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MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 14/1994

Endliche Modelltheorie

27.3 bis 2.4.1994

Die Tagung fand unter Leitung von H.-D. Ebbinghaus (Freiburg), J. Flum (Freiburg) und Y. Gurevich (Ann Arbor) statt.

Die Endliche Modelltheorie bildet ein Grenzgebiet zwischen der mathematischen Logik und der theoretischen Informatik. Im Mittelpunkt des Interesses standen hier mathematische Fragen.

Ein zentraler Bereich der Endlichen Modelltheorie ist die Untersuchung der Ausdrucksstärke verschiedener Erweiterungslogiken der Logik der ersten Stufe im Bereich endlicher Strukturen. In mehreren Vorträgen wurden Fragmente der Logik der zweiten Stufe, insbesondere die monadische zweite Stufe, Fixpunktlogiken und Erweiterungen der ersten Stufe um verallgemeinerte Quantoren beleuchtet.

Diskutiert wurden weiterhin 0-1-Gesetze, ein interessantes Phänomen, das nur im Bereich endlicher Modelle auftritt und auch in der Theorie der Zufallsgraphen eine Rolle spielt.

Bezüge zur Informatik wurden in einigen Vorträgen über deskriptive Komplexitätstheorie deutlich. Hier war insbesondere der Zusammenhang der logischen Definierbarkeit von Problemen und deren Approximierbarkeit von Interesse.

Die Tagung war die erste ihrer Art. Das gab auch Anlaß, über Methoden, Tragweite und Ziele der Endlichen Modelltheorie zu diskutieren.

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Vortragsauszüge:

M. Ajtai

The Independence of the modulo p Counting Principles

The modulo p counting principle is a first-order axiom schema saying that it is possible to count modulo p the number of elements of the first-order definable subsets of the universe (and of the finite Cartesian products of the universe with itself) in a consistent way. It trivially holds on every finite structure. An equivalent form of the mod p counting principle is the following: there are no two first-order definable equivalence relations Φ and Ψ on a (first-order definable) subset X of the universe A (or of A^i for some $i = 1, 2, \ldots$) with the following properties: (a) each class of Φ contains exactly p elements, and (b) each class of Ψ with one exception contains exactly p elements, the exceptional class contains 1 element. We show that the mod p counting principles, for various prime numbers p, are independent in a strong sense.

A. Dawar

The Expressive Power of Generalized Quantifiers

This talk covers two papers — one of them jointly with Lauri Hella. We consider the problem whether there is a logic for the class PTIME on structures that are not necessarily ordered. We show that there is no such logic obtained by extending the least fixed–point logic (LFP) by means of finitely many Lindström quantifiers, even over a fixed signature. We show that if there is any logic that captures PTIME, then there is one that is an extension of LFP by an infinite sequence of quantifiers satisfying a strong uniformity condition. This happens if and only if there is a problem in PTIME, complete for this class with respect to first-order reductions.

M. de Rougemont

The Expressiveness of Non-Uniform Datalog

We define the class of non-uniform Datalog programs (DAC) which combine the recursive feature coming from Datalog together with the non-uniformity of the boolean circuits. A query is $DAC(w; h)$ definable for two functions $w, h : \mathbb{N} \to \mathbb{N}$ if there is a sequence of Datalog programs $\mathcal{P} = \{P_n : n \in \mathbb{N}\}$, where P_n has width

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$w(n)$, polynomial height, and a closure ordinal $h(n)$, such that for each n, P_n defines the query on databases of size n.

We study the expressive power of such classes and establish some hierarchy results using the techniques of chain queries.

[Joint work with I. Guessarian]

R. Fagin

Finite model theory: A Personal Perspective

Finite model theory is a study of the logical properties of finite mathematical structures. Among the topics discussed in this talk are:

(1) *Difference between the model theory of finite structures and infinite structures*
Most of the classical theorems of logic fail for finite structures, which gives us challenge to develop new concepts and tools, appropriate for finite structures.

(2) *The relationship between finite model theory and complexity theory*
Surprisingly enough, it turns out that in some cases we can characterize complexity classes (such as NP) in terms of logic, where is no notion of machine, computation, or time.

(3) *0-1-law*
There is a remarkable phenomenon which says that certain properties (such as those expressible in first-order logic) are either almost sure true or almost sure false.

(4) *Descriptive complexity theory*
Here we consider how complex a formula must be to express a given property.

R. Fagin

Descriptive complexity — winning strategies

I discuss two sufficient conditions for the second player (the "duplicator") to have a winning strategy in an Ehrenfeucht-Fraïssé game on graphs. These are used to give much simpler proofs of the known results that connectivity and directed reachability are not in monadic NP. Furthermore, the conditions can be used to give stronger results than known before in the case of built-in relations.

This talk represents joint work with Arora, Stockmeyer, and Vardi.

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E. Grädel

Logical Definability of Counting Functions

The relationship between counting functions and logical expressibility is explored. The most well studied class of counting functions is #P, which consists of the functions counting the accepting computation paths of a nondeterministic polynomial-time Turing machine. For a logic L, $\#L$ is the class of functions on finite structures (of a fixed signature) counting the tuples $(\bar{T}, \bar{c})$ satisfying a given formula $\psi(\bar{T}, \bar{c})$ in L. Saluja, Subrahmanyam and Thakur showed that on classes of ordered structures #FO=#P (where FO denotes first-order logic) and that every function in $\#\Sigma_1$ has a fully randomized approximation scheme. We give a probabilistic criterion for membership in $\#\Sigma_1$ (on unordered structures). A consequence is that functions counting the number of cliques, the number of Hamilton cycles, and the number of pairs with distance greater than two in a graph, are not contained in $\#\Sigma_1$. It is shown that on ordered structures $\#\Sigma_1^1$ captures the previously studied class spanP. On unordered structures #FO is a proper subclass of #P and $\#\Sigma_1^1$ is a proper subclass of spanP; in fact, no class $\#L$ contains all polynomial-time computable functions on unordered structures. However, it is shown that on unordered structures every function in #P is identical almost everywhere with some function #FO, and similarly for $\#\Sigma_1^1$ and spanP. Finally, it is shown that #FO is closed under various operations under which #P is closed, but that #FO is not closed under other operations under which #P would be closed only if certain generally believed assumptions in complexity theory failed. [Joint work with K. Compton]

E. Grandjean

Monadic Logical Definability of NP-complete problems

It is well-known that (existential) monadic second-order logic *with linear order* exactly characterizes regular languages (Büchi 1960). On the other hand, J.F. Lynch (1982) proved that each language in NTIME(n) (linear time on a nondeterministic Turing machine) can be defined by an existential monadic second-order formula *involving addition*. (Compare this with Fagin's Theorem (1974): A language is NP iff it can be defined by an existential second-order formula of any arity.)

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Very few natural NP-complete problems belong to NTIME(n) (e.g. Knapsack). On the other hand, the author recently noticed (1993) that *many of them* (e.g. the 21 original problems of R. Karp, 1972) *belong to NLIN*, the corresponding class for RAMs. In fact we prove that each problem in NLIN can be defined in Lynch's logic (existential monadic second-order with addition).

This result is proved by essentially using the *exact* characterization of the class NLIN by existential second-order logic *with unary functions* (Grandjean, 1985-90-93): the new trick is an encoding of each unary function by a unary relation on a slightly bigger domain.

Improvement: Recently J.F. Lynch (1992) proved that the class NTIME(n) is captured by existential monadic second-order formulas (with +) where the first-order part of the formula is $\forall^*\exists^*$. We obtain the same result for NLIN (and then for the 21 problems of R. Karp).

Hence a proof that a concrete problem is not definable in this logic would yield a proof that this problem does not belong to NLIN and then requires *strictly more* deterministic (or nondeterministic) *time* than many (most?) natural NP-complete problems.

[Joint work with F. Olive]

M. Grohe

Arity Hierarchies

Partial fixed-point logic PFP is obtained by augmenting first-order logic by a fixed-point operator. If we restrict the arity of this operator to be $\leq k$ (for a positive integer k) we get the k-ary fragment PFP^k of PFP. We call the hierarchy $(\mathrm{PFP}^k)_{k\geq 1}$ the arity hierarchy of PFP.

Similarly we define the arity hierarchy for transitive closure logic ($(\mathrm{TC}^k)_{k\geq 1}$) and deterministic transitive closure logic ($(\mathrm{DTC}^k)_{k\geq 1}$).

We prove that for each $k \geq 2$ $DTC^k \not\subseteq TC^{k-1}$ and $TC^k \not\subseteq PFP^{k-1}$. In fact we prove that this holds even on the class of graphs.

As a corollary we get that the arity hierarchies are strict for the logics mentioned above and also for other common fixed-point logics.

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Y. Gurevich

Rigid Structures

This is a joint work with Saharon Shelah. Using probabilistic methods, we construct finite rigid structures depending on parameter k such that no $L^k_{\infty\omega}$ formula with counting quantifiers distinguishes between particular different elements. Further we get a finitely axiomatizable subclass of finite rigid structures where no $L^{\omega}_{\infty\omega}$ formula with counting quantifiers defines a linear order.

L. Hella

Fixpoint logic vs generalized quantifiers

Neil Immerman proved in 1987 that, in the presence of linear order, first–order logic extended by the uniform sequence of alternating transitive closure operators, FO($ATC^{<\omega}$), captures PTIME. Later E. Dahlhaus showed that a variant of the ATC–operator captures least fixpoint logic, LFP, even without linear order. Quite recently, Martin Grohe defined generalized quantifiers $Q_{\mathcal{I}}$ and $Q_{\mathcal{P}}$ such that FO($Q^{\leq\omega}_{\mathcal{I}}$) and FO($Q^{\leq\omega}_{\mathcal{P}}$) capture inflationary fixpoint logic and partial fixpoint logic, respectively.
We prove that for every monotone quantifier Q there is another quantifier Q_{ATC} such that FO($Q^{<\omega}_{ATC}$) and LFP($Q^{<\omega}$) have equal expressive power on the class of all finite structures. The quantifier Q_{ATC} is essentially a coding of a semantic game for LFP($Q^{<\omega}$)–formulas.

I. Hodkinson

0–1–laws and infinitary logics

The talk discusses some results of Kolaitis & Vardi and Dawar & Hella, the main one being that if C is a class of finite structures and $k < \omega$, then C has a 0–1–law in the infinitary logic $L^k_{\infty\omega}$ iff, modulo the almost sure theory $T(C)$ of C, there are only finitely many first–order formulas written with k variables, and $T(C)$ decides every k–variable sentence.
Thus, for example, if $T(C)$ is ω–categorical then C has a 0–1–law in $L^k_{\infty\omega}$ for all finite k, a theorem of Kolaitis & Vardi. Some examples illustrating these notions were given, and it was pointed out that an analogue of the theorem holds for the extension of $L^k_{\infty\omega}$ by a finite set of generalised quantifiers.

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Ph. Kolaitis

Polynomial-Time Optimization, Parallel Approximation and Fixpoint Logic

We initiate a study of polynomial-time optimization from the perspective of descriptive complexity theory. We establish that the class of polynomial-time and polynomially bounded optimization problems with ordered finite structures as instances can be characterized in terms of the *stage functions* of positive first-order formulae, i.e., the functions that compute the number of iterations in the "bottom up" evaluation of the least fixpoints of such formulae. After this, we study the stage functions of several first-order formulae whose least fixpoints form natural P-complete problems and show that they are not NC-approximable within any factor of the optimum, unless P=NC. Finally, we prove that certain polynomial-time optimization problems are complete with respect to a new kind of restricted reductions that preserve parallel approximability and are definable using quantifier-free formulae.

[Joint work with N. Thakur]

C. Lautemann

Logics for context-free languages

We want to investigate subclasses of NP, characterised by logics $\exists\mathcal{B} f.o.$ where $\mathcal{B}$ is a class of binary relations, e.g. order relations: $\exists < f.o.$, successor relations: $\exists suc\ f.o.$, etc. As a first step we restrict ourselves to string logic and show that the class of context-free languages can be characterized by such a logic, using *matchings*, where $M \subseteq \{1,\ldots,n\}^2$ is a matching
iff $\forall i,j,k,l$: whenever $(i,j) \in M$ then

- $(j,i) \in M$, • $j \neq i$, • $(i,k) \in M \rightarrow k = j$, and
- $(k,l) \in M \wedge i \leq k \leq j \rightarrow i \leq l \leq j$.

[Joint work with T. Schwentick, D. Thérieu]

D. Leivant

Old and new transfer principles in logic-based complexity

Transfer principles bring a measure of unity to the multitude of approaches to computational complexity. An old example of a transfer principle is the Schönfinkel-Howard mapping of proofs to functional programs.

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In this talk we introduce the transfer principle of boundedness. It states that subterms of computationally-potent elements of a free algebra are also computationally-potent. This implies a transfer of results in predicative recurrence theory to analogous results in Finite Model theory.

J. Lynch

Convergence Laws for the Infinitary Language of Random Graphs

The infinitary language $L^{\omega}_{\infty\omega}$ of graphs is the extension of the first-order language of graphs where infinite conjunctions and disjunctions of arbitrary sets of formulas are allowed, provided only finitely many distinct variables occur among the formulas. Let $p(n)$ be a function from the natural numbers to $[0,1]$. A random graph on n vertices has edge probability $p(n)$ if, for every pair of vertices $i, j \in n$, $\{i, j\}$ is an edge of the graph with probability $p(n)$. For any sentence σ, $\mathrm{pr}(\sigma, n)$ is the probability that the random graph on n vertices satisfies σ. Previous work by Kolaitis and Vardi has shown that when $p(n)$ is constant, for all $\sigma \in L^{\omega}_{\infty\omega}$, $\mathrm{pr}(\sigma, n)$ is asymptotic 0 or 1. We consider $p(n) = n^{-\alpha}$, where $\alpha > 0$, and will show that $\mathrm{pr}(\sigma, n)$ always converges when $\alpha < 1$ is irrational or $\alpha > 1$. The convergence result for the first case is joint work with J. Tyszkiewicz. In fact, for every $\sigma \in L^{\omega}_{\infty\omega}$, there is a first-order sentence σ' such that $\mathrm{pr}(\sigma \leftrightarrow \sigma', n)$ converges to 1.

J. Makowsky

Arity vs Alternation in Second-Order Logic

Let $\hat{\Sigma}_n$ be the second order hierarchy with the restriction that $\exists U \forall V \exists W \ldots \varphi \in \hat{\Sigma}_n$ if φ is a first-order $\forall^*\exists^*$-sentence.

$\hat{\Sigma}_1$ still captures NP, and $\hat{\Sigma}_n$ captures $\hat{\Sigma}^p_n$ of the polynomial hierarchy.

Now let $\hat{\Sigma}^{(d)}_n$ ($d \in \mathbb{N}$) be the $\hat{\Sigma}_n$ sentences with all second-order variables of arity $\leq d$.

Theorem: *For every n, d there is a sentence $\theta_{n,d} \in \hat{\Sigma}^{(d+4)}_{n+2}$ which is not equivalent to any sentence in $\hat{\Sigma}^{(d)}_n$.*

The proof uses self-satisfying sentences, i.e. let $\mathfrak{A}_\varphi$ be the structure which corresponds to the string φ.

Theorem: *Let AUTOSAT-FOL be the set of self-satisfying first-order sentences. AUTOSAT-FOL is PSPACE-complete.*

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[Joint work with Y. Pnueli]

M. Otto

Explicitly Symmetric Circuits and FO

We consider infinitary boolean circuits where computations are explicitly invariant with respect to the choice of representation of the input structure. This condition is put in terms of automorphisms of the circuit induced by relabellings of the input nodes. The resulting *symmetric circuits* provide an isomorphism preserving model of circuit computation.

To characterize $L^{\omega}_{\infty\omega}$, infinitary logic with a bounded number of variables, a weak local size restriction is introduced: a symmetric circuit is *locally polynomial* if the orbits of its nodes under localizations of the automorphism group are polynomially bounded.

The following characterizations are obtained:

- symmetric, locally polynomial circuits $\equiv L^{\omega}_{\infty\omega}$
- symmetric, locally polynomial circuits of finite depth $\equiv$ FO

Generalizing to networks in an obvious way we obtain

- symmetric, locally polynomial networks with finitely many orbits $\equiv$ PFP

I.A. Stewart

Context-Sensitive Transitive Closure

We introduce a new logical operator CSTC (context-sensitive transitive closure) and show that incorporating this operator into first-order logic (with successor) enables us to capture the complexity class PSPACE. We also show that by varying how the operator is applied we can capture the classes P, NP, the classes of the Polynomial Hierarchy PH, and PSPACE. We also give applications of these characterizations by showing that P and NP coincide with those problems accepted by two new classes of program schemes; by producing some new generic complete problems for various complexity classes; and by giving a simple proof that first-order logic incorporated with the least fixed-point operator captures P.

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J. Tyszkiewicz

Non-convergence results via extension axioms

In the theory of asymptotic probabilities extension axioms have been used as a typical tool to prove 0–1–laws, mainly for first-order logic.
We present a technique that allows us, given a 0–1–law for some logic proven by extension axioms, to construct a nonconvergence proof for some extension of the logic under consideration. The typical inferences are:

1. nonconvergence for monadic second order logic derived from a 0–1–law for first order logic

2. nonconvergence for fixpoint logic from the 0–1–law for first-order logic

3. nonconvergence for first-order logic over signature $\sigma \dot{\cup} \tau$ from two 0–1–laws for first-order logic over signatures σ and τ.

J. Väänänen

The Hierarchy Theorem for Generalized Quantifiers

The concept of a generalized quantifier was defined by Per Lindström in 1966. Our main result says that on finite structures different similarity types give rise to different classes of generalized quantifiers. More exactly, for every similarity type t there is a generalized quantifier of type t which is not definable in the extension of first-order logic by all generalized quantifiers of type smaller than t. This was proved for unary similarity types by Per Lindström in 1993. We extend his method to arbitrary similarity types.
This is a joint work with L. Hella and K. Luosto.

Problem Session

1. *(H.-D. Ebbinghaus)* In classical model theory, the methodological scope of important logics has been clarified by characterization theorems such as Lindström's theorems on first-order logic or Barwise's theorem on $L_{\infty\omega}$. In order to explore model theoretic properties in the finite, one should try to perform a similar program for this case. In particular, is there a Lindström-type theorem for fixed-point logic ?

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2. *(R. Fagin)* A *monadic NP* class is a class defined by an existential monadic second-order sentence.

Problem: Does one unary relation symbol suffice ? That is, is every monadic NP class (such as 3-colorability) definable as $\exists S\varphi$, where S is a single unary relation symbol?

3. *(R. Fagin)* The *monadic hierarchy* consists of classes definable by sentences $Q_1S_1 \ldots Q_kS_k\varphi$, where the S_i's are unary relation symbols, the Q_i's are $\exists$ or $\forall$, and φ is first-order.

Problem: Is the hierarchy strict? Or does it collapse to some fixed number of alterations of second-order quantifiers?

Fact: If the polynomial hierarchy is strict then so is the monadic hierarchy. But we would like to prove this without complexity assumptions.

4. *(J. Flum)* FO^2, the fragment of FO consisting of sentences with at most two variables, is decidable.

Does Σ_1^1 over FO^2 have a 0–1-law?

5. *(E. Grädel/A. Dawar)* Is PLANARITY in FP or $L^{\omega}_{\infty\omega}$?

Is 3-COLORABILITY in $L^{\omega}_{\infty\omega}$?

(or other natural NP-complete problems on unordered structures)

6. *(E. Grandjean)* Prove that the decision problem T_2 of the first-order random theory of *two binary relations* is reducible to the similar problem T_1 *for only one binary relation* via a linear time bounded reduction. That would imply that T_1 and T_2 have exactly the same time complexity.

7. *(E. Grandjean)* Show that for each n there is a boolean circuit C_n that can sort n integers (in binary notation) in the range $0, \ldots, n^k$ (k fixed) so that the circuit C_n

- has $O(n(log\ n)^2)$ gates
- and is computable in time $O(n(log\ n)^3)$ (that means: in time linear in the length of its description) on a Turing machine.

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Remark: We hope to get this result by a careful inspection of the sorting network of [Ajtai, Komlos, Szemeredi, 1993] which sorts n integers in time $O(log\ n)$ with n registers.

8. *(E. Grandjean)* Investigate the class of graph properties π that can be defined by an existential second-order formula with unary functions only, i.e.

$G = (V, E)$ belongs to π

iff G satisfies a formula of the form $\exists f_1, \ldots, f_k\ \psi(E, f_1, \ldots, f_k)$

(where the f_i are unary functions).

(a) Study the extent and the robustness of this class.

(b) Prove that some problems do not belong to it. (E.g. is G edge-colorable with d colors where $d = degree(G)$?)

9. *(Ph. Kolaitis)* A Preservation Problem in Finite Model Theory

Suppose φ is a first-order sentence that is preserved under extensions and homomorphisms on finite models. Is φ equivalent to an existential positive sentence on finite models ?

Background: (a) preservation under extensions fails finitely (Tait/Gurevich & Shelah)

(b) preservation under homomorphisms fails finitely (Ajtai & Gurvich)

(c) A positive answer to the above problem will yield as an easy corollary the theorem of Ajtai & Gurevich that a Datalog program is bounded if and only if it defines a first-order property.

10. *(J. Lynch)* Let L_k be the fragment of binary second-order language of graphs consisting of sentences of the form

$$\exists R_1 \ldots \exists R_k \forall x_1 \ldots \forall x_k \exists y_1 \ldots \exists y_k\ \tau(x_1, \ldots, x_k, y_1, \ldots, y_k, E, R_1, \ldots, R_k)$$

where $R_1, \ldots, R_k$ are binary second-order variables and E is interpreted as the graph edge relation. Let $L = \bigcup_k L_k$.

(a) Find an isomorphism invariant property of graphs that is not definable in L. That is, find a collection of graphs C such that there is no $\sigma \in L$ for which

$$G \in C \iff G \models \sigma\,.$$

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(b) Similar, but for L_k. For what k does this become hard?

11. *(J. Lynch)* What classes of random finite structures have relevance to:

(a) database theory

(b) statistical verification of programs

(c) algorithm analysis

12. *(J.A. Makowsky)* Let L be a logic, $\varphi \in L[\tau \cup R]$.

Definition: φ is ***invariant under order*** if for every finite τ-structure $\mathfrak{A}$ and two linear orderings $<_1^{\mathfrak{A}}, <_2^{\mathfrak{A}}$ on it we have $(\mathfrak{A}, <_1^{\mathfrak{A}}) \models \varphi \iff (\mathfrak{A}, <_2^{\mathfrak{A}}) \models \varphi$.

Problem: Is there a logic $L \subset FP$ or $\subset L^{\omega}_{\infty\omega}$ such that for every order invariant φ there is $\psi \in L[\tau]$ (without order symbol) such that $\varphi \equiv \psi$?

Notes: (a) If L satisfies the Interpolation Theorem (Δ-Interpolation suffices) then this is true.

(b) There is an order-invariant φ in FOL such that no such ψ exists (Gurevich).

13. *(I. Stewart)* Take an arbitrary NP-complete problem Ω and incorporate the corresponding sequence of Lindström quantifiers into first-order logic to get the logic $(\pm\Omega)^*[FO]$ (there is a quantifier for each arity à la Immerman's transitive closure logic, but no built-in relations such as successor; also "$\pm$" tells us that we can apply Ω within negation signs and "$*$" tells us that we may nest applications of Ω as we like).

Question: Is there a logic $(\pm\Omega)^*[FO]$ with a 0–1-law ?

Note that $HP^*[FO] = NP$ (Dahlhaus) if we have two constants available. (HP=Hamiltonian Path)

Question: Does there exist a complete problem for NP via quantifier-free translations without constants or built-in relations ?

This second question harks back to Lovász and Gács (1977). Also, Blass an Harary have asked for a logic L which can express Hamilton Cycle and which has a 0–1–law.

Berichterstatter: Martin Grohe (Freiburg)

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