Refining and Delegating Strategic Ability in ATL

Dimitar P. Guelev
Institute of Mathematics and Informatics
Bulgarian Academy of Sciences
Sofia, Bulgaria
gelevdp@math.bas.bg

We propose extending Alternating-time Temporal Logic (ATL) by an operator $\langle i \sqsubseteq \Gamma\rangle\varphi$ to express that i can distribute its powers to a set of sub-agents Γ in a way which satisfies ATL condition φ on the strategic ability of the coalitions they may form, possibly together with others agents. We prove the decidability of model-checking of formulas whose $\langle . \sqsubseteq .\rangle$-subformulas have no inner occurrences of $\langle . \sqsubseteq .\rangle$.

Introduction

The basic co-operation modality of Alternating-time Temporal Logics (ATL, [AHK97, AHK02]) invites perceiving agent coalitions as single agents who enjoy the combined powers of the coalition members. We investigate an operator to reverse this, by addressing the possibility to partition the strategic ability of a single agent among several sub-agents. We write $\langle i \sqsubseteq \Gamma\rangle\varphi$ to denote that agent i can partition its strategic ability among the members of a set of fresh sub-agents Γ in a way which satisfies φ, a formula written in terms of the new agents Γ who assume i's powers, and the other original agents, except i. For example, a purchase scenario with the vendor represented by salesperson *SP* and delivery team *DT* can be described as

$$\langle \mathit{vendor} \sqsubseteq \mathit{SP},\mathit{DT}\rangle \left(\begin{array}{l} \langle\langle \mathit{customer},\mathit{SP}\rangle\rangle\Diamond \mathit{purchase\ agreement} \wedge \\ [[\mathit{SP}]]\Box(\mathit{purchase\ agreement} \Rightarrow \langle\langle \mathit{DT},\mathit{customer}\rangle\rangle \circ \mathit{delivery}) \end{array}\right).$$

The combined powers of all of i's sub-agents are always equal to i's:

$$\langle\langle \Delta\cup\{i\}\rangle\rangle\varphi \Leftrightarrow [i \sqsubseteq \Gamma]\langle\langle(\Delta\setminus\{i\})\cup\Gamma\rangle\rangle\varphi$$

where $[i \sqsubseteq \Gamma]$ stands for $\neg\langle i \sqsubseteq \Gamma\rangle\neg$. Coalitions $\Delta \not\supseteq \Gamma$ may be weaker than i, but also have abilities contributed by agents from $\Delta\setminus\Gamma$. The realizability of schemes such as the example one generally depends on the basic composition of agents' actions. For instance, simple mechanisms make it always possible to deny the *proper* subsets of Γ all substantial strategic ability or make Γ use simple majority vote as indicated by the validity of the formula:

$$\neg\langle\langle\emptyset\rangle\rangle\varphi \wedge \langle\langle i\rangle\rangle\varphi \Rightarrow \langle i \sqsubseteq \Gamma\rangle \bigwedge_{\Delta\subsetneq\Gamma} \neg\langle\langle\Delta\rangle\rangle\varphi \wedge \langle i \sqsubseteq \Gamma\rangle \bigwedge_{\Delta\subset\Gamma,|\Delta|\leq|\Gamma\setminus\Delta|} \neg\langle\langle\Delta\rangle\rangle\varphi \wedge \bigwedge_{\Delta\subseteq\Gamma,|\Delta|>|\Gamma\setminus\Delta|} \langle\langle\Delta\rangle\rangle\varphi.$$

Subtracting strategic ability from one agent and transfering it in the form of a virtual sub-agent to another is a way of implementing *delegation*. Refinement can be instrumental in expressing the *alienability* of the ability in question. E.g.,

$$\langle\langle i\rangle\rangle \circ \mathit{unlock} \wedge \neg\langle\langle j\rangle\rangle \circ \mathit{unlock} \wedge \langle i \sqsubseteq i',\mathit{key}\rangle(\neg\langle\langle i'\rangle\rangle \circ \mathit{unlock} \wedge \langle\langle \underbrace{j,\mathit{key}}_{j'}\rangle\rangle \circ \mathit{unlock})$$

states the possibility of giving i's *unlock*ing ability separate identity *key* which enables its passage to j. The relevant vocabulary introduced consists of *key* itself, $\{j,\mathit{key}\}$ for j *key*-in-hand and i' for i without *key*, respectively.

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Notably we investigate refining and delegating powers and not responsibilities as in, e.g., [NR02]. Sub-agents can pursue their own goals. As it becomes clear below, they do so by influencing the choice of actions on behalf of their super-agent with the share of the super-agents' power given to them. Unlike proper delegation as in, e.g., [vdHWW10] and [BFD02], where givers and receivers of control co-exist, just $\langle i \sqsubseteq \Gamma\rangle$ is about *replacing* i by its sub-agents Γ.

Our main result about ATL with $\langle . \sqsubseteq .\rangle$ in this paper is a model-checking procedure for the subset in which the arguments of $\langle . \sqsubseteq .\rangle$ are supposed to be $\langle . \sqsubseteq .\rangle$-free, on finite CGMs.

Structure of the paper After brief formal preliminaries on ATL on GCMs, we introduce our proposed operator and model-checking algorithm. We conclude by briefly commenting on some more related work, assessing our result and mentioning some work in progress.

1 Preliminaries

Definition 1 (concurrent game structures and models) A *concurrent game structure* (CGS) for some given set of agents $\Sigma = \{1,\dots,N\}$ is a tuple of the form $\langle W, \langle Act_i : i \in \Sigma\rangle, o\rangle$ where

W is a non-empty set of *states*;

Act_i is a non-empty set of *actions*, $i \in \Sigma$; given a $\Gamma \subseteq \Sigma$, Act_Γ stands for $\prod\limits_{i\in\Gamma} Act_i$;

$o : W \times Act_\Sigma \to W$ is a *transition* function.

A *concurrent game model* (CGM) for Σ and atomic propositions AP is a tuple of the form $\langle W, \langle Act_i : i \in \Sigma\rangle, o, V\rangle$ where $\langle W, \langle Act_i : i \in \Sigma\rangle, o\rangle$ is a CGS for Σ and $V \subseteq W \times AP$ is a valuation relation.

In the sequel we always assume Act_i, $i \in \Sigma$ to be pairwise disjoint.

Below we write a_Γ to indicate that $a \in Act_\Gamma$ where $\Gamma \subseteq \Sigma$. If $a \in Act_\Delta$ and $\Gamma \subseteq \Delta$, then a_Γ also stands for the subvector of a consisting of the actions for the members of Γ. Given disjoint $\Gamma, \Delta \subseteq \Sigma$, we write $a_\Gamma \cdot b_\Delta$ for $c \in Act_{\Gamma\cup\Delta}$ which is defined by putting $c_i = a_i$ for $i \in \Gamma$ and $c_i = b_i$ for $i \in \Delta$.

Definition 2 (ATL **on CGMs)** The syntax of ATL formulas φ is given by the BNF

$$\varphi, \psi ::= \bot \mid p \mid (\varphi \Rightarrow \psi) \mid \langle\langle\Gamma\rangle\rangle \circ \varphi \mid \langle\langle\Gamma\rangle\rangle(\varphi \mathsf{U} \psi) \mid [[\Gamma]](\varphi \mathsf{U} \psi)$$

where p ranges over atomic propositions and Γ ranges over finite sets of agents. Satisfaction of ATL formulas are defined in terms of strategies. A *strategy* for $i \in \Sigma$ in CGM $M = \langle W, \langle Act_i : i \in \Sigma\rangle, o, V\rangle$ is a function from W^+ to Act_i. Given a vector of strategies $s_\Gamma = \langle s_i : i \in \Gamma\rangle$ for the members of $\Gamma \subseteq \Sigma$, the possible outcomes of Γ starting from state w and following s_Γ is the set of infinite runs

$$\mathrm{out}(w, s_\Gamma) = \{w^0 w^1 \ldots \in W^\omega : w^0 = w, w^{k+1} = o(w^k, a^k), a^0 a^1 \ldots \in Act_\Sigma^\omega,\ a_\Gamma^k = s_\Gamma(w^0 \ldots w^k), k < \omega\}.$$

Assuming a fixed M, we write S_Γ for the set of all vectors of strategies for Γ in M. Satisfaction is defined on CGMs M, states $w \in W$ and formulas φ:

$M, w \not\models \bot$		
$M, w \models p$	iff	$V(w, p)$
$M, w \models \varphi \Rightarrow \psi$	iff	either $M, w \models \psi$ or $M, w \not\models \varphi$
$M, w \models \langle\langle\Gamma\rangle\rangle \circ \varphi$	iff	there exists an $s_\Gamma \in S_\Gamma$ s. t. $w^0 w^1 \ldots \in \mathrm{out}(w, s_\Gamma)$ implies $M, w^1 \models \varphi$
$M, w \models \langle\langle\Gamma\rangle\rangle(\varphi \mathsf{U} \psi)$	iff	there exists an $s_\Gamma \in S_\Gamma$ s. t. for any $w^0 w^1 \ldots \in \mathrm{out}(w, s_\Gamma)$ there exists a $k < \omega$ s. t. $M, w^0 \models \varphi, \ldots, M, w^{k-1} \models \varphi$ and $M, w^k \models \psi$
$M, w \models [[\Gamma]](\varphi \mathsf{U} \psi)$	iff	for every $s_\Gamma \in S_\Gamma$ there exists a $w^0 w^1 \ldots \in \mathrm{out}(w, s_\Gamma)$ and a $k < \omega$ s. t. $M, w^0 \models \varphi, \ldots, M, w^{k-1} \models \varphi$ and $M, w^k \models \psi$

$\top$, $\neg$, $\vee$, $\wedge$ and $\Leftrightarrow$ and the remaining combinations of $\langle\langle.\rangle\rangle$ and $[\![.]\!]$ with the temporal connectives $\circ$, $\Diamond$ and $\Box$ are regarded as derived constructs. See, e.g., [AHK02] for the definitions.

We write $\Sigma(\varphi)$ for the set of agents which are mentioned in formula φ.

2 Refining Strategic Ability in ATL: $\mathrm{ATL}_{\sqsubseteq}$

Definition 3 (Γ-to-i homomorphisms of CGMs) Given Σ and AP, an $i \in \Sigma$ and some non-empty set of agent names Γ which is disjoint with Σ, consider CGMs $M = \langle W, \langle Act_j : j \in \Sigma\rangle, o, V\rangle$ and $M' = \langle W', \langle Act'_j : j \in \Sigma'\rangle, o', V'\rangle$ for AP, and Σ and $\Sigma' = (\Sigma \setminus \{i\}) \cup \Gamma$, respectively. A mapping $h : \prod\limits_{j\in\Gamma} Act'_j \to Act_i$ is a Γ*-to-*i *homomorphism from* M' *to* M, if

$W' = W$, $V' = V$ and $Act_j = Act'_j$ for $j \in \Sigma \setminus \{i\}$;

range $h = Act_i$ and $o'(w,a) = o(w, a_{\Sigma\setminus\{i\}} \cdot h(a_\Gamma))$ for all $w \in W$ and all $a \in Act'_{\Sigma'}$.

Informally, if M is a Γ-to-i homomorphism of M, then the strategic ability of i in M is distributed among the new agents $j \in \Gamma$ in M'. For each action a_i of i in M there exists a vector of actions a_Γ for the members of Γ in M' such that $h(a_\Gamma) = a_i$. Together with the correspondence between the outcome functions o and o' of the two models, this means that the combined powers of the members of Γ in M' are equal to those of i in M, but proper sub-coalitions of Γ may be less powerful. Next we introduce the operator which is central to this work.

Definition 4 (refinement operator) Let M, i and Γ be as above. Let $\Sigma(\varphi) \subseteq (\Sigma \setminus \{i\}) \cup \Gamma$. Then

$$M, w \models \langle i \sqsubseteq \Gamma\rangle\varphi$$

iff there exist an M' for Σ' and AP such that $M', w \models \varphi$, and a Γ-to-i homomorphism from M' to M.

The occurrences of $j \in \Gamma$ in $\langle i \sqsubseteq \Gamma\rangle\varphi$ are *bound* in the usual sense. Informally, $\langle i \sqsubseteq \Gamma\rangle\varphi$ means that i can distribute its powers among the members of Γ so that φ holds in about the new set of agents. Its dual $[i \sqsubseteq \Gamma]\varphi$ means that φ holds regardless of how the powers of i are distributed among the agents from Γ.

3 Model-checking $\langle . \sqsubseteq . \rangle$-Flat $\mathrm{ATL}_{\sqsubseteq}$

$\langle . \sqsubseteq . \rangle$-flat $\mathrm{ATL}_{\sqsubseteq}$ is the subset of $\mathrm{ATL}_{\sqsubseteq}$ in which no occurrences of $\langle . \sqsubseteq . \rangle$ are allowed in the scope of $\langle . \sqsubseteq . \rangle$. Therefore our task amounts to providing an algorithm for deciding whether $M, w \models \langle i \sqsubseteq \Gamma\rangle\varphi$ for φ with no further occurrences of $\langle . \sqsubseteq . \rangle$. Our algorithm combines ATL model checking and solving satisfiability in the $\langle\langle.\rangle\rangle\circ$-subset of ATL, or, equivalently, in Coalition Logic [Pau02].

We only do the case of $\langle i \sqsubseteq \Gamma\rangle\varphi$ with φ being a boolean combination of $\langle\langle.\rangle\rangle\circ$-formulas with boolean combinations of atomic propositions as the arguments of $\langle\langle.\rangle\rangle\circ$ in detail here. Let CGM M be as above and consider a CGM $M' = \langle W, \langle Act'_i : i \in \Sigma'\rangle, o', V\rangle$, $\Sigma' = \Sigma \setminus \{i\} \cup \Gamma$, and a Γ-to-i homomorphism h from M' to M. Consider a $\langle\langle\Delta\rangle\rangle \circ \chi \in \mathrm{Subf}(\varphi)$. For $M', w \models \langle\langle\Delta\rangle\rangle \circ \chi$ to hold, there should be a vector of actions a_Δ such that, for any $b_{\Gamma\setminus\Delta}$, $a_{\Delta\setminus\Gamma} \cdot h(a_{\Delta\cap\Gamma} \cdot b_{\Gamma\setminus\Delta})$ gives $\Delta \setminus \Gamma \cup \{i\}$ a strategy to achieve $\circ\chi$ in M. For a fixed $a_{\Delta\setminus\Gamma}$ this means

$$h(a_{\Delta\cap\Gamma} \cdot b_{\Gamma\setminus\Delta}) \in \{a_i \in Act_i : \forall c_{\Sigma\setminus(\Delta\cup\{i\})} M, o(w, a_{\Delta\setminus\Gamma} \cdot a_i \cdot c_{\Sigma\setminus(\Delta\cup\{i\})}) \models \chi\} \qquad (1)$$

Henceforth we write $A_{i,a_{\Delta\setminus\Gamma},w,\chi}$ for the subset of Act_i in (1).

Now consider a CGM $\overline{M} = \langle \overline{W}, \langle \overline{Act}_i : i \in \Gamma\rangle, \overline{o}, \overline{V}\rangle$ for Γ as the set of agents, $\overline{AP} = Act_i$ as the set of atomic propositions and $\overline{W} = Act_i \cup \{w^0\}$ as the set of states. Let $\overline{V}(w,a)$ be equivalent to $w = a$ for

$a \in Act_i$, thus enabling reference to each individual action of i. The intended meaning of the states of $\overline{M}$ from Act_i is to represent the possible choices of i's actions by the members of Γ, and w^0 is a distinguished reference state. Let $\overline{Act}_j = Act'_j$ for $j \in \Gamma$, and let $\overline{o}(w^0, a) = h(a)$ for all $a \in \overline{Act}_\Gamma$. Then

$$\overline{M}, w^0 \models \langle\langle \emptyset \rangle\rangle \circ \bigvee_{a \in Act_i} a \wedge \bigwedge_{a,b \in Act_i, a \neq b} \langle\langle \emptyset \rangle\rangle \circ \neg(a \wedge b) \wedge \bigwedge_{a \in Act_i} \langle\langle \Gamma \rangle\rangle \circ a, \tag{2}$$

since each of i's actions can be enforced by its representing coalition Γ.

Let the translation $\mathtt{t}$ replace subformulas of φ of the form $\langle\langle \Delta \rangle\rangle \circ \chi$ by their corresponding

$$\bigvee_{a_{\Delta\setminus\Gamma} \in Act_{\Delta\setminus\Gamma}} \langle\langle \Delta \cap \Gamma \rangle\rangle \circ \bigvee_{a_i \in A_{i, a_{\Delta\setminus\Gamma}, w, \chi}} a_i.$$

Then $M, w \models \langle i \sqsubseteq \Gamma \rangle \varphi$ is equivalent to $\overline{M}, w^0 \models \mathtt{t}(\varphi)$.

Conversely, let a model $\overline{M} = \langle \overline{W}, \langle \overline{Act}_i : i \in \Gamma \rangle, \overline{o}, \overline{V} \rangle$ exist such that $\overline{M}, w^0 \models \mathtt{t}(\varphi)$ and (2) hold. Then we can define an M' and a Γ-to-i homomorphism h to witness $M, w \models \langle i \sqsubseteq \Gamma \rangle \varphi$ as follows. We put $Act'_j = \overline{Act}_j$, $j \in \Gamma$. For every $a_\Gamma \in \overline{Act}_\Gamma$, we define $h(a_\Gamma)$ as the unique $a_i \in Act_i$ such that $\overline{M}, o(w^0, a_\Gamma) \models a_i$. We determine o' from the identity $o'(w, a) = o(w^0, h(a))$. Now a direct check shows that $M, w \models \langle i \sqsubseteq \Gamma \rangle \varphi$.

Hence, the existence of a model $\overline{M}$ which satisfies $\mathtt{t}(\varphi)$ and (2) at some state is equivalent to the satisfaction of φ at the given state w of the given M. Since satisfiability of formulas such as $\mathtt{t}(\varphi)$ and (2) is solvable, this entails the solvability of model-checking $\langle . \sqsubseteq . \rangle$-formulas.

4 Concluding Remarks

Related Work There is an analogy between our $\langle . \sqsubseteq . \rangle$ and the refinement quantifier of *Refinement Modal Logic* [BvDF$^+$12] and its extensions to special classes of multimodal frames [HFD12]. Formal studies focusing on controlling the decisions of self-interested delegates can be found in [KW12, EPW13]. A notion of *refinement* of alternating transition systems, ATL's original type of models from [AHK97], allowing, unlike [AHKV98], different sets of agents to be related, was studied in [RS01]. Abstraction techniques with the agents being just *knowers* were studied in [ED07, CDLR09]. Abstraction involving over- and under-approximation of coalitions to contain model size was proposed in [KL11]. A formalization of teaming sub-agents under a scheduler as turn-based simulation was proposed in [GF10, GPS13]. The revised form [JMS13] of *modular interpreted systems* [JÅ07] looks more fit to capture varying numbers of agents. Distinctively, our setting is about varying the set of agents in a system by just redistributing strategic ability, with the overall activities which the system unchanged.

The Model-checking Algorithm By a routine effort, our model-checking algorithm extends to formulas of the form $\langle i_1 \sqsubseteq \Gamma_1 \rangle \ldots \langle i_m \sqsubseteq \Gamma_m \rangle \varphi$, which are needed for modelling several parties interacting through representatives. However, in its part beyond the $\langle\langle . \rangle\rangle \circ$ subset, which is not included here, the algorithm is nowhere close to optimal and therefore can mostly serve as proof of the decidability of model-checking for $\langle . \sqsubseteq . \rangle$-flat $\mathrm{ATL}_\sqsubseteq$ in principle.

Some Work in Progress $\langle . \sqsubseteq . \rangle$ admits a definition with no reference to Γ-to-i homomorphisms, which enables translating the $\langle\langle . \rangle\rangle\circ$-subset of $\mathrm{ATL}_\sqsubseteq$ into a promising looking subset of many-sorted predicate logic or, similarly, into $\langle\langle . \rangle\rangle\circ$-subsets of explicit strategy languages such as in [CHP07, MMV10]. Exploring the tractability of the translated formulas is one way of addressing satisfiability in $\mathrm{ATL}_\sqsubseteq$, which is yet to be done. The translation gives rise to a companion operator, which holds some promise as the means for indirect axiomatization. Regarding direct axiomatization, for any fixed i and Γ, $\langle i \sqsubseteq \Gamma \rangle$ is a

KD- and, with some adjustment to compensate for switching to the local agent vocabulary $\Sigma \setminus \{i\} \cup \Gamma$, also a **T**-modality. We have also established some non-trivial specific basic equivalences leading to a normal form, and a conventional-looking rule for introducing negative occurrences of $\langle . \sqsubseteq . \rangle$, but still lack sufficiently strong axioms for the positive occurrences.

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