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Automata Theory: Infinite Computations

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Report on the Dagstuhl-Seminar

"Automata Theory: Infinite Computations"

(6.1.-10.1.1992)

Organizers: K. Compton (Ann Arbor), J.E. Pin (Paris), W. Thomas (Kiel)

The subject of the seminar, "infinite computations in automata theory", has developed into a very active field with a wide range of applications, including specification of finite state programs, efficient algorithms for program verification, decidability of logical theories, automata theoretic approaches to analysis and topology, and fractal geometry.

The response to the invitations was very positive: 37 scientists from 12 countries participated, which is about the maximum to be housed at Schloss Dagstuhl. The seminar started or refreshed contacts especially between Eastern and Western research groups; it was successful in joining the efforts to solve some of the fundamental problems in the theory, and helped to support promising new developments.

The program of talks is presented here in five sections:

- Automata and infinite sequences
- Automata on infinite traces
- Tree languages, tree automata, and infinite games
- Logical aspects
- Combinatorial aspects

In the first section, contributions on finite automata accepting or generating infinite sequences are collected. This includes new results on classical problems, like the complementation problem for ω-automata (N. Klarlund), the introduction of appropriate syntactic congruences (B. Le Saee), and the extension of semigroups by infinite products (R.R. Redziejowski). The subject of multiplicities (measures for the range of different computations on given inputs) was addressed in the talks of D. Perrin as well as J. Karhumäki (who applied it to introduce a new way of computing real functions by finite automata). Other contributions were concerned with the class of locally testable ω-languages (Th. Wilke), with relations defined by two tape ω-automata (Ch. Frougny), and with a unified framework for specifying and verifying programs using recursive automata on ω-sequenees (L. Staiger).

An interesting application of infinite computations in automata theory is the analysis of concurrent (and usually nonterminating) programs. A well developed theory for modelling concurrency is that of "Mazurkiewicz traces", in which certain partial orders (instead of words) are used as representations of computations. The recent development of a theory combining both features ("automata on infinite traces") was presented in three contributions (by A. Petit, P. Gastin, and V. Diekert).

A central subject of the seminar was the famous result of M.O. Rabin on complementation for finite automata on infinite trees. The special role of Rabin's theorem rests on several facts. First, it makes possible an automata theoretic treatment of logical systems (including proofs of decidability), in particular for monadic second-order theories and logics of programs. Secondly, its proof is tightly connected with the existence of winning strategies in "infinite games", a topic which recently attracts much attention in the study of nonterminating reactive systems. A third aspect is the intriguing difficulty of the proof of Rabin's theorem, which has motivated several approaches for simplification. New results in this subject were presented in four lectures during the seminar: by E.A. Emerson, A.W. Mostowski, P.E. Schupp, and S. Zeitman. In an additional evening session Paul Schupp gave a detailed exposition of his proof of Rabin's theorem. Two further contributions treated alternative and refined versions of Rabin tree automaton definability, namely definability of tree properties in fixed point calculi (D. Niwinski) and by restricted acceptance conditions for tree automata (J. Skurczynski).

Since about thirty years, an important application of finite automata has been their use in the study of monadic second-order theories. These and related logical aspects were treated in talks collected in the fourth section below. A.L. Semenov and An. A. Muchnik gave a survey of Russian work on this subject, concerning extensions of Büchi's successor arithmetic and a strengthening of Rabin's decidability result for the monadic theory of the infinite binary tree. B. Courcelle and G. Sénizergues showed results on monadic second-order logic over graphs (in particular, on definable graph transformations, and on graphs determined by automatic groups). Logical definability in connection with limit laws in model theory and with problems of circuit complexity were presented by K. Compton and H. Straubing.

The final section summarizes lectures which are devoted to more combinatorial questions (in this case not necessarily applied to infinite objects). The subjects here were decidability and complexity results on tiling pictures with given dominoes (D. Beauquier), the invertibility of automaton definable functions (C. Choffrut), and new schemes for language generation motivated by mechanisms of DNA splicing (T. Head).

The talks were supplemented by lively discussions, joint work in small groups, and three long night sessions: On Tuesday evening, A. Muchnik presented his extension of the Shelah-Stupp Theorem (showing that the tree unravelling of a structure has a decidable monadic theory if the given structure has). On Wednesday, H. Straubing explained his reduction of general first-order definitions of regular word sets to first-

order definitions with modulo counting predicates only. P. Schupp presented on Thursday night his proof on simulation of alternating automata by nondeterministic tree automata, thus giving a simplified proof of Rabin's theorem.

Summing up, the meeting made possible a very productive exchange of ideas and results; it will stimulate the research of those who participated and already has led to the solution of open problems. The friendly atmosphere in the house, the most efficient work of the secretary team and last not least the perfect kitchen were appreciated very much. In the name of the participants, the organizers would like to thank the staff for their efforts in making the stay at Schloss Dagstuhl so pleasant and fruitful.

K. Compton
J.E. Pin
W. Thomas

Abstracts of Talks

Definability in Weak Monadic Second-Order Logic of Some Infinite Graphs

G. Sénizergues (Bordeaux)

We prove the following result, which is a partial solution to a conjecture of B. Courcelle [stated in ICALP 89]:

Let G be an equational 1-graph such that
(1) G has a spanning tree of finite degree
(2) for every pair of vertices (v,v') there are only finitely many edges
then G is definable in weak monadic second-order logic.

The main ideas of the proof are:

- a notion of automatic graph (which is a natural extension of that of automatic group, defined by [Cannon-Epstein-Holt-Paterson-Thurston, Research report of Warwick's university])
- such graphs are definable by first-order "colored" formula
- each graph G fulfilling (1), (2) is the result of a "half-turn-relabelling" of some automatic graph.

Automata on Infinite Objects, Monadic Theories, and Complexity

A. Muchnik, A.L. Semenov (Moscow)

A survey of results obtained by the Mathematical Logic and Computer Science Group at the Institute of New Technologies (Moscow and St. Petersburg) is presented. The results belong to Konstantin Gorbunov, Andrei Muchnik, Alexei Semenow, Anatol' Slisenko, Sergey Soprunov. Some of the results were proved in parallel with Western research.

Major topics are the following. Conditions of decidability for the monadic theory of a structure $<\omega; \leq, P>$, where P is an unary predicate (or a tuple of unary predicates). Almost periodic ω-words P and the corresponding monadic theories. Double infinite words. The Muchnik proof for Rabin Theorem. A generalization of Shelah-Stupp Theorem by adding the unary predicate of equality of two last symbols in a sequence. The uniformization problem in different monadic theories. The complexity of complementation and determinization operations. Arbitrary graphs, their combinatorial properties, new bounds, connections with complexity for finite graphs and decidability for infinite. An example of predicate on tree for which the weak monadic theory is decidable and the monadic theory is undecidable. Non-existence of a maximal decidable weak monadic theory.

Some of the results were discussed in Semenov's paper at MFCS'84 (Springer Lecture Notes in Computer Science) and some were proved in Semenov's, Math. USSR Izvestija, 1984.

Circuit Complexity, Finite Automata and Generalized First-Order Logic

H. Straubing (Boston)

Let FO[<] denote the class of languages in A^* defined by first-order sentences in which all the atomic formulas are of the form $x<y$ and $Q_a x$ (meaning that the symbol in position x is a). It is well-known that FO[<] is exactly the class of star-free, or aperiodic, regular languages. (McNaughton)

We can generalize this in two ways: introduce new <u>modular quantifiers</u>: $\exists_r^q x\, \varphi(x)$ means the number of positions such that $\varphi(x)$ is congruent to r modulo q. Alternatively, introduce new <u>numerical predicates</u>: these are atomic formulas, such as $x<y$, that do not depend on which input symbol appears in the given positions. Extending the above notation, letter $\mathcal{N}$ denotes the class of all numerical predicates:

<u>Conjecture</u>

$$(FO+\{\exists_s^q : 0\leq s<q\})[\mathcal{N}] \cap \text{Regular languages} =$$
$$(FO+\{\exists_s^q : 0\leq s<q\})[<,\{x \equiv 0 (\text{mod } r) : r>0\}]$$

This conjecture is closely connected to problems concerning the complexity of constant-depth circuits. It is known to be true when $q = 1$ or q is a prime power. It is equivalent to the conjecture that the circuit complexity class ACC is strictly contained in NC^1. The conjecture has been proved in a special case: Let $\mathcal{M}$ denote the class of <u>unary</u> numerical predicates. Then

<u>Theorem</u>

$$(FO+\{\exists_s^q : 0\leq s<q\})[<,\mathcal{M}] \cap \text{Regular languages} =$$
$$(FO+\{\exists_s^q : 0\leq s<q\})[<,\{x \equiv 0 (\text{mod } r) : r>0\}].$$