

Part B

START PAGE

MARIE SKŁODOWSKA–CURIE ACTIONS

Individual Fellowships (IF)
Call: H2020-MSCA-IF-2014

PART B

“ReACT”

“A Realizability Approach to Complexity Theory”

This proposal is to be evaluated as:

[Standard EF]

	LIST OF PARTICIPANTS	3
	START PAGE COUNT	4
1.	SUMMARY	4
2.	EXCELLENCE	4
3.	IMPACT	11
4.	IMPLEMENTATION	12
	STOP PAGE COUNT	15
5.	CV OF THE EXPERIENCED RESEARCHER	15
6.	CAPACITIES OF THE PARTICIPATING ORGANISATIONS	19
7.	ETHICAL ASPECTS	21
8.	LETTERS OF COMMITMENT OF PARTNER ORGANISATIONS	21

List of Participants

Participants	Legal Entity Short Name	Academic (tick)	Non-academic (tick)	Country	Dept. / Division / Laboratory	Supervisor	Role of Partner Organisation
<u>Beneficiary</u>							
– University of Copenhagen  UNIVERSITY OF COPENHAGEN	UCPH	✓		DENMARK 	Department of Computer Science 	Jakob Grue Simonsen 	
<u>Partner Organisation</u>							
–							

Data for non-academic beneficiaries

Name	Location of research premises (city / country)	Type of R&D activities	No. of full employees	No. of employees in R&D	Web site	Annual turnover (approx. in Euro)	Enterprise status (yes/no)	SME status (yes/no)

1 Summary

Complexity theory lies at the intersection between mathematics and computer science, and studies the amount of resources needed to run a specific program (complexity of an algorithm) or solve a particular problem (complexity of a problem). The ReACT project will build on recent work in *realizability models for linear logic* to provide new characterizations of existing complexity classes, in particular **L** (logarithmic space) and **P** (polynomial time). The final goal is that these characterizations will enable researchers to attack long-standing open problems in complexity theory by using mathematical techniques, tools and invariants from the fields of operators algebras and dynamical systems. The *complexity-through-realizability* techniques developed by the ReACT project will provide a unified framework for studying many computational paradigms and their associated computational complexity theory grounded on well-studied mathematical concepts. This will allow comparison of complexity classes defined from different computational paradigms (e.g. sequential and quantum computation), as well as establish a theory of complexity for computational paradigms currently lacking such a theory (e.g. concurrent processes).

Even though it has been an established discipline for more than 50 years¹, many questions in complexity theory, even basic ones, remain open. During the last twenty years, researchers have developed new approaches based on logic: they offer solid, machine-independent, foundations and provide new tools and methods. Amongst these approaches, the fields of Descriptive Complexity (DC) and Implicit Computational Complexity (ICC) lead to a number of new characterizations of complexity classes. These works laid grounds for both theoretical results² and applications such as typing systems for complexity constrained programs and type inference algorithms for statically determining complexity bounds.

The ReACT project will develop a *complexity-through-realizability* approach related to those established logic-based approaches (DC and ICC). It inherits their strengths: it is machine-independent, it provides tools and methods from logic and it gives grounds for the above mentioned applications. Furthermore, it improves these crucially as it builds on state-of-the-art theoretical results on realizability models for linear logic³ using well-studied mathematical concepts from operators algebras and dynamical systems. As a consequence, it opens the way to use against complexity theory's open problems the many techniques, tools and invariants that were developed in these mathematical disciplines.

The ReACT project has two objectives. The **first objective**, decomposed into three concrete, feasible and precise goals, aims at establishing this new approach to complexity as an emerging and promising field of study on the basis that it captures, generalizes and extends the techniques developed by previous approaches such as DC and ICC. The **second objective** is more exploratory and thus corresponds to a single, high-risk but high-reward, goal investigating how the new methods and techniques derived from the mathematical foundations of our approach can be used to address open problems in complexity.

2 Excellence

2.1 Quality, innovative aspects and credibility of the research (including inter/multidisciplinary aspects)

The ReACT project deals with *complexity-through-realizability* techniques founded on alternative definitions of the notions of algorithms and complexity classes. The ReACT project will demonstrate that these definitions capture and generalize standard ones, offering a unified homogeneous framework for

¹J. Hartmanis and R. Stearns. "On the computational complexity of algorithms". In: *Transactions of the American Mathematical Society* 117 (1965).

²N. Immerman. "Nondeterministic space is closed under complementation". In: *Structure in Complexity Theory Conference*. 1988.

³T. Seiller. "Interaction Graphs: Graphings". In: *CoRR* abs/1405.6331 (2014).

the study of complexity classes. These techniques derive from several fields of research: realizability models for linear logic, implicit computational complexity (ICC) and descriptive complexity (DC).

The first three goals deal with the first objective of the project: obtaining foundational results which will establish the *complexity-through-realizability* approach as an independent research field. Those correspond to three natural sequential steps: show the *complexity-through-realizability* techniques (i) are coherent with classical theory, (ii) generalize and improve state-of-the-art techniques, and finally (iii) provide the first homogeneous theory of complexity for several computational paradigms. The fourth, and last, goal, concerns the second objective: use well-established mathematical techniques, tools and invariants from operator algebras and dynamical systems for addressing open problems in complexity.

Goal1. Complexity-through-realizability *techniques yield characterizations of usual complexity classes*. Too many classes exist for attempting to characterize them all; this goal will therefore focus on a selection of important classes. Techniques from previous work⁴ will be easily adapted for characterizing both deterministic and non-deterministic logarithmic space as well as a family of sublogarithmic classes corresponding to the hierarchy of k -head two-way automata. An adaptation of recent work by Baillot⁵ will lead to characterizations of **P** and the exponential hierarchy.

Goal2. Complexity-through-realizability *techniques extend and improve previous work*. We will show the definition of algorithms proposed by Gurevich⁶ to be a specific case of our definition of algorithm. Complexity-through-realizability techniques will also be shown to generalize the quantitative realizability technique developed by Hoffman and dal Lago⁷ as well as ICC techniques.

Goal3. Complexity-through-realizability *techniques apply to a wide variety of computational paradigms*, for instance process calculi, probabilistic/quantum computation, and cellular automata. For probabilistic and quantum computation, this will allow characterizations of probabilistic and quantum complexity classes. In other cases such as concurrent programs where no established complexity theory exists, this will provide a viable and well-grounded foundation for such a theory.

Goal4. *Explore the possibility of using existing mathematical invariants for solving open problems in complexity theory*. In particular, ℓ^2 -Betti numbers⁸ seem good candidates for this purpose.

State of the art. Complexity Theory is concerned with the study of how many resources are needed to perform a specific computation or to solve a given problem. The study of *complexity classes* – sets of problems which need a comparable amount of resources to be solved, lies at the intersection of mathematics and computer science. Although a very active and established field for more than fifty years⁹, a number of basic problems remain open, for instance the celebrated “millennium problem” of whether **P** equals **NP** or the less publicized but equally important question of whether **P** equals **L**. In recent years, several results have greatly modified the landscape of complexity theory by showing that proofs of separation (i.e. inequality) of complexity classes are hard to come by, pointing out the need to develop new theoretical methods. The most famous work¹⁰ defines a notion of *natural proof* comprising all previously developed proof methods and shows that no “natural proof” can succeed in proving separation.

⁴J.-Y. Girard. “Normativity in Logic”. In: *Epistemology versus Ontology*. Ed. by Peter Dybjer et al. Vol. 27. Logic, Epistemology, and the Unity of Science. Springer, 2012, pp. 243–263. ISBN: 978-94-007-4434-9, 978-94-007-4435-6; C. Aubert and T. Seiller. “Characterizing co-NL by a group action”. In: *CoRR* abs/1209.3422 (2012); C. Aubert and T. Seiller. “Logarithmic Space and Permutations”. In: *CoRR* abs/1301.3189 (2013).

⁵P. Baillot. “Elementary Linear Logic Revisited for Polynomial Time and an Exponential Time Hierarchy”. In: *APLAS*. ed. by Hongseok Yang. Vol. 7078. Lecture Notes in Computer Science. Springer, 2011, pp. 337–352.

⁶Y. Gurevich. “Specification and Validation Methods”. In: ed. by Egon Börger. New York, NY, USA: Oxford University Press, Inc., 1995. Chap. Evolving Algebras 1993: Lipari Guide, pp. 9–36. ISBN: 0-19-853854-5.

⁷U. dal Lago and M. Hofmann. “Realizability Models and Implicit Complexity”. In: *Theo. Comp. Sci.* 412 (2011).

⁸D. Gaboriau. “Invariants ℓ^2 de relations d’équivalence et de groupes”. In: *Publications Mathématiques de l’Institut des Hautes Études Scientifiques* 95 (2002).

⁹A. Cobham. “The intrinsic computational difficulty of functions”. In: *Proceedings of the 1964 CLMPS*. 1965; S. Cook. “The complexity of theorem-proving procedures”. In: *Proceedings of the 3rd ACM Symposium on Theory of Computing*. 1971; J. Hartmanis and R. Stearns. “On the computational complexity of algorithms”. In: *Transactions of the AMS* 117 (1965); W. Savitch. “Relationship between nondeterministic and deterministic tape classes”. In: *Journal of Computer and Systems Sciences* 4 (1970).

¹⁰A. A. Razborov and S. Rudich. “Natural proofs”. In: *Journal of Computer and System Sciences* 55 (1997).

Mathematicians have then tried to give characterizations of complexity classes that differ from the original machine-bound definitions, hoping to enable methods from radically different areas of mathematics. Efforts in this direction lead to the development of **Descriptive Complexity**, a field which studies the types of logics whose individual sentences characterize exactly particular complexity classes. Early developments were the 1974 Fagin-Jones-Selman results¹¹ characterizing the classes **NEXP** and **NP**. Many such characterizations have then been given¹² and the method led Immerman to a proof of the celebrated Immerman-Szelepcsényi theorem¹³ stating the two complexity classes **coNL** and **NL** are equal (though Szelepcsényi's proof does not use logic-based methods).

Implicit Computational Complexity (ICC) develops a related approach whose aim is to study algorithmic complexity only in terms of restrictions of languages and computational principles. It has been established since Bellantoni and Cook' landmark paper¹⁴, and following work by Leivant and Marion¹⁵. It is now a very active field at the international level, particularly in the EU, with a number of dedicated sites and research projects: Munich (Hofmann, Schwichtenberg, and Schöpp), Torino and Bologna (Dal Lago, Martini, Ronchi Della Rocca, Gaboardi), the French ANR COMPLICE and ELICA (Paris 13 University, LORIA, ÉNS Lyon), the Danish COLA project (Copenhagen). A specialized workshop, DEVELOPMENTS IN IMPLICIT COMPUTATIONAL COMPLEXITY, is organized every year as part of the EUROPEAN JOINT CONFERENCES ON THEORY AND PRACTICE OF SOFTWARE (ETAPS). Amongst the different approaches to ICC, several results were obtained by considering syntactic restrictions of *linear logic*¹⁶, a refinement of intuitionistic logic which accounts for the notion of resources. Linear logic introduces a modality $!$ marking the “possibility of duplicating” a formula A : the formula A shall be used exactly once, while the formula $!A$ can be used any number of times. Modifying the rules governing this modality then yields variants of linear logic having computational interest: this is how constrained linear logic systems, for instance **BLL**¹⁷ and **ELL**¹⁸, are obtained. However, only a limited number of complexity classes were characterized in this way, and the method seems to be limited by its syntactic aspect: while it is easy to modify existing rules, it is much harder to find new, alternative, rules from scratch. The approach taken by the ReACT project does not suffer from these limitations, allowing for subtle distinctions unavailable to the syntactic techniques of ICC.

Concurrently to these developments in computational complexity, and motivated by disjoint questions and interests, Girard initiated the **Geometry of Interaction (GoI)** program¹⁹. This research program aims at obtaining particular kinds of *realizability* models (called GoI models) for linear logic. Realizability was first introduced²⁰ as a way of making the Brouwer-Heyting-Kolmogorov interpretation of constructivism and intuitionistic mathematics precise; the techniques were then extended to classical logic, for instance by Krivine²¹, and linear logic. The GoI program naturally and quickly arose as a well-suited tool for the study of computational complexity. Using the first GoI model²², Abadi, Gonthier and

¹¹R. Fagin. “Generalized first-order spectra and polynomial-time recognizable sets”. In: *SIAM-AMS Proc.* Vol. 7. 1974; N. Jones and A. Selman. “Turing machines and the spectra of first-order formulas”. In: *Journal of Symbolic Logic* 39 (1974).

¹²K. J. Compton and E. Grädel. “Logical definability of counting functions”. In: *J. Comput. Syst. Sci.* 53 (1996); A. Dawar and E. Grädel. “The descriptive complexity of parity games”. In: *LMCS* 5213 (2008); E. Grädel and Y. Gurevich. “Tailoring recursion for complexity”. In: *Journal of Symbolic Logic* 60 (1995).

¹³Immerman, “Nondeterministic space is closed under complementation”; R. Szelepcsényi. “The method of forcing for nondeterministic automata”. In: *Bulletin of the EATCS* 33 (1987).

¹⁴S. Bellantoni and S. Cook. “A new recursion-theoretic characterization of the polytime functions”. In: *Computational Complexity* 2 (1992).

¹⁵D. Leivant and J.-Y. Marion. “Lambda calculus characterizations of poly-time”. In: *Fundam. Inform.* 19 (1993); D. Leivant and J.-Y. Marion. *Ramified recurrence and computational complexity II: Substitution and poly-space*. 1994.

¹⁶J.-Y. Girard. “Linear logic”. In: *Theoretical Computer Science* 50.1 (1987), pp. 1–101.

¹⁷J.-Y. Girard, A. Scedrov, and P. J. Scott. “Bounded linear logic: a modular approach to polynomial-time computability”. In: *Theoretical Computer Science* 97 (1992).

¹⁸V. Danos and J.-B. Joinet. “Linear Logic & Elementary Time”. In: *Information and Computation* 183 (2003).

¹⁹J.-Y. Girard. “Towards a geometry of interaction”. In: *Proceedings of the AMS Conference on Categories, Logic and Computer Science*. 1989.

²⁰S. C. Kleene. “On the interpretation of intuitionistic number theory”. In: *Journal of Symbolic Logic* 10 (1945).

²¹J.-L. Krivine. “Typed lambda-calculus in classical Zermelo-Fraenkel set theory”. In: *Arch. Mathematical Logic* 40 (2001).

²²J.-Y. Girard. “Geometry of Interaction I: Interpretation of System F”. in: *Proc. Logic Colloquium*. 1989.

Lévy²³ showed the optimality of Lamping’s reduction in lambda-calculus²⁴. It was also applied in implicit computational complexity²⁵, and was the main inspiration behind dal Lago’s context semantics²⁶. More recently, it lead to a series of results in the form of new characterizations of the classes **coNL**²⁷ and **L**²⁸. Unfortunately, although the construction of GoI models and the characterizations of classes are founded on similar techniques, they are two distinct, unrelated, constructions. The approach developed in the ReACT project will in particular bridge this gap and provide similar characterizations which will moreover allow the use of both logical and realizability-specific methods.

Methodology. About ten years ago, Girard showed²⁹ that the restriction to the unit ball of a von Neumann algebra of the so-called “feedback equation”, which represents the execution of programs in GoI models, always has a solution. Moreover, previous and subsequent work showed the obtained GoI model interprets, depending on the choice of the von Neumann algebra, either full linear logic³⁰ or the constrained system ELL which characterizes elementary time computable functions³¹. This motivated the following informal conjecture: “the unit ball of a von Neumann algebra $\mathfrak{M}$ is a model of computation and the choice of $\mathfrak{M}$ corresponds to complexity constraints”.

This deep and promising idea turned out to be slightly inexact and seemingly difficult to exploit³². Indeed, the expressivity of the logic interpreted in the model depends not only on the enveloping algebra $\mathfrak{N}$ but also on a maximal abelian sub-algebra (masa) $\mathfrak{A}$ of $\mathfrak{N}$. Complexity constraints should therefore correspond to couples $(\mathfrak{N}, \mathfrak{A})$ of a von Neumann algebra $\mathfrak{N}$ and a masa $\mathfrak{A}$ in $\mathfrak{N}$. This makes it difficult to extend the approach to other constrained logical systems, as the theory of masa in von Neumann algebras is an involved subject matter still containing large numbers of basic but difficult open problems.

However, very recent work by Seiller describing a systematic approach³³ for defining GoI models provides the foundational grounds for a new, tractable way of exploiting these ideas. Seiller considers a generalization of graphs, named *graphings*³⁴, which are both *geometric realizations* of graphs on a measure space $(X, \mathcal{B}, \mu)$ and generalized measured dynamical system. The construction is then parametrized by two monoids describing the model of computation and a map describing the realizability structure:

- a monoid Ω used to associate weights to edges of the graphs;
- a monoid $\mathfrak{m}$ – called *microcosm* – of measurable maps from $(X, \mathcal{B}, \mu)$ to itself;
- a measurable map $m : \Omega \rightarrow \bar{\mathbf{R}}_{\geq 0}$, defining *orthogonality* – accounting for linear negation.

A Ω -weighted graphing in $\mathfrak{m}$ is then defined as a directed graph F whose edges are weighted by elements in Ω , whose vertices are measurable subsets of the measurable space $(X, \mathcal{B})$, and whose edges are *realized* by elements of $\mathfrak{m}$, i.e. for each edge e there exists an element ϕ_e in $\mathfrak{m}$ such that $\phi_e(s(e)) = t(e)$, where s, t denote the source and target maps. Based on this notion, and an orthogonality relation defined from the map m , Seiller obtained a systematic method for constructing realizability models for linear logic summarized in the following theorem.

Theorem 1 (Seiller³⁵). *Let Ω be a monoid, $\mathfrak{m}$ a microcosm and $m : \Omega \rightarrow \bar{\mathbf{R}}_{\geq 0}$ a measurable map. There*

²³G. Gonthier, M. Abadi, and J.-J. Lévy. “The Geometry of Optimal Lambda Reduction”. In: *POPL*. 1992.

²⁴J. Lamping. “An Algorithm for Optimal Lambda Calculus Reduction”. In: *POPL*. 1990.

²⁵P. Baillot and M. Pedicini. “Elementary complexity and geometry of interaction”. In: *Fundamenta Informaticae* 45 (2001).

²⁶U. dal Lago. “The Geometry of Linear Higher-order Recursion”. In: *ACM Trans. Comput. Logic* 10 (2009).

²⁷Girard, “Normativity in Logic”; Aubert and Seiller, “Characterizing co-NL by a group action”.

²⁸Aubert and Seiller, “Logarithmic Space and Permutations”; C. Aubert et al. “Logic Programming and Logarithmic Space”. In: *arXiv preprint arXiv:1406.2110* (2014).

²⁹J.-Y. Girard. “Geometry of Interaction IV: the Feedback Equation”. In: *Logic Colloquium '03*. 2006.

³⁰J.-Y. Girard. “Geometry of Interaction III: Accommodating the Additives”. In: *Advances in Linear Logic*. 1995.

³¹Thomas Seiller. “Logique dans le facteur hyperfini : géométrie de l’interaction et complexité”. PhD thesis. Université Aix-Marseille, 2012.

³²Seiller, “Logique dans le facteur hyperfini : géométrie de l’interaction et complexité”; T. Seiller. “A Correspondence between Maximal Abelian Sub-Algebras and Linear Logic Fragments”. In: *CoRR* abs/1408.2125 (2014).

³³Seiller, “Interaction Graphs: Graphings”.

³⁴G. Levitt. “On the cost of generating an equivalence relation”. In: *Ergodic Theory and Dynamical Systems* 15 (1995); D. Gaboriau. “Coût des relations d’équivalence et des groupes”. In: *Inventiones Mathematicae* 139 (2000), pp. 41–98.

³⁵Seiller, “Interaction Graphs: Graphings”.

exists a deterministic and a non-deterministic GoI model of multiplicative-additive linear logic whose objects are Ω -weighted graphings in $\mathfrak{m}$ and whose orthogonality depends on m .

A microcosm $\mathfrak{m}$ generates, by the Feldman-Moore construction³⁶, a couple $(\mathfrak{A}, \mathfrak{N})$ where $\mathfrak{A}$ is a maximal abelian subalgebra of the von Neumann algebra $\mathfrak{N}$. This theorem thus generalizes Girard’s result since it shows that a microcosm (i.e. a couple $(\mathfrak{A}, \mathfrak{N})$) induces *two* models of computation: a deterministic model (the equivalent of Girard’s unit ball restriction) and a non-deterministic model (not available to Girard techniques because of divergence issues). It shows in fact much more as it exhibits an infinite family of structures of realizability models (parametrized by the map $m : \Omega \rightarrow \mathbf{R}_{\geq 0} \cup \{\infty\}$) on any model obtained from a microcosm. This extends drastically Girard’s approach for which only two such structures were defined until now: an “orthogonality-as-nilpotency” structure in the algebra $\mathcal{L}(\mathbb{H})$ ³⁷ and another one defined using the Fuglede-Kadison determinant³⁸ in the type II_1 hyperfinite factor³⁹.

This result provides the foundation of the *complexity-through-realizability* techniques that will be developed by the ReACT project. The obtained hierarchy of models provides an interesting middle-ground between usual computational models, for instance automata, and mathematical techniques from operator algebras and dynamical systems. The notion of Ω -weighted $\mathfrak{m}$ -graphings for given monoid Ω and microcosm $\mathfrak{m}$ yields a very general yet tractable mathematical notion of algorithm, interpreting in a natural way the microcosm $\mathfrak{m}$ as a set of computational principles. It comprises Girard’s interpretation of pure lambda-calculus (a Turing complete model of computation) in terms of operators⁴⁰, but it is not restricted to sequential algorithms as it will be shown to provide an interpretation of probabilistic and quantum programs. Moreover, it provides characterizations of usual complexity classes as types of predicates on binary integers $\mathbf{Nat}_2 \Rightarrow \mathbf{Bool}$. As foreseen in a recent note⁴¹, an adaptation of the methods employed in earlier work on application of GoI models to complexity⁴² will yield a correspondence between a part of this hierarchy of models and a hierarchy of sublogarithmic classes.

Novelty and Quality. The definitions of algorithms and complexity constraints studied by the ReACT project will offer a uniform, homogeneous, machine-independent approach to complexity theory founded on well-established, studied and understood mathematical notions. As such, the methods developed in this setting, adapted from DC/ICC as well as new, will be applicable to probabilistic and quantum classes as much as usual classes; in particular, it will offer a framework where comparison between non-classical and classical classes can be performed. It will also extend to computational paradigms where no established complexity theory exists, providing a strong and coherent proposition for such.

It will extend the approach of ICC and DC as it will go beyond the syntactical restrictions the latter are suffering from. In particular, it will provide a new method for defining logical systems corresponding to complexity classes: the realizability model construction gives a systematic way to define a logic corresponding to the underlying computational model. It will also extend the GoI model approach to complexity by reconciling the logical and complexity aspects, allowing the use of logical methods.

Lastly, the approach developed by the ReACT project does not naturally fall into the usual pitfalls for the obtention of separation results. Indeed, defining and dealing with the notion of oracle would involve changes in the very definition of graphings. Moreover, a proof of separation obtained from our techniques would not easily be shown to be a “natural proof”: the restriction of our notion of algorithms to size-restricted inputs and the original algorithm would be indistinguishable. Therefore, it provides a framework which will potentially offer methods for separation results.

³⁶J. Feldman and C. C. Moore. “Ergodic equivalence relations, cohomology, and von Neumann algebras. I”. in: *Transactions of the American mathematical society* 234.2 (1977), pp. 289–324.

³⁷Girard, “Geometry of Interaction I: Interpretation of System F”.

³⁸B. Fuglede and R. V. Kadison. “Determinant theory in finite factors”. In: *Annals of Mathematics* 56.2 (1952).

³⁹J.-Y. Girard. “Geometry of Interaction V: Logic in the Hyperfinite Factor.” In: *Theoretical Computer Science* 412 (2011).

⁴⁰J.-Y. Girard. “Geometry of Interaction II: Deadlock-free Algorithms”. In: *Proc. of COLOG 1988, LNCS 417*. 1988.

⁴¹T. Seiller. “Interaction Graphs and Complexity”. Extended Abstract. 2014.

⁴²Aubert and Seiller, “Characterizing co-NL by a group action”; Aubert and Seiller, “Logarithmic Space and Permutations”.

2.2 Clarity and quality of transfer of knowledge/training for the development of the researcher in light of the research objectives

The fellow will serve as an intermediate for the development of collaboration between local researchers working on Complexity Theory and researchers involved in the French ANR project ELICA (2014-2018). The research funds associated with the Marie Curie grant will be in part used to organize at least one workshop gathering international experts, about 18 months into the project. This will reinforce the fellow's experience concerning organizational matters, aiding his future transition to a permanent position in the research sector, a knowledge transfer reinforced by the scientist in charge's Master degree in Business Administration and experience as DIKU's Head of Research.

The fellow will learn from the both the scientist in charge and postdoctoral students under his supervision: Jonas Frey (COLA project postdoc) and Tobias Heindel (Marie Curie fellow). He will thus acquire, through regular working groups and specialized seminars as well as regular weekly meetings with the scientist in charge, knowledge about topics related to the ReACT project, e.g. realizability toposes (Frey), complexity theory of rule-based systems (Heindel), theory of dynamical systems and their invariants (Simonsen), term-rewriting and topos-theoretic approach to ICC (Simonsen). Conversely, the fellow will be given the opportunity to share his expertise on realizability models for linear logic and their application to computational complexity through regular seminars and advanced courses. He will also have the option to take active participation in the training of students at all levels and the supervision of student's projects as well as masters and PhD theses.

Apart from interactions at DIKU, the fellow will also benefit from the presence of two research groups in the Department of Mathematics of UCPH whose subjects relate to the ReACT project. The research team on non-commutative geometry will provide him with an opportunity to keep in touch with recent developments in the theory of operator algebras, while interactions with researchers from the research team on topology will allow the fellow to reinforce his knowledge about topological invariants. Beyond offering the fellow the opportunity to interact with researchers from these disciplines, the existence of those research teams at the UCPH will provide him access to advanced courses and seminars that will help him achieve the specific training task which is part of the work plan for the fellowship (section 4.1).

Finally, the fellow will have the option to follow numerous training programs for improving researcher skills organized by the UCPH, such as pedagogical courses to improve teaching skills.

2.3 Quality of the supervision and the hosting arrangements

The Department of Computer Science (DIKU) at the University of Copenhagen (UCPH) was founded in 1970 by later Turing Award Winner Peter Naur. DIKU hosts 32 permanent scientific staff members, 25 postdocs, and 35 PhD students. It has a sustained record of academic excellence evident both by international research awards (e.g. the Turing award, the ACM Programming Languages Achievement Award) and the high international profile of its alumni (e.g. the Vice Chancellor of the Danish IT University, the Director of the Fraunhofer Institute for Software and Systems Engineering in Dortmund).

The fellow will be part of the research group around the scientist in charge (currently 2 post docs, 2 PhD students and a research programmer) and will, as the scientist in charge, be formally embedded in both the Human-Centered Computing Group (providing office space, ancillary staff, and other local physical support), and the Algorithms and Programming Group (providing scientific sparring and mentoring). Both research groups have an extended international track record, with a 5-year collective publication record of over 200 papers at top international venues such as ACM POPL and ACM STOC.

Qualifications and experience of the supervisor(s). The scientist in charge is an internationally recognized expert on the mathematical treatment of computation and programming languages and has published a substantial number of papers in highly respected scholarly journals in theoretical computer science (e.g. Information and Computation, ACM Trans. Comp. Log., Theory of Computing Systems).

The scientist in charge has published extensively in the area of term rewriting and logic, particularly concerning superrecursive complexity hierarchies, and has a track record of publications in computa-

tional complexity as applied to dynamical systems⁴³. He has ongoing, sustained research collaborations with several international experts from the area of computational complexity (e.g. the Academic College Tel-Aviv Yafo, the Department of Mathematics at the University of Oslo, the Department of Computer Science at the University of Innsbruck). He holds a PhD degree from the University of Copenhagen and is one of only four scientists at DIKU to hold a Habilitation degree, having supervised more than 35 Master’s students, 4 Doctoral students, and a post-doctoral scholar (with two more post-doctoral scholars joining his group in late 2014). Also, he has ample management experience, currently serving as DIKU’s Head of Research and holding a Master’s degree in Business Administration from Heriot-Watt University. He is the recipient of the Danish government’s Sapere Aude Elite Research Leader grant and the principal investigator of the 800 000 Euro COLA project in Implicit Computational Complexity.

2.4 Capacity of the researcher to reach and re-enforce a position of professional maturity in research

The fellow is a recognized international expert in the area of realizability models for linear logic – geometry of interaction models – and their application to complexity theory, as illustrated by his numerous invitations to give doctoral courses and/or talks on the subject. His work on the subject of geometry of interaction models has lead him to develop a systematic approach which unifies and extends all previous works on the subject, encompassing the last forty years of research in the area. At the same time, he was a major drive force in the development of a new approach to computational complexity. He was granted a postdoctoral fellowship by the French Labex CARMIN to spend a year in the prestigious “Institut des Hautes Études Scientifiques” (IHÉS) in order to develop further this new approach.

In all of his publications, the fellow has been a main author, which is not reflected by the alphabetical order that is common in mathematics and computer science. These publications are mostly long papers written for journals (more than 46 pages on average, 54 pages on average for single-authored papers) involving advanced mathematical methods from a large spectrum of domains: graph theory⁴⁴, operator algebras⁴⁵, measure theory⁴⁶, proof theory⁴⁷, automata theory⁴⁸, category theory⁴⁹ and of course complexity theory⁵⁰. The number of single-authored publications, the fact that he never co-authored with his advisors and his obtaining a CARMIN fellowship show his independence and maturity as well as his capacity to set his own research objectives and attain them. The large-spectrum of techniques from different fields of mathematics used in his work demonstrates his open-mindedness, his broad scientific schooling and his capability to learn new techniques. The fellow was also active in creating and sustaining interactions between researchers. He has organized numerous events, obtaining funding when necessary, and took part in several national projects: ANR CHOCO (Curry-Howard for Concurrency), ANR LOGOI (Logic and Geometry of Interaction), COMPLICE (Implicit Computational Complexity), RECRE (Rewriting, Realizability), LOCI (Ludics and Linguistics).

⁴³J. G. Simonsen. “On the Computational Complexity of the Languages of General Symbolic Dynamical Systems and Beta-Shifts”. In: *Theoretical Computer Science* 410 (2009); J.G. Simonsen. “On the Computability of the Topological Entropy of Subshifts”. In: *Discrete Mathematics and Theoretical Computer Science* 8 (2006); S.B. Andersen and J.G. Simonsen. “Term Rewriting Systems as Topological Dynamical Systems”. In: *Proceedings of RTA ’12*. 2012.

⁴⁴T. Seiller. “Interaction Graphs: Multiplicatives”. In: *Annals of Pure and Applied Logic* 163 (2012); T. Seiller. “Interaction Graphs: Additives”. In: *Accepted for publication in Annals of Pure and Applied Logic* (2014).

⁴⁵Seiller, “Interaction Graphs: Multiplicatives”; Seiller, “A Correspondence between Maximal Abelian Sub-Algebras and Linear Logic Fragments”; Aubert and Seiller, “Characterizing co-NL by a group action”; Aubert and Seiller, “Logarithmic Space and Permutations”.

⁴⁶Seiller, “Interaction Graphs: Graphings”; T. Seiller. “Interaction Graphs: Exponentials”. In: *CoRR* abs/1312.1094 (2013).

⁴⁷Seiller, “Interaction Graphs: Exponentials”; A. Naibo, M. Petrolo, and T. Seiller. “On the Computational Meaning of Axioms”. In: *hal-00930222* (2014).

⁴⁸Aubert and Seiller, “Characterizing co-NL by a group action”; Aubert and Seiller, “Logarithmic Space and Permutations”.

⁴⁹Seiller, “Interaction Graphs: Additives”; C. Eberhart, T. Hirschowitz, and T. Seiller. “Fully-abstract concurrent games for pi”. In: *arXiv preprint arXiv:1310.4306* (2013).

⁵⁰Aubert and Seiller, “Characterizing co-NL by a group action”; Aubert and Seiller, “Logarithmic Space and Permutations”; Seiller, “Interaction Graphs: Exponentials”; Aubert et al., “Logic Programming and Logarithmic Space”.

3 Impact

3.1 Enhancing research- and innovation-related human resources, skills, and working conditions to realise the potential of individuals and to provide new career perspectives

The Marie Curie fellowship will provide training that will complement the fellow's competitive research profile with further secondary skills that are indispensable for a successful academic career. In particular, the UCPH has a tradition to offer postdoctoral researchers the opportunity, if they wish so, of getting involved in teaching. The fellow will be given the possibility to co-supervise Master's and PhD students. The fellowship will furthermore give him the opportunity to improve his skills concerning organizational matter, an aspect of his training reinforced by both his planned organization of a workshop involving international experts and the supervision of the scientist in charge who holds a Masters degree in Business Administration and serves as DIKU's Head of Research.

This additional training concerning organizational matters will improve the fellow's profile to make him an excellent candidate for lecturer or assistant professor positions, which require proof of management and leadership skills. The Marie Curie fellowship will also provide the fellow with working experience in a foreign country, an important if not essential asset for most academic positions. Lastly, the acquired experience in supervising students and his research experience's enrichment will allow the fellow to prepare a habilitation thesis within the two years subsequent to the end of the fellowship.

The fellowship will also allow the fellow to expand his network internationally. He will meet at UCPH a number of researchers working in related fields (postdoctoral researchers from the COLA projects, other Marie Curie fellows, researchers from DIKU and the Mathematics Departments of UCPH). Moreover, the fellow will have access, through already established cooperation with the scientist in charge, to new contacts among international experts on subjects of interest for the ReACT project (e.g. Amir Ben-Amram (Tel-Aviv), Lars Kristiansen (Oslo) and Georg Moser (Innsbruck)). Furthermore, research funds associated with the fellowship will be allocated to create and maintain relations with foreign researchers through workshop organization, invitations, stays abroad and communications at international venues.

The ReACT project will be a first exploration of a wide and deep new research direction, and will, as such, provide grounds for a more involved subsequent research project, for instance an ERC starting grant. The fellow will profit from the experience of both the UCPH services and the scientist's in charge for writing grant proposals, preparing his future career as well as the aftermath of the ReACT project.

3.2 Effectiveness of the proposed measures for communication and results dissemination

Communication and public engagement strategy of the action. The fellow plans to organize at least one workshop, about 18 months into the project, with the research funds allocated with the Marie Curie fellowship. Ideally, two such workshops will be organized by collaborating with related European projects (the COLA project in Copenhagen, the French ANR ELICA), at the end of the first and second years. This will be an appropriate occasion for the fellow to communicate his results in his research community. The fellow will also be given an opportunity to take part in several events involving the UCPH as well as some Danish organizations of High Schools and Primary Schools, including the "Danish Academy for Talented Youth" and the "Danish Youth Association of Science". This will allow him to pursue his commitment to dissemination at High School, Middle School and Primary School levels, which began by his involvement in "Hippocampe" and "Math a Modeler" courses.

Dissemination of the research results. The fellow also plans to write journal and conference papers. The most involved theoretical results will be submitted to the best ranked journals in the fields of logic and complexity theory, e.g. LOGICAL METHODS IN COMPUTER SCIENCE and MATHEMATICAL STRUCTURES IN COMPUTER SCIENCE. Those results published in journal papers will be subject to communications at international workshops, e.g. LOGIC AND COMPUTATIONAL COMPLEXITY (LCC), DEVELOPMENT IN IMPLICIT COMPUTATIONAL COMPLEXITY (DICE). The fellow also plans to submit conference paper to disseminate those results that can be exposed appropriately within the imposed page

limits, such as the IEEE’s LOGIC IN COMPUTER SCIENCE (LICS) conference series or the EACSL’s COMPUTER SCIENCE LOGIC (CSL) conference series. The fellow will also be given the option to take an active part in teaching and supervising students, an opportunity to disseminate his results both at undergraduate and graduate levels. Concerning the matter of his publications, the fellow will be particularly attentive to the accessibility of his work, and will adhere to EU’s policies regarding open access.

Exploitation of results and intellectual property. At the time of writing this project, it seems that exploitation of results and intellectual property is not expected to be an issue concerning the expected results. If these questions became important to deal with due to the evolution of the project, the fellow will be supported by UCPH services and in particular the TechTrans (Technology Transfert) office whose purpose is to help researchers concerning these specific issues.

4 Implementation

4.1 Overall coherence and effectiveness of the work plan, including appropriateness of the allocation of tasks and resources

The goals of the ReACT project naturally decomposed into two groups corresponding to the two objectives (section 1): the first three goals and the fourth goal. The working plan reflects this dichotomy: the fellow will work on the three first goals one after the other while keeping a constant research effort towards **Goal 4**. The sequentiality in the work plan for **Goals 1-3** is consistent with their aim: first show the *complexity-through-realizability* techniques to be an adequate approach for complexity theory (**Goal1**), then show these techniques generalize and improve previous methods (**Goal2**) and then show they apply to a more general framework (**Goal3**).

Below follows a description of the decomposition of the different goals into work packages together with a risk estimation; the list of milestones appears in section 4.2. Each work package is associated with deliverables in the form of previously unpublished theorems. Roughly, work packages are labelled *low risk* when they consist in simple adaptations of established techniques; *medium risk* when refining of previous works and techniques will be needed; and *high risk* when new techniques will be developed.

Goal1 (first 6 months). *Two work packages.* Both packages are low risk as simple adaptations of previous results⁵¹. **WP1.1** (low risk) Characterize sub-logarithmic space classes, in particular **REG**, **L**, and **NL**. **WP1.2** (low risk) Characterize super-logarithmic space classes, in particular **P**, **NP** and **EXP**.

Goal2 (next 6 months). *Two work packages.* **WP2.1** (low risk) Show that quantitative realizability and ICC techniques are particular cases of our approach. This is a low risk work package as previous methods used to obtain realizability models capturing the ICC logical system ELL⁵² can be adapted. **WP2.2** (medium risk) Show the notion of graphing captures Gurevich’s notion of abstract state machines (ASM). An ASM is intuitively a kind of automata on first-order structures and such objects can be seen as graphings⁵³; this is considered medium risk as no previous work attempted to relate ASMs and GoI.

Goal3 (next 12 months). *Three work packages.* **WP3.1** (low risk) Show that our notion of algorithms captures that of probabilistic/quantum computation. This is a low risk work package as the fellow already undertook preliminary work in this direction in collaboration with quantum computing expert B. Valiron. **WP3.2** (medium risk) Obtain characterizations of probabilistic/quantum complexity classes. This is considered a medium risk work package because of its dependency on WP3.1, making it difficult to assess at this time the amount of work needed to adapt previous methods. **WP3.3** (high risk) Show that concurrent processes and cellular automata are particular cases of graphings and study the corresponding complexity theory. A GoI approach to cellular automata theory has never been attempted. For concurrent processes, although some work has been carried out to adapt some GoI techniques, they were not concerned with the obtention of realizability models.

⁵¹ Aubert and Seiller, “Characterizing co-NL by a group action”; Aubert and Seiller, “Logarithmic Space and Permutations”; Baillot, “Elementary Linear Logic Revisited for Polynomial Time and an Exponential Time Hierarchy”.

⁵² Seiller, “Interaction Graphs: Exponentials”.

⁵³ Seiller, “Interaction Graphs: Graphings”.

Goal4 (two years). *Three work packages.* **WP4.1** (no risk) Training in operator algebras and dynamical systems, focused on homological/cohomological invariants (first nine months). **WP4.2** (medium risk) Find mathematical invariants providing a method for proving two complexity classes are equal. This is a medium-to-high risk work package as preliminary discussions with specialists of graphings suggest that ℓ^2 Betti numbers provide a good candidate for such an invariant. **WP4.3** (high risk) Find suitable mathematical invariants for proving equality and/or inequality of complexity classes. This task presents the higher risks: obtaining methods for separation of complexity classes has been shown to be an extremely difficult task. For the very same reason, it is also high-reward as it would provide, with the characterizations of **L** and **P** (WP1.1 and WP1.2), high hopes of a separation result for these two classes.

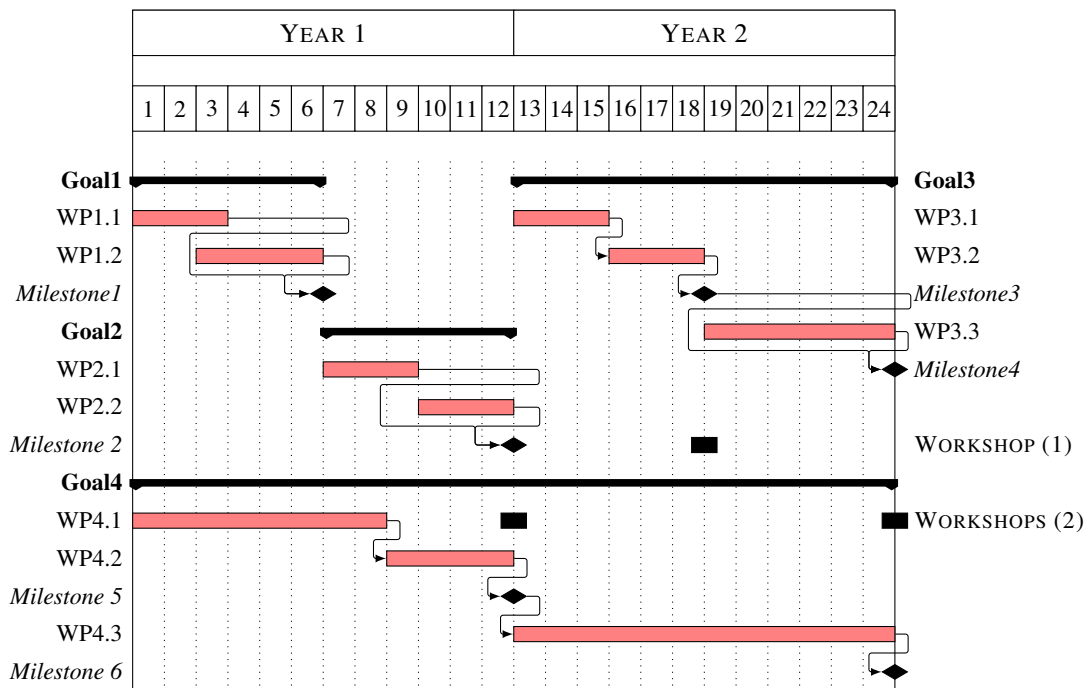


Figure 1: Gantt Chart

The chart shows the two possibilities concerning the organization of workshops: (1) One workshop is organized with the fellowship's research funds, (2) Co-organization with other research projects leads to two workshops.

4.2 Appropriateness of the management structure and procedures, including quality management and risk management

The UCPH accountancy office will monitor project finances and provide monthly reports to both the fellow and the scientist in charge, while DIKU's research support unit (2.5 full-time equivalents) will assist them with any management concerns, including the production of reports.

The first year of the ReACT project is concerned with low-risk goals. Indeed, some of the results are simple adaptation of previous work. The fellow and scientist in charge will have weekly meetings and assess the progress of each ongoing work package. Also, they will continuously re-evaluate risks and in particular risk handling during these weekly meetings. The work plan is moreover constructed so that an evaluation of the project's progress and eventual reassessments of future goals can be performed every six months. Those are represented by the six milestones shown in the Gantt chart above; those correspond to natural steps in the development of the project, namely they correspond to the obtention of a series of results, providing grounds for a research report destined to be published, showing that the *complexity-through-realizability* techniques: (**Milestone1**) capture usual (sequential) complexity classes; (**Milestone2**) extend and generalize previous work; (**Milestone3**) extend to quantum/probabilistic computation; (**Milestone4**) extend to concurrent processes and cellular automata; (**Milestone5**) provide methods for proving equality of classes; (**Milestone6**) provide methods for proving separation results.

We will now describe, for each medium and high risk work package, of how these risks will be handled. **WP2.2** *modification of the expected result*: instead of showing that ASM are particular cases of graphings, we might obtain a precise characterization of the set of those ASM that can be represented as graphings. **WP3.2** *modification of the expected result*: we will adapt the definition of complexity classes to obtain characterization of quantum and/or probabilistic classes. **WP3.3** *modification of the framework*: we will find a suitable generalization of the notion of graphings which will allow for the representation of concurrent processes and cellular automata. **WP4.2** *time extension*: extend the work package as long as necessary, pushing **WP4.3**. **WP4.3** *modification of the expected results*: study the refinement of the invariant considered in **WP3.2** from a mathematical point of view.

4.3 Appropriateness of the institutional environment (infrastructure)

UCPH has much experience in helping international employees, many of whom supported by Marie Curie grants. Services of the UCPH are devoted to help foreign employees in finding living accommodation as well as dealing with administrative tasks due to mobility (contracts, taxes, etc.). The fellow will therefore receive help not only on his arrival, but for the whole time of his stay, whenever necessary. This will allow him to attend to all administrative aspects of Marie Curie grants, such as preparation of deliverables in a best possible form. Moreover, it is the mission of the International Staff Mobility Office, the Accommodation Office and the University's mentor program to welcome fellows and offer help to successfully make the necessary practical arrangements. The International Staff Mobility Office addresses general and particular aspects of settling in, the Accommodation Office of the faculty specializes in finding suitable housing for long or short term stays, and many volunteers help new arrivals to orient themselves in their new environment and familiarize these with everyday details of academic and social life in Copenhagen through the University's mentor program.

The administrative management will further be supported by the EU Office of the UCPH – which has existed since 2002 and has been involved in the management of several EU projects, and the North Campus Administration of the Faculty of science – which handles the financial and personnel aspects of national and international research projects including EU projects. The Faculty of Science was the recipient of 81 Marie Curie Individual Fellowships in FP7 and has great experience of project administration, leaving the fellow free to focus on scientific aspects of the project by lightening the administrative task load. Furthermore, DIKU will furnish office space, access to scientific papers from all major publishers, books, and computing facilities. The fellow will be on the same corridor as the scientist in charge, who will actively participate in research on the project.

4.4 Competences, experience and complementarity of the participating organisations and institutional commitment

The ReACT project will establish the *complexity-through-realizability* techniques as a promising emerging field of study. These techniques stem from historically disjoint domains: ICC and DC on one hand, and realizability for linear logic on the other. It moreover involves mathematical techniques from the fields of operator algebras and dynamical systems, fields which had almost no interaction with logic and complexity theory in the past. The fellow is an expert of realizability for linear logic, and has great experience working with techniques from operator algebras and complexity theory, most particularly ICC techniques. The scientist in charge's unique common expertise in both logical approaches to complexity theory (ICC and DC) and the theory of dynamical systems will perfectly complement the fellow's strengths to ensure the success of the project.

The scientist in charge's experience as DIKU's Head of Research and his Master's degree in Business Administration will ensure the fellow's training in organizational matters. The scientist's in charge experience in supervising students and his extended international network will provide the fellow with a unique opportunity to complement his competitive research profile and allow him to prepare a habilitation thesis within two years subsequent to the project. The training and foreign research experience provided by his stay at UCPH will therefore be a major step in the career development of the fellow.

5 CV of the Experienced Researcher

Personal Informations

Name Thomas SEILLER
 Birthdate February 4th, 1984
 Family Married with one child
 Website <http://www.ihes.fr/~seiller/>
 ORCID <http://orcid.org/0000-0001-6313-0898>

Positions

2013–2014 **Post-Doctoral Researcher**, *IHÉS*, Bures-sur-Yvette.
 2012–2013 **Post-Doctoral Researcher**, *INRIA*, Chambéry.
 2011–2012 **Assistant Professor**, *Université de Savoie*, Chambéry.
 2008–2011 **PhD candidate**, *Université de la Méditerranée*, Marseille.
 2008–2011 **Teaching Assistant**, *Université de la Méditerranée*, Marseille.

Education

2008–2012 **PhD**, *Aix-Marseille University*, Marseille.
 2006–2008 **Master**, *Paris 7 University - Denis Diderot*, Paris.

PhD thesis

title *Logic in the Hyperfinite Factor: Geometry of Interaction and Complexity.*
 supervisors Jean-Yves Girard and Laurent Regnier.
 defense Defended on November 13th, 2012.
 jury Pierre-Louis Curien (rapporteur, CNRS), Jean-Yves Girard (advisor, CNRS),
 Martin Hyland (rapporteur, University of Cambridge), Olivier Laurent
 (president, ENS Lyon) Laurent Regnier (advisor, Aix-Marseille University),
 Philip Scott (University of Ottawa).

Doctoral Courses

Course **Paris 1 University**, *June 2009*, 15 hours course. Paris, France
 Course **Thematic School "Linear Logic, Ludics and Geometry of Interaction"**,
August 27th – September 1st, 2012, 1h30 course. Paraty, Brazil
 Course **Summer School on Linear Logic and Geometry of Interaction**, *August*
27th-31st, 2013, 1h30 course. Turin, Italy
 Course **Oberseminar "Logik und Sprachtheorie"**, *October 29th, 2013*, 4 hours
 course. Tübingen, Germany

Communications (Invitations)

Talk **"Logic of Programming" seminar**, IML.
March 4th, 2010, Marseille, France.
 Talk **"Logic, Computation and Reasoning" seminar**, LIPN.
May 5th, 2010, Paris, France.
 Talk **"Realizability and Type Theory" seminar**, Team πR^2 INRIA/PPS.
June 16th, 2010, Paris, France.

- Talk **"Logic Team Seminar"**, LAMA.
Chambéry, France.
- Talk **"Logic of Programming" seminar**, IML.
December 1st, 2011, Marseille, France.
- Talk **"Logic, Computation and Reasoning" seminar**, LIPN.
January 12th, 2012, Paris, France.
- Talk **ANR project LOGOI meeting**.
June 14th, 2012, Marseille, France.
- Talk **ANR project RECRE meeting**.
October 11th, 2012, Lyon, France.
- Talk **"PPS Seminar"**, PPS.
January 24th, 2013, Paris, France.
- Talk **ANR project LOGOI meeting**.
February 1st, 2013, Marseille, France.
- Talk **"Logic Team Seminar"**, LAMA.
February 21st, 2013, Chambéry, France.
- Talk **"LAMA Seminar"**, LAMA.
April 4th, 2013, Chambéry, France.
- Talk **ANR project LOGOI meeting**.
June 10th-11st, 2013, Paris, France.
- Talk **"68nqrt" Seminar**, IRISA/INRIA.
June 13th, 2013, Rennes, France.
- Talk **Summer School on Linear Logic and Geometry of Interaction**.
August 31st, 2013, Turin, Italy.
- Talk **GdR IM meeting**.
January 28th, 2014, Paris, France.
- Talk **Séminaire de Mathématiques**, IHÉS.
February 25th, 2014, Bures-sur-Yvette, France.
- Talk **"Logic, Computation and Reasoning" seminar**, LIPN.
28/03/2014, Paris, France.
- Talk **"Algorithmics, Complexity and Logic Laboratory" seminar**, LACL.
31/03/2014, Paris, France.
- Talk **Workshop "Higher Order Computation: Types, Complexity, Applications"**, Institut Henri Poincaré.
16/06/2014, Paris, France.

Communications (Workshops and Conferences)

- Talk **"Graphs of Interaction: Multiplicatives"**, March 20th-21st, 2010.
GaLoP V (Games for Logic and Programming Languages), ETAPS 2010 Workshop, Paphos, Cyprus.
- Talk **"Logical Constants from a Computational Point of View"**, January 20th-21st, 2011.
ANR project LOCI meeting, CIRM, Marseille, France.
- Talk **"Graphs of Interaction: Additives"**, November 7th-11th, 2011.
Workshop on Linear Logic (Geometry of Interaction, Traced Monoidal Categories and Implicit Complexity), Kyoto, Japan.
- Talk **"Graphs of Interaction: Additives"**, January 30th – March 2nd, 2012.
Logic and Interaction 2012, CIRM, Marseille, France.
- Talk **"Interaction Graphs: Additives"**, June 25th-28th, 2012.
LICS 2012 (Logic In Computer Science), Dubrovnik, Croatia.

- Talk **"Interaction Graphs: Additives"**, June 29th, 2012.
GaLoP VII (Games for Logic and Programming languages), Dubrovnik, Croatia.
- Talk **"Espace Logarithmique et Permutations"**, February 15th, 2013.
GEOCAL Meeting, Lyon, France.
- Talk **"Logarithmic Space and Permutations"**, March 17th, 2013.
DICE 2013 (Developments in Implicit Computational Complexity), Rome, Italy.
- Talk **"Interaction Graphs and Complexity"**, March 25th, 2014.
GEOCAL Meeting, Bordeaux, France.

Other Research Activities

- Organization **Working Group on Geometry of Interaction, Reunions in Paris and Marseille**. From 2008 to the creation of the ANR project LOGOI.
- Organization **Interdisciplinary Working Group for PhD Students, Reunions in Paris and Marseille**. In 2010 and 2011.
- Organization **Symposium "The meaning of Axioms"**, 14th CLMPS congress. In 2011.
SPEAKERS: DENIS BONNAY, GILLES DOWEK, ALEXANDRE MIQUEL, ALBERTO NAIBO, MATTIA PETROLO, SAMUEL TRONCON
- Organization **"Séances de Mathématiques" seminar, IML, Marseille**. From 2010 to 2011.

Teaching Experience

- 2012-2013 **Exercise Sessions and Practice Sessions in Computer Science (first year students)**, *Université de Savoie*, 40 hours.
- 2011-2012 **Exercise Sessions and Practise Sessions in Computer Science (first, second and third year students)**, *Université de Savoie*, 176 hours.
- 2008-2011 **Lectures in Mathematics (third year students)**, *Université de la Méditerranée*, 108 hours.

Other Teaching Activities

- 2012-2013 **Co-organization of a "Maths à modeler" course**, *Université de Savoie*, .
- 2008-2011 **Participation to "Hippocampe" courses**, *Université de la Méditerranée*, I participated to five such courses.

Grants/Awards

- 2013 **One-Year CARMIN postdoctoral fellowship**, for a combined stay at the "Institut des Hautes Études Scientifiques" and the "Institut Henri Poincaré".
- 2009 **Travel Grant**, from/for the "Operator Algebras and Applications" summer school in Lisbon.
- 2008 **Three-Years PhD fellowship**, from the french "Ministry of Higher Education and Research".
- 2007 **One-Year grant "Bourse d'excellence"**, from the french "Ministry of Higher Education and Research".

Publications

- Journal **Interaction Graphs: Multiplicatives**, *Annals of Pure and Applied Logic* 168 (2012), pp. 1808-1837. DOI: 10.1016/j.apal.2012.04.005

Contents. This paper defines a combinatorial approach to J.-Y. Girard’s geometry of interaction in the hyperfinite factor, replacing operator-algebraic notion by usual graph-theoretical notions. In particular, it is shown that the Fuglede-Kadison determinant in the type II_1 hyperfinite factor can be computed as a measure of the sets of cycles in a graph.

Journal **Interaction Graphs: Additives**, *accepted for publication in Annals of Pure and Applied Logic*. arXiv:1205.6558

Contents. This paper presents a parametrized construction of a Geometry of Interaction model (GoI model) for Multiplicative Additive Linear Logic (MALL). Contrarily to former constructions dealing with additive connectives, we are able to solve here the known issue of obtaining a denotational semantics for MALL by introducing a notion of observational equivalence. This work is shown to generalize all previously considered GoI models and pinpoints an essential property, named the trefoil property, which underlies them.

Conference **Logic Programming and Logarithmic Space**, *accepted at 12th Asian Symposium on Programming Languages and Systems (APLAS 2014)*, with C. Aubert, M. Bagnol, and P. Pistone. arXiv:1406.2110

Contents. This paper presents an algebraic view on logic programming, related to proof theory and more specifically linear logic and geometry of interaction. Within this construction, a characterization of logspace (deterministic and non-deterministic) computation is given via a syntactic restriction, using an encoding of words that derives from proof theory.

Submitted Papers

Submitted **Characterizing co-NL by a Group Action**, *arXiv:1209.3422*, with C. Aubert. 2012

Contents. In a previous paper, Girard proposes to use his recent construction of a geometry of interaction in the hyperfinite factor in an innovative way to characterize complexity classes. This work provides a complete proof that the complexity class co-NL can be characterized using this new approach. We introduce as a technical tool the non-deterministic pointer machine, a concrete model to computes algorithms in logarithmic space.

Submitted **Logarithmic Space and Permutations**, *arXiv:1301.3189*, with C. Aubert. 2013

Contents. In a previous paper, the authors showed how Girard proposal succeeds in obtaining a new characterization of co-NL languages as a set of operators acting on a Hilbert Space. In this paper, we extend this work by showing that it is also possible to define a set of operators characterizing the class L of deterministic logarithmic space languages.

Submitted **Fully Abstract Concurrent Games for Pi**, *arXiv:1310.4306*, with C. Eberhart and T. Hirschowitz. 2013

Contents. This paper introduces a semantics for Milner’s pi-calculus with three main novelties. First, it provides a fully-abstract model for fair testing equivalence, whereas previous semantics covered variants of bisimilarity and the may and must testing equivalences. Second, it is based on reduction semantics, whereas previous semantics were based on labelled transition systems. Finally, it has a strong game semantical flavor in the sense of Hyland-Ong and Nickau. Indeed, our model may both be viewed as an innocent presheaf semantics and as a concurrent game semantics.

Submitted **On the Computational Meaning of Axioms**, *hal-00930222*, with A. Naibo and M. Petrollo. 2014

- Contents.** An anti-realist theory of meaning suitable for both logical and proper axioms is investigated. As opposed to other anti-realist accounts, like Dummett-Prawitz verificationism, the standard framework of classical logic is not called into question. In particular, semantical features are not limited solely to inferential ones, but also computational aspects play an essential role in the process of determination of meaning. In order to deal with such computational aspects, a relaxation of syntax is shown to be necessary. This leads to a general kind of proof theory, where the objects of study are not typed objects like deductions, but rather untyped ones, in which formulas have been replaced by geometrical configurations.
- Submitted **Interaction Graphs: Graphings**, *arXiv:1405.6331*. 2014
Contents. This paper extends the approach developed in previous papers on Interaction Graphs by considering a generalization of graphs named graphings, which is in some way a geometric realization of a graph. This very general framework leads to a number of new models of multiplicative-additive linear logic which generalize Girard’s geometry of interaction models and opens several new lines of research in computational complexity and quantum computation.
- Submitted **Interaction Graphs: Exponentials**, *arXiv:1312.1094*. 2014
Contents. This paper tackles the complex issue of defining exponential connectives in the Interaction Graphs framework. In order to succeed in this, we use the notion of graphings, a generalization of graphs which was defined in earlier work. We explain how one can define a GoI model for Elementary Linear Logic (ELL) with second-order quantification, a sub-system of linear logic that captures the class of elementary time computable functions.
- Submitted **A Correspondance between Maximal Abelian Sub-Algebras and Linear Logic Fragments**, *arXiv:1408.2125*. 2014
Contents. This papers exhibits a correspondence between a classification of maximal abelian sub-algebras (MASAs) proposed by Jacques Dixmier and fragments of linear logic. We expose for this purpose a modified construction of Girard’s hyperfinite geometry of interaction which interprets proofs as operators in a von Neumann algebra. The expressivity of the logic soundly interpreted in this model is dependent on properties of a MASA which is a parameter of the interpretation.
-
- In Preparation**
- In Prep. **Logical Constants from a Computational Point of View**, with A. Naibo and M. Petrolo.
Contents. The topic of this paper is the problem of characterizing the meaning of logical constants. Our proposal stands in the line of proof-theoretic semantics, exploiting in an essential way the proofs-as-programs correspondence. We first present the inferentialist position in order to point out some of its problems. Their analysis and solutions are carried out in the light of the Curry-Howard correspondence. It is on this basis that we can formulate a necessary condition for logicity, which naturally emerges from the computational point of view adopted here.
- In Prep. **Full Abstraction for Fair Testing in Pi**, with C. Eberhart and T. Hirschowitz.
Contents. This is the long version of the submitted conference paper *Fully abstract concurrent games for Pi*.
- In Prep. **Note de Lecture sur *The Blind Spot* de J.-Y. Girard**, *Gazette des Mathématiciens*, with C. Rétoré.
Contents. This is a short lecture note on J.-Y. Girard’s book “The Blind Spot” that should appear in the October 2014 bulletin of the french mathematical society.

6 Capacities of the Participating Organisations

University of Copenhagen (UCPH)	
General Description	The scientist in charge is an internationally recognized expert on the mathematical treatment of computation and programming languages who published a substantial number of papers in highly respected scholarly journals in theoretical computer science. He is part of the “Human-Centered Computing and Algorithms” and “Programming Languages” groups at the Department of Computer Science (DIKU) at UCPH, which have an extended international track record, with over 200 papers at top international venues in the last 5 years, and both a Turing award winner and an ACM Programming Languages Achievement award winner among their alumni. DIKU was founded in 1970 by later Turing Award Winner Peter Naur. It hosts undergraduate and graduate studies in the fields of Algorithms and Programming Languages, Image Processing and Machine Learning, and Human-Centered Computing, with local interdisciplinary collaboration (departments of Physics, Mathematics, Economics, etc.), as well as a several international research collaborations. It hosts 32 permanent scientific staff members, 25 postdocs, and 35 PhD students. Its sustained record of academic excellence is evidenced by international research awards (e.g., the Turing award, the ACM Programming Languages Achievement Award) and the consistent high international profile of its scientific alumni (e.g. the vice chancellor of the Danish IT University, the Director of the Fraunhofer Institute for Software and Systems Engineering in Dortmund). Founded in 1479, UCPH is one of northern Europe’s oldest universities. It has over 40.000 students and 5.000 academic staff, is consistently ranked among the top 100 universities in the world, and has a long-standing record of outstanding academic achievement, including 8 Nobel prize laureates.
Role and Commitment of key persons (supervisor)	The scientist in charge will collaborate scientifically with the fellow, including having formalized weekly meetings. The fellow will interact with local group members: postdocs Jonas Frey and Tobias Heindel and PhD students, experts in programming languages, lambda calculus, and computability theory, notably Prof. Henglein, Filinski and Mogensen.
Key Research Facilities, Infrastructure and Equipment	The fellow will be given an office including desk, furniture, whiteboard and internet access. State-of-the-art computing facilities are maintained both by the Faculty of Science IT services and DIKU.
Independent research premises?	The UCPH maintains independent research premises.
Previous Involvement in Research and Training Programmes	The scientist in charge supervised over 35 master’s theses, 4 PhDs, a postdoc, and will host a Marie Curie fellow from fall 2014. He participated as a faculty member in several formalized training networks for PhD students and postdocs, notably the Foundations for Innovative Research-based Software Technologies (FIRST) graduate training network involving UCPH, the IT University of Denmark, and the Technical University of Denmark.
Current involvement in Research and Training Programmes	The fellow and the scientist in charge will be part of the APL and HCC sections of DIKU, which both participate in several formal research training networks for doctoral and postdoctoral scholars, including roles as coordinating institution in "Algorithms and Data Structures for Trees" (partnering with Princeton University’s local coordinator, Turing award winner Robert Tarjan), and hosting role for the International School on Imaging and Machine Learning Research (IMLRS).
Relevant Publications and/or research/innovation products	Ketema, Simonsen, "Infinitary Combinatory Reduction Systems". Information and Computation 209(6), 2011. Simonsen, "On the Computational Complexity of the Languages of General Symbolic Dynamical Systems and Beta-Shifts". Theoretical Computer Science 410, 2009. Simonsen "On the Computability of the Topological Entropy of Subshifts" Discrete Mathematics and Theoretical Computer Science 8, 2006. de Carvalho, Simonsen, "An Implicit Characterization of the Polynomial-Time Decidable Sets by Cons-Free Rewriting". Proc. RTA-TLCA '14. Andersen, Simonsen, "Term Rewriting Systems as Topological Dynamical Systems". Proceedings of RTA '12.

7 Ethical Aspects

There are no ethical sensitive issues associated with the subject of this proposal.

8 Letters of Commitment of Partner Organisations

No letters of commitment are needed for this proposal.

ENDPAGE

MARIE SKŁODOWSKA–CURIE ACTIONS

Individual Fellowships (IF)
Call: H2020-MSCA-IF-2014

PART B

“ReACT”

“A Realizability Approach to Complexity Theory”

This proposal is to be evaluated as:

[Standard EF]