Département
D2: Formal Methods

Équipe MOCQUA

Designing the Future of Computational Models

Loria

Laboratoire lorrain de recherche en informatique et ses applications

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En partenariat avec

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A2.1.1. – Semantics of programming languages

A2.1.13. – Quantum programming languages

A4.2. – Correcting codes

A4.2.1. – Quantum error correction

A4.5.1. – Static analysis

A7. – Theory of computation

A7.3. – Calculability and computability

A7.3.1. – Computational models and calculability

A7.3.2. – Computability

A8.1. – Discrete mathematics, combinatorics

A8.13. – Quantum computing

A8.13.4. – Measurement based quantum computing

A8.13.8. – Fault-tolerant quantum computing

A8.13.10. – ZX calculus

Other research topics and application domains

B4. – Energy

B6. – IT and telecom

Contents

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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 levers 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 international conference WORDS 2025 has been organised in Nancy, from June 30 to July 4th 2025, by several members of the team and colleagues at IECL. WORDS is a biannual international conference, and one of the main scientific events in this research area. It devoted to combinatorics on words (sequences of symbols) and its links to algorithms, algebra, dynamics and number theory, as well as its applications.

  The conference has gathered over 60 participants for one week, and the program featured five keynote lectures by Daniel Gabrić (University of Guelph, Canada), France Gheeraert (Université Picardie Jules Vernes, Amiens, France), Idrissa Kaboré (Université Polytechnique de Bobo-Dioulasso, Burkina Faso), Martin Lustig (Aix-Marseille Université, France) and Markus Whiteland (Loughborough University, UK), as well as 20 contributed talks and an open problem session. The proceedings of the conference, co-edited by Guilhem Gamard, have been published in the LNCS series (volume 15729).

7 Latest software developments, platforms, open data

7.1 Latest software developments

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/`

Contact: Nazim Fates

Participant: an anonymous participant

Partners: ENS Lyon, Université de Lorraine

7.2 Open data

8 New results

8.1 Quantum stack

Participants: Miriam Backens, Colin Blake, Nathan Claudet, Kinnari Dave, Noé Delorme, Sébastien Draux, Alexandre Guernut, Emmanuel Hainry, Emmanuel Jeandel, Romain Péchoux, Simon Perdrix, Mário Silva, Vivien Vandaele.

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 and Graphical Languages for Quantum Computing

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.

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 [95], solving a problem that had been open for more than 30 years. Previously, only certain fragments equipped with a complete equational theory were known, but these fragments were non-universal and efficiently classically simulatable [126, 85, 86, 118].

In our work, we introduced a minimal equational theory for quantum circuits and proved its minimality, i.e., each rule is necessary to ensure completeness [94]. We also showed that any complete equational theory must contain an unbounded family of equations. More specifically, for any number of qubits, there exists a particular equation involving that number of qubits which cannot be derived from equations acting on a strictly smaller number of qubits [94]. This unexpected result reveals a fundamental property of quantum circuits.

This year, we have introduced a new formalism for quantum circuits, called controlled props [99], which will be presented at FoSSaCs 2026. A quantum circuit can be defined in terms of generators composed sequentially and in parallel—forming, from a category-theoretic perspective, a prop. We extended this concept by introducing controlled props, which include an additional constructor: the control. For any given circuit, one can define a controlled version of it.

We proposed a simple axiomatisation of controlled props with three main objectives. First, to formalise the notion of quantum control, which is currently a very important topic in the development of quantum computing. Second, to use control as a constructor as a natural way to avoid the need for an unbounded number of axioms; indeed, we proved that quantum circuits described within this formalism admit simple, bounded and intuitive axiomatisations. Finally, since control is already used as a constructor in several quantum programming languages, such as Quipper, the use of controlled props facilitates the compilation of these languages into quantum circuits.

Tensor-Plus calculus The Tensor-Plus calculus is a formalism which aims at describing the interaction between multiplicative structures, such as Quantum Circuits, and additive structures, such as Linear Optics circuits. This is done through the lens of category theory, in particular, symmetric monoidal categories with a semi-additive structure. Kostia Chardonnet and collaborators showed how the Tensor-Plus is an internal language for such categories [66].

8.1.2 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 [110] 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 [48]. This result has been accepted at STAC 2025 and 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 [93]. 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 [90].

However, the complexity of this algorithm remained unknown, as it depends on two parameters: the size of a minimal local set cover and the complexity of solving linear systems that may involve an exponentially large number of equations. We proposed an alternative algorithm that we proved to run in quasi-polynomial time $O(n^{\ln n})$ to decide whether two graphs of order n are related by generalized local complementation, or, equivalently, whether two graph states (or more generally, stabilizer states) are LU-equivalent. To achieve this, we proved that any graph can be covered by a polynomial number of minimal local sets (which can be computed efficiently) and we bounded the order of the generalized local complementation. This work has been accepted at ICALP 2025 [57].

Flow properties and flow-preserving rewriting. 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) [42]. The flow-finding algorithms have been implemented in *Graphix*, an open-source library for working with measurement-based quantum computations [127].

Building on the algebraic formulation, we explored with Thomas Perez under which conditions new qubits can be inserted into a measurement-based quantum computation while preserving the existence of different types of flow [47].

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 Quantum programming languages

This year we obtained several results related to quantum programming languages and their logical foundations. These contributions range from purely logical systems and proof-theoretic techniques, to quantum lambda-calculi and mixed-state computation, as well as a broader conceptual synthesis.

Algebraic Extension of Intuitionistic Linear Logic. In [36], we present the $L^S_!$-calculus, an algebraic extension of Intuitionistic Linear Logic. This calculus allows for linear combinations of terms, providing a logical foundation for algebraic effects such as superposition. We provide a categorical model for the system, establishing a precise correspondence between syntax and semantics. This work has been published in the Journal of Logic and Computation.

IMALL with a Mixed-State Modality. In [49], we introduce $\mathscr{B}$-IMALL, a proof language for Intuitionistic Multiplicative Additive Linear Logic extended with a modality $\mathscr{B}$ to account for mixed-state quantum computation. The system integrates pure and mixed quantum computation within a single logical framework, supports linear combinations of terms, and treats measurement as a definable proof construct rather than a primitive constant. Cut-elimination is defined via a composite reduction relation combining algebraic normalisation with deterministic evaluation, and is shown to be sound and adequate with respect to a categorical semantics based on finite-dimensional Hilbert spaces and C^*-algebras. We further show that every linear map on $\mathbb{C}^{2^n}$ is representable in the pure fragment, illustrating the expressiveness of the system through examples such as quantum teleportation and the quantum switch. This work was published at APLAS 2025.

A Quantum-Control Lambda-Calculus with Multiple Measurement Bases. In [52], we introduce Lambda-SX, a typed quantum lambda-calculus that extends the quantum-control paradigm by supporting multiple measurement bases. The calculus refines the type system of Lambda-S to track duplicability relative to different bases, allowing measurements and control to be expressed directly at the term level without reducing all observations to the computational basis. We formalise the syntax, typing rules, subtyping, and operational semantics of the system, and establish key meta-theoretical properties, including subject reduction, progress, and strong normalisation of well-typed terms. This work was published at APLAS 2025.

Proving Termination With CPO. In [75], we investigate the use of the computability path ordering (CPO) as a practical tool for proving termination of complex cut-elimination calculi. We introduce a new CPO rule that improves its behaviour with respect to transitivity, reducing the need to explicitly construct intermediate terms in termination arguments. The approach is illustrated through a series of increasingly expressive logical calculi, culminating in a quantum extension with algebraic structure and non-deterministic measurement rules, whose termination had previously only been conjectured. This work was presented informally at HOR 2025; the full draft is available on HAL.

Uniform Interpretation of Parallelism. In [51], we propose a uniform interpretation of parallelism in intuitionistic logic, going beyond standard approaches based on monads and biproducts. Although not specific to quantum computation, this interpretation provides a logical account of parallelism that is compatible with algebraic and linear structures arising in quantum calculi. This work has been published at FSTTCS 2025.

Towards a Computational Quantum Logic. Finally, in an invited paper at CiE 2025 [46], we provide an overview of our ongoing research programme towards a computational quantum logic. We discuss the challenges and recent progress in defining logical systems that capture the computational principles of quantum mechanics, and articulate a unifying perspective connecting the results described above.

8.2.2 Resource analysis of quantum programs

In [40], we have presented an imperative quantum programming language and a set of criteria that ensures programs compute polynomial time computable functions. More formally, programs satisfying those criteria capture exactly the complexity class FBQP, or capture exactly quantum functions computable with uniform families of polynomial quantum circuits. We also present a compilation algorithm that takes such a program and for any number of qubits creates a quantum circuit of size polynomial in this number of qubits. This algorithm was improved in [55] where the compiled circuit is of optimal size, thus solving a problem known as *branch sequentialization* [132], which identifies the issue that the natural compilation of superposed branches in a quantum algorithm yields a circuit of exponential size. This work was presented at the *10th International Conference on Formal Structures for Computation and Deduction* (FSCD 2025).

In [54], we modified the previous language and criteria in order to capture the class of polylogarithmic time quantum algorithm, FBQPOLYLOG. This constitutes the first characterization of FBQPOLYLOG using a programming language. We also show that we can compile those programs into quantum circuits of polylogarithmic depth (and polynomial size), thus recovering the inclusion FBQPOLYLOG ⊆ QNC, but this inclusion is known to be strict, hence showing that some QNC quantum functions, such as parity, cannot be programmed in a way satisfying the new criteria. This work was presented at the *Mathematical Foundations of Computer Science* (MFCS 2025) conference.

8.2.3 Descriptive complexity of topological invariants

We have studied the problem of distinguishing topological spaces with the minimal amount of complexity level, measured by descriptive set theory. In particular, they have given a complete description at the first complexity level, and at the second complexity level in the case of finite topological graphs. The results have been published in the Annals of Pure and Applied Logic [27].

8.2.4 Presentations of topological spaces

We have studied a notion of presentation of countably-based topological spaces. We have surprisingly shown that every such space has a computable presentation. This work, already mentioned in the previous activity report, has just been published in the Journal of Symbolic Logic [41].

8.2.5 Characterization of second-order polytime

We published [39] in the journal *Logical Methods in Computer Science*. This is an extended version of a work published at Foundations of Software Science and Computation Structures - 25th International Conference (FoSSaCS 2022) [12]. This paper presents characterizations of the class BFF, the second-order counterpart of the class of polynomial time computable function. Those characterizations belong to the field of implicit computational complexity and rely on a typed programming language layered with simply typed terms. It makes use of a tiering discipline, such discipline have already been used to characterize various complexity classes, thus illustrating the versatility of this method. The result presented in this paper is a first tractable, implicit, sound, and complete characterization of BFF, thus solving a problem that had been open for 20 years.

8.3 Dynamical systems and combinatorics

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

Regarding Axis 3 of the team, we have contributions on cellular automata, on probabilistic and enumerative combinatorics, on links between computational models and statistical physics, 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 Cellular automata

We studied the stochastic combination of two deterministic rules, called diploid cellular automata: at each time step each cell independently applies one rule with a given probability λ and the other rule with probability 1 -λ. Following a proposition initially made Roy et al., we investigated the subset of the 168 *endogamous* rules, that is, the diploid rules formed by a rule and one of its symmetric (reflection or conjugation). Even with such a restriction, these diploids have a great diversity of dynamics. We studied the cases where the average convergence time has a logarithmic, linear, or quadratic scaling law and show that this characterisation is useful to understand the behaviour of these endogamous rules [53].

We studied the controllability problem for cellular automata, that is, the ability to guide a system from an initial state to a desired one within a limited (and possibly minimum) time interval. We examined this notion in the context of Boolean one-dimensional cellular automata of finite length. Depending on the local evolution rule, we investigated whether it is possible to control the evolution of the system by imposing particular values on the boundary conditions. We showed that the control problem can be formulated as a Boolean satisfiability (SAT) problem and can thus be addressed using SAT solvers. These observations allowed us to state that only peripherally-linear rules are fully controllable, while for other rules, the reachability ratio, that is, the fraction of controllable pairs of initial and final configurations, is vanishing when the system size grows to infinity [28].

During the three-month stay of Anna Nenca (University of Gdansk, Poland) in the MOCQUA team, we investigated how SAT solvers could ease the design of cellular automata with specific properties, for instance their abilities to solve the parity classification problem. These first results allowed us to identify a series of interesting questions which are currently under investigation.

During the Master's internship of Nassima Ait Sadi, we studied the property of self-correction in cellular automata, with a focus on the correction of k-colorings for the most diffcult ones [76], that is, for $k = 3$ and $k = 4$. A rule was proposed to correct the three-colorings with a probability 1, in other words, a rule which fails only on a neglectable subset of the initial configurations.

8.3.2 Enumerative combinatorics or combinatorics of partially ordered sets

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 planned to be defended in 2026). They are concerned with inversion sequences, which are integer sequences $(\sigma_1, \ldots, \sigma_n)$ such that $0 \leq \sigma_i < i$ for all $1 \leq i \leq n$. The study of pattern-avoiding inversion sequences began in two independent articles [119, 98], 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 [115].

In his long article [44] (published in 2025), 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. Going even further, Benjamin obtains 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.

In the second (and shorter) article [45] (also published in 2025), Benjamin focuses on proving algebraicity of generating functions using generating trees. More precisely, he 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.

In a third article in preparation, Benjamin addresses a question of different nature regarding pattern-avoiding inversion sequences. Indeed, excluded patterns in this context are not required to be inversion sequence, and Benjamin examines, for any excluded pattern ρ, the smallest set of *inversion sequences* whose avoidance is equivalent to the avoidance of ρ. Doing so, he corrects an error in [115] on an upper bound for the maximal length of such an inversion sequence.

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 articles, both published in 2025.

The first one [35] 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 [81]. 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 [31] 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 [111]. 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 [33], 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.

The article [33] has been published in 2025, but has been available as a preprint earlier. It has attracted some attention, and the notion of middle order has already been generalized. Indeed, inspired by our work, L. Schwob (PhD student at Marne-la-Vallée) defines generalized middle orders as distributive lattices on permutations that interpolate between the weak order and the Bruhat order (our original middle order being the first one that was studied), and explores the properties of these lattices. This is achieved through ideals in the root poset of the symmetric group, and is further generalized by L. Schwob to other Coxeter groups.

The interval poset of permutations The paper [30] was revised and published in 2025, but results from the research internship of B. Izart in our team (June-September 2021), and from the visit of L. Cioni to Loria (September-October 2021).

The goal of this research project was to investigate the links between interval posets of permutations and substitution decomposition trees. The interval poset of a permutation is the set of intervals of a permutation, ordered with respect to inclusion. It has been introduced and studied in [129]. Substitution decomposition trees, on the other hand, are a rather classical tool in the study of permutation classes, which was not used in [129].

We first describe a procedure to obtain the interval poset of a permutation from its substitution decomposition tree. We then give alternative proofs of some of the results in [129], and we solve the open problems that it posed (and some other enumerative problems) using techniques from symbolic and analytic combinatorics. Finally, we compute the Möbius function on interval posets.

We note that our article [30] has sparkled the interest for these objects by another group of researchers [82, 83].

8.3.3 Geometric or probabilistic combinatorics

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, now CNRS researcher at Paris 13). We have presented our results in 2024 at the conference SOCG, one of the main conferences in discrete geometry. The journal version of our work has been published in 2025 [32].

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.

We note that our chirotope trees have been further investigated by others; in particular, [107] describes an efficient (polynomial) algorithm to compute the chirotope tree.

Record-biased permutations. We worked for several years 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 [34], currently accepted pending minor revision. 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.

Scaling limits of families of graphs and permutations. We report here on the latest result and current project of a collaboration with LIPN, IECL, CMAP and LISN. The purpose of this collaboration is to establish limit shape results for combinatorial structures (like permutations or graphs) constrained to avoiding substructures, often using methods from analytic combinatorics (which is original in the landscape of the research on this topic). More precisely, we study families of permutations or graphs defined by the avoidance of substructures, and we answer (formally) the (informally phrased) question: "if we choose uniformly at random an object of large size in the considered family, what does it look like?".

In the paper [29] (revised and published in 2025), we consider the three following families of graphs: distance-hereditary graphs, 2-connected distance-hereditary graphs and 3-leaf power graphs (the latter two being subclasses of the first one). We prove that the scaling limit of uniform random graphs in each of these families, with respect to the Gromov–Prokhorov topology, is the famous Brownian Continuum Random Tree of Aldous. Although such results are quite expected for families of graphs that are "almost trees" (like the ones we consider), our approach to establish this result is original, relying on the split decomposition of graphs (from the graph algorithms and graph theory literature) and on analytic combinatorics.

Our newer project (started in 2024, continued in 2025, and still work in progress) goes back to permutations. It aims at building an automatic framework for describing limit shapes (precisely, limiting *permutons*) of uniform permutations in classes for which a specification by so-called proof-trees is provided. This covers in particular all classes defined by the avoidance of any two patterns of size 4. This project combines two recent developments. First, the software PermPAL developed by M. H. Albert, C. Bean, A. Claesson, E. Nadeau, J. Pantone and H. Ulfarsson [79] allows for the automatic discovery of specifications by proof-trees (defined in [79]) for families of pattern-avoiding permutations, from which enumeration can (sometimes) also be solved automatically, and from which random samplers are obtained. Second, and although the proof-trees encoding permutations are different from the substitution decomposition trees we have often been working with in our series of paper deriving limit shape results for permutations, they share the essential property that the occurrence of patterns in permutations can be tracked on these trees. This allows to adapt the methodology for proving limit shape results through analytic combinatorics that we have develop over the years to this new context. Our goal is to do this is a way that can be automatized, and perhaps integrated to PermPAL in the long term.

Scaling limits of inversion sequences, words, and dimensional tables of integers. This new project has started in 2025, as part of the ANR-funded project called LOUCCOUM (Large Objects Under Combinatorial Constraints and Outside Uniform Models).

The starting idea is to define a good notion to express limit shape results for inversion sequences (the combinatorial objects are the core of B. Testart's PhD thesis), similarly to the notions of permutons for permutations, or graphons for graphs, for instance. By now, it has become clear that the good notion, which we have named "tablon", will be an appropriate framework for describing not only limits of inversion sequences, but also of other types of words on a possibly infinite alphabet, and even more broadly of two-dimensional tables of integers (hence the name tablon). As a first result to witness that tablons are a good notion, we proved that tablon limits are characterized by substructure-densities, just like permutons and graphons are. This is still a work in progress, with one aspect that consists in establishing the theoretical foundations for tablons, and another that consists in obtaining (possibly universal) limiting tablon results.

8.3.4 Analysis of B2B exchange graphs

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 [102]. In our 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. Finding a set of invoices which maximises the amount of debt reduced given a quantity of loanable funds is an NP-complete problem.

In 2025, we focused on improving the integral debt netting algorithms that has been developped by Joannes Guichon during his PhD's second year. We were able to improve the computation time by more than an order of magnitude while maintaining nearly the same result quality [65, 58, 69, 70]. We also added an additional layer of depth to the algorithms by introducing the possibility of limiting the available financing, allowing simulations that are closer to realistic scenarios.

8.3.5 Local generation of tilings

During the research initiation internship of Tom Favereau, we 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. This work, already mentioned in the previous actvity report, has been published in Ergodic Theory and Dynamical Systems [37].

8.3.6 Links between computational models and statistical physics

Léo Gayral made progress on a project ongoing since their PhD, regarding the emergence of chaotic behaviours in statistical physics models induced by finite-range interactions, themselves deeply tied to the combinatorial structure of Subshifts of Finite Type, both at their local and global scale. In particular, by embedding Turing machines into the tilings, thus by twisting the combinatorial properties of the SFTs, one can establish links between (non)-computable properties of Turing machines and analytical properties of the corresponding statistical physics models.

In the original article, that finally got published in Nonlinearity [38], we proved a realisation result for any Π_2-computable set of Ground States, completed by a Π_2 upper bound for a broader class of models. In a new work [68] currently submitted for publication, by expanding the previously used embedding of Turing machines, we establish the existence of a family of models for which the set of Ground States is highly non-robust under finite-range perturbations of the potential function.

A new ongoing project has branched from these ideas, in collaboration with Mathieu Hoyrup, regarding computability properties for the maximising measures in the field of Ergodic Optimisation, and should hopefully lead to new results next year.

8.3.7 Topological invariants of tiling spaces

In the study of tilings, we may encounter tilesets that appear visually similar but yield wildly different combinatorial structures for the sets of admissible tilings. The converse also holds: some tilesets may appear dissimilar but give rise to isomorphic sets of admissible tilings. A common solution to that problem is to import invariants from algebraic topology (cohomology, fundamental groups, etc.) and to apply them to sets of tilings. This requires endowing sets of tilings with a topology. We have proven that the usual topology utilized for this purpose is in fact equivalent to the well-known compact-open topology, and also to the very convenient point-open topology. Stating that equivalence has required to fully rework the formal definition of what a "tiling" even is and to redevelop the whole theory from that new definition. We used this equivalence to obtain a full characterization of the compact topological spaces, which slightly differs from the expected one but only for technical reasons. Finally we made significant progress on various cohomological calculations which were not possible to do with the old definitions.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Emmanuel Jeandel, Simon Perdrix.

The team has been supervising two CIFRE PhD this year:

- In collaboration with Atos/Eviden, defended in January 2025: Vivien Vandaele, worked 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, worked 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. The thesis has been interrupted for medical reasons and the PhD student has decided to resign in August 2025.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Participation in other International Programs

CSIC Project 22520220100073UD

Participants: Alejandro Díaz-Caro.

Title: Computación Cuántica, Cálculo Lambda y sus Modelos Categóricos

Institution: Universidad de la República, Uruguay

Dates: January 2023 – December 2025

Coordinators: Octavio Malherbe and Alejandro Díaz-Caro

Summary: This project deals with the logical-mathematical foundations of programming languages for quantum computing. The idea is to extend the strong connection between programming languages, logic, and category theory (known as Curry-Howard-Lambek correspondence), to the quantum case, studying quantum extensions to the lambda calculus, quantum extensions to certain formal logics, and their categorical models. Understanding the logical structures of quantum computing has several concrete consequences. On the one hand, it sheds some light on quantum mechanics and its mathematical model. On the other hand, it allows the programming languages for quantum computing to be extended to be able to express programs that, although they are physically feasible, current languages do not allow them to be expressed (e.g., the so-called “quantum switch”). Furthermore, sufficiently expressive logics will serve to verify quantum programs.

ANR International THERMOGAMAS (ANR-24-CE40-3348)

Participants: Léo Gayral.

Title: Thermodynamical and geometrical approach to multi dimensional aperiodic structures

Partner Institution(s):
- Institut de mathématiques de Bordeaux, France
- Instituto de Matemática Estatística e Ciência da Computação, Brazil

Dates: Dec. 2024 – Nov. 2027

Coordinator: Philippe Thieullen

Local members: Léo Gayral

Summary: The objective of the project is to understand how and under which form an ordered structure can emerge at the phase transition from a disordered system. Ordered structure is understood in the sense that the structure possesses a low complexity as a quasi-crystal, or an aperiodic geometric structure as a tiling or a Delone set, or a computable combinatorial structure as a sub-shift of finite type, a substitution, a recursively enumerable language. A disordered system is understood in the sense that, above a critical value of the temperature, each unit of the system behaves randomly independently from the others, and below that value, the system undergoes a sharp transition to a well structured pattern. The emergence of an order is understood in the sense that the set of Gibbs measures at positive temperature tends to structure itself as the system is cooling. Three main axes of research will be developped: a first axe about the study of minimizing configurations of the Frenkel-Kontorova model, a second axe on the study of gradient Gibbs measures on lattices, a third axe on the thermodynamical formalism of the Delone sets or tilings. The three axes are tighly interwinded in the sense that a Delone set is deformed version of a lattice, a Frenkel-Kontorova model is also a gradient type model coupled with en external periodic potential. The objective of the project is to understand how, in the three cases, the previous models can be seen as structures at the ground level of low complexity in the sense of quasy-cristals, obtained as limit of thermodynamical systems as the temperature tends to zero.

The project intends to bring together experts in Dynamical systems, Thermodynamical formalism, Gibbs field, aperiodic geometry, and combinatoric and computability theory. In both coutries, France and Brazil, researchers or PhD students of the project are working independently. It is the purpose of the project to share our knowledge to young researchers in both contries.

Webpage: THERMOGAMAS

Total Amount: 382,495€

10.2 International research visitors

10.2.1 Visits of international scientists

Other international visits to the team

Octavio Malherbe

Status: Professor

Institution of origin: Universidad de la República

Country: Uruguay

Dates: 1 to 28 February 2025

Context of the visit: In the framework of the QCOMICAL project to work with Alejandro Díaz-Caro.

Mobility program/type of mobility: Research stay

Lucas Romero

Status: PhD Student

Institution of origin: Universidad de Buenos Aires

Country: Argentina

Dates: 1 February to 31 July 2025

Context of the visit: PhD student of Alejandro Díaz-Caro. In the framework of the QCOMICAL project to work with his advisor.

Mobility program/type of mobility: Research stay

Cristian Sottile

Status: PhD Student

Institution of origin: Universidad de Buenos Aires

Country: Argentina

Dates: 25 to 27 June 2025

Context of the visit: PhD student of Alejandro Díaz-Caro. In the framework of the QCOMICAL project to work with his advisor.

Mobility program/type of mobility: Research stay

Malena Ivnisky

Status: PhD Student

Institution of origin: Universidad de Buenos Aires

Country: Argentina

Dates: 28 June to 12 July 2025

Context of the visit: PhD student of Alejandro Díaz-Caro. In the framework of the QCOMICAL project to work with her advisor.

Mobility program/type of mobility: Research stay

Nicolás Monzón

Status: Master Student

Institution of origin: Universidad de la República

Country: Uruguay

Dates: 3 to 14 November 2025

Context of the visit: Master student of Alejandro Díaz-Caro. In the framework of the QCOMICAL project to work with his advisor.

Mobility program/type of mobility: Research stay

Anna Nenca

Status: Assistant Professor

Institution of origin: University of Gdansk

Country: Poland

Dates: August to November 2025

Context of the visit: Collaboration with Nazim Fatès.

Mobility program/type of mobility: Research stay

10.2.2 Visits to international teams

Research stays abroad

Alejandro Díaz-Caro

Visited institution: Universidad de Buenos Aires

Country: Argentina

Dates: July 28 to August 15, 2025

Context of the visit: In the framework of the QCOMICAL project.

Mobility program/type of mobility: Research stay

Alejandro Díaz-Caro

Visited institution: Universidad de Buenos Aires

Country: Argentina

Dates: November 17 to 28, 2025

Context of the visit: In the framework of the QCOMICAL project.

Mobility program/type of mobility: Research stay and Master 2 intensive course

Alejandro Díaz-Caro

Visited institution: Universidad de la República

Country: Uruguay

Dates: December 1 to 12, 2025

Context of the visit: In the framework of the QCOMICAL project.

Mobility program/type of mobility: Research stay

Nathan Claudet and Simon Perdrix

Visited institution: VirginiaTech

Country: US

Dates: May 26 to 31, 2025

Context of the visit: Invitation to participate to the workshop "Bridging Classical Theory and Quantum Innovation".

Mobility program/type of mobility: Research stay and participation to a workshop.

Miriam Backens

Visited institution: Simon Fraser University

Country: Canada

Dates: May 20–24, 2025

Context of the visit: Invitation to participate in the workshop Mathematical Foundations of Quantum Advantage.

Mobility program/type of mobility: Research stay and participation in a workshop.

10.3 European initiatives

10.3.1 Horizon Europe

QCOMICAL QCOMICAL project on cordis.europa.eu

Title: Quantum Computing and its Calculi

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

Partners:

- Nnria, 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
- Università degli Studi di Urbino Carlo Bo (UNIURB), Italy

Inria contact: Simon Perdrix

Coordinators: 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 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: Kristel Michielsen

Summary: The aim of HPCQS is to prepare European research, industry and society for the use and federal operation of quantum computers and simulators. These are future computing technologies that are promising to overcome the most difficult computational challenges. HPCQS is developing the programming platform for the quantum simulator, which is based on the European ATOS Quantum Learning Machine (QLM), and the deep, low-latency integration into modular HPC systems based on ParTec's European modular supercomputing concept. A twin pilot system, developed as a prototype by the European company Pasqal, will be implemented and integrated at CEA/TGCC (France) and FZJ/JSC (Germany), both hosts of European Tier-0 HPC systems. The pre-exascale sites BSC (Spain) and CINECA (Italy) as well as ICECH (Ireland) will be connected to the TGCC and JSC via the European data infrastructure FENIX. It is planned to offer quantum HPC hybrid resources to the public via the access channels of PRACE. To achieve these goals, HPCQS brings together leading quantum and supercomputer experts from science and industry, thus creating an incubator for practical quantum HPC hybrid computing that is unique in the world. The HPCQS 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 (where 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 2029

Coordinator: Simon Perdrix

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

Partner Institution(s): Inria, Université Grenoble Alpes, CNRS Paris Villejuif, Sorbonne Université, CEA Grenoble, Institut National Polytechnique Grenoble, Université d'Aix-Marseille, Université de Bordeaux, Comue Université Bourgogne Franche Comté, Université de Bretagne Sud, Université de Lyon I, 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 2029

Coordinator: Anthony Leverrier (Cosmiq, Inria Paris)

Local Coordinator: Simon Perdrix (replacing Christophe Vuillot)

Local Members: Nazim Fates, Emmanuel Jeandel, Simon Perdrix

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

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

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair

- Alejandro Díaz-Caro was the general chair of the 1st QCOMICAL School on Quantum and Classical Programming Languages and Semantics. November 3 to 7, 2025, at Nancy.

Member of the organizing committees

- Several members of the team (or associated with the team) have been involved in the organization of the conference WORDS 2025 in Nancy: Mathilde Bouvel, Guilhem Gamard, Damien Jamet, Pierre-Adrien Tahay and Benjamin Testart.
- Alejandro Díaz-Caro, Simon Perdrix, and Kostia Chardonnet organised the 1st QCOMICAL School on Quantum and Classical Programming Languages and Semantics. November 3 to 7, 2025, at Nancy.
- Miriam Backens co-organised Dagstuhl Seminar 25382: Quantum Error Correction Meets ZX-Calculus. September 14–19, 2025, Dagstuhl, Germany.
- Léo Gayral: organizer of Scienc.e.s 2025, an interdisciplinary and intersectional event about Academia and Society.

11.1.2 Scientific events: selection

Chair of conference program committees

- Alejandro Díaz-Caro: co-chair of the 22nd International Conference on Quantum Physics and Logic (QPL 2025).
- Guilhem Gamard co-chair of the program committee of the international conference WORDS 2025 (roughly 50 papers submitted and 30 accepted). The proceedings have been published in the Springer LNCS series.
- Romain Péchoux: co-chair of the special session on quantum computing Computability in Europe 2025.

Member of the conference program committees

- Miriam Backens: QIP 2026, PlanQC 2026
- Miriam Backens, Alejandro Díaz-Caro, Emmanuel Jeandel, Simon Perdrix : QPL 2025.
- Alejandro Díaz-Caro: PlanQC 2025, LSFA 2025, SBLP 2025.
- Nazim Fatès: AUTOMATA 2025, ASCAT 2025
- Léo Gayral: Scienc.e.s 2025
- Romain Péchoux: Computability in Europe 2025.
- Simon Perdrix: MFPS 2025

Reviewer

- Miriam Backens: reviewer for CSL 2025, STOC 2025
- Alejandro Díaz-Caro: reviewer for LICS 2025, QPL 2025, LSFA 2025, SBLP 2025, PlanQC 2025
- Simon Forest: reviewer for LICS 2025
- Léo Gayral: reviewer for WORDS 2025, UCNC 2025
- Emmanuel Hainry: reviewer for CiE 2025, FOCS 2025
- Mathieu Hoyrup: reviewer for CiE 2025, ICALP 2025, MFCS 2025
- Romain Péchoux: reviewer for CiE 2025, FSCD 2025, FSTTCS 2025

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
  - member of the editorial board of Annals of Combinatorics
- Alejandro Díaz-Caro: associated editor of IEEE Transactions on Emerging Topics in Computing.
- Alejandro Díaz-Caro and Simon Perdrix: guest editors of the Special Issue on Quantum Physics and Logic at the Journal of Logical and Algebraic Methods in Programming.
- 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 Logical Methods in Computer Science (LMCS).

Reviewer - reviewing activities

- Miriam Backens: reviewer for Information and Computation
- Mathilde Bouvel: reviewer for Advances in Applied Mathematics, Discrete Mathematics and Theoretical Computer Science, and Combinatorial Theory
- Alejandro Díaz-Caro: reviewer for Journal of Logic and Computation
- Simon Forest: reviewer for Advances in Mathematics,
- Guilhem Gamard: reviewer for Forum of Mathematicians, σ
- Emmanuel Hainry: reviewer for Logical Methods in Computer Science
- Mathieu Hoyrup: reviewer for Foundations of Computational Mathematics, Information and Computation, Journal of Logic and Computation, Mathematical Structures in Computer Science, Computability
- Romain Péchoux: reviewer for Theoretical Computer Science and Logical Methods in Computer Science
- Simon Perdrix: reviewer for Quantum.

11.1.4 Invited talks

- Miriam Backens gave:
  - an invited talk at the 2nd FoQaCIA workshop (Braga, Portugal)
  - an invited tutorial at the École Jeunes Cherchereuses en Informatique Fondamentale et ses Mathématiques (Caen, France)
  - an invited tutorial and talk at the Journées 2025 du GT Scalp (Paris, France)
  - an invited tutorial at the 1st QCOMICAL School on Quantum and Classical Programming Languages and Semantics (Nancy, France)
- Alejandro Díaz-Caro gave:
  - an invited talk at the special session on quantum computing at Computing in Europe 2025

  - an invited talk at the XIV Conference on Quantum Foundations: From Foundations to Quantum Computing - Celebrating IYQ2025 (CQF 2025)
  - an invited talk at the ASQ3: Algorithms and Software Quests in Quantum Qomputing
  - an invited talk at the XIV Workshop on Philosophical Logic
  - an invited talk at the Argentinian Symposium on Quantum Computing at 54JAIIO

- Simon Forest gave an invited talk at the Advances in Interactive and Quantitative Semantics workshop (Marseille, France)
- Emmanuel Hainry gave an invited talk at the IRN CloVe Workshop on Computational Complexity (Copenhagen, Denmark)
- Mathieu Hoyrup gave an invited talk at the Online Logic Seminar and the Cross-Alps Logic Seminar
- Simon Perdrix gave
  - an invited talk at the special session on quantum computing at Computing in Europe 2025
  - an invited talk at Quantazur days (Nice, France)
  - an invited talk at Séminaire *Les Rendez-vous de l'informatique*, organised by MENESR.
  - an invited tutorial at the 1st QCOMICAL School on Quantum and Classical Programming Languages and Semantics (Nancy, France)

11.1.5 Leadership within the scientific community

- Miriam Backens, Mathilde Bouvel and Léo Gayral are members of the Comité PÉDI (Parité, Équité, Diversité, Inclusion) of the GDR IFM. Léo Gayral is also webmaster for this committee.
- Mathilde Bouvel: member of the steering committee of the conference series *Permutation Patterns*
- Nazim Fatès: chair of the IFIP WG1.5 on *Cellular Automata and Discrete Complex Systems*, member of the steering committee of AUTOMATA 2025.
- Romain Péchoux was vice-chair of the MSCA Fellowshing program, European Research Agency, 2025.
- Simon Perdrix: co-head of the groupe de travail Informatique Quantique at GdR IFM.

11.1.6 Scientific expertise

- Mathilde Bouvel served as external evaluator for a conference proposal at the Banff conference center (Canada)
- Emmanuel Hainry was member of a CoS for a MCF position, Université de Lorraine, 2025.
- Emmanuel Jeandel: member of the scientific counsel of GDR IFM
- Romain Péchoux was member of:
  - a CoS for a CPJ, Université Paris Saclay, 2025.
  - a CoS for a Full Professor position, University of Innsbruck, 2025.
- Simon Perdrix was member of:
  - a CoS for a CPJ, Université de Bordeaux, 2025.
  - of the Jury Inria CRCN / ISFP, Grenoble, 2025.

11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

- Licence
  - Miriam Backens. *Algorithmes et Complexité*, École des Mines, 10h.
  - Mathilde Bouvel. *Algorithmes et Complexité*, École des Mines, 10h.
  - Alejandro Díaz-Caro. *Lógica y Programación*, L3, Universidad Nacional de Quilmes, 56h.
  - Nazim Fatès. *Introduction à l'intelligence artificielle*, Seminar to the students of Engineering School (cours d'ouverture), Telecom Nancy, université de Lorraine, 3h.
  - Simon Forest. *Conception Objet*, Université de Lorraine, 30h. *Logique*, Université de Lorraine, 14h.
  - Guilhem Gamard. *Systèmes de Gestion de Bases de données,* 30h.
- Master
  - Miriam Backens. *Informatique quantique*, M1, Université de Lorraine, 12h.
  - Alejandro Díaz-Caro. *Características de Lenguajes de Programación*, M1, Universidad Nacional de Quilmes, 56h.
  - Alejandro Díaz-Caro. *Fundamentos de Lenguajes para Computación Cuántica*, M2, Universidad de Buenos Aires, 20h.
  - Nazim Fatès:
    - *Séminaire d'ouverture à l'intelligence artificielle*, Master 1 Sciences cognitives, université de Lorraine, 10h
    - *Introduction à l'intelligence artificielle*, IAE Nancy School of Management, Marketing et Gestion Commerciale, université de Lorraine, 3h
    - *Introduction à l'intelligence artificielle*, ENSEM, Conférences industrielles ISN, 2h.
  - Simon Perdrix. *Informatique quantique*, M1, Université de Lorraine, 12h.
  - Guilhem Gamard. *Réseaux,* 50h.

11.2.1 Supervision

- Miriam Backens supervised the PhD of Tommy McElvanney at University of Birmingham (5th year, defended February 25th, 2025).
- Miriam Backens supervised the PhD of Piotr Mitosek at University of Birmingham (4th year, defended July 21st, 2025).
- Miriam Backens supervised the internship of Jules Dupont (École des Mines Nancy, until June 2025).
- Miriam Backens is supervising the internship of Victor Gasse (École des Mines Nancy).
- Mathilde Bouvel and Emmanuel Jeandel are supervising the PhD of Benjamin Testart (4th year).
- Alejandro Díaz-Caro is supervising the PhD of Malena Ivnisky (4th year) at Universidad de Buenos Aires.
- Alejandro Díaz-Caro is supervising the PhD of Cristian Sottile (5th year) at Universidad de Buenos Aires.
- Alejandro Díaz-Caro is supervising the PhD of Rafael Romero (5th year) at Universidad de Buenos Aires.
- Alejandro Díaz-Caro is supervising the Master of Science of Nicolás Monzón (2nd year) at Universidad de la República.

- Nazim Fatès is supervising the PhD of Joannès Guichon (4th year) with Sylvain Contassot-Vivier (LORIA).
- Nazim Fatès has supervised the Master 2 internship of Nassima Ait Sadi.
- Simon Forest and Pierre Clairambault (LIS, Marseille) and Raphaëlle Crubillé (LIS, Marseille) are supervising the PhD of Victor Blanchi (2nd year).
- Mathieu Hoyrup and Guilhem Gamard are supervising the PhD of Alexis Terrassin (2nd year).
- Guilhem Gamard supervised the masters “long projects” (similar to internships) of Ahmed Imed Eddine Kheddim and that of Youva Amiar and Djedjiga Ait Slimani.
- Mathieu Hoyrup and Benjamin Hellouin (LISN) are supervising the PhD of Rémi Pallen (2nd year).
- Emmanuel Jeandel and Léo Gayral are supervising the PhD of Vivien Ducros (1st year).
- Emmanuel Jeandel and Julien Provilard are supervising the PhD of Théo Joffroy (1st year).
- Emmanuel Jeandel and Christophe Vuillot are supervising the PhD of Alexandre Guernut (4th year, defended Mai 13 2025).
- Emmanuel Jeandel supervised the masters internship of Vivien Ducros and Theo Joffroy (until aug 2025).
- Romain Péchoux and Christophe Chareton (Research Engineer, CEA) are supervising the PhD of Jad Issa (2nd year).
- Romain Péchoux and Simon Perdrix are supervising the PhD of Kathleen Barsse (2nd year).
- Romain Péchoux and Vladimir Zamdzhiev (ISFP, Inria Paris-Saclay) are supervising the PhD of Kinnari Dave (3rd year, defended December 17th 2025).
- Romain Péchoux and Emmanuel Hainry are supervising the PhD of Thomas Vinet (2nd year).
- Romain Péchoux and Emmanuel Hainry are supervising the PhD of Mario Silva (4th year, defended July 7th 2025).
- Simon Perdrix is supervising the PhD of Noé Delorme (3rd year).
- Simon Perdrix and Miriam Backens are supervising the PhD of Colin Blake (2nd year).
- Simon Perdrix and Mathilde Bouvel supervised the PhD of Nathan Claudet (3rd year, defended November 17th 2025).
- Simon Perdrix and Titouan Carette are supervising the PhD of Thomas Perez (2nd year).

11.2.2 Juries

- Miriam Backens:
  - was a member of the jury for the PhD of Nicolas Heurtel, Université Paris-Saclay, defended on June 11th, 2025.
  - was external examiner for the program *Master in Mathematics and Foundations of Computer Science*, University of Oxford, UK.
- Mathieu Hoyrup was rapporteur of the PhD of Ahmed Mimouni, Université Paris-Créteil, defended on October 24th 2025.
- Emmanuel Jeandel:
  - was rapporteur of the HDR of Sébastien Labbé, Université de Bordeaux, defended June 4 2025.

  - was a member of the jury of HDR of Pierre-Jean Spaenlehauer, Université de Lorraine, defended February 2 2025.
  - was rapporteur of the PhD of Nicolas Heurtel, Université Paris-Saclay, defended June 11 2025.

- Romain Péchoux:
  - was rapporteur of the PhD of Andrea Colledan, Universita di Bologna, defended the April 9th 2025.
  - was rapporteur of the PhD of Adriano Barile, Universita di Torino, defended the September 19th 2025.

- Mathilde Bouvel was a member of the jury for the PhD of Solal Gaudin, Université Lyon 1, defended on September 22nd, 2025.

- Simon Perdrix:
  - was external examiner for DPhil (PhD) of Lia Yeh, Oxford University, October 28th, 2025.
  - was member of the PhD of Pierre Botteron, Université de Toulouse, July 9th, 2025.
  - was member of the PhD of Colm Helleher, Université de Bourgogne Europe, October 2nd, 2025.

11.2.3 Educational and pedagogical outreach

- Miriam Backens gave a presentation about their research to high-school students and undergraduates at the online school *BeyondQuantum: Introduction to Quantum and Research* on May 12th, 2025.

- Miriam Backens and Kostia Chardonnet contributed the chapter "L'informatique quantique et le ZX" [60] to the book *Informatique fondamentale et ses Mathématiques : Une photographie en 2025* [59].

- Mathilde Bouvel made a short presentation of her research to first-year students of the *Ecole des Mines de Nancy*, on December 16th, 2025.

- Alejandro Díaz-Caro gave a short presentation of his research at the Summer School on "Mathematical Aspects of Quantum Information", at *Institut Pascal*, *Université Paris-Saclay* in June 2025.

11.3 Popularization

11.3.1 Specific official responsibilities in science outreach structures

- Alejandro Díaz-Caro: member of the steering committee of the yearly winter school *Escuela de Ciencias Informáticas* (Universidad de Buenos Aires)

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

- Interview (in Spanish) about quantum computing. Alejandro Díaz-Caro. EstudioTech YouTube channel. May 10, 2025.

- Minicourse via Instagram (in Spanish) *"Qué son los algoritmos cuánticos"*. Alejandro Díaz-Caro. Fundación Sociedades Digitales. November 5, 2025.

- Nazim Fatès: Remembering and Celebrating the Life of Kenichi Morita, contribution on reversible computing, remebrance day in honour of Pr Morita.

11.3.3 Participation in Live events

- Live debate (in Spanish) *"Computación Cuántica: Debate de especialistas"*. Alejandro Díaz-Caro. Fundación Sociedades Digitales YouTube channel. November 21, 2025.
- Nazim Fatès:
  - "Peut-on faire confiance à l'intelligence-artificielle ?", Colloque du lycée Saint-Sigisbert, Nancy, February 6, 2025.
  - Talk on artificial intelligence for the lycée Vatelot in Toul: "*Ecce robot* : remarques sur la question de l'intelligence-artificielle", March 7, 2025.
  - Wide-audience talk on the theme "Aux sources de l'intelligence-artificielle – Quelques repères avant, pendant et après le siècle de Descartes", Forum IRTS, Nancy, April 24, 2025.
  - Animation of a three-hour talk and debate with Erasmus+ students from Europe and North Africa, AMSED association, Strasbourg, July 24, 2025.

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.

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[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.

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[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.

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[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.

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