Quantum Neural Network (QNN)
- Connecting Quantum and Brain with Optics -

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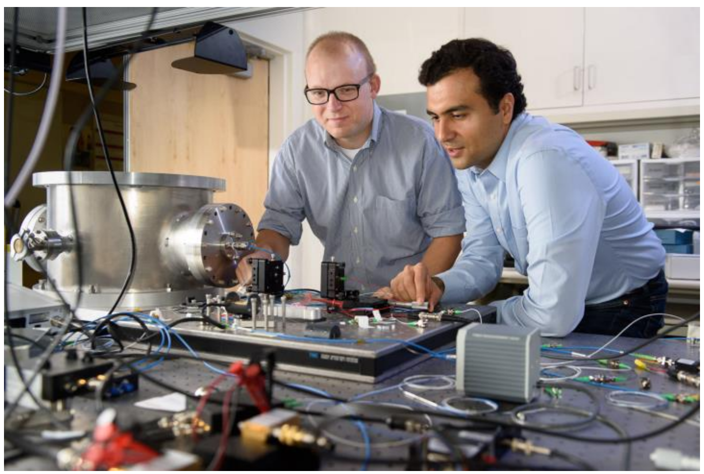


Stanford (2014)
4 neurons, 12 synapses

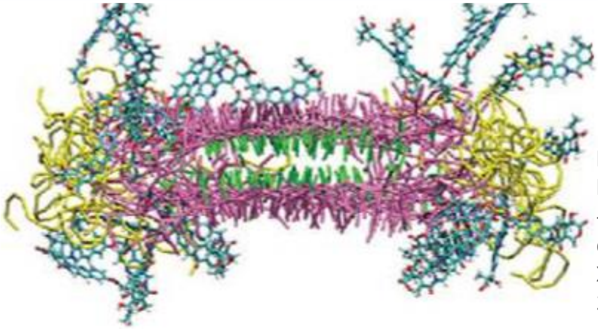
NTT (2016)
2K neurons, 4M synapses

NTT (2019)
Prototype

NTT IR Day (Tokyo, September 26, 2019)

What problems to be solved?

Combinatorial Optimization Problems



https://www.semanticscholar.org/paper/Filamentous-supramolecular-peptide-drug-conjugates-Yang-Xu/a3062f178bde8f7b3156309a3042e199f86cb5e7

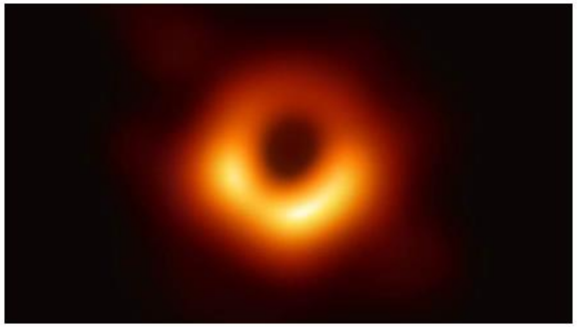
Lead optimization for discovery of

- small molecule drug
- peptide drug
- biocatalyst

https://ja.storyblocks.com/stock-image/smart-city-and-wireless-communication-network-abstract-image-visual-internet-of-things-mono-blue-tone--roiwpowejgj044z2ev

Resource optimization in

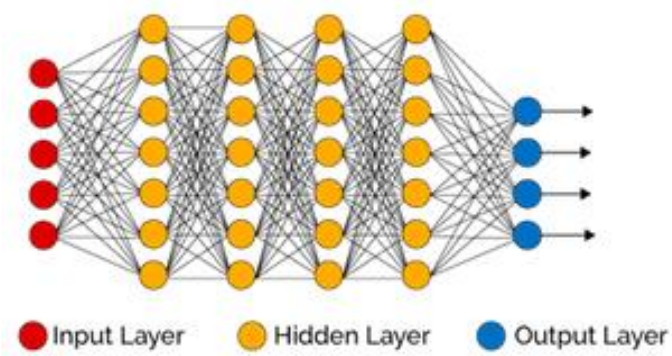
- wireless communication
- logistics
- scheduling



https://ja.wikipedia.org/wiki

Compressed sensing (sparse coding) in

- Astronomy
- Magnetic Resonance Imaging (MRI)
- Computed Tomography (CT)



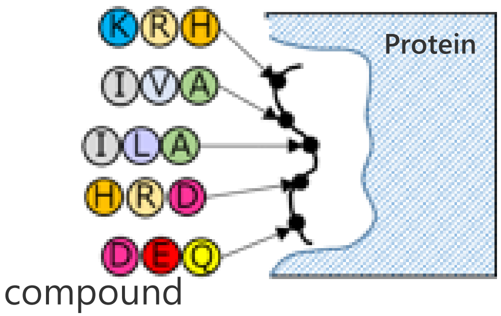
https://iartificial.net/redes-neuronales-desde-cero-i-introduccion/

Deep machine learning in

- Self-driving cars
- Healthcare
- Voice and image recognition

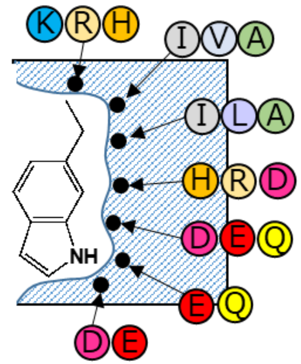
Lead Optimization

- Drug discovery:
  Identify a group of compounds that are attached most stably to a target protein.



Search space
~ 10^{46} (compounds)
Machine size
~ 4000 (neurons)

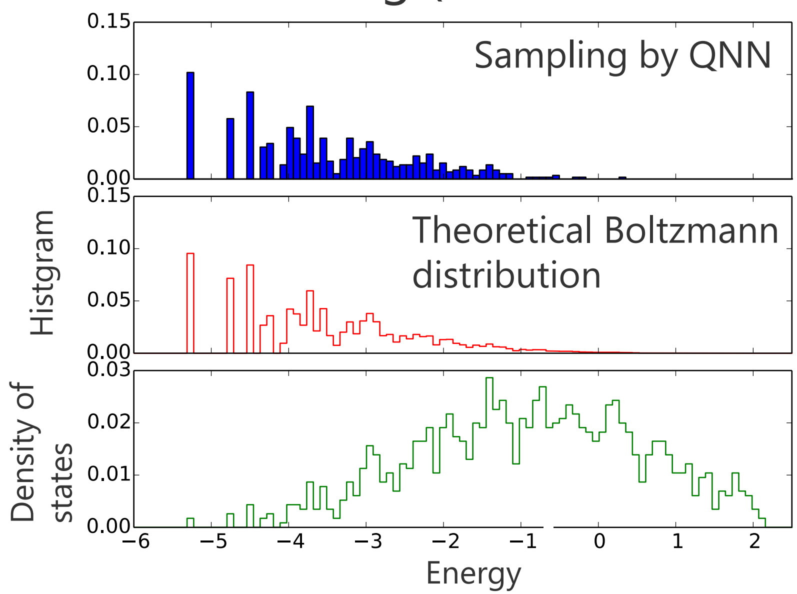
- Biocatalyst discovery:
  Identify a group of proteins that can capture most stably a target compound.



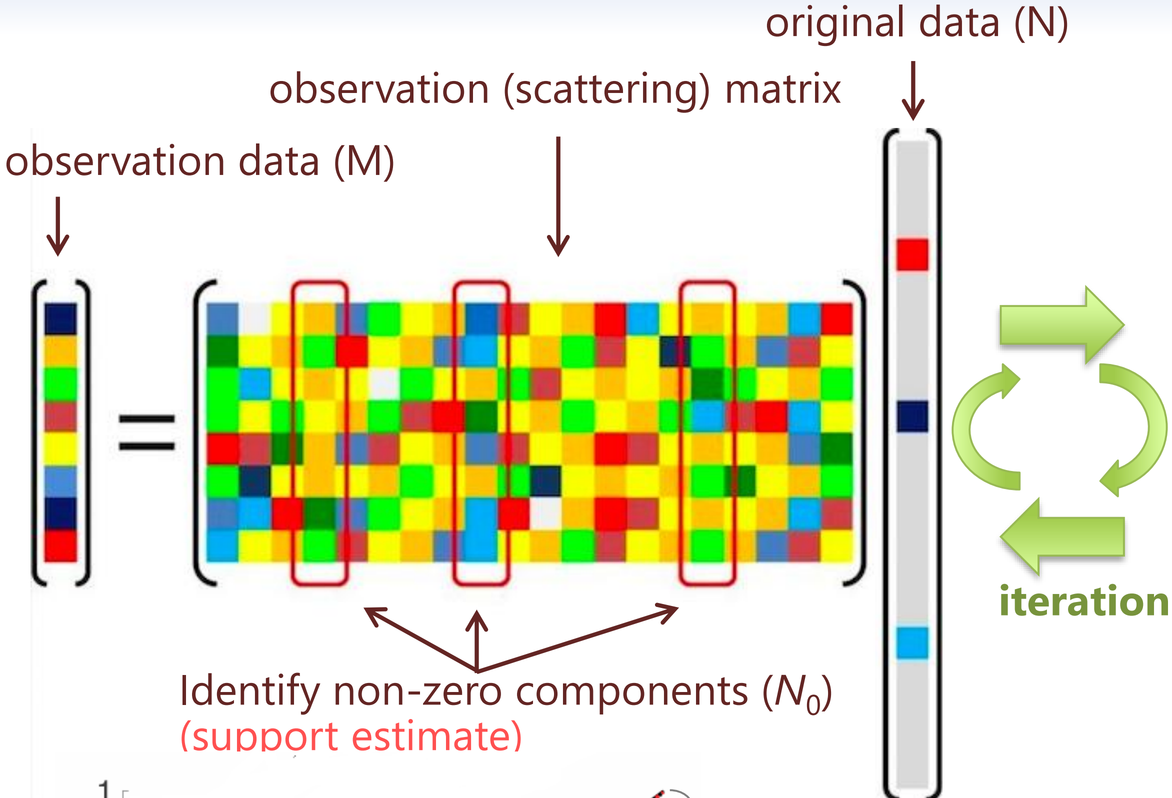
Search space
~ 10^{690} (proteins)
Machine size
~ 60,000 (neurons)

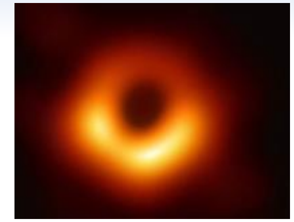
There are only 10^{80} atoms in the observable universe!

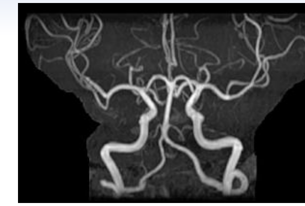
- small molecule drug (6 sites/6 atomic species)

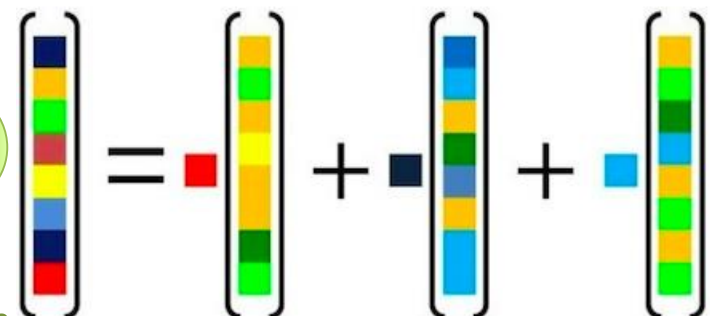


Compressed Sensing (Sparse Coding)

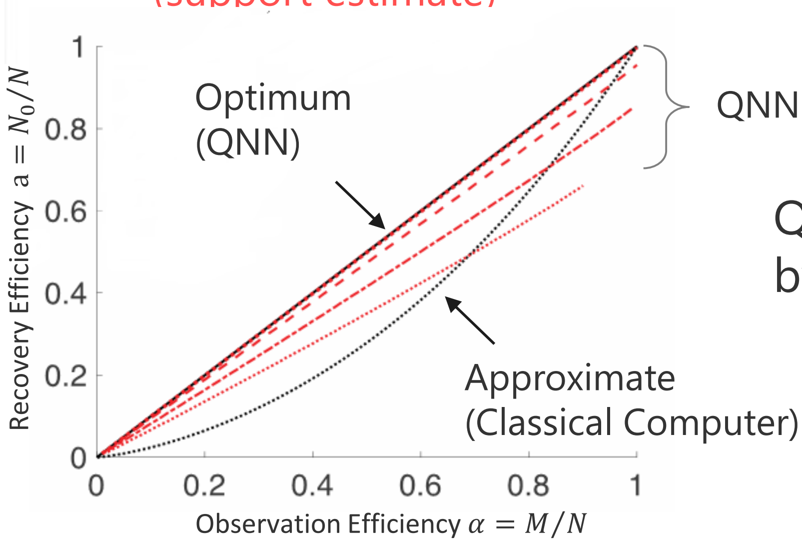



Black Hole


MRI/CT



Solve N_0 unknowns
(inverse matrix computation)



QNN saturates the theoretical limit (Optimum) by deep compressed sensing.

Quantum Computing – Dream or Nightmare -

The Idea of Quantum Computing

Superposition

A gate voltage in classical computer is either 0(V) or 1(V), while qubit in quantum computer is simultaneously |0> state and |1> state.

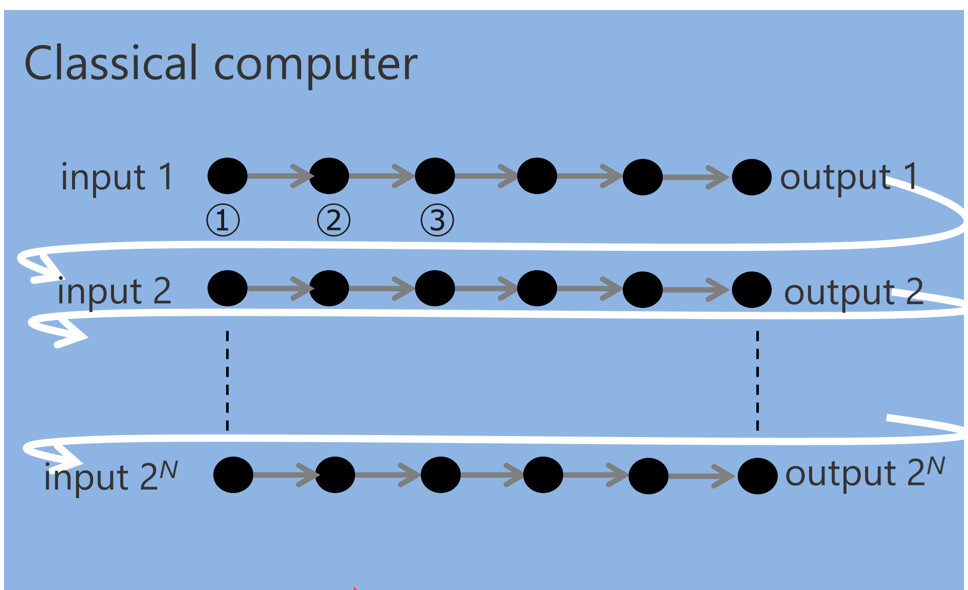
first qubit, second qubit, N-th qubit

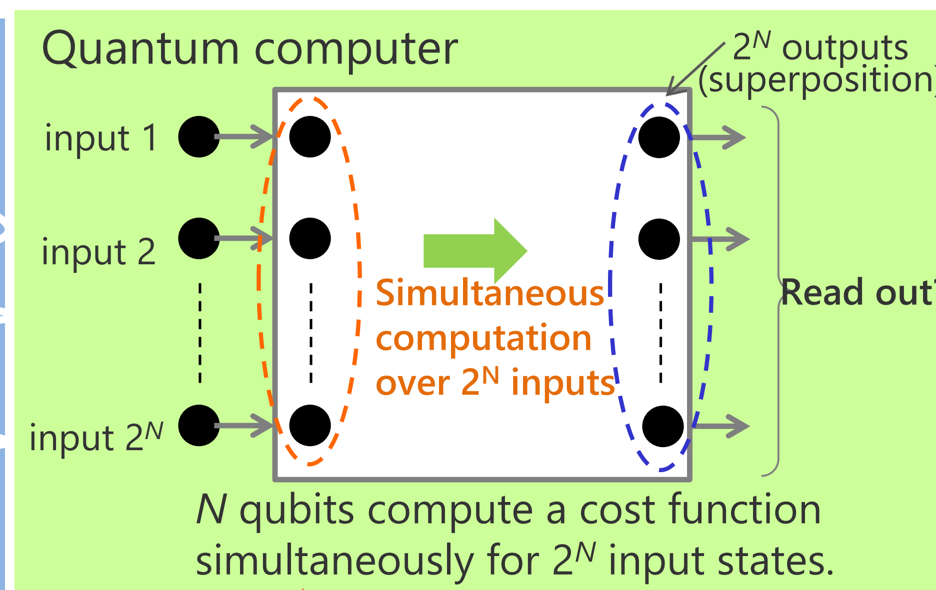
$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_1 \otimes \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_2 \cdots\cdots\cdots\cdots \otimes \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_N$$

$$= \frac{1}{\sqrt{2^N}}\left(|0\rangle_1|0\rangle_2 \cdots |0\rangle_N + |0\rangle_1|0\rangle_2 \cdots |1\rangle_N \cdots\cdots\cdots\cdots + |1\rangle_1|1\rangle_2 \cdots |1\rangle_N\right)$$

state 1, state 2, State 2^N

***N* qubits can represent 2^N different states simultaneously, while *N* classical gates can represent only one state.**



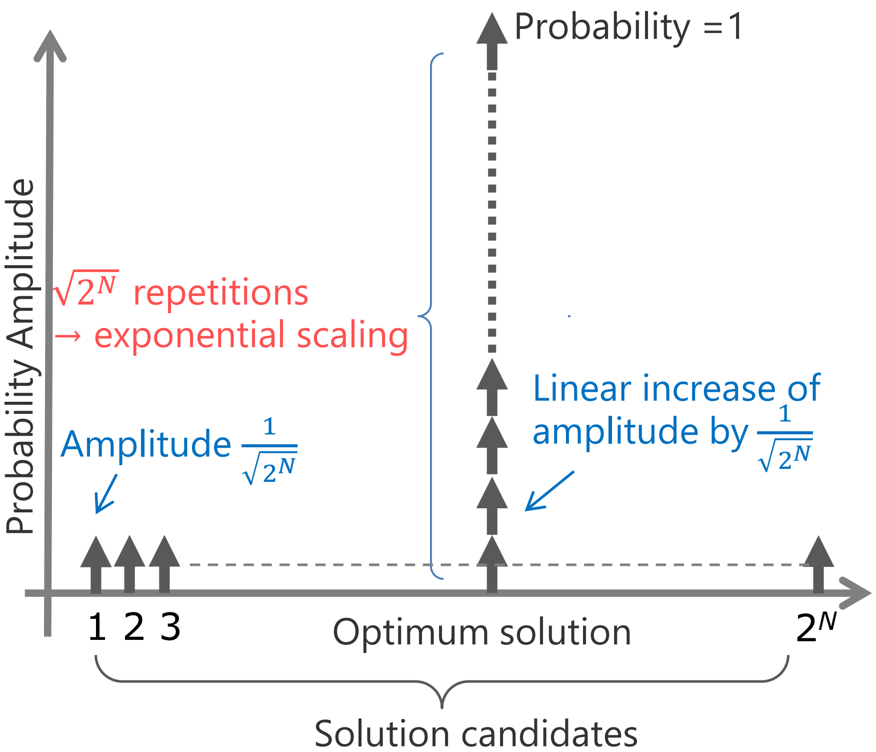


Brute Force Search

Single Run

Weakness of Quantum Computing

Grover (optimum) algorithm (1997)



Optimum algorithm is still highly inefficient.

Time-to-Solution by an ideal quantum computer for the Combinatorial Optimization Problem (Ising model)

Problem Size N (bits)	Time-to-Solutions T_s
20	4×10^{-3} s
50	6×10^{2} s
100	2×10^{10} s (~700 years)
150	6×10^{17} (s) (~20B years)

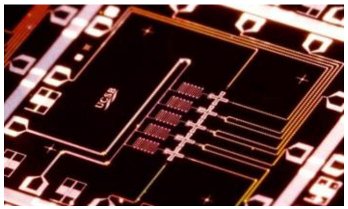
An ideal quantum computer, with no decoherence, no gate error and all-to-all qubit coupling with 1 ns gate time, cannot find a solution even for small-size combinatorial optimization problems.

NTT’s Vision
- Let’s try a fundamentally different approach -

Quantum Neural Network (QNN)

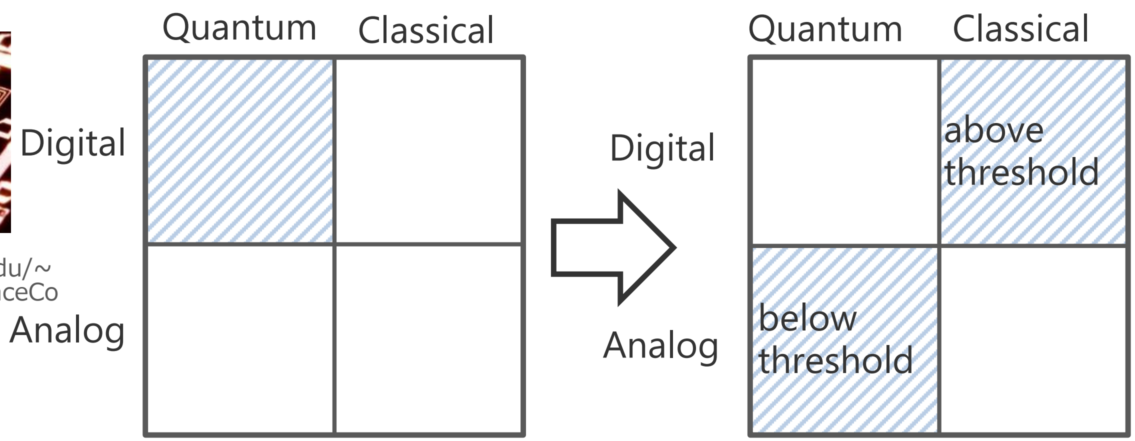
- From quantum only to **quantum and classical simultaneously**

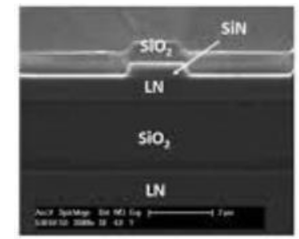
Artificial two-level atom @ 10 mK　　　Optical parametric oscillator @ 300 K



https://web.physics.ucsb.edu/~martinisgroup/photos/SurfaceCodeThreshold.jpg

Superconducting circuit

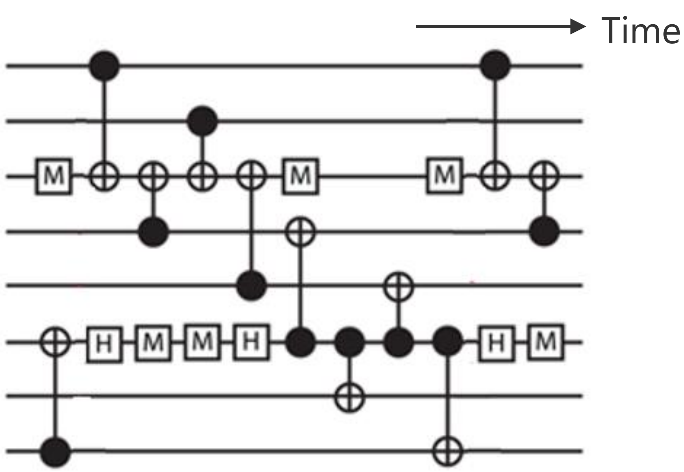




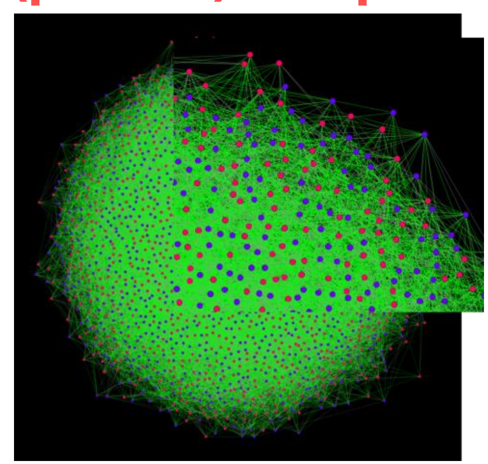
https://optoelectronics.ece.ucsb.edu/sites/default/files/2017-06/C1007_0.pdf

Thin-Film periodically poled $LiNbO_3$ waveguide

- From local (sequential) computation to **global (parallel) computation**



Quantum computer



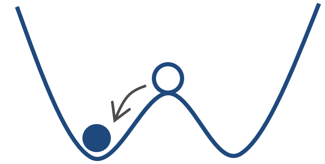
Quantum neural network

Why do we need classical resources ?

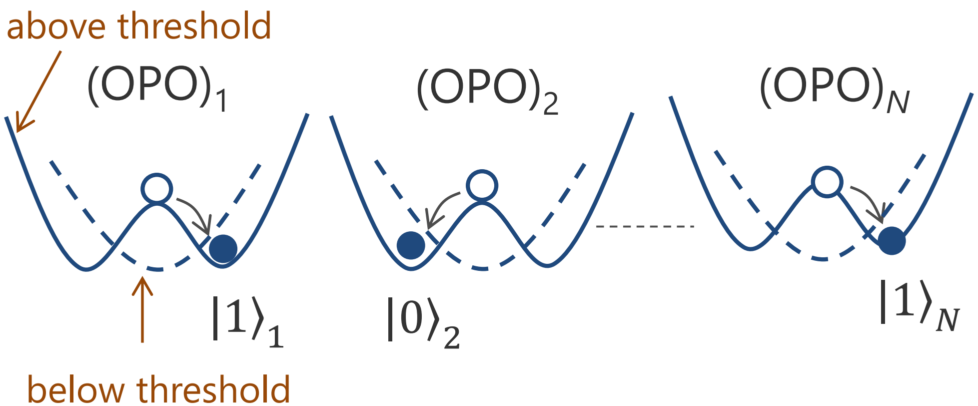
- Irreversible Decision Making and Exponential Amplitude Amplification -

Yoichiro Nambu

Spontaneous symmetry breaking

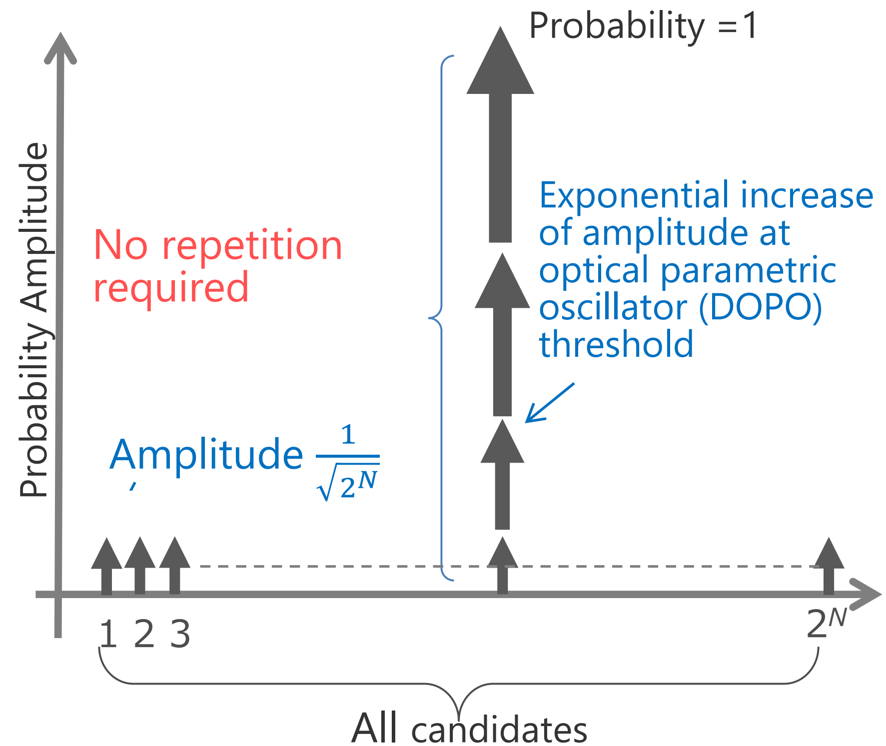


Quantum correlation induced collective symmetry breaking
for decision making



This critical phenomenon is completed in a time interval of a photon lifetime (μsec ~ msec)

Exponential amplitude amplification in optical parametric oscillators



This process is triggered by quantum correlation and completed by classical effects.

Time-to-Solution
for the Combinatorial Optimization Problems (Ising model)

Problem Size	Theoretical Quantum Computing *	Experimental Quantum Heuristic Machines		
		Quantum Computing **	Quantum Annealing ***	Quantum Neural Network
N = 20	4 x 10^{-3} (s)	6 x 10^{2} (s)	1.1 x 10^{-5} (s)	1.0 x 10^{-4} (s) (← ~10^7)
N = 55	6 x 10^{2} (s)	---	2.0 x 10^{3} (s)	3.7 x 10^{-4} (s) (← ~10^7)
N = 100	2 x 10^{10} (s) (~700 years)	---	---	2.5 x 10^{-3} (s)
N = 150	6 x 10^{17} (s) (~20B years)	---	---	5.4 x 10^{-2} (s)

* Theoretical limit (no decoherence, no gate error, all-to-all connections, 1 ns gate time)

** Rigetti Quantum Computer (Quantum Approximate Optimization Algorithm, Dec. 2017)

*** D-WAVE 2000Q @ NASA Ames (March 2019)

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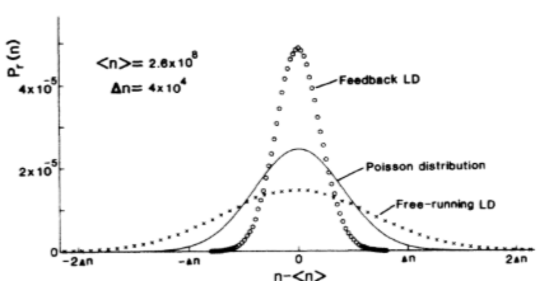
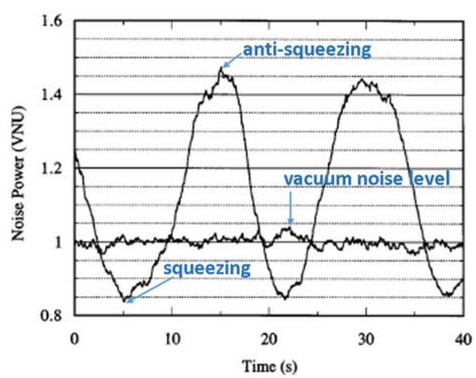
NTT Laboratories
- Past 40 years and next 40 years -

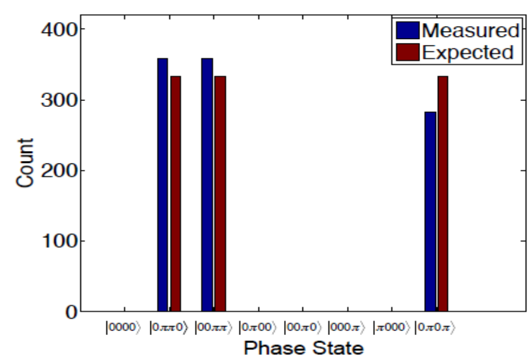
Basic Research on Quantum Computing at NTT Laboratories
– Past 40 years –

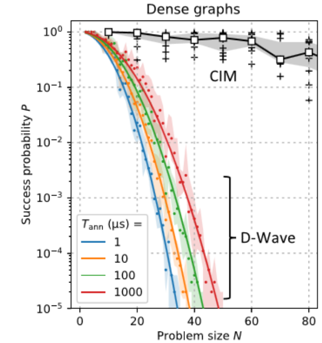
1980 — 1990 — 2000 — 2010 — 2020

- **1979**: Coherent optical communications proposed
- **1986**: Measurement-induced control of quantum states
- **1988**: Optical parametric oscillator with measurement-feedback proposed
- **1995**: Squeezed vacuum state pulses from PPLN-OPO
- **2002**: Differential Phase Shift (DPS) quantum communication proposed
- **2014**: Coherent Ising machine (CIM)
- **2016**: Scalable quantum neural network demonstrated
- **2019**: Benchmark against QC and QA



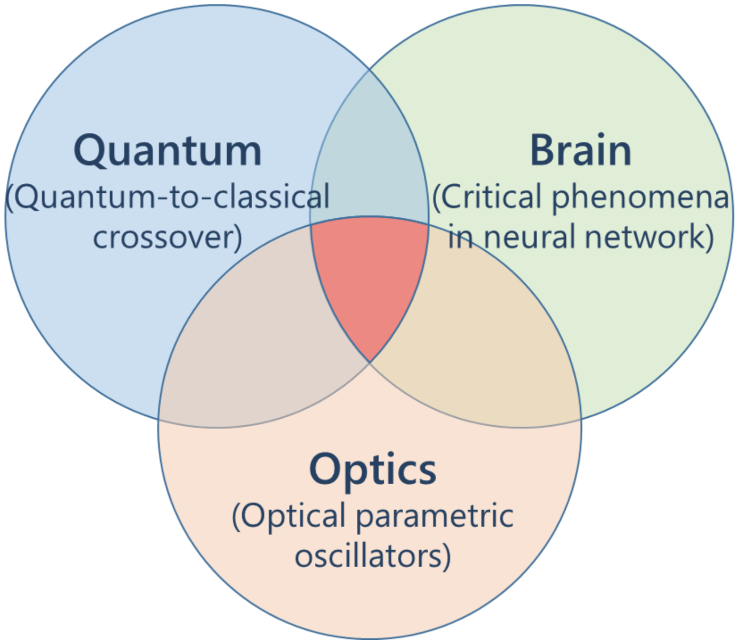




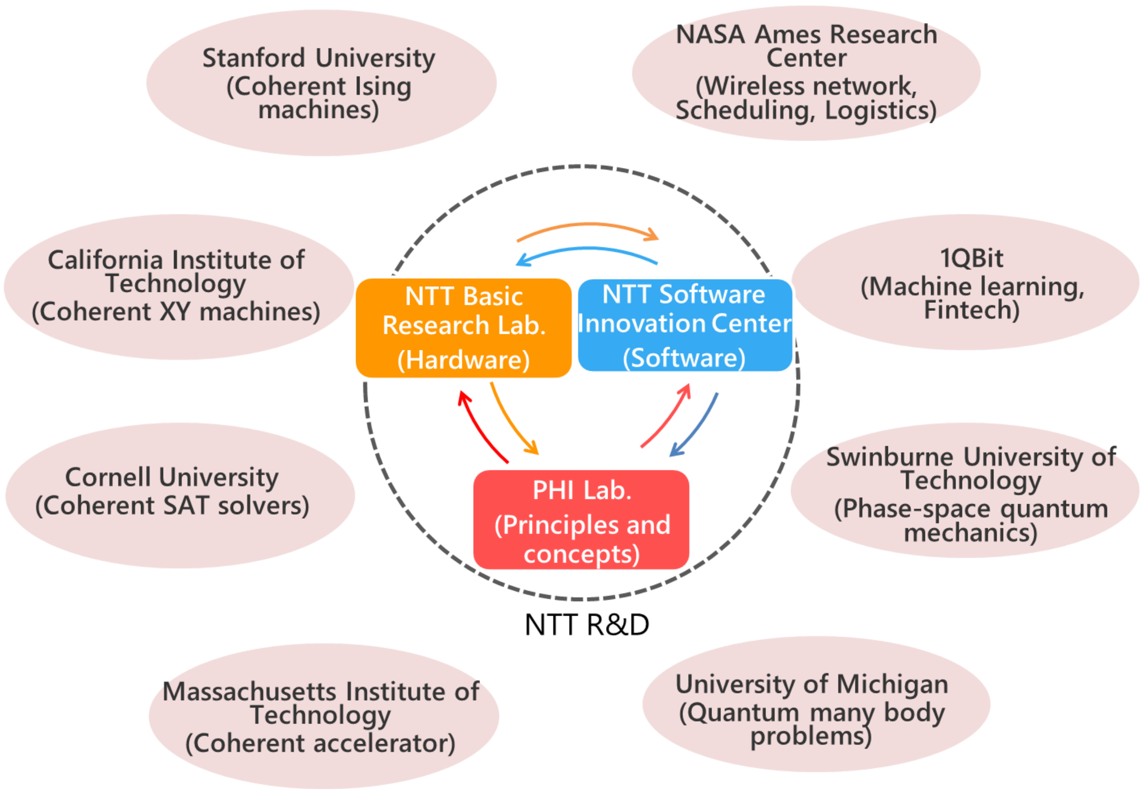


Basic Research on Quantum Computing at NTT Laboratories
- Next 40 Years -

Next Frontier



Industry-Academia Open Laboratory



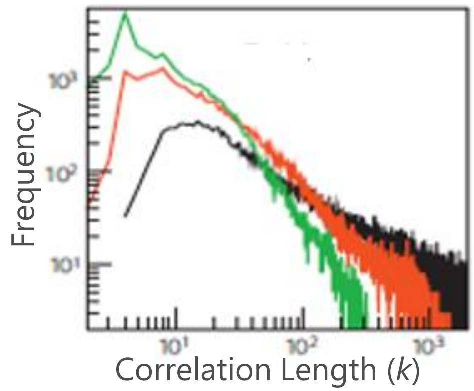
Future Prospect

A human brain is already a quantum computer?

A. Levina et al., Nat. Phys. 3, 857 (2007); D. R. Chialvo et al., Nat. Phys. 6, 744 (2010)

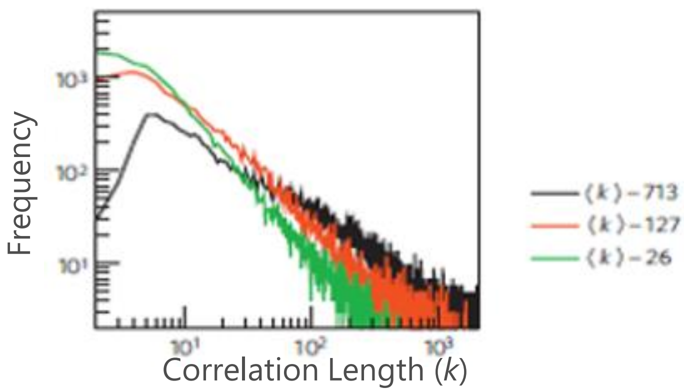
At the oscillation threshold of Ising spin networks,

1. spin-to-spin correlation occurs across all scales (→ communication)
2. randomness is maximum (→ information storage)
3. responsibility is maximum (→ signal amplification)



Ising Spin Network
at Phase Transition Point

correspondence

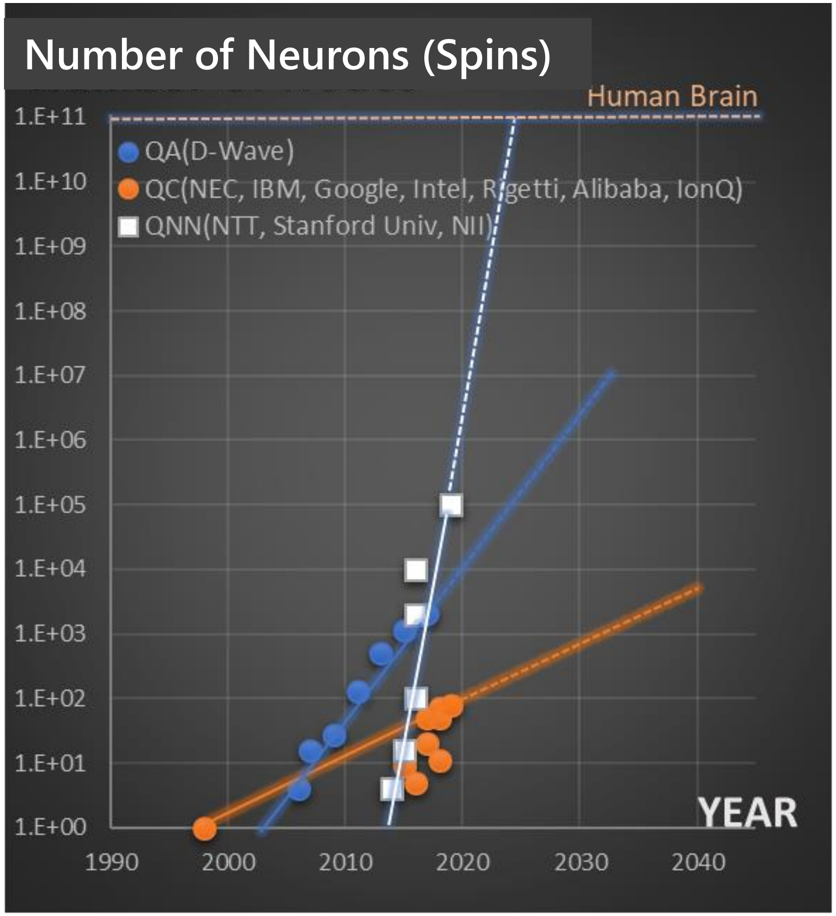


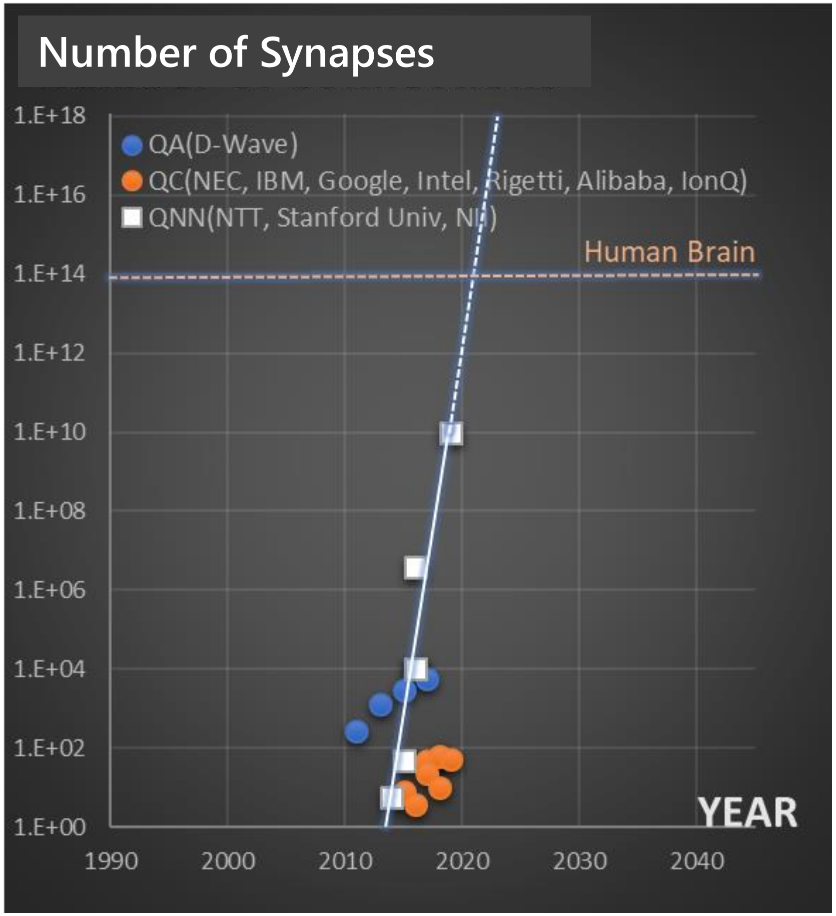
Human Brain
at Default Mode (f-MRI data)

How large number of neurons collectively interact to produce emergent properties like cognition and consciousness?

Editorial: John Beggs, Phys. Rev Lett. 114 220001 (2015).

Scalability of Three Quantum Machines and Human Brain





Number of Neurons → Problem size

Number of Synapses → Computational Capability

Thank you

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https://ntt-research.com/phi/

NTT Basic Research Laboratories

https://www.brl.ntt.co.jp/e/index.html