RESEARCH CENTRE

Inria Saclay Centre at Université Paris-Saclay

IN PARTNERSHIP WITH:

Université Paris-Saclay

2023

ACTIVITY REPORT

Project-Team

QUACS

Quantum Computation Structures

IN COLLABORATION WITH: Laboratoire de Méthodes Formelles

DOMAIN

Algorithmics, Programming, Software and Architecture

THEME

Proofs and Verification

Inria

Contents

Project-Team QUACS

Creation of the Project-Team: 2021 December 01

Keywords

Computer sciences and digital sciences

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- A2.4. – Formal method for verification, reliability, certification
- A2.4.1. – Analysis
- A2.4.3. – Proofs
- A6.5. – Mathematical modeling for physical sciences
- A7.1.4. – Quantum algorithms
- A7.2.3. – Interactive Theorem Proving
- A8. – Mathematics of computing
- A8.6. – Information theory

Other research topics and application domains

- B5.11. – Quantum systems

1 Team members, visitors, external collaborators

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- Vladimir Zamdzhiev [INRIA, ISFP]

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- Shane Mansfield [Quandela]
- Simon Perdrix [INRIA]
- Zeno Toffano [CENTRALE]

2 Overall objectives

Quantum information processing is one of the rising forces of the information era. Encoding information within quantum systems and manipulating them promises to lead to great advantages, with three main application domains: quantum cryptography, quantum simulation, and quantum algorithmics. To understand its strengths and limits, we take a transversal stance and seek to capture which resources are granted to us by nature, at the fundamental level, for the sake of computing (e.g. quantum and spatial parallelism). We do so by abstracting away physics' ability to compute, into formal models of quantum computation (e.g. quantum automata and graph rewriting models). We then verbalize its main structures as quantum programming languages (e.g. quantum lambda-calculus, process algebra). Actually, the process goes both ways, when developments in quantum programming languages lead to the discovery of new structures which may or may not be compilable into formal models of quantum computation, raising the sometimes fascinating question of the physicality of these resources.

3 Research program

3.1 Quantum simulation

One usually distinguishes three main fields of applications of Quantum Computing: quantum cryptography (short-term), quantum simulation (mid-term), quantum algorithmic (long-term). Quantum simulation then divides into two subfields: continuous-time quantum simulation, which is very physicky and consists of ad hoc emulation of one Hamiltonian by another, and discrete-time quantum simulation, which is much closer to quantum algorithmic: this is where we stand. In particular, we focus on the provision of a quantum-circuit description of the dynamics of fundamental particles. In particular, as we design these quantum simulation schemes, our focus is on retaining the symmetries of the simulated model. This is both a matter of efficiency and correctness. For instance, our discretizations have a maximum speed of propagation of the information, which coincides with the speed of light in the simulated system, as a first step towards retaining Lorentz symmetry. Similarly, our discretizations exhibit the gauge symmetries that motivate the different fundamental particles. The long term goal of this program is to provide a satisfactory quantum-circuit descriptions of the whole standard model of particle physics.

3.2 Semantics and Programming

In the research program on Semantics, the QuaCS team is working on developing mathematical methods and tools that formulate the precise meaning and behavior of (quantum) systems, processes, type systems and programming languages, other formal languages and computational models. This includes, but is not limited, to the following:

- Operational semantics: a mathematically precise description of the dynamics of quantum programs and other computational models (e.g., the small-step semantics of quantum lambda calculi, token-machine semantics of quantum diagrammatic calculi).

- Mathematical and denotational semantics: a mathematical interpretation of a quantum programming language, process theory, diagrammatic calculus, etc., which is always expected to be sound and often expected to be adequate or complete.

This line of research is focused on identifying fundamental connections between the static specification (e.g. syntax) of quantum languages, their dynamic behavior (e.g. operational semantics) and their mathematical interpretation (e.g. denotational semantics) with the intention of developing each of these components further.

3.3 Graphical languages and optimization for quantum computation

The QuaCS team is involved in the development and study of graphical calculi such as quanctum circuits, ZX-, ZW-, ZH-calculi, but also languages for linear optics, such as the LOv-calculus. These languages are supposed to represent particular features of quantum computing, and hence are designed with a particular semantics in mind. A question of interest in the field is that of completeness with respect to that semantics : the ability to graphically turn any two equivalent diagrams into one another, making it possible to entirely reason within the language. The team is interested in the structure quantum operators have, that can be exhibited by the graphical approach, and depending on the model of computation at hand. It then becomes possible to study the links between the graphical languages, and hence, between the different models of computation. Recently, some focus has been put in the use of graphical languages for the study of indefinite causal orders, a extension to the usual quantum computation model, where not only data is quantum, but also the control flow of the program, which is allowed by the theory but still not well understood.

4 Application domains

4.1 Quantum simulation

Feynman's invention of Quantum Computing really came out of a frustration: that of seeing classical computers take such a long time to simulate quantum systems. His intuition was that «quantum computers» would do a better job at simulating quantum systems. There is not the slightest doubt indeed that quantum simulation will have major outcomes for society. Thinking about it, most of the objects that surround us (cars, computers, furniture...) are designed on computers, thanks to the fact that we can prototype and simulate them on classical computers. That is, up to a certain scale. Below that we are left in the dark as quantum effects come into play, yielding an exponential blow up of the cost or simulation. For now. But, the day we will have good quantum computers and good quantum simulation algorithms to run upon them, we will be able to simulate these particles, atoms, molecules and the way they interact. Consequently we will be able to design specific-purpose molecules, materials, nanotechnologies, with applications in chemistry, biochemistry, electronics, mechanics. At QuaCS we focus on the bottom layer: the quantum-simulation algorithms for fundamental particles. After all, to be able to efficiently simulate fundamental interactions is to be able to simulate virtually everything, from first principles. An added bonus of this strand of research is that usually when we express some physics as a quantum algorithm, it becomes way simpler, more explanatory.

4.2 Semantics and Programming

This line of research can reveal interesting connections between mathematical structures, computational models, type systems and other formal languages. Ideally, one endpoint of such a connection can be used to influence the design and development of the other endpoint, because these connections can allow us to improve our understanding of the different aspects of the (quantum) systems and computational models under consideration.

For instance, monads in category theory were the inspiration for introducing monads in programming languages. Another example includes categorical quantum mechanics which lead to the development of the ZX-calculus along with other useful tools, such as PyZX/QuiZX, which may be used for optimisation of quantum circuits and classical simulation of quantum processes.

4.3 Graphical languages and optimization for quantum computation

One of the main features of graphical languages is that they can be made abstract enough to remove unnecessary clutter and ease reasoning on quantum operators. This has several consequences : They are rather intuitive to work with, while at the same time being completely formal They can provide an intermediate representation of quantum programs, with enough abstraction to reason about and modify the program during compilation. The most illustrative example of such modification is circuit optimisation, where the goal is to reduce the number of "expensive" quantum gates in the circuit, which can be achieved by turning the circuit into a ZX-diagram, then using its equational theory to perform the reduction. Together with the simplification heuristic, it is possible to exploit this "uncluttering" effect to perform more efficient classical simulation of quantum programs. It can be exploited to perform automated verification of quantum programs.

5 New software, platforms, open data

5.1 New platforms

5.1.1 Perceval: A Software Platform for Discrete Variable Photonic Quantum Computing

Participants: Benoît Valiron, Nicolas Heurtel, Shane Mansfield.

[6]

We introduce Perceval , an open-source software platform for simulating and interfacing with discrete-variable photonic quantum computers, and describe its main features and components. Its Python front-end allows photonic circuits to be composed from basic photonic building blocks like photon sources, beam splitters, phase-shifters and detectors. A variety of computational back-ends are available and optimised for different use-cases. These use state-of-the-art simulation techniques covering both weak simulation, or sampling, and strong simulation. We give examples of Perceval in action by reproducing a variety of photonic experiments and simulating photonic implementations of a range of quantum algorithms, from Grover's and Shor's to examples of quantum machine learning. Perceval is intended to be a useful toolkit for experimentalists wishing to easily model, design, simulate, or optimise a discrete-variable photonic experiment, for theoreticians wishing to design algorithms and applications for discrete-variable photonic quantum computing platforms, and for application designers wishing to evaluate algorithms on available state-of-the-art photonic quantum computers.

6 New results

6.1 Completeness of Sum-Over-Paths for Toffoli-Hadamard and the Dyadic Fragments of Quantum Computation

Participants: Renaud Vilmart.

[16]

We consider the Toffoli-Hadamard fragment of quantum computing (one of the simplest universal fragment), in the setting of "Sum- Over-paths", a symbolic approach to efficiently representing quantum processes, used for specification and verification, e.g. in CEA's Qbrick tool. We show that a simple set of equations makes the framework complete. We then extend this result to all dyadic fragments of quantum computing (used e.g. in the QFT in Sho'r algorithm). [cite] (associated special issue paper under reviewing).

6.2 Compositionality of Planar Perfect Matchings

Participants: Renaud Vilmart, Titouan Carette.

[10]

We show that graphical language ZW-calculus has tight links with counting perfect matchings in graphs. From the equational theory of ZW, we were able to reprove Kasteleyn's result which is that the counting problem becomes polynomial when the graph is planar. Our proof is purely graphical and very different from Kasteleyn's. It highlights an efficiently simulable fragment of ZW, something of interest for optimisation and classical simulation, paths that we are currently exploring.

6.3 Complete Graphical Language for Hermiticity-Preserving Superoperators

Participants: Renaud Vilmart, Titouan Carette, Timothée Hoffreumon.

[8]

We introduce the first complete universal graphical language for Hermiticity-preserving superoperators. Antiunitarity, and negativity in the density matrix formalism, although non physical, is a useful tool for physicists, and is now useable in a ZX-like graphical language.

6.4 A Complete Equational Theory for Quantum Circuit

Participants: Alexandre Clement, Nicolas Heurtel, Shane Mansfield, Simon Perdrix.

[14, 13]

We introduce the first complete equational theory for quantum circuits. More precisely, we introduce a set of circuit equations that we prove to be sound and complete: two circuits represent the same unitary map if and only if they can be transformed one into the other using the equations. The proof is based on the properties of multi-controlled gates – that are defined using elementary gates – together with an encoding of quantum circuits into linear optical circuits, which have been proved to have a complete axiomatisation.

6.5 Quantum Circuit Completeness: Extensions and Simplifications

Participants: Alexandre Clement, Renaud Vilmart.

[12]

The first completeness result for arbitrary quantum circuits, involved a few non-intuitive and hard to use equations. We simplify the equational thoery here, first for the most constrained case of unitary circuits, then simplify it further in settings that allow ancillary qubits.

6.6 On new PageRank computation methods using quantum computing

Participants: Théodore Chapuis-Chkaiban, Zeno Toffano, Benoît Valiron.

[4]

In this paper we propose several new quantum computation algorithms as an original contribution to the domain of PageRank algorithm theory, Spectral Graph Theory and Quantum Signal Processing. We first propose an application to PageRank of the HHL quantum algorithm for linear equation systems. We then introduce one of the first Quantum-Based Algorithms to perform a directed Graph Fourier Transform with a low gate complexity. After proposing a generalized PageRank formulation, based on ideas stemming from Spectral Graph Theory, we show how our quantum directed graph Fourier Transform can be applied to compute our generalized version of the PageRank.

6.7 Adjustable-depth quantum circuit for position-dependent coin operators of discrete-time quantum walks

Participants: Ugo Nzongani, Pablo Arnault.

[20]

Discrete-time quantum walks with position-dependent coin operators have numerous applications. For a position dependence that is sufficiently smooth, it has been provided in an approximate quantum-circuit implementation of the coin operator that is efficient. If we want the quantum-circuit implementation to be exact (e.g., either, in the case of a smooth position dependence, to have a perfect precision, or in order to treat a non-smooth position dependence), but the depth of the circuit not to scale exponentially, then we can use the linear-depth circuit of the previous reference, which achieves a depth that is linear at the cost of introducing an exponential number of ancillas. In this paper, we provide an adjustable-depth quantum circuit for the exact implementation of the position-dependent coin operator. This adjustable-depth circuit consists in (i) applying in parallel, with a linear-depth circuit, only certain packs of coin operators (rather than all of them as in the original linear-depth circuit), each pack contributing linearly to the depth, and in (ii) applying sequentially these packs, which contributes exponentially to the depth.

6.8 Central Submonads and Notions of Computation: Soundness, Completeness and Internal Languages

Participants: Titouan Carette, Louis Lemonnier, Vladimir Zamdzhiev.

[9]

Monads in category theory are algebraic structures that can be used to model computational effects in programming languages. We show how the notion of "centre", and more generally "centrality", i.e. the property for an effect to commute with all other effects, may be formulated for strong monads acting on symmetric monoidal categories. We identify three equivalent conditions which characterise the existence of the centre of a strong monad (some of which relate it to the premonoidal centre of Power and Robinson) and we show that every strong monad on many well-known naturally occurring categories does admit a centre, thereby showing that this new notion is ubiquitous. More generally, we study central submonads, which are necessarily commutative, just like the centre of a strong monad. We provide a computational interpretation by formulating equational theories of lambda calculi equipped with central submonads, we describe categorical models for these theories and prove soundness, completeness and internal language results for our semantics.

6.9 Type-safe Quantum Programming in Idris

Participants: Vladimir Zamdzhiev.

[15]

Variational Quantum Algorithms are hybrid classical-quantum algorithms where classical and quantum computation work in tandem to solve computational problems. These algorithms create interesting challenges for the design of suitable programming languages. In this paper we introduce Qimaera, which is a set of libraries for the Idris 2 programming language that enable the programmer to implement hybrid classical-quantum algorithms where the full power of the elegant Idris language works in synchrony with quantum programming primitives. The two key ingredients of Idris that make this possible are (1) dependent types which allow us to implement unitary quantum operations; and (2) linearity which allows us to enforce fine-grained control over the execution of quantum operations so that we may detect and reject many physically inadmissible programs. We also show that Qimaera is suitable for variational quantum programming by providing implementations of two prominent variational quantum algorithms – QAOA and VQE. *Remark: most of the work was done in 2021 when Vladimir was a member of the MOCQUA team.*

6.10 A quantum simulation algorithm for 3+1 QED

Participants: Pablo Arrighi.

[5]

We achieved the first quantum cellular automaton model for real-life interacting particles, namely electrons and photons, a.k.a 3+1 quantum electrodynamics. We motivated our construction by proposing a discrete version of a fundamental symmetry of Physics, namely gauge symmetry, which turns out to be reminiscent of fault-tolerance in Computer Science. This opens the way for natively discrete formulations of quantum field theories, otherwise renowned for their ill-definedness.

6.11 Addressable Quantum Gates

Participants: Pablo Arrighi, Marin Costes, Benoît Valiron.

[3]

We extended the circuit model of quantum computation so that the wiring between gates is soft-coded within registers inside the gates. The addresses in these registers can be manipulated and put into superpositions. This aims at capturing indefinite causal orders and making their geometrical layout explicit: we expressed the quantum switch and the polarizing beam-splitter within the model. In this context, the names used as addresses should not matter beyond the wiring they describe; i.e., quantum evolutions should commute with “renamings.” We have shown that these quantum evolutions can still act non-trivially upon the names.

6.12 Graph Subshifts

Participants: Pablo Arrighi.

[7]

We proposed a definition of graph subshifts of finite type. These are sets of graphs that are defined by forbidding finitely many local patterns. This is interesting because it is a natural generalisation of both 1/ the notions of subshifts of finite type from classical symbolic dynamics and 2/ finitely presented groups from combinatorial group theory. In this paper, we focussed on the question whether such local conditions can rigidify the shape of the graph.

6.13 Measurement events relative to temporal quantum reference frames

Participants: Esteban Castro.

Publication

We compare two known consistent models for the emergence of time evolution as correlations between a system and a quantum clock. The two models give the same predictions when the clocks are ideal but differ radically in the nonideal case. We clarify the operational interpretation of each, explaining the discrepancy.

6.14 Graphical Language for Tensor and Coproduct

Participants: Kostia Chardonnet, Marc De Visme, Renaud Vilmart, Benoît Valiron.

We refined previous works on the "Many-World Calculus" (MWC), a graphical language designed to expand quantum circuits to fully capture quantum supperposition, into the "Tensor-Plus Calculus" (TPC). The TPC is a graphical language that bridge the gap between languages like quantum circuits or the ZX-calculus, where two wires in parallel corresponds to a pair of data, and languages for quantum linear optic, where two wires in parallel correspond to two alternative paths that photons can take. Contrary to the MWC, the TPC does not rely on an additional structure of "worlds": the language is minimalistic, the additional structure is fully implicit and can be deduced by the way the functions are plugged into one another. We provide a complete equational theory for this language, and a clear categorical presentation.

7 Bilateral contracts and grants with industry

Quandela

Participants: Benoît Valiron, Pablo Arrighi, Nicolas Heurtel.

In the context of a PhD funded by CIFRE, QuaCS and Quandela are building a collaboration on the study of quantum linear optics. The approach is both theoretical –with the development of a formal language for reasoning on optical circuits, and practical, targeted towards simulation.

8 Partnerships and cooperations

8.1 International initiatives

QISS (John Templeton grant)

Participants: Pablo Arnault, Pablo Arrighi, Esteban Castro, Marc de Visme, Benoit Valiron, Renaud Vilmart, Vladimir Zamdzhiev.

Title: The Quantum Information Structure of Spacetime

Partner Institutions:

- Institute for Quantum Optics and Quantum Information, Vienna
- Rotman Institute for Philosophy, Western University
- Center for Theoretical Physics, Aix-Marseille University
- Quantum Group and Clarendon Laboratory, University of Oxford
- Perimeter Institute
- University of Paris-Saclay, Quantum Computation Structures group
- Quantum Information and Computation Initiative, HKU
- Okinawa Institute of Science and Technology
- University of California Santa Barbara, Physics dpt
- Center for Quantum Information and Communication, Brussels
- Quantum Information Laboratory, Rome La Sapienza University
- Penn State University, Institute for Gravitation and the Cosmos
- Center for Mathematical Sciences, UNAM
- Bard College, New York
- ETH Zürich
- The University of Melbourne
- Royal Holloway, University of London
- Universität Bonn

Date: 2023-2026

Additionnal info:

QISS aims to found the physics of quantum spacetime on an information theoretical basis, bring within reach empirical access to quantum gravity phenomenology leveraging rapidly advancing quantum technologies, and promote interactions between physicists and philosophers. The broader scope of the consortium is to establish a long term research program that brings together the represented communities, towards the common goal of unravelling the Quantum Information Structure of Gravity.
QISS was initially conceived from interactions between the Quantum Gravity Group of the Center for Theoretical Physics and the Laboratory of Informatics and Systems at the University of Aix-Marseille, France. It was concretely conceived as an international collaborative project in fundamental research during an exploratory meeting held at the Slovak Academy of Sciences, Bratislava, in November 2018. QISS took off by a generous three year first phase grant by the John Templeton Foundation awarded to the Center for Space, Time and the Quantum that administers the project. A second phase grant was subsequently awarded to the QISS project by JTF.

8.2 European initiatives

HPCQS (EuroHPC project)

Participants: Pablo Arnault, Pablo Arrighi, Esteban Castro, Marc de Visme, Benoit Valiron, Renaud Vilmart, Vladimir Zamdzhiev.

Title: High Performance Computer – Quantum Simulator hybrid

Partner Institution:

- Jülich Supercomputing Centre (JSC), Germany
- ParTec, Germany
- Commissariat à l'énergie atomique et aux énergies alternatives (CEA), France
- Grand équipement national de calcul intensif (GENCI), France
- Barcelona Supercomputing Centre (BSC), Spain
- CINECA - Consorzio Interuniversitario, Italy
- Irish Centre for High End Computing (ICHEC), Ireland
- BULL SAS (ATOS), France
- FlySight, Italy
- ParityQC, France
- Sorbonne Université, France
- CentraleSupelec, France
- INRIA, France
- Consiglio Nazionale delle Ricerche (CNR), Italy
- The University of Innsbruck, Austria
- Fraunhofer IAF, Germany
- Eurice - European Research and Project Office GmbH, Germany

Date: 2021-2024

Additionnal info:

The project HPCQS aims to integrate two quantum simulators, each controlling about 100+ quantum bits (qubits) in two already existing supercomputers:

- the supercomputer Joliot Curie of GENCI, the French national HPC organisation, located in France;
- the JUWELS supercomputer of the Jülich Supercomputing Centre (JSC), located in Germany.

In doing so, HPCQS will become an incubator for quantum-HPC hybrid computing that is unique in the world.

The seamless integration of quantum hardware with classical computing resources will enable research entities and industries to exploit new quantum technologies and find solutions to complex challenges in physics, chemistry and numerical optimisation with practical applications, for example, to materials and drug design, logistics and transportation.

HPCQS will develop the programming platform for the quantum simulator and offer cloud-based access to users and researchers. The project will build an open and evolutionary infrastructure that aims at expanding in the future by including a diversity of quantum computing platforms at different technology readiness levels in an HPC system and by allowing the integration of other European partners. The HPCQS infrastructure is a first step towards a European quantum computing infrastructure in synergy with the ongoing European efforts to establish a world-leading HPC infrastructure.

8.3 National initiatives

EPiQ (PEPR Quantique)

Participants: Pablo Arnault, Pablo Arrighi, Esteban Castro, Marc de Visme, Benoit Valiron, Renaud Vilmart, Vladimir Zamdzhiev.

Title: Etude de la pile quantique : Algorithmes, modèles de calcul et simulation pour l'informatique quantique

Partner Institutions:
- INRIA, France
- CNRS, France
- CEA, France

Date: 2022-2027

Additionnal info:

The French quantum computing research community has always been at the forefront of international research. It thus provides the foundations for an ambitious strategy aiming at: (1) Understanding the advantages and limits of quantum computing via both quantum complexity research and the discovery and enhancement of algorithms (2) Defining the framework for quantum computation using high-level languages, comparison of computational models as well as using their relations for program optimization (3) Develop simulation tools to anticipate the performances of algorithms on noisy quantum machines. Algorithmic aspects are key in the field of quantum computing which witnesses a tremendous intensification of research efforts worldwide. Indeed, in addition to determining the design and the construction of hardware quantum processors, algorithms also constitute the interface through which users will solve their practical use cases leading to potential economic gain. Based on the outstanding French position, our project aims at developing algorithmic techniques for both noisy quantum machines (NISQ) and fault-tolerant ones so as to facilate their practical implementation. To this end, a first Work Package (WP) is dedicated to algorithmic techniques, a second one focuses on computational models and languages so as to facilitate the programming of quantum machines and to optimize the code execution steps. Lastly, the third WP aims at developing the simulation techniques of quantum computers.

EQIP (Inria challenge project)

Participants: Pablo Arnault, Pablo Arrighi, Esteban Castro, Marc de Visme, Benoit Valiron, Renaud Vilmart, Vladimir Zamdzhiev.

Title: Engineering for Quantum Information Processors

Partner Institution:
- INRIA, France

Date: 2021-2024

Additionnal info:

While the technological development that has led us from the abacus to today's supercomputers or even to the latest achievements of machine learning are quite spectacular, one should not forget that they all fit the very same model of computation, formalized by Turing in the 1930s, and therefore fall under the umbrella of classical computing. Quantum physics has played a major role in this story through the 1st quantum revolution which gave birth to the transistor, the laser and the micro-processor. Rather surprisingly, the impact of quantum physics on the theory of computation is very likely still in its infancy. There is little doubt that an unprecedented shift will occur in the decades to come and that an entirely new form of computing will be dominant in 50 years (and probably much sooner). This is the object of the 2nd quantum revolution which will harness the quantum properties of matter and light to process data much more efficiently than is possible by purely classical means. The scope of applications remains hard to delineate at this point but covers a large spectrum of human activities: simulation of quantum systems will be crucial to develop new medicine, help fighting climate change by developing better materials to store or transport energy, reducing CO2 emissions by developing efficient processes to capture CO2; quantum computing will also be instrumental to solve optimization problems intractable today. At the same time, quantum technologies will dramatically impact cryptography and requires to implement important changes right now.
If the first glimpse of this second quantum revolution can be traced back to visionaries like Feynman or Deutsch in the early 80s, the fields of quantum computation and quantum simulation really took off in the last decade or so. The long-term objective of this line of work is to build a large universal quantum computer and the main scientific challenges today are to identify potential approaches for scaling up the small quantum processors consisting of a few tens of qubits already available, to anticipate how to program these new machines, and to understand what new capabilities will become accessible once quantum computing becomes available.

TaQC (ANR)

Participants: Pablo Arnault, Pablo Arrighi, Esteban Castro, Marc de Visme, Benoit Valiron, Renaud Vilmart, Vladimir Zamdzhiev.

Title: Taming Quantum Causality

Partner Institutions:
- UPSaclay - LMF Université Paris-Saclay - Laboratoire Méthodes Formelles
- Inria Centre de Recherche Inria de Lyon - AT-LYS
- NEEL Institut Néel
- LARSIM Commissariat à l'énergie atomique et aux énergies alternatives

Date: 2023-2027

Additionnal info:

Quantum technologies provide advantages by exploiting non-classical resources, such as superposition or entanglement. Recently, it has been realized that one can obtain new advantages by exploiting causal structures that are inherently quantum. This quantum "causal indefiniteness" constitutes a novel resource and opens new perspectives in quantum information. Despite foundational progress and several experimental realizations, the concrete implications for quantum computing nevertheless remain poorly understood so far. In this project we will work to bridge this gap and to develop quantum causality as a new non-classical resource on par with superposition and entanglement.
To achieve this, we will develop three directions. (1) Firstly, we will develop a Generalised Probabilistic Theories approach to understand causal indefiniteness within a larger class of models. This will help

clarify which causally indefinite process are physical and what precise role is played by genuinely non-classical resources such as superposition and entanglement. (2) Secondly, we will go beyond the standard example of the "quantum switch" to study more concrete models of causally indefinite computation. In doing so, we will systematically explore the possible applications of causal indefiniteness and unveil the potential of causally indefinite computations. (3) Finally, we will use ZX-Calculus to harness the capabilities of causal indefiniteness at the compilation level. Using ZX-Calculus as a springboard towards programming causally indefinite computations will help us optimize the use of this new resource.
Together, these goals work towards our ultimate objective of finding the right arguments in the right language to give causal indefiniteness a unique place among the leading conceptual and empirical paradigms of quantum information.

HQI (National Quantum Plan project)

Participants: Pablo Arnault, Pablo Arrighi, Esteban Castro, Marc de Visme, Benoit Valiron, Renaud Vilmart, Vladimir Zamdzhiev.

Title: Hybrid HPC-Quantum platform and a research program

Partner Institutions:
- INRIA, France
- CNRS, France
- CEA, France
- GENCI, France
- France Universités, France
- ANR, France
- PIA4, France
- France Relance, France

Date: 2022-2027

Additionnal info:

In January 4th 2022, one year after the National Quantum Plan was announced by the French President, Neil Abroug, the national strategy coordinator, launched HQI: France Hybrid HPC-QC Initiative.

HQI is an integrated initiative. It combines a hybrid computing platform that couples several quantum processors with GENCI's Joliot-Curie supercomputer hosted at TGCC (CEA), and an academic and industrial research program with user enablement.

This HPC-QC hybridization is an innovative and unique initiative that will benefit from the renowned expertise of the CEA/TGCC (Très Grand Centre de Calcul) teams in infrastructure operation, security and support to the scientific community.

The HQI initiative aims at serving the needs of French and European, academic and industrial research scientists, who want to evaluate free of charge, on a public infrastructure, the potential of quantum computing for their applications and develop international collaborations to foster open research.

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Full Organisation of an International Conference

Participants: Vladimir Zamdzhiev, Benoît Valiron, Shane Mansfield, Augustin Vanrietvelde, Renaud Vilmart, Pablo Arrighi.

Quantum Physics and Logic (QPL) is an annual conference that brings together academic and industry researchers working on mathematical foundations of quantum computation, quantum physics, and related areas. It is one of the flagship conference for the topics of the QuaCS team. The main focus is on the use of algebraic and categorical structures, formal languages, type systems, semantic methods, as well as other mathematical and computer scientific techniques applicable to the study of physical systems, physical processes, and their composition. Work applying quantum-inspired techniques and structures to other fields (such as linguistics, artificial intelligence, and causality) is also welcome.

The 2023 edition of QPL happened in July 2023. It was hosted in Paris by Inria and Quandela. Shane Mansfield, Benoît Valiron, and Vladimir Zamdzhiev were PC and OC co-chairs. Additionally, Pablo Arrighi, Renaud Vilmart and Augustin Vanrietvelde were PC and OC members, and most members of the QuaCS teams were involved to some degree (reviewing paper, logistics, etc).

A record 152 submissions (excluding withdrawals and retractions) were considered for review by the PC. QPL 2023 had 54 accepted submissions in the non-proceedings track and 14 accepted submissions in the proceedings track. Most of the talks were presented during parallel sessions, but a selection of talks were presented during plenary sessions in the mornings. The program also had several poster sessions and one session dedicated to showcasing accepted programming tool submissions. There was also an industry session where industrial sponsors of QPL 2023 were given an opportunity to present their companies. The industry session consisted of two talks – one by Quandela (Diamond Sponsor) and one by Quantinuum (Gold Sponsor).

The QPL 2023 conference featured an award for Best Student Paper. Papers eligible for the award were those where all the authors are students at the time of submission. The PC decided to award the Best Student Paper award for QPL 2023 to Cole Comfort (Department of Computer Science, University of Oxford) for his paper "The Algebra for Stabilizer Codes".

9.1.2 Other scientific events

Member of the conference program committees

- Benoît Valiron for ESOP'24
- Vladimir Zamdzhiev for ACT'23

Reviewer

- Benoit Valiron for ESOP'24, WADT'23, PLDI'23
- Renaud Vilmart for ACT'23, FoSSaCS'23, LiCS'23, QPL'23

9.1.3 Journal

Member of the editorial boards

- Pablo Arrighi for TCS-C
- Benoît Valiron for LMCS (since summer 2023)

Reviewer - reviewing activities

- Pablo Arrighi for Physical Review A, Foundations of Physics
- Renaud Vilmart for Quantum, TQE
- Vladimir Zamdzhiev for Quantum

9.1.4 Invited talks

- Benoît Valiron for EDF-CEA-Inria summer school (), *From Programming Language to Low Level interfaces.*

9.1.5 Scientific expertise

- Benoît Valiron and Vladimir Zamdzhiev: members of the IFIP TC1/TC2 Working Group on Foundations of Quantum Computation ()

9.1.6 Research administration

- Renaud Vilmart took the supervision of Groupe de Travail Informatique Quantique (GT IQ), from GdR IM
- Benoît Valiron is the PI of WP2 of PEPR-EPIQ.
- Pablo Arrighi is the PI of the Paris-Saclay node of the QISS consortium.
- Pablo Arrighi and Benoît Valiron are Executive committee members of the Quantum center of Saclay.

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

Participants: Pablo Arnault.

- Foundations of Quantum Information in M1-MPRI and M1-QDCS.

Participants: Benoît Valiron.

- Various teaching at CentraleSupelec, for a total of 198h (equivalent TD).
- Introductory course on Quantum computation and Programming in M1-QDCS.
- Introductory course on Quantum computation and Programming in Arteq.

Participants: Renaud Vilmart.

- Computer science project in L2-InfoMaths.
- Initiation to functional programming in L2-InfoMaths.
- Advanced quantum computation and error correction in M2-QDCS.
- Elements of computer science for quantum technologies in Arteq.

Participants: Marc De Visme.

- Elements of computer science for quantum technologies in Arteq.

Participants: Vladimir Zamdzhiev.

- Introduction to Categories in M1-MPRI.
- Initiation to Research in M1-MPRI.
- Logique in L3-ENS Paris Saclay

9.2.2 Teaching administration

Participants: Pablo Arrighi, Esteban Castro.

- Pablo Arrighi is co-responsible for the M1 MPRI of the Faculty of Science of U, and co-responsible for the M1 & M2 QDCS of the Faculty of Science of U. Paris-Saclay. Both until September 2023
- Esteban Castro is co-responsible for the M1 & M2 QDCS of the Faculty of Science of U. Paris-Saclay, starting from September 2023

9.2.3 Supervision

- Benoît Valiron has co-supervised 4 PhD students in 2023: Kostia Chardonnet (defense in january 2023), Nicolas Heurtel, Louis Lemonier, and Jérome Ricciardi.
- Pablo Arrighi has co-supervised 6 PhD students in 2023: Kostia Chardonnet (defense in january 2023), Dogukan Bakircioglu, Octave Mestoudjian, Marin Costes, Nicolas Heurtel, and Louis Lemonnier.
- Vladimir Zamdzhiev has co-supervised 2 PhD stuendes in 2023: Kinnari Dave, and Louis Lemmonier.

9.2.4 Juries

- Pablo Arrighi was external examiner for the PhD thesis of Aurélien Emmanuel and Matteo Luigi.
- Pablo Arrighi was member of the permanent position recuitement comitties of the Chaire d'excellence AMU, of an assistant profesor position at Télécom Paris IPP, and of a permanent CRCN reseearcher position at Inria Alpes and at Inria Lyon.
- Pablo Arnault was reviewer for the PhD thesis of Andreu Angles-Castillo, Universidad de Valencia.

9.3 Popularization

9.3.1 Internal or external Inria responsibilities

- Renaud Vilmart was member of Inria Saclay's Conseil Scientifique
- Marc de Visme was member of LMF's Conseil Scientifique.
- Pablo Arrighi was elected council member at the UPSaclay Graduate school of Computer Science.

9.3.2 Interventions

Participants: Pablo Arrighi.

- *¿Cuál es la diferencia entre el pasado y el futuro ? Un modelo de juguete con flecha del tiempo demostrable sin hipótesis de pasado.*[1], Depatments of Physics and Computer Science, Universidad de Buenos Aires, November 2023 and Universidad de la República, Montevideo, November 2003.
- *Café de las Ciencias : Computadora cuántica, ¿la computadora definitiva ?*[2], Centro Cultural de la Ciencia (C3) of the Ministry of Sciences, Buenos Aires, November 2023.

10 Scientific production

10.1 Major publications

[1] A. Clément, N. Heurtel, S. Mansfield, S. Perdrix and B. Valiron. 'A Complete Equational Theory for Quantum Circuits'. In: *38th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS)*. 2023 38th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS). Boston, United States: IEEE, July 2023, pp. 1–13. DOI: 10.1109/LICS56636.2023.10175801. URL: https://hal.science/hal-03926757.

[2] N. Eon, G. D. Molfetta, G. Magnifico and P. Arrighi. 'A relativistic discrete spacetime formulation of 3+1 QED'. In: *Quantum* 7 (8th Nov. 2023), p. 1179. DOI: 10.22331/q-2023-11-08-1179. URL: https://hal.science/hal-03944082.

10.2 Publications of the year

International journals

[3] P. Arrighi, C. Cedzich, M. Costes, U. Rémond and B. Valiron. 'Addressable quantum gates'. In: *ACM Transactions on Quantum Computing* 4.3 (24th Apr. 2023), pp. 1–41. DOI: 10.1145/3581760. URL: https://hal.science/hal-03936367.

[4] T. Chapuis-Chkaiban, Z. Toffano and B. Valiron. 'On new PageRank computation methods using quantum computing'. In: *Quantum Information Processing* 22.3 (Mar. 2023), p. 138. DOI: 10.1007/s11128-023-03856-y. URL: https://centralesupelec.hal.science/hal-04056045.

[5] N. Eon, G. D. Molfetta, G. Magnifico and P. Arrighi. 'A relativistic discrete spacetime formulation of 3+1 QED'. In: *Quantum* 7 (8th Nov. 2023), p. 1179. DOI: 10.22331/q-2023-11-08-1179. URL: https://hal.science/hal-03944082.

[6] N. Heurtel, A. Fyrillas, G. D. Gliniasty, R. Le Bihan, S. Malherbe, M. Pailhas, E. Bertasi, B. Bourdoncle, P.-E. Emeriau, R. Mezher, L. Music, N. Belabas, B. Valiron, P. Senellart, S. Mansfield and J. Senellart. 'Perceval: A Software Platform for Discrete Variable Photonic Quantum Computing'. In: *Quantum* 7 (21st Feb. 2023), p. 931. DOI: 10.22331/q-2023-02-21-931. URL: https://hal.science/hal-03874624.

International peer-reviewed conferences

[7] P. Arrighi, A. Durbec and P. Guillon. 'Graph Subshifts'. In: *Unity of Logic and Computation*. 19th Conference on Computability in Europe, CiE 2023. Vol. 13967. Lecture Notes in Computer Science. Batumi, Georgia: Springer Nature Switzerland, 19th July 2023, pp. 261–274. DOI: 10.1007/978-3-031-36978-0_21. URL: https://hal.science/hal-04310695.

[1] Past or future : what's the difference ? A toy model provably featuring a time arrow without past hypothesis.
[2] Science coffee : Is the quantum computer the ultimate computer ?

[8] T. Carette, T. Hoffreumon, É. Larroque and R. Vilmart. 'Complete Graphical Language for Hermiticity-Preserving Superoperators'. In: 38th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS) 2023. Boston, United States, 9th Feb. 2023, pp. 1–22. DOI: 10.1109/LICS56636.2023.10175712. URL: https://hal.science/hal-04001823.

[9] T. Carette, L. Lemonnier and V. Zamdzhiev. 'Central Submonads and Notions of Computation: Soundness, Completeness and Internal Languages'. In: 2023 38th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS). Boston (MA), United States, 2023. DOI: 10.1109/LICS56636.2023.10175687. URL: https://hal.science/hal-03662565.

[10] T. Carette, E. Moutot, T. Perez and R. Vilmart. 'Compositionality of planar perfect matchings: A universal and complete fragment of ZW-calculus'. In: 50th International Colloquium on Automata, Languages, and Programming (ICALP 2023). Vol. 261. Paderborn, Germany, 17th Feb. 2023, 120:1–120:17. DOI: 10.4230/LIPIcs.ICALP.2023.120. URL: https://hal.science/hal-04002282.

[11] K. Chardonnet, A. Saurin and B. Valiron. 'A Curry-Howard Correspondence for Linear, Reversible Computation'. In: *31st EACSL Annual Conference on Computer Science Logic (CSL 2023)*. CSL 2023 - 31st EACSL Annual Conference on Computer Science Logic. Varsovie (Warsaw), Poland: Schloss Dagstuhl - Leibniz-Zentrum für Informatik, 2023. DOI: 10.4230/LIPIcs.CSL.2023.13. URL: https://hal.science/hal-04308283.

[12] A. Clément, N. Delorme, S. Perdrix and R. Vilmart. 'Quantum Circuit Completeness: Extensions and Simplifications'. In: International Conference on Computer Science Logic CSL 2024. Naples, Italy, Feb. 2024. URL: https://hal.science/hal-04016498.

[13] A. Clément, N. Heurtel, S. Mansfield, S. Perdrix and B. Valiron. 'A Complete Equational Theory for Quantum Circuits'. In: 18th Conference on the Theory of Quantum Computation, Communication and Cryptography (TQC 2023). Aveiro, Portugal, 24th July 2023. URL: https://hal.science/hal-04318291.

[14] A. Clément, N. Heurtel, S. Mansfield, S. Perdrix and B. Valiron. 'A Complete Equational Theory for Quantum Circuits'. In: *38th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS)*. 2023 38th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS). Boston, United States: IEEE, July 2023, pp. 1–13. DOI: 10.1109/LICS56636.2023.10175801. URL: https://hal.science/hal-03926757.

[15] L.-J. Dandy, E. Jeandel and V. Zamdzhiev. 'Type-safe Quantum Programming in Idris'. In: *Lecture Notes in Computer Science*. ESOP 2023 - European Symposium on Programming. Vol. LNCS-13990. Programming Languages and Systems. Paris, France: Springer, 17th Apr. 2023, pp. 507–534. DOI: 10.1007/978-3-031-30044-8_19. URL: https://inria.hal.science/hal-03519238.

[16] R. Vilmart. 'Completeness of Sum-Over-Paths for Toffoli-Hadamard and the Dyadic Fragments of Quantum Computation'. In: CSL 2023 - 31st EACSL Annual Conference on Computer Science Logic. Vol. 252. Warsaw, Poland, 11th Jan. 2023, 36:1–36:17. DOI: 10.4230/LIPIcs.CSL.2023.36. URL: https://hal.science/hal-03654438.

Scientific book chapters

[17] C. Chareton, S. Bardin, D. Lee, B. Valiron, R. Vilmart and Z. Xu. 'Formal Methods for Quantum Algorithms'. In: *Handbook of Formal Analysis and Verification in Cryptography*. 1. CRC Press, 1st Aug. 2023, pp. 319–422. DOI: 10.1201/9781003090052-7. URL: https://hal.science/hal-04311441.

Reports & preprints

[18] P. Arrighi, D. M. Giuseppe, I. Márquez-Martín and A. Pérez. *Dirac equation as a quantum walk over the honeycomb and triangular lattices*. June 2018. DOI: 10.1103/PhysRevA.97.062111. URL: https://amu.hal.science/hal-03594743.

[19] A. Clément, N. Delorme and S. Perdrix. *Minimal Equational Theories for Quantum Circuits*. 13th Nov. 2023. URL: https://hal.science/hal-04399210.

[20] U. Nzongani and P. Arnault. *Adjustable-depth quantum circuit for position-dependent coin operators of discrete-time quantum walks*. 16th Jan. 2024. URL: https://hal.science/hal-04396459.

[21] U. Nzongani, J. Zylberman, C.-E. Doncecchi, A. Pérez, F. Debbasch and P. Arnault. *Quantum circuits for discrete-time quantum walks with position-dependent coin operator*. 13th Jan. 2023. URL: https://hal.science/hal-03938358.