

Mission of Physics & Informatics Laboratories

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Abstract

At the Physics & Informatics Laboratories (PHI Labs) of NTT Research, Inc., we explore a new principle that will bring about a revolution in information processing technology in the interdisciplinary area between quantum physics and brain science, and it is here where we have positioned our research field. We will focus on quantum-classical crossover physics and critical phenomena in neural networks. We will concentrate, in particular, on optical implementation as a means of achieving a simple, elegant, and practical implementation of a computer that is based on this new principle, specifically on the optical parametric oscillator that can achieve quantum neural networks at room temperature. This article introduces the concepts, technologies, and target applications making up this research field at PHI Labs.

Keywords: combinatorial optimization problem, quantum neural network, optical parametric oscillator

1. Quantum neural networks using optical parametric oscillators

The development of new oscillators for generating coherent electromagnetic waves and the expansion of their application fields has a history marked by a rivalry between oscillators based on two different principles. In electrical engineering terms, one is a negative-resistance oscillator requiring no pump-source coherence, and the other is a nonlinear reactance oscillator requiring coherent pump waves. The development of oscillators for various frequency bands began with the emergence of negative-resistance oscillators that are easy to achieve. This was followed by the development of nonlinear reactance oscillators that generate a coherent wave with less noise.

The development of optical oscillators covering a broad wavelength band from ultraviolet to infrared is no exception to this historical rivalry. A laser, which is an optical negative-resistance oscillator, was developed in 1960 through the work of Theodore Maiman of Hughes Research Laboratories [1]. This was followed by the development of an optical nonlinear reactance oscillator as an optical parametric oscillator (in particular, an oscillator generating continuous

waves for practical use) in 1968 by Stephen Harris and Robert Byer of Stanford University [2].

The foundation of optical communication technology, which blossomed in the 20th century, was the laser, but it is our future vision that the foundation of optical information processing technology of the 21st century will be the optical parametric oscillator. This type of parametric oscillator behaves like an analog device with strong quantum properties in the pump region below an oscillation threshold and like a digital device with strong classical properties in the pump region above the threshold. As described below, future information processing technology will require both quantum computing resources and classical computing resources, and the optical parametric oscillator is practically the only device that can simultaneously achieve this dual quantum-classical nature at room temperature.

We have been researching the neural networks using optical parametric oscillators as neurons and using such a configuration in an attempt to solve combinatorial optimization problems and quantum many-body problems that have posed a challenge to the modern computer [3] (**Fig. 1**). Regarding another element (synapse connections) making up a neural network, there are two methods of implementing a

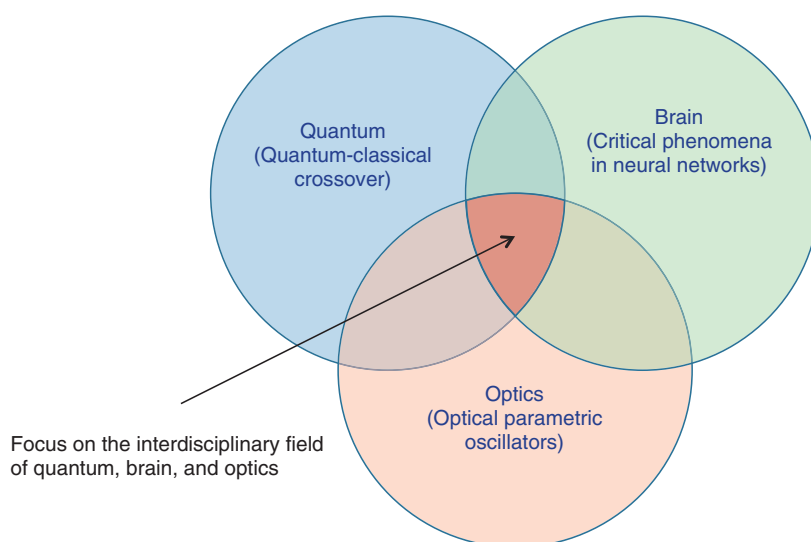


Fig. 1. Research fields at Physics & Informatics Laboratories (PHI Labs).

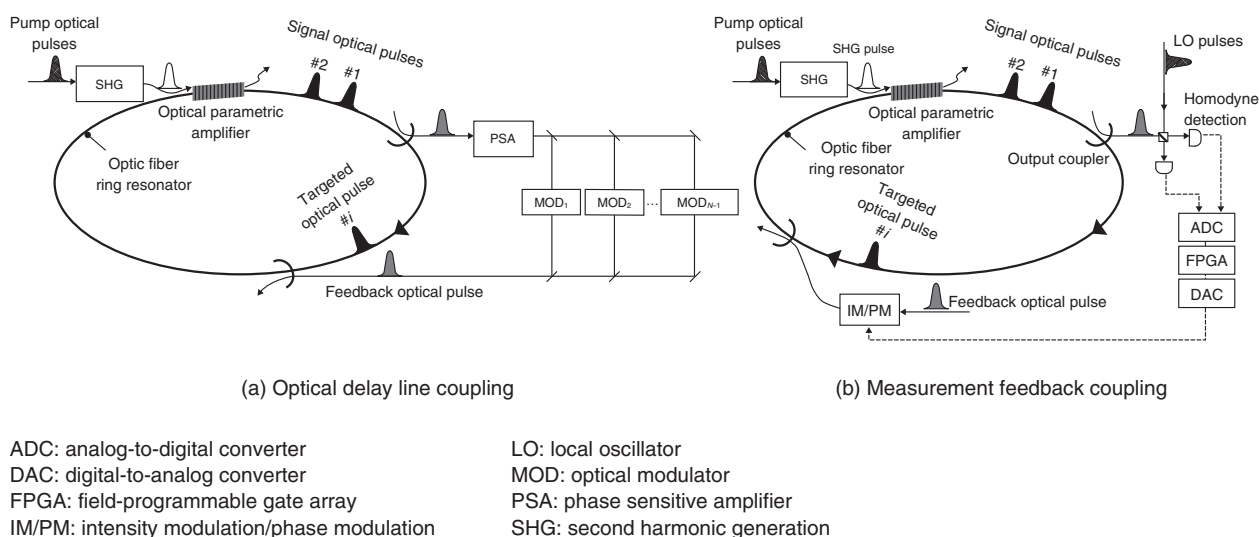


Fig. 2. Neural network configuration based on optical parametric oscillators.

fully connected neural network in which synapse connections are formed between all neurons (**Fig. 2**). These methods use N optical parametric oscillator pulses circulating in an optical fiber ring cavity of 1 to 10 km for N neurons instead of using N optical parametric oscillators, a scheme that achieves N defect-free uniform neurons simultaneously within a single cavity [4–6].

The optical delay line coupling method (**Fig. 2(a)**) can achieve $N(N-1)$ synapse coupling coefficients

$[J_{ij}]$ through $(N-1)$ optical delay lines and the same number of optical modulators [4]. With this method, $(N-1)$ input pulses j simultaneously couple with a single target pulse i at each time point via coupling coefficient J_{ij} , so $N(N-1)$ J_{ij} coefficients are implemented for each round trip to achieve the above for all N target pulses. This method has the advantage of simplifying the implementation of synapse coupling having directionality ($J_{ij} \neq J_{ji}$).

The measurement feedback coupling method

(Fig. 2(b)), on the other hand, can achieve $N(N-1)$ all-synapse coupling with just a single measurement feedback circuit [5, 6]. The former method is thought to be applicable to the implementation of large-scale, high-speed, and sparsely coupled neural networks and to quantum many-body problems. The latter method, however, is thought to be applicable to the implementation of medium-scale, high-order nonlinear coupling and densely coupled neural networks and to combinatorial optimization problems.

2. Application fields

This section introduces the application fields envisioned for quantum neural networks using optical parametric oscillators.

2.1 Combinatorial optimization problems

The Ising model is highly representative of combinatorial optimization problems. This model can be implemented through the use of degenerate optical parametric oscillators in which the signal wave and idler wave have identical frequencies [3]. As a result of recent improvements in hardware technology for achieving a degenerate optical parametric oscillator network together with the advancement in associated algorithms, the performance of the coherent Ising machine, a type of quantum neural network, is making significant gains. In fact, it is becoming superior to the quantum annealing machine—a type of quantum computer specialized for combinatorial optimization problems—and von Neumann computers implementing advanced algorithms such as Breakout Local Search [7, 8]. Expectations are high that the era of solving a variety of combinatorial optimization problems will eventually arrive by mapping them to the Ising model to achieve a general-purpose optimization solver. Application algorithms are now being developed for specific problems such as lead optimization in drug discovery and the development of optimum biocatalysts, resource allocation in wireless communication networks, scheduling and logistics, and sparse coding in compressed sensing.

The XY model, on the other hand, is highly representative of optimization problems involving continuous variables. A coherent XY machine for solving this type of problem can be implemented by a non-degenerate optical parametric oscillator network in which the signal and idler waves have different frequencies [9]. Application algorithms are being developed for specific optimization problems solvable using a coherent XY machine such as social network

diagnosis (community detection) and portfolio optimization in the Fintech field.

Still another type of problem representative of combinatorial optimization problems is the satisfiability (SAT) problem. A coherent SAT solver that can solve this problem with good efficiency can be achieved by configuring a recurrent neural network with degenerate optical parametric oscillators [10]. One specific type of problem that could be solved by a coherent SAT solver is hardware/software verification.

The concept of quantum-inspired optimization has recently been attracting attention as a practical solver targeting combinatorial optimization problems. Instead of actually constructing an optical (or superconducting) parametric oscillator network, we apply this concept, which is aimed at obtaining optimal solutions by programming the quantum mechanical equations of motion that describe the experimental quantum neural network as an algorithm in a standard digital circuit such as a field-programmable gate array and conducting a type of numerical simulation [8, 11].

2.2 Quantum many-body problems

The development of new tools for achieving efficient numerical simulations with good accuracy of electron behavior within a solid, especially of correlated electron systems having strong interactions among electrons, is essential to searching for new materials (material informatics) and discovering new phenomena (topological physics). In particular, two-dimensional systems in which electrons are confined by two-dimensional potential forces exhibit novel quantum phenomena not found in ordinary three-dimensional systems. However, unlike three-dimensional systems, numerical simulations based on mean-field approximation tend to break down in two-dimensional systems, and it is also difficult to obtain exact solutions in two-dimensional systems as in one-dimensional systems.

This state of affairs led to the idea that the properties of a two-dimensional electron system could be understood by artificially implementing its electrons in a separate quantum system whose Hamiltonian could be easily controlled, then observing the behavior of this artificial two-dimensional quantum system. This is the concept of quantum simulation [12]. There has been much research on simulating electron properties in solids using a variety of physical systems such as cold atoms, trapped ions, and superconducting circuits.

The development of such a quantum simulator is

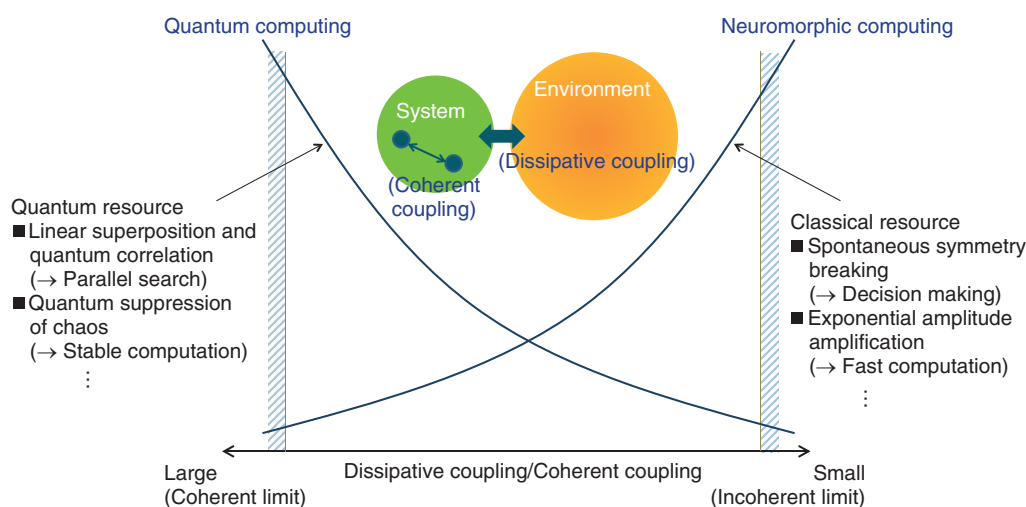


Fig. 3. Computing with quantum and classical resources.

still at the stage of basic research. In the future, however, we expect it to become competitive with traditional approaches in condensed matter physics and quantum chemistry that implement a variety of approximate numerical calculation techniques (such as dynamic or cluster mean-field theory, quantum Monte Carlo methods, and tensor network methods) as algorithms in high performance computing equipment. Diverse factors, such as simulation accuracy, speed, equipment size, cost, and ease of maintenance, will determine what approach survives as future technology.

We consider equipment that uses light to simulate electrons to be the future vision of a quantum simulator that can achieve a competitive edge over traditional techniques [13].

3. Quantum-classical crossover physics

The quantum-classical crossover problem refers to the question of when and how quantum theory, which has been successful in describing the microscopic world, crosses over into classical theory, which rules over the macroscopic world. This question is the most fundamental theme for quantum physicists. One theoretical model that can make this problem easy to understand is an open system in which a system having a few degrees of freedom couples with an environment having many (or infinite) degrees of freedom [14]. As shown in **Fig. 3**, as dissipative coupling between the system and environment (decoherence) becomes smaller compared with the strength of

coherent coupling within the system, quantum computing resources become more effective, such as quantum parallel search using linear superposition and quantum suppression of classical chaos using quantum interference. For this reason, it has been thought up to now that a quantum computer should be developed in a region that makes dissipative coupling with the environment as small as possible. Concepts such as quantum error correcting codes and topological quantum computers have emerged along this line of thinking.

As dissipative coupling with the environment becomes larger, however, there is an increase in the effectiveness of classical computing resources, such as irreversible decision making of a final solution by spontaneous symmetry breaking and exponential amplification of the amplitude of the selected final solution, as stable classical information. It has therefore been thought that a neuromorphic computer that mimics the function and mechanism of human nerve cells or acquires ideas based on human ways of thinking should be developed in a robust classical region that would make dissipative coupling with the environment as large as possible and completely remove quantum coherence in the system.

We consider that the computer of the future should be developed specifically in this quantum-classical crossover region in which the two types of computing resources—quantum and classical—can be used simultaneously. An optical parametric oscillator network is a unique hardware solution that can freely move about this quantum-classical crossover region

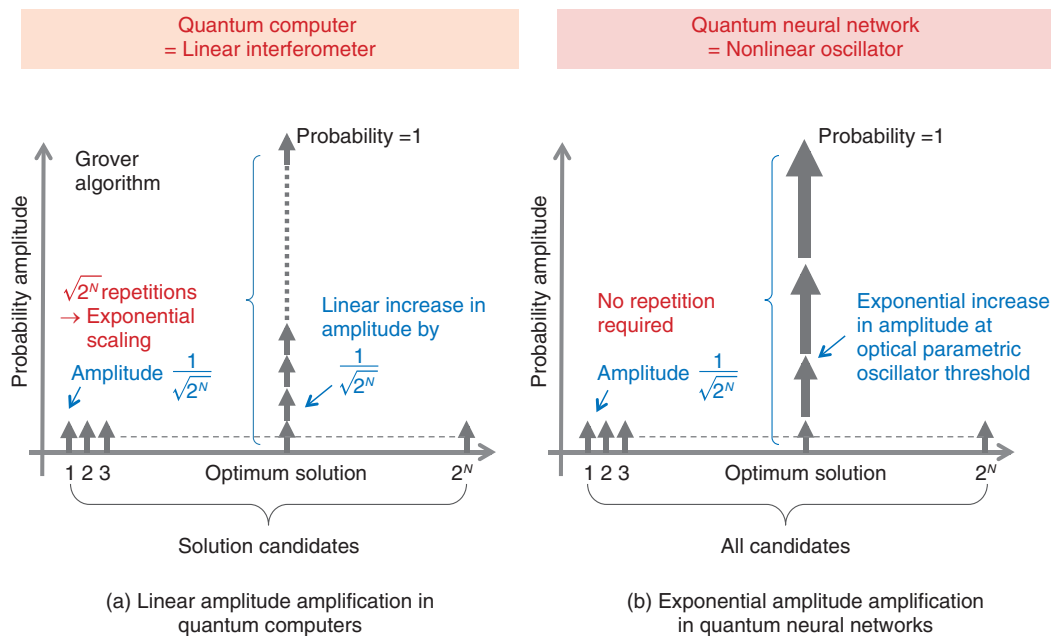


Fig. 4. Two computational methods for combinatorial optimization problems.

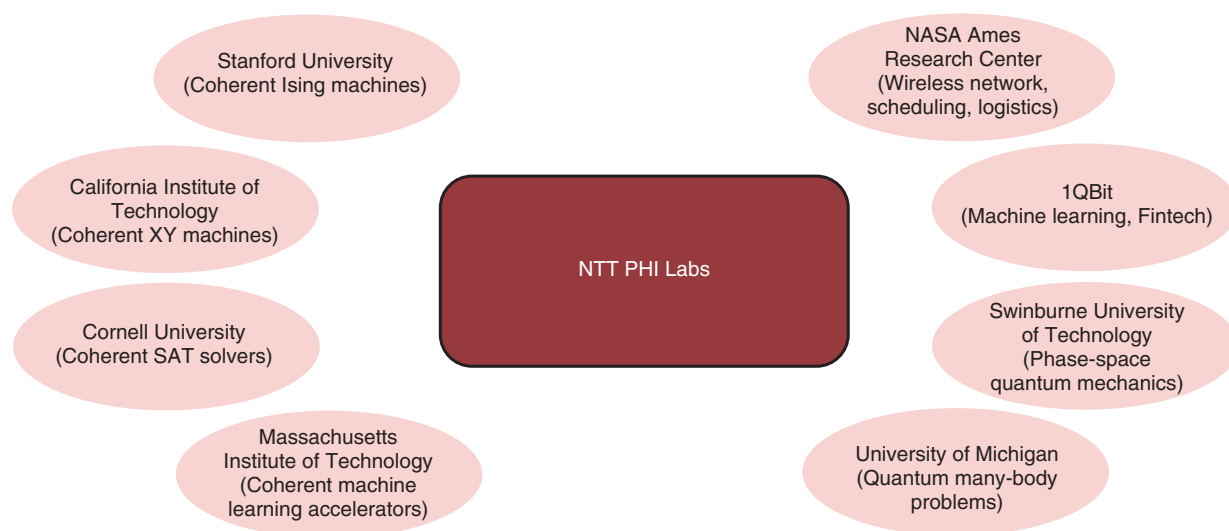
by adjusting the pump rate. This approach has something in common with recent thinking by neuroscientists known as “computing at criticality” in which advanced functions of the human brain (consciousness, cognition, and decision-making) are based on types of phase transitions and critical phenomena in a massive neural network [15].

4. Why are classical computing resources also necessary?

A method for solving combinatorial optimization problems using only quantum computing resources is shown in **Fig. 4(a)**. This method first expresses all (2^N) candidates of the solution of a given problem as linear superposition states, each having the same probability amplitude ($1/\sqrt{2^N}$). Then, after identifying the optimal solution by some methods such as the phase estimation algorithm, it amplifies the amplitude of that particular state from $1/\sqrt{2^N}$ to 1 and attenuates the amplitudes of all other states from $1/\sqrt{2^N}$ to 0. Finally, by conducting projective measurements of 0 or 1 against N quantum bits, it determines an optimal solution with a probability close to 100%. The bottleneck with this method lies in how to amplify the amplitude of the optimal solution and how to attenuate the amplitudes of all other states that are not an optimal solution.

An optimal method for achieving this goal using a quantum computer was discovered by L. K. Grover [16]. Repeating this routine called Grover iteration a total of $\sqrt{2^N}$ times obtains the above final state. This means that exponential time must be spent in solving a combinatorial optimization problem using a quantum computer. The theoretical limits of the computational time needed to complete this Grover iteration for problem sizes of $N = 20, 50, 100$, and 150 bits are 4×10^{-3} s, 6×10^2 s, 2×10^{10} s, and 6×10^{17} s. It is assumed that there is no decoherence and no gate error, and consequently no need for using quantum error correcting codes, and that fully connected bits are implemented so that non-localized two-bit gates can be freely implemented at a high speed of 1 ns. It is also assumed that the optimal solution to a given problem can be identified instantaneously by a new and independent algorithm, which is yet to be discovered. Yet, even with such an idealized quantum computer, the above result shows that it would take about 20 billion years to amplify the probability amplitude of the optimal solution from $1/\sqrt{2^N}$ to 1 for an extremely small problem of $N = 150$ bits.

What would be the computational time for solving the same type of problem with a coherent Ising machine? As shown in **Fig. 4(b)**, since N optical parametric oscillator pulses below the oscillation threshold are in 0-phase and π -phase linear superposition



We will collaborate with NTT Software Innovation Center and NTT Basic Research Laboratories in the future.

Fig. 5. PHI Labs and its partners.

states, all solution candidates can be expressed as linear superposition states, each having the same probability amplitudes ($1/\sqrt{2^N}$) in the same manner as the quantum computer. At this time, if the pump rate is increased to the oscillation threshold, the optimal solution having minimum network loss gives rise to single-mode oscillation, and that amplitude is exponentially amplified from its initial value ($1/\sqrt{2^N}$) to its final value (1) in a time comparable to a photon lifetime (on the order of μs – ms) at most [3]. This exponential amplification is a characteristic phenomenon in a classical (open) system that cannot be achieved in a quantum system. The computational times (experimental results) for obtaining optimal solutions to the same combinatorial optimization problem (Ising model) with a coherent Ising machine are 1.0×10^{-4} s, 3.7×10^{-4} s, 2.5×10^{-3} s, and 5.4×10^{-2} s [7].

With the exception of special problems having hidden periodicity (factorization, discrete logarithm, etc.), this example shows that classical computing resources, such as exponential amplitude amplification, will be essential to future computers for solving general combinatorial optimization problems at high speed in addition to quantum computing resources in the manner of linear superposition.

We emphasize that a quantum computing based on Grover iteration is an exact solver while a coherent Ising machine is a heuristic solver, for which the theoretical upper bound of computation time is not

established for coherent Ising machines yet.

5. Research partners

The development of quantum neural networks using optical parametric oscillators targeting combinatorial optimization problems and quantum many-body problems is moving forward at NTT. PHI Labs is actively promoting joint research with outside research institutions to fulfill its responsibility of searching out new concepts and principles (Fig. 5).

The left side of the research partner diagram in Fig. 5 consists mainly of the experimental group. The Stanford University team (Professor Hideo Mabuchi, Professor Martin Fejer, Associate Professor Benjamin Lev, Associate Professor Surya Ganguli, Assistant Professor Amir Safavi-Naeini) is researching coherent Ising machines based on optical or superconducting parametric oscillator networks and critical phenomena in neural networks. The Cornell University team (Assistant Professor Peter McMahon) is researching coherent SAT solvers based on recurrent optical parametric oscillator networks. The California Institute of Technology team (Assistant Professor Alireza Marandi) is researching coherent XY machines based on non-degenerate optical parametric oscillator networks. The Massachusetts Institute of Technology team (Associate Professor Dirk Englund, Professor William Oliver) is researching

Table 1. Two quantum computational models.

	Unitary quantum computation (Quantum computing)	Dissipative quantum computation (Quantum neural network)
Principles	Unitary rotation of state vectors in isolated quantum systems	Self-organization in open quantum systems
Proposals	Deutsch (1985): Quantum parallelism Shor (1994): Factoring and discrete logarithm	Zurek (2003): Quantum Darwinism, Quantum chaos Verstraete, Wolf and Cirac (2009): Universal quantum computation by dissipation
Resource	Quantum entanglement	Quantum discord
Merits	Transparent physics Established theoretical limit	Robust against noise and gate error
Demerits	Sensitive to noise and gate error	Complicated physics Theoretical limit unknown
Applications	Problems with hidden periods or structures	Problems without hidden periods or structures

coherent accelerators (targeting deep machine learning) based on optical homodyne mixers and also fabrication of superconducting parametric oscillator networks.

The right side of the research partner diagram in Fig. 5 consists of the theoretical group. The NASA Ames Research Center team (Quantum Artificial Intelligence Laboratory: QuAIL Lead Eleanor Rieffel) is researching application algorithms for wireless networks, scheduling, logistics, and other areas. The IQBit team (Group Head Pooya Ronagh) is researching application algorithms for machine learning. The Swinburne University of Technology team (Professor Peter Drummond, Professor Margaret Reid) is researching quantum stochastic differential equations by using the phase-space method. The University of Michigan team (Professor Franco Nori) is researching quantum simulations of non-Abelian anyon particles and topological physics.

Finally, **Table 1** summarizes the differences between conventional quantum computers and new quantum neural networks that we are researching.

6. Conclusion

The first AT&T-NTT executive meeting took place more than 30 years ago, and meetings were subsequently held annually at an AT&T or NTT research laboratory. At that time, I was one of the members from the NTT laboratories then headed by NTT senior executive vice president Yasusada Kitahara and remember well my visit to Bell Labs in New Jersey. The president of Bell Labs (to whom I was intro-

duced) was British, the vice president in charge of research was German, and the executive director overseeing the physics department was Indian. The director of theoretical physics (commonly known as Physics 001) was American, and it was he who gave the keynote talk at this first AT&T-NTT executive meeting. I cannot forget the reprimand that he received at that time from Dr. Arno Penzias, the vice president of research (and recipient of the 1978 Nobel Prize in Physics), who said “If you speak that fast, you will lose half of your audience in the room!” My dream was to one day make the NTT laboratories into a place with such diversity and caliber—we stood at the starting line of that endeavor.

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He received a Ph.D. from the University of Tokyo in 1978 and joined NTT Basic Research Laboratories. He became a Professor of Applied Physics and Electrical Engineering at Stanford University in 1992. He also became a Professor at the National Institute of Informatics (NII) in 2003. He is currently a Professor (emeritus) at Stanford University and NII, and an NTT R&D Fellow. He received many distinctions for his work, including the Carl Zeiss Research Award (1992), Nishina Memorial Prize (1992), IEEE/LEOS Quantum Electronics Award (2000), Medal with Purple Ribbon (2005), Hermann A. Haus Lecturer of MIT (2010), and Okawa Prize (2011). His research focuses on quantum information processing, quantum optics, and mesoscopic physics, especially quantum neural networks and coherent Ising machines.