

Verification of Multi-agent Systems with Imperfect Information and Public Actions

Francesco Belardinelli
Laboratoire IBISC,
Université d'Evry,
Evry, France
belardinelly@ibisc.fr

Alessio Lomuscio
Department of Computing
Imperial College
London, UK
a.lomuscio@imperial.ac.uk

Aniello Murano
Univ. Federico II,
Naples, Italy
murano@na.infn.it

Sasha Rubin
Univ. Federico II,
Naples, Italy
sasha.rubin@unina.it

ABSTRACT

We analyse the verification problem for synchronous, perfect recall multi-agent systems with imperfect information against a specification language that includes strategic as well as epistemic operators. While the general problem is known to be undecidable we show that if the agents' actions are public then verification is decidable, and we establish that the computational complexity is 2EXPTIME -complete. To illustrate the formal framework we consider two well-known epistemic and strategic puzzles with imperfect information and public actions: the muddy children puzzle and the classic game of battleships.

1. INTRODUCTION

Autonomous agents and multi-agent systems (MAS) appear in diverse scenarios, including communication and security protocols [2, 17], planning [4], etc. As these applications grow larger, validation and verification techniques are required. Model checking is a logic-based technique for the verification of complex and distributed systems. The idea is to model the system S as a structure M_S (typically a labeled graph), model the specification P as a formula φ_P in some sufficiently expressive logic, and decide whether the formula φ_P is true in the structure M_S , written $M_S \models \varphi_P$ [7, 3].

The logics for MAS specification are typically modal logics with modal operators to reason about temporal, epistemic, strategic, doxastic, and other properties of agents. In particular, there is an extensive literature on logics with epistemic and strategic operators. The reason for such combinations is that both modalities are key to reason about interacting agents: knowledge is a prerequisite for rational action, while actions change the epistemic state of agents. In this paper we consider the logic $\text{ATL}_{\mathbb{K},\mathbb{C},\mathbb{D}}^*$, i.e., the extension of ATL^* by epistemic operators. This is a powerful logic which can express, for instance, the realisability problem (sometimes called synthesis).

A central property of realistic MAS is that agents have imperfect information, i.e., they only have a local view of the system. This feature is key to model relevant scenarios such as partial observability games [36]. Further, one important class of agents are those with perfect recall, i.e., they base

their actions on everything that they have observed. Perfect-recall is important in computer science and well-studied in the field of epistemic logics [11]: it is not only a convenient idealisation of memory-bounded agents, but also especially suited for modeling worst-case adversaries, e.g., intruders in cryptographic protocols.

Unfortunately, even simple specification logics, such as ATL with imperfect information and perfect recall, have undecidable model-checking problem [1, 9]. Naturally, it is of interest to find restricted cases in which model-checking is decidable. Such restrictions typically take three forms: restricting the syntax of the logic (e.g., by removing strategic abilities and considering $\text{LTL}_{\mathbb{K}}$, the extension of LTL with individual-knowledge operators [37]), restricting the semantics (e.g., by requiring strategy quantifiers vary over memoryless-strategies [35]), or by restricting the class of structures under consideration. In this paper we examine the third option.

Contribution. We identify a large and interesting class of iCGS (imperfect-information concurrent game structures) that we call public-action iCGS (PA-iCGS). In contrast to general iCGS [9], we prove that model-checking the full logic $\text{ATL}_{\mathbb{K},\mathbb{C},\mathbb{D}}^*$ on PA-iCGS is decidable, specifically 2EXPTIME -complete. Thus, the (joint) complexity of model-checking is the same as that of ATL^* with perfect information [1]. Moreover, we show that this class is not merely a mathematical nicety, but it corresponds to an important class of MAS, namely the class in which agents have imperfect information, synchronous perfect recall, and whose actions are immediately made public, i.e., all actions are visible to all agents. The class PA-iCGS captures games of imperfect information in which the initial deal is hidden but all bids, bets and moves are observable to all players (e.g., Bridge, Poker, Battleships, etc.), fair division protocols in which all actions are public (e.g., classic cake cutting algorithms), selected broadcast protocols [38], blackboard systems in which a public database is read and written by agents [30], auctions and auction-based mechanisms [10].

To prove decidability we use an automata-theoretic approach. We encode strategies by trees in such a way that, assuming that all actions are public, tree-automata can be used to process them. We remark that without this assumption (that all actions are public) no encoding of strategies by trees would work (since the model checking problem in this case is undecidable [1, 9]).

Related Work. In order to reason formally about multi-agent systems, temporal logics such as LTL, CTL, CTL^* , which are useful for reasoning about monolithic systems,

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have been extended with strategy quantifiers [1] and epistemic modalities [18]. The resulting languages allow for a number of modelling choices on the underlying semantics: perfect vs. imperfect information, perfect vs. imperfect recall, state-based vs. history-based semantics [1, 18, 13, 35, 19, 8, 14, 29].

Assuming imperfect information and perfect recall, as we do in this paper, often results in intractable model-checking. For instance, the model-checking problem for ATL in this setting is undecidable [9], as is the realisability problem for the extension $LTL_{\mathbb{K},\mathbb{C}}$ of LTL with epistemic operators, including common knowledge [37]. It is such undecidability results that have spurred the search for restricted settings in which model checking is decidable and possibly tractable.

As expected, restricting the logic lowers the complexity. We list some notable examples: the realisability problem for $LTL_{\mathbb{K}}$ with only individual knowledge is non-elementary complete [37], model-checking ATL with only “communicating coalitions” (i.e., coalitions use their distributed knowledge instead of their individual knowledge) is decidable and non-elementary [8, 14]; and, model-checking ATL in which all coalitions operate with a single indistinguishability relation reduces ATL to its singleton-coalition fragment [21].

Also, restricting the class of structures (iCGS) over which these languages are interpreted lowers the complexity. Such restrictions typically take one of two forms: i) on the information sets of the agents; ii) on the the architectures that govern communication. Notable examples of i) may require that: all agents have the same information sets [25]; that the information sets form a hierarchy [31], or that, over time, they infinitely often form a hierarchy [5]. A notable example of ii) are characterisations of the architectures for which distributed synthesis is decidable [12, 34], thus generalising earlier results on linear architectures [31, 22].

More closely related to the present contribution are broadcast environments (which restrict the underlying iCGS) and that can capture epistemic puzzles and games of imperfect information such as Bridge [38]. The most relevant result for broadcast environments is that synthesis of linear-temporal logic with individual-knowledge operators is decidable [38]. Not only can we express this synthesis problem, but it is strictly more expressive, as it can alternate strategic quantifiers mentioning overlapping coalitions. A detailed discussion of the significance of [38] is given in Section 4.

We also mention that the power of actions that are public announcements has been studied in depth (Dynamic Epistemic Logic, Public Announcement Logic, epistemic protocols [39]). However, this line of research differs semantically and syntactically from our work. In particular, in these works modal operators are model transformers, and coalitions are not explicitly named in the language.

Finally, we stress that unlike all of the restrictions mentioned above our decidability result holds for an expressive logic of strategy, knowledge and time, that allows for arbitrary indistinguishability relations. We restrict iCGS so that every action is visible to every agent. This restriction covers a wealth of interesting applications [38, 30, 10].

2. GAMES WITH PUBLIC ACTIONS AND STRATEGIC-EPISTEMIC LOGIC

In this section we define the game model and the logic. The model is the subclass of imperfect information concurrent

game structures (iCGS) that only have public actions (PA-iCGS). The logic is $ATL_{\mathbb{K},\mathbb{C},\mathbb{D}}^*$, an extension of Alternating Time Temporal Logic (ATL^*) which includes strategic operators ($\langle\langle A \rangle\rangle$ for $A \subseteq Ag$) as well as epistemic operators for individual-knowledge (\mathbb{K}_a for $a \in Ag$), common-knowledge (\mathbb{C}_A for $A \subseteq Ag$), and distributed-knowledge (\mathbb{D}_A for $A \subseteq Ag$).

Notation. For an infinite or non-empty finite sequence $u \in X^\omega \cup X^+$ write u_i for the i th element of u , i.e., $u = u_0u_1 \dots$. The empty sequence is denoted ϵ . The length of a finite sequence $u \in X^*$ is denoted $|u|$, its last (resp. first) element is denoted $last(u)$ (resp. $first(u)$). Note that $last(\epsilon) = first(\epsilon) = \epsilon$. For $i < |u|$ write $u_{\leq i}$ for the prefix $u_0 \dots u_i$. For a vector $v \in \prod_i X_i$ we denote the i -th co-ordinate of v by $v(i)$. In particular, for $F \in \prod_i (X_i)^Y$ we may write $F(i) \in X^Y$ and $F(i)(y) \in X_i$.

2.1 iCGS with only Public Actions

We begin with the standard definition of imperfect information concurrent game structures [6, 9].

DEFINITION 1 (iCGS). An imperfect information concurrent game structure (iCGS) is a tuple

$$S = \langle Ag, AP, \{Act_a\}_{a \in Ag}, S, S_0, \delta, \{\sim_a\}_{a \in Ag}, \lambda \rangle$$

where:

- Ag is the finite non-empty set of agent names;
- AP is the finite non-empty set of atomic propositions;
- Act_a is the finite non-empty set of actions for $a \in Ag$;
- S is the finite non-empty set of states;
- $S_0 \subseteq S$ is the non-empty set of initial states;
- $\delta : S \times \text{ACT} \rightarrow S$ is the transition function, where the set ACT of joint-actions is the set of all functions $J : Ag \rightarrow \bigcup_a Act_a$ such that $J(a) \in Act_a$. The transition function assigns to every state s and joint-action J , a successor state $\delta(s, J)$;
- $\sim_a \subseteq S^2$ is the indistinguishability relation for agent a , which is an equivalence relation; the equivalence class $[s]_a$ of $s \in S$ under \sim_a is called the observation set of agent a ;
- $\lambda : AP \rightarrow 2^S$ is the labeling function that assigns to each atom p the set of states $\lambda(p)$ in which p holds.

Perfect-information is treated as a special case:

DEFINITION 2 (PERFECT-INFORMATION). A concurrent game structure (CGS) is an iCGS for which $\sim_a = \{(s, s) : s \in S\}$ for all $a \in Ag$.

We now give a brief and to-the-point definition of what it means for an iCGS to only have public actions, i.e., all actions are visible to all agents. This determines a subclass of iCGS that we call PA-iCGS.

DEFINITION 3 (PA-iCGS). An iCGS only has public actions if for every agent $a \in Ag$, states $s, s' \in S$, and joint actions $J, J' \in \text{ACT}$, if $J \neq J'$ and $s \sim_a s'$ then $\delta(s, J) \not\sim_a \delta(s', J')$. We write PA-iCGS for the class of iCGS that only have public actions.

This definition says that if an agent a cannot distinguish between two states, but different joint actions are performed in each of these states (because, for instance, some other agent can distinguish them), then the agent can distinguish between the resulting successor states.

One way to generate an iCGS only having public actions is to ensure that i) the state records the last joint-action played, thus S is of the form $T \times (\text{ACT} \cup \{\epsilon\})$, where ϵ refers to the situation that no actions have yet been played, and ii) the indistinguishability relations \sim_a satisfy that if $(t, J) \sim_a (t', J')$ then $J = J'$. Similar conditions have been considered in the literature, e.g., *recording contexts* in [11].

In the remainder of this section we define what it means for an agent to have *synchronous perfect-recall* [11].

Synchronous perfect-recall under imperfect information. A *path* in S is a non-empty infinite or finite sequence $\pi_0\pi_1 \dots \in S^\omega \cup S^+$ such that for all i there exists a joint-action $J(i) \in \text{ACT}$ such that $\pi_{i+1} \in \delta(\pi_i, J(i))$. Paths that start with initial states are called *histories* if they are finite and *computations* if they are infinite. The set of computations in S is written $\text{comp}(S)$, and the set of computations in S that start with history h is written $\text{comp}(S, h)$. We define $\text{hist}(S)$ and $\text{hist}(S, h)$ similarly.

We use the following notation: if \sim is a binary relation on S we define the extension of \sim to histories as the binary relation \equiv on $\text{hist}(S)$ define by $h \equiv h'$ iff $|h| = |h'|$ (i.e., synchronicity) and $h_j \sim h'_j$ for all $j \leq |h|$ (i.e., perfect recall). We give three particular instantiations. If \sim_a is the indistinguishability relation for agent a , then we say that two histories h, h' are *indistinguishable to agent a* , if $h \equiv_a h'$. For $A \subseteq \text{Ag}$, let $\sim_A^C = (\cup_{a \in A} \sim_a)^*$, where $*$ denotes the reflexive transitive closure (wrt. composition of relations), and its extension to histories is denoted \equiv_A^C . For $A \subseteq \text{Ag}$, let $\sim_A^D = \cap_{a \in A} \sim_a$, and its extension to histories is denoted \equiv_A^D . **Strategies.** A *deterministic memoryfull strategy*, or simply a *strategy*, for agent a is a function $\sigma_a : \text{hist}(S) \rightarrow \text{Act}_a$. A strategy σ_a is *uniform* if for all $h \equiv_a h'$, we have $\sigma(h) = \sigma(h')$. The set of uniform strategies is denoted $\Sigma(S)$. All strategies in the rest of the paper are uniform (although sometimes we will stress this fact and write “uniform strategy”).

For $A \subseteq \text{Ag}$, let $\sigma_A : A \rightarrow \Sigma(S)$ denote a function that associates a uniform strategy σ_a with each agent $a \in A$. We write $\sigma_A(a) = \sigma_a$, and call σ_A a *joint strategy*.

For $h \in \text{hist}(S)$ write $\text{out}(S, h, \sigma_A)$, called the *outcomes of σ_A from h* , for the set of computations $\pi \in \text{comp}(S, h)$ such that π is consistent with σ_A , that is, $\pi \in \text{out}(S, h, \sigma_A)$ iff (i) $\pi_{\leq |h|-1} = h$; (ii) for every position $i \geq |h|$, there exists a joint-action $J_i \in \text{ACT}$ such that $\pi_{i+1} \in \delta(\pi_i, J_i)$, and for every $a \in A$, $J_i(a) = \sigma_A(a)(\pi_{\leq i})$. We may drop S and write simply $\text{out}(h, \sigma_A)$. Notice that, if $A = \emptyset$, then $\text{out}(h, \sigma_A)$ is the set of all paths starting with h (this is because σ_A is the empty function and (ii) above places no additional restrictions on the computations).

2.2 The Logic $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$

In this section we define the logic $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$. Its syntax has been called ATEL^* (cf. [18]), and we interpret it on iCGS with history-based semantics and imperfect information.

Syntax. Fix a finite set of *atomic propositions (atoms)* AP and a finite set of *agents* Ag . The *history* (φ) and *path* (ψ) *formulas over AP and Ag* are built using the following

grammar:

$$\begin{aligned} \varphi &::= p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \mathbb{K}_a\varphi \mid \mathbb{C}_A\varphi \mid \mathbb{D}_A\varphi \mid \langle\langle A \rangle\rangle\psi \\ \psi &::= \varphi \mid \neg\psi \mid \psi \wedge \psi \mid \mathbb{X}\psi \mid \psi \cup \psi \end{aligned}$$

where $p \in AP$, $a \in \text{Ag}$, and $A \subseteq \text{Ag}$.

The class of $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$ *formulas* is the set of history formulas generated by the grammar. The *temporal operators* are \mathbb{X} (read “next”) and \mathbb{U} (read “until”). The *strategy quantifier* is $\langle\langle A \rangle\rangle$ (“the agents in A can enforce ψ ”), and the *epistemic operators* are \mathbb{K}_a (“agent a knows that”), \mathbb{C}_A (“it is common-knowledge amongst A that”), and \mathbb{D}_A (“the agents in A distributively know that”).

Semantics. Fix an iCGS S . We simultaneously define, by induction on the formulas, $(S, h) \models \varphi$ where $h \in \text{hist}(S)$ and φ is a history formula, and $(S, \pi, m) \models \psi$ where $\pi \in \text{cmp}(S)$, $m \geq 0$, and ψ is a path formula:

$$\begin{aligned} (S, h) \models p &\quad \text{iff } \text{last}(h) \in \lambda(p), \text{ for } p \in AP. \\ (S, h) \models \neg\varphi &\quad \text{iff } (S, h) \not\models \varphi. \\ (S, h) \models \varphi_1 \wedge \varphi_2 &\quad \text{iff } (S, h) \models \varphi_i \text{ for } i \in \{1, 2\}. \\ (S, h) \models \langle\langle A \rangle\rangle\psi &\quad \text{iff for some joint strategy } \sigma_A \in \Sigma(S), \\ &\quad (S, \pi, |h| - 1) \models \psi \text{ for all } \pi \in \text{out}(h, \sigma_A). \\ (S, h) \models \mathbb{K}_a\varphi &\quad \text{iff for every history } h' \in \text{hist}(S), \\ &\quad h' \equiv_a h \text{ implies } (S, h') \models \varphi. \\ (S, h) \models \mathbb{C}_A\varphi &\quad \text{iff for every history } h' \in \text{hist}(S), \\ &\quad h' \equiv_A^C h \text{ implies } (S, h') \models \varphi. \\ (S, h) \models \mathbb{D}_A\varphi &\quad \text{iff for every history } h' \in \text{hist}(S), \\ &\quad h' \equiv_A^D h \text{ implies } (S, h') \models \varphi. \\ (S, \pi, m) \models \varphi &\quad \text{iff } (S, \pi_{\leq m}) \models \varphi, \text{ for } \varphi \text{ a history formula.} \\ (S, \pi, m) \models \neg\psi &\quad \text{iff } (S, \pi, m) \not\models \psi. \\ (S, \pi, m) \models \psi_1 \wedge \psi_2 &\quad \text{iff } (S, \pi, m) \models \psi_i \text{ for } i \in \{1, 2\} \\ (S, \pi, m) \models \mathbb{X}\psi &\quad \text{iff } (S, \pi, m + 1) \models \psi. \\ (S, \pi, m) \models \psi_1 \cup \psi_2 &\quad \text{iff for some } j \geq m, (S, \pi, j) \models \psi_2, \text{ and} \\ &\quad \text{for all } k \text{ with } m \leq k < j, \text{ we have} \\ &\quad (S, \pi, k) \models \psi_1. \end{aligned}$$

For a history formula φ , write $S \models \varphi$ to mean that $(S, s) \models \varphi$ for every $s \in S_0$.

We isolate some important fragments.

1. The fragment $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}$ consists of history formulas φ defined by the grammar above, except with the following path formulas: $\psi ::= \mathbb{X}\varphi \mid \varphi \cup \varphi$
2. The fragment ATL (resp. ATL^*) consists of formulas of $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}$ (resp. $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$) that do not mention epistemic operators.
3. The CTL operator \mathbb{E} (resp. \mathbb{A}) is definable in ATL^* by $[[\emptyset]]$ (resp. $\langle\langle \emptyset \rangle\rangle$). In particular, $\text{CTL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$ is a syntactic fragment of $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$. The fragment of $\text{CTL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}$ consisting of formulas of the form $\mathbb{A}\psi$, where ψ is a path formula, is denoted $\text{LTL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}$. Finally, LTL is the fragment of $\text{LTL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}$ that does not mention epistemic operators.

REMARK 1. *The definition of the semantics of $\langle\langle A \rangle\rangle\psi$ is the “objective” semantics of $\langle\langle A \rangle\rangle$, and captures the idea that a designer is reasoning about the existence of strategies. On the other hand, “subjective” semantics capture the idea that agents themselves are reasoning about the existence of strategies [35]. In Section 3.1 we define subjective semantics and extend our main result to deal with these.*

Model Checking. We state the main decision problem of this work.

DEFINITION 4 (MODEL CHECKING). *Let \mathcal{C} be a class of iCGS and \mathcal{F} a sublanguage of $\text{ATL}_{\mathbb{K},\mathcal{C},\mathcal{D}}^*$. Model checking \mathcal{C} against \mathcal{F} specifications is the following decision problem: given $S \in \mathcal{C}$ and $\varphi \in \mathcal{F}$ as input, decide whether $S \models \varphi$.*

Model checking is undecidable in general. Actually, it is undecidable even if \mathcal{C} consists of all iCGS with $|Ag| = 3$ and \mathcal{F} consists of the single formula $\langle\langle\{1,2\}\rangle\rangle Gp$, see [9]. In Section 3 we prove that model checking PA-iCGS against $\text{ATL}_{\mathbb{K},\mathcal{C},\mathcal{D}}^*$ specifications is decidable.

2.3 Examples

We illustrate this definition with two scenarios: the epistemic puzzle of the muddy children [11], and a generalisation of the game Battleships to multiple players. We model (or sketch) the scenario as an iCGS only having public actions, and supply representative formulas of $\text{ATL}_{\mathbb{K},\mathcal{C},\mathcal{D}}^*$.

Muddy Children. We express this classic puzzle, as presented, e.g., in [11], in slightly different terms. There are n children, k of them with mud on their foreheads. Each child can see the forehead (and thus the muddy state) of all the other children, but not their own. Then the father enters the scene. The father can see the foreheads of all the muddy children. Each person can only make truthful statements about what they know.

The classic question is: what one statement can the father make that will lead each muddy child to learn that she is indeed muddy. The answer is that the father declares, assuming that $k \geq 1$, that “at least one of you is muddy”.

There are a number of modeling decisions one can make to formalise this scenario, e.g., we must decide on the exact set of actions. Let $Ag = \{F\} \cup \{1, 2, \dots, n\}$. We give the father two actions, i.e., $Act_F = \{\exists m, \neg \exists m\}$. We give the i th child two actions, i.e., $Act_i = \{\text{know_muddy}, \neg \text{know_muddy}\}$. The set of states is $S = \{0, 1\}^n \cup (\text{ACT} \cup \{\epsilon\})$. If the current state is (v, J) then $v_i = 1$ (resp. $v_i = 0$) means that the i th child is (resp. is not) muddy, and J is the most recent joint action (ϵ means that no joint action has yet taken place). The set of initial states is $S_0 = \{0, 1\}^n \times \{\epsilon\}$. The transition relation simply updates the last joint action: $\delta((v, J), J') = (v, J')$. The father is perfectly informed so $\sim_F = \{(s, s) : s \in S\}$, and each child only does not see herself, so $\sim_i = \{((v, J), (v', J')) : \bigwedge_{j \neq i} v_j = v'_j, J = J'\}$. Finally, the atoms are $AP = \{m_i : i \leq n\} \cup \{\alpha_a : \alpha \in Act_a, a \in Ag\}$. Finally, define $\lambda(m_i) = \{(s, J) : s_i = 1\}$ and $\lambda(\alpha_a) = \{(s, J) : J(a) = \alpha\}$. So m_i means that the i th child is muddy, and α_a means that agent a 's last action was $\alpha \in Act_a$. It is straightforward to check that we have defined an iCGS only having public actions.

Define the shorthand formula $\text{Kw}_a\phi$, read “agent a knows whether ϕ ”, by the formula $\mathbb{K}_a\phi \vee \mathbb{K}_a\neg\phi$. Consider the formula:

$$\langle\langle\{f, 1, \dots, m\}\rangle\rangle[(\bigwedge_{a \in Ag} G(X\alpha_a \rightarrow \text{Kw}_a\alpha)) \wedge F(\bigwedge_{i \leq c} \text{Kw}_i m_i)]$$

where the first conjunction is over $a \in Ag, \alpha \in Act_a$. This expresses that all the agents have a truthfull strategy so that eventually each child will know whether or not she is muddy.

The reader might wonder what would happen if we don't explicitly express that the actions are truthful. Consider the

following formula that says that the father has a strategy such that eventually the children know their muddy state:

$$\langle\langle\{f\}\rangle\rangle F \bigwedge_{i \leq c} \text{Kw}_i m_i$$

This formula is true. Indeed, a strategy for the father is to play action $\exists m$ at the i th step iff the i th child is muddy.

In the next scenario, what agents see changes over time (unlike in the muddy children scenario). In both scenarios, what agents hear gets updated over time.

Battleships. We consider a game of battleships with three players. Each player has a 10×10 -board with numeric coordinates from bottom-left $(0, 0)$ to top-right $(9, 9)$. Initially, each player can only see her own board. On her board each player displays her battleships: one carrier of size 5, two battleships of size 4, three cruisers of size 3, four submarines also of size 3, and five destroyers of size 2. We assume that ships are displayed either horizontally or vertically. As is standard, overlapping is not allowed.

Here we consider a synchronous version of battleships, structured in 2-phase rounds, where in phase 1 every player broadcasts the name p of a player and cell (n, m) of p 's board to attack. Then, in phase 2, the players truthfully state whether they have been hit or missed and the boards are updated accordingly. A player is eliminated once all her ships have been destroyed. The last player standing, if there is one, wins the game. The relevant atoms in this game are win_i and $lose_i$ which state whether player i has won or lost. It is a routine exercise to build an iCGS only having public actions from this description. We only mention that the assumption that players are truthful can be built in to the iCGS, i.e., by limiting the available actions a player has in state 2.

Now consider the formula:

$$\langle\langle\{1, 2\}\rangle\rangle F \langle\langle\{1, 3\}\rangle\rangle F(lose_2 \vee \langle\langle\{1\}\rangle\rangle F win_1)$$

This expresses that player 1 can collude with each of her enemies, in order to weaken player 2 or win the game.

3. DECIDABILITY OF PA-iCGS

In this section we prove that model checking PA-iCGS against $\text{ATL}_{\mathbb{K},\mathcal{C},\mathcal{D}}^*$ specifications is decidable. This should be contrast with the fact that model checking arbitrary iCGS against ATL specifications is undecidable [9].

THEOREM 1. *Model checking PA-iCGS against $\text{ATL}_{\mathbb{K},\mathcal{C},\mathcal{D}}^*$ specifications is 2EXPTIME-complete.*

The bulk of this section is devoted to proving decidability. We then establish the complexity, and discuss further extensions of the result. Before giving the proof, we introduce an encoding μ of histories.

DEFINITION 5. *Let S be an iCGS. Let $\mu : S_0 \times \text{ACT}^* \rightarrow \text{hist}(S)$ denote the function mapping (s_0, u) to the history starting at the initial state s_0 that results from the sequence of joint actions $u \in \text{ACT}^*$. That is, $\mu(s_0, u)$ is the history h such that $h_0 = s_0, h_j = \delta(h_{j-1}, u_{j-1})$ for $1 \leq j \leq |u|$.*

For PA-iCGS, the encoding is actually a bijection:

REMARK 2. *Let S be a PA-iCGS. Since each \sim_a is reflexive, $\delta(s, \cdot) : \text{ACT} \rightarrow S$ is injective for every $s \in S$. Thus,*

$\mu : S_0 \times \text{ACT}^* \rightarrow \text{hist}(\mathbf{S})$ is a bijection. In particular, for every $h \in \text{hist}(\mathbf{S})$ and $s \in S_0$ there exists a unique $u \in \text{ACT}^*$ such that $\mu(s, u) = h$. This bijection allows us to encode histories of \mathbf{S} by (unique) elements of $S_0 \times \text{ACT}^*$.

An immediate consequence of having only public actions, but one that forms the foundation of our decidability proof, is that the moment different joint actions are taken, two histories become distinguishable.

LEMMA 1. *Let \mathbf{S} be a PA-iCGS. For all $a \in \text{Ag}$, $u, u' \in \text{ACT}^*$ and $s, s' \in S_0$, if $\mu(s, u) \equiv_a \mu(s', u')$ then $u = u'$.*

PROOF. If $\mu(s, u) \equiv_a \mu(s', u')$ then $|u| = |u'|$ and, for all $0 \leq j \leq |u|$, $\mu(s, u)_j \sim_a \mu(s', u')_j$. By the definition of having only public actions, $u_j = u'_j$ for all $j < |u|$. \square

We prove Theorem 1 in the rest of this section. We use an automata-based marking algorithm. Such algorithms have been successfully applied to a number of logics, including CTL* [23] and ATL* [1] in the perfect information setting.

Automata theory. Since our proof uses an automata-theoretic approach we now fix notations of word and tree automata. We remark that we only make use of standard properties of automata operating on finite words, infinite words, and infinite trees [24].

A *deterministic finite-word automaton* (DFW) is a tuple $M = (\Sigma, S, s_0, \rho, F)$ where Σ is the *input alphabet*, S is the finite set of *states*, $s_0 \in S$ the *initial state*, $\rho : S \times \Sigma \rightarrow S$ the *deterministic transition function*, and $F \subseteq S$ the set of *final states*. The *run* of M on $u \in \Sigma^*$ is the finite sequence $s_0 s_1 \dots s_{|u|}$ where $\delta(s_i, u_i) = s_{i+1}$ for all $i < |u|$. The automaton *accepts* a word $u \in \Sigma^*$ iff the run of M on u ends in a final state. A DFW is *empty* if it accepts no word. A set of strings $X \subseteq \Sigma^*$ is called *regular* if there is a DFW M that accepts $u \in \Sigma^*$ iff $u \in X$.

We also make use of automata operating on infinite words $\alpha \in \Sigma^\omega$: a *deterministic parity word automata* (DPW) is a tuple $P = (\Sigma, S, s_0, \rho, c)$ where all components are as for DFW except that $c : S \rightarrow \mathbb{Z}$ is the *colouring function*. The run of P on $\alpha \in \Sigma^\omega$ is the infinite sequence $s_0 s_1 \dots$ such that $\delta(s_i, \alpha_i) = s_{i+1}$ for all i . The automaton *accepts* a word α iff the smallest color k for which there are infinitely many i with $c(s_i) = k$ is even (where $s_0 s_1 \dots$ is the run of M on α).

We also make use of automata operating on trees. A *deterministic parity tree automata* (DPT) is a tuple $T = (\Sigma, D, S, s_0, \rho, c)$ where all components are as for a DPW except that D is the finite set of *directions*, and $\rho : S \times \Sigma \rightarrow S^D$. The automaton operates on Σ -labelled D -ary branching trees, i.e., functions $f : D^* \rightarrow \Sigma$. A *branch* of t is an infinite sequence $\beta \in D^\omega$. The *run* of T in input t is the Q -labeled D -ary branching tree $g : D^* \rightarrow Q$ such that $g(\epsilon) = s_0$ and $g(ud) = \delta(g(u), t(u))$. The automaton *accepts* the tree f iff for every $\beta \in D^\omega$ (called a branch), the smallest color k for which there are infinitely i with $g(\beta_i) = k$ is even.

The classes of DFW and DPW are effectively closed under the Boolean operations (complementation and intersection). Also, DFW, DPW and DPT can be effectively tested for emptiness. Finally, we make use of the following important fact connecting linear temporal logic with automata:

PROPOSITION 1 ([40, 33]). *Every LTL formula ψ over atoms AP can be effectively converted into a DPW P_ψ with input alphabet 2^{AP} that accepts a word $\alpha \in 2^{AP}$ iff $\alpha \models \psi$.*

Moreover, the DPW has double-exponentially many states and single-exponentially many colours.

Proof outline. We proceed by induction on the formula φ to be checked. We build a DFW that accepts all encodings of histories h such that $(\mathbf{S}, h) \models \varphi$. Precisely, we build a DFW M_φ^s that accepts a sequence of joint actions $u \in \text{ACT}^*$ iff $(\mathbf{S}, \mu(s, u)) \models \varphi$. The atomic case is immediate, and the Boolean cases follow from the effective closure of DFW under complementation and intersection. The $\varphi = \mathbb{K}_a \varphi'$ case is done by simulating the DFW $M_{\varphi'}^t$ for $t \in S_0$, and recording whether or not $\mu(s, u) \sim_a \mu(t, u)$; the other knowledge operators are similar. The strategic operator $\varphi = \langle\langle A \rangle\rangle \psi$ is done as follows: first we show that we can assume ψ is an LTL formula, and then we build a DPW for the formula ψ , so that the DFW simulates the DPW, and when the input ends we use a tree automaton to decide if there is a joint strategy that ensures that the DPW accepts all computations consistent with that joint strategy.

Generalisation of the labeling function. We first generalise the labeling function of iCGS so that atoms are regular sets of histories (instead of state labelings).

DEFINITION 6. *A generalised iCGS is a tuple*

$$\mathbf{S} = \langle \text{Ag}, AP, \{\text{Act}_a\}_{a \in \text{Ag}}, S, S_0, \delta, \{\sim_a\}_{a \in \text{Ag}}, \Lambda \rangle$$

where all entries are as for iCGS, except that $\lambda : AP \rightarrow 2^S$ is replaced by a function $\Lambda : AP \rightarrow 2^{\text{hist}(\mathbf{S})}$ such that $\Lambda(p) \subseteq \text{hist}(\mathbf{S})$ is a regular set of histories, i.e., there exists a DFW over the alphabet S accepting $h \in \text{hist}(\mathbf{S})$ iff $h \in \Lambda(p)$.

Then, we redefine the atomic case of the semantics of $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$: $(\mathbf{S}, h) \models p$ iff $h \in \Lambda(p)$. It is immediate that generalised iCGS are indeed more general than iCGS:

LEMMA 2. *Let \mathbf{S} be an iCGS with labeling function λ . The generalised iCGS \mathbf{S}' with labeling $\Lambda(p) = \{h \in \text{hist}(\mathbf{S}) : \text{last}(h) \in \lambda(p)\}$ has the property that $\mathbf{S} \models \varphi$ iff $\mathbf{S}' \models \varphi$ (for all formulas φ of $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$).*

PROOF. First, note that $\Lambda(p)$ is regular since a DFW can read the history h and store in its state whether or not the last state it read is in $\lambda(p)$ or not. Second, the fact that $\mathbf{S} \models \varphi$ iff $\mathbf{S}' \models \varphi$ holds by a straightforward induction on the structure of φ . \square

A *generalised PA-iCGS* is a generalised iCGS that only has public actions, i.e., it satisfies the condition in Definition 3 (which does not depend on the labeling). For the rest of the proof we view \mathbf{S} as a generalised PA-iCGS.

Inductive Statement. Let \mathbf{S} be a generalised PA-iCGS. For every history formula φ and initial state $s \in S_0$ we will build a DFW M_φ^s such that for every $u \in \text{ACT}^*$,

$$M_\varphi^s \text{ accepts } u \text{ iff } (\mathbf{S}, \mu(s, u)) \models \varphi.$$

From this it is easy to get the decidability stated in the theorem: simply check that ϵ is accepted by every M_φ^s with $s \in S_0$.

We build the DFW M_φ^s , simultaneously for all $s \in S_0$, by induction on φ .

φ is an atom. Say $\varphi = p \in AP$ and let $s \in S_0$. The required DFW M_φ^s should accept $u \in \text{ACT}^*$ iff $\mu(s, u)$ is accepted by the DFW $\Lambda(p)$. To do this we define M_φ^s to simulate \mathbf{S} and the DFW $R = (S, Q, q_0, \rho, F)$ for $\Lambda(p)$ in parallel, i.e., by taking a product of \mathbf{S} and R . Formally,

define $M_\varphi^s = (\text{ACT}, S \times Q, (\iota, q_0), \tau, F')$ where the transition function τ maps state (s, q) and input $a \in \text{ACT}$ to state $(\delta(s, a), \rho(q, s))$, and the final states F' are of the form (s, q) where $\rho(q, s) \in F$.

φ is a **Boolean combination**. Let $s \in S_0$. The Boolean combinations follow from the effective closure of DFW under complementation and intersection. Indeed, $M_{\neg\varphi}^s$ is formed by complementing the final states of M_φ^s , and $M_{\varphi_1 \wedge \varphi_2}^s$ is the product of the $M_{\varphi_i}^s$ s.

φ is of the **form** $\mathbb{K}_a\varphi'$. Let $s \in S_0$. By induction, we have DFW M_φ^t , for $t \in S_0$. The required DFW should accept a string u iff, for every $t \in S_0$, if $\mu(s, u) \equiv_a \mu(t, u)$ then M_φ^t accepts u .

To do this, the DFW will simulate, in parallel, each M_φ^t , for $t \in S_0$. This is done by forming their product, i.e., the states of the product are $q : S_0 \rightarrow Q$ where Q is the union of the state sets of the M_φ^t , for $t \in S_0$, and there is a transition in the product from q to q' on input $J \in \text{ACT}$ if for each $t \in S_0$ there is a transition in M_φ^t from $q(t)$ to $q'(t)$ in input J . Instrument this product by recording, on input $u \in \text{ACT}^*$ a function $f_u : S_0 \rightarrow S$ and a set $G_u \subseteq S_0$ with the following properties:

- $f_u(t) = \text{last}(\mu(t, u))$
- $t \in G_u$ iff for every prefix v of u , $f_v(s) \sim_a f_v(t)$ (thus, initially $G_\epsilon = \{t \in S_0 : t \sim_a s\}$, and the moment $f_v(s) \not\sim_a f_v(t)$ we remove t from G_v).

A state $\langle f, G, q \rangle$ is final if, for every $t \in G$ it is also the case that $q(t)$ is a final state of M_φ^t .

φ is of the **form** $\mathbb{C}_A\varphi'$. This is identical to the \mathbb{K}_a case except replace \sim_a by \sim_A^C and replace \equiv_a by \equiv_A^C .

φ is of the **form** $\mathbb{D}_A\varphi'$. This is identical to the \mathbb{K}_a case except replace \sim_a by \sim_A^D and replace \equiv_a by \equiv_A^D .

φ is of the **form** $\langle\langle A \rangle\rangle\psi$. We proceed in two steps. First, we show how to linearise path formulas, and then we show how to encode strategies as trees so that we can build the promised DFW.

Linearising path formulas. One can think of an $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$ path formula ψ as an LTL formula $\text{lin}(\psi)$ over a fresh set of atoms $\text{max}(\psi)$, the maximal history subformulas of ψ . This translation of $\text{ATL}_{\mathbb{K}, \mathbb{C}, \mathbb{D}}^*$ path formulas to LTL formulas does not make use of the assumption that the iCGS \mathbb{S} only has public actions, and it is analogous to the translation of ATL^* (or CTL^*) path formulas to LTL formulas over maximal state subformulas [23, 1].

We briefly discuss the translation. Let $\text{max}(\psi)$ be the set of history subformulas of ψ that are maximal, i.e., a history formula $\varphi \in \text{max}(\psi)$ iff it occurs in ψ and that occurrence is not a subformula of any other occurrence of a history subformula of ψ . If ψ is a path formula, define $\text{lin}(\psi)$ to be the LTL formula where for each $\varphi \in \text{max}(\psi)$ there is a fresh atom $\boxed{\varphi}$ such that every occurrence of φ in ψ is replaced by $\boxed{\varphi}$. For example, consider $\psi = (p \cup \langle\langle A \rangle\rangle \mathbb{K}_a p) \vee \times \neg \mathbb{C}_A p$. The history subformulas of ψ are $\{p, \langle\langle A \rangle\rangle \mathbb{K}_a p, \mathbb{K}_a p, \neg \mathbb{C}_A p, \mathbb{C}_A p\}$. Then $\text{max}(\psi) = \{p, \langle\langle A \rangle\rangle \mathbb{K}_a p, \neg \mathbb{C}_A p\}$.¹ Thus $\text{lin}(\psi)$ is the LTL formula $(\boxed{p} \cup \langle\langle A \rangle\rangle \boxed{\mathbb{K}_a p}) \vee \times \boxed{\neg \mathbb{C}_A p}$ over the atoms $\boxed{\varphi}$ for $\varphi \in \text{max}(\psi)$. Since, by induction, we have built

¹Note that although p has a non-maximal occurrence in ψ , it is included in $\text{max}(\psi)$ since it has at least one occurrence which is maximal, i.e., on the left-side of \cup .

DFW for each boxed atom, for the remainder of the proof we assume that ψ is an LTL formula.

Construction of $M_{\langle\langle A \rangle\rangle\psi}^s$ for an LTL formula ψ . We will build a DPW $E_{\psi, s}$ over ACT that accepts $\alpha \in \text{ACT}^\omega$ iff $(\mathbb{S}, \mu(s, \alpha)) \models \psi$. The promised DFW $M_{\langle\langle A \rangle\rangle\psi}^s$ reads $u \in \text{ACT}^*$ and simulates $E_{\psi, s}$. Suppose after reading u the state of $E_{\psi, s}$ is q . Then $M_{\langle\langle A \rangle\rangle\psi}^s$ accepts, i.e., q is defined to be a final state of $M_{\langle\langle A \rangle\rangle\psi}^s$, iff there exists uniform σ_A such that for every $\alpha \in \text{ACT}^\omega$, if $\mu(s, u \cdot \alpha) \in \text{out}(\mathbb{S}, \mu(s, u), \sigma_A)$ then α is accepted by $E_{\psi, s}$ starting from state q (and thus $(\mathbb{S}, \mu(s, u)) \models \langle\langle A \rangle\rangle\psi$, as required). These latter synthesis problems (one for each q) are solved offline by constructing DPT $F_{\psi, s, q}$ and testing them for non-emptiness. We now show how to build the automata $E_{\psi, s}$ and $F_{\psi, s, q}$.

Construction of DPW $E_{\psi, s}$. To build $E_{\psi, s}$, begin by writing $AP(\psi)$ for the finite set of atoms appearing in ψ . First, for each $p \in AP(\psi)$, let D^p be a DFW for the regular set $\{u \in \text{ACT}^* : \mu(s, u) \in \Lambda(p)\}$. Second, by Proposition 1, every LTL formula ψ can be converted into a DPW D_ψ over alphabet 2^{AP} that accepts all word models of that formula. Let Q_ψ be the states and $\Delta_\psi : Q_\psi \times 2^{AP(\psi)} \rightarrow Q_\psi$ the transition of the DPW. Now, the DPW $E_{\psi, s}$ simulates D_ψ and each DFW D^p . The automaton does this by storing and updating a state $q_u \in Q_\psi$ and a function f_u such that $f_u(p)$ is the state of D^p (i.e., $f_u : AP(\psi) \rightarrow Q$ where Q is the union of states of the D^p s). Transitions of $E_{\psi, s}$ are as follows: from state $\langle q_u, f_u \rangle$ and input $d \in \text{ACT}$ the next state $\langle q_{ud}, f_{ud} \rangle$ satisfies that $q_{ud} = \Delta_\psi(q_u, Z)$ where $p \in Z$ iff $f_u(p)$ is a final state of D^p , and $f_{ud}(p)$ is the state resulting from applying the transition function of D^p to the state $f_u(p)$ and input d . Define the colour of $\langle q, f \rangle$ to be the same as the colour in D_ψ of the state q , and $\langle q, f \rangle$ is an initial state if q is an initial state in D_ψ . The following is straightforward to prove:

LEMMA 3. *The DPW $E_{\psi, s}$ accepts $\alpha \in \text{ACT}^\omega$ if and only if $(\mathbb{S}, \mu(s, \alpha)) \models \psi$.*

Construction of DPT $F_{\psi, s, q}$. To solve the synthesis problem we will encode strategies as trees and use tree-automata. Encode a strategy σ of agent a by the ACT-branching tree

$$T_\sigma : \text{ACT}^* \rightarrow (\text{Act}_a)^{S_0}$$

where, for $u \in \text{ACT}^*$, $T_\sigma(u)(t) = \sigma(\mu(t, u))$. By Lemma 1, σ is uniform iff T_σ satisfies the property

$$\mu(t, u) \sim_a \mu(t', u) \Rightarrow T_\sigma(u)(t) = T_\sigma(u)(t') \quad (1)$$

LEMMA 4. *The set of encodings T_σ of uniform strategies σ of agent a is recognised by a DPT.*

PROOF. To do this, it is sufficient to build a DPT that accepts a tree T iff T has property (1). Informally, for every pair of different states $t, t' \in S_0$, the DPT keeps a bit that is initialised to 1 (signifying that it must verify that $T(u)(t) = T(u)(t')$), and as soon as it finds that $\mu(t, u) \not\sim_a \mu(t', u)$ it sets the bit to 0, which signals that it no longer has to ensure $T_\sigma(u)(t) = T_\sigma(u)(t')$. \square

Encode a set of uniform strategies σ_A (for $A \subseteq \text{Ag}$) as the convolution T_{σ_A} of their individual encodings, i.e.,

$$T_{\sigma_A} : \text{ACT}^* \rightarrow \prod_{a \in A} (\text{Act}_a)^{S_0}$$

where $T_{\sigma_A}(u)(a) = T_{\sigma_a}(u)$. Running the automata for σ_a in parallel yields:

LEMMA 5. For every $A \subseteq Ag$, the set of encodings of joint uniform strategies σ_A is recognised by a DPT.

Finally, in order to solve the synthesis problem for state q , we define a DPT $F_{\psi,s,q}$ that accepts T_{σ_A} iff every $\alpha \in \text{ACT}^\omega$, if $\mu(s, \alpha)$ is consistent with σ_A then α is accepted by $E_{\psi,s}$ starting from q .

The DPT $F_{\psi,s,q}$ works as follows: it reads T_{σ_A} as input and, on every branch $\alpha \in \text{ACT}^\omega$ of the tree, simulates $E_{\psi,s}$ starting from q , and accepts that branch if both $E_{\psi,s}$ is accepting and $\mu(s, \alpha)$ is consistent with σ_A . This can be done by a tree-automaton because a) $E_{\psi,s}$ is deterministic and thus it can be run on all paths of the tree (i.e., this step would not be possible if $E_{\psi,s}$ were a non-deterministic automaton); and b) checking if $\mu(s, \alpha)$ is consistent with σ_A is simply a matter of checking that $\alpha_0(a) = \sigma_A(a)(s)$ and $\alpha_{i+1}(a) = \sigma_A(a)(\mu(s, \alpha_{\leq i}))$, for every $i \in \mathbb{N}$ and $a \in A$.

Final states of DFW $M_{\langle\langle A \rangle\rangle\psi}^s$. Finally, define the state q of $M_{\langle\langle A \rangle\rangle\psi}^s$ to be a final state iff the DPT $F_{\psi,s,q}$ is non-empty (a decidable condition).

This completes the construction of $M_{\langle\langle A \rangle\rangle\varphi}^s$, and the proof of decidability.

3.1 Complexity

In this section we analyse the complexity of our decision procedure for a fixed number of agents. We then establish the lower bound by a reduction from a problem known to be 2EXPTIME-hard.

First, we calculate $\|\varphi\|$, the number of states of M_φ^s , for each case:

1. Atomic: $\|p\| = O(1)$ for $p \in AP$.
2. Negation: $\|\neg\varphi\| = \|\varphi\|$.
3. Conjunction: $\|\varphi \wedge \varphi'\| = \|\varphi\| \times \|\varphi'\|$.
4. Epistemic: $\|\mathbb{K}_a\varphi\| = (2 \times |S| \times \|\varphi\|)^{|S|}$, and the same for $\|\mathbb{C}_A\varphi\|$ and $\|\mathbb{D}_A\varphi\|$.
5. Strategic: $\|\langle\langle A \rangle\rangle\psi\| = 2^{2^{O(\text{lin}(\psi))}} \times \|\tilde{\psi}\|^{|\text{AP}(\text{lin}(\psi))|} \times O(2^{|\text{S}^2|})$ where $\text{lin}(\psi)$ is the linearisation of ψ , $\tilde{\psi}$ is the largest history subformula of ψ , and $\text{AP}(\cdot)$ is the set of atomic predicates occurring in its argument.

The last case requires some explanation. The DPT accepting the set of all joint-strategies σ_A has size $O(2^{|\text{S}^2|})$, and has two colours. The DPW D_ψ has double-exponentially many states and single-exponentially many colours (in the size of $\text{lin}(\psi)$) [40, 33]. The DPW $E_{\psi,s}$ has $2^{2^{O(\text{lin}(\psi))}} \times \|\tilde{\psi}\|^{|\text{AP}(\psi)|}$ many states. The DPT $F_{\psi,s,q}$ has $2^{2^{O(\text{lin}(\psi))}} \times \|\tilde{\psi}\|^{|\text{AP}(\psi)|} \times O(2^{|\text{S}^2|})$ many states and $2^{O(\text{lin}(\psi))}$ many colours. This gives the stated value of $\|\langle\langle A \rangle\rangle\psi\|$.

Second, we calculate the time for constructing the DFW M_φ^s . In the first four cases this cost is polynomial in the size of the DFW, i.e., $\|\varphi\|$. For the strategy case we incur a cost to calculate the final states, i.e., solving the emptiness of the DPT $F_{\psi,s,q}$. The cost of solving the emptiness of a DPT with n states and m colours is at most $n^{O(m)}$ [20]. Thus, the time for constructing M_φ^s is at most $n^{O(m)}$ where $n = 2^{2^{O(\text{lin}(\psi))}} \times \|\tilde{\psi}\|^{|\text{AP}(\text{lin}(\psi))|} \times O(2^{|\text{S}^2|})$ and $m = 2^{O(\text{lin}(\psi))}$.

Finally, let $z = |S| + |\varphi|$. The time for constructing M_φ^s of each step of the procedure can be bounded above by $2^{2^{O(z)}} \times$

$|\Lambda|^{2^{O(z)}}$ where $|\Lambda|$ is the size of the largest DFW representing atoms of the generalised PA-iCGS (a maximum exists since AP is finite). Since there are at most z such steps, the time for constructing, and thus the size, of the resulting DFW is $2^{2^{O(z^2)}}$. Testing if ϵ is accepted by this automaton has no additional cost. Thus, our algorithm runs in 2EXPTIME.

Lower-Bound. To prove the lower bound in Theorem 1 we reduce from a known 2EXPTIME-hard problem, i.e., model checking a CGS with $Ag = \{a, b\}$ against a formula of the form $\langle\langle \{a\} \rangle\rangle\psi$ for an LTL formula ψ [31, 32]. One can translate a two-player CGS S into a polynomially larger CGS S' with public actions such that $S \models \varphi$ iff $S' \models \varphi$. Indeed, the agents, actions, and atoms are the same, $S' = S \times (\text{ACT} \cup \{\epsilon\})$, $S'_0 = S_0 \times \{\epsilon\}$, $\delta'((s, d), d') = (\delta(s, d'), d')$, and $\lambda'(p) = \{(s, d) : s \in \lambda(p)\}$ (note that because S has two-players, $|\text{ACT}| = |\text{Act}_1| \times |\text{Act}_2|$, and thus $|S'|$ is polynomial in the size of S).

3.2 Subjective Semantics

In this section we show that our result still holds if we use subjective semantics instead of objective semantics.

Our definition of semantics of $\langle\langle A \rangle\rangle\psi$ is called “objective” (see Remark 1). An alternative definition is called “subjective”: replace “for all $\pi \in \text{out}(h, \sigma_A)$ ” by “for all $\pi \in \bigcup_{a \in A, h' \equiv_a h} \text{out}(S, h', \sigma_A)$ ” in the semantics $(S, h) \models \langle\langle A \rangle\rangle\psi$. Subjective semantics expresses, intuitively, that the agents A know that a given strategy will guarantee a certain outcome. We remark that in this case \mathbb{K}_a is definable in terms of $\langle\langle A \rangle\rangle$, i.e., $\langle\langle a \rangle\rangle\varphi \cup \varphi$.

The decidability proof of Theorem 1 is for objective semantics. To deal with subjective semantics proceed as follows. For $u \in \text{ACT}^*$ let $T_u^s \subseteq S_0$ be the set of t such that there exists $a \in A$ with $t \equiv_a s$. The DFW $M_{\langle\langle A \rangle\rangle\psi}^s$ simulates $E_{\psi,t}$ for all $t \in T_u^s$. After reading u , each automaton $E_{\psi,t}$ for $t \in T_u^s$ is in some state, say q_t . The DFW is required to accept u iff there exists a joint strategy σ_A such that for every $\alpha \in \text{ACT}^*$ and $t \in T_u^s$, if $\mu(t, u \cdot \alpha) \in \text{out}(S, \mu(t, u), \sigma_A)$ then α is accepted by $E_{\psi,t}$ starting from q_t . In order to decide the right-hand side we build the DPT F_{ψ,t,q_t} for $t \in T_u^s$ (as we did above for s). Then we check if the intersection of the automata F_{ψ,t,q_t} (for $t \in T_u^s$) is non-empty.

4. COMPARISON WITH BROADCAST ENVIRONMENTS

The work most closely related to ours is [38] in which the authors show that one can decide if a given formula of knowledge and linear-time, which we denote LK, is realisable (by a tuple of uniform strategies) assuming that the environment is a “broadcast environment”. In this section we denote the logic from [38] by LK.

The relationship with [38] is twofold: i) the realisability problem for LK can be reduced to model checking $\text{ATL}_{\mathbb{K}}^*$ specifications, and ii) our notion of “having only public actions” (Definition 3) is orthogonal to “broadcast environments”.

More to the point, the previously best-known decidability result concerning iCGS having only public actions follows from [38] and states that synthesis of LK formulas is decidable. This result is a special case of Theorem 1 in which we can effectively model-check (with optimal computational complexity) against $\text{ATL}_{\mathbb{K}, \text{C}, \text{D}}^*$ specifications. In the rest of this section we supply the justifications for i) and ii).

i) LK realisability can be reduced to model-checking $\text{ATL}_{\mathbb{K}}^*$.

We show how to reduce the realisability problem for LK to the model checking problem for $\text{ATL}_{\mathbb{K}}^*$. To do so, we first recall the syntax and semantics of LK from [38]. The syntax is defined as the set of formulas ψ generated by the following grammar:

$$\psi ::= p \mid \neg\psi \mid \psi \wedge \psi \mid \mathbf{X}\psi \mid \psi \mathbf{U}\psi \mid \mathbb{K}_a\psi$$

where $p \in AP$, $a \in Ag$, and $A \subseteq Ag$ is non-empty.

The semantics \models_{LK} is defined over (S, π, m) where S is an iCGS, $\pi \in \text{cmp}(S)$ and $n \in \mathbb{N}$. We denote the satisfaction relation \models_{LK} to distinguish it from \models . The Boolean and temporal operators are as usual:

$$\begin{aligned} (S, \pi, m) \models_{\text{LK}} p & \quad \text{iff } \pi_m \in \lambda(p) \\ (S, \pi, m) \models_{\text{LK}} \neg\psi & \quad \text{iff } (S, \pi, m) \not\models_{\text{LK}} \psi \\ (S, \pi, m) \models_{\text{LK}} \psi_1 \wedge \psi_2 & \quad \text{iff } (S, \pi, m) \models_{\text{LK}} \psi_i \text{ for } i \in \{1, 2\} \\ (S, \pi, m) \models_{\text{LK}} \mathbf{X}\psi & \quad \text{iff } (S, \pi, m+1) \models_{\text{LK}} \psi \\ (S, \pi, m) \models_{\text{LK}} \psi_1 \mathbf{U}\psi_2 & \quad \text{iff for some } j \geq m, (S, \pi, j) \models_{\text{LK}} \psi_2, \\ & \quad \text{and for all } k \text{ with } m \leq k < j, \\ & \quad (S, \pi, k) \models_{\text{LK}} \psi_1 \end{aligned}$$

The epistemic operator \mathbb{K}_a is follows:

$$(S, \pi, m) \models_{\text{LK}} \mathbb{K}_a\psi \text{ iff } (S, \pi', m') \models_{\text{LK}} \psi \text{ for all } \pi' \in \text{cmp}(S) \text{ such that } \pi_{\leq m} \equiv_a \pi'_{\leq m'} \text{ (in particular, } m = m').$$

An LK-formula ψ is *realisable* if there exists a uniform strategy σ_A such that for all $s_0 \in S_0$ and all $\pi \in \text{out}(S, s_0)$, we have that $(S, \pi, 0) \models \psi$.

We now present the reduction. Let ψ be a formula of LK. Define $\hat{\psi}$, a path formula of $\text{CTL}_{\mathbb{K}}^*$, by recursively replacing $\mathbb{K}_a\psi$ by $\mathbb{K}_a A \hat{\psi}$. We claim that for all iCGS S , ψ is realisable in S iff $S \models \langle\langle Ag \rangle\rangle \hat{\psi}$. To see this it is sufficient to establish the following inductive hypothesis: $(S, \pi, m) \models_{\text{LK}} \psi$ iff $(S, \pi, m) \models \hat{\psi}$. To prove the inductive hypothesis use that the following are equivalent to $(S, \pi, m) \models_{\text{LK}} \mathbb{K}_a\psi$:

1. $(S, \pi', m) \models_{\text{LK}} \psi$ for all $\pi' \in \text{cmp}(S)$ such that $\pi'_{\leq m} \equiv_a \pi_{\leq m}$ (by the definition of \models_{LK});
2. $(S, \pi', m) \models \hat{\psi}$ for all $\pi' \in \text{cmp}(S)$ such that $\pi'_{\leq m} \equiv_a \pi_{\leq m}$ (by the inductive hypothesis);
3. $(S, \pi, m) \models \mathbb{K}_a A \hat{\psi}$ (by definition of \models).

ii) Broadcast environments and PA-iCGS are incomparable. We briefly describe how [38] models “broadcast environment”. That work defines an interpreted systems (see [11] for background on these) in which each agent’s local state consists of a private part (that only depends on its local actions) and a shared part (that depends on the joint actions, but that is the same for all agents). In our terminology a broadcast environment is an iCGS with $Ag = \{e, 1, 2, \dots, n\}$ whose state set is of the form $S = L_e \times \prod_{i \leq n} L_i$ (for some finite sets L_a for $a \in Ag$), and whose transition maps state (l_e, l_1, \dots, l_n) and joint-action $J \in \text{ACT}$ to the state $(\tau_e(l_e, J), \tau_1(l_1, J(1)), \dots, \tau_n(l_n, J(n)))$ where $\tau_e : L_e \times \text{ACT} \rightarrow L_e$ and $\tau_i : L_i \times \text{Act}_i \rightarrow L_i$ are functions (similar to the evolution functions in interpreted systems), except that L_i for $i \neq e$ does not depend on joint-actions, only on local actions). Finally, define $(l_e, l_1, \dots, l_n) \sim_i (l'_e, l'_1, \dots, l'_n)$ iff $l_i = l'_i$ and $F(l_e) = F(l'_e)$ where $F : L_e \rightarrow O$ is a function mapping environment states to some fixed set O of observations (note that F and O are independent of i , and thus all agents have the same observation of the environment).

Now, the set of PA-iCGS is incomparable (wrt. subset) with these iCGS. On the one hand, setting $L_e = \text{ACT} = O$ and F to be the identity function, results in an iCGS having only public actions. On the other hand, we allow L_i to depend on the joint-actions (not just the local actions).

5. CONCLUSION

In this paper we advanced the state-of-the-art by putting forward a class of CGS with imperfect information, namely the iCGS only having public actions, which admit a decidable model checking problem, even in the presence of perfect recall. This is in marked contrast with the fact that even realisability of safety properties on arbitrary iCGS is undecidable [9]. Specifically, we considered a rich family of formal languages to express complex strategic and epistemic properties of agents in MAS. These are the extensions $\text{ATL}_{\mathbb{K}, \text{C}, \text{D}}$ and $\text{ATL}_{\mathbb{K}, \text{C}, \text{D}}^*$ of the alternating-time temporal logics ATL and ATL^* respectively, with operators for individual, common, and distributed knowledge. We provided these languages with a semantics in terms of iCGS, according to both the objective and subjective interpretation of ATL modalities. Most importantly, we identified a subclass of iCGS – those having only public actions, or PA-iCGS – for which we were able to prove that the model-checking problem is decidable. The interest of these results lies in the fact that PA-iCGS capture many important MAS scenarios, including certain games of imperfect information, epistemic puzzles, blackboard systems, face to face communication, etc. Indeed, all scenarios mentioned in previous work on broadcast environments [27, 38] can be captured by PA-iCGS.

A number of extensions of ATL^* have been proposed in order to naturally express classic solutions concepts (like Nash Equilibria) [15, 16, 28, 29]. It is an intriguing question if model checking PA-iCGS against epistemic extensions of these strategy logics is decidable.

Notwithstanding their generality, there are many features of MAS that are not naturally expressed within PA-iCGS or broadcast environments. We discuss some of them:

Asynchronous recall. Social media like Twitter only have public actions, but are more naturally modeled as asynchronous MAS (rather than synchronous systems, as we do).

Bounded-recall. Games like Bridge and Stratego are interesting to play in part because humans have to remember some of the history of a play, a feature that might be modeled by bounded recall (rather than perfect recall). However, restricting agents to finite-memory strategies also results in undecidability on arbitrary iCGS [41]. On the other hand, our proof implies that if a formula $\langle\langle A \rangle\rangle \psi$ is true then there are finite-memory strategies witnessing this fact, and if a formula $\mathbb{K}_a \varphi$ is true then there is a finite-state machine that accepts exactly the histories making $\mathbb{K}_a \varphi$ true. This suggests that our results can be used to model agents of bounded-recall.

Clocks. In certain variations of matching card games (like Egyptian Ratscrew) speed and timing feature prominently, which would require clocks be added to iCGS.

Probability. Several scenarios, such as card games and security protocols, involve probability either at the level of the iCGS or at the level of strategies.

In future work we plan to investigate the points raised above, as well as to develop optimal model checking algorithms for fragments of $\text{ATL}_{\mathbb{K}, \text{C}, \text{D}}^*$ and to implement them in an extension of the MCMAS tool for MAS verification [26].

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