The Impact of Strategies and Information in Model Checking for Multi-Agent Systems

Vadim Malvone

LTCI, Télécom Paris, Institut Polytechnique de Paris,
Palaiseau, France

`vadim.malvone@telecom-paris.fr`

System correctness is one of the most crucial and challenging objectives in software and hardware systems. With the increasing evolution of connected and distributed systems, ensuring their correctness requires the use of formal verification for multi-agent systems. In this paper, we present a summary of certain results on model checking for multi-agent systems that derive from the selection of strategies and information for agents. Additionally, we discuss some open directions for future research.

1   Introduction

The problem of assuring systems correctness is particularly felt in hardware and software design, especially in safety-critical scenarios. When we talk about a safety-critical system, we mean the one in which failure is not an option. To face this problem, several methodologies have been proposed. Among these, Model Checking (MC) [11, 10] results to be very useful. This approach provides a formal-based methodology to model systems, to specify properties via temporal logics, and to verify that a system satisfies a given specification.

Notably, first applications of model checking just concerned closed systems, which are characterized by the fact that their behavior is completely determined by their internal states. Unfortunately, model checking techniques developed to handle closed systems turn out to be quite useless in practice, as most of the systems are open and are characterized by an ongoing interaction with other systems. To overcome this problem, model checking has been extended to Multi-Agent Systems (MAS). In the latter context, temporal logics have been extended to temporal logics for the strategic reasoning such as Alternating-time Temporal Logic (ATL) [2] and Strategy Logic (SL) [21].

Given the logics under exam, there are two key aspects in MAS to determine the model checking complexity: the type of strategies and the agents' information. A strategy is a generic conditional plan that prescribes an action at each step of the MAS. There are two main classes of strategies: *memoryless* and *memoryfull*. In the former case, agents choose an action by considering only the current state, while in the latter case, agents choose an action by considering the full history of the MAS. Regarding information, we distinguish between *perfect* and *imperfect* information MAS. The former corresponds to a basic setting in which every agent has full knowledge about the MAS. However, real-life scenarios often involve situations where agents must act without having all relevant information at hand. In computer science, these situations occur, for example, when some variables of a system are internal/private and not visible to an external environment. In MAS models, imperfect information is usually modeled by setting an indistinguishability relation over the states of the MAS. This feature deeply impacts on the MC complexity. For example, ATL and SL become undecidable in the context of imperfect information and memoryfull strategies [12].

In this paper, we present a review of results on model checking for multi-agent systems concerning strategy classes and agent visibility, and explore potential directions for future research.

Outline In Section 2, we recall the definition of concurrent game structures and the syntax of ATL and SL. Then, in Section 3, we review the main classes of strategies and the concept of information. In Section 4, we revisit the model checking complexities for the aforementioned contexts. Finally, we conclude by providing some future directions in Section 5.

2 Model and logics for MAS

In this section, we recall the definition of a formal model for MAS and the syntax of two well-known logics for strategic reasoning: ATL and SL.

We start by recalling the definition of concurrent game structures [2].

Definition 1 *Given sets Ag of agents and AP of atoms, a* concurrent game structure (CGS) *is a tuple* $M = \langle S, s_0, \{Act_i\}_{i \in Ag}, \{\sim_i\}_{i \in Ag}, d, \delta, V \rangle$ *such that:*

- *S is a finite, non-empty set of* states, *with* initial state $s_0 \in S$.

- *For every* $i \in Ag$, Act_i *is a finite, non-empty set of* actions.
  Let $Act = \bigcup_{i \in Ag} Act_i$ *be the set of all actions, and* $ACT = \prod_{i \in Ag} Act_i$ *the set of all* joint actions, *i.e., tuples of actions.*

- *For every* $i \in Ag$, $\sim_i$ *is a relation of* indistinguishability *between states, that is, an equivalence relation on S. Given states* $s, s' \in S$, $s \sim_i s'$ *iff s and s' are said to be* observationally indistinguishable *for agent i.*

- *The* protocol function $d : Ag \times S \to (2^{Act} \setminus \emptyset)$ *defines the availability of actions so that for every* $i \in Ag$, $s \in S$, *(i)* $d(i,s) \subseteq Act_i$ *and (ii)* $s \sim_i s'$ *implies* $d(i,s) = d(i,s')$.

- *The* transition function $\delta : S \times ACT \to S$ *assigns a successor state* $s' = \delta(s, \vec{\alpha})$ *to each state* $s \in S$, *for every joint action* $\vec{\alpha} \in ACT$ *such that* $a_i \in d(i,s)$ *for every* $i \in Ag$, *that is,* $\vec{\alpha}$ *is* enabled *at s.*

- $V : S \times AP \to \{\top, \bot\}$ *is a* two-valued labelling function.

According to Def. 1, a CGS describes the interactions of a group *Ag* of agents, starting from the initial state $s_0 \in S$, following the transition function δ. The latter is constrained by the availability of actions to agents, as specified by the protocol function *d*. A history $h \in S^+$ is a finite (non-empty) sequence of states.

Now, we recall the syntax of Alternating-time Temporal Logic [2].

Definition 2 (*ATL**) *The state (φ) and path (ψ) formulas in ATL* are defined as follows, where* $p \in AP$ *and* $\Gamma \subseteq Ag$:

$$\varphi \quad ::= \quad p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \langle\!\langle \Gamma \rangle\!\rangle \psi$$
$$\psi \quad ::= \quad \varphi \mid \neg\psi \mid \psi \wedge \psi \mid X\psi \mid (\psi U \psi) \mid (\varphi R \varphi)$$

Formulas in ATL* are all and only the state formulas.

ATL extends Computation Tree Logic (CTL) [9] in which the existential *E* and the universal *A* path quantifiers are replaced with strategic modalities of the form $\langle\langle\Gamma\rangle\rangle$ and $[[\Gamma]]$, where Γ is a set of agents. A formula $\langle\langle\Gamma\rangle\rangle\psi$ is read as *"the agents in coalition Γ have a strategy to achieve ψ"*. The meaning of temporal operators *next X* and *until U* is standard [11]. Operators *unavoidable* $[[\Gamma]]$, *release R*, *finally F*, and *globally G* can be introduced as usual.

The formulas in the ATL fragment of ATL* are obtained from Def. 2 by restricting path formulas ψ to the temporal operators.

To conclude this section, we recall the syntax of Strategy Logic [21].

Definition 3 (SL Syntax) *Given the set AP of atoms, variables Var, and agents Ag, the formal syntax of SL is defined as follows, where $p \in AP$, $x \in Var$, and $a \in Ag$:*

$$\varphi \quad ::= \quad p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid X\varphi \mid \varphi U\varphi \mid \varphi R\varphi \mid \exists x\varphi \mid \forall x\varphi \mid (a,x)\varphi$$

SL syntactically extends Linear-time Temporal Logic (LTL) [23] with two *strategy quantifiers*, the existential $\exists x$ and universal $\forall x$, along with an *agent binding* (a,x), where a is an agent and x a variable. Intuitively, these additional elements can be respectively interpreted as *"there exists a strategy x"*, *"for all strategies x"*, and *"bind agent a to the strategy associated with the variable x"*.

3   Classes of Strategies and Information

In this section, we recall some definitions of strategies and of agents' information.

In Definition 1, we have defined an indistinguishability relation for each agent involved in the model. When every $\sim_i$ is the identity relation, *i.e.*, $s \sim_i s'$ iff $s = s'$, we obtain a CGS with *perfect information* [2]. When the latter is not true, we assume that every agent *i* has *imperfect information* about the exact state of the system. That is, in any state *s*, *i* considers all states s' that are indistinguishable for *i* from *s* to be epistemically possible [13]. The indistinguishability relations are extended to histories in a synchronous, pointwise way, *i.e.*, histories $h, h' \in S^+$ are *indistinguishable* for agent $i \in Ag$, or $h \sim_i h'$, iff (i) $|h| = |h'|$ and (ii) for all $j \leq |h|$, $h_j \sim_i h'_j$.

Now, we have all the ingredients to present the different definitions of strategies. First, we start with a class of strategies in which the agents determine their actions by considering only the current state of the MAS.

Definition 4 (Memoryless Strategy) *A memoryless strategy for agent $i \in Ag$ is a function $f_i : S \to Act_i$ such that for each state $s \in S$, (i) $f_i(s) \in d(i,s)$; and (ii) $s \sim_i s'$ implies $f_i(s) = f_i(s')$.*

By Def. 4, any strategy for agent *i* must return actions that are enabled for *i* (i.e. condition (i)). Additionally, whenever two states are indistinguishable for *i*, the same action is returned (i.e. condition (ii)). This latter introduces the concept of *uniformity*, where an agent can select a strategy that adheres to its visibility. Notice that, for the case of perfect information, condition (ii) is satisfied by any function $f_i : S \to Act_i$.

The notion of memoryless strategy is considered too weak for an agent. For this reason, the concept of memoryfull strategy has been introduced.

Definition 5 (Memoryfull Strategy) *A memoryfull strategy for agent $i \in Ag$ is a function $f_i : S^+ \to Act_i$ such that for all histories $h, h' \in S^+$, (i) $f_i(h) \in d(i, last(h))$; and (ii) $h \sim_i h'$ implies $f_i(h) = f_i(h')$.*

As for the memoryless case, memoryfull strategies must adhere to the protocol function and indistinguishability relation.

Between these two approaches, i.e. memoryless and memoryfull, several different classes of bounded strategies have been proposed, including works by Ågotnes and Walther [1], Brihaye et al. [8], Vester [27], and Belardinelli et al. [6]. In this work, we focus our attention to natural strategies [18]. The idea behind natural strategies is to adopt the view of bounded rationality, and look at "simple" strategies in specification of agents' abilities. This notion has been introduced in both ATL and SL in the context of perfect [17] and imperfect information [5, 19]. Here, we focus on the definition provided in [19].

A natural strategies is an *ordered list of guarded actions*, i.e., sequences of pairs (ϕ_i, α_i) such that: ϕ_i is a condition, and α_i is an action. That is, a natural strategy is a rule-based representation in which the first rule whose condition holds in the current execution of the MAS is selected, and the corresponding action is executed.

With respect to the nature of the conditions, it is possible to define different classes of natural strategies. We start by recalling the notion of *uniform natural memoryless strategy*.

Definition 6 *In an uniform natural memoryless strategy for any agent a, the conditions are defined over epistemic formulas as follows:*

$$\psi ::= \top \mid K_a\varphi \mid \neg\psi \mid \psi \wedge \psi$$
$$\varphi ::= p \mid \neg\varphi \mid \varphi \wedge \varphi \mid K_b\varphi$$

where p is an atomic proposition, b an agent, and K_i is the knowledge operator for any agent i. Intuitively, a formula $K_i\varphi$ can be interpreted as "the agent i knows φ".

So, we have formulas that are prefixed by K_a and then possibly combined by boolean operators. In other words, the formulas are always boolean conditions on a's knowledge. As discussed in [17], to define *natural memoryless strategy* in the perfect information case, we can replace epistemic formulas with boolean formulas only.

To improve the abilities of the agents, natural strategies have also been defined with recall. In particular, to evaluate properties over histories instead of states, a way to define conditions is to use regular expressions with the standard constructors $\cdot, \cup, *$ representing concatenation, nondeterministic choice, and finite iteration, respectively. Thus, to define a *natural strategies with recall* in the perfect information context, we can use regular expressions over boolean formulas. Similarly, to define a *uniform natural strategies with recall* in the imperfect information context, we can use regular expressions over epistemic formulas.

In the next section, we will provide the main model checking results for the above mentioned classes.

4   Model Checking Complexities

Here, we discuss the model checking complexities for ATL and SL in terms of memoryless, memoryfull, and natural strategies in the perfect and imperfect information context.

First, we can analyze ATL. As you can see in Table 1, in the worst case, that is imperfect information and perfect recall strategies, the problem becomes undecidable, while in the perfect information case, the problem is polynomial. An interesting point of ATL is that memoryless and memoryfull strategies are equivalent in the perfect information case. This is because ATL is too weak in expressive power.

To overcome this problem, there is ATL*. In this logic, strategic and temporal operators are decoupled to express more complex strategic objectives. As you can see in Table 2, the model checking complexity becomes solvable in polynomial space in the memoryless case, double-exponential time in

ATL	perfect information	imperfect information
memoryless	*PTIME*-complete [2]	Δ_2^P-complete [26]
memoryfull	*PTIME*-complete [2]	undecidable [12]

Table 1: Model checking complexities for ATL.

ATL*	perfect information	imperfect information
memoryless	*PSPACE*-complete [26]	*PSPACE*-complete [26]
memoryfull	2*EXPTIME*-complete [2]	undecidable [12]

Table 2: Model checking complexities for ATL*.

the memoryfull and perfect information case, and again undecidable in the memoryfull and imperfect information case. To address the latter problem, some works have either focused on an approximation to perfect information [3], developed notions of bounded memory [6], or employed hybrid techniques [14, 15]. Despite its expressiveness, ATL* suffers from the strong limitation that strategies are treated only implicitly in the semantics of strategic operators. This restriction makes the logic less suited to formalize several important solution concepts, such as the Nash Equilibrium [22].

To gain expressive power, we need to move to Strategy Logic. As shown in Table 3, the model checking problem becomes intractable in the memoryfull case. Given the relevance of this logic, several fragments have been proposed [21, 4]. Among others, we would like to mention Strategic Logic One Goal that has the same model checking complexity as ATL* but more expressive power, and Strategic Logic Simple Goal that has the same model checking complexity as ATL but more expressive power.

In all the above-mentioned logics, the model checking problem is undecidable in the worst case. In the last few years, a natural way to represent strategies has been studied. From the definition of natural strategies, two variants of ATL and SL have been proposed. In these variants, called NatATL [18] and NatSL [5], the strategic operators are equipped with graded modalities that represent the complexity of the natural strategies in achieving the temporal objectives. As you can see in Tables 4 and 5 the model checking problem has a complexity less than or equal *PSPACE*.

Can this approach solve all the problems related to model checking for MAS? Unfortunately (or fortunately for researchers), there are several open problems related to what we have summarized in this work. We will discuss some of them in the following section.

5   Future Directions

As promised throughout the paper, in this section, we will discuss some directions for future research. We will summarize these aspects with respect to the three main features related to the formal verification

SL	perfect information	imperfect information
memoryless	-	*PSPACE*-complete [20]
memoryfull	non-elementary [21]	undecidable [12]

Table 3: Model checking complexities for SL.

NatATL	perfect information	imperfect information
memoryless	Δ_2^P-complete [18]	Δ_2^P-complete [19]
with recall	*PSPACE*-complete [18]	*PSPACE*-complete [19]

Table 4: Model checking complexities for NatATL.

NatSL	perfect information	imperfect information
memoryless	-	*PSPACE*-complete [5]
with recall	-	*PSPACE*-complete [5]

Table 5: Model checking complexities for NatSL.

of multi-agent systems, namely: strategies, information, and logics.

About strategies: find the good representation.   As we briefly discussed along the paper, both memoryless and memoryful strategies are not suitable choices. In fact, memoryless and memoryfull are too weak and strong, respectively, to describe agents' abilities. The weakness of memoryless strategies is a gain in terms of complexity, and the strength of memoryfull strategies is paid in terms of complexity. In addition, memoryfull strategies cannot be used to implement a model checker due to their domain over histories. As we mentioned earlier, there are some bounded versions between memoryless and memoryfull, but there is a lot of work to do to standardize the good choice. For instance, in the context of natural strategies, there are various aspects that require attention, such as defining the appropriate notion of complexity for these strategies. In the above-mentioned works, the authors have proposed the total size of the strategy as complexity, i.e., the overall complexity is the sum of all the symbols involved in the conditions. Is this the best way to define the complexity of a strategy? This is an open problem that needs to be investigated.

About information: perfect and imperfect is not enough.   We believe there is significant work to be done in this area. For instance, it seems too reductive to consider only white (i.e. perfect information) and black (i.e. imperfect information) settings. We advocate the need to define a taxonomy for imperfect information. As discussed earlier in the paper, some approaches try to make some MAS with imperfect information decidable. However, the authors in [5, 3, 16] do not give a specific class of MAS with imperfect information that is decidable. Currently, only the class of hierarchical information has been proposed [25, 24] and analyzed in SL [7].

About logics: find the gap between ATL and SL.   The two logics for the strategic reasoning discussed in this work suffer from two main problems on two different sides. On one hand, ATL has a good model checking complexity, but it cannot express several solution concepts such as the Nash Equilibrium. The strong limitation of ATL is that it treats strategies only implicitly in the semantics of its modalities. So, it is weak in expressiveness. On the other hand, SL is the more powerful logic for the strategic reasoning, but its model checking problem is not tractable. So, the full logic cannot have practical applications. The idea is to define a new logic for the strategic reasoning that can incorporate the positive features of ATL in terms of complexity and the good features of SL in terms of expressiveness. We understand that this is not a simple challenge, and finding a perfect trade-off between ATL and SL may be difficult. However, we see this need and want to go all the way on this point.

References

[1] Thomas Ågotnes & Dirk Walther (2009): *A Logic of Strategic Ability Under Bounded Memory*. J. Log. Lang. Inf. 18(1), pp. 55–77. Available at `https://doi.org/10.1007/s10849-008-9075-4`.

[2] Rajeev Alur, Thomas A. Henzinger & Orna Kupferman (2002): *Alternating-time temporal logic*. J. ACM 49(5), pp. 672–713. Available at `https://doi.org/10.1145/585265.585270`.

[3] Francesco Belardinelli, Angelo Ferrando & Vadim Malvone (2023): *An abstraction-refinement framework for verifying strategic properties in multi-agent systems with imperfect information*. Artif. Intell. 316, p. 103847. Available at `https://doi.org/10.1016/j.artint.2022.103847`.

[4] Francesco Belardinelli, Wojciech Jamroga, Damian Kurpiewski, Vadim Malvone & Aniello Murano (2019): *Strategy Logic with Simple Goals: Tractable Reasoning about Strategies*. In Sarit Kraus, editor: *Proceedings of the Twenty-Eighth International Joint Conference on Artificial Intelligence, IJCAI 2019, Macao, China, August 10-16, 2019*, ijcai.org, pp. 88–94. Available at `https://doi.org/10.24963/ijcai.2019.13`.

[5] Francesco Belardinelli, Wojtek Jamroga, Vadim Malvone, Munyque Mittelmann, Aniello Murano & Laurent Perrussel (2022): *Reasoning about Human-Friendly Strategies in Repeated Keyword Auctions*. In Piotr Faliszewski, Viviana Mascardi, Catherine Pelachaud & Matthew E. Taylor, editors: *21st International Conference on Autonomous Agents and Multiagent Systems, AAMAS 2022, Auckland, New Zealand, May 9-13, 2022*, International Foundation for Autonomous Agents and Multiagent Systems (IFAAMAS), pp. 62–71. Available at `https://www.ifaamas.org/Proceedings/aamas2022/pdfs/p62.pdf`.

[6] Francesco Belardinelli, Alessio Lomuscio, Vadim Malvone & Emily Yu (2022): *Approximating Perfect Recall when Model Checking Strategic Abilities: Theory and Applications*. J. Artif. Intell. Res. 73, pp. 897–932. Available at `https://doi.org/10.1613/jair.1.12539`.

[7] Raphaël Berthon, Bastien Maubert, Aniello Murano, Sasha Rubin & Moshe Y. Vardi (2021): *Strategy Logic with Imperfect Information*. ACM Trans. Comput. Log. 22(1), pp. 5:1–5:51. Available at `https://doi.org/10.1145/3427955`.

[8] Thomas Brihaye, Arnaud Da Costa Lopes, François Laroussinie & Nicolas Markey (2009): *ATL with Strategy Contexts and Bounded Memory*. In Sergei N. Artëmov & Anil Nerode, editors: *Logical Foundations of Computer Science, International Symposium, LFCS 2009, Deerfield Beach, FL, USA, January 3-6, 2009. Proceedings*, Lecture Notes in Computer Science 5407, Springer, pp. 92–106. Available at `https://doi.org/10.1007/978-3-540-92687-0_7`.

[9] Edmund M. Clarke & E. Allen Emerson (1981): *Design and Synthesis of Synchronization Skeletons Using Branching-Time Temporal Logic*. In Dexter Kozen, editor: *Logics of Programs, Workshop, Yorktown Heights, New York, USA, May 1981*, Lecture Notes in Computer Science 131, Springer, pp. 52–71. Available at `https://doi.org/10.1007/BFb0025774`.

[10] E.M. Clarke, O. Grumberg, D. Kroening, D. Peled & H. Veith (2018): *Model Checking, second edition*. Cyber Physical Systems Series, MIT Press. Available at `https://books.google.fr/books?id=OJV5DwAAQBAJ`.

[11] E.M. Clarke, O. Grumberg, D. Peled & D.A. Peled (1999): *Model Checking*. The Cyber-Physical Systems Series, MIT Press. Available at `https://books.google.fr/books?id=Nmc4wEaLXFEC`.

[12] Catalin Dima & Ferucio Laurentiu Tiplea (2011): *Model-checking ATL under Imperfect Information and Perfect Recall Semantics is Undecidable*. CoRR abs/1102.4225. arXiv:1102.4225.

[13] R. Fagin, J.Y. Halpern, Y. Moses & M. Vardi (2004): *Reasoning About Knowledge*. A Bradford Book, MIT Press. Available at `https://doi.org/10.7551/mitpress/5803.001.0001`.

[14] Angelo Ferrando & Vadim Malvone (2022): *Towards the Combination of Model Checking and Runtime Verification on Multi-agent Systems*. In Frank Dignum, Philippe Mathieu, Juan Manuel Corchado & Fernando de la Prieta, editors: *Advances in Practical Applications of Agents, Multi-Agent Systems, and Complex Systems Simulation. The PAAMS Collection - 20th International Conference, PAAMS 2022, L'Aquila, Italy,*

July 13-15, 2022, Proceedings, Lecture Notes in Computer Science 13616, Springer, pp. 140–152. Available at `https://doi.org/10.1007/978-3-031-18192-4_12`.

[15] Angelo Ferrando & Vadim Malvone (2023): *How to Find Good Coalitions to Achieve Strategic Objectives*. In Ana Paula Rocha, Luc Steels & H. Jaap van den Herik, editors: *Proceedings of the 15th International Conference on Agents and Artificial Intelligence, ICAART 2023, Volume 1, Lisbon, Portugal, February 22-24, 2023*, SCITEPRESS, pp. 105–113. Available at `https://doi.org/10.5220/0011778700003393`.

[16] Angelo Ferrando & Vadim Malvone (2023): *Towards the Verification of Strategic Properties in Multi-Agent Systems with Imperfect Information*. In Noa Agmon, Bo An, Alessandro Ricci & William Yeoh, editors: *Proceedings of the 2023 International Conference on Autonomous Agents and Multiagent Systems, AAMAS 2023, London, United Kingdom, 29 May 2023 - 2 June 2023*, ACM, pp. 793–801. Available at `https://dl.acm.org/doi/10.5555/3545946.3598713`.

[17] Wojciech Jamroga, Vadim Malvone & Aniello Murano (2017): *Reasoning about Natural Strategic Ability*. In Kate Larson, Michael Winikoff, Sanmay Das & Edmund H. Durfee, editors: *Proceedings of the 16th Conference on Autonomous Agents and MultiAgent Systems, AAMAS 2017, São Paulo, Brazil, May 8-12, 2017*, ACM, pp. 714–722. Available at `http://dl.acm.org/citation.cfm?id=3091227`.

[18] Wojciech Jamroga, Vadim Malvone & Aniello Murano (2019): *Natural strategic ability*. *Artif. Intell.* 277. Available at `https://doi.org/10.1016/j.artint.2019.103170`.

[19] Wojciech Jamroga, Vadim Malvone & Aniello Murano (2019): *Natural Strategic Ability under Imperfect Information*. In Edith Elkind, Manuela Veloso, Noa Agmon & Matthew E. Taylor, editors: *Proceedings of the 18th International Conference on Autonomous Agents and MultiAgent Systems, AAMAS '19, Montreal, QC, Canada, May 13-17, 2019*, International Foundation for Autonomous Agents and Multiagent Systems, pp. 962–970. Available at `http://dl.acm.org/citation.cfm?id=3331791`.

[20] Bastien Maubert, Munyque Mittelmann, Aniello Murano & Laurent Perrussel (2021): *Strategic Reasoning in Automated Mechanism Design*. In Meghyn Bienvenu, Gerhard Lakemeyer & Esra Erdem, editors: *Proceedings of the 18th International Conference on Principles of Knowledge Representation and Reasoning, KR 2021, November 3-12, 2021*, pp. 487–496. Available at `https://doi.org/10.24963/kr.2021/46`.

[21] Fabio Mogavero, Aniello Murano, Giuseppe Perelli & Moshe Y. Vardi (2014): *Reasoning About Strategies: On the Model-Checking Problem*. *ACM Trans. Comput. Log.* 15(4), pp. 34:1–34:47. Available at `https://doi.org/10.1145/2631917`.

[22] R.B. Myerson (1991): *Game Theory: Analysis of Conflict*. Harvard University Press. Available at `https://books.google.fr/books?id=E8WQFRCsNr0C`.

[23] Amir Pnueli (1977): *The Temporal Logic of Programs*. In: *18th Annual Symposium on Foundations of Computer Science, Providence, Rhode Island, USA, 31 October - 1 November 1977*, IEEE Computer Society, pp. 46–57. Available at `https://doi.org/10.1109/SFCS.1977.32`.

[24] Amir Pnueli & Roni Rosner (1990): *Distributed Reactive Systems Are Hard to Synthesize*. In: *31st Annual Symposium on Foundations of Computer Science, St. Louis, Missouri, USA, October 22-24, 1990, Volume II*, IEEE Computer Society, pp. 746–757. Available at `https://doi.org/10.1109/FSCS.1990.89597`.

[25] John H. Reif (1984): *The Complexity of Two-Player Games of Incomplete Information*. *J. Comput. Syst. Sci.* 29(2), pp. 274–301. Available at `https://doi.org/10.1016/0022-0000(84)90034-5`.

[26] Pierre-Yves Schobbens (2003): *Alternating-time logic with imperfect recall*. In Wiebe van der Hoek, Alessio Lomuscio, Erik P. de Vink & Michael J. Wooldridge, editors: *1st International Workshop on Logic and Communication in Multi-Agent Systems, LCMAS 2003, Eindhoven, The Netherlands, June 29, 2003, Electronic Notes in Theoretical Computer Science* 85, Elsevier, pp. 82–93. Available at `https://doi.org/10.1016/S1571-0661(05)82604-0`.

[27] Steen Vester (2013): *Alternating-time temporal logic with finite-memory strategies*. In Gabriele Puppis & Tiziano Villa, editors: *Proceedings Fourth International Symposium on Games, Automata, Logics and Formal Verification, GandALF 2013, Borca di Cadore, Dolomites, Italy, 29-31th August 2013, EPTCS* 119, pp. 194–207. Available at `https://doi.org/10.4204/EPTCS.119.17`.