Frank Stephan – Research and Publications

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Biography

Frank Stephan was born in Germany and visited primary and secondary schools in Wuppertal until 1983 when he obtained the Abitur, the German equivalent of A-levels. He studied at the University of Karlsruhe (Technical Highschool) and obtained the diploma in computer science in 1989 and the doctorate in mathematics in 1990. He worked at the University of Karlsruhe (T.H.) until 1995, from 1995 until 2003 at the University of Heidelberg, from 2003 until 2004 at the National ICT Australia at the University of New South Wales and since 2004 at the National University of Singapore. While working in Heidelberg, Frank Stephan received in 1999 the habilitation degree, a German postdoctoral degree comparable to the second doctorate of Russian scientists. Frank Stephan has been an editor of The Journal of Symbolic Logic for six years and is currently on the editorial board of Information and Computation, Journal of Computer and System Sciences, Computability and Acta Informatica.

Research

His research areas are recursion theory and applications growing out of it: bounded queries, Kolmogorov complexity, inductive inference, complexity theory and model theory. Furthermore, he works in automata theory and in particular in the areas of automatic structures and the learnability of automatic families.

Bounded Queries

A set A is (m, n)-recursive iff there is a recursive function f mapping n-tuples of different natural numbers to n-tuples of bits such that for all different $x_1, x_2, \ldots, x_n$ there are at least m indices $k \in \{1, 2, \ldots, n\}$ where the corresponding bits agree with the characteristic function: $f_k(x_1, x_2, \ldots, x_n) = A(x_k)$.

Martin Kummer and Frank Stephan [7] investigate the recursion-theoretic properties of the (m, n)-recursive sets. They show that simple $(m, 2m)$-recursive sets are hypersimple but not hyperhypersimple while there are a maximal sets A and a simple but not hypersimple set B such that both, A and B, are $(m, 2m + 1)$-recursive for every m. Furthermore, it is shown that every $(1, n)$-recursive set is autoreducible.

In their paper "Approximable Sets", Richard Beigel, Martin Kummer and Frank Stephan [8] study polynomial time versions of (m, n)-recursive sets and show that no such set can be NP-complete unless P = NP. This was a hot topic and this paper [8] was one of three papers at the conference "Structure in Complexity Theory" which obtained a main result; Stephan as the youngest author of all these three papers involved was then permitted to give a joint address to the conference on the topic. The paper [8] deals also with related notions like easily countable and shows that no NP-complete set is Turing reducible to an easily countable set. Here a set is easily countable iff there is a constant k such that a polynomial time function f produces on any distinct k inputs $x_1, x_2, \ldots, x_k$ a value $f(x_1, x_2, \ldots, x_k) \in \{0, 1, \ldots, k\}$ which is different from $A(x_1) + A(x_2) + \ldots + A(x_k)$. This paper is the most-cited paper of Frank Stephan according to Google Scholar.

Furthermore investigations deal with the inclusion problem: Martin Kummer and Frank Stephan [147] give an alternative prooff for Timothy McNicholl's result that the inclusion problem $\{(m, n, h, k)$: every (m, n)-recursive set is (h, k)-recursive$\}$ is decidable.

Cristian Calude, Rusins Freivalds, Sanjay Jain and Frank Stephan [112] did follow-up work with respect to the ability of pushdown automata to (m, n)-compute sets. Here the situation differs from the situation in recursion theory and finite automata, as the pushdown automaton has to maintain a stack which is jointly for all n inputs. This leads to the result that there is a deterministic context-free set which is recognised by a $(1, 1)$-PDA but not by a $(2, 2)$-PDA. In the recursion-theoretic and complexity-theoretic and finite automata frameworks, these two criteria are equal. Further results clear up the situation.

Degrees of Strong Reducibilities

Frank Stephan [26] investigated the structure of the m-degrees, p-degrees and btt-degrees inside non-recursive tt-degrees. Carl Jockusch constructed 1969 an infinite ascending chain of m-degrees within a given arbitrary tt-degree and asked whether there is also an infinite antichain of m-degrees. Furthermore, he showed in 1968 that every tt-degree contains at least 3 positive degrees and asked whether this result is optimal. Alexander Dëgtev analyzed the situation with respect to btt-degrees and showed that every non-recursive tt-degree contains at least 2 btt-degrees. These results were extended in [26] as follows: every tt-degree contains infinite ascending and infinite descending chains of btt-degrees as well as infinite antichains; this result transfers immediately to m-degrees. But for positive reducibility, the lower bound of Carl Jockusch is already optimal, since there are tt-degrees containing exactly 3 positive degrees. These tt-degrees might be taken to be recursively enumerable or hyperimmune-free. But they must be minimal within the lattice of tt-degrees. Other possible cardinalities of the positive degrees inside the tt-degrees are 19, 219, 4231, ... and ∞; but the cardinality can never be even.

Kejia Joyce Ho and Frank Stephan [33] studied the bounded classes of recursively enumerable sets where a class is bounded if there is an incomplete set B such that every A in the class is m-reducible to B. They showed that the class of effectively simple sets is bounded by a simple set, that the class of maximal sets is not bounded, that some bounded class intersects every weak btt-degree, that the recursively enumerable sets within a Turing degree are bounded iff this Turing degree is low_2 and that this result does not hold with Q-degrees in place of Turing degrees.

Learning from Positive Data

Inductive inference studies learning in the limit; here a class S is Ex-learnable iff there is a recursive learner M such that M reads — in arbitrary or even adversary order with repetitions — all elements of a set $L \in S$ and outputs at the same time a sequence $e_0, e_1, \ldots$ of hypotheses for S such that almost all e_n are the same correct index e for L; Ex-learning can be relaxed to

BC-learning by requiring only semantic convergence in place of syntactic convergence, that is, while almost all e_n must be an index for L it is no longer required that $e_n = e_{n+1} = e_{n+2} = \ldots$ for some n. On the other side, the more restictive criterion of Fin-learning would require that e_0 is already the correct index.

Frank Stephan and Yuri Ventsov [28] investigated the question on relations between properties of recursive mathematical structures on the one side and the learnability of natural substructures from positive data on the other side. For example, the class of all ideals of a recursive ring can be learned under the criterion BC iff the ring is Noetherian and under the criterion Fin[K] iff the ring is Artinian. The intermediate criterion Ex does not have a beautiful characterization; for some rings, it even depends on the chosen representation of the ring whether the class of ideals is Ex-learnable or not. A further question addressed in this work is what knowledge on the given mathematical structure is necessary in order to construct a learner.

In the paper "When Unlearning Helps", Ganesh Baliga, John Case, Wolfgang Merkle and Frank Stephan [66] showed that there is a class S of recursively enumerable sets which can be Ex-learned from positive data, but which does not have a decisive Ex-learner — where a learner is decisive iff it never returns to a once abandoned hypothesis. This solves a problem open since 1986. In addition to this, they compared the notions of non U-shaped learning and decisive learning. A non U-shaped learner for a class S has the property that it never changes from a correct to an incorrect hypothesis, that is, it never "unlearns" something which it had already learnt. One can easily see that decisive learners are non U-shaped, but the converse is not true. Indeed, every Ex-learnable class has an explanatory non U-shaped learner. In contrast to this, for BC-learning, there is a class which is BC-learnable but not non U-shaped BC-learnable.

A new area growing out of this paper and in particular the study of non U-shaped learning became popular. Indeed, the notion had been investigated in psychological studies before, but not in inductive inference. Lorenzo Carlucci, John Case, Sanjay Jain and Frank Stephan [67] investigated when vacillatory learnable classes are contained in non U-shaped behaviourally correct learnable classes. The answer was that whenever the learner vacillates in the limit between at most two indices, then one can replace this learner by a non U-shaped behaviourally correct learner. But if the vacalliatory learner might vacillate in the limit between up to three indices then this inclusion breaks down. Further results can be found in the survey [166] by Sanjay Jain and Frank Stephan on this field.

Sanjay Jain and Frank Stephan supervised the honours year thesis of Ye Nan and investigated with him the question, to which extent one can prescribe the hypothesis space in learning. Here the central question was whether a given class can be learnt using any desired hypothesis space; if so, an additional question was whether one can synthesize a learner using that hypothesis space just from an index of that space. The investigations fall into two cases, one for uniformly recursive and one for uniformly r.e. hypothesis spaces. Ye Nan received for his work an Outstanding Undergraduate Investigator Award. Sanjay Jain, Frank Stephan and Nan Ye obtained in this paper "Prescribed learning of r.e. classes" [74] the important result that every behaviourally correctly learnable class has a prudent behaviourally correct learner, which in addition can be found effectively. This result solved a long-standing open problem in inductive inference, which was open since an error had been discovered in an earlier paper claiming the statement in 1988. The joint work was presented at the Converence on Algorithmic Learning Theorey 2007 and appeared in 2009 in Theoretical Computer Science. Additional work on the case of uniformly recursive hypothesis spaces was published in 2008 in Fundamentae Informaticae [65].

Inductive Inference of Functions

A class of recursive functions S is robustly Ex-learnable (BC-learnable) iff, for every total recursive operator Θ, the class $\Theta(S)$ is Ex-learnable (BC-learnable). John Case, Sanjay Jain, Frank Stephan and Rolf Wiehagen [43] showed that there are robustly Ex-learnable classes S which are not uniformly robustly BC-learnable, that is, one cannot compute a BC-learner for $\Theta(S)$ from a program for Θ. Furthermore, it is shown that every uniformly robust Ex-learnable class S also has an Ex-learner satisfying some weak notion of consistency introduced by Janis Bārzdins 1974.

Frank Stephan and Thomas Zeugmann [32] reconsidered the following class S which played an important role in the fundamental paper of Blum and Blum from 1975: $S = \{f : (\exists$ total and monotone $\Phi_e)$ $(\forall x)\,[f(x) = 1 \Leftrightarrow x$ is enumerated into K within $\Phi_e(x)$ computational steps$]\,\}$. They showed that this class is not a subclass of a uniformly recursive family of functions what was left open by Blum and Blum. Furthermore, S becomes unlearnable when "total and monotone Φ_e" is weakened to "total Φ_e". Further aspects of this work deal with the question which connections are between learnability and recursion-theoretic properties of a recursively enumerable set A when K is replaced by the set A in the above definition of S.

Susanne Kaufmann and Frank Stephan [25] investigated to which extend the usage of oracles by a learner depends on the syntactic presentation of the oracle. The idea is that the learner should succeed with any oracle repesenting the class in a certain syntacitic form. It turned out that for learning in the limit, lists of all functions to be learnt are more usefull than predictors (which predict almost all values of the function to be learned correctly) or classifiers (which converge to 1 iff the function to be learnt belongs to the given class). Martingales, that is, betting strategies succeeding on every function of the class to be learnt, turned out to be completely useless as an oracle for learning.

Sanjay Jain, Qinglong Luo and Frank Stephan [93] investigated for classes which are represented as automatic families, whether these can have a learner which maintains all data in form of a string and which updates this memory for each datum using an automatic functions; furthermore the hypotheses of the learner are also indices of the automatic family and also computed from the memory by an automatic function. This model has matching restrictions on the class to be learnt and the way the learner works and turned out to be an interesting model for learning; various follow-up work deals with this learning model [86, 92, 99, 102, 103, 177].

Kolmogorov complexity

Kolmogorov complexity measures the complexity of a finite object (string or number) by the length of the shortest input string to a universal machine U which produces this string: in short, $C(x) = \min\{|p| : U(p) = x\}$. Often one does not consider all machines but only those where the domain is prefix-free, that is, where no member of the domain is a proper prefix of another member. In that case one speaks of the prefix-free Kolmogorov complexity H. The importance of the latter can be seen from the characterization that a set A is Martin-Löf random iff $H(A(0)A(1)A(2)\ldots A(n)) \geq n$ for almost all n.

Antonín Kučera had constructed a PA-complete set where the Turing degree does not contain a Martin-Löf random set. This stands in contrast to the fact that all Martin-Löf random sets which are above the halting problem K with respect to Turing reducibility are also PA-complete. Therefore Klaus Ambos-Spies and Antonín Kučera asked what the general situation of the Martin-Löf random sets not Turing above the halting problem is; in particular whether some of them can be PA-complete. In a short paper, Frank Stephan [168] proved that every

PA-complete Martin-Löf random set is already Turing hard for the halting problem; hence the answer to the question of Ambos-Spies and Kučera is negative. So this paper establishes that there are two types of Martin-Löf random sets: those above the halting problem with high computational power and those which are PA-incomplete and therefore fail to extend certain $\{0,1\}$-valued partial-recursive functions to total ones. This result also shows that the result of Gács and Kučera that every Turing degree above K contains a Martin-Löf random set is optimal; one cannot replace K in this theorem by any other set $A \not\geq_T K$.

Richard Beigel, Harry Buhrman, Peter Fejer, Lance Fortnow, Piotr Grabowski, Luc Longpré, Andrej Muchnik, Frank Stephan and Leen Torenvliet [48] studied the following question: Given an oracle A, how difficult is it to enumerate the Kolmogorov function $x \mapsto C(x)$ relative to A. More precisely, assume that an algorithm enumerates for every input x of length n up to $k(n)$ many values such that $C(x)$ is among these. What can be said about the function k? The three main results are the following: (1) If A is recursive then $k(n) \geq r \cdot n$ for some real constant $r > 0$ which depends on the universal machine U on which C is based. (2) If $k(n)$ is a constant (independent of n) then the oracle A must be Turing above the halting problem K, hence every oracle A which can enumerate $C(x)$ in constantly many trials can in fact already compute $C(x)$. (3) There exists an r.e., Turing-incomplete set A such for every non-decreasing and unbounded recursive function k, the Kolmogorov function is $k(n)$-enumerable relative to A. So result (2) says that the Kolmogorov function is a natural example of a function which needs more than constant enumeration complexity for oracles not above K. Similar such functions are well known, for example the cardinality function mapping each input of the form $(n, x_1, x_2, \ldots, x_n)$ to the n-fold sum $K(x_1) + K(x_2) + \ldots + K(x_n)$ of the corresponding values of the characteristic function of K and the function mapping each input of the form $(n, x_1, x_2, \ldots, x_n)$ to the corresponding vector $(K(x_1), K(x_2), \ldots, K(x_n))$ of the characteristic function; these two examples can be derived from Beigel's Nonspeedup Theorem and Kummer's Cardinality Theorem. But while those examples would work for every oracle, the example of the Kolmogorov function here is more specific for the halting problem K.

Andre Nies, Frank Stephan and Sebastian A. Terwijn [46] compare various notions of algorithmic randomness. In particular they show that a set A is Martin-Löf random relative to K if and only if there is a constant c such that $C(A(0)A(1)\ldots A(n)) \geq n - c$ for infinitely many n. The 'only if' direction was obtained independently by Joseph Miller. This characterization can be extended to the case of time-bounded C-complexity. Furthermore, they show that the notions of Martin-Löf randomness, recursive randomness and Schnorr randomness can be separated in every high Turing degree while the same notions coincide in every non-high degree. An additional result is that every hyperimmune Turing degree contains a set which is Schnorr random but not Martin-Löf random while in the hyperimmune-free degrees the notions of Kurtz random, Schnorr random and Martin-Löf random coincide.

Wolfgang Merkle and Frank Stephan [170] solved several open problems on C-reducibilities and H-reducibilities by linking them to Turing reductions. Here $A \leq_C B$ iff there is a constant c such that $C(A(0)A(1)A(2)\ldots A(n)) \leq C(B(0)B(1)B(2)\ldots B(n)) + c$ for all n; the definition of H-reducibility is analogous. Merkle and Stephan showed that there are minimal C-degrees which in addition coincide with minimal H-degrees and that there is a minimal pair of C-degrees given by two r.e. sets forming a minimal pair in the Turing degrees. Also it is shown that nontrivial meets can exist but that there are also pairs of C-degrees without a meet. A minimal pair of H-degrees given by Σ^0_2-sets was constructed bringing down the known bound of it.

Johanna Franklin and Frank Stephan [77] study Schnorr-trivial sets and give a new characterization by proving that A is Schnorr-trivial iff for every $f \leq_{tt} A$ there is a recursive function

g with

$$\forall f \leq_{tt} A \, \exists \text{ recursive } g \, \forall n \, [f(n) \in \{g(2^n), g(2^n)+1, g(2^n+2), \ldots, g(2^{n+1}-1)\}].$$

Franklin and Stephan solved an open problem by proving that Schnorr trivial sets are closed under join and therefore form an ideal in the truth-table degrees. In contrast to this, they showed that the Schnorr trivial sets are not closed under weak truth-table reducibility. They also proved that a set A is Schnorr-trivial iff every Schnorr random set B is also Schnorr random truth-table relative to A; that is, the Schnorr trivial sets are those which are truth-table low for Schnorr-randomness.

Model Theory

The main topic of model theory is how structures can be presented and whether such presentations are isomorphic. In general, given a structure, say a ring $(R, +, \cdot)$, a presentation of this ring would be a base set A and two functions $f, g : A \times A \to A$ such that there is a bijection $h : R \to A$ satisfying $h(x+y) = f(h(x), h(y))$ and $h(x \cdot y) = g(h(x), h(y))$ for all x, y. One is in particular interested in models where the domain is either the set of natural numbers or a regular set over a finite alphabet and where the considered operations like f, g in this example are recursive functions.

In the paper "Applications of Kolmogorov Complexity to Computable Model Theory", Bakhadyr Khoussainov, Pavel Semukhin and Frank Stephan [61] considered the well-known question whether there exists a complete theory with the following four properties: (1) there are several countable models; (2) for each uncountable cardinal there is only one model; (3) all computable models are isomorphic via a recursive permutation; (4) only the saturated model is computable. The answer was affirmatively and it used a construction which is based on Kolmogorov complexity. This proof method permitted to simplify the construction much. Furthermore, a variation of the construction permitted to construct a theory where only the saturated model has an r.e. presentation and this is computably categorical; again for this theory, there are countably many countable models and for each uncountable cardinal exact one model.

Bakhadyr Khoussainov, Andre Nies, Sasha Rubin and Frank Stephan [64, 161, 162] studied the field of automatic structures where the domain and the graphs of all relations and functions involved have to be recognized by a finite automaton. Sample results include that the random graph does not have an automatic presentation and a characterizations of the automatically presentable linear orders is obtained. Furthermore it is shown that the automorphism problem for the class of all automatic structures is a Σ^1_1-complete problem.

Pavel Semukhin and Frank Stephan [97] studied automatic structure from a model-theoretic viewpoint and answered several questions of Khoussainov and Nerode. They inparticular showed the following: (1) There is an uncountably categorical but not countably categorical theory for which only the prime model is automatic; (2) There are complete theories with exactly $3, 4, 5, \ldots$ countable models, respectively, and every countable model is automatic; (3) There is a complete theory for which exactly 2 models have an automatic presentation; (4) There is a complete theory with countably many countable models for which the saturated model has an automatic presentation but the prime model does not have one.

Sanjay Jain, Bakhadyr Khoussainov, Frank Stephan, Dan Teng and Siyuan Zou [124] investigated to which extent one can represent more involved structure when one permits for some but not necessary all functions and relations in the structure that not the relation or function itself is automatic but only the derived relation or function when all but one of the inputs to the relation or function are chosen as constants. While for some structures like countable ordinals with addition and order, this concept is very powerful and all the corresponding structures are represented, there are other structures like finitely generated groups with undecidable word problem which cannot be represented this way. In this paper, a particular emphasis is given to natural structures like the the ordered ring of the integers over a square-root and the derived ordered fields. Also some natural structures are provided which are not semiautomatic.

Block Pumpable Languages

Christopher Chak, Rusins Freivalds, Frank Stephan and Henrietta Tan [113] investigated the notion of block pumpable sets. Ehrenfeucht, Parikh and Rozenberg had demonstrated that a language is regular iff it satisfies a block pumping condition; this condition is a type of pumping lemma applying to both, the language and its complement. One can weaken this condition to requiring the block pumping lemma to hold only for the language itself – as done with the traditional pumping lemma – and obtains the notion of block pumpable languages. These has nice closure properties: the block pumpable languages are closed under intersection, union, concatenation and automatic mappings; however, they are not closed under Kleene star. Furthermore, one can also obtain a pumping lemma for pumping at k places simultaneously. Some question remained open in the work of Chak, Freivalds, Stephan and Tan [113]: most notably the constants obtained in the construction are all obtained using Ramsey's Theorem and thus are very large; usually, when constructing pumping conditions on regular sets, the constants are bounded by the number of states of an nfa; therefore one might ask whether better bounds can be obtained also in the general case where the nfa is not available.

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