Summary of professional accomplishments

Jarosław A. Miszczak

January 30th, 2013

1. Name and Surname

Jarosław Adam Miszczak

2. Obtained diplomas and degrees

- Doctoral diploma defended in the discipline of computer science with honors on the 4th of July 2008 in front of the Scientific Council of the Institute of Theoretical and Applied Informatics, Polish Academy of Sciences in Gliwice.
- Master's degree in physics with specialization in the field of theoretical physics and quantum computing defended on the 7th of May 2003 at the Faculty of Mathematics, Physics and Chemistry at the University of Silesia in Katowice.

3. Previous employment in scientific institutions

- **Since 10/2001** Institute of Theoretical and Applied nformatics. From 10/2001 to 05/2003 as a programmer, from 05/2003 to 07/2008 as an assistant, from 08/2008 as an asisstant professor.
- **10/2008–12/2008** Masaryk University, Brno, Czech Republic. Postdoctoral research associate at the position of assistant professor in the group of prof. Josef Gruska at the Department of Computer Science.
- **10/2004–09/2005** University of Silesia in Katowice. Research and teaching assistant in the Department of Theoretical Physics at the Faculty of Mathematics, Physics and Chemistry.

4. Indication of the scientific achievement

a) Title of the scientific achievement

Modelling of quantum informatics systems with the use of quantum programming languages and symbolic computation

b) author, title of publication, year of publication, name of publisher

Scientific achievement consists of a monograph published in an international publishing house

[A] J.A. Miszczak, *High-level structures for quantum computing*, Morgan and Claypol Publishers, San Rafael, California, U.S.A., May 2012, volume #6 of the series *Synthesis Lectures on Quantum Computing*, pp. 1-129. ISBN: 9781608458516

and monothematic series of four publications published in scientific journals included in the Journal Citation Report database

[B] J.A. Miszczak, *Models of quantum computation and quantum programming languages*, Bulletin of the Polish Academy of Sciences-Technical Sciences , Vol. 59, No. 3 (2011), pp. 305-324.
IF: 0,945

[C] J.A. Miszczak, *Singular value decomposition and matrix reorderings in quantum information theory*, International Journal of Modern Physics C, Vol. 22, No. 9 (2011), pp. 897-918.
IF: 1,005

[D] J.A. Miszczak, *Generating and using truly random quantum states in Mathematica*, Computer Physics Communications, Vol. 183, No. 1 (2012), pp. 118-124.
IF: 3,268

[E] J.A. Miszczak, *Employing online quantum random number generators for generating truly random quantum states in Mathematica*, Computer Physics Communications, Vol. 184 (2013), pp. 257–258.
IF: 3,268

c) discussion of the above scientific works and results together with a discussion of their possible applications

Introduction

The main result of the work presented in the scientific achievement is the development of methods for modelling objects used to describe information processing in quantum computing systems. Such a description depends on the type of system under consideration. In the most general case, one can consider in this context two types of quantum systems – closed systems and open systems.

Closed systems provide the idealization of physical systems, which does not take into account the impact of the environment on the process of information processing. The description of such systems uses the pure state formalism (elements of a finite-dimensional complex vector space), and the information processing is described in the language of quantum gates, which, from the geometric point of view, represent unitary rotations.

In the case of open systems, the influence of the environment on a quantum system used to process the information cannot be neglected. The state of the system is represented by the density operator (positive definite operator with trace 1), while the transformations of the states are described by quantum operations, *ie.* completely positive mappings preserving the trace. Many phenomena crucial for the analysis of quantum information processing, such as errors or interception of information, can be modelled as an interference from the environment. For this reason, the study of such systems is crucial for the technical realizations of quantum computing systems.

My works comprising the presented scientific achievement were focused on important issues that arise in the modelling of quantum information processing, both in closed and open systems. The results, presented in the publications listed in the achievement, concern the representation of quantum information processing in closed systems, modelling of quantum operations in open composite systems and the application of quantum sources of randomness in simulations of quantum states and operations.

The results described below were obtained mainly through the implementation of three research projects in which I performed the role of a manager. Two of them – the project IP2010 052270 *Analysis and modelling of local properties of quantum states and operations* and IP2011 036371 *Application of geometrical methods for the analysis of quantum states and operations* – have received funding from the Ministry of Science and Higher Education under the Iuventus Plus program for years 2011-2014. The third project – N N516 475440 *Application of quantum game theory in modelling of quantum information transmission* – received funding from the National Science Centre in 2011-2013. The work on the high-level description of quantum information processing has been also conduced in part during the research project N N519 442339 *Distributed environment for numerical analysis of the quantum information theory* conducted in 2010-2013 under the supervision of dr. inż. R. Winiarczyk.

High-level description of quantum information processing

The first research problem, which was investigated in the publications presented in the scientific achievement, concerns the abstract description of quantum information processing. My work in this area was conducted as the continuation of the results obtained during my work on the doctorate thesis. The motivation for this research was the close connection between the formal representation of quantum computing and the mathematical formalism used in quantum mechanics. The issue arises in the situation when one needs to operate on data structures, which do not have a direct representation in the form of quantum states. This can be illustrated by using an example of quantum sorting algorithm, when one needs to operate on numerical data types and implement arithmetic operations on these types.

The problem of the use of abstract models to describe quantum information processing work was investigated in work [B]. I presented there the main constraints that arise in the design of quantum high-level programming languages. It turns out that both the quantum imperative and quantum functional languages do not provide the level of abstraction needed in order to create quantum programs without referencing to the internal representation of the state as a vector in the complex vector space. This is a major obstacle when it is necessary to operate on data that do not have direct representation in the form of state vectors. In addition, the existing languages do not provide the syntax elements necessary for the implementation of quantum protocols and algorithms based on mixed states. In particular, they do not allow the manipulation of mixed states in composite systems, which is necessary in the description of the manipulation of quantum entanglement in open quantum systems.

In paper [B] the quantum model of high-level programming language based on the model of quantum random access memory machine (QRAM) was also presented. This work was developed in the monograph [A]. The results presented there provide a uniform specification of the most important models of quantum computation, allowing for a high-level description of quantum information processing.

The other contribution of the monograph [A] is the identification of the elements crucial for the design of quantum programming languages that allow the development of programs for quantum machines apart from the physical and mathematical representations of states and the evolution of states. Among these elements one can point out the ability to manipulate quantum abstract data types, the syntax allowing the use of conditional statements with logical conditions preset by the states of quantum registers and the ability to initialize the state of quantum machines with a specified probability distribution. These elements are crucial to improve the process of creating programs that use the potential of quantum machines in isolation from the physical and mathematical representations of states by providing abstraction layer between these representations and device-independent description of the algorithms

Description of quantum operations on composite quantum systems

The implementation of quantum information processing in physical systems requires the consideration of the external environment impact, which may result in the occurrence of errors and the outflow of information from the system. For this reason, in order to describe quantum protocols and algorithms it is necessary to use the formalism of mixed states, which are formally represented by density matrices.

Quantum information processing, understood as the time evolution of the density matrix, is described in this formalism by completely positive maps on the space of quantum states. The most important resource in quantum information processing is quantum entanglement that appears in the description of states of complex systems, both closed and open. It is therefore essential for quantum computing to understand the structure of completely positive mappings acting on composite open quantum systems.

One of the results obtained as a part of the presented achievement concerns the representation of the results of such mappings. Results concerning the methods of analysing quantum operations acting on composite systems presented in [C] are based on the Singular Value Decomposition. In this work the matrix representation of quantum operations on the systems with the structure of the tensor product of two separate systems was derived and generalized. This derivation generalizes to any unitary space with the structure of the tensor product of arbitrary number of subsystems.

The construction method for the matrix representation of quantum operations on complex systems described in [C] greatly simplifies the implementation of algorithms for the analysis of quantum states and operations. The obtained results were used to develop software based on the functional paradigm. This software allows the analysis of algebraic properties of quantum states and operations with the use of symbolic computation.

The method can also be used for the implementation of high-level quantum programming language providing mechanisms for operating on open systems. This allows overcoming one of the key constraints of the currently used quantum programming languages as described in [A].

The use of quantum sources of randomness

The last area of research undertaken in the works presented as the part of the achievement, is the development of methods for the use of quantum random number generators in simulations. The results obtained in this area are focused on the development of methods for the statistical analysis of quantum states and operations that allow the use of the sources of truly random numbers obtained using the principles of quantum mechanics.

Due to the complex structure of the space of quantum states and the space of quantum operations, in many cases it is essential to tackle the problems related to these structures with the use of simulation methods. Often in such cases, it is necessary to prepare the sample of random states or operations with a specific random properties.

The devices using the statistical nature of quantum objects to generate random numbers – quantum random number generators – are now one of the most important applications of the principles of quantum mechanics. They are increasingly implemented in technical systems and scientific applications requiring the delivery of high-quality random numbers.

In paper [D] a software package for harnessing Quantis quantum random number generator developed by ID Quantique SA is presented. This generator allows the acquisition of random data using a path selection uncertainty mechanism. The method presented in [D] allows using these data for the purpose of analysing quantum states and operations in the environment for symbolic computing. The developed methods were used to determine the local spectrum of density matrices and to examine the distribution of the average value for the fidelity of one-qubit states. Their performance was also tested in random number generation, assuming various usage scenarios for the generator.

Further work on the use of quantum randomness sources has been conducted in collaboration with PicoQuant GmbH and the Department of Physics, Humboldt University in Berlin. PicoQuant GmbH company is the manufacturer of the instruments used to build fast random number generator based on the nature of quantum phenomena. In [E] the generator based on HydraHarp 400 system from PicoQuant GmbH was used. This system provides Time Interval Analyzer (TIA) and Time-Correlated Single Photon Counting (TCSPC) and can be used to generate random numbers with maximal efficiency 150Mb/s.

The results obtained in the area of exploiting the quantum sources of randomness have been used to develop and implement effective methods of delivering high-quality random numbers in the simulation of physical phenomena. The research in this area was based on the results published in [D] and [E]. The results have been deployed by PicoQuant GmbH company to create simulation software based on Monte Carlo method.

Summary

The topics presented in the achievement focused on the development of new methods for the modelling of quantum information processing, in particular for the implementation of symbolic methods and quantum programming languages in this research areas. The results obtained in this regard include:

- identification of the limitations of existing quantum programming languages and the key elements for the development of quantum programs using abstract data types,
- unified description of the structure of quantum programming languages based on the model of quantum Turing machine and quantum random access machine,
- development of methods of constructing the matrix representation of quantum operations acting on the composite open systems,
- application of functional programming methods to develop prototype software to manipulate and analyse density matrices and quantum operations,
- application of quantum randomness sources for simulation studies of quantum information processing in closed and open systems,
- implementation of the efficient methods to enable the use of high-quality random numbers for simulations of physical phenomena.

5. Discussion of other research achievements[1]

a) Overview of achievements

Introduction

During the scientific work carried out after obtaining a doctoral degree, not listed in the achievements in section 4), I obtained the results associated with several aspects of quantum information processing. My work has been largely dedicated to the mathematical formalism of quantum states and operations discrimination used in quantum information theory. I have also studied the geometric properties of quantum states. To a lesser extent, I have also supported the continuation of research in the field of quantum game theory undertaken before obtaining a

[1]Publication numbers provided in accordance with the attachment *List of publications.*

doctorate. During the last year I focused on the problems of the safe transmission of quantum information and issues related to the information transfer in quantum networks.

The results described below, obtained after defending a doctoral degree, have been carried out in the scope of four research grants under my supervision. I have conducted the study of geometric properties of quantum states and operations as a manager of two research projects funded by the Polish Ministry of Science and Higher Education, funded in 2011-2014 under the Iuventus Plus program. My work on the theory of quantum games was supported by the Polish National Science Centre under grant N N516 475440 *Application of quantum game theory in modelling of quantum information transmission*, where I am currently a project manager. This subject is also continued in the framework of the Polish National Science Centre grant N N516 475440 *Quantum games and their implementation*, which is implemented at the University of Silesia in Katowice under the supervision of prof. dr. hab. J. Sładkowskiego and in which I am the main contractor.

In the period after obtaining my doctorate I have also participated as a main contractor or a contractor in four grants funded by the National Science Centre and as a contractor in a European Grant founded under the 7th Framework Programme.

Properties of quantum states and operations

The results I have obtained in the area of the foundations of quantum information theory and quantum mechanics concerned the properties of quantum fidelity, the application of these properties for the problem of state discrimination, analysing the spaces with the tensor product structure and the application of the properties of the space of quantum states in quantum information theory.

In [16] I applied the von Neumann trace inequality for the product of singular values to obtain the bound for the local discrimination of quantum mixed states. This bound can be used to evaluate the performance of quantum protocols, which are based on the assumption that communicating parties can only implement their actions on the local subspaces, representing subsystems in their possession. I presented my results on two international conferences devoted to quantum information theory – in form of a talk and a poster.

My subsequent research in the area of mathematical foundations of quantum informatics concerned the bounds for quantum fidelity. In [14] I co-authored a proof for the bound for quantum fidelity provided in terms of new quantity – namely the superfidelity. This bound was used to construct a quantum circuit, which can be used to estimate quantum fidelity between two quantum mixed states using an optical setup. Superfidelity was subsequently used in [15] to provide the bounds for the distinguishability of quantum states. These results were further developed in [11], where my main contribution was the construction of a quantum circuit for distinguishing quantum operations using laboratory setup. Superfidelity was also used to define a metric on the space of quantum states and to develop a method of generating random quantum states with probability induced by this metric [6]. I presented the results concerning the bounds for quantum fidelity in the form of posters during two international conferences and in the form of two talks during my research visits to international research groups working in the filed of quantum information theory.

In the area of application of geometrical methods for investigating the properties of quantum states I worked on the mathematical properties of the states space with the tensor product structure. My results in this scope were published in two papers. In [10] I introduced a notion of *product numerical range* and provided its basic properties, and in [13] I used this notion to redefine various problems in quantum information theory. I presented the results from this area as talks during my three research visits to international research groups working in quantum information theory.

Further development of the notion of product numerical range were presented in my papers [3] and [9] devoted to the measure defined as a probability distribution on the numerical range of a matrix. This distribution is induced by the Fubini-Study metric on complex projective space, *ie.* the measure which generates the unique uniform distribution on the space of pure quantum states. As the numerical measure defined in such manner reflects the structure of the space of quantum states analogously to the process of light absorption in a continuous medium, in my papers it was refered to as *numerical shadow*.

Quantum game theory

In the area of quantum game theory I worked on the influence of the environment on the execution of quantum games. My research in this scope included the investigation of the theoretical models of quantum noise and the influence of the hidden dimensions on the realization of quantum games in physical setup.

In [17] I discussed the influence of quantum errors on the quantum game based on an entangled state shared by all players. The results in this area are important for the physical realization of quantum games. The obtained results allow the description of a dependence of the payoff characteristics on the type of noise which is present in the communication channel.

My recent research in the area of quantum game theory concerned the influence of unknown degrees of freedom on the realization of quantum games in spin chain systems. In [4] I created a model, in which one of the players has the ability to operate on an extended subsystem and, thanks to this, is allowed to choose from the richer space of allowed operations. The investigated relation is analogous to the situation where only one of the players knows about the quantum nature of the device used to play the game and by using this knowledge can the implement strategies inaccessible to the second (classical) player. The obtained results allowed determining the conditions for the physical realization of the quantum game on a spin chain, which allow harnessing the discussed advantage.

Quantum communication

During the last year I conducted the research on the transmission of quantum information. In this area, I published the results on the possibility of increasing the security of quantum direct communication protocol.

In [2] I proved that by increasing the number of bases used in the control mode of the quantum *ping-pong* protocol for direct secure communication, it is possible to increase the probability of eavesdropping detection. Results published in this paper include the bounds for this probability. They are crucial for the technical implementation of quantum information processing, as they allow for the precise security analysis of the discussed protocol.

Currently I continue my research in the area of secure direct quantum communication and modelling of quantum networks as as a supervisor of the Polish National Science Centre project UMO-2011/03/D/ST6/00413 *Methods of development, modelling and analysis of quantum internetworking protocols*. One of the goals of this project is to develop a team of young researchers working on the problems of quantum internetworks in the Institute of Theoretical and Applied Informatics, Polish Academy of Sciences

b) Discussion of popularization and teaching activities

Popularization activities

My main popularization activities were concentrated on the administration and editing of the Quantiki.org project developed in cooperation with the Centre for Quantum Technologies operating on the National University of Singapore.

The project was created for the purpose of dissemination of the recent results in the area of quantum information processing. In 2010 it was extended with the ability to publish information about groups working in quantum information theory and with the platform for supporting scientific mobility. Project Quantiki.org is currently the largest international project for scientists working in the area of quantum information processing.

My other branch of popularization activities was conducted in years 2006-2011 as an WWW Open Directory editor. I was responsible for supervision of submissions and entries in the categories *Theoretical Computer Science*, and, in particular, in the category *Quantum Information*.

Teaching activities

I gained teaching experience during my work as a teaching assistant at the University of Silesia in Katowice and Silesian University of Technology in Gliwice.

In the years 2003-2004 I was responsible for teaching the basics of operating systems and the basics of numerical methods at the Department of Physics, Mathematics and Chemistry at the University of Silesia in Katowice.

In 2006 I worked as a trainer at the coaching company Demo operating under the auspices of the Higher School of Information Technology in Katowice. My responsibilities were teaching of Linux operating system administration, web application programming and preparation of multimedia presentations.

W 2010 I participated in the *Modern management tools in business* project executed at the Faculty of Organisation and Management of the Silesian University of Technology. I was responsible for the preparation and execution of the laboratory devoted to the use of open source software in a company.

From 2004 to 2007 I participated in the actions organized by the Silesian branch of the Polish Linux Users Gropup. In the scope of my actions I presented talks – during conferences Jesień Linuksowa 2004 and Pingwinaria 2005 – about the utilization of open source software in scientific work and functional text processing. In 2007 I co-organized a series of lectures, presented at the Faculty of Automatic Control, Electronics and Computer Science, devoted to the modern programming tools based on the open source model.

In the scope of my teaching activities, I co-supervised a master's thesis on the translation of quantum programming languages. The results obtained in this thesis were published in [23].

....

Jarosław A. Miszczak