Quantum Information Science and Technology Project

NATIONAL QUANTUM ROADMAP PROJECT

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ONR grant no. N00014-03-1-0726
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Précis

Quantum Information Science and Technology Project

Asian Technology Information Program, Tokyo, Japan

I recently completed a series of research assessments for quantum information science and technology programs across East Asia, where I was based within the Quantum Information Science and Technology Project (**QUIST**) at Asian Technology Information Program (ATIP) offices in metropolitan Roppongi Hills, Tokyo, Japan. ATIP is a nonprofit science and technology information resource that works to promote East-West information exchange, as well as providing timely reporting to governments, research institutes and corporations worldwide.

My responsibilities for the project included briefing principal US policy and funding agency directors under auspices of the US quantum information science research community: DARPA QuIST and NSA ARDA (DTO, now IARPA) Quantum Information Science Program (QISP). My reports were subsequently distributed to US government scientists and researchers across DoD, DoE, the IC, and throughout US national labs. These reports, as comprehensive national assessments compiled under my authority for the project, went on to serve as inception for the first prototype of the official US Government Quantum Roadmap—a sentiment conveyed directly in person at the *IEEE Quantum Photonics Symposium* by none other than its Chairman, Los Alamos National Laboratory principal investigator, Dr. Richard Hughes.

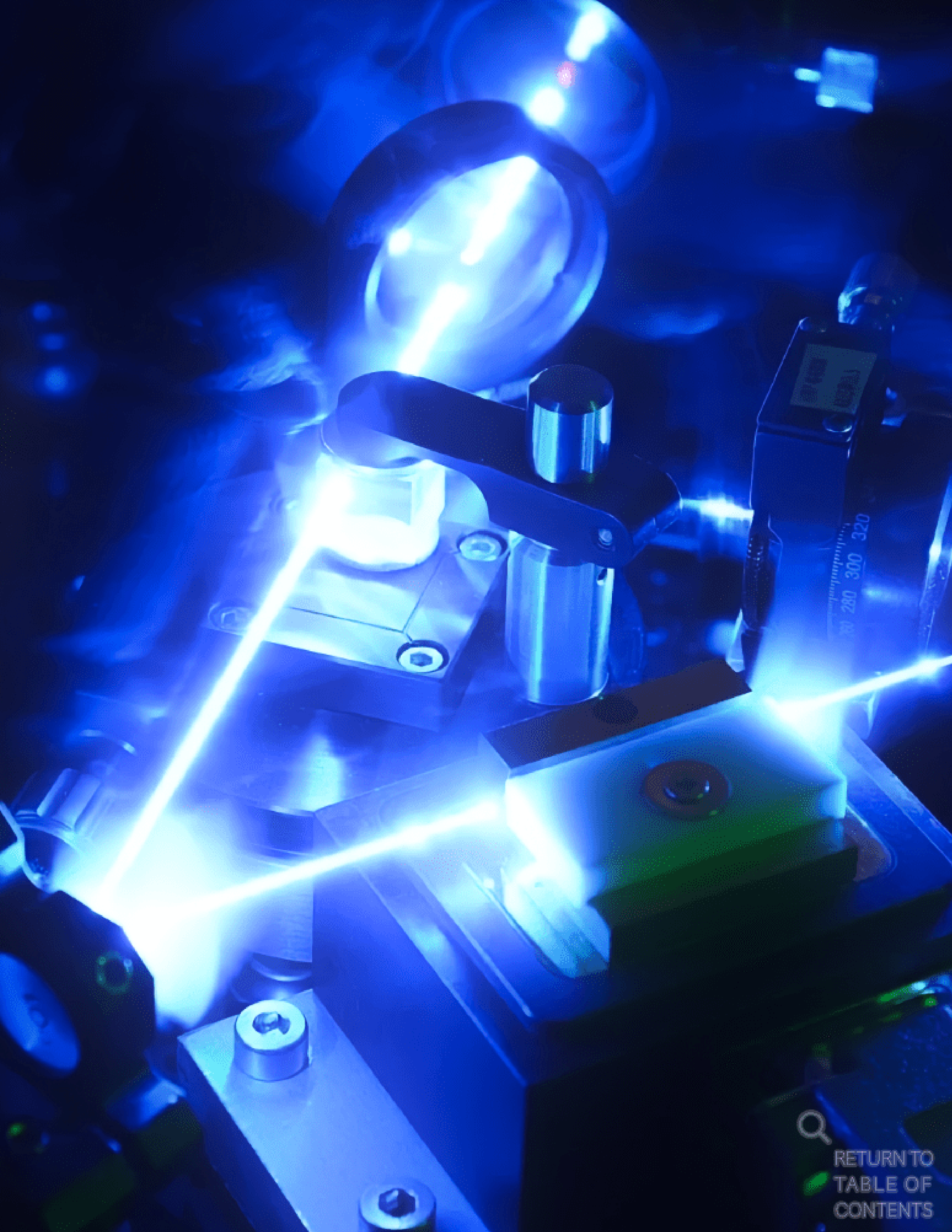
While assigned to the region, I held meetings and interviews with Nobel laureates and lab directors, traveled throughout East Asia to leading national research centers to evaluate advanced activities in quantum information science — both experimental laboratory divisions and theoretical research — with a core focus on areas such as solid-state quantum computing, cryptography and communications, metrology, imaging and holography, and quantum algorithms research. Technologies predicated upon the phenomena of quantum entanglement and coherence promise to convey revolutionary advances to research and industry that are difficult to overestimate. The simultaneous spin-off effects of these advances promise to transform society over the coming century just as deeply and profoundly as classical computers — networked together, miniaturized following Moore's Law exponential doubling on a clockwork timescale — transformed the last.

Concurrent international collaborations through *Starlab*, including Serguei Krasnikov research division alumnus, quantum topologist Romàn Zapatrin led to our development of a novel quantum learning model at the intersection of quantum topology and neural networks. In *International Journal of Theoretical Physics* Vol. **43**, No. 10, we introduce a quantum fast-training pattern recognition model, superposed quantum network topologies*, viz.*, *adaptive quantum networks*. A distinguishing feature of our model lies in its ability to utilize coherent superposition of unique topological configurations of neural networks for the training phase of network development.

My experience with the QUIST Project provided a singular opportunity to establish valuable international research collaborations, and conveyed a unique vantage point to take part in the forefront of developments in the field. Please find attached for your review select written content from QUIST project briefings.

Table of Contents

QUANTUM INFORMATION SCIENCE AND TECHNOLOGY PROJECT



RETURN TO
TABLE OF
CONTENTS

Spacetime from Quantum Topology

Christopher Altman and Romàn R. Zapatrin

Abstract

Using adaptive quantum networks, we show how virtual spacetime structures emerge. Quantum parallelism, which is used to facilitate simultaneous training and revision of virtual network structures, gives rise to parallel evolution of linear superposed networks, providing optimal reconfiguration of whole-network quantum structure. The latter is interpreted under the model of virtual quantum spacetime. The main feature of this approach is that topology becomes a quantum value, subject to change under objective measurement.

1 Introduction

Over the last few decades, artificial neural networks (ANNs) have gained increasing interest, finding applications in various domains such as business planning, medicine, engineering, geology, and physics. ANNs have shown remarkable efficiency in solving tasks related to forecasting, planning, control and classification. ANNs are a powerful modeling tool, able to simulate complex dependencies. Due to their generic nonlinearity, the dimensionality — the required resources of the ANN — are smaller than those used in standard, linear optimization methods. The essential property of ANNs is their ability to be trained. Loosely speaking, instead of attempting to develop a theory, the network is trained on sample sets which it then learns to associate over a given domain or multimodal domains.

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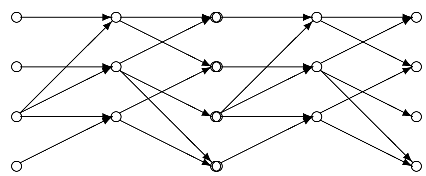
ANNs are a natural and intuitive field to explore, as they draw inspiration from the structure of real biological systems. One of the basic tasks of neural networks is to function as perceptrons, that is, to recognize signals for which we have no structural theory—for instance, to recognize visual patterns.

2 Training principles for ANNs

In this section, we review the basic principles on which perceptrons are based, their learning and training in classical setting, and show how Rota algebras—introduced above—emerge in their description. We shall deal with multilayered feedforward NNs, such as



that is, their nodes can be arranged in layers so that (i) no nodes in a given layer communicate, and (ii) the signals propagate only consecutively, via layers. The state of a given neural network is the set of values, numerical or vectorial, assigned to its nodes. A time-step propagation changes the perceptron's state so that the value of a node i at time $t+1$ depends on its own value and the values of nodes adjacent to i at time t.

Besides their multilayered, high-dimensional structure, the filtering and recognizing power of neural networks is based on the nonlinearity of their transition functions. In some cases, in particular while dealing with stability or elasticity issues, we may use linear approximations. This is exactly the case we explore in this paper: optimal topological configurations are assumed to be robust under small permutations [1].

Training. Initially, one starts with a set of patterns for which the classification is known. Usually by means of heuristic methods, the topological structure of the network is chosen and then trained via input of known patterns and subsequent adjustment of network parameters (transition functions). Output signals are correlated with patterns from different classes, to be well-separated with respect to certain criterion. The most popular method to adjust transition functions is error backpropagation (see, for instance,[2]).

Performance. Signal propagation in the linear approximation can be viewed as a matrix multiplication, which reduces to a number of arithmetic operations. The more links there are between neurons, the more computational resources are consumed by the process of pattern recognition. In order for a neural network to be faster, we should seek sparser configurations.

Therefore, the criterion for 'good matching' should also take performance into consideration. As an example we consider the approach of *fast neural networks*, which are weakly connected multilayered feedforward neural networks [1]. The idea of these networks grows from the FFT—the fast Fourier transform. When finding optimal configurations of such networks, we restrict the allowed links between neurons and force networks to be sparse.

3 From graphs to matrices

The core idea of the suggested approach is to convert the primary component of artificial neural networks – directed acyclic graphs (DAGs) – into a more general structure, which naturally complies with quantum parallelism. The latter inevitably means that this should be a linear structure in order to support superpositions. In [24] the idea to replace DAG by appropriate sets of linear matrices (associated further with appropriate quantum variables) was suggested.

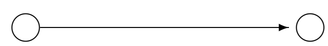
The training paradigm remains the same as it was in conventional ANNs – standard performance criteria are used, such as Root Mean Square Error (RMSE) between targets and outputs of the neural network, the correlation (called ***R***-value) between the outputs and tar-gets an so on, the are only reclassified in terms of unitary matrices and matrix operations. The main peculiarity is that the result of training optimization is then a matrix, or a set of matrices, rather than a directed acyclic graph, as is seen in a standard, 'literal' approach.

We use the term *adaptive neural networks* for these structures. However, the primary objects subject to revision and training are operators in linear spaces – which can be realized, for instance, as quantum observables, rather than as explicitly defined neural networks. What do these matrices have to do with ANNs? In order to implement the result, that is, to recover the initial graph structure upon derivation of the appropriate solution, the Rota algebraic spatialization procedure [10] is applied.

Within our approach, the topology of a feedforward artificial neural network, $\mathcal{N}$, is described by the TEMPLATE MATRIX $\mathbf{A}$ of the appropriate directed acyclic graph (DAG), which is formed as follows:

$$\mathbf{A}_{jk} = \begin{cases} *, \text{ if } j \to k \text{ in } \mathcal{N} \\ 0, \text{ otherwise} \end{cases} \tag{1}$$

where $*$ stands for a wildcard – any number, and the set of such numerical matrices form an algebra [12] as it is closed under multiplication. The main property of $\mathbf{A}$ is that the synaptic weights 'follow' it – namely, if $\mathbf{A}_{jk} = 0$, then $w_{jk} = 0$. This differs from the standard description in terms of adjacency matrices, and the difference is that the matrix is not numeric. The simplest example is provided by a two-vertex DAG with one arrow

$\mathcal{N} =$  (2)

whose template matrix is

$$\mathbf{A} = \begin{pmatrix} * & * \\ 0 & * \end{pmatrix} \tag{3}$$

In general, taking various matrices A by substituting the asterisk in template matrix ***etempl*** by numbers we may form various products ***esigprop***. The resulting set of matrices is called the Rota algebra of N . It can be verified that this set is closed under sums and matrix products, and thus qualifies as a closed algebra. This description is explicated under greater detail in [24].

4 Conventional training in linear terms

Given a feedforward neural network $\mathcal{N}$, consider the linear space $\mathcal{H}$, whose basis is labeled by the nodes of $\mathcal{N}$. A vector $\vec{x} \in \mathcal{H}$ is associated with a state of the network, namely the j-th component of $\vec{x}$is the activity in node j. Note that the state of $\mathcal{N}$ captures the activities of *all* nodes, so a convention is required to define the default activity value of the nodes, we set its initial value to zero.

Initial activation associated with input vector $\mathbf{x}_0$ corresponds to changing values of only a part of nodes – specifically those in the input layer. The signal then propagates through $\mathcal{N}$, and we describe this activation by a linear operator W in $\mathcal{H}$. We start with $\mathbf{x}_0$, then :

$$\mathbf{x}_0 \mapsto \mathbf{x}_1 = \mathbf{x}_0 W \mapsto \dots \mapsto \mathbf{x}_{\text{out}} = \mathbf{x}_n = \mathbf{x}_0 W^n \tag{4}$$

following n steps. Recall that postfix notation for operators acting on vectors is employed in this instance. The crucial feature of the suggested approach is that signal propagation is now described by iteration of *the same* operator W.

We emphasize that the operator W completely specifies the ANN in question, so from this step forward, the operator W, rather than the collection of weights, as in the traditional backpropagation approach, will be subject to training. A quantum analog of backpropagation training method has been described in [24]. We do not dwell on details, as the main point is that the result is a matrix, or a set of matrices, which may *not* be – as they are – associated with any DAG. We have no nodes, no arrows, just matrices. How to recover the spatial structure of the obtained optimal network? For that function, Rota's spatialization procedure is to be applied.

5 Rota topology: the emergence of spacetime structures

The matrix formalism deals with objects having no specific spatiotemporal features. We call them continuously-evolving, superposed topologies, but these topologies are yet 'spaceless' (while not 'timeless,' as we are speaking of their evolution in time, with respect to the proper time of the experimenter). The possibility to transfer them into spacetime manifold fluctuations was studied in quantum gravity.

The key point of the spatialization procedure is the following: consider the full matrix algebra $\mathcal{A}$ as a linear space. From this perspective, the Rota algebras Ω described by etempl are just linear subspaces of $\mathcal{A}$. Having a procedure which – starting from a subset of $\mathcal{A}$ – creates a topological space, providing the capability to discuss superposed configurations of differing neural networks. In this section we present a procedure which – starting from a given subspace of $\mathcal{A}$ – pro-duces a set, and endows it with a topology that can be associated with certain acyclic directed graphs.

When the set of nodes is fixed, Rota algebras provide a suitable machinery to describe topol-ogy changes, which are expressed in terms of creation and annihilation of edges. In terms of template matrices etempl, these operations are adding or removing asterisks from the ap-propriate templates. In a fixed basis, a Rota algebra is a subspace of a full matrix algebra
$\mathcal{A}$ – therefore adding or removing asterisks is equivalent to adding or removing basis vec-tors. Thus, any particular Rota algebra is a linear subspace of Ω. The basic idea of our

approach is to associate *any* subspace of Ω with an appropriate directed acyclic graph.

The first step of the spatialization procedure is then creating or finding points of the incidence algebra Ω, which will become nodes of the future graph:

$$\{\,\text{points}\,\} = \{\,\text{irreducible representations}\,\} \tag{5}$$

For commutative algebras this is a well-known Gel'fand transform, but in our case the algebra Ω is essentially non-commutative. We may, of course, consider a special case when Ω is commutative, but it will yield nothing but a trivial discrete topology on the set of the obtained points.

Rota topology. The primary function is to denote by $\mathbf{M}$ the set of points (that is, IRRs - irreducible representations) of Ω, each of which we shall associate with a prime ideal in Ω. Then there is an explicit algorithm, which associates a transitive graph with a subalgebra. The graph, in turn, can be treated as a topology on the set of its vertices (=points=IRRs). Note that in general, the Rota topology can be defined upon any set of ideals, and it is not necessary for Ω to be an algebra. Any linear subspace is suited for this purpose. The detailed description of the formalism can be found in [8].

To obtain an idea as to how the spatialization procedure works, it can be loosely described as finding the appropriate linear transformation, which renders the given set of matrices to that of upper triangular ones, which, in turn, resemble incidence matrices of appropriate DAGs. These graphs are the result of the spatialization.

6 Concluding remarks

As outlined in the mathematical formalism, it should be noted that *adaptive quantum networks*, as coherent quantum metastructures, are not standard neural networks. Rather, they are defined as superposed linear spaces, a meta-system whose subspaces consist of neural networks—just as a superposed wavefunction possesses an identity distinct from its constituent classical counterpart under influence of environmental interaction. In the ideal case, only following convergence to the predesignated, target network *minima* under backpropagation training, is projection via the spatialization procedure applied to convert the metasystem into a classical artificial neural network. As graphs are automatically produced as a consequence of this spatialization procedure, no *ab initio* association of states with graphs is requisite to implement the model into a candidate physical structure.

Coherent quantum information processing architectures both well-suited for implementation of adaptive quantum networks, and demonstrating promising experimental progress to date include highly-entangled, cluster state quantum computers suggested by Raussendorf and Briegel [13] and recent implementation by Zeilinger [14], high-dimensional Josephson junction qubit arrays [15], optical lattice traps in Bose-Einstein condensates [16], thin-layer diamond nanofilms [17], as well as novel materials currently under development by research teams active worldwide. Implementation of the training algorithm requires a relatively limited number of physical constraints to be satisfied—high-dimensional superposition, multiple degrees of internal freedom, and sufficient timescale under decoherence-free coherent state evolution. Consequently, adaptive quantum networks may be implemented both in state-of-the-art quantum technologies, as well as unexpectedly demonstrated within naturally-occurring, dynamic molecular complexes, such as brain microtubules [20] or proteomics in molecular biology [21, 23]. Several natural systems have been observed to exhibit interference properties and high degrees of internal freedom – including fullerenes [19], tetraphenyl-porphyrin [19], small biomolecules [19], and chlorophyll [21]. Contrary to conventional expections, Briegel *et al.* recently demonstrated persistent, driven entanglement in non-equilibrium quantum systems coupled to a hot and noisy environment, in which the presence of environmental noise plays a constructive role in maintaining recurring quantum entanglement. As such, promising candidates in coherent quantum information processing technologies, condensed matter systems, and biophysics are all potential areas of investigation for experimental implementation of adaptive quantum networks.

Acknowledgements

We highly appreciate the friendly inspiration provided by Ignazio Licata.

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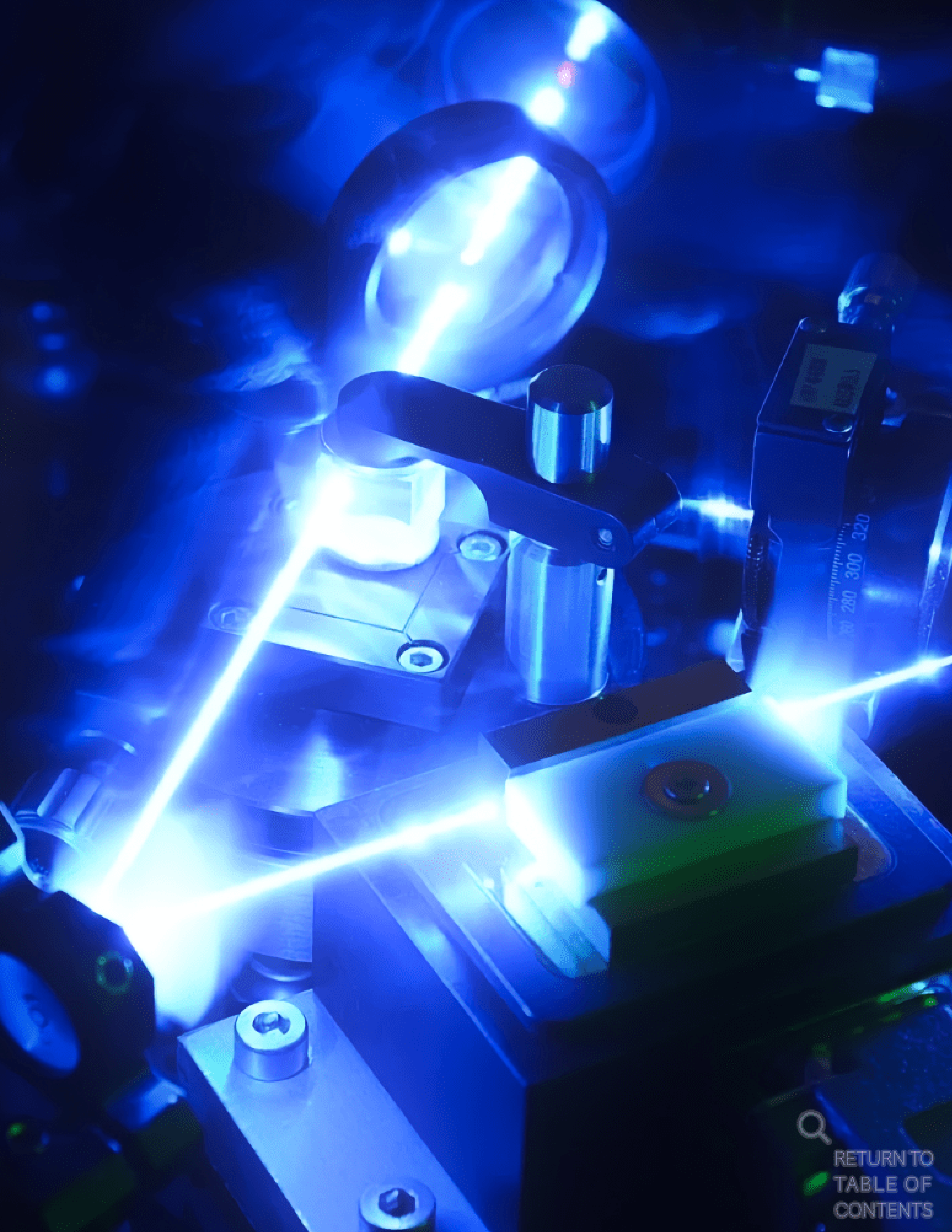

RETURN TO TABLE OF CONTENTS

International Journal of Theoretical Physics, Vol. 43, No. 12, December 2004 (© 2004)

Superpositional Quantum Network Topologies

Christopher Altman,[1,2] Jarosław Pykacz,[3,4] and Romàn R. Zapatrin[5,6]

We introduce superposition-based quantum networks composed of (i) the classical perceptron model of multilayered, feedforward neural networks and (ii) the algebraic model of evolving reticular quantum structures as described in quantum gravity. The main feature of this model is moving from particular neural topologies to a quantum metastructure which embodies many differing topological patterns. Using quantum parallelism, training is possible on superpositions of different network topologies. As a result, not only classical transition functions, but also topology becomes a subject of training. The main feature of our model is that particular neural networks, with different topologies, are *quantum states*. We consider high-dimensional dissipative quantum structures as candidates for implementation of the model.

KEY WORDS: Neural networks; quantum topology.

1. INTRODUCTION

Quantum learning networks have been suggested to offer new domains for quantum algorithm design (Behrman *et al.*, 1999; Chrisley, 1993; Ventura and Martinez, 1997). Machine-learning–inspired architectures are self-organizing, robust, and ideal for such tasks as pattern recognition and associative processing. Contemporary quantum network models convey their advantage using superposed quantum states on a fixed topological background. We suggest superposed quantum *topologies* as a novel approach to quantum neural networks, and present a model of learning and evolving superposed quantum network topologies, or SQNTs. The mathematical basis of this model is predicated upon two existing formalisms:

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- Neural networks: the classical learning model of pattern recognition (Dorogov, 2001; Rumelhart *et al.*, 1986).
- Algebraic quantum foam model: the formalism which describes superposed and continuously evolving discrete structures (Raptis and Zapatrin, 2001; Zapatrin, 1998).

In order to show how our model can be implemented we consider multidimensional quantum systems admitting highly degenerate states as described in (Savvidy, 2000) and the Bose–Einstein condensate as outlined in Vitiello (1995).

An overview of the model is arranged as follows. We begin with a classical perceptron model, namely, of a multilayered feedforward, weakly connected neural network. Then we extend this model, making it quantum by admitting the existence of superpositions of differing topological structures of neural networks using Rota algebraic formalism (Zapatrin, 1998) as applied to describe the evolution of reticular patterns of quantum space-times. This means that

1. we admit that the topological structure of a perceiving entity can change, and
2. we admit that these changes may be continuous.

At first sight these two requirements look contradictory: how can discrete structures evolve continuously? These requirements are reconciled in quantum mechanics. Along these lines we present the model of superposition-based quantum network topologies.

2. INTERLUDE ON RETICULAR QUANTUM SPACE-TIME FORMALISM

Before coming to SQNT models in more detail and for the sake of self-consistency, we recall the necessary constructions from quantum mechanics used to describe reticular quantum space-time. The main feature of the quantum mechanical description of a physical system is that we pass from configuration space to a complex linear space, called the STATE SPACE of the system. We shall consider systems with finite configuration spaces, therefore their state spaces will be finite-dimensional Hilbert spaces $\mathcal{H} = \mathbf{C}^N$. Suppose we have a system whose configuration space is $\{1, \ldots, n\}$. According to quantum mechanics, it can be in pure (that is, dispersion free) superposed state such as

$$|\psi\rangle = \cos\alpha|1\rangle + e^{i\phi}\sin\alpha|2\rangle \tag{1}$$

Quantum observables, that is, measuring apparata are described by self-adjoint operators in the state space of the system in question. The values of the observables are the eigenvalues of the operators; they are always real. Note that mutually commuting (thus having the same eigenvectors) observables are associated with the same measuring apparatus—they are interconverted just by relabelling the pointer's values. To specify an observable K, we consider a decomposition of the unit operator by orthogonal projectors and associate a *number* with each projector. In Dirac notation this reads:

$$K = \sum_i k_i |i\rangle\langle i| \tag{2}$$

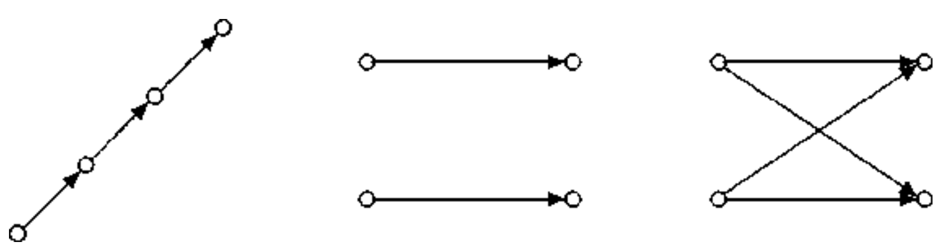
2.1. Spatialization

The *spatialization procedure* was developed in Raptis and Zapatrin (2001) for the purpose of describing space-time foam. Its primary feature is to associate discrete structures, rather than numerical values (2), with subspaces of the state space. More specifically, in standard quantum mechanics the state space is defined as a Hilbert space, that is, a complex linear space with an inner product, $\mathbf{H} \times \mathbf{H} \to \mathbf{C}$. Each subspace of $\mathbf{H}$ can be associated only with its dimension as an integer. We associate with each subspace $\mathcal{C}$ a disjoint graph, whose number of vertices equals its dimension, dim $\mathcal{C}$.

The spatialization procedure links some of the vertices, thus associating the subspace $\mathcal{C}$ with richer structure than a cardinal number. The only requirement is for $\mathcal{H}$ to be endowed with an associative product structure, rather than an inner product. In some cases this structure already exists, for instance, when $\mathcal{H}$ is a tensor product of two copies of the same state space $\mathbf{H}$, that is $\mathcal{H} = \mathbf{H} \otimes \mathbf{H}$. The associative product is defined on factorable vectors as

$$\phi \otimes \phi' \cdot \psi \otimes \psi' = \langle \phi', \psi \rangle \cdot \phi \otimes \psi'$$

and then extended by linearity (this is nothing but a usual matrix product). The spatialization procedure is briefly outlined as follows: with any directed acyclic transitive graph G with N vertices its Rota algebra is associated $\mathcal{A}$, whose elements are $N \times N$ matrices of the following form. They have zero entries a_{ik} when the vertices i, k are not connected in the graph G. For instance, consider the graphs



(3)

For these examples, the appropriate Rota algebras take the following form

$$\begin{pmatrix} * & * & * & * \\ 0 & * & * & * \\ 0 & 0 & * & * \\ 0 & 0 & 0 & * \end{pmatrix} \quad \begin{pmatrix} * & 0 & * & 0 \\ 0 & * & 0 & * \\ 0 & 0 & * & 0 \\ 0 & 0 & 0 & * \end{pmatrix} \quad \begin{pmatrix} * & 0 & * & * \\ 0 & * & * & * \\ 0 & 0 & * & 0 \\ 0 & 0 & 0 & * \end{pmatrix} \tag{4}$$

For a detailed account of Rota algebras and the spatialization formalism supplied with examples the reader is referred to Appendices A, B and Raptis and Zapatrin (2001) and Zapatrin (1998).

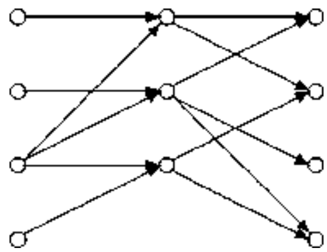
2.2. Neural Metastructures

The main feature of the proposal put forward in this paper is to shift from a particular structure of neural network as perceptron to something different: a metasystem whose *states* are perceptrons. This is accomplished as follows. Superposed quantum neural networks are themselves linear spaces rather than neural networks. With each subspace of the state space of SQNT—which is its quantum property, see (2) above—a particular neural network configuration is associated using the above mentioned spatialization procedure. In Section 3 we suggest to use the quantum features of SQNTs to enhance the performance of the main task in neural networks, namely, their training.

Realistic physical candidates to implement SQNTs have already been proposed. The first is based upon the Bose–Einstein condensate, on which a quantum brain model has been suggested by G. Vitiello (Vitiello, 1995). A second model has been suggested by Savvidy (2000). Both have the crucial property needed for our purposes, namely they have many individual degrees of freedom and admit superpositions. We emphasize that no ab initio association of states with graphs is needed, as graphs are automatically produced as a consequence of the spatialization procedure. SQNT implementation can also be modelled classically as demonstrated in Werbos (2002), a broad class of quantum algorithms can be simulated on classical systems.

3. NEURAL NETWORKS AND ROTA ALGEBRAS

One of the basic tasks of neural networks is to function as perceptrons, that is to recognize signals for which we have no structural theory, for instance, to recognize visual patterns. In this section, we review the basic principles on which perceptrons are based, their learning and training in classical setting and show how Rota algebras introduced above emerge in their description. We shall deal with multilayered feedforward NNs, such as



that is, their nodes can be arranged in layers so that (i) no nodes in a given layer communicate and (ii) the signals propagate only consecutively via layers. The state of a given neural network is the set of values, numerical or vectorial, assigned to its nodes. A time-step propagation changes the perceptron's state so that the value of a node i at time $t+1$ depends on its own value and the values of nodes adjacent to i at time t.

Besides their multilayered, high-dimensional structure the filtering and recognizing power of neural networks is based on the nonlinearity of their transition functions. In some cases, in particular while dealing with stability or elasticity issues, we may use linear approximations. This is exactly the case we explore in this paper: optimal topological configurations are assumed to be robust under small permutations (Dorogov, 2001).

3.1. Training

Initially one starts with a set of patterns for which the classification is known. Usually by means of heuristic methods, the topological structure of the network is chosen and then trained via input of known patterns and subsequent adjustment of network parameters (transition functions). Output signals are correlated with patterns from different classes to be well-separated with respect to certain criterion. The most popular method to adjust transition functions is error backpropagation (see, for instance, Rumelhart *et al.*, 1986).

3.2. Performance

Signal propagation in the linear approximation can be viewed as a matrix multiplication, which reduces to a number of arithmetic operations. The more links there are between neurons, the more computational resources are consumed by the process of pattern recognition. In order for a neural network to be faster, we should seek for sparser configurations.

Therefore, the criterion for "good matching" should also take performance into consideration. As an example we consider the approach of *fast neural networks*, which are weakly connected multilayered feedforward neural networks

(Dorogov, 2001). The idea of these networks grows from the FFT—fast Fourier transform. When finding optimal configurations of such networks, we restrict the allowed links between neurons and force networks to be sparse. Note that in our setting this requirement is followed automatically as we are confined by the dimensionality of the state space $\mathcal{H}$.

4. SUPERPOSITION-BASED TRAINING

The basic proposal of this paper is to replace training of particular neural network configurations with training of superposed ones. This can be achieved in the following steps:

(i) SQNT is treated as a system described by quantum mechanical formalism, in our special case represented by a matrix algebra $\mathcal{A}$. Note that the term "quantum" here is a mere indication of the rules of behavior of the object on which the SQNT is implemented, whatever be its "real" nature.
(ii) Input signals are vectors from a representation space of the algebra $\mathcal{A}$, as are output signals. Connection weights are represented by the matrix elements, and can further be represented by matrices of linear operators consequent of the spatialization procedure.
(iii) Learning is a matching algorithm which selects a subset $\mathcal{C}$ of $\mathcal{A}$ for which the criterion of matching between input and output signals is optimal. At this step we obtain the optimal configuration on the metalevel.
(iv) In order to pass to a particular neural network structure, we consider a subalgebra (rather than a subset) of $\mathcal{A}$ which is the nearest to the subset $\mathcal{C}$.

Now let us dwell on the above issues. For the first step, an appropriate physical system for SQNT to be implemented should be found. The main requirement which it has to satisfy is to possess sufficiently many degrees of freedom with controlled access to them. The initial candidates for these purposes are entangled quantum registers on which quantum computers are based. An alternative model can be considered using the Bose–Einstein condensate (Vitiello, 1995).

So, we start with a quantum system S with sufficiently many degrees of freedom. To implement item (ii), we must draw the distinction between the classes of states treated as states of the input register and between the states responsible for the operations of multiplication. This step does not affect the overall performance of the future perceptron, as it has to be done only once (this is analogous to building a computer). The work of the SQNT is to evolve according to a prescribed evolution, starting from the initial state (=a pattern to recognize) to the final one (=its classification identifier).

An algorithm seeking for best matching (iii) can be realized as follows. We feed in a pattern from a given sample set (=given prescribed state) and then let it evolve. The evolution is set in such a way that it realizes the multiplication operation. To be more precise, we consider any available evolution U_t and then label the states of SQNT in such a way that for the unit time δt the resulting action of $U_{\delta t}$ would be multiplication of appropriate elements. This is possible due to the arbitrary nature of labeling of eigenstates of operators (see Section 1).

The condition for learning to be successful is that the input vector from a sample set should be unchanged. In physical terms, this means patterns from the sample set should be eigenvectors for the energy operator responsible for the evolution. Why do we require it? The point is that we would like our output signals to be well separated, that is, they should be stable with respect to small variations of the input vector. This, in turn, requires the states of the overall register (*input*, *output*) to be orthogonal. If they are eigenstates of the generator of the evolution, this holds automatically. We denote by $\mathcal{C}$ the appropriate eigenspace and call it Calculation Subspace.

The last item (iv) is a kind of "classical correspondence principle" in quantum mechanics. SQNT operates as it is—namely, it undergoes quantum evolution—but if we would like to represent (perhaps with some losses) its work in terms of neural networks, we proceed in the following way. We deal with the calculation subspace $\mathcal{C}$ of our state space, which we obtained as a result of the best matching algorithm, and we have the evolution operator in our disposal which is interpreted as multiplication.

The spatialization procedure can be applicable to $\mathcal{C}$ only if it is closed with respect to the multiplication, while this requirement may not hold for eigenspaces of the energy operator. That is why, following the lines of quantum mechanics, we consider the nearest *subalgebra* to $\mathcal{C}$ and immediately interpret it as a neural network. This suggestion is in full accordance with quantum measurement theory, where the wave function of the system immediately "collapses" to an eigenstate of the appropriate operator.

5. CONCLUDING REMARKS

Presently only a handful of quantum algorithms exist, and these are confined to a limited set of specialized applications. Quantum learning architectures offer the potential to expand this domain to a much broader class of functionality. We have outlined the fundamentals of a quantum fast-training pattern recognition model—*superpositional quantum network topologies*, or SQNT—which provides a rich source for the development of a novel class of quantum algorithms. The distinguishing feature of our model lies in its ability to utilize coherent superposition of unique topological configurations of neural networks.

We suggest two ways to implement our model in physical media based on high-dimensional dissipative quantum systems (Savvidy, 2000; Vitiello, 1995). Quantum simulation methods offer an immediate candidate for study of the model: nonclassical dynamics can be efficiently simulated on ensembles of states of classical Turing machines ruled by second-order differential equations, see Werbos (2002) for more detail. It should be mentioned that although macroscopic physical systems are composed of quantum components, quantum phenomena in the macroscopic realm are usually invisible due to averaging over a large number of degrees of freedom. Nevertheless, the existence of macroscopic systems exhibiting quantum properties cannot be neglected in many subdomains of the life sciences, especially in molecular biology (Aerts *et al.*, 1993). For example, A. S. Davydov in his book "Biology and Quantum Mechanics" (Davydov 1982) studied collective soliton excitations in large protein molecules and applied them to such biological phenomena as membrane transport, nerve impulse conduction, and muscle contraction. Extending beyond relevance to the current model, we suggest this could be a potential explanation of the surprisingly high adaptation capabilities of living organisms. Classical models of learning and response to continuously changing environments require immense computational resources. We interpret this as a signal that perhaps quantum models could be more efficient for this purpose.

APPENDIX A: ROTA ALGEBRAS OF TRANSITIVE GRAPHS

Rota Algebras in Dirac Notation

Let X be a reflexive transitive graph. For brevity a pair of nodes i, j of X connected by an arrow $i \rightarrow j$ is said to be Tending. Consider the linear space Ω whose basis $|i\rangle\langle j|$ is labelled by tending pairs $i \rightarrow j$ of nodes of X.

$$\Omega(X) = \left\{ \sum_{i,j \in X} |i\rangle\langle j| \quad \text{such that} \quad i \rightarrow j \right\} \tag{5}$$

In the sequel, when no confusion occurs, we omit the notation of the graph X in parentheses and simply write

$$\Omega = \Omega(X)$$

Define the product on Ω by setting it on its basic elements:

$$|i\rangle\langle j||k\rangle\langle l| = \begin{cases} |i\rangle\langle l|, & \text{if} \quad j = k \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

Note that $|i\rangle\langle l|$ in (6) is always well-defined since the graph X is assumed to be transitive, that is why the existence of darts $i \rightarrow j$ and $j \rightarrow k$ always enables the existence of $i \rightarrow k$. The space Ω with the product (6) is called the Rota Algebra of the topological space (X, $\rightarrow$). These algebras were first introduced in Rota (1968) in the context of combinatorial theory.

The Matrix Representation of Rota Algebras

Given the Rota algebra of a transitive graph X, its standard matrix representation is obtained by choosing the basis of Ω consisting of the elements of the form $|i\rangle\langle k| = \mathbf{e}_{ik}$, with ik ranging over all tending pairs $i \to k$ of nodes of X. The matrices $\mathbf{e}_{ik}$ (called matrix units) are defined as follows:

$$\mathbf{e}_{ik}(m, n) = \begin{cases} 1, \ m = i \quad \text{and} \quad n = k \, (\text{provided } i \to k) \\ 0, \quad\quad\quad\quad\quad \text{otherwise} \end{cases} \tag{7}$$

where $\mathbf{e}_{ik}(m, n)$ stands for the element in the mth row and the nth column of the matrix $\mathbf{e}_{ik}$. We can also extend the ranging to *all* pairs of elements of X by putting $\mathbf{e}_{ik} \equiv 0$ for $i \nrightarrow k$. Then the product (6) reads:

$$\mathbf{e}_{ik} e_{i'k'} = \delta_{ki'} \mathbf{e}_{ik'} \tag{8}$$

To specify a Rota algebra in the standard matrix representation we fix the template matrix replacing the unit entries in the incidence matrix I_{ik} of the graph X:

$$I_{ik} = \begin{cases} 1, & i \to k \\ 0, & \text{otherwise} \end{cases}$$

by wildcards $*$ ranging independently over all numbers. For instance, the algebra associated with the two-node graph $\cdot \to \cdot$ has the the following template matrix

$$\Omega(\cdot \to \cdot) = \begin{pmatrix} * & * \\ 0 & * \end{pmatrix} = \left\{ \begin{pmatrix} a & b \\ 0 & c \end{pmatrix} | a, b, c \in \mathbf{C} \right\}$$

So, we see that any transitive graph can be described in terms of a finite-dimensional algebra (for further details we refer to Zapatrin, 1998).

APPENDIX B: SPATIALIZATION PROCEDURE

Here we describe the spatialization procedure which associates a graph with an arbitrary finite-dimensional algebra.

The Emergence of Nodes

Let us start with a given finite-dimensional associative (and noncommutative, in general) algebra Ω. According to standard conceptions and methods of modern algebraic geometry, as well as the general algebraic approach to physics, we introduce the points of Ω as its irreducible representations (IRs). So, the first step of the specialization procedure is creating (or finding) points of Ω (which will become nodes of the future graph):

$$\{\text{points}\} = \{\text{IRs}\} \tag{9}$$

Standard Set With Nonstandard Topology

When the first spatialization step in a standard way (9) is done we may wish to proceed by connecting the set of nodes by arrows. This problem is mathematically equivalent to equipping the set of points of the algebra by a topology. There are standard recipes for this step as well like, say, the Zariski topology on the prime spectrum of Ω. Unfortunately, on finite-dimensional algebras this topology is always discrete, which leaves us no chance to fit the above requirement of being non-Hausdorff (i.e., not T_2). In terms of graphs that means that the standard recipes can not help us to create arrows. So, we are compelled to find another topology. For these purposes the Rota topology is suggested (first it was introduced in Zapatrin, 1998).

Let Ω be a finite-dimensional algebra. Denote by X the set of points of Ω, each of which we shall associate with a prime ideal in Ω. Consider two points (representations of Ω) $i, j \in X$ and denote by ker i, ker j their kernels. Both of them, being kernels of representations, are two-sided ideals in Ω, in particular, subsets of Ω, hence both of the following expressions make sense:

$$\ker\, i \cap \ker\, j \subset \Omega \quad \text{and} \quad \ker\, i \cdot \ker\, j \subset \Omega$$

the latter denoting the product of subsets of $\Omega : \ker\, i \cdot \ker\, j = \{a \in \Omega | \exists u \in \ker\, i, v \in \ker\, j : uv = a\}$. Since ker i, ker j are ideals, we always have the inclusion $\ker\, i \cdot \ker\, j \subseteq \ker\, i \cap \ker\, j$ which may be strict or not. Define the relation $\propto$ on X as follows:

$$i \propto j \quad \text{if and only if} \quad \ker i \ \ \ker\, j \neq \ker\, i \cap \ker\, j \tag{10}$$

Then the Rota Topology is the weakest one in which $i \propto j$ implies the convergence $i \to j$ of the point i to the point j. Explicitly, the necessary and sufficient conditions for i to converge to j in the Rota topology reads:

$$i \to j \quad \text{if and only if} \quad \exists k_0, \ldots, k_t, \ldots, k_n | k_0 = i, \quad k_n = j;\ k_{t-1} \propto k_t \tag{11}$$

This operation is called the transitive closure of the relation $\propto$. Note that, in general, the Rota topology can be defined on any set of ideals.

It was proved by Stanley (1986) that in that particular case when Ω is the Rota algebra of a reflexive transitive graph, then its spatialization X endowed with the Rota topology (11) is homeomorphic to the initial topological space. However, in general if we have two reflexive transitive graphs and an arrow-preserving mapping between them, their Rota algebras may *not* be homomorphic. Recently, "good" classes of reflexive transitive graphs topological spaces were discovered for which the transition to Rota algebras is functorial (Breslav and Zapatrin, 2000; Zapatrin, 2001). In our approach, it supports the existence of the classical limit.

ACKNOWLEDGMENTS

The authors highly appreciate the attention to their work offered by A. Dorogov, S. Krasnikov, and P. Werbos. This work was carried out within the ATIP Quantum Information Science and Technology Project, the project G.0335.02 of the Flemish Fund for Scientific Research and the research program "*Quantum Theory in the Early Universe*," under the auspices of the Russian Basic Research Foundation (RFFI).

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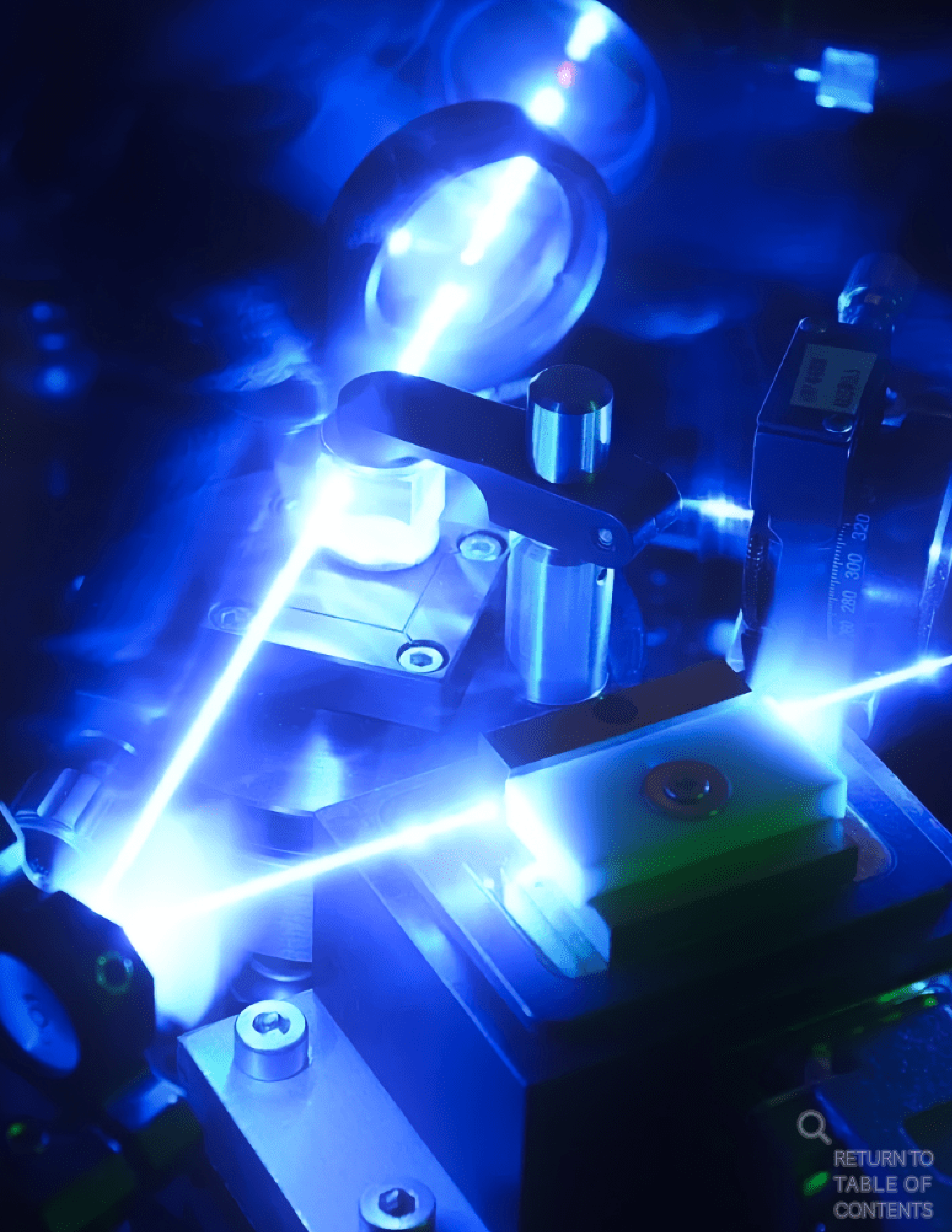

RETURN TO
TABLE OF
CONTENTS

Int J Theor Phys (2010) 49: 2991–2997
DOI 10.1007/s10773-009-0103-1

Backpropagation Training in Adaptive Quantum Networks

Christopher Altman · Romàn R. Zapatrin

Received: 31 October 2008 / Accepted: 21 July 2009 / Published online: 31 July 2009

Abstract We introduce a robust, error-tolerant adaptive training algorithm for generalized learning paradigms in high-dimensional superposed quantum networks, or *adaptive quantum networks*. The formalized procedure applies standard backpropagation training across a coherent ensemble of discrete topological configurations of individual neural networks, each of which is formally merged into appropriate linear superposition within a predefined, decoherence-free subspace. Quantum parallelism facilitates simultaneous training and revision of the system within this coherent state space, resulting in accelerated convergence to a stable network attractor under consequent iteration of the implemented backpropagation algorithm. Parallel evolution of linear superposed networks incorporating backpropagation training provides quantitative, numerical indications for optimization of both single-neuron activation functions and optimal reconfiguration of whole-network quantum structure.

Keywords Neural networks · Quantum topology · Adaptive learning

1 Introduction

Artificial neural networks are routinely applied to resolve unstructured or multivariate machine learning problems such as high-speed pattern recognition, image processing and associative pattern matching tasks. Due to their novelty, however, quantum neural networks remain relatively uncharted in the artificial intelligence and quantum algorithms communities. Several groups [1–4] have outlined preliminary quantum network architectures; each novel approach contributes significant insights towards application methodology, alternative implementations and underlying modal interpretation—however, widespread and effective

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universal implementation of quantum neural networks remains an open research question, as both theoretical and experimental toolsets are still in the incipient stages of development and maturation.

A common underlying thread shared by quantum network proposals to date is that each implements superposition of neural transition functions upon a single, fixed topological foundation. In this letter, we expand upon a novel framework initially introduced in [5], which diverges from prior network models by fine-tuning not only optimization of neural transition functions—but by fully reconfiguring the connective physical *topology* of the quantum network itself. The mathematical formalism employed for this approach descends from the Rota algebraic spatialization procedure of evolving reticular quantum structures, which was initially developed in [6] to address superposed topological manifolds of space-time foam as described in quantum gravity. Subsequently, not only neuron weighting and *transition functions*—but also linear superposition of the *network topology* itself—are subject to training and revision within this coherent state space.

We formally incorporate the standard backpropagation training algorithm initially introduced by Werbos in [7]. Repeated iteration of training series results in convergence of sample output to a stable network attractor corresponding to the lowest energy configuration space between *given input* and *desired output* layer. Following convergence to this minimum, the superposed linear network is converted upon measurement to a conventional, classical neural network by consequent application of the Rota algebraic projection formalism.

2 'Linear' Neural Networks—Dual contexts

Traditional computers execute algorithms—that is, they follow a specific set of instructions to arrive at a solution to a given problem. Artificial neural networks, by contrast, learn by trial and error: training through example. In a specific class of neural networks—multilayered, *feedforward* neural networks—signals are allowed to propagate only forward: there is no feedback process in the training phase. These connection patterns are formally classified as mathematical structures known as POSETS—partially ordered sets, or DIRECTED ACYCLIC GRAPHS—DAGS.

In this letter, we convert the primary component of artificial neural networks—directed acyclic graphs—into a set of linear matrices. The training optimization protocol is then reclassified in terms of unitary matrices and matrix operations. The result of training optimization is then a matrix, rather than a directed acyclic graph. In order to recover the initial graph structure upon derivation of the appropriate solution, the Rota algebraic spatialization procedure [8] is applied to recover the appropriate graph.

Herein we use the term *adaptive neural networks*. However, the primary objects subject to revision and training are operators in linear spaces—which can be realized, for instance, as quantum observables, rather than as explicitly defined neural networks. In our paper, we shall use the term 'linear' under two separate contexts. The first definition implies restriction to linear artificial neural networks, as we defer application of nonlinear network optimization problems to a subsequent manuscript. In this letter, we focus solely upon optimized approach and applications of *linear* neural networks.

The second usage of *linearization* is the standard linear formalism central to quantum mechanics. This is the basis of our mathematical approach, and is outlined in further detail. The topology of a feedforward artificial neural network, $\mathcal{N}$, is described by the TEMPLATE

MATRIX **A** of the appropriate directed acyclic graph, which is formed as follows:

$$\mathbf{A}_{jk} = \begin{cases} *, & \text{if } j \to k \text{ in } \mathbf{M}, \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where $*$ stands for a wildcard—any number, and the set of such numerical matrices form an algebra [10] as it is closed under multiplication. The main property of **A** is that the synaptic weights 'follow' it—namely, if $\mathbf{A}_{jk} = 0$, then $w_{jk} = 0$.

Returning to picture (2) of signal propagation in $\mathcal{N}$, taking various matrices **A**—and allowing them only to comply with the template matrix (1)—we form various products (2). The resulting set of matrices is called the ROTA ALGEBRA of **M**. It can be verified that this set is closed under sums and matrix products, and thus qualifies as a closed algebra. This description is explicated under greater detail in [5].

Given a feedforward neural network $\mathcal{N}$ with the set of nodes **M**, consider the linear space $\mathcal{H}$, whose basis is labeled by the elements of **M**. A vector $\mathbf{x} \in \mathcal{H}$ is associated with a state of the network, namely the j-th component of **x** is the activity in node j. Note that the state of $\mathcal{N}$ captures the activities of *all* nodes, so a convention is required to define the default activity value of the nodes—which are thus set to zero.

Initial activation corresponds to changing values of only a part of nodes—specifically those in the input layer. The signal then propagates through $\mathcal{N}$, and we describe this activation by a linear[1] operator W in $\mathcal{H}$. The time in which the signal requires to advance is described as the following evolution of the state of the simulator: We start with an initial input vector $\mathbf{x}_0$, thus:

$$\mathbf{x}_0 \mapsto \mathbf{x}_1 = \mathbf{x}_0 W \mapsto \cdots \mapsto \mathbf{x}_{\text{out}} = \mathbf{x}_n = \mathbf{x}_0 W^n \tag{2}$$

following n steps. Recall that postfix notation is employed in this instance.

The crucial feature of the suggested approach is that signal propagation is now described by iteration of *the same* operator W. From this step forward, the operator W, rather than the collection of weights as in the traditional backpropagation approach, will be subject to training.

3 Performing Standard Operations in Linearized Form

In this section, we reformulate classical neuron activity, propagation, and error backpropagation methods in linear terms. A first detail to consider is the process of signal propagation in terms of Rota algebras. We initially have a register—a sequence of unique numbers defining the artificial neural network state—and view it as a vector **x** in the appropriate linear space. Following formula (2), we consecutively act upon the register, following elements of the Rota algebra. Initially, setup is defined as $x = 0$. Recall that the entries of **x** correspond to activities of a single neuron. When the initial signal is input, this results in the fragment of **x** corresponding to the input layer acquiring the appropriate values, while the remainder is still set to zero. The application of W activates the neurons of the second layer. Following this action, the first fragment bears the input values, and the second fragment corresponds to the net inputs of the second layer. This activation function is then applied forward throughout the network.

[1] Recall that in this paper we focus solely on linear neural networks.

The final vector, $\mathbf{x}_n$, possesses the following structure, consisting of blocks corresponding to layers—the input block contains corresponding input data, and the intermediate blocks contain net inputs from the previous layers. This captures the property that as the signal propagates through the network, the intermediate neurons retain their values. On the other hand, this requirement is not essential—within the same model, we may also consider artificial neural networks with simultaneous signal inputs at the propagation point of a single input pattern. When presented with a given training set, the overall error function may be minimized by solving the equation,

$$\frac{\partial}{\partial W} A W^n - T = 0. \tag{3}$$

One disadvantage at this point is that as the dimensionality of the state space grows, the exact solution of this equation may become intractable, at which point approximation methods such as gradient descent may need to be employed. To implement this, an error backpropagation method is required. The initial error vector δ is set to be zero. Just as in (2), the backpropagation process can then be described. The input, δ_0, is defined as the difference between the fragment of the output $\mathbf{x}_n$ of the forthpropagation process and the target vector $\mathbf{t}$. The expression for updated errors is the product of these two factors: the first factor can be expressed as $W\mathbf{x}_{n-t}$. The second factor can be expressed as $\delta_t W^T$, where W^T is the transposed matrix. In accordance with agreement that the states of $\mathcal{N}$ are diagonal matrices, rather than vectors, the product of the two factors is well-defined. As a result,

$$\delta_{t+1} = W\mathbf{x}_{n-t}\delta_t W^T. \tag{4}$$

The standard weighting adjustment formula can then be written in compact form, using the adjacency matrix $\mathbf{A}$ of the directed acyclic graph associated with our network:

$$W^{\text{upd}} = W^{\text{ini}} + \delta_n \cdot \mathbf{A}\mathbf{x}_n. \tag{5}$$

This procedure is then applied recurrently until required error values converge to a minimum within predesignated boundary tolerances. It should be noted that there is no novel formalism at this early stage of the procedure—this step is but a reformulation of a standard algorithm in supervised learning.

4 Mathematics of Spatialization

The key point of the spatialization procedure (first introduced in a different context in [6]) is the following: consider the full matrix algebra $\mathcal{A}$ as a linear space. From this perspective, the Rota algebras Ω described by (1) are just linear subspaces of $\mathcal{A}$. Having a procedure which—starting from a subset of $\mathcal{A}$—creates a topological space, providing the capability to discuss superposed configurations of differing neural networks. In this section we present a procedure which—starting from a given subspace of $\mathcal{A}$—produces a set, and endows it with a topology that can be associated with certain acyclic directed graphs.

When the set of nodes is fixed, Rota algebras provide a suitable machinery to describe topology changes, which are expressed in terms of creation and annihilation of edges. In terms of template matrices (1), these operations are adding or removing asterisks from the appropriate templates. In a fixed basis, a Rota algebra is a subspace of a full matrix algebra $\mathcal{A}$—therefore adding or removing asterisks is equivalent to adding or removing basis vectors. Thus, any particular Rota algebra is a linear subspace of Ω. The basic idea of our approach is to associate *any* subspace of Ω with an appropriate directed acyclic graph.

Spectra—the emergence of nodes. The notion of a spectrum is tightly related with that of an ideal. Suppose again that we have an algebra of functions $\mathcal{A}$ on a set $\mathbf{M}$. Fix a point $m \in \mathbf{M}$, and consider the subset $\mathcal{I} \subseteq \mathcal{A}$ of functions f such that $f(m) = 0$. First, $\mathcal{I}$ itself is an algebra. Furthermore, for any $f \in \mathcal{A}$ and any $h \in \mathcal{I}$ the product fh is always an element of $\mathcal{I}$. Such subsets $\mathcal{I}$ are called ideals of the algebra $\mathcal{A}$. Points of $\mathbf{M}$ are in one-to-one correspondence with the MAXIMAL IDEALS of $\mathcal{A}$[2] and $\mathbf{M}$ is called SPECTRUM[3] of $\mathcal{A}$.

In the case wherein $\mathcal{A}$ has infinite dimension, such as in a linear space, there are different, non-equivalent and nontrivial topologies which can be defined on $\mathcal{A}$. There are standard recipes for this step: for example, the Zariski topology on the prime spectrum of Ω. Unfortunately, on finite-dimensional algebras this topology is always discrete—which leaves us no chance to fit the requirement of being non-Hausdorff. In terms of graphs, that means that the standard recipes can be utilized to create directed arrows. Thus, we are compelled to find another topology. For these purposes, the Rota topology was suggested in [8].

Suppose we are given a finite-dimensional associative—and non-commutative, in general—algebra Ω. According to standard conceptions and methods of modern algebraic geometry, as well as the general algebraic approach to physics, we introduce the points of Ω as its irreducible representations (IRs). The first step of the spatialization procedure is then creating or finding points of Ω, which will become nodes of the future graph:

$$\{\text{points}\} = \{\text{IRs}\}. \tag{6}$$

Rota topology. Denote by $\mathbf{M}$ the set of points of Ω, each of which we shall associate with a prime ideal in Ω. Consider two points (representations of Ω) $i, j \in \mathbf{M}$ and denote by $\ker i, \ker j$ their kernels. Both of them, being kernels of representations, are two-sided ideals in Ω, in particular, subsets of Ω, hence both of the following expressions make sense:

$$\ker i \cap \ker j \subset \Omega \quad \text{and} \quad \ker i \cdot \ker j \subset \Omega.$$

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The Rota topology is then the weakest one in which $i \propto j$ implies convergence $i \to j$ of the point i to the point j. Explicitly, the necessary and sufficient conditions for i to converge to j in the Rota topology reads:

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MATRIX **A** of the appropriate directed acyclic graph, which is formed as follows:

$$\mathbf{A}_{jk} = \begin{cases} *, & \text{if } j \to k \text{ in } \mathbf{M}, \\ 0, & \text{otherwise}, \end{cases} \quad (1)$$

where $*$ stands for a wildcard—any number, and the set of such numerical matrices form an algebra [10] as it is closed under multiplication. The main property of **A** is that the synaptic weights 'follow' it—namely, if $\mathbf{A}_{jk} = 0$, then $w_{jk} = 0$.

Returning to picture (2) of signal propagation in $\mathcal{N}$, taking various matrices **A**—and allowing them only to comply with the template matrix (1)—we form various products (2). The resulting set of matrices is called the ROTA ALGEBRA of **M**. It can be verified that this set is closed under sums and matrix products, and thus qualifies as a closed algebra. This description is explicated under greater detail in [5].

Given a feedforward neural network $\mathcal{N}$ with the set of nodes **M**, consider the linear space $\mathcal{H}$, whose basis is labeled by the elements of **M**. A vector $\mathbf{x} \in \mathcal{H}$ is associated with a state of the network, namely the j-th component of **x** is the activity in node j. Note that the state of $\mathcal{N}$ captures the activities of *all* nodes, so a convention is required to define the default activity value of the nodes—which are thus set to zero.

Initial activation corresponds to changing values of only a part of nodes—specifically those in the input layer. The signal then propagates through $\mathcal{N}$, and we describe this activation by a linear[1] operator W in $\mathcal{H}$. The time in which the signal requires to advance is described as the following evolution of the state of the simulator: We start with an initial input vector $\mathbf{x}_0$, thus:

$$\mathbf{x}_0 \mapsto \mathbf{x}_1 = \mathbf{x}_0 W \mapsto \cdots \mapsto \mathbf{x}_{\text{out}} = \mathbf{x}_n = \mathbf{x}_0 W^n \quad (2)$$

following n steps. Recall that postfix notation is employed in this instance.

The crucial feature of the suggested approach is that signal propagation is now described by iteration of *the same* operator W. From this step forward, the operator W, rather than the collection of weights as in the traditional backpropagation approach, will be subject to training.

3 Performing Standard Operations in Linearized Form

In this section, we reformulate classical neuron activity, propagation, and error backpropagation methods in linear terms. A first detail to consider is the process of signal propagation in terms of Rota algebras. We initially have a register—a sequence of unique numbers defining the artificial neural network state—and view it as a vector **x** in the appropriate linear space. Following formula (2), we consecutively act upon the register, following elements of the Rota algebra. Initially, setup is defined as $x = 0$. Recall that the entries of **x** correspond to activities of a single neuron. When the initial signal is input, this results in the fragment of **x** corresponding to the input layer acquiring the appropriate values, while the remainder is still set to zero. The application of W activates the neurons of the second layer. Following this action, the first fragment bears the input values, and the second fragment corresponds to the net inputs of the second layer. This activation function is then applied forward throughout the network.

[1] Recall that in this paper we focus solely on linear neural networks.

The final vector, $\mathbf{x}_n$, possesses the following structure, consisting of blocks corresponding to layers—the input block contains corresponding input data, and the intermediate blocks contain net inputs from the previous layers. This captures the property that as the signal propagates through the network, the intermediate neurons retain their values. On the other hand, this requirement is not essential—within the same model, we may also consider artificial neural networks with simultaneous signal inputs at the propagation point of a single input pattern. When presented with a given training set, the overall error function may be minimized by solving the equation,

$$\frac{\partial}{\partial W} A W^n - T = 0. \tag{3}$$

One disadvantage at this point is that as the dimensionality of the state space grows, the exact solution of this equation may become intractable, at which point approximation methods such as gradient descent may need to be employed. To implement this, an error backpropagation method is required. The initial error vector δ is set to be zero. Just as in (2), the backpropagation process can then be described. The input, δ_0, is defined as the difference between the fragment of the output $\mathbf{x}_n$ of the forthpropagation process and the target vector $\mathbf{t}$. The expression for updated errors is the product of these two factors: the first factor can be expressed as $W\mathbf{x}_{n-t}$. The second factor can be expressed as $\delta_t W^T$, where W^T is the transposed matrix. In accordance with agreement that the states of $\mathcal{N}$ are diagonal matrices, rather than vectors, the product of the two factors is well-defined. As a result,

$$\delta_{t+1} = W\mathbf{x}_{n-t}\delta_t W^T. \tag{4}$$

The standard weighting adjustment formula can then be written in compact form, using the adjacency matrix $\mathbf{A}$ of the directed acyclic graph associated with our network:

$$W^{\mathrm{upd}} = W^{\mathrm{ini}} + \delta_n \cdot \mathbf{A}\mathbf{x}_n. \tag{5}$$

This procedure is then applied recurrently until required error values converge to a minimum within predesignated boundary tolerances. It should be noted that there is no novel formalism at this early stage of the procedure—this step is but a reformulation of a standard algorithm in supervised learning.

4 Mathematics of Spatialization

The key point of the spatialization procedure (first introduced in a different context in [6]) is the following: consider the full matrix algebra $\mathcal{A}$ as a linear space. From this perspective, the Rota algebras Ω described by (1) are just linear subspaces of $\mathcal{A}$. Having a procedure which—starting from a subset of $\mathcal{A}$—creates a topological space, providing the capability to discuss superposed configurations of differing neural networks. In this section we present a procedure which—starting from a given subspace of $\mathcal{A}$—produces a set, and endows it with a topology that can be associated with certain acyclic directed graphs.

When the set of nodes is fixed, Rota algebras provide a suitable machinery to describe topology changes, which are expressed in terms of creation and annihilation of edges. In terms of template matrices (1), these operations are adding or removing asterisks from the appropriate templates. In a fixed basis, a Rota algebra is a subspace of a full matrix algebra $\mathcal{A}$—therefore adding or removing asterisks is equivalent to adding or removing basis vectors. Thus, any particular Rota algebra is a linear subspace of Ω. The basic idea of our approach is to associate *any* subspace of Ω with an appropriate directed acyclic graph.

Spectra—the emergence of nodes. The notion of a spectrum is tightly related with that of an ideal. Suppose again that we have an algebra of functions $\mathcal{A}$ on a set $\mathbf{M}$. Fix a point $m \in \mathbf{M}$, and consider the subset $\mathcal{I} \subseteq \mathcal{A}$ of functions f such that $f(m) = 0$. First, $\mathcal{I}$ itself is an algebra. Furthermore, for any $f \in \mathcal{A}$ and any $h \in \mathcal{I}$ the product fh is always an element of $\mathcal{I}$. Such subsets $\mathcal{I}$ are called ideals of the algebra $\mathcal{A}$. Points of $\mathbf{M}$ are in one-to-one correspondence with the MAXIMAL IDEALS of $\mathcal{A}$[2] and $\mathbf{M}$ is called SPECTRUM[3] of $\mathcal{A}$.

In the case wherein $\mathcal{A}$ has infinite dimension, such as in a linear space, there are different, non-equivalent and nontrivial topologies which can be defined on $\mathcal{A}$. There are standard recipes for this step: for example, the Zariski topology on the prime spectrum of Ω. Unfortunately, on finite-dimensional algebras this topology is always discrete—which leaves us no chance to fit the requirement of being non-Hausdorff. In terms of graphs, that means that the standard recipes can be utilized to create directed arrows. Thus, we are compelled to find another topology. For these purposes, the Rota topology was suggested in [8].

Suppose we are given a finite-dimensional associative—and non-commutative, in general—algebra Ω. According to standard conceptions and methods of modern algebraic geometry, as well as the general algebraic approach to physics, we introduce the points of Ω as its irreducible representations (IRs). The first step of the spatialization procedure is then creating or finding points of Ω, which will become nodes of the future graph:

$$\{\text{points}\} = \{\text{IRs}\}. \tag{6}$$

Rota topology. Denote by $\mathbf{M}$ the set of points of Ω, each of which we shall associate with a prime ideal in Ω. Consider two points (representations of Ω) $i, j \in \mathbf{M}$ and denote by $\ker i, \ker j$ their kernels. Both of them, being kernels of representations, are two-sided ideals in Ω, in particular, subsets of Ω, hence both of the following expressions make sense:

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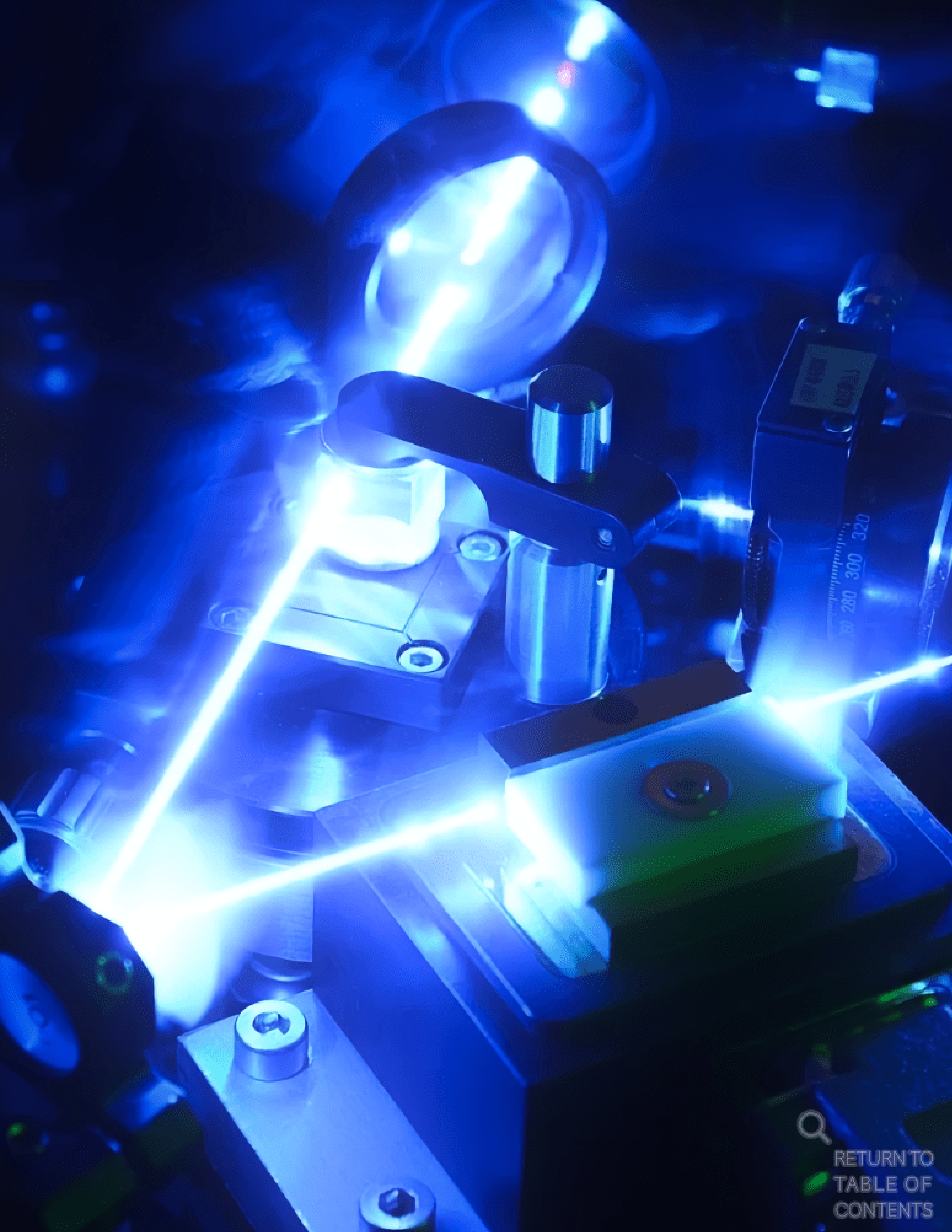

RETURN TO TABLE OF CONTENTS

Microlens array fabrication via microjet printing technologies

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We review recent advances in optical microlens array fabrication using piezoelectric microchannel mounted nozzles to deposit polymer droplets to various substrates via drop-on-demand (DOD) fashion. The technique produces microlenses in a similar fashion to photoresist and can be employed to produce spherical and nonspherical lenses on the order of 20μm to 3mm at rates of up to 25 kHz on demand. Advantages include high reproducibility, flexibility and process automation while offering a simple and cost-effective fabrication solution to produce microlens arrays in multiple application domains.

Keywords: MEMS, optical fabrication technology, drop-on-demand, microjet, microlens arrays

Introduction

Microlens arrays offer a unique enabling technology in critical domains such as sensors, communications, metrology, and medical imaging, often providing solutions where other technologies prove unsuitable, unwieldy or cost-prohibitive. Beam collimation and focusing, astronomy, tele-communications and optical switching, industrial manufacturing, hybrid sensors and defense and security applications are heavily reliant on optical lenses and microlens array integrated components.

Multiple fabrication techniques have been developed to provide solutions given design and specification constraints, which sometimes require one-off, customized lens and optical components. Traditional optical fabrication technologies often require cleanroom or multistep fabrication setups, using fused silica or silicon photo-lithography processes. Other common fabrication processes employ resist processing, epitaxial growth, reactive ion etching, hot pressing or mechanical fabrication, which are often costly or labor-intensive [1].

Microjet printing technology

Microjet fabrication offers an affordable alternative to conventional manufacturing techniques, employing a single-step process with superior flexibility to produce microlens arrays ranging from 20μm to 5mm [2], offering high repeatability, accuracy and lens-to-lens uniformity [3]. The process offers competitive precision while remaining a low-cost, highly-automated and integrated manufacturing technology.

Inkjet printing is a familiar and relatively mature industry, and the well-supported industrial infrastructure and ubiquity of off-the-shelf printing solutions offers microjet lens array fabrication as a low barrier-to-entry, cost-effective and low complexity fabrication process.

The fabrication process allows for single-step molding and mounting, which further reduces complexity and costs. Robust thermal durability and high coupling efficiency offer further incentives to utilize microjet-produced microlens arrays as an alternative to traditional photolithographic production.

Two distinct classes of microjet fabrication are in widespread use [4] – continuous stream microjet and drop-on-demand (DOD). Continuous microjet printing is often employed in industrial applications such as product labeling, proofing and textile printing. However, the fluid jet in a continuous microjet stream printing breaks apart into uniform droplets, typically 50μm to 80μm in diameter en route to the substrate, due to Rayleigh instability induced by amplification of capillary waves in the stream [5]. While continuous stream microjet systems have higher throughput for industrial applications, they are more complex to operate and offer less precision than piezoelectric channel, drop-on-demand microdispensing commonly employed for the fabrication of microlens components.

Drop-on-demand production

Drop-on-demand microlens fabrication consists of a basic setup utilizing a heated fluid reservoir coupled to a piezoelectric ceramic, through which a machined nozzle dispenses uniform polymer droplets to the substrate mounted to an *xyz* microcontroller as illustrated in fig. 1. As the drops are rotationally symmetrical, minimization of surface tension leads to spherical lens formation. Automated microcontrollers allow for lens spacing of ~1μm, focal lengths up to 1%, and sphericity to a quarter wavelength at 1550nm [5].

Commonly employed optical polymers incorporate UV sensitive hybrid organic-inorganic sols in combination with photo-initiator [6]. Once deposited to substrate, the polymer is cured through exposure to UV illumination. Variation in UV curing time can be employed to modify lens shape, depth of field, and lens height, and tailoring sol-gel composition can further modify refractive index [6].

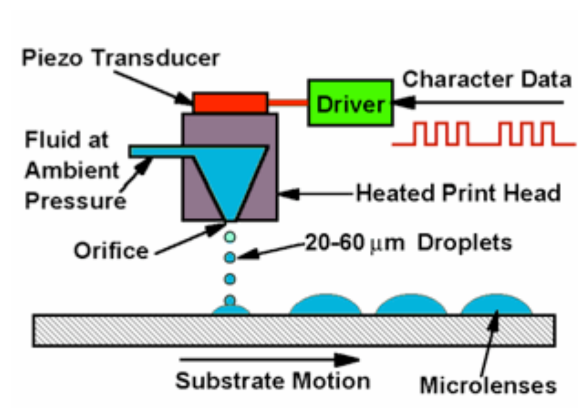

Figure 1: Schematic of a microlens array produced via drop-on-demand method [2].

Automated control over lens parameters can be induced by variance of print head temperature, substrate temperature, or drive input waveform to optimize performance for a given application. Volume of dispensed polymer can be varied to modify curvature or height of the microlens for a given diameter of microlens. Recent work utilizing solvent mixtures has led to the production of aspherical microlenses [7]. Hemi-elliptical and doublet lenses can be formed by depositing lenses closer together and allowing them to merge [2]. Multimode waveguides may further be produced by line depositing droplets, which coalesce to form a single unit as in fig. 2.

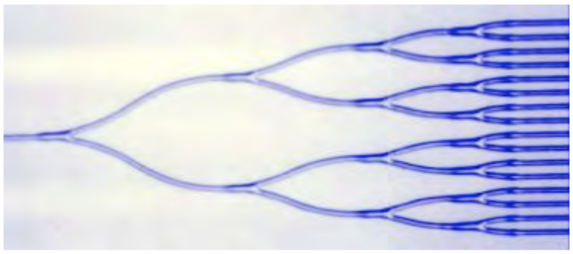

Figure 2: 100μm waveguide splitter [2].

Novel applications

The flexibility and affordability of drop-on-demand printing allows for microlens production in sectors previously limited to more costly or labor-intensive fabrication methods. Interdisciplinary collaboration has lead to several innovative uses of microoptics and microelectronics composite systems:

Optical neural networks offer high-speed processsing and enormous throughput potential. Microlens array-based neural networks have been developed at IBM Zürich using stacked planar diffractive microlens arrays for illumination, imaging and recurrent fan-in [8].

MicroFab Technologies Inc. has produced high-dimensional microlens arrays for use as free-space optical interconnects in massively parallel VCSEL† datacom photonic switches under DARPA VIVACE research grant "VCSEL based interconnects in VLSI Architectures for Computational Enhancement" [9], fig. 3.

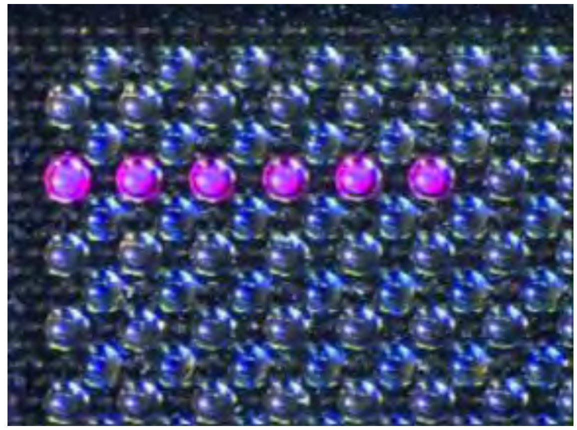

Figure 3: Smart pixel microlens array in a vertical-cavity surface-emitting laser module with six lenses active [2].

Microlenses can be tip-mounted to gradient index of refraction (GRIN) rods and cylindrical optical fiber arrays as beam collimators and waveguides, as well as directly mounted to optical fiber tips to reduce signal loss and increase transmission efficiency [5], as illustrated in figs. 4 and 5.

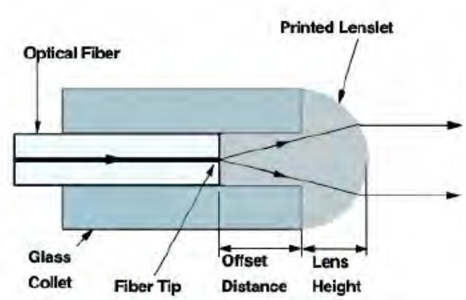

Figure 4: Microlens beam collimator printed onto a single-mode optical fiber [8].

In medical, environmental monitoring and defense applications, optical sol-gels with enhanced porosity have been doped with

† Vertical-cavity surface-emitting laser

biochemical sensors to produce micro-optical fiber composites for potential use in both clinical diagnosis and environmental biochemical sensing [2].

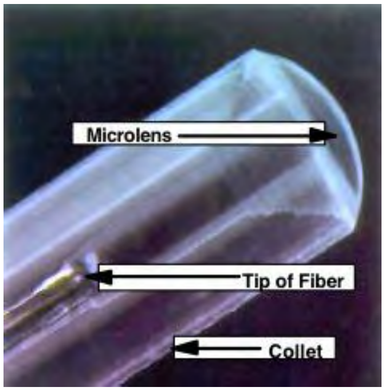

Figure 5: Microlens beam collimator printed onto a single-mode optical fiber [10].

Conclusion and Future Directions

As costs decline and microjet deposition precision advances, fabricated microlens arrays will continue to offer a cost-effective production alternative to conventional lithographic fabrication processes. More broadly, innovations in optical fabrication will continue to grow in both scope and scale as new technologies emerge which call for novel design solutions and lens specifications.

Microlens arrays have already shown potential in scalable quantum information processing, an emerging field which promises to undergo rapid growth as practical implementations reach maturity. Arrays have been employed to generate noiseless subsystems in neutral atom traps [10, 11] – typically, a two-dimensional array of spherical, diffractive microlenses with focal length of 625μm and lens diameter of 125μm is used in combination with a diode laser to localize neutral ^{85}Rb atoms in a magnetooptical trap for selective addressing and coherent information processing [11], as shown in schematic 6. Linear optical quantum information processing elements have endowed rapid progress in sub-shotnoise quantum metrology and quantum imaging applications. Recent work has shown that scalable quantum computation is possible using only linear optical elements and single-photon sources and detectors [12].

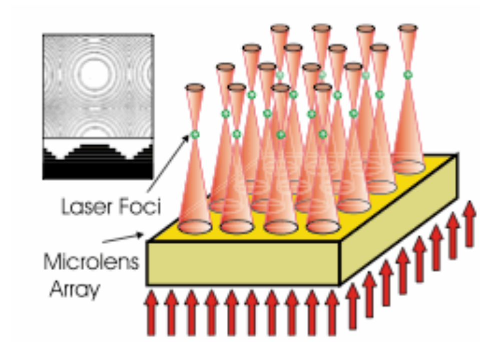

Figure 6: A single laser is focused on a two-dimensional microlens array. Multiple foci allow for selective positioning, trapping and addressing of neutral ^{85}Rb atoms [13].

In quantum cryptography, coherent optical networks have been deployed to offer guaranteed secure communication links using entangled photon sources to provide encryption of critical data. This year, the government of Geneva will conduct its elections using coherent optical networks developed by *id Quantique*, as the first step of the Swiss Quantum initiative under the EU SECOQC Sixth Framework Programme [14].

Continuing advances in optics and photonics will serve as enabling technologies for these rapidly-progressing technological innovations – which in turn will trigger second-order impacts as society and culture adapt to these disruptive technologies. As the drive for miniaturization continues, microlens arrays will play a prominent role in many of these applications.

Acknowledgements

I highly appreciate the generous guidance, inspiration and advice offered by Oliver Fähnle, Mark Meeder, Pim Messelink, Yvonne van Aalst-van der Graaf, Silvania Pereria, Bas Swinkels, and Adele Behar.

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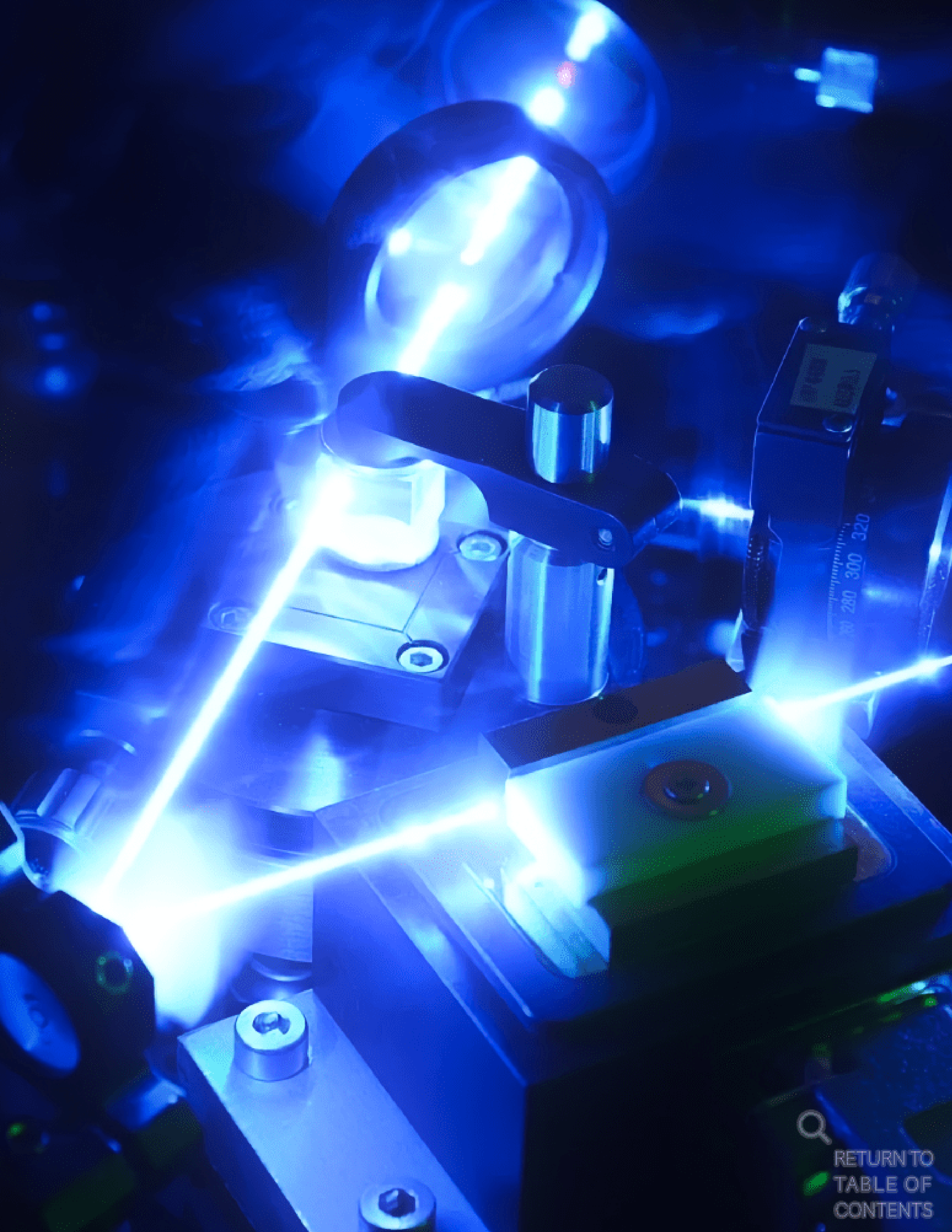

RETURN TO TABLE OF CONTENTS

RIKEN Quantum Dynamics Research

Frontier Research Laboratory

This ATIP report summarizes the recent activities of the Frontier Research Laboratory, Single Quantum Dynamics Research Group at RIKEN. RIKEN is a world leader in quantum computing research, and with collaborator NEC has been responsible for a number of *world's-first* achievements in the field of superconducting nanoelectronics.

Keywords *Superconducting quantum computing, Josephson junction, coherence, entanglement, charge qubit, CNOT gate*

1. INTRODUCTION

Quantum computers take advantage of the superpositional logic of quantum mechanics to allow for dramatic increases in computational efficiency. Superconducting qubits are a promising solid-state candidate towards meeting the DiVincenzo criteria[i] necessary to construct a quantum computer. These solid-state systems show potential for quantum computing applications by forming the qubit component of a quantum computer, presenting a major advantage over atomic-scale qubit systems: (1) they are sensitive to parameters that can be engineered, (2) they are scalable, and (3) they can be manufactured using conventional photolithography techniques. NEC-RIKEN has assembled a strong team of international researchers to investigate the potential of solid-state quantum computing, and has taken a leading role in the study and control of single quantum dynamics in these systems.

2. EXECUTIVE SUMMARY

- The four groups constituting RIKEN's Frontier Research Laboratory Single Quantum Dynamics Research Group: the *Digital Materials Laboratory*, the *Macroscopic Quantum Coherence Laboratory*, the *Quantum Nanoscale Magnetics Laboratory*, and the *Quantum Phenomena Observation Technology Laboratory*, are working in collaboration with NEC to evaluate the potential of superconducting qubits for scalable

Research funded in part by ONR grant N00014-03-1-0726 • ARDA/DTO • IARPA • DARPA QuIST

quantum computation. RIKEN performs the theoretical work while NEC handles the experimental component of the research.

- NEC recently demonstrated the world's first CNOT (controlled NOT) gate between two qubits, a significant accomplishment towards the realization of practical quantum computing. Recent analysis by the *Digital Materials Laboratory* has verified the signatures of entanglement between two qubits in the experiment.

- RIKEN plans further studies in multi-qubit interaction and noise control to determine the viability of scalable quantum computing based upon superconducting circuits.

Impact & Assessment

The NEC-RIKEN collaboration is a world leader in quantum computing research, and has been responsible for a series of breakthroughs in the field. RIKEN assists NEC in performing the theoretical calculations necessary for fabrication and experimental activities. Accomplishments include realization of the first CNOT gate, the first experimental demonstration of two-qubit entanglement, and the first controlled phase gate. Research performed through the NEC-RIKEN collaboration continues to redefine the boundaries of knowledge and understanding in multi-qubit systems.

3. THE FRONTIER RESEARCH LABORATORY

RIKEN's *Frontier Research Laboratory* performs studies in long-term, high-risk research with opportunity for substantial long-term benefits to industry and society. Its primary mission is on target-oriented projects with significant potential impact. Total funding for the second half of fiscal year 2003 ($1=100Y) was USD $14.05 million. A total of approximately 205 researchers are part of the group; approximately 35 of those are foreign researchers. The laboratory is divided into five divisions as follows:

(1) *Single Quantum Dynamics Research Group*
(2) *Supra-Biomolecular Systems Research Group*
(3) *Spatio-temporal Functional Materials Research Group*
(4) *Photodynamics Research Center*
(5) *Bio-mimetic Control Research Center*

This report focuses on relevant activities of the *Single Quantum Dynamics Research Group.* Led by Group Director Dr. Akira TONOMURA, the group is further divided into (4) major divisions working together with NEC to provide theoretical studies and analysis of multi-qubit interaction in superconducting Josephson junction-based qubits:

(1) Digital Materials Laboratory (Dr. Franco NORI)
(2) Macroscopic Quantum Coherence Laboratory (Dr. Jaw-Shen TSAI)
(3) Quantum Nanosale Magnetics Laboratory (Yoshichika OTANI)
(4) Quantum Phenomena Observation Technology Laboratory (Dr. Akira TONOMURA)

4. SINGLE QUANTUM DYNAMICS RESEARCH OVERVIEW

4.1 Digital Materials Laboratory

Dr. Franco NORI heads the *Digital Materials Laboratory*, which performs theoretical studies of complex dynamics in materials. Areas of focus at the laboratory include (i) computational condensed matter physics, (ii) quantum computing using Josephson-junction qubits, and (iii) vortex dynamics in superconductors.

Two of the major obstacles to quantum computing are scalability and controlled connectivity between selected qubits. Dr. NORI's research team has proposed a Josephson charge qubit-based quantum computing circuit architecture that resolves these two central problems, linking any two arbitrary qubits through tuned magnetic fields. Two *dc*-SQUIDs (superconducting quantum interference devices) per Cooper pair box, linked through common inductance, can be activated to yield interbit coupling regardless of location on the chip (Fig. 1). This achievement makes possible an efficient method to implement a scalable quantum computer.

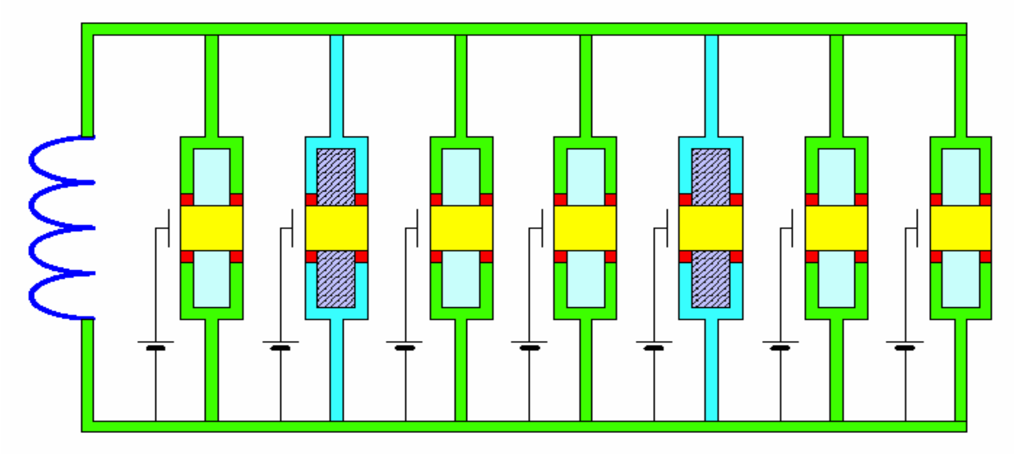

Fig 1. Schematic diagram of a seven-qubit micro-circuit (NORI Lab). A tuned magnetic field (blue) can be applied to control flow of charge in Cooper pair boxes (yellow) through Josephson junction barriers (red) linked via a superconducting loop.

The NEC-RIKEN demonstration of the world's first CNOT gate between two qubits on 30 October, 2003 was a *world's first*, and a significant accomplishment towards the realization of practical quantum computation. Subsequent analysis of this experimental data by quantum information researcher Dr. Todd TILMA of Dr. NORI's *Digital Materials Laboratory* has verified the signatures of entanglement between the two qubits. Entanglement is an essential feature in multi-qubit interaction, and this is an important step towards strengthening the results of the laboratory.

4.2 Macroscopic Quantum Coherence Laboratory

Led by Dr. Jaw-Shen TSAI, the *Macroscopic Quantum Coherence Laboratory* studies the properties of macroscopic quantum coherence in small Josephson junction circuits. Focus areas include (i) coupled two-qubit systems, (ii) single-shot readout of a qubit, and (iii) suppression of decoherence mechanisms in the system. Previous accomplishments of the laboratory include coherent control of the quantum state in a single Cooper pair box-based qubit, and a novel fabrication technique for nanoscale tunnel junctions (Fig. 2). TSAI's group has fabricated high-quality Nb (niobium) SET (single-electron transistors) by developing a process for nanoscale tunnel junctions much more flexible than those based on electron bean lithography. Experiments performed on these transistors at low temperatures, T = 0.04 - 40 K, yield single electron charging energy $E_C / k_B > 1$ K.

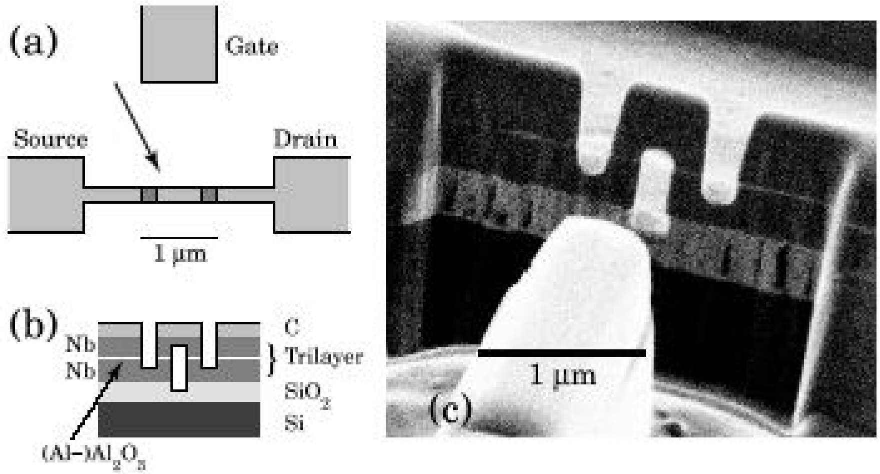

Fig 2. Niobium single-electron transistor (a) top view (b) side view (c) focused ion beam secondary-electron image from top view (TSAI Lab)

4.3 Quantum Nanoscale Magnetics Laboratory

Led by Dr. Yoshichika OTANI, the *Quantum Nanoscale Magnetics Laboratory* uses theoretical and experimental approaches to study the static and dynamic properties of nanoscale magnetics. Areas of interest include (i) studies of the static and magnetic properties of nanoscale magnets and (ii) studies on spin injection-induced magnetization reversal and magnetic phase transition (Fig. 3).

Significant achievements of the OTANI Lab include discovery of a novel quantum behavior in which application of an electrical current to extremely thin magnetic wire induces magnetic domain structure-based changes, such as magnetic vortices and single-domains, in the current. Experimental study of spin injection-induced magnetization reversal found a 0.3 ! m spin diffusion length in Cu (copper) by measuring the extraordinary Hall effect originating from spin current. This spin-injection induced magnetism will be applied to research into the development of novel spintronic devices.

Also under study are the behavioral dynamics of domain walls trapped in magnetic nanostructures while under the influence of *dc* current. The depinning field of the trapped domain wall is drastically reduced when electrons flow negatively to exert magnetic torque due to spin-momentum transfer.

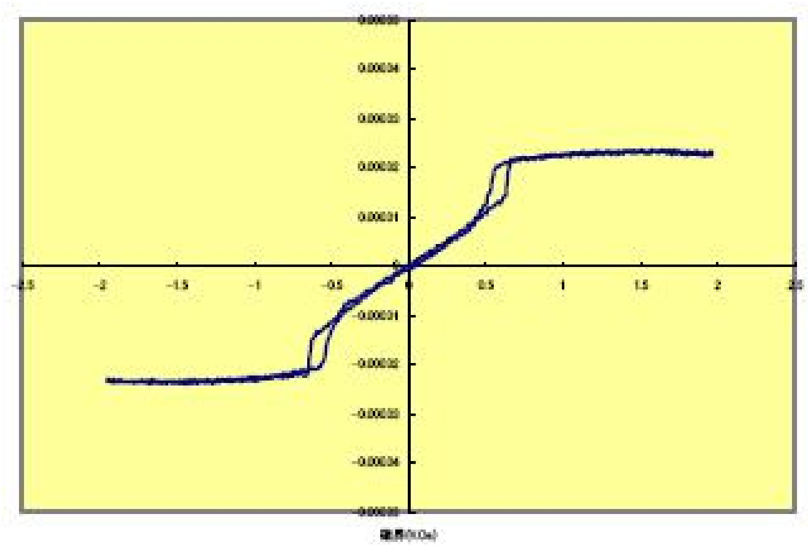

Fig 3. High sensitivity, high magnetic field Micro Kerr effect measurement data (OTANI Lab)

4.4 Quantum Phenomena Observation Technology Laboratory

Dr. Akira TONOMURA, the *Single Quantum Dynamics Research Group* Director, also leads the *Quantum Phenomena Observation Technology Laboratory,* which develops advanced technologies for directly observing electric and magnetic fields in nanoscopic regions. Focus areas of the laboratory include (i) development of novel techniques for electron interferometry and (ii) observation of magnetic and other materials through electron interferometry.

Observation and understanding of quantum phenomena at the nanoscale is essential to the construction of nanodevices and nanomaterials with novel properties and functions. TONOMURA is widely renowned for his development of electron microscope holography, which uses a high-brightness field-emission electron beam, enabling indirect imaging of quantum phenomena that otherwise cannot be observed directly.

Electron holography has been used to experimentally verify the Aharonov-Bohm effect, and more recently to directly observe the unconventional behavior of vortex motion in high-temperature superconductors. The 1-MV holography electron microscope (construction completed by the TONOMURA Lab in April 2000) set world records for lattice fringe resolution of 0.0498 nm. Dr. TONOMURA has received several honors and accolades in recognition of this research, and continues to refine the understanding of unconventional vortex behavior using Lorentz microscopy.

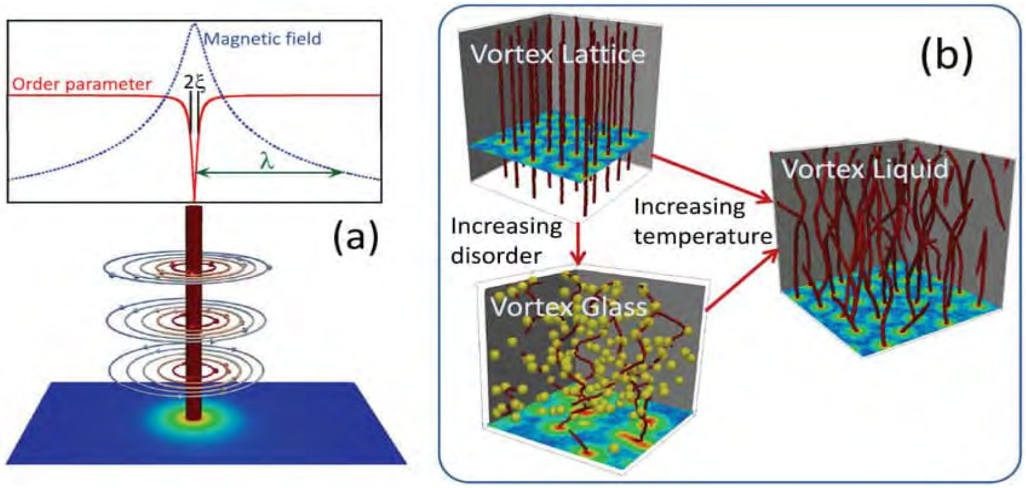

Fig 4. Vortices in a high-temperature superconductor (TONOMURA Lab)

5. FUTURE OUTLOOK

Quantum information science is a rapidly advancing, multidisciplinary field, and research efforts underway to bring about its realization are of the highest caliber. However, decoherence and noise factors currently prohibit the construction of a practical quantum computer. Multi-qubit and environmental interaction lead to complex internal dynamics that are highly susceptible to noise or disturbance. Extensive long-term oriented theoretical and experimental research is necessary to evaluate the feasibility of such a device. RIKEN's continued research into measurement, noise and decoherence is a key to mastering the control of these systems.

6. CONCLUSIONS

The construction of practical quantum computers remains a long-term research objective: the path between feasibility and implementation remains largely unmapped. Superconducting qubits require temperatures on order of degrees milli-Kelvin, and require near-perfect physical isolation to prevent decoherence. This last step is critical in making them viable for quantum computing applications – the macroscopic size of superconducting arrays makes them uniquely susceptible to environmental disturbance. Better isolation, measurement and error correction techniques will be required to link qubits together for quantum computation. RIKEN's *Frontier Research Laboratory* has taken a leading role in this effort, and ATIP will continue to closely monitor the activities and successes of their research programs.

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[i] **DiVincenzo criteria for quantum computation**

(1) a scalable physical system with well-characterized qubits
(2) the ability to initialize the state of the qubits to a simple standard state
(3) long relevant decoherence times
(4) a universal set of quantum gates
(5) qubit-specific measurement capacity
(6) the ability to interconvert stationary and flying qubits
(7) the ability to faithfully transmit flying qubits between specified locations

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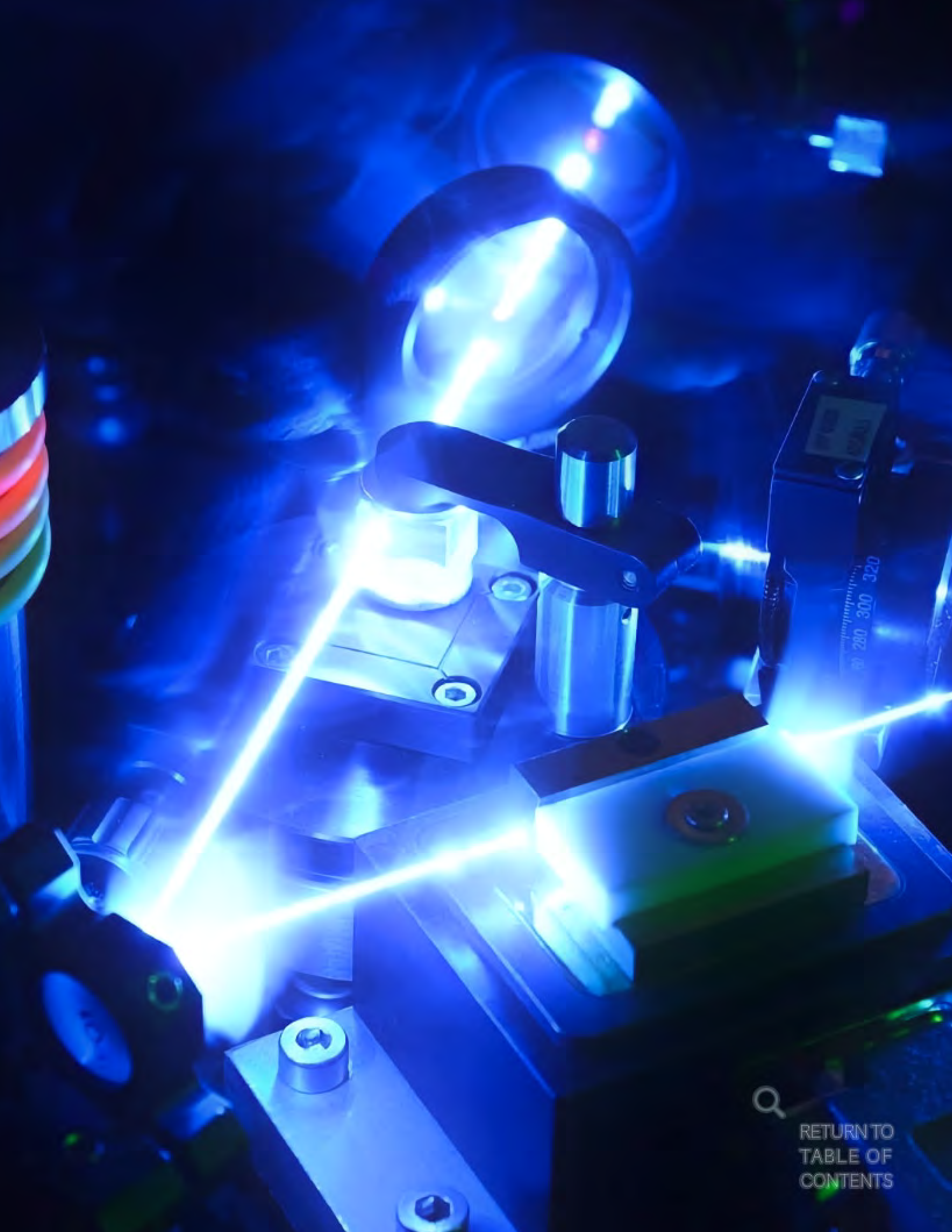

RETURN TO
TABLE OF
CONTENTS

Korean Quantum Information Research

Korea Institute for Advanced Studies and Seoul National University

This ATIP report summarizes the recent visit to Seoul, Korea to visit principal investigators in the field of quantum information science and technology. Prof. Jaewan KIM, of the Korea Institute for Advanced Studies, is organizing the first international workshop on quantum information science in Korea next year to precede the Japanese ERATO conference on quantum information, and Prof. Dong Pyo CHI leads a quantum algorithm-oriented research program at Seoul National University.

Keywords *Quantum algorithms, communications, computing, cryptography, imaging, metrology, information science and technology*

1. EXECUTIVE SUMMARY

- Quantum algorithms research is a young field in Korea and has yet to achieve the infrastructure required to attain consistent advances on par with the international community.
- Attention from the Korean national government has increased in the last year and a number of new initiatives have been proposed to accelerate the organizational development of quantum information science at the national level.
- Prof. Jaewan KIM, of the Korea Institute for Advanced Studies, is organizing the first international workshop on quantum information science in Korea next year to precede the Japanese ERATO conference on quantum information.
- Prof. Dong Pyo CHI, of Seoul National University, leads a quantum algorithm-oriented research group whose accomplishments include a modification to Grover's algorithm for searching a database with multiple solutions.

Impact & Assessment

Increasing attention is being paid to the field of quantum information and communications research in Korea: five major research programs have been commenced in order to stimulate the emergence of an infrastructure that can produce results on par with the

Research funded in part by ONR grant N00014-03-1-0726 • ARDA/DTO • IARPA • DARPA QuIST

international community. Though still in its infancy, research is rapidly expanding in response to international competition as corporate and national funding agencies recognize the long-term necessity of quantum information technologies.

2. NATIONAL RESEARCH INITIATIVES

2.1 National Funding Agencies

Korean national funding in the field of quantum information science originates from four primary government agencies: (1) the **Ministry of Industry and National Resources**, whose funding is characterized by an interest in practical, demonstrable research capable of short-term realization; (2) the **Ministry of Information and Communications**, whose interests include fundamental, basic research of longer-term character, and is possibly engaged in classified research unavailable in the public domain; (3) the **Ministry of Science and Technology**, which has the largest resources available for funding, and is currently supporting three of the five Korean national research projects in quantum information; and (4) the **Ministry of Education**, which is closely related to Ministry of Science and Technology.

2.2 National Research Programs

The Korean national government has allocated funding to five quantum information research programs, as follows:

MOST National Research Laboratory
Principal investigator Prof. Soon-Chil LEE, of the Korean Advanced Institute of Science and Technology (KAIST), conducts research in nuclear magnetic resonance (NMR) and solid-state based quantum computing architectures, and has constructed a four-qubit NMR based quantum computer. The (1-professor, 5 student) project was initiated in 2000 and has a five-year duration at 1.8×10^{8} won per year. Funding is sourced from the Ministry of Science and Technology (MOST). The group has conducted related work in single-electron spin detection of up to 100 electrons, as well as developing software for programmable quantum computing.

MOE Brain Korea 21 (BK21)

Established under Prof. Hai-Woong LEE of the KAIST physics department, the *Brain Korea 21* Project (3 professors, 4 postdoctoral researchers, 15 students) investigated 'quantum optical information processing.' Funding was granted through the Korean Ministry of Education.

MOST Creative Research Initiative

The iQUIPS, or *intelligent quantum information processing*, *Creative Research Initiative* (2 professors, 5 postdoctoral researchers) is funded by the Korean Ministry of Science and Technology. The project is led by Prof. D. AHN of the University of Seoul's electrical engineering department. Prof. AHN will soon move to Korean University. AHN's group researches of quantum-dot based information processing. A three-year project, funding is valued at 5×10^8 won per year.

MOE Quantum Information Science

A three-year project (8 professors, 1 postdoctoral researcher, 10-15 students) in quantum information science was initiated by the Ministry of Education in July 2002 to study fundamental issues towards developing future technologies. Composed of five university groups, including two experimental groups, funding is valued at 2.5×10^8 won per year. Areas of focus include optical quantum entanglement, quantum cryptography experiments, and theoretical questions related to quantum information applications.

MOST Next-generation Security Project

Funded by the Ministry of Science and Technology, the *Next-generation Security Project* conducts research in cryptosystems based on mathematical complexity (classical public-key cryptography) as well as a number of advanced topics such as nano-implementation of cryptography, ubiquitous cryptosystems and standardized protocols, and quantum cryptography. Led by Prof. Jaewan KIM, the quantum cryptography project (9 PhD researchers, 15 students) is based on a 3+4 year funding cycle at 8×10^8 won per year, initiated 2003. Single-photon systems will be investigated for the first three years of the project, followed by four years of research in areas such as coherent state systems and quantum repeaters.

3. KOREA INSTITUTE FOR ADVANCED STUDIES

The **Korea Institute for Advanced Studies** (KIAS) is an educational research institution whose activities focus on fundamental research in math, physics, and computational science problems such as protein folding, genomics, and quantum computing. KIAS functions in a role analogous to the United States' Princeton Institute for Advanced Study, and plays a central role in Korean national research initiatives in quantum information science and technology. Led by Prof. Jaewan KIM, who is organizing the first Korean international workshop on quantum information, the quantum information group is actively engaged in a number of topics such as quantum cryptography, communications, quantum information theory, theoretical studies of quantum computing using Josephson-junction qubits, quantum imaging and metrology. Prof. KIM most recently published a paper on quantum holography in the Proceedings of SPIE, *The International Society for Optical Engineering*.

3.1 KIAS Research Activities

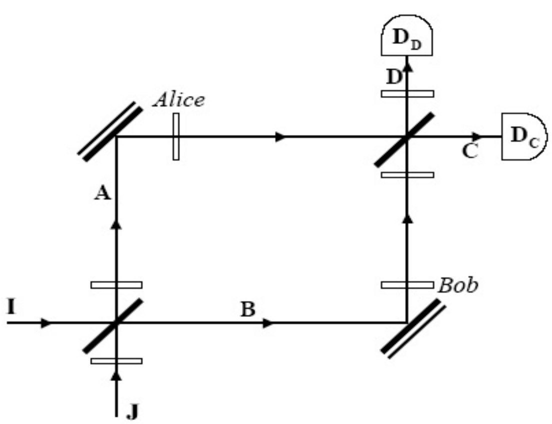

FIG 1. ***Single-particle Bell inequality*.**
Single particle version of Bell's inequality test with a Mach-Zender interferometer. A single photon and vacuum are incident on the beam splitter (with a pair of – π/2 phase shifter) from the input ports I and J, respectively. The reflected wave A and the transmitted wave B are recombined at the second beam splitter (with a pair of – π/2 phase shifter). Alice and Bob, located somewhere along the pathway of the reflected wave A and the transmitted wave B, respectively, each have a phase shifter which they may or may not use [1].

In collaboration with Hai-Woong LEE, also of KIAS, Prof. Jaewan KIM has performed experiments in single particle entanglement and quantum teleportation using linear optical devices. LEE and KIM consider the photon as qubit, for example to construct a quantum optical model of the Fredkin gate, and proposed a scheme for quantum teleportation based upon single-photon entanglement. Single-particle nonlocality was studied through analysis of the Bell inequality (Fig 1).

Prof. KIM is also interested in the study of quantum imaging and metrology for the potential of developing novel applications, and is concerned with the short-term oriented nature of today's corporate and academic environment that neglects basic research. As new knowledge and new technology move 'hand-in-hand,' KIM feels it of importance to devote resources to long-term, fundamental research questions, even those with no foreseeable commercial applications.

Dr. Sangchul OH, a member of the research group at KIAS, is a physicist whose interests include superconducting quantum computing using charge qubits. Dr. OH has studied the behavioral dynamics of two-qubit gates and probability of success of the CNOT operation in relation to rise and fall of pulse time (Fig 2). Numerical analysis of both ideal and superconducting charge qubits illustrates that error rate grows quadratically in finite rise and fall times.

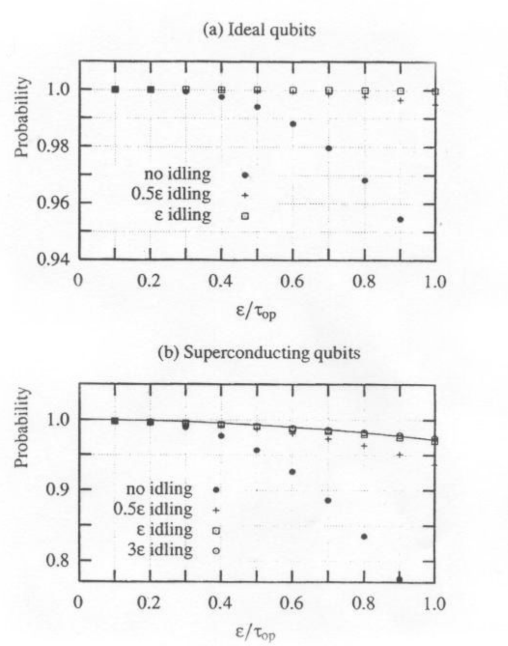

FIG 2. ***Probability of success of the CNOT gate.*** Probability of success on the action of the CNOT gate as a function of the ratio of the rise and fall time to the operation time: (a) ideal qubits, (b) superconducting charge qubits. Idle times prevent the tails of pulses from overlapping. The solid line is the fitting function that shows the quadratic growth of error in rise and fall times [3].

The KIAS quantum information group collaborates closely with researchers at Seoul National University. Soojoon LEE, a research fellow in the KIAS group, has worked in collaboration with Seoul National University researcher Dong Pyo CHI to examine initialization-free quantum algorithms, entanglement and entanglement measures, and quantum cryptographic key distribution protocols. Seoul National University research activities are summarized in the following section (**3**).

3. SEOUL NATIONAL UNIVERSITY

Seoul National University research in quantum algorithms is led by mathematician Prof. Dong Pyo CHI. Research problems of interest to the group include harmonic maps, dynamical systems (symbolic dynamics and billiard problems), and quantum mechanics (quantum computation and quantum chaos). Prof. CHI has developed a novel quantum algorithm [5] for database searching with zero error probability where the number of solutions is more than a quarter of the sample, utilizing a modified Grover operator of arbitrary phase (Fig 3). Results are obtained after a single query.

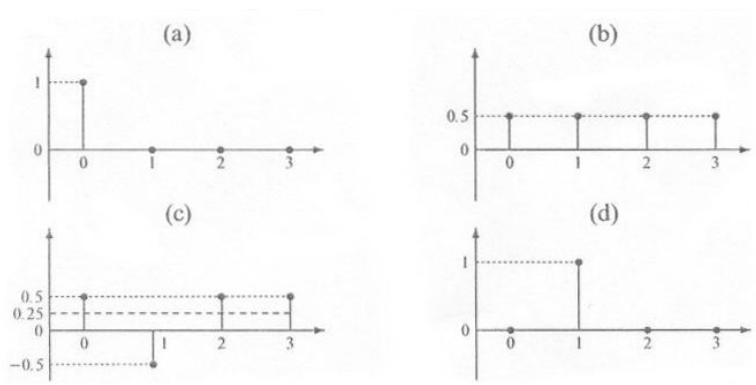

FIG 3. ***Modified Grover algorithm*.** The effect of the Grover algorithm when *N* = 4 and the solution is *j* = 1.

CHI's former student Jinsoo KIM, who co-developed the modified Grover search algorithm, is supervising a number of graduate students who hope to develop a mature Korean research program in quantum algorithms. KIM's research interests include generalization of the Deutsch-Jozsa algorithm, initialization-free algorithms, error-correcting Maximum Distance Separable (MDS) codes, and cryptographic protocols. Recent work in [6] develops a quantum algorithm that works without *a priori* knowledge of the state of the auxiliary register. With no need for initialization, it becomes possible to compose an auxiliary register from any arbitrary qubit, even an entangled qubit occupied by other computational processes.

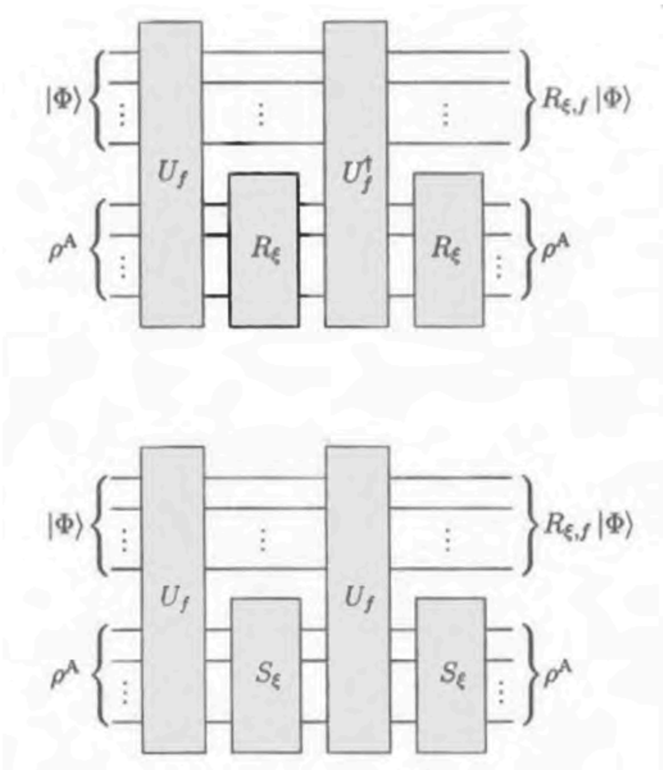

FIG 5. ***Initialization free circuits.*** Quantum circuits for initialization-free functional phase rotation: the state of the auxiliary register is described by a density operator ρ^A.

Prof. CHI's group is also interested in the phenomenon of entanglement and entanglement measures such as negativity and entanglement of formation. A recent paper [7] examines the two-parameter class of states $\rho(\alpha, \gamma)$ in a 2 x n system, calculating negativity and lower and upper bounds on entanglement of formation (Fig 4). Calculated results show that an arbitrary state can be transformed into $\rho(\alpha, \gamma)$ by means of local operations and classical communication, and is invariant under unitary operations of the form U x U on a 2 x n quantum system.

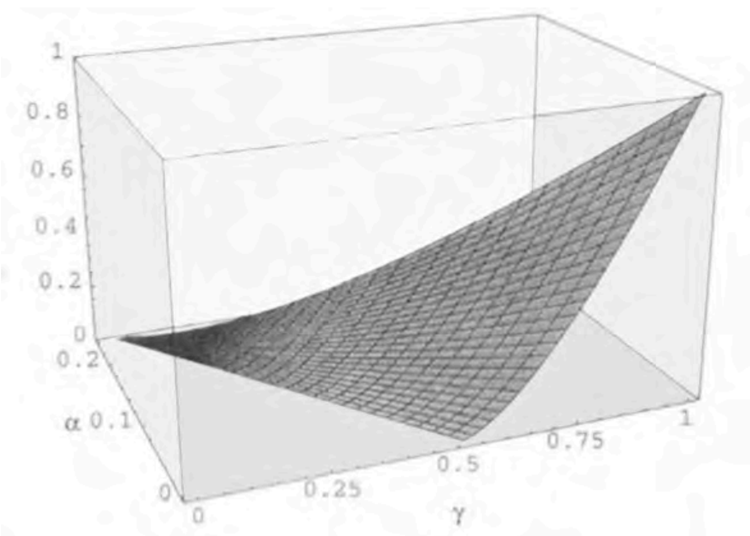

FIG 4. ***Lower bound on entanglement of formation*** for $\rho(\alpha, \gamma)$ for $1/2 \leq (n - 2)\,\alpha + \gamma \leq 1$ in a 2 x 4 system.

Seoul National University's quantum algorithms research is still in its formative stages, and presently lacks sufficient influence to attract funding from corporate and government sponsors. Though it will likely take a number of years before the program reaches enough maturity to begin making consistent contributions to the field, an increasing number of Seoul National University graduate students are being attracted to its quantum information science group. Prof. CHI and Prof. KIM are actively encouraging graduate students to pursue related studies, and as the program grows it will play a more significant role in Korean national research in the years to come.

4. FUTURE OUTLOOK

The potential of quantum information science has only begun to make an impact substantial enough to attract Korean national and corporate interests. Two years ago Prof. Jaewan KIM tried, without success, to stimulate interest in quantum cryptography at Samsung Research and Development. They have, however, recently taken interest in the topic and are rumored to have initiated a program in quantum cryptography.

Korean research is in need of a strong leader to convey the vision of quantum information science to short term-oriented research groups. Prof. KIM is poised to play this role; he has attended several government advisory meetings with the Korean Ministry of Telecommunications. Through his leadership of the first Korean international workshop on quantum information, he has the potential to ignite interest in young researchers and draw the necessary attention for funding from larger interest groups. Prof. CHI's group, though still in its formative stages, will continue to benefit from its collaboration with the Korea Institute for Advanced Studies and Prof. Jaewan KIM.

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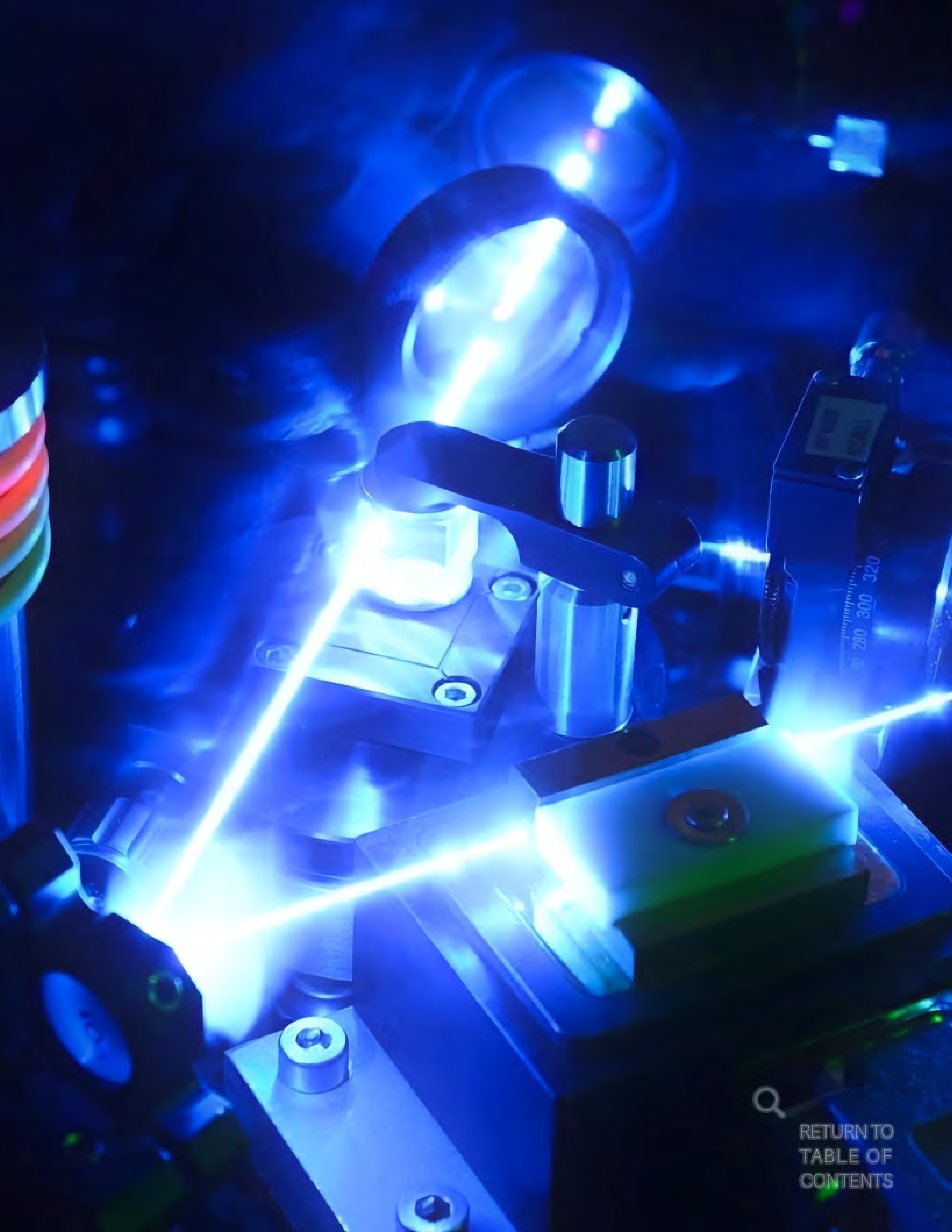


RETURN TO TABLE OF CONTENTS

SOKENDAI Quantum Information Science

The Graduate University for Advanced Studies

This ATIP report summarizes the recent site visit to the laboratory of Dr. Nobuyuki IMOTO, of SOKENDAI, The Graduate University for Advanced Studies, on 06 December 2003. Dr. Nobuyuki IMOTO is a leading Japanese researcher working to advance the state of the art in quantum information and communications.

Keywords *Quantum bit commitment, communications, computing, cryptography, game theory, information, optics*

1. EXECUTIVE SUMMARY

- SOKENDAI's Prof. Nobuyuki IMOTO performs research in the areas of quantum information processing (theory and experiment), quantum optics (theory and experiment), atom trapping and Bose-Einstein condensation (theory).
- IMOTO's research group was responsible for the world's first experimental achievement of coherent photonics -based entanglement extraction.
- IMOTO's recent work in quantum game theory and bit commitment aims to bridge the gap between short- and long-term research milestones in quantum information science.
- IMOTO is the representative for the Japanese CREST program's coherent photonics-related activities.

Impact & Assessment

Prof. Nobuyuki IMOTO is a leading Japanese researcher in the field of quantum information and communications. He was selected by Prof. Yoshihisa YAMAMOTO (NII) to represent photonics-related activities for the CREST research program in recognition of his significant achievements in the field, including the first experimental demonstration of entanglement extraction of weakly entangled photon pairs. IMOTO's research in quantum game theory and multiparty quantum computation is important to the mid- to long-term success of Japanese national research activities.

2. QUANTUM INFORMATION SCIENCE RESEARCH

Prof. Nobuyuki IMOTO joined the SOKENDAI Graduate University for Advanced Studies from NTT in 1994 to establish the Research Group on Quantum Information Processing, bringing his roughly 10 years of experience as an experimentalist and 10 years of experience as a theorist. Since this time the IMOTO group has been responsible for a number of significant achievements in the field of quantum information and communications technologies. IMOTO's interests are diverse, ranging from quantum game theory and bit commitment to coherent optics and Bose-Einstein condensation.

2.1 Quantum information processing

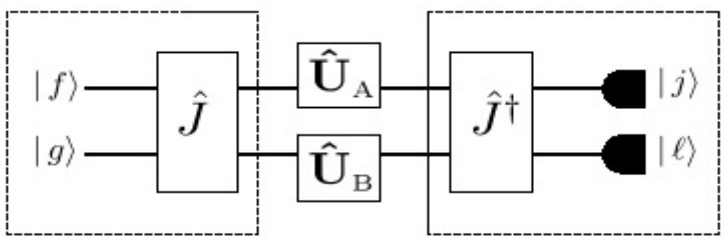


FIG 1. **Quantum game theory.**
Schematic configuration of the quantum version of 2×2 strategic games. The operations inside the dotted boxes are performed by the referee [2].

Quantum information is a rapidly growing field of research that is critical to future communications security applications. IMOTO's research efforts focus on a number of key applications that are important to the mid- term future of quantum information science. IMOTO's research interests in this area include quantum game theory, quantum Shannon information and compressibility, bit commitment and multiparty quantum computation.

Game theory offers a number of insights into politics, economics and social dynamics, and played a critical role in preventing escalation of conflict between the US and USSR during the Cold War. Quantum game theory differs from its classical counterpart in a number of key cases, some of which may find utility in strategic cases: for example, the tools of quantum game theory resolve the classical *Prisoner's Dilemma*. IMOTO's work in game theory and quantum and classical correlations among players [2, 3] has shown the effects of quantum and classical correlations using the *Samaritan's Dilemma,* resulting in previously unobserved unique or multiple *Nash equilibria*.

Most recently IMOTO has studied the quantum equivalent of Shannon information and compressibility [1] in conjunction with information source channel capacity based on asymptotically small error, showing that the incompressible part of broadcast information corresponds to pure quantum information.

This work has applications in quantum broadcast conditions and in the classification of quantum cryptography. Of related interest is the problem of quantum key distribution [4] and bit commitment [6] between two parties: IMOTO has future plans to research multi-party computation and discreet comparison.

2.2 Quantum optics

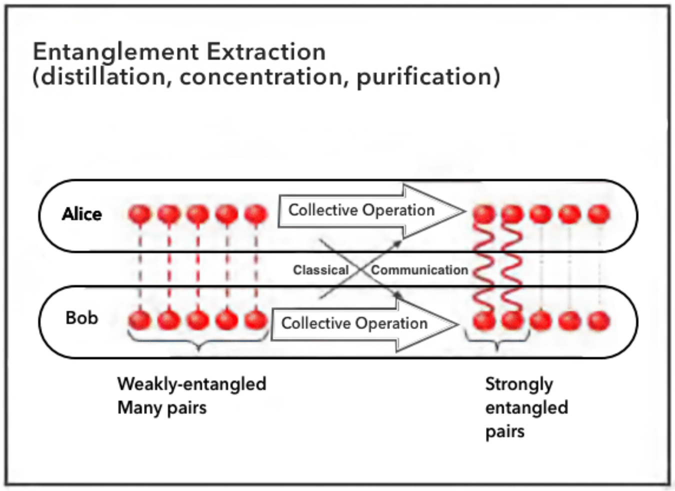
Entangled photon pairs generated through parametric down-conversion are rapidly degraded through natural coupling with their environment. For quantum communications to be feasible, there must be a reliable way to regenerate this entanglement. IMOTO's work in quantum optics theory and experiment showed the first experimental confirmation of "probabilistic entanglement extraction," [7] *entanglement extraction* in weakly entangled photon pairs to correct for transmission over a noisy channel.

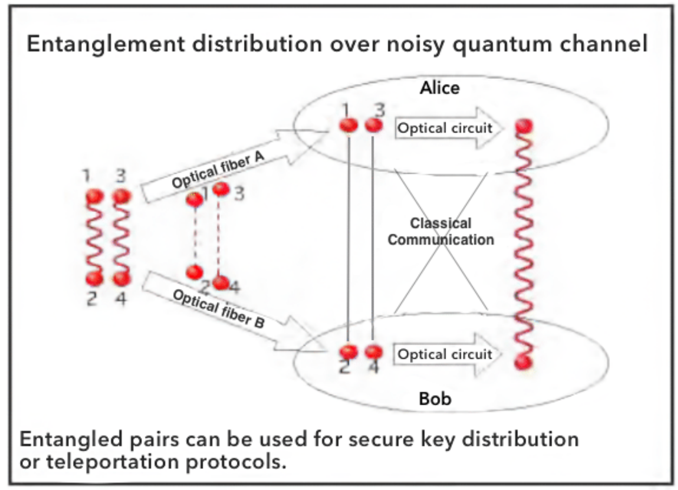
This accomplishment was reported in *Nature* **421** (January 23, 2003).

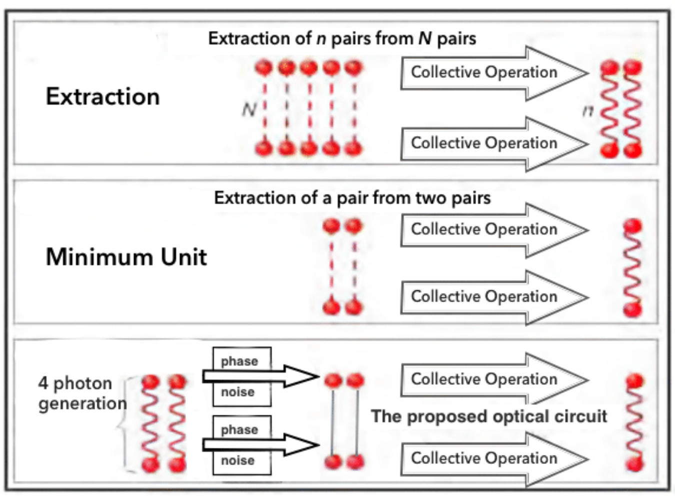
IMOTO's method extracts highly entangled photon pairs from a larger number of weakly entangled pairs through local operations and classical communication. Two polarization-entangled photon pairs are distributed through a channel that induces phase noise to the particles. The proposed optical circuit extracts a polarization-entangled pair from two *decohered* photon pairs. Entanglement is experimentally verified through fidelity (1.05), visibility (1.0), and lower bound entanglement of formation (1~0) measures.

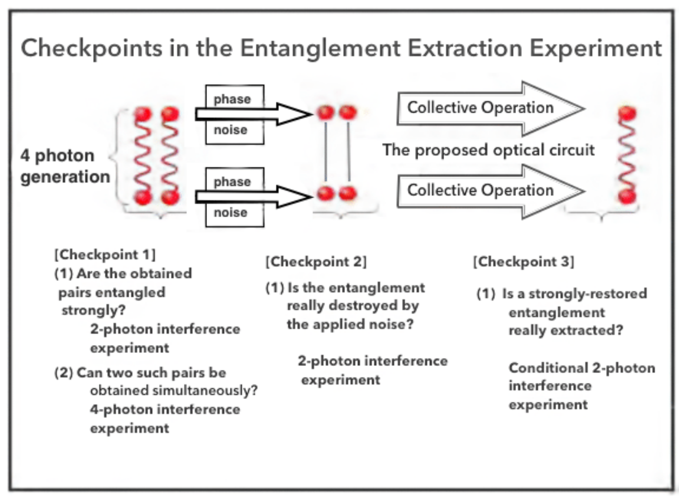
Disadvantages include the length of time required to perform the experiment, which is on order of ~40 hours; each photon pair is released on average every 2 – 3 minutes.

Entanglement extraction experiment









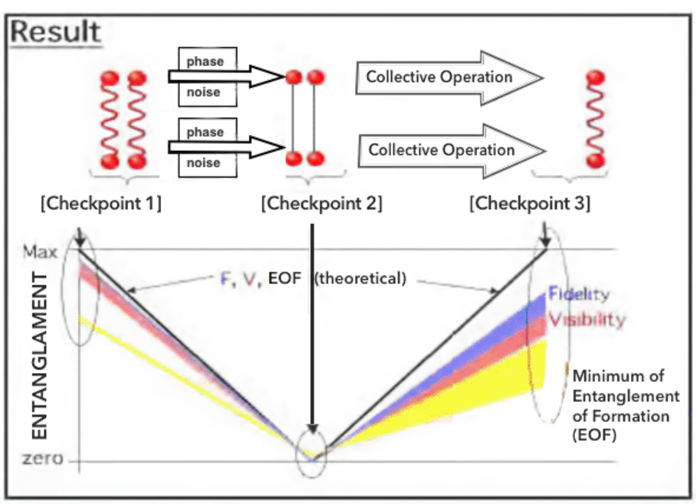


FIG 2. **Entanglement extraction.**

Experimental entanglement extraction from weakly entangled photon pairs using local operations and classical communication [7].

2.3 Atom Trapping and Bose-Einstein Condensation

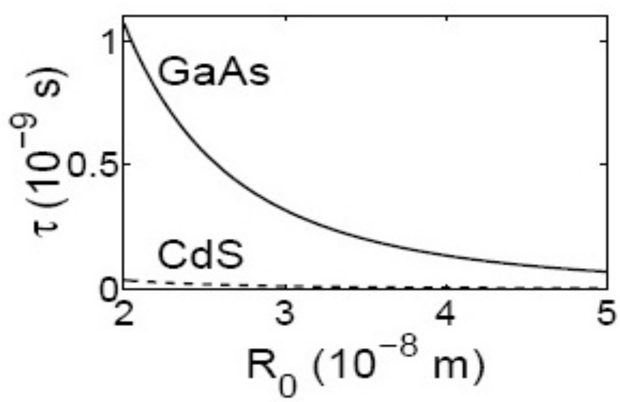


FIG. 3. Quantum dot decoherence. Characteristic time as a function of size 200 °A < R0 < 500 °A for the CdS and GaAs microcrystallites when the systems are initially in the superposition of the vacuum and single-exciton states [5].

Entanglement is central to quantum information processing, yet it remains a poorly understood phenomenon with no general underlying theory. Through experimental studies of entanglement and decoherence in quantum dots, a promising candidate for quantum information carriers, [5] IMOTO hopes to attain a deeper understanding of the nature of entanglement in multi-particle systems.

In theoretical studies of Bose-Einstein condensation, IMOTO has shown it possible to substantially increase the maximum size of BECs through theoretical optimization of rf frequency sweeping, and has performed studies of BEC ground state and weak excitation properties of *spin*-**2** bosons in these condensates.

3. IMOTO AND GROUP ACTIVITIES

IMOTO has been deeply involved with the NTT Research Group, as well as many of his colleagues and collaborators. Following in IMOTO's footsteps, who moved from the NTT Basic Research Laboratory (BRL) to SOKENDAI in March 1999, associate professor Masato KOASHI joined IMOTO's laboratory from the NTT Basic Research Laboratory in September 1999. KOASHI's research focuses on Shannon information compression, the two-photon interference experiment, and information source channel capacity.

IMOTO previously worked with Prof. Yoshihisa YAMAMOTO of the National Institute of Informatics (NII) – leaders of the NTT group, in 1988-89 at NTT Basic Research

Laboratories, until YAMAMOTO moved to Stanford University. YAMAMOTO was selected as supervising director of the new CREST 2004 quantum-related research and development programs. YAMAMOTO then selected IMOTO as a research leader of the CREST coherent photonics-related activities.

IMOTO was sub-group leader of five photonics related groups in the CREST program, "*Mesoscopic Correlated Electronics*," led by Yoshiro HIRAYAMA of NTT. This program was initiated in December 1998 and terminated November 2003. HIRAYAMA took over the lead of the research team at NTT when Seigo TARUCHA moved to The University of Tokyo in 1998.

IMOTO is still acting as research professor at NTT, and maintains close collaboration with NTT Basic Research Laboratories. IMOTO is also actively collaborating with Prof. HIRANO (Gakushu-in University), Associate Prof. Shigeki TAKEUCHI (Hokkaido University), Masahide SASAKI (CRL), and Masashi Ban (Hitachi). IMOTO's focus is entanglement and manipulation, and TAKEUCHI focuses on theoretical studies of the CNOT gate.

4. FUTURE OUTLOOK

IMOTO is interested in the mid-range to long-term outlook of quantum information science, and is concerned that industry and government sponsorship will wane as quantum communications become practical while quantum computing remains a long-term research goal. To this end he is working in the area of quantum game theory and bit commitment to establish theoretical milestones with mid-term achievable applications. Though he has had no substantial research progress since this April's entanglement extraction publication in *Nature*, he has been invited to speak at a number of workshops and conferences on the matter, most recently the Budmerice, Slovakia meeting on *Few qubit applications of quantum information processing* from 11-14 December 2003.

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6. SOKENDAI RESEARCH MEMBERS 2002-2003

Nobuyuki IMOTO	Professor
Masato KOASHI	Associate Professor
Sahin K. OZDEMIR	JST/CREST Postdoctoral Researcher
Liu YU-XI	JSPS Postdoctoral Researcher
Takashi YAMAMOTO	Third-year doctoral student
Koji NAGATA	Third-year doctoral student
Kiyoshi TAMAKI	Second-year doctoral student
Jun'ichi SHIMAMURA	First-year doctoral student
Yuhki TOKUNAGA	First-year doctoral student

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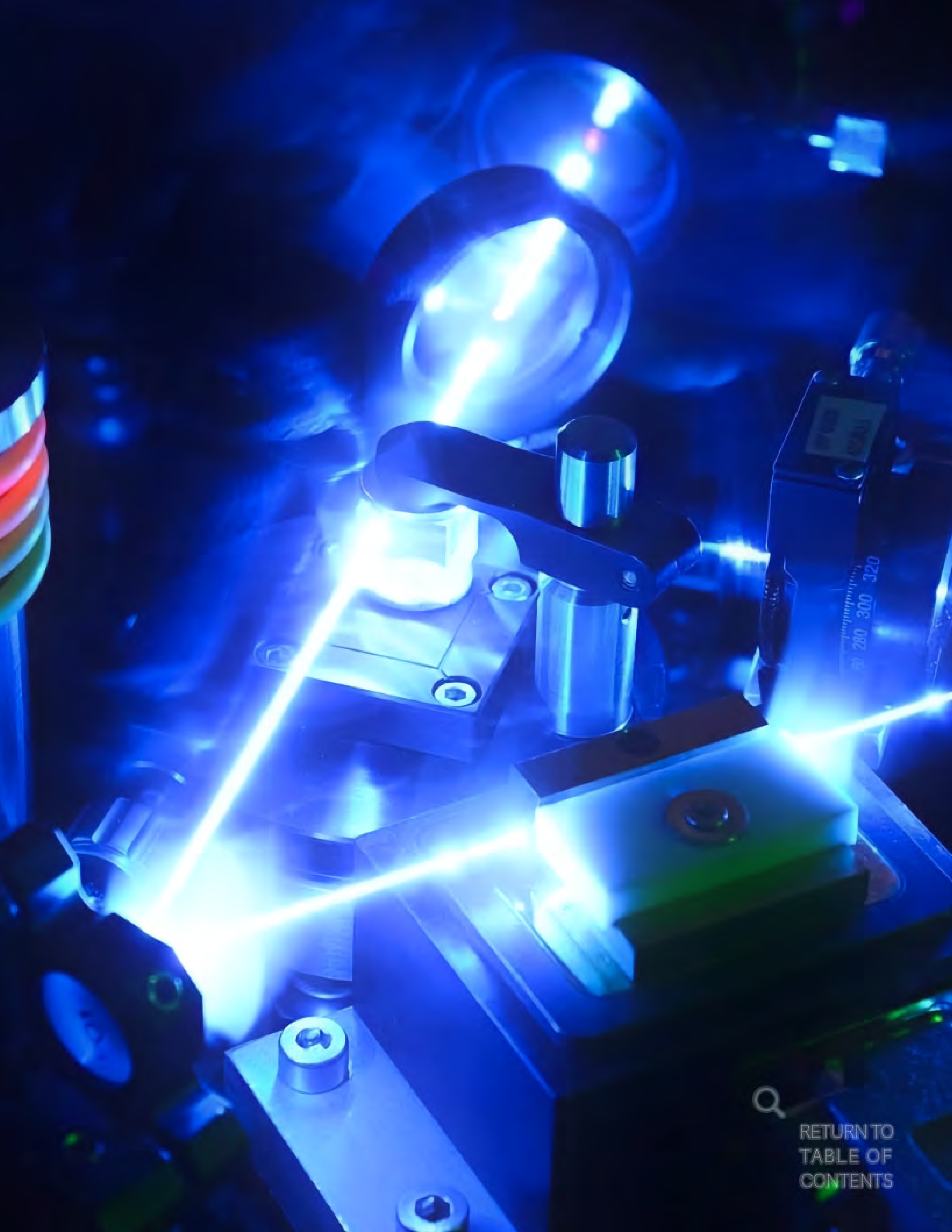

RETURN TO
TABLE OF
CONTENTS

Tokyo University of Science
Quantum Algorithms Research

Frontier Research Center for Computational Sciences

This ATIP report summarizes the recent visit to the laboratory of Prof. Masanori OHYA at Tokyo University of Science. Prof. OHYA is member of the Department of Information Sciences, Director of the Education Research Organization for Information Science and Technology, and Director of the Frontier Research Center for Computational Sciences. His work in quantum information science focuses on quantum algorithms, chaos and complexity.

Keywords *Quantum algorithms, chaos, computing, cryptography, information science and technology*

1. EXECUTIVE SUMMARY

- Prof. Masanori OHYA leads the quantum information initiative at Tokyo University of Science, Frontier Research Center for Computational Sciences.
- OHYA's research interests include quantum information theory, quantum entropy, quantum computing, quantum algorithms, quantum teleportation, quantum gates, and quantum cryptography.
- OHYA's wider research interests in information theory include complex dynamics, systems analysis, novel methods of chaos modeling and measurements, mathematical processing of brain dynamics, information finance, and information genomics.
- OHYA hopes to expand the domain of traditional quantum Turing machines to harness chaotic dynamics for useful computation.

Impact & Assessment

Prof. Masanori OHYA leads quantum information studies at Tokyo University of Science, maintaining diverse and high-profile collaborations at both domestic and international levels. OHYA's primary research objective is to expand the definition of quantum Turing machines to approach the study of NP-complete problems using traditional quantum computing in conjunction with chaotic dynamics. OHYA claims to have developed a novel quantum computing algorithm which in principle holds the potential to solve NP-complete problems in polynomial time.

Research funded in part by ONR grant N00014-03-1-0726 • ARDA/DTO • IARPA • DARPA QuIST

2. RESEARCH BACKGROUND

2.1 Collaborations

Prof. OHYA is a program leader and highly active in collaborations with researchers both in Japan and abroad. In addition to his role as professor at Tokyo University of Science, OHYA is Director of the Education Research Organization for Information Science and Technology and Director of the Frontier Research Center for Computational Sciences. He is an associate member at IIAS, the International Institute for Advanced Studies at Kyoto University, which functions in a role analogous to the United States Princeton Institute for Advanced Study.

OHYA's collaborators at International Institute for Advanced Studies include Dr. Noboru WATANABE (Tokyo University of Science) and Prof. Izumi KOJIMA (Kyoto University). Prof. OHYA is also co-author and collaborator with noted mathematician Prof. Takeyuki HIDA (Meiji University, emeritus professor of Nagoya University) and his student Prof. Nobuaki OBATA (Tohuku University).

At the international level, Prof. OHYA actively collaborates with Prof. Luigi ACCARDI (University of Rome), Russian mathematician Igor V. VOLOVICH (Steklov Mathematical Institute), Prof. Karl-Heinz FICHTNER (Friedrich-Schiller-University at Jena), and Prof. Jeff KIMBLE (California Institute of Technology). OHYA was responsible for introducing Prof. HIDA to Prof. ACCARDI, and recently hosted the International Conference on Quantum Information (01 - 03 Nov 2003) with these two leading researchers.

2.2 Research Topics

Prof. OHYA obtained his PhD in mathematics from Rochester University (UK). His initial work was in quantum entropy [1], but this has grown to encompass collaborative research efforts in a diverse range of problems in information processing and quantum information science including quantum entropy, quantum computing, quantum algorithms, quantum teleportation, quantum gates, and quantum cryptography. OHYA's wider research interests in the area of information processing include complex dynamics systems analysis, novel methods of chaos modeling and measurements, mathematical processing of brain dynamics, information finance, and information genomics.

3. SPECIFIED ACTIVITIES

Prof. OHYA proposes to expand quantum Turing computation to harness chaotic dynamics in a novel approach towards the P=NP computational complexity problem. In collaboration with Prof. Natsuki MASUDA, OHYA demonstrated that the SAT (satisfiability) problem – and following, all NP problems – can be solved in polynomial time by means of a quantum algorithm if the superposition of two orthogonal vectors |0> and |1> can be physically detected via a mathematical proof outlined in [2].

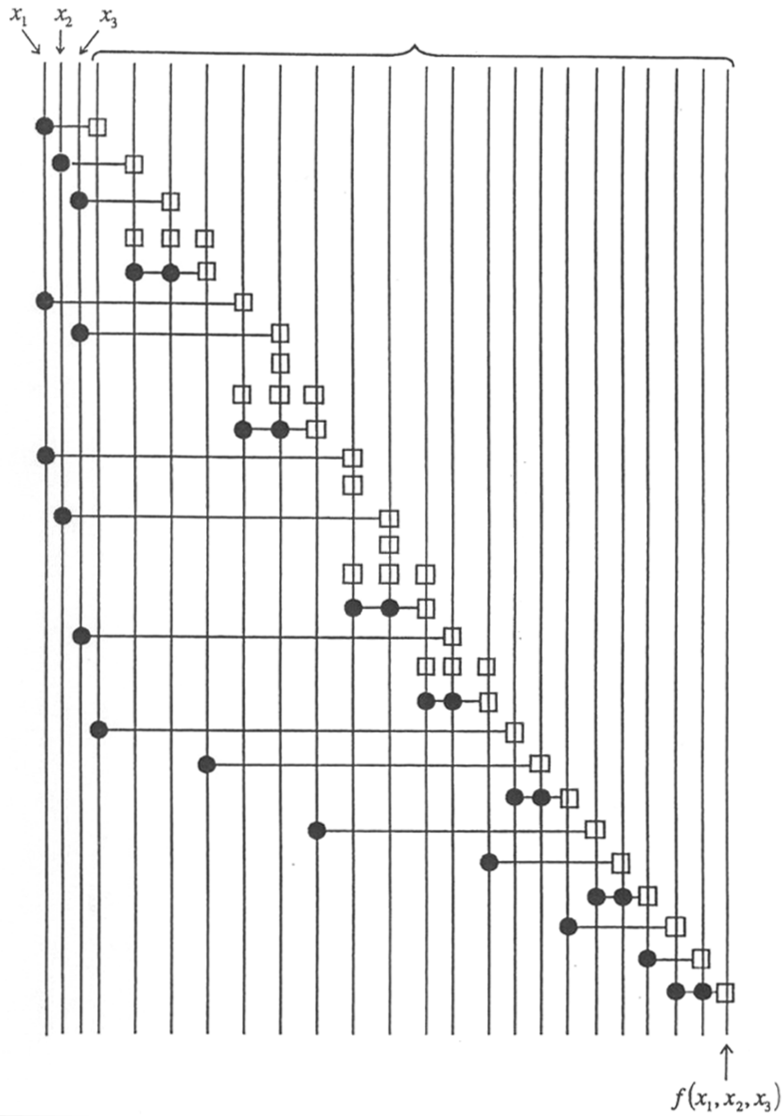

FIG 4. **NP Problem in Quantum Algorithms.** Complexity of the quantum algorithm for SAT [2].

The approach combines the traditional quantum Turing machine with a quantum chaotic dynamics amplifier based on a logistic map. A proposed implementation employs an atomic quantum computer with quantum gates described by Hartree-Fock equations, allowing for the construction of nonlinear quantum gates adhering to Fermi statistics. The proposed stochastic quantum computer consists of two blocks: (1) an ordinary quantum computer and (2) a quantum computer performing computations of the classical logistic map. Application of these dynamics is interesting not only for problems such as the NP-complete complexity problem, but also holds relevance for studies in quantum communications theory.

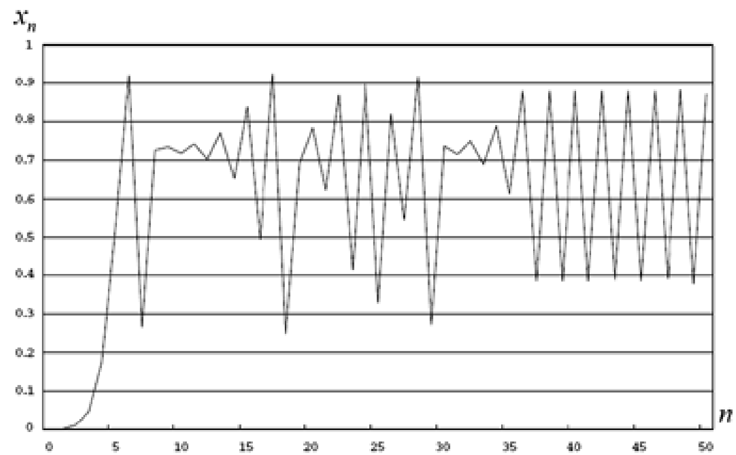

FIG 5. **Chaotic dynamics.** Change of x_n w.r.t. time n [3].

4. CONCLUSIONS

Associate Prof. Masanao OZAWA (Tohoku University) firmly defends the traditional Turing model of computation and maintains that OHYA's chaotic quantum computing model is not theoretically viable. However, the two remain engaged in constructive collaboration. OHYA's most recent work in chaotic quantum computing is still in its earliest pilot stages, and requires a more rigorous mathematical definition to explore its feasability as a novel method of quantum computation. ATIP will continue to monitor the progress of this research and report on any substantial developments in the future.

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asian technology information program

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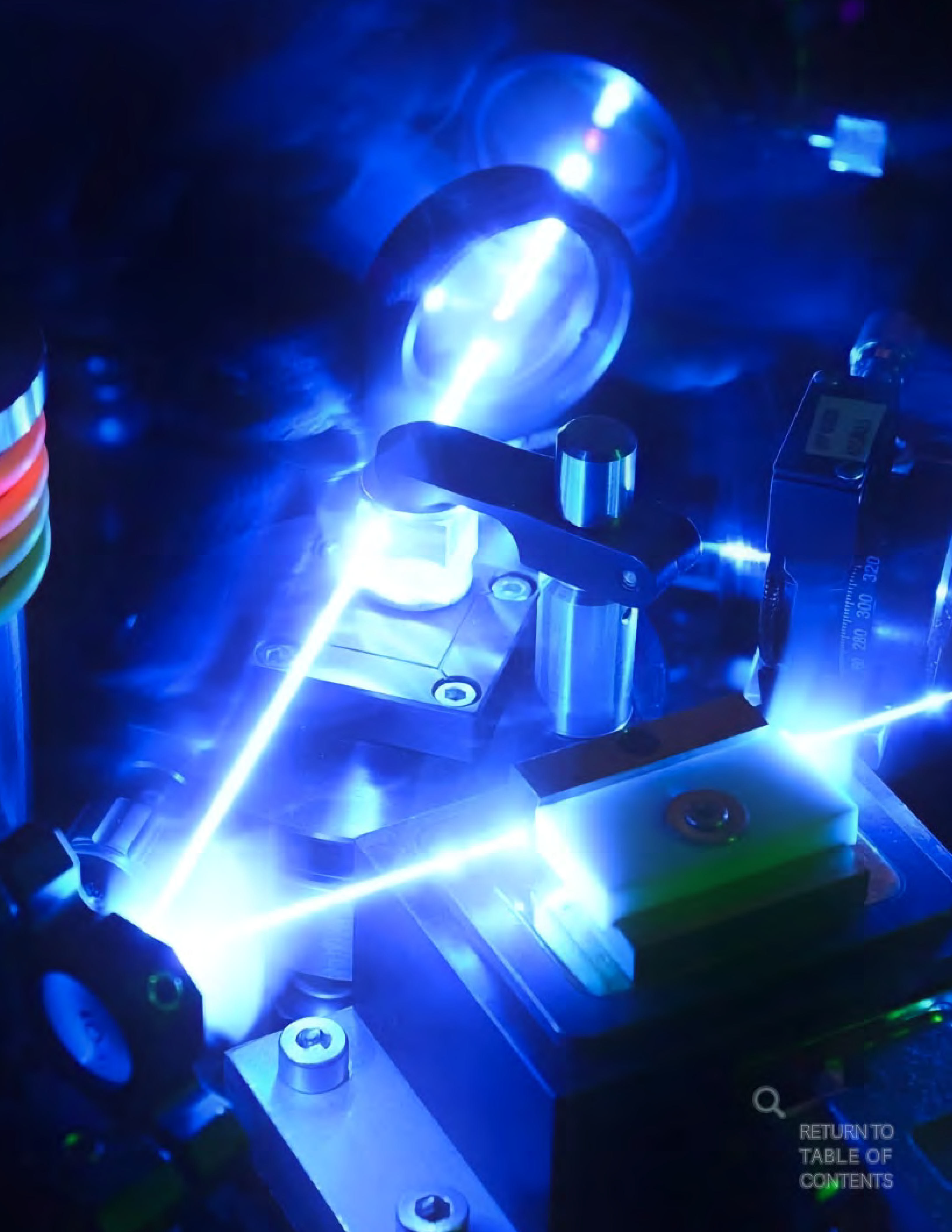

RETURN TO TABLE OF CONTENTS

QUANTUM CIRCUIT COMPLEXITY RESEARCH

NISHINO Lab, Tokyo University of Electrocommunications

This ATIP report summarizes the recent site visit to the laboratory of theoretical computer scientist Tetsuro NISHINO, of The University of Electro-communications, Tokyo on 14 November 2003. Dr. NISHINO's research focuses upon quantum computation, neural networks, and circuit complexity theory.

Keywords Quantum computation, cryptography, neural networks, circuit complexity

1. EXECUTIVE SUMMARY

- NISHINO's work in NMR (nuclear magnetic resonance)-based *bulk quantum computation* has identified key differences in contrast to standard quantum Turing machines and defined advantages over Grover's search against secret-key cryptosystems
- NISHINO is performing quantum computing simulations to minimize quantum circuit complexity for any given Boolean function and has introduced a recurrent network model for the implementation of quantum neural networks
- NISHINO has demonstrated that a single-layer quantum perceptron can solve the XOR problem, a task impossible for classical perceptrons, and hopes to study the properties of quantum neural networks in both NMR and coherent photonics-based quantum computers

Impact & Assessment

Japanese progress in quantum algorithms research is underrepresented in contrast to its well-established position as a leader in quantum computing hardware development. The *Soumu-sho* Roadmap on Japan's strategy for the realization of quantum information and communications technologies has added two quantum information scientists to its roster: Dr. Hideki IMAI (The University of Tokyo) and Dr. Osamu HIROTA (Tamagawa Gaku-en University). They are expected to increase the national emphasis upon quantum information theory. Dr. Tetsuo NISHINO and Dr. Kazuo IWAMA (Kyoto University) are two of the foremost Japanese researchers in

Research funded in part by ONR grant N00014-03-1-0726 • ARDA/DTO • IARPA • DARPA QuIST

quantum algorithms – NISHINO's research was recently selected for *Center of Excellence* funding by MEXT, the Ministry of Education, Culture, Sports, Science and Technology.

2. RESEARCH OVERVIEW

Dr. Tetsuo NISHINO's work in quantum computation is centered upon the following goals: 1) to show an inherent difficulty of some problems using methods in circuit and quantum complexity theory, and 2) to find new computation models, such as quantum Turing machines and neural networks, which can perform essentially faster computations than traditional models. NISHINO's long term research objectives are to elucidate the nature of computability and the $P \neq NP$ computational complexity problem using quantum computation as a tool. More immediate aims include the exploration of the learning characteristics of quantum neural networks using NMR-based quantum computing, which provides an experimental framework for testing novel quantum algorithms.

2.1 Bulk Quantum Turing Machines

A recent paper [1] demonstrates that NMR-based quantum computation differs from standard models of quantum computing. NISHINO defines this model as the *bulk quantum Turing machine*, or BQTM. In a quantum Turing machine, or QTM, qubit values α and β are amplitudes. A superposition of qubit states, $\alpha|0> + \beta|1>$, has an equal observation probability of {0, 1} upon readout: $|\alpha|^2(|\beta|)^2$. However, as NMR quantum computation is a spin system, {-1, +1} upon measurement an expectation value of the real number $|\beta|^2 - |\alpha|^2$ is observed. Readout of a traditional quantum Turing bit completely destroys superposition; however, in NMR-based quantum computing superposition can be preserved over repeated measurements. BQTM can provide specific advantages over the model of quantum Turing machines: for example, bulk quantum computation has been shown to be more effective than Grover's algorithm against secret-key cryptosystems [3].

2.2 Quantum Circuit Complexity

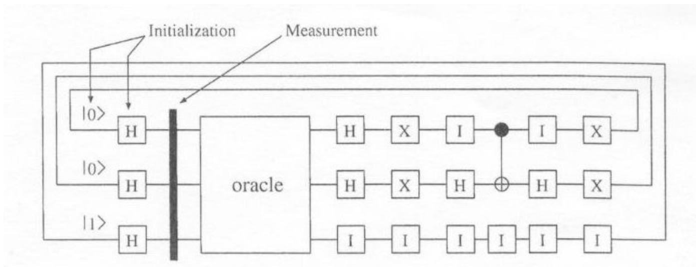

Fig 1. A Quantum Recurrent Circuit for Grover's Algorithm when $N = 4$

NISHINO's group is currently performing simulations of quantum systems for the optimization of quantum circuits to minimize both the depth and number of qubits required for any given Boolean function [2]. In [1], NISHINO introduced a quantum recurrent circuit model in order to define a feedback mechanism for the creation of quantum neural networks. His collaboration with the experimental group of Prof. KITAGAWA of Osaka University has further shown that a single-layer quantum perceptron is capable of solving the XOR problem, a task not possible for classical single-layer perceptrons.

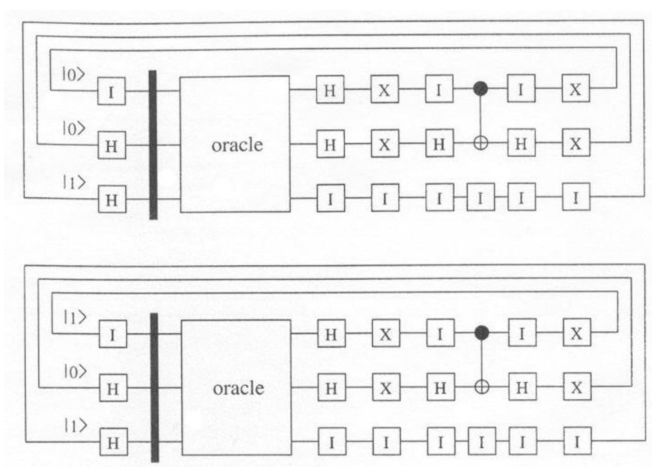

Fig 2. Quantum Recurrent Circuit When $n = 2$

2.3 Challenges to Quantum Circuit Design

NISHINO is working under a three-year COE (*Center of Excellence*, under Japanese Ministry of Education, Culture, Sports, Science and Technology) funded project with focus upon coherent photonics science, and has interest in the implementation of quantum neural networks via coherent photonics. Though the properties of photonic neural networks have been extensively studied, quantum photonic neural networks are an unexplored domain. Research in quantum learning architectures offers the potential to expand the application of quantum computing algorithms to a much broader class of functionality, and is important to the long-term objective of general-purpose quantum computing.

3. CONCLUSIONS

ATIP believes it important to continue monitoring the progress of NISHINO and collaborators; any fundamental progress in quantum algorithms is important to reconciling this shortcoming in Japanese quantum information research. In particular, quantum neural networks are a novel development that remains largely uncharted to date. We will continue to report on any updates from this lab.

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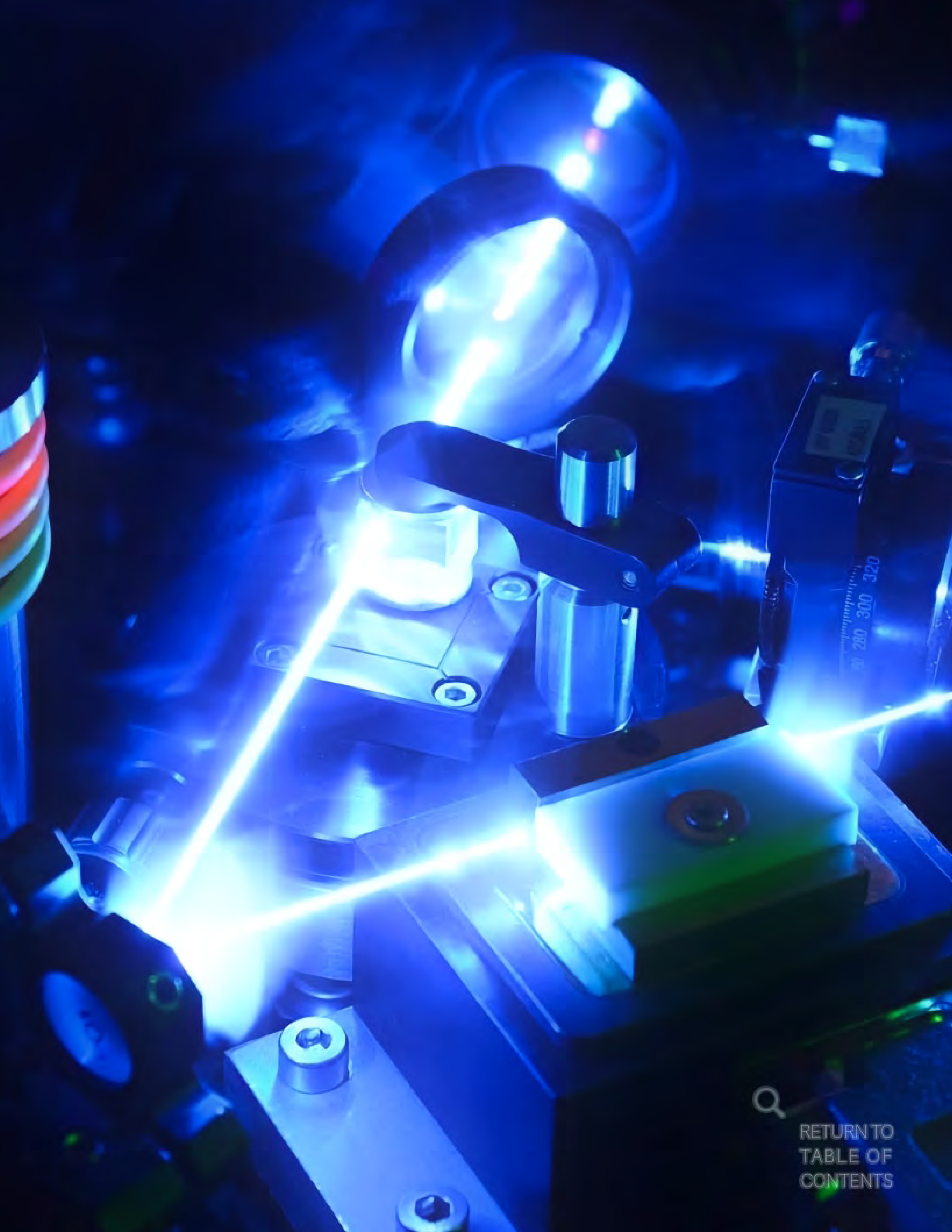

RETURN TO
TABLE OF
CONTENTS

QUANTUM R&D PROGRAMS OF JAPAN

Quantum Information Science and Technology Project

Asian Technology Information Program

ABSTRACT: This report summarizes quantum-related R&D programs for 2004 announced from Telecommunication Advancement Organization (TAO) under *Soumusho*, the Ministry of Public Management, Home Affairs, Posts and Telecommunications in August, and Japan Science and Technology Agency (JST) under MEXT, the Ministry of Education, Culture, Sports, Science and Technology on September 18th.

KEYWORDS: Government Policy on Science and Technology, Information Systems, Telecommunications, Cryptography, Communications, Computing, Remote Sensing, Quantum Information Science, Research and Development Program, Quantum Technology

COUNTRY: Japan

REPORT CONTENTS

Research funded in part by ONR grant N00014-03-1-0726 • ARDA/DTO • IARPA • DARPA QuIST

1. INTRODUCTION

Quantum Information Science is an important theme in the field of IT (Information Technology), which is one of four most-focused R&D fields of Japanese government as well as fields of biology, environment and nanotechnology. The Ministry of Education, Culture, Sports, Science and Technology (MEXT) is assisting many IT-related R&D programs through the Japan Science and Technology Agency (JST) under the authority of MEXT. *Soumu-sho*, the Ministry of Public Management, Home Affairs, Posts and Telecommunications, is also assisting telecommunication-related R&D programs through Telecommunications Advancement Organization of Japan (TAO) under the authority of *Soumu-sho. Soumu-sho* has a roadmap on quantum information and communications research and development.

This year, JST announced their 2004 program on new quantum-related R&D fields. JST established two programs, one “CREST” and the other “PRESTO (Sakigake)”. *Soumu-sho* announced their new strategy on quantum information and communication technology with a revised roadmap. For quantum cryptographic communications, they aim to realize medium-distance, tens of kilometers cryptographic communications within five years. They aim to establish an experimental test-bed for high-speed communications based on quantum information technologies by 2007, and to realize secure quantum information and communications networks between 2020–2030. TAO, under the authority of *Soumu-sho*, also announced 2004 programs on quantum technology, with particular focus on quantum communications.

This report summarizes the Japanese R&D strategy on quantum information and communications announced by *Soumu-sho*, quantum-related R&D programs for 2004 announced from TAO under *Soumu-sho*, and quantum-related R&D programs for 2004 by JST under MEXT.

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QUANTUM R&D PROGRAMS OF JAPAN

Quantum Information Science and Technology Project

Asian Technology Information Program, Tokyo, Japan

EXECUTIVE SUMMARY

- JST under MEXT has announced their 2004 quantum-related R&D programs.
- *Soumu-sho* announced their new R&D strategy on quantum information and communications.
- TAO under Soumu-sho announced their 2004 quantum-related R&D programs specified in quantum information and communications.

2. NEW STRATEGY ON QUANTUM R&D OF JAPANESE SOUMU-SHO

The Japanese *Soumu-sho* research committee for quantum information and communication, chaired by Reona EZAKI, President of Shibaura Institute of Technology, announced their long-term research strategy on next-generation quantum information and communications on November 20. Telecommunications research comes under the authority of *Soumu-sho*, the Ministry of Public Management, Home Affairs, Posts and Telecommunications. Their target of realizing secure quantum cryptographic communications, in conjunction with “quantum information and communications networks” is set at 2020–2030. They suggest three fields based on quantum information technology: *cryptography*, *communications*, and *networks* as future centers of research.

For quantum cryptographic communications, they aim to realize mid-distance, tens of kilometers, secure quantum cryptographic communications within five years, to establish an experimental test-bed for high-speed communications based on quantum information technologies by 2007, and realize secure quantum information and communications networks between 2020–2030. They also propose to create “open laboratories” for direct interaction between researchers of different fields. Prof. Hideki IMAI of The University of Tokyo, who compiled their report, stressed that “quantum information and communications technology will be social infrastructures for society in twenty years. Japan should steadily advance this program.”

This roadmap announced in November is the revised version of their former roadmap, shown as a figure in the attached documents for the nanotechnology meeting of CSTP, the *Council of Science and Technology Policy*, on April 23, 2001, heretofore unpublished as a written document.

Major Funding Organization for National Research Programs in Japan

Funding Organization	Authorizing Ministry	Total Annual Budget 2002 ($M)	Research Aims
JSPS ***Japan Society for the Promotion of Science***	**MEXT** Ministry of Education, Culture, Sports, Science and Technology	1500	*Basic research for universities*
JST ***Japan Science and Technology Agency***	**MEXT** Ministry of Education, Culture, Sports, Science and Technology	1200	*Mission-oriented basic research for universities and national laboratories*
NEDO ***New Energy and Industrial Technology Development Organization***	**METI** Ministry of Economy, Trade and Technology	3500	*Application-oriented research for industry, university, national lab collaborations*
TAO ***Telecommunications Advancement Organization***	***Soumo-sho*** Ministry of Public management, Home Affairs, Posts and Telecommunications	80	*Specialized in telecommunications for university, national labs, industry*

Quantum Information and Communications R&D Roadmap

Applications	Time Period	Technology
Cryptography	*2004-08*	Realization of Quantum Cryptography Systems, Mid-Distance without Relay ~100km, BB84, E91, B92, YK, Y-00, etc.
	2008-13	Realization of Quantum Security Systems, Quantum Entanglement, Quantum Memory Extension to Portable Security Systems
	2013-20	Enhancement of Quantum Security Systems
Communications	*2007-15*	Realization of Prototype Quantum Communications, Quantum Coding Technology, Quantum Basket Decoding
	2013-20	Realization of Small Device Quantum Communication, Solid, Photo-Quantum Gate, Integrated Quantum Basket Decoding
	2020-30	Realization of Quantum Information and Communications, Networks, Quantum Interface, Quantum Dispersion Processing
Networks	*2008-13*	Realization of Quantum Relays, Quantum Teleportation, Long-Distance Transport, 100km~
	2013-20	Realization of Prototype Quantum Internet, Implementation of Multi-party Protocol

Quantum Theoretical Research and Device Systems Technology

Area of Focus	Time Period	Description
Theoretical Research	*2003-08*	Quantum Cryptography Protocol, Security Verification
	2003-10	Quantum Certification Protocol, Multipartite entanglement protocols,2005-10 Security Verification
	2003-08	Establishment of Quantum and Classical Hybrid Coding Theory, Quantum Circuit Architecture Theory
	2003-08	Theory on Generation and Control of Non-classical Gaussian State and Photon Number State
	2003-05	Single Photon Detector, Single Photon Generator
	2003-08	Photon Number Identification Device
Device System Technology	*2005-10*	Technology on Generation and Control of Correlated Photon Pairs
	2005-10	Quantum Memory, Quantum State Retention
	2005-10	Solid Qubit Control Technology, Quantum Dots, Superconducting Elements, Decoherence-resistant technologies
	2005-13	Photonic Quantum Gate Technology Micro Opto-Resonator, EIT etc
	2006-15	Solid Quantum Dots Integration Circuit Technology, Development of Coherent Physics System and Integration Technology
	2006-15	Technology on Quantum Interface of Photo-Solid. Transfer Technology of Photon/Electronic Spin State
	2006-15	Photon/Atomic System state, Combination of Quantum Device and Communication Channel
	2010-20	Technology on Generation and Control of Multipartite Quantum Entanglement
	2010-2020	Solid Quantum Dots Integration Circuit Technology
	2010-2020	Development of Coherent Physics System and Integration Technology
	2020	Large-Scale Quantum Memory
	2020	Quantum Processors

3. 2004 QUANTUM-RELATED R&D PROGRAMS BY TAO UNDER SOUMU-SHO

3.1 R&D Plan for Quantum Information and Communications Technology

The Japanese R&D plan for quantum information and communications technology is based on the policy report titled "Towards the creation of 21 century revolutionary quantum information and communication technology" issued by the research study group of SOUMU-SHO on 2000 June.

In 2001 JFY, a research promoting system started and the funding aid to the proposed research on theory, the verification research on theory by Communication Research Laboratory (CRL), a research Institute of SOUMU-SHO, and verification and establishment of technology by TAO.

Proposed R&D plans were as follows:

Quantum Cryptography Technology

- *Development of quantum key distribution*
- *Development of quantum security system technologies*
- *Realization of secure quantum networks*

Quantum Communications Technology

- *Realization of prototype quantum communications*
- *Realization of quantum communications in specified application*
- *Realization of quantum communications networks*

3.2 SOUMU-SHO, TAO and CRL

Soumu-sho, the *Ministry of Public Management, Home Affairs, Posts and Telecommunications,* supports national research and development project on telecommunications both independently and through its parent organization, the *Telecommunications Advancement Organization* (TAO). CRL is the only research institute under the authority of *Soumu-sho.*

TAO announced two quantum programs, Quantum Cryptography and Quantum Entanglement. In 2004 JPY, Quantum Cryptography program is in their third year of a five-year program, and *Quantum Entanglement* starts in 2004.

In April 2004, CRL and TAO will be reorganized as an independent administration organization with a new name, the National Institute of Information and Communications Technology (NICT).

3.2.1 THIRD YEAR PLAN OF EXISTING PROGRAM: QUANTUM CRYPTOGRAPHY

(1) Research Target

The national R&D program aims to realize quantum cryptography from the standpoint of applied technology and engineering. With this technology, absolute security will be established supplementing modern cryptography, which is limited to an algorithmic security basis vulnerable to Shor's algorithm.

Experimental verification by optics will be done, with the aim of establishing a fusion between optical communications technology with existing network infrastructure

Applications to the actual security technology on information are actively under investigation.

This program aims to establish following four key fundamental technologies of quantum cryptography and its supporting technologies.

(1) Single photon generation technology
(2) Single photon detection technology
(3) RNG (Random number generation) technology
(4) QKD (quantum key distribution) systems technology

(2) Research Term

The research term of this R&D program is five years, starting in 2001 JFY through 2005 JFY.

(3) Research Organization

Research entrusted companies and representative persons are as follows.

(a) Mitsubishi Electric Corporation (organizing company), Mitsuru MATSUI
(b) NEC Corporation, Kazuo NAKAMURA
(c) The University of Tokyo, Prof. Hideki IMAI

(4) Research budget plan

2001 JFY	130,000,000 JPY	1.13 M USD
2002	150,000,000	1.30
2003	187,500,000	1.63
2004	192,500,000	1.67
2005	211,000,000	1.83

Amounts in USD were calculated based on the exchange ration of 1 USD = 115 JPY

(5) Research tasks and its developer

(a) *Single photon generation technology* Mitsubishi Electric Corporation
(b) *Single photon detection technology* Mitsubishi Electric Corporation

(c) *Random number generation technology*

Mitsubishi Electric Corporation

(d) *Quantum key distribution system technology*

d1. *Data processing technology in quantum cryptography with safety and high efficiency*

Mitsubishi Electric Corporation

d2. *Highly efficient method for optical sending and receiving system*

Mitsubishi Electric Corporation

d3. *Integrated quantum cryptography system fused with existing security system*

Mitsubishi Electric Corporation

d4. *Quantum cryptography and protocol technology based on the new scheme*

Mitsubishi Electric Corporation

d5. *Modulation, demodulation, and phase coherence technology of quantum optical signals*

NEC Corporation

d6. *Fabrication technology of monolithic device for modulation and demodulation*

NEC Corporation

d7. *On-board quantum cryptography system technology*

NEC Corporation

d8. *Multi-wave quantum cryptography network technology*

NEC Corporation

d9. *Individual certification, error correction, and secrecy enhancing software*

The University of Tokyo

d10. *Security analysis and research on multi party protocols*

The University of Tokyo

(6) Research achievements

(6.1) *Single photon generation technology: Patent applications and publications*

Patent applications	6
Publications	37

(6.2) Main achievements of this program to date:

(a) Succeeded in developing the integrated quantum cryptography system at the world's longest distance, 87km. The new system is based on their newly-developed single photon detector in the communication band regime. They also succeeded in realizing a practical integrated quantum cryptography system that can be integrated with existing cryptography. The gap between high-speed data transmission and very slow rate of quantum cryptographic key sharing was resolved.

(b) Demonstration of fundamental experiments using an on-board quantum cryptography system, which can be applied to the single photon source of quantum correlated photon pairs generated through nonlinear crystal parametric down-conversion.

(c) Proposed, evaluated, and improved a safety method for error correction method with LDPC sign.

3.2.2 NEW PROPOSAL: COMMUNICATION TECHNOLOGY BASED ON QUANTUM ENTANGLED PHOTON PAIRS

(1) Research themes

Research and development of communication technology based on quantum-entangled photon pairs (QEPPs) has the following three principal objectives.

(a) QEPP **generation** technology

(b) QEPP **detection** technology

(c) QEPP **systems** technology

(2) Research targets of this program

This R&D target is meant to establish technologies, stable and controllable QEPP generation technology, highly efficient QEPP detection technology, and to develop quantum signal transport technology needed for the realization of long-distance quantum communication systems.

QEPP technology was selected to avoid the fragility of the quantum state of single photon systems, to make it possible to transport the quantum state continuously, and to realize long-distance – more than 100km – transportation of quantum information.

(3) Research term and schedule

The program term of three years begins in 2005 and goes through 2007.

An outline of the research term is shown in Table 4.

Table 4 QEPP Research Plan

	2005	**2006**	**2007**
Generation technology of quantum entangled photon pairs	Basic design	Prototype production and experiment	Experiment and evaluation
Detection technology of quantum entangled photon pairs	Basic design	Prototype production and experiment	Experiment and evaluation
System technology on quantum entangled photon pairs	Basic design	Prototype production and experiment	Experiment and evaluation

(4) R&D tasks

(a) *QEPP generation technology*

The goal of this task is to develop and establish a non-Poisson type QEPP generation technology in the fully controlled state in the wavelength region of communication.

Stable and regular generation of photon pairs correlated through quantum entanglement is one of the aims.

(b) *QEPP detection technology*

The goal is to develop and establish QEPP detection technology needed for QEPP system development, with high detection efficiency in the regular communication wavelength range.

(c) *QEPP system technology*

The goal is develop quantum signal transport technology needed for long-distance quantum information and communication system based on the QEPP resources.

(5) Discussion

(5.1) Research background

(a) In Japan, basic research on quantum entanglement is limited to being competitively conducted by universities, companies, and independent administrative institutes. On the contrary, in Europe and the United States, *national projects with large-scale budgets* are conducted in the field of basic research and experimental verification for the actual use of the system based on QEPP technology.

(b) Parametric down-conversion technology is widely used for generating QEPP via irradiating laser pulse on the surface of non-linear crystals. However, the efficiency of this method is limited to being between 10^{-9}–10^{-5}, rather low in generating entangled photon pairs, and difficult to control both timing and numbers of the generated photons.

(c) Lately, QEPP generation technology based on quantum dots is being used to overcome the problems in (2), but on-demand production is not yet realized.

(d) Photon detectors with high quantum efficiency are needed for the detection of entangled states.

Photon detectors with 70% quantum efficiency are already offered commercially.

Associate Prof. TAKEUCHI and Prof. SASAKI group of Hokkaido University developed a photon detector with quantum efficiency 88±5%, the world's highest. The output voltage of this detector can be controlled by the input photon numbers.

In the research public subscription system of Soumu-sho, AIST developed a photon detector with quantum efficiency 19% and dark counting rate 1.25×10^{-4}, also quantum efficiency 17.3% and dark count ratio 0.86×10^{-4} in the wavelength region of 800nm.

Also in the TAO sponsored research, “R&D of Quantum Cryptography Technology”, Mitsubishi Electric Corporation developed photon detector with quantum efficiency more than 15% and dark counting ratio 2×10^{-6}.

But quantum efficiency of all these detectors is not fully high for the high efficiency detection of the entangled states.

(e) Quantum teleportation is proposed for long distance communication of quantum information. However, actual long-distance experiments on quantum teleportation have been limited to two km in optical fibers by Geneva University, *et al.*

(f) Quantum entanglement extraction (*distillation*) is proposed to restore weakened quantum entanglement states by noise and loss during long-distance transport of entangled states.

Prof. IMOTO's group of SOKEN-DAI has experimentally verified entanglement restoration by extracting one photon pair from four photons composing two photon pairs, using the phase modulation method.

(5.2) Needs for this R&D

(a) This R&D aims to realize long-distance (more than 100km) transport of quantum information through successive transport of quantum states using entangled photon pairs.

(b) This government R&D program supports the development of technologies on generation and detection of quantum entangled states. This is the most important key technology for establishing a quantum-based communication network and is also important as key elemental technology for quantum computation. For the development of these technologies, we need long-term, high-risk projects that are too difficult for single universities or companies.

(c) In Europe and the United States, national R&D programs of developing technologies on generation and detection of quantum entangled states have already been initiated. These technologies are extremely important key technologies, and also produce extensive ripple effects for the development of communications technology based upon quantum information.

(5.3) Relations with similar R&D

(a) This R&D program has a clear goal to apply the developed technologies on the quantum entangled states for the realization of communications technology based upon quantum information.

A few R&D programs on quantum entangled states by JST and by the public research system of Soumu-sho are based on fundamental physical properties and on the verification of basic principles.

(b) This R&D program aims to develop long distance, more than 100km, and communication system of quantum information using resources of completely controlled quantum entangled photon pairs.

R&D program on the realization of quantum cryptography key distribution system in the TAO sponsored research, "R&D of Quantum Cryptography Technology" is focused on the single photon and the transport distance is limited to less than 100km.

(5.4) R&D Goal

(a) This R&D program aims to establish technologies for generating quantum entangled photon pairs at certain fixed time with high stability and controllability in the communication wavelength range. The target of repeating cycle for generating quantum entangled photon pairs is less than 1! second.

(b) Also this R&D program aims to establish detection technology of quantum entangled photon pairs with the quantum efficiency of 30% level for the quantum entangled photon pairs in the communication wavelength range.

(c) For the realization of long distance (more than hundreds km) communication of quantum information, this R&D program will perform experimental verification of the principle on quantum transport based on entangled photon pairs.

(5.5) Expected ripple effects

The following ripple effects are expected:

(a) Relay technologies using quantum entangled photon pairs as resources will be established.

(b) The approach will come much closer to long-distance communication systems, on order of hundreds of kilometers, based upon quantum information.

(c) Many breakthroughs in research for quantum computing are expected.

(d) Contribution to the development of new security technologies based upon quantum certification are expected.

(5.6) Standardization

This R&D program is not yet in the stage of standardization, because this program is in the basic research stage.

4. 2004 QUANTUM-RELATED R&D PROGRAMS BY JST UNDER MEXT

In September 2004, JST released their 2004 program on new quantum-related fields. JST has initiated two programs, one "CREST" type and the other "PRESTO (*Sakigake*)" type.

4.1 MEXT & JST

Japan Science and Technology Agency (JST) is a statutory organization under Ministry of Education, Culture, Sports, Science and Technology (MEXT).

MEXT is funding for R&D programs on Science and Technology through MEXT itself, JST for mission-oriented basic research and The Japan Society for the Promotion of Science (JSPS, *Gakushin* for short) for basic research.

JST R&D activities are summarized in **Table 5.**

Table 5 JST R&D Programs

ERATO
Exploratory Research for Advanced Technology

ICORP
International Cooperative Research Project

PRESTO
Precursory Research for Embryonic Science and Technology ,"Sakigake" in Japanese

CREST
Core Research for Evolutionary Science and Technology

4.2 New research programs, Two JST 2004 quantum-R&D programs

4.2.1 CREST programs in the research area:

Creation of new technology for the realization of quantum information processing systems

Core Research for Evolutionary Science and Technology (**CREST**) is the research program which utilizes the research potential of universities, independent administrative institutions, national and public institutes, special corporations and private enterprises. JST selects research directors and research proposals from above-mentioned research teams through public solicitation.

MEXT added a new strategic sector, "Development of a technological infrastructure for the realization of quantum information processing that introduces innovations into information communication technology" and selected a new research area, "Creation of new technology for the realization of quantum information processing system", and Prof. Yoshihisa YAMAMOTO of National Institute for Informatics as the research area supervisor.

Prof. YAMAMOTO as the research supervisor selected research proposals from submitted proposals in consultation with area advisors.

Research expenditure: 40–200 million JPY

* 0.3–1.7M USD, as 120 JPY/USD per year on average. Research period limited to five years.

The outline of the new research is as follows:

Strategic Sector:

Development of a technological infrastructure for the realization of quantum information processing that introduces innovations into information communication technology.

Research Area:

Creation of new technology for the realization of quantum information processing systems

Research Supervisor:

Yoshihisa YAMAMOTO	Professor at Stanford University and NII Japan

Area Advisor:

Makoto GONOKAMI	Professor at The University of Tokyo
Seigo TARUCHA	Professor at The University of Tokyo
Akio HOSOYA	Professor at Tokyo Institute of Technology
Tsutomu YABUZAKI	Professor at Kyoto University
Roy LANG	Professor at Tokyo University of Agriculture and Technology
Miki WADACHI	Professor at University of Tokyo

Proposals from 5 research units selected from 21 proposals are as follows:

(1) "Development of new functionality on quantum operation processing using photons"
Nobuyuki IMOTO, Prof. of SOKEN-DAI

(2) "*R&D of superconducting qubit systems*"
Jaw-Shen TSAI, NEC Corporation

(3) "*Development of quantum operations system using neutral atoms*"
Fujio SHIMIZU, Visiting Prof. of NTT Basic Science Labs.

(4) "*Development of basic technologies for quantum information processing using atomic ensembles*"
Yoshiro TAKAHASHI, Associate Prof. of Kyoto Univ.

(5) "*Quantum entanglement control for quantum networks*"
Akira FURUSAWA, Associate Professor of The Univ. of Tokyo.

4.2.2 PRESTO *"Sakigake"* programs in Quantum Information

Precursory Research for Embryonic Science and Technology (PRESTO or "Sakigake" in Japanese) is a young scientists research promotion project. Research groups including 1 to 2 researchers or technicians are organized to conduct research.

The outline of the new research area is as follows:

Strategic Sector: "Development of a technological infrastructure for the realization of quantum information processing that introduces innovations into information communication technology" (No.1 of Table 6), and "Creation of nanodevices/materials/systems for overcoming integration/function limits in data processing and communications" (No.11 of Table 6)

Research Area: Quantum Information

Research Supervisor:

Akio HOSOYA	Professor at Tokyo Institute of Technology

Area Advisor:

Hiroshi IMAI	Professor at The University of Tokyo
Keiichi EDAMATSU	Professor at The University of Tokyo
Masanao OZAWA	Professor at Tohoku University
Katsuhiro KITAGAWA	Professor at Osaka University
Masahide SASAKI	Communication Research Lab
Shin TAKAGI	Professor at Fuji Tokohu Univ.

Shigeki TAKEUCHI	Associate Professor of Hokkaido University
Jaw-Shen TSAI	NEC Corporation
Fujio MINAMI	Prof. of Tokyo Institute of Technology
Yoshihisa YAMAMOTO	Prof. of National Institute of Informatics

The following 5 programs were selected as PRESTO programs from 19 proposed programs.

(1) "Determination and measurement of quantum states to enable quantum entanglement optimized recovery protocol derivation" Satoru ISHIZAKA, Basic Research Lab, NEC Corporation.

(2) "Controlling quantum states with Josephson Junction superconducting resonators"
Haruhisa KITANO, Research Associate, The University of Tokyo.

(3) "Multi-photon operation in single qubit dot"
Takashi KURODA. Nanomaterials Lab.
National Institute for Materials Science (NIMS).

(4) "Analysis of quantum computers as multi-body quantum systems"
Akira SHIMIZU, Associate Prof. of The Univ. of Tokyo

(5) "Next-generation quantum cryptographic protocols using quantum keys"
Mio MURAO, Associate Prof. of The Univ. of Tokyo

4.3 Strategic sector of MEXT

4.3.1 Existing Strategic sectors of MEXT

Existing strategic sectors for R&D programs: In this Japanese fiscal year, MEXT began two new sectors including quantum research, as shown in the following table.

Table 6. Strategic Sectors of MEXT

Name of Strategic Sector	*Starting Year*
Development of a technological infrastructure for the realization of quantum information processing that introduces innovations into information communication technology	*JFY 2003*
Elucidation of the human lifelong learning mechanisms based on knowledge of brain science, with an intention to provide a solution to problems in education	*JFY 2003*
Investigation of sugar chain function for realizing effective development of innovative drugs for combating cancer and viral infection and establishment of technology for application	*JFY 2002*
Establishment of basic technology for utilizing genome information for realizing tailor-made medical treatment without side effects based on individual genetic information	*JFY 2002*
Establishment of next-generation integration simulation technology for realizing advanced treatment and precision product design based on the phenomena of atomic/molecular level in the medical treatment and information industry	*JFY 2002*
Creation of functional materials/system that utilize nano biotechnology for realizing a noninvasive medical treatment system	*JFY 2002 & 2003*
Creation of nanodevice/material/system for overcoming integration/function limits in data processing and communications	*JFY 2002 & 2003*
Creation of nano materials/systems for realizing environmental conservation and advanced energy recycling to minimize stress on the environment	*JFY 2002 & 2003*
Technological innovation through protein analysis based on gene information	*JFY 2001*
Searching and creating leading-edge basic technology targeting at realization of advanced medical care	*JFY 2001*
Building high-speed, large-capacity information processing technology by a new principle	*JFY 2001*
Forecasting water circulation and building a utilization system	*JFY 2001*
Realization of an aging society full of vitality through technological innovation	*JFY 2000*
Technological innovation by the development of new functions at the molecular level	*JFY 1998*
Building up of a Social System Aimed at Resource Recycling and Minimum Energy Requirements	*JFY 1998*
Challenge to unknown areas with large possibility	*JFY 1996*
Elucidation of brain function	*JFY 1996*

4.3.2 A new quantum-related strategic sector starting JFY 2004, "Development of a technological infrastructure for the realization of quantum information processing that introduces innovations into information communication technology"

(1) Summary

Development of a technological infrastructure for the realization of quantum information processing that introduces innovations into information communication technology

(2) Specific Objectives

This research will seek to achieve the objectives listed below to meet the following goals: Identifying the most effective approaches and developing a technological infrastructure to support the realization of quantum information processing technology by undertaking research and development of quantum information processing elements using photons, electron spin and nuclear spin while concurrently promoting comprehensive research and development, including algorithms, circuits and systems, and implementing that in a competitive environment with aim of realizing quantum information processing enabling ultra-high-speed calculation and large-capacity communications by taking advantage of the quantum dynamical entanglement effect.

Research and development of quantum devices leading to the realization of quantum information processing technology (higher performance, use of multiple quantum bits, extended lifespan, enhanced stabilization), research and development of algorithms, systems, etc., for realizing quantum information processing technology

(2) Background of Objectives and Socioeconomic Imperatives

One long-range issue in the establishment of quantum information processing is simultaneously executing multiple calculations taking advantage of the phenomenon of quantum superposition and realizing ultra-high-speed calculation overall. At the dawn of its realization, it will result in significant innovation in the information communication industry. Specifically, it is expected that it will be possible to instantaneously complete massive calculations for simulating structure or performance of pharmaceuticals or advanced nanomaterials, which take years or decades to complete with present-day supercomputers, as well as the ultimate assurance of communication security and the decryption of complex codes.

Though it is a long-range research aim, large-scale projects are already underway in Europe, the U.S.A. and Australia and competition is intensifying. If organized initiatives are not promoted in Japan to avoid lagging behind, basic patents will probably be acquired overseas, resulting in shortcomings in international competitiveness.

Initiatives for the realization of technology in quantum information processing are at an extremely fundamental stage at present and many elements of uncertainty remain; however, it is expected that new IT-related markets will be consequential from the fundamental technologies required for quantum computer development.

Given the above, it will also be necessary to promote prompt efforts in Japan on a national basis for the development of this technology.

(3) Scientific Justification for the Objectives

As initiatives realizing quantum information technology, the development of devices realizing qubits as the basic unit is being promoted and, at the present stage, development has gone beyond devices realizing single qubits to devices realizing multiple qubits. The phenomenon of quantum entanglement is gradually being explored using these devices.

In order to realize quantum information technology using quantum devices, it is necessary to develop new algorithms for computational operations, as well as devices to enable use with multiple qubits and extend their lifespan. The goal for the time being is to realize a device capable of basic logical operations that combines these aspects.

As mentioned above, we are currently at a stage, basic though it may be, that shows the direction leading to the development of quantum devices, and it is expected that concentrated and strategic initiatives will lead to a major breakthrough.

Since the development of fundamental technology for the realization of quantum information processing enables international initiatives in this field, competition is globally intensifying and activities abroad are being pursued as national projects.

Independent initiatives are being undertaken at research institutes in Japan considering this situation; it is also necessary to pursue it strategically as national goals.

In addition, since long-term research and development will be required in this field and those activities are currently being conducted by young researchers, an important key is the implementation of research and development that employs the young researchers who will be the driving force for the next generation. In light of the above,

It is of vital importance to identify the most useful approach and set the pace worldwide for the establishment of fundamental technology for quantum information processing by concurrently promoting multiple approaches within a competitive environment. It is furthermore necessary to consider that young researchers take opportunities in this research and development.

(4) Focused Research Period

New research subjects will be solicited over the three periods from FY2003 through FY2005 and the research period will be generally five years per research issue. Research issues that produce outstanding research results will be eligible for an extension of the research period after undergoing evaluation.

5. CONCLUSION

The Japanese government is strongly assisting Information Technology (IT) and quantum-related R&D programs. Governmental assistance for quantum-related R&D is being done through the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and through Soumu-sho, the Ministry of Public Management, Home Affairs, Posts and Telecommunications. The Ministry of Economy, Trades and Technology (METI) is not playing big role in the quantum-related fields yet, but if METI starts to play a more leading role in this field, the age of quantum-related technology is close at hand.

Quantum Information Science is an important theme in the field of IT, which is one of four most-focused R&D fields of Japanese government as well as fields of biology, environment and nanotechnology.

MEXT is assisting many IT-related R&D programs through Japan Science and Technology Agency (JST) under the authority of MEXT. Soumu-sho also assists telecommunication-related R&D programs through Telecommunications Advancement Organization of Japan (TAO) under the authority of Soumu-sho.

Soumu-sho is the only ministry that has announced a strategy and roadmap on quantum information and communications R&D. This year, JST announced their 2004 program on new quantum-related R&D fields. JST starts two programs, one by “CREST” type and the other by “PRESTO (*Sakigake*)” type*. Soumu-sho* announced their new strategy in this November on R&D of quantum information and communication technology with revised roadmap.

For quantum cryptographic communications, the organization aims to realize mid-distance cryptographic communications within five years, to establish an experimental test-bed for high-speed communications based on quantum information technologies by 2007, and realize secure quantum information and communications networks between 2020–2030.

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6. CONTACTS

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* TAO has been reorganized into NICT
NICT: National Institute of Information and Communications Technology
ERATO Quantum Computation and Information Project, Japan Science and Technology (JST)

atip
asian technology information program

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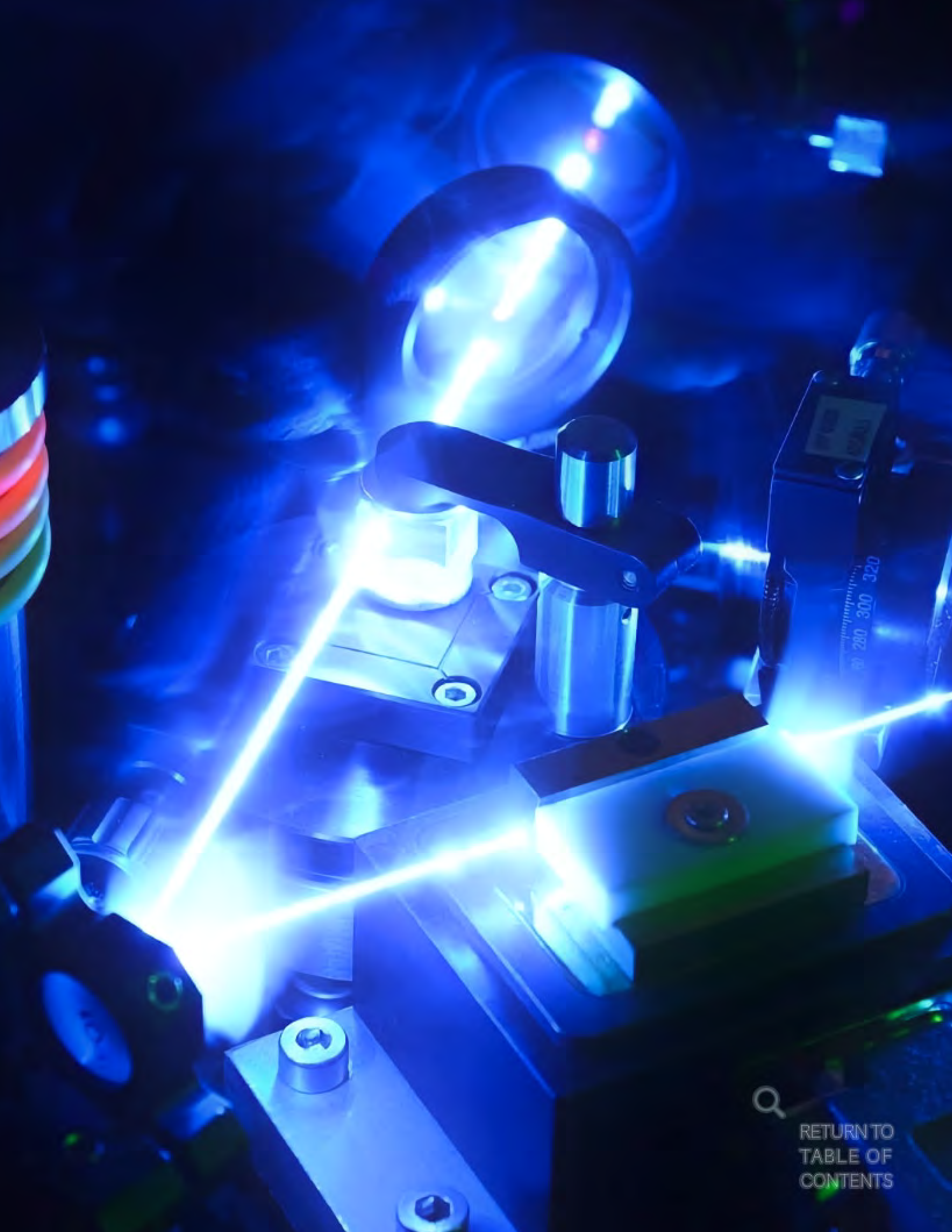

RETURN TO
TABLE OF
CONTENTS

The International Conference on Quantum Information

Tokyo University of Science

This ATIP report covers the recent International Conference on Quantum Information (ICQI) held at the Tokyo University of Science. Japanese government financing in this area has intensified in response to growing international competition in the field of quantum information technologies.

Keywords Quantum coding, computation, communications, cryptography, information

The Embassy of Italy, Tokyo has recently sponsored a series of joint scientific conferences in Japan to stimulate multidisciplinary discussion of potential enabling technologies for quantum computing, and to encourage interaction between the mathematical, physical and engineering communities. The first of these conferences was held from 1–3 November at the Tokyo University of Technology. Principal organizers of the event included Prof. Takeyuki HIDA (white noise theory), of Meiji University and emeritus professor of Nagoya University; Prof. Masanori OHYA (quantum information) of Tokyo University of Science; and Prof. Luigi ACCARDI (quantum information), of the University of Rome.

Research funded in part by ONR grant N00014-03-1-0726 • ARDA/DTO • IARPA • DARPA QuIST

Overview

Quantum information technologies are of vital importance to Japanese national security and competitive viability in the international economy. The Japanese government has redoubled its efforts in quantum information science and has emphasized strategic lines of research towards the realization of scalable quantum computation. The Italian Embassy has a long history of close relations with the Japanese scientific community and wishes both to maintain ties and to foster new collaborations in this rapidly growing field. This series of joint conferences is being held in a small, intimate setting of approximately 50 senior government and academic scientists from across the spectrum in order to stimulate close interaction between researchers. Research talks were presented on mathematical, physical, engineering and industrial aspects of quantum information science. Approximately 50% of presentations were given by Japanese nationals; remaining talks were given by Italian and other European community researchers.

Research highlights

- **Room-temperature Bose-Einstein condensation**
  Hideyo OKUSHI, AIST Tsukuba Diamond Research Center, Japan
  The AIST Tsukuba Diamond Research Center has observed sharp 235-nm exciton emission characteristic of Bose-Einstein condensation in fabricated single-crystal diamond film semiconductors. If exciton lifetimes are long enough, it is possible that Bose-Einstein condensation can occur in these diamond films even at room temperature. The Center is currently working on a detailed examination of these results and is expected to release a full report in coming weeks. Funding sources are CREST/MEXT (5-year project initiated 2002; USD $0.8 M for year 2003). The Japanese government has subsequently initiated a larger diamond research project through NEDO/METI (3-year project initiated 2003; USD $5.0 M for year 2003).

- **Bose-Einstein condensates in optical lattices and quantum information**
  Ennio ARIMONDO, Pisa University, Italy
  The Arimondo group is studying properties of Bose-Einstein condensates as a candidate for quantum information processing. Coherent state control of the Bose-Einstein condensate is achieved via laser and evaporative cooling to 50-300 nK; BEC radius = 2-30 ! m. Two counterpropagating lasers interfere to form gratings of light that control the motion of the matter waves, breaking the

condensate into a multi-qubit system. Quantum gates are constructed through controlled phase shift injected through individual atomic collisions. Technological limitations to this approach include (i) single-atom detection and (ii) addressing and detecting a single qubit.

- **Macromolecule interference experiments**
  Anton ZEILINGER, University of Vienna, Austria
  Prof. Anton Zeilinger presented on mesoscopic interference experiments being conducted by his team at the University of Vienna, Austria. Current experiments utilize molecules of range 1-2 nm: examples include fluorinated fullerenes and tetraphenylporphyrin, a biomolecule present in chlorophyll and hemoglobin. A tentative next step is to attain these results with insulin. Re-analysis of experimental data to date shows a mass scaling factor of 10x every 18 months: Zeilinger's personal conviction is that there is no inherent macroscopic limit to demonstration of quantum interference properties in
- matter.

- **NEC Demonstration of CNOT gate in a Josephson junction charge qubit**
  Tsuyoshi YAMAMOTO, NEC, Japan
  As reported in *Nature* (30 Oct), NEC RIKEN has demonstrated conditional gate operations in an integrated two-qubit Josephson junction circuit. Yamamoto presented these findings in a talk focused upon demonstration of control and refinement of a coherent 2x2 level system, though many at the meeting were skeptical that entanglement between qubits has not been been demonstrated satisfactorily.

- **Quantum cryptography**
  Giuseppe CASTAGNOLI, ELSAG SpA, Italy
  ELSAG SpA presented on its quantum cryptography research program using spontaneous parametric down-conversion to create entangled photon pairs. Photon sequences detected by either user are exploited to generate a secure shared key by BB84 protocol. Experimental results yield 2400 bits/second key rate at a few meters; 1200 bits/second key rate at ~450 meters; visibility 98%, qubit error rate ~1%, and coincidence rate of ~7%. Future plans include miniaturization of quantumware and scalability to user networks using an optical switch: ELSAG has ambitions to move this technology into the commercial sector as soon as it becomes viable.

Future Challenges

The leading majority of European scientists present voiced concern over the lack of emphasis on theoretical considerations in the ARDA Roadmap. There is optimism that forthcoming European and Japanese roadmaps will fill this gap, though fundamental and algorithms research is underrepresented as a whole. The outlook to the future is optimistic; though the field is still in its infancy, research progress has been encouraging to date and there are no barriers foreseen to progressively bringing quantum information technologies out of academia and into the world of industrial applications.

Joint Italy-Japan Research Projects

Quantum Information and Computation

Bari	Waseda
Catania	Tokyo University
Como-Insubria	Tokyo Institute of Technology
Milano	Fuji Tokoha
Palermo	Ryukyus
Pisa SNS	Yamanashi
	NTT

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Research funded in part by **ONR grant N00014-03-1-0726 • ARDA/DTO • IARPA • DARPA QuIST**

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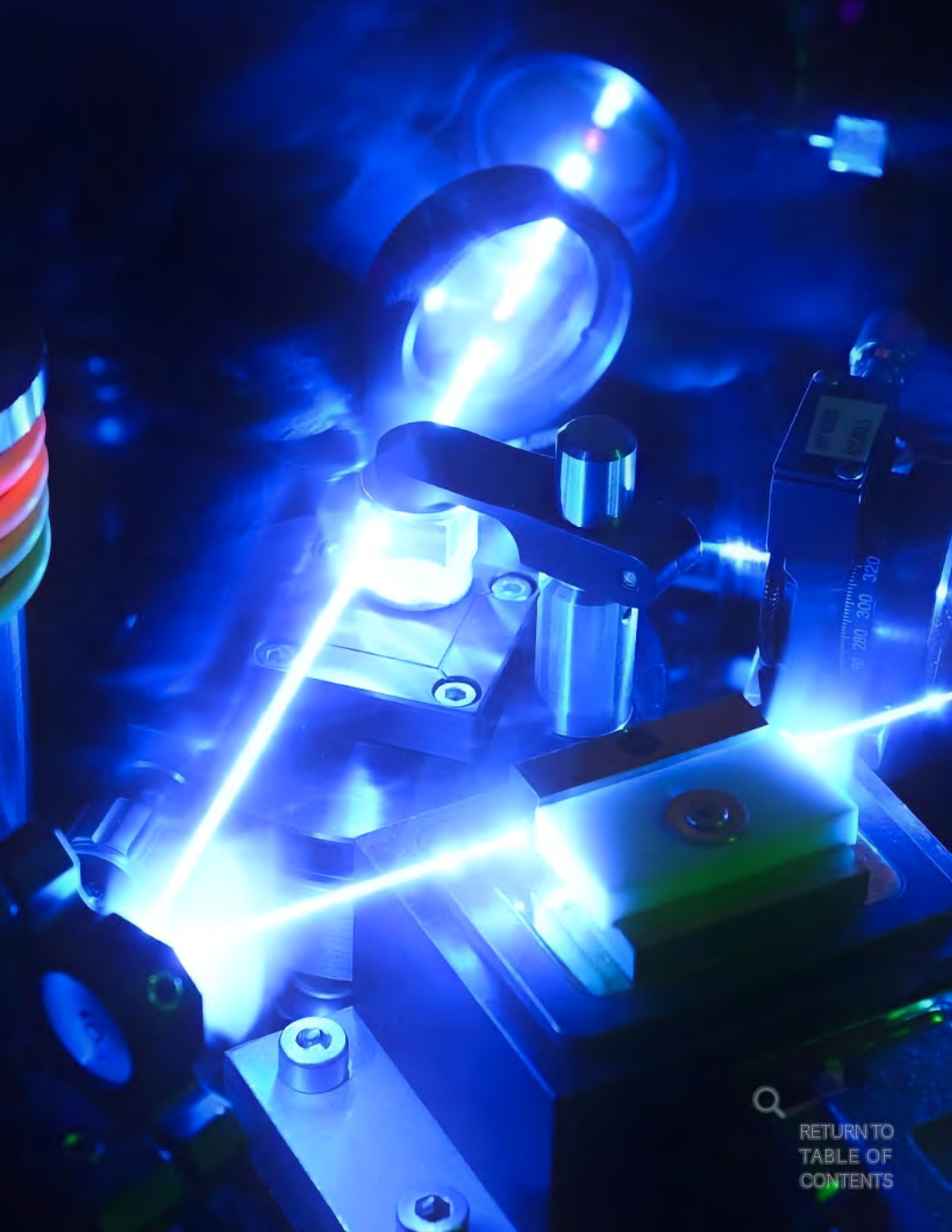


RETURN TO TABLE OF CONTENTS

International Conferences, Workshops, and Symposia (2001 – 2020)

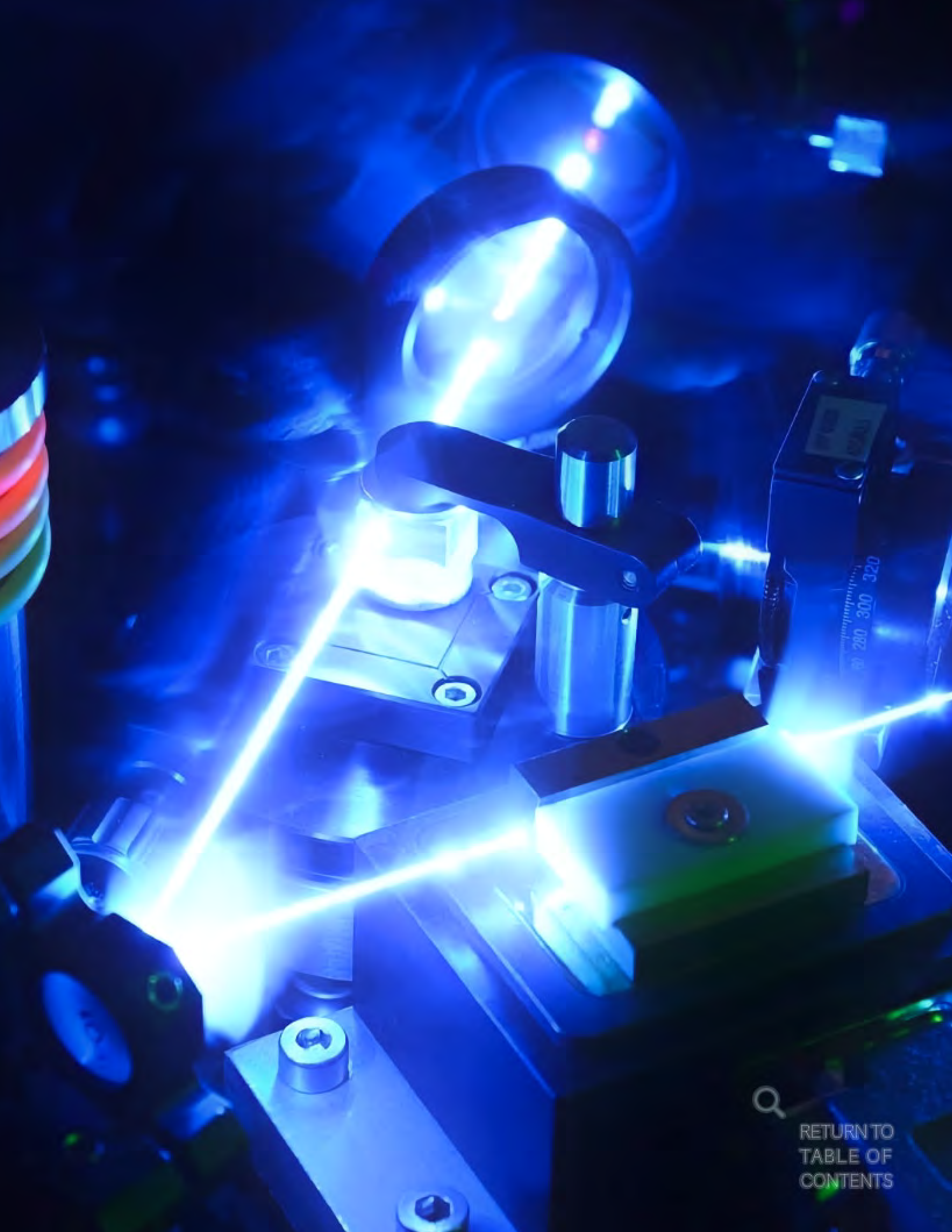
Google Scholar • Wiki • Weblog • Astronaut Selection

Astronautics · Breakthrough Physics · Quantum Technology · The Future of Spaceflight

2020 *Space Mastery* · *Portugal*
2020 *To the Stars and Beyond:* Deep Tech & AI · *San Francisco*
2020 International Astronautical Congress, 71st IAF · ESA
2020 SpaceCom 2020, Enabling Commercial Space · *Colorado Springs*
2019 Quantum Information Processing with Superconducting Circuits · *Sydney*
2019 Materials Frontiers to Empower Quantum Computing · *Sydney*
2019 Quantum Technology: The Second Revolution · *Sydney*
2018 FutureHack · *Tokyo*
2018 American School of Japan · *Tokyo*
2018 Laurus International School of Science · *Tokyo*
2018 *Future of the Global Energy System,* Institute for the Future · *San Francisco*
2016 *Keizai* · US-Japan Commercial Spaceflight · *San Francisco*
2016 Effective Altruism Summit · *San Francisco*
2016 Hive Global Leadership Forum · *San Francisco*
2016 RSA Information Security · *San Francisco*
2015 Hive Global Leadership Forum · *San Francisco*
2015 Further Future · TED Meets Burning Man · *Las Vegas*
2015 Hive Global Leadership Forum · *San Francisco*
2015 DefCon Information Security · *Las Vegas*
2015 Black Hat Information Security · *Las Vegas*
2014 The Future of Commercial Spaceflight · *Silicon Valley Space Center*
2014 Yuri's Night: The First Manned Orbital Spaceflight · *Los Angeles*
2013 IEEE Quantum Photonics: *The Next Frontier of Quantum Communications* · *Hawai'i*
2013 Yuri's Night: The First Manned Orbital Spaceflight · *Hawai'i*
2012 NASA-ESA-JAXA-CSA Pacific International Space Center for Exploration Systems · *Hawai'i*
2012 NASA/CSF Next-Generation Suborbital Researchers Conference · *Palo Alto*
2012 Quantum Information and Nanoscale Optoelectronics · *Berkeley*
2012 Yuri's Night: The First Manned Orbital Spaceflight · *Los Angeles*
2012 Inaugural Quantum Future Technologies Conference · *NASA Ames Research Center*
2011 Quantum Coherence in Excitation Energy Transfer · *Berkeley*
2011 *The Future of Spaceflight* · Mobile Monday, Invited keynote · *Amsterdam*
2011 Delft-Leiden Biannual Casimir Symposium · *Leiden*
2011 Alain Aspect: The Second Quantum Revolution · *Leiden*
2011 ESA-TNO Space Pier Day · *The Hague*
2010 Kavli-Delft Center for Bionanoscience, Founding Conference · *Delft*
2010 *Quantum Mechanics in Higher-Dimensional Hilbert Spaces*, Int'l Akademie Traunkirchen · *Austria*
2010 *What is real in the quantum world?* Int'l Akademie Traunkirchen · *Austria*
2010 NASA/ESA/JAXA/CSA Pacific International Space Center for Exploration Systems · *Hawai'i*
2009 NASA/JAXA Japan-US Science, Technology and Space Applications Program · *Hawai'i*
2009 From Foundations of Quantum Mechanics to Quantum Information · *Delft*
2009 Distributed European Infrastructure for Supercomputing Applications (DEISA) · *Amsterdam*
2009 Partnership for Advanced Computing in Europe (PRACE) · *Amsterdam*
2008 Quantum Decoherence and Quantum Information Science, Lorentz Center · *Amsterdam*
2008 Triennial Conference on Low-Temperature Condensed Matter Physics XXV · *Amsterdam*
2008 International Conference on Quantum Structures · *Brussels*
2007 Workshop on Time Symmetry in Quantum Mechanics · *Brussels*
2007 Optical Fabrication Technologies, Coherence and Metrology · *Switzerland*
2006 The Best of Nanoscience – International Symposium for Hans Mooij · *Delft*
2006 SPIE Defense and Security Applications of Quantum Information Science · *Orlando*
2005 *New Computational Paradigms:* Neural Nets, Quantum, Molecular and Biocomputing · *Amsterdam*
2005 UNESCO Physics for Tomorrow, UNESCO Headquarters · *Paris*
2004 RSA Information Security · *Barcelona*
2004 SPIE Defense and Security Applications of Quantum Information Science · *Orlando*
2003 Gordon Research Conference on Quantum Information · *Santa Barbara*
2003 Quantum Information Technology IX · *Tokyo*
2003 International Conference on Quantum Information · *Tokyo*
2002 NATO Advanced Research Workshop on Quantum Chaos · *Lake Como*
2002 National Science Foundation Coding Theory and Quantum Computing · *Vienna*
2002 United Nations International Student Conference Amsterdam · *The Netherlands*
2002 International Conference on High-Energy Physics XXXI · *Amsterdam*
2001 World Technology Summit · *London*
2001 French Senate Hearing on the Future of Artificial Intelligence · *Paris*
2001 US Government Conference on High Performance Computing · *Salishan*
2001 National Security Agency · *Fort Meade*

Recipient of the annual RSA Information Security Award
Outstanding Achievement in Government Policy

November, 2004
Barcelona, Spain



RETURN TO
TABLE OF
CONTENTS