RESEARCH CENTRE

Inria Nancy - Grand Est Center

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2022

ACTIVITY REPORT

Project-Team

MOCQUA

Designing the Future of Computational Models

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

DOMAIN

Algorithmics, Programming, Software and Architecture

THEME

Security and Confidentiality

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Project-Team MOCQUA

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2 Overall objectives

The goal of the Mocqua team is to tackle challenges coming from the emergence of new or future computational models. The landscape of computational models has indeed changed drastically in the last few years: the complexity of digital systems is continually growing, which leads to the introduction of new paradigms, while new problems arise due to this larger scale (tolerance to faulty behaviors, asynchronicity) and constraints of the present world (energy limitations). In parallel, new models based on physical considerations have appeared. There is thus a real need to accompany these changes, and we intend to investigate these new models and try to solve their intrinsic problems by computational and algorithmic methods.

While the bit remains undeniably the building block of computer architecture and software, it is fundamental for the development of new paradigms to investigate computations and programs working with inputs that cannot be reduced to finite strings of 0's and 1's. Our team will focus on a few instances of this phenomenon: programs working with qubits (quantum computing), programs working with functions as inputs (higher-order computation) and programs working in infinite precision (real numbers, infinite sequences, streams, coinductive data, ...).

3 Research program

3.1 Quantum computing

While it can be argued that the quantum revolution has already happened in cryptography [47] or in optics [46], quantum computers are far from becoming a common commodity. This is despite the fact that many teams worldwide, both academic and industrial, are nowadays focusing much of their efforts on building quantum computers. Indeed the challenges ahead to reach practical, sizable and accurate quantum computers remain tremendous.

Today's quantum devices are small in scale and still very noisy and are therefore called NISQ devices (for Noisy Intermediate Scale Quantum). They all differ fundamentally on the hardware substrate, and it is quite hard to predict which solution will finally be adopted. While some effort is underway to understand and utilize the potential of these NISQ devices, scaling up and implementing fault-tolerant and quantum error correction schemes will eventually become crucial for the potential of quantum computing to be reached.

As these devices are developed and scale up, the importance of software to operate them and programming languages to program them will grow. The practical applications in sight will require tighter interactions within the quantum stack, which extends from hardware to algorithms. Given its recent emergence, the landscape of quantum programming languages is constantly evolving. Comparably to compiler design, the foundation of quantum software therefore relies on an intermediate representation that is suitable for manipulation, easy to produce from software and easily encodable into hardware. A graphical language now firmly established as the choice for this is the ZX-calculus.

Many research questions are now to be addressed. For instance, what are the correct formalism and approaches for quantum programming languages? How to develop practical, and useful algorithms? What role can graphical intermediate representations such as ZX-calculus play in interaction between compilers and hardware with different characteristics, like lattice surgery fault-tolerance or quantum optics? Which quantum error correcting codes and fault-tolerant schemes can make large scale quantum computing reachable?

3.2 Higher-order computing

While programs often operate on natural numbers or finite structures such as graphs or finite strings, they can also take functions as inputs. In that case, the program is said to perform higher-order computations, or to compute a higher-order functional. Functional programming or object-oriented programming are important paradigms allowing higher-order computations.

While the theory of computation is well developed for first-order programs, difficulties arise when dealing with higher-order programs. There are many non-equivalent ways of presenting inputs to such programs: an input function can be presented as a black-box, encoded in an infinite binary sequence, or sometimes by a finite description. Comparing those representations is an important problem. A particularly useful application of higher-order computations is to compute with infinite objects that can be represented by functions or symbolic sequences. The theory works well in many cases (to be precise, when these objects live in a topological space with a countable basis [59]), but is not well understood in other interesting cases. For instance, when the inputs are the second-order functionals (of type $(\mathbb{N} \to \mathbb{N}) \to (\mathbb{N} \to \mathbb{N})$), the classical theory does not apply and many problems are still open.

3.3 Dynamical systems

The most natural example of a computation with infinite precision is the simulation of a dynamical system. The underlying space might be $\mathbb{R}^n$ in the case of the simulation of physical systems, or the Cantor space $\{0,1\}^{\mathbb{Z}}$ in the case of discrete dynamical systems.

From the point of view of computation, the main point of interest is the link between the long-term behavior of a system and its initial configuration. There are two questions here: (a) predict the behavior, (b) design dynamical systems with some prescribed behavior. The first will be mainly examined through the angle of reachability and more generally control theory for hybrid systems.

The model of cellular automata will be of particular interest. This computational model is relevant for simulating complex global phenomena which emerge from simple interactions between simple components. It is widely used in various natural sciences (physics, biology, etc.) and in computer science, as it is an appropriate model to reason about errors that occur in systems with a great number of components.

The simulation of a physical dynamical system on a computer is made difficult by various aspects. First, the parameters of the dynamical systems are seldom exactly known. Secondly, the simulation is usually not exact: real numbers are usually represented by floating-point numbers, and simulations of cellular automata only simulate the behavior of finite or periodic configurations. For some chaotic systems, this means that the simulation can be completely irrelevant.

4 Application domains

4.1 Quantum computing

Quantum Computing is currently the most promising technology to extend Moore's law, whose end is expected to be reached soon with engraving technologies struggling to reduce transistor size. Thanks to promising algorithmic and complexity theoretic results on its computational power, quantum computing will represent a decisive competitive advantage for those who will control it.

Quantum Computing is also a major security issue, since it allows us to break today's asymmetric cryptography. Hence, mastering quantum computing is also of the highest importance for national security concerns. Small-scale quantum computers already exist and recent scientific and technical advances suggest that the construction of the first *practical* quantum computers will be possible in the coming years.

As a result, the major US players in the IT industry have embarked on a dramatic race, mobilizing huge resources: IBM, Microsoft, Google and Intel have each invested huge sums of money, and are devoting significant budgets to attract and hire the best scientists on the planet. Some states have launched ambitious national programs, including the United Kingdom, the Netherlands, Canada, China, Australia, Singapore, and very recently Europe, with the 10-year FET Flagship program in Quantum Engineering. The French government also recently announced its Plan Quantique – a 1.8 billion euros initiative to develop quantum technologies.

An important pillar of the Plan Quantique concerns the development of Large Scale Quantum computers. This will come with progress all across the quantum stack.

The Mocqua team contributes to the computer science approach to quantum computing, with expertise ranging all across the quantum stack from quantum software to fault-tolerance and quantum error-correction. We aim at a better understanding of the power and limitations of the quantum computer, and therefore of its impact on society. We also contribute to ease the development of the quantum computer by filling gaps across the quantum stack from programming languages to compilation and intermediate representations for fault-tolerant implementations on hardware.

4.2 Higher-order computing

The idea of considering functions as first-class citizens and allowing programs to take functions as inputs has emerged since the very beginning of theoretical computer science through Church's λ-calculus and is nowadays at the core of functional programming, a paradigm that is used in modern software and by digital companies (Google, Facebook, ...). In the meantime higher-order computing has been explored in many ways in the fields of logic and semantics of programming languages.

One of the central problems is to design programming languages that capture most of, if not all, the possible ways of computing with functions as inputs. There is no Church thesis in higher-order computing and many ways of taking a function as input can be considered: allowing parallel or only sequential computations, querying the input as a black-box or via an interactive dialog, and so on.

The Kleene-Kreisel computable functionals are arguably the broadest class of higher-order continuous functionals that could be computed by a machine. However their complexity is such that no current programming language can capture all of them. Better understanding this class of functions is therefore fundamental in order to identify the features that a programming language should implement to make the full power of higher-order computation expressible in such a language.

4.3 Simulation of dynamical systems by cellular automata

We aim at developing various tools to simulate and analyse the dynamics of spatially-extended discrete dynamical systems such as cellular automata. The emphasis of our approach is on the evaluation of the robustness of the models under study, that is, their capacity to resist various perturbations.

In the framework of pure computational questions, various examples of such systems have already been proposed for solving complex problems with a simple bio-inspired approach (e.g. the decentralized gathering problem [51]). We are now working on their transposition to various real-world situations. For example when one needs to understand the behaviour of large-scale networks of connected components such as wireless sensor networks. In this direction of research, a first work has been presented on how to achieve a decentralized diagnosis of networks made of simple interacting components and the results are rather encouraging [53]. Nevertheless, there are various points that remain to be studied in order to complete this model for its integration in a real network.

We have also tackled the evaluation of the robustness of a swarming model proposed by A. Deutsch to mimic the self-organization process observed in various natural systems (birds, fishes, bacteria, etc.) [2]. We now wish to develop our simulation tools to apply them to various biological phenomena where many agents are involved.

We are also currently extending the range of applications of these techniques to the field of economy. We have started a collaboration with Massimo Amato, a professor in economy at the Bocconi University in Milan. Our aim is to propose a decentralized view of a business-to-business market and totally decentralized, agent-oriented models of such markets. Various banks and large businesses have already expressed their interest in such modelling approaches.

5 Social and environmental responsibility

The main footprint of the research activities of the team is due the attendance of scientific events. We give preference to participation by videoconference or to travel by train for events in Europe.

Given our topics of research, their environmental impact is modest. However, we have cooperated in the last three years with EDF though a CIFFRE PhD on quantum algorithms for optimisation problems with applications in fleet electric vehicle charging.

6 Highlights of the year

6.1 Awards

The paper "Complete and tractable machine-independent characterizations of second-order polytime. FoSSaCS 2022" [24] has received the EATCS best paper award at ETAPS 2022 (ETAPS best papers). It provides a first tractable (i.e., decidable in polynomial time), implicit (no external knowledge on the complexity), and complete (capturing all functions) characterization of the class of Basic Feasible Functionals (BFF), that is, due to Cook-Kapron Theorem, considered to be the mainstream notion for polynomial time on second-order programs. This solves an issue that was opened for 20 years.

7 New software and platforms

7.1 New software

7.1.1 FiatLux

Keywords: Cellular automaton, Multi-agent, Distributed systems

Scientific Description: FiatLux is a discrete dynamical systems simulator that allows the user to experiment with various models and to perturb them. It includes 1D and 2D cellular automata, moving agents, interacting particle systems, etc. Its main feature is to allow users to change the type of updating, for example from a deterministic parallel updating to an asynchronous random updating. FiatLux has a Graphical User Interface and can also be launched in a batch mode for the experiments that require statistics.

Functional Description: FiatLux is a cellular automata simulator in Java specially designed for the study of the robustness of the models. Its main distinctive features are to allow users to perturb the updating of the system (synchrony rate) and the topology of the grid.

News of the Year: The latest version of the software incorporates improvements that were implemented by Océane Chazé, a second-year student at Télécom Nancy. She improved the User Interface by simplifying the interactions with the grid of cells. She also improved the software by introducing new features which allow users to encode initial conditions and transitions rules in a more elaborate way. This allows users to import some well-known models from external websites, e.g. Langton's self-reproducing rule or "classical" patterns in the Game of Life.

URL: https://project.inria.fr/fiatlux/

Contact: Nazim Fates

Participants: Nazim Fates, Olivier Boure

Partners: ENS Lyon, Université de Lorraine

7.1.2 ComplexityParser

Name: ComplexityParser

Keywords: Static analysis, Complexity, Static typing

Functional Description: ComplexityParser is a static complexity analyzer for Java programs using a tier-based typing discipline. If a program is typable, this guarantees its runtime to be polynomial on the condition that it halts. The type inference is automatic, its complexity is linear in the size of the input program in practice.

URL: https://gitlab.inria.fr/complexityparser/complexityparser

Contact: Romain Péchoux

7.1.3 Qimaera

Name: Qimaera

Keyword: Quantum programming

Functional Description: 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. We introduce Qimaera, which is a set of libraries for the Idris 2 programming language that enable the programmer to implement (variational) quantum algorithms where the full power of the elegant Idris language works in synchrony with quantum programming primitives that we introduce. The two key ingredients of Idris that make this possible are (1) dependent types which allow us to implement unitary (i.e. reversible and controllable) quantum operations, and (2) linearity which allows us to enforce fine-grained control over the execution of quantum operations that ensures compliance with the laws of quantum mechanics. We demonstrate that Qimaera is suitable for variational quantum programming by providing implementations of the two most prominent variational quantum algorithms – QAOA and VQE. To the best of our knowledge, this is the first implementation of these algorithms that has been achieved in a type-safe framework.

URL: https://github.com/zamdzhiev/Qimaera

Publication: hal-03519238

Contact: Vladimir Zamdzhiev

Participants: Liliane-Joy Dandy, Emmanuel Jeandel, Vladimir Zamdzhiev

8 New results

8.1 Computability over topological spaces

Participants: Djamel Eddine Amir, Mathieu Hoyrup.

8.1.1 Fixed-point property for represented spaces

A space with a structure has the fixed-point property if every structure-preserving function from the space to itself has a fixed-point. We investigate which spaces have the fixed-point property for computable multivalued functions. We prove in particular that among the countably-based topological spaces, they are exactly the omega-continuous domains, an important class coming from semantics of programming languages. We apply our results to identify the complexity of indexing a basis of a topological space. Our article has been accepted in the *Annals of Pure and Applied Logic* [17].

8.1.2 Algorithmic properties of sets

We investigated the relationship between the computability of sets and their topological properties. More precisely, we are studying which sets have "computable type", which is the property that any algorithm that semidecides the set can be converted into an algorithm that fully decides the set. We have obtained a topological characterization of this property for a large class of sets, namely the finite simplicial complexes. Our results give an easy way of determining whether a given set has computable type. In particular we have settled the question for famous sets from topology: the dunce hat, and Bing's house. An article is currently submitted.

We have also obtained a partial characterization of this property using homology theory. Essentially, this property is related to the fact that every point belongs to a cycle, a notion provided by homology, extending the notion of cycle in a graph. We obtained a complete characterization of the finite simplicial complexes having computable type, the result was presented in ICALP [20].

8.2 Dynamical systems

Participants: Nazim Fatès, Emmanuel Jeandel, Guilhem Gamard.

8.2.1 Probabilistic cellular automata for problem solving

We designed new solutions to the cellular automata parity problem [41]. The model is an interacting particles system, that is, a particular kind of stochastic cellular automton where cells are updated by pairs, randomly chosen at each time step. We analysed the convergence properties of two rules and show that they possess the required properties to classify the parity of the initial configurations. We present a formal analysis of the classification time, as well as numerical simulations, to establish that the classification time scales quadratically with the number of cells.

Our work on a bio-inspired mechanism for data clustering has finally been published [28]. Our method uses amoebae which evolve according to cellular automata rules: they contain the data to be processed and emit reaction-diffusion waves at random times. The waves transmit the information across the lattice and cause other amoebae to react, by being attracted or repulsed. The local reactions produce small homogeneous groups which progressively merge and realize the clustering at a larger scale.

We continued our work with Régine Marchand (IECL, Université de Lorraine) and Irène Marcovici (IECL, Université de Lorraine) on the problem of detecting failures in a distributed network [54]. The question that drives our research is to find out how we can detect that the failure rate has exceeded a given threshold without any central authority when some components progressively break down.

The special issue on complex systems following the SOLSTICE'19 conference was published. Entitled "Discrete Models of Complex Systems: recent trends and analytical challenges", it contains 13 papers devoted to exploring differents topics related to the theme of complex sytems and non-classical models of computation (cellular automata, boolean networks, etc.) [15].

8.2.2 Diagrams for symbolic dynamics

One of the main open question in the field of symbolic dynamics is to decide whether the conjugacy problem is computable. This is a problem on shifts of finite type, that can be reformulated in terms of matrices. Two matrices M and N with nonnegative integer coefficients are said to be strong-shift-equivalent in one step if $M = RS$ and $N = SR$ for nonnecessarily square matrices R and S with nonnegative integer coefficients. Strong shift equivalence is the reflexive and transitive closure of this relation.

In [55] we show how to use results from category theory, in particular the concept of PROPs as used for instance in the ZX-calculus, to provide a purely categorical version of this question. Rather than just a technical exercise, we show in the same paper that we can recover many invariants of strong shift equivalence rather surprisingly by considering preexisting categories with bialgebras that are well known in mathematics. Whether the approach could lead to the computability of strong shift equivalence remains to be seen.

This paper was presented this year in the conference (without proceedings) ACT.

8.2.3 Analysis of graphs in the field of economics

In collaboration with Massimo Amato and Lucio Gobbi (Bocconi University and University of Trento), we developed some economic and operational foundations of a new method of financing companies' financial obligations [52]. In this new banking business model, a network funder sets an optimal combination of netting and financing. Given a network of companies and their respective invoices, and under the condition of a full settlement of the invoices, we applied a multilateral netting algorithm to the network, conceived as an oriented multi-graph. Our problem, which is NP-complete, was to find a set of invoices which maximises the amount of debt reduced given a quantity of loanable funds. After designing a policy which finds a trade-off for the funding, we tested our methods on an empirical dataset from an electronic invoicing operator consisting of more than 60,000 companies. The first results show that this method is economically significant and feasible and these methods are now investigated in more details in the MURENE project, with the PhD of Joannès Guichon.

8.2.4 Rice-like theorems on automata networks

In collaboration with Pierre Guillon, Guillaume Theyssier and Kévin Perrot (respectively I2M, I2M, LIS, all Aix-Marseille University), we obtained very general complexity lower bounds on automata networks, a type of dynamical system that resembles generalized cellular automata. Any problem expressible in Monadic Second-Order logic on a reasonable condition that satisfies a mild technical condition is either trivial, or NP-hard, or coNP-hard. In particular it is not possible to design a polynomial-time solvable question on automata networks (even on purpose). Recently we showed that, should the mild technical condition be negated, either the MSO problem is also computationally hard, or standard complexity assumptions do not hold.

8.3 Implicit computational complexity

Participants: Emmanuel Hainry, Romain Péchoux, Simon Perdrix, Vladimir Zamdzhiev.

8.3.1 Characterizations of the class of Basic Feasible Functionals

In [16], we have provided a characterization of the class of Basic Feasible Functionals (BFF), the second-order counterpart of the class FP of first-order functions computable in polynomial time. Several characterizations have been suggested in the literature, but none of these present a programming language with a type system guaranteeing this complexity bound. The characterization of BFF based on an imperative language with oracle calls using a tier-based type system whose inference is decidable. BFF is exactly the class of second-order functionals in the simply-typed lambda-closure of functions computable by typed and terminating programs.

The result of [16] has been improved in [24], where it is shown that:

- the simply-typed lambda-closure can be internalized in the programming language so that no external lambda-closure (i.e., on the computed functions) is required to ensure completeness,

- the termination requirement on programs can be specified to some tractable instance (a restriction of size-change termination decidable in polynomial time),
- the inference remains decidable.

To sum up, [24] provides a first implicit, tractable, and complete and, hence, has solved a problem opened for 20 years. This paper has obtained the EATCS best paper award at ETAPS 2022.

8.3.2 Quantum expectation transformers

In [21], we introduce a new kind of expectation transformer for a mixed classical-quantum programming language. This semantic approach relies on a new notion of a cost structure, which we introduce, and which can be seen as a specialization of the Kegelspitzen of Keimel and Plotkin. This weakest precondition analysis is both sound and adequate with respect to the operational semantics of the language. Using the induced expectation transformer, a formal analysis methods for the expected cost analysis and expected value analysis of classical-quantum programs can be performed. The usefulness of this technique is illustrated by computing the expected cost of several well-known quantum algorithms and protocols, such as coin tossing, repeat until success, entangled state preparation, and quantum walks.

8.4 Enumerative and probabilistic combinatorics of some discrete objects

Participants: Mathilde Bouvel, Benjamin Testart.

8.4.1 Preimages under the bubblesort operator.

This is a joint project with Luca Ferrari (University Florence, Italy) and his PhD student Lapo Cioni (who visited Loria for a month in the Fall 2021).

The bubblesort operator B is a operator acting on permutations (seen as arrays of numbers) like the bubblesort algorithm, but stopping after having scanned the array only once. For example, $\mathsf{B}(451362) = 413526$. It is one of several operators on permutations which “partially sort” permutations (in a sense that can be made precise), like the most famous stacksort operator S or the queuesort operator Q.

In the article [14], we study preimages of permutations under the bubblesort operator B, in a fashion similar to what has been done for S and Q in the past. We achieve a description of these preimages much more complete than what is known for the more complicated sorting operators S and Q. We describe explicitly the set of preimages under B of any permutation π from the left-to-right maxima of π, showing that there are $2k-1$ such preimages if k is the number of these left-to-right maxima. We further consider, for each n, the tree T_n recording all permutations of size n in its nodes, in which an edge from child to parent corresponds to an application of B (the root being the identity (or sorted) permutation $12\dots n$), and we present several properties of these trees.

8.4.2 Random cographs

This paragraph concerns three papers published in 2022, which already appeared as preprints in RA of previous years. They are joint papers with Frédérique Bassino (LIPN, Université Paris Nord), Michael Drmota (TU Wien, Austria), Valentin Féray (IECL, Université de Lorraine), Lucas Gerin (CMAP, École Polytechnique), Mickaël Maazoun (Oxford’s Department of Statistics, UK) and Adeline Pierrot (LISN, Université Paris-Sud).

Cographs form one of the simplest hereditary graph classes. They can be defined as the graphs not containing the path with 4 vertices as an induced subgraph. A characterization of cographs which is essential for us is the following: cographs are the graphs which can be encoded by trees in a specific family, called *cotrees*.

In [12] and [11], we are interested in the asymptotic properties of uniform random cographs when the number of vertices tends to infinity. To achieve these results, we use a methodology inspired from our previous work on permutation, the latest paper of this series being [13].

In the first paper [12], we prove convergence towards a Brownian limiting object in the space of graphons, which we call the *Brownian cographon*. We then show that the degree of a uniform random vertex in a uniform cograph with n vertices is of order n, and converges after normalization to the Lebesgue measure on $[0,1]$. We finally analyze the vertex connectivity (i.e. the minimal number of vertices whose removal disconnects the graph) of random connected cographs, and show that this statistics converges in distribution without renormalization. Our proofs use the encoding of cographs via cotrees, combined with the symbolic method and singularity analysis.

In the second paper [11], we focus on independent sets (or equivalently, cliques) in uniform random cographs. First, we prove that, with high probability as n gets large, the largest independent set in a uniform random cograph with n vertices has size $o(n)$, answering a question of Kang, McDiarmid, Reed and Scott. The proof relies on the convergence to the Brownian cographon, and on the self-similarity properties of this object. Second, and unexpectedly given the above results, we show that for $\beta > 0$ sufficiently small, the expected number of independent sets of size βn in a uniform random cograph with n vertices grows exponentially fast with n. This time the proof relies on singularity analysis of the associated bivariate generating functions.

In [11], we also prove permutation analogues of all the results mentioned above.

8.4.3 Scaling limits of graph classes through split decomposition

This is a joint project with Frédérique Bassino (LIPN, Université Paris Nord), Valentin Féray (IECL, Université de Lorraine), Lucas Gerin (CMAP, École Polytechnique) and Adeline Pierrot (LISN, Université Paris-Sud). With this group of authors, we have an established collaboration, started approximately ten years ago and which continues until today (see also the previous paragraph). The common theme of the research we do together is to establish limit shape results for constrained combinatorial structures, using methods from analytic combinatorics (which is original in the landscape of the research on this topic). More precisely, we study families of permutations or graphs defined by the avoidance of substructures, and we answer (formally) the (informally phrased) question: "if we choose uniformly at random an object of large size in the considered family, what does it look like?".

In the paper [35], we consider the three following families of graphs: distance-hereditary graphs, 2-connected distance-hereditary graphs and 3-leaf power graphs (the latter two being subclasses of the first one). We prove that the scaling limit of uniform random graphs in each of these families, with respect to the Gromov–Prokhorov topology, is the famous Brownian Continuum Random Tree of Aldous. Although such results are quite expected for families of graphs that are "almost trees" (like the ones we consider), our approach to establish this result is original, relying on the split decomposition of graphs (from the graph algorithms and graph theory literature) and on analytic combinatorics.

8.4.4 Convergence law for 231-avoiding permutations

In earlier work with Michael Albert and Valentin Féray, we compared the expressibility of two logics on permutations, called TOOB (*theory of one bijection*, seeing permutations as a bijection) and TOTO (*theory of two orders*, seeing permutations as a pair of total orders). In the recent paper [32], we focus on TOTO, and study a different problem. Namely, we investigate the existence of 0/1 or convergence laws when the domain is restricted to families of permutations avoiding patterns, similarly to a classical approach in the study of graphs.

Specifically, we prove that the class of 231-avoiding permutations satisfies a convergence law (but not a 0/1 law). In other words, for any first-order sentence ψ in the language TOTO of two total orders, the probability $p_n(\psi)$ that a uniform random 231-avoiding permutation of size n satisfies ψ admits a limit as n is large. Moreover, we establish two further results about the behaviour and value of $p_n(\psi)$: (i) it is either bounded away from 0, or decays exponentially fast; (ii) the set of possible limits is dense in $[0,1]$. Our tools come mainly from analytic combinatorics and singularity analysis. We hint at possible generalisations to other families of pattern-avoiding permutaitons.

8.4.5 Enumeration of pattern-avoiding inversion sequence

The results presented here have been obtained by Benjamin Testart during his Master internship and the first few weeks of his PhD thesis. They are concerned with inversion sequences, which are integer sequences $(\sigma_1,\ldots,\sigma_n)$ such that $0 \le \sigma_i < i$ for all $1 \le i \le n$. The study of pattern-avoiding inversion sequences began in two independent articles [56, 49]. These two initial articles solved the enumeration of inversion sequences avoiding a single pattern for every pattern of length 3 except the patterns 010 and 100. The case 100 was recently solved by Mansour and Yildirim.

The paper [43], solves the final case by making use of a decomposition of inversion sequences avoiding the pattern 010. This decomposition needs to take into account the maximal value, and the number of distinct values occurring in the inversion sequence. The method is then expanded to solve the enumeration of inversion sequences avoiding the pairs of patterns $\{010,000\}$,$\{010,110\}$, $\{010,120\}$, and $\{010,201\}$ (solving therefore also $\{010,210\}$ whose enumeration is already known to coincide with that of $\{010,201\}$). For each family of pattern-avoiding inversion sequences considered, its enumeration requires the enumeration of some family of constrained words avoiding the same patterns, a question which Benjamin also solves along the way.

8.5 Graphical Languages for Quantum computing

Participants: Alexandre Clément, Emmanuel Jeandel, Simon Perdrix, Margarita Veshchezerova.

8.5.1 Development of the ZX-Calculus

This year, we have contributed in several ways to the foundations and the applications of the ZX-calculus, a diagrammatic language for quantum computing.

One of the main contribution concerns the development of a framework for adding two ZX-diagrams. In the ZX-calculus, each diagram represent a matrix. The formalism makes it easy to compose them sequentially or in parallel (which corresponds mathematically to multiplication and tensor product), but there is no easy way to obtain, from two diagrams representing matrices M_1 and M_2, a diagram that represent their addition, the matrix $M_1 + M_2$.

Addition might not appear at first as an important property when manipulating diagrams that represents quantum evolution, but it appears naturally when trying to automatically differentiate diagrams: Indeed, the differentiation of a product MN involves the sum $\partial MN + M\partial N$. Differentation of ZX-diagrams is central in many application in quantum machine learning, or quantum optimisation. For instance, it is an interesting potential development of a work in collaboration with EDF and the start-up Pasqal that has been published this year [23], a case study of an quantum optimisation in the field of smart-charging of electric vehicles.

This framework was developed by E. Jeandel, S. Perdrix and M. Veshchezerova and was presented this year in FSCD 2022 [30].

8.5.2 Optimising resources for quantum coherent control

Coherent control of quantum computation can be used to improve some quantum protocols and algorithms.

This year, we have extended the PBS-calculus [48], a graphical language for coherent control which is inspired by quantum optics. This language can be used to describe coherently controlled quantum computation. Our main contribution is the development of procedure for optimising the resources required by a PBS-diagram for solving a particular task: we introduce an efficient procedure to minimise the number of oracle queries of a given diagram. We also consider the problem of minimising both the number of oracle queries and the size of the diagram. We show that this optimisation problem is NP-hard in general, but introduce an efficient heuristic that produces optimal diagrams when at most one query to each oracle is required.

This result has been presented at MFCS'22 [29].

8.5.3 LOv-calculus, a language for optical quantum computing

We have started this year a fruitful collaboration with the start-up Quandela, which is working on the development of an optical-based quantum computer. The objective was the development of a graphical but formal language for describing quantum computing based on quantum optical devices. In collaboration with the Inria Quacs team, we have introduced the LOv-calculus, a graphical language for reasoning about linear optical quantum circuits with so-called vacuum state auxiliary inputs. We equiped the language with an equational theory that we proved to be sound and complete: two LOv-circuits represent the same quantum process if and only if one can be transformed into the other with the rules of the LOv-calculus. We give a confluent and terminating rewrite system to rewrite any polarisation-preserving LOv-circuit into a unique triangular normal form, inspired by the universal decomposition of Reck et al. (1994) for linear optical quantum circuits.

This paper has been presented at MFCS'22 [22]. Notice that based on this result, we have more recently introduced the fist complete equational theory for quantum circuits, solving a 30-year open problem for the most comonly used model in quantum computing. This last result is currently available as a pre-print [39].

8.6 Quantum, probabilistic and substructural programming languages

Participants: Agustín Borgna, Emmanuel Jeandel, Vladimir Zamdzhiev.

8.6.1 Encoding High-level Quantum Programs as SZX-diagrams

The Scalable ZX-calculus is a compact graphical language used to reason about linear maps between quantum states. These diagrams have multiple applications, but they frequently have to be constructed in a case-by-case basis. In this work we present a method to encode quantum programs implemented in a fragment of the linear dependently typed Proto-Quipper-D language as families of SZX-diagrams. We define a subset of translatable Proto-Quipper-D programs and show that our procedure is able to encode non-trivial algorithms as diagrams that grow linearly on the size of the program.

This paper has been presented at QPL'2022 [27].

8.6.2 Variational quantum programming in idris

Variational Quantum Algorithms [58, 57, 50] 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, because they have to be able to accommodate both classical and quantum programming primitives simultaneously.

As part of this research project, we develop a set of libraries for the Idris 2 programming language that enable the programmer to implement (variational) quantum algorithms where the full power of the elegant Idris language works in synchrony with quantum programming primitives that we introduce. The two key ingredients of Idris that make this possible are (1) dependent types which allow us to implement unitary (i.e. reversible and controllable) quantum operations; and (2) linearity which allows us to enforce fine-grained control over the execution of quantum operations that ensures compliance with the laws of quantum mechanics. We demonstrate that our libraries, named Qimaera, are suitable for variational quantum programming by providing implementations of the two most prominent variational quantum algorithms – QAOA [50] and VQE [58]. To the best of our knowledge, this is the first implementation of these algorithms that has been achieved in a type-safe framework.

The results of this work are described in a preprint [40], that has been accepted in 2023 in the conference ESOP. The software is open-source, available under the MIT license here. These results were obtained during the (bachelor) internship of Liliane-Joy Dandy in our team and she was awarded the **"Research Internship Prize"** at École Polytechnique for her work.

8.6.3 Semantics for variational quantum programming

The results in the previous research project show how we may approach variational quantum programming within an existing programming language. As part of this research project, we adopt a more theoretical and formal viewpoint and we consider a type system for variational quantum programming and we show how to design a suitable mathematical semantics for it.

In particular, we consider a programming language that can manipulate both classical and quantum information. Our language is type-safe and designed for variational quantum programming. The classical subsystem of the language is the Probabilistic FixPoint Calculus (PFPC), which is a lambda calculus with mixed-variance recursive types, term recursion and probabilistic choice. The quantum subsystem is a first-order linear type system that can manipulate quantum information. The two subsystems are related by mixed classical/quantum terms that specify how classical probabilistic effects are induced by quantum measurements, and conversely, how classical (probabilistic) programs can influence the quantum dynamics. We also describe a sound and computationally adequate denotational semantics for the language. Classical probabilistic effects are interpreted using a recently-described commutative probabilistic monad on DCPO. Quantum effects and resources are interpreted in a category of von Neumann algebras that we show is enriched over (continuous) domains. This strong sense of enrichment allows us to develop novel semantic methods that we use to interpret the relationship between the quantum and classical probabilistic effects. By doing so we provide the first denotational analysis that relates models of classical probabilistic programming to models of quantum programming.

The results of this project are published in POPL'22 [25].

8.7 Compilation of quantum circuits

Participants: Timothée Goubault de Brugière, Simon Perdrix, Vivien Vandaele, Christophe Vuillot.

8.7.1 Compilation of Clifford isometries

This work is in collaboration with Simon Martiel (Atos). An important subset of quantum circuits is the group of Clifford circuits. It is efficiently simulable classically but only needs the addition of a single non-Clifford gate, usually the single-qubit T gate, to become universal. It is very common to target the universal gate set Clifford+T for a fault-tolerant implementation of quantum circuits. Being able to compile and optimize Clifford circuits, particularly the two-qubit count or depth constitute a crucial task in the development of the quantum computing stack. In [38] we propose a framework for the compilation of Clifford isometries. This framework encompass previous normal forms and permit to derive efficient synthesis algorithms. We demonstrate the use of this framework by benchmarking several synthesis algorithms derived from it and showing improvements of the 2-qubit count and depth for circuits taken from quantum chemistry experiments.

8.7.2 Hadamard count minimization in Clifford+T circuits

This work is in collaboration with Simon Martiel (Atos). When compiling quantum circuit with the gate set Clifford+T, one usually tries to minimize the number of T gates. This is because T gates are usually more costly to implement fault-tolerantly. This minimization problem when there are no Hadamard gates in the circuit is well understood. To handle the general case one can optimize around Hadamard gates or use some gadgetisation techniques. In both cases minimizing the number of Hadamard gate in the circuit beforehand can also help reducing the number of T gates overall. Lead by Vivien Vandalele for his PhD we are currently in the process of writing a paper tackling this problem.

8.8 Quantum error correcting codes and fault-tolerance

Participants: Alexandre Guernut, Emmanuel Jeandel, Christophe Vuillot.

This work was done in collaboration with Anthony Leverrier (Inria Paris) and Simon Apers (IRIF, CNRS). Our work on quantum pin codes [19] has been published in IEEE Transactions on Information Theory. In this work we defined a purely combinatorial structure, quantum pin codes, generalizing quantum color code which are defined from certain tessellations of manifolds and which feature some interesting properties for the implementation of transversal phase gates. This work was done in collaboration with Nikolas Breuckmann (University of Bristol)

Our work on quantum XYZ-product codes [18], has been published in Quantum. In this work we define a quantum code construction and analyze some of its properties such as the dimension and bounds on the minimal distance.

8.8.1 Dehn twists on 2D color codes

Quantum error correcting code with good encoding rates promise to reduce the cost of fault-tolerant quantum computation by reducing the number of physical qubits needed for a target level of protection and number of logical qubit needed. The savings come at the price of more complex procedures for the implementation of gates on logical qubits within the code. One technique for homological codes from 2D manifold is to apply a Dehn twist to a handle of the surface which implements a CNOT between the logical qubits of the handle. Lead by Alexandre Guernut for his PhD we are studying the generalization of Dehn-twists to other 2D codes, namely color codes.

8.8.2 Quantum rotor codes

This work is a collaboration in progress with Barbara Terhal (Delft University) and Allessandro Ciani (Forschungszentrum Jülich). Quantum systems in real laboratories do not always consist in a set of qubits but often systems with a richer structure for their Hilbert space. For instance they are often infinite dimensional, as are quantum oscillators or quantum rotors. Exploiting the structure and knowledge of the full physical system when designing quantum error correcting codes is a promising way of reducing the overhead of error correction. Quantum error correction with quantum oscillators have been well studied either for encoding qubits within quantum oscillators (the field of bosonic codes) or encoding oscillators in several oscillators for which several no-gos have been proven. Quantum rotors can be thought of intermediate systems between qubits (finite) and quantum oscillators (infinite and continuous). We are studying quantum error correcting codes for quantum rotors both encoding finite or infinite logical information. The codes we defined encoding finite systems have some similarity with so-called protected superconducting qubits such as the 0-π qubit. Moreover our construction generalizes to more protected qubits potentially realizable in superconducting circuits.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Emmanuel Jeandel, Simon Perdrix, Christophe Vuillot.

The team is supervising two CIFRE PhDs in collaboration with industry partners.

One is a partnership with EDF: Margarita Veshchezerova worked on “Quantum Computing for Combinatorial Optimisation” under the supervision of Emmanuel Jeandel and Simon Perdrix from the team, and Marc Porcheron at EDF. Margarita Veshchezerova defended her PhD thesis on December 16th 2022.

One is with ATOS: Vivien Vandaele is working on “Optimisation du calcul quantique tolérant aux fautes par le ZX-Calculus” under the supervision of Simon Perdrix and Christophe Vuillot from the team, and Simon Martiel at ATOS.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Inria associate team not involved in an IIL or an international program

QASAR

Title: Quantum Architectures, Small And Reliable

Duration: 2022 onwards

Coordinator: Nikolas Breuckmann (niko.breuckmann@bristol.ac.uk)

Partners:

- University College London London (Royaume-Uni)
- University of Bristol (Royaume-Uni)

Inria contact: Christophe Vuillot

Summary: Quantum computation promises to speed–up certain problems of interest that would be infeasible to solve using today's (classical) computing paradigms. Although much progress towards the implementation of quantum computers has been made in the past 10 years, there remain formidable challenges such as coping with the noise inevitably present in quantum devices. While in principle we now know how to correct errors in quantum devices, it has been shown that the amount of resource overhead is still forbiddingly high. This poses a significant obstacle for the viability of quantum computing in the near- and mid-term. The objective for the associated team is to establish strong foundations for fault-tolerant quantum computation in realistic and practical settings. For this, a systematic understanding of the fault-tolerant computation capabilities of small quantum codes is required. This includes small block codes using qubits as well as small codes leveraging hardware control for error correction like bosonic codes. These kind of small setups are the most mature today. In the near future it will be possible to link them in a modular way and that is why anticipating distributed architecture is also a priority.

TCPRO3

Title: Termination and Complexity Properties of Probabilistic Programs

Duration: 2020 onwards

Coordinator: Georg Moser (georg.moser@uibk.ac.at)

Partners:

- University of Innsbruck (Autriche)

Inria contact: Romain Péchoux

Summary: Probabilistic languages consist in higher-order functional, imperative languages, and reduction systems with sampling and conditioning primitive instructions. While deep theoretical results have been established on the semantics properties of such languages, applications of termination and complexity analysis are restricted to academic examples so far. The associate team TCPro3 has the aim to contribute to the field by developing methods for reasoning on quantitative properties of probabilistic programs and models. Extensions of these methods on quantum programs will be studied.

10.1.2 STIC/MATH/CLIMAT AmSud projects

STIC AmSud - QAPLA

Title: Quantum aspects of programming languages

Duration: 2021 – 2022

Coordinator: Alejandro Díaz-Caro (adiazcaro@icc.fcen.uba.ar)

Partners:

- CONICET / U. Buenos Aires (Argentina)
- Universidad de la República (Uruguay)
- Inria
- CNRS

Inria contact: Gilles Dowek, Simon Perdrix

Summary: The design of quantum programming languages is a rich framework that allows studying intrinsic properties of the computation we are modelling, such as parallelism, entanglement, superposition, etc; also, it is a way to study new logics (quantum logics with a computational ground), as well as to study classical logics from a new perspective. Finally, studying the foundational bases of programming languages gives a path to develop proper implementations. This project proposes to study several aspects of quantum programming languages, with different ap- proaches (quantum control/classical data, quantum control and data, categorical techniques, semantical techniques, realizability). The final aim is to merge different approaches in order to study from logics to implementations.

10.2 International research visitors

10.2.1 Visits of international scientists

Other international visits to the team

Alexander Frank

Status researcher

Institution of origin: Universidad Andres Bello

Country: Chile

Dates: 04/07/2022 to 21/07/2022

Context of the visit: research stay

Mobility program/type of mobility: Marie Curie European project RISE "Computing with Infinite Data"

10.2.2 Visits to international teams

Research stays abroad

Simon Perdrix

Visited institution: U. Buenos Aires

Country: Argentina

Dates: 14/01/2022 to 01/02/2022

Context of the visit: STIC AMSud QAPLA

Mobility program/type of mobility: Research stay

Romain Péchoux

Visited institution: U. Buenos Aires

Country: Argentina

Dates: 21/11/2022 to 02/12/2022

Context of the visit: STIC AMSud QAPLA

Mobility program/type of mobility: Research stay

Christophe Vuillot

Visited institution: University College London

Country: United-Kingdom

Dates: 22/08/2022 to 28/08/2022

Context of the visit: QASAR associated team

Mobility program/type of mobility: Research stay

10.3 European initiatives

10.3.1 Horizon Europe

NEASQC

Participants: Emmanuel Jeandel, Simon Perdrix, Romain Péchoux, Christophe Vuillot.

Title: NExt ApplicationS of Quantum Computing

Partner Institution(s):

- ATOS-Bull
- Université de Lorraine
- AstraZeneca
- Cesga
- EDF
- HQS
- HSBC
- ICHEC
- Tilde
- Total
- University of Leiden
- Universidade da Coruna

Duration: 01/09/2020-31/08/2024

Summary: The project brings together academic experts and industrial end-users to investigate and develop a new breed of Quantum-enabled applications that can take advantage of NISQ (Noise Intermediate-Scale Quantum) systems in the near future. NEASQC is use-case driven. Along with EDF we are investigating smart energy management in this context.

10.3.2 H2020 projects

HPCQS HPCQS project on cordis.europa.eu

Title: High Performance Computer and Quantum Simulator hybrid

Duration: From December 1, 2021 to November 30, 2025

Partners:

- Institut National de Recherche en Informatique et Automatique (INRIA), France
- Grand Equipement National de Calcul Intensif (GENCI), France
- National University of Ireland Galway (NUI GALWAY), Ireland
- Forschungszentrum Julich GMBH (FZJ), Germany
- Parity Quantum Computing GMBH (ParityQC), Austria
- Fraunhofer Gesellschaft zur Forderung der Angewandten Forschung EV (FHG), Germany
- Commissariat à l'énergie atomique et aux énergies alternatives (CEA), France
- Eurice European Research and Project Office GMBH, Germany
- Consiglio Nazionale delle Ricierche (CNR), Italy
- Bull SAS (Bull), France
- Flysight SRL, Italy
- Partec AG (Partec), Germany
- Universitaet Innsbruck (UIBK), Austria
- Cineca Consorzio Interuniversitario (Cineca), Italy
- Centre National de la Recherche Scientifique CNRS (CNRS), France
- Centrale Supélec (CentraleSupélec), France
- Barcelona Supercomputing Center Centro Nacional de Supercomputacion (BSC CNS), Spain
- Sorbonne Université, France

Inria contact: Luc Giraud

Coordinator: Kristel Michielsen

Summary: The aim of HPCQS is to prepare European research, industry and society for the use and federal operation of quantum computers and simulators. These are future computing technologies that are promising to overcome the most difficult computational challenges. HPCQS is developing the programming platform for the quantum simulator, which is based on the European ATOS Quantum Learning Machine (QLM), and the deep, low-latency integration into modular HPC systems based on ParTec's European modular supercomputing concept. A twin pilot system, developed as a prototype by the European company Pasqal, will be implemented and integrated at CEA/TGCC (France) and FZJ/JSC (Germany), both hosts of European Tier-0 HPC systems. The pre-exascale sites BSC (Spain) and CINECA (Italy) as well as ICECH (Ireland) will be connected to the TGCC and JSC via the European data infrastructure FENIX. It is planned to offer quantum HPC hybrid resources to the public via the access channels of PRACE. To achieve these goals, HPCQS brings together leading quantum and supercomputer experts from science and industry, thus creating an incubator for practical quantum HPC hybrid computing that is unique in the world. The HPC-QS technology will be developed in a co-design process together with selected exemplary use cases from chemistry, physics, optimization and machine learning suitable for quantum HPC hybrid calculations. HPCQS fits squarely to the challenges and scope of the call by acquiring a quantum device with two times 100+ neutral atoms. HPCQS develops the connection between the classical supercomputer and the quantum simulator by deep integration in the modular supercomputing architecture and will provide cloud access and middleware for programming and execution of applications on the quantum simulator through the QLM, as well as a Jupyter-Hub platform with safe access guarantee through the European UNICORE system to its ecosystem of quantum programming facilities and application libraries.

10.4 National initiatives

10.4.1 ANR

ANR PRCE SoftQPro (ANR-17-CE25-0009)

Participants: Simon Perdrix, Emmanuel Jeandel, Emmanuel Hainry, Romain Péchoux.

Title: Solutions logicielles pour l'optimisation des programmes et ressources quantiques

Partner Institution(s):

- LORIA, France
- ATOS-Bull, France
- LRI, France
- CEA-Saclay, France

Duration: Dec. 2017 - Jun. 2023

Summary: Quantum computers can theoretically solve problems out of reach of classical computers. We aim at easing the crucial back and forth interactions between the theoretical approach to quantum computing and the technological efforts made to implement the quantum computer. Our software-based quantum program and resource optimisation (SoftQPRO) project consists in developing high level techniques based on static analysis, certification, transformations of quantum graphical languages, and optimisation techniques to obtain a compilation suite for quantum programming languages. We will target various computational model back-ends (e.g. QRAM, measurement-based quantum computations) as well as classical simulation. Classical simulation is central in the development of the quantum computer, on both ends: as a way to test quantum programs but also as a way to test quantum computer prototypes. For this reason we aim at designing sophisticated simulation techniques on classical high-performance computers (HPC).

ANR PRCI VanQuTe (ANR-17-CE24-0035)

Participants: Simon Perdrix, Emmanuel Jeandel.

Title: Validation of near-future quantum technologies

Partner Institution(s):

- LIP6, France
- LORIA, France
- NTU, Singapore
- SUTD, Singapore
- NUS, Singapore

Duration: Fev. 2018 - Jan. 2022

Summary: In the last few years we have seen unprecedented advances in quantum information technologies. Already quantum key distribution systems are available commercially. In the near future we will see waves of new quantum devices, offering unparalleled benefits for security, communication, computation and sensing. A key question to the success of this technology is their verification and validation.

Quantum technologies encounter an acute verification and validation problem. On the one hand, since classical computations cannot scale-up to the computational power of quantum mechanics, verifying the correctness of a quantum-mediated computation is challenging. On the other hand, the underlying quantum structure resists classical certification analysis. Members of our consortium have shown, as a proof-of-principle, that one can bootstrap a small quantum device to test a larger one. The aim of VanQuTe is to adapt our generic techniques to the specific applications and constraints of photonic systems being developed within our consortium. Our ultimate goal is to develop techniques to unambiguously verify the presence of a quantum advantage in near future quantum technologies.

10.4.2 Other initiatives

PEPR EPIQ - Plan Quantique

Participants: Simon Perdrix, Guilhem Guilhem, Emmanuel Hainry, Emmanuel Jeandel, Romain Péchoux, Christophe Vuillot, Vladimir Zamdzhiev.

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

Coordinator: Simon Perdrix

Partner Institution(s):

- Inria,
- Université Grenoble Alpes
- CNRS Paris Villejuif
- Sorbonne Université
- CEA Grenoble
- Institut National Polytechnique Grenoble
- Université d'Aix-Marseille
- Université de Bordeaux
- Comue Université Bourgogne Franche Comté
- Université de Bretagne Sud
- Université de Lyon I (Claude Bernard)
- Université de Lorraine
- CentralSupelec
- Université Paris-Saclay
- Ecole Nationale des Ponts et Chaussées
- Université Paris Cité

Duration: Jan. 2022 - Dec 2027

Summary: Despite its relatively small size, 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:

- Understanding the advantages and limits of quantum computing via both quantum complexity research and the discovery and enhancement of algorithms
- Defining the framework for quantum computation using high-level languages, comparison of computational models as well as using their relations for program optimization

- 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.

PEPR NISQ2LSQ - Plan Quantique

Participants: Simon Perdrix, Emmanuel Jeandel, Christophe Vuillot, Nazim Fates.

Title: NISQ2LSQ

Coordinator: Anthony Leverrier

Partner Institution(s):

- Inria,
- CNRS
- CEA
- Université Grenoble Alpes
- ENS Lyon
- Sorbonne Université
- Université Paris-Saclay
- Université Paris Cité
- Université de Bordeaux
- CEA-LETI
- Université d'Aix-Marseille
- Université de Rouen
- Université de Limoges
- Alice&Bob (Startup)
- Quandela (Startup)

Duration: Jan. 2022 - Dec 2027

Summary: This project aims at accelerating the R&D efforts in the theory and conception of hardware-efficient fault- tolerant quantum codes. As far as codes are concerned, the project will focus on two of the most promising solutions, namely bosonic codes and Low-Density Parity-Check (LDPC) codes. On the hardware side, the targetted platforms are superconducting qubits and photonic ones. The main goal of the project is to provide a protoype of a cat-qubit-based quantum processor that is fault-tolerant at first order. Then we will move on to demonstrate fault tolerance at order 2 which will pave the way to scaling up our solution towards a Large Scale Quantum (LSQ) computer by the end of the project. In the photonics realm, different options for scaling up are possible. That is why we will focus on defining and experimentally realizing computational architectures relying on the Measurement-Based Quantum Computation framework and exploiting both cat codes and LDPC codes. On the LDPC codes topic, our goal is to develop optimal codes in terms of encoding rate and error correction as well as efficient decoding algorithms and LDPC-specific fault-tolerant logical operations. In order to integrate them to photonic- or Rydberg-atom-based thechnologies, we fill focus on developping codes that are as small as possible and that have a limited number of long-range interaction.

HQI - Plan Quantique

Participants: Simon Perdrix, Romain Péchoux, Christophe Vuillot.

Title: HQI

Coordinator: Jacques-Charles Lafoucriere

Partner Institution(s):

- CEA,
- Inria
- CNRS
- Centre de Physique Théorique, Ecole Polytechnique (CPHT)
- Sorbonne Université (SU)
- Université Grenoble Alpes (UGA)
- Université Paris-Saclay (UPS)
- Université de Bordeaux (UB)
- École Normale Supérieure (ENS)
- École Normale Supérieure de Lyon (ENSL)
- École nationale supérieure de techniques avancées (ENSTA)
- Bull SAS (ATOS)
- Grand equipement national de calcul intensif (GENCI)
- Quandela SAS (QUANDELA)
- Qubit Phamarceuticals (QuBP)
- VeriQloud (VQ)
- WeLinQ (WELINQ)

Duration: Apr. 2022 - Apr. 2027

Summary: Following the announcement made in January 2021 of the National Quantum Strategy by the President of the French Republic, the SGPI entrusted the CEA, GENCI and Inria with the responsibility of setting up a national hybrid HPC quantum-computing platform named HQI. The project to set up this platform consists of purchases of quantum computers, research and development entrusted to industrialists and academics as well as support for communities using the platform.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

- Simon Perdrix participated to the organisation of EQIP Challenge workshop in Strasbourg Nov. 2022.

Member of the conference program committees

- Mathilde Bouvel and Emmanuel Jeandel are members of the program committee of STACS 2023, respectively in Track A and B (see webpage).
- Romain Péchoux is member of the program committee of the 34th Symposium on Implementation and Application of Functional Languages (IFL 2022), (see webpage).
- Simon Perdrix is member of the program committee of the19th International Conference on Quantum Physics and Logic (QPL'22), (see webpage) and of the 17th Conference on the Theory of Quantum Computation, Communication and Cryptography, University of Illinois (TQC'22) at Urbana-Champaign (see webpage).
- Christophe Vuillot was member of the technical program committee of the 4th International Workshop on Quantum Resource Estimation (QRE2022), (see webpage).

Reviewer

- Mathilde Bouvel has been a reviewer for FPSAC 2023.
- Guilhem Gamard has been a reviewer for STACS 2023 and LATIN 2022.
- Romain Péchoux has been reviewer for ISMVL 2022, FSCD 2022, and STACS 2022.
- Simon Perdrix has been reviewer for MFCS 2022, STACS 23, QIP 2023.
- Christophe Vuillot has been a reviewer for TQC 2022.

11.1.2 Journal

Member of the editorial boards

- Mathilde Bouvel: Member of the editorial board of the journal *Annals of combinatorics*
- Nazim Fatès: Member of the editorial board of the *Journal of cellular automata*. He co-edited a special issue of *Physica D* on the theme "Discrete Models of Complex Systems: recent trends and analytical challenges" (last articles published in 2022).
- Emmanuel Jeandel: Member of the editorial board of the journal *RAIRO-ITA*.

Reviewer - reviewing activities

- Mathilde Bouvel has been a reviewer for Journal of Symbolic Computation, and Discrete Applied Mathematics.
- Guilhem Gamard has been a reviewer for Advances in Applied Mathematics.
- Romain Péchoux has been a reviewer for AMC Transactions on Computational Logic, Information and Computation, and Logical Methods in Computer Science.
- Simon Perdrix has been a reviewer for Open-access journal Compositionality (see webpage).
- Christophe Vuillot has been a reviewer for Nature, Nature Communications, npj quantum information and Quantum.

11.1.3 Invited talks

- Romain Péchoux has given an invited talk at the LoReL's seminar, 28 of November 2022, CONICET, Buenos Aires, (see webpage).
- Nazim Fatès has given an invited talk at the Summer Solstice Workshop on Complex systems, May 2022.
- Mathilde Bouvel has given invited talks at the London Colloquia in Combinatorics, Queen Mary University, London, (see webpage), and at the Permutation Patterns conference, Valparaiso University, Indiana, USA, (see webpage).

11.1.4 Leadership within the scientific community

Nazim Fatès is the head of the IFIP working group 1.5 on Cellular Automata and Discrete Complex Systems.

11.1.5 Scientific expertise

Romain Péchoux has been expert and referee for the HORIZON MSCA call.

Nazim Fatès was a member of a working group, lead by the INRS Institute[1], which conducted a foresight exercises devoted to the theme "L'intelligence artificielle au service de la santé et sécurité au travail, enjeux et perspectives à l'horizon 2035". The working group, composed of about twenty persons from the academic and industrial areas, presented their work on November 18, 2002, at the Maison de la RATP in Paris, with 90 in-person participants et more than 400 participants online. A 226-page report was produced and a short synthesis document was diffused.

11.1.6 Research administration

- Romain Péchoux is principal investigator of the Inria associate team TC(Pro)^3.
- Christophe Vuillot is the principal investigator of the Inria associated team QASAR, and workpackage leader PEPR NISQ2LSQ.
- Simon Perdrix is coordinator of PEPR EPIQ, WP leader for EQIP Inria Challenge.

11.2 Teaching - Supervision - Juries

- Licence
  - Guilhem Gamard:
    - Systems programming, 42h, L2 and L3 Informatique
    - Databases, 42h, L2 and L3 Informatique
    - Networking, 21h, L3 Informatique
  - Emmanuel Hainry:
    - Algorithmics, 71h, L1, IUT Nancy Brabois.
    - Dynamic Web, 31h, L1, IUT Nancy Brabois.
    - Developing Full Stack Applications, 38h, L1, IUT Nancy Brabois.
    - Automating Operating Systems, 72h, L2, IUT Nancy Brabois.
    - Complexity, 21h, L2, IUT Nancy Brabois.
    - Full Stack Project, 8h, L2, IUT Nancy Brabois.
  - Emmanuel Jeandel:
    - Algorithmics and Programming 1, 60h, L1 Maths-Info

[1] The INRS institute is the reference body for occupational risk prevention in France.

    * Networking, 60h, L2 and L3 Informatique.
    * Functional Programming, 14h, L3 Informatique.
    * System Administration, 24h, Licence Pro Informatique Paysagère.
  - Romain Péchoux:
    * Propositional logic, L1 MIASHS, 35 HETD.
    * Computer architecture, L2 MIASHS, 68 HETD
    * Algorithmic complexity, L3 MIASHS, 37 HETD
  - Julien Provillard
    * Object-oriented programming, L3 Informatique, 44h
- Master
  - Nazim Fatès:
    * Invited professor in the University of Gdansk, Poland. Lectures on cellular automata to Master 2 students (24 hours online, 8 hours in presence)
    * Systèmes distribués adapatifs, Master 2 AVR, université de Lorraine, 12 hours
    * Introduction à l'intelligence artificielle, IAE Nancy School of Management, Marketing et Gestion Commerciale, université de Lorraine, 3h
  - Guilhem Gamard:
    * Networking, 58h, M1 Informatique
  - Isabelle Gnaedig:
    * Rule-based Programming, 28 hours, M2, Telecom-Nancy, Université de Lorraine, Nancy, France.
  - Emmanuel Jeandel:
    * Algorithmics and Complexity, 30h, M1 Informatique
    * Networking, 24h, M1 Informatique
  - Romain Pechoux:
    * OO design and UML, M1 MIASHS, 54 HETD
  - Simon Perdrix:
    * Informatique Quantique, 15h, M2 Telecom Paris Tech
    * Algorithmique Quantique, 4h, M1 UTT.
    * Informatique Quantique, 12h, M1 Informatique
  - Julien Provillard
    * Design patterns, 40h, M1 Informatique
    * Analysis and software design, 23h, M1 Informatique
  - Christophe Vuillot:
    * Informatique Quantique, 12h, M1 Informatique

11.2.1 Supervision

- PhD: Robert Booth, "Formalismes pour la vérification de technologies quantiques", Start: November 2018, Advisors: Damian Markham and Simon Perdrix. Robert defended in February 2022.
- PhD: Margarita Veshchezerova, "Quantum Computing for Combinatorial Optimisation", Start: October 2019, Advisors: Emmanuel Jeandel and Simon Perdrix, joint supervision with Marc Porcheron at EDF (CIFRE). Margarita defended in December 2022.
- PhD in progress: Djamel Eddine Amir, "Computability of subsets of topological spaces", Start: October 2020, Advisors: Emmanuel Jeandel and Mathieu Hoyrup.

- PhD in progress: Agustin Borgna "Vers une formalisation d'une cha^ıne de compilation pour un ordinateur quantique", Start: October 2019, Advisors: Simon Perdrix and Benoit Valiron (LMF).
- PhD in progress: Nathan Claudet, "Structures fondamentales et applications des états graphes et du calcul par mesures", Start: October 2022 (Master internship from March to September 2022), Advisors: Simon Perdrix and Mathilde Bouvel.
- PhD in progress: Alexandre Clément, "Graphical Languages for Quantum Control", Start: September 2019, Advisors: Emmanuel Jeandel and Simon Perdrix.
- PhD in progress, Kinnari Vijay Dave, "Quantum programming with (co)inductive types", Start: November 2022, Advistors: Romain Péchoux and Vladimir Zamdzhiev.
- PhD in progress: Alexandre Guernut, "Efficient Fault-Tolerant Quantum Computation with Quantum LDPC Codes", Start: October 2021, Advisors: Emmanuel Jeandel and Christophe Vuillot.
- PhD in progress: Joannès Guichon, "B2B exchange networks and liquidity-saving mechanism by mutualisation of debt", Start: October 2022, Advisors: Nazim Fatès and Sylvain Contassot-Vivier.
- PhD in progress: Mario Machado Da Silva, "Computational complexity of reversible computations and applications to quantum programming", Start: October 2021, Advisors: Emmanuel Hainry and Romain Péchoux.
- PhD in progress: Benjamin Testart, "Énumération et formes limites des tables d'inversions évitant des motifs", Start: October 2022 (Master internship from March to September 2022), Advisors: Mathilde Bouvel and Emmanuel Jeandel.
- PhD in progress: Vivien Vandaele, "Optimisation du calcul quantique tolérant aux fautes par le ZX-Calculus", Start: September 2021, Advisors: Simon Perdrix and Christophe Vuillot, joint supervision with Simon Martiel at ATOS (CIFRE).

11.2.2 Juries

- Emmanuel Jeandel participated in the PhD defense of Justine Basselin (Université de Lorraine)
- Emmanuel Jeandel reviewed the PhD manuscript of Kostia Chardonnet (Université Paris-Saclay), Quentin Guilmant (Ecole Polytechnique) and Solène Esnay (Université Toulouse III)
- Mathilde Bouvel reviewed the PhD manuscripts of Benoît Corsini (McGill, Montréal, Canada), and of Michal Opler (Charles University, Prague, Czech Republic).
- Simon Perdrix participated in the PhD defense of Amélia Durbec (Aix Marseille Université), of Richard East (Université Grenoble Alpes), and of Adrien Suau (Université Montpellier).

11.3 Popularization

11.3.1 Articles and contents

- Nazim Fatès, « L'intelligence artificielle, un défi pour l'être humain », RCF Nancy, émission « Destination inconnue », interview with Nicolas Dufour, November 2022.
- Nazim Fatès, « Lumière sur l'intelligence artificielle », Podcast Science en Lumière, interview with Véronique Bronner, May 2022.

11.3.2 Education

- Nazim Fatès, « Visite guidée de quelques automates cellulaires liés à la modélisation de phénomènes urbains », online talk for the students of the Classes préparatoires of the lycée Henri-Poincaré, Nancy.

11.3.3 Interventions

- Nazim Fatès, « Le temps passe-t-il pour l'intelligence artificielle ? », Wide-audience conference in the program Sciences et société, Nancy, March 31, 2022.
- Guilhem Gamard and Emmanuel Jeandel, « le puzzle de l'informaticien », stand at the « nuit des chercheur.e.s » science festival, Nancy, September 30, 2022.

12 Scientific production

12.1 Major publications

[1] A. Callard and M. Hoyrup. 'Descriptive complexity on non-Polish spaces'. In: *STACS 2020 - 37th Symposium on Theoretical Aspects of Computer Science*. Ed. by S. D.-.-L.-Z. fuer Informatik. Vol. 154. Montpellier, France, Mar. 2020, p. 16. DOI: 10.4230/LIPIcs.STACS.2020.8. URL: https://hal.inria.fr/hal-02298815.

[2] N. Fatès, V. Chevrier and O. Bouré. 'Is there a trade-off between simplicity and robustness? Illustration on a lattice-gas model of swarming'. In: *Probabilistic Cellular Automata*. Ed. by P.-Y. Louis and F. R. Nardi. Emergence, Complexity and Computation. Springer, 2018. DOI: 10.1007/978-3-319-65558-1_16. URL: https://hal.inria.fr/hal-01230145.

[3] N. Fatès, I. Marcovici and S. Taati. 'Two-dimensional traffic rules and the density classification problem'. In: *International Workshop on Cellular Automata and Discrete Complex Systems, AUTOMATA 2016*. Vol. 9664. Lecture Notes of Computer Science. Zürich, France, June 2016. DOI: 10.1007/978-3-319-39300-1_11. URL: https://hal.inria.fr/hal-01290290.

[4] H. Férée, E. Hainry, M. Hoyrup and R. Péchoux. 'Characterizing polynomial time complexity of stream programs using interpretations'. In: *Journal of Theoretical Computer Science (TCS)* 585 (Jan. 2015), pp. 41–54. DOI: 10.1016/j.tcs.2015.03.008. URL: https://hal.inria.fr/hal-01112160.

[5] I. Gnaedig and H. Kirchner. 'Proving Weak Properties of Rewriting'. In: *Theoretical Computer Science* 412 (2011), pp. 4405–4438. DOI: 10.1016/j.tcs.2011.04.028. URL: http://hal.inria.fr/inria-00592271/en.

[6] E. Hainry, B. Kapron, J.-Y. Marion and R. Péchoux. 'A tier-based typed programming language characterizing Feasible Functionals'. In: *LICS '20 - 35th Annual ACM/IEEE Symposium on Logic in Computer Science*. Saarbrücken, Germany: ACM, July 2020, pp. 535–549. DOI: 10.1145/3373718.3394768. URL: https://hal.inria.fr/hal-02881308.

[7] E. Hainry and R. Péchoux. 'Objects in Polynomial Time'. In: *APLAS 2015*. Ed. by X. Feng and S. Park. Vol. 9458. Lecture Notes in Computer Science. Pohang, South Korea: Springer, Nov. 2015, pp. 387–404. DOI: 10.1007/978-3-319-26529-2_21. URL: https://hal.inria.fr/hal-01206161.

[8] E. Jeandel, S. Perdrix and R. Vilmart. 'A Complete Axiomatisation of the ZX-Calculus for Clifford+T Quantum Mechanics'. In: *The 33rd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2018*. Proceedings of the 33rd Annual ACM/IEEE Symposium on Logic in Computer Science. Oxford, United Kingdom, July 2018, pp. 559–568. DOI: 10.1145/3209108.3209131. URL: https://hal.archives-ouvertes.fr/hal-01529623.

[9] E. Jeandel, S. Perdrix and R. Vilmart. 'Diagrammatic Reasoning beyond Clifford+T Quantum Mechanics'. In: *The 33rd Annual Symposium on Logic in Computer Science*. Proceedings of the 33rd Annual ACM/IEEE Symposium on Logic in Computer Science. Oxford, United Kingdom, July 2018, pp. 569–578. DOI: 10.1145/3209108.3209139. URL: https://hal.archives-ouvertes.fr/hal-01716501.

[10] X. Jia, B. Lindenhovius, M. Mislove and V. Zamdzhiev. 'Commutative Monads for Probabilistic Programming Languages'. In: 2021 36th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS). LICS '21: Proceedings of the 36th Annual ACM/IEEE Symposium on Logic in Computer Science 19. Rome, Italy: IEEE, 29th June 2021, pp. 1–14. DOI: 10.1109/LICS52264.2021.9470611. URL: https://hal.inria.fr/hal-03519225.

12.2 Publications of the year

International journals

[11] F. Bassino, M. Bouvel, M. Drmota, V. Feray, L. Gerin, M. Maazoun and A. Pierrot. 'Linear-sized independent sets in random cographs and increasing subsequences in separable permutations'. In: *Combinatorial Theory* 2.3 (2022), https://escholarship.org/uc/item/23340676. DOI: 10.5070/C62359179. URL: https://hal.archives-ouvertes.fr/hal-03366684.

[12] F. Bassino, M. Bouvel, V. Féray, L. Gerin, M. Maazoun and A. Pierrot. 'Random cographs: Brownian graphon limit and asymptotic degree distribution'. In: *Random Structures and Algorithms* 60.2 (Mar. 2022), pp. 166–200. DOI: 10.1002/rsa.21033. URL: https://hal.archives-ouvertes.fr/hal-02412976.

[13] F. Bassino, M. Bouvel, V. Féray, L. Gerin, M. Maazoun and A. Pierrot. 'Scaling limits of permutation classes with a finite specification: a dichotomy'. In: *Advances in Mathematics* 405 (27th Aug. 2022), p. 108513. DOI: 10.1016/j.aim.2022.108513. URL: https://hal.archives-ouvertes.fr/hal-02412965.

[14] M. Bouvel, L. Cioni and L. Ferrari. 'Preimages under the bubblesort operator'. In: *The Electronic Journal of Combinatorics* 29.4 (18th Nov. 2022), https://www.combinatorics.org/ojs/index.php/eljc/article/view/v29i4p32. DOI: 10.37236/11390. URL: https://hal.archives-ouvertes.fr/hal-03844028.

[15] A. Deutsch, N. A. Fatès and D. Makowiec. 'Discrete models of complex systems: Recent trends and analytical challenges'. In: *Physica D: Nonlinear Phenomena* 436 (Aug. 2022), p. 133328. DOI: 10.1016/j.physd.2022.133328. URL: https://hal.inria.fr/hal-03905157.

[16] E. Hainry, B. Kapron, J.-Y. Marion and R. Péchoux. 'A tier-based typed programming language characterizing Feasible Functionals'. In: *Logical Methods in Computer Science* 18.1 (24th Feb. 2022), p. 31. DOI: 10.46298/LMCS-18(1:33)2022. URL: https://hal.inria.fr/hal-03722168.

[17] M. Hoyrup. 'The fixed-point property for represented spaces'. In: *Annals of Pure and Applied Logic* 173.5 (May 2022). URL: https://hal.inria.fr/hal-03117745.

[18] A. Leverrier, S. Apers and C. Vuillot. 'Quantum XYZ Product Codes'. In: *Quantum* (14th July 2022). DOI: 10.22331/q-2022-07-14-766. URL: https://hal.inria.fr/hal-03108325.

[19] C. Vuillot and N. P. Breuckmann. 'Quantum Pin Codes'. In: *IEEE Transactions on Information Theory* (26th Apr. 2022). DOI: 10.1109/TIT.2022.3170846. URL: https://hal.science/hal-02351417.

International peer-reviewed conferences

[20] D. E. Amir and M. Hoyrup. 'Computability of finite simplicial complexes'. In: ICALP. Paris, France, July 2022. URL: https://hal.inria.fr/hal-03564904.

[21] M. Avanzini, G. Moser, R. Péchoux, S. Perdrix and V. Zamdzhiev. 'Quantum Expectation Transformers for Cost Analysis'. In: Symposium on Logic In Computer Science LICS '22. Haifa, Israel, 2nd Aug. 2022. URL: https://hal.inria.fr/hal-03540366.

[22] A. Clément, N. Heurtel, S. Mansfield, S. Perdrix and B. Valiron. 'LO_v-Calculus: A Graphical Language for Linear Optical Quantum Circuits'. In: *Leibniz International Proceedings in Informatics (LIPIcs)*. 47th International Symposium on Mathematical Foundations of Computer Science (MFCS 2022). Vol. 241. Vienna, Austria, 22nd Aug. 2022, 35:1–35:16. DOI: 10.4230/LIPIcs.MFCS.2022.35. URL: https://hal.science/hal-03926660.

[23] C. Dalyac, L. Henriet, E. Jeandel, W. Lechner, S. Perdrix, M. Porcheron and M. Veshchezerova. 'Qualifying quantum approaches for hard industrial optimization problems. A case study in the field of smart-charging of electric vehicles'. In: ROADEF 2022 - 23ème congrès annuel de la Société Française de Recherche Opérationnelle et d'Aide à la Décision. Villeurbanne - Lyon, France, 23rd Feb. 2022. URL: https://hal.archives-ouvertes.fr/hal-03595391.

[24] E. Hainry, B. M. Kapron, J.-Y. Marion and R. Péchoux. 'Complete and tractable machine-independent characterizations of second-order polytime'. In: FoSSaCS 2022 - 25th International Conference on Foundations of Software Science and Computation Structures. Vol. 13242. Lecture Notes in Computer Science. Munich, Germany: Springer International Publishing, 29th Mar. 2022, pp. 368–388. DOI: 10.1007/978-3-030-99253-8_19. URL: https://hal.inria.fr/hal-03722245.

[25] X. Jia, A. Kornell, B. Lindenhovius, M. Mislove and V. Zamdzhiev. 'Semantics for Variational Quantum Programming'. In: POPL 2022 - 49th ACM SIGPLAN Symposium on Principles of Programming Languages. Philadelphia, United States, 16th Jan. 2022. DOI: 10.1145/3498687. URL: https://hal.inria.fr/hal-03519235.

[26] A. E. Laouir and A. Imine. 'On Privacy of Multidimensional Data Against Aggregate Knowledge Attacks'. In: *Lecture Notes in Computer Science*. PSD 2022 : PRIVACY IN STATISTICAL DATABASES 2022. Vol. 13463. International Conference on Privacy in Statistical Databases, PSD 2022. Paris, France: Springer Cham, 30th Sept. 2022, p. 13. DOI: 10.1007/978-3-031-13945-1_7. URL: https://hal.inria.fr/hal-03917682.

Conferences without proceedings

[27] A. Borgna and R. Romero. 'Encoding High-level Quantum Programs as SZX-diagrams'. In: QPL2022. Oxford, United Kingdom, 27th June 2022. URL: https://hal.archives-ouvertes.fr/hal-03794958.

Scientific book chapters

[28] A. Saint-Jore, N. A. Fatès and E. Jeandel. 'Amoebae for clustering: a bio-inspired cellular automata method for data classification'. In: *Automata and Complexity*. Vol. 42. Springer, Cham, 20th Apr. 2022, pp. 417–432. DOI: 10.1007/978-3-030-92551-2_23. URL: https://hal.inria.fr/hal-02973830.

Edition (books, proceedings, special issue of a journal)

[29] A. Clément and S. Perdrix, eds. *Resource Optimisation of Coherently Controlled Quantum Computations with the PBS-Calculus*. MATHEMATICAL FOUNDATIONS OF COMPUTER SCIENCE. INTERNATIONAL SYMPOSIUM. 47TH 2022. (MFCS 2022) (2 PARTS) 241. 22nd Aug. 2022. DOI: 10.4230/LIPIcs.MFCS.2022.36. URL: https://hal.archives-ouvertes.fr/hal-03926639.

[30] E. Jeandel, S. Perdrix and M. Veshchezerova, eds. *Addition and Differentiation of ZX-Diagrams*. 2022. DOI: 10.4230/LIPIcs.FSCD.2022.13. URL: https://hal.inria.fr/hal-03886288.

Doctoral dissertations and habilitation theses

[31] M. Hoyrup. 'Topological Aspects of Representations in Computable Analysis'. Université de Lorraine, 9th Jan. 2023. URL: https://hal.inria.fr/tel-03932408.

Reports & preprints

[32] M. Albert, M. Bouvel, V. Féray and M. Noy. *Convergence law for 231-avoiding permutations*. 20th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03908625.

[33] D. E. Amir and M. Hoyrup. *Comparing computability in two topologies*. 23rd June 2022. URL: https://hal.inria.fr/hal-03702999.

[34] D. E. Amir and M. Hoyrup. *Strong computable type*. 7th Oct. 2022. URL: https://hal.inria.fr/hal-03806572.

[35] F. Bassino, M. Bouvel, V. Féray, L. Gerin and A. Pierrot. *Scaling limit of graph classes through split decomposition*. 4th Oct. 2022. URL: https://hal.archives-ouvertes.fr/hal-03797906.

[36] R. Booth and T. Carette. *Complete ZX-calculi for the stabiliser fragment in odd prime dimensions*. 29th Apr. 2022. URL: https://hal.archives-ouvertes.fr/hal-03655398.

[37] R. Booth, U. Chabaud and P.-E. Emeriau. *Contextuality and Wigner negativity are equivalent for continuous-variable quantum measurements*. 7th Jan. 2022. URL: https://hal.archives-ouvertes.fr/hal-03516755.

[38] T. G. de Brugière, S. Martiel and C. Vuillot. *A graph-state based synthesis framework for Clifford isometries*. 15th Dec. 2022. URL: https://hal.inria.fr/hal-03902438.

[39] A. Clément, N. Heurtel, S. Mansfield, S. Perdrix and B. Valiron. *A Complete Equational Theory for Quantum Circuits*. 6th Jan. 2023. URL: https://hal.archives-ouvertes.fr/hal-03926757.

[40] L.-J. Dandy, E. Jeandel and V. Zamdzhiev. *Qimaera: Type-safe (Variational) Quantum Programming in Idris*. 10th Jan. 2022. URL: https://hal.inria.fr/hal-03519238.

[41] N. A. Fatès. *An asynchronous cellular system that solves the parity problem*. Inria Nancy Grand-Est, 2022. URL: https://hal.inria.fr/hal-03894581.

[42] E. Hainry, R. Péchoux and M. Silva. *A programming language characterizing quantum polynomial time*. 12th Dec. 2022. URL: https://hal.inria.fr/hal-03895081.

[43] B. Testart. *Inversion sequences avoiding the pattern 010*. 14th Dec. 2022. URL: https://hal.science/hal-03933075.

[44] C. Vuillot. *Planar Floquet Codes*. 7th Feb. 2022. URL: https://hal.inria.fr/hal-03375918.

Other scientific publications

[45] E. Hainry, R. Péchoux and M. Silva. 'An imperative programming language characterizing FBQP'. In: QPL 2022 - Quantum Physics and Logic. Oxford, United Kingdom, 27th June 2022. URL: https://hal.inria.fr/hal-03895106.

12.3 Cited publications

[46] A. Aspect, P. Grangier and G. Roger. 'Experimental tests of realistic local theories via Bell's theorem'. In: *Phys. Rev. Lett.* 47 (1981), p. 460.

[47] C. H. Bennett and G. Brassard. 'Quantum cryptography: Public key distribution and coin tossing'. In: *Proceedings of IEEE international Conference on Computers, Systems and Signal Processing, Bangalore, India*. New York: IEEE Press, 1984, p. 175.

[48] A. Clément and S. Perdrix. 'PBS-Calculus: A Graphical Language for Coherent Control of Quantum Computations'. In: *45th International Symposium on Mathematical Foundations of Computer Science (MFCS 2020)*. Ed. by J. Esparza and D. Kráľ. Vol. 170. Leibniz International Proceedings in Informatics (LIPIcs). Prague, Czech Republic, Aug. 2020, 24:1–24:14. DOI: 10.4230/LIPIcs.MFCS.2020.24. URL: https://hal.archives-ouvertes.fr/hal-02929291.

[49] S. Corteel, M. A. Martinez, C. D. Savage and M. Weselcouch. 'Patterns in Inversion Sequences I'. In: *Discrete Mathematics and Theoretical Computer Science* 18.2 (2016).

[50] E. Farhi, J. Goldstone and S. Gutmann. *A Quantum Approximate Optimization Algorithm*. 2014. arXiv: 1411.4028 [quant-ph].

[51] N. Fatès. 'Solving the decentralised gathering problem with a reaction-diffusion-chemotaxis scheme - Social amoebae as a source of inspiration'. In: *Swarm Intelligence* 4.2 (2010), pp. 91–115. URL: http://dx.doi.org/10.1007/s11721-010-0038-4.

[52] N. A. Fatès, M. Amato and L. Gobbi. 'The economics and algorithmics of an integral settlement procedure on B2B network'. preprint available on SSRN. Dec. 2021. URL: https://hal.inria.fr/hal-03475245.

[53] N. Gauville. 'Système robuste de diagnostic décentralisé à l'aide d'automates cellulaires simples'. MA thesis. Université de Lorraine (Nancy), Sept. 2018. URL: https://hal.inria.fr/hal-01894581.

[54] N. Gauville, N. Fatès and I. Marcovici. 'Diagnostic décentralisé à l'aide d'automates cellulaires'. In: *JFSMA 2019 - 27emes Journées Francophones sur les Systèmes Multi-Agents*. ISBN 9782364937192. Institut de Recherche en informatique de Toulouse et l'Association française pour l'Intelligence Artificielle. Toulouse, France: Cépaduès, July 2019, p. 96–105. URL: https://hal.inria.fr/hal-02195799.

[55] E. Jeandel. 'Strong shift equivalence as a category notion'. working paper or preprint. July 2021. URL: https://hal.inria.fr/hal-03286679.

[56] T. Mansour and M. Shattuck. 'Pattern avoidance in inversion sequences'. In: *Pure Mathematics and Applications* 25.2 (2015), pp. 157–176.

[57] J. R. McClean, J. Romero, R. Babbush and A. Aspuru-Guzik. 'The theory of variational hybrid quantum-classical algorithms'. In: *New Journal of Physics* 18.2 (2016), p. 023023.

[58] A. Peruzzo, J. McClean, P. Shadbolt, M.-H. Yung, X.-Q. Zhou, P. J. Love, A. Aspuru-Guzik and J. L. O'brien. 'A variational eigenvalue solver on a photonic quantum processor'. In: *Nature communications* 5.1 (2014), pp. 1–7.

[59] K. Weihrauch. *Computable Analysis*. Springer, 2000.