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**Inria Associate Teams programme**

**Final report 2024**  
**(max 6 pages)**

**Associate Team acronym: TC(Pro)<sup>3</sup>**

**Period of activity: 2020-2024**

**Principal investigator (Inria): Romain Péchoux**

**Principal investigator (partner): Georg Moser**

**Other investigators: Martin Avanzini (Inria Sophia)**

**Key words (according to Inria scientific cartography) - scientific themes and application domains: probabilistic programs, quantum programs, resource control, complexity**

**Associate Team website: <https://members.loria.fr/RPechoux/ea-tcpro>**

## **1. Overview of the activities**

### **1.1. Short visits (< 1 month)**

- October 2020, Martin Avanzini to Innsbruck, 2 weeks, work with Georg Moser.
- July 2021, Martin Avanzini to Innsbruck, 2 weeks, work with Georg Moser.
- November 2022, Andrea Colledan, Romain Péchoux to Paris Saclay, 2 days, work with Vladimir Zamdzhiev.
- November 2022, Romain Péchoux, Vladimir Zamdzhiev and Simon Perdrix to Innsbruck, 1 week.
- August 2023, Martin Avanzini to Innsbruck, 3 weeks, work with Georg Moser.
- November 2023, Martin Avanzini to Nancy, 1 week, work with Romain Péchoux, Emmanuel Hainry, and Simon Perdrix.
- August 2023, Martin Avanzini to Innsbruck, 2 weeks, work with Georg Moser.
- November 2023, Martin Avanzini to Nancy, 1 weeks, work with Romain Péchoux and Emmanuel Hainry.
- August 2024, Martin Avanzini to Innsbruck, 2 weeks, work with Georg Moser.
- December 2024, Alejandro Diaz-Caro, Emmanuel Hainry and Romain Péchoux to Inria Sophia, work with Martin Avanzini

### **1.2. Seminars**

- September 2020: Kick-off meeting: thursday the 24th of September 2020 (online meeting), 10 am.
- 2nd meeting: 2nd of December 2020 (online).
- 3rd meeting: 22nd of May 2021 (online).
- 4th meeting: ~~6th of July 2021~~: 13th of July 2021 (online).
- 5th meeting: 10th of September 2021 (online).
- 6th meeting: 18th-21st of October 2021 (Nancy).

- work session: 25th of November 2021 (online) (Quantum Expectation transformers)
- work session: 30th of November 2021 (online) (Quantum Expectation transformers)
- work session: 5th of January 2022 (online) (Quantum Expectation transformers)
- work session: 13rd of January 2022 (online) (Quantum Expectation transformers)
- work session: 3rd of February 2022 (online) (Probabilistic SCT)
- talk on formal Methods for Quantum Programs by Georg Moser: 23 or march 2022, quantum physics department, University of Innsbruck
- talk on quantum expectation transformers by Vladimir Zamdzhiev at QPL 2022: 30th of June 2022, Oxford, UK
- talk on quantum expectation transformers by Vladimir Zamdzhiev at LICS 2022: 2nd of August 2022, Haifa, Israel
- 7th meeting: 2-4 of November 2022, departement of computer science, University of Innsbruck. Talk by Andrea Colledan « A refinement type-and-effect system for quantum circuit description languages » the 3rd of November 10:00 am, SR 2, ICT building.
- Talk of Romain Péchoux at POPL 2023
- work session: 24th of January 2023 (online) (ANR)
- work session: 31th of January 2023 (online) (ANR)
- work session: 14th of February 2023 (online) (ANR)
- work session: 21st of February 2023 (online) (ANR)
- work session: 28th of February 2023 (online) (ANR)
- work session: 7th of March 2023 (online) (Quantum expectation transformers)
- work session: 14th of March 2023 (online) (Quantum expectation transformers)
- work session: 21st of March 2023 (online) (Quantum expectation transformers)
- work session: 5th of April 2023 (online) (Quantum expectation transformers)
- work session: 12th of April 2023 (online) (Quantum expectation transformers)
- work session: 26th of April 2023 (online) (Quantum expectation transformers)
- work session: 17th of May 2023 (online) (Quantum expectation transformers)
- work session: 24th of May 2023 (online) (Quantum expectation transformers)
- work session: 31st of May 2023 (online) (Quantum expectation transformers)
- work session: 28th of June 2023 (online) (Quantum expectation transformers)
- Kinnari Dave, Emmanuel Hainry, Emmanuel Jeandel, Vladimir Zamdzhiev, Romain Péchoux, Simon Perdrix, Mario Silva attended QPL 2023 from the 17th to the 21st of July 2023
- 8th meeting: 4 of December 2023 (online), ANR discussion
- work session: 11th of December 2023 (online), ANR discussion
- work session: 10th of January 2024 (online), ANR discussion
- work session: 12th of March 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 19th of March 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 26th of March 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 9th of April 2024 (online), (Quantum expectation transformers for higher-order programs)
- talk of Romain Péchoux at ESOP 2024

- work session: 16th of April 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 23th of April 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 30th of April 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 7th of May 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 14th of May 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 21st of May 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 28th of May 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 4th of June 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 11th of June 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 18th of June 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 25th of June 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 2nd of July 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 9th of July 2024 (online), (Quantum expectation transformers for higher-order programs)
- participation of Kinnari Dave, Alejandro Diaz-Caro, Romain Péchoux, and Mario Silva to QPL 2024.
- talk of Romain Péchoux at QPL 2024.
- work session: 3rd of September 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 10th of September 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 17th of September 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 24th of September 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 1st of October 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 8th of October 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 15th of October 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 29th of October 2024 (online), (Quantum expectation transformers for higher-order programs)

- work session: 5th of November 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 12th of November 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 27th of November 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 3rd of December 2024 (online), (Quantum expectation transformers for higher-order programs)
- work session: 10th of December 2024 (online), (Quantum expectation transformers for higher-order programs)
- Visit of Alejandro Diaz-Caro, Emmanuel Hainry and Romain Péchoux to Inria Sophia.
- work session: 14th of January 2025 (online), (Quantum expectation transformers for higher-order programs)
- work session: 20th of January 2025 (online), (Quantum expectation transformers for higher-order programs)

### 1.3. **Joint workshops**

- QPL 2022, Oxford
- QPL 2023, Paris
- QPL 2024, Buenos Aires

### 1.4. **Submission of joint projects**

#### 1.4.1. **On the French side**

In 2024, we have submitted a ANR-FWF PRCI proposal of 700 k€ with University of Innsbruck, University of Linz, LORIA and Inria Saclay. The project was not funded and we are planning to resubmit it in 2025. Our aim is to study the resource control of quantum program both at the higher-level (quantum PL) and at the low-level (quantum circuits, MBQC, ZX-calculus).

#### 1.4.2. **On the Partner's country side**

See above.

### 1.5. **Co-organization of scientific events**

*QPL 2023 and 2024. Vladimir Zamdzhiev and Alejandro Diaz caro were PC chair.*

### 1.6. **Students co-supervision**

Vladimir Zamdzhiev and Romain Péchoux are supervising Kinnari Dave (start 2022). Romain Péchoux and Emmanuel Hainry are supervising Mario Silva (start 2021). Romain Péchoux and Simon Perdrix are supervising Kathleen Barsse (start 2024). Romain Péchoux and Simon Perdrix are supervising Thomas Vinet (start 2024).

## 2. **Scientific achievements**

The major goal of the associate team TC(Pro)<sup>3</sup> is to develop methods for reasoning on quantitative properties of probabilistic programs and models. Such tools have applications in quantum computing as quantum programs can be considered as particular cases of probabilistic transition systems where measurement plays the role of probabilistic choice.

We establish our objective along the following axes:

- development of novel methods for ensuring termination properties (e.g. almost sure termination) and complexity properties (e.g. average case polynomial time) of probabilistic programs, with a particular emphasis on automated techniques.
- lifting of the aforementioned techniques to the new languages emerging in statistical reasoning (e.g. Anglican, Church,...) and quantum computing (e.g. QPL).
- follow up of the developed methods integration in the tool TcT. To date, TcT is among the most powerful tools to reason about the complexity (and termination) of various forms of programs (e.g. rewrite systems, imperative and functional programs).

Related to the proposal, some results have already been obtained by the members of the associated team since 2020 (see publications below):

- We have introduced a quantum PL with inductive datatypes [1] and their operational and denotational semantics in an adequacy theorem. The consideration of inductive datatypes is a non trivial extension of quantum PLs in terms of semantics as it requires to consider infinite-dimensional spaces.
- We have extended the expected cost transformers to a probabilistic programming language with non-determinism [2]. Hence guaranteeing that a program that passes the analysis has an given expected runtime. Moreover, the results have been implemented.
- We have extended the ert-calculus for reasoning about the cost of imperative probabilistic programs to the context of higher-order, probabilistic functional programs [3].
- We have extended expectation transformers to a quantum programming language with measurement, thus obtaining a new notion of quantum expectation transformers (qet) [4,5]. In particular, it shows that qet can be used to compute the expected runtime, the expected value, and also to define a denotational semantics of the language.
- We have introduced a new noninterference policy to capture the class of functions computable in polynomial time on an object-oriented programming language [6]. This policy makes a clear separation between the standard noninterference techniques for the control flow and the layering properties required to ensure that each « security » level preserves polynomial time soundness, and is thus more expressive than existing tractable characterizations of polynomial time based on safe recursion. Despite the fact that this noninterference policy is  $\Pi_1^0$ -complete, we show that it can be instantiated to some decidable and conservative instance using shape analysis techniques.
- We have extended the tool *eco-imp* for reasoning about costs of probabilistic programs [7] to (i) permit reasoning about arbitrary expectations (ii) deal with a more realistic imperative language with recursive procedures and local variables.
- We have adapted light linear logic based type systems to quantum programs with quantum control flow to characterize a class of quantum programs that can be compiled to quantum circuits of polynomial size [8].
- In [9,10], we have studied the hardness of distinct well-known problem (e.g., almost-sure termination, positive almost-sure termination) on quantum programs over Clifford+T and delineated their complexity in the arithmetical hierarchy. Moreover, we have studied synthesis of quantum expectation transformers introduced in [3] on Clifford+T and polynomials of bounded degree and shown that it can be solved in doubly exponential time.
- We have extended the notion of expectation transformers to a higher-order quantum programming language [11] and shown that it allows to compute the expected cost and expected value of such programs.

### 3. Production & Impact

#### 3.1. Joint publications

1. Romain Péchoux, Simon Perdrix, Mathys Rennela and Vladimir Zamdzhiev, Quantum Programming with Inductive Datatypes: Causality and Affine Type Theory, FOSSACS 2020.
2. Martin Avanzini, Georg Moser, Michael Schaper, A Modular Cost Analysis for Probabilistic Programs, OOPSLA 2020.
3. Martin Avanzini, Gilles Barthe, Ugo Dal Lago, On continuation-passing transformations and expected cost analysis, ICFP 2021.
4. Martin Avanzini, Georg Moser, Romain Péchoux, Simon Perdrix, and Vladimir Zamdzhiev, Quantum Expectation Transformers for Cost Analysis, LICS 2022.
5. Martin Avanzini, Georg Moser, Romain Péchoux, Simon Perdrix, and Vladimir Zamdzhiev, Quantum Expectation Transformers for Cost Analysis, QPL 2022, non proceedings paper.
6. Emmanuel Hainry and Romain Péchoux, a general noninterference policy for polynomial time, POPL 2023.
7. Martin Avanzini, Georg Moser, and Michael Schaper. Automated Expected Value Analysis of Recursive Programs, PLDI 2023.
8. Alejandro Díaz-Caro, Emmanuel Hainry, Romain Péchoux and Mário Silva. Light types and polynomial time for quantum lambda-calculi, QPL 2023, poster.
9. Martin Avanzini, Georg Moser, Romain Péchoux and Simon Perdrix. On the Hardness of Analyzing Quantum Programs Quantitatively, ESOP 2024.
10. Martin Avanzini, Georg Moser, Romain Péchoux and Simon Perdrix. On the Hardness of Analyzing Quantum Programs Quantitatively, QPL 2024.
11. Martin Avanzini, Alejandro Diaz-Caro, Emmanuel Hainry, Romain Péchoux. Expectation-based Analysis of Higher-Order Quantum Program. Submitted.

#### 3.4. Demos & videos

[https://www.youtube.com/watch?v=z\\_3ZKfIQUO](https://www.youtube.com/watch?v=z_3ZKfIQUO)

#### 3.5. Current position of students and postdocs involved in the associate team

Kinnari Dave: defense planned october 2025

Mario Silva: defense planned june 2025

Kathleen Barse: defense planned june 2027

Thomas Vinet: defense planned june 2027

### 4. Future of the partnership

*See ANR submission above*

### 5. Self-Assessment

*We have obtained publications in major PL conferences (A and A\* - LICS, ESOP, POPL, ...) so this associate team was a great success.*

### 6. Feed-back on the Associate Team program

This financial support is very helpful. However a main drawback is not to be able to fund participations to conferences. In general, members of an associate team have a very much constrained schedule and being able to meet when participating to a conference would be a valuable added value to the programme.