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Aims and Scope
The periodical *Dagstuhl Reports* documents the program and the results of Dagstuhl Seminars and Dagstuhl Perspectives Workshops.
In principal, for each Dagstuhl Seminar or Dagstuhl Perspectives Workshop a report is published that contains the following:

- an executive summary of the seminar program and the fundamental results,
- an overview of the talks given during the seminar (summarized as talk abstracts), and
- summaries from working groups (if applicable).

This basic framework can be extended by suitable contributions that are related to the program of the seminar, e. g. summaries from panel discussions or open problem sessions.

Contact
Schloss Dagstuhl – Leibniz-Zentrum für Informatik
Dagstuhl Reports, Editorial Office
Oktavie-Allee, 66687 Wadern, Germany
reports@dagstuhl.de
http://www.dagstuhl.de/dagrep

Report from Dagstuhl Seminar 17361

Finite and Algorithmic Model Theory

Edited by

Anuj Dawar[1], Erich Grädel[2], Phokion G. Kolaitis[3], and Thomas Schwentick[4]

1 **University of Cambridge, GB,** anuj.dawar@cl.cam.ac.uk
2 **RWTH Aachen, DE,** graedel@informatik.rwth-aachen.de
3 **University of California – Santa Cruz, US,** kolaitis@cs.ucsc.edu
4 **TU Dortmund, DE,** thomas.schwentick@tu-dortmund.de

Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 17361 "Finite and Algorithmic Model Theory".

Seminar September 3–8, 2017 – http://www.dagstuhl.de/17361
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Edited in cooperation with Nils Vortmeier

1 Executive Summary

Anuj Dawar
Erich Grädel
Phokion G. Kolaitis
Thomas Schwentick

Topic and Goals of the Seminar

Finite and Algorithmic Model Theory (FAMT) encompasses a number of research themes united around common methods for analysing the expressive power of logical formalisms on structures that are either finite or can be finitely represented. These are precisely the structures that can serve as inputs to computation and, for this reason, FAMT is intimately connected to computer science. Over the past decades the subject has developed through a close interaction between theoretical computer science and closely related areas of mathematics, including logic and combinatorics, and a strong research community has been forged, with a common research agenda which has influenced several important areas of computer science. The last Dagstuhl-like meeting of this research community before this seminar had been Aux Houches in 2012.

The principal goals of the seminar have been the following:

1. To identify fresh research challenges in the area of finite and algorithmic model theory, arising from the main application areas and to make new connections between core research in FAMT and emerging application areas, such as logic and learning.

2. To transfer knowledge from emerging methods and techniques in core FAMT to application areas.
3. To strengthen the research community in FAMT, especially by integrating younger members into it.

Organisation and Activities

The organisers developed a schedule consisting of three invited one-hour survey talks, more focussed regular contributions proposed by the participants, an open problem session, and a final discussion about the state and perspectives on the future of FAMT. The three survey talks were given by

- Wied Pakusa (Oxford) on recent achievements concerning the quest for a logic for polynomial time, focussing on Rank Logic and on Choiceless Polynomial Time,
- Dan Suciu (Washington) on highlights of the connections between FAMT and databases.
- Martin Grohe (Aachen) on new developments in machine learning and connections to FAMT.

In addition, 22 other participants gave regular talks on their recent work on topics of FAMT. A further social highlight was a superb concert on Thursday evening performed by Jan Van den Bussche (violin), Wolfgang Thomas (violin) and Jouko Väänänen (piano).

Outcomes

The seminar exceeded our expectations in achieving our principal goals. The invited talk by Pakusa gave an overview on the status of the ongoing pursuit for a logic for PTIME, and demonstrated the depth and technical sophistication that FAMT has reached. This talk was complemented by several insightful presentations on new and deep work on core topics of finite model theory. A particular highlight was the double presentation by Torunczyk and Siebertz, who brought in new methods from stability theory to the study of the finite model theory of sparse structures.

The invited talks by Grohe and Suciu explored new connections between the core methods of finite model theory and emerging areas of applications. These talks were also complemented by several other talks on new directions in FAMT and on interactions of FAMT with other areas. In particular, Grädel's talk focussed on new work in the area of database provenance, while Atserias' talk discussed a priori unexpected connections between constraint satisfaction and quantum information theory.

Overall, the presentations at the seminar were highly stimulating, and we know through discussions during and after the seminar that the new work presented has motivated others to take up the explorations of these questions. Based on the feedback received, we believe that this seminar will serve as a catalyst for new research directions in FAMT.

The organizers regard the seminar as very successful. As reflected in the final discussion, there was a consistent sentiment expressed by the participants that the FAMT community is in very healthy state. There are interesting new developments and exciting results in different directions, there is a strengthening of traditional connections to areas, such as databases and verification, but also new connections are emerging with such areas as knowledge representation, learning theory, logics for dependence and independence, and quantum information theory. Finally, and perhaps more importantly, there is an infusion of

several outstanding young researchers who have the interest and hold the promise to advance FAMT in the years to come.

The participants clearly expressed the wish to a have a next meeting of the FAMT community, be it in Dagstuhl or elsewhere, within the next two to three years.

The organizers are grateful to the Scientific Directorate of the Center for its support of this workshop and the staff of Schloss Dagstuhl for the perfect organisation of our stay and their hospitality.

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3 Overview of Talks

3.1 Advice Automatic Structures and Uniformly Automatic Classes

Faried Abu Zaid (TU Ilmenau, DE)

Joint work of Faried Abu Zaid, Erich Grädel, Frederic Reinhardt
Main reference Faried Abu Zaid, Erich Grädel, Frederic Reinhardt: "Advice Automatic Structures and Uniformly Automatic Classes", in Proc. of the 26th EACSL Annual Conference on Computer Science Logic, CSL 2017, August 20-24, 2017, Stockholm, Sweden, LIPIcs, Vol. 82, pp. 35:1–35:20, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
URL http://dx.doi.org/10.4230/LIPIcs.CSL.2017.35

We study structures that are automatic with advice. These are structures that admit a presentation by finite automata (over finite or infinite words or trees) with access to an additional input, called an advice. Over finite words, a standard example of a structure that is automatic with advice, but not automatic in the classical sense, is the additive group of rational numbers.

By using a set of advices rather than a single advice, this leads to the new concept of a parameterised automatic presentation as a means to uniformly represent a whole class of structures. The decidability of the first-order theory of such a uniformly automatic class reduces to the decidability of the monadic second-order theory of the set of advices that are used in the presentation. Such decidability results also hold for extensions of first-order logic by regularity preserving quantifiers, such as cardinality quantifiers and Ramsey quantifiers.

To investigate the power of this concept, we present examples of structures and classes of structures that are automatic with advice but not without advice, and we prove classification theorems for the structures with an advice automatic presentation for several algebraic domains. In particular, we prove that the class of all torsion-free Abelian groups of rank one is uniformly omega-automatic and that there are uniform omega-tree-automatic presentation of the class of all Abelian groups up to elementary equivalence and the class of all countable divisible Abelian groups. On the other hand we show that every uniformly omega-automatic class of Abelian groups must have bounded rank.

While for certain domains, such as trees and Abelian groups, it turns out that automatic presentations with advice are capable of presenting significantly more complex structures than ordinary automatic presentations, there are other domains, such as Boolean algebras, where this is provably not the case. Further, advice seems not be of much help for representing some particularly relevant examples of structures with decidable theories, most notably the field of reals.

3.2 Generalized Satisfiability Problems via Operator Assignments

Albert Atserias (UPC – Barcelona, ES)

Joint work of Albert Atserias, Phokion G. Kolaitis, Simone Severini
Main reference Albert Atserias, Phokion G. Kolaitis, Simone Severini: "Generalized Satisfiability Problems via Operator Assignments", in Proc. of the Fundamentals of Computation Theory - 21st International Symposium, FCT 2017, Bordeaux, France, September 11-13, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10472, pp. 56–68, Springer, 2017.
URL https://doi.org/10.1007/978-3-662-55751-8_6

Schaefer introduced a framework for generalized satisfiability problems on the Boolean domain and characterized the computational complexity of such problems. We investigate an algebraization of Schaefer's framework in which the Fourier transform is used to represent constraints by multilinear polynomials in a unique way. The polynomial representation of constraints gives rise to a relaxation of the notion of satisfiability in which the values to variables are linear operators on some Hilbert space. For the case of constraints given by a system of linear equations over the two-element field, this relaxation has received considerable attention in the foundations of quantum mechanics, where such constructions as the Mermin-Peres magic square show that there are systems that have no solutions in the Boolean domain, but have solutions via operator assignments on some finite-dimensional Hilbert space. We obtain a complete characterization of the classes of Boolean relations for which there is a gap between satisfiability in the Boolean domain and the relaxation of satisfiability via operator assignments. To establish our main result, we adapt the notion of primitive-positive definability (pp-definability) to our setting, a notion that has been used extensively in the study of constraint satisfaction problems. Here, we show that pp-definability gives rise to gadget reductions that preserve satisfiability gaps. We also present several additional applications of this method. In particular and perhaps surprisingly, we show that the relaxed notion of pp-definability in which the quantified variables are allowed to range over operator assignments gives no additional expressive power in defining Boolean relations.

3.3 On computability and tractability for infinite sets

Mikolaj Bojanczyk (University of Warsaw, PL)

Joint work of Mikolaj Bojanczyk, Szymon Toruńcyzk

We propose a definition for computable functions on definable sets. Definable sets are possibly infinite data structures that can be defined using a fixed underlying relational structure. We show that, under suitable assumptions on the underlying structure, a programming language called definable while programs captures exactly the computable functions. Next, we introduce a complexity class called fixed dimension polynomial time, which intuitively speaking describes polynomial computation on definable sets. We show that this complexity class contains all functions computed by definable while programs with suitably defined resource bounds. Proving the converse inclusion would prove that Choiceless Polynomial Time with Counting captures order invariant polynomial time on finite graphs.

3.4 Conservative Extensions in Fragments of First-Order Logic

Carsten Lutz (Universität Bremen, DE)

Joint work of Jean Christoph Jung, Mauricio Martel, Thomas Schneider, Frank Wolter
Main reference Jean Christoph Jung, Carsten Lutz, Mauricio Martel, Thomas Schneider, Frank Wolter: "Conservative Extensions in Guarded and Two-Variable Fragments", in Proc. of the 44th International Colloquium on Automata, Languages, and Programming, ICALP 2017, July 10-14, 2017, Warsaw, Poland, LIPIcs, Vol. 80, pp. 108:1–108:14, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
URL http://dx.doi.org/10.4230/LIPIcs.ICALP.2017.108

In the area of description logic (DL), deciding whether a logical theory is a conservative extension of another theory is a fundamental reasoning task with applications in ontology modularity and reuse, ontology versioning, and ontology summarization. It is known that conservative extensions are decidable in many DLs and that they can often be characterized elegantly in term of model theoretic notions. In this talk, we consider the decidability of conservative extensions in more expressive decidable fragments of first-order logic such as the two-variable fragment and the guarded fragment. We show undecidability for these two fragments and decidability for the two-variable guarded fragment. The latter rests on a model-theoretic characterization that is considerably more complex than for many standard DLs.

3.5 Expressive Power of Entity-Linking Frameworks

Ronald Fagin (IBM Almaden Center – San Jose, US)

Joint work of Douglas Burdick, Lucian Popa, Phokion G. Kolaitis, Ronald Fagin, Wang-Chiew Tan
Main reference Douglas Burdick, Ronald Fagin, Phokion G. Kolaitis, Lucian Popa, Wang Chiew Tan: "Expressive Power of Entity-Linking Frameworks", in Proc. of the 20th International Conference on Database Theory, ICDT 2017, March 21-24, 2017, Venice, Italy, LIPIcs, Vol. 68, pp. 10:1–10:18, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
URL http://dx.doi.org/10.4230/LIPIcs.ICDT.2017.10

We develop a unifying approach to declarative entity linking by introducing the notion of an entity linking framework and an accompanying notion of the certain links in such a framework. In an entity linking framework, logic-based constraints are used to express properties of the desired link relations in terms of source relations and, possibly, in terms of other link relations. The definition of the certain links in such a framework makes use of weighted repairs and consistent answers in inconsistent databases. We demonstrate the modeling capabilities of this approach by showing that numerous concrete entity linking scenarios can be cast as such entity linking frameworks for suitable choices of constraints and weights. By using the certain links as a measure of expressive power, we investigate the relative expressive power of several entity linking frameworks and obtain sharp comparisons. In particular, we show that we gain expressive power if we allow constraints that capture non-recursive collective entity resolution, where link relations may depend on other link relations (and not just on source relations). Moreover, we show that an increase in expressive power also takes place when we allow constraints that incorporate preferences as an additional mechanism for expressing "goodness" of links.

3.6 Machine Learning and Algorithmic Model Theory

Martin Grohe (RWTH Aachen, DE)

Joint work of Martin Grohe, Christof Löding, Martin Ritzert

After giving some general background in machine learning, I introduced a declarative model theoretic framework for learning. Then I talked about recent positive and negative learnability results that we obtained within this framework for learning models defined in first-order and monadic second-order logic.

References

1 Martin Grohe, Christof Löding, and Martin Ritzert. Learning MSO-definable hypotheses on string. In S. Hanneke and L. Reyzin, editors, *Proceedings of the 28th International Conference on Algorithmic Learning Theory*, volume 76 of *Proceedings of Machine Learning Research*, 2017.

2 M. Grohe and M. Ritzert. Learning first-order definable concepts over structures of small degree. In *Proceedings of the 32nd ACM-IEEE Symposium on Logic in Computer Science*, 2017.

3.7 Provenance Analysis for Logic and Games

Erich Grädel (RWTH Aachen, DE)

Provenance analysis for database transformations is used to track the provenance or dependence of computed facts from different input items. For positive query languages, such as (unions of) conjunctive queries or datalog, it has been shown that provenance analysis can been done via interpretations in commutative semirings, to answer questions about the trust in, the cost of, or the required clearance level for derived facts, or the number of derivation trees that are available for establishing such a fact.

We generalize this analysis to logics that include negation, such as full FO and LFP, exploiting connections between logic and games. Beyond the already familiar applications to query evaluation (and hence logic), provenance analysis also has interesting interpretations in finite and infinite games to answer more subtle questions than just who wins the game, such the number or costs of winning strategies, or issues such as confidence and trustin game-theoretic settings. The mathematical basis of this approach are interpretations of logics and games in ω-commutative or absorptive semirings of polynomials or power series.

This is joint work with Val Tannen.

3.8 Dependence logic vs. constraint satisfaction

Lauri Hella (University of Tampere, FI)

Joint work of Lauri Hella, Phokion G. Kolaitis
Main reference Lauri Hella, Phokion G. Kolaitis: "Dependence Logic vs. Constraint Satisfaction", in Proc. of the 25th EACSL Annual Conference on Computer Science Logic, CSL 2016, August 29 - September 1, 2016, Marseille, France, LIPIcs, Vol. 62, pp. 14:1–14:17, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2016.
URL http://dx.doi.org/10.4230/LIPIcs.CSL.2016.14

During the past decade, dependence logic has emerged as a formalism suitable for expressing and analyzing notions of dependence and independence that arise in different scientific areas. The sentences of dependence logic have the same expressive power as those of existential second-order logic, hence dependence logic captures NP on the class of all finite structures. We identify a natural fragment of universal dependence logic and show that, in a precise sense, it captures constraint satisfaction. This tight connection between dependence logic and constraint satisfaction contributes to the descriptive complexity of constraint satisfaction and elucidates the expressive power of universal dependence logic.

3.9 Combinatorial Properties of the Weisfeiler-Leman Algorithm

Sandra Kiefer (RWTH Aachen, DE)

Joint work of Brendan McKay, Ilia Ponomarenko, Pascal Schweitzer, Erkal Selman
Main reference Sandra Kiefer, Ilia Ponomarenko, Pascal Schweitzer: "The Weisfeiler-Leman dimension of planar graphs is at most 3", in Proc. of the 32nd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2017, Reykjavik, Iceland, June 20-23, 2017, pp. 1–12, IEEE Computer Society, 2017.
URL http://dx.doi.org/10.1109/LICS.2017.8005107

The Weisfeiler-Leman algorithm is a combinatorial procedure that plays a crucial role both in theoretical and practical research on the graph isomorphism problem. For every k there is a k-dimensional version of the algorithm, which repeatedly refines a partition of the set of k-tuples of vertices of the input graph. The final partition can often be used to distinguish non-isomorphic graphs and for every pair of graphs, there is some dimension of the algorithm that decides isomorphism of the two graphs. We have established upper bounds on this dimension for some graph classes.

By the famous correspondence by Cai, Fürer and Immerman, a graph is identified by the k-dimensional Weisfeiler-Leman algorithm if and only if it is definable in $C^{(k+1)}$, first order logic with counting and restricted to $k+1$ variables. Thus, our dimension bounds also yield bounds on the logical complexity of the graph classes.

In order to gain a better understanding of its dynamics and precise complexity, we have also studied the number of iterations of the algorithm until stabilization, which corresponds to the quantifier depth of the corresponding counting logic.

In this talk, I gave an introduction to the mechanisms of the algorithm, presented some of our results in this field (see also [1], [2], [3]) and related them to open questions for future work.

References

1 S. Kiefer, P. Schweitzer, and E. Selman. *Graphs Identified by Logics with Counting*. Proceedings of MFCS 2015.

2 S. Kiefer and P. Schweitzer. *Upper Bounds on the Quantifier Depth for Graph Differentiation in First Order Logic*. Proceedings of LICS 2016.
3 S. Kiefer, I. Ponomarenko, and P. Schweitzer. *The Weisfeiler-Leman Dimension of Planar Graphs is at most 3*. Proceedings of LICS 2017.

3.10 Green's Relations in Finite Automata

Manfred Kufleitner (Universität Stuttgart, DE)

Joint work of Lukas Fleischer, Manfred Kufleitner
Main reference Lukas Fleischer, Manfred Kufleitner: "Green's Relations in Finite Transformation Semigroups", in Proc. of the Computer Science - Theory and Applications - 12th International Computer Science Symposium in Russia, CSR 2017, Kazan, Russia, June 8-12, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10304, pp. 112–125, Springer, 2017.
URL https://doi.org/10.1007/978-3-319-58747-9_12

Green's relations are a fundamental tool in the structure theory of semigroups. They can be defined by reachability in the (right/left/two-sided) Cayley graph. The equivalence classes of Green's relations then correspond to the strongly connected components. We study the complexity of Green's relations in semigroups generated by transformations on a finite set. Our first result shows that, in the worst case, the number of equivalence classes is in the same order of magnitude as the number of elements. Another important parameter is the maximal length of a chain of strongly connected components. Our second result (the main contribution) is an exponential lower bound for this parameter. There is a simple construction for an arbitrary set of generators. However, the proof for a constant size alphabet is rather involved. We also investigate the special cases of unary and binary alphabets. All these results are extended to deterministic finite automata and their syntactic semigroups. The technical report is available on arXiv [1].

References

1 Lukas Fleischer, Manfred Kufleitner. *Green's Relations in Finite Transformation Semigroups*. CoRR arXiv, abs/1703.04941, 2017.

3.11 Locality of counting logics

Dietrich Kuske (TU Ilmenau, DE)

Joint work of Dietrich Kuske, Nicole Schweikardt
Main reference Dietrich Kuske, Nicole Schweikardt: "First-Order Logic with Counting: At Least, Weak Hanf Normal Forms Always Exist and Can Be Computed!", CoRR, Vol. abs/1703.01122, 2017.
URL http://arxiv.org/abs/1703.01122

We introduce the logic FOCN($\mathbb{P}$) which extends first-order logic by counting and by numerical predicates from a set $\mathbb{P}$, and which can be viewed as a natural generalisation of various counting logics that have been studied in the literature.

We obtain a locality result showing that every FOCN($\mathbb{P}$)-formula can be transformed into a formula in Hanf normal form that is equivalent on all finite structures of degree at most d. A formula is in Hanf normal form if it is a Boolean combination of formulas describing the neighbourhood around its tuple of free variables and arithmetic sentences

with predicates from $\mathbb{P}$ over atomic statements describing the number of realisations of a type with a single centre. The transformation into Hanf normal form can be achieved in time elementary in d and the size of the input formula. From this locality result, we infer the following applications:

1. The Hanf-locality rank of first-order formulas of bounded quantifier alternation depth only grows polynomially with the formula size.
2. The model checking problem for the fragment FOC($\mathbb{P}$) of FOCN($\mathbb{P}$) on structures of bounded degree is fixed-parameter tractable (with elementary parameter dependence).
3. The query evaluation problem for fixed queries from FOC($\mathbb{P}$) over fully dynamic databases of degree at most d can be solved efficiently: there is a dynamic algorithm that can enumerate the tuples in the query result with constant delay, and that allows to compute the size of the query result and to test if a given tuple belongs to the query result within constant time after every database update.

3.12 Static Analysis of Agent-Based Models

James F. Lynch (Clarkson University – Potsdam, US)

Agent-based models are a class of dynamical systems whose states are populations of discrete elements called agents. The states evolve as the agents interact according to rules which may be probabilistic. Computer scientists have developed languages and software tools for specifying and analysing agent-based models, in particular agent-based models of biochemical reaction networks. One problem they have investigated is how to determine if an agent-based model can be abstracted to a simpler model that preserves relevant aspects of its behavior.

We formalize agent-based models as stochastic processes whose states are metafinite models, and we define a notion of abstraction. Our main results are conditions that imply an abstraction is sound, and further conditions that imply it preserves the Markov property.

This work extends earlier work of the author,

- A Logical Characterization of Individual-Based Models, Proc. 23rd Ann. IEEE Symp. on Logic in Computer Science, 379-390, 2008.

and

- J. Feret, V. Danos, J. Krivine, R. Harmer, and W. Fontana, Internal coarse-graining of molecular systems, Proc. Natl. Acad. Sci. USA, 106, 6453–6458, 2009.
- J. H. Feret, H. Koeppl, and T. Petrov, Stochastic fragments: A framework for the exact reduction of the stochastic semantics of rule-based models, Int. J. of Software and Informatics, 7, 527–604, 2013.
- J. H. Feret,T. Henzinger, H. Koeppl, T. Petrov, Lumpability abstractions of rule-based systems, Theoretical Comp. Sci., 431, 137-164, 2012.

3.13 Common Knowledge? Cayley!

Martin Otto

Joint work of Felix Canavoi, Martin Otto
Main reference Felix Canavoi, Martin Otto: "Common knowledge and multi-scale locality analysis in Cayley structures", in Proc. of the 32nd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2017, Reykjavik, Iceland, June 20-23, 2017, pp. 1–12, IEEE Computer Society, 2017.
URL http://dx.doi.org/10.1109/LICS.2017.8005072

The usual epistemic setting of S5 structures (multi-modal Kripke structures with equivalence relations) forms an elementary class. Up to bisimulation it is first-order interpretable in a dual class of plain vertex-coloured graphs. Bisimilar companions with acyclicity properties that make them suitable for a locality-based Ehrenfeucht-Fraïssé analysis can be obtained in products with Cayley groups of large girth [2]. The extension of this scenario that deals with common knowledge (with accessibility relations for coalitions of agents based on reachability/transitive closures) is inherently non-elementary and seems averse to locality based techniques. Up to bisimulation, however, this common knowledge setting admits a natural and direct algebraic interpretation in Cayley groups. It turns out that (finite) Cayley groups with non-trivial acyclicity properties offer bisimilar companions that lend themselves to a locality based Ehrenfeucht-Fraïssé analysis despite the long-range, multi-scale reachability relations of common knowledge. Characterisation theorems of common knowledge logic based on this approach were presented in [1]; in this talk I would focus on the underlying concepts and methods.

References

1 F. Canavoi and M. Otto. *Common knowledge and multi-scale locality analysis in Cayley structures*. Proceedings of LICS 2017.
2 A. Dawar and M. Otto. *Modal characterisation theorems over special classes of frames*. Annals of Pure and Applied Logic, 161:1–42, 2009.
3 M. Otto. *Modal and guarded characterisation theorems over finite transition systems*. Annals of Pure and Applied Logic, 130:173–205, 2004.
4 M. Otto. *Highly acyclic groups, hypergraph covers and the guarded fragment*. Journal of the ACM, 59:1, 2012.

3.14 Proof Complexity of Constraint Satisfaction Problems

Joanna Ochremiak (University Paris-Diderot, FR)

Joint work of Albert Atserias, Joanna Ochremiak
Main reference Albert Atserias, Joanna Ochremiak: "Proof Complexity Meets Algebra", in Proc. of the 44th International Colloquium on Automata, Languages, and Programming, ICALP 2017, July 10-14, 2017, Warsaw, Poland, LIPIcs, Vol. 80, pp. 110:1–110:14, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
URL http://dx.doi.org/10.4230/LIPIcs.ICALP.2017.110

I showed that the most studied propositional and semi-algebraic proof systems behave well with respect to the standard CSP reductions. As an application I presented two unconditional gap theorems, which say that CSPs that admit small size refutations in some classical proof systems are exactly the CSPs which can be solved by local consistency methods. Finally, I gave examples of proof systems with good behaviour with respect to reductions and simultaneously small size refutations beyond bounded width.

3.15 Rank Logic and Choiceless Polynomial Time

Wied Pakusa (University of Oxford, GB)

The search for a logic which captures polynomial time remains one of the most important challenges in the area of finite model theory. The task is to find a logical system which can express precisely those properties of finite structures, say of finite graphs, that can be decided by polynomial-time algorithms. In my talk I survey recent results about the expressive power of Rank Logic and Choiceless Polynomial Time. To date, these two logics are considered to be the most promising candidates for capturing polynomial time.

3.16 VC-density of nowhere dense graph classes

Sebastian Siebertz (University of Warsaw, PL)

Joint work of Michał Pilipczuk, Sebastian Siebertz, Szymon Toruńczyk
Main reference Michal Pilipczuk, Sebastian Siebertz, Szymon Toruńczyk: "On Wideness and Stability", CoRR, Vol. abs/1705.09336, 2017.
URL http://arxiv.org/abs/1705.09336

The notion of *Vapnik-Chervonenkis dimension*, short *VC-dimension*, was introduced by Vapnik and Chervonenkis [2] and independently by Shelah [9] (a formula has the *independence property* if and only if it has infinite VC-dimension) and has found important applications in statistical learning theory, logic, discrete and computational geometry and many other areas.

Formally, VC-dimension is defined as follows. Let A be a set and let $\mathcal{F} \subseteq \mathcal{P}ow(A)$ be a family of subsets of A. For a set $X \subseteq A$ let $X \cap \mathcal{F} := \{X \cap F : F \in \mathcal{F}\}$. The set X is *shattered by* $\mathcal{F}$ if $X \cap \mathcal{F} = \mathcal{P}ow(X)$. The VC-dimension of $\mathcal{F}$ is the maximum size of a set X that is shattered by $\mathcal{F}$. One of the main uses of VC-dimension is the Sauer-Shelah-Lemma [2, 8, 10], which states that the cardinality of a set family $\mathcal{F}$ on a ground set A with VC-dimension d satisfies $|\mathcal{F}| \leq \sum_{i=0}^{d} \binom{|A|}{i} \in \mathcal{O}(|A|^d)$. This motivates the definition of *VC-density*, which describes the asymptotic growth of finite set families (as the size of the ground set A goes to infinity).

VC-density in model theory studies the asymptotic growth of arbitrary finite definable families. More precisely, let $\psi(\bar{x}, \bar{y})$ be a first-order formula, where $\bar{x}$ is an m-tuple and $\bar{y}$ is an n-tuple of variables. Let $\mathfrak{A}$ be a structure and let A be a set of elements of $\mathfrak{A}$. Then the set of *ψ-types* or *ψ-traces* over A in $\mathfrak{A}$ is the set

$$S_\psi(\mathfrak{A}, A) = \{\{\bar{a} \ \in A^m : \mathfrak{A} \models \psi(\bar{a}, \bar{b})\} : \bar{b} \in V(\mathfrak{A})^n\}.$$

In my talk I will present the following theorem (which will appear in [7]) concerning the number of types in sparse graph classes, which characterizes exactly the monotone graph classes of minimal VC-density.

▶ **Theorem 1.** *Let $\mathcal{C}$ be a class of graphs and let $\psi(\bar{x}, y)$ be a first-order formula, where $\bar{x}$ is an m-tuple and $\bar{y}$ is an n-tuple of variables.*

1. *If $\mathcal{C}$ is nowhere dense, then for every $\epsilon > 0$ there exists a constant c such that for every $G \in \mathcal{C}$ and every $A \subseteq V(G)$, we have $|S_\psi(A, G)| \leq c \cdot |A|^{n+\epsilon}$.*

2. *If $\mathcal{C}$ has bounded expansion, then there exists a constant c such that for every $G \in \mathcal{C}$ and every $A \subseteq V(G)$, we have $|S_\psi(A, G)| \leq c \cdot |A|^n$.*

The main tools applied to prove the theorem are Gaifman's Locality Theorem [5], a closure lemma developed in [3, 4] and new bounds characterizing nowhere dense graph classes as uniform quasi-wide [6, 7]. Our result generalizes the recent result of Bobkov [1] that nowhere dense classes are dp-minimal (a notion define by Shelah in [11]).

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3.17 Finite and Algorithmic Model Theory

Dan Suciu (University of Washington – Seattle, US)

Joint work of Mahmoud Abo Khamis, Hung Q. Ngo, Dan Suciu
Main reference Mahmoud Abo Khamis, Hung Q. Ngo, Dan Suciu: "What Do Shannon-type Inequalities, Submodular Width, and Disjunctive Datalog Have to Do with One Another?", in Proc. of the 36th ACM SIGMOD-SIGACT-SIGAI Symposium on Principles of Database Systems, PODS 2017, Chicago, IL, USA, May 14-19, 2017, pp. 429–444, ACM, 2017.
URL http://dx.doi.org/10.1145/3034786.3056105

We survey the following topics connecting finite model theory and algorithms: tree decomposition of conjunctive queries, upper bounds for full conjunctive queries, worst case optimal algorithms for conjunctive queries, and the submodular width and associated algorithms for Boolean conjunctive queries.

3.18 The Fluted Fragment Revisited

Lidia Tendera (University of Opole, PL)

Joint work of I. Pratt-Hartmann, W. Szwast, L. Tendera
Main reference Ian Pratt-Hartmann, Wieslaw Szwast, Lidia Tendera: "Quine's Fluted Fragment is Non-Elementary", in Proc. of the 25th EACSL Annual Conference on Computer Science Logic, CSL 2016, August 29 - September 1, 2016, Marseille, France, LIPIcs, Vol. 62, pp. 39:1–39:21, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2016.
URL https://doi.org/10.4230/LIPIcs.CSL.2016.39

We revisit the fluted fragment (FL) of first-order logic, originally identified by Quine, in which the order of quantification of variables matches their order of appearance as arguments to predicates. Fluted formulas arise naturally as first-order translations of quantified English sentences in which no quantifier-rescoping occurs. Also Boolean modal logic maps, under the standard first-order translations, to FL. However, even the two-variable restriction of FL is not contained in other decidable fragments of first-order logic identified by considering the standard translation of modal logic (e.g. guarded fragment, unary negation fragment or guarded negation fragment).

In [P-HST 16] we have shown that the satisfiability problem for this fragment has non-elementary complexity; more precisely, we consider, for all m greater than 1, the intersection of the fluted fragment and the m-variable fragment of first-order logic. We showed that this subfragment forces (m/2)-tuply exponentially large models, and that its satisfiability problem is (m/2)-NExpTime-hard. We rounded off showing that the m-variable fluted fragment has the m-tuply exponential model property, and that its satisfiability problem is in m-NExpTime.

We are interested in seeing if there are other useful applications of FL or of its restrictions to some bounded number of variables (greater than two).

3.19 On Monadic Transitive Closure Logic MTC

Wolfgang Thomas (RWTH Aachen, DE)

Monadic transitive closure Logic MTC is the extension of first-order logic by the construct that allows to pass from a formula $F(x, y)$ to $F^*(x, y)$, expressing that a path from x to y exists where each step is accordance with F. Parameters are also admitted; then one proceeds from $F(x, y, z_1, ..., z_n)$ to $F^*(x, y, z_1, ..., z_n)$. MTC is a very natural logic for expressing reachability properties. We survey results on the expressive power of MTC over the domains of finite words, finite ranked trees, and (labelled or unlabelled) finite two-dimensional grids. Over words, precisely the regular languages are definable in MTC (and it is open whether in general a nesting of the MTC-operator is necessary). Over trees, MTC is located strictly between tree-walking automata and standard tree automata (as shown in results of Bojanczyk, Colcombet, Segoufin, ten Cate, and others). Over grids the power of MTC is not yet clear; we are lacking a good method to establish non-definability results for MTC. Such a method is needed – for example – to show that there are sets of unlabelled grids that are definable in existential monadic second-order logic EMSO but not in MTC; an example suggested by N. Schweikardt is the set of unlabelled grids of dimensions $n \times 2^n$. The definability in EMSO is clear by expressing a 0-1-labelling of the grid columns that represents a binary counter from 0 to $(2^n) - 1$.

3.20 Sparsity and Stability

Szymon Torunczyk (University of Warsaw, PL)

Joint work of Sebastian Siebertz, Michał Pilipczuk
Main reference Michal Pilipczuk, Sebastian Siebertz, Szymon Toruńczyk: "On Wideness and Stability", CoRR, Vol. abs/1705.09336, 2017.
URL http://arxiv.org/abs/1705.09336

I will talk about some recent developments in the study of the connections between nowhere-denseness (introduced by Nesetril and Ossona de Mendez), uniform quasi-wideness (introduced by Dawar) and stability (developed by Shelah).

The slides are available at https://www.mimuw.edu.pl/~szymtor/talks/dag17/stability.html.

3.21 Descriptive complexity of arithmetic circuit classes

Heribert Vollmer (Leibniz Universität Hannover, DE)

Joint work of Arnaud Durand, Anselm Haak, Juha Kontinen, Heribert Vollmer

We study the class $\#AC^0$ of functions computed by constant-depth polynomial-size arithmetic circuits of unbounded fan-in addition and multiplication gates. Inspired by Immerman's characterization of the Boolean class AC^0, we develop a model-theoretic characterization of

$\#AC^0$, which can be interpreted as follows: Functions in $\#AC^0$ are exactly those functions counting winning strategies in first-order model checking games.

Extending this, we introduce a new framework for a descriptive complexity approach to arithmetic computations. We define a hierarchy of classes based on the idea of counting assignments to free function variables in first-order formulas. We completely determine the inclusion structure and show that $\#P$ and $\#AC^0$ appear as classes of this hierarchy. In this way, we unconditionally place $\#AC^0$ properly in a strict hierarchy of arithmetic classes within $\#P$. We determine which classes in the hierarchy are feasible.

3.22 Dynamic Complexity: What we can do

Nils Vortmeier (TU Dortmund, DE)

Joint work of Samir Datta, Raghav Kulkarni, Anish Mukherjee, Thomas Schwentick, Nils Vortmeier, Thomas Zeume
Main reference Samir Datta, Anish Mukherjee, Thomas Schwentick, Nils Vortmeier, Thomas Zeume: "A Strategy for Dynamic Programs: Start over and Muddle Through", in Proc. of the 44th International Colloquium on Automata, Languages, and Programming, ICALP 2017, July 10-14, 2017, Warsaw, Poland, LIPIcs, Vol. 80, pp. 98:1–98:14, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
URL http://dx.doi.org/10.4230/LIPIcs.ICALP.2017.98
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DynFO, as defined by Patnaik and Immerman, is the class of queries that can be dynamically maintained using first-order logic to update the query result and possibly further auxiliary relations, whenever the input changes. Recently, several interesting maintainability results were obtained. For example, it was shown that the following queries are in DynFO:

- Reachability in arbitrary directed graphs
- Undirected reachability under first-order defined insertions
- MSO-definable queries on graphs with bounded treewidth

In this talk, I will give an overview of these developments. The talk is complemented by the talk by Thomas Zeume on lower bounds in dynamic complexity.

3.23 Hanf Locality and Invariant Elementary Definability

Scott Weinstein (University of Pennsylvania, US)

Joint work of Steven Lindell, Henry Towsner, Scott Weinstein

We introduce some notions of invariant elementary definability which extend the notions of first-order order-invariant definability, and, more generally, definability invariant with respect to arbitrary numerical relations. In particular, we study invariance with respect to

expansions which depend not only on (an ordering of) the universe of a structure, but also on the particular relations which determine the structure; we call such expansions presentations of a structure. We establish two locality results in this context. The first is an extension of the original Hanf Locality Theorem to boolean queries which are invariantly definable over classes of locally finite structures with respect to elementary, neighborhood-bounded presentations. The second is a non-uniform version of the Fagin-Stockmeyer-Vardi Hanf Threshold Locality Theorem to boolean queries which are invariantly definable over classes of bounded degree structures with respect to elementary, neighborhood-bounded, local presentations.

3.24 Symmetric Circuits for Rank Logic

Gregory Wilsenach (University of Cambridge, GB)

Joint work of Anuj Dawar, Gregory Wilsenach

Anderson and Dawar (2014) showed that fixed-point logic with counting (FPC) can be characterised by uniform families of polynomial-size symmetric circuits. We give a similar characterisation for fixed-point logic with rank (FPR) by means of symmetric circuits including rank gates. This analysis requires a significant extension of previous methods to deal with gates computing Boolean functions which are not themselves symmetric. In particular, we show that the support theorem of Anderson and Dawar can be extended to circuits whose gates satisfy a property that we term "matrix-symmetry".

3.25 Dynamic Complexity: What we cannot do

Thomas Zeume (TU Dortmund, DE)

Joint work of Thomas Schwentick, Nils Vortmeier, and Thomas Zeume
Main reference Thomas Zeume: "The dynamic descriptive complexity of k-clique", Inf. Comput., Vol. 256, pp. 9–22, 2017.
URL http://dx.doi.org/10.1016/j.ic.2017.04.005
Main reference Thomas Zeume, Thomas Schwentick: "On the quantifier-free dynamic complexity of Reachability", Inf. Comput., Vol. 240, pp. 108–129, 2015.
URL http://dx.doi.org/10.1016/j.ic.2014.09.011

In the dynamic descriptive complexity framework of Patnaik and Immerman, the result of a database query is updated by logical formulas after the insertion or deletion of tuples. The formulas may use additional auxiliary relations that need to be updated as well.

In this talk I will discuss the current status of proving lower bounds in this dynamic context. The talk complements the talk by Nils Vortmeier on recent upper bounds in dynamic complexity.

4 Open problems

4.1 An open problem on gaps for vertex cover

Albert Atserias (UPC – Barcelona, ES)

In short, the open problem is this: Find pairs of graphs with the same numbers of vertices, one of which does not have vertex covers that are significantly smaller than the set of all vertices, the second of which does have vertex covers of size about half the number vertices, and yet the two graphs are indistinguishable by k-variable first-order logic with counting quantifiers for large values of k.

Problem Statement

Prove (or disprove) that, for every positive integer k and every positive real ϵ there exist infinitely many positive integers n, and pairs of n-vertex graphs G_n and H_n, that satisfy the following conditions:

1. every vertex cover of G_n has size at least $(1-\epsilon)n$,
2. some vertex cover of H_n has size at most $(1/2+\epsilon)n$, and
3. $G_n \equiv_{\mathrm{C}^k} H_n$, where $\equiv_{\mathrm{C}^k}$ denotes indistinguishability by k-variable counting logic C^k.

A vertex cover in a graph is a set of vertices that touches all the edges. Counting logic is the smallest class of formulas that contains the atomic formulas and is closed under negation, disjunction, and counting quantifiers of the type $\exists^{\geq t}x$ for some positive integer t. The meaning of $\exists^{\geq t}x$ is that there are at least t many witnesses for x. In the k-variable fragment of counting logic, denoted by C^k, all variables are in $x_1,\ldots,x_k$ (and can be reused).

Background

For $k \leq 2$ the problem is solved [3], but the problem is open even for $k = 3$. A variant of the question asks for the fastest growing integer function $k(n)$ for which for every ϵ there exist infinitely many n, and n-vertex graphs G_n and H_n, that satisfy all three conditions with the third replaced by $G_n \equiv_{\mathrm{C}^{k(n)}} H_n$. If C^k is replaced by standard k-variable first-order logic L^k, then the problem is solved for any $k = o(\log n)$ [3].

Back to C^k, the problem was first raised in [4, 5, 2] as a way of proving that, on n-vertex graphs, the Sherali-Adams hierarchy of LP relaxations requires $\Omega(k)$ many levels to be able to improve over the 2-approximation factor that is achieved by the standard LP relaxation of vertex cover. This specific consequence is known to be true for any $k = n^{o(1)}$ [6]. The work in [7] shows that the solution to the problem as stated would imply that any fixed number of levels of the Lasserre hierarchy of SDP relaxations fails to improve over the 2-approximation factor. Unlike the Sherali-Adams hierarchy, this limitation of the Lasserre hierarchy is an open problem even for fixed but small numbers of levels.

The PCP Theorem implies that the size of the minimum vertex cover is NP-hard to approximate within some constant $c > 1$ [1], which has been shown to be at least 1.36 [8], and the Unique Games Conjecture implies the problem is NP-hard to approximate within any constant that is smaller than 2 [9].

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4.2 Some open problems regarding (quasi-)monotone arithmetic circuits for expressing positive integers

Kousha Etessami (University of Edinburgh, GB)

A "hard" problem

[Allender, Bürgisser, Kjeldgaard-Pedersen, Miltersen,2006]:

PosSLP: Given an *arithmetic circuit* (Straight Line Program) with gates $\{+, *, -\}$, with integer inputs, decide whether the output is > 0.

PosSLP basically captures all of polynomial time in the unit-cost arithmetic RAM model of computation.

▶ **Theorem 1** ([ABKM'06]). *There is a P-time (Turing) reduction from the* ***square-root sum problem*** *to PosSLP, and PosSLP can be decided in the* Counting Hierarchy*: $P^{P^{P^{P^{P^{P}}}}}$.*

(Nothing better is known as an upper bound or lower bound for PosSLP.)

Some open problems

Question: Can we obtain better complexity bounds for PosSLP?

Here is a very basic approach: Given a $\{+,*,-\}$-circuit, C , guess a monotone $\{+,*\}$-circuit, C', as a "witness of positivity", and verify $\mathrm{val}(C - C') = 0$ in co-RP, where $\mathrm{val}(C)$ is the value of the output of the circuit. (Checking equality to 0 is ACIT-equivalent ([ABKM'06]). ACIT is a variant of polynomial identify testing, where the polynomial is represented by a circuit, and ACIT is decidable in co-RP.) For $a \in \mathbb{N}$, let $\tau(a)$ denote size of smallest $\{+,*,-\}$-circuit expressing a. Let $\tau_+(a)$ denote size of smallest monotone $\{+,*\}$-circuit expressing a.

▶ **Conjecture 2** ("τ vs. τ^+ Conjecture"). *This approach does not work. In other words there exists a family $\langle a_n \rangle_{n\in\mathbb{N}}$ of positive integers, such that $\tau(a_n) \in O(n)$, but such that for some fixed constant $c > 0$ $\tau_+(a_n) \in 2^{\Omega(n^c)}$.*

▶ Remark (Valiant'79). proved an exponential lower bound separating the power of monotone vs. non-monotone circuits for expressing families of monotone polynomials (namely, the perfect matching polynomials for planar graphs). This does not imply any lower bounds in the integer setting (at least not in any direct way).

The current state of knowledge for Conjecture 1 is abismal: [Saranurak-Jindal'12] show there is an infinite family of positive numbers (namely $a_n := 2^{2^n} - 1$), such that $\tau_+(a_n) \geq \tau(a_n) + 1$.

It seems "obvious" that much better lower bounds should be possible for "harder" families of numbers. (But not for $a_n = 2^{2^n} - 1$ itself: we easily have $\tau_+(a_n) \leq 2n + 1$ for these.) In fact (joint work with [P. Sinclair, undergraduate thesis project, U. of Edinburgh, 2016]): if some seemingly plausible number-theoretic conjectures hold, then one can (very slightly) improve on the additive $\tau_+(a_n) \geq \tau(a_n) + 1$ lower bound by [Saranurak-Jindal'12], making it $\tau_+(a_n) \geq \tau(a_n) + 3$. (But of course this is nowhere near what we need to establish Conjecture 1. At this point even a super-linear lower bound would be a mini-breakthrough.)

A potentially better approach

Definition: call an arithmetic circuit, C, *quasi-monotone* if it consists of some arbitrary $\{+,*,-\}$-subcircuits, C_i, $i = 1,\ldots,k$, whose *squares* $(C_i)^2$ are the only inputs to a monotone $\{+,*\}$-circuit, C', whose output gate gives the output value of the entire circuit C.

Note: these circuits generalize both monotone circuits and sums of squares (S.O.S.).

Better approach for attempting to improve the complexity of PosSLP: Given a $\{+,*,-\}$-circuit, C , guess a pair of quasi-monotone circuits C' and C'' as a "witness of positivity" for C , & verify the equality $\mathrm{val}((C'' + 1) * C - C') = 0$, which can be done in co-RP.

Here is a **very optimistic** conjecture:

▶ **Conjecture 3** ("Very effective Positivestellensatz for integers"). *This works: there exists a polynomial $p(x)$, such that for any $a \in \mathbb{N}$ with $\tau(a) = n$, there exist quasi-monotone circuits C'_a and C''_a, such that* $\mathtt{size}(C'_a) \leq p(n)$ *and* $\mathtt{size}(C''_a) \leq p(n)$*, and such that*

$$a = \frac{\mathrm{val}(C'_a)}{\mathrm{val}(C''_a + 1)} \ .$$

If true, this conjecture would of course imply that PosSLP $\in$ **MA**.
This would be a big improvement over the current best known upper bound, which is in the counting hierarchy.
(I first presented these conjectures at a workshop in Princeton, in honor of Yannakakis's 60th birthday, in 2013. I thought there would be a lot more progress by now.)

4.3 Limit laws for random expansions of product structures

Erich Grädel (RWTH Aachen, DE)

Joint work of Faried Abu Zaid, Erich Grädel, Anuj Dawar, Matthias Hoelzel, Wied Pakusa

Let $\mathfrak{A}$ be a finite structure with a finite (not necessarily relational) vocabulary σ, and let τ be another finite relational vocabulary with $\sigma \cap \tau = \emptyset$. For each n, let $\mathfrak{A}^n$ be the n-fold product of $\mathfrak{A}$, defined in the usual way. We consider the probability spaces $S^n_\tau(\mathfrak{A})$ consisting of all $\sigma \cup \tau$-expansions of $\mathfrak{A}^n$, with the uniform probability distribution.

For every sentence $\psi \in \mathrm{FO}(\sigma \cup \tau)$, let $\mu_n(\psi)$ denote the probability that a randomly chosen structure $\mathfrak{B} \in S^n_\tau$ is a model of ψ.

Problem: *Give a complete classification of those finite structures $\mathfrak{A}$ for which the following limit law holds: For every finite relational vocabulary τ and for every sentence $\psi \in \mathrm{FO}(\sigma \cup \tau)$ there exists a (dyadic rational) number q such that*

$$\lim_{n\to\infty} \mu_n(\psi) = q.$$

Partial answers. We have proved in [1] that such a limit law holds for $\mathfrak{A} = (\mathbb{Z}_p, +, 0)$, for any prime p, not just for FO but also for $L^\omega_{\infty\omega}$. The proof generalizes the classical techniques, based on extension axioms, for proving the 0-1 law for FO and $L^\omega_{\infty\omega}$ on random graphs and random finite relational structures. As a consequence (and this was the motivation for considering this problem) it follows that the summation problem for Abelian groups is not definable in LFP, see [1]. I then conjectured that such a limit law might in fact hold for *any* finite structure $\mathfrak{A}$.

However, this fails dramatically: Mathias Hoelzel (unpublished) has proved that no such limit law holds even in the very simple case where $\mathfrak{A} = (\{0, 1\}, \leq)$. Indeed, based on Kaufmann's proof of the nonconvergence law for monadic second-order logic on random finite structures [2], one can show that there is a first-order formula $\phi(x, y)$ of a vocabulary $\{\leq\} \cup \tau$, that almost surely defines a linear order on $S^n_\tau(\mathfrak{A})$, as n goes to ∞. From this one easily obtains a sentence ψ which, for growing n, almost surely expresses that n is even, and which hence has no asymptotic probability on the spaces $S^n_\tau(\mathfrak{A})$.

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4.4 Counting/Decision for FO

Dan Suciu (University of Washington – Seattle, US)

URL http://materials.dagstuhl.de/files/17/17361/17361.DanSuciu1.Slides.pptx

We propose an open problem on probabilistic inference over symmetric structures.

4.5 Intermediate size lower bounds for set-containment join in the relational algebra with aggregates

Jan Van den Bussche (Hasselt University, BE)

The relational algebra with aggregates extends first-order logic with arithmetic functions and aggregate operators [1]. In the standard relational algebra, without arithmetic or aggregates (but order comparisons are allowed), it is known that every expression for testing nonemptiness of the set-containment join must produce intermediate results of quadratic size [2]. It is an open question whether this also holds for the relational algebra with aggregates.

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4.6 Some Questions about Invariant Definability

Scott Weinstein (University of Pennsylvania, US)

In my talk at the Dagstuhl Seminar on "Finite and Algorithmic Model Theory," entitled *Hanf Locality and Elementary Invariant Definability* (based on work joint with Steven Lindell and Henry Towsner), I posed some questions about the strength of invariant definability over restricted classes o f structures. Let $\mathcal{F}^d$ be the collection of finite structures over some fixed finite relational signature τ whose Gaifman graphs are of degree $< d \leq \omega$, (so $\mathcal{F}^\omega$ is the collection of all finite τ-structures) and let $\mathcal{K}^\omega$ be the collection of all structures whose Gaifman graphs are *locally finite*, that is, the degree of every node in the Gaifman graph of the structure is finite. A *local order* on a structure A is a ternary relation $\prec (x, y, z)$ on the universe $|\mathsf{A}|$ of A such that for every $a \in |\mathsf{A}|$, the binary relation $\prec (a, y, z)$ linearly orders the neighbors of a in the Gaifman graph of A. For a given class of τ-structures $\mathcal{C}$, we write $\mathbf{FO}[\mathcal{C}]$ for the collection of boolean queries over $\mathcal{C}$ that are defined by first-order τ-sentences, $\mathbf{FO}(<)[\mathcal{C}]$ for the collection of boolean queries over $\mathcal{C}$ that are defined by first-order $\tau \cup \{<\}$-sentences that are order-invariant over $\mathcal{C}$, and $\mathbf{FO}(\prec)[\mathcal{C}]$ for the collection of boolean queries over $\mathcal{C}$ that are defined by first-order $\tau \cup \{\prec\}$-sentences that are local-order-invariant over $\mathcal{C}$. We posed the following questions.

1. For all $d < \omega$, $\mathbf{FO}(<)[\mathcal{F}^d] = \mathbf{FO}[\mathcal{F}^d]$?
   (It is well-known that $\mathbf{FO}(<)[\mathcal{F}^\omega] \neq \mathbf{FO}[\mathcal{F}^\omega]$.)
2. For all $d \leq \omega$, $\mathbf{FO}(\prec)[\mathcal{F}^d] = \mathbf{FO}[\mathcal{F}^d]$?
   (Of course, it may be that the answer is different for $d < \omega$ and for ω, as some anticipate is the case for question 1.)
3. $\mathbf{FO}(<)[\mathcal{K}^\omega] = \mathbf{FO}[\mathcal{K}^\omega]$?
4. $\mathbf{FO}(\prec)[\mathcal{K}^\omega] = \mathbf{FO}[\mathcal{K}^\omega]$?

Participants

- Faried Abu Zaid
TU Ilmenau, DE
- Albert Atserias
UPC – Barcelona, ES
- Christoph Berkholz
HU Berlin, DE
- Dietmar Berwanger
ENS – Cachan, FR
- Mikolaj Bojanczyk
University of Warsaw, PL
- Thomas Colcombet
University Paris-Diderot, FR
- Claire David
University Paris-Est – Marne-la-Vallée, FR
- Anuj Dawar
University of Cambridge, GB
- Arnaud Durand
Paris Diderot University, FR
- Kousha Etessami
University of Edinburgh, GB
- Ronald Fagin
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- Phokion G. Kolaitis
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- Dietrich Kuske
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Universität Bremen, DE
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University of Pennsylvania, US
- Gregory Wilsenach
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- Thomas Zeume
TU Dortmund, DE

Report from Dagstuhl Seminar 17371

Deduction Beyond First-Order Logic

Edited by

Jasmin Christian Blanchette[1], Carsten Fuhs[2], Viorica Sofronie-Stokkermans[3], and Cesare Tinelli[4]

1 **Vrije Universiteit Amsterdam, NL,** j.c.blanchette@vu.nl
2 **Birkbeck, University of London, GB,** carsten@dcs.bbk.ac.uk
3 **Universität Koblenz-Landau, DE,** sofronie@uni-koblenz.de
4 **The University of Iowa – Iowa City, US,** cesare-tinelli@uiowa.edu

Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 17371 "Deduction Beyond First-Order Logic." Much research in the past two decades was dedicated to automating first-order logic with equality. However, applications often need reasoning beyond this logic. This includes genuinely higher-order reasoning, reasoning in theories that are not finitely axiomatisable in first-order logic (such as those including transitive closure operators or standard arithmetic on integers or reals), or reasoning by mathematical induction. Other practical problems need a mixture of first-order proof search and some more advanced reasoning (for instance, about higher-order formulas), or simply higher-level reasoning steps. The aim of the seminar was to bring together first-order automated reasoning experts and researchers working on deduction methods and tools that go beyond first-order logic. The seminar was dedicated to the exchange of ideas to facilitate the transition from first-order to more expressive settings.

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1 Executive Summary

Jasmin Christian Blanchette
Carsten Fuhs
Viorica Sofronie-Stokkermans
Cesare Tinelli

Much research on automated deduction has traditionally focused on automated reasoning in first-order logic. First-order logic with equality is generally considered a sweet spot on the logic design continuum. Yet, from the point of view of several applications it can be too restrictive as a modeling and reasoning tool. In recent years, there has been a realization that while first-order reasoning is very useful to discharge the bulk of proof obligations, it must be tightly integrated with richer features to be useful in many applications. Practical

problems often need a mixture of first-order proof search and some more advanced reasoning, for instance, about non-first-order-axiomatisable theories, higher-order formulas, or simply higher-level reasoning steps.

First-order logic cannot be used to finitely axiomatize many interesting theories, such as those including transitive closure operators, inductive predicates, datatypes, and standard arithmetic on integers or reals. Even provers that provide native support for some of these theories typically fail to prove trivial-looking problems because they lack general support for mathematical induction. Some applications need a richer set of constructs than those provided by first-order logic such as, for instance, the separating conjunction ($*$) and magic wand ($-\!\!*$) connectives of Separation Logic or the disjunctive well-foundedness predicates used in HSF, a popular approach to software model checking based on first-order Horn logic.

There are potential synergies between automatic first-order proving and verification methods developed in the context of richer logics. However, they have not received enough attention by the various deduction sub-communities so far. In general, there is a cultural gap between the various deduction communities that hinders cross-fertilization of ideas and progress.

This Dagstuhl Seminar brought together experts in automated reasoning in first-order logic and researchers working on deduction methods and tools that go beyond first-order logic. The latter included specialists on proof methods for induction, proof planning, and other higher-order or higher-level procedures; and consumers of deduction technology whose specification languages contain non-first-order features. The main goal of the seminar was to exchange ideas and explore ways to facilitate the transition from first-order to more expressive settings.

Research questions that were discussed and answered at the seminar included the following:

- What higher-order features do applications need, and what features can be incorporated smoothly in existing first-order proof calculi and provers?
- How can we best extend first-order reasoning techniques beyond first-order logic?
- Can proof-assistant-style automation and first-order reasoning techniques be combined in a synergetic fashion?
- What are good strategies for automatic induction and coinduction or invariant synthesis?
- Is a higher layer of reasoning, in the spirit of proof planning, necessary to solve more difficult higher-order problems?

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3 Overview of Talks

3.1 What QFBAPA can do for Description Logics

Franz Baader (TU Dresden, DE)

Joint work of Franz Baader, Andreas Ecke
Main reference Franz Baader, Andreas Ecke: "Extending the Description Logic ALC with More Expressive Cardinality Constraints on Concepts", in Proc. of the 3rd Global Conf. on Artificial Intelligence (GCAI 2017), EPiC Series in Computing, Vol. 50, pp. 6–19, EasyChair, 2017.
URL http://dx.doi.org/10.29007/f3hh

Considered from an abstract point of view, Description Logics (DLs) allow their users to state inclusion constraints between concepts (i.e., sets) and to state cardinality constraints for concepts and role successors. The constraints that can be formulated in DLs are usually of a very restricted form. We show that, by using the quantifier-free fragment of Boolean Algebra with Presburger Arithmetic (QFBAPA) to formulate constraints on sets and their cardinalities, we can considerably extend the expressive power without increasing the complexity of reasoning.

3.2 Automating Free Logic in HOL, with an Experimental Application in Category Theory

Christoph Benzmüller (FU Berlin, DE)

Joint work of Christoph Benzmüller, Dana S. Scott
Main reference Christoph Benzmüller, Dana S. Scott: "Axiomatizing Category Theory in Free Logic", CoRR, Vol. abs/1609.01493, 2016.
URL http://arxiv.org/abs/1609.01493

A shallow semantical embedding of free logic in classical higher-order logic is presented, which enables the off-the-shelf application of higher-order interactive and automated theorem provers for the formalisation and verification of free logic theories. Subsequently, this approach is applied to a selected domain of mathematics: starting from a generalization of the standard axioms for a monoid a stepwise development of various, mutually equivalent foundational axiom systems for category theory is presented. As a side-effect of this work some (minor) issue in a prominent category theory textbook has been revealed.

The purpose of this work is not to claim any novel results in category theory, but to demonstrate an elegant way to "implement" and utilize interactive and automated reasoning in free logic, and to present illustrative experiments.

References

1 Christoph Benzmüller and Dana Scott. Automating free logic in Isabelle/HOL. In G.-M. Greuel, T. Koch, P. Paule, and A. Sommese, editors, *Mathematical Software – ICMS 2016, 5th International Congress, Proceedings*, volume 9725 of *LNCS*, pages 43–50, Berlin, Germany, 2016. Springer. URL: http://christoph-benzmueller.de/papers/C57.pdf, doi:10.1007/978-3-319-42432-3_6.

2 Christoph Benzmüller and Dana S. Scott. Axiomatizing category theory in free logic. *arXiv, http://arxiv.org/abs/1609.01493*, 2016.

3 Christoph Benzmüller. Universal Reasoning, Rational Argumentation and Human-Machine Interaction. *arXiv, http://arxiv.org/abs/1703.09620*, 2017.

3.3 Towards Strong Higher-Order Automation for Fast Interactive Verification

Jasmin Christian Blanchette (Vrije Universiteit Amsterdam, NL)

We believe that first-order automatic provers are the best tools available to perform most of the tedious logical work inside proof assistants. From this point of view, it seems desirable to enrich superposition and SMT (satisfiability modulo theories) with higher-order reasoning in a careful manner, to preserve their good properties. Representative benchmarks from the interactive theorem proving community can guide the design of proof rules and strategies. With higher-order superposition and higher-order SMT in place, highly automatic provers could be built on modern superposition provers and SMT solvers, following a stratified architecture reminiscent of that of modern SMT solvers. We hope that these provers will bring a new level of automation to the users of proof assistants. These challenges and work plan are at the core of the Matryoshka project, funded for five years by the European Research Council. We encourage researchers motivated by the same goals to get in touch with us, subscribe to our mailing list, and join forces.

3.4 Building a Proof Checker with Partial Functions

Hans de Nivelle (University of Wroclaw, PL)

Main reference Hans de Nivelle: "Theorem proving for classical logic with partial functions by reduction to Kleene logic", J. Log. Comput., Vol. 27(2), pp. 509–548, 2017.
URL http://dx.doi.org/10.1093/logcom/exu071

In 2010–2013 I developed a 3-valued logic for partial functions. During 2013–2014, I tried to integrate this logic into an interactive proof checker. This attempt was unsuccessful. The system worked, but the main goal, to obtain a truly user friendly proof checker, was not obtained. In this talk, I summarize a new attempt, which has not been implemented yet, hoping to get feedback. I discuss the following components:

- The basics of the underlaying 3-valued logic and how to generalize this logic to higher-order.
- How I think that one should build theories (using the little theory approach of Farmer, Guttman and Thayer). Theories can be substantive or adjective in nature.
- Type Reductions. Explicit type conditions are useful, but turned out unpleasant in practical use, especially in higher-order. I explain how conventional, more user-friendly type declarations can be translated into explicit type declarations by means of reduction.

3.5 Scalable Fine-Grained Proofs for Formula Processing

Pascal Fontaine (LORIA & Inria – Nancy, FR)

Joint work of Haniel Barbosa, Jasmin Christian Blanchette, Simon Cruanes, Daniel El Ouraoui, Pascal Fontaine
Main reference Haniel Barbosa, Jasmin Christian Blanchette, Pascal Fontaine: "Scalable Fine-Grained Proofs for Formula Processing", in Proc. of the Automated Deduction - CADE 26 - 26th International Conference on Automated Deduction, Gothenburg, Sweden, August 6-11, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10395, pp. 398–412, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-319-63046-5_25

We presented a framework for processing formulas in automatic theorem provers, with generation of detailed proofs. The main components are a generic contextual recursion algorithm and an extensible set of inference rules. Clausification, skolemization, theory-specific simplifications, and expansion of 'let' expressions, and beta-reduction are instances of this framework. With suitable data structures, proof generation adds only a linear-time overhead, and proofs can be checked in linear time. We implemented the approach in the SMT solver veriT. This allowed us to dramatically simplify the code base while increasing the number of problems for which detailed proofs can be produced, which is important for independent checking and reconstruction in proof assistants. This talk presented material accepted at CADE 2017 and at PxTP 2017.

3.6 Harnessing First Order Termination Provers Using Higher Order Dependency Pairs

Carsten Fuhs (Birkbeck, University of London, GB)

Joint work of Carsten Fuhs, Cynthia Kop
Main reference Carsten Fuhs, Cynthia Kop: "Harnessing First Order Termination Provers Using Higher Order Dependency Pairs", in Proc. of the Frontiers of Combining Systems, 8th International Symposium, FroCoS 2011, Saarbrücken, Germany, October 5-7, 2011. Proceedings, Lecture Notes in Computer Science, Vol. 6989, pp. 147–162, Springer, 2011.
URL https://doi.org/10.1007/978-3-642-24364-6_11

Many functional programs and higher order term rewrite systems contain, besides higher order rules, also a significant first order part. We discuss how an automatic termination prover can split a rewrite system into a first order and a higher order part. The results are applicable to all common styles of higher order rewriting with simple types, although some dependency pair approach is needed to use them.

This talk is based on joint work with Cynthia Kop. A corresponding paper has appeared in the proceedings of FroCoS 2011.

3.7 Automated Complexity Analysis for Java Programs

Jürgen Giesl (RWTH Aachen, DE) and Florian Frohn

Joint work of Florian Frohn, Jürgen Giesl
Main reference Florian Frohn, Jürgen Giesl: "Complexity Analysis for Java with AProVE", in Proc. of the Integrated Formal Methods - 13th International Conference, IFM 2017, Turin, Italy, September 20-22, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10510, pp. 85–101, Springer, 2017.
URL https://doi.org/10.1007/978-3-319-66845-1_6

Automated termination analysis is an important area in program verification which goes beyond classical first-order reasoning. While AProVE is one of the most powerful tools for termination analysis of Java since many years, we now extend our technique in order to analyze the complexity of Java programs as well.

Our approach first executes the program symbolically on an abstract domain which uses heap predicates in addition to the usual first-order constructs. Based on this symbolic execution, we develop a novel transformation of (possibly heap-manipulating) Java programs to integer transition systems (ITSs). This allows us to apply existing complexity analyzers for standard first-order ITSs in order to infer runtime bounds for Java programs. We demonstrate the power of our implementation on an established benchmark set.

3.8 Why user experiments matter for automated reasoning

Reiner Hähnle (TU Darmstadt, DE)

Joint work of Martin Hentschel, Reiner Hähnle, Richard Bubel
Main reference Martin Hentschel, Reiner Hähnle, Richard Bubel: "An empirical evaluation of two user interfaces of an interactive program verifier", in Proc. of the 31st IEEE/ACM International Conference on Automated Software Engineering, ASE 2016, Singapore, September 3-7, 2016, pp. 403–413, ACM, 2016.
URL http://dx.doi.org/10.1145/2970276.2970303

I argue why empirical research, such as experimental studies, are a valuable form of contribution in automated reasoning and should have a place in our conferences and journals.

3.9 Automating Proofs by (co)-Induction and Theory Exploration

Moa Johansson (Chalmers University of Technology – Göteborg, SE)

Joint work of Moa Johansson, Nicholas Smallbone, Koen Claessen, Dan Rosen, Irene Lobo Valbuena
Main reference Moa Johansson: "Automated Theory Exploration for Interactive Theorem Proving: - An Introduction to the Hipster System", in Proc. of the Interactive Theorem Proving - 8th International Conference, ITP 2017, Brasília, Brazil, September 26-29, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10499, pp. 1–11, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-319-66107-0_1

One of the more challenging aspects in automating all but the simplest inductive proofs is how to discover auxiliary lemmas. In our recent work, we have taken a "bottom-up" approach to lemma discovery using theory exploration. Theory exploration is a technique

for automatically discovering interesting lemmas using testing. A richer background theory can then be constructed, allowing harder theorems to be proved automatically. I will show a demo of our theory exploration system Hipster for Isabelle/HOL, and explain a bit about how it works.

Earlier work on lemma discovery by proof-planning critics took the opposite "top-down" approach: here proof failures were analysed in an attempt to patch the failed proof. This worked very well for many cases were the missing lemma was a simple generalisation of the stuck proof state (called lemma calculation), but less well when the required lemma for instance was a generalisation of the original conjecture.

I believe lemma discovery by theory exploration could fit very nicely in with systems like Sledgehammer. It can work as a complement when useful facts are missing from the available libraries, for example in new theory developments. Unlike proof-critics, it is not dependent on particular proof-planning heuristics and systems (like rippling), and could therefore more easily be used in conjunction with first- or higher-order automated provers.

3.10 What else can automation do for proof assistants

Cezary Kaliszyk (Universität Innsbruck, AT)

Joint work of Łukasz Czajka, Thibault Gauthier, Cezary Kaliszyk

I this talk I will present the progress in automation for proof assistants. I will introduce the hammer for Coq, which can now re-prove 40% of the theorems in the Coq standard library fully automatically. I will discuss combining hammer-style premise selection with learning to use tactics and discuss automation optimizations for reasoning about types in a logical framework.

References

1 Łukasz Czajka and Cezary Kaliszyk. Hammer for Coq: Automation for Dependent Type Theory. Submitted, 2017
2 Thibault Gauthier, Cezary Kaliszyk, and Josef Urban. TacticToe: Learning to reason with HOL4 Tactics. LPAR 2017, volume 46 of EPiC, pp. 125–143. 2017

3.11 Efficient Interpolant generation algorithms based on quantifier elimination: EUF, Octagons, ...

Deepak Kapur (University of New Mexico – Albuquerque, US)

In a paper in 2006, Kapur, Majumdar and Zarba observed a connection between quantifier elimination and interpolant generation which was probably well-known but not explicitly reported in the literature on automated reasoning and formal methods. Since then I have been investigating how to develop heuristics for quantifier elimination to generate interpolants. Particularly, there is no need to have access to a proof to generate interpolants, a methodology widely used in the formal methods community.

I will start with an interpolant generation algorithm in the quantifier-free theory of equality over uninterpreted symbols. Even though there are many algorithms reported in the literature, there is little investigation about their complexity. Interpolants generated are simple and can be efficiently represented using new symbols defined in terms of common symbols. This is followed by an interpolant generation algorithm for octagonal formulas, which is of complexity $O(n^3)$, where n is the number of variables; an interpolant generated is a conjunction of octagonal formulas. Combination methods for interpolant generation over subtheories can be developed as well. Another interesting outcome is an efficient algorithm for generating congruence closure of conditional equations.

3.12 Higher-order Term Rewriting

Cynthia Kop (Radboud University Nijmegen, NL)

One of the key problems in higher-order term rewriting is that there is no true consensus of what, exactly, "higher-order term rewriting" means. There are disagreements on the necessity of including types and/or binders, and various–sometimes incompatible–definitions.

In this talk, I have discussed a number of different styles of higher-order term rewriting, their strengths and weaknesses, and the rough differences between them. I have also discussed some of the technology for proving termination, in particular the notion of computability.

3.13 An Abstraction-Refinement Framework for Reasoning with Large Theories

Konstantin Korovin (University of Manchester, UK)

Joint work of Konstantin Korovin, Julio Cesar Lopez Hernandez
Main reference Julio Cesar Lopez Hernandez, Konstantin Korovin: "Towards an Abstraction-Refinement Framework for Reasoning with Large Theories", in IWIL@LPAR 2017, Vol. 1, pp. 119-123, Kalpa Publications in Computing, EasyChair, 2017.
URL https://doi.org/10.29007/4zh8

We presented an approach to reasoning with large theories which is based on the abstraction-refinement framework [1]. The proposed approach consists of over-approximations, under-approximations and their combination. We discussed different abstractions and refinement strategies for reasoning with large first-order theories.

References

1 Julio Cesar Lopez Hernandez and Konstantin Korovin. Towards an Abstraction-Refinement Framework for Reasoning with Large Theories. IWIL@LPAR 2017, vol. 1, Kalpa Publications in Computing, EasyChair, 2017.

3.14 Constrained Resolution via (Almost) First-order Theorem Provers

Tomer Libal (Inria Saclay – Île-de-France, FR)

When considering how to use techniques from first-order theorem proving in higher-order provers, the ideal would be to use the first-order theorem provers themselves. In order to deal with the complexities which arise when dealing with higher-order terms, these provers are sometimes being applied in a constrained manner within higher-order ones. We consider a possible approach of isolating the (almost) first-order content of higher-order formulae by pre-processing and then using existing first-order provers in order to obtain a (partial) proof. This proof will be pending the successful discharge of constraints generated in the pre-processing step. An advantage of this approach is its ability to use the full spectrum of capabilities of first-order theorem provers, such as indexing, redundancy elimination, etc.

3.15 Root-balanced Trees: Verified Algorithms Analysis

Tobias Nipkow (TU München, DE)

Main reference Tobias Nipkow: "Verified Root-Balanced Trees", in Proc. of the Programming Languages and Systems - 15th Asian Symposium, APLAS 2017, Suzhou, China, November 27-29, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10695, pp. 255–272, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-319-71237-6_13

This talk presents recent work on verifying complexity of functional programs in Isabelle/HOL [1, 2, 3]. The focus of the presentation will be on the amortized complexity of a brand of search trees (invented by Andersson) where rebalancing happens only when the tree becomes badly unbalanced at the root. This is accompanied by a general discussion on modelling techniques for timing analysis and on automatic proofs of functional correctness.

References

1 Tobias Nipkow. Amortized Complexity Verified. Interactive Theorem Proving 2015, LNCS 9236, Springer, 2015.
2 Tobias Nipkow. Automatic Functional Correctness Proofs for Functional Search Trees. Interactive Theorem Proving 2016, LNCS 9807, Springer, 2016.
3 Tobias Nipkow. Verified Root-Balanced Trees. Asian Symposium on Programming Languages and Systems 2017, LNCS, Springer, 2017.

3.16 Difference between Program Verification via Hoare Logic and Rewriting Induction

Naoki Nishida (Nagoya University, JP)

Joint work of Naoki Nishida, Shinnosuke Mizutani
Main reference Shinnosuke Mizutani, Naoki Nishida, "Transforming Proof Tableaux of Hoare Logic into Inference Sequences of Rewriting Induction", Workshop on Rewriting Techniques for Program Transformations and Evaluation, Oxford, UK, September 8, 2017.
URL https://www.cs.ox.ac.uk/conferences/fscd2017/preproceedings_unprotected/WPTE_Mizutani.pdf

In this talk, I first introduce rewriting induction on constrained term rewriting and then introduce a transformation of a proof tableau of Hoare logic into an inference sequence of constrained rewriting induction. Finally, I discuss difference between program verification via these two approaches.

3.17 Featherweight alias control using types

Andrei Paskevich (University of Paris Sud – Orsay, FR)

Joint work of Andrei Paskevich, Léon Gondelman, Jean-Christophe Filliâtre
Main reference Jean-Christophe Filliâtre, Léon Gondelman, Andrei Paskevich, "A Pragmatic Type System for Deductive Verification", Technical report, Inria hal-01256434, 2016.
URL https://hal.inria.fr/hal-01256434

In the context of deductive verification, it is customary today to handle programs with pointers using either separation logic, dynamic frames, or explicit memory models. Yet we can observe that in numerous programs, a large amount of code fits within the scope of Hoare logic, provided we can statically control aliasing. When this is the case, the code correctness can be reduced to simpler verification conditions which do not require any explicit memory model. This makes verification conditions more amenable both to automated theorem proving and to manual inspection and debugging.

In this talk, we show a method of such static aliasing control for a programming language featuring nested data structures with mutable components. Our solution is based on a type system with singleton regions and effects.

3.18 Automating Separation Logic Reasoning using SMT Solvers

Ruzica Piskac (Yale University – New Haven, US)

Main reference Ruzica Piskac, Thomas Wies, Damien Zufferey: "Automating Separation Logic Using SMT", in Proc. of the Computer Aided Verification - 25th International Conference, CAV 2013, Saint Petersburg, Russia, July 13-19, 2013. Proceedings, Lecture Notes in Computer Science, Vol. 8044, pp. 773–789, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-39799-8_54

Separation logic (SL) follows a discipline of local reasoning that mimics human intuition about how to prove the correctness of heap-manipulating programs. Central to this discipline is the frame rule, a Hoare logic proof rule that decomposes the global heap into a footprint,

the region on which a program fragment operates, and a frame, the region that remains untouched by the program fragment. Automation of the frame rule involves the actual inference of the frame from SL assertions expressing the global heap and the footprint.

In this talk, I present reductions of decidable separation logic fragments to decidable first-order theories that fit well into the SMT framework. We show how these reductions can be used to automate satisfiability, entailment, frame inference, and abduction problems for separation logic using SMT solvers. Our approach provides a simple method of integrating separation logic into existing verification tools that provide SMT backends, and an elegant way of combining separation logic fragments with other decidable first-order theories.

3.19 Friends with benefits: Coinduction and corecursion in Isabelle/HOL

Andrei Popescu (Middlesex University – London, GB)

Joint work of Andrei Popescu, Jasmin Blanchette, Dmitriy Traytel, Aymeric Bouzy, Andreas Lochbihler, and others
Main reference Jasmin Christian Blanchette, Aymeric Bouzy, Andreas Lochbihler, Andrei Popescu, Dmitriy Traytel: "Friends with Benefits - Implementing Corecursion in Foundational Proof Assistants", in Proc. of the Programming Languages and Systems - 26th European Symposium on Programming, ESOP 2017, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2017, Uppsala, Sweden, April 22-29, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10201, pp. 111–140, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-662-54434-1_5

Isabelle/HOL has been recently endowed with an infrastructure for coinductive datatypes (codatatypes), corecursive functions and coinductive proofs. A codatatype's corecursion and coinduction schemes evolve in tandem by learning of new "friendly" operators from the user.

3.20 Fast and Slow Synthesis Procedures in SMT

Andrew Joseph Reynolds (University of Iowa – Iowa City, US)

Joint work of Andrew Joseph Reynolds, Cesare Tinelli, Clark Barrett, Viktor Kuncak, Morgan Deters, Tim King
Main reference Andrew Reynolds, Morgan Deters, Viktor Kuncak, Cesare Tinelli, Clark W. Barrett: "Counterexample-Guided Quantifier Instantiation for Synthesis in SMT", in Proc. of the Computer Aided Verification - 27th International Conference, CAV 2015, San Francisco, CA, USA, July 18-24, 2015, Proceedings, Part II, Lecture Notes in Computer Science, Vol. 9207, pp. 198–216, Springer, 2015.
URL http://dx.doi.org/10.1007/978-3-319-21668-3_12

Recent techniques for automated synthesis in SMT solvers follow two paradigms. The first is based on first-order quantifier instantiation, and can be used to tackle a restricted but fairly common class of properties, known as single invocation properties. The second relies on a deep embedding of the synthesis problem into the theory of inductive datatypes, which can then be solved using enumerative syntax-guided techniques. This talk focuses on the advantages and disadvantages of these two paradigms, and how they can potentially be combined.

3.21 Synthesising Regular Sets and Relations with a SAT Solver

Philipp Rümmer (Uppsala University, SE)

Joint work of Ondrej Lengál, Anthony Widjaja Lin, Rupak Majumdar, Philipp Rümmer
Main reference Anthony W. Lin, Philipp Rümmer: "Liveness of Randomised Parameterised Systems under Arbitrary Schedulers", in Proc. of the Computer Aided Verification - 28th International Conference, CAV 2016, Toronto, ON, Canada, July 17-23, 2016, Proceedings, Part II, Lecture Notes in Computer Science, Vol. 9780, pp. 112–133, Springer, 2016.
URL https://doi.org/10.1007/978-3-319-41540-6_7

We consider the problem of verifying liveness for systems with a finite, but unbounded, number of processes, commonly known as parameterised systems. Typical examples of such systems include distributed protocols (e.g., for the dining philosopher problem). Unlike the case of verifying safety, proving liveness is still considered extremely challenging, especially in the presence of randomness in the system. We introduce an automatic method of proving liveness for randomised parameterised systems under arbitrary schedulers. Viewing liveness as a two-player reachability game (between Scheduler and Process), our method is a CEGAR approach that synthesises a progress relation for Process that can be symbolically represented as a finite-state automaton. The method constructs a progress relation by means of a suitable Boolean encoding and incremental SAT solving. Our experiments show that our algorithm is able to prove liveness automatically for well-known randomised distributed protocols, including Lehmann-Rabin Randomised Dining Philosopher Protocol and randomised self-stabilising protocols (such as the Israeli-Jalfon Protocol). To the best of our knowledge, this is the first fully-automatic method that can prove liveness for randomised protocols.

3.22 Automated Forgetting, Uniform Interpolation and Second-Order Quantifier Elimination

Renate Schmidt (University of Manchester, GB)

Joint work of Renate Schmidt, Andrzej Szalas, Patrick Koopmann, Yizheng Zhao

Forgetting transforms a knowledge base into a compact representation by eliminating undesired symbols, which allows users to focus on specific parts of ontologies in order to create decompositions and restricted views for in depth analysis or sharing with other users. Forgetting is also useful for information hiding, explanation generation, semantic difference computation and ontology debugging. Other names for forgetting are: second-order quantifier elimination uniform interpolation, variable elimination, predicate elimination, and projection. Because forgetting is an inherently difficult problem – it is much harder than standard reasoning (satisfiability and validity testing) – and very few logics are known to be complete for forgetting (or have the uniform interpolation property), there has been insufficient research on the topic and few forgetting tools are available.

In my presentation gave a brief overview of the methods and success stories of three forgetting tools: SCAN which performs second-order quantifier elimination [1, 2], LETHE which solves the uniform interpolation problem for many expressive description problems extending ALC [3, 4], and FAME which computes semantic forgetting solutions for description logics of different expressivity [5, 6].

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3.23 Towards a classification of ATP proof tasks (part 2)

Stephan Schulz (Duale Hochschule Baden-Württemberg – Stuttgart, DE)

Automated theorem provers for first-order logic search for proofs in an infinite and highly branching search space. To be successful, they critically depend on various search heuristics or strategies. Experience shows that different strategies perform well on different problems. In this work, we try to automate the process of assigning a good strategy for a given problem via machine learning. In a first step, we use extensive test data to automatically cluster problems into classes showing similar behaviour under different strategies, using a combination of PCA for dimensionality reduction and k-means clustering to group similar problems. In a second step, we then learn properties of these clusters using standard machine learning techniques and a set of signature-structural features. Initial results already suggest better performance than the previous method of hand-selecting features and feature value splits for the classification.

3.24 Compositional entailment checking for theories based on separation logic

Mihaela Sighireanu (University Paris-Diderot, FR)

Joint work of Constantin Enea, Mihaela Sighireanu, and Zhilin Wu
Main reference Constantin Enea, Mihaela Sighireanu, Zhilin Wu: "On Automated Lemma Generation for Separation Logic with Inductive Definitions", in Proc. of the Automated Technology for Verification and Analysis - 13th International Symposium, ATVA 2015, Shanghai, China, October 12-15, 2015, Proceedings, Lecture Notes in Computer Science, Vol. 9364, pp. 80–96, Springer, 2015.
URL http://dx.doi.org/10.1007/978-3-319-24953-7_7

The core of the SPEN solver is a semi-decision procedure for checking entailment between separation logic formulas with inductive predicates. In this talk, I'll briefly present this procedure and its extensions for theories combining separation logic with arithmetic, set, and inductive types constraints.

3.25 On Symbol Elimination in Theory Extensions

Viorica Sofronie-Stokkermans (Universität Koblenz-Landau, DE)

Main reference Viorica Sofronie-Stokkermans: "On Interpolation and Symbol Elimination in Theory Extensions", in Proc. of the Automated Reasoning - 8th International Joint Conference, IJCAR 2016, Coimbra, Portugal, June 27 - July 2, 2016, Proceedings, Lecture Notes in Computer Science, Vol. 9706, pp. 273–289, Springer, 2016.
URL http://dx.doi.org/10.1007/978-3-319-40229-1_19

Many problems in computer science (e.g. in program verification) can be reduced to checking satisfiability of ground formulae w.r.t. a theory which can be a standard theory (for instance linear arithmetic) or a complex theory (typically the extension of a base theory $\mathcal{T}_0$ with additional function symbols axiomatized by a set $\mathcal{K}$ of formulae, or a combination of theories). SMT solvers are tuned for efficiently checking satisfiability of ground formulae in increasingly complex theories; the output can be "satisfiable", "unsatisfiable" – or possibly "unknown" if incomplete methods are used, or else termination cannot be guaranteed.

More interesting is to go beyond yes/no answers, i.e. to consider parametric systems – in which the parameters can be values or functions – and infer constraints on the parameters which guarantee that certain properties are met (for instance constraints which guarantee the unsatisfiability of certain formulae). Such constraints can be obtained by performing quantifier elimination or, more generally, symbol elimination.

In this talk we present a symbol elimination method in extensions of a theory $\mathcal{T}_0$ with additional function symbols whose properties are axiomatised using a set $\mathcal{K}$ of clauses. We analyze situations in which we can perform symbol elimination in a hierarchical way, relying on existing mechanisms for symbol elimination in $\mathcal{T}_0$. This is for instance possible if the theory $\mathcal{T}_0$ allows quantifier elimination. We present various applications of this method. The results are described in [1].

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3.26 Flexible Theorem Proving in Modal Logics

Alexander Steen (FU Berlin, DE)

Joint work of Alexander Steen, Christoph Benzmüller, Alexander Steen, Tobias Gleißner
Main reference T. Gleißner, A. Steen, C. Benzmüller: "Theorem Provers For Every Normal Modal Logic," in Proc. of the 21st Int'l Conf. on Logic for Programming (LPAR-21), Artificial Intelligence and Reasoning, Maun, Botswana, 7-12th May 2017, EPiC Series in Computing, Vol. 46, pp. 14–30, EasyChair, 2017.
URL https://doi.org/10.29007/jsb9

Computer-assisted reasoning in non-classical logics is of increasing interest in artificial intelligence (AI), computer science, mathematics and philosophy. Several powerful automated and interactive theorem proving systems have been developed over the past decades. However, with a few exceptions, most of the available systems focus on classical logics only. In particular for quantified variants there are only few systems available to date. In this talk, I present a uniform automation approach for a wide range of different modal logics. It is based on a shallow embedding into classical higher-order logic and can flexibly account for semantical variations of the desired modal logic at hand. Based on a specification of the modal logic's semantics, a procedure is presented that algorithmically translates the source problem into a classical (non-modal) HOL problem. This procedure was implemented within Leo-III and as a stand-alone pre-processing tool, ready to use in conjunction with any THF-compliant theorem prover. The choice of the concrete modal logic is thereby specified within the problem as a meta-logical statement. By combining our tool with one or more THF-compliant theorem provers we accomplish the most widely applicable modal logic theorem prover available to date, i.e. no other available prover covers more variants of propositional and quantified modal logics. Despite this generality, our approach remains competitive, at least for quantified modal logics, as our experiments demonstrate.

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3.27 Cyclic Proofs with Ordering Constraints

Sorin Stratulat (University of Lorraine – Metz, FR)

Main reference Sorin Stratulat: "Cyclic Proofs with Ordering Constraints", in Proc. of the Automated Reasoning with Analytic Tableaux and Related Methods - 26th International Conference, TABLEAUX 2017, Brasília, Brazil, September 25-28, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10501, pp. 311–327, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-319-66902-1_19

CLKID$^\omega$ is a sequent-based cyclic inference system able to reason on first-order logic with inductive definitions. The current approach for verifying the soundness of CLKID$^\omega$ proofs is based on expensive model-checking techniques leading to an explosion in the number of states.

We propose proof strategies that guarantee the soundness of a class of CLKID$^\omega$ proofs if some ordering and derivability constraints are satisfied. They are inspired from previous

works about cyclic well-founded induction reasoning, known to provide effective sets of ordering constraints. A derivability constraint can be checked in linear time. Under certain conditions, one can build proofs that implicitly satisfy the ordering constraints.

3.28 Symbolic Execution and Program Synthesis

Thomas Ströder (Metro Systems GmbH – Düsseldorf, DE)

Joint work of Thomas Ströder, Jürgen Giesl, Marc Brockschmidt, Florian Frohn, Carsten Fuhs, Jera Hensel, Peter Schneider-Kamp, Cornelius Aschermann
Main reference Thomas Ströder, Jürgen Giesl, Marc Brockschmidt, Florian Frohn, Carsten Fuhs, Jera Hensel, Peter Schneider-Kamp, Cornelius Aschermann: "Automatically Proving Termination and Memory Safety for Programs with Pointer Arithmetic", J. Autom. Reasoning, Vol. 58(1), pp. 33–65, 2017.
URL http://dx.doi.org/10.1007/s10817-016-9389-x

Symbolic execution is a very powerful and flexible technique to obtain abstract representations of program behaviors. From the abstraction, we synthesize programs in simple formal languages for which sophisticated analyses of the properties we are interested in exist (of course, the program synthesis must retain all relevant properties such that results for the analyzed programs carry over to the original programs). Using this approach, we can reduce higher-order reasoning problems to pure first-order reasoning. We illustrate this approach by an example termination analysis of the strlen C program and give a brief outlook why METRO is interested in such research topics.

3.29 Recent Improvements of Theory Reasoning in Vampire

Martin Suda (TU Wien, AT)

Joint work of Giles Reger, Martin Suda, Andrei Voronkov
Main reference M. Suda, G. Reger, A. Voronkov: "Unification with abstraction and theory instantiation in saturation-based reasoning", EasyChair Preprint no. 1, EasyChair, 2017.
URL https://doi.org/10.29007/hsh2

Over the past years Vampire has been progressively improving its ability to reason with quantifiers and theories. Originally theory reasoning was only via theory axioms and evaluation but over the past year two new techniques have been introduced. The first is the recent work of AVATAR modulo theories, previously presented, for ground theory reasoning. The second, the focus of this talk, consists of two new methods for reasoning with non-ground theory clauses (where we currently focus on the theory of arithmetic). The first new method is *unification with abstraction* where the notion of unification is extended to introduce constraints where theory terms may not otherwise unify, e.g., $p(2)$ may unify with $\neg p(x+1) \vee q(x)$ to produce $2 \neq x+1 \vee q(x)$. This abstraction is performed lazily, as needed, to allow the superposition theorem prover to make as much progress as possible without the search space growing too quickly. The second new method utilises theory constraint solving (an SMT solver) to perform reasoning within a clause to find an instance where we can remove theory literals. This utilises the power of SMT solvers for theory reasoning with non-ground clauses, reasoning which is currently achieved by the addition of prolific theory axioms. Additionally, this second method can be used to discharge the constraints

introduced by unification with abstraction. These methods were implemented within the Vampire theorem prover and experimental results show that they are useful for solving currently unsolved problems.

3.30 SMT-LIB 3: Bringing higher-order logic to SMT

Cesare Tinelli (University of Iowa – Iowa City, US)

Joint work of Clark Barrett, Pascal Fontaine, Cesare Tinelli

The SMT-LIB standard defines a common input/output language of commands to communicate with solvers for Satisfiability Modulo Theories (SMT) via a textual interface. The widely adopted most recent version of the standard, Version 2.6, is based on an extension of many-sorted first-order logic. Historically, has been adequate in most cases because SMT solvers are themselves based on automated reasoning techniques for first-order logic. A growing number of tools (interactive theorem provers, in particular) that leverage the power of SMT solvers, however, are based on more powerful logics. This forces the developers of these tools to implement often complex encodings of their problems in the less powerful logic of SMT-LIB 2. Given the interest of some SMT solver developers in extending their tools to higher-order logics, it would be beneficial for the field to extend the SMT-LIB 2 standard to some basic higher-order logic. This would simplify current encodings to SMT and might also improve runtime performance. This talk proposes a higher-order version of SMT-LIB based on simple type theory with rank-1 polymorphism. A distinguishing feature of the new version is that it is largely backward compatible with SMT-LIB 2, which means that applications and solvers not interested to the higher-order logic extensions are not affected. Non-backward-compatible portions are essentially orthogonal to the higher-order logic extension. They address other shortcomings of the current standard related to the way a user can specify the particular logical fragment the input problem belongs to.

3.31 Beyond Deduction

Josef Urban (Czech Technical University – Prague, CZ)

Joint work of Josef Urban, Thibault Gauthier, Jan Jakubuv, Cezary Kaliszyk, Jiri Vyskocil
Main reference Cezary Kaliszyk, Josef Urban: "Learning-Assisted Automated Reasoning with Flyspeck", J. Autom. Reasoning, Vol. 53(2), pp. 173–213, 2014.
URL http://dx.doi.org/10.1007/s10817-014-9303-3

The talk will describe several ways of applying machine learning methods in theorem proving and some ways of combining learning and deduction in feedback loops.

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Participants

- Franz Baader
TU Dresden, DE
- Christoph Benzmüller
FU Berlin, DE
- Nikolaj S. Bjorner
Microsoft Corporation – Redmond, US
- Jasmin Christian Blanchette
VU University of Amsterdam, NL
- James Brotherston
University College London, GB
- Chad E. Brown
Czech Technical University – Prague, CZ
- Hans de Nivelle
University of Wroclaw, PL
- Pascal Fontaine
LORIA & INRIA – Nancy, FR
- Carsten Fuhs
Birkbeck, University of London, GB
- Jürgen Giesl
RWTH Aachen, DE
- Georges Gonthier
INRIA Saclay – Île-de-France, FR
- Reiner Hähnle
TU Darmstadt, DE
- Swen Jacobs
Universität des Saarlandes, DE
- Moa Johansson
Chalmers University of Technology – Göteborg, SE
- Cezary Kaliszyk
Universität Innsbruck, AT
- Deepak Kapur
University of New Mexico – Albuquerque, US
- Chantal Keller
University of Paris Sud – Orsay, FR
- Cynthia Kop
University of Copenhagen, DK
- Konstantin Korovin
University of Manchester, GB
- K. Rustan M. Leino
Microsoft Corporation – Redmond, US
- Tomer Libal
INRIA Saclay – Île-de-France, FR
- Tobias Nipkow
TU München, DE
- Naoki Nishida
Nagoya University, JP
- Andrei Paskevich
University of Paris Sud – Orsay, FR
- Ruzica Piskac
Yale University – New Haven, US
- Andrei Popescu
Middlesex University – London, GB
- Andrew Joseph Reynolds
University of Iowa – Iowa City, US
- Philipp Rümmer
Uppsala University, SE
- Renate Schmidt
University of Manchester, GB
- Stephan Schulz
Duale Hochschule Baden-Württemberg – Stuttgart, DE
- Thomas Sewell
Data61 – Sydney, AU
- Natarajan Shankar
SRI – Menlo Park, US
- Mihaela Sighireanu
University Paris-Diderot, FR
- Viorica Sofronie-Stokkermans
Universität Koblenz-Landau, DE
- Alexander Steen
FU Berlin, DE
- Sorin Stratulat
University of Lorraine – Metz, FR
- Thomas Ströder
Metro Systems GmbH – Düsseldorf, DE
- Martin Suda
TU Wien, AT
- Laurent Théry
INRIA Sophia Antipolis, FR
- Cesare Tinelli
University of Iowa – Iowa City, US
- Josef Urban
Czech Technical University – Prague, CZ
- Christoph Weidenbach
MPI für Informatik – Saarbrücken, DE

Report from Dagstuhl Seminar 17372

Cybersafety in Modern Online Social Networks

Edited by

Jeremy Blackburn[1], Emiliano De Cristofaro[2], Michael Sirivianos[3], and Thorsten Strufe[4]

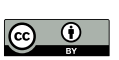
1 **University of Alabama at Birmingham, US,** blackburn@uab.edu
2 **University College London, GB,** e.decristofaro@ucl.ac.uk
3 **Cyprus University of Technology – Lemesos, CY,** michael.sirivianos@cut.ac.cy
4 **TU Dresden, DE,** thorsten.strufe@tu-dresden.de

Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 17372 "Cybersafety in Modern Online Social Networks." The main motivation behind the seminar stems from the increased relevance of threats and challenges in the context of cybersafety, especially in modern online social networks, where the range of malicious activities perpetrated by malevolent actors is regrettably wide. These include spreading malware and spam, controlling and operating fake/compromised accounts, artificially manipulating the reputation of accounts and pages, and spreading false information as well as terrorist propaganda.The reasons for the success of such attacks are manifold. The users of social networking services tend to extend their trust of the services and profiles of their acquaintances to unknown users and other third parties: despite the service providers' attempts at keeping their audiences identifiable and accountable, creating a fake profile, also in another person's name, is very simple. Even partially or fully taking over a profile is comparatively easy, and comes with the benefit of the trust this profile has accrued over time, as many credentials are easy to acquire. Further, even seemingly innocuous issues such as the design and presentation of user interfaces can result in implications for cybersafety. The failure to understand the interfaces and ramifications of certain online actions can lead to extensive over-sharing. Even the limited information of partial profiles may be sufficient for abuse by inference on specific features only. This is especially worrisome for new or younger users of a system that might unknowingly expose information or have unwanted interactions simply due to not fully understanding the platform they are using.

Unfortunately, research in cybersafety has looked at the various sub-problems in isolation, almost exclusively relying on algorithms aimed at detecting malicious accounts that act similarly, or analyzing specific lingual patterns. This ultimately yields a cat-and-mouse game, mostly played on economic grounds, whereby social network operators attempt to make it more and more costly for fraudsters to evade detection, which unfortunately tends to fail to measure and address the impact of safety threats from the point of view of regular individuals. This prompts the need for a multi-faceted, multi-disciplinary, holistic approach to advancing the state of knowledge on cybersafety in online social networks, and the ways in which it can be researched and protected. Ultimately, we want to work towards development of a cutting-edge research agenda and technical roadmap that will allow the community to develop and embed tools to detect malice within the systems themselves, and to design effective ways to enhance their safety online.

This seminar was intended to bring together researchers from synergistic research communities, including experts working on information and system security on one hand, and those with expertise in human/economic/sociological factors of security on the other. More specifically, in the field of cybersafety, there exist a number of interconnected, complex issues that cannot be addressed in isolation, but have to be tackled and countered together. Moreover, it is necessary for these challenges to be studied under a multi-disciplinary light. Consequently, we identified and focused on the most relevant issues in cybersafety, and explored both current and emerging solutions. Specifically, we discussed four problems that are the most pressing both in terms of



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negative impact and potential danger on individuals and society, and challenging open research problems requiring a multi-disciplinary approach: Cyberbullying & Hate Speech, CyberFraud & Scams, Reputation Manipulation & Fake Activities, and Propaganda.

Overall, the seminar was organized to include a number of long talks from senior experts in the field, covering the four main topics above, followed by a series of short talks from the participants about work in progress and recent results, and finally working groups to foster collaborations, brainstorming, and setting of a research agenda forward.

Seminar September 10–13, 2017 – http://www.dagstuhl.de/17372
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1 Executive Summary

Jeremy Blackburn
Emiliano De Cristofaro
Gianluca Stringhini
Michael Sirivianos
Thorsten Strufe

The Dagstuhl Seminar 17372 "Cybersafety in Modern Online Social Networks" was a short two and a half day seminar, which took place September 10th–13th, 2017. Its main goal was to bring together researchers from various research areas related to cyberfraud and cybersafety in online social network, and to inspire them to exchange results, practical requirements, and ethical/legal implications related to user-driven research.

First Day. The seminar started with a short self-introduction of all the participants, then, we had an initial brainstorming session to identify main topics of interest, various aspects involved in them, and a balance in terms of interdisciplinary representation. Specifically, we focused on scams happening in online social network and hate speech, while paying special attention to the protection of minors. The aspects discussed were related to algorithmic, user, understanding/modeling, ethical, and privacy aspects of working in this line of research.

The brainstorming session concluded with the discussion of the following tangible research directions:

1. We should work on detection, prevention, and mitigation of hate speech.
2. All solutions should be in accordance of regulations.
3. We should pay particular attention to false positives, as users can easily lose their trust in the platform.
4. We should take into consideration the role of proxies, which act as biases on the data.
5. We should focus on counter-terrorism research that aims to distinguish vulnerable population in order to recruit them for propaganda purposes.

We then had four long talks throughout the day. The first speaker, Jeremy Blackburn (University of Alabama at Birmingham, US), described his work on cyberbullying and hate

speech that includes studying behavior on video games as well as fringe Web communities like 4chan. The second speaker, Filippo Menczer (Indiana University – Bloomington, US) ,presented how misinformation is spread on Twitter. Specifically, he presented how false information as well as the respective fact-checking efforts are diffused on the Twitter network. The third speaker, Gianluca Stringhini (University College London, GB) presented his work on cyberfraud and scams, focusing on deceptive techniques employed by malicious users in order to scam benign users on online dating sites. The last speaker of the first day was Awais Rashid (Lancaster University, GB), who described his work related to child sex offenders and how he coordinated with Police bodies in order to undertake research on this topic. Also, he presented the ethical considerations when doing research with sensitive data, like those used for this study.

Second Day. The morning of the second day focused on giving an overview of work done on a variety of topics related to the main topics of the seminar (through short talks from the participants). More specifically, Zinaida Benenson (Universitat Erlangen – Nurnberg, DE), described her work on spear fishing, where malicious users aim to deceive users by sending email that contain malicious URLs. Then, Michael Sirivianos (Cyprus University of Technology- Lemesos, CY) presented his work on how to combat friend spam by analyzing the underlying network of social rejections. The next talk was by Alexandra Olteanu (IBM TJ Watson Research Center – Yorktown Heights, US), who discussed some preliminary results on work done on hate speech. Srijan Kumar (Stanford University, US) then showed how sockpuppet accounts are used in social networks to change and manipulate the opinions of other users of the platform. Savvas Zannettou (Cyprus University of Technology – Lemesos, CY) presented his research on how news propagates across multiple Web communities, and how to measure their influence. Then, Manuel Egele (Boston University, US), presented COMPA, which is a system that captures the behavioral profile of the user in order to identity possible account compromises. Huy Kang Kim (Korea University – Seoul, KR) talked about malicious users exploiting video games to make money. Next, Oana Goga (MPI-SWS – Saarbrucken, DE) described how online identities can be strengthen by combining multiple weak identities. The last talk was by Julien Freudiger (Apple Computer Inc. – Cupertino, US), who covered public privacy and safety guidelines used at Apple.

The afternoon was dedicated to two parallel working groups focused on discussions around a particular topic, specifically, one was about future directions on hate speech research, and another about ethical considerations that researchers should keep in mind when working with users or user data.

Third Day. The final day of the seminar had two more parallel working groups, one on research directions related to cyberfraud in online social network, and another on algorithmic biases and possible solutions to avoid it. We then had a discussion summarizing the work and the discussion done in the various working groups and ended up with ideas for future events, collaborations, and follow-ups.

Acknowledgments. The organizers of this workshop acknowledge research funding from the European Union's Horizon 2020 Research and Innovation programme under the Marie Skłodowska-Curie Grant Agreement No 691025. The organizers would like to thank the Schloss Dagstuhl for the professional, productive, and enjoyable atmosphere it provides and for their invaluable support. Finally, we are grateful to and Seda Guerses for taking notes during two of the working groups and to Savvas Zannettou for coordinating the writing of this report and taking notes throughout the seminar.

2 Contents

3 Overview of Talks

In this section, we provide an overview of the talks given at our Dagstuhl seminar, ordered alphabetically, as per the speaker's last name.

3.1 Spear Phishing: Email versus Facebook

Zinaida Benenson (Universität Erlangen-Nürnberg, DE)

Joint work of F. Gassmann, A. Girard, N. Hintz, R. Landwirth, A. Luder

Security incidents often start with a click on an infected link or attachment in a spear phishing message. Methods that persuade users to execute the fatal click are getting more and more sophisticated, making defense especially difficult. Drawing from results of an experiment where we sent to over 1600 users an email or a Facebook message with a link to (non-existing) party pictures from a non-existing person, we argue that a carefully targeted and timed message could deceive virtually everyone. Addressing targets by names seems to be especially important via email, resulting in much higher efficiency than messages with non-personalized greetings. On Facebook, however, this targeting technique does not make any difference. The most frequently reported reason for clicking was curiosity (34%), followed by the explanations that the message fit recipient's expectations (27%). Moreover, 16% thought that they might know the sender. These results show that people's decisional heuristics are relatively easy to misuse in a targeted attack, making defense especially challenging.

3.2 From Pool's Closed to Gas The Kikes

Jeremy Blackburn (University of Alabama at Birmingham, US)

Main reference Gabriel Emile Hine, Jeremiah Onaolapo, Emiliano De Cristofaro, Nicolas Kourtellis, Ilias Leontiadis, Riginos Samaras, Gianluca Stringhini, Jeremy Blackburn: "Kek, Cucks, and God Emperor Trump: A Measurement Study of 4chan's Politically Incorrect Forum and Its Effects on the Web", in Proc. of the Eleventh International Conference on Web and Social Media, ICWSM 2017, Montréal, Québec, Canada, May 15-18, 2017., pp. 92–101, AAAI Press, 2017.
URL https://aaai.org/ocs/index.php/ICWSM/ICWSM17/paper/view/15670

The Internet has allowed for unprecedented flow of information, revolutionized global commerce, and been embraced as a ubiquitous communication channel that enables world wide communities. However, much of what exists now on the Web was not conceived of when it was created, and its pervasive nature has revealed gaps in our understanding, enabling a proliferation of abusive behavior causing real-world harm in ways never really imagined. Cyberbullying, online harassment, and hate speech have quickly reached epidemic proportions. Their effects spill over into the real world, with sometimes violent consequences. While this type of behavior has been studied in offline contexts, its relatively quick growth online has left us with substantial gaps in our knowledge, gaps we must fill if we hope to combat it.

As a first step, we must understand the real-world psychology behind this behavior. For example, substantial literature has shown that the bully label is not one-size-fits-all. Instead, there are multiple types of bullies and harassers, each with unique motivations and views

of their victims. Once we understand the underlying rationale, we can begin exploring the features of the online world that enable the proliferation of this behavior. Here, we must examine how things like relative anonymity and asymmetric communication channels can empower harassers, enable recruitment of organized hate speech campaigns, etc.

While theory and controlled experiments can provide us with insight, they lack empirical evidence. Thus, the next step is to seek out and measure this behavior in the wild. For example, we have studied toxic behavior in online video games using a dataset of millions of incidents. While our findings must certainly be placed in the context of online games, they also have confirmed theories and controlled experiments on the bystander effect and cultural differences in the perception of aggressive and harassing behavior.

Finally, in the past several months a more worrying trend has appeared: organized and politically motivated hate speech and harassment. We have studied this phenomena through the lens of 4chan's Politically Incorrect board, or /pol/. 4chan occupies a somewhat unique position; somewhere just in between the shallow Web and the deep Web. Its anonymous and ephemeral nature has resulted in a community that is responsible for a substantial amount of Internet culture, but also a substantial amount of problems. We examined the usage of hate speech on /pol/ finding it to be significantly higher than on Twitter. We then made a first attempt at measuring raiding behavior. Semi-organized attacks on social web services. Finally, we examine some of the methods of propaganda that this new breed of harassers uses to spread their message and recruit new members.

The end goal of this line of research is to mitigate the damage that these social disruptors exhibit. After a basic understanding of how they work, and potential psychological motivators, we can begin to discuss strategies for dealing with them. Such efforts will require an interdisciplinary approach, with inputs from social scientists as well as computer scientists. Unlike many traditional computer security related questions, we have a further responsibility to design systems to aid victims of these attacks. Although the Web was not designed with these problems in mind, by engaging in cybersafety research, we can continue to ensure the Web remains an open space for all.

3.3 Compromised Social Network Accounts – Detection and Incentives

Manuel Egele (Boston University, US)

Historically, attackers relied on Sybil or fake accounts to perpetrate their deeds on online social networks. Lately, however, these actors increasingly compromise legitimate accounts to execute their attacks. Compromising legitimate accounts has significant advantages for an attacker. For example, statistical detection approaches that rely on profile characteristics for detection (e.g., profile creation date, distribution of friends or followers) are no longer applicable for detection as these features are perfectly innocuous for benign accounts. Thus, to detect compromised accounts, we developed and present COMPA, a system that models an account's normal behavior over time in a behavioral profile. If a new message posted to an account violates this profile, COMPA considers this as a potential compromise. COMPA then sets out to find a campaign of compromises by identifying accounts that posted similar messages that also violate their accounts' respective behavioral profiles. COMPA successfully detects thousands of campaigns on both, Facebook and Twitter over the duration of three months.

The evaluation of COMPA revealed that Twitter features a prolific ecosystem of so-called follower-markets. These markets are pyramid schemes where volunteer users (victims) allow miscreants to post to their accounts and get additional followers in return. As the attackers control the accounts of their victims, they can sell these accounts as followers to paying customers. In the second part of the talk we shed light on some of these markets and the structures underlying them. Our analysis indicate that the earning potential for attackers who implement such schemes is in the tens of thousands of dollars per month.

3.4 Privacy & Safety at Apple

Julien Freudiger (Apple Computer Inc. – Cupertino, US)

Protecting user privacy is a core principal in the Apple ecosystem. We discuss a couple of approaches to build great features with privacy, including differential privacy, a technique to learn from users in aggregate while protecting individual user privacy.

3.5 Strengthening Weak Identities Through Inter-Domain Trust Transfer

Oana Goga (MPI-SWS – Saarbrücken, DE)

Joint work of G. Venkatadri, C. Zhong, B. Viswanath, N. Sastry, K. Gummadi

On most current websites untrustworthy or spammy identities are easily created. Existing proposals to detect untrustworthy identities rely on reputation signals obtained by observing the activities of identities over time within a single site or domain; thus, there is a time lag before which websites cannot easily distinguish attackers and legitimate users. In this paper, we investigate the feasibility of leveraging information about identities that is aggregated across multiple domains to reason about their trustworthiness. Our key insight is that while honest users naturally maintain identities across multiple domains (where they have proven their trustworthiness and have acquired reputation over time), attackers are discouraged by the additional effort and costs to do the same. We propose a flexible framework to transfer trust between domains that can be implemented in today's systems without significant loss of privacy or significant implementation overheads. We demonstrate the potential for inter-domain trust assessment using extensive data collected from Pinterest, Facebook, and Twitter. Our results show that newer domains such as Pinterest can benefit by transferring trust from more established domains such as Facebook and Twitter by being able to declare more users as likely to be trustworthy much earlier on (approx. one year earlier).

3.6 Game BOTs (and economic scale of their black money)

Huy Kang Kim (Korea University – Seoul, KR)

In the past few years, online games have become popular and have been generating huge profits. As online games become popular and the boundary between virtual and real economies blurs, cheating in games has proliferated in volume and method. Malicious game users do cheating play to level up and accumulate cyber assets in an easy and fast manner without sufficient effort. One of the most widely used tools for cheating in online games is the game bot, which enables users to cheat in a convenient way by automatically performing the required actions. There are also professionally industrialized groups, called as "gold farming group (GFG)", are running numerous machines and runs multiple client programs or game bots to maximize the profit from the online game. They also provide money laundering service to exchange cyber money to real money.

3.7 An Army of Me: Sockpuppets in Online Discussion Communities

Srijan Kumar (Stanford University, US)

Joint work of J. Cheng, J. Leskovec, V. S. Subrahmanian

In online discussion communities, users can interact and share information and opinions on a wide variety of topics. However, some users may create multiple identities, or sockpuppets, and engage in undesired behavior by deceiving others or manipulating discussions. In this work, we study sockpuppetry across nine discussion communities, and show that sockpuppets differ from ordinary users in terms of their posting behavior, linguistic traits, as well as social network structure. Sockpuppets tend to start fewer discussions, write shorter posts, use more personal pronouns such as “I”, and have more clustered ego-networks. Further, pairs of sockpuppets controlled by the same individual are more likely to interact on the same discussion at the same time than pairs of ordinary users. Our analysis suggests a taxonomy of deceptive behavior in discussion communities. Pairs of sockpuppets can vary in their deceptiveness, i.e., whether they pretend to be different users, or their supportiveness, i.e., if they support arguments of other sockpuppets controlled by the same user. We apply these findings to a series of prediction tasks, notably, to identify whether a pair of accounts belongs to the same underlying user or not. Altogether, this work presents a data-driven view of deception in online discussion communities and paves the way towards the automatic detection of sockpuppets.

The talk is based on the research paper of the paper with the same title presented at the 26th International World Wide Web Conference, 2017.

3.8 The spread of misinformation in social media

Filippo Menczer (Indiana University – Bloomington, US)

Joint work of C. Shao, G. Ciampaglia, O. Varol, A. Flammini

As social media become major channels for the diffusion of news and information, they are also increasingly attractive and targeted for abuse and manipulation. This talk overviews ongoing network analytics, data mining, and modeling efforts to understand the spread of misinformation online and offline. I present machine learning methods to detect astroturf and social bots, as well as theoretical models to study how fake news and fact-checking compete for our collective attention. These efforts will be framed by a case study in which, ironically, our own research became the target of a coordinated disinformation campaign.

3.9 Hate Speech: Thoughts on the Role of User Aspects & External Events

Alexandra Olteanu (IBM TJ Watson Research Center – Yorktown Heights, US)

The last years have seen an increase in hateful utterances in online social platforms; and this increase has, at times, resulted in harassment and hate crimes on the ground. In this talk, I raise three key questions related to hateful speech online, and present a few preliminary results: (1) Given that there is no universally accepted definition for what constitutes hate speech, how do we evaluate systems dealing with such controversial and subjective concepts? (2) In addition, the lack of a clear definition, can also result in variation in how and when users interpret an online message as hate speech. Thus, another key question is how do user aspects impact the way in which they perceive online hateful chatter? (3) Finally, empirical evidence suggest that external events often trigger an increase in hateful speech online. How can we quantify the impact of external events on the prevalence and type of hateful chatter online?

3.10 Your words betray you! The role of language in cyber crime investigations

Awais Rashid (Lancaster University, GB)

Online social media and networks are increasingly utilized in cyber criminal activities. Sophisticated criminals often take steps to avoid revealing critical information about themselves or their activities. This poses significant challenges for legitimate law enforcement activity to protect victims and apprehend criminals. In this talk I will reflect on experiences in two large-scale projects and discuss the challenges of analyzing online activities of cyber criminals, including deception and the use of specialized vocabulary to share illegal sexual materials.

I will then highlight how advances in computational analysis of natural language can help overcome these challenges. Both projects have seen real-world deployments, so the talk will cover both scientific value of linguistic analysis in this context and insights from practical experiences in law enforcement settings. I will conclude by discussing the implications for cyber safety research and the need for a shift – to a multi-disciplinary approach for tackling cyber crime.

3.11 Combating Friend Spam Using Social Rejections

Michael Sirivianos (Cyprus University of Technology – Lemesos, CY)

Joint work of Q. Cao, X. Yang, K. Munagala
Main reference Qiang Cao, Michael Sirivianos, Xiaowei Yang, Kamesh Munagala: "Combating Friend Spam Using Social Rejections", in Proc. of the 35th IEEE International Conference on Distributed Computing Systems, ICDCS 2015, Columbus, OH, USA, June 29 - July 2, 2015, pp. 235–244, IEEE Computer Society, 2015.
URL http://dx.doi.org/10.1109/ICDCS.2015.32

Unwanted friend requests in online social networks (OSNs), also known as friend spam, are among the most evasive malicious activities. Friend spam can result in OSN links that do not correspond to social relationship among users, thus pollute the underlying social graph upon which core OSN functionalities are built, including social search engine, ad targeting, and OSN defense systems. To effectively detect the fake accounts that act as friend spammers, we propose a system called Rejecto. It stems from the observation on social rejections in OSNs, i.e., even well maintained fake accounts inevitably have their friend requests rejected or they are reported by legitimate users. Our key insight is to partition the social graph into two regions such that the aggregate acceptance rate of friend requests from one region to the other is minimized. This design leads to reliable detection of a region that comprises friend spammers, regardless of the request collusion among the spammers. Meanwhile, it is resilient to other strategic manipulations. To efficiently obtain the graph cut, we extend the Kernighan-Lin heuristic and use it to iteratively detect the fake accounts that send out friend spam. Our evaluation shows that Rejecto can discern friend spammers under a broad range of scenarios and that it is computationally practical.

3.12 Cyberfraud and Scams

Gianluca Stringhini (University College London, GB)

Fraud perpetrated by humans (rather than bots) is becoming an increasing problem on online services. Due to its nature, the techniques designed to identify malicious activity are not enough to detect and mitigate it. This talks covers the problems of online dating scams and identity theft, highlighting some research challenges and findings coming from our recent research.

3.13 The Web Centipede: Understanding How Web Communities Influence Each Other Through the Lens of Mainstream and Alternative News Sources

Savvas Zannettou (Cyprus University of Technology – Lemesos, CY)

Joint work of T. Caulfield, E. De Cristofaro, N. Kourtellis, I. Leontiadis, M. Sirivianos, G. Stringhini, J. Blackburn
Main reference Savvas Zannettou, Tristan Caulfield, Emiliano De Cristofaro, Nicolas Kourtellis, Ilias Leontiadis, Michael Sirivianos, Gianluca Stringhini, Jeremy Blackburn: "The web centipede: understanding how web communities influence each other through the lens of mainstream and alternative news sources", in Proc. of the 2017 Internet Measurement Conference, IMC 2017, London, United Kingdom, November 1-3, 2017, pp. 405–417, ACM, 2017.
URL http://dx.doi.org/10.1145/3131365.3131390

As the number and diversity of news sources on the Web grows, so does the opportunity for alternative sources of information production. The emergence of mainstream social networks like Twitter and Facebook makes it easier for misleading, false, and agenda driven information to quickly and seamlessly spread online, deceiving people or influencing their opinions. Moreover, the increased engagement of tightly knit communities, such as Reddit and 4chan, compounds the problem as their users initiate and propagate alternative information not only within their own communities, but also to other communities and social media platforms across the Web. These platforms thus constitute an important piece of the modern information ecosystem which, alas, has not been studied as a whole. In this paper, we begin to fill this gap by studying mainstream and alternative news shared on Twitter, Reddit, and 4chan. By analyzing millions of posts around a variety of axes, we measure how mainstream and alternative news flow between these platforms. Our results indicate that alt-right communities within 4chan and Reddit can have a surprising level of influence on Twitter, providing evidence that "fringe" communities may often be succeeding in spreading these alternative news sources to mainstream social networks and the greater Web.

4 Working groups

4.1 Algorithmic Biases

Seda F. Guerses (KU Leuven, BE) and Savvas Zannettou (Cyprus University of Technology – Lemesos, CY)

This working group focused on various biases that exist in research, ranging from biases in data, annotations, algorithms and systems.

Some examples include:

- **Biases in Dataset.** The use of snowball sampling for data acquisition eventually leads to datasets with biases, as one is more likely to get high degree nodes.
- **Biases in Annotation.** In many cases, we employ manual annotators to label our dataset. However, there are cases where the annotations are not trivial and people may not agree. This fact may introduce un-wanted biases in our dataset during the annotation phase.

- **Algorithmic Biases.** Some decision making algorithms have been shown to discriminate on the basis of race and other protected categories. For example, an example used in the US criminal justice was shown to lead to increased criminalization and imprisonment of African American men.

During the discussions, the participants realized that bias can exist in multiple forms and there are a lot of challenges when defining bias. Therefore, as an open research direction, we discussed possible definitions of biases, and if tools can be implemented that will aim to detect biases in algorithms and/or systems. Also, evaluating the percentage and impact of biases on systems is not a straightforward task, as this depends on the use case as well as the criticality of the used data.

4.2 Ethics

Seda F. Guerses (KU Leuven, BE) and Savvas Zannettou (Cyprus University of Technology – Lemesos, CY)

This working group focused on the discussion of ethical considerations when doing research. We started from observing a lack of general guidelines with regard to the ethical aspects of research and usually this comes to the Institutional Review Board (IRB) of the involved institutions. Also, we noted that there are a lot of risks when doing cybersecurity experiments with real users.

In such cases we should make sure that we enforce subject integrity, i.e., making users aware of the underlying risks. Also, in the case of interdisciplinary studies, there is a need of close communication between the involved researchers, as ethical issues may arise in one of the multiple dimensions of the study.

As the main research direction for this Working Group, we proposed the compilation of general ethics guidelines that can assist researchers in understanding on whether their research ideas are ethical or not and what actions should be done to make sure of the legality of the research.

4.3 Cyberfraud

Savvas Zannettou (Cyprus University of Technology – Lemesos, CY)

This working group focused on the problem of cyberfraud. We acknowledged that cyberfraud has evolved the last few years, as we observed events of political distraction as well as the generation of fake news. To this end, we identified the following research problems:

1. How do all scams (e.g., buying likes, etc) relate to the interference of election?
2. Evaluating approaches can be difficult, as one method can mitigate the problem on one Web community but users can go to a different community, hence the problem persists.
3. What make political actors thrive? There is a need to identify the techniques that these actor use.

4. How to identify malicious intentions from benign ones?
5. Automated detection tools will generate false positives, which is something that needs to be carefully addressed as users might lose trust in the Web platform.

As the main research direction for this Working Group, we proposed the compilation of a cyberfraud taxonomy where we will cover the whole spectrum of cyberfraud. Specifically, it should contain the various tools exploited by malicious users (e.g., bots), the motives behind the act of scamming users online as well as the various involved actors, and the various types of fraudulent activities.

4.4 Hate Speech

Savvas Zannettou (Cyprus University of Technology – Lemesos, CY)

This working group focused on the definition and possible research directions for the emerging problem of hate speech in online Web communities. We observed that there is no formal definition for hate speech, therefore, we proposed that a formal definition should include the bias of the offender as well as his intentions, the targeted group (based on its traits), and the victim's perspective.

Nevertheless, there are a lot of open questions regarding hate speech:

1. When does a post qualify to be hate speech? Only if is in public or in private too?
2. How to identify the intentions of the offender? For instance, a post might be treated as a joke from the offender's perspective.
3. If we manage to detect hate speech how we mitigate the problem?

For the latter, we noted that silencing is not a viable solution, as users will lose trust in the Web community. Therefore, we proposed the implementation of solutions that aim to counter the speech rather than stopping it, decrease the visibility of the hateful content, create a support service to help the victim overcome the effect from the insults, and develop containment systems that will stop the diffusion process within the Web community.

The main tangible research directions that were discussed during this working group include:

1. Understanding the effects of different definition or detection mechanisms for hate speech;
2. Evaluating strategies after the detection of hate speech;
3. Contagion experiments on Web communities, e.g. Twitter and the followers network; and
4. Comparing multiple intervention mechanisms as well as tackling hate speech in multiple languages.

Participants

- Zinaida Benenson
Universität Erlangen-Nürnberg, DE
- Jeremy Blackburn
University of Alabama at Birmingham, US
- Emiliano De Cristofaro
University College London, GB
- Julien Dreux
Facebook – London, GB
- Manuel Egele
Boston University, US
- Julien Freudiger
Apple Computer Inc. – Cupertino, US
- Oana Goga
MPI-SWS – Saarbrücken, DE
- Seda F. Gürses
KU Leuven, BE
- Huy Kang Kim
Korea University – Seoul, KR
- Christiane Kuhn
TU Dresden, DE
- Srijan Kumar
Stanford University, US
- Ilias Leontiadis
Telefónica Research – Barcelona, ES
- Filippo Menczer
Indiana University – Bloomington, US
- Prateek Mittal
Princeton University, US
- Alexandra Olteanu
IBM TJ Watson Research Center – Yorktown Heights, US
- Awais Rashid
Lancaster University, GB
- Ahmad-Reza Sadeghi
TU Darmstadt, DE
- Stefan Schiffner
ENISA – Athens, GR
- Michael Sirivianos
Cyprus University of Technology – Lemesos, CY
- Gianluca Stringhini
University College London, GB
- Thorsten Strufe
TU Dresden, DE
- Savvas Zannettou
Cyprus University of Technology – Lemesos, CY

Report from Dagstuhl Seminar 17381

Recent Trends in Knowledge Compilation

Edited by

Adnan Darwiche[1], Pierre Marquis[2], Dan Suciu[3], and Stefan Szeider[4]

1 **UCLA, US,** darwiche@cs.ucla.edu
2 **Artois University – Lens, FR,** marquis@cril.univ-artois.fr
3 **University of Washington – Seattle, US,** suciu@cs.washington.edu
4 **TU Wien, AT,** sz@ac.tuwien.ac.at

Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 17381 "Recent Trends in Knowledge Compilation".

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1 Executive summary

Adnan Darwiche
Pierre Marquis
Dan Suciu
Stefan Szeider

Knowledge compilation (KC) is a research topic which aims to investigate the possibility of circumventing the computational intractability of hard tasks, by preprocessing part of the available information, common to a number of instances. Pioneered almost three decades ago, KC is nowadays a very active research field, transversal to several areas within computer science. Among others, KC intersects knowledge representation, constraint satisfaction, algorithms, complexity theory, machine learning, and databases.

The results obtained so far take various forms, from theory (compilability settings, definition of target languages for KC, complexity results, succinctness results, etc.) to more practical results (development and evaluation of compilers and other preprocessors, applications to diagnosis, planning, automatic configuration, etc.). Recently, KC has been positioned as providing a systematic method for solving problems beyond NP, and also found applications in machine learning.

The goal of this Dagstuhl Seminar was to advance both aspects of KC, and to pave the way for a fruitful cross-fertilization between the topics, from theory to practice.

The program included a mixture of long and short presentations, with discussions. Several long talks with a tutorial flavor introduced the participants to the variety of aspects in knowledge compilation and the diversity of techniques used. System presentations as well as an open problem session were also included in the program.

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3 Talks

3.1 A Circuit-Based Approach to Efficient Enumeration

Antoine Amarilli (Télécom ParisTech, FR)

Joint work of Antoine Amarilli, Pierre Bourhis, Louis Jachiet, Stefan Mengel
Main reference Antoine Amarilli, Pierre Bourhis, Louis Jachiet, Stefan Mengel: "A Circuit-Based Approach to Efficient Enumeration", in Proc. of the 44th International Colloquium on Automata, Languages, and Programming, ICALP 2017, July 10-14, 2017, Warsaw, Poland, LIPIcs, Vol. 80, pp. 111:1–111:15, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
URL http://dx.doi.org/10.4230/LIPIcs.ICALP.2017.111

Enumeration is the task of computing efficiently multiple solutions to a computational problem, one after another. This task has been studied in knowledge compilation, where we compile problems to circuits and enumerate their satisfying assignments. However, it has also been studied in database theory and logics to show constant-delay enumeration results for query evaluation, e.g., for monadic second-order logic on trees.

We show how to recapture these database theory results via a knowledge compilation approach. To do so, we compile the database query to a circuit that represents all its answers in a factorized way. We then present an efficient algorithm to enumerate the satisfying valuations of the circuit. Our algorithm works on structured d-DNNFs and focuses on valuations of constant Hamming weight to achieve the constant-delay bound.

3.2 Knowledge Compilation: Representations and Lower Bounds

Paul Beame (University of Washington – Seattle, US)

Joint work of Jerry Li, Vincent Liew, Sudeepa Roy, Dan Suciu

We survey a variety of representations of Boolean functions and summarize the connections between these representations and exact model counting algorithms.

We then discuss our work showing a variety of lower bounds for several of these representations, including decision-DNNFs, SDDs, and DNNFs, as well as applications of those lower bounds.

Finally, we discuss a more general representation suitable for exact model counting for which we are not aware of any lower bounds for explicit Boolean functions.

3.3 Provenance for tree-like instances: a bridge between database and knowledge compilation

Pierre Bourhis (CNRS – Lille, FR)

The notion of provenance is well known notion in database to explain the contribution of the data to the computation of the query. This notion has some practical use in particular in probabilistic data evaluation. In this context, Jha and Suciu showed that if the provenance

can be expressed by well-known classes of circuits then probabilistic data evaluation becomes tractable. Following this path, we show that the provenance of expressive queries over trees can be expressed by a well-known class of circuits d-DNNF and then derive a set of interesting properties from this result.

3.4 Circuit Treewidth, Sentential Decision, and Query Compilation

Simone Bova (TU Wien, AT)

Joint work of Simone Bova, Stefan Szeider
Main reference Simone Bova, Stefan Szeider: "Circuit Treewidth, Sentential Decision, and Query Compilation", in Proc. of the 36th ACM SIGMOD-SIGACT-SIGAI Symposium on Principles of Database Systems, PODS 2017, Chicago, IL, USA, May 14-19, 2017, pp. 233–246, ACM, 2017.
URL http://dx.doi.org/10.1145/3034786.3034787

The evaluation of a query over a probabilistic database boils down to computing the probability of a suitable Boolean function, the lineage of the query over the database. The method of query compilation approaches the task in two stages: first, the query lineage is implemented (compiled) in a circuit form where probability computation is tractable; and second, the desired probability is computed over the compiled circuit. A basic theoretical quest in query compilation is that of identifying pertinent classes of queries whose lineages admit compact representations over increasingly succinct, tractable circuit classes. In this talk, we focus on queries whose lineages admit circuit implementations with small treewidth, and investigate their compilability within tame classes of decision diagrams. In perfect analogy with the characterization of bounded circuit pathwidth by bounded OBDD width (Jha and Suciu, 2012), we show that a class of Boolean functions has bounded circuit treewidth if and only if it has bounded SDD width. Sentential decision diagrams (SDDs) are central in knowledge compilation, being essentially as tractable as OBDDs but exponentially more succinct. By incorporating constant width SDDs and polynomial size SDDs, we refine the panorama of query compilation for unions of conjunctive queries with and without inequalities.

3.5 Updating the Knowledge Compilation Map

Simone Bova (TU Wien, AT)

Joint work of Simone Bova, Florent Capelli, Stefan Mengel, Friedrich Slivovsky
Main reference Simone Bova, Florent Capelli, Stefan Mengel, Friedrich Slivovsky: "Knowledge Compilation Meets Communication Complexity", in Proc. of the Twenty-Fifth International Joint Conference on Artificial Intelligence, IJCAI 2016, New York, NY, USA, 9-15 July 2016, pp. 1008–1014, IJCAI/AAAI Press, 2016.
URL http://www.ijcai.org/Abstract/16/147

Introduced by Darwiche and Marquis (2002), the knowledge compilation map offers a systematic framework to assess alternative representations of propositional theories relative to their succinctness and tractability. In this tutorial talk we exploit the recently established connection between knowledge compilation and communication complexity to update and refine the information originally incorporated in the knowledge compilation map.

3.6 Non FPT Lower Bounds for Restricted Decision DNNF

Florent Capelli (INRIA Lille, FR)

Many algorithms are known to exploit the structure of a CNF formula to solve #SAT efficiently on some families of formulas. In particular, for every k, we know how to solve #SAT in time $2^{\Omega(k)} \cdot poly(|F|)$ for a CNF F whose incidence graph has treewidth k. However, the algorithm used to solve #SAT in this case is very different from the one used by most practical tools solving #SAT, which are based on #DPLL, a generalisation of DPLL. It is known that such tools can efficiently exploit the fact that the treewidth of the primal graph of F is bounded but it is not clear if such tools can exploit the incidence treewidth of the formula.

In this talk, we give a partial answer to this question by showing that some natural restrictions of #DPLL cannot solve formulas whose incidence graph has treewidth k.

3.7 Knowledge compilation and compression using interval representations of Boolean functions.

Ondrej Cepek (Charles University – Prague, CZ)

Joint work of Radek Husek, Ondrej Cepek
Main reference Ondrej Cepek, Radek Husek: "Recognition of tractable DNFs representable by a constant number of intervals", Discrete Optimization, Vol. 23, pp. 1–19, 2017.
URL http://dx.doi.org/10.1016/j.disopt.2016.11.002

In this talk we shall focus on a less common way how to represent Boolean functions, namely on representations by intervals of truepoints or by closely related representation by switch-lists. Let f be a Boolean function and let us fix some order of its n variables. The input binary vectors can be now thought of as binary numbers (with bits in the prescribed order) ranging form 0 to $2^n - 1$. An interval representation is then an abbreviated TT (truth table) or MODS (models) representation, where instead of writing out all the input vectors (binary numbers) with their function values, we write out only those binary numbers x for which $f(x) = 1$ (x is a truepoint of f) and simultaneously $f(x-1) = 0$ ($x-1$ is a falsepoint of f) and those binary numbers y for which $f(y) = 1$ (y is a truepoint of f) and simultaneously $f(y+1) = 0$ ($y+1$ is a falsepoint of f). Thus the function is represented by an ordered list of such pairs $[x, y]$ of integers, each pair specifying one interval of truepoints. Note that $x = y$ for those pairs which represent an interval with a single truepoint. In this talk we shall also consider a related representation by switch-lists. A switch is a vector (binary number) x such that $f(x-1) \neq f(x)$. A switch-list is an ordered list of all switches of a given function (under a given order of variables).

There are two natural problems connected to such representation: (1) a knowledge compilation problem, i.e. a problem of transforming a given representation of a Boolean function (Boolean formula, binary decision diagram, Boolean circuit ...) into an interval or switch-list representation, and (2) a knowledge compression problem, i.e. a problem of finding the shortest interval or switch-list representation among those which represent the given function (which amounts to finding such an order of variables). We will summarize

known results about these two problems and present generalizations in both areas. The main result is a polynomial time algorithm that for a Boolean function (given by a tractable formula) outputs a shortest interval and switch-list representations, provided that the number of switches (intervals) is bounded by a constant. This algorithm can be also thought of as a polynomial time recognition algorithm for the class of k-switch (or k-interval) functions given by a tractable formula for any fixed k.

3.8 Optimized Framework based on Rough Set Theory for Big Data Pre-processing in Certain and Imprecise Contexts

Zaineb Chelly Dagdia (Aberystwyth University, GB)

Joint work of Christine Zarges, Gaël Beck, Mustapha Lebbah, Juan J. Merelo Guervós

Over the last decades, the amount of data has increased in an unprecedented rate, leading to a new terminology: "Big Data". Big data are specified by their Volume, Variety, Velocity and by their Veracity/Imprecision. Based on these 4V specificities, it has become difficult to quickly acquire the most useful information from the huge amount of data at hand. Thus, it is necessary to perform data pre-processing as a first step. In spite of the existence of many techniques for this task, most of the state-of-the-art methods require additional information for thresholding and are neither able to deal with the big data veracity aspect nor with their computational requirements. We aim at presenting current progress and insights of this Marie Skłodowska Curie project that aims at filling the mentioned major research gaps by proposing solutions based on Rough Set Theory for data pre-processing and Randomized Search Heuristics for optimization. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 702527.

3.9 Using Knowledge Compilation to Solve PP^{PP}-Complete Problems

YooJung Choi (UCLA, US)

Knowledge compilation has been successfully used to solve "Beyond NP" problems, including some PP-complete and NP^{PP}-complete probabilistic queries. This approach compiles problems into Boolean circuits with certain properties that guarantee linear-time query evaluation. This talk will discuss how knowledge compilation can be used to answer queries that are complete for the more intractable complexity class PP^{PP}. In particular, we show how to solve a canonical PP^{PP}-complete problem MAJ-MAJ-SAT in linear time by compiling the problem instance into a special type of Sentential Decision Diagrams (SDDs) called a constrained SDD. In addition, to demonstrate the practical value of the proposed approach, we will adapt it to answer the Same-Decision Probability (SDP) and Expected Same-Decision Probability (E-SDP) queries for Bayesian networks, which quantify the robustness of threshold-based decisions and have been proposed as stopping and selection criteria for Bayesian decision making.

3.10 A Framework for Parameterized Compilability

Ronald de Haan (University of Amsterdam, NL)

Joint work of Ronald de Haan, Simone Bova, Neha Lodha, Stefan Szeider
Main reference Simone Bova, Ronald de Haan, Neha Lodha, Stefan Szeider: "Positive and Negative Results for Parameterized Compilability," Technical report AC-TR-16-003, Algorithms and Complexity Group, TU Wien, 2016.
URL https://www.ac.tuwien.ac.at/files/tr/ac-tr-16-003.pdf

Many fundamental problems do not admit a polynomial-size compilation that allows queries to be answered in polynomial time. A typical example of such a problem is the problem of deciding whether a given CNF formula (offline input) entails a given clause (online query). The compilability framework of Cadoli, Donini, Liberatore and Schaerf [1] allows us to investigate when poly-size compilations are possible, and when not.

The perspective of parameterized complexity makes it possible to extend the notion of feasible compilability. In addition to the input size, we consider a problem parameter. We then aim to compile the offline instance into an fpt-size compilation, such that online queries can be answered in fpt-time. This could improve the potential of the approach of compilation.

To investigate the boundary between what is fpt-size compilable and what is not, a different theoretical framework is needed. Chen initiated the development of such a framework [2], that we recently extended. In this talk, we explain this framework, and how it can be used. As a running example, we use the problem of clause entailment for CNF formulas. We present both positive and negative parameterized compilability results for various parameters for clause entailment.

References

1 Cadoli, M.; Donini, F. M.; Liberatore, P.; and Schaerf, M. 2002. Preprocessing of intractable problems. *Information and Computation* 176(2):89–120.
2 Chen, H. 2005. Parameterized compilability. In *Proceedings of IJCAI 2005, the 19th International Joint Conference on Artificial Intelligence.*

3.11 A Structural Approach to Model Counting

Robert Ganian (TU Wien, AT)

Joint work of Robert Ganian, Stefan Szeider

The boolean satisfiability problem (SAT) and its generalization to model counting (#SAT) are fundamental problems with a strong overlap into knowledge compilation. One of the basic approaches used to design exact algorithms for these problems is to exploit the structure of variable-clause interactions captured in terms of various graph representations of CNF formulas. The most successful way of doing this is with the use of the structural parameter called treewidth. After reviewing the fundamentals of how treewidth can be used to solve SAT and #SAT, we proceed to provide an overview of very recent advances made in this direction.

References

1 Robert Ganian and Stefan Szeider. *New Width Parameters for Model Counting.* SAT 2017

3.12 Colour Refinement: A Simple Partitioning Algorithm with Applications From Graph Isomorphism Testing to Machine Learning

Martin Grohe (RWTH Aachen, DE)

Colour refinement is a simple algorithm that partitions the vertices of a graph according their "iterated degree sequences". It has very efficient implementations, running in quasilinear time, and a surprisingly wide range of applications. The algorithm has been designed in the context of graph isomorphism testing, and it is used an important subroutine in almost all practical graph isomorphism tools. Somewhat surprisingly, other applications in machine learning, probabilistic inference, and linear programming have surfaced recently.

In the first part of my talk, I will introduce the basic algorithm as well as higher dimensional extensions known as the k-dimensional Weisfeiler-Lehman algorithm. I will also discuss an unexpected connection between colour refinement and a natural linear programming approach to graph isomorphism testing. In the second part of my talk, I will discuss various applications of colour refinement.

3.13 Efficiently Enumerating Minimal Triangulations

Batya Kenig (Technion – Haifa, IL)

Joint work of Nofar Carmeli, Benny Kimelfeld
Main reference Nofar Carmeli, Batya Kenig, Benny Kimelfeld: "Efficiently Enumerating Minimal Triangulations", in Proc. of the 36th ACM SIGMOD-SIGACT-SIGAI Symposium on Principles of Database Systems, PODS 2017, Chicago, IL, USA, May 14-19, 2017, pp. 273–287, ACM, 2017.
URL http://dx.doi.org/10.1145/3034786.3056109

We present an algorithm that enumerates all the minimal triangulations of a graph in incremental polynomial time. Consequently, we get an algorithm for enumerating all the proper tree decompositions, in incremental polynomial time, where "proper" means that the tree decomposition cannot be improved by removing or splitting a bag. The algorithm can incorporate any method for (ordinary, single result) triangulation or tree decomposition, and can serve as an anytime algorithm to improve such a method. We describe an extensive experimental study of an implementation on real data from different fields. Our experiments show that the algorithm improves upon central quality measures over the underlying tree decompositions, and is able to produce a large number of high-quality decompositions.

3.14 On Compiling (Online) Combinatorial Learning Problems

Frederic Koriche (Artois University – Lens, FR)

In various machine learning applications, the learning problem can be viewed as an interactive process, or repeated game, between the learner and its environment. During each trial of

the game, the learner chooses a predictor from its hypothesis class, and simulaneously, the environment selects an instance. Then, the instance is presented to the learner, which incurs a loss. In this online learning framework, everything is fine when all components of the game are convex. Yet, for many learning tasks of interest in AI, the hypothesis class is combinatorial by nature, and hence, convex optimization algorithms cannot be applied to this setting.

This talk will address the following question: what about compiling the hypothesis space?

Knowledge compilation indeed looks promising for investigating (online) combinatorial learning problems, by compiling a probability distribution on the hypothesis class into an appropriate structure, and by iteratively updating this structure according to incoming instances. We will illustrate this approach by considering several online combinatorial learning problems, including learning conjunctive functions, and graphical probabilistic models.

3.15 Solving very hard SAT problems: a form of partial KC

Oliver Kullmann (Swansea University, GB)

We (Marijn Heule, Victor Marek and me) solved in 2016 the Boolean Pythagorean Triples Problem https://en.wikipedia.org/wiki/Boolean_Pythagorean_triples_problem via SAT. In the first half of the talk I explain the problem, in the second part I explain the underlying method for such very hard (but relatively small) problems, the "Cube-and-Conquer" (C&C) paradigm. The outstanding feature of C&C is that it combines “old and new” (DPLL and CDCL), and I will discuss the fundamental intuitions for this symbiosis.

3.16 SAT by MaxSAT: From NP to Beyond NP and Back Again

Joao Marques-Silva (University of Lisbon, PT)

This talks starts by briefly overviewing recent work on practically efficient algorithms for maximum satisfiability, namely algorithms that iteratively compute unsatisfiable cores and, among these, those that exploit minimum hitting sets. Afterwards, the talk investigates reductions of decision problems to Horn Maximum Satisfiability. It is shown that such reductions enable polynomial refutations of the pigeonhole principle. This in turn motivates a number of research questions.

3.17 Probabilistic Logic Programming and Knowledge Compilation

Wannes Meert (KU Leuven, BE)

Joint work of Jonas Vlasselaer, Guy Van den Broeck, Anton Dries, Angelika Kimmig, Hendrik Blockeel, Jesse Davis, Luc De Raedt

In this talk I'll present the ProbLog probabilistic logic programming system. First, I will introduce the semantics, methodology and system. Thus wat is available today. Second, I will focus on some of our current progress and challenges. This includes incremental compilation (e.g. approximate inference), continuous observations (e.g. sensor measurements), and compiling resource-aware circuits (e.g. memory or energy).

https://dtai.cs.kuleuven.be/problog

3.18 A Dichotomy for Compiling Constraint Satisfaction Problems to Read-Once Decision Diagrams

Stefan Mengel (CNRS, CRIL – Lens FR)

In this talk I presented ongoing work on a dichotomy for compiling constraint satisfaction problems into read-once decision programs that states the following: For every finite constraint language Γ one of the following is true:

- the satisfying assignments of any Γ-formula can be compiled into a multivalued, ordered decision diagram (MODD) in polynomial time, or
- there are Γ-formulas formulas such that compiling them into MODD takes exponential size.

I give the criterion that determines which of the two statements is true. Moreover, I instantiate the dichotomy for the Boolean domain and discuss possible extensions.

This is unpublished, ongoing work.

3.19 BDD/ZDD-based knowledge indexing and real-life applications

Shin-ichi Minato (Hokkaido University, JP)

URL http://art.ist.hokudai.ac.jp/~minato/

BDD (Binary Decision Diagram) [1] is a classical data structure for representing a Boolean function. BDD-based algorithms were developed mainly for VLSI logic design in early 1990s. ZDD (Zero-suppressed BDD) [2] is a variant of BDD, customized for representing a set of combinations, often appear in solving combinatorial problems. BDDs and ZDDs have become more widely known since D. Knuth intensively discussed them in his famous series of books in 2009 [3]. Although a quarter of a century has passed since the original idea of BDD-based operations by R. Bryant [1], there are still many interesting research topics ongoing. One of the most important topics is a fast algorithm of constructing a ZDD which

compactly indexes all the paths in a given graph structure, presented by Knuth [3]. This work is important because many kinds of practical problems are efficiently solved by some variations of this algorithm. In this talk, I will give an overview of the brief history and the basic techniques on BDDs/ZDDs. We then look over some recent research topics from the view point of knowledge indexing.

References

1 R. E. Bryant, "Graph-based algorithms for Boolean function manipulation," *IEEE Transactions on Computers*, vol. C-35, no. 8, pp. 677–691, 1986.
2 S. Minato, "Zero-suppressed BDDs for set manipulation in combinatorial problems," in *Proc. of 30th ACM/IEEE Design Automation Conference (DAC'93)*, 1993, pp. 272–277.
3 D. E. Knuth, *The Art of Computer Programming: Bitwise Tricks & Techniques; Binary Decision Diagrams*. Addison-Wesley, 2009, vol. 4, fascicle 1.

3.20 Efficient Representations for the Modal Logic S5

Alexandre Niveau (Caen University, FR)

Joint work of Niveau, Alexandre; Zanuttini, Bruno
Main reference Alexandre Niveau, Bruno Zanuttini: Efficient Representations for the Modal Logic S5. IJCAI 2016
URL http://www.ijcai.org/Abstract/16/177

In this talk, I presented our ongoing investigation about efficient representations of subjective formulas in the modal logic of knowledge, $\mathsf{S5}$, and more generally of sets of sets of propositional assignments. One motivation for this work is contingent planning, for which many approaches use operations on such formulas, and can clearly take advantage of efficient representations.

This study was started by Bienvenu, Fargier & Marquis [1], who introduced the parameterized language $\mathsf{S5} - \mathsf{DNF}_{\mathsf{L},\mathsf{L}'}$ (L and L' being the languages used at the propositional level). In a paper last year [2], we introduced the language of Epistemic Splitting Diagrams, with the aim of providing more compact representations, and we compared it to two promising instances of $\mathsf{S5} - \mathsf{DNF}_{\mathsf{L},\mathsf{L}'}$, both from the complexity-theoretic viewpoint of the knowledge compilation map and also through preliminary experiments inspired by contingent planning.

References

1 Meghyn Bienvenu, Hélène Fargier, & Pierre Marquis (2010). "Knowledge Compilation in the Modal Logic S5." In: Proceedings of the 24th AAAI Conference on Artificial Intelligence (AAAI 2010).
2 Alexandre Niveau & Bruno Zanuttini (2016). "Efficient Representations for the Modal Logic S5." In: Proceedings of the 25th International Joint Conference on Artificial Intelligence (IJCAI 2016).

3.21 In-Database Factorized Learning

Dan Olteanu (University of Oxford, GB)

Main reference Mahmoud Abo Khamis, Hung Q. Ngo, XuanLong Nguyen, Dan Olteanu, Maximilian Schleich: "In-Database Learning with Sparse Tensors", CoRR, Vol. abs/1703.04780, 2017.
URL http://arxiv.org/abs/1703.04780

In this talk I will overview work on compilation of join queries into lossless factorized representations. The primary motivation for this compilation is to avoid redundancy in the representation of query results in relational databases. The relationship between the standard listing representation of relations and equivalent factorized representations is on a par with the relationship between a propositional formula in disjunctive normal form and equivalent circuits. For any join query, we give asymptotically tight bounds on the size of its factorized results and on the time to compute them. We show that these factorized results can be arbitrarily more succinct than their equivalent listing representations.

I will also discuss an application of factorized joins to learning regression models over databases. On-going joint work [1] with LogicBlox collaborators shows that in-database factorized learning can speed up real analytical workloads in the retailer domain by several orders of magnitude over state-of-the-art systems.

This work is based on long-standing collaboration with Maximilian Schleich (Oxford) and Jakub Zavodny (Oxford) and more recent collaboration with Mahmoud Abo Khamis (LogicBlox), Hung Ngo (LogicBlox), and XuanLong Nguyen (Michigan).

References

1 Mahmoud Abo Khamis, Hung Q. Ngo, XuanLong Nguyen, Dan Olteanu, and Maximilian Schleich. In-database learning with sparse tensors. *CoRR*, abs/1703.04780, 2017. To appear in ACM PODS 2018.

3.22 Partial matching width and lower bounds for read-once branching programs

Igor Razgon (Birkbeck, University of London, GB)

Many algorithms are known to exploit the structure of a CNF formula to solve #SAT efficiently on some families of formulas. In particular, for every k, we know how to solve #SAT in time $2^{\Omega(k)} \cdot poly(|F|)$ for a CNF F whose incidence graph has treewidth k. However, the algorithm used to solve #SAT in this case is very different from the one used by most practical tools solving #SAT, which are based on #DPLL, a generalisation of DPLL. It is known that such tools can efficiently exploit the fact that the treewidth of the primal graph of F is bounded but it is not clear if such tools can exploit the incidence treewidth of the formula.

In this talk, we give a partial answer to this question by showing that some natural restrictions of #DPLL cannot solve formulas whose incidence graph has treewidth k.

3.23 From knowledge of humans performing everyday activities to the service robots

Lisset Y. Salinas Pinacho (ifib – Bremen, DE)

Joint work of Alexander Wich, Andrei Haidu, Michael Beetz

Humans perform daily manipulation tasks as a routine, which might not present a hight level of complexity while performing, because they poses commonsense knowledge that was acquired since infancy. However, a system which does not own the enormous amount of information that humans have, when trying to perform the same tasks, faces a huge challenge. This kind of system have been named service robots, which are expected to perform autonomously and accurately to be accepted as human's companions. Even when this robots present high manipulation performance nowadays, they are still unable to perform as well as humans. Part of the challenge while performing a daily task successfully is to find the right sources of the required knowledge. Some available sources of commonsense knowledge are, which are unfortunately still incomplete, knowledge bases and datasets from either humans or robots performing a task. By following this idea, the commonsense knowledge obtained in this work comes from different sources as the KnowRob knowledge base [1] and knowledge of humans performing daily tasks, extracted from videos and virtual reality environments [2]. The knowledge from these last mentioned sources has still to be represented and available for later use of service robot. In this work is presented the representation structure using the ideas presented by the KnowRob system, and the knowledge retrieve system. As well as the open platform openEASE [3] to analyse and visualize the data is presented.

References

1 M. Tenorth and M. Beetz, "Knowrob – knowledge processing for autonomous personal robots," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4261–4266, October 2009.
2 A. Haidu and M. Beetz, "Action recognition and interpretation from virtual demonstrations," in *International Conference on Intelligent Robots and Systems (IROS)*, (Daejeon, South Korea), pp. 2833–2838, 2016.
3 M. Beetz, M. Tenorth, and J. Winkler, "Opean-ease: A knowledge processing service for robots and robotics/ ai researchers," tech. rep., TZI-Bericht 74, Universität Bremen, 2014.

3.24 Compiling Deep Nets

Scott Sanner (University of Toronto, CA)

Aside from standard uses of deep neural networks for supervised and unsupervised learning, we may want to reason about the learned deep network itself. For example, we may wish to know what completion of a partial input maximizes the (probability of an) output. Or if we train deep a generative model, we may wish to make arbitrary probabilistic queries with arbitrary evidence on this model without resorting to sampling. But how do we compile deep networks to representations amenable to efficient MPE, MAP, or marginal query style inferences? In this talk, I will present some initial directions for such deep network compilations.

3.25 Provenance Circuits and Knowledge Compilation in ProvSQL

Pierre Senellart (ENS – Paris, FR)

This talk describes the ProvSQL system, whose goal is to add support for (m-)semiring provenance and uncertainty management to PostgreSQL databases, in the form of a PostgreSQL extension/module/plugin. It is work in progress at the moment.

Probability computation in ProvSQL relies knowledge compilation tools, such as c2d, d4, or dsharp, to compile a circuit expressing the provenance of a query into a d-DNNF, whose probability can be evaluated. We explain this process in this talk and demonstrate the specific use case of knowledge compilation for probabilistic data management.

ProvSQL is freely available for download from https://github.com/PierreSenellart/provsql

3.26 Just-In-Time Compilation of Knowledge Bases

Laurent Simon (University of Bordeaux, FR)

Joint work of Laurent Simon, Gilles Audemard, Jean-Marie Lagniez

Since the first principles of Knowledge Compilation (KC), most of the work has been focused in finding a good compilation target language in terms of compromises between compactness and expressiveness. The central idea remained unchanged in the last fifteen years: an off-line, very hard, stage, allows to "compile" the initial theory in order to guarantee (theoretically) an efficient on-line stage, on a set of predefined queries and operations. We propose a new "Just-in-Time" approach for KC. Here, any knowledge Base (KB) will be immediately available for queries, and the effort spent on past queries will be partly amortized for future ones. To guarantee efficient answers, we rely on the tremendous progresses made in the practical solving of SAT and incremental SAT applicative problems. Even if each query may be theoretically hard, we show that our approach outperforms previous KC approaches on the set of classical problems used in the field, and allows to handle problems that are out of the scope of current approaches.

3.27 First-Order Knowledge Compilation

Guy Van den Broeck (UCLA, US)

This talk gives an overview of recent developments in knowledge compilation for first-order logic. We focus the discussion on solving the (weighted) model counting task on first-order knowledge bases. This task received a lot of attention recently, as it underlies probabilistic database query evaluation [1], as well as inference and learning in statistical relational models [2]. The knowledge compilation approach faces several challenges: what is the appropriate first-order circuit language, like NNF, that supports tractable model counting, how to effectively compile first-order sentences into this language. We also discuss how

first-order compilation and counting are fundamentally different from their propositional counterparts.

References

1 Guy Van den Broeck and Dan Suciu. Query Processing on Probabilistic Data: A Survey, Foundations and Trends in Databases, Now Publishers, 2017.
2 Guy Van den Broeck. Lifted Inference and Learning in Statistical Relational Models, PhD thesis, KU Leuven, 2013

3.28 Inside d4

Jean-Marie Lagniez (IUT de Lens, FR)

Joint work of Jean-Marie Lagniez, Pierre Marquis

We present and evaluate a new compiler, called D4, targeting the Decision-DNNF language. As the state-of-the-art compilers C2D and Dsharp targeting the same language, D4 is a top-down tree-search algorithm exploring the space of propositional interpretations. D4 is based on the same ingredients as those considered in C2D and Dsharp (mainly, disjoint component analysis, conflict analysis and non-chronological backtracking, component caching). D4 also takes advantage of a dynamic decomposition approach based on hypergraph partitioning, used sparingly. Some simplification rules are also used to minimize the time spent in the partitioning steps and to promote the quality of the decompositions. Experiments show that the compilation times and the sizes of the Decision-DNNF representations computed by D4 are in many cases significantly lower than the ones obtained by C2D and Dsharp.

References

1 Jean-Marie Lagniez and Pierre Marquis, "An Improved Decision-DNNF Compiler," in *IJCAI 2017*, pp. 667-673, 2017.

4 System Presentations

4.1 The SDD and miniC2D Packages

Arthur Choi (UCLA, US) and Adnan Darwiche (UCLA, US)

URL http://reasoning.cs.ucla.edu/sdd/

The SDD Package is a system for constructing, manipulating and optimizing Sentential Decision Diagrams (SDDs). It further provides a compiler from CNF/DNF to SDDs, with dynamic variable and vtree search. The system further supports the apply operator (for conjoining/disjoining two SDDs), and support for queries such as (weighted) model counting, cardinality minimization, etc. In the upcoming version 2.0 release, the SDD Package will be open source, with improved dynamic search, and support for X-constrained vtrees. Moreover, the package will provide new, powerful primitives to facilitate the development of dynamic search algorithms.

The miniC2D package is a model counter, as well as a system for top-down compilation of CNFs/DNFs to (decision) SDDs. The package is open-source, and provides a framework for building new compilers and new model counters from SAT solvers.

The SDD Package is available at http://reasoning.cs.ucla.edu/sdd/ and the miniC2D package is available at http://reasoning.cs.ucla.edu/minic2d/.

4.2 Computing Problem Decompositions of Small Width with Local Improvement

Neha Lodha (TU Wien, AT)

Joint work of Johannes Fichte, Neha Lodha, Sebastian Ordyniak, Stefan Szeider

Many otherwise hard computational counting or optimisation tasks can be solved efficiently if a structural decomposition of small width of the instance is provided. Finding decompositions of optional or close to optimal width has been of interest for decades. In this talk we will show how we extended exact approaches as well as improved heuristically obtained upper bounds using local improvements. The two width parameters we focused on are branchwidth and treewidth. Our experiments show that the local improvement method for both branchwidth and treewidth are able to decrease the width of decompositions significantly.

References

1 Neha Lodha, Sebastian Ordyniak, Stefan Szeider. *A SAT Approach to Branchwidth*. SAT 2016
2 Neha Lodha, Sebastian Ordyniak, Stefan Szeider. *SAT-Encodings for Special Treewidth and Pathwidth*. SAT 2017
3 Johannes Klaus Fichte, Neha Lodha, Stefan Szeider. *SAT-Based Local Improvement for Finding Tree Decompositions of Small Width*. SAT 2017

4.3 Knowledge Compilation Tools

Joao Marques-Silva (University of Lisbon, PT)

Primer

Formula compilation by generation of prime implicates or implicants finds a wide range of applications in AI. Recent work on formula compilation by prime implicate/implicant generation often assumes a Conjunctive/Disjunctive Normal Form (CNF/DNF) representation. However, in many settings propositional formulae are naturally expressed in non-clausal form. Despite a large body of work on compilation of non-clausal formulae, in practice existing approaches can only be applied to fairly small formulae, containing at most a few hundred variables. We describe two novel approaches for the compilation of non-clausal formulae either with prime implicants or implicates, that is based on propositional Satisfiability (SAT) solving. These novel algorithms also find application when computing all prime implicates of

a CNF formula. The proposed approach is shown to allow the compilation of non-clausal formulae of size significantly larger than existing approaches.

HFLUBBER and IP-HORN

In knowledge compilation, the Horn Least Upper Bound (Horn LUB) of a formula F refers to the strongest Horn theory entailed by F. In [2], two SAT-based tools for computing Horn LUBs were proposed: HFLUBBER and IP-HORN. Both are based on successively querying a SAT solver in the lookout for so-called Horn prime-implicates.

References

1 Alessandro Previti, Alexey Ignatiev, Antonio Morgado and J. Marques-Silva. *Prime Compilation of Non-clausal Formulae*. IJCAI 2015
2 Carlos Mencía, Alessandro Previti and Joao Marques-Silva. *SAT-Based Horn Least Upper Bounds*. SAT 2015

4.4 Qute: A Dependency Learning QBF Solver

Friedrich Slivovsky (TU Wien, AT)

Joint work of Peitl, Tomáš; Slivovsky, Friedrich; Szeider, Stefan
Main reference Tomás Peitl, Friedrich Slivovsky, Stefan Szeider: "Dependency Learning for QBF", in Proc. of the Theory and Applications of Satisfiability Testing - SAT 2017 - 20th International Conference, Melbourne, VIC, Australia, August 28 - September 1, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10491, pp. 298–313, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-319-66263-3_19
URL https://www.ac.tuwien.ac.at/research/qute/

Qute is a solver for quantified Boolean formulas (QBFs) based on quantified conflict-driven constraint learning (QCDCL). Its key feature is a new technique for exploiting variable independence which we call *dependency learning* [1]. The resulting version of QCDCL enjoys improved propagation and increased flexibility in choosing variables for branching while retaining ordinary (long-distance) Q-resolution as its underlying proof system.

References

1 Tomáš Peitl, Friedrich Slivovsky, and Stefan Szeider. *Dependency Learning for QBF*. SAT 2017

4.5 ForcLift and PySDD

Wannes Meert (KU Leuven, BE)

ForcLift

- Method: Lifted /First-Order Weighted Model Counting
- Tasks:
  - Partition function of relational probabilistic model (e.g. MLN)
  - Marginal / conditional probabilities

```
Generate_GLB
Input: a set of clauses Σ = {C_1, C_2, ..., C_n}.
Output: a greatest Horn lower-bound of Σ.
begin
    L := the lexicographically first Horn–
         strengthening of Σ
    loop
        L' := lexicographically next Horn–
              strengthening of Σ
        if none exists then exit loop
        if L ⊨ L' then L := L'
    end loop
    remove subsumed clauses from L
    return L
end
```

Figure 1 Algorithm for generating a greates Horn lower-bound.

- Parameter and structure learning
- Available from https://github.com/UCLA-StarAI/Forclift

PySDD: SDD Python Wrapper

SDD wrapper formerly used in ProbLog (cython based). Seperate package is work in progress.

5 Open Problems

5.1 Revisiting Horn Approximations to Clausal Theories

Henry Kautz (University of Rochester, USA)

Horn upper-bounds and Horn lower-bounds

Let Σ be a set of clauses. The sets Σ_{lb} and Σ_{ub} of Horn clauses are respectively a Horn lower-bound and a Horn upper-bound of Σ iff

$$\mathcal{M}(\Sigma_{lb}) \subseteq \mathcal{M}(\Sigma) \subseteq \mathcal{M}(\Sigma_{ub}),$$

or, equivalently,

$$\Sigma_{lb} \models \Sigma \models \Sigma_{ub}.$$

Acylic Horn Theories

A set of Horn clauses is acyclic iff

- Its predicates can be numbered such that for every clause, the predicate in the positive literal (if any) has a higher number than any predicate in a negative literal.
- In each clause, every variable in a positive literal appears in a negative literal.

Finding Acyclic Horn Lower Bounds

Search through ways to transform the source theory to acyclic Horn by
- Deleting all but one positive literal in each clause.
- Deleting a minimal number of negative literals from the clauses such that the resulting theory is non-recursive.
- Return any LB found this way that does not strictly entail some other LB.

Question 1: is the result always a greates lower bound?

Compiling Prolog to ASP

Prolog extends Horn logic with negation as failure.
- Negation as failure operator may appear in front of literals in the body of a clause.
- Undecidable
- Some programs cannot be given coherent semantics.

Answer set programming (ASP) restricts Prolog to stratified theories.
- Decidable
- Each program has stable set semantics.

Question 2: Can ASP GLBs of Prolog programs be found by a version of Generate_GLB?

5.2 Bounds on the DNNF size of Disjoint Sums

Stefan Mengel (CNRS, CRIL – Lens FR)

Consider Boolean functions $f(x_1, \ldots, x_k)$ and $f(y_1, \ldots, y_r)$ for which we have DNNF lower bounds, where $\{x_1, \ldots, x_k\} \cap \{y_1, \ldots, y_r\} = \emptyset$. What can we say about the DNNF size of $f(x_1, \ldots, x_k) \wedge f(y_1, \ldots, y_r)$?

5.3 Compilation of CNFs into Decision DNNFs parameterized by Incidence Treewidth

Igor Razgon (Birkbeck, University of London, GB)

The incidence graph of a CNF F is the undirected bipartite graph which has the variables and clauses of F for vertices, and a variable v is adjacent to a clause C if v occurs in C. It is known that CNFs admit FPT-size compilation into d-DNNFs, parameterized by incidence treewidth. However, it is open whether *CNFs admit FPT-size compilation into decision DNNFs, parameterized by incidence treewidth.*

A closely related question is the following: *Do unsatisfiable CNFs admit FPT-size resolution refutations, parameterized by incidence treewidth?*

5.4 Smoothing in Subquadratic Time

Guy Van den Broeck (UCLA, US)

An NNF is *smooth* if, for every disjunction C in the NNF, each disjunct of C mentions the same variables. That is, if $C_1, \ldots, C_n$ are the children of or-node C, then $vars(C_i) = vars(C_j)$, where $1 \leq i, j \leq n$.

A (d-)DNNF can be transformed in into a smooth (d-)DNNF in quadratic time. *But can smoothing be performed in subquadratic time?*

5.5 On the VC-dimension of DNNF and SDD

Frederic Koriche (Artois University – Lens, FR)

A central problem in learning theory is to determine the sample complexity of concept classes. Roughly, the sample complexity of a concept class C is the number of examples required to output a concept (from the given class) with good generalization behavior. This complexity measure is intrinsically related to the VC-dimension of C, which is the maximum size of any set of examples that can be labeled in any possible way using concepts taken from C. Although the VC-dimension of binary decision trees and DNF formulas is well-known, an interesting open question is to identify (or at least, to approximate) the sample complexity of nontrivial subclasses of DNNF and SDD (e.g. decision DNNF formulas of bounded depth, SDD of size polynomial in the dimension of examples, etc.)

5.6 First Order Model Counting

Dan Suciu (University of Washington – Seattle, US)

$\#P_1$ is the class of functions in $\#P$ over a unary input alphabet (also called *tally problems*).

We know that there exist (symmetric) First Order Model Counting (FOMC) queries that $\#P_1$-hard. Open problems:

- Give an example of query where FOMC is $\#P_1$-hard.
- Characterize the class of FOMC queries in P or the class of queries that is $\#P_1$-complete.

Participants

- Antoine Amarilli
Télécom ParisTech – Paris, FR
- Lameck Mbangula Amugongo
Namibia Univ. of Science & Technology – Windhoek, NA
- Paul Beame
University of Washington – Seattle, US
- Arpita Biswas
Indian Institute of Science – Bangalore, IN
- Pierre Bourhis
CNRS – Lille, FR
- Simone Bova
TU Wien – Vienna, AT
- Florent Capelli
INRIA – Lille, FR
- Ondrej Cepek
Charles University – Prague, CZ
- Zaineb Chelly Dagdia
Aberystwyth University – Aberystwyth, GB
- Arthur Choi
UCLA – Los Angeles, US
- YooJung Choi
UCLA – Los Angeles, US
- Adnan Darwiche
UCLA – Los Angeles, US
- Ronald de Haan
University of Amsterdam – Amsterdam, NL
- Hélène Fargier
University of Toulouse – Toulouse, FR
- Robert Ganian
TU Wien – Vienna, AT
- Martin Grohe
RWTH Aachen – Aachen, DE
- Henry A. Kautz
University of Rochester – Rochester, US
- Batya Kenig
Technion – Haifa, IL
- Frederic Koriche
Artois University – Lens, FR
- Oliver Kullmann
Swansea University – Swansea, GB
- Jean-Marie Lagniez
Artois University – Lens, FR
- Neha Lodha
TU Wien – Vienna, AT
- Meena Mahajan
Institute of Mathematical Sciences – Chennai, IN
- Joao Marques-Silva
University of Lisbon – Lisbon, PT
- Pierre Marquis
Artois University – Lens, FR
- Wannes Meert
KU Leuven – Leuven, BE
- Stefan Mengel
CNRS, CRIL – Lens FR
- Shin-ichi Minato
Hokkaido University – Hokkaido, JP
- Alexandre Niveau
Caen University – Caen, FR
- Jakob Nordström
KTH Royal Institute of Technology – Stockholm, SE
- Dan Olteanu
University of Oxford – Oxford, GB
- Igor Razgon
Birkbeck, University of London – London, GB
- Subhrajit Roy
IBM Research – Melbourne, AU
- Lisset Y. Salinas Pinacho
ifib – Bremen, DE
- Scott Sanner
University of Toronto – Toronto, CA
- Rahul Santhanam
University of Oxford – Oxford, GB
- Marco Schaerf
Sapienza University of Rome – Rome, IT
- Pierre Senellart
ENS – Paris, FR
- Laurent Simon
University of Bordeaux – Bordeaux, FR
- Friedrich Slivovsky
TU Wien – Vienna, AT
- Dan Suciu
University of Washington – Seattle, US
- Stefan Szeider
TU Wien – Vienna, AT
- Guy Van den Broeck
UCLA – Los Angeles, US

Report from Dagstuhl Seminar 17382

Approaches and Applications of Inductive Programming

Edited by

Ute Schmid[1], Stephen H. Muggleton[2], and Rishabh Singh[3]

1 **Universität Bamberg, DE,** ute.schmid@uni-bamberg.de
2 **Imperial College London, GB,** s.muggleton@imperial.ac.uk
3 **Microsoft Research – Redmond, US,** rishabh@csail.mit.edu

Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 17382 "Approaches and Applications of Inductive Programming". After a short introduction to the state of the art to inductive programming research, an overview of the introductory tutorials, the talks, program demonstrations, and the outcomes of discussion groups is given.

Seminar September 17–20, 2017 – http://www.dagstuhl.de/17382
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1 Executive summary

Ute Schmid

Inductive programming (IP) addresses the automated or semi-automated generation of computer programs from incomplete information such as input-output examples, constraints, computation traces, demonstrations, or problem-solving experience [5]. The generated – typically declarative – program has the status of a hypothesis which has been generalized by induction. That is, inductive programming can be seen as a special approach to machine learning. In contrast to standard machine learning, only a small number of training examples is necessary. Furthermore, learned hypotheses are represented as logic or functional programs, that is, they are represented on symbol level and therefore are inspectable and comprehensible [17, 8, 18]. On the other hand, inductive programming is a special approach to program synthesis. It complements deductive and transformational approaches [20, 14, 2]. In cases where synthesis of specific algorithm details that are hard to figure out by humans inductive reasoning can be used to generate program candidates from either user-provided data such as test cases or from data automatically derived from a formal specification [16].

Inductive program synthesis is of interest for researchers in artificial intelligence since the late sixties [1]. On the one hand, the complex intellectual cognitive processes involved in producing program code which satisfies some specification are investigated, on the other hand methodologies and techniques for automating parts of the program development process are explored. One of the most relevant areas of application of inductive programming techniques is end-user programming [3, 12, 4]. For example, the Microsoft Excel plug-in Flashfill synthesizes programs from a small set of observations of user behavior [8, 7, 6]. Related

applications are in process mining and in data wrangling [11]. Inductive programming in general offers powerful approaches to learning from relational data [15, 13] and to learning from observations in the context of autonomous intelligent agents [10, 17]. Furthermore, inductive programming can be applied in the context of teaching programming [19, 21].

Recent Trends and Applications

When the first Dagstuhl Seminar on Approaches and Applications of Inductive Programming took place in 2013, the following trends could be identified:

- Combining different approaches to inductive programming to leverage their complementary strengths.
- New inductive programming approaches based on adapting and using well-developed techniques such as SAT-solving.
- Putting inductive programming to application, for example in the areas of automated string manipulations in spreadsheets or web programming.
- Applying concepts of inductive programming to cognitive models of learning structural concepts.

One of the major outcomes of the first Dagstuhl Seminar was a joint publication in the Communications of the ACM [8] where these trends and first applications and results were described. In the seminar 2015, the following additional trends were identified:

- Evaluation of inductive programming approaches – in relation to general intelligence and in relation to standard machine learning.
- Application of inductive programming to teaching programming.
- Inductive programming as a model of human inductive learning.

The main outcomes of the second seminar were (1) a joint publication in the Artificial Intelligence Journal with respect to the evaluation of computational models solving intelligence test problems – among them inductive programming systems [9], (2) a joint publication addressing comprehensibility as a second criterium to evaluate machine learning approaches besides accuracy [18], and (3) a NIPS'2016 workshop on Neural Nets and Program Induction[1].

Based on the results of the second seminar, the focus of the third seminar has been on the following aspects:

- Identifying the specific contributions of inductive programming to machine learning research and applications of machine learning, especially identifying problems for which inductive programming approaches more suited than standard machine learning approaches, including deep learning.
- Establishing criteria for evaluating inductive programming approaches in comparison to each other and in comparison to other approaches of machine learning and providing a set of benchmark problems.
- Discussing current applications of inductive programming in enduser programming and programming education and identifying further relevant areas of application.
- Establishing stronger relations between cognitive science research on inductive learning and inductive programming.

In the seminar, we brought together researchers from different areas of computer science – especially from machine learning, AI, declarative programming, and software engineering

[1] https://uclmr.github.io/nampi/

– and researchers from cognitive psychology interested in inductive learning as well as in teaching and learning computer programming. Furthermore, participants from industry presented current as well as visionary applications for inductive programming.

The seminar was opened with lecture style talks introducing the four major approaches of inductive programming: Inductive functional programming, inductive logic programming, inductive probabilistic logical programming, and programming by example.

Talks covered current developments of IP algorithms, challenging applications –especially in data wrangling and in education –, and relations of IP to cognition.

In addition, several system demons and tutorials were given: Igor and EasyIgor (by Sebastian Seufert and Ute Schmid), MagicHaskeller (by Susumu Katayama), Sketch (by Armando Solar-Lezama), PROSE (by Oleksandr Polozov), Slipcover (by Fabrizio Riguzzi), and TaCLe (by Luc De Raedt).

The following topics were identified and further discussed in working groups during the seminar:

- How to determine relevancy of background knowledge to reduce search?
- Integrating IP with other types of machine learning, especially Deep Learning?
- Data wrangling as exiting area of application.

Additional topics identified as relevant have been anomaly detection, noise, robustnes, as well as non-example based interaction (e.g., natural language).

Concluding remarks and future plans

In the wrapping-up section, we collected answers to the question

"What would constitute progress at Dagstuhl 2019?"

The most prominent answers were

- make available systems, data sets (via IP webpage[2])
- compare systems
- common vocabulary, work on applications attempted by others: drawing problems, string transformation, general ai challenge, benchmarks starexec, learn robot strategy, grammar learning what is inductive programming
- open problems

As the grand IP challenge we came up with: **An IP program should invent an algorithm publishable in a serious journal (e.g., an integer factorization algorithm) or win a programming competition!**

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2 Table of Contents

3 Introductory Talks

3.1 A Short Introduction to Inductive Functional Programming

Ute Schmid (Universität Bamberg, DE)

Joint work of Ute Schmid, Emanuel Kitzelmann
Main reference Pierre Flener, Ute Schmid: "An introduction to inductive programming", Artif. Intell. Rev., Vol. 29(1), pp. 45–62, 2008.
URL http://dx.doi.org/10.1007/s10462-009-9108-7

In this talk, a short introduction to inductive functional programming is given. Specifically, a brief outline of the history of inductive functional programming is presented. The milestone system Thesys (Summers, 1977) is introduced. Current developments are presented with a focus on our own system Igor.

3.2 Inductive Logic Programming

Stephen H. Muggleton (Imperial College London, GB)

Main reference Stephen H. Muggleton: "Meta-Interpretive Learning: Achievements and Challenges (Invited Paper)", in Proc. of the Rules and Reasoning – International Joint Conference, RuleML+RR 2017, London, UK, July 12-15, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10364, pp. 1–6, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-319-61252-2_1

Meta-Interpretive Learning (MIL) is a recent Inductive Logic Programming technique aimed at supporting learning of recursive definitions. A powerful and novel aspect of MIL is that when learning a predicate definition it automatically introduces sub-definitions, allowing decomposition into a hierarchy of reuseable parts. MIL is based on an adapted version of a Prolog meta-interpreter. Normally such a meta-interpreter derives a proof by repeatedly fetching first-order Prolog clauses whose heads unify with a given goal. By contrast, a meta-interpretive learner additionally fetches higher-order meta-rules whose heads unify with the goal, and saves the resulting meta-substitutions to form a program. This talk will overview theoretical and implementational advances in this new area including the ability to learn Turing computabale functions within a constrained subset of logic programs, the use of probabilistic representations within Bayesian meta-interpretive and techniques for minimising the number of meta-rules employed. The talk will also summarise applications of MIL including the learning of regular and context-free grammars, learning from visual represention with repeated patterns, learning string transformations for spreadsheet applications, learning and optimising recursive robot strategies and learning tactics for proving correctness of programs. The talk will conclude by pointing to the many challenges which remain to be addressed within this new area.

3.3 A Short Introduction to Probabilistic Logic Programming

Luc De Raedt (KU Leuven, BE)

Joint work of Luc De Raedt, Angelika Kimmig
Main reference Luc De Raedt, Angelika Kimmig: "Probabilistic (logic) programming concepts", Machine Learning, Vol. 100(1), pp. 5–47, 2015.
URL http://dx.doi.org/10.1007/s10994-015-5494-z

In this introductory talk, a short introduction to probabilistic programming principles was given. It was centered around the distribution semantics of Sato and the probabilistic programming language Problog.

3.4 Programming By Examples for Data Transformation and Integration

Rishabh Singh (Microsoft Research – Redmond, US)

In this talk, I will briefly summarize some of the past work in building efficient programming by example (PBE) systems for data wrangling tasks using Version-space algebras [3]. There are four key parts of designing such PBE systems: 1) designing an expressive and concise domain-specific language (DSL) for constructing the hypothesis space, 2) designing efficient data structures to succinctly represent an exponential number of programs in polynomial space, 3) a learning algorithm that learns a set of consistent programs in the DSL that conform to a set of user-provided input-output examples, and finally 4) a ranking function for selecting the most likely programs. I will then present some of the more recent systems we have built with new advances on top of a similar methodology in the domains of semantic data transformations [2], input-driven data mainpulation [1], and data integration from web sources [4].

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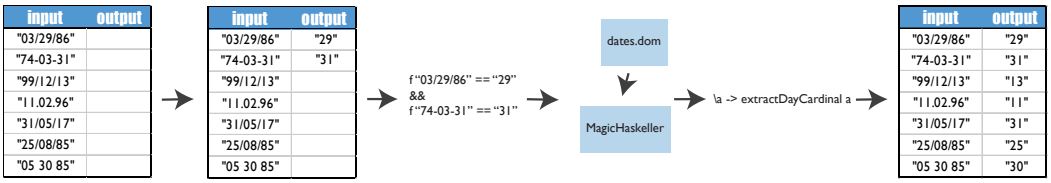

Figure 1 System functionality. Once the user provides input/output examples and the domain (DBBK), the system tries to induce the possible transformation to be applied.

4 Overview of Talks

4.1 The BigLambda Project

Aws Albarghouthi (University of Wisconsin, Madison, US)

In this talk, I cover various pieces of the BigLambda project, which aims to synthesize data analysis programs from examples. First, I discuss the BigLambda system and how it synthesizes MapReduce-style programs that can execute in parallel. Second, I describe how one can extract domain-knowledge of a synthesis domain by observing test runs of an API. Third, I will describe future problems involving synthesizing programs under privacy constraints.

4.2 Domain Specific Induction for Data Wrangling Automation

Lidia Contreras-Ochando (Technical University of Valencia, ES)

Joint work of Lidia Contreras-Ochando, César Ferri, José Hernández-Orallo, Susumu Katayama, Fernando Martínez-Plumed, María José Ramírez-Quintana
Main reference Lidia Contreras-Ochando, Cèsar Ferri, José Hernández-Orallo, Fernando Martínez-Plumed, María José Ramírez-Quintana, Susumu Katayama: "Domain specific induction for data wrangling automation (Demo)", Automatic Machine Learning Workshop (AutomML) @ ICML 2017, Sidney, Australia, 2017.
URL http://users.dsic.upv.es/ flip/papers/AutoML_ICML2017.pdf

Inside the data science process, data wrangling is the step that involves transforming data, cleaning datasets and combining them to create new ones, and this step can consume up to 80% of the project time [1]. Automating data wrangling process is essential to reduce time and cost in our projects. Our proposal to solve this problem includes the use of general-purpose inductive programming learning systems with general-purpose declarative languages, using an appropriate library that defines a domain-specific background knowledge [2]. The overall idea is to automate the process of transforming data from one format to another, depending on the data domain and using MagicHaskeller as the inductive programming system, with only one or few examples (Figure 1). Our approach is able to solve several problems by using the correct domain independently of the data format.

Acknowledgments. This work has been partially supported by the EU (FEDER) and the Spanish MINECO project TIN 2015-69175-C4-1-R (LOBASS) and by Generalitat Valenciana under ref. PROMETEOII/2015/013 (SmartLogic). Lidia Contreras was supported by FPU-ME grant FPU15/03219.

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4.3 Learning Higher-Order Logic Programs through Abstraction and Invention

Andrew Cropper (Imperial College London, GB) and Stephen H. Muggleton (Imperial College London, GB)

Main reference Andrew Cropper, Stephen H. Muggleton: "Learning Higher-Order Logic Programs through Abstraction and Invention", in Proc. of the Twenty-Fifth International Joint Conference on Artificial Intelligence, IJCAI 2016, New York, NY, USA, 9-15 July 2016, pp. 1418–1424, IJCAI/AAAI Press, 2016.
URL http://www.ijcai.org/Abstract/16/204

Many tasks in AI require the design of complex programs and representations, whether for programming robots, designing game-playing programs, or conducting textual or visual transformations. This paper [1] explores a novel inductive logic programming approach to learn such programs from examples. To reduce the complexity of the learned programs, and thus the search for such a program, we introduce higher-order operations involving an alternation of Abstraction and Invention. Abstractions are described using logic program definitions containing higher-order predicate variables. Inventions involve the construction of definitions for the predicate variables used in the Abstractions. The use of Abstractions extends the Meta-Interpretive Learning framework and is supported by the use of a user-extendable set of higher-order operators, such as *map*, *until*, and *ifthenelse*. Using these operators reduces the textual complexity required to express target classes of programs. We provide sample complexity results which indicate that the approach leads to reductions in the numbers of examples required to reach high predictive accuracy, as well as significant reductions in overall learning time. Our experiments demonstrate increased accuracy and reduced learning times in all cases. We believe that this paper is the first in the literature to demonstrate the efficiency and accuracy advantages involved in the use of higher-order abstractions.

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4.4 Learning Constraints in Spreadsheets and Tabular Data

Luc De Raedt (KU Leuven, BE)

Joint work of Samuel Kolb, Sergey Paramonov, Tias Guns, Luc De Raedt
Main reference Samuel Kolb, Sergey Paramonov, Tias Guns, Luc De Raedt: "Learning constraints in spreadsheets and tabular data", Machine Learning, Vol. 106(9-10), pp. 1441–1468, 2017.
URL http://dx.doi.org/10.1007/s10994-017-5640-x

Spreadsheets, comma separated value files and other tabular data representations are in wide use today. However, writing, maintaining and identifying good formulas for tabular data and spreadsheets can be time-consuming and error-prone. We investigate the automatic learning of constraints (formulas and relations) in raw tabular data in an unsupervised way. We represent common spreadsheet formulas and relations through predicates and expressions whose arguments must satisfy the inherent properties of the constraint. The challenge is to automatically infer the set of constraints present in the data, without labeled examples or user feedback. This approach is based on inductive programming.

4.5 Applying ILP to Sequence Induction Tasks

Richard Evans (Google DeepMind – London, GB)

We describe a system for solving Hofstadter's "Seek Whence" tasks. This is an inductive logic program system, that uses (broadly) Kantian constraints to group its percepts into persistent objects, changing over time, according to causal laws. This system is able to achieve human-level performance in the "Seek Whence" domain.

Similar to Hofmann, Kitzelmann, and Schmid [1], we avoid domain-specific heuristics, and focus on a domain-independent solution to this task. We claim that the prior constraints we use, inspired by Kant's Principles in the Critique of Pure Reason, are domain-independent prior knowledge.

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4.6 What's behind this model?

Cesar Ferri Ramirez (Technical University of Valencia, ES)

Joint work of Raül Fabra Boluda, César Ferri, José Hernández-Orallo, Fernando Martínez-Plumed, María José Ramírez-Quintana

Machine learning is being widely used in applications related to security or applications that deal with confidential information. Examples of these applications are spam detection, malware classification, detection of network intrusion ... In many of these cases, data

can be actively manipulated by an intelligent adversary. Those adversarial agents can also try to extract and mimic (possibly confidential) machine learning models aiming at taking advantage of them and, in this way, evade detections and alarms. Many of the developed methods to manipulate/attack models are technique-based. This implies that these methods have been defined considering that they know the family of the machine learning technique (decision trees, neural networks,...) used to learn the target model that they want to manipulate. In this work we propose some methods to capture information about models (seen as black boxes). The information we plan to obtain is: family of the learning technique, significance of the different members of the feature space and the possible existence of attribute transformations. Our first approach is based on mimeting the target models, and then from the mimetic models. we extract meta-features by the application of meta-learning techniques. We also discuss about the feasibility of extracting knowledge in declarative models. Examples of details we want to discover from declarative models are: the existence of relational patterns between features, recursive patterns in the model, or the existence of attribute transformations, such as the use of propositionalisation for complex features. We also discuss about the feasibility of extracting knowledge from declarative models such as the existence of relational patterns between features, recursive patterns in the model, or the existence of attribute transformations (for instance, propositionalisation for complex features).

Acknowledgments. This work has been partially supported by the EU (FEDER) and the Spanish MINECO project TIN 2015-69175-C4-1-R (LOBASS) and by Generalitat Valenciana under ref. PROMETEOII/2015/013 (SmartLogic).

4.7 Interacting with Program Synthesis by Example: Designing Around Human Cognition

Elena Glassman (University of California – Berkeley, US)

Joint work of Elena Glassman, Gustavo Soares, Andrew Head, Ryo Suzuki, Lucas Figueredo, Bjoern Hartmann, Loris D'Antoni
Main reference Andrew Head, Elena Glassman, Gustavo Soares, Ryo Suzuki, Lucas Figueredo, Loris D'Antoni, Björn Hartmann: "Writing Reusable Code Feedback at Scale with Mixed-Initiative Program Synthesis", in Proc. of the Fourth ACM Conference on Learning @ Scale, L@S 2017, Cambridge, MA, USA, April 20-21, 2017, pp. 89–98, ACM, 2017.
URL http://dx.doi.org/10.1145/3051457.3051467

This talk is motivated by recent successes and challenges in designing interfaces for interacting with example-driven synthesis backends, i.e., MistakeBrowser and FixPropagator [Head et al. 2017]. I then explain Variation Theory, a well-tested theory of how humans form hypotheses, i.e., learn concepts and rules, from examples. Finally, I discuss how interfaces in the future can help (1) users accurately teach programs to example-driven synthesis backends and (2) communicate those learned programs back to the user.

4.8 The Draughtsman's Assistant

Stephen H. Muggleton (Imperial College London, GB)

Abstraction is an essential and defining property of human learning and thought. Human programmers use abstraction to define meaningful variables, data types, procedures, parameters, conditions and hierarchical problem decomposition. This presentation provides a demonstration of the idea of programming by drawing using the Metagol_AI system. We assume a human teacher draws diagrams on a 2D array and a Meta-Interpretretive Learner uses primitives from the Postscript drawing language to build programs which imitate the drawings. It is assumed programs for drawing symbols, such as an L, from a single example. Abstraction and invention mechanisms can then be used to learn numbers, such as two three or four which can be applied to L to produce multiple instances of L. Incremental learning is then used to build larger programs by building on previously learned programs.

4.9 Towards Ultra-Strong Machine Learning Comprehensibility of Programs Learned with ILP

Stephen H. Muggleton (Imperial College London, GB)

Joint work of Ute Schmid, Christina Zeller, Tarek Besold, Alireza Tamaddoni-Nezhad, Stephen Muggleton
Main reference Ute Schmid, Christina Zeller, Tarek Besold, Alireza Tamaddoni-Nezhad, Stephen Muggleton: "How Does Predicate Invention Affect Human Comprehensibility?", in Proc. of the Inductive Logic Programming – 26th International Conference, ILP 2016, London, UK, September 4-6, 2016, Revised Selected Papers, Lecture Notes in Computer Science, Vol. 10326, pp. 52–67, Springer, 2016.
URL http://dx.doi.org/10.1007/978-3-319-63342-8_5

During the 1980s Michie defined Machine Learning in terms of two orthogonal axes of performance: *predictive accuracy* and *comprehensibility of generated hypotheses*. Since predictive accuracy was readily measurable and comprehensibility not so, later definitions in the 1990s, such as that of Mitchell, tended to use a one-dimensional approach to Machine Learning based solely on predictive accuracy, ultimately favouring statistical over symbolic Machine Learning approaches. In this presentation we provide a definition of comprehensibility of hypotheses which can be estimated using human participant trials. We present the results of experiments testing human comprehensibility of logic programs learned with and without predicate invention. Results indicate that comprehensibility is affected not only by the complexity of the presented program but also by the existence of anonymous predicate symbols.

4.10 Learning from Observation

Katsumi Inoue (National Institute of Informatics – Tokyo, JP)

Two approaches to Learning from Observation are given in this talk. One is Meta-level abduction (MLA), and the other is Learning from interpretation transition (LFIT). In MLA, abduction is performed at the meta-level, enabling us to abduce rules and predicate/object invention. In LFIT, relational dynamics is learned from transition of states of a system in the form of state transition rules.

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4.11 MagicHaskeller-based Incrementally Learning Agent

Susumu Katayama (University of Miyazaki, JP)

This presentation introduced a general AI agent with incremental learning that uses MagicHaskeller. In addition, experiences of applying the agent to Round 1 of General AI Challenge was presented.

4.12 SUPERVASION project – Supervision by Observation using Inductive Programming

David Nieves Cordones (Technical University of Valencia, ES)

Joint work of David Nieves Cordones, Carlos Monserrat, José Hernández-Orallo
Main reference C. Monserrat, J. Hernandez-Orallo, J.-F. Dolz, M.-J. Ruperez, P. Flach: "Knowledge acquisition by abduction for skills monitoring: Application to surgical skills" In Inductive Logic Programming, 2016.
URL http://ilp16.doc.ic.ac.uk/program/papers/24

We present some progress in the project SUPERVASION, part of which was presented at ILP16 [1]. This project proposes a system for automated monitoring of apprentices using information from one high-level explanation given by an expert (a narrative) and one (or very few) video-recorded executions of the procedure. This process of supervision is divided in two phases: knowledge acquisition, where system learns from expert examples; and online supervision, in which the automated supervisor assists as a virtual expert to the trainee during the training. Also, we use Event Calculus [2] for logical reasoning about observable properties and abstract concepts in time. The newly system has been used to learn and detect the starting and ending points of high-level fluents in different trainings in minimally invasive surgery. The experimental results show the potential of the developed tool.

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4.13 Programming Not Only by Examples

Hila Peleg (Technion – Haifa, IL)

Joint work of Hila Peleg, Shaorn Shoham, Eran Yahav

In recent years, there has been tremendous progress in automated synthesis techniques that are able to automatically generate code based on some intent expressed by the programmer. A major challenge for the adoption of synthesis remains in having the programmer communicate their intent. When the expressed intent is coarse-grained (for example, restriction on the

expected type of an expression), the synthesizer often produces a long list of results for the programmer to choose from, shifting the heavy-lifting to the user. An alternative approach, successfully used in end-user synthesis is programming by example (PBE), where the user leverages examples to interactively and iteratively refine the intent. However, using only examples is not expressive enough for programmers, who can observe the generated program and refine the intent by directly relating to parts of the generated program.

We present a novel approach to interacting with a synthesizer using a granular interaction model. Our approach employs a rich interaction model where (i) the synthesizer decorates a candidate program with debug information that assists in understanding the program and identifying good or bad parts, and (ii) the user is allowed to provide feedback not only on the expected output of a program, but also on the underlying program itself. That is, when the user identifies a program as (partially) correct or incorrect, they can also explicitly indicate the good or bad parts, to allow the synthesizer to accept or discard parts of the program instead of discarding the program as a whole.

We show the value of our approach in a controlled user study. Our study shows that participants have strong preference to using granular feedback instead of examples, and are able to provide granular feedback much faster.

4.14 Probabilistic Inductive Logic Programming with SLIPCOVER

Fabrizio Riguzzi (University of Ferrara, IT)

Joint work of Fabrizio Riguzzi, Elena Belliodi
Main reference Elena Bellodi, Fabrizio Riguzzi: "Structure learning of probabilistic logic programs by searching the clause space", TPLP, Vol. 15(2), pp. 169–212, 2015.
URL http://dx.doi.org/10.1017/S1471068413000689

The combination of logic and probability is very useful for modeling domains with complex and uncertain relationships among entities. Machine learning approaches based on such combinations have recently achieved important results, originating the fields of Statistical Relational Learning, Probabilistic Inductive Logic Programming and, more generally, Statistical Relational Artificial Intelligence.

Probabilistic languages based on Logic Programming are particularly promising because of the large body of techniques for inference and learning developed in Logic Programming. Sato's distribution semantics [9] is a possible worlds semantics that emerged as one of the more prominent approach for giving a meaning to Probabilistic Logic Programs. It is adopted by many languages such as the Independent Choice Logic, PRISM, Logic Programs with Annotated Disjunctions, CP-logic and ProbLog.

The talk will illustrates the basics of semantics and inference for these languages and will present the SLIPCOVER system [2] for Probabilistic Inductive Logic Programming. SLIPCOVER learns both the structure and the parameters of Logic Programs with Annotated Disjunctions and CP-logic by performing clause revision followed by greedy theory search.

The talk will also present the cplint on SWISH [6, 1] (http://cplint.ml.unife.it) web application for experimenting with SLIPCOVER. The application can also be used to

- perform probabilistic inference with the PITA [7, 8] and MCITYRE algorithms [5]
- perform Inductive Logic Programming with Aleph [10]
- draw ROC and Precision-Recall curves [3, 4].

These features will be briefly discusses in the talk.

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4.15 Human Learning in the Michalski Train Domain

Ute Schmid (Universität Bamberg, DE)

Joint work of Ute Schmid, Jonas Troles, Johannes Birk, Christina Zeller

Human-like computing (HLC) is relevant for designing AI systems which allow for a comprehensible interaction between humans and machines. One aspect of HLC is to get a better understanding of human cognitive processes. We are interested in comparing human relational learning with ILP and conducted a first experiment to explore how good humans are to learn rules off different structural complexity in the Michalski train domain. We could show, that a simple linear recursive rule can be generalized nearly as efficiently as a conjunction of features while a rule characterizing a relation between objects which can occur at an arbitrary position is nearly as difficult to learn as a disjunction.

4.16 Learning and Decision-making in Artificial Animals

Claes Strannegård (Chalmers University of Technology Göteborg, SE)

I will discuss artificial ecosystems with animals and plants that live in blocks worlds, e.g. in the Minecraft environment. The artificial animals (or animats) are capable of perception, learning, decision-making, and action. Moreover, they have fixed sets of needs for certain

resources, e.g. water and energy. If an animat runs out of some resource, then it dies by definition. The learning and decision-making mechanisms are the same for all animats. The sole goal for all animats is to avoid death. The animats perceive their environment by means of extended boolean circuits. These circuits evolve over time according to a fixed set of rules for learning and forgetting. The animats are capable of sexual or asexual reproduction. In the sexual case, two animats with similar enough genome are able to reproduce under certain circumstances. Together these mechanisms give rise to autonomous ecosystems of animats that interact with each other and continuously adapt to changing environments by learning and evolution.

4.17 Learning to Forget – First Explorations

Michael Siebers (Universität Bamberg, DE)

Joint work of Michael Siebers, Ute Schmid, Kyra Göbel, Cornelia Niessen

I present recent advances in the Dare2Del-Project. The goal of the project is to assess the irrelevance of digital objects. In this talk I will focus on files in an artificial file system. A first representation is shown together with preliminary results on the learning of the derived target predicate. I conclude with challenges posed by the learning task.

4.18 Neural Program Synthesis

Rishabh Singh (Microsoft Research – Redmond, US)

Main reference Rishabh Singh, Pushmeet Kohli: "AP: Artificial Programming", in Proc. of the 2nd Summit on Advances in Programming Languages, SNAPL 2017, May 7-10, 2017, Asilomar, CA, USA, LIPIcs, Vol. 71, pp. 16:1–16:12, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
URL http://dx.doi.org/10.4230/LIPIcs.SNAPL.2017.16

The key to attaining general artificial intelligence is to develop architectures that are capable of learning complex algorithmic behaviors modeled as programs[1, 2, 3, 4]. The ability to learn programs allows these architectures to learn to compose high-level abstractions with complex control-flow, which can lead to many potential benefits: i) enable neural architectures to perform more complex tasks, ii) learn interpretable representations (programs which can be analyzed, debugged, or modified), and iii) better generalization to new inputs (like algorithms). In this talk, I will present some of our recent work in developing neural architectures for learning complex regular-expression based data transformation programs from input-output examples, and will also briefly discuss some other applications such as program repair[6] and fuzzing[5] that can benefit from learning neural program representations.

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5 Working groups

5.1 Meta-Knowledge and Relevance of Background Knowledge

Stephen H. Muggleton, Ute Schmid, Fabrizio Riguzzi, Susumu Katayama, Andrew Cropper, Hila Peleg, Richard Evans

Motivation

Imagine a life-long learning system, which learns new functions (or predicates) from examples during a series of teaching episodes. At the end of each episode the learned functions are added to the library of those available for definitions in subsequent episodes. As the system's library of functions expands we need to decide how to prevent the progressive build-up of available functions swamping the search. We refer to this as the **Relevance Problem**. In particular, we need a method for efficiently identifying a small subset of the available functions which should be used in each new episode. This is a hard and, as yet, unsolved problem for Inductive Programming.

Identifying Relevant Background Knowledge

The Relevance Problem has some similarities to the Frame Problem, which involves finding an adequate collections of axioms for a viable description of a robot environment. In the case of building a learning assistant the Relevance Problem would be critical for applications such as developing a "personal background knowledge manager".

Concrete Proposals

Below are a list of the concrete proposals for relevance detection.

1. Order the functions according to how frequently they are used.
2. Annotating functions with type information, and then consider only functions whose types match the input/output pairs in the provided examples.
3. Simply do not bothering remembering learned functions from previous episodes but instead invent (or reinvent) new ones as needed.
4. Look at analogous functions: eg this function has the right form, but it operates on lists, not trees.
5. Generalise metarules from background definitions to form a template. This could be done by abstracting out the particular variables and predicates used.
6. Store a set of input/output pairs for each learned function, and use this to filter suitable functions.

Further Ideas

The group also discussed the related issue of IP systems which invent new data-types as needed to solve a problem. The idea of creating new data-types is a core ingredient of real programming, and the group agreed it should be studied within IP. Also we discussed the fact that knowing what is relevant requires knowing what we know and what we do not know. For this purpose it was suggested we need some way of modelling our ignorance, such as auto-epistemic logic. Andrew Cropper and Stephen Muggleton have shown that all programs over dyadic predicates can be subsumed by a single pair of metarules. Ute Schmid asked whether it is possible that there is one individual metarule that subsumes all of them? (A Scheffer's stroke for metarules). We also discussed whether it would be possible to mine Prolog programs from github to extract a library of background predicates?

Conclusion

Program Induction presently faces a bottleneck in only ever being able to construct small programs. The group agreed that solving the Relevance Problem was key in overcoming this bottleneck and suggested a variety of approaches which might be implemented and tested to see how effective they are.

5.2 Combining Inductive Programming with Machine Learning

Rishabh Singh, Oleksandr Polozov, Cesar Ferri Ramirez, Aws Albarghouthi, Katsumi Inoue, Michael Siebers, Christina Zeller

There has been a lot of recent interest in using machine learning techniques, especially deep learning techniques, for learning programs from inductive specifications such as input-output examples. There are three main reasons for this surge in recent interest: 1) Learning programs allows neural architectures to perform complex algorithmic tasks compared to simple classification tasks, 2) the prior coming from the underlying hypothesis space in terms of the Domain-specific language of programs allows the learnt models to generalize better on unseen data, and finally 3) the learnt models (in the form of programs) are more interpretable, which can be inspected, verified, and even modified.

There are many ways in which machine learning techniques can aid in the synthesis process to learn programs. One idea can be to automatically learn a policy to perform efficient search over a large space of programs. There has been some recent work (e.g. Neural Turing Machines, Neural Random Access Machines) in embedding program semantics in a differentiable manner such that the programs can be learned using gradient descent based optimization techniques in an end-to-end manner. Some other approaches such as RobustFill learn a generative model of programs in a language conditioned on the examples by learning a function that predicts expansions in a context-free grammar (DSL). Finally, there can be some approaches to combine symbolic search approaches (such as VSA, constraint-solving, integer programming etc.) with machine learning techniques to guide and reduce the search space of programs.

One of the key tasks in inductive programming is to define a good hypothesis space that is expressive enough to express a large class of desired programs but at the same concise enough for efficient search. Machine learning techniques can be used to automatically construct such hypothesis spaces given a large amount of data in a given domain. For example, they can be used to learn idioms/sub-routines that are commonly used over a large number of tasks, which can be used to add new operators in the DSL. One longer term goal would be to see if the learning techniques may help in constructing the complete DSL from scratch only from data.

Some specification mechanisms are inherently noisy and ambiguous. For example, consider specifications in the form of hand drawings, natural language, or pictures. Converting these ambiguous specifications into a formal representation requires machine learning techniques such that the specifications can become usable. Even for deterministic specifications such as FlashFill input-output example strings, there can sometimes be noise in the example strings. Since the traditional synthesis techniques are sound, they will either generate a very complex

program for such noisy examples or return no program if there is no DSL program that is consistent with all noisy examples. Using machine learning techniques can aid these systems to tolerate some noise in the specification and make the synthesis process more robust.

Inductive Programming techniques can also be used for helping machine learning techniques. For example, inductive programming can be used to automate the search of neural network architectures that work best for a given dataset. We can design a DSL consisting of neural network primitives, which can then be searched to compute new networks that compose the primitives with an objective to achieve the best performance on a dataset. Inductive programming can also be used for preprocessing background knowledge and generate new features for machine learning systems. Finally, inductive programming techniques can also be useful for learning hierarchical symbolic structures on top of low-level black box modules that are learnt using machine learning. For example, consider the task of summing up all the digits in a vehicle number plate, where the blackbox modules would be digit recognition functions, whereas the learnt symbolic structure will iterate over the digits of the recognized number.

To summarize, Inductive programming and machine learning techniques can greatly benefit from each other, and it is exciting to see a lot of progress happening currently in both fronts. We expect even more synergy between the two research areas in coming years.

5.3 IP for Data Wrangling

Frank Jäkel, Lidia Contreras-Ochando, Luc De Raedt, Martin Möhrmann

In data science the usual work flow starts with data collection and ends with an analysis script that distills the insights from the data. In between, there is a lot of data wrangling: The data need to be imported from sometimes esoteric file formats and need to be transformed into appropriate data structures. Data scientists spend most of their time on writing custom code for data wrangling, checking and rechecking the correctness of data transformations and the integrity of the data.

IP systems can help automate this process by learning data transformations from examples. However, while for small data sets a data scientist can check by hand that data wrangling code does what it is supposed to do and, e.g., also covers edge cases, exceptions or coding errors, for large data sets this is not possible. Hence, IP support tools for data scientists have to be interactive and help them discover potential problems by, e.g., grouping similar cases for bulk inspection or flagging suspicious or uncertain cases in an active learning mode. Otherwise it is unlikely that IP systems will be trusted, especially by power users.

Luckily, small training sets of hand-checked examples can not only be used for learning data transformation but also to automatically generate tests by learning constraints. For example, if all input strings in a hand-checked subset are of length four, then this constraint can be learned (e.g. with Sketch) and input data that violate this constraint can be discovered without the user having to write an explicit test. Such interactive IP system that also uncover implicit assumptions about the data have the potential to provide substantial increases in productivity for data scientists.

Participants

- Aws Albarghouthi
University of Wisconsin – Madison, US
- Peter Buhler
IBM Research Zurich, CH
- Lidia Contreras-Ochando
Technical University of Valencia, ES
- Andrew Cropper
Imperial College London, GB
- Luc De Raedt
KU Leuven, BE
- Richard Evans
Google DeepMind – London, GB
- Cesar Ferri Ramirez
Technical University of Valencia, ES
- Elena Glassman
University of California – Berkeley, US
- Katsumi Inoue
National Institute of Informatics – Tokyo, JP
- Frank Jäkel
PSIORI – Freiburg, DE
- Susumu Katayama
University of Miyazaki, JP
- Martin Möhrmann
Universität Osnabrück, DE
- Stephen H. Muggleton
Imperial College London, GB
- David Nieves Cordones
Technical University of Valencia, ES
- Hila Peleg
Technion – Haifa, IL
- Oleksandr Polozov
Microsoft Corporation – Redmond, US
- Fabrizio Riguzzi
University of Ferrara, IT
- Ute Schmid
Universität Bamberg, DE
- Sebastian Seufert
Universität Bamberg, DE
- Michael Siebers
Universität Bamberg, DE
- Rishabh Singh
Microsoft Research – Redmond, US
- Armando Solar-Lezama
MIT – Cambridge, US
- Claes Strannegård
Chalmers University of Technology – Göteborg, SE
- Janis Voigtländer
Universität Duisburg-Essen, DE
- Christina Zeller
Universität Bamberg, DE

Report from Dagstuhl Seminar 17391

Deep Learning for Computer Vision

Edited by

Daniel Cremers[1], Laura Leal-Taixé[2], and René Vidal[3]

1 **TU München, DE,** `cremers@tum.de`
2 **TU München, DE,** `leal.taixe@tum.de`
3 **Johns Hopkins University – Baltimore, US,** `rvidal@cis.jhu.edu`

Abstract

The field of computer vision engages in the goal to enable and enhance a machine's ability to infer knowledge and information from spatial and visual input data. Recent advances in data-driven learning approaches, accelerated by increasing parallel computing power and a ubiquitous availability of large amounts of data, pushed the boundaries of almost every vision related subdomain. The most prominent example of these machine learning approaches is a so called deep neural network (DNN), which works as a general function approximator and can be trained to learn a mapping between given input and target output data. Research on and with these DNN is generally referred to as Deep Learning. Despite its high dimensional and complex input space, research in the field of computer vision was and still is one of the main driving forces for new development in machine and deep learning, and vice versa.

This seminar aims to discuss recent works on theoretical and practical advances in the field of deep learning itself as well as state-of-the-art results achieved by applying learning based approaches to various vision problems. Our diverse spectrum of topics includes theoretical and mathematical insights focusing on a better understanding of the fundamental concepts behind deep learning and a multitude of specific research topics facilitating an exchange of knowledge between peers of the research community.

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1 Executive Summary

René Vidal
Daniel Cremers
Laura Leal-Taixé

The paradigm that a machine can learn from examples much like humans learn from experience has fascinated researchers since the advent of computers. It has triggered numerous research developments and gave rise to the concept of artificial neural networks as a computational paradigm designed to mimic aspects of signal and information processing in the human brain.

There have been several key advances in this area including the concept of back- propagation learning (essentially gradient descent and chain rule differentiation on the network weight vectors) by Werbos in 1974, later popularized in the celebrated 1984 paper of Rumelhart,

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Hinton and Williams. Despite a certain success in pattern recognition challenges like handwritten digit classification, artificial neural networks dropped in popularity in the 1990s with alternative techniques such as support vector machines gaining attention.

With increasing computational power (and in particular highly parallel GPU architectures) and more sophisticated training strategies such as layer-by-layer pretraining, supervised backpropagation and dropout learning, neural networks regained popularity in the 2000s and the 2010s. With deeper network architectures and more training data, their performance has drastically improved. Over the last couple of years, they have outperformed numerous existing algorithms on a variety of computer vision challenges such as object recognition, semantic segmentation and even stereo and optical flow estimation.

The aim of this Dagstuhl Seminar is to bring together leading experts from the area of machine learning and computer vision and discuss the state-of-the-art in deep learning for computer vision. During our seminar, we will address a variety of both experimental and theoretical questions such as:

1. In which types of challenges do deep learning techniques work well?
2. In which types of challenges do they fail? Are there variations of the network architectures that may enable us to tackle these challenges as well?
3. Which type of network architectures exist (convolutional networks, recurrent networks, deep belief networks, long short-term memory networks, deep Turing machines)? What advantages and drawbacks does each network architecture bring about?
4. Which aspects are crucial for the practical performance of deep network approaches?
5. Which theoretical guarantees can be derived for neural network learning?
6. What properties assure the impressive practical performance despite respective cost functions being generally non-convex?

2 Table of Contents

3 Overview of Talks

3.1 Statistics, Computation and Learning with Graph Neural Networks

Joan Bruna Estrach (New York University, US)

Many problems across applied sciences, from particle physics to recommender systems, are formulated in terms of signals defined over non-Euclidean geometries, and also come with strong geometric stability priors. In this talk, I presented techniques that exploit geometric stability in general geometries with appropriate graph neural network architectures. I showed that these techniques can all be framed in terms of local graph generators such as the graph Laplacian. I presented some stability certificates, as well as applications to computer graphics, particle physics and graph estimation problems. In particular, I described how graph neural networks can be used to reach statistical detection thresholds in community detection, and attack hard combinatorial optimization problems, such as the Quadratic Assignment Problem.

3.2 A picture of the energy landscape of deep neural networks

Pratik Chaudhari (UCLA, US)

I discussed some peculiarities of the residual surface discovered in the statistical physics literature, and a recently developed algorithm named Entropy-SGD that exploits them. Entropy-SGD can be shown to compute the solution of a viscous Hamilton-Jacobi PDE, which leads to a non-greedy, stochastic optimal control counterpart of SGD that is provably faster. This analysis establishes a previously unknown link between tools of statistical physics, non-convex optimization and the theory of PDEs. In the limit as the viscosity goes to zero, the non-viscous Hamilton-Jacobi PDE leads to the well-known proximal point iteration via the Hopf-Lax formula, thereby providing another link to classical techniques in convex optimization. Moreover, Entropy-SGD includes as special cases some of the most popular algorithms in the deep learning literature, e.g., distributed algorithms like Elastic-SGD as well as algorithms in Bayesian machine learning. It enjoys exceptional empirical performance and obtains state-of-the-art generalization errors with optimal convergence rates, all without any extra hyper-parameters to tune.

3.3 Recent Advances in Deep Learning at the Computer Vision Group TUM

Daniel Cremers (TU München, DE)

A short overview of Deep Learning Activities in our group.

3.4 Deep Learning for Sensorimotor Control

Alexey Dosovitskiy (Intel Deutschland GmbH – Feldkirchen, DE)

Deep learning, including deep reinforcement learning, is recently being actively used for learning sensorimotor control – producing useful actions in environments based on sensory inputs. I talked about deep RL, imitation learning, and issues with end-to-end learning for sensorimotor control.

3.5 Do semantic parts emerge in Convolutional Neural Networks?

Vittorio Ferrari (University of Edinburgh, GB)

Study of whether CNNs trained for object classification spontaneously learn semantic parts in their internal representation.

3.6 Proximal Backpropagation

Thomas Frerix (TU München, DE)

We offer a generalized point of view on the backpropagation algorithm, currently the most common technique to train neural networks via stochastic gradient descent and variants thereof. Specifically, we show that backpropagation of a prediction error is equivalent to sequential gradient descent steps on a quadratic penalty energy. This energy comprises the network activations as variables of the optimization and couples them to the network parameters. Based on this viewpoint, we illustrate the limitations on step sizes when optimizing a nested function with gradient descent. Rather than taking explicit gradient steps, where step size restrictions are an impediment for optimization, we propose proximal backpropagation (ProxProp) as a novel algorithm that takes implicit gradient steps to update the network parameters.

3.7 Recurrent Neural Networks and Open Sets

Jürgen Gall (Universität Bonn, DE)

The first part of the talk dealt with recurrent neural networks (RNNs). RNNs are used in Computer Vision in two ways. Either for modeling temporal relations or for converting an iterative algorithm into an end-to-end learning system. For the latter case, I gave an example that converts a BoW model based on KMeans into a neural network. The second

part of the talk addresses the limitations of closed sets benchmarks, which do not reflect the characteristics of real-world problems. I briefly discussed an domain adaptation approach with open sets.

3.8 Towards deep multi view stereo

Silvano Galliani (ETH Zürich, CH)

Is it possible to learn Multi View Stereo? I presented recent advances using supervised and unsupervised learning to solve Multi View Stereo.

3.9 Optimization with Deep Learning

Raja Giryes (Tel Aviv University, IL)

Brief description on recent results related to how it is possible to solve optimization problems efficiently with deep learning.

3.10 Semantic Jitter and Look-Around Policies

Kristen Grauman (University of Texas – Austin, US)

I presented our recent work using deep learning to predict missing visual data, for two very different goals. The first considers the problem where the missing data are entire training examples; we propose "semantic jitter" to generate realistic synthetic images for training fine-grained relative attributes. The second considers the case where the missing data are yet-unseen portions of a scene or 3D object; we proposed a reinforcement learning approach to obtain exploratory policies that actively select new observations to reconstruct the full scene or 3D object, thereby learning how to look around intelligently.

3.11 Global Optimization of Positively Homogeneous Deep Networks

Benjamin Haeffele (Johns Hopkins University – Baltimore, US)

I discussed sufficient conditions of the neural network training problem that guarantee when local minima are globally optimal and show that a global minimum can be reached via local descent from any initialization. The key required conditions are that both the network output and the regularization on the network parameters needs to be positively homogeneous of the same degree, with the regularization specifically constructed to control the network size.

3.12 Deep Depth From Focus

Caner Hazirbas (TU München, DE)

Depth from Focus (DFF) is one of the classical ill-posed inverse problems in computer vision. Most approaches recover the depth at each pixel based on the focal setting which exhibits maximal sharpness. Yet, it is not obvious how to reliably estimate the sharpness level, particularly in low-textured areas. In this paper, we propose *Deep Depth From Focus* (DDFF) as the first end-to-end learning approach to this problem. Towards this goal, we create a novel real-scene indoor benchmark composed of 4D light-field images obtained from a plenoptic camera and ground truth depth obtained from a registered RGB-D sensor. Compared to existing benchmarks our dataset is 30 times larger, enabling the use of machine learning for this inverse problem. We compare our results with state-of-the-art DFF methods and we also analyze the effect of several key deep architectural components. These experiments show that DDFFNet achieves state-of-the-art performance in all scenes, reducing depth error by more than 70% w.r.t. classic DFF methods.

3.13 Learning by Association and Associative Domain Adaptation

Philip Häusser (TU München, DE)

In many real-world scenarios, labeled data for a specific machine learning task is costly to obtain. Semi-supervised training methods make use of abundantly available unlabeled data and a smaller number of labeled examples. We propose a new framework for semi-supervised training of deep neural networks inspired by learning in humans. "Associations" are made from embeddings of labeled samples to those of unlabeled ones and back. The optimization schedule encourages correct association cycles that end up at the same class from which the association was started and penalizes wrong associations ending at a different class. The implementation is easy to use and can be added to any existing end-to-end training setup. We demonstrate the capabilities of learning by association on several data sets and show that it can improve performance on classification tasks tremendously by making use of additionally available unlabeled data. Finally, we show that the proposed association loss produces embeddings that are more effective for domain adaptation compared to methods employing maximum mean discrepancy as a similarity measure in embedding space.

3.14 Towards universal networks: from Ubernet to Densereg

Iasonas Kokkinos (Facebook AI Research, FR and University College London, GB)

I presented an overview of a work on training one network to solve many computer vision tasks – and learning one task (image-to-surface correspondence) to solve many computer vision problems. We also covered works on links between MRFs and CNNs.

3.15 Hybrid RNN-HMM models for action recognition

Hildegard Kühne (Universität Bonn, DE)

With the increasing demand for large scale data, the need of hand annotated data for the training of such system becomes more and more impractical. One way to avoid frame-based human annotation is the use of action order information to learn the respective action classes. In this context, we propose a hierarchical approach to address the problem by combining a framewise RNN model with a coarse probabilistic inference.

3.16 Continual and lifelong learning

Christoph H. Lampert (IST Austria – Klosterneuburg, AT)

I discussed some recent work from our group towards continual and lifelong learning, and showed examples of open problems.

3.17 Out with the old? CNNs for image-based localization

Laura Leal-Taixé (TU München, DE)

Deep learning solutions for camera pose regression for indoor and outdoor scenes have become popular in recent years. CNNs allow us to learn suitable feature representations for localization that are robust against motion blur and illumination changes. LSTM units can then be used on the CNN output for structured dimensionality reduction, leading to drastic improvements in localization performance. Nonetheless, quantitative experiments show that SIFT-based methods are still superior to CNN-based methods, except for indoor localization, where textureless regions and repetitive structures are common. I will also present our recent advances in relative pose estimation and start a discussion on how to teach epipolar geometry to Deep Learning architectures.

3.18 Structured Multiscale Deep Networks

Stephane Mallat (Ecole Polytechnique – Palaiseau, FR)

Deep neural networks compute invariants to translations, deformations and much more complex transformations. I explained how one can structure these networks with progressively more prior information for computer vision. The goal is to better understand their mathematical properties and reduce the number of training samples.

3.19 Learning Proximal Operators

Michael Möller (Universität Siegen, DE)

There are two typical approaches to solving inverse problems in imaging. Variational methods define an energy based on possible solutions in such a way that a low value of the energy corresponds to a solution with desirable properties, and subsequently minimize this energy. Learning based approaches define a parameterized function from the data to the space of solutions and learn the optimal parameters of this mapping from a set of exemplary training images. In this talk I discussed and analyzed the approach to replace the proximal operator of a regularization within a minimization algorithm by a denoising neural network to combine some advantages of both types of methods, variational and learning based techniques.

3.20 Geometric Deep Learning

Emanuele Rodolà (Uni. of Lugano, CH & Sapienza Univ – Rome, IT)

The past decade in computer vision research has witnessed the re-emergence of "deep learning", and in particular convolutional neural network (CNN) techniques, allowing to learn powerful image feature representations from large collections of examples. CNNs achieve a breakthrough in performance in a wide range of applications such as image classification, segmentation, detection and annotation. Nevertheless, when attempting to apply the CNN paradigm to 3D shapes (feature-based description, similarity, correspondence, retrieval, etc.) one has to face fundamental differences between images and geometric objects. Shape analysis and geometry processing pose new challenges that are non-existent in image analysis, and deep learning methods have only recently started penetrating into these communities. The purpose of this talk was to overview the foundations and the current state of the art on learning techniques for geometric data analysis. Special focus was put on deep learning techniques (CNN) applied to Euclidean and non-Euclidean manifolds for tasks of shape classification, retrieval and correspondence. The talk presented in a new light the problems of shape analysis and geometry processing, emphasizing the analogies and differences with the classical 2D setting, and showing how to adapt popular learning schemes in order to deal with 3D shapes.

3.21 Self-Supervised Deep Learning from Video

Rahul Sukthankar (Google Research – Mountain View, US)

I covered a couple of recent efforts from my group on extracting depth, ego-motion, etc. from unlabeled video with the hope of stimulating discussion/interest rather than presenting finished results.

3.22 Challenges for Deep Learning in Robotic Vision

Niko Sünderhauf (Queensland University of Technology – Brisbane, AU)

I talked about current challenges for deep learning in robotic vision. Where does deep learning fail when deployed on a robot? What unique challenges arise from operation in unconstrained, everyday scenarios? During the workshop, I discussed ideas for a new benchmark challenge to complement COCO and similar existing challenges, with a focus on robotic vision related problems such as open-set operations, incremental learning, active learning, and active vision.

3.23 VQA, and why it's asking the wrong questions

Anton van den Hengel (University of Adelaide, AU)

Visual Question Answering is one of the applications of Deep Learning that is pushing towards real Artificial Intelligence. It turns the training process around by only defining the question after the training has taken place, and in the process, changes the task fundamentally. This talk covered some of the high-level questions about the types of challenges Deep Learning can be applied to, and how we might separate the things its good at from those that it's not.

3.24 Learning CNN filter resolution using multi-scale structured receptive fields

Jan Van Gemert (TU Delft, NL)

The design of subsampling layers in a CNNs is a matter of trial and error. In addition, the filter-size in a single layer is typically hard-coded to be the same. Here I questioned this design. Instead of hard-coding we aim to learn the resolution. We do this by coupling resolution to the standard deviation (σ) of a Gaussian blur kernel, and then learn CNN filters by learning coefficients of a local differential Gaussian basis. Preliminary results show that global resolution can be learned by optimizing σ, and –in contrast to pixel filters CNNs– is robust to removing the subsampling layers.

3.25 Self-learning visual objects

Andrea Vedaldi (University of Oxford, GB)

I showed an approach to learn the intrinsic structure of visual object categories without the use of any manual supervision. The method learns a mapping that associates to image pixels a 2D embedding which identifies points of the 3D surface of the underlying deformable object class. The key property of this mapping is to be equivariant, i.e. consistent with image transformations. While these transformations naturally arise from a viewpoint change or an object deformation, we showed that synthetic warps are sufficient to learn such an embedding well. This is a simple yet powerful technique that can learn reliable object landmarks without the need to label them manually in examples. For human faces, I also showed empirically that the learned landmarks are highly-consistent with manually-supervised ones.

3.26 Mathematics of Deep Learning

René Vidal (Johns Hopkins University – Baltimore, US)

A mini-tutorial summarizing recent advances in understanding the mathematical properties of deep networks, including stability, generalization, and optimization.

3.27 A Primal Dual Network for Low-Level Vision Problems

Christoph Vogel (TU Graz, AT)

In the past, classic energy optimization techniques were the driving force in many innovations and are a building block for almost any problem in computer vision. Efficient algorithms are mandatory to achieve real-time processing, needed in many applications like autonomous driving. However, energy models – even if designed by human experts – might never be able to fully capture the complexity of natural scenes and images. Similar to optimization techniques, Deep Learning has changed the landscape of computer vision in recent years and has helped to push the performance of many models to never experienced heights. Our idea of a primal-dual network is to combine the structure of regular energy optimization techniques, in particular of first order methods, with the flexibility of Deep Learning to adapt to the statistics of the input data.

4 Working groups

4.1 Open Sets and Robotics

Jürgen Gall (Universität Bonn, DE)

Standard benchmarks in computer vision use a closed set evaluation protocol, i.e. training and test data are sampled from the same data source and it is ensured that all categories in the test data are also present in the training data. For many applications like robotics, however, the closed set assumption of standard benchmarks is unrealistic and just increasing the number of classes and size of the datasets will not advance the field towards realistic open set scenarios, where the test data contains many classes that are not part of the training data. Indeed, for any application that requires to interact within an unconstrained environment, it will be infeasible to cover all cases. In particular rare cases are unlikely to be present in the training data. For an open set scenario, there are several levels of difficulty a system has to tackle. In the simplest setting, the system has to recognize that it does know the class, when it sees an instance from a class that has not been part of the training data. The system, however, has also to recognize rare instances of the classes that do not occur in the training data. On the next level, the system has to be able to learn new classes or adapt to changes in the categories, for instances, when a category needs to be split into several finer categories. This can include active learning, where a system actively requests labels from a human. On the long term, systems or robots have to solve tasks that they have not previously executed or trained on. Although there are several publications on open sets and a few workshops on this topic have been recently organized, open sets have so far received only little attention in the research community. One reason is the lack of benchmarks for open sets, which require a more elaborate evaluation process than closed set benchmarks.

The working group also discussed the ideal representation of the environment for an autonomous system. Categories, as they are commonly used for analyzing images or videos, have been developed for communication and human categories do not necessary make sense from a perceptional or robotics perspective. It is also clear that categories are insufficient to represent the world, but the ideal representation of a scene remains an open research questions. It might be a combination of categories, attributes, affordances but also some fluent representations that cannot be captured by any taxonomy. It is also an open question if a generic perception model should be developed first, which can be used for all kinds of tasks, or if the perception model should be learned from a large set of tasks, which need to be solved by a robot.

4.2 Object Recognition

Kristen Grauman (University of Texas – Austin, US), Pratik Chaudhari (UCLA, US), Vittorio Ferrari (University of Edinburgh, GB), Raja Giryes (Tel Aviv University, IL), Iasonas Kokkinos (Facebook AI Research, FR and University College London, GB), and Andrea Vedaldi (University of Oxford, GB)

We discussed four topics. The first was whether the output of object recognition and/or detection systems can be used to solve other tasks better. For example, if we can recognize objects and their location in an image, we can use this information to infer their albedo, or perhaps their 3D shape. It was noted that monocular depth estimation may not require explicit recognition of objects, but at the same time it appears to be less transferable across domains and settings. If the semantic labels generated by a model are available, they can be sued to run local and class-specific models for another task. Alternatively, semantic labels can be used to constrain the output of a neural networks to be more consistent with the "meaning" of the image. For example, you can use that in order to reconstruct an image of a scene compatible with a given semantic layout.

The second topic that was discussed was whether we there exists a "holy-grail" supervisory signal, i.e. a learning task that would be sufficient to learn all interesting properties of natural images, replacing sub tasks such as boundary detection, object recognition, normal estimation, depth estimation etc. This appears to be related to finding a "vision complete" problem and is probably not an image-based signal, but rather a RL signal. It was also noted that certain problems such as 3D reconstruction are very generically applicable and do not tap human-induced semantics. Active vision can also be used to more efficiently transfer representations across domain changes.

The third topic that was discussed was how to construct networks that can reason about object instances. There are two approaches: fully-convolutions and region based networks, the latter explicitly iterating on each object instance. There was no consensus on which one will win out, but it was noted that the region-based approaches have clear advantages in terms of representation invariance and simplification of the network architecture. The problem of exploring different instances is connected to the one of neuron binding in the brain, which is also not well understood.

The final topic was the one of self-supervision. We raised a new distinction between natural self-supervision (as predicting motion frames in a video from other frames) and artificial (such as super-resolution, jigsaw puzzles, and so on). It seems that there are self-supervision tasks that can learn an ample array of vision "primitives" from unsupervised data.

4.3 Deep Learning for 3D and Graphs

Emanuele Rodolà (Uni. of Lugano, CH & Sapienza Univ – Rome, IT)

The main focus of discussion for the "Deep Learning for 3D and Graphs" group was on the adoption of deep learning techniques to address problems involving geometric data, and vice

versa, on the use of geometric reasoning within deep learning pipelines. To the surprise of the participants, we found that most deep learning approaches dealing with 3D or geometric data place the main focus of attention on synthesis problems – as opposed to traditional "axiomatic" approaches where the bulk of the work is on the analysis and processing of 3D data. While on the one hand this shift of focus is somewhat surprising, on the other hand it can be justified by noting that deep learning is primarily useful precisely in this kind of problems, i.e., whenever training data can be easily generated and the inverse function is hard (if not impossible) to model axiomatically. The second topic of discussion (what can geometry do for deep learning) has received limited attention from the community so far, and the working group faced difficulties when attempting to identify approaches that explore this direction, as well as potential avenues for future research. The discussion converged toward "constrained deep learning", namely on the increasing necessity to impose hard constraints in deep learning pipelines, which traditionally operate in an unconstrained regime. Constrained problems often arise when dealing with geometry, for example, when the objects of interest are camera motions (which live on the Lie group of rotations), normal fields (which live on the sphere), or Laplace-like operators (whose discretizations live on the manifold of fixed-rank positive semi-definite matrices). While imposing such constraints as hard requirements is commonly achieved "implicitly" by resorting to ad-hoc representations (e.g., quaternions for rotations), the group agreed that there is a global need for ways to satisfy hard constraints when such workarounds are not possible.

4.4 Deep Learning for Time Series

Jan Van Gemert (TU Delft, NL)

The working group focused on deep learning for time series, with video and music, as examples of this domain.

The consensus was that motion in video is difficult for deep networks to learn. Current approaches such as Flownet and Flownet 2.0 learn motion in the form of optical flow. These methods do well, but do not (yet) enhance over traditional 'hand-crafted' optical flow methods. One issue could be the size of the data. Ground truth motion patterns are difficult to obtain, limiting current datasets either to synthetic ground truth, or using hand-crafted optical flow as the labels.

The analogy of object recognition in images is action recognition in video. The field has not converged on a specific solution and results are typically fused with 'hand-crafted' methods such as optical flow. We identified three main approaches in action recognition:

1. LSTM on frames: Extract pre-trained deep network features per frame, and learn a recurrent network (LSTM) on these frames. LSTMs have proved quite successful for modeling words in a text. Yet, for video the LSTMs have proved applicable, e.g. for video captioning, but for action recognition it does not yet lead to great breakthroughs.
2. 3D convolutions. The natural extension of convolutions in 2D images to 3D videos is using 3D convolutions. There has been quite some work on this, but it also does not yet lead to significant improvements. The reasons could be that all possible motion and appearance has to be learned from scratch. Which would require orders or magnitude more data than is available.

3. Two-stream fusion of optical flow and RGB. The (arguably) best results are obtained by the 'two-stream' approach, which processes a video in two streams: an 'appearance' stream using only RGB and a 'motion' stream by using optical flow. The results of the two streams are then merged together to obtain a final prediction.

Various combinations of these 3 building blocks have also been observed; e.g.: 3D convolution on optical flow.

For music recognition, it is remarkable that the best results have been obtained by first converting the music to a 2D spectrogram. A spectrogram bins a 1D signal in various frequencies, which is then processed over the whole signal with an overlapping window. This gives a 2D output, and the current best practice is using a 2D CNN to do image recognition on this 'image'.

In conclusion, seems to be a consensus in the working group that in contrast to image classification, object detection, semantic segmentation where deep learning yielded a substantial increase in performance motion is different. The lack of clear improvements points to some fundamental difference between motion and spatial information. Compared to a 3D image (e.g. MRI) a video is quite different. The motion is potentially causal, and perhaps should be treated differently, and the question is how to proceed.

Participants

- Joan Bruna Estrach
New York University, US
- Pratik Chaudhari
UCLA, US
- Daniel Cremers
TU München, DE
- Alexey Dosovitskiy
Intel Deutschland GmbH – Feldkirchen, DE
- Vittorio Ferrari
University of Edinburgh, GB
- Thomas Frerix
TU München, DE
- Jürgen Gall
Universität Bonn, DE
- Silvano Galliani
ETH Zürich, CH
- Ravi Garg
University of Adelaide, AU
- Raja Giryes
Tel Aviv University, IL
- Kristen Grauman
University of Texas – Austin, US
- Benjamin Haeffele
Johns Hopkins University – Baltimore, US
- Philip Häusser
TU München, DE
- Caner Hazirbas
TU München, DE
- Iasonas Kokkinos
Facebook AI Research, FR and University College London, GB
- Hildegard Kühne
Universität Bonn, DE
- Christoph H. Lampert
IST Austria – Klosterneuburg, AT
- Laura Leal-Taixé
TU München, DE
- Stephane Mallat
Ecole Polytechnique – Palaiseau, FR
- Michael Möller
Universität Siegen, DE
- Emanuele Rodolà
Uni. of Lugano, CH & Sapienza Univ – Rome, IT
- Niko Sünderhauf
Queensland University of Technology – Brisbane, AU
- Rahul Sukthankar
Google Research – Mountain View, US
- Anton van den Hengel
University of Adelaide, AU
- Jan Van Gemert
TU Delft, NL
- Andrea Vedaldi
University of Oxford, GB
- René Vidal
Johns Hopkins University – Baltimore, US
- Christoph Vogel
TU Graz, AT

Report from Dagstuhl Seminar 17392

Body-Centric Computing

Edited by

Steve Benford[1], Kristina Höök[2], Joseph Marshall[3], Florian Mueller[4], and Dag Svanes[5]

1 **University of Nottingham, GB,** steve.benford@nottingham.ac.uk
2 **KTH Royal Institute of Technology – Stockholm, SE,** kia@sics.se
3 **University of Nottingham, GB,** joe.marshall@nottingham.ac.uk
4 **RMIT University – Melbourne, AU,** floyd@floydmueller.com
5 **NTNU – Trondheim, NO,** dag.svanes@ntnu.no

Abstract

The rise of technology that can support the active human body – in contrast to the previously prevalent paradigm of interacting with computers while sitting still – such as wearables, quantified self systems and mobile computing highlights an opportunity for a new era of "body-centric computing". However, most work in this area has taken quite an instrumental perspective, focusing on achieving extrinsic performance objectives. Phenomenology, however, highlights that it is also important to support the experiential perspective of living an active life, that is, technology should also help people focus on their lived experiences and personal growth to deepen their understanding and engagement with their own bodies.

We find that despite the work on embodiment, the use of technology to support the corporeal, pulsating and felt body has been notably absent. We believe the reason for this is due to limited knowledge about how to understand, analyse and correlate the vast amount of data from the various sensors worn by individuals and populations in real-time so that we can present it in a way that it supports people's felt experience. In order to drive such an agenda that supports both instrumental and experiential perspectives of the active human body, this seminar brings together leading experts, including those who are central to the development of products and ideas relating to wearables, mobile computing, quantified self, data analysis and visualization, exertion games and computer sports science. The goal is to address key questions around the use of sensor data to support both instrumental and experiential perspectives of the active human body and to jump-start collaborations between people from different backgrounds to pioneer new approaches for a body-centric computing future.

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1 Executive Summary

Florian Mueller
Josh Andres
Joseph Marshall
Dag Svanes

Joint work of all attendees
Main reference Florian 'Floyd' Mueller, Damon Young: "Five Lenses for Designing Exertion Experiences", in Proc. of the 2017 CHI Conference on Human Factors in Computing Systems, Denver, CO, USA, May 06-11, 2017., pp. 2473–2487, ACM, 2017.
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The rise of technology that can support the active human body – in contrast to the previously prevalent paradigm of interacting with computers while sitting still – such as wearables, quantified self systems and mobile computing highlights an opportunity for a new era of "body-centric computing". However, most work in this area has taken quite an instrumental perspective, focusing on achieving extrinsic performance objectives. Phenomenology, however, highlights that it is also important to support the experiential perspective of living an active life, that is, technology should also help people focus on their lived experiences to deepen their understanding and engagement with their own bodies. We find that despite the work on embodiment, the use of technology to support the corporeal, pulsating, felt body has been notably absent. We believe the reason for this is due to limited knowledge about how to understand, analyse and correlate the vast amount of data from the various sensors worn by individuals and populations in real-time so that we can present it in a way that it supports people's felt experience. In order to drive such an agenda that supports both instrumental and experiential perspectives of the active human body, this seminar brought together leading experts from industry and academia, including those who are central to the development of products and ideas relating to wearables, mobile computing, quantified self, data analysis and visualization, sports science, exertion games, computer sports science as well as phenomenology. The goal was to address key questions around the use of sensor data to support both instrumental and experiential perspective of the active human body and to jump-start collaborations between people from different backgrounds to pioneer new approaches for a body-centric computing future.

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3 Introduction

Josh Andres (IBM Research – Melbourne, AU), Joseph Marshall (University of Nottingham, GB), Florian Mueller (RMIT University – Melbourne, AU), and Dag Svanes (NTNU – Trondheim, NO)

In late 2017, 23 researchers and academics from Europe, Australia and the USA gathered for a week to discuss the future of body-centric computing. Dagstuhl, a non-profit center for computer science research, which is located in a rural area in Germany and provided the workshop space in an 18th-century picturesque castle, hosted the seminar. The goal of the seminar was to discuss the future of what it means to design interactive technology when centering on the human body; a trend highlighted by emerging technologies such as wearables, quantified self systems, mobile computing and exertion games, which stand in stark contrast to the previously prevalent paradigm of interacting with computers while sitting still. The motivation for the seminar stemmed from the realization that until today, most work in this area has taken quite an instrumental perspective, focusing on achieving extrinsic performance objectives, such as "who jogged the most miles this week?" while rewarding athletic performance and "personal bests". However, theories, such as phenomenology, have highlighted that it is also important to support the experiential perspective of living an active life, that is, technology should also help people focus on their lived experiences and personal growth to deepen their engagement with their own bodies. Despite the work on embodiment, the use of technology to support the corporeal, pulsating and felt body has been notably absent, the organizers of the seminar proposed. One reason for this could be that there is limited knowledge about how to understand, analyse and correlate the vast amount of data from the various sensors worn by individuals so that we can present it in a way that it supports people's felt experience. Another issue is that HCI researchers typically do not have direct knowledge of or training in how the corporeal, pulsating and felt body works as a complex organo-socio-system. In order to drive such an agenda that supports instrumental, experiential and in-bodied perspectives of the active human body, the seminar brought together leading experts on the intersection between the human body and interactive technology to discuss key questions around the use of interactive systems to support both instrumental and experiential perspectives to pioneer new approaches for what we propose to frame as a body-centric computing future. Body-centric computing we propose touches on a number of areas focused on supporting healthy, happy and productive people and societies. The core areas are health, including prevention, rehabilitation, disease management and cognitive/physical performance. Another core area is wellbeing, supporting pleasure and connectedness. Sport, or insights from sport science, is another core area, where the perspectives of the body as a site for constant performance, training, learning and improvement being important aspects. Entertainment, including gaming, is also another core area. The seminar began with talks by all attendees, in which they presented their work in the area, their theoretical perspective that guides their work, and a description of their most and least favorite body-centric computing projects. After the presentations concluded, no more slides were used for the remainder of the week, with all activities being conducted either as a round table, standing up, outside or exercising, fitting with the seminar theme. Furthermore, any group activities were supplemented movement practices to involve the whole body to support a "the brain as part of the body" approach. This physical in support of the cognitive/social was further supplemented by optional morning and evening activities,

such as playing golf, jogging, cycling, hiking or slacklining. The structure of the seminar was based around theory, design and their intersection, as that pertains to body-centric computing. From the start, it was acknowledge that if concerning oneself with technology that supports the active human body, not one particular theory will suffice, but rather, that a mix of theories will need to be engaged in, with all their weaknesses and strengths, with the big picture being what we get from studying this.

3.1 Interactivity session

An interactivity-style session involved participants trying out each other's body-centric computing systems. These were hands-on experiences where participants involved their bodies, and they were asked to think about what instrumental, but also experiential perspectives the design actively supported. Joe Marshall (University of Nottingham) set up a swing where the user wears an HMD and sees a virtual world that responds to the movement of the swing. This work elicited questions around how movement can be deliberately fed back to the user in an altered fashion to elicit novel entertainment experiences.

Anna Lisa Martin-Niedecken from the Zurich University of the Arts presented her dual flow-based fitness game "Plunder Planet" Martin-Niedecken, 2017 #1429 that adapts to players' abilities in real-time, provoking questions around what role technology plays in allowing people to experience their bodies in an individual and social context.

Lifetree by Patibanda et al. [3] is a VR game that aims to teach proper breathing technique. Participants who tried out the game said that their experience elicited questions such as what role technology can play in promoting wellbeing, where a major challenge to wellbeing today seems to be the prevalence of technology. Florian 'Floyd' Mueller from RMIT University in Australia presented various headphones that use noise-cancelling, in-ear and bone conduction technologies in order to raise the question whether we can say if one particular technology is more body-centric than another. Dag Svanaes from the Norwegian

Figure 1 VR on a swing

Figure 2 "Plunder Planet" cooperative multiplayer-setup at Dagstuhl.

Figure 3 "Plunder Planet" single player-setup with two different controllers (Source: ZHdK).

University of Science and Technology presented an interactive tail [4] that moves in response to the hip-movement of the user, controlled via sensors and actuators. This work elicited questions around the role of the body in human-computer integration experiences. Perttu Hämäläinen from Aalto University in Finland presented his work on using AI to predict and animate movement in virtual worlds, provoking questions around how AI can inform the movement of embodied systems such as exoskeletons or the tail mentioned above.

3.1.1 Methods for body-centric computing

Methods for how to design body-centric computing were not only heavily debated, but also tried out through a design exercise. This included activities where the goal is to diffuse levels of attention on and through the body. First, activities were undertaken with closed eyes where the goal was to shift attention to various body parts just by focusing one's level of bodily attention. To contrast this, activities where followed where there was the goal was to achieve no attention or limited focus, for example, we were asked by Thecla Shiphorst (Simon-Frasier University, Canada) to walk very slowly through the surrounding forestry, in silence.

The goal to diffuse attention was later compared by participants with the cross-eye concentration action required to see random dot autostereograms. Through this diffused attention, a heightened awareness using the body was aimed to achieve to sense the experience. As part of this experience, participants were asked to pick three moments that they found memorable, and "imprint" them by pressing the index finger and thumb together so it squeezes the other hand, leaving a tactile experience of that particular moment. These imprints where then used to accomplish the design task to design an interactive shape-changing chair. The intention was to seek inspiration from lived experiences, while stressing that "slow" can be an inspirational quality when it comes to body-centric computing.

Figure 4 Walking very slowly through the surrounding forestry, in silence.

Figure 5 One of the design outcomes.

3.1.2 Designing a chair without chairs

The design of the final chair was not as important as how participants got there, with all teams applauding that the imprinting methods helped them to quickly agree on a particular feeling their designed chair should elicit. In particular, participants applauded that the slow-walking-in-the-woods activity allowed them to get into the right state of mind. Furthermore, without this prior activity, participants thought consensus would not have been reached so quickly, as such, they believed that the silence – in contrast to a default "discussion" activity – actually created a community. Participants also found that the activity seemed to help solidify the experience, and it appeared to built a sense of trust that then facilitated to take risks during the design phase. The activity appeared to function as way to gaining clear and focused design qualities. In particular, participants found it remarkable that the activity did not aim to make connections, but rather focused on the experience to contribute to a common ground or shared starting point for the design exercise. Although the "actual" design time was relatively short, participants found that the time spent on the sensitizing activity was well spent and accelerated the following activity task. Participants also noted that through the exercise, they were much more at easy combining things during the design phase that perhaps otherwise would have not made much sense if we were in a critical state, the "anything goes" state of mind is perhaps more productive than being "critical, smart, and the brilliant designer you always want to be". Overall, the activity reminded participants how much their state of mind affects their design process, and when it comes to body-centric computing, how important these pre-activities are before getting into the "actual" design task.

Questions that were raised were whether such an activity for body-centric computing could also work in distributed teams, and how it would work with people skeptical of such an approach? What if the design team works in a build environment, could this approach also work in a dense city environment? Furthermore, which step of the design process could it best be incorporated? Participants also asked for studies that would compare the results of such design activities where people would engage in body-centric activities vs. not, how would the outcome change? What other forms of "warm-up" activities do exist? Are some of them more individual than others, and how does that affect collaborative design? Furthermore, as it is hard to design body-centered without taking your own bodily experiences into account, how does one manage the tension between self-centered and body-centered? Where do methods such as user-centred design fit in here? Furthermore, it was noted that design that come out of such activities often fall into a "meditation genre", such as the somaesthetic yoga mat [1], however, could such activities also be used to design for also bodily, but less meditative actions? For example, what would happen if you start designing right after a jog? It was also noted that this particular activity focused on designing from our experiences, whereas in reality, a more clear brief is usually given, hence the design process might therefore unfold differently, even if the same activity is engaged in. Participants also observed that two lines of conversations emerged when reflecting on the activity, one was about designing for the human body from the lens of what is good for the human, while the second lie is about designing new experiences that are experiential and not necessarily good for the human body; however, they do not necessarily need to stand in contrast, as Mueller and Young previously highlighted [2]. Participants also tried out taking on a first, second and third-person perspective when designing for the human body [4]. The first person perspective is concerned with the personal, felt perspective of the body, whereas the second perspective is concerned with the interdependencies between bodies, and the third person perspective is concerned with the external, more "objective" view on the body. Discussions that followed from this highlighted that the first third person perspective is probably the most prevalent in most of today's available wearable technology systems, with a few emerging systems also considering the first person perspective. The second person perspective is probably the hardest to grasp, with not many examples being available as guidance.

3.2 Why body-centric computing?

In a collaborative sharing exercise, participants deliberated on their motivations for working on body-centric computing. The answers varied and included to help people live a healthier life, personal enjoyment of physical play, the aim to facilitate personal growth, to do good for others, promote physical activity and movement skill learning, create feelings of empowerment, improved quality of life, to facilitate health and wellbeing, enabling experiences for people with disabilities who cannot have them, to understand what it means to be human and as a counterpoint to the current mind-focused technological landscape.

3.2.1 Collaborative working sessions at Dagstuhl

Others said that based on the realization that every human has a body, and we design technology for humans, it is a necessity for every designer to be body-centric.

3.3 Open questions around body-centric computing

There are many open questions around body-centric computing, in order to group and prioritize them and to identify what is important for the seminar participants, we created an open market, where representatives of an open question could "pitch" the question and form groups to team up, with the intention to form groups who collaboratively work on the identified topic. One particular open question that arose was how to articulate bodily experiences for design. At the moment, there is only limited knowledge of how to communicate, share and articulate bodily experiences. This is not only relevant for in-team communication in the design process, but also an integral part of the user interaction with an artifact. It is further assumed that the ability of articulating an experience has an effect on the ability to discriminate between nuances of the experience, thereby reconfiguring and refining the experience as it unfolds. Participants related this to the Sapir-Whorf hypothesis, which suggests that people speaking different languages, with varying numbers of words to describe different colours, also have a varying ability to discriminate between nuances. Drawing on this, better ways of designing for intimacy, empathy, mindfulness and sociality should be the result, allowing for a critical intertwinement between the human body and these experiences. Another open-question is how much knowledge about the human body one needs to design for body-centric computing? Of course, one might argue that the more the better, however, one position was that it is also impractical to expect all designers take kinesiology courses; others questioned if that is the case. Is there some basic knowledge that might be sufficient, or do we always need to bring experts in? For example, HCI curricula currently teach aspects of the vision system and Fitts' Law about our perceptual and performance capacities. Does our new interest in pervasive, body-centric computing not require us to add in more specific knowledge about other relevant physio-chemico-hormonal

Figure 6 Using VR to disrupt awareness of space to force relearning of how to navigate in the physical world.

processes? If so, how do we provide designers with the necessary knowledge to draw from and interpret their own bodily experiences with confidence? Overall, there is a need for more methods and concepts for personalized and adaptive body-centric systems based on fine-grained knowledge of the human body. Another question that emerged is how to respect experiences of body changes. For instance, how do we design for restricted movement? This question arose from the discussion around whether physical restriction could be used as a mean to facilitate empathy for people living with physical disabilities.

In result, how can we design body-centric computing systems that affect movement, like physical restrictions, to facilitate limits across life course and experience? And how can designers create these experiences and ensure they are accurate (if they are meant to reflect a "real" experience)? Such an exploration could, for example, lead to exertion games in which the player starts off with a physical constraint like a distorted view that impacts orientation in the virtual world along with coordination of movement in the real world, and then through leveling up experiences increased empowerment. This progressive approach could be a way to design for transformation and development yet acknowledging that real-life strength and flexibility develops over months rather than individual exercise sessions, using technology to make this larger timespan more immediately visible and explorable. Another open question concerns the role of technologies that have caused a disconnection between humans and their bodies. One example is the mobile phone: on the one hand there is the concern that mobile phones have disengaged people from their bodies and their co-located people. On the other hand, people have cultivated intimate bodily relationships with their mobile phones, for a

quirky example see the phantom vibration syndrome, where people think their mobile phone is vibrating when it is not. There are also many technical open questions around body-centric computing, a particular pertinent one was identified as detecting when people touch each other, and to what extent. Certainly solutions already exist, however, they are often not very portable, require tethering or are not very low-power. Developing systems that can unobtrusively sense human touch that is mobile and can be worn for long periods is still technically very challenging. The researchers highlighted emerging technologies in this space, such as advanced AI and machine learning that will make it increasingly possible to infer information such as a user's full body movement from just head tracking. For example, one current technical limitation to advance the field has been identified as affordable exoskeletons. Exoskeletons are powerful devices to amplify human movement, however, they are not generally available and if so very expensive. Furthermore, a shortage of prototyping tools for body-centric computing is also limiting the field, for example, the Lilipads for wearable computing predict a recent advancement in this direction. Finally, another important underexplored area concerns ethics around body-centric computing. Moving the body comes with certain risks, however, these risks have value in and of themselves, and interaction designers need to be aware of how to deal with this. Participants argued that the alternative is to design for stillness, which might not facilitate immediate injury, but ultimately leads to obesity and unhappiness, something that all participants aimed to avoid.

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4 Overview of talks

4.1 Josh Andres – IBM Research Australia & RMIT University

Josh Andres (IBM Research – Melbourne, AU)

I Lead UX, design at IBM research Aus, where we also work on HCI projects and partner with universities to collaborate. More narrowly we are focusing on: exertion, integration, body/sense augmentation, system led moments. To study the user experience. I believe that BC-C will offer us a perspective to support personal growth through bodily affordances (specially movement, self sensing, and as a collective citizen). Also, by supporting experiences where human capability is augmented with a blend of wellbeing and entertainment.

4.2 Playful Physical Computing for Health and Wellbeing

Kathrin Gerling (University of Lincoln, GB)

I am a researcher with a background in Computer Science affiliated with KU Leuven, Belgium. My main research areas are human-computer interaction, games and accessibility. I am

particularly interested in when and how technology can be leveraged to support healthy lifestyles and improve wellbeing. My previous research has included movement-based play for older adults and people using wheelchairs, exploring basic issues around accessibility and directly working with people to create engaging and empowering playful experiences.

Body-centric computing in the context of games and playful experiences faces a number of unique problems. Much of our work starts out with a technology-centric design approach that risks the introduction of early constraints rather than asking questions around the body of the player and the experience intended by the designer and developer. For example, many games-related projects addressing older adults (including my own work) choose a technology (such as accelerometer controls or camera-based systems) and desired health outcome (e.g., reduction of sedentary behaviour), but fail to provide an in-depth exploration of the relationship between the ageing body, physical activity, and playful technology, and the implications for game development.

A key research challenge for body-centric game development therefore emerges from the need for a better understanding of the relationship between our bodies and playful technologies to enable us to develop systems that are empowering, engaging and effective in terms of outcomes for health and wellbeing.

4.3 Body-Centric Interfaces for People with Atypical Bodies

Nicholas Graham (Queen's University – Kingston, CA)

Body-centric computing can enhance the abilities of people with atypical bodies. I describe the design of an exergame allowing children with cerebral palsy to engage in physical activity, and through networked play, to socially engage with their peers. Participatory design revealed that children with cerebral palsy enjoy fast-paced action games, similar to those played by their typically-developing friends. I show how games can be designed to provide this fast action play while adapting to deficits in gross motor function, fine motor function, and visual-spatial processing. Our Liberi exergame has been used in home and clinical settings.

4.4 Marianne Graves Petersen

Marianne Graves Petersen (Aarhus University, DK)

Marianne Graves Petersen is associate professor on University of Aarhus, Computer Science Department since 2006. She has Ph.D from Computer Science Department, University of Aarhus on thesis "Designing for Learning in Use of Everyday Artefacts".

She has numerous research area including human-computer interaction, interaction design, pervasive computing and home-oriented IT.

4.5 Stefan Göbel

Stefan Göbel (TU Darmstadt, DE)

Dr. Stefan Göbel is an assistant professor with a permanent position as academic councilor, lecturer and head of the Serious Games group at the Multimedia Communications Lab at Technische Universität Darmstadt (TUD). Research topics cover the development (authoring, creation), (personalized, adaptive) control and (technology-enhanced) evaluation (and effect measurement) of Serious Games. Dr. Göbel is also driving the interdisciplinary key research area on "Serious Games" at TUD level (www.serious-games.tu-darmstadt.de)and provides lectures and practical courses in Serious Games and Game Technologies. Dr. Göbel has extensive experience in initiating, managing and coordinating projects – both publicly funded and industrial – on regional and (inter)national level. Examples include the EU projects INVISIP (personal role: initiator and S/T coordinator), art-E-fact (coordinator), INSCAPE, U-CREATE, 80Days and ALFRED (both management board and WP lead); currently he is coordinating the ADVENTURE approach. Application fields cover Storytelling-based Edutainment appliances and Serious Games for training, education and health (e.g. in the field of Ambient Assisted Living). Stefan Göbel holds a PhD in computer science from TUD and has long-term experience in Graphic Information Systems (GIS; topic of the dissertation is 'Graphic-Interactive Access to Geodata Archives', being prepared at the Fraunhofer Institute for Computer Graphics), Interactive Digital Storytelling, Edutainment and Serious Games. Dr. Göbel is the author of 100+ peer reviewed publications and serves as PC member and reviewer at different conferences (e.g. ACM Multimedia, CHI, ICME, Edutainment, EC-GBL, ICEC or FDG) and organizations (e.g. European Commission, Austrian Science Found and Swiss National Science Foundation). 2003 Dr. Göbel initiated and hosted (as well as 2004 and 2006) the International Conference on Technologies in Interactive Digital Storytelling and Entertainment (TIDSE), which merged with the International Conference on Virtual Storytelling (ICVS) to form the International Conference on Interactive Digital Storytelling (ICIDS) late 2008. In 2005 Dr. Göbel initiated the GameDays as national 'science meets business' workshop for Serious Games. Since that time he is permanently hosting the GameDays on an annual basis in cooperation with Hessen-IT, TU Darmstadt and other institutions from academia and industry. Since 2010, major parts of the GameDays have been implemented as International Conference (fully dedicated) on Serious Games.

4.6 Empowerment, Curiosity, AI (in exergames)

Perttu Hämäläinen (Aalto University, FI)

My talk comprises two parts: First, I explain how my work has been centered around creating feelings of empowerment and competence for the user as a mover, and also a curious exploration of the diversity of human movement. The two concepts are intertwined; we are by nature curious, and empowerment and competence as a mover – either through skill development or technology – endows us with the capability of exploring. Both empowerment/competence and curiosity are also central concepts of the psychology of intrinsic

motivation. Curiosity drives an organism to explore in the absence of extrinsic rewards, and helps in building a rich understanding of the world, which is useful in adapting to new situations and problems. On the other hand, we are also driven towards activities where we feel competence and achievement of overcoming challenges. Taken together, competence and curiosity provides an explanation for many forms of open-ended play, where animals and children come up with movement challenges for themselves and each other, exploring the movement affordances of the environment. A great example of this is provided in this video: https://www.youtube.com/watch?v=58-atNakMWw.

The second part of my talk concerns the future, issuing a call for arms of sort to investigate the possibilities of AI technology in exergames, in particular the emerging technology of movement AI, which enables biomechanically valid simulated characters to improvise movements without animation data, based on high-level goals given by the game designers. I envision three main categories of use: AI as movement opponent, AI as movement partner, and AI as game tester; the latter means that instead of recruiting players to test an exergame with their bodies, it is increasingly possible to have a simulated body take the role of the player and learn to play the game. The essential research question is what kinds of player experience data can such simulated testing predict, e.g., exertion level, movement difficulty, specific muscles exerted, and accessibility or playability with disabilities.

4.7 Martin Jonsson

Martin Jonsson (Södertörn University – Huddinge, SE)

Martin Jonsson presented some of his research on the interplay between body, experience and material, in the context of interaction design. The research includes activities in schools where sensor based interactive systems was used to create bodily experiences around abstract physical concepts such as energy. Other research activities explores design and tinkering with hybrid digital and physical materials and the relation between the formulation of experience and certain qualities of these hybrid materials. Finally a recent strand of Martins research concerns how to develop interactive technologies that supports an increased understanding and awareness of the body, along the lines of the somaesthetics philosophy, emphasizing how all our experiences are fundamentally grounded in how we perceive the world though and with our body.

4.8 Bodily Play Experiences for Fun (Only)

Joseph Marshall (University of Nottingham, GB)

In this presentation, I describe two exertion games which I have been involved in building which explore different aspects of physical play. In Balance of Power, players score points by moving other players to their side of the play space; how they do that is entirely up to them. This rugby inspired computer game is deliberately designed to engender forceful physical contact. VR Playground uses a VR headset on a playground swing to create an

exciting thrill ride, where the forces of the swing are redirected into zooming along a road or jumping over high buildings. These two experiences highlight my approach of building high energy physical games and experiences simply for the pleasure of playing and to explore the nature of play; I also briefly discuss my scepticism of the widespread claims that such physical game-play will improve player health.

4.9 Playful and Holistic Workout Experiences

Anna Lisa Martin-Niedecken (Zürcher Hochschule der Künste, CH)

Anna Lisa Martin-Niedecken is a Senior Researcher at the Subject Area in Game Design, Zurich University of the Arts. With her background in sports science her R&D work mainly focuses on movement-based games. She is particularly interested in how technology shapes gameplay and bodily experiences in the individual and social play context. One of her current R&D projects is on exergame fitness training. The adaptive exergame fitness game environment «Plunder Planet» was designed with and for children and young adolescents and combines user-centered designs on the levels of body, technology and play (physical and virtual). Beside her R&D work, Anna is teaching BA and MA (game) design students in the field of Serious & Applied Games.

4.10 Long-term self-tracking of personal health

Jochen Meyer (OFFIS – Oldenburg, DE)

Numerous wearable and personal networked health devices are available that allow self-tracking of behaviors such as physical activity or sleep, vital parameters such as heart rate or body composition, and other health parameters such as fitness. These devices are low-cost, easy to use also by technical and medical layperson, and can be used extended periods of time in real life. The primary promise of these devices often is on behavior change such as becoming more fit or losing weight. However their true value may lie in use cases such as giving insights into one's own health, raising awareness for health, or supporting decision making. We need research to investigate questions such as how to design systems that support these use cases, or how they influence one's own health.

4.11 Body-Centric Computing: Experiencing the Body as Play

Florian Mueller (RMIT University – Melbourne, AU)

I propose that one part of body-centric computing is to enable people to experience their body as digital play. This is grounded in sports philosophy that argues for the value of personal

growth facilitated through physical activity that ultimately ends in the good life, helping us to figure out who we are, who we want to be and how to get there. I illustrate this thinking by presenting recent work from the Exertion Games Lab, including a balance game using a digitally-controlled galvanic vestibular stimulation system, a game using a wireless pill, and a wearable robotic arm that augments the eating experience. http://exertiongameslab.org

4.12 Elena Márquez Segura

Elena Márquez Segura (University of California – Santa Cruz, US)

I did my PhD in Human-Computer Interaction, at Uppsala University (Sweden), and Stockholm University (Sweden). Before that, I completed a BEng & MEng degree in Telecommunication Engineering at Universidad de Sevilla, Seville (Spain) and studied a master's program in Interactive Systems Engineering at KTH, Stockholm (Sweden). That's maybe what allows me to do research in this field of Human-Computer Interaction and Interaction Design, but what drives my research is my passion for play and playfulness, for interesting social experiences in collocated settings, and for movement. Movement has been central during my whole life. I've engaged with multiple sports as a practitioner as well as an instructor – I'm trained as an AntiGravity Fitness, BarreConcept, and STOTT Pilates instructor.

In my talk, I suggest representative papers in my work and that of others, a bundle of keywords with representative theories and methods that I've used in my work, and a few exemplars in my work, which I think can speak to a body-centric design perspective. I conclude highlighting how works of others present here in Dagstuhl have informed my research and design practice and expressing my excitement about how we will potentially inspire one another and the possibility of further collaborations.

4.13 Corina Sas

Corina Sas (Lancaster University, GB)

My research interests include human-computer interaction, interaction design, user experience, designing tools and interactive systems to support high level skill acquisition and training such as creative and reflective thinking in design, autobiographical reasoning, emotional processing and spatial cognition. This work explores and integrates wearable bio sensors, lifelogging technologies and virtual reality. Analytical orientations: ethnographic and experimental studies, design thinking and design rationale.

4.14 Thecla Schiphorst

Thecla Schiphorst (Simon Fraser University – SIAT, CA)

Thecla Schiphorst is Associate Director and Associate Professor in the School of Interactive Arts and Technology at Simon Fraser University in Vancouver, Canada. Her background in dance and computing form the basis for her research in embodied interaction, focusing on movement knowledge representation, tangible and wearable technologies, media and digital art, and the aesthetics of interaction. Her research goal is to expand the practical application of embodied theory within Human Computer Interaction. She is a member of the original design team that developed Life Forms, the computer compositional tool for choreography, and collaborated with Merce Cunningham from 1990 to 2005 supporting his creation of new dance with the computer. Thecla has an Interdisciplinary MA under special arrangements in Computing Science and Dance from Simon Fraser University (1993), and a Ph.D. (2008) from the School of Computing at the University of Plymouth.

4.15 m.c. schraefel

m.c. schraefel (University of Southampton, GB)

prof m.c. schraefel, phd,fbcs, ceng, cscs (lower case deliberate). Professor of Computer Science and Human Performance, Fellow, british computer society, Research Chair, Royal Academy of Engineering, Chartered Engineer. Head, Agents Interaction and Complexity Group And now a wee bit more: Deputy Head of Department, Research, and current REF champion (for those in the UK) for CS.

Wellth Lab Research FOCUS – How to design information systems to support the brain-body connection for lifetime quality of life, including, fitness to learn, fitness to play, fitness to perform optimally, always; to understand through these paths how to enhance innovation, creativity and discovery.

4.16 Designing from and for the Body with Technology

Anna Stahl (RISE SICS – Kista, SE)

When designing for the the body we need to engage in body exercises since this is our design material. In this presentation I bring up two examples describing senzitizing activities that were part of the design process and influenced the outcome, walks in the forest and engaging in the pragmatic philosophy of Somaeasthetics. From the forest walks we propose being, bringing, bridging as important elements in the design process to. From the practicing and designing from Somaesthetics we extracted four experiential qualities that can be used in generative designs; subtle guidance, making space, intimate correspondence and articulation

4.17 Dag Svanæs

Dag Svanes (NTNU – Trondheim, NO)

Svanæs received his Ph.D. in Human-Computer Interaction (HCI) from NTNU. His research over the last 15 years has been in the fields of HCI and Interaction Design. His main focus has been on user-centered design methods and basic theory of interaction. A common theme is the importance of non-cognitive aspects of human-computer interaction – often called embodied interaction. At a practical level this involves a focus on the physical, bodily and social aspects of interaction. In his research he makes use of role play and low-fidelity prototyping in realistic settings to involve end-users in the design process.

4.18 Jakob Tholander

Jakob Tholander (Stockholm University, SE)

I am senior researcher at the MobileLife centre at the Department of Computer and Systems Sciences, Stockholm University. I also hold a position in Media Technology at Södertörn University. I do research in human-computer interaction with a particular interest in tangible and embodied interaction both from a practical design oriented perspective as well as through contributions on a more conceptual level. Recently, I have been focusing on exploring how to design technology for bodily engaging interactions such as movement.

4.19 Elise van den Hoven

Elise van den Hoven (University of Technology – Sydney, AU)

Elise van den Hoven (www.elisevandenhoven.com) is affiliated to the University of Technology Sydney, Eindhoven University of Technology, University of Dundee and the Australian Research Council's Centre of Excellence in Cognition and its Disorders. Her research interests are in Design research, Human-Computer Interaction, Interaction Design, User Experience Design and User-Centered Design. Her favourite application areas are in Physical, Tangible and Embodied Interaction and Human Memory and Remembering. She combines these two in the Design research program Materialising Memories (www.materialisingmemories.com). This program aims to support everyday human remembering activities, including everyday digital photo sharing with family and friends, remembering someone who passed away, or supporting people living with dementia and their carers. Elise' theoretical perspective on the topic of this Dagstuhl could be summarized by the following keywords: Tangible/Embodied Interaction, Embodied Cognition, External/Distributed Cognition and Epistemic Action. On the same topic she recommends the following of her own papers:

References

1 *Grasping gestures: Gesturing with physical artifacts*. AIEDAM journal, special issue on The Role of Gesture in Designing, 2011.
2 *Embodied Metaphors in Tangible Interaction Design*. Personal and Ubiquitous Computing journal, 2012.
3 *Physical Games or Digital Games? Comparing Support for Mental Projection in Tangible and Virtual Representations of a Problem-Solving Task*. TEI, 2013.

Inspiring work is done by Joanna Berzowska, for example, the Skorpions project (www.xslabs.net/skorpions) which deals with kinetic electronic garments.

4.20 Technology based Healthcare Innovations for Active and Healthy Ageing

Rainer Wieching (Universität Siegen, DE)

Demographic change is a huge challenge for western societies. Diseases and related health problems in the ageing society may increase dependency of older adults and their need for care. A consequence might be reduced quality of life of older adults and increased costs for healthcare systems. Hence, there is a large interest in innovative and effective ICT-based solutions that delay older adults' need for health care services, improve their quality of life and thus mitigate the pressure on healthcare systems. Body centric computing (BCC) provides interesting opportunities for designing technologies that support active and healthy ageing (AHA) in older adults sustainably. The design process should involve older adults themselves and relevant stakeholders in the respective healthcare system. Mixed method approaches, i.e. combining qualitative and quantitative methods provide a detailed understanding of relevant practices and attitudes with respect to health, quality of life and technology use for AHA support of older adults and their interactions with relevant stakeholders. Qualitative and quantitative data needs to be collected from older adults and relevant secondary stakeholders like care givers, policy makers or health insurance companies should also be included in participatory design of such AHA support systems. Study setup should therefore embedded in living lab structures and randomized controlled trials (RCT) to ensure value sensitive design and evidence based data and appropriate outcomes of the design process.

Research results illustrate that the combination of innovative BCC technologies and their alignment towards older adults' social contexts and environments may increase their motivation to use technologies for AHA support and address their heterogeneous practices and attitudes more accurately. BCC solution should be designed to support the individual but also collaboration and cooperation between older adults and relevant stakeholders with respect to AHA. While doing so BCC technologies for AHA may consider different health areas and involve older adults' social environment to ease the integration into daily lives of older adults and thus create opportunities for long-term use and sustainable health impacts.

4.21 Resource-Efficient Intra-Body Communication

Florian Wolling (Universität Siegen, DE)

In body-centric computing, wearable devices are frequently utilized to detect certain events or even to continuously measure body parameters and motion. For most applications it is expedient to relay those data to a more powerful yet bigger device such as a smartphone that, finally, processes, interprets, and visualizes the data. For the transmission usually Bluetooth, WiFi, or other popular wireless technologies are utilized while cables are, usually, not reasonable due to a reduced wearing comfort and fatigue. In his presentation, Florian Wolling from the University of Siegen in Germany introduces body-coupled communication, a technique that is situated between conductive and radio frequency transmission. It is a promising yet less-explored method to use the user's body as a bounded medium, and the modulation of its natural electric field for communication between body-worn devices. The signals are induced capacitively into the body and detected likewise with two interspacing electrodes. While radio transmission suffers from a high energy consumption, shadowing, and motion effects, body-coupled communication is an energy-efficient alternative that uses the limited distribution volume of the human body and low baseband frequencies. Outside the body, the signal strength decays very fast with $1/r^3$ and, thus, prevents eavesdropping. Consequently, the approach enables the design of less obtrusive wearable devices with smaller dimensions and longer battery life.

Participants

- Josh Andres
IBM Research – Melbourne, AU
- Kathrin Gerling
University of Lincoln, GB
- Stefan Göbel
TU Darmstadt, DE
- Nicholas Graham
Queen's University – Kingston, CA
- Marianne Graves Petersen
Aarhus University, DK
- Perttu Hämäläinen
Aalto University, FI
- Martin Jonsson
Södertörn University – Huddinge, SE
- Elena Márquez Segura
University of California – Santa Cruz, US
- Joseph Marshall
University of Nottingham, GB
- Anna Lisa Martin-Niedecken
Zürcher Hochschule der Künste, CH
- Jochen Meyer
OFFIS – Oldenburg, DE
- Florian Mueller
RMIT University – Melbourne, AU
- Corina Sas
Lancaster University, GB
- Thecla Schiphorst
Simon Fraser University – Surrey, CA
- m.c. schraefel
University of Southampton, GB
- Anna Stahl
RISE SICS – Kista, SE
- Dag Svanes
NTNU – Trondheim, NO
- Jakob Tholander
Stockholm University, SE
- Elise van den Hoven
University of Technology – Sydney, AU
- Rainer Wieching
Universität Siegen, DE
- Florian Wolling
Universität Siegen, DE