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# Epistemic Planning: Perspectives on the Special Issue

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**Abstract**

Epistemic planning is the enrichment of automated planning with epistemic notions such as knowledge and belief. In general, single-agent epistemic planning considers the following problem: given an agent's current state of knowledge, and a desirable state of knowledge, how does it get from one to the other? In multi-agent epistemic planning, the current and desirable states of knowledge might also refer to the states of knowledge of other agents, including higher-order knowledge like ensuring that agent A doesn't get to know that agent B knows P. Single-agent epistemic planning is of central importance in settings where agents need to be able to reason about their own lack of knowledge and, e.g., make plans of how to achieve the required knowledge. Multi-agent epistemic planning is essential for coordination and collaboration among multiple agents, where success can only be expected if agents are able to reason about the knowledge, uncertainty and capabilities of other agents. It is a relatively recent area of research involving several sub-areas of artificial intelligence, such as automated planning, decision-theoretic planning, epistemic logic, strategic reasoning and knowledge representation & reasoning. In order to achieve formalisms and systems for epistemic planning that are both expressive and practically efficient, it is necessary to combine state of the art from several such sub-areas of artificial intelligence that have so far been considered mostly in separation. Application areas of epistemic planning include mobile service robots, explaining planning, game playing, human-robot interaction and social robotics.

For this special issue of AIJ, we invited papers on theory, applications, and implemented systems of epistemic planning. In this document, we summarize the accepted papers whilst recapping the essentials of epistemic planning.

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## 1. Introduction

*Automated planning* is of central concern in high-level symbolic AI research, with applications in logistics, robotics and service composition. In the simple case of an agent operating in a known world using deterministic actions, the output of a planner is just a sequence of actions to be performed to the effect that it achieves a desired goal state. *Epistemic planning* is the enrichment of planning with epistemic notions, in particular *knowledge and belief*, including higher-order knowledge, i.e., knowledge about what other agents know, knowledge about what someone knows about someone else, etc. In general, *single-agent epistemic planning* considers the following problem: given my current state of knowledge, and a desirable state of knowledge, how do I get from one to the other? In *multi-agent epistemic planning*, the current and desirable states of knowledge might also refer to the states of knowledge of other agents, including higher-order knowledge like ensuring that agent $a$ doesn't get to know that agent $b$ knows $p$. Single-agent epistemic planning is of central importance in settings where agents need to be able to reason about their own lack of knowledge and e.g. make plans of how to achieve the required knowledge. Multi-agent epistemic planning is essential for *coordination and collaboration* in multi-agent systems, where success can only be expected if agents are able to reason about the knowledge, uncertainty and capabilities of other agents.

Epistemic planning is a relatively recent field involving aspects of automated planning, knowledge representation and epistemic logic. It has attracted attention from researchers in all of these areas. This has led to new synergies and collaborations between these otherwise relatively independent research communities. Since 2014, three international workshops dedicated to the subject have been organised at Dagstuhl, Germany (2014, 2017) and at the Lorentz Centre, the Netherlands (2015). Many of the attendants of these workshops are among the contributors to this special issue. The workshops were instrumental in increasing the awareness of epistemic logic to researchers in automated planning, and vice versa. In fact, the 2014 workshop directly led leading researchers in knowledge representation and automated planning to adopt ideas from dynamic epistemic logic in their own research [1, 2]. Conversely, the workshop inspired researchers in epistemic logic to study problems in automated planning [3, 4, 5, 6, 7]. In addition to these papers, the recent years have seen a number of other epistemic planning publications combining automated planning, knowledge representation and dynamic epistemic logic [8, 9, 10, 11, 1, 12, 13, 3, 2, 14, 15, 15, 16, 17].

Epistemic planning has promising application potentials in all domains involving autonomous agents (e.g. robots or softbots) that require skills both in planning and in reasoning about knowledge and belief (of themselves and others). In the very least, these include instances of game playing, such as coordination and cooperation scenarios [18]. Another fundamental place for epistemic planning is to provide the foundations for building artificial agents with social intelligence. Social intelligence is understood as the ability to make sense of the actions of other agents and to react reasonably. This ability is central to regulating acceptable interactions between people [19]. Social intelligence in AI is for instance relevant to human-computer interaction and social robotics. Social robotics is a subfield of robotics that takes the enabling of social intelligence seriously. Epistemic reasoning offers a formal theory of attributing mental states to agents, and thus, epistemic planning offers a natural framework for real-world planning with social robots [20, 21, 22, 23]. While the current state of the art in social robotics somewhat eschews a formal approach to modelling beliefs and knowledge, epistemic planning is well positioned to fill the gap.

## 2. Components of epistemic planning

Epistemic planning is inherently multi-disciplinary involving the areas of automated planning, epistemic logic, and knowledge representation & reasoning. In order to achieve formalisms and systems for epistemic planning that are both expressive and practically efficient, it is necessary to combine state of the art from all three areas. Below we briefly describe these three component areas of epistemic planning.

*Automated planning.* The area of automated planning is almost as old as AI itself. The first automated planner was introduced by Newell, Shaw and Simon in the fifties under the name *general problem solver* [24]. Recent years have brought a huge advance on scalability of automated planning systems by employing smart search techniques such as heuristic search [25], SAT [26], BDDs [27], and other techniques. At the same time, planning researchers strive to capture planning settings that are more challenging than the classical setting [28]. For instance, planning under uncertainty, multi-agent planning and planning taking beliefs into account are current research topics. This calls for researchers in planning to investigate formalisms in other areas that can help in creating these more expressive planning formalisms. For instance, to create a formalism for planning with multiple agents where each agent can reason about the beliefs of the other agents, one can adopt ideas from epistemic logic and its dynamic and temporal extensions.

*Epistemic logic and its extensions. Epistemic logic* covers logical formalisms for reasoning about knowledge and belief, usually in the form of modal logics with Kripke semantics [29]. In the last 20 years it was extended in several ways in order to account for time and actions: with temporal operators from (branching or linear) temporal logic; with strategic operators from alternating-time temporal logic; with program operators from dynamic logic. All these systems are typically based on the semantics of modal logic, and often focus on information (ex)change and the dynamics of knowledge and belief. Paradigmatic examples are *epistemic temporal logic* (*ETL*) [30], *alternating-time temporal epistemic logic* (*ATEL*) [31], and *dynamic epistemic logic* (*DEL*) [32, 33] (including public announcement logic [34]). One of the main technical features of dynamic epistemic logic is the incorporation of events and actions into the modal framework by the notions of action model (alias event model) and product update [32]. One possible framework for epistemic planning is then achieved by defining action schemes in terms of these events and actions of dynamic epistemic logic. This idea was first pursued by Bolander and Andersen [35], but independently conceived by several other researchers [36, 37, 38].

*Knowledge representation and reasoning.* This has been an important focus of research in AI since its inception. John McCarthy's seminal work provided the foundation for research on reasoning about actions and change (RAC), which is crucial in planning. This program of research was further advanced by Raymond Reiter and colleagues at the University of Toronto [39], the Texas Action Group [40], Erik Sandewall and colleagues [41], and by Bob Kowalski and researchers studying the Event Calculus [42]. Following Moore's formalization of sensing actions [43], Scherl and Levesque [44] gave a foundational characterization of sensing actions in the situation calculus. A modal reconstruction of that characterization was considered in [45], which has dynamic logic-like modalities in addition to operators for knowledge. This has since been extended for verification and planning [46]. A closely related formalism is the fluent calculus [47]. The Scherl-Levesque model was given a transition function-based formulation by Son and Baral [48]. These and other works form the foundation for epistemic planning with a single agent. Recently Baral and colleagues have done initial groundwork on combining reasoning about actions and change with dynamic epistemic logic to characterize actions and change in multi-agent domains [8]. Liu and Levesque have likewise studied the incorporation of action models from dynamic epistemic logic into the situation calculus [49]. The study of multi-agent reasoning and programming has been studied in the situation calculus in earlier works, too [50, 51, 52].

## 3. Themes within epistemic planning

Below we list some of the main current themes with epistemic planning and how they relate to the papers of this special issue. A more in-depth description of some of these themes as well as their state of the art and open problems can be found in the report from the most recent Dagstuhl workshop on epistemic planning [53].

### *3.1. Formal representation of knowledge and belief*

An epistemic planning framework should provide a way of representing the agents' knowledge and distinguishing it from the true state of the world. Classical propositional planning does not require such a distinction: knowledge is represented either as propositional formulas (conjunctions of atoms/literals) or as propositional valuations (mappings of atoms into truth values). The former approach we call the *syntactic* or *sentential-based* approach and the latter we call the *semantic* or *model-theoretic* approach. In propositional planning, there is most often no difference between the two approaches, since even in the sentential-based approach states are most often simply represented as a conjunction of literals (as in STRIPS and PDDL). Since there is a trivial isomorphism between (consistent) conjunction of propositional literals and propositional valuations, whether we represent states by conjunctions of literals or valuations doesn't really matter. However, for epistemic planning this is different, since we need richer formulas and richer semantic structures. In the sentential-based approach, we need formulas of some suitable epistemic logic with operators for knowledge and/or belief. In the model-theoretic approach, we need Kripke models or other semantic objects that can model uncertainty concerning the current state. We cannot trivially translate back and forth between these. Actually, the representations are somewhat dual: An epistemic state represented as a formula is a representation of *knowledge* (it lists what is known), whereas a corresponding (Kripke) model is a representation of *uncertainty* (it represents what can't be distinguished). This has the consequence that states represented by formulas grow in size when the knowledge increases, whereas Kripke models reduce in size when the knowledge increases. Which representation is most compact therefore depends significantly on the level of knowledge and uncertainty of the planning agents in the domain at hand. This special issue contains both papers following the sentential-based approach (for instance [54, 55]) and the model-theoretic approach (for instance [56, 57]).

While most epistemic planning frameworks take knowledge and belief to be purely binary concepts, the special issue also contains two papers about probabilistic knowledge [58, 59]. Furthermore, most existing frameworks for epistemic planning are based on a propositional epistemic logic, that is, a logic without variables and quantifiers. This potentially reduces the expressivity and ease of defining actions in epistemic planning, since there is then no easy way to define an action schema like $move(X, Y)$, where $X$ and $Y$ are variables, for moving an arbitrary object $X$ to an arbitrary location $Y$. One of the papers of this special issue proposes to generalise DEL-based epistemic planning to a setting of first-order DEL [60]. Along these lines, in [59], first-order actions over continuous probabilistic spaces are considered. Such languages can be seen as the first-order situation calculus analogue to epistemic probabilistic logic [61, 62]. The article [58] also investigates the issue of probabilistic actions but in the context of epistemic narratives. A further paper in the special issue that goes beyond binary knowledge is [63] where the agent's knowledge can have various degrees of precision.

### *3.2. Formal representation of actions*

Beyond representing knowledge about the initial state and the goal, epistemic planning also requires representing the agents' knowledge about actions: both together make up domain descriptions. It is therefore a relevant objective of epistemic planning to find suitable action description languages that make it as easy as possible to specify epistemic actions. There is currently no language for describing epistemic actions that everybody in the community agrees is practically suitable. This contrasts with classical planning where there are domain description languages like STRIPS, ADL, $SAS^+$ and PDDL [64], with the language family PDDL being the "industry standard". There is no similar standard for domain descriptions in epistemic planning. Agreeing on a single such language or family of languages, like PDDL in classical planning, can be expected to make implemented systems more widely usable and mutually comparable.

A related issue is to identify and broaden the list of action types relevant to epistemic planning. In terms of communicative actions we can for instance at least distinguish between announcements, questions, requests and instructions. There is however a trade-off between the expressivity of a language and how neatly and compactly actions within it can be described.

Two of the papers of the special issue consider domain description languages based on game description languages (GDL) [65, 66]. GDLs have been developed independently of the development of epistemic planning, but with the recent interest in generalising GDLs to also cover epistemic games, the two areas of research have become very close. One of the papers of this special issue [66] specifically compares epistemic planning based on DEL with the epistemic game description language GDL-III. Game description languages offer an alternative way of describing epistemic planning domains with certain advantages as discussed by Engesser *et al.* [66].

Another paper of this special issue [56] talks about the general problem of designing good domain description languages, and proposes a concrete language that allows us to represent a class of event models in a compact and intuitive way.

### *3.3. Solution concepts*

Once a language for the description of domains has been settled on, one may define planning tasks and their solutions. Just as in classical planning, all existing approaches to epistemic planning consider planning tasks that are made up of three ingredients: the description of a domain, of the initial situation, and of the goal. There is more diversity when it comes to solutions. In classical planning, there is only a single agent, and this agent plans and acts in a static environment (an environment that only changes as an effect of the actions of the agent). In that setting there are basically two natural solution concepts [67]: *sequential plans* are appropriate when the agent cannot gain additional knowledge from executing actions (e.g. if the environment is deterministic and the agent has full knowledge about it, or if the agent has no sensors to learn more about the environment); otherwise *conditional plans* are appropriate. In epistemic settings, it is not sufficient to have a plan that achieves a goal: the agent also needs to *know how* to achieve the goal, in terms of having sufficient information to execute the plan and know that the goal is true. For example, suppose there are two doors, such that there is treasure behind the left one, and there is nothing behind the right one, and the agent know that there is a treasure but does not know behind which door it is. A sequential plan to achieve the goal is to simply open the left door and pick up the treasure; a conditional plan that does not depend on the fact that the treasure is behind the left door is: if the treasure is behind the left door then open the left door, otherwise open the right door. But for both plans the agent fails to know that they achieve the goal. In order to allow the agent to conclude that the goal will be reached, the conditions of 'if-then-else' alternatives should not be facts but knowledge. The branching conditions of knowledge-based programs as studied in [68] explicitly appeal to what the planning agent knows. There, it is shown that knowledge-based programs are more succinct than conditional plans that simply branch and loop on observations. In the presence of nondeterminism, there might be a range of different correctness criteria for plans with loops, which is explored in [69] of this special issue.

The setting where multiple agents act comes with more solution concepts, depending on whether agents compete or collaborate. In the latter case they may collaborate in different ways: this depends on their communication means and may range from a centralised scheduler telling each agent what to do (as e.g. in [57]) to fully decentralised planning where each agent has to come up with her own plan based on the knowledge available to her (as e.g. in [70, 16]). In the case of centralized planning some authors have proposed to reduce epistemic planning tasks to classical planning tasks, as also considered in this special issue [71, 57]. The case of competition relates to game-theoretic settings where the agents' plans should achieve their goals whatever other agents do. It also relates to epistemic extensions of the game description language GDL as studied in [65, 66].

Instead of finding solutions to planning tasks one may as well be interested in deciding the existence of a solution. This motivates the study of the *knowing-how* modality, either in isolation or in combination with the standard 'knowing-that' modality, which is done in two articles in this special issue [72, 63].

### *3.4. Implemented systems and benchmark problems*

Several of the papers of this special issue report on implemented systems for epistemic planning [54, 55, 57]. In order to have some common ground to compare different approaches and systems, we also need to have good benchmark problems. In areas such as automated theorem proving, SAT, machine learning, and automated planning, such benchmarks already play an important role in driving the research. In the case of epistemic planning, benchmarks should be truly epistemic, meaning problems in which the epistemic dimension—knowledge and ignorance—cannot easily be disregarded. Works such as [1] and several papers of this special issue [54, 55, 57] have attempted to introduce classical planning-style benchmarks to the area of epistemic planning. However, in the current situation, coming up with a set of commonly agreed benchmarks seems to be quite demanding. One of the issues is that to form a common set of benchmark problems, we first need a common domain description language for epistemic planning, and that we don't yet have, cf. the discussion above.

It should be noted that since epistemic logic and its extensions make use of complex semantic structures, and given that the area is in its early years, there is still considerable research on the logical foundations. Therefore, there are many rigorous articles, including in this special issue, that study theoretical issues: such as syntactic and semantic variants for epistemic planning, complexity and decidability, modelling languages, and so on. These papers, more often than not, do not yet investigate an implementation, and that makes the benchmarking issue very pertinent but also deeply challenging.

### *3.5. Computational Complexity and Fragments*

Unrestricted epistemic planning based on DEL is undecidable, meaning that its plan existence problem is undecidable [35]. Several papers of this special issue propose more well-behaved fragments of epistemic planning that are decidable [54, 55, 57]. Of these, the first two use the sentential-based approach, whereas the last uses the model theoretic approach. However, in all three cases, a fundamental part of the solution is to syntactically restrict the set of allowable formulas. And in all three cases, the authors argue that despite the restrictions, many interesting scenarios of epistemic planning can still be represented. Another paper of this special issue [73] seeks out to address the borderline between decidable and undecidable fragments of epistemic planning in more general terms, looking at how the syntactic complexity of actions impact the computational complexity of the resulting plan existence problem. This is done in a setting of DEL-based planning, so action complexity is measured in terms of modal depth of pre- and post-conditions.

## 4. Description of the Papers of This Special Issue

This section briefly summarises the papers contained in the special issue. We start by single-agent planning approaches and then turn to multi-agent approaches. For the latter we first present papers focussing on representation languages and then those addressing reasoning aspects.

### *4.1. Single-Agent Approaches*

In this subsection, we focus on the papers of this special issue covering the single-agent approaches.

*Vaishak Belle: "Analyzing generalized planning under nondeterminism" [69].* This paper analyzes solution concepts for generalized plans when non-deterministic and probabilistic actions with effects in a continuous space are possible. It generalizes the notion of termination and goal satisfaction for these cases and relates the different possible solution concepts to each other, providing a much more granular view on solution concepts than the ones discussed in the literature so far. Although the analysis starts by extending the epistemic situation calculus, the solution concepts are developed and discussed in a general framework of generalized plans, so that the results are broadly applicable.

*Vaishak Belle and Hector J. Levesque: "Regression and progression in stochastic domains" [59].* This paper is about projection, which is the problem of deciding whether some successor state can result from the execution of an action in the preceding state. It can be solved either by progressing the preceding state or by regressing the successor state; both progression and regression are suitable building blocks for planners. The paper starts from an extension of the Situation Calculus by degrees of belief, noisy actions, and noisy sensing that is due to Bacchus et al. [74]. In this framework the authors generalise the standard Situation Calculus definitions of progression and regression from the non-probabilistic to the probabilistic case.

*Fabio Aurelio D'Asaro, Antonis Bikakis, Luke Dickens and Rob Miller: "Probabilistic reasoning about epistemic action narratives" [58].* This paper studies reasoning about actions in the presence of probabilistic knowledge and noisy effectors and sensors. Classically, most works in reasoning about actions assume that knowledge and actions are deterministic. Driven by problems in robotics among other domains, there is a need for logical languages with an explicit account of quantifying uncertainty with quantitative models of fallible actions. In this work, they introduce the epistemic probabilistic event calculus, and study its properties. They also establish its relation to other popular formalisms for degrees of belief and noisy actions, such as the situation calculus extension by Bacchus et al. [74]. Such languages permit epistemic planning in a rich and complex language where goals can be probabilistic belief and plans need to account for noise and failure.

*Jorge A. Baier and Sheila A. McIlraith: "Knowledge-based programs as building blocks for planning" [71].* This is one of two contributions to the special issue about knowledge-based programs (KBPs) as first introduced by Fagin et al. [75]. The paper by Baier and McIlraith is about the problem of single-agent planning with (KBPs) and sensing. It investigates under which conditions such programs can be mapped into Reiter's basic action theories and then fed into standard contingent planners. This is part of a line of research whose aim is to use Golog programs as building blocks for planning [76, 77]. The Golog programs under concern are composed from primitive actions using sequence, test, if-then-else, and bounded while-loops, and their execution depends on the agent's knowledge. For these programs the authors propose an offline semantics which appeals to knowledge rather than truth to decide how a program is executed. They restrict their attention to self-sufficient, deterministic and loop-free programs. Self-sufficiency means that the agent knows how to execute the program: when executing an if-then-else statement, the agent knows whether the condition holds so that she knows whether to execute the 'then' branch or the 'else' branch; technically, the hypothesis makes that knowledge coincides with truth. Determinism makes that programs effects can be represented with effect axioms and is required because situation calculus effect axioms can only describe actions with deterministic effects. Loop-freeness makes it possible to generalise the regression of a formula w.r.t. an action to regression w.r.t. a program. Together, the three restrictions allow them to compute preconditions, effects, and sensed conditions of programs via regression w.r.t. programs. The paper reports on preliminary experimental results about a simple example with several rooms and objects that are spread over these rooms and whose location is unknown; the goal is to bring all objects to a given room.

*Bruno Zanuttini, Jérôme Lang, Abdallah Saffidine and François Schwarzentruber: "Knowledge-based programs as succinct policies for partially observable domains" [68].* This is the second contribution about KBPs to this special issue. It analyzes KBPs in partially observable domains and studies their representational power as compact policies. KBPs have been used widely in the reasoning about actions and planning literature. They are essentially protocols conditioned on what the agent knows at the time of execution, and can involve branches and loops. Intuitively, they are very related to so-called finite state reactive automatons used in contingent planning, where based on the current observation, the agent may branch or loop on actions. Although they have the same level of expressivity, there is a tradeoff: the paper shows that KBPs are much more succinct, but they require more effort to execute because they refer to the state of the current knowledge. This paper is indicative of the close links between epistemic planning, iterative and conditional planning and knowledge-based programs.

*Yanjun Li and Yanjing Wang: "Planning-based knowing how: A unified approach" [72].* This is one of two contributions to the special issue studying the modality of "knowing how to achieve a goal". It examines several semantics of a single-agent knowing-how operator that is added to the knowing-that operator of standard epistemic logic. In this approach, epistemic planning is viewed as model-checking whether a particular knowing-how formula is true. It is based on the idea that an agent knows how to achieve a goal if there is a plan of which the agent knows it achieves the goal. Ten different definitions of knowing-how are obtained by varying the basic constructs with which plans are built, such as if-then-else conditionals and while loops. The authors give an axiomatization and prove that it is complete for all ten semantics, thereby establishing a robust characterisation of the properties of the knowing-how concept.

*4.2. Multi-Agent Approaches: Representation Aspects*

We now turn to approaches taking multiple agents into account. We first group the papers focusing on the representation aspect and then, in the next subsection, turn to those focusing on reasoning.

*Pavel Naumov and Jia Tao: "Knowing-how under uncertainty" [63].* This is the second paper about the knowing-how modality. It studies a logic having multiple modal operators of knowing-that and knowing-how, where the latter is viewed as uniform strategic ability. It extends the authors' previous work by adding degrees. Semantically, the indistinguishability relation of standard epistemic logic is replaced by epistemic distance measures that are associated to each agent and that may be interpreted as a margin of error. Then a formula of the form $K_a^c\varphi$, for $a$ an agent and $c$ a real number ($a$'s epistemic distance metric), is true if $\varphi$ is true in all states at distance at most $c$; a formula of the form $H_a^c\varphi$ ('$a$ has ability to enforce $\varphi$ given epistemic distance $c$') is true if $a$ has an action that results in $\varphi$ if executed in any state at distance $c$, regardless of what other agents do simultaneously. In other words: $K_a^c\varphi$ says that agent $a$, with precision $c$, knows $\varphi$; and $H_a^c\varphi$ says that agent $a$, with precision $c$, knows how to ensure $\varphi$. The main contribution of the paper is an axiomatisation of the validities of the logic.

*Thorsten Engesser, Robert Mattmüller, Bernhard Nebel and Michael Thielscher: "Game description language and dynamic epistemic logic compared" [66].* A recent game description language language, GDL-III, is in this paper compared to DEL. The comparison is both made informally in terms of ease of representation in the two formalisms, and formally in terms of relative expressive strength. It is shown that a rich fragment of GDL-III can be translated into DEL, and the translation is exemplified on a simplified version of the collaborative epistemic game Hanabi. It is symmetrically shown that DEL can be translated into GDL-III. One of the added values of providing these translations is to see how the observation tokens of GDL-III can be represented by edge-conditions in DEL. Observation tokens help to specify epistemic actions very succinctly in GLD-III, and similar succinctness can then be achieved in DEL using edge-conditions. Preserving the best of GLD-III and DEL might lead to a future epistemic domain description language that is relatively expressive, concise and easy to use, as the authors note. Another potential impact of the paper is to help in reducing the gap between people working in DEL and people working on (epistemic) game description languages and (epistemic) general game playing.

*Chitta Baral, Gregory Gelfond, Enrico Pontelli, and Tran Cao Son: "An action language for multi-agent domains" [56].* This paper addresses the issue of designing a domain description language that allows the compact and intuitive specification of multi-agent planning domains. The language that is introduced, called $m\mathcal{A}^*$, builds heavily on action languages such as $\mathcal{A}, \mathcal{B}$, and $C$ [78] that have been developed in the area of reasoning about actions for single-agent domains. The semantics is heavily influenced by DEL. States are pointed S5 Kripke models and the action semantics is given using so-called update models, which are very similar to the event models of DEL. The main difference is that the update models are generated from the specifications of the awareness of agents about facts or action occurrences. This arguably allows for a more compact and more intuitive representation of actions than is possible with event models. As stated by the authors, one important line of future research is the development of efficient automated reasoning and planning methods. Another is the extension of the language in different directions.

*Andrés Occhipinti Liberman, Andreas Achen and Rasmus Kræmmer Rendsvig: "Dynamic term-modal logics for first-order epistemic planning" [60].* This paper studies a first-order extension of dynamic epistemic logic (DEL). DEL has become one of the most popular logical languages for propositional epistemic planning, especially in analyzing the decidability and undecidability divide. But most planning languages use first-order representations, involving free variables, including actions such as $move(X,Y)$ to mean move object $X$ to location $Y$, and goals such as $\exists x.\ Knows\ [On(x, Table)]$ to mean there is an object that the robot knows to be on the table. The paper studies how such a first-order language with countably infinite sets of objects could be integrated with DEL and considers questions about axiomatization and decidability. In particular, to define the semantics of actions, they consider product update over first-order structures. A compact characterisation of action schemas is also provided, inspired by PDDL. On the logical front, the semantics is defined using term-modal logics. By relating their work to PDDL and first-order knowledge representation languages, this proposal provides a bridge between planning formalisms and DEL in embracing lifted representations for actions and domains.

### *4.3. Multi-Agent Approaches: Reasoning Aspects*

We now turn to the reasoning aspect, starting with solution concepts.

*Hans van Ditmarsch, Wiebe van der Hoek, and Louwe B. Kuijer: "The Logic of Gossiping" [70].* This paper provides a logical analysis of gossip protocols. This is a form of peer-to-peer communication for the spreading of information that is much used and studied in distributed computing and that was recently investigated in the area of dynamic epistemic logics [79, 80]. In the basic version of the problem there are $n$ agents each of which is the only one to know some piece of information. They can communicate via phone calls and their (joint) goal is that all agents become experts, i.e., that they know all secrets. When there is a centralised scheduler then the goal can be achieved with $2n-4$ calls, and it is known that one cannot do better. That version is used as an illustrating example by Cooper et al. in this issue. But in less controlled settings, for example, when lacking a central authority, or when the calls are made at random, the study of the gossip problem becomes much more involved. The present paper is about that decentralised case. It then becomes useful to establish "epistemic protocols", which are instructions of the form "if condition $X$ is true, then agent $Y$ should call agent $Z$." Thus, there is a close connection between gossip protocols and epistemic planning. The authors define 18 variants of the gossip problem depending on 3 parameters: privacy of the calls (public, semi-public, private), direction of the call (the sender sends their secrets to the caller, the caller sends their secrets to the caller, or both) and observability of the call (the information is gained before collecting or after collecting secrets). Semantically, the authors start from the notion of an initial model where each agent at least knows her own secret; a gossip model is then generated from an initial model and a finite sequence of calls. They then completely characterize the valid formulas of each call type by providing 18 axiomatisations. They also prove decidability of the model checking problems.

*Hai Wan, Biqing Fang and Yongmei Liu: "A general multi-agent epistemic planner based on higher-order belief change" [55].* This paper describes a logical formalisation of multi-agent epistemic planning, and a piece of planning software (the MEPK planner) based on that formalisation. The paper follows the sentential approach to epistemic planning, using KD45 as the underlying logic. States are described by syntactically restricted formulas, so-called alternating cover disjunctive formulas (ACDFs). Disjunctive representations make epistemic planning closer to planning based on belief states (sets of propositional states), which is classically solved using AND-OR tree search. The planning algorithm presented in this paper, and implemented in the MEPK planner, is also an AND-OR tree search algorithm. ACDFs have the full expressive power of epistemic logic in the sense that for any formula there exists an equivalent ACDF formula (that might however be exponentially longer). The resulting plan existence problem is however still decidable, since the set of actions that their framework allows is limited. The framework allows two types of actions, deterministic actions with conditional effects and sensing actions. Crucially, none of these can increase the uncertainty of the involved agents, which is what saves decidability. More formally, if we modelled these actions semantically as action models, no update with these actions could increase the model size, and hence decidability is immediately guaranteed. Still, a lot of interesting and relevant planning tasks are solvable under these constraints, as the paper shows. The paper considers a number of interesting planning domains, and provides experimental results on how well their implemented system behaves on these domains. At the time of writing, the only existing epistemic planning systems that produce conditional plans (policies) seem to be the one introduced here and the one by Bolander *et al.* [23].

*Guifei Jiang, Dongmo Zhang, Laurent Perrussel, and Heng Zhang: "Epistemic GDL: A logic for representing and reasoning about imperfect information game" [65].* This paper aims at developing a logical system that can be used in the context of game description languages in order to deal with partial information. The main intention is to provide a reasoning tool that permits one to empower an agent to reason about the state of a game, possible actions etc., where one has only partial observability. Although one can achieve such a goal by embedding game description logics such as GDL-II or GDL-III into existing logical systems such as ATEL or DEL, the main drawback is that these logics usually incur high computational costs, i.e., model-checking is, e.g., 2EXPTIME-hard in case of a GDL-II embedding into ATEL. The proposed extension of GDL by the authors on the other hand have a model-checking problem that is located at the second level of the polynomial hierarchy, i.e., much more efficient. One of the reasons is apparently that the players are assumed to have imperfect recall. In summary, EGDL presents an interesting point in the expressiveness/efficiency tradeoff dimension for systems that support epistemic reasoning in a dynamic multi-agent setting.

In the rest of the section we overview papers focussing on the complexity of reasoning and its taming by moving to appropriate fragments of the language.

*Thomas Bolander, Tristan Charrier, Sophie Pinchinat, and François Schwarzentruber: "DEL-based epistemic planning: Decidability and complexity" [73].* This paper provides a comprehensive survey on known undecidability and complexity results about epistemic plan existence for DEL, it provides new proofs, and it generalizes them in order to provide a complete classification along the dimension of the expressive power of pre- and post-conditions of epistemic actions. In particular, one unsettled case is identified, which is the case when the preconditions can have modal depth one and no postconditions are permitted. Decidability is only achieved when no modal operators are permitted in pre- and postconditions. By further restricting the logic to disallowing postconditions or having only public actions, one can achieve even PSPACE-completeness, which means that the problem is not harder than classical planning. All in all, the paper provides a perfect starting point into the adventure of identifying other fragments of DEL that can be of use by admitting a decidable plan existence problem.

*Christian Muise, Vaishak Belle, Paolo Felli, Sheila McIlraith, Tim Miller, Adrian R. Pearce, and Liz Sonenberg: "Efficient multi-agent epistemic planning: Teaching planners about nested belief" [54].* This paper investigates restrictions of the full language of epistemic logic in order to obtain better computational properties of multi-agent planning with higher-order beliefs. The logic of belief can be either KD or KD45. In order to overcome the general undecidability of epistemic planning, the authors follow a proposal of Lakemeyer and Lespérance [81] and do not use the full language but restrict epistemic formulas to boolean combinations of what they call restricted modal literals: propositional variables preceded by sequences of epistemic operators and negations. Moreover, action effects can only add or delete such epistemic literals. It is shown that such planning problems can be compiled into classical planning problems, thus enabling the use of classical planners for epistemic planning. The paper reports on some experiments based on this encoding.

*Martin C. Cooper, Andreas Herzig, Faustine Maffre, Frédéric Maris, Elise Perrotin and Pierre Régnier: "A lightweight epistemic logic and its application to planning" [57].* This paper also studies restrictions of the full language of (dynamic) epistemic logic to achieve more well-behaved frameworks for epistemic planning. The paper studies epistemic planning based on so-called observability atoms. An observability atom is a particular kind of epistemic formula, a sequence of 'knowing whether' operators followed by a propositional atom. Hence, observability atoms can describe things like "I know whether you know whether $p$". The language proposed in the paper uses propositional logic over these observability atoms. We therefore cannot describe arbitrary epistemic formulas in the language, but the authors argue that it is still sufficiently expressive to formalise a wide range of epistemic situations and planning tasks. The attraction of this restricted language is its simplicity as well as its computational complexity. Satisfiability is NP-complete and the plan existence problem is PSPACE-complete. The complexity of the plan existence problem comes from translating planning tasks into classical planning. The allowed actions are deterministic actions with conditional effects, where preconditions and effects are described in the propositional language over observability atoms.

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