Report from Dagstuhl Seminar 24111

Logics for Dependence and Independence: Expressivity and Complexity

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Abstract

This report documents the programme and outcomes of Dagstuhl Seminar "Logics for Dependence and Independence: Expressivity and Complexity" (24111). This seminar served as a follow-up seminar to the highly successful seminars "Dependence Logic: Theory and Applications" (13071), "Logics for Dependence and Independence" (15261) and "Logics for Dependence and Independence" (19031). A key objective of the seminar was to bring together researchers working in dependence logic and in application areas (for this edition with a particular emphasis on the areas of hyperproperties and formal linguistics), so that they can communicate state-of-the-art advances and embark on a systematic interaction. The goal was especially to reach those researchers who have recently started working in this thriving area, as well as researchers working on several aspects of complexity studies of team-based logics as well as expressivity issues, in particular in the just mentioned application areas. In particular, bringing together researchers from areas of theoretical studies with the application areas aimed at enhancing the synergy between the different communities working on dependence logic.

1   Executive Summary

Heribert Vollmer (Leibniz Universität Hannover, DE)
Juha Kontinen (University of Helsinki, FI)
Jonni Virtema (University of Sheffield, GB)
Fan Yang (Utrecht University, NL)

Dependence and independence are interdisciplinary notions that are pervasive in many areas of science. They appear in domains such as mathematics, computer science, statistics, quantum physics, and game theory. The systematic development of logical and semantical structures for these notions via the logics of dependence and independence has exposed surprising connections between these areas.

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Logics for dependence and independence are new tools for modeling dependencies and interaction in dynamical scenarios. Reflecting this, these logics often have higher expressive power and complexity than classical logics used for these purposes previously. During the past decade, pioneering results on logics for dependence and independence has been disseminated in a spectrum of respected international conferences such as LICS, MFCS, JELIA, LPAR, CSL, AiML, and FSTTCS, and in top journals in the areas of logic and theoretical computer science. Although significant progress has been made in understanding the computational side of these novel logics (see Section 2 for some examples) still many central questions remain unsolved so far. In addition to addressing the open questions, the seminar also aims at boosting the exchange of ideas and techniques between team-based logics and the application areas.

The complexity and expressivity aspects of logics in propositional, modal and first-order team semantics have been studied extensively during the past decade. Recently, the complexity theoretic focus has turned to the (parameterized) complexity of logically defined counting and enumeration problems as well as algebraic complexity of probabilistic and real-valued logics. Furthermore, the expressivity and complexity of the novel temporal team logics are also not yet well understood.

Logics for real valued data and probabilistic reasoning

Algorithmically, first-order dependence and independence logic correspond exactly to the complexity class NP and to the existential fragment of second-order logic (ESO) while inclusion logic corresponds to the complexity class P over ordered finite structures. Recent discoveries on the connections between so-called probabilistic independence logic and logics on real valued data have revealed similar fundamental connections to a computation paradigm that uses real numbers as primitive entities (so-called BSS paradigm). These probabilistic logics have fascinating connections to the area of information theory via the notion of entropy, which can be adopted as a dependency in the probabilistic team semantics framework.

Applications to Hyperproperties and Formal Verification

An emerging area of applications for team semantics is the area of Hyperproperties. In the field of formal verification an execution of a system is modeled by a trace depicting the evolution of the system over discrete time. Traceproperties, ubiquitous in formal verification, are properties of systems that boil down to verifying that each trace of the system satisfies that property. Hyperproperties on the other hand are properties of systems that cannot be reduced to checking properties of individual execution traces of the system in isolation, but are instead properties of sets of traces. These properties are of vital importance in applications concerning security and information flow. A canonical example here is bounded termination; one cannot check whether there exists a uniform time bound for some action by checking computation traces in isolation. Other examples include security policies such as *non-interference* and *secure information flow*.

Applications to Formal Linguistics

Team semantics was also proven to be a fruitful tool for formal linguistics, especially for *inquisitive semantics* and the study of *free choice inferences*. Inquisitive semantics is a unified formal framework for analyzing both statements and questions in natural language. It is known that inquisitive logic essentially adopts team semantics and can thus be viewed as a variant of propositional dependence logic. This connection has already sparked a significant

amount of interest and new research at the interface of the two fields. On a different line of research, recently a bilateral modal logic based on team semantics, called BSML, was developed to model free choice inferences in natural language, where an atom NE studied in the context of propositional team logics plays a central role. Very recent works have studied the logical properties of BSML, and promising broader applications of the team semantics method along this line are yet to be explored.

Organization of the Seminar and Activities

The seminar brought together 42 researchers from mathematical logic, natural language semantics, and theoretical computer science. The participants consisted of both senior and junior researchers, including a number of postdoctoral researchers and advanced graduate students.

Participants were invited to present their work and to communicate state-of-the-art advances. Over the five days of the seminar, 29 talks of various lengths took place. Introductory and tutorial talks of 60 minutes were scheduled prior to the seminar. The remaining slots were filled with shorter talks, mostly scheduled after the seminar commenced. Furthermore the seminar included an open problem session and a concluding perspectives address.

The tutorial talks took place in the beginning of the week in order to establish a common background for the different communities that came together for the seminar. The presenters and topics were:

- Jonni Virtema: Introduction to Team Semantics
- Erika Ábrahám: (Probabilistic) Hyperproperties
- Maria Aloni: Logic and Language: Linguistic Applications of Team Semantics
- Till Miltzow: Existential Theory of the Reals
- Cheuk Ting Li: The Undecidability of Probabilistic Conditional Independence Implication

In addition, the seminar consisted of 24 shorter contributed talks, addressing various topics concerning expressibility, complexity and applications of team-based logics.

A one hour long open problem session was held on Wednesday morning, just before the hike ("Open Problem Walk"). It was moderated by Juha Kontinen. The session was announced already on Monday morning to give participants the opportunity to register for the session. Besides a couple of shorter contributions on decidability of Team-LTL (by Martin Zimmerman), expressivity of different forms of implications when added to inclusion (predicate) logic (by Jouko Väänänen), and expressivity of propositional independence logic (by Fan Yang), the session consisted of three longer introductions of the following open problems:

- Is PosSLP, the question if a given straight-line program (over the integers with operations of addition, multiplication and subtraction) computes a positive number, solvable in polynomial time? It is conjectured that NP with an oracle to PosSLP equals the complexity class $\exists \mathbb{R}$. (*Till Miltzow*)
- Are all probabilistic conditional independence implications derivable from information inequalities? (*Milan Studený*)
- Identify tractable fragment for model checking for dependence logic, that is, fragments with an effective syntax that are "natural" and "useful" in the sense that they can express interesting computational problems in a relatively straightforward way, have strictly higher expressive power than first-order logic FO, and have a polynomial-time model checking in data complexity. (*Phokion Kolaitis*)

The participants were asked to contribute more open problems to a collection in form of an Overleaf project.

The seminar ended with a perspectives address given by Jouko Väänänen just before Friday lunch.

Concluding Remarks

The seminar achieved its aim of bringing together researchers from various related communities to share state-of-the-art research. Considerable exchange took place between researchers in the application areas of hyperproperties and formal semantics and those working more theoretically on complexity and expressivity questions of team-based logics. The organizers left ample time for interaction outside of this schedule of talks and, as a result, many fruitful discussions between participants took place throughout the afternoons and evenings.

The organizers regard the seminar as a significant success. Bringing together researchers from different areas fostered valuable interactions and led to fruitful discussions. Feedback from the participants was very positive as well.

Finally, the organizers wish to express their gratitude to the Scientific Directorate of the Center for its support of this Dagstuhl Seminar.

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Open problems

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3 Overview of Talks

3.1 (Probabilistic) Hyperproperties

Erika Ábrahám (RWTH Aachen, DE)

Four decades ago, Lamport used the notion of trace properties as a means to specify the correctness of individual executions of concurrent programs. This notion was later formalized and classified by Alpern and Schneider to safety and liveness properties. Temporal logics like LTL and CTL were built based on these efforts to give formal syntax and semantics to requirements of trace properties. Subsequently, verification algorithms were developed to reason about individual executions of a system.

However, it turns out that many interesting requirements are not trace properties. For example, important information-flow security policies (e.g. noninterference, observational determinism) or service level agreements (e.g. mean response time, percentage uptime) cannot be expressed as properties of individual execution traces of a system. Rather, they are properties of sets of execution traces, also known as hyperproperties. Temporal logics such as HyperLTL and HyperCTL* have been proposed to provide a unifying framework to express and reason about hyperproperties.

This talk focussed on a special class of hyperproperties: we asked the question what are hyperproperties in the context of systems with random behavior. We discussed what are relevant probabilistic relations between independent executions of a system, how we can formally express them in a temporal logic, and how we can decide the truth of such statements.

3.2 Logic and Language - Linguistic applications of team semantics

Maria Aloni (University of Amsterdam, NL)

In the first part of the talk I surveyed linguistic applications of team-based logics including IF-logic (branching and exceptional scope of indefinites) [Hintikka and Sandu 1998], inquisitive (epistemic) logic (questions, attitude verbs) [Ciardelli, Groenendijk and Roelofsen 2018] and Bilateral State-Based Modal Logic (non-classical inference, including free choice)[Aloni 2022]. In the second part I presented an application of a two-sorted dependence logic [Väänänen 2007] to capture cross-linguistic variations in the expression of specificity [Aloni and Degano 2022].

Indefinites are known to give rise to different scopal (specific vs nonspecific) and epistemic (known vs unknown) uses. Farkas and Brasoveanu [2020] explained these specificity distinctions in terms of stability vs. variability in value assignments of the variable introduced by

the indefinite. Typological research [Haspelmath, 1997] showed that indefinites have different functional distributions with respect to these uses. In the talk I presented a two-sorted dependence logic, with dependence, inclusion and variation atoms, where Farkas and Brasoveanu [2020]'s ideas can be rigorously formalised. I further applied the framework to explain typological variety of indefinites, their restricted distribution and licensing conditions, and some diachronic developments of indefinite forms.

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3.3 Deep inference sequent calculi for propositional logics with team semantics

Aleksi Ilari Anttila (University of Amsterdam, NL)

While natural deduction- and Hilbert-style axiomatizations of logics employing team semantics such dependence logic and inquisitive logic have been extensively studied, the development of sequent calculi and proof theory in general for these logics appears to have been hindered by the factors such as the fact these logics are not closed under uniform substitution. The sequent calculi which have been constructed for these logics thus far have been labelled or multi-type systems. We propose a different approach: by appending a few deep inference-style rules (rules which can act not only on the immediate subformulas and main connectives of formulas, but also on subformulas and connectives deeper within a formula) to a standard Gentzen-style calculus, we obtain a very simple system for at least one of these logics.

3.4　Conditionals for union-closed languages

Fausto Barbero (University of Helsinki, FI)

Are team logics logics? In the 70's, a similar criticism was addressed to quantum logic, on the basis that the latter lacks a (proof-theoretically) well-behaved conditional operator. Similarly, many of the languages considered in the literature on team semantics lack (and fail to define) an adequate conditional, and as a consequence they are not amenable to simple Hilbert-style axiomatizations. This situation was cleared by the discovery that downward closed languages can be enriched with a well-behaved conditional (the inquisitive implication), in many cases without increase in expressive power (propositional case) or, at least, without losing the property of downward closure.

It is less clear what could be taken as a conditional for languages that are not downward closed. As an interesting special case, the literature is rich with union-closed languages, e.g. inclusion logics and languages with possibility operators or relevant disjunctions. I will show that there is no conditional that preserves union closure and satisfies the key proof-theoretical constraints of modus ponens and the deduction theorem. Such an operator is missing not only for the whole class of union-closed languages, but also when trying to extend some specific individual languages.

I will then consider four candidates for the role of conditional for union closed languages: four binary operators that preserve union closure, respect restricted forms of modus ponens and the deduction theorem, and share many properties with what is usually considered a "conditional".

3.5　Hyperteams for compositionality and determinacy in logics for games

Dario Della Monica (University of Udine, IT)

Team semantics is the compositional infrastructure at the basis of so-called logics for (in)dependencies [1, 2, 3], making it possible to specify the set of first-order variables upon which another first-order variable value is allowed to depend on, overruling the standard linear dependence relation imposed by the quantification prefix.

On the one hand, this ability comes in handy for modeling games with incomplete information, where moves of one player may be dependent on only some of the moves of the other player, while being independent of the other ones. On the other hand, teams (i.e., sets of assignments) are meant to collect the uncertainty about possible evaluations of only a subset of variables, e.g., the universally quantified ones; it is thus possible to only specify dependencies for the remaining variables, e.g., the existentially quantified ones.

To overcome this asymmetry, which strides with the symmetric treatment of players in games, we extend the notion of teams with the one of hyperteams (i.e., sets of teams), thus allowing for a symmetric treatment of existentially and universally quantified variables.

We study variants of both Quantified Propositional Temporal Logic (QPTL) and First-Order Logic (FOL), replacing their standard semantics with one based on hyperteams, thus obtaining Good-for-Game QPTL (GFG-QPTL) [4] and Alternating Dependence/Independence-Friendly Logic (ADIF) [5]. Both these logics enjoy determinacy, which makes them particularly apt to model 2-player zero-sum games. We provide both compositional and game-theoretic semantics, and study the complexity of satisfiability (for GFG-QPTL) and model checking (for both GFG-QPTL and ADIF) problems.

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3.6   Modular SAT-based techniques for reasoning tasks in team semantics

Arnaud Durand (Paris Cité University, FR), Juha Kontinen (University of Helsinki, FI), and Jouko Väänänen (University of Helsinki, FI)

We study the complexity of reasoning tasks for logics in team semantics. Our main focus is on the data complexity of model checking but we also derive new results for logically defined counting and enumeration problems. Our approach is based on modular reductions of these problems into the corresponding problems of various classes of Boolean formulas. We illustrate our approach via several new tractability/intractability results.

3.7   The propositional logic of teams

Fredrik Engström (University of Gothenburg, SE)

Logics based on team semantics often fail to be substitutional, limiting any algebraic treatment, and rendering schematic uniform proof systems impossible. This shortcoming can be attributed to the flatness principle, commonly adhered to when generating team semantics.

Investigating the formation of team semantics from algebraic semantics, and disregarding the flatness principle, we present the logic of teams, LT, a substitutional logic in which important propositional team logics are axiomatisable as fragments. Starting from classical propositional logic and Boolean algebras, we give a semantics for LT by considering the algebras that are powersets of Boolean algebras B, i.e., of the form P(B), equipped with internal (pointwise) and external (set theoretic) connectives. Furthermore, we present a well-motivated complete and sound labelled natural deduction system for LT.

3.8 Second-Order Hyperproperties

Hadar Frenkel (CISPA - Saarbrücken, DE)

We introduce Hyper2LTL, a temporal logic for the specification of hyperproperties that allows for second-order quantification over sets of traces. Unlike first-order temporal logics for hyperproperties, such as HyperLTL, Hyper2LTL can express complex epistemic properties like common knowledge, Mazurkiewicz trace theory, and asynchronous hyperproperties. The model checking problem of Hyper2LTL is, in general, undecidable. For the expressive fragment where second-order quantification is restricted to smallest and largest sets, we present an approximate model-checking algorithm that computes increasingly precise under- and overapproximations of the quantified sets, based on fixpoint iteration and automata learning. We report on encouraging experimental results with our model-checking algorithm, which we implemented in the tool HySO.

3.9 Strongly First Order Dependencies and Dual Negation in Team Semantics

Pietro Galliani (University of Insubria - Varese, IT)

Much (although not all) of the work in the area of Team Semantics assumes that all expressions are in negation normal form (and, in particular, that no negated dependence atoms can appear).

I will argue that, even though this choice has valid historical reasons and is appropriate for certain logics based on Team Semantics, in general there is no compelling reason not to introduce (dual) negation; and I will re-examine the question of finding out which dependency families lead to logics that are reducible to First Order Logic in this more general setting.

3.10   Hidden Variables in Quantum Mechanics and Logics for Dependence and Independence

Erich Grädel (RWTH Aachen, DE)

We study hidden-variable models from quantum mechanics, and their abstractions in purely probabilistic and relational frameworks, by means of logics of dependence and independence, based on team semantics. We show that common desirable properties of hidden-variable models can be defined in an elegant and concise way in dependence and independence logic. The relationship between different properties, and their simultaneous realisability can thus been formulated and a proved on a purely logical level, as problems of entailment and satisfiability of logical formulae. Connections between probabilistic and relational entailment in dependence and independence logic allow us to simplify proofs. In many cases, we can establish results on both probabilistic and relational hidden-variable models by a single proof, because one case implies the other, depending on purely syntactic criteria. We also discuss the 'no-go' theorems by Bell and Kochen-Specker and provide purely logical variants of the latter, introducing non-contextual choice as a team-semantical property.

3.11   Temporal Team Semantics Revisited

Jens Gutsfeld (TU Braunschweig, DE)

In this talk, we study a novel approach to asynchronous hyperproperties by reconsidering the foundations of temporal team semantics. We consider three logics: TeamLTL, TeamCTL and TeamCTL*, which are obtained by adding quantification over so-called time evaluation functions controlling the asynchronous progress of traces. We then relate synchronous to our new logics and show how it can be embedded into them. We discuss that the model checking problem for with Boolean disjunctions is highly undecidable by encoding recurrent computations of non-deterministic 2-counter machines. Finally, we present a translation from to Alternating Asynchronous Büchi Automata and obtain decidability results for the path checking problem as well as restricted variants of the model checking and satisfiability problems.

3.12   Conditional independence on semiring relations

Miika Hannula (University of Helsinki, FI)

Conditional independence plays a foundational role in database theory, probability theory, information theory, and graphical models. Many properties of conditional independence are shared across various domains, and to some extent these commonalities can be studied through a measure-theoretic approach. In this talk we consider an alternative approach via semiring relations, defined by extending database relations with tuple annotations from some commutative semiring. Integrating various interpretations of conditional independence in this context, we investigate how the choice of the underlying semiring impacts the corresponding axiomatic and decomposition properties.

3.13   Implication problems for some qualitative and quantitative dependencies

Minna Eveliina Hirvonen (University of Helsinki, FI)

A dependence or independence atom is a statement that some variables are in some sense (in)dependent. A set of atoms S is said to logically imply another atom s if every suitable object (e.g. a database or a distribution) that satisfies all of the atoms in S also satisfies the atom s. An implication problem is the task of deciding whether a given set of atoms S logically implies another given atom s.

In this talk, I will present some axiomatization results for implication problems for classes that combine different types of qualitative and quantitative atoms. We consider two different implication problems that combine well-known qualitative and quantitative atoms with two lesser-known quantitative atoms: unary marginal identity and unary marginal distribution equivalence. A unary marginal identity states that two variables x and y are identically distributed. A unary marginal distribution equivalence states that the multiset consisting of the marginal probabilities of all the values for variable x is the same as the corresponding multiset for y.

The first one of these implication problems combines unary marginal identity and unary marginal distribution equivalence with functional dependency. The second implication problem combines the two atoms with probabilistic independence. Both implication problems have a sound and complete axiomatization and a polynomial-time algorithm.

3.14 Approximate dependence atoms

Matilda Häggblom (University of Helsinki, FI)

In the team semantic setting, Väänänen (2017) defined and axiomatized approximate dependence atoms suitable for cases when "almost dependence" is permittable. An approximate dependence atom is satisfied by a team if there exists a large enough subteam that satisfies the corresponding usual dependence atom.

We aim to define and axiomatize approximate versions of other dependence atoms, such as exclusion and inclusion. Depending on the properties of the atom, such as downward closure or the lack thereof, different definitions of the atoms' approximate versions might be needed. We present some preliminary results regarding axiomatizations of approximate exclusion and anonymity atoms.

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3.15 Approximate Implication for Probabilistic Graphical Models

Batya Kenig (Technion - Haifa, IL)

The graphical structure of Probabilistic Graphical Models (PGMs) represents the conditional independence (CI) relations that hold in the modeled distribution. The premise of all current systems-of-inference for deriving conditional independence relations in PGMs, is that the set of CIs used for the construction of the PGM hold exactly. In practice, algorithms for extracting the structure of PGMs from data discover approximate CIs that do not hold exactly in the distribution. In this work, we ask how the error in this set propagates to the inferred CIs read off the graphical structure. More precisely, what guarantee can we provide on the inferred CI when the set of CIs that entailed it hold only approximately? In this talk, I will describe new positive and negative results concerning this problem.

3.16 Expressive power: BSML and Propositional Independence Logic

Søren Brinck Knudstorp (University of Amsterdam, NL)

In recent work, Aloni, Anttila and Yang (2023) present two extensions of the modal team logic BSML, demonstrating their expressive completeness for all properties [invariant under bounded bisimulation] and all union-closed properties, respectively, and leave open the

problem of characterizing the expressive power of BSML. Continuing this line of work, we solve this problem by showing that BSML is expressively complete for all convex, union-closed properties.

We then shift our focus to independence logic, characterizing the expressive power of propositional independence logic with the inquisitive disjunction.

3.17   Characterizing Data Dependencies

Phokion G. Kolaitis (University of California - Santa Cruz, US)

Data dependencies are integrity constraints that the data at hand ought to obey. After functional dependencies were introduced by E.F. Codd in the 1970s, several other kinds of data dependencies were defined and extensively studied. Eventually, it was realized that essentially all data dependencies are either equality generating dependencies (egds) or tuple generating dependencies (tgds); the former generalize functional dependencies, while the latter generalize inclusion dependencies, multi-valued dependencies, and full tgds. In 1987, Makowsky and Vardi characterized full tgds and egds in terms of their structural properties, such as domain independence, closure under direct products, and modularity. The aim of this talk is to present characterizations of arbitrary tgds and egds that employ a new notion of locality. This is joint work with Marco Console and Andreas Pieris.

3.18   The undecidability of probabilistic conditional independence implication

Cheuk Ting Li (The Chinese University of Hong Kong, HK)

The probabilistic conditional independence implication problem is to decide whether a given statement on the conditional independence among several random variables is implied by a given list of such statements. This problem was shown to be undecidable, that is, there is no algorithm that is guaranteed to solve this problem. We will also describe the relation between this problem and the periodic tiling problem, and its implication on network coding.

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3.19   Parameterized Complexity of Weighted Team Definability

Yasir Mahmood (Universität Paderborn, DE)

This Talk is based on our recent article with the same title: Parameterized Complexity of Weighted Team Definability In this article, we study the complexity of weighted team definability for logics with team semantics. This is a natural analogue of one of the most studied problems in parameterized complexity, the notion of weighted Fagin-definability, which is formulated in terms of satisfaction of first-order formulas with free relation variables. We focus on the parameterized complexity of weighted team definability for a fixed formula φ of central team-based logics. Given a first-order structure A and the parameter value $k \in N$ as input, the question is to determine whether $(A, T) \models \varphi$ for some team T of size k. We show several results on the complexity of this problem for dependence, independence, and inclusion logic formulas. Moreover, we also relate the complexity of weighted team definability to the complexity classes in the well-known W-hierarchy as well as paraNP.

3.20   A Parameterized View on the Complexity of Dependence Logic

Arne Meier (Leibniz Universität Hannover, DE)

In this talk, we give an overview of different parameterisations in propositional dependence logic as well as for first-order dependence logic. We start with a short primer on parameterised complexity theory and then dive into the results for the two dependence logic variants mentioned.

3.21   Existential Theory of the Reals

Till Miltzow (Utrecht University, NL)

During the seminar at Dagstuhl, I gave a presentation about ER-complete problems. We gave many examples of ER-complete problems from different domains. We showed techniques to show ER-completeness, that are different from reductions for NP-completeness. Furthermore, we explained some common phenomena, like high solution precision and topological universality.

3.22 A Set Based Semantics for Asynchronous TeamLTL

Max Sandström (University of Sheffield, GB)

In this talk I will present a relaxed set based variant of asynchronous linear temporal logic under team semantics. Linear temporal logic (LTL) is used in system verification to write formal specifications for reactive systems. However, some relevant properties, e.g. non-inference in information flow security, cannot be expressed in LTL. A class of such properties that has recently received ample attention is known as hyperproperties. Team semantics offers an avenue to capture such hyperproperties. The asynchronous variant I will present gives a bottom-up approach to capturing hyperproperties, as the asynchronous variant is expressively equivalent with LTL, but it grows in expressivity quickly with extensions. I will introduce the extensions of TeamLTL with the Boolean disjunction and a fragment of the extension of TeamLTL with the Boolean negation, where the negation cannot occur in the left-hand side of the Until-operator or within the Global-operator. I will present complexity results of the model checking problem, as well as some results relating the logics with other logics capturing hyperproperties.

Based on Joint work with Juha Kontinen and Jonni Virtema.

3.23 Lattices of abstract conditional independence models and their implication-based description

Milan Studený (The Czech Academy of Sciences - Prague, CZ)

In a recent manuscript [2], an abstract approach to *conditional independence* (CI) structures has been introduced. The approach was inspired by the idea of deriving further probabilistically valid implications among CI statements based on the idea of *self-adhesion* of CI models. That particular method is an abstraction of an information-theoretical method to derive non-Shannon information-theoretical inequalities, based on the so-called *copy lemma* [9, 4, 8, 3].

The talk was, however, devoted solely to a limited sub-topic of the manuscript. Specifically, it dealt with an important class of abstract CI frames which are closed under 3 basic operations: copying, marginalization and intersection. Many of standard classes of CI structures, including classic probabilistic CI structures fall into this class of CI frames.

The point is that then, for every variable set N, the family of respective CI models forms a lattice relative to inclusion of models. Therefore, one can apply the results from lattice theory [1] and *formal concept analysis* [5] to describe such lattices of models in terms of the corresponding abstract functional dependence relation [7]. Particular concepts of *pseudo-closed sets* relative to a Moore family and *canonical implicational basis* [6] then offer a kind of simplest standard description in terms of implications among CI statements. Such description can then be interpreted as a kind of "axiomatization" of the respective CI models.

In the talk, the above mentioned concept of an abstract CI frame was introduced, including three basic examples. Substantial related results from lattice theory and the formal concept analysis were then recalled and illustrated by a simple running example.

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3.24   Guarded Hybrid Team Logics

Marius Tritschler (TU Darmstadt, DE)

Hybrid team logics are inspired by hybrid modal logics where binders can be used to bind (and later reference) assignments. In the team setting, bound teams may be referenced as regular relations. We find that Hybrid Team Logic and its positive and negative fragments are equivalent to well-known team logics. Further, we can analyze guarded versions of these logics to find that guarded hybrid logics share some prominent properties of classical guarded logics, while also overcoming some of the limitations of atom-based guarded team logics.

3.25   Introduction to team semantics

Jonni Virtema (University of Sheffield, GB)

In this talk I will give an introduction to team semantics. I will start by covering motivation, basic definitions, and results from the classical era of team semantics (2007-2017). I will cover the most important aspects first-order team semantics, and briefly discuss how this

approach can be adapted to the propositional and modal contexts. In the second half of my talk, I will introduce two of the most important recent advancements in team semantics relevant to this meeting; namely probabilistic team semantics and temporal team semantics.

3.26 Consistent Query Answering with Respect to Primary Keys: Past Research and Future Challenges

Jef Wijsen (University of Mons, BE)

We consider database instances that may violate their primary key constraints. A repair of such a database instance is an inclusion-maximal consistent subset of it. For a fixed Boolean query q, the decision problem CERTAINTY(q) takes a database instance as input, and asks whether q holds true in every repair. It is known that for every self-join-free Boolean conjunctive query q, CERTAINTY(q) falls in one of three complexity classes: FO, L-complete, or coNP-complete; furthermore, it can be decided, given q, which of the three cases holds. However, the complexity classification of CERTAINTY(q) for Boolean conjunctive queries q with self-joins remains a notorious open problem. This presentation provides an overview of previous research and the ongoing challenges concerning the study of CERTAINTY(q) for Boolean conjunctive queries.

4 Open problems

4.1 Model checking LTL with team semantics

Martin Zimmermann (Aalborg University, DK)

Linear Temporal Logic (LTL) is arguably the most important specification language for trace properties, properties specifying requirements on individual execution traces of a system. With team semantics, LTL is naturally able to express properties of multiple traces, which allows to express information-flow properties. This extends the expressiveness of plain LTL.

The model-checking problem asks whether a given system satisfies a given specification. For LTL (and hence also LTL under team semantics without splitjunctions), model checking is in PSPACE [1] while it is highly undecidable if one allows Boolean negation [2]. However, the decidability of LTL under team semantics with splitjunctions but without Boolean negation is still unresolved.

In this talk, I will introduce team semantics for LTL, present some useful results, highlight some challenges one has to overcome when trying to solve the problem, and end with a call to arms: let us solve the problem.

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