MCMAS-SLK: A Model Checker for the Verification of Strategy Logic Specifications

Petr Čermák¹, Alessio Lomuscio¹, Fabio Mogavero², and Aniello Murano²

¹ Imperial College London, UK
² Università degli Studi di Napoli Federico II, Italy

1 Introduction

Model checking has come of age. A number of techniques are increasingly used in industrial setting to verify hardware and software systems, both against models and concrete implementations. While it is generally accepted that obstacles still remain, notably handling infinite state systems efficiently, much of this work involves refining and improving existing techniques such as predicate abstraction.

At scientific level a major avenue of work remains the development of verification techniques against rich and expressive specification languages. Over the years there has been a natural progression from checking reachability only, to a large number of techniques (BDDs, BMC, abstraction, etc) catering for LTL [24], CTL [10], and CTL* [11]. More recently, ATL and ATL* [3] were introduced to analyse systems in which some components, or agents, can enforce temporal properties on the system. The paths so identified correspond to infinite games between a coalition and its complement. ATL is well explored theoretically and at least two toolkits now support it [4, 16, 17].

It has however been observed that ATL* suffers from a number of limitations when one tries to apply it to multi-agent system reasoning and games [1, 2, 5, 19, 27]. One of these is the lack of support for binding strategies explicitly to various agents or to the same agent in different contexts [22, 23]. To overcome this and other difficulties, Strategy Logic (SL) has been put forward. By using SL a number of multi-agent based specifications involving cooperation become naturally expressible. Also, key game-theoretic properties such as Nash equilibria, which were previously not logically-representable, can easily be captured in SL.

In this paper, we describe MCMAS-SLK, a first model checker for SL. This tool supports the verification of SL specifications (hence ATL* and CTL*), the synthesis of agents’ strategies to satisfy a given parametric specification, as well as basic counterexample generation. MCMAS-SLK, released as open-source, implements novel labelling algorithms for SL, encoded on BDDs, and reuses existing algorithms for the verification of epistemic specifications [25].

2 Epistemic Strategy Logic

Syntax. Strategy logic (SL) has been introduced as a powerful formalism to reason about various equilibria concepts in non-zero sum games and sophisticated
cooperation concepts in multi-agent systems [8, 23]. These are not expressible in
previously explored logics including those in the ATL** hierarchy. We here put
forward an epistemic extension of SL by adding a family of knowledge operators,
as well as modalities for group knowledge [13].

Formulas in epistemic strategy logic, or strategy logic with knowledge (SLK),
are built by the following grammar over atomic propositions \( p \in AP \), variables
\( x \in V_r \), and agents \( a \in Ag \) (\( A \subseteq Ag \) denotes a set of agents):

\[
\varphi ::= p \mid \neg \varphi \mid \varphi \land \varphi \mid X \varphi \mid \varphi U \varphi \mid \langle \langle x \rangle \rangle \varphi \mid (a, x) \varphi \mid K_a \varphi \mid D_A \varphi \mid C_A \varphi.
\]

SLK extends LTL [24] by means of an existential strategy quantifier \( \langle \langle x \rangle \rangle \) and
agent binding \( (a, x) \). It also includes the epistemic operators \( K_a \), \( D_A \), and \( C_A \)
for individual, distributed, and common knowledge [13]. Intuitively, \( \langle \langle x \rangle \rangle \) can be
read as “there exists a strategy \( x \) such that \( \varphi \) holds”, whereas \( (a, x) \varphi \) stands for
“bind agent \( a \) to the strategy associated with the variable \( x \) in \( \varphi \)”. The epistemic
formula \( K_a \varphi \) stands for “agent \( a \) knows that \( \varphi \)”; \( D_A \varphi \) encodes “the group \( A \) has
distributed knowledge of \( \varphi \)”; while \( C_A \varphi \) represents “the group \( A \) has common
knowledge of \( \varphi \)”. Similarly to first-order languages, we use \( \text{free}(\varphi) \) to represent
the free agents and variables in a formula \( \varphi \). Formally, \( \text{free}(\varphi) \subseteq Ag \cup V_r \) contains
(i) all agents having no binding after the occurrence of a temporal operator and
(ii) all variables having a binding but no quantification. For simplicity, we here
consider only formulas where the epistemic modalities are applied to sentences,
i.e., formulas without free agents or variables. The extension is not problematic.
To establish the truth of a formula, the set of strategies over which a variable can
range needs to be determined. For this purpose the set \( \text{sharing}(\varphi, x) \) is introduced.
It denotes the set of agents sharing the variable \( x \) within the formula \( \varphi \).

\textbf{Semantics.} Differently from other treatments of SL, originally defined on
concurrent game structures, we here define the logic on \textit{interpreted systems} [13].
Doing so enables us to integrate the logic with epistemic concepts. In such a
system each agent is modelled in terms of its local states (given as a set of vari-
ables), a set of actions, a protocol specifying what actions may be performed
at a given state, and a local evolution function returning a target local state
given a local state and a joint action for all the agents in the system. Interpreted
systems are attractive for their modularity, they naturally express systems with
incomplete information, and are amenable to verification [14, 16]. The concepts
of \textit{path}, \textit{play}, \textit{strategy}, and \textit{assignment} (for agents and variables), can be defined
analogously to concurrent game structures. We refer to [21, 23] for a detailed
presentation. Intuitively, a strategy identifies paths on the model on which a
temporal-epistemic formula needs to be verified. Various variants of interpreted
systems have been studied; many of them differ in the notion of memory associ-
ated with the agents. We here adopt the memoryless version, at times referred
to as observational semantics. Under memoryless semantics local states of the
agents do not necessarily include the local history of the run. Consequently, pro-
tocols and strategies are also memoryless. Note that this markedly differs from
the previous perfect recall semantics of SL, which are defined on memoryful
strategies.
Given an interpreted system $\mathcal{I}$ having $G$ as a set of global states, a state $g \in G$, and an assignment $\chi$ defined on $\text{free}(\varphi)$, we write $\mathcal{I}, \chi, g \models \varphi$ to indicate that the SLK formula $\varphi$ holds at $g$ in $\mathcal{I}$ under $\chi$. The semantics of SLK formulas is inductively defined by using the usual LTL interpretation for the atomic propositions, the Boolean connectives $\neg$ and $\land$, as well as the temporal operators $\mathcal{X}$ and $\mathcal{U}$. All epistemic modalities are interpreted as standard by relying on various notions of equality on the underlying local states [13]. The inductive cases for strategy quantification $\langle \langle x \rangle \rangle$ and agent binding $(a, x)$ are given as follows. $\mathcal{I}, \chi, g \models \langle \langle x \rangle \rangle \varphi$ iff there is a memoryless strategy $f$ for the agents in $\text{sharing}(\varphi, x)$ such that $\mathcal{I}, \chi[a \mapsto f], g \models \varphi$ where $\chi[a \mapsto f]$ is the assignment equal to $\chi$ except for the variable $x$, for which it assumes the value $f$. $\mathcal{I}, \chi, g \models (x, a) \varphi$ iff $\mathcal{I}, \chi[a \mapsto \chi(x)], g \models \varphi$, where $\chi[a \mapsto \chi(x)]$ denotes the assignment $\chi$ in which agent $a$ is bound to the strategy $\chi(x)$.

**Model Checking and Strategy Synthesis.** Given an interpreted system $\mathcal{I}$, an initial global state $g_0$, and an assignment $\chi$ defined on $\text{free}(\varphi)$, the model checking problem concerns determining whether $\mathcal{I}, \chi, g_0 \models \varphi$. Conversely, given an interpreted system $\mathcal{I}$ and an initial global state $g_0$, the strategy synthesis problem concerns determining an assignment $\chi$ such that $\mathcal{I}, \chi, g_0 \models \varphi$.

It is worth recalling that the model checking problem of both ATL and ATL* with memoryless strategies and imperfect information against interpreted systems is in PSPACE [7]. The related procedure demonstrating the complexity can be adapted to show that the same result applies to SLK. It follows that SLK has the same complexity even though it is more expressive than ATL*. Indeed, SLK can describe Nash equilibria as we show in the following sections.

### 3 MCMAS-SLK

**State Labelling Algorithm.** The model checking algorithm for SLK extends the corresponding ones for temporal logic in two ways. Firstly, it takes as input not only a formula, but also a binding which assigns agents to variables. Secondly, it does not merely return sets of states, but sets of pairs $\langle g, \chi \rangle$ consisting of a state $g$ and an assignment of variables to strategies $\chi$. A pair $\langle g, \chi \rangle \in \text{Ext}$ is called an extended state; intuitively, $\chi$ represents the strategy assignment under which the formula holds at state $g$.

Given an SLK formula $\varphi$ and a binding $b \in \text{Bnd} \triangleq \text{Ag} \rightarrow \text{Vr}$, the model checking algorithm $\text{Sat}: \text{SLK} \times \text{Bnd} \rightarrow 2^{\text{Ext}}$ returning a set of extended states is defined as follows, where $a \in \text{Ag}$ is an agent and $x \in \text{Vr}$ a variable:

- $\text{Sat}(p, b) \triangleq \{ (g, \chi) : g \in h(p) \land \chi \in \text{Asg} \}$, with $p \in \text{AP}$;
- $\text{Sat}(\neg \varphi, b) \triangleq \neg(\text{Sat}(\varphi, b))$;
- $\text{Sat}(\varphi_1 \land \varphi_2, b) \triangleq \text{Sat}(\varphi_1, b) \cap \text{Sat}(\varphi_2, b)$;
- $\text{Sat}((a, x)\varphi, b) \triangleq \text{Sat}(\varphi, b[a \mapsto x])$;
- $\text{Sat}(\langle \langle x \rangle \rangle \varphi, b) \triangleq \{ (g, \chi) : \exists f \in \text{Str}_\text{sharing}(\varphi, x). \langle g, \chi[x \mapsto f] \rangle \in \text{Sat}(\varphi, b) \}$;
- $\text{Sat}(\mathcal{X} \varphi, b) \triangleq \text{pre}(\text{Sat}(\varphi, b), b)$;
- $\text{Sat}(\varphi_1 \mathcal{U} \varphi_2, b) \triangleq \text{lfp}_X[\text{Sat}(\varphi_2, b) \cup \{ \text{Sat}(\varphi_1, b) \cap \text{pre}(X, b) \}]$;
Above we use \( \text{pre}(C, b) \) to denote the set of extended states that temporally preclude \( C \) subject to binding \( b \); \( \text{neg}(C) \) stands for the set of extended states logically incompatible with \( C \); \( \text{St}_{\text{sharing}(\varphi, x)} \) is the set of strategies shared by the agents bound to the variable \( x \) in the formula \( \varphi \); finally, \( \sim_\alpha \) represents the epistemic accessibility relation for agent \( \alpha \). The set of global states of an interpreted system \( I \) satisfying a given formula \( \varphi \in \text{SLK} \) is calculated from the algorithm above by computing \( \|\varphi\|_I \triangleq \{ g \in G : \langle g, \varnothing \rangle \in \text{Sat}(\varphi, \varnothing) \} \).

**BDD Translation.** In what follows we summarise the steps required to implement the labelling algorithm above using OBDDs [6].

Given an interpreted system \( I \) and an SLK formula \( \varphi \), we can use Boolean variables to represent a global state and a joint action as Boolean vectors \( \overline{v} = (v_1, \ldots, v_N) \) and \( \overline{w} = (w_1, \ldots, w_M) \), respectively [25]. Similarly, an assignment \( \chi \) can be represented as a Boolean vector \( \overline{\pi} = (u_1, \ldots, u_K) \) where \( K = \sum_{x \in \mathcal{V}_r} \) \( \sum_{S \in G/\sim^C_{\text{sharing}(\varphi, x)}} \left[ \log_2 \left\| \bigcap_{g \in S} \bigcap_{l \in \text{sharing}(\varphi, x)} \text{P}_a(l_a(g)) \right\| \right] \) and \( \sim^C_\chi \) denotes the common epistemic accessibility relation for agents \( A \subset \mathcal{A} \) (derived from \( \sim_\alpha \)). Intuitively, for each variable \( x \in \mathcal{V}_r \) and set of shared local states \( S \in G/\sim^C_{\text{sharing}(\varphi, x)} \), we store which action should be carried out. This demonstrates the large number of boolean variables needed to encode extended states, which constitutes a major bottleneck in SLK verification.

An extended state \( \langle g, \chi \rangle \in \text{Ext} \) is then represented as a conjunction of the Boolean variables in \( \overline{\pi}_g \) and \( \overline{\pi}_x \). A set of extended states can be expressed as the disjunction of the Boolean formulas encoding each extended state.

Given a binding \( b \in \text{Bnd} \), we can encode (as in [18]) the protocol \( P(\overline{v}, \overline{w}) \), the evolution function \( t(\overline{v}, \overline{w}, \overline{v}') \), and the strategy restrictions \( S^k(\overline{v}, \overline{w}, \overline{\pi}) \). The temporal transition can be encoded as \( R^t_k(\overline{v}, \overline{v}', \overline{\pi}) = \bigvee_{\overline{v} \in \text{Act}} t(\overline{v}, \overline{v}', \overline{v}') \wedge P(\overline{v}, \overline{w}) \wedge S^t_k(\overline{w}, \overline{w}, \overline{\pi}) \). Observe that we quantify over actions, encoded as \( \overline{w} \), as in [18], but we store the variable assignment in the extra parameter \( \overline{\pi} \). Quantification over the variable assignment is performed when a strategy quantifier is encountered.

Given this, the algorithm \( \text{Sat}(\cdot, \cdot) \) can be translated into operations on BDDs representing the encoded sets of states.

**MCMAS-SLK.** The model checker MCMAS-SLK [20] contains an implementation of the procedure described previously. To do this, we took MCMAS as baseline [16]. MCMAS is an open-source model checker for the verification of multi-agent systems against ATL and epistemic operators. We used MCMAS for parsing input and used some of its existing libraries for handling counter-examples, which were extended to handle SLK modalities. The symbolic semantics and the labelling algorithm are entirely novel. Note that MCMAS supports neither LTL nor ATL*; both subsumed by SLK.

MCMAS-SLK takes as input a system description given in the form of an ISPL file [10] providing the agents in the system, their possible local states, their protocols, and their evolution functions. Upon providing SLK specifications, the checker calculates the set of reachable extended states, encoded as OBDDs, and
computes the results by means of the labelling algorithm described previously. If the formula is not satisfied, a counterexample is provided.

4 Experimental Results and Conclusions

Evaluation. To evaluate the proposed tool, we present the experimental results obtained while verifying the dining cryptographers protocol \[9,16\] and a variant of the cake-cutting problem \[12\]. The experiments were run on an Intel Core i7-2600 CPU 3.40GHz machine with 8GB RAM running Linux kernel version 3.8.0-34-generic. Table 4 reports the results obtained when verifying the dining cryptographers protocol against the CTLK specification $\phi_{\text{CTLK}} \equiv \mathcal{A}\mathcal{G}\psi$ and the SLK specification $\phi_{\text{SLK}} \equiv \mathcal{G}\mathcal{G}\psi$, with $\mathcal{G}\psi \equiv \neg\langle \langle x \rangle \rangle\neg\psi$, where:

$\psi \equiv \left(\text{odd} \land \neg\text{paid}_1\right) \rightarrow \left(\mathcal{K}_c, \left(\text{paid}_2 \lor \cdots \lor \text{paid}_n\right)\right) \land \left(\neg\mathcal{K}_c, \text{paid}_2 \land \cdots \land \neg\mathcal{K}_c, \text{paid}_n\right)$

$\phi \equiv \left[x_1\right] \cdots \left[x_n\right] \left[x_{\text{env}}\right] (c_1, x_1) \cdots (c_n, x_n) (\text{Environment}, x_{\text{env}})$

Table 1. Verification results for the dining cryptographers protocol.

| $n$ crypts | possible states | reachable states | reachability (s) | CTLK (s) | SLK (s) |
|------------|----------------|------------------|------------------|----------|---------|
| 10         | $3.80 \times 10^{14}$ | 45056           | 4.41             | 0.30     | 2.11    |
| 11         | $9.13 \times 10^{17}$ | 98304           | 1.79             | 0.04     | 5.51    |
| 12         | $2.19 \times 10^{20}$ | 212992          | 2.43             | 0.02     | 11.78   |
| 13         | $5.26 \times 10^{23}$ | 458752          | 2.17             | 0.11     | 32.41   |
| 14         | $1.26 \times 10^{26}$ | 983040          | 2.08             | 0.09     | 85.29   |
| 15         | $3.03 \times 10^{29}$ | $2.10 \times 10^9$ | 22.67            | 0.33     | 171.61  |
| 16         | $7.27 \times 10^{32}$ | $4.46 \times 10^9$ | 7.13             | 0.09     | 451.41  |
| 17         | $1.74 \times 10^{35}$ | $9.44 \times 10^9$ | 9.77             | 0.13     | 768.34  |

$\phi_{\text{CTLK}}$ is the usual epistemic specification for the protocol \[16\] and $\phi_{\text{SLK}}$ is its natural extension where strategies are quantified. The results show that the checker can verify reasonably large state spaces. The performance depends on the number of Boolean variables required to represent the extended states. In the case of SLK specifications, the number of Boolean variables is proportional to the number of strategies (here equal to the number of agents). The last two columns of Table 1 show that the tool’s performance, when verifying SLK formulas, drops considerably faster than for CTLK. This is because CTLK requires no strategy assignments and extended states collapse to plain states. In contrast, the performance for CTLK is dominated by the computation of the reachable state space.

We now turn to evaluate MCMAS-SLK functionalism with respect to strategy synthesis and specifications expressing Nash equilibria. Specifically, we consider a variation of the model for the classic cake-cutting problem \[12\] in which a set of $n$ agents take turns to slice a cake of size $d$ and the environment responds by trying to ensure the cake is divided fairly. We assume that at each even round the agents concurrently choose how to divide the cake; at each odd round the environment decides how to cut the cake and how to assign each of the pieces to
a subset of the agents. Therefore, the problem of cutting a cake of size $d$ between $n$ agents is suitably divided into several simpler problems in which pieces of size $d' < d$ have to be split between $n' < n$ agents. The multi-player game terminates once each agent receives a slice.

The model uses as atomic propositions pairs $(i, c) \in [1, n] \times [1, d]$ indicating that agent $i$ gets a piece of cake of size $c$. The existence of a protocol for the cake-cutting problem is given by the following SL specification $\varphi$:

$$
\varphi \triangleq \langle x \rangle(\varphi_F \land \varphi_S),
$$

- $\varphi_F \triangleq \llbracket y_1 \rrbracket \ldots \llbracket y_n \rrbracket(\psi_{NE} \rightarrow \psi_E)$ ensures that the protocol $x$ is fair, i.e., all Nash equilibria $(y_1, \ldots, y_n)$ of the agents guarantee equity of the splitting;
- $\varphi_S \triangleq \llbracket y_1 \rrbracket \ldots \llbracket y_n \rrbracket \psi_{NE}$ ensures that the protocol has a solution, i.e., there is at least one Nash equilibrium;
- $\psi_{NE} \triangleq \bigwedge_{i=1}^n(\bigwedge_{v=1}^d(\llbracket z \rrbracket y_i p_i(v)) \rightarrow (\bigvee_{c=1}^d \llbracket p_i(c) \rrbracket))$ ensures that if agent $i$ has a strategy $z$ allowing him to get from the environment a slice of size $v$ once the strategies of the other agents are fixed, he is already able to obtain a slice of size $c \geq n$ by means of his original strategy $y_i$ (this can be ensured by taking $\llbracket \triangleright \rrbracket (\text{Environment}, x)(1, y_1) \ldots (n, y_n), \llbracket \triangleright \rrbracket (\text{Environment}, x)(1, y_1) \ldots (i, z) \ldots (n, y_n)$, and $p_i(c) \triangleq F(i, c)$);
- $\psi_E \triangleq \llbracket \triangleright \rrbracket \bigwedge_{i=1}^n p_i([d/n])$ ensures that each agent $i$ is able to obtain a piece of size $\lfloor d/n \rfloor$ ($\triangleright$ and $p_i$ are the same as in the item above).

We were able to verify the formula $\varphi$ defined above on a system with $n = 2$ agents and a cake of size $d = 2$. Moreover, we automatically synthesized a strategy $x$ for the environment. Details of the synthesized strategy can be found in the accompanying package and at [20]. We were not able to verify larger examples; for example with $n = 2, d = 3$, there are 29 reachable states, the encoding requires 105 Boolean variables and the intermediate BDDs have order of $10^9$ nodes. This should not be surprising given the difficulty of the cake-cutting problem.

**Conclusions.** In this paper we presented MCMAS-SLK, a novel symbolic model checker for the verification of systems against specifications given in SLK. A notable feature of the approach is that it allows for the automatic verification of sophisticated game concepts such as various forms of equilibria, including Nash equilibria. We are not aware of any other toolkit that enables the verification of SL or SLK; so we are unable to provide a direct comparison. Since MCMAS-SLK also supports epistemic modalities, this further enables us to express specifications concerning individual and group knowledge of cooperation properties; these are commonly employed when reasoning about multi-agent systems. Other tools supporting epistemic or plain ATL specifications exist [4,14–16]. In our experiments we found that the performance of MCMAS-SLK on the ATL and CTLK fragments was comparable to that of MCMAS, one of the leading checkers for multi-agent systems. This is because we adopted an approach in which the colouring with strategies is specification-dependent and is only performed after the set of reachable states is computed.
As described, a further notable feature of MCMAS-SLK is the ability to synthesise behaviours for multi-player games, thereby going beyond the classical settings of two-player games. In the future we intend to parallelise some of the routines developed in order to speed-up the verification time of SLK specifications.

References

1. T. Ágotnes, V. Goranko, and W. Jamroga. Alternating-Time Temporal Logics with Irrevocable Strategies. In *TARK’07*, pages 15–24, 2007.
2. T. Ágotnes and D. Walther. A Logic of Strategic Ability Under Bounded Memory. *JLLI*, 18(1):55–77, 2009.
3. R. Alur, T.A. Henzinger, and O. Kupferman. Alternating-Time Temporal Logic. *JACM*, 49(5):672–713, 2002.
4. R. Alur, T.A. Henzinger, F.Y.C. Mang, S. Qadeer, S.K. Rajamani, and S. Tasiran. MOCHA: Modularity in Model Checking. In *CAV’98*, LNCS 1427, pages 521–525. Springer, 1998.
5. T. Brihaye, A. Da Costa Lopes, F. Laroussinie, and N. Markey. ATL with Strategy Contexts and Bounded Memory. In *LFCS’09*, LNCS 5407, pages 92–106. Springer, 2009.
6. R.E. Bryant. Graph-Based Algorithms for Boolean Function Manipulation. *TC*, 35(8):677–691, 1986.
7. N. Bulling, J. Dix, and W. Jamroga. Model Checking Logics of Strategic Ability: Complexity. In *Specification and Verification of Multi-Agent Systems*, pages 125–159. Springer, 2010.
8. K. Chatterjee, T.A. Henzinger, and N. Piterman. Strategy Logic. *IC*, 208(6):677–693, 2010.
9. D. Chaum. The Dining Cryptographers Problem: Unconditional Sender and Recipient Untraceability. *JC*, 1:65–75, 1988.
10. E.M. Clarke and E.A. Emerson. Design and Synthesis of Synchronization Skeletons Using Branching-Time Temporal Logic. In *LP’81*, LNCS 131, pages 52–71. Springer, 1981.
11. E.A. Emerson and J.Y. Halpern. “Sometimes” and “Not Never” Revisited: On Branching Versus Linear Time. *JACM*, 33(1):151–178, 1986.
12. S. Even and A. Paz. A Note on Cake Cutting. *DAM*, 7:285–296, 1984.
13. R. Fagin, J.Y. Halpern, Y. Moses, and M.Y. Vardi. *Reasoning about Knowledge*. MIT Press, 1995.
14. P. Gammie and R. van der Meyden. MCK: Model Checking the Logic of Knowledge. In *CAV’04*, LNCS 3114, pages 479–483. Springer, 2004.
15. M. Kacprzak, W. Nabiałek, A. Niewiadomski, W. Penczek, A. Pórola, M. Szreter, B. Wozna, and A. Zbrzezny. VerICS 2007 - a Model Checker for Knowledge and Real-Time. *Fl*, 85(1-4):313–328, 2008.
16. A. Lomuscio, H. Qu, and F. Raimondi. MCMAS: A Model Checker for the Verification of Multi-Agent Systems. In *CAV’09*, LNCS 5643, pages 682–688. Springer, 2009.
17. A. Lomuscio and F. Raimondi. MCMAS: A Model Checker for Multi-agent Systems. In *TACAS’06*, LNCS 3920, pages 450–454. Springer, 2006.
18. A. Lomuscio and F. Raimondi. Model Checking Knowledge, Strategies, and Games in Multi-Agent Systems. In *AAMAS’06*, pages 161–168. International Foundation for Autonomous Agents and Multiagent Systems, 2006.
19. A.D.C. Lopes, F. Laroussinie, and N. Markey. ATL with Strategy Contexts: Expressiveness and Model Checking. In FSTTCS’10, LIPIcs 8, pages 120–132. Leibniz-Zentrum fuer Informatik, 2010.

20. MCMAS-SLK - A Model Checker for the Verification of Strategy Logic Specifications. http://vas.doc.ic.ac.uk/software/tools/.

21. F. Mogavero, A. Murano, G. Perelli, and M.Y. Vardi. Reasoning About Strategies: On the Model-Checking Problem. Technical report, arXiv, 2011.

22. F. Mogavero, A. Murano, G. Perelli, and M.Y. Vardi. What Makes ATL* Decidable? A Decidable Fragment of Strategy Logic. In CONCUR ’12, LNCS 7454, pages 193–208. Springer, 2012.

23. F. Mogavero, A. Murano, and M.Y. Vardi. Reasoning About Strategies. In FSTTCS’10, LIPIcs 8, pages 133–144. Leibniz-Zentrum fuer Informatik, 2010.

24. A. Pnueli. The Temporal Logic of Programs. In FOCS’77, pages 46–57. IEEE Computer Society, 1977.

25. F. Raimondi and A. Lomuscio. Automatic Verification of Multi-Agent Systems by Model Checking via Ordered Binary Decision Diagrams. JAL, 5(2):235–251, 2007.

26. R. van der Meyden and K. Su. Symbolic Model Checking the Knowledge of the Dining Cryptographers. In CSFW’04, pages 280–291. IEEE Computer Society, 2004.

27. D. Walther, W. van der Hoek, and M. Wooldridge. Alternating-Time Temporal Logic with Explicit Strategies. In TARK’07, pages 269–278, 2007.