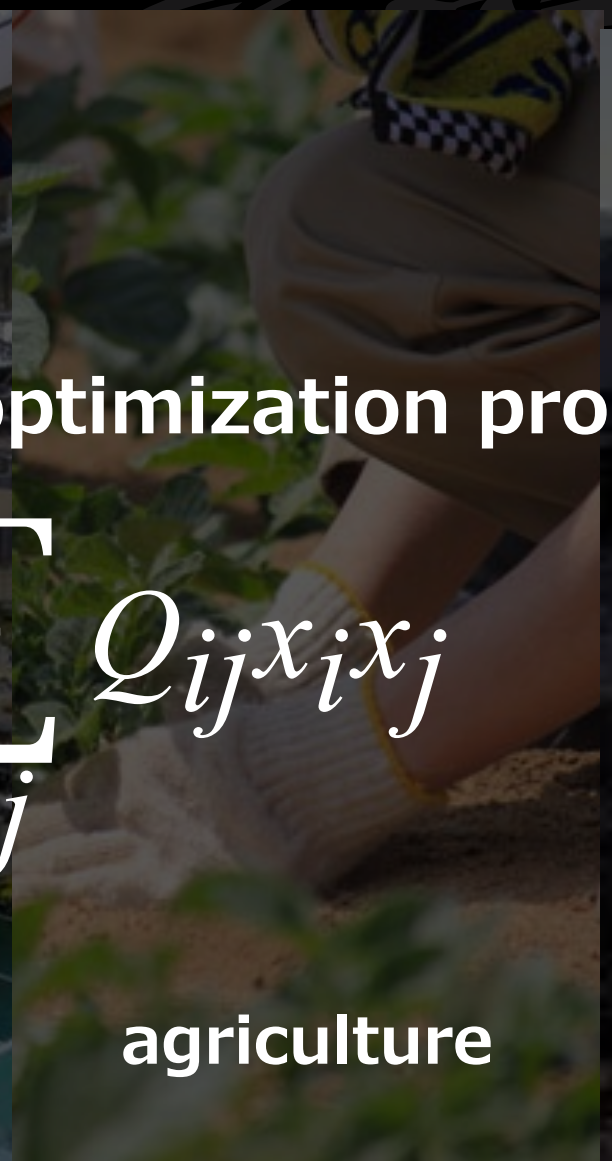
Quantum annealing in real industry

Target







Combinatorial optimization problem

$$E(x) = \sum_{i,j} Q_{ij} x_i x_j$$

logistics

manufacture

agriculture

disaster prevention

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Quantum annealing in real industry

Target

T-QARD：東北大学量子アニーリング研究開発センター

Tohoku university Quantum Annealing Research and Development

Application to real world

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SUPERPOSITIONED TALENTS AND ARTISTIC RESONANCE STATION

Quantum annealing in real industry

Target

Tohoku University QARD -Break limit of your potential-

T-QARD Research Network

Institute for creative future

T-QARD：東北大学量子アニーリング研究開発センター

Tohoku university Quantum Annealing Research and Development

- ✓ Starting from JST-START project
- ✓ Promoting Collaborative researches
- ✓ Established two startups: Sigma-i Co., Ltd., and Jij Inc.

✓We perform various collaborations with companies

✓Automated guided veheciles with DENSO Corp.

M. Ohzeki, A. Miki, M. J. Miyama and M. Terabe: Front. Comput. Sci., (2019)

✓Hotel recommendation「Jaran」 with Recruit Life Style

N. Nishimura, K. Tanahashi, K. Suganuma, M. J. Miyama and M. Ohzeki:Front. Comput. Sci., 16 (2019)

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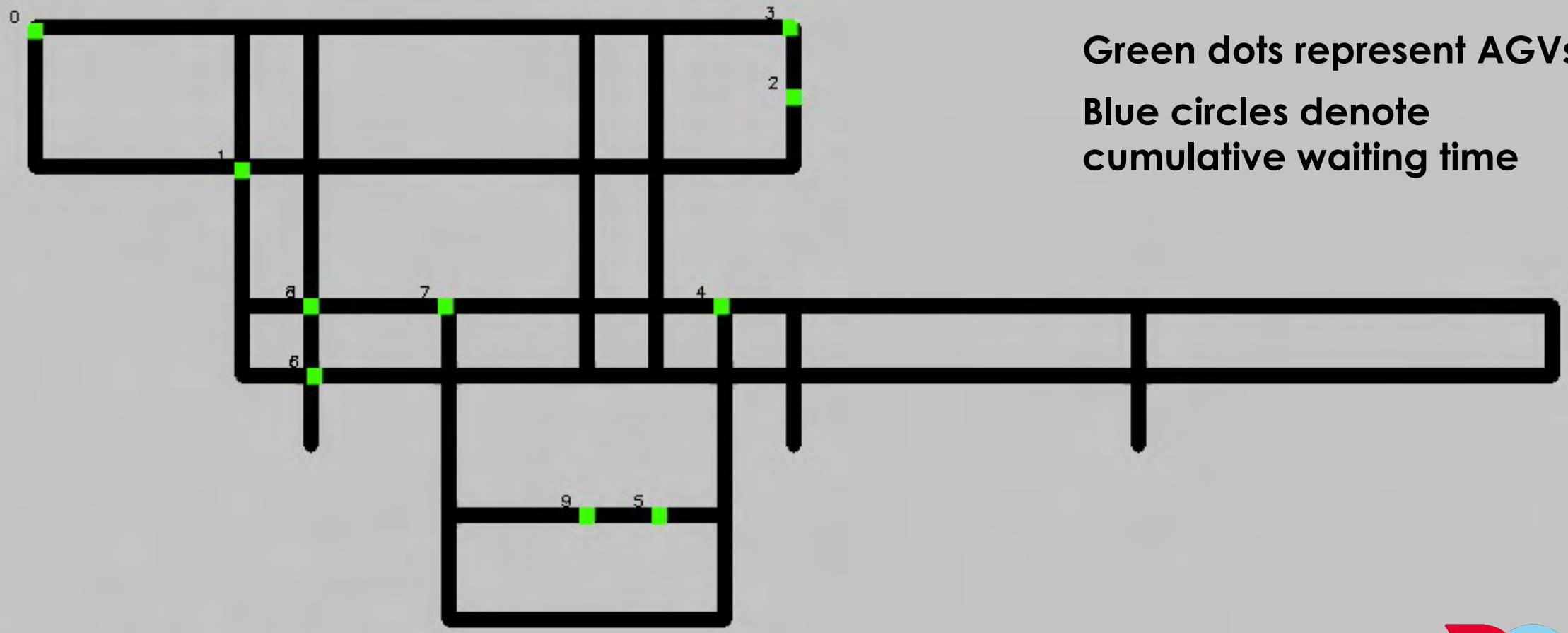
Quantum annealing in real industry

DENSO: Automated Guided Vehicles

Tohoku University QARD | T-QARD Research Network
Institute for creative future



Green dots represent AGVs

Blue circles denote cumulative waiting time

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DENSO × QUANTUM

Quantum annealing in real industry

DENSO: Automated Guided Vehicles

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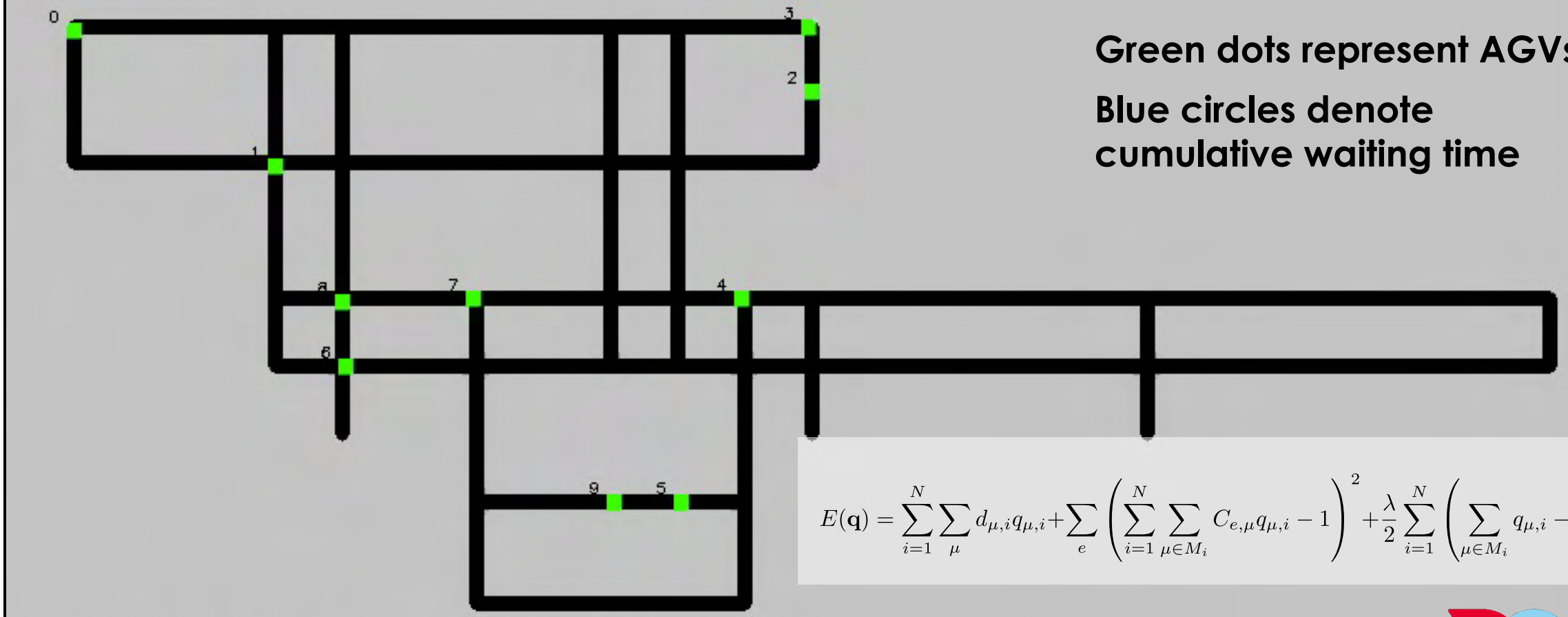

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$$E(\mathbf{q}) = \sum_{i=1}^{N} \sum_{\mu} d_{\mu,i} q_{\mu,i} + \sum_{e} \left(\sum_{i=1}^{N} \sum_{\mu \in M_i} C_{e,\mu} q_{\mu,i} - 1 \right)^2 + \frac{\lambda}{2} \sum_{i=1}^{N} \left(\sum_{\mu \in M_i} q_{\mu,i} - 1 \right)^2$$

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DENSO × QUANTUM

Quantum annealing in real industry

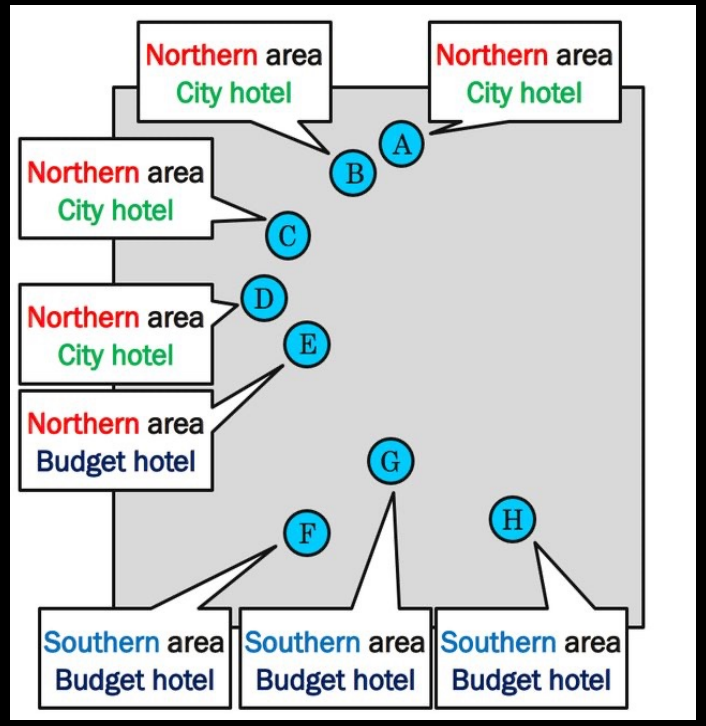
Recruit Life Style: Jaran

Optimization in Jaran service

N. Nishimura, K. Tanahashi, K. Suganuma, M. J. Miyama and M. Ohzeki : Front. Comput. Sci., 16 (2019)

working hypothesis
Listing of similar regions and classes lead to decrese of the number of bookings.

We employ D-Wave machines for a better listing with increase in diversity



$$\text{maximize} \sum_{i\in I}\sum_{j\in J} p_{ij}x_{ij} - w\sum_{i\in I}\sum_{i'\in I}\sum_{j\in J}\sum_{j'\in J} f_{ii'}d_{jj'}x_{ij}x_{i'j'}$$

$$\text{subject to} \sum_{i\in I} x_{ij} = 1,\ j \in J,$$

1. C. North City hotel	1. D. North City hotel	1. B. North City hotel
2. B. North City hotel	2. B. North City hotel	2. G. South Budget hotel
3. D. North City hotel	3. F. South Budget hotel	3. A. North City hotel
4. A. North City hotel	4. A. North City hotel	4. E. North Budget hotel
5. E. North Budget hotel	5. E. North Budget hotel	5. H. South Budget hotel
6. F. South Budget hotel	6. G. South Budget hotel	6. C. North City hotel
7. G. South Budget hotel	7. C. North City hotel	7. F. South Budget hotel
8. H. South Budget hotel	8. H. South Budget hotel	8. D. North City hotel

Increase in diversity

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Quantum annealing in real industry

T-QARD: Evacuation System

Kochi city

Tohoku University QARD | T-QARD Research Network

Institute for creative future

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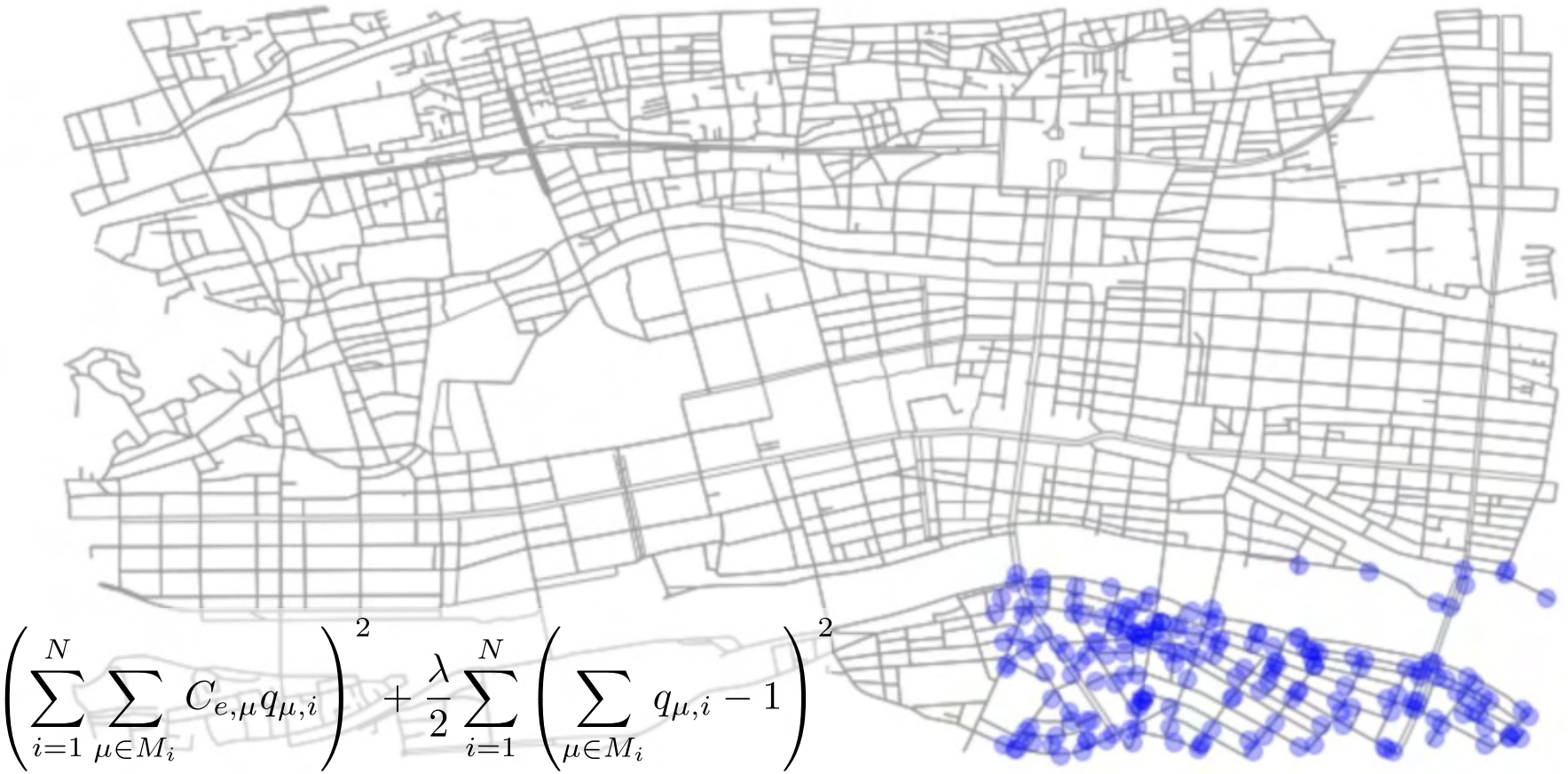

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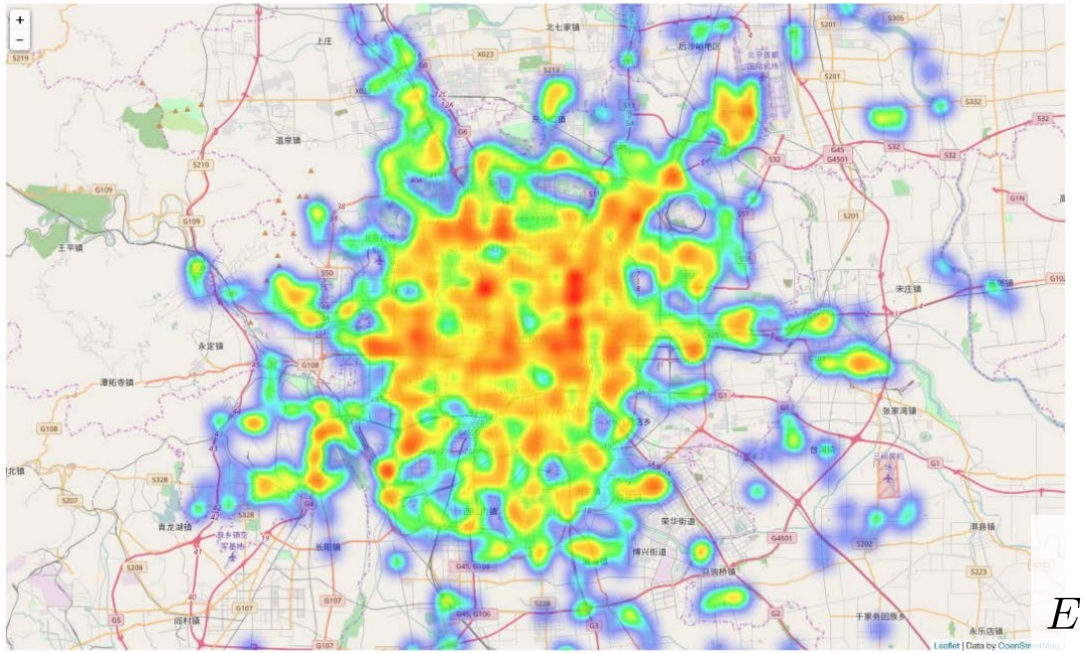
Quantum annealing in real industry

Bible in applications of quantum annealer

Traffic optimization in Beijing

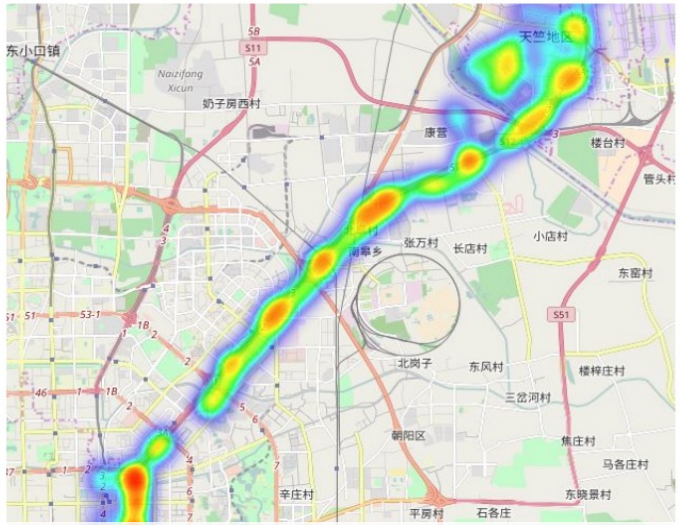
Traffic in the city

- 10.000 cars



Detail: route to the Airport

- 418 cars



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→ We assigned each of the 418 cars 3 possible routes to reach the airport

→ Size of the problem space: 3^418

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Quantum annealing in real industry

Collaborations with many companies

DENSO
Kyocera
Kyocera Communication System
NEC
NEC solution innovator
Aisin AW
Nomura Security
BMW
JFE Steel
Nippon Steel
etc

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Quantum annealing in real industry

D-Wave Qubits 2020
(https://www.youtube.com/watch?v=TdynvPoHxQE)

BMW : Optimization of common parts and vehicle type diversity

Black-box optimization

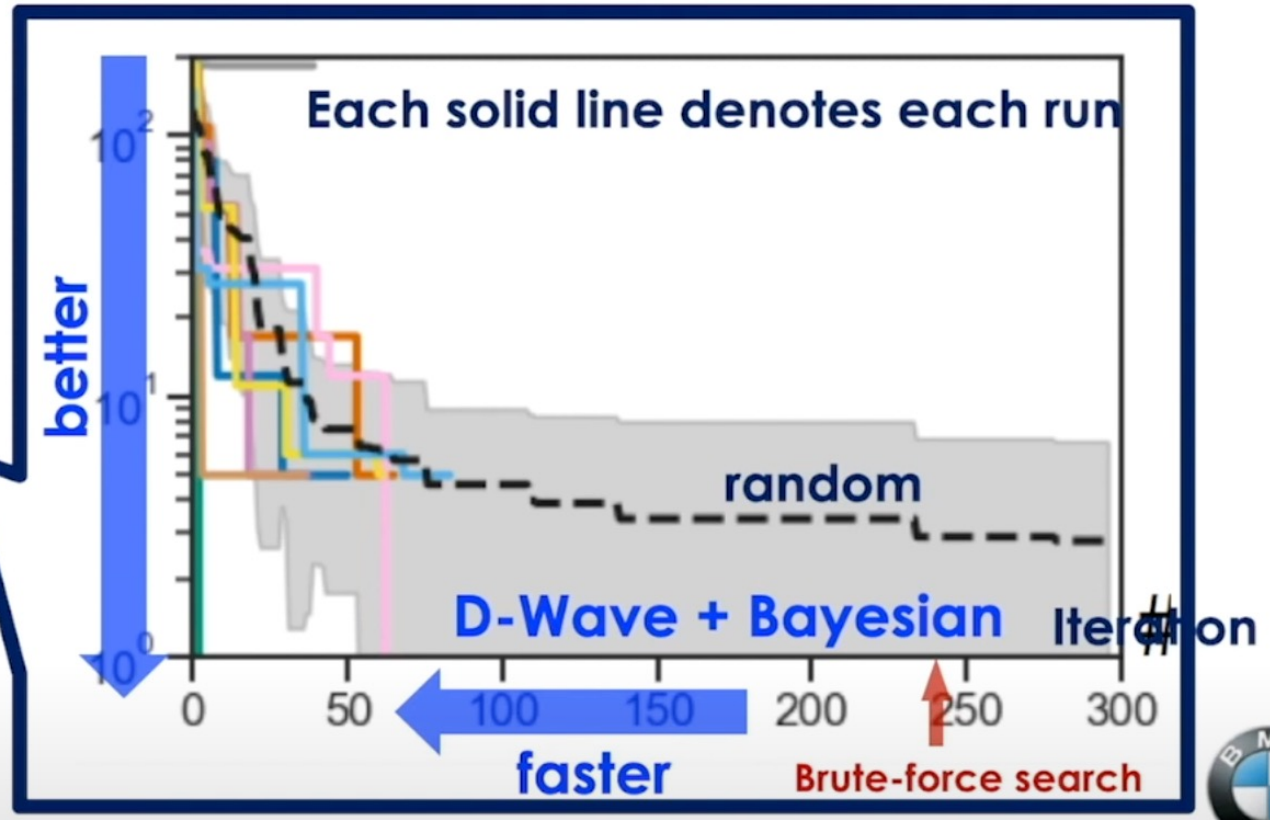
$$E(\mathbf{x}) = -\sum_{i,j} Q_{ij} x_i x_j$$

Inference of suitable form for quantum annealer

$$\max_{\mathbf{x}} \{\mathrm{SC}(\mathbf{x})\} \quad \text{subject to} \quad \mathrm{CI}(\mathbf{x}) = k$$

by comparison between outputs and actual data

Efficiently find the optimal balance.



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For Further development

2018 18th July
Tohoku University and Tokyo Tech has signed a cooperation agreement
also with Keio Uniersity in 2019

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DEC. 2020

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JOINT RESEARCH GROUP

FOR QUANTUM COMPUTING

東北大学量子コンピューティング
共同研究講座始動

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DENSO
Kyocera
Kyocera Communication System
Sigma-i
Sumitomo Cooporation
SCSK

We are always looking for companies to participate

For Further development

Jij

Deployment of middleware and services that utilize quantum annealing

established in 2018.29th November

“Solve hard problems”

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Sigma-i

Integrate your ideas, our eyes and I

Academic tech company,
True academy-industry integration,
For a better world

Scientists themselves will spread technology to society.

established in 2019.4th April

“A future where everyone can shine”

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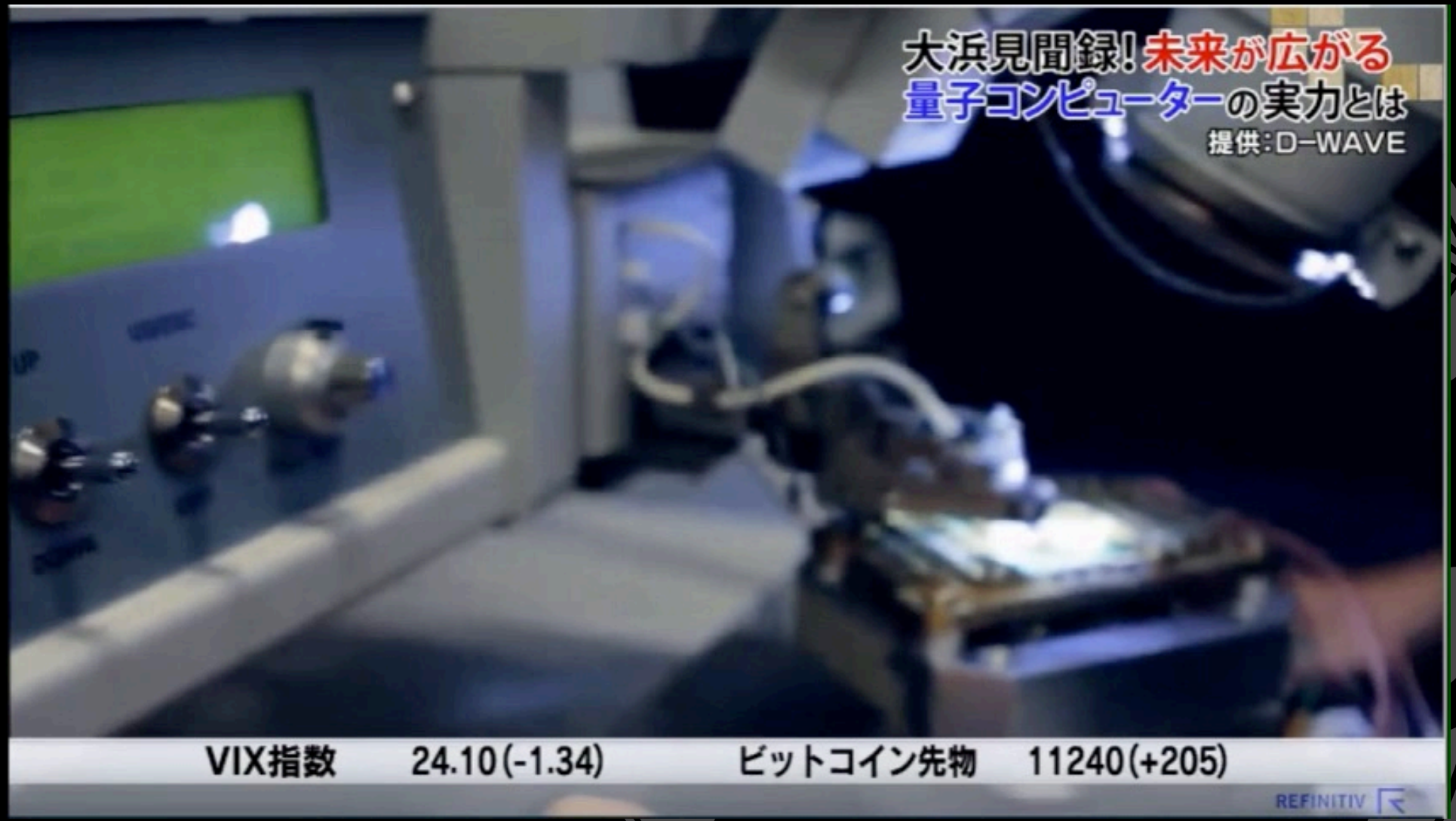
3つの"i"が未来を創造する

For Further development



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Summary

Quantum annealing becomes industry technology

- ✓ D-Wave advantage has 5000+ qubits
- ✓ D-Wave hybrid deal with a million variables
- ✓ Recently D-Wave hybrid directly solves integer problems

Many companies challenge to find a killer application

- ✓ Cost vs benefit (1 hour for QA: 0.2-0.3 million yens)
- ✓ Classical Solvers can deal with a huge number of system but qubo…
- ✓ No applications with quantum nontrivial property until now…
  - ✓ Only optimization
  - ✓ Boltzmann machine?

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