RESEARCH CENTRE

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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

Proofs and Verification

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2 Overall objectives

Our research project is positioned to explore the flourishing landscape of computational models, addressing both contemporary challenges and fundamental questions. Our cutting-edge research objectives aim to comprehend the power and limits of these new computation models, analyse their properties, enhance their usability, and understand their asymptotic behavior. This involves establishing the theoretical framework essential for the development of these computation models and facilitating their usage.

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 focuses 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, ...).

In the Mocqua team, we address problems that can lie at the interface with physics, biology, or mathematics. We employ tools and methods originating from computer science, that we sometimes enrich through these interdisciplinary interactions.

3 Research program

The research program of the Mocqua team is focusing on the following three main objectives:

1. **Resource optimization and estimation.** *Optimizing* resources is obviously a constant preoccupation in many circumstances. In computational models, resources are traditionally time (number of program steps) and space (size of memory), but they could be more exotic, such as entanglement or program size. Efficient resource optimization requires a deep understanding of the studied model and its properties. We aim to develop a quantum circuit optimizer based on the fundamental properties of this formalism, particularly the basic algebra of quantum circuits revealed by our recent results on quantum circuit completeness, and also the properties of the ZX-calculus. Another fundamental task in quantum computing is the development of efficient error-correcting codes that are both efficient and frugal enough to correct more errors than those introduced by the extra instructions required to implement them.

   The optimization of resources has a natural and often necessary prerequisite: *resource estimation*. We aim to develop static analysis methods and tools to establish bounds on the resources required by a given program, utilizing methodologies and techniques from the field of Implicit Computational Complexity. Applications are diverse, including the characterization of polynomial time for probabilistic, high-order, or quantum computations.

2. **Establishing power and limits of models of computation.** Beyond the optimization of a particular piece of code, we aim to understand the power and the limits of computational models. For instance, a deeper understanding of the capabilities and limitations of NISQ (noisy intermediate scale quantum) computers currently attracts considerable interest. Another example is our recent result establishing a Rice-like theorem for automata networks, which can represent biological behaviors. Higher-order computation models have inherent limitations due to the potentially infinite nature of their inputs, but the finite amount of time or space resources of the model. One of our objectives is to investigate these limitations, which can often be expressed as a form of continuity of the algorithm w.r.t. its input. Therefore, we are led to study the intimate relationship between computability and topology. Another objective is to understand the extra power, if any, of allowing coherent control in quantum computing.

3. **Description of the asymptotic behavior of discrete structures.** To understand the behavior of a computational model like cellular automata, or discrete structures, like graphs or permutations, one of the main lever is to evaluate their asymptotics. We intend to address this question in several ways.

   One first step is to estimate how many possible configurations a given system can take, which can be challenging. We intend to continue contributing to such questions, developing further some of the methods of enumerative combinatorics, like the generating trees and kernel method.

   Finding efficient ways to *generate* typical large structures is an essential step in the research that aims at describing their asymptotic behavior, and will continue to play an important role in our work, on cellular automata, permutations or quantum graph states, for instance.

   This allows us to follow an experimental approach whose observations help us formulate, and then (dis)prove, conjectures of two kinds. The first kind consists in estimating or bounding the value of a numerical parameter on the object, like the number of attractors or the growth of the number of periodic points. In some sense, here we forget about the underlying object, and keep only the parameter relevant to the problem studied. The second kind consists in describing the global behavior of the object or system itself as size or time goes to infinity, like the convergence of cellular automata, or the limit shapes of constrained graphs, permutations or other related objects like inversion sequences. Here, on the contrary, we keep the object or system entirely, but consider it only “from far”, forgetting irrelevant details.

To achieve these ambitious objectives, we will build upon the current team structure, which has demonstrated its efficiency in the previous period, focusing on three key axes:

- **Research axis 1: Quantum stack.** Graphical quantum languages like quantum circuits, ZX-calculus, linear optical languages; quantum error correcting codes; models of quantum computing.
- **Research axis 2: Higher order computing.** Static analysis of quantum, probabilistic, or classical programs; computability; quantum coherent control.
- **Research axis 3: Dynamical systems.** Cellular automata; tilings; automata networks; combinatorial/discrete objects.

4 Application domains

4.1 Axis 1: Quantum Stack

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 international industry players have embarked on a dramatic race, mobilizing huge resources, like IBM, Microsoft, Google. Several strat ups have been created recently, including French ones like Quandela, Pasqual and Alice&Bob. Some states have launched ambitious national programs, including the European Union, with the 10-year FET Flagship program in Quantum Engineering, and France with the Plan Quantique.

The development of the quantum stack is of key importance in the current development of the quantum computer and has a key role in the community with a strong complementarity with the development of quantum technologies. One can cite the study of computational models, like measurement-based quantum computing or optical quantum computing; progresses in fault tolerent quantum computing; and optimisation of codes as key applications.

4.2 Axis 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.

Higher-order computing provides a model for computations involving real numbers and other mathematical objects that cannot be finitely represented. Indeed, such infinite objects can be encoded as functions or streams of bits, which can then be given as inputs to a higher-order program. This method raises many questions, such as the impact of the encoding on the solvability and complexity of problems, and its relationship with the mathematical structures underlying the spaces of objects, such as a topology or a partial order.

Quantum programming languages and static analysis are of both theoretical and practical importance in the development of quantum computers, addressing an increasing number of considerations.

4.3 Axis 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. 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. 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.). 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 modeling 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 recent past with EDF though a CIFRE PhD on quantum algorithms for optimisation problems with applications in fleet electric vehicle charging. Some members of the team are participating to the Quantum Energy Initiative.

6 Highlights of the year

- The quantum circuit model is ubiquitous in quantum computing. In recent years, we have introduced the first complete equational theory for quantum circuits [72, 42]. Solving this problem, which was open for more than 30 years, opens new avenues for quantum circuit transformations, including circuit optimisation and hardware constraint satisfaction. This year we have greatly simplified this axiomatisation, by removing large and non-intuitive equations, leading to an equational theory that we have proved to be minimal (each equation is provably underivable from the other ones). To our knowledge, this is the first minimality result for a quantum language. This simplification, presented at LICS'24 [41], demonstrates that equations acting on an unbounded number of qubits are necessary for quantum reasoning. It also eases the practical applications of circuit rewritings.

- Noninterference-based type disciplines were introduced in the field of implicit computational complexity in 2011 and have since been successfully applied to ensure complexity properties of programs (bounded runtime, bounded memory). This approach in particular yielded characterizations of complexity classes such as FPtime (functions computable in polynomial time), FPspace (polynomial space), and BFF (tractable functions of second order) in various paradigms including imperative programs, parallel programs, or object oriented programs. This year, we introduced a declassification policy in this framework, presented at LICS'24 [45]. Declassifying allows to relax the noninterference constraints but poses problems as, for example, declassifying a single bit in a loop already allows to generate exponential functions. We designed the semantics and typing of the declassifying construct so that we still manage to define languages allowing declassification in loops that characterize exactly FPtime and BFF respectively.

- In many problems on point sets in discrete geometry, the exact coordinates of the points are not the most relevant data. Instead, the solution to the problem depends only on the relative positions of the points among themselves. The abstract objects describing these point sets through the relative positions of their points are called order types, or chirotopes, and have been extensively studied, see e.g. [67]. In our work [36], joint with members of Gamble and IECL and presented at SOCG 2024, we introduce a new approach for the study of chirotopes. Namely, we bring to this context the idea of substitution decomposition for discrete structures, introduced by Möhring and Radermacher [79], and whose further developments as modular decomposition of graphs and substitution decomposition of permutations have had applications in algorithms, combinatorics, and probability. Some details on the results we obtained can be found in Section 8.3.4 below, but the most important contribution is certainly to set the foundations for a new and original approach to the study of chirotopes, which opens avenues for future works on these objets.

7 New software, platforms, open data

7.1 New software

7.1.1 FiatLux

Keywords: Cellular automaton, Multi-agent, Distributed systems, Numerical simulations

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.

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

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8 New results

8.1 Quantum stack

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Quantum software is crucial in the development of the quantum computer. In the Mocqua team, we contribute to the development of the quantum stack with several complementary results, from models of quantum computation, to quantum circuits and error correcting codes.

8.1.1 Quantum Circuits

The *quantum circuit* model is the most standard model of quantum computing. Quantum circuits are ubiquitous in quantum computing, serving as both a low-level language and, surprisingly, a higher-level language used to describe certain quantum algorithms. We have introduced the first complete equational theory for quantum circuits, for reasoning on quantum circuits; we have also introduced new techniques for quantum circuit optimisation.

Completeness for Quantum Circuits. With the current advances in quantum technologies and quantum software, it is essential to develop formalisms for transforming and reasoning about quantum circuits. This is crucial for optimizing their size or depth, adapting code to architectural constraints, making it fault-tolerant, or verifying the equivalence of two circuits.

To achieve these goals, quantum circuits can be equipped with equational theories that enable the transformation of circuits using rules that are preferably simple and intuitive. These rules allow the replacement of a circuit fragment with an equivalent circuit. An equational theory is considered complete when, for any pair of circuits representing the same quantum evolution, there is a way to transform one into the other using only the rules of the equational theory.

We have recently introduced the first complete equational theory for quantum circuits [72], a problem which was open for more than 30 years. Indeed the only fragments equipped with a complete equational theory before, were non-universal and efficiently classically simulatable [80, 65, 66, 77]. This year we have extended this completeness results to more expressive models of quantum circuits including ancillary qubits and quantum measurements . This result has been presented at CSL'24 [42]. Finally, we have introduced a minimal equational theory for vanilla quantum circuits (i.e. the standard model of quantum circuits without ancillary qubits) that we have proved to be minimal, i.e. each rule is necessary for the completeness [41] that has been presented at LICS 2024. One of the main and original contributions of this paper is demonstrating that the use of a rule acting on an unbounded number of qubits is necessary for completeness.

Hadamard count minimization in Clifford+T circuits. We have introduced an algorithm which essentially optimally minimizes the number of Hadamard in a Clifford+T circuit. 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 (that consists in replacing a Hadamard with a few other operations requiring in particular an extra qubit). In both cases minimizing the number of Hadamard gate in the circuit beforehand can also help reducing the number of T gates overall.

This work has been done in collaboration with Simon Martiel (Atos), and has been publish in the ACM journal Transactions on Quantum Computing [81].

8.1.2 Quantum error correcting codes and fault-tolerance

Quantum error correcting codes are crucial in the quest of a fault-tolerant large-scale quantum computer. We have contributed to the development of fault-tolerant logical gates on toric codes, we have also introduced a new family of multimode bosonic codes, the quantum tiger codes, which opens up a new avenue in the field of bosonic codes to find efficient multimode bosonic codes with the promise of reducing hardware cost of quantum error correction.

Fault-tolerant Clifford gates on toric codes. Quantum error correcting codes 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 qubits needed. The savings come at the price of more complex procedures for the implementation of gates on logical qubits within the code. Alexandre Guernut for his PhD proposed a set of constant depth, fault-tolerant gates generating the Clifford group acting on copies of the toric code and evaluated the performance of these gates. The set combines several techniques, such as transversal and fold-transversal gates as well as instantaneous Dehn twists and shows very good performance. The preprint is awaiting review, [54].

Tiger codes. 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. The work [63] is a collaboration with Yijia Xu (University of Maryland), Yixu Wang (Tsinghua University) and Victor Albert (University of Maryland). Following-up on previous work which introduced quantum rotor codes [34], this work introduced tiger codes, showing how rotor codes could be embedded into bosonic modes to give multimode bosonic codes. Many pre-existing isolated examples of bosonic codes are subsumed by this new framework which also opens a big avenue for finding new codes. Because of their similarities with existing codes already implemented today, there is a clear path to have them implemented in practice in the future. Understanding the error correcting properties of these tiger codes can be done by directly studying the properties of the underlying rotor code which makes the search for new codes simplified.

Quantum error correcting codes are crucial in the quest of a fault-tolerant large-scale quantum computer. We have contributed to the development of surface codes, we have also introduced a new family of quantum codes, the quantum rotor codes, finally and may be more surprisingly, we have shown that minimalist error correcting codes can be used in near-term experiments for demonstrating a separation between classical and quantum computers.

Fault-tolerant Clifford gates on toric codes. Quantum error correcting codes 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 qubits 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 gate between the logical qubits of the handle. Alexandre Guernut for his PhD studied the generalization of Dehn-twists to other 2D codes, namely color codes. We discovered that in practice for small system size the color code Dehn twists were spreading too much the noise. Therefore we switched gears by unfolding the color code to two copies of the toric code and set out to design and evaluate the performance of a generating set of the Clifford group on toric codes that would have a constant-depth implementation. The numerical results are now promising and a paper is in preparation.

Quantum rotor codes. The work [34] 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 has 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 as 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. This was submitted and accepted for publication in Communication in Mathematical Physics.

Robust Sparse IQP Sampling in Constant depth. In collaboration with the Inria teams Quantic and Cosmiq we studied the problem of making the sparse instantaneous quantum polynomial-time (IQP) sampling problem robust to noise and constant depth, therefore making it more accessible to near-term experiments. Sparse IQP sampling problems are problems that are demonstrably hard to sample from with a classical computer but straightforward for a quantum computer and hence candidates for demonstration of quantum advantage. The problem is that convincing advantage needs to be able to scale up the quantum circuit which cannot be done in the presence of noise. This work shows how to use the minimal amount of quantum error correction necessary to be able to scale while correcting errors. This work has been accepted for a plenary talk at the QIP2024 conference [46].

8.1.3 Graph states and Measurement-based quantum computing

There are various models of quantum computation. Whereas unitary evolutions are at the heart of the standard model of quantum computing, measurement-based quantum computing (MBQC) is an alternative model introduced more than 20 years ago, which consists in performing quantum measurements over a large entangled initial resource called a *graph state*. This year, we solved an open problem concerning the graphical characterization of entanglement in graph states, contributed to advancements in measurement-based quantum computing (MBQC), and made progress on a recent graph-state-based protocol called k-parability, which serves as a primitive for distributed quantum computing.

Graphical characterisation of entanglement graph states. Two graph states have the same entanglement if they can be transformed in each other by means of local unitary transformations. Whereas it is well known that local complementation, preserve entanglement, the converse is however not true: in 2007 [74] an example of two graphs that represent the same entanglement but cannot be transformed into each other by means of local complementations has been pointing out, leaving as an open question a graphical characterisation of entanglement for graph states . We have introduced this year a generalisation of local complementation that captures the entanglement of graph states [40]. This result has been accepted at STAC 2025 and will also be presented at QIP 2025, the main conference in quantum computing. This graphical characterisation of entanglement is strongly based on a particular graph structure called minimal local set cover for which we have introduced an efficient algorithm this year, presented at WG'24 as a purely graph theory result [39]. Notice that our algorithm for minimal local set cover has been used recently by Adam Burchardt, Jarn de Jong, Lina Vandré for introducing an algorithm for deciding the entanglement equivalence of graph states [69].

Small pairable states and Vertex minor universality. A k-pairable n-qubit state is a resource state that allows Local Operations and Classical Communication (LOCC) protocols to generate pairs of maximally entangled 2-qubit states among any k-disjoint pairs of the n qubits. The best known resource states, introduced by Bravyi et al. [68], had a number of qubits growing exponentially with the parameter k. We have shown the existence of 'small' pairable quantum states with a number n of qubits polynomial in k. We have also established bounds on the pairability, relating this quantity to other graph parameters, in particular the local minimal degree. We have also extended the notion of pairability to vertex minor universality, a natural graph property. A preliminary work on this subject has been done in collaboration with Mehdi Mhalla (LIG, Grenoble) [71]. We then extended the results with Stéphan Thomassé (LIP, ENS Lyon), Valentin Savin and Maxime Cautrès (CEA Grenoble), leading to a publication at ICALP 2024 [70].

Algebraic formulation of Pauli flow. A measurement-based quantum computation must satisfy so-called flow properties in order to be implementable in a robustly deterministic way. It is known how to find flow structures in polynomial time when they exist; nevertheless, their lengthy and complex definitions often hinder working with them. We simplified these definitions by providing a new linear algebraic formulation of Pauli flow, the most general type of flow, in terms of properties of two matrices arising from the adjacency matrix of the underlying graph. Using this formulation, we obtained $\mathcal{O}(n^3)$ algorithms for finding Pauli flow, improving on previously-known algorithms; we also proved that these new algorithms are optimal barring progress in the computational complexity of matrix multiplication. This work was done in collaboration with Piotr Mitosek (University of Birmingham) [60].

8.2 Higher order computing

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Our results on Axis 2 are mainly twofold: (1) the development of programming languages, and in particular their use for static analysis of resources; and (2) the computability over topological spaces, as well as a characterisation of polynomial time in object-oriented programming languages.

8.2.1 Resource analysis of quantum programs

In [35], we have studied quantitative properties of quantum programs. Properties of interest include (positive) almost-sure termination, expected runtime or expected cost, that is, for example, the expected number of applications of a given quantum gate, etc. After studying the completeness of these problems in the arithmetical hierarchy over the Clifford+T fragment of quantum mechanics, we have expressed these problems using a variation of a quantum pre-expectation transformer, a weakest pre-condition based technique that allows to symbolically compute these quantitative properties. Under a smooth restriction—a restriction to polynomials of bounded degree over a real closed field—we show that the quantitative problem, which consists in finding an upper-bound to the pre-expectation, can be decided in time double-exponential in the size of a program, thus providing, despite its great complexity, one of the first decidable results on the analysis and verification of quantum programs. Finally, we sketch how the latter can be transformed into an efficient synthesis method.

8.2.2 Computable type

In [29] we have solved an open problem about a computability property of compact spaces called computable type. We have shown that this property is not closed under finite products. In order to build a counter-example, we have proved a characterization of this property in terms of homotopy of functions from a space to a sphere.

Our work on reducing the comparison between two computability notions to a comparison between two topologies, mentioned in the previous report, has been published in [28].

8.2.3 Presentations of topological spaces

In [59] we have studied a notion of presentation of countably-based topological spaces. We have surprisingly shown that every such space has a computable presentation.

8.2.4 Declassification policy for complexity analysis

In [45], we improved the expressivity of noninterference techniques for complexity by introducing a controlled declassification instruction. Noninterference-based type systems statically guarantee, via soundness, the property that welltyped programs compute functions of a given complexity class, e.g., the class FP of functions computable in polynomial time. These characterizations are also extensionally complete – they capture all functions – but are not intensionally complete as some polytime algorithms are rejected. This impact on expressive power is an unavoidable cost of achieving a tractable characterization. To circumvent this issue, an avenue arising from security applications is to find a relaxation of noninterference based on a declassification mechanism that allows critical data to be released in a safe and controlled manner. Following this path, we presented a new and intuitive declassification policy preserving FP-soundness and capturing strictly more programs than existing noninterference-based systems. We show the versatility of the approach: it also provides a new characterization of the class BFF of second-order polynomial time computable functions in a second-order imperative language, with first-order procedure calls. Type inference is tractable: it can be done in polynomial time.

8.3 Dynamical systems and combinatorics

Participants: Mathilde Bouvel, Nazim Fatès, Guilhem Gamard, Joannès Guichon, Mathieu Hoyrup, Emmanuel Jeandel, Julien Provillard, Benjamin Testart.

Regarding Axis 3 of the team, we have contributions on probabilistic cellular automata, on probabilistic and enumerative combinatorics, and also in analysis of graphs in the field of economics. The latter have been developed in the context of the exploratory research action Murene.

8.3.1 Probabilistic cellular automata for problem solving

We presented two stochastic cellular automata that classify the parity of initial conditions [43]. The model is an interacting particles system where cells are updated by pairs, randomly chosen at each time step. A first rule was proposed, with a symmetry between 0's and 1's. This rule classifies the parity of the initial configurations thanks to a non-biased random walk of the frontiers between 0's and 1's. We presented an analysis of the classification time, as well as numerical simulations, to establish that the classification time scales quadratically with the number of cells. In a second time, breaking the state symmetry, we proposed an improvement of this rule with the simultaneous use of two classifying systems. This work was presented at AUTOMATA 2024, the 30th International Workshop on Cellular Automata and Discrete Complex Systems [43].

8.3.2 Classification of asynchronous cellular automata

Reversibility is a well-studied property for deterministic cellular automata but it is only partially explored when randomness appears in the update. We presented a detailed study of 21 finite-size elementary cellular automata with a fully asynchronous updating and periodic boundary conditions [32]. We estimated their degree of reversibility by counting the number of recurrent configurations as a function of the size of the automaton (number of cells). We showed that these rules exhibit various qualitative behaviours: some rules show a "strong reversibility" with a number of recurrent configurations that grows exponentially, while other rules have a "weak reversibility" with a linear growth. We also analysed the structure of the communication graph and report various scaling relations for the number of recurrent communication classes. We identified the cases where the divisibility of the size by 2 or 3 introduces some discontinuities in the behaviour. This study completes the characterization of the 256 elementary cellular automata with regard to their recurrence properties. These results were published in *Theoretical Computer Science* [32].

8.3.3 Enumerative or bijective combinatorics

Enumeration of pattern-avoiding inversion sequences. The results presented here have been obtained by Benjamin Testart during his PhD thesis (which started in 2022, and is running until 2025). 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 [78, 73], which 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 Kotsireas, Mansour and Yildirim [76].

In a 2022 preprint (not meant for publication, and subsumed by [61]), Benjamin solves the final case by making use of a decomposition of inversion sequences avoiding the pattern 010 according to original parameters. The method is then expanded to solve the enumeration of inversion sequences avoiding several pairs of patterns containing 010, most of the time solving also the enumeration of some family of constrained words as an auxiliary problem.

In his paper [61] (that is currently submitted to a journal), Benjamin in addition managed to obtain all missing enumerations for inversion sequences avoiding a pair of patterns of size 3 (17 such families in total). To achieve this, Benjamin has used in original ways the (established) method of generating trees in a few cases, and has otherwise used several decompositions of inversion sequences that he introduced.

Benjamin has a second paper currently submitted (to the DMTCS special issue that follows the conference *Permutation Patterns 2024*). In this paper [62], he focuses on proving algebraicity of generating functions using generating trees. More precisely, Benjamin studies two families of inversion sequences, provides a generating tree construction (which is original), and derives from it their algebraic generating function. (Although one case was know by another approach, the second one was only conjectured so far.) As expected in works of this type, the kernel method comes into play, but remarkably involves some original aspects that may well be useful elsewhere.

Enumeration of pattern-avoiding alternating sign matrices. Permutations can be described as square binary matrices containing exactly one 1 in each row and each column (using their classical permutation matrix representation). A common generalization of permutations consists in allowing entries 0, 1 and -1 in square matrices, imposing that in each row (resp. column), the non-zero entries alternate in sign and sum to 1. These objects are called alternating sign matrices (ASMs), and their study has been a challenging topic in enumerative combinatorics for the past four decades. However, so far, it seems that there have been very few studies of pattern-avoidance in ASMs, while this is a classical and rich topic in the combinatorics of permutations.

Therefore, in a collaborative project involving ASM experts and permutation patterns experts , we have explored the topic of pattern-avoiding ASMs. There are two different and natural ways to do so, which resulted in two different preprints this year.

The first one [52], coauthored by M. Bouvel with R. Smith and J. Striker, investigates the notion that we name *key-avoidance* in ASMs. Indeed, there is a classical procedure in the ASMs literature, that associates to each ASM a permutation, called its *key*. In this work, we enumerate ASMs whose key avoids a given set of permutation patterns in several instances. We show that ASMs whose key avoids 231 are permutations, thus the many known enumerations for a set of permutation patterns including 231 extends to ASMs. We furthermore enumerate by the Catalan numbers ASMs whose key avoids both 312 and 321. We also show ASMs whose key avoids 312 are in bijection with the gapless monotone triangles defined by Ayyer, Cori and Gouyou-Beauchamps in 2011. Thus key-avoidance generalizes the notion of 312-avoidance studied there, answering a question left open in their work. Finally, we enumerate ASMs with a given key avoiding 312 and 321 using a connection to Schubert polynomials, thereby deriving an interesting Catalan identity.

The second one [48], coauthored by M. Bouvel with E. Egge, R. Smith, J. Striker and J. Troyka, focuses on another way of defining avoidance of patterns in ASMs, by looking at submatrices, and which we refer to as *classical avoidance*. This has already appeared once in the literature, in a paper by Johansson and Linusson in 2007 [75]. We completely classify the asymptotic behavior of the number of ASMs classically avoiding a single permutation pattern. In particular, we give a uniform proof of an exponential upper bound for the number of ASMs classically avoiding one of twelve particular patterns, and a super-exponential lower bound for all other single-pattern avoidance classes. We also show that for any fixed integer k, there is an exponential upper bound for the number of ASMs that classically avoid any single permutation pattern and contain precisely k negative ones. Finally, we prove that there must be at most 3 negative ones in an ASM which classically avoids both 2143 and 3412, and we exactly enumerate the number of them with precisely 3 negative ones.

The middle order on permutations Two extremely well-known partial orders exist on permutations of any given size: the Bruhat order, and the weak order. In this joint work [50] of M. Bouvel with L. Ferrari and B. Tenner, we introduce a third natural such partial order. Specifically, we define a partial order P_n on permutations of any given size n, which is the image of a natural partial order on inversion sequences.

We call this the “middle order”. We demonstrate that the poset P_n refines the weak order on permutations and admits the Bruhat order as a refinement, justifying the terminology. These middle orders are distributive lattices and we establish some of their combinatorial properties, including characterization and enumeration of intervals and boolean intervals (in general, or of any given rank), and a combinatorial interpretation of their Euler characteristic. We further study the (not so well-behaved) restriction of this poset to involutions, obtaining a simple formula for the Möbius function of principal order ideals there.

8.3.4 Probabilistic or geometric combinatorics

Scaling limits of families of intersection graphs. This is the latest result of a collaboration of M. Bouvel 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) which started over ten years ago. The purpose of this collaboration is to establish limit shape results for combinatorial structures (like permutations or graphs) constrained by the avoidance of substructures, often using methods from analytic combinatorics (which is original in the landscape of the research on this topic).

In [47], we obtain the scaling limits of random graphs drawn uniformly in three families of intersection graphs: permutation graphs, circle graphs, and unit interval graphs. The two first families typically generate dense graphs (with a quadratic number of edges), and in these cases we prove almost sure convergence to an explicit deterministic graphon. Uniform unit interval graphs are nondense and we prove convergence in the sense of Gromov–Prokhorov after normalization of the distances.

Our newer project, started during the past year, goes back to permutations. It aims at describing limit shapes (precisely, limiting *permutons* – which are the analogues of graphons in this context) of uniform permutations in classes defined by the avoidance of any two patterns of size 4.

Record-biased permutations. With C. Nicaud and C. Pivoteau, M. Bouvel has had an on-going project for several years, focused on the study of a non-uniform distribution on permutations biased by their number of records that we call *record-biased permutations*. This project has come to a conclusion with the article [51]. There, we give several generative processes for record-biased permutations, explaining also how they can be used to devise efficient (linear) random samplers. For several classical permutation statistics, we obtain their expectation using the above generative processes, as well as their limit distributions in the regime that has a logarithmic number of records (as in the uniform case). Finally, increasing the bias to obtain a regime with an expected linear number of records, we establish the convergence of record-biased permutations to a deterministic permuton, which we fully characterize.

Decomposition of order types, with applications to counting problems. This topic, at the interface of combinatorics and discrete geometry, has emerged as the result of a collaboration between several teams in Nancy, and involves M. Bouvel, V. Feray (IECL, Université de Lorraine), X. Goaoc (Gamble) and F. Koechlin (post-doc with X. Goaoc and V. Feray until September 2023). It is presented in a long preprint [49], and has been accepted as a talk at the conference SOCG, one of the main conferences in discrete geomery [36]. In this work, we introduce and study an original notion of decomposition of planar point sets (or rather of their chirotopes, also called order types) as trees decorated by smaller chirotopes. This decomposition is based on the concept of mutually avoiding sets, and adapts in some sense the modular decomposition of graphs (or its cousin the substitution decomposition of permutations) in the world of chirotopes. We prove that the associated tree always exists and is unique up to some appropriate constraints. We also show how to compute the number of triangulations of a chirotope efficiently, starting from its tree and the (weighted) numbers of triangulations of its parts.

8.3.5 Analysis of graphs in the field of economics

In economy, a major issue is the potential lack of liquidity for settling the debts generated by payment delays among companies. 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. 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.

We compared different methods to detect structures or communities that could be helpful for debt netting algorithms. The structure of such networks is not currently well known. We give hints on how to sort and identify the type of B2B invoice graphs. In particular, we addressed the possibility to identify relevant communities in such networks. This work was presented in 2023 in the conference Complex networks and it was published in 2024 [44]. In 2024, we focused on developing debt netting algorithms and assessing their performance under various parameter settings, guided by specific economic constraints and expectations.

8.3.6 Local generation of tilings

Mathieu Hoyrup and Tom Favereau, during a research initiation internship, studied the possibility of generating tilings in a local way. We have proposed two definitions capturing this intuition and developed techniques to classify tilings according to these definitions. We have started a systematic classification of small Wang tilesets. The results are written in [57] and [58], currently submitted.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Emmanuel Jeandel, Simon Perdrix, Christophe Vuillot.

The team is currently supervising two CIFRE PhD:

- In collaboration with Atos/Eviden, which started in 2021: 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 Cyril Allouche from ATOS.
- In collaboration with Quandela, which started in 2024: Sébastien Draux, is working on "Cadre formel pour l'informatique quantique photonique" under the supervision of Simon Perdrix and Emmanuel Jeandel from the team, and Shane Mansfield from 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 ->

Coordinator: Nikolas Breuckmann (n.breuckmann@ucl.ac.uk)

Partners:

- University College London London (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 -> 2024

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 TCPro^3 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.

10.2 International research visitors

10.2.1 Visits to international teams

Research stays abroad

Nazim Fates

Visited institution: Universidad Adolfo Ibañez

Country: Chile

Dates: Oct. 7 - Oct. 29, 2024.

Context of the visit: collaboration

Mobility program/type of mobility: research stay

Nazim Fates

Visited institution: University of Florence and IFNF

Country: Italy

Dates: Nov. 28 - Dec. 11, 2024.

Context of the visit: collaboration

Mobility program/type of mobility: research stay

10.3 European initiatives

10.3.1 Horizon Europe

QCOMICAL

Participants: Alejandro Díaz-Caro, Simon Perdrix.

QCOMICAL project on cordis.europa.eu

Title: Quantum Computing and its Calculi

Duration: From December 1, 2024 to November 30, 2028

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- UNIVERSITA DEGLI STUDI DI CAGLIARI (UNICA), Italy
- UNIVERSIDAD DE LA REPUBLICA (UdelaR), Uruguay
- UNIVERSITA DI PISA (UNIPI), Italy
- UNIVERSITE GRENOBLE ALPES (UGA), France
- UNIVERSIDAD DE BUENOS AIRES (BUENOSAIRES UNIVERSITY), Argentina
- UNIVERSITE PARIS XII VAL DE MARNE (UPEC), France
- QUANDELA, France
- UNIVERSIDAD NACIONAL DE QUILMES (UNQ), Argentina
- UNIVERSITE PARIS CITE (UPCité), France
- UNIVERSITE PARIS-SACLAY, France
- UNIVERSITE D'AIX MARSEILLE (AMU), France
- CENTRALESUPELEC, France
- Universita' degli Studi di Urbino Carlo Bo (UNIURB), Italy

Inria contact: Simon Perdrix

Coordinator: Benoît Valiron and Alejandro Díaz-Caro

Summary: Quantum computing can be thought of in multiple ways. Among those ways, it can be seen as a computational model of quantum mechanics. Studying this model may have implications for our understanding of physics. It can also be seen as a new computational paradigm, with implications for computation, algorithms, and logic. Additionally, it can be viewed as a computational device that requires programming. Therefore, it is necessary to design and study programming languages for this purpose. The study of the foundations of quantum programming languages, type theory, and logic through the Curry-Howard correspondence may shed light on our understanding of quantum mechanics. Furthermore, it may lead to the development of new logics or the understanding of new structures in classical logic. Lastly, implementing these languages will enhance the way we program the new computers when they become widely used.

In this project, we propose to study these various aspects of quantum computing, specifically focusing on the foundations of programming languages.

10.3.2 H2020 projects

HPCQS

Participants: Simon Perdrix, Christophe Vuillot.

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
- UNIVERSITY OF GALWAY (OLLSCOIL NA GAILLIMHE), Ireland
- FORSCHUNGSZENTRUM JULICH GMBH (FZJ), Germany
- PARITY QUANTUM COMPUTING GMBH (ParityQC), Austria
- FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV (Fraunhofer), Germany
- COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (CEA), France
- EURICE EUROPEAN RESEARCH AND PROJECT OFFICE GMBH, Germany
- CONSIGLIO NAZIONALE DELLE RICERCHE (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
- CENTRALESUPELEC, France
- BARCELONA SUPERCOMPUTING CENTER CENTRO NACIONAL DE SUPERCOMPUTACION (BSC CNS), Spain
- SORBONNE UNIVERSITE, France

Inria contact: Luc Giraud

Coordinator:

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 Alarice (ANR-24-CE48-7504)

Title: Bornes de complexité générales pour les systèmes dynamiques finis

Duration: Jan. 2025 – Dec. 2030

Coordinator: Kévin Perrot

Local members: Guilhem Gamard

Summary: We endeavor to prove meta-theorems giving general lower bounds on the complexity of vast classes of problems whose input is a finite dynamical systems. In a sense, those theorems would emulate the Rice theorem in the finite world (thence undecidability is replaced with NP-completeness).

Total Amount: 350,000€

ANR LOUCCOUM (ANR-24-CD40-7809)

Title: Large Objects Under Combinatorial Constraints and Outside Uniform Models

Duration: Jan. 2025 – Dec. 2029

Coordinator: Lucas Gerin

Local members: Mathilde Bouvel, Benjamin Testart

Summary: The study of random combinatorial structures (such as trees, graphs, words and permutations) is a very active field of research, with motivations and applications in a wide variety of fields: computer science, biology, physics, complex systems, etc.

In all these contexts, randomness is often used to model unknown characteristics of the problem. Often, questions can be reduced to the following: given a family of combinatorial objects and an integer n, what are the typical properties of a random object of size n (possibly, as n tends to infinity)?

This question has led to profound and varied results concerning the asymptotic behavior of uniform graphs, permutations, trees, . . .

However, this raises the question of the choice of probability distributions on our combinatorial objects. This project aims to study *non-uniform* random models, in particular around permutations and related objects (trees, graphs).

The non-uniform schemes considered here are of different natures, like:

- biased distributions with respect to certain combinatorial parameters;
- multiple conditioning: objects conditioned both by size and by other simple parameters;
- combinatorial structures constrained to avoid patterns.

Total Amount: 384,817€

10.4.2 Other initiatives

PEPR EPIQ - Plan Quantique

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

Duration: Jan. 2022 - Dec 2027

Coordinator: Simon Perdrix

Local Members : Miriam Backens, Guilhem Gamard, Emmanuel Hainry, Emmanuel Jeandel, Romain Péchoux, Simon Perdrix, Christophe Vuillot.

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, Université de Lorraine, CentraleSupelec, Université Paris-Saclay, Ecole Nationale des Ponts et Chaussées, Université Paris Cité

Summary: 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.

Total Amount: 13,5 million euros

PEPR NISQ2LSQ - Plan Quantique

Title: NISQ2LSQ

Duration: Jan. 2022 - Dec 2027

Coordinator: Anthony Leverrier (Cosmiq, Inria Paris)

Local Coordinator: Christophe Vuillot

Local Members: Nazim Fates, Emmanuel Jeandel, Simon Perdrix, Christophe Vuillot

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)

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.

Total Amount: 10 million euros

HQI - Plan Quantique

Title: HQI

Duration: Apr. 2022 - Apr. 2027

Coordinator: Jacques-Charles Lafoucrière (CEA)

Local Coordinator: Simon Perdrix

Local Members: Romain Péchoux, Simon Perdrix, Christophe Vuillot

Partner Institution(s): CEA, Inria, CNRS, Centre de Physique Théorique, Sorbonne Université, Université Grenoble Alpes, Université Paris-Saclay, Université de Bordeaux, École Normale Supérieure, École Normale Supérieure de Lyon, École nationale supérieure de techniques avancées, Atos-Bull SAS (Eviden (formerly Atos)), Grand equipement national de calcul intensif, Quandela SAS, Qubit Phamarceuticals, VeriQloud, WeLinQ.

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.

Total Amount: 36 million euros

10.5 Regional initiatives

Maquest - Maison du Quantique Grand Est

Title: Maquest

Duration: Jan. 2025 - Dec. 2027

Coordinator: Guido Pupillo (Unistra)

Local Coordinator: Simon Perdrix

Local Members: Simon Perdrix, Miriam Backens

Partner Institution(s): Unistra, UTT Troyes, URCA Reims, Centre Inria de l'Université de Lorraine

Summary: The mission of the Maison du Quantique du Grand Est - MaQuEst project is to consolidate and position and strategically position the Grand Est region as a leading centre in the national and European high-performance computing (HPC) and quantum computing landscape. (HPC) and quantum computing, with 3 physical sites and 3 antennae to cover the region. The Grand Est region is home to a booming quantum ecosystem, characterised by cutting-edge research and educational educational programmes, cross-border collaboration and established multidisciplinary quantum established multidisciplinary quantum computing initiatives. The MaQuEst project represents an opportunity to increase awareness and to develop use cases that can drive advances in the region's biotechnology, artificial intelligence and nanotechnology industries. and finance industries, and thus help to strengthen France's position as a world leader in hybrid in hybrid computing. MaQuEst aims to develop collaborations between the worlds of industry and business entrepreneurial world, i.e. potential users of quantum technologies, and the academic world in the the Grand Est region, also involving quantum technology suppliers and facilitators. quantum technologies. Ultimately, this 'Maison du Quantique du Grand-Est' will encourage the adoption of quantum and hybrid computing by creating synergies between the expertise of the two worlds, so as to generate concrete and useful use cases, as well as and productivity gains through the dissemination of quantum science innovations across the regional, national and cross-border economic fabric. regional, national and cross-border economic fabric.

Total Amount: 12 millions euros (appel national Maison du Quantique Genci-CEA) + 12 millions euros (Région Grand Est).

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair

- Alejandro Díaz-Caro: QPL 2024.

Member of the organizing committees

- Mathilde Bouvel: organizer of an Oberwolfach mini-workshop on permutation patterns, one week, January-February 2024.
- Mathilde Bouvel and Guilhem Gamard: organizer of Words 2025. (Work started in 2024.)

11.1.2 Scientific events: selection

Chair of conference program committees

- Alejandro Díaz-Caro: QPL 2024.
- Guilhem Gamard: Words 2025. (Work started in 2024.)

Member of the conference program committees

- Miriam Backens: QPL 2024
- Nazim Fatès: AUTOMATA 2024, ASCAT 2024, ACRI 2024
- Mathieu Hoyrup: CiE 2024
- Emmanuel Jeandel: QPL 2024
- Simon Perdrix: LICS 2024, QPL 2024, MCU 2024

Reviewer

- Miriam Backens: reviewer for LICS 2024, CSL 2025, STOC 2025
- Emmanuel Hainry: reviewer for CiE 2024, Fossacs 2024.
- Mathieu Hoyrup: reviewer for ICALP 2024, MFCS 2024, CiE 2024.
- Romain Péchoux: reviewer for FSCD 2024, ICTCS 2024, ISMVL 2024, LICS 2024.

11.1.3 Journal

Member of the editorial boards

- Miriam Backens: member of the editorial board of *Quantum journal*
- Mathilde Bouvel: executive editor of the *European Journal of Combinatorics*
- Mathilde Bouvel: member of the editorial board of *Annals of Combinatorics*
- Alejandro Díaz-Caro: member of the editorial board of the *IEEE Transactions on Emerging Topics in Computing*
- Nazim Fatès : member of the editorial board of the *Journal of cellular automata*
- Emmanuel Jeandel: member of the editorial board of *RAIRO-ITA*
- Simon Perdrix: member of the editorial board of *LMCS (Logical Methods in Computer Science)*

Reviewer - reviewing activities

- Mathilde Bouvel: one referee report for *DMTCS (Permutation Patterns special issue)*
- Nazim Fates: review for *Natural Computing* and *Theoretical computer science*
- Guilhem Gamard: review for *Forum of Mathematicians*
- Emmanuel Hainry: review for *LMCS (Logical Methods in Computer Science)*
- Mathieu Hoyrup: reviews for *Annals of Pure and Applied Logic, Discrete and Continuous Dynamical Systems, Journal of the ACM, Computability*
- Romain Péchoux: two reviews for *MSCS (Mathematical Structure in Computer Science)*
- Julien Provillard: review for *Nonlinearity*

11.1.4 Invited talks

- Miriam Backens: talk at workshop *Foundations of Quantum Computational Advantage*, Perimeter Institute, Canada, April 2024.
- Miriam Backens: course (3h) at the summer school *New trends in computing*, Strasbourg, September 2024.
- Miriam Backens: talk at *Graphix* workshop, Paris, November 2024.
- Mathilde Bouvel: course (4h) at the *Ecole jeunes chercheurs du GDR-IFM*, Nantes, June 2024.
- Mathilde Bouvel: Talk at the national days of the GT CombAlg of the GDR-IFM, Lyon, October 2024.
- Simon Perdrix: talk at *Graphix* workshop, Paris, November 2024.
- Simon Perdrix: talk at *"Quantum Circuit Design Automation" workshop*, Banff International Research Station, June 2024 (videos).
- Christophe Vuillot: Talk at 804.WE-Heraeus Seminar, in Bad Honnef, Germany, January 2024
- Christophe Vuillot: Talk at the workshop on Advaces in Quantum Coding Theory, at Simons Institute, Berkeley US, February 2024
- Christophe Vuillot: Talk at the workshop on Quantum Error Correction meets operator Algebra, at the University of Oslo, June 2024
- Christophe Vuillot: Course on bosonic codes at the ML4Q summer school at the Bethe center, Bonn, September 2024.

11.1.5 Leadership within the scientific community

- Mathilde Bouvel: member of the steering committee of the series of conferences *Permutation Patterns*
- Nazim Fatès: head of the IFIP WG 1.5 on *Cellular Automata and Discrete Complex Systems*
- Mathieu Hoyrup: member of the steering committee of the series of workshops *Computability and Complexity in Analysis*

11.1.6 Scientific expertise

- Emmanuel Hainry has been an external evaluator on a research project for the ANR.
- Emmanuel Jeandel: member of a CoS for a professor position in Paris-Cité, IRIF.
- Emmanuel Jeandel: member of a CoS for a associate professor position in Université de Lorraine, Loria
- Romain Péchoux: member of a CoS for an associate professor position in quantum computing at CentraleSupélec.
- Simon Perdrix: member of a CoS for a associate professor position in Aix Marseille Université, LIS.
- Simon Perdrix: member of doctoral commission at LORIA.

11.1.7 Research administration

- Romain Péchoux: vice-chair of Horizon Europe MSCA.
- Simon Perdrix: coordinator EPIQ project, part of the PEPR quantique
- Simon Perdrix: WP leader in Défi Inria EQIP.
- Simon Perdrix: co-head of GT IQ at GdR IFM.
- Simon Perdrix: local PIQ representative.

11.2 Teaching - Supervision - Juries

- Licence
  - Miriam Backens
    - Algorithms and Complexity, 21h
  - Nazim Fatès
    - Introduction à l'intelligence artificielle, Seminar to the students of Engineering School (cours d'ouverture), Telecom Nancy, université de Lorraine, 3h
  - Guilhem Gamard:
    - Systems (Posix) programming, L2 and L3 Informatique, 42h
    - Computer Networks, L2 and L3 Informatique, 36h
    - Advanced Databases, L3 Informatique, 36h
  - Isabelle Gnaedig:
    - To the limits of the computable, Opening course-conference of the collegium "Lorraine INP", Université de Lorraine, 6h.
  - Emmanuel Hainry:
    - Dynamic We, L1, IUT Nancy Braboisb, 31h.
    - Developing Full Stack Applications, L1, IUT Nancy Brabois, 38h.

    * Automating Operating Systems, L2, IUT Nancy Brabois, 42h.
  - Emmanuel Jeandel:
    * Programming, L1 Mathématiques, 30h
    * Algorithms, L1 Mathématiques, 30h
    * Computer Science, L1 Mathématiques CPU, 20h
    * Functional Programming, L3 Informatique, 14h
    * Networking, L2 and L3 Informatique, 90h
    * System Administration, Licence Infographie Paysagère, 24h
  - Julien Provillard:
    * Programming, L1 Mathématiques, 12h
    * Object-oriented programming, L2 Informatique, 62h
    * Graphical user interface, L2 Informatique, 48h
    * Semester project, L2 Informatique, 54h

- Master
  - Alejandro Díaz-Caro:
    * Characteristics of Programming Languages, M2 Informatique, 28h
    * Logique and Programming, M1 Informatique, 28h
  - Nazim Fatès:
    * Séminaire d'ouverture à l'intelligence artificielle, Master 1 Sciences cognitives, université de Lorraine, 11h
    * Introduction à l'intelligence artificielle, IAE Nancy School of Management, Marketing et Gestion Commerciale, université de Lorraine, 3h
  - Guilhem Gamard:
    * Advanced Computer Networks, M1 Informatique, 66h
    * Databases and Information Systems, M1 Informatique, 40h
  - Isabelle Gnaedig:
    * Rule-based Programming, M2, Telecom-Nancy, Université de Lorraine, 28h
  - Emmanuel Jeandel:
    * Advanced Compter Networks, M1 Informatique, 24h
  - Simon Perdrix:
    * Informatique quantique, M1, 12h.
  - Julien Provillard:
    * Analysis and software design, M1 Informatique, 56h
    * Semester project, M1 Informatique, 10h
    * Programming paradigms, M2 IL, 33h

11.2.1 Supervision

- Miriam Backens has supervised the PhD of George Kaye (University of Birmingham, UK, defense 11 September 2024) with Dan Ghica.
- Miriam Backens is supervising the PhD of Tommy McElvanney (University of Birmingham, UK, awaiting defense) with Martín Escardo.
- Miriam Backens is supervising the PhD of Piotr Mitosek (4th year, University of Birmingham, UK) with Paul Blain Levy.
- Miriam Backens is supervising the internship of Jules Dupont (École des Mines Nancy).

- Miriam Backens and Simon Perdrix are supervising the PhD of Colin Blake (1st year).
- Miriam Backens and Simon Perdrix are supervising the PhD of Noé Delorme (2nd year).
- Miriam Backens and Simon Perdrix are supervising the PhD of Nathan Claudet (3rd year).
- Mathilde Bouvel has supervised the internship of Aditi Muthkhod (Bachelor level at CMI, Chennai, India)
- Mathilde Bouvel and Emmanuel Jeandel are supervising the PhD of Benjamin Testard (3rd year).
- Alejandro Díaz-Caro is supervising the PhD of Cristian Sottile (5th year, of a 5-year program in Argentina).
- Alejandro Díaz-Caro is supervising the PhD of Rafael Romero (5th year, of a 5-year program in Argentina) with Octavio Malherbe.
- Alejandro Díaz-Caro is supervising the PhD of Malena Ivnisky (4th year, of a 5-year program in Argentina) with Octavio Malherbe.
- Alejandro Díaz-Caro is supervising the internship of Luciano Barletta (M2, UNR, Argentina).
- Alejandro Díaz-Caro is supervising the internship of Francisco Herrero (M1, UBA, Argentina).
- Alejandro Díaz-Caro is supervising the internship of Tomás Miguez (M1, UBA, Argentina).
- Alejandro Díaz-Caro is supervising the internship of Nicolás Monzón (M2, UADE, Argentina).
- Alejandro Díaz-Caro is supervising the internship of Carlos Miguel Sotto (M2, UBA, Argentina).
- Nazim Fatès is supervising the PhD of Joannès Guichon (3rd year) with Sylvain Contassot-Vivier (LORIA).
- Nazim Fatès has supervised the Master 2 internship of Nicolas Barreau (univ. de Lorraine, sciences cognitives).
- Emmanuel Hainry and Romain Péchoux have supervised the internship of Florent Ferrari (L3, ENS Lyon).
- Emmanuel Hainry and Romain Péchoux are supervising the PhD of Mario Silva (4th year).
- Emmanuel Hainry and Romain Péchoux are supervising the PhD of Thomas Vinet (1st year) .
- Mathieu Hoyrup has supervised the internship of Alexis Terrassin (M2, LMFI).
- Mathieu Hoyrup has supervised the internship of Tom Favereau (École des Mines de Nancy).
- Mathieu Hoyrup and Guilhem Gamard are supervising the PhD of Alexis Terrassin (1st year).
- Emmanuel Jeandel and Christophe Vuillot are supervising the PhD of Alexandre Gernut (4th year).
- Romain Péchoux and Simon Perdrix are supervising the PhD of Kathleen Barsse (1st year).
- Romain Péchoux is supervising the PhD of Kinnari Dave (3rd year) with Vladimir Zamdzhiev (Inria Saclay).
- Romain Péchoux is supervising the PhD of Issa Jad (1st year) with Christophe Chareton (CEA Saclay).
- Simon Perdrix and Christophe Vuillot, then Emmanuel Jeandel, are supervising the PhD of Sébastien Draux (1st year).
- Simon Perdrix has supervised the internship of Colin Blake (M2 MPRI).
- Simon Perdrix and Christophe Vuillot are supervising the PhD of Vivien Vandaele (4th year).

11.2.2 Juries

- Miriam Backens: external examiner for the programme *Master in Mathematics and Foundations of Computer Science*, University of Oxford, UK; external examiner for the Masters thesis of Benjamin Caldwell (University of Chicago, US), January 2024; external examiner for the PhD thesis of Muhammad Hamza Waseem (University of Oxford, UK), December 2024
- Mathilde Bouvel: member of the jury for the PhD defense of Zéphyr Salvy, December 2024, Marne-la-Vallée.
- Nazim Fatès: member of the habilitation thesis committee of Barbara Wolnik, Univeristy of Gdansk, Poland, April 2024.
- Mathieu Hoyrup: member of the jury for the PhD defense of Léo Paviet-Salomon, December 2024, Caen.
- Emmanuel Jeandel: member of the jury for the PhD thesis of Ugo Giocanti (Université Grenoble-Alpes), Nicolas Bitar (Université Paris-Saclay), Bastien Laboureix (Université de Lorraine). reviewer for the HDR defense of Benoît Valiron (Université Paris-Saclay)
- Romain Péchoux: rapporteur for the PhD thesis of Andrea Colledan, Universita di Bologna.
- Simon Perdrix: external examiner for the PhD of Kyriakos Georgiade (UCL London) ; President of jury for the PhD defense of Uta Isabella Meyer (Sorbonne Université); member of the jury for the PhD defense of Raphaël Mothe (Université Grenoble Alpes).
- Christophe Vuillot: member of the jury for the PhD defense of Aurélie Denys, April 2024.

11.3 Popularization

11.3.1 Productions (articles, videos, podcasts, serious games, ...)

Nazim Fatès published an article in the *Alliage* journal, entitled « Que faire de l'expression "intelligence artificielle" ? » [30].

11.3.2 Participation in Live events

- Miriam Backens: talk at online school *Introduction to Quantum Research for Girls*, June 2024.
- Mathilde Bouvel: closing conference at the *Tournoi français des jeunes mathématiciennes et mathématiciens*, Nancy, April 2024.
- Nazim Fatès:
  - Talk for the high-schhol teachers : Les machines peuvent-elles « apprendre » ? at the Journées NSI, LORIA, April 3, 2024.
  - Talk on artificial intelligence for the lycée Vatelot in Toul ; April 18, 2024.
  - Wide-audience talk on the theme « Intelligence artificielle : entre technoscience et alchimie » in the Université populaire et participative de Vandœuvre (UP^{2}V) ; May 15, 2024.
  - Talk « Visages de l'infini en informatique », at the Marathon des sciences in the Astronomy festival of Fleurance, August 3, 2024.

12 Scientific production

12.1 Major publications

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

[2] 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.science/hal-02412965.

[3] O. Bournez, D. Graça and E. Hainry. 'Computation with perturbed dynamical systems'. In: *Journal of Computer and System Sciences* 79.5 (Aug. 2013), pp. 714–724. DOI: 10.1016/j.jcss.2013.01.025. URL: http://hal.inria.fr/hal-00861041.

[4] 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.

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] 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://inria.hal.science/hal-03722245.

[13] E. Hainry and R. Péchoux. 'A General Noninterference Policy for Polynomial Time'. In: POPL 23. Vol. 7. Boston, United States, 9th Jan. 2023, pp. 806–832. DOI: 10.1145/3571221. URL: https://inria.hal.science/hal-04190355.

[14] 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.

[15] M. Hoyrup. 'Descriptive complexity on non-Polish spaces II'. In: *ICALP*. Saarbrücken, Germany, July 2020. DOI: 10.4230/LIPIcs.ICALP.2020.132. URL: https://hal.inria.fr/hal-02483114.

[16] M. Hoyrup. 'The decidable properties of subrecursive functions'. In: *International Colloquium on Automata, Languages, and Programming (ICALP) 2016*. 43rd International Colloquium on Automata, Languages, and Programming, ICALP 2016, July 12-15, 2016, Rome, Italy. Rome, Italy, July 2016. DOI: 10.4230/LIPIcs.ICALP.2016.108. URL: https://hal.inria.fr/hal-01308224.

[17] M. Hoyrup and W. Gomaa. 'On the extension of computable real functions'. In: *32nd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2017, Reykjavik, Iceland, June 20-23, 2017*. IEEE Computer Society, 2017, pp. 1–12. DOI: 10.1109/LICS.2017.8005067. URL: https://doi.org/10.1109/LICS.2017.8005067.

[18] E. Jeandel. 'Computability of the entropy of one-tape Turing Machines'. In: *STACS - Symposium on Theoretical Aspects of Computer Science*. Ed. by E. Mayr and N. Portier. Vol. 25. LIPCS. First version. Lyon, France, Mar. 2014, pp. 421–432. DOI: 10.4230/LIPIcs.STACS.2014.421. URL: https://hal.inria.fr/hal-00785232.

[19] 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.

[20] 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.

[21] E. Jeandel and M. Rao. 'An aperiodic set of 11 Wang tiles'. In: *Advances in Combinatorics* (6th Jan. 2021). DOI: 10.19086/aic.18614. URL: https://inria.hal.science/hal-01166053.

[22] E. Jeandel and P. Vanier. 'Hardness of Conjugacy, Embedding and Factorization of multidimensional Subshifts of Finite Type'. In: *STACS - 30th International Symposium on Theoretical Aspects of Computer Science*. Ed. by N. Portier and T. Wilke. Vol. 20. Leibniz International Proceedings in Informatics (LIPIcs). Christian-Albrechts-Universität zu Kiel. Kiel, Germany: Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, Feb. 2013, pp. 490–501. DOI: 10.4230/LIPIcs.STACS.2013.490. URL: http://hal.inria.fr/hal-00840384.

[23] 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.

[24] S. Perdrix and Q. Wang. 'Supplementarity is Necessary for Quantum Diagram Reasoning *'. In: *41st International Symposium on Mathematical Foundations of Computer Science (MFCS 2016)*. Vol. 58. Leibniz International Proceedings in Informatics (LIPIcs). Krakow, Poland, Aug. 2016, 76:1–76:14. DOI: 10.4230/LIPIcs.MFCS.2016.76. URL: https://hal.archives-ouvertes.fr/hal-01361419.

[25] R. Vilmart. 'A Near-Minimal Axiomatisation of ZX-Calculus for Pure Qubit Quantum Mechanics'. In: LICS 2019 - 34th Annual ACM/IEEE Symposium on Logic in Computer Science. Vancouver, Canada, 24th June 2019. DOI: 10.1109/LICS.2019.8785765. URL: https://hal.science/hal-01963426.

[26] 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.

12.2 Publications of the year

International journals

[27] M. Albert, M. Bouvel, V. Féray and M. Noy. 'Convergence law for 231-avoiding permutations'. In: *Discrete Mathematics and Theoretical Computer Science*. Permutation Patterns 2023 26.1 (2nd Apr. 2024). DOI: 10.46298/dmtcs.11751. URL: https://hal.science/hal-03908625.

[28] D. E. Amir and M. Hoyrup. 'Comparing computability in two topologies'. In: *The Journal of Symbolic Logic* 89.3 (2024), pp. 1–19. DOI: 10.1017/jsl.2023.17. URL: https://inria.hal.science/hal-03702999 (cit. on p. 11).

[29] D. E. Amir and M. Hoyrup. 'The surjection property and computable type'. In: *Topology and its Applications* 355 (Oct. 2024), p. 109020. DOI: 10.48550/arXiv.2306.14542. URL: https://inria.hal.science/hal-04140772 (cit. on p. 11).

[30] N. Fatès. 'What to do with the term 'artificial intelligence'?' In: *Alliage : Culture - Science - Technique* 84 (Nov. 2024). URL: https://hal.science/hal-04752646 (cit. on p. 27).

[31] L. Paletta, A. Leverrier, A. Sarlette, M. Mirrahimi and C. Vuillot. 'Robust sparse IQP sampling in constant depth'. In: *Quantum* 8 (6th May 2024), p. 1337. DOI: 10.22331/q-2024-05-06-1337. URL: https://inria.hal.science/hal-04696925.

[32] S. Roy, N. Fatès and S. Das. 'Reversibility of Elementary Cellular Automata with fully asynchronous updating: an analysis of the rules with partial recurrence'. In: *Theoretical Computer Science* (2024). DOI: 10.1016/j.tcs.2024.114721. URL: https://inria.hal.science/hal-04456320. In press (cit. on p. 12).

[33] D. Ruiz, J. Guillaud, A. Leverrier, M. Mirrahimi and C. Vuillot. 'LDPC-cat codes for low-overhead quantum computing in 2D'. In: *Nature Communications* 16.1 (26th Jan. 2025), p. 1040. DOI: 10.1038/s41467-025-56298-8. URL: https://inria.hal.science/hal-04887011.

[34] C. Vuillot, A. Ciani and B. Terhal. 'Homological Quantum Rotor Codes: Logical Qubits from Torsion'. In: *Communications in Mathematical Physics* 405.2 (20th Feb. 2024), p. 53. DOI: 10.1007/s00220-023-04905-4. URL: https://inria.hal.science/hal-04057182 (cit. on p. 9).

International peer-reviewed conferences

[35] M. Avanzini, G. Moser, R. Péchoux and S. Perdrix. 'On the Hardness of Analyzing Quantum Programs Quantitatively'. In: *Lecture Notes in Computer Science*. ESOP 2024 - 33rd European Symposium on Programming. Vol. Lecture Notes in Computer Science. Programming Languages and Systems : 33rd European Symposium on Programming, ESOP 2024, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2024, Luxembourg City, Luxembourg, April 6–11, 2024, Proceedings, Part II LNCS-14577. Luxembourg, Luxembourg, 2024, p. 28. DOI: 10.1007/978-3-031-57267-8_2. URL: https://inria.hal.science/hal-04349874 (cit. on p. 11).

[36] M. Bouvel, V. Féray, X. Goaoc and F. Koechlin. 'A Canonical Tree Decomposition for Chirotopes'. In: *40th International Symposium on Computational Geometry (SoCG 2024)*. 40th International Symposium on Computational Geometry (SoCG 2024). Leibniz International Proceedings in Informatics (LIPIcs). Athens, Greece: Schloss Dagstuhl – Leibniz-Zentrum für Informatik, 2024. DOI: 10.4230/LIPIcs.SoCG.2024.23. URL: https://hal.science/hal-04851138 (cit. on pp. 7, 14).

[37] M. Cautrès, N. Claudet, M. Mhalla, S. Perdrix, V. Savin and S. Thomassé. 'Vertex-Minor Universal Graphs for Generating Entangled Quantum Subsystems'. In: *European Association for Theoretical Computer Science (EATCS)*. ICALP 2024 51st EATCS International Colloquium on Automata, Languages and Programming. Tallinn, Estonia: Schloss Dagstuhl – Leibniz-Zentrum für Informatik, 2024. DOI: 10.4230/LIPIcs.ICALP.2024.36. URL: https://hal.science/hal-04632835.

[38] K. Chardonnet, L. Lemonnier and B. Valiron. 'Semantics for a Turing-Complete Reversible Programming Language with Inductive Types'. In: *9th International Conference on Formal Structures for Computation and Deduction (FSCD 2024). Leibniz International Proceedings in Informatics (LIPIcs)*. FSCD 2024 - 9th International Conference on Formal Structures for Computation and Deduction. Vol. 299. 19. Tallinn, Estonia: Schloss Dagstuhl – Leibniz-Zentrum für Informatik, 2024, 19:1–19:19. DOI: 10.4230/LIPIcs.FSCD.2024.19. URL: https://hal.science/hal-04636603.

[39] N. Claudet and S. Perdrix. 'Covering a Graph with Minimal Local Sets'. In: WG 2024: 50th International Workshop on Graph-Theoretic Concepts in Computer Science. Gozd Martuljek, Slovenia, 16th Feb. 2024. URL: https://hal.science/hal-04869465 (cit. on p. 10).

[40] N. Claudet and S. Perdrix. 'Local equivalence of stabilizer states: a graphical characterisation'. In: STACS: 42nd International Symposium on Theoretical Aspects of Computer Science. Jena, Germany, 2025. URL: https://hal.science/hal-04869503 (cit. on p. 10).

[41] A. Clément, N. Delorme and S. Perdrix. 'Minimal Equational Theories for Quantum Circuits'. In: LICS '24: 39th Annual ACM/IEEE Symposium on Logic in Computer Science. Proceedings of the 39th Annual ACM/IEEE Symposium on Logic in Computer Science 27. Tallinn, Estonia: ACM, 8th July 2024, pp. 1–14. DOI: 10.1145/3661814.3662088. URL: https://hal.science/hal-04399210 (cit. on pp. 7, 8).

[42] 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. DOI: 10.4230/LIPIcs.CSL.2024.20. URL: https://hal.science/hal-04016498 (cit. on pp. 7, 8).

[43] N. A. Fatès. 'Asynchronous cellular system that solves the parity problem'. In: 30th International Workshop on Cellular Automata and Discrete Complex Systems. Vol. LNCS. Lecture Notes in Computer Science 14782. Durham (GB), France: Springer Nature Switzerland, 2024, pp. 133–145. DOI: 10.1007/978-3-031-65887-7_9. URL: https://inria.hal.science/hal-03894581 (cit. on p. 12).

[44] J. Guichon, N. A. Fatès, S. Contassot-Vivier and M. Amato. 'Properties of B2B invoice graphs and detection of structures'. In: Complex Networks 2023. Vol. 1143. Studies in Computational Intelligence. Menton, France: Springer Nature Switzerland, 21st Feb. 2024, pp. 444–455. DOI: 10.1007/978-3-031-53472-0_37. URL: https://inria.hal.science/hal-04230839 (cit. on p. 15).

[45] E. Hainry, B. M. Kapron, J.-Y. Marion and R. Péchoux. 'Declassification Policy for Program Complexity Analysis'. In: LICS '24: 39th Annual ACM/IEEE Symposium on Logic in Computer Science. Tallinn Estonia, France: ACM, 8th July 2024, pp. 1–14. DOI: 10.1145/3661814.3662100. URL: https://inria.hal.science/hal-04742085 (cit. on pp. 7, 11).

Conferences without proceedings

[46] L. Paletta, A. Leverrier, A. Sarlette, M. Mirrahimi and C. Vuillot. 'Robust sparse IQP sampling in constant depth'. In: QIP2024. Taipei, Taiwan, 6th May 2024, p. 1337. DOI: 10.22331/q-2024-05-06-1337. URL: https://inria.hal.science/hal-04312163 (cit. on p. 10).

Reports & preprints

[47] F. Bassino, M. Bouvel, V. Féray, L. Gerin and A. Pierrot. *Dense and nondense limits for uniform random intersection graphs*. 12th Feb. 2024. URL: https://hal.science/hal-04456866 (cit. on p. 14).

[48] M. Bouvel, E. S. Egge, R. N. Smith, J. Striker and J. M. Troyka. *Enumeration of pattern-avoiding alternating sign matrices: An asymptotic dichotomy*. 12th Nov. 2024. URL: https://hal.science/hal-04850999 (cit. on p. 13).

[49] M. Bouvel, V. Féray, X. Goaoc and F. Koechlin. *A canonical tree decomposition for order types, and some applications*. 15th Mar. 2024. URL: https://hal.science/hal-04528939 (cit. on p. 14).

[50] M. Bouvel, L. Ferrari and B. E. Tenner. *Between weak and Bruhat: the middle order on permutations*. May 2024. URL: https://hal.science/hal-04758809 (cit. on p. 13).

[51] M. Bouvel, C. Nicaud and C. Pivoteau. *Record-biased permutations and their permuton limit*. 3rd Sept. 2024. URL: https://hal.science/hal-04850989 (cit. on p. 14).

[52] M. Bouvel, R. Smith and J. Striker. *Key-avoidance for alternating sign matrices*. 9th Aug. 2024. URL: https://hal.science/hal-04758832 (cit. on p. 13).

[53] A. Díaz-Caro, E. Hainry, R. Péchoux and M. Silva. *A feasible and unitary quantum programming language*. 4th Mar. 2024. URL: https://inria.hal.science/hal-04266203.

[54] A. Guernut and C. Vuillot. *Fault-Tolerant Constant-Depth Clifford Gates on Toric Codes*. 27th Nov. 2024. URL: https://inria.hal.science/hal-04808742 (cit. on p. 9).

[55] J. Guichon, S. Contassot-Vivier and N. Fatès. *Integral B2B Debt Netting: Model and Static Algorithm*. 14th Feb. 2025. URL: https://hal.science/hal-04947742.

[56] E. Hainry, R. Péchoux and M. A. Machado da Silva. *Branch Sequentialization in Quantum Polytime*. 6th Dec. 2024. URL: https://inria.hal.science/hal-04823282.

[57] M. Hoyrup and T. Favereau. *Local generation of tilings*. 13th Nov. 2024. URL: https://inria.hal.science/hal-04876047 (cit. on p. 15).

[58] M. Hoyrup and T. Favereau. *Local generation of tilings: the even bicolor Wang tilesets*. 13th Nov. 2024. URL: https://inria.hal.science/hal-04876051 (cit. on p. 15).

[59] M. Hoyrup, A. Melnikov and K. M. Ng. *Computable topological presentations*. 19th Dec. 2024. URL: https://inria.hal.science/hal-04848634 (cit. on p. 11).

[60] P. Mitosek and M. Backens. *An algebraic interpretation of Pauli flow, leading to faster flow-finding algorithms*. 30th Oct. 2024. URL: https://hal.science/hal-04894204 (cit. on p. 11).

[61] B. Testart. *Completing the enumeration of inversion sequences avoiding one or two patterns of length 3*. 13th Dec. 2024. URL: https://hal.science/hal-04837010 (cit. on p. 13).

[62] B. Testart. *Generating trees growing on the left for pattern-avoiding inversion sequences*. 8th Nov. 2024. URL: https://hal.science/hal-04837024 (cit. on p. 13).

[63] Y. Xu, Y. Wang, C. Vuillot and V. V. Albert. *Letting the tiger out of its cage: bosonic coding without concatenation*. 14th Nov. 2024. URL: https://inria.hal.science/hal-04808736 (cit. on p. 9).

Scientific popularization

[64] I. Assayakh, J. Guichon, P.-A. Rault and C. Treuillier. 'IZLife'. In: *Think before loading*. 2024. URL: https://hal.univ-lorraine.fr/hal-04509340.

12.3 Cited publications

[65] X. Bian and P. Selinger. 'Generators and Relations for 2-Qubit Clifford+T Operators'. In: *Proceedings of QPL'22, Electronic Proceedings in Theoretical Computer Science* 394 (Nov. 2023), pp. 13–28. DOI: 10.4204/eptcs.394.2. URL: http://dx.doi.org/10.4204/EPTCS.394.2 (cit. on p. 8).

[66] X. Bian and P. Selinger. 'Generators and Relations for 3-Qubit Clifford+CS Operators'. In: *Proceedings QPL'23, Electronic Proceedings in Theoretical Computer Science* 384 (Aug. 2023), pp. 114–126. DOI: 10.4204/eptcs.384.7. URL: http://dx.doi.org/10.4204/EPTCS.384.7 (cit. on p. 8).

[67] A. Björner, M. Las Vergnas, B. Sturmfels, N. White and G. M. Ziegler. *Oriented matroids*. Encyclopedia of Mathematics and its Applications. 46. Cambridge University Press, 1999 (cit. on p. 7).

[68] S. Bravyi, Y. Sharma, M. Szegedy and R. De Wolf. 'Generating k EPR-pairs from an n-party resource state'. In: *QIP2023, arXiv:2211.06497* (2022) (cit. on p. 10).

[69] A. Burchardt, J. de Jong and L. Vandré. *Algorithm to Verify Local Equivalence of Stabilizer States*. 2024. arXiv: 2410.03961 [quant-ph]. URL: https://arxiv.org/abs/2410.03961 (cit. on p. 10).

[70] M. Cautrès, N. Claudet, M. Mhalla, S. Perdrix, V. Savin and S. Thomassé. 'Vertex-minor universal graphs for generating entangled quantum subsystems'. working paper or preprint. Feb. 2024. URL: https://hal.science/hal-04480666 (cit. on p. 10).

[71] N. Claudet, M. Mhalla and S. Perdrix. 'Small k-pairable states'. working paper or preprint. Dec. 2023. URL: https://hal.science/hal-04320674 (cit. on p. 10).

[72] 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)*. Boston, United States: IEEE, June 2023, pp. 1–13. DOI: 10.1109/LICS56636.2023.10175801. URL: https://hal.science/hal-03926757 (cit. on pp. 7, 8).

[73] 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) (cit. on p. 12).

[74] Z. Ji, J. Chen, Z. Wei and M. Ying. 'The LU-LC conjecture is false'. In: (2007). eprint: 0709.1266 (cit. on p. 10).

[75] R. Johansson and S. Linusson. 'Pattern avoidance in alternating sign matrices'. In: *Annals of Combinatorics* 11.3-4 (2007), pp. 471–480 (cit. on p. 13).

[76] I. Kotsireas, T. Mansour and G. Yildirim. 'An algorithmic approach based on generating trees for enumerating pattern-avoiding inversion sequences'. In: *Journal of Symbolic Computation* 120 (2024). Article 102231 (cit. on p. 13).

[77] J. Makary, N. J. Ross and P. Selinger. 'Generators and Relations for Real Stabilizer Operators'. In: *Proceedings of the 18th International Conference on Quantum Physics and Logic, QPL 2021* (Gdansk, Poland, and online, 7th–11th June 2021). Ed. by C. Heunen and M. Backens. Vol. 343. EPTCS. 2021, pp. 14–36. DOI: 10.4204/EPTCS.343.2 (cit. on p. 8).

[78] T. Mansour and M. Shattuck. 'Pattern avoidance in inversion sequences'. In: *Pure Mathematics and Applications* 25.2 (2015), pp. 157–176 (cit. on p. 12).

[79] R. H. Möhring and F. J. Radermacher. 'Substitution decomposition for discrete structures and connections with combinatorial optimization'. In: *Annals of Discrete Math* 19 (1984), pp. 257–356 (cit. on p. 7).

[80] P. Selinger. 'Generators and relations for n-qubit Clifford operators'. In: *Logical Methods in Computer Science* Volume 11, Issue 2 (June 2015). DOI: 10.2168/LMCS-11(2:10)2015. URL: http://lmcs.episciences.org/1570 (cit. on p. 8).

[81] V. Vandaele, S. Martiel, C. Vuillot and S. Perdrix. 'Optimal Hadamard gate count for Clifford+T synthesis of Pauli rotations sequences'. In: *ACM Transactions on Quantum Computing* (Feb. 2023). DOI: 10.1145/3639062. URL: https://hal.science/hal-03991154 (cit. on p. 9).