Strategic Abilities of Asynchronous Agents: Semantic Side Effects

Extended Abstract

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ABSTRACT

Recently, we have proposed a framework for verification of agents' abilities in asynchronous multi-agent systems, together with an algorithm for automated reduction of models [14, 16]. The semantics was built on the modeling tradition of distributed systems. As we show here, this can sometimes lead to counterintuitive interpretation of formulas when reasoning about the outcome of strategies.

KEYWORDS

Alternating-time temporal logic; asynchronous systems; semantics

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1 INTRODUCTION

Alternating-time temporal logic **ATL*** [3, 4, 28] allows to express important functionality and safety requirements in a simple and intuitive way. Moreover, algorithms and tools for verification of strategic abilities have been in constant development for almost 20 years [1, 2, 5–10, 12, 13, 17–19, 21–23, 25, 26]. It has been recently proposed how to adapt the semantics of **ATL*** to asynchronous models [14, 16]. We show that the semantics leads to counterintuitive interpretation of strategic properties [15]. First, the semantics disregards finite paths. In consequence, it evaluates some intuitively losing strategies as winning, and vice versa. Secondly, the representations and their execution semantics (inherited from concurrent systems [27]) do not capture the asymmetry between agents that control which branch to take, and those receiving their choices.

2 MODELS OF MULTI-AGENT SYSTEMS

We first recall the models of asynchronous interaction in MAS, proposed in [14] and inspired by [11, 20, 27].

Definition 2.1 (Asynchronous MAS). An *asynchronous multi-agent system (AMAS)* S consists of n agents $\mathbb{A}\mathrm{gt} = \{1, \ldots, n\}$, each associated with a tuple $A_i = (L_i, \iota_i, Evt_i, R_i, T_i)$ including a set of *local states* $L_i = \{l_i^1, l_i^2, \ldots, l_i^{n_i}\}$, an *initial state* $\iota_i \in L_i$, and a set of *events* $Evt_i = \{\alpha_i^1, \alpha_i^2, \ldots, \alpha_i^{m_i}\}$. An agent's *repertoire of choices* $R_i : L_i \to 2^{Evt_i} \setminus \{\emptyset\}$ selects the events available at each local state.

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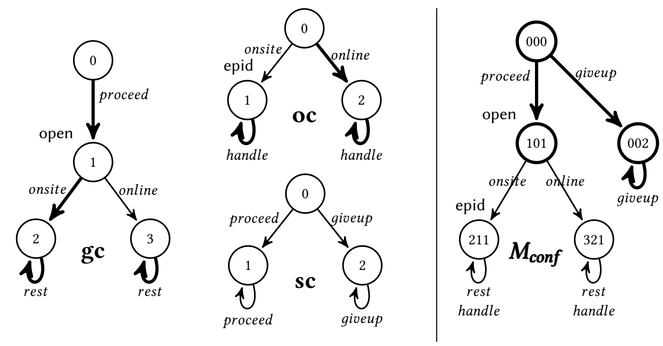

Figure 1: The AMAS from Ex. 2.4 and its model M_{conf}. In bold: strategy of coalition $\{gc, oc\}$ and the transitions it enables.

$T_i : L_i \times Evt_i \rightharpoonup L_i$ is a *local transition function* such that $T_i(l_i, \alpha)$ is defined iff $\alpha \in R_i(l_i)$. $Evt = \bigcup_{i \in \mathbb{A}\mathrm{gt}} Evt_i$ is the set of all events, and $Agent(\alpha) = \{i \in \mathbb{A}\mathrm{gt} \mid \alpha \in Evt_i\}$ is the set of agents whose repertoires include event α. Each agent i is endowed with a disjoint set of its *local propositions* $\mathcal{PV}_i$, and their *valuation* $V_i : L_i \to 2^{\mathcal{PV}_i}$. $\mathcal{PV} = \bigcup_{i \in \mathbb{A}\mathrm{gt}} \mathcal{PV}_i$ is the set of all local propositions.

We use the standard execution semantics from concurrency models, i.e., interleaving with synchronization on shared events.

Definition 2.2 (Model). Let S be an AMAS with n agents. Its *model* $IIS(S)$ extends S with: (i) the set of global states $St \subseteq L_1 \times \ldots \times L_n$, including an *initial state* $\iota = (\iota_1, \ldots, \iota_n)$; (ii) the *global transition function* $T : St \times Evt \rightharpoonup St$, defined by $T(g_1, \alpha) = g_2$ iff $T_i(g_1^i, \alpha) = g_2^i$ for all $i \in Agent(\alpha)$ and $g_1^i = g_2^i$ for all $i \in \mathbb{A}\mathrm{gt} \setminus Agent(\alpha)$; (iii) the *global valuation* of propositions $V : St \to 2^{\mathcal{PV}}$, defined as $V(l_1, \ldots, l_n) = \bigcup_{i \in \mathbb{A}\mathrm{gt}} V_i(l_i)$.

Definition 2.3 (Enabled events). $\alpha \in Evt$ is *enabled* at $g \in St$ if $g \xrightarrow{\alpha} g'$ for some $g' \in St$; $enabled(g)$ is the set of such events.

Moreover, let $A = (1, \ldots, m)$ and $\overrightarrow{\alpha}_A = (\alpha_1, \ldots, \alpha_m)$. $\beta \in Evt$ is *enabled by* $\overrightarrow{\alpha}_A$ *at* $g \in St$ iff for every $i \in Agent(\beta) \cap A$, we have $\beta = \alpha_i$, and for every $i \in Agent(\beta) \setminus A$, it holds that $\beta \in R_i(g^i)$. We denote the set of such events by $enabled(g, \overrightarrow{\alpha}_A)$. Clearly, $enabled(g, \overrightarrow{\alpha}_A) \subseteq enabled(g)$.

Example 2.4 (Conference in times of epidemic). Consider an AMAS consisting of the Steering Committee Chair (sc), the General Chair (gc), and the Organizing Committee Chair (oc). Faced with the Covid-19 epidemics, sc can decide to give up the conference, or send a signal to gc to proceed and open the meeting. Afterwards,

gc decides, and notifies oc, whether the conference will be run on site or online. In the former case, the epidemiologic risk is much higher, indicated by the atomic proposition epid. The AMAS and its model are shown in Figure 1.

3 REASONING ABOUT ABILITIES: ATL*

Let $\mathcal{PV}$ be a set of propositions and $\mathbb{A}\text{gt}$ the set of all agents. The syntax of *alternating-time temporal logic* **ATL*** [4, 28] is defined as:

$$\varphi ::= \mathrm{p} \mid \neg\varphi \mid \varphi \wedge \varphi \mid \langle\langle A\rangle\rangle\gamma, \qquad \gamma ::= \varphi \mid \neg\gamma \mid \gamma \wedge \gamma \mid \mathrm{X}\,\gamma \mid \gamma\,\mathrm{U}\,\gamma,$$

where $\mathrm{p} \in \mathcal{PV}$, $A \subseteq \mathbb{A}\text{gt}$, X stands for "next", and U for "strong until" ($\gamma_1\,\mathrm{U}\,\gamma_2$ denotes that γ_1 holds until γ_2 becomes true). The other operators, Boolean connectives, $\top$, and $\bot$ are defined as usual.

A *positional imperfect information (*ir*) strategy for i* is a function $\sigma_i \colon L_i \to Evt_i$ such that $\sigma_i(l) \in R_i(l)$ for each $l \in L_i$ [28]. The set of such strategies is denoted by Σ_i^{ir}. Collective strategies Σ_A^{ir} for $A \subseteq \mathbb{A}\text{gt}$ are defined as usual. By $\sigma_A(g) = (\sigma_1(g), \ldots, \sigma_m(g))$, we denote the tuple of selections of coalition $A = (1, \ldots, m)$ at state g. An infinite sequence of global states and events $\pi = g_0\alpha_0 g_1\alpha_1 g_2 \ldots$ is called a *path* if $g_j \xrightarrow{\alpha_j} g_{j+1}$ for every $j \geq 0$. The set of all paths in model M starting at state g is denoted by $\Pi_M(g)$.

The *outcome* of strategy $\sigma_A \in \Sigma_A^{\mathrm{ir}}$ in state $g \in St$ is the set $out_M(g, \sigma_A) \subseteq \Pi_M(g)$ such that $\pi = g_0\alpha_0 g_1\alpha_1 g_2 \cdots \in out_M(g, \sigma_A)$ iff $g_0 = g$, and $\forall j \geq 0\ \alpha_j \in enabled(\pi[j], \sigma_A(\pi[j]))$.

A path π satisfies *concurrency-fairness* (**CF**) if there is no event α enabled in all states of π from $\pi[n]$ on and such that for every α_j actually executed in $\pi[j]$, $j = n, n+1, \ldots$, we have $Agent(\alpha) \cap Agent(\alpha_j) = \emptyset$ [14]. Let $\Pi_M^{\mathbf{CF}}(g)$ be the set of all such paths starting at g and $out_M^{\mathbf{CF}}(g, \sigma_A) = out_M(g, \sigma_A) \cap \Pi_M^{\mathbf{CF}}(g)$. The ir-semantics of **ATL*** [14] in asynchronous MAS is defined by the clause:

$M, g \models_{\mathrm{ir}} \langle\langle A\rangle\rangle\gamma$ iff there is a strategy $\sigma_A \in \Sigma_A^{\mathrm{ir}}$ s.t. $out_M(g, \sigma_A) \neq \emptyset$ and $\forall \pi \in out_M(g, \sigma_A)$ we have $M, \pi \models_{\mathrm{ir}} \gamma$.

Moreover, the *concurrency-fair semantics* $\models_{\mathrm{ir}}^{\mathbf{CF}}$ is obtained by replacing $out_M(g, \sigma_A)$ with $out_M^{\mathbf{CF}}(g, \sigma_A)$ in the above clause.

Example 3.1. Clearly, formula $\langle\langle gc, oc\rangle\rangle\mathrm{G}\,\neg\mathrm{epid}$ holds in the conference model M_{conf}, in both $\models_{\mathrm{ir}}$ and $\models_{\mathrm{ir}}^{\mathbf{CF}}$ semantics. To see that, fix $\sigma_{gc}(1) = online = \sigma_{oc}(0)$ in the collective strategy of $\{gc, oc\}$.

4 SEMANTIC PROBLEMS

We describe two kinds of problematic phenomena that follow from adding the concept of strategic ability to representations and models derived from concurrency theory, the way it was defined in [14].

4.1 Deadlock Strategies and Finite Paths

An automata network is typically required to produce no deadlock states. In case of AMAS, the situation is more delicate. Even if the AMAS as a whole produces no deadlocks, some strategies might, which makes the interpretation of strategic modalities cumbersome. We illustrate this on the following example.

Example 4.1. Consider the 3-agent AMAS and its model M_{conf}, which are depicted in Figure 1. Clearly, M_{conf} has no deadlock states. Let us now look at the collective strategies of coalition $\{gc, oc\}$, with agent sc serving as the opponent. It is easy to see that the coalition has no way to prevent the opening of the conference, i.e., it cannot prevent the system from reaching state 101. However, the strategy depicted in Figure 1 produces only one *infinite* path, namely $(000\,giveup\,002\,giveup\ \ldots)$. Since the semantics in Section 3 disregards finite paths, we get $M_{conf}, 000 \models_{\mathrm{ir}} \langle\langle gc, oc\rangle\rangle\mathrm{G}\,\neg\mathrm{open}$ and $M_{conf}, 000 \models_{\mathrm{ir}}^{\mathbf{CF}} \langle\langle gc, oc\rangle\rangle\mathrm{G}\,\neg\mathrm{open}$, which is counterintuitive.

Things can get even trickier. For the ir-semantics, it may happen that the outcomes of some (or even all) strategies of a coalition are empty, which leads to situations where the intuitive meaning of a strategic formula differs significantly from its formal interpretation.

Example 4.2. Let us add the transition $0 \xrightarrow{proceed} 0$ in agent oc, and remove the transitions labeled with $giveup$ in agent sc. The resulting model M'_{conf} has no deadlock states, yet all the joint strategies of $\{gc, oc\}$ produce only finite runs. Since finite paths are not included in the outcome sets, and the semantics in Section 3 rules out strategies with empty outcomes, we get that $\neg\langle\langle gc, oc\rangle\rangle\mathrm{F}\,\top$, which seems definitely wrong.

Notice that removing the non-emptiness requirement from the semantic clause in Section 3 does not help. In that case, any joint strategy of $\{gc, oc\}$ could be used to demonstrate that $\langle\langle gc, oc\rangle\rangle\mathrm{G}\,\bot$.

4.2 Strategies in Asymmetric Interaction

In this section, we point out that AMAS is too restricted to model the strategic aspects of asymmetric synchronization (e.g., a sender sending a message to a receiver) in a natural way.

Example 4.3. Consider the global state 101 of the conference model M_{conf}, i.e., the state where it has just been decided to proceed with the conference. In that state, we have $\langle\langle gc\rangle\rangle\mathrm{G}\,\neg\mathrm{epid}$, meaning that the GC chair can make sure that the epidemic risk is always low. This is achieved by gc selecting $online$ at its local state 1. Then, the next transition can be obtained only if the oc module synchronizes with gc on event $online$. On the other hand, we also have that $\langle\langle oc\rangle\rangle\mathrm{F}$ epid holds at $M_{conf}, 101$, which is obtained by the OC's strategy selecting $onsite$ at 0. That is rather odd, in particular it violates the standard postulate of superadditivity [24].

The problem arises because the repertoire functions in AMAS are based on the assumption that the agent can choose any single event in $R_i(l_i)$. This does not allow for a natural specification of the situation when the transition is determined by another agent.

5 CONCLUSIONS

In this paper, we reconsider the asynchronous semantics of strategic ability for multi-agent systems, proposed recently in [14]. We show that adding strategic reasoning on top of the modeling machinery, inherited from distributed systems, leads to counterintuitive interpretation of formulas. We identify two main sources of problems. First, the execution semantics does not handle reasoning about deadlock-inducing strategies well. Secondly, the class of representations lacks constructions to resolve the tension between the asymmetry imposed by strategic operators on the one hand, and the asymmetry of interaction, e.g. between communicating parties.

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