Department of Foundations of Computer Science

THEORETICAL COMPUTER SCIENCE

The research performed in the Department of Foundations of Computer Science lies in the intersection of algebra, logic and computer science. The main themes are automata and formal languages, tree automata and term rewriting, weighted tree automata, logics on words and trees, finite model theory, fixed point operators in computer science, and axiomatic questions.

I. ALGEBRA & LOGIC IN COMPUTER SCIENCE

SEMIRINGS AND SEMIMODULES

In [12], we introduced inductive *-semirings as a generalization of Kozen's Kleene algebras, We proved that inductive *-semirings are iteration semirings and they are closed under several algebraic constructions. In [10, 14, 15] we studied semiring-semimodule pairs equipped with a *- and $^\omega$-operation. We established several algebraic properties of these structures and studied several subclasses where the *- and $^\omega$-operations are defined using a partial order, a completely additive structure and/or an infinite product. We used these algebraic structures to give an abstract treatment of Büchi-automata and weighted Büchi-automata on infinite words. In [13], we applied these structures to context-free languages over ω-words. In [16], we defined algebraically complete semirings as an extension of inductive *-semirings. One of the most fundamental nontrivial normal form theorems for context-free languages is the Greibach normal form theorem. We established Greibach's normal form theorem in all algebraically complete semirings.

CATEGORICAL ALGEBRAS

In [3], we generalized the notion of partially ordered algebras to categorical algebras. An important result in partially ordered algebras that has many applications in Computer Science is that each ordered algebra can be completed into a continuous ordered algebra preserving all valid inequalities. We extended this result to categorical algebras and discussed several applications in Computer Science.

REGULAR WORDS

Regular words were introduced by Courcelle in the late 70's. His motivation came from recursive program schemes. They were subsequently studied by Thomas and Heilbrunner. Courcelle raised several important problems regarding the equational axiomatization of regular words and the decidability of the equational theory. Courcelle's questions for axiomatization were completely solved in [1, 2]. We also gave a P-time algorithm to decide the equational theory. This greatly improves an earlier algorithm of Thomas with no explicit upper bound for its complexity.

AXIOMATIC THEORY OF AUTOMATA

In [11], we gave an introduction to the axiomatic theory of automata and languages developed earlier by Conway, Bloom, Ésik and Kuich.

LOGIC ON WORDS

Linear temporal logic has the same expressive power as aperiodic automata. In order to be able to express modular counting and other properties of words, Wolper introduced Extended Linear Temporal Logic. In [7], we bridged Wolper's logic and the Krohn-Rhodes decomposition theory of finite automata and gave an algebraic characterization of Wolper's logic.

LOGIC ON TREES

Temporal logics can be classified into linear time and branching time logics. The latter logics can be viewed as logics on trees. Important branching time logics are CTL (Computational Tree Logic) and CTL*. In both logics, one can define only regular properties. However, it is an open problem to give a decidable characterization of those regular properties (given by a finite tree automaton) definable in these logics. An algebraic approach to deal with this and related problems in formal logic has been developed in the papers [4–6, 8, 9] using pseudovarieties of finite algebras and the cascade product (wreath product). The method developed in these papers reduces the characterization of the expressive power to the membership problem in pseudovarieties of finite algebras.

ACKNOWLEDGEMENTS

The above research has been supported by the grants 53öu1 and 60öu12 of the Austrian-Hungarian Action Found, the grant T046686 of the National Foundation of Hungary for Scientific Research (OTKA), and the ESF Research Network AUTOMATHA.

REFERENCES

[1] S. L. Bloom and Z. Ésik. Axiomatizing omega and omega-op power on words, *Theoretical Informatics and Applications*, 38(2004), 3–18.

[2] S. L. Bloom and Z. Ésik. The equational theory of regular words, *Information and Computation*, 197(2005), 55–89.

[3] S. L. Bloom and Z. Ésik. Completing Categorical Algebras, *Proc. Fourth IFIP Conf. Theoretical Computer Science TCS-2006*, Springer, 2006, 231–250.

[4] Z. Ésik. An algebraic characterization of the expressive power of temporal logics on finite trees, Part 1, *Proc. 1st International Conference on Algebraic Informatics*, Aristotle University of Thessaloniki, 2005, 53–78.

[5] Z. Ésik. An algebraic characterization of the expressive power of temporal logics on finite trees, Part 2, *Proc. 1st International Conference on Algebraic Informatics*, Aristotle University of Thessaloniki, 2005, 79–100.

[6] Z. Ésik. An algebraic characterization of the expressive power of temporal logics on finite trees, Part 3, *Proc. 1st International Conference on Algebraic Informatics*, Aristotle University of Thessaloniki, 2005, 101–110.

[7] Z. Ésik. A note on Wolper's logic, *Proc. Workshop on Semigroups and Automata*, Lisboa, 2005, electronic.

[8] Z. Ésik. Characterizing CTL-like Logics on Finite Trees, *Theoretical Computer Science*, 356(2006), 136–152.

[9] Z. Ésik. Cascade Products and Temporal Logics on Finite Trees, *Electronic Notes in Theoretical Computer Science*, 162(2006), 163–166.

[10] Z. Ésik and W. Kuich. An algebraic generalization of omega-regular languages, *Proc. MFCS 04*, LNCS 3153, Springer, 2004, 648–659.

[11] Z. Ésik and W. Kuich. Equational Axioms for a Theory of Automata, *Formal Languages and Applications, Studies in Fuzziness and Soft Computing 148*, Carlos Martin-Vide, Victor Mitrana, Gheorghe Paun (Eds.), Springer, 2004, 183–196.

[12] Z. Ésik and W. Kuich. Inductive *-semirings, *Theoretical Computer Science*, 324(2004), 3–33.

[13] Z. Ésik and W. Kuich. A semiring-semimodule generalization of ω-context-free languages, *Theory is Forever*, LNCS 3113, Springer, 2004, 68–80.

[14] Z. Ésik and W. Kuich. A semiring-semimodule generalization of ω-regular languages, Part 1, *J. Automata, languages, and Combinatorics*, 10(2005), 203–242.

[15] Z. Ésik and W. Kuich. A semiring-semimodule generalization of ω-regular languages, Part 2, *J. Automata, languages, and Combinatorics*, 10(2005), 243–264.

[16] Z. Ésik, H. Leiss. Algebraically complete semirings and Greibach normal form, *Annals of Pure and Applied Logic*, 103(2005), 173-203.

II. AUTOMATA AND FORMAL LANGUAGES

WEIGHTED TREE AUTOMATA

In [1], we proved a general Kleene theorem applicable to weighted tree automata and formal power series over trees, finite or infinite. In [5] we gave a survey of results on weighted tree automata and tree transducers. In [4], we studied fuzzy subsets of algebras including algebras of trees and established a triple equivalence between equational, rational and recognizable fuzzy sets.

In [2] we showed that the cost-finiteness of tree automata with costs over finitely factorizing and monotonic semirings is decidable. We showed that it is also decidable whether a tree automaton with costs over a finitely factorizing, monotonic, and naturally ordered semiring is bounded with respect to the natural order.

In [18], we compared the classes of tree series which are recognizable by (a) multilinear mappings over some finite dimensional K-vector space, where K is a field, (b) K-Σ-tree automata, where K is a commutative semiring, (c) weighted tree automata over K, where K is a semiring, (d) finite, polynomial tree automata over K, where K is a commutative and continuous semiring, (e) polynomially-weighted tree automata, where K is a semiring, and (f) weighted tree automata over M-monoids.

TREE SERIES TRANSDUCERS

The first definition of the semantics of a tree series transducer, called algebraic semantics, is based on a tree series substitution that does not take into account the number of the occurrences of the substitution variables. In [16] we introduced tree series transducers of which the semantics takes into account that number. We compared the computation power of the two models.

In [17] we defined a tree series transducer model with an operational style semantics and called this model weighted tree transducer. We showed that tree series transducers with algebraic semantics and weighted tree transducers are semantically equivalent.

In [11] we generalized the famous tree transducer hierarchy of J. Engelfriet for tree series transducers over commutative, idempotent and positive semirings.

ALGEBRAIC PROPERTIES OF REGULAR TREE LANGUAGES

In [3], we showed that regular tree languages can be axiomatized by a few simple equations and the least fixed point rule. This extends a result of Kozen from words to trees. In [8], we introduced a new algebraic framework for the study of varieties of tree languages in relation to logic.

MULTI BOTTOM-UP TREE TRANSDUCERS

In [12] we defined deterministic multi bottom-up tree transducers and showed that they are semantically equivalent with deterministic top-down tree transducers with regular look-ahead. Then in [13] we compared the computation power of linear deterministic multi bottom-up tree transducers and eight well-known classes of deterministic bottom-up and deterministic top-down tree transducers.

SHAPE PRESERVING TREE TRANSDUCERS

Shape-preserving tree transducers generalize length-preserving sequential machines. In [10] we showed that shape-preserving top-down tree transducers are equivalent to finite-state relabelings. Moreover, we proved that it is decidable if a top-down tree transducer is shape preserving. In [20] it was proved that shape-preserving bottom-up tree transducers are also equivalent to finite-state relabelings. The decidability of the shape-preserving property for bottom-up tree transducers was proved in [21].

PEBBLE TREE TRANSDUCERS

In [14, 15], we investigated pebble tree transducers and macro pebble tree transducers. We showed that the circularity problem and the strong circularity problem for pebble tree transducers is decidable and that the weak circularity problem for pebble macro tree transducers is decidable. Moreover, we proved several decomposition results for macro pebble tree transducers.

In [22], n-pebble tree-walking automata with alternation were defined. It was shown that tree languages recognized by these devices are exactly the regular tree languages. Then it was shown that the deterministic and noncircular pebble alternating tree-walking automata are strictly less powerful than their nondeterministic counterparts.

STORAGE-TO-TREE TRANSDUCERS

In [19] it was shown that the class of tree transformations induced by regular storage-to-tree transducers with positive look-ahead is equal to the composition of the class of transformations induced by regular storage-to-tree transducers with the class of linear homomorphisms. It was also proved that the classes of transformations induced by both IO and OI context-free-storage-to-tree transducers are closed under positive look-ahead and composition with linear homomorphisms.

TREE AUTOMATA AND TERM REWRITE SYSTEMS

In [27] several characterizations and decidability results were obtained for ground tree transformations and congruence relations induced by tree automata.

TERM REWRITE SYSTEMS PRESERVING RECOGNIZABILITY

Salomaa showed that linear monadic term rewrite systems effectively preserve recognizability. We [31] showed that there are finitely many descendants of any recognizable tree language L for all linear monadic term rewrite systems, and we gave these descendants through finitely many linear monadic term rewrite systems. We [29] showed that right-linear half-monadic term rewrite systems effectively preserve recognizability. Using this property, we [29] showed that termination and convergence are decidable properties for right-linear half-monadic term rewrite systems.

GROUND TERM REWRITING

We [28] showed that for any given finitely generated congruences ρ and τ over the term algebra, it is decidable if the intersection of ρ and τ is a finitely generated congruence. If the answer is yes, then we can effectively construct a finite relation U over ground terms such that the congruence closure of U is equal to the intersection of ρ and τ.

We [30] showed that for a given left-linear right-ground term rewrite system R it is decidable if there is a ground term rewrite system S such that the restriction of the rewriting relation of R to ground terms is equal to the rewriting relation of S. If the answer is yes, then one can effectively construct such a ground term rewrite system S.

HIGHER DIMENSIONAL AUTOMATA

In [6], we defined parenthesizing automata, that operates on higher dimensional words (i.e., on elements of free algebras with several independent associative operations). We have extended several basic results of the classical theory of automata to parenthesizing automata including the equivalence to algebraic recognizability and monadic-second order definability. In [7], we described infinite higher dimensional words in algebraic frameworks and gave graph-theoretic descriptions of them. Based on these results parenthesizing Büchi-automata was defined with generalization of the above mentioned classical results [24, 25]. In [23], it was shown that the classes of languages that can be accepted by parenthesizing automata with at most i pairs of parentheses form a strict hierarchy, for $i \geq 0$. The aim of [26] is to relate parenthesizing automata to the work of Hashiguchi, Ichihara and Jimbo on binoid languages.

OTHER

In [9] we gave a short introduction to tree transducers for those who just would like to get an insight into the field.

ACKNOWLEDGEMENTS

The above research has been supported by the grants 53öu1 and 60öu12 of the Austrian-Hungarian Action Found, the grants 36/2005 and 45/2002 of the Deutsche Akademische Austauch Dienst (DAAD) and the Hungarian Scholarship Committee (MÖB), the grants T046686 and T030084 of the National Foundation of Hungary for Scientific Research (OTKA), and a Széchenyi István Scholarship of the Hungarian Ministry of Education.

REFERENCES

[1] S. L. Bloom and Z. Ésik. An Extension Theorem with an Application to Formal Tree Series, *J. of Automata, Languages and Combinatorics* 8(2003), 145–185.

[2] B. Borchardt, Z. Fülöp, Z. Gazdag, and A. Maletti. Bounds for Tree Automata with Polynomial Costs, *J. of Automata, Languages and Combinatorics*, 10(2005), 107–157.

[3] Z. Ésik. Axiomatizing the equational theory of regular tree languages, *J. Logic and Algebraic Programming*, to appear.

[4] Z. Ésik and L. Gwangu. Fuzzy Tree Auotomata, *Fuzzy Sets and Systems*, to appear.

[5] Z. Ésik and W. Kuich. Formal Tree Series, *J. of Automata, Languages and Combinatorics* 8(2003), 219–285.

[6] Z. Ésik and Z. L. Németh. Higher dimensional automata, *J. of Automata, Languages and Combinatorics.*, 9(2004), 3–29.

[7] Z. Ésik and Z. L. Németh. Algebraic and graph-theoretic properties of infinite n-posets, *Theoretical Informatics and Applications*, 39(2005), 305–322.

[8] Z. Ésik and P. Weil. Algebraic recognizability of regular tree languages, *Theoretical Computer Science*, 340(2005), 291–321.

[9] Z. Fülöp. An Introduction to Tree Transducers, *Formal Methods in Computing* (Eds. M. Ferenczi, A. Pataricza and L. Rónyai), Akadémiai Kiadó Budapest, 2005, 199–258.

[10] Z. Fülöp and Zs. Gazdag. Shape Preserving Top-Down Tree Transducers, *Theoretical Computer Science*, 304(2003), 315–339.

[11] Z. Fülöp, Zs. Gazdag, and H. Vogler. Hierarchies of Tree Series Transformations, *Theoretical Computer Science*, 314(2004), 387–429.

[12] Z. Fülöp, A. Küehnemann, and H. Vogler. A bottom-up characterization of deterministic top-down tree transducers with regular look-ahead, *Information Processing Letters*, 91(2004), 57–67.

[13] Z. Fülöp, A. Küehnemann, and H. Vogler. Linear Deterministic Multi Bottom-up Tree Transducers, *Theoretical Computer Science*, 347(2005), 275–287.

[14] Z. Fülöp and L. Muzamel. Recent Results on Pebble Macro Tree Transducers, *Proc. of the 1st International Conference on Algebraic Informatics*, Thessaloniki, 2005, 281–284.

[15] Z. Fülöp and L. Muzamel. Circularity, Composition, and Decomposition Results for Pebble Macro Tree Transducers, *J. of Automata, Languages and Combinatorics*, to appear.

[16] Z. Fülöp and H. Vogler. Tree Series Transformations that Respect Copying, *Theory of Computing Systems*, 36(2003), 247–293.

[17] Z. Fülöp and H. Vogler. Weighted Tree Transducers, *J. of Automata, Languages and Combinatorics*, 9(2004), 31–54.

[18] Z. Fülöp and H. Vogler. A Comparison of Several Models of Weighted Tree Automata, Technical Report, Technical University of Dresden, Faculty of Informatics, TUD-FI06-08, 2006.

[19] T. Hornung and S. Vágvölgyi. Storage-to-tree transducers with look-ahead, *Theoretical Computer Science*, 329(2004), 115–158.

[20] Zs. Gazdag. Shape Preserving Bottom-up Tree Transducers, *J. of Automata, Languages and Combinatorics*, 10(2005), 483–534.

[21] Zs. Gazdag. Decidability of the Shape Preserving Property of Bottom-Up Tree Transducers, *International Journal of Foundations of Computer Science*, 17(2006), 395-413.

[22] L. Muzamel. Pebble Alternating Tree-Walking Automata and Their Recognizing Power, *Acta Cybernetica*, to appear.

[23] Z. L. Németh. A hierarchy theorem for regular languages over free bisemigroups, *Acta Cybernetica*, 16(2004), 567–577.

[24] Z. L. Németh. Automata on infinite biposets, *Proc. Automata and Formal Languages, 11th Int. Conf., AFL 2005*, Szeged, 2005, 213–226.

[25] Z. L. Németh. Automata on infinite biposets, *Acta Cybernetica*, 18(2006), 765–797.

[26] Z. L. Németh. On the regularity of binoid languages: A comparative approach, *Preproc. 1st International Conference on Language and Automata Theory and Applications, LATA 2007*, Tarragona, 2007, to appear.

[27] S. Vágvölgyi. On Ground Tree Transformations and Congruences Induced by Tree automata, *Theoretical Computer Science*, 304(2003), 449–459.

[28] S. Vágvölgyi. Intersection of Finitely Generated Congruences over Term Algebra, *Theoretical Computer Science*, 300(2003), 209–234.

[29] S. Vágvölgyi. Right-Linear Half-Monadic Term Rewrite Systems, *Theoretical Computer Science*, 309(2003), 195–211.

[30] S. Vágvölgyi. Term Rewriting Restricted to Ground Terms, *Theoretical Computer Science*, 302(2003), 135–165.

[31] S. Vágvölgyi. Descendants of a recognizable tree language for sets of linear monadic term rewrite rules, *Information Processing Letters*, 99(2006), 111-118.

OTHER ACTIVITIES

I. EDITED BOOKS

In the period 2003–3006, the members of the Department of Foundations of Computer Science edited or co-edited the following books and special journal issues.

1. AFL 05, Special Issue of Acta Cybernetica, Volume 17, Number 4, 2006.
2. Automata and Formal Languages, Special Issue of Theoretical Computer Science, Volume 366, Number 3, 2006.
3. Recent Advances in Formal Languages and Applications, Studies in Computational Intelligence 25, Springer-Verlag, 2006.
4. Computer Science Logic, Proceedings of CSL 2006, LNCS 4207, Springer-Verlag, 2006.
5. Automata and Formal Languages, Proceedings of the 11th International Conference, AFL 2005, Dobogókő, May 17–20, 2005.
6. Process Algebra, Special Issue of Theoretical Computer Science, Volume 335, Number 2-3, 2005.
7. Proceedings of the 4th Conference for PhD Students, CSCS 2004, Special Issue of Acta Cybernetica, Volume 17, Number 2, 2005.
8. Developments in Language Theory, DLT 2003, Special Issue of Theoretical Computer Science, Volume 327, Number 3, 2004.
9. Fixed Points in Computer Science 03, Warsaw, Special Issue of Theoretical Informatics and Applications, Volume 38, Number 4, 2004.
10. Fixed Points in Computer Science 02, Copenhagen, Special Issue of Theoretical Informatics and Applications, Volume 37, 271–391, 2003.
11. Process algebra: Open problems and future directions, PA'03, Bologna, Italy, July 21–25, 2003, BRICS Notes Series NS-03-3, 2003.
12. Developments in Language Theory, Proceedings of the 7th International Conference, DLT 2003, LNCS 2710, Springer, 2003.
13. Proceedings of the 3rd Conference for PhD Students, CSCS 2002, Special Issue of Acta Cybernetica, Volume 16, Number 2, 2003.

II. ORGANIZED CONFERENCES

In the period 2003–3006 the Department of Foundations of Computer Science has organized the following conferences and workshops:

1. Computer Science Logic, CSL 2006, Szeged, Hungary, September 25–29, 2006.
2. Logic and Combinatorics, Satellite Workshop of CSL 2006, Szeged, Hungary, September 23–24, 2006.
3. Algebraic Theory of Automata and Logic, Satellite Workshop of CSL 2006, Szeged, Hungary, September 30 and October 1, 2006.
4. Automata and Formal Languages, 11th International Conference, AFL 2005, Dobogókő, Hungary, May 17–20, 2005.
5. Developments in Language Theory, 7th International Conference, DLT 2003, Szeged, Hungary, July 7–11, 2003.