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

Lead optimization for discovery of
- small molecule drug
- peptide drug
- biocatalyst

Resource optimization in
- wireless communication
- logistics
- scheduling

Compressed sensing (sparse coding) in
- Astronomy
- Magnetic Resonance Imaging (MRI)
- Computed Tomography (CT)

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: $\sim 10^{46}$ (compounds)
  - Machine size: $\sim 4000$ (neurons)

- **Biocatalyst discovery:** Identify a group of proteins that can capture most stably a target compound.
  - Search space: $\sim 10^{690}$ (proteins)
  - Machine size: $\sim 60,000$ (neurons)

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

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

![Diagram showing small molecule drug and biocatalyst discovery](image-url)
Compressed Sensing (Sparse Coding)

Identify non-zero components ($N_0$) (support estimate)

Original data (N) → Observation (scattering) matrix → Observation data (M)

Solve $N_0$ unknowns (inverse matrix computation)

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

Optimum (QNN)

Approximate (Classical Computer)

Recovery Efficiency $\alpha = N_0 / N$

Observation Efficiency $\alpha = M / N$
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 $|0\rangle$ state and $|1\rangle$ state.

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

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

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

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Classical computer

- **Brute Force Search**
- **input 1**
- **output 1**
- **input 2**
- **output 2**
- **input $2^N$**
- **output $2^N$**

Quantum computer

- **Single Run**
- **input 1**
- **input 2**
- **input $2^N$**
- **2$^N$ outputs (superposition)**
- **Read out?**

*N* qubits compute a cost function simultaneously for $2^N$ input states.
Weakness of Quantum Computing

Grover (optimum) algorithm (1997)

- Probability = 1
- $\sqrt{2^N}$ repetitions, exponential scaling
- Amplitude $\frac{1}{\sqrt{2^N}}$
- Linear increase of amplitude by $\frac{1}{\sqrt{2^N}}$

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

<table>
<thead>
<tr>
<th>Problem Size $N$ (bits)</th>
<th>Time-to-Solutions $T_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4 x $10^{-3}$ s</td>
</tr>
<tr>
<td>50</td>
<td>6 x $10^2$ s</td>
</tr>
<tr>
<td>100</td>
<td>2 x $10^{10}$ s (≈700 years)</td>
</tr>
<tr>
<td>150</td>
<td>6 x $10^{17}$ s (≈20B years)</td>
</tr>
</tbody>
</table>

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.

Optimum algorithm is still highly inefficient.
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

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

Superconducting circuit

Quantum computer

Quantum neural network

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

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

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

Thin-Film periodically poled LiNbO₃ waveguide
Why do we need classical resources?
- Irreversible Decision Making and Exponential Amplitude Amplification

Quantum correlation induced collective symmetry breaking for decision making

This critical phenomenon is completed in a time interval of a photon lifetime ($\mu$sec $\sim$ msec)

Exponential amplitude amplification in optical parametric oscillators

Spontaneous symmetry breaking

This process is triggered by quantum correlation and completed by classical effects.
## Time-to-Solution
for the Combinatorial Optimization Problems (Ising model)

<table>
<thead>
<tr>
<th>Problem Size</th>
<th>Theoretical Quantum Computing</th>
<th>Experimental Quantum Heuristic Machines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>Theoretical limit</td>
<td>Quantum Computing</td>
</tr>
<tr>
<td></td>
<td>(no decoherence, no gate error, all-to-all connections, 1 ns gate time)</td>
<td></td>
</tr>
<tr>
<td>$N = 20$</td>
<td>$4 \times 10^{-3}$ (s)</td>
<td>$6 \times 10^{2}$ (s)</td>
</tr>
<tr>
<td>$N = 55$</td>
<td>$6 \times 10^{2}$ (s)</td>
<td>---</td>
</tr>
<tr>
<td>$N = 100$</td>
<td>$2 \times 10^{10}$ (s)</td>
<td>---</td>
</tr>
<tr>
<td>$N = 150$</td>
<td>$6 \times 10^{17}$ (s)</td>
<td>---</td>
</tr>
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</table>

* Rigetti Quantum Computer (Quantum Approximate Optimization Algorithm, Dec. 2017)
** D-WAVE 2000Q @ NASA Ames (March 2019)
NTT Laboratories
- Past 40 years and next 40 years -
### Basic Research on Quantum Computing at NTT Laboratories – Past 40 years –

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
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<tbody>
<tr>
<td>1980</td>
<td>Coherent optical communications proposed</td>
</tr>
<tr>
<td>1986</td>
<td>Optical parametric oscillator with measurement-feedback proposed</td>
</tr>
<tr>
<td>1988</td>
<td>Measurement-induced control of quantum states</td>
</tr>
<tr>
<td>1979</td>
<td>Squeezed vacuum state pulses from PPLN-OPO</td>
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<tr>
<td>1995</td>
<td>Differential Phase Shift (DPS) quantum communication proposed</td>
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<td>2002</td>
<td>Coherent Ising machine (CIM)</td>
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<tr>
<td>2014</td>
<td>Scalable quantum neural network demonstrated</td>
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Basic Research on Quantum Computing at NTT Laboratories - Next 40 Years -

Next Frontier

- Quantum (Quantum-to-classical crossover)
- Brain (Critical phenomena in neural network)
- Optics (Optical parametric oscillators)

Industry-Academia Open Laboratory

- Stanford University (Coherent Ising machines)
- NASA Ames Research Center (Wireless network, Scheduling, Logistics)
- California Institute of Technology (Coherent XY machines)
- IQBit (Machine learning, Fintech)
- Cornell University (Coherent SAT solvers)
- Swinburne University of Technology (Phase-space quantum mechanics)
- Massachusetts Institute of Technology (Coherent accelerator)
- University of Michigan (Quantum many body problems)
Future Prospect
A human brain is already a quantum computer?


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)

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

Scalability of Three Quantum Machines and Human Brain

Number of Neurons (Spins)

- QA(D-Wave)
- QC(NEC, IBM, Google, Intel, Rigetti, Alibaba, IonQ)
- QNN(NTT, Stanford Univ, NII)

Number of Synapses

- QA(D-Wave)
- QC(NEC, IBM, Google, Intel, Rigetti, Alibaba, IonQ)
- QNN(NTT, Stanford Univ, NII)

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