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Automata Theory: Infinite Computations

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Gesellschafter: Universität des Saarlandes,
Universität Kaiserslautern,
Universität Karlsruhe,
Gesellschaft für Informatik e.V., Bonn

Träger: Die Bundesländer Saarland und Rheinland Pfalz.

Bezugsadresse: Geschäftsstelle Schloß Dagstuhl
Informatik, Bau 36
Universität des Saarlandes
W - 6600 Saarbrücken
Germany
Tel.: +49 -681 - 302 - 4396
Fax: +49 -681 - 302 - 4397
e-mail: office@dag.uni-sb.de

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 Saec), 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-sequences (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

I. AUTOMATA AND INFINITE SEQUENCES

Rational ω-Relations. Application to the Representation of Real numbers

Ch. Frougny (Paris)

[joint work with J. Sakarovitch, Paris]

We consider rational ω-relations, i.e. relations of infinite words which are recognized by finite 2-automata (with the Büchi acceptance condition). We show that a rational ω-relation recognized by a finite 2-automaton with a bounded delay can be synchronized, that is, can be recognized by a letter-to-letter 2-automaton. We prove that a deterministic rational ω-relation is a countable intersection of open sets. The geography of the set of rational ω-relations is described as follows:

$$\begin{array}{ccccc} & & \omega\text{-DSynch}_2 & \subset & \omega\text{-DRat}_2 \\ & & \cap & & \cap \\ \omega\text{-CwRat}_2 & \subset & \omega\text{-Synch}_2 & \subset & \omega\text{-Rat}_2 \end{array}$$

The inclusions $\omega\text{-DRat}_2 \subset \omega\text{-Rat}_2$ and $\omega\text{-Synch}_2 \subset \omega\text{-Rat}_2$ are undecidable; but $\omega\text{-DSynch}_2 \subset \omega\text{-Synch}_2$ is decidable. We have $\omega\text{-DSynch}_2 = \omega\text{-Synch}_2 \cap \omega\text{-DRat}_2$. As an application, we consider the representation of real numbers in base β, where β is a real number >1. The normalization is the function which maps any β-representation of a number x onto the greedy one, called the β-expansion. We show that, if the normalization is a rational function, then it is synchronized. This allows to prove that the normalization in base β is rational if and only if the set of infinite words having value 0 in base β is recognizable by a finite automaton.

Finite Automata Computing Real Functions

J. Karhumäki (Turku)

[joint work with K. Culik II, Columbia, S.C., and
D. Derencourt, M. Latteux, A. Terlutte, Lille]

We introduce a new application of finite automata to compute real functions $[0,1] \rightarrow R$. This research is motivated by computer graphics, a need to generate pictures, and is closely related to the theory of rational formal power series. We use a nondeterministic automaton with multiplicities, R-Σ-automaton in terms of Eilenberg, to compute such a function as follows. A real x in [0,1] is identified with an ω-word in $\{0,1\}^\omega$, with its binary representation bin(x), and then the value of the function on x is the multiplicity of bin(x) determined by the considered automaton. In order to guarantee that such functions are always defined we restrict our considerations to so-called level automata which among other things do not allow any other loops than loops from a state into itself.

We prove among other things that

- such automata can compute all polynomials (in one or several unknowns), but cannot compute any other smooth functions, i.e. functions having all the derivatives;
- to compute a polynomial of degree n at least n+1 states are needed;
- there exists a four state automaton which computes a continuous function having no derivative at any point;
- given a level automaton there exists another one which computes the integral of the function determined by the first automaton;
- it is decidable whether an automaton defines a continuous or smooth function, as well as whether two such automata define the same function.

Progress Measures for Complementation of ω-Automata

N. Klarlund (Aarhus)

We discuss a new approach to the complementation problem for finite-state automata on infinite words. Instead of using usual combinatorial or algebraic properties of transition relations, we show that a graph-theoretic approach based on progress measures is a potent tool for complementing ω-automata.

We apply progress measures to the classical problem of complementing Büchi automata and obtain a simple, optimal method. Our technique also applies to Streett automata for which we also obtain an optimal method.

A Syntactic Approach to Deterministic ω-automata

B. Le Saec (Bordeaux)

[joint work with Do Long Van, I. Litovski]

We propose unified characterizations, by means of right congruence, to various classes of rational ω-language. A family of ω-languages which admit a unique minimal table transition ω-automaton is introduced: The prefix-recognizable ω-languages. The syntactic congruence of those ω-languages is equal to the cycle congruence of their minimal automaton. This cycle congruence is a new one we proposed for the ω-automata.

Multiplicities in ω-Automata

D. Perrin (Paris)

We propose to consider a Büchi automaton as an automaton with multiplicities in the arctic semiring $\mathcal{A} = \langle N \cup -\infty, \max, + \rangle$ in such a way that the multiplicity of a word w in A^+ is equal to the maximum of the number of final states on a path labeled w starting where appropriate.

This gives first, by restriction to the reduced arctic semiring $\mathcal{RA} = \langle \{-\infty,0,1\}, \max, + \rangle$ a matrix representation of the quotient of A^+ under the Büchi congruence. This may be more interesting in some cases than the usual embedding into the Schützenberger product of two copies of the ordinary transition monoid of the automaton.

Second, it is possible to associate with the automaton a new semigroup defined as follows: we first compute the (infinite) monoid M_1 of matrices in the arctic semiring. We take the closure M_2 of this monoid in the ω-arctic semiring obtained by adding a point at infinity ω to **N** as a limit of increasing sequences. We finally take the image M_3 of M_2 in the reduced ω-arctic semiring $\langle \{-\infty,0,1,\omega\}, \max,+ \rangle$. We propose to compute M_3 using a method identical to the algorithm of H. Leung (see I. Simon, MFCS 88). There remains to find a good interpretation of the coefficients of the elements of M_3.

Adding an Infinite Product to a Semigroup

R.R. Redziejowski (Lidingö)

A semigroup $(S,\cdot)$ is extended with an ω-argument operation Π: $S^N \to Q$ where Q is a certain set, possibly disjoint with S. The operation Π is required to satisfy three axioms, expressing generalized associativity compatible with the semigroup operation.

It follows from the axioms and the Ramsey lemma that for a finite S, Π can have only a finite number of distinct values, all reducible to the form se^{ω} where $s,e \in S$ and $e^2=e$.

Homomorphism and a unique free algebra are defined for the class of semigroups extended with the operation Π. The purpose of the construction is to express recognizability of ω-languages in a way analogous to that of finite-word languages (directly in terms of a homomorphism into a finite algebraic structure).

Recursive Automata on Infinite Words and the Verification of Concurrent Programs

L. Staiger (Siegen)

In 1987 Vardi presented a framework based on recursive automata that unifies a large number of trends in the area of specification and verification of concurrent programs.

Here the program and specification are considered as recursive automata P and S, respectively, which accept the sets of possible execution systems. In this talk we showed how several restrictions on the behaviour of the automata P and S, as their branching behaviour or the underlying alphabet, influence the complexity of the verification problem, which was shown to be Π^1_2-complete for arbitrary nondeterministic specifications S.

As a general method we used the description of the accepted languages of infinite words via the arithmetical hierarchy of languages of finite and infinite words.

Locally Threshold Testable ω-Languages and $F_\sigma \cap G_\delta$ - Sets

Th. Wilke (Kiel)

It is proved that a ω-language is weakly locally threshold testable with bound L for the length of counted factors if and only if it is locally threshold testable with the same parameter and belongs to the Borel class $F_\sigma \cap G_\delta$. As a consequence we obtain that it is decidable whether a formula in sequential calculus is equivalent to a first order formula with successor.

II. AUTOMATA ON INFINITE TRACES

Automata for Infinite Traces

A. Petit (Paris)

[joint work with P. Gastin]

Trace languages provide a very natural semantics for concurrent processes. In particular, the behaviours of finite state systems are described by recognizable trace languages, which form hence a basic family. For infinite traces, this family has been introduced by means of recognizing morphisms and characterized by co-rational expressions. Here, we study finite automata for recognizable trace languages. Diamond automata (i.e. automata on infinite traces) with classical acceptance conditions for infinite word paths do not necessarily accept closed languages. Therefore, a major issue addressed here is the definition of the notion of trace path and of the good class of (infinite) trace automata. By construction, such an automaton accepts always a recognizable trace language. Conversely, our second aim is to prove that Büchi trace automata characterize the family of recognizable languages of infinite traces.

Büchi Asynchronous Cellular Automata

P. Gastin (Paris)

[joint work with A. Petit]

Asynchronous automata, introduced by W. Zielonka, form a very important subclass of automata for finite traces. In this talk we extend these automata to infinite traces using a suitable Büchi-like acceptance condition. Next we prove that the class of language accepted by some Büchi asynchronous cellular automaton is exactly the family of recognizable languages of real traces. To this purpose, we give effective constructions for the union, the intersection, the concatenation and the infinite iteration of asynchronous automata.

Some Open Problems on Deterministic Automata for Infinite Traces

V. Diekert (Stuttgart)

[joint work with P. Gastin and A. Petit]

The talk addresses to the problem whether every recognizable language of infinite traces can be accepted by some deterministic automaton. In fact, the hope is that there will be an asynchronous automaton which is deterministic and has some local Muller-acceptance condition.

However, even the existence of a deterministic I-diamond automaton is open. The condition of being I-diamond is much weaker and demands only that $q \cdot ab = q \cdot ba$ for all states q and independent letters $a,b \in X$,$(a,b) \in I$. As a candidate of trace languages which are accepted by I-diamond-deterministic Büchi-automata we introduce trace limits. As a first result we show that these languages are recognizable.

III. TREE LANGUAGES, TREE AUTOMATA, AND INFINITE GAMES

Complexity of Tree Automata and Logics of Programs

E.A. Emerson (Austin)

[joint work with C.S. Jutla, IBM Watson]

There is an intimate relationship between finite state automata on infinite trees and temporal and modal logics of programs. The standard paradigm nowadays for testing satisfiability of branching time temporal logics is reduction to the nonemptiness problem for tree automata. We improve the complexity of testing nonemptiness of tree automata and of testing satisfiability for a number of significant temporal logics of programs.

We show that we can test nonemptiness of pairs (and complemented pairs) tree automata in time polynomial in the number of states and exponential in the number of pairs, while we also show the problem is NP-complete (coNP-complete, respectively) in general. This multiparameter analysis enables us to obtain exponentially improved, essentially tight bounds for a number of temporal logics of programs: CTL* is deterministic double exponential time complete, while PDL-Δ and the Mu-Calculus are deterministic exponential time complete.

We also show that the (full) Mu-calculus is expressively equivalent to pairs tree automata. Since the Mu-Calculus is syntactically and semantically closed under complementation, we obtain the complementation lemma for tree automata as an easy corollary.

We also believe that our techniques and results demonstrate the power of temporal logic and the Mu-Calculus for specifying and reasoning about automata and games.

Games with Forbidden Positions

A.W. Mostowski (Gdansk)

Games of infinite trees using the table of an alternating automaton [Muller, Schupp, TCS 54 (1987)] are investigated. The first player chooses a transition, then the second player chooses a direction (or, simultaneously with the first player, a transition from a dual table). For the investigated games some nodes are forbidden to enter in some states and the winning conditions are supposed to be strong Rabin chain conditions [Mostowski, TCS 83 (1991)].

The determinancy theorem for such games is proved and the winning strategies are described. They are, loosely speaking, iterations of typical max-min strategies and in a node depend only on the last state reached and on the future which is given by the subtree having a root in the node. Contrary to the strategies described by Gurevich and Harrington, Muchnik, and A. and V. Yakhnis they need no extra information from the past of the game (even recognizable by an automaton as in [Yakhnis, Yakhnis, Ann. Pure Appl. Logik 48 (1990)]. The paper is self contained and uses neither determination theorems for other games nor complementation lemma.

Problems in μ-Calculus

D. Niwinski (Warsaw)

Many phenomena of infinite computations can be adequately characterized by fixed point definitions, usually involving both least and greatest fixed point operators. We investigate definability of sets of infinite trees by fixed points, and compare it to other modes of definability, namely by automata and logics. Nice coincidences and correspondences can be seen, involving the concept of a "fixed point hierarchy" of alternation of least and greatest fixed point operators. However, a problem of infinity of this hierarchy, in the presence of intersection as a basic operation, remains still open and amounts to a problem if a hierarchy of Rabin indices for alternating automata is infinite. Another important problem concerning μ-calculus is that of characterizing the valid formulas in terms of some complete finitary proof system. It seems that application of infinite games (played on tableaux) may give some evidence here.

Simulating Alternating Automata by Nondeterministic Automata

P.E. Schupp (Urbana)

We give a new and simple proof that an alternating automaton M on infinite trees can be simulated by a nondeterministic automaton N. This gives a new proof of Rabin's and, simultaneously, of McNaughton's Theorem in the strong version due to Safra, and generalizes Safra's result. Let $|M|$ denote the number of states of M. If M uses the defined acceptence by one complemented pair (this condition includes Büchi and co-

Büchi) then $|N|$ is $2^{O(|M| \cdot \log|M|)}$. If M uses Muller acceptance, then $|N|$ is two exponentials in $|M|$.

In proving the result we consider, as is now usual, the acceptance of M as being defined by the existence of a winning strategy in an infinite game. In contrast with the arguments of Gurevich and Harrington and Muchnik this proof is not by induction or rank functions.

Automata on Trees with Weak Acceptance Conditions

J. Skurczynski (Gdansk)

We construct a weak SkS formula describing the set of infinite trees accepted by an automaton with weak Muller conditions. Making use of the theorem on infinity of a hierarchy of weak SkS formulas, we show that the weak Muller index can be arbitrarily great.

Unforgettable Forgetful Determinacy

S. Zeitman (Detroit)

Infinite games between two players have recently found application in computer science as models of nonterminating computations in which, for example, an operating system must interact with a potentially hostile environment. Natural specifications on such computations give rise to a class of games to which the Forgetful Determinacy Theorem of Yuri Gurevich and Leo Harrington apply. This theorem first appeared as part of a simpler proof of the most difficult part of Michael Rabin's proof that the monadic second-order theory of the infinite binary tree is decidable. An independent proof of Rabin's result was given by Andre Muchnik. The original proof of the Forgetful Determinacy Theorem was sketchy and became a source of frustration for many. J. Donald Monk presented an expanded and complete version of the proof as part of a seminar on Rabin's result and related topics. Recently, Alexander and Vladimir Yakhnis gave a proof that strenthened the theorem by providing more explicit strategies for the players. Still, there seems to be interest in a more compact proof to this much-used result, and this talk provides one. It should be stressed that the proof presented is conceptually the same as the one by Yakhnis and Yakhnis, although it is done in the framework of the original result, and it illuminates some notions involved by defining them in a related game which we call the "forgetful game".

IV. LOGICAL ASPECTS

A Monadic Second-Order Limit Law for Unary Functions

K. Compton (Roquencourt and Ann Arbor)

Let C be a class of structures, C_n be the structures in C with universe $\{0,...,n-1\}$, and, for a sentence φ, let $\mu_n(\varphi)$ be the fraction structures in C_n satisfying φ. We say that C has a limit law for a logic L if $\mu(\varphi) = \lim_{n\to\infty}\mu_n(\varphi)$ is defined for all sentences φ in L. We show that the class of unary functions has a limit law for monadic second-order logic.

The proof uses generating series techniques and a type of theorem known in classical analysis as a Tauberian theorem. The idea is that generating series enumerating classes of structures can be developed using ideas from the theory of N-rational series and the asymptotics of the coefficients of the series may than be obtained using a Tauberian theorem.

Finally, we note that many limit laws for finite random structures have analogues for infinite random structures. We pose the problem of finding an appropriate setting to investigate limit laws for infinite unary functions.

Monadic Second-Order Definability Properties of Infinite Graphs

B. Courcelle (Bordeaux)

Equational graphs can be characterized in several equivalent ways: (1) as initial solutions of systems of graph equations, (2) as graphs having regular tree-decompositions, (3) as graphs which are both definable in monadic-second order logic and have finite tree-width. Graphs definable (by monadic second-order formulas) in equational graphs are equational.

The talk has shown the important role of monadic second-order graph transductions in these results.

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>

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

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>

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

V. COMBINATORIAL ASPECTS

Games with Dominoes

D. Beauquier (Paris)

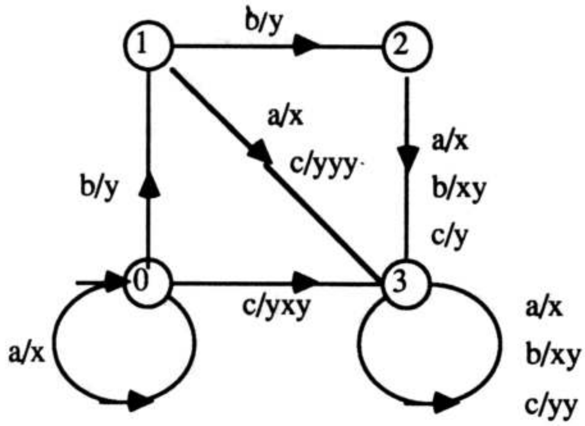
There exists a linear algorithm to decide whether a finite picture (union of unit squares) is tilable by dominoes. Secondly there is a sufficient condition for a picture without holes to decide whether it has no unique tiling by horizontal bars of some length $m \geq 2$, and vertical bars of length $n \geq 2$ (for dominoes the condition holds also for pictures with holes).

Thirdly, if a finite picture without holes admits a tiling T with bars h_m, v_n, it admits a unique tiling iff there is no subtiling of T covering the rectangle R(m,n) (for dominoes, the condition is available for pictures with holes).

Some Questions on Sequential Bijections Between Free Monoids

C. Choffrut (Paris)

Given two free finitely generated monoids A* and B*, a sequential function is a mapping realized by a deterministic transducer, i.e., by a finite deterministic automaton with input alphabet A and equipped with an output alphabet B. If A = {a,b,c} and B = {x,y}, then the following sequential transducer realizes a function f in which, for instance, f(cc) = yxyyy and f(abab) = xyxxy holds.



The question we raise originates from Eilenberg's textbook where an example is given of a sequential function defining a bijection from A* onto B* ("Automata, Languages and Machines", Vol. A, Academic Press, 1974, p. 305; the above deterministic transducer also realizes a sequential bijection). In Eilenberg's example, the condition Card(A) = 3 and Card(B) = 2 holds.

More generally, we prove that a necessary and sufficient condition for a sequential bijection to exist is: Card(A)≥Card(B). Our construction makes use of complete suffix codes of the cardinality of A, but we ignore whether or not this is necessary (in the current example we have the suffix code {x,xy,yy}). A further step would be to construct all sequential bijections. Yet, though we have some clues of how to get new examples from old ones, we ignore what the general method could be. It is not difficult to see that the problem reduces to obtaining the characteristic series of B* as the solution of certain types of linear systems of equations where the unknowns are rational series in the indeterminates B with coefficients in the natural numbers **N**. For instance the current example gives rise to the following system where $L_0 = B^*$. Intuitively L_i, $i = 0,\dots,3$, represents all the outputs obtained when starting to read an input in state i:

$$
\begin{aligned}
L_0 &= 1 + xL_0 + yL_1 + yxyL_3\\
L_1 &= 1 + yL_2 + (x+yyy)L_3\\
L_2 &= 1 + (x+xy+y)L_3\\
L_3 &= 1 + (x+xy+yy)L_3
\end{aligned}
$$

The idea would be to transform this system while still preserving B* as a solution.

Splicing Schemes and DNA

T. Head (Binghamton)

Splicing systems were introduced by the speaker (Bull. Math. Biology (1987) 737-759) as language generating devices that imitate the action of sets or restriction enzymes and a ligase on double stranded DNA molecules. The existing literature on these formal systems is summarized. This previous work has been concerned only with strings as models of linear molecules. However, DNA molecules occur naturally in both linear and circular form. It is now proposed that splicing theory deal with both linear and circular strings and their interactions. New problems are proposed which the speaker hopes members of the audience or their students will solve. An extended version of this talk is available on request from the speaker.

Dagstuhl-Seminar 9202 Participants

Daniele **Beauquier**
LITP
Université Paris VII
75252 Paris Cedex 05
France
beauquier@litp.ibp.fr
tel.: +33 46 60 55 15

Véronique **Bruyère**
Université de Mons-Hainaut
Faculté des Sciences
15 Avenue Maistriau
7000 Mons
Belgium
sbruyere@rm1.vmh.ac.be
tel.: +32-65-37 3444

Christian **Choffrut**
LITP
Université Paris VII
2 Place Jussieu
75252 Paris Cedex 05
France
cc@litp.ibp.fr

Kevin **Compton**
INRIA
Domaine de Voluceau
Rocquencourt
BP 105
78153 Le Chesnay Cedex
France
compton@margaux.inria.fr
tel.: +33 1 39 63 56 88

Bruno **Courcelle**
Université Bordeaux - I
Laboratoire Bordelais de
Recherche en Informatique
351 Cours de la Liberation
33405 Talence Cedex
France
courcell@geocub.greco-prog.fr
tel.: +33 56 84 60 86

Max **Dauchet**
Université de Lille 1
LIFL
Batiment M 3
59655 Villeneuve d'Ascq Cedex
France
dauchet@lifl.lifl.fr
tel.: +33-20 43 45 88

Volker **Diekert**
Universität Stuttgart
Institut für Informatik
Breitwiesenstraße 20-22
W-7000 Stuttgart 80
Germany
diekert@informatik.uni-stuttgart.de
tel.: +49-711 78 16 329

Werner **Ebinger**
Universität Stuttgart
Institut für Informatik
Breitwiesenstraße 20-22
W-7000 Stuttgart 80
Germany
ebinger@informatik-uni-stuttgart.de
tel.: +49-711 78 16 401

E. Allen **Emerson**
University of Texas at Austin
Department of Computer Sciences
Taylor Hall 2.124
Austin TX 78712-1188
USA
emerson@cs.utexas.edu
tel.: +1 512 471 9537

Christiane **Frougny**
LITP
Institut Blaise Pascal
4 Place Jussieu
75252 Paris Cedex 05
France
frougny@litp.ibp.fr
tel.: +33 1 44 27 70 95

Paul **Gastin**
LITP - IBP
Université Paris VI
4 Place Jussieu
75252 Paris Cedex 05
France
gastin@litp.ibp.fr
tel.: +33 1 44 27 53 91

Leucio **Guerra**
LITP
Université Paris VII
2 Place Jussieu
75252 Paris Cedex 05
France

Thomas J. **Head**
SUNY at Binghamton
Dept. of Mathematical Sciences
Binghamton NY 13902
USA
tjhead@bingvaxu.cc.binghamton.edu
tel.: +1 607 777 21 47

Hendrik Jan **Hoogeboom**
University of Leiden
Department of Computer Science
P.O. Box 9512

NL-2300 RA **Leiden**
The Netherlands
hjh@rulwinw.LeidenUniv.nl
tel.: +31 71 27 7062 / 7065 (Secr.)

Juhani **Karhumäki**
University of Turku
Dept. of Mathematics
20500 Turku 50
Finland
karhumak@utu.cs.fi
tel.: +358-21-6335613

Nils **Klarlund**
University of Aarhus
Dept. of Computer Science
Ny Munkegade 116
8000 Aarhus C
Denmark
klarlund@daimi.aau.dk

Michel **Latteux**
Université de Lille 1
LIFL
Batiment M 3
59655 Villeneuve d'Ascq Cedex
France
latteux@lifl.lifl.fr
tel.: +33 20 43 42 67

Bertrand **Le Saec**
Université de Bordeaux I
Laboratoire Bordelais de
Recherche en Informatique
351 Cours de la Liberation
33405 Talence Cedex
France
tel.: +33 56 84 65 29

Igor **Litovski**
Université de Bordeaux I
Departement d'Informatique
351 Cours de la Libération
33405 Talence Cedex
France
lito@geocub.greco-prog.fr

A.W. **Mostowski**
Uniwersytet Gdanski
Institut Matematyki
Wita Stwosza 57
80-952 Gdansk
Poland
tel.: +48-58-522212

Andrej A. **Muchnik**
Institute of New Technologies
Kirovogradskaya ul. 11
Moscow 113587
Russia
postmaster@globlab.msk.su
tel.: +7 095 311 4427

Damian **Niwinski**
University of Warsaw
Inst. of Mathematics
U1. Banacha 2
00-913 Warsaw 59
Poland
NIWINSKI@PLEARN.PL
tel.: +48 22 22 10 50 (home)

Dominique **Perrin**
LITP
Université Paris VII
2 Place Jussieu
75252 Paris Cedex 05
France
dp@litp.ibp.fr
tel.: +33 1 44 27 28 45

Antoine **Petit**
Université Paris Sud
Laboratoire de Recherche en Informatique
Bat 490
91405 Orsay Cedex
France
petit@lri.lri.fr
tel.: +33 1 69 41 66 09

Jean-Eric **Pin**
LITP
Université Paris VI
4 Place Jussieu
75252 Paris Cedex 05
France
pin@litp.ibp.fr

Roman R. **Redziejowski**
IBM Nordic Laboratory
P.O. Box 962
18109 Lidingö
Sweden
tel.: +46 8 636 6263

Antonio **Restivo**
Universita degli Studi di Palermo
Dipt. di Matematica ed Applicazioni
Via Archirafi 34
90123 Palermo
Italy
restivo@ipamat.cres.it
tel.: +39 91 60 40 307

Paul E. **Schupp**
University of Illinois
Dept. of Mathematics
273 Altgeld Hall
1409 West Green Street
Urbana IL 61801
USA
schupp@symcom.math.uiuc.edu
tel.: +1 217 333 1610 / 3350

Alexei L. **Semenov**
Institute of New Technologies
Kirovogradskaya ul. 11
Moscow 113587
Russia
postmaster@globlab.msk.su
tel.: +7 095 315 08 08

Geraud **Senizergues**
University of Warwick (till July 1992)
Mathematics Institute
Coventry CV4 7AL
Great Britain
ges@maths.warwick.ac.uk

Jerzy **Skurczynski**
Uniwersytet Gdanski
Institut Matematyki
Wita Stwosza 57
80-952 Gdansk
Poland
tel.: +48 58 41 49 14

Ludwig **Staiger**
Universität - GH - Siegen
Programmiersprachen
Postfach 10 12 40
5900 Siegen
Germany
tel.: +49-2238 51 580 (home)

Howard **Straubing**
Boston College
Dept. of Computer Science
Chestnut Hill MA 02167
USA
straubin@beuxs1.bc.edu
tel.: +1 617 552 39 77

Wolfgang **Thomas**
Universität Kiel
Institut für Informatik
Olshausenstraße 40
W-2300 Kiel 1
Germany
wt@informatik.uni-kiel.dbp.de
tel.: +49-431 880 44 80

Thomas **Wilke**
Universität Kiel
Institut für Informatik
Olshausenstraße 40
W-2300 Kiel 1
Germany
tw@informatik.uni-kiel.dbp.de
tel.: +49-431 880 46 62

Suzanne **Zeitman**
Wayne State University
Department of Computer Science
Detroit Michigan 48202
USA
sze@cs.wayne.edu

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