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Sylvain Schmitz · Igor Potapov (Eds.)

Reachability Problems

14th International Conference, RP 2020
Paris, France, October 19–21, 2020
Proceedings

Springer

Editors
Sylvain Schmitz
Université de Paris
Paris, France

Igor Potapov
University of Liverpool
Liverpool, UK

ISSN 0302-9743 ISSN 1611-3349 (electronic)
Lecture Notes in Computer Science
ISBN 978-3-030-61738-7 ISBN 978-3-030-61739-4 (eBook)
https://doi.org/10.1007/978-3-030-61739-4

LNCS Sublibrary: SL1 – Theoretical Computer Science and General Issues

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Preface

This volume contains the papers presented at the 14th International Conference on Reachability Problems (RP 2020), organized by the University of Paris, France. Previous events in the series were located at: Université Libre de Bruxelles, Belgium (2019), Aix-Marseille University, France (2018), Royal Holloway, University of London, UK (2017), Aalborg University, Denmark (2016), the University of Warsaw, Poland (2015), the University of Oxford, UK (2014), Uppsala University, Sweden (2013), the University of Bordeaux, France (2012), the University of Genoa, Italy (2011), Masaryk University, Czech Republic (2010), École Polytechnique, France (2009), The University of Liverpool, UK (2008), and University of Turku, Finland (2007).

The aim of the conference is to bring together scholars from diverse fields with a shared interest in reachability problems, and to promote the exploration of new approaches for the modeling and analysis of computational processes by combining mathematical, algorithmic, and computational techniques. Topics of interest include (but are not limited to): reachability for infinite state systems; rewriting systems; reachability analysis in counter/timed/cellular/communicating automata; Petri nets; computational game theory, computational aspects of semigroups, groups, and rings; reachability in dynamical and hybrid systems; frontiers between decidable and undecidable reachability problems; complexity and decidability aspects; predictability in iterative maps; and new computational paradigms.

We are very grateful to our invited speakers, who gave the following talks:

- **Valérie Berthé**, University of Paris, IRIF, CNRS, France:
  "On Decision Problems for Substitutions in Symbolic Dynamics"
- **Patricia Bouyer-Decitre**, CNRS, ENS Paris-Saclay, France:
  "When are Finite Games Finite-Memory Determined?"
- **Kousha Etessami**, The University of Edinburgh, UK:
- "Computing a Fixed Point of a Monotone Function, and Some Applications"
- **Orna Kupferman**, The Hebrew University, Israel:
  "Games with Full, Longitudinal and Transverse Observability"
- **Dirk Nowotka**, Kiel University, Germany:
  "Word Equations: From Theory to Practice"

The conference received 25 submissions (17 regular and 8 presentation-only submissions) from which 3 regular papers were withdrawn. Each submission was carefully reviewed by three Program Committee (PC) members. Based on these reviews, the PC decided to accept 8 regular papers. The members of the PC and the list of external reviewers can be found on the next pages. We are grateful for the high quality work produced by the PC and the external reviewers. Overall this volume contains 8 contributed papers and 2 papers from invited speakers which cover their talks.

The conference also provided the opportunity for other young and established researchers to present work in progress or work already published elsewhere. This year, in addition to 8 regular submissions, the PC selected 8 high-quality presentations on various reachability aspects in theoretical computer science. A list of accepted talk-only submissions is given below:

PrIC3: Property Directed Reachability for MDPs
Kevin Batz, Sebastian Junges, Benjamin Lucien Kaminski, Joost-Pieter Katoen, Christoph Matheja, and Philipp Schröer
Abstract: IC3 has been a leap forward in symbolic model checking. This paper proposes PrIC3 (pronounced pricy-three), a conservative extension of IC3 to symbolic model checking of MDPs. Our main focus is to develop the theory underlying PrIC3. Alongside, we present a first implementation of PrIC3 including the key ingredients from IC3 such as generalization, repushing, and propagation. This paper has been published in the CAV 2020 proceedings.

Higher-Order Nonemptiness Step by Step
Paweł Parys
Abstract: We show a new simple algorithm that checks whether a given higher-order grammar generates a nonempty language of trees. The algorithm amounts to a procedure that transforms a grammar of order n to a grammar of order $n - 1$, preserving nonemptiness, and increasing the size only exponentially. After repeating the procedure n times, we obtain a grammar of order 0, whose nonemptiness can be easily checked. Since the size grows exponentially at each step, the overall complexity is n-EXPTIME, which is known to be optimal. More precisely, the transformation (and hence the whole algorithm) is linear in the size of the grammar, assuming that the arity of employed nonterminals is bounded by a constant. The same algorithm allows to check whether an infinite tree generated by a higher-order recursion scheme is accepted by an alternating safety (or reachability) automaton, because this question can be reduced to the nonemptiness problem by taking a product of the recursion scheme with the automaton. A proof of correctness of the algorithm is formalized in the proof assistant Coq. Our transformation is motivated by a similar transformation of Asada and Kobayashi (2020) changing a word grammar of order n to a tree grammar of order $n - 1$. The step-by-step approach can be opposed to previous algorithms solving the nonemptiness problem "in one step", being compulsorily more complicated. This paper was submitted to the FSTTCS 2020 conference.

The Strahler Number of a Parity Game
Laure Daviaud, Marcin Jurdzinski, and K. S. Thejaswini
Abstract: The Strahler number of a rooted tree is the largest height of a perfect binary tree that is its minor. The Strahler number of a parity game is proposed to be defined as the smallest Strahler number of the tree of any of its attractor decompositions. It has been proven that parity games can be solved in quasi-linear space and in time that is polynomial in the number of vertices n and linear in $(d/2k)^k$, where d is the number of priorities and k is the Strahler number. This complexity is quasi-polynomial because the Strahler number is at most logarithmic in the number of vertices. The proof is based on a new construction of small Strahler-universal trees. It is shown that the Strahler

number of a parity game is robust, and hence arguably a natural, parameter: it coincides with its alternative version based on trees of progress measures – and remarkably – with the register number defined by Lehtinen (2018). It follows that parity games can be solved in quasi-linear space and in time that is polynomial in the number of vertices and linear in $(d/2k)^k$, where k is the register number. This significantly improves the running times and space achieved for parity games of bounded register number by Lehtinen (2018) and by Parys (2020). The running time of the algorithm based on small Strahler-universal trees yields a novel trade-off $k \cdot lg(d/k) = O(log\ (n))$ between the two natural parameters that measure the structural complexity of a parity game, which allows solving parity games in polynomial time. This includes special cases, for example the asymptotic settings of those parameters covered by the results of Calude, Jain, Khoussainov, Li, and Stephan (2017), of Jurdzinski and Lazic (2017), and of Lehtinen (2018), and it significantly extends the range of such settings, for example to $d = 2^{O(\sqrt{\lg n})}$ and $k = O(\sqrt{\lg n})$. This paper was published in the ICALP 2020 proceedings.

Cost Automata, Safe Schemes, and Downward Closures
David Barozzini, Lorenzo Clemente, Thomas Colcombet, and Paweł Parys
Abstract: Higher-order recursion schemes are an expressive formalism used to define languages of possibly infinite ranked trees. They extend regular and context-free grammars, and are equivalent to simply typed λY-calculus and collapsible pushdown automata. In this work we prove, under a syntactical constraint called safety, decidability of the model-checking problem for recursion schemes against properties defined by alternating B-automata, an extension of alternating parity automata for infinite trees with a boundedness acceptance condition. We then exploit this result to show how to compute downward closures of languages of finite trees recognized by safe recursion schemes. This paper was published in the ICALP 2020 proceedings.

Decidability of cutpoint isolation for probabilistic finite automata on letter-bounded inputs
Paul Bell and Pavel Semukhin
Abstract: We show the surprising result that the cutpoint isolation problem is decidable for probabilistic finite automata where input words are taken from a letter-bounded context-free language. A context-free language $\mathcal{L}$ is letter-bounded when $\mathcal{L} \subseteq a_1^* a_2^* \cdots a_\ell^*$ for some finite $\ell > 0$ where each letter is distinct. A cutpoint is isolated when it cannot be approached arbitrarily closely. The decidability of this problem is in marked contrast to the situation for the (strict) emptiness problem for PFA which is undecidable under the even more severe restrictions of PFA with polynomial ambiguity, commutative matrices, and input over a letter-bounded language, as well as to the injectivity problem which is undecidable for PFA over letter-bounded languages. We provide a constructive nondeterministic algorithm to solve the cutpoint isolation problem, which holds even when the PFA is exponentially ambiguous. We also show that the problem is at least NP-hard and use our decision procedure to solve several related problems. This paper was published in the CONCUR 2020 proceedings.

On Polynomial Recursive Sequences
Michaël Cadilhac, Filip Mazowiecki, Charles Paperman, Michał Pilipczuk, and Géraud Sénizergues
Abstract: We study the expressive power of polynomial recursive sequences, a nonlinear extension of the well-known class of linear recursive sequences. These sequences arise naturally in the study of nonlinear extensions of weighted automata, where (non)expressiveness results translate to class separations. A typical example of a polynomial recursive sequence is $b_n = n!$. Our main result is that the sequence $u_n = n^n$ is not polynomial recursive. This work was published in the proceedings of ICALP 2020.

The Complexity of Reachability in Affine Vector Addition Systems with States
Mikhail Raskin and Michael Blondin
Abstract: Vector addition systems with states (VASS) are widely used for the formal verification of concurrent systems. Given their tremendous computational complexity, practical approaches have relied on techniques such as reachability relaxations, e.g., allowing for negative intermediate counter values. It is natural to question their feasibility for VASS enriched with primitives that typically translate into undecidability. Spurred by this concern, we pinpoint the complexity of integer relaxations w.r.t. arbitrary classes of affine operations. More specifically, we provide a trichotomy on the complexity of integer reachability in VASS extended with affine operations (affine VASS). Namely, we show that it is NP-complete for VASS with resets, PSPACE-complete for VASS with (pseudo-)transfers and VASS with (pseudo-)copies, and undecidable for any other class. We further present a dichotomy for standard reachability in affine VASS: it is decidable for VASS with permutations, and undecidable for any other class. This yields a complete and unified complexity landscape of reachability in affine VASS. This work has previously appeared in the proceedings of LICS 2020.

Additionally, we present our ongoing work on the possible complexity of reachability and integer reachability in specific affine VASS. We obtain for every nontrivial computable predicate p a corresponding A-VASS such that its integer reachability and reachability for that VASS are equivalent to p under 1-1 polynomial reductions. In the other words, unlike the case matrix classes specific instances can have virtually arbitrary complexity of reachability and integer reachability relations.

An Approach to Regular Separability in Vector Addition Systems
Wojciech Czerwiński and Georg Zetzsche
Abstract: We study the problem of regular separability of languages of vector addition systems with states (VASS). It asks whether for two given VASS languages K and L, there exists a regular language R that includes K and is disjoint from L. While decidability of the problem in full generality remains an open question, there are several subclasses for which decidability has been shown: It is decidable for (i) one-dimensional VASS, (ii) VASS coverability languages, (iii) languages of integer VASS, and (iv) commutative VASS languages. We propose a general approach to deciding regular separability. We use it to decide regular separability of an arbitrary VASS language from any language in the classes (i), (ii), and (iii). This generalizes all previous results, including (iv). This paper was published in the LICS 2020 proceedings.

So overall, the conference program consisted of five invited talks, eight presentations of contributed papers, and eight informal presentations in the area of reachability problems stretching from results on fundamental questions in mathematics and computer science to efficient solutions of practical problems.

It is a pleasure to thank the team behind the EasyChair system and the Lecture Notes in Computer Science team at Springer, who together made the production of this volume possible in time for the conference. Finally, we thank all the authors and invited speakers for their high-quality contributions, and the participants for making RP 2020 a success. We are also very grateful to Alfred Hofmann for the continuous support of the event in the last decade, to the Research Institute on the Foundations of Computer Science, and Springer for their financial sponsorship.

October 2020

Sylvain Schmitz
Igor Potapov

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Abstracts of Invited Talks

On Decision Problems for Substitutions in Symbolic Dynamics

Valérie Berthé

Université de Paris, IRIF, CNRS, F-75013 Paris, France
berthe@irif.fr

Abstract. In this survey, we discuss decidability issues for symbolic dynamical systems generated by substitutions. Symbolic dynamical systems are discrete dynamical systems made of infinite sequences of symbols, with the shift acting on them. Substitutions are simple rules that replace letters by string of letters and allow the generation of infinite words. We focus here on symbolic dynamical systems that are generated by infinite compositions of substitutions, allowing to go beyond the case of the iteration of a single substitution. This is the so-called *S*-adic framework. Motivated by decidability and ergodic questions, we focus on questions dealing with the convergence of products of nonnegative matrices and associated Lyapounov exponents.

Keywords: Substitutions · Symbolic dynamics · Decidability · Lyapunov exponents · Primitive matrix · Perron–Frobenius theorem

This work was supported by the Agence Nationale de la Recherche through the project Codys (ANR-18-CE40-0007).

When are Finite Games Finite-Memory Determined?

Patricia Bouyer

Université Paris-Saclay, CNRS, ENS Paris-Saclay, France
bouyer@lsv.fr

Abstract. In their CONCUR 2005 paper [1], Gimbert and Zielonka gave a complete characterization of preference relations for which memoryless optimal strategies always exist in finite turn-based (two-player antagonistic) games. As an important consequence of their characterization, they furthermore establish that two-player games are memoryless determined for a given preference relation if and only if their one-player counterparts are both memoryless determined. This is of utmost practical importance, since it allows to infer memoryless determinacy of two-player games by proving memoryless determinacy of one-player games (which is likely to be much easier).

Though memoryless strategies are the simplest ones and therefore much more desirable, more complex objectives often require memory (finite or infinite). In most cases, ad-hoc proofs are designed to analyze the required memory, and despite some effort, no such elegant characterization had been proposed for memoryless optimal strategies earlier.

We present here a complete characterization of preference relations for which *arena-independent* finite-memory optimal strategies always exist, which generalizes the work by Gimbert and Zielonka to the finite-memory case. This result enjoys the same important practical corollary as the memoryless case, which allows one to deduce finite-memory determinacy results of two-player games from finite-memory determinacy of one-player games. This characterization strictly generalizes the Gimbert-Zielonka characterization for memoryless optimal strategies, and covers the case of arena-independent memory (for instance for multiple parity objectives or for lower- and upper-bounded energy objectives). The setting of arena-dependent finite memory (as needed by multiple lower-bounded energy objectives) requires further investigation.

This talk is based on joint work with Stéphane Le Roux, Youssouf Oualhadj, Mickael Randour, and Pierre Vandenhove. The technical paper is published in the proceedings of CONCUR 2020 [2].

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2. Bouyer, P., Roux, S.L., Oualhadj, Y., Randour, M., Vandenhove, P.: Games where you can play optimally with arena-independent finite memory. In: Proceedings of the 31st International Conference on Concurrency Theory (CONCUR 2020), LIPIcs, vol. 171, pp. 24:1–24:22 (2020). Schloss Dagstuhl - Leibniz-Zentrum für Informatik

Computing a Fixed Point of a Monotone Function, and Some Applications

Kousha Etessami

School of Informatics, The University of Edinburgh, UK
kousha@inf.ed.ac.uk

Abstract. The task of computing a fixed point of a monotone function arises in a variety of applications.

In this talk I shall describe some recent work in which we have studied the computational complexity of computing a (any) fixed point of a given monotone function that maps a finite d-dimensional grid lattice with sides of length $N = 2^n$ to itself, where the monotone function is presented succinctly via a boolean circuit with $d \cdot n$ input gates and $d \cdot n$ output gates. The underlying ordering, $\leq$, of this lattice is the standard coordinate-wise partial order on d-dimensional vectors in $[N]^d$. By Tarski's theorem, a function $f : [N]^d \rightarrow [N]^d$ always has a fixed point if it is monotone, or else it has a pair $x, y \in [N]^d$ that witness non-monotonicity, meaning where $x \leq y$ but $f(x) \nleq f(y)$. We refer to the corresponding total search problem of either finding a fixed point or finding a witness pair for non-monotonicity, given such a succinctly presented function $f : [N]^d \rightarrow [N]^d$, as the `Tarski` problem.

It turns out that `Tarski` subsumes a number of important problems, including some prominent equilibrium computation problems. In particular, we showed that computing the value of Condon's turn-based simple stochastic (reachability) games, as well as the more general problem of computing, within the given desired accuracy $\epsilon > 0$, the value of Shapley's original stochastic games is reducible to `Tarski`. We showed that `Tarski` is contained in both the total search complexity classes PLS and PPAD. Many questions remain open. I will discuss some of them.

(This talk describes joint work with C. Papadimitriou, A. Rubinstein, and M. Yannakakis, that appeared in the ITCS 2020 proceedings.)

Games with Full, Longitudinal, and Transverse Observability

Orna Kupferman

School of Computer Science and Engineering, The Hebrew University, Israel

Abstract. Design and control of multi-agent systems correspond to the synthesis of winning strategies in games that model the interaction between the agents. In games with *full observability*, the strategies of players depend on the full history of the play. In games with partial observability, strategies depend only on observable components of the history. We survey two approaches to partial observability in two-player turn-based games with behavioral winning conditions. The first is the traditional *longitudinal observability*, where in all vertices, the players observe the assignment only to an observable subset of the atomic propositions. The second is the recently studied *transverse observability*, where players observe the assignment to all the atomic propositions, but only in vertices they own.

O. Kupferman—Supported in part by the Israel Science Foundation, grant No. 2357/19.

Word Equations: From Theory to Practice

Dirk Nowotka

Kiel University, Germany

The existential theory of word equations has been of considerable interest for quite some time. Popularized during the 60's in an attempt to solve Hilbert's 10th problem, it was only shown in 1977 that the theory is decidable by Makanin's seminal work. Since then a large body of work has emerged about solvability, compactness, and complexity questions of word equations. Until today, however, the theory is not fully understood. For example, questions about the membership of solving word equations in NP or the decidability of the existential theory of word equations with length predicate are still open. In recent years, however, the theory of word equations has also gained very practical interest. So called string solvers are becoming more and more interesting in software analysis and access control systems of cloud computing services.

We are going to survey the state of the art of the theory of word equations and sketch its role in practical applications in this talk.

Contents

Invited Papers

On Decision Problems for Substitutions in Symbolic Dynamics 3
Valérie Berthé

Games with Full, Longitudinal, and Transverse Observability 20
Orna Kupferman

Regular Papers

Reachability Set Generation Using Hybrid Relation Compatible Saturation . . . 37
Shruti Biswal and Andrew S. Miner

Case Study: Reachability and Scalability in a Unified Combat-Command-and-Control Model 52
Sergiy Bogomolov, Marcelo Forets, and Kostiantyn Potomkin

Qualitative Multi-objective Reachability for Ordered Branching MDPs 67
Kousha Etessami and Emanuel Martinov

Quantum-over-Classical Advantage in Solving Multiplayer Games 83
Dmitry Kravchenko, Kamil Khadiev, Danil Serov, and Ruslan Kapralov

Efficient Restrictions of Immediate Observation Petri Nets 99
Michael Raskin and Chana Weil-Kennedy

Binary Expression of Ancestors in the Collatz Graph 115
Tristan Stérin

The Collatz Process Embeds a Base Conversion Algorithm 131
Tristan Stérin and Damien Woods

The Complexity of the Label-Splitting-Problem for Flip-Flop-Nets 148
Ronny Tredup

Author Index 165