

The Inria logo is written in a red, cursive script font.

Activity Report 2019

Team MOCQUA

**Designing the Future of Computational
Models**

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Nancy - Grand Est

THEME
Proofs and Verification

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Team MOCQUA

Creation of the Project-Team: 2020 March 01

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Computer Science and Digital Science:

- A2.3.2. - Cyber-physical systems
- A2.4.1. - Analysis
- A6.5. - Mathematical modeling for physical sciences
- A7.1.4. - Quantum algorithms
- A7.2. - Logic in Computer Science
- A7.3. - Calculability and computability
- A8.1. - Discrete mathematics, combinatorics
- A8.3. - Geometry, Topology
- A8.6. - Information theory

Other Research Topics and Application Domains:

- B9.5.1. - Computer science
- B9.5.2. - Mathematics
- B9.5.3. - Physics

1. Team, Visitors, External Collaborators

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- Nazim Fatès [Inria, Researcher]
- Isabelle Gnaedig [Deputy team leader, Inria, Researcher]
- Mathieu Hoyrup [Inria, Researcher]
- Simon Perdrix [CNRS, Researcher, HDR]

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- Emmanuel Jeandel [Team leader, Univ de Lorraine, Professor, HDR]
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- Irène Marcovici [Univ de Lorraine, Associate Professor]
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- Francesco Arzani [CNRS, until Oct 2019]
- Donald Stull [Inria, until Aug 2019]
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PhD Students

- Agustin Borgna [CNRS, from Oct 2019]
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- Pierre Mercuriali [Univ de Lorraine]
- Margarita Veshchezerova [EDF, from Oct 2019]
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- Karim Boutamine [Univ de Lorraine, from Jun 2019 until Aug 2019]

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Administrative Assistants

Sophie Drouot [Inria]
Sylvie Hilbert [CNRS, from Jun 2018]

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Victor Selivanov [Ershov Institute of Informatics, Sep 2019]
Kihara Takayuki [Nagoya Univ, Sep 2019]

2. Overall Objectives

2.1. Designing the future of computational models

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

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

3. Research Program

3.1. Quantum Computing

While it can be argued that the quantum revolution has already happened in cryptography [39] or in optics [38], quantum computers are far from becoming a common commodity, with only a few teams around the world working on a practical implementation. In fact, one of the most commonly known examples of a quantum computer, the D-Wave 2X System, defies the usual definition of a computer: it is not general-purpose, and can only solve (approximately) a very specific hardwired problem.

Most current prototypes of a quantum computer differ fundamentally on the hardware substrate, and it is quite hard to predict which solution will finally be adopted. The landscape of quantum programming languages is also constantly evolving. Comparably to compiler design, the foundation of quantum software therefore relies on an intermediate representation that is suitable for manipulation, easy to produce from software and easily encodable into hardware. The language of choice for this is the ZX-calculus.

Regardless of the actual model that will be accepted by the industry, it is becoming clear that some of the hurdles into scaling up quantum computers from a few qubits to very large arrays will remain. As an example, current implementations of quantum computers working on hundreds of qubits indeed are not able to form and maintain all possible forms of entanglement between qubits. This raises two questions. First, does this restrict the computational power, and the supposed advantage of the quantum computer over the classical computer? Second, how to ensure that a quantum program that was designed for a theoretical quantum computer will work on the practical implementations? This will be investigated, in particular by providing static analysis methods for evaluating a priori how much entanglement a quantum program needs.

3.2. Higher-Order Computing

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

While the theory of computation is well developed for first-order programs, difficulties arise when dealing with higher-order programs. There are many non-equivalent ways of presenting inputs to such programs: an input function can be presented as a black-box, encoded in an infinite binary sequence, or sometimes by a finite description. Comparing those representations is an important problem. A particularly useful application of higher-order computations is to compute with infinite objects that can be represented by functions or symbolic sequences. The theory works well in many cases (to be precise, when these objects live in a topological space with a countable basis [42]), but is not well understood in other interesting cases. For instance, when the inputs are the second-order functionals (of type $(\mathbb{N} \rightarrow \mathbb{N}) \rightarrow (\mathbb{N} \rightarrow \mathbb{N})$), the classical theory does not apply and many problems are still open.

3.3. Dynamical Systems

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

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

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

The simulation of a physical dynamical system on a computer is made difficult by various aspects. First, the parameters of the dynamical systems are seldom exactly known. Secondly, the simulation is usually non exact: real numbers are usually represented by floating-point numbers, and simulations of cellular automata only simulate the behavior of finite or periodic configurations. For some chaotic systems, this means that the simulation can be completely irrelevant.

4. Application Domains

4.1. Quantum Computing

Quantum Computing is currently the most promising technology to extend Moore's law, whose end is expected with the engraving at 7 nm, in less than 5 years. Thanks to the exponential computational power it will bring, it 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. Recent scientific and technical advances suggest that the construction of the first quantum computers will be possible in the coming years.

As a result, the major US players in the IT industry have embarked on a dramatic race, mobilizing huge resources: IBM, Microsoft, Google and Intel have each invested between 20 and 50 million euros, and are devoting significant budgets to attract and hire the best scientists on the planet. Some states have launched ambitious national programs, including Great Britain, the Netherlands, Canada, China, Australia, Singapore, and very recently Europe, with the upcoming 10-year FET Flagship program in Quantum Engineering.

While a large part of these resources are going towards R-&-D in quantum hardware, there is still an important need and real opportunities for leadership in the field of quantum software.

The Mocqua team contributes to the computer science approach to quantum computing, aka the quantum software approach. We aim at a better understanding of the power and limitations of the quantum computer, and therefore of its impact on society. We also contribute to ease the development of the quantum computer by filling the gap between the theoretical results on quantum algorithms and complexity and the recent progresses in quantum hardware.

4.2. Higher-Order Computing

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

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

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

4.3. Simulation of Dynamical Systems by Cellular Automata

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

In the framework of pure computational questions, various examples of such systems have already been proposed for solving complex problems with a simple bio-inspired approach (e.g. the decentralized gathering problem [40]). 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 [5]. 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 question of the evaluation of the robustness of a swarming model proposed by A. Deutsch to mimic the self-organization process observed in various natural systems (birds, fishes, bacteria, etc.) [2]. We now wish to develop our simulation tools to apply them to various biological phenomena where a great number of agents are implied.

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 examine how to propose a decentralized view of a business-to-business market and propose agent-oriented and totally decentralized models of such markets. Various banks and large businesses have already expressed their interest in such modelling approaches.

5. Highlights of the Year

5.1. Highlights of the Year

The ZX-calculus is a powerful diagrammatic language which can be used to reason on quantum computing. The ZX-calculus is also an essential tool for the development of the quantum computer allowing for instance optimisation of quantum programs. Indeed the ZX-calculus is equipped with an equational theory which allows one to transform and optimize quantum programs. A few years ago, we have proved the first completeness result of the ZX-calculus [41] [28], guaranteeing that two equivalent evolutions can be transformed one into the other thanks to the equational theory. Its completeness gives to the ZX-calculus a competitive advantage compared to the other models of quantum computation, like the quantum circuits, for which no complete equational theory is known.

In [31], Renaud Vilmart introduced a new, simple, and meaningful equational theory for the ZX-calculus, based on the famous Euler angle decomposition. Renaud participated to the various previous results of the team on this subject during his PhD thesis in the Mocqua team, and culminated with this sole author paper published at LICS for which he obtained the best student paper award.

5.1.1. Awards

Best student paper award at LICS'19 for Renaud Vilmart. [31].

6. New Software and Platforms

6.1. FiatLux

KEYWORDS: Cellular automaton - Multi-agent - Distributed systems

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

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

- Participants: Nazim Fatès and Olivier Boure
- Partners: ENS Lyon - Université de Lorraine
- Contact: Nazim Fatès
- URL: <http://fiatlux.loria.fr/>

6.2. ComplexityParser

KEYWORDS: Complexity - Static typing - Parsing

FUNCTIONAL DESCRIPTION: ComplexityParser is a static complexity analyzer of Java programs written in Java (approximately 5000 lines of code). The program consists in a type inference and checking program based on the data tiering principle. It allows the program to certify that the typed program has a polynomial time complexity.

- Participants: Olivier Zeyen, Emmanuel Hainry, Romain Pécoux and Emmanuel Jeandel
- Contact: Emmanuel Hainry

7. New Results

7.1. Semicomputable points in Euclidean spaces

- Participants: Mathieu Hoyrup, Donald Stull

Many natural problems/objects from theoretical computer science and logic are not decidable/computable, but semidecidable/semicomputable only: the halting problem, provability, domino problem, attractors of dynamical systems, etc. We pursue our program to study semicomputable objects in a systematic way. In this work, we focus on objects that can be described by finitely many real numbers, in particular polynomials and disks in the plane. Such objects can be identified with points of Euclidean spaces. We therefore introduce and study a notion of semicomputable point in Euclidean spaces, providing a multi-dimensional analog of a well-known unidimensional notion. The study involves ideas from linear algebra, convex analysis and computability. This work was presented at MFCS 2019 [27].

7.2. Computability on quasi-Polish spaces

- Participants: Mathieu Hoyrup, Cristobal Rojas, Victor Selivanov, Donald Stull

Descriptive Set Theory (DST) is a branch of topology which interacts very nicely with computability and logic. Indeed, these three theories involve measuring the complexity of describing objects in different ways (respectively as combinations of open sets, by programs, by formulae), which are intimately related. However, DST is traditionally developed on spaces relevant to mathematical analysis (Polish spaces), but not to theoretical computer science. The recently introduced quasi-Polish spaces are a much broader class of spaces including for instance Scott domains, important in functional programming. However, how to compute in such spaces is still not well-understood. In particular, quasi-Polish spaces can be characterized in many ways, so one has to choose the right definition to start with. We compare the computable versions of some of them, proving their non-equivalence, and focus on one of them, providing evidence that this notion is probably the right one. This work was presented at DCFS 2019 [26].

7.3. Degree spectra of Polish spaces

- Participants: Mathieu Hoyrup, Takayuki Kihara, Victor Selivanov

Mathematical objects can encode information. An obvious example is given by subsets of the plane: a text printed on a sheet of paper is a subset of the plane conveying information. However, when the object is submitted to deformations, what information can still be conveyed? What information is invariant under such deformations?

It is the core question in computable structure theory: for instance, what can be encoded in an infinite graph, which can be decoded from the structure itself and not from a particular presentation of the graph? Mathematically, what information is robust under graph isomorphism? It happens that much information can be encoded, for instance by using the lengths of the cycles in the graph.

Algebraic structures have been thoroughly studied from this perspective. However, the study of topological structures is almost inexistant, and more difficult (they are continuous while algebraic structures are often discrete). For instance, what information can be encoded in a subset of the plane, which is stable under continuous deformations (homeomorphisms)?

We have tackled this question during the visit of Takayuki Kihara and Victor Selivanov, and obtained many interesting results. For instance, we have proved that no direct information can be encoded (for instance, no infinite binary sequence can be extracted by an algorithm, unless the sequence is already computable). However, limit information can be encoded (for instance, a binary sequence can be encoded in such a way that a double-sequence converging to it can be extracted from the object by an algorithm). It is still open whether a single limit is possible.

A paper is still in preparation.

7.4. Computable SFTs

- Participants: Emmanuel Jeandel and Pascal Vanier

Previous works by the two participants have shown that there is a striking similarity between subshifts of finite type (tilings, coloring of the plane that do not contain a given set of patterns) and finitely presented groups (finitely generated groups with a finite number of equations).

This analogy can be described intuitively as follows: colors in subshifts corresponds to the generators of the groups, forbidden patterns correspond to the equations. Finite type is the same as finite presentation, and minimal subshifts correspond to simple groups.

The article [29] develops this analogy to computable objects: It is well known by the Higman-Thompson theorem that a finitely generated group is computable iff it is a subgroup of a simple group which is itself a subgroup of a finitely presented group. In this article, we give an equivalent for subshifts : a subshift is computable iff it is the restriction of a minimal subshift which is itself the restriction of a subshift of finite type.

7.5. Probabilistic cellular automata for problem solving

- Participants: Nazim Fatès, Irène Marcovici

Directly related to the theme exposed in Sec. 4.3, we examined the problem of self-stabilisation, as introduced by Dijkstra in the 1970's, in the context of cellular automata [33]. More precisely, we examined how to stabilise k -colourings, that is, infinite grids which are coloured with k distinct colours in such a way that adjacent cells have different colours. The idea is that if, for any reason (e.g., noise, previous usage, tampering by an adversary), the colours of a finite number of cells in a valid k -colouring are modified, thus introducing errors, we can correct the system into a valid k -colouring by using local rules only. In other words, we designed cellular automaton rules which, starting from any finite perturbation of a valid k -colouring, reach a valid k -colouring in finite time. We discussed the different cases depending on the number of colours k , and propose some deterministic and probabilistic rules which solve the problem for $k \neq 3$. We also explained why the case $k = 3$ is more delicate. Finally, we proposed some insights on the more general setting of this problem, passing from k -colourings to other tilings (subshifts of finite type).

In the same spirit, we addressed the problem of detecting failures in a distributed network [30]. Our question is: if some components can break down over time, how can we detect that the failure rate has exceeded a given threshold without any central authority? We want to estimate the global state of the network, only through local interactions of components with their neighbours. In particular, we wish to reach a consensus on an alert state when the failure rate exceeds a given threshold. We used a cellular automaton in order to propose solutions in the case of a network with a grid structure. We compared three methods of self-organisation that are partly inspired by physical and biological phenomena. As an application, we envisioned sensor networks or any type of decentralised system with a great number of components.

Concerning the fundamental properties of asynchronous cellular automata, we presented a tutorial on the convergence properties of the 256 Elementary Cellular Automata under the fully asynchronous updating, that is, when only one cell is updated at each time step. We regrouped the results which have been presented in different articles and exposed a full analysis of the behaviour of finite systems with periodic boundary conditions. Our classification relies on the scaling properties of the average convergence time to a fixed point. We presented the different scaling laws that can be found, which fall in one of the following classes:

logarithmic, linear, quadratic, exponential and non-converging. The techniques for quantifying this behaviour rely mainly on Markov chain theory and martingales. Most behaviours can be studied analytically but there are still many rules for which obtaining a formal characterisation of their convergence properties is still an open problem.

Our article on the global synchronisation problem was finally published [21]. In this problem, one is asked to find a cellular automaton which has the property that every initial condition evolves into a homogeneous blinking state. We studied this simple inverse problem for the case of one-dimensional systems with periodic boundary conditions. Two paradoxical observations were made: (a) despite the apparent simplicity of finding rules with good statistical results, there exist no perfect deterministic solutions to this problem, (b) if we allow the use of randomness in the local rule, constructing “perfect” stochastic solutions is easy. For the stochastic case, we give some rules for which the mean time of synchronisation varies quadratically with the number of cells and ask if this result can be improved. To explore more deeply the deterministic rules, we code our problem as a SAT problem and use SAT solvers to find rules that synchronise a large set of initial conditions.

7.6. Diagrammatic quantum computing

- Participants: Titouan Carette, Dominic Horsman, Emmanuel Jeandel, Simon Perdrix, Renaud Vilmart.

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

Emmanuel Jeandel, Simon Perdrix, and Renaud Vilmart have introduced a general normal form for ZX-diagrams implying completeness results for various (almost all) fragments of quantum mechanics [28]. Renaud Vilmart has also introduced the simple, meaningful axiomatisation of the full ZX-calculus [31]. This two papers have been published at LICS’19.

Titouan Carette, Emmanuel Jeandel, Simon Perdrix, and Renaud Vilmart, have introduced a new simple categorical construction allowing to deal with non pure quantum evolutions (i.e. involving quantum measurements, discard of quantum systems, and probability mixtures). When this new construction coincides with the existing constructions, it provides simpler axiomatisation. For instance, this construction provides a complete equational theory for an extension of the ZX-calculus for arbitrary (non necessary pure) quantum evolutions. This result has been published at ICALP’19 [24].

Titouan Carette, Dominic Horsman (from LIG Grenoble) and Simon Perdrix have provided an axiomatisation for a scalable ZX-calculus where each wire represents a register of qubits, instead of a single qubit in the standard ZX-calculus. The scalable ZX-calculus allows compact representation of quantum algorithms, protocols and quantum codes. This result has been published at MFCS’19 [23]

7.7. Causal Graph Dynamics

- Participants: Pablo Arrighi, Simon Martiel, Simon Perdrix.

Causal Graph Dynamics extend Cellular Automata to arbitrary time-varying graphs of bounded degree. The whole graph evolves in discrete time steps, and this global evolution is required to have a number of symmetries: shift-invariance (it acts everywhere the same) and causality (information has a bounded speed of propagation). Pablo Arrighi (LIS, Marseille), Simon Martiel (Atos-Bull) and Simon Perdrix have considered a natural physics-like symmetry, namely reversibility. In particular, they extended two fundamental results on reversible cellular automata, by proving that the inverse of a causal graph dynamics is a causal graph dynamics, and that these reversible causal graph dynamics can be represented as finite-depth circuits of local reversible gates. These results have been published in the journal *Natural Computing* [16].

7.8. Contextuality in multipartite pseudo-telepathy graph games

- Participants: Anurag Anshu, Peter Høyer, Mehdi Mhalla, and Simon Perdrix.

Analyzing pseudo-telepathy graph games, Anurag Anshu, Peter Høyer, Mehdi Mhalla, and Simon Perdrix proposed a way to build contextuality scenarios exhibiting the quantum advantage using graph states. A new tool, called multipartiteness width, is introduced to investigate which scenarios are hard to decompose and to show that there exist graphs generating scenarios with a linear multipartiteness width. These results have been published in the Journal of Computer and System Science [15].

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- Project acronym: **ANR PRCE SoftQPro (ANR-17-CE25-0009)**
Project title: Solutions logicielles pour l'optimisation des programmes et ressources quantiques.
Duration: Dec. 2017 - Dec. 2022
Coordinator: Simon Perdrix
Other partners: Atos-Bull, LRI, CEA-Saclay.
Participants: Simon Perdrix, Emmanuel Jeandel, Emmanuel Hainry, and Romain Péchoux
Abstract: Quantum computers can theoretically solve problems out of reach of classical computers. We aim at easing the crucial back and forth interactions between the theoretical approach to quantum computing and the technological efforts made to implement the quantum computer. Our software-based quantum program and resource optimisation (SoftQPRO) project consists in developing high level techniques based on static analysis, certification, transformations of quantum graphical languages, and optimisation techniques to obtain a compilation suite for quantum programming languages. We will target various computational model back-ends (e.g. QRAM, measurement-based quantum computations) as well as classical simulation. Classical simulation is central in the development of the quantum computer, on both ends: as a way to test quantum programs but also as a way to test quantum computer prototypes. For this reason we aim at designing sophisticated simulation techniques on classical high-performance computers (HPC).
- Project acronym: **ANR PRCI VanQuTe (ANR-17-CE24-0035)**
Project title: Validation of near-future quantum technologies.
Duration: Fev. 2018 - Jan. 2022
Coordinator: Damian Markham (Laboratoire d'informatique de Paris 6)
Other partners: NTU (Nanyang Technological University), SUTD (Singapore University of Technology and Design), NUS (National University of Singapore), LIP6 (Laboratoire d'informatique de Paris 6)
Participants: Simon Perdrix, Emmanuel Jeandel
Abstract: In the last few years we have seen unprecedented advances in quantum information technologies. Already quantum key distribution systems are available commercially. In the near future we will see waves of new quantum devices, offering unparalleled benefits for security, communication, computation and sensing. A key question to the success of this technology is their verification and validation.

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

8.1.2. Other initiatives

- Quantex. Project acronym: PIA-GDN/Quantex. (initially an ITEA3 project finally funded by the *Grands défis du Numérique / Programme d'investissements d'avenir*).
Project title: Simulation/Emulation of Quantum Computation.
Duration: Feb. 2018 - Jan 2021.
Coordinator: Huy-Nam Nguyen (Atos Bull).
Other partners: Atos-Bull, LRI, CEA Grenoble.
Participants: Simon Perdrix (WP leader), Emmanuel Jeandel
Abstract: The lack of quantum computers leads to the development of a variety of software-based simulators to assist in the research and development of quantum algorithms. This proposal focuses on the development of a combined software-based and hardware-accelerated toolbox for quantum computation. A quantum computing stack including specification language, libraries and optimisation/execution tools will be built upon a well-defined mathematical framework mixing classical and quantum computation. Such an environment will be dedicated to support the expression of quantum algorithms for the purpose of investigation and verification.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

Mathieu Hoyrup participates in the Marie-Curie RISE project Computing with Infinite Data coordinated by Dieter Spreen (Univ. Siegen) that has started in April 2017.

8.3. International Initiatives

8.3.1. Participation in Other International Programs

ECOS-Sud A17C03 QuCa - 01/2018 - 12/2020. **Quantum Calculi**. Funded by MinCyT and ECOS France. Argentine Director: A. Díaz-Caro (UNQ/CONICET), French Director: G. Dowek (Inria, LSV, ENS Paris-Saclay)

Permanent members: P. Arrighi (Aix-Marseille) - J.-Y. Marion (LORIA) - P. E. Martínez López (UNQ) - S. Perdrix - B. Valiron (CentraleSupélec).

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Alonso Herrera: Universidad Andrés Bello, Chile.
- Takayuki Kihara : Nagoya University, Japan.
- Damiano Mazza, CNRS, LIPN.
- Victor Selivanov: Ershov Institute of Informatics Systems, Novosibirsk, Russia.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

Simon Perdrix visited Universita Buenos Aires, Universita de Quilmes and Conicet for two weeks in November 2019. The visit was part of the QuCa Ecos Sud project and was partially funded by LIA SINFIN.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. General Chair, Scientific Chair

- Mathieu Hoyrup was chair and organizer of the workshop **MLA 2019**.
- Jointly with Andreas Deutsch (TU Dresden, Germany), Nazim Fatès was chair and organizer of **SOLSTICE 2019**, Summer Solstice Conference on Discrete Models of Complex Systems.

9.1.1.2. Member of the Conference Program Committees

- Mathieu Hoyrup was member of the PC of CiE 2019.
- Romain Péchoux was member of the PC of DICE and FOPARA 2019.
- Nazim Fatès was member of the PC of AUTOMATA 2019.
- Simon Perdrix was member of the PC of QPL'19.

9.1.1.3. Reviewer

Romain Péchoux was reviewer for DICE and FOPARA 2019, FOSSACS 2019, ICALP 2019, and ISMVL 2019.

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- Emmanuel Jeandel is member of the Editorial Board of RAIRO-ITA.
- Nazim Fatès is a member of the Editorial board of the *Journal of cellular automata*.

9.1.2.2. Reviewer - Reviewing Activities

- Romain Péchoux was reviewer for Information Processing Letters and Journal of Automated Reasoning.
- Nazim Fatès served as a reviewer for the *SIAM Journal on Discrete Mathematics* (SIDMA) and for *Informatica*.

9.1.3. Invited Talks

Romain Péchoux gave an invited talk at Shonan seminar #151 on higher order complexity theory and its applications.

9.1.4. Leadership within the Scientific Community

- Romain Péchoux is guest coeditor of the Theoretical Computer Science, special issue on Implicit Computational Complexity, DICE 2016-2018.
- Nazim Fatès is the vice-president of the **IFIP WG 1.5** on Cellular Automata and Discrete Complex Systems. He is a guest coeditor of a **special issue** of *Natural computing* on the theme “Discrete Models of Complex Systems: recent trends and analytical challenges”. This call for papers follows the SOLSTICE 2019 conference (Dresden, Germany, July 2019).

9.1.5. Scientific Expertise

- Romain Péchoux is Rapporteur and Expert for the Marie Curie IF call of the European Commission, ERA.
- Nazim Fatès was an evaluator for a funding project of the **CONICYT**, the Chilean *Comisión Nacional de Investigación Científica y Tecnológica*.
- Simon Perdrix was member of the HCERES evaluation committee of G-SCOP.

- Simon Perdrix was member of the committee "La Recherche" award (Prix du Magazine La Recherche) 2019.

9.1.6. Research Administration

- Emmanuel Hainry was member of the CNU (Conseil National des Universités), Section 27 until 2019, nov 18th.
- Simon Perdrix is elected member and scientific secretary of the CNRS section 6.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Licence
 - Isabelle Gnaedig:
 - * To the limits of the computable, 6 hours, Opening course-conference of the collegium "Lorraine INP", Université de Lorraine, Nancy, France.
 - Emmanuel Hainry:
 - * Operating Systems, 30h, L1, IUT Nancy Brabois, Université de Lorraine, Nancy, France.
 - * Algorithmics, 40h, L1, IUT Nancy Brabois.
 - * Dynamic Web, 60h, L1, IUT Nancy Brabois.
 - * Databases, 30h, L1, IUT Nancy Brabois.
 - * Object Oriented Languages, 16h, L2, IUT Nancy Brabois.
 - * Complexity, 30h, L2, IUT Nancy Brabois.
 - Emmanuel Jeandel:
 - * Algorithmics and Programming 1, 60h, L1 Maths-Info, Université de Lorraine, Nancy, France.
 - * Algorithmics and Programming 4, 30h, L3 Informatique.
 - * Modeling Using Graph Theory, 30h, L3 Informatique.
 - * Networking, 15h, L3 Informatique.
 - * Formal Languages, 30h, L2-L3 Informatique.
 - Romain Péchoux had an Inria delegation (2018-2019).
- Master
 - Isabelle Gnaedig:
 - * Rule-based Programming, 24 hours, M2, Telecom-Nancy, Université de Lorraine, Nancy, France.
 - Emmanuel Hainry:
 - * Mathematics for Computer Science, 15h, M1 TAL, Institut des Sciences du Digital: Management et Cognition, Université de Lorraine, Nancy, France.
 - Mathieu Hoyrup:
 - * Mathematics for Computer Science, 15h, M1 TAL, Institut des Sciences du Digital: Management et Cognition, Université de Lorraine, Nancy, France.
 - Emmanuel Jeandel:
 - * Algorithmics and Complexity, 30h, M1 Informatique, Université de Lorraine, Nancy, France.
 - * Quantum Computing, 15h, M1 Informatique.

- Nazim Fatès:
 - * Systèmes distribués adaptatifs, 10h, Master 2, informatique, Université de Lorraine, Nancy, France.
 - * Agents intelligents et collectifs, 15h, Master 1, sciences cognitives.
 - * Modèles de calcul, 12h, Master 2, informatique.

9.2.2. Supervision

- Mathieu Hoyrup supervised the L3 internship of Antonin Callard (ENS Paris Saclay), about descriptive set theory on represented spaces.
- Emmanuel Hainry and Romain Péchoux supervised the L3 internship of Olivier Zeyen (FST, Université de Lorraine), on implementing a complexity parser for Java.
- Nazim Fatès supervised the internship of Karim Boutamine and Maxime Thaon, students of Master 1 in Cognitive Sciences (Université de Lorraine) and the internship of Baptiste Collet, student of Licence 3 at École normale supérieure de Paris.
- PhD: Renaud Vilmart, “Langages graphiques pour calculer et raisonner en quantique”, defended september 2019, Advisors: Emmanuel Jeandel and Simon Perdrix.
- PhD in progress: Titouan Carette, “Langage diagrammatique pour l’ordinateur quantique”, Start: October 2018, Advisors: Emmanuel Jeandel and Simon Perdrix.
- PhD in progress: Pierre Mercuriali, “Calcul à base de médiane et structures médianes pour la classification”, Start: October 2016, Advisors: Miguel Couceiro and Romain Péchoux.
- PhD in progress: Robert Booth, “Formalismes pour la vérification de technologies quantiques”, Start: November 2018, Advisors: Damian Markham and Simon Perdrix.
- PhD in progress: Alexandre Clément, “Graphical Languages for Quantum Control”, Start: September 2019, Advisors: Emmanuel Jeandel and Simon Perdrix.
- PhD in progress: Margarita Veshchezerova, “Quantum Computing for Combinatorial Optimisation”, Start: October 2019, Advisors: Emmanuel Jeandel and Simon Perdrix, joint supervision with Marc Porcheron at EDF (CIFRE).

9.2.3. Juries

- Emmanuel Jeandel participated in the PhD defense of Florian Bridoux (Université d’Aix-Marseille), François Pirot (Université de Lorraine and Rahtboud University) and Alexandre Talon (ENS Lyon).
- Emmanuel Jeandel reviewed the PhD thesis of Paulina Cecchi (University of Santiago and Université Paris-Diderot) and Ilya Galanov (Université de Villetaneuse).
- Nazim Fatès reviewed the PhD of Adam Dzedzej (University of Gdańsk, Poland) and served as the main external examiner during the PhD defense.
- Simon Perdrix was external reviewer for the PhD thesis of Kang Feng Ng (Oxford University), March 2019.
- Simon Perdrix was reviewer for the PhD thesis of Matthew Amy (University of Waterloo, Canada), January 2019.
- Simon Perdrix reviewed the PhD thesis of Ghazal Kachigar (University of Bordeaux), December 2019.

9.3. Popularization

9.3.1. Articles and contents

- The scientific magazine *La Recherche* re-published an article by Nazim Fatès and Irène Marcovici, with the title “Les automates cellulaires jouent le jeu”, in a Special issue devoted to the theme “Les maths et le réel” (September 2019) [34]. The original article “Automates cellulaires : la complexité dans les règles de l’art” (2018), was modified with minor changes for this special issue.

- Interviews of Simon Perdrix about the Google's result on quantum advantage. La tribune (online article) ; Sciences et Avenir (November 2019 - paper journal and online articles), We demain (online article).

9.3.2. Education

Nazim Fatès participated to a workshop destined to the high-school teachers which were training on the « Information et sciences du numérique » module.

In the lycée Saint-Exupéry de Saint-Dizier: he gave three one-hour conferences destined to students, related to the film *Imitation game* on Alan Turing (March 18).

9.3.3. Interventions

Nazim Fatès was invited to give various talks on the question of artificial intelligence:

- With the European parliamentary association (APE), he was invited to talk to European MP's on the theme « Is Europe ready for artificial intelligence? » (Strasbourg, February 13).
- In the « Sciences et société » cycle of IUT Charlemagne (September 26).
- With the association « Jardin des sciences », cycle « intelligences » destined to a wide public, University of Strasbourg (October 10).
- With the association **Femmes responsables** (November 20).

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