Rational Capability in Concurrent Games

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ABSTRACT

We extend concurrent game structures (CGSs) with a simple notion of preference over computations and define a minimal notion of rationality for agents based on the concept of dominance. We use this notion to interpret a CL and an ATL languages that extend the basic CL and ATL languages with modalities for rational capability, namely, a coalition's capability to *rationally* enforce a given property. For each of these languages, we provide results about the complexity of satisfiability checking and model checking as well as about axiomatization.

KEYWORDS

Logics for Multi-Agent Systems; Rationality; Strategic Reasoning

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1 INTRODUCTION

The field of logics for multi-agent systems has been very active in the last twenty years. Different logics have been proposed and their proof-theoretic, complexity and algorithmic aspects for satisfiability and model checking studied in detail. The list of logics in this area is long. It includes alternating-time temporal logic (ATL) [2, 21], its "next"-fragment called coalition logic (CL) [19, 41], the logic of agency STIT [10, 12], and the more expressive strategy logic (SL) [15, 38]. A widely used semantics for interpreting these logics is based on concurrent game structures (CGSs), transition systems in which state-transitions are labeled by joint actions of agents. A CGS allows us to represent the repeated interaction between multiple agents in a natural way as well as their choices and strategies. It is similar to the game-theoretic concept of dynamic game in which players move sequentially or repeatedly. But an element that is missing from CGSs compared to dynamic games is the preference of the agents. Indeed, most logics for multi-agent systems including ATL, CL, SL and STIT abstract away from the agents' preferences as they are only interested in representing and reasoning about the *game form*, namely, the way an outcome is determined based on the agents' concurrent choices over time.

In this paper we extend CGSs with a basic concept of preference. This is in order to have a semantics that allows us to represent a game in its entirety, capturing both its aspects (the game form and the agents' preferences), and consequently to reason about rational choices and strategies in the game. Specifically, we introduce a new class of structures called CGS with preferences (CGSP) that includes one preference ordering for each agent at each state in the underlying CGS. An agent's preference at a given state is relative to the set of computations (or histories) starting at this state. We consider an interesting subclass of CGSP with *stable preferences* in which agents' preferences do not change over time. This reminds the notion of time consistency of preferences studied in economics, in opposition to time inconsistency [18]. We employ CGSP to interpret two novel languages R-ATL and R-CL (ATL/CL with minimal rationality) that extend the basic ATL and CL languages with modal operators for *rational* capability, namely, a coalition's capability to enforce a given outcome by choosing a *rational* strategy. The notion of rationality that we use to define these operators is based on strong dominance: the collective strategy of a coalition is rational insofar as the individual strategies that compose it are not strongly dominated. It is a minimal notion of rationality since it does not require the agent to reason about what others will choose. It simply requires an agent not to play a strategy that is beaten by another of its strategies regardless of what the others choose. In [28], it is shown that this minimal dominance-based requirement of rationality is particularly suitable for defining the deontic notion of obligation, namely, what an agent or coalition ought to do. The general idea of refining the capability operators of ATL by restricting quantification to the agents' rational strategies is shared with Bulling et al. [14]. But unlike us, they do not extend CGSs with an explicit notion of preference. In their semantics sets of plausible/rational strategies can be only referred to via atomic plausibility terms (constants) whose interpretation is "hardwired" in the model. A similar idea can also be found in [36] in which rational STIT ("seeing to it that") modalities are introduced.

For each of the languages we introduce, results about the complexity of satisfiability checking and model checking as well as about axiomatization are provided. In particular, the following are the main results of the paper:

- tree-like model property for R-ATL;
- polynomial embeddings of R-ATL into ATL under the stable preference assumption, and of R-CL into CL both under the stable preference assumption and with no assumption;
- thanks to the embeddings, tight complexity results of satisfiability checking for R-ATL and R-CL;
- a sound and complete axiomatization for the logic R-CL;
- a model checking algorithm for R-ATL for the class of concurrent game structures with short-sighted preferences.

The paper is organized as follows. In Section 2, we discuss related work. In Section 3, we present the semantic foundation of our framework. Then, in Section 4, we introduce the languages of

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R-ATL and R-CL. Section 5 is devoted to the tree-like model property, the embeddings and the complexity results for our logics. In Section 6 we deal with axiomatization, while in Section 7 we move to model checking. Detailed proofs are available on [32].

2 RELATED WORK

Several works have studied logics for reasoning about preferences, without considering the strategic and temporal dimensions. In particular, van Benthem and Liu [42] proposed a dynamic logic of knowledge update and preference upgrade, where incoming suggestions or commands change the preference relations. Lorini [35] presented a general logical framework for reasoning about agents' cognitive attitudes, which captures concepts of knowledge, belief, desire, and preference. Grossi et al. [23] investigated four different semantics for conditional logics based on preference relations over alternatives. The semantics differ in the way of selecting the most preferred alternative, which includes maximality, optimality, unmatchedness, and acceptability.

Two of the most important developments in logics for strategic reasoning are ATL [2] and SL [38]. Both these logics have been considered in the imperfect information setting [7, 8, 29]. Unlike ATL, SL can express complex solution concepts (such as dominant strategy equilibrium) and thus capture some notions of rationality. However, in both logics, agents' preferences are not modeled intrinsically, instead, their goals can be represented as Boolean formulas. A way to incorporate preferences in those logics is to include atomic propositions stating that the utility of an agent is greater than or equal to a given value [5], which requires an exhaustive enumeration for each relevant utility threshold. The extensions of ATL and SL with quantitative semantics [11, 30] generalize fuzzy temporal logics and capture quantitative goals. This approach has been recently used to represent agents' utilities in mechanism design [37].

The dominance relation among strategies has been considered alongside specifications in temporal logics [3, 4]. These works provide algorithms for synthesizing best-effort strategies, which are maximal in the dominance order, in the sense that they achieve the agent goal against a maximal set of environment specifications.

Rationality in concurrent games is typically associated with agents' knowledge and preferences. Know-How Logic with the Intelligence [40] captures rational agents' capabilities that depend on the intelligence information about the opponents' actions. The interplay between agents' preferences and their knowledge was described in [39]. A sound, complete, and decidable logical system expressing higher-order preferences to the other agents was given in [31]. However, none of these three papers address the connection between rational agents' capabilities and their preferences.

Our work is also related to the research on rational verification and synthesis. The first is the problem of checking whether a temporal goal is satisfied in some or all game-theoretic equilibria of a CGS [1, 27]. Rational synthesis consists in the automated construction of such a model [16, 17]. Different types of agent objectives have been considered, including Boolean temporal specifications [26], mean payoff [24], and lexicographical preferences [25]

While being able to analyze multi-agent systems with respect to solution concepts, both rational verification and model-checking SL specifications face high complexity issues. In particular, key decision problems for rational verification with temporal specifications are known to be 2EXPTIME-complete [27] and model-checking SL is non-elementary for memoryful agents [38].

ATL with plausibility [14] allows the specification of sets of rational strategy profiles, and reason about agents' play if the agents can only play these strategy profiles. The approach considers plausibility terms, which are mapped to a set of strategy profiles. The logic includes formulas of the form $(\text{set-pl}\,\omega)\varphi$, meaning that "assuming that the set of rational strategy profiles is defined in terms of the plausibility terms ω, then, it is plausible to expect that φ holds". This idea was extended in [13] to a variant of SL for imperfect information games. However, as emphasized in the introduction, Bulling et al. do not represent agents' preferences in their semantics. This is a crucial difference between their work and ours. Our main focus is on extending CGSs with preferences, studying the dynamic properties of agents' preferences in concurrent games, and defining a logic of rational capability with the help of the semantics combining CGSs with preferences.

3 SEMANTICS

In this section, we first define the basic elements of the semantics: the notions of concurrent game structure (CGS), computation and strategy. Then, we extend a CGS with preferences and use the resulting structure to define the notion of dominated strategy.

3.1 Preliminaries

Let $\mathbb{P}$ be a countable set of atomic propositions and $\mathbb{AGT} = \{1, \ldots, n\}$ a finite set of agents. A coalition is a (possibly empty) set of agents from $\mathbb{AGT}$. Coalitions are denoted by $C, C', \ldots$ $\mathbb{AGT}$ is also called the grand coalition. The following definition introduces the concept of concurrent game structure (CGS), as defined in [10].

DEFINITION 1 (CGS). *A concurrent game structure (CGS) is a tuple $M = \big(W, \mathbb{ACT}, (\mathcal{R}_\delta)_{\delta\in\mathbb{JACT}}, \mathcal{V}\big)$ with*

- *W a non-empty set of worlds (or states),*
- *$\mathbb{ACT}$ a set of action names and $\mathbb{JACT} = \mathbb{ACT}^n$ the corresponding set of joint action names,*
- *$\mathcal{R}_\delta \subseteq W \times W$ a transition relation for joint action δ,*
- *$\mathcal{V} : W \longrightarrow 2^{\mathbb{P}}$ a valuation function,*

such that for every $w \in W$ and $\delta \in \mathbb{JACT}$:

*(C1) $\mathcal{R}_\delta$ is deterministic (*collective choice determinism*),*[1]
*(C2) if $\delta(1) \in C_1(w), \ldots, \delta(n) \in C_n(w)$ then $\mathcal{R}_\delta(w) \neq \emptyset$ (*independence of choices*),*
*(C3) $\mathcal{R}$ is serial (*neverending interaction*),*[2]

where

$$\mathcal{R} = \bigcup_{\delta\in\mathbb{JACT}} \mathcal{R}_\delta,$$

$$C_i(w) = \{a \in \mathbb{ACT} : \exists\delta \in \mathbb{JACT} \text{ s.t. } \mathcal{R}_\delta(w) \neq \emptyset \text{ and } \delta(i) = a\}.$$

The previous definition slightly differs from the usual definition of CGS used for interpreting ATL [21] and strategy logic (SL) [38]. In particular a CGS, as defined in Definition 1, is a multi-relational structure, *alias* Kripke model, the kind of structure traditionally

[1]A relation $\mathcal{R}$ is deterministic if $\forall w, v, u \in W$, if $w\mathcal{R}v$ and $w\mathcal{R}u$ then $v = u$.
[2]A relation $\mathcal{R}$ is serial if $\forall w \in W, \exists v \in W$ s.t. $w\mathcal{R}v$.

used in modal logic. Every joint action is associated to a binary relation over states satisfying certain properties, while in the usual semantics for ATL and SL a transition function is used that maps a state and a joint action executable at this state to a successor state. The two variants are interdefinable. We use the multi-relational variant of CGS since it is particularly convenient for proving the model-theoretic and proof-theoretic results in the rest of the paper.

The relation $\mathcal{R}_\delta$ with $\delta \in \mathbb{JACT}$ is used to identify the set of states $\mathcal{R}_\delta(w) = \{v \in W : w\mathcal{R}_\delta v\}$ that are reachable from state w when the agents collectively choose joint action δ at state w, that is, when every agent i chooses the individual component $\delta(i)$ at state w. $\mathcal{R}_\delta(w) = \emptyset$ means that the joint action δ cannot be collectively chosen by the agents at state w. The set $C_i(w)$ in the previous definition corresponds to agent i's choice set at state w, i.e., the set of actions that agent i can choose at state w (or agent i's set of available actions at w). Note that an agent's choice set may vary from one state to another, i.e., it might be the case that $C_i(w) \neq C_i(v)$ if $w \neq v$. Constraint C1 captures *collective choice determinism*: the outcome of a collective choice of all agents is uniquely determined. Constraint C2 corresponds to the *independence of choices* assumption: if agent 1 can individually choose action $\delta(1)$, agent 2 can individually choose action $\delta(2)$,..., agent n can individually choose action $\delta(n)$, then the agents can collectively choose joint action δ. More intuitively, this means that agents can never be deprived of choices due to the choices made by other agents. Constraint C3 corresponds to the *neverending interaction* assumption: every state in a CGS has *at least one successor*, where the successor of a given state is a state which is reachable from the former via a collective choice of all agents.

For notational convenience, in the rest of the paper, sometimes use the abbreviation $TRel \stackrel{\text{def}}{=} (\mathcal{R}_\delta)_{\delta\in\mathbb{JACT}}$ to indicate a profile of transition relations, and write $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ instead of $M = \big(W, \mathbb{ACT}, (\mathcal{R}_\delta)_{\delta\in\mathbb{JACT}}, \mathcal{V}\big)$ for a CGS.

Example 1 (Crossing road). *Assume a model M_{cross} representing a system with two vehicles (denoted v_1 and v_2) that need to decide how to act when approaching intersections. Each vehicle can either go straight on (Move) or wait (Skip). Their goal is to cross the road, but they prefer to avoid collisions, which happen when they go straight at the same time. M_{cross} is represented by Figure 1. The initial state is denoted with init, while crash denotes the failure state (i.e., a collision occurred). The proposition c_1 (similarly, c_2) indicates the situation in which the vehicle v_1 has crossed (resp., v_2).*

The following definition introduces the notions of path and computation, two essential elements of temporal logics and logics for strategic reasoning.

Definition 2 (Path and computation). *A* path *in a CGS $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ is a sequence $\lambda = w_0w_1w_2\ldots$ of states from W such that $w_k\mathcal{R}w_{k+1}$ for all $k \geq 0$, where we recall $\mathcal{R} = \bigcup_{\delta\in\mathbb{JACT}}\mathcal{R}_\delta$. The set of all paths in M is denoted by $Path_M$. Given a path λ of length higher than k' and $k \leq k'$, the k-th element of λ is denoted by $\lambda(k)$. A* computation *(or* full path*) in M is a path $\lambda \in Path_M$ such that there is no $\lambda' \in Path_M$ of which λ is a proper prefix. The set of all computations in M is denoted by $Comp_M$. The set of all computations in M starting at world $w \in W$ (i.e., whose first element is w) is denoted by $Comp_{M,w}$.*

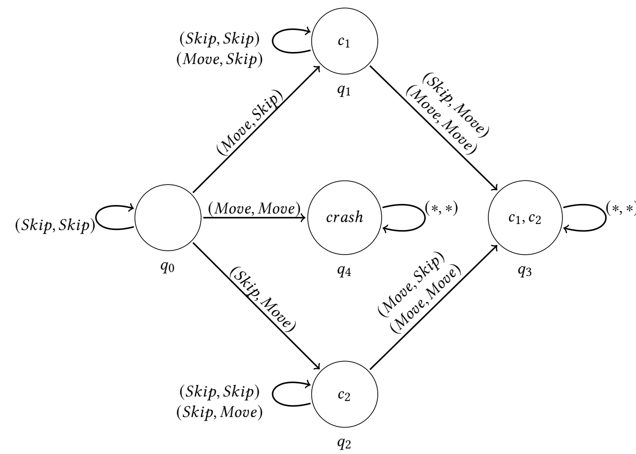

Figure 1: Model M_{cross} representing a system with two vehicles approaching an intersection. Arrows represent transitions between states and are labeled by joint actions of v_1 and v_2. $(*, *)$ denotes any action.

From Constraint C3 in Definition 1, it is easy to prove the following fact.

Fact 1. *If $\lambda \in Comp_M$ then λ is infinite.*

An agent's individual perfect recall strategy is nothing but the specification of a choice for the agent at the end of every finite path in a CGS. It is formally defined as follows.

Definition 3 (Individual strategy). *Let $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ be a CGS. A (perfect recall) strategy for agent i in M is a function f_i that maps every finite path $w_0 \ldots w_k \in Path_M$ to a choice $f_i(w_0 \ldots w_k) \in C_i(w_k)$ available to agent i at the end of this finite path, where again we recall $\mathcal{R} = \bigcup_{\delta\in\mathbb{JACT}}\mathcal{R}_\delta$.*

A collective strategy is the assignment of an individual strategy to each agent.

Definition 4 (Collective strategy). *Let $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ be a CGS. A collective strategy for a coalition C in M is a function $\mathcal{F}_C$ that associates every agent $i \in C$ to a strategy $\mathcal{F}_C(i)$ for i in M. The set of collective strategies for coalition C in M is denoted by Str_M^C. Its elements are denoted by $\mathcal{F}_C, \mathcal{F}'_C, \ldots$*

Given a coalition C, $\mathcal{F}_C \in Str_M^C$ and $\mathcal{F}'_{\mathbb{AGT}\setminus C} \in Str_M^{\mathbb{AGT}\setminus C}$, we define $\mathcal{F}_C \oplus \mathcal{F}'_{\mathbb{AGT}\setminus C} \in Str_M^{\mathbb{AGT}}$ to be the composition of the two strategies:

$$\mathcal{F}_C \oplus \mathcal{F}'_{\mathbb{AGT}\setminus C}(i) = \mathcal{F}_C(i) \text{ if } i \in C,$$
$$\mathcal{F}_C \oplus \mathcal{F}'_{\mathbb{AGT}\setminus C}(i) = \mathcal{F}'_{\mathbb{AGT}\setminus C}(i) \text{ otherwise.}$$

Given an initial state w and a collective strategy for a coalition C we can compute the set of computations generated by this strategy starting at w.

Definition 5 (Generated computations). *Let $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ be a CGS, $w \in W$ and $\mathcal{F}_C \in Str_M^C$. The set $\mathcal{O}_M(w, \mathcal{F}_C)$ denotes the set of all computations $\lambda = w_0w_1w_2\ldots$ in $Comp_M$ such that $w_0 = w$ and for every $k \geq 0$, there is $\delta \in \mathbb{JACT}$ such that:*

- $\mathcal{F}_C(i)(w_0 \ldots w_k) = \delta(i)$ *for all* $i \in C$, *and*
- $w_k \mathcal{R}_\delta w_{k+1}$.

$O_M(w, \mathcal{F}_C)$ is the set of computations in M generated by coalition C's collective strategy $\mathcal{F}_C$ starting at state w. Note that the set $O_M(w, \mathcal{F}_{\mathbb{AGT}})$ is a singleton because of Constraint C1 for collective choice determinism. The unique element of $O_M(w, \mathcal{F}_{\mathbb{AGT}})$ is denoted by $\lambda^{M,w,\mathcal{F}_{\mathbb{AGT}}}$.

Note also that there is a single strategy $\mathcal{F}_\emptyset$ for the empty coalition, the one which makes no assignments at all. Thus, $O_M(w, \mathcal{F}_\emptyset) = Comp_{M,w}$.

3.2 Adding Preferences

In this section, we extend the notion of CGS of Definition 1 with preferences.

Definition 6 (CGS with preferences). *Let* $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ *be a CGS. A preference structure for M is a tuple* $\Omega_M = (\preceq_{i,w})_{i \in \mathbb{AGT}, w \in W}$ *where, for every* $i \in \mathbb{AGT}$ *and* $w \in W$, $\preceq_{i,w}$ *is total preorder over* $Comp_{M,w}$. *We call the pair* (M, Ω_M) *a CGS with preferences (CGSP). As usual, we write* $\lambda' \prec_{i,w} \lambda$ *if* $\lambda' \preceq_{i,w} \lambda$ *and* $\lambda \not\preceq_{i,w} \lambda'$.

We say that the CGSP (M, Ω_M) *has stable preferences if the following condition holds:*

$$(\mathbf{SP})\ \forall w, v \in W, \forall \lambda, \lambda' \in Comp_{M,v}, \text{ if } w\mathcal{R}v \text{ then } \big(\lambda' \preceq_{i,v} \lambda \text{ iff } w\lambda' \preceq_{i,w} w\lambda\big).$$

Constraint **SP** for stable preferences captures the fact that an agent's preference is stable over time: an agent prefers a computation λ to a computation λ' starting at the same world v if and only if it prefers the precursor of λ (i.e., $w\lambda$) to the precursor of λ' (i.e., $w\lambda'$) at each predecessor w of v.

Example 2 (Crossing road (cont.)). *Let us resume our example. The preference relations* $\preceq_{v_1,w_0}$ *and* $\preceq_{v_2,w_0}$ *of agents* v_1 *and* v_2 *(resp.) in state* w_0 *is illustrated in Figure 2 (preference relation over the other states are analogous). The intuition of the preference of each agents* v_i *is that the less preferred situation for each agent is when there is a collision (the computation indicated with* $-_i$*). Additionally, the agents prefer computations in which he crossed (indicated by* $+_i$*) to the ones he did not (*$=_i$*). We denote by* $P_{cross} = (M_{cross}, \Omega_{M_{cross}})$ *the CGS* M_{cross} *with preferences* $\Omega_M = (\preceq_{i,w})_{i \in \mathbb{AGT}, w \in W}$.

The strategies in which the agent performs Move in the initial state is not dominated, because it may lead to the state where he crossed or to a collision. On the other hand, the strategy in which the agent waits (action Skip) when only the other agent has crossed is dominated by the strategy in which he moves whenever agent v_2 *has crossed.*

The following definition introduces the notion of dominated strategy, the essential constituent of minimal rationality for agents.

Definition 7 (Dominated strategies). *Let* $P = (M, \Omega_M)$ *be a CGSP with* $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ *a CGS and* $\Omega_M = (\preceq_{i,w})_{i \in \mathbb{AGT}, w \in W}$ *a preference structure for M,* $i \in \mathbb{AGT}$, $w \in W$, *and* $\mathcal{F}_{\{i\}}, \mathcal{F}'_{\{i\}} \in Str_M^{\{i\}}$. *We say that at world w agent i's strategy* $\mathcal{F}'_{\{i\}}$ *dominates agent i's strategy* $\mathcal{F}_{\{i\}}$ *iff*

$$\forall \mathcal{F}''_{\mathbb{AGT}\setminus\{i\}} \in Str_M^{\mathbb{AGT}\setminus\{i\}}, \lambda^{M,w,\mathcal{F}_{\{i\}} \oplus \mathcal{F}''_{\mathbb{AGT}\setminus\{i\}}} \prec_{i,w} \lambda^{M,w,\mathcal{F}'_{\{i\}} \oplus \mathcal{F}''_{\mathbb{AGT}\setminus\{i\}}}.$$

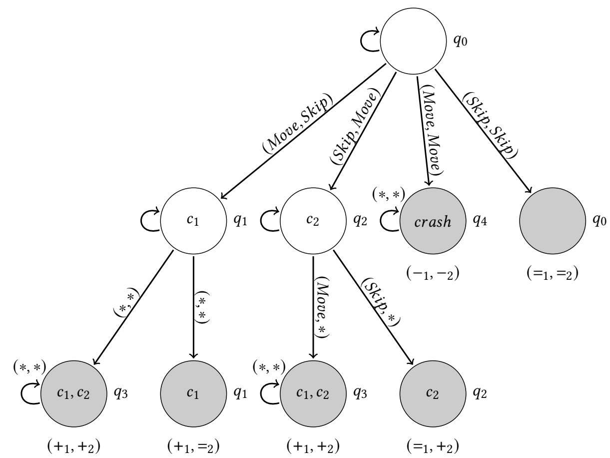

Figure 2: Representation of the unravelling of M_{cross} from the initial state (w_0). Branches represent (groups of) computations. Transitions are labeled by the action taken by v_1 and $*$ denotes any action. Self-loops indicate computations where the state is repeated. Grey states indicate computations with an infinite suffix that repeats on the same state. Labels in the form under the grey states represent the preference relations $\preceq_{v_1,w_0}$ and $\preceq_{v_2,w_0}$ of the agents v_1 and v_2, respectively. Computations labeled with $+_i$ are strictly preferred to $=_i$ by agent v_i, and $=_i$ are strictly preferred to $-_i$ by agent v_i (where $i = \{1, 2\}$).

Agent i's strategy $\mathcal{F}_{\{i\}}$ *is said to be dominated at w if there exists another strategy* $\mathcal{F}'_{\{i\}}$ *of i which dominates* $\mathcal{F}_{\{i\}}$ *at w. Agent i's set of dominated strategies at w is denoted by* $Dom^i_{M,w}$.

In the next section we introduce a novel language that extends the language of ATL with a family of operators for rational capability. It will be interpreted by means of the notion of CGSP.

4 LANGUAGE

The language of R-ATL (ATL with *minimal rationality*), denoted by $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$, is defined by the following grammar:

$$\begin{aligned} \varphi, \psi \quad ::= \quad & p \mid \neg\varphi \mid \varphi \wedge \psi \mid \langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi \mid \langle\!\langle C \rangle\!\rangle \mathsf{G}\varphi \mid \langle\!\langle C \rangle\!\rangle (\varphi \mathsf{U} \psi) \\ & \langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi \mid \langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}\varphi \mid \langle\!\langle C \rangle\!\rangle^{rat} (\varphi \mathsf{U} \psi), \end{aligned}$$

where p ranges over $\mathbb{P}$ and C ranges over $2^{\mathbb{AGT}}$. The other Boolean connectives and constructs $\vee, \rightarrow, \leftrightarrow, \top, \bot$ are defined as abbreviations in the usual way.

On the one hand, formulas $\langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi$, $\langle\!\langle C \rangle\!\rangle \mathsf{G}\varphi$ and $\langle\!\langle C \rangle\!\rangle (\varphi \mathsf{U} \psi)$ capture the notion of strategic capability. They have the usual ATL readings: $\langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi$ has to be read "coalition C has a strategy at its disposal which guarantees that φ is going to be true in the next state", while $\langle\!\langle C \rangle\!\rangle \mathsf{G}\varphi$ has to be read "coalition C has a strategy at its disposal which guarantees that φ will always be true". Finally, $\langle\!\langle C \rangle\!\rangle (\varphi \mathsf{U} \psi)$ has to be read "coalition C has a strategy at its disposal which guarantees that φ will be true until ψ is true". On the other hand, formulas $\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi$, $\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}\varphi$ and $\langle\!\langle C \rangle\!\rangle^{rat} (\varphi \mathsf{U} \psi)$ capture the notion of *rational* strategic capability: $\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi$ has to be read "coalition C has a *rational* strategy at its disposal which guarantees that φ is going to be true in the next state", $\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{G}\varphi$ has to be read "coalition C has a *rational* strategy at its disposal which guarantees that φ will always be true". Finally, $\langle\!\langle C\rangle\!\rangle^{rat}(\varphi \mathbin{\mathsf{U}} \psi)$ has to be read "coalition C has a *rational* strategy at its disposal which guarantees that φ will be true until ψ is true".

Formulas of the language $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$ are evaluated relative to a pair (P, w) with $P = (M, \Omega_M)$ a CGSP, $M = (W, \mathbb{ACT}, \mathit{TRel}, \mathcal{V})$ a CGS, Ω_M a preference structure for M and $w \in W$, as follows:

$$
\begin{aligned}
(P,w) \models p &\iff p \in \mathcal{V}\big(\lambda(0)\big),\\
(P,w) \models \langle\!\langle C\rangle\!\rangle \mathsf{X}\varphi &\iff \exists \mathcal{F}_C \in \mathit{Str}^C_M \text{ s.t. } \forall \lambda \in O(w,\mathcal{F}_C),\\
&\qquad \big(P,\lambda(1)\big) \models \varphi,\\
(P,w) \models \langle\!\langle C\rangle\!\rangle \mathsf{G}\varphi &\iff \exists \mathcal{F}_C \in \mathit{Str}^C_M \text{ s.t. } \forall \lambda \in O(w,\mathcal{F}_C),\\
&\qquad \forall k > 0, \big(P,\lambda(k)\big) \models \varphi,\\
(P,w) \models \langle\!\langle C\rangle\!\rangle (\varphi \mathbin{\mathsf{U}} \psi) &\iff \exists \mathcal{F}_C \in \mathit{Str}^C_M \text{ s.t. } \forall \lambda \in O(w,\mathcal{F}_C),\\
&\qquad \exists k > 0 \text{ s.t. } \big(P,\lambda(k)\big) \models \psi \text{ and}\\
&\qquad \forall h \in \{1,\dots,k-1\}, \big(P,\lambda(h)\big) \models \varphi,\\
(P,w) \models \langle\!\langle C\rangle\!\rangle^{rat} \mathsf{X}\varphi &\iff \exists \mathcal{F}_C \in \mathit{Str}^C_M \text{ s.t. } \forall i \in C,\\
&\qquad \mathcal{F}_C|_{\{i\}} \notin \mathit{Dom}^i_{M,w} \text{ and}\\
&\qquad \forall \lambda \in O(w,\mathcal{F}_C), \big(P,\lambda(1)\big) \models \varphi,\\
(P,w) \models \langle\!\langle C\rangle\!\rangle^{rat} \mathsf{G}\varphi &\iff \exists \mathcal{F}_C \in \mathit{Str}^C_M \text{ s.t. } \forall i \in C,\\
&\qquad \mathcal{F}_C|_{\{i\}} \notin \mathit{Dom}^i_{M,w} \text{ and}\\
&\qquad \forall \lambda \in O(w,\mathcal{F}_C),\\
&\qquad \forall k > 0, \big(P,\lambda(k)\big) \models \varphi,\\
(P,w) \models \langle\!\langle C\rangle\!\rangle^{rat} (\varphi \mathbin{\mathsf{U}} \psi) &\iff \exists \mathcal{F}_C \in \mathit{Str}^C_M \text{ s.t. } \forall i \in C,\\
&\qquad \mathcal{F}_C|_{\{i\}} \notin \mathit{Dom}^i_{M,w} \text{ and}\\
&\qquad \forall \lambda \in O(w,\mathcal{F}_C),\\
&\qquad \exists k > 0 \text{ s.t. } \big(P,\lambda(k)\big) \models \psi \text{ and}\\
&\qquad \forall h \in \{1,\dots,k-1\}, \big(P,\lambda(h)\big) \models \varphi,
\end{aligned}
$$

where $\mathcal{F}_C|_{\{i\}}$ is the restriction of function $\mathcal{F}_C$ to $\{i\} \subseteq C$. Note that the difference between the strategic capability operators and the *rational* strategic capability operators lies in the restriction to non-dominated (minimally rational) strategies. While the ATL strategic capability operators existentially quantify over the set of collective strategies of the coalition C (i.e., $\exists \mathcal{F}_C \in \mathit{Str}^C_M$), their rational counterparts existentially quantify over the set of collective strategies of the coalition C such that all their individual components are not dominated (i.e., $\forall i \in C, \mathcal{F}_C|_{\{i\}} \notin \mathit{Dom}^i_{M,w}$).

The following fragment defines the language of R-CL (CL with *Minimal Rationality*), denoted by $\mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$:

$$\varphi, \psi \quad ::= \quad p \mid \neg\varphi \mid \varphi \wedge \psi \mid \langle\!\langle C\rangle\!\rangle \mathsf{X}\varphi \mid \langle\!\langle C\rangle\!\rangle^{rat} \mathsf{X}\varphi,$$

where p ranges over $\mathbb{P}$ and C ranges over $2^{\mathbb{AGT}}$.

The languages $\mathcal{L}_{\text{ATL}}(\mathbb{P}, \mathbb{AGT})$ of ATL and $\mathcal{L}_{\text{CL}}(\mathbb{P}, \mathbb{AGT})$ of CL are defined as usual:

- $\mathcal{L}_{\text{ATL}}(\mathbb{P}, \mathbb{AGT})$ is the fragment of $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$ with no formulas $\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{X}\varphi$, $\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{G}\varphi$, $\langle\!\langle C\rangle\!\rangle^{rat}(\varphi \mathbin{\mathsf{U}} \psi)$, and
- $\mathcal{L}_{\text{CL}}(\mathbb{P}, \mathbb{AGT})$ is the fragment of $\mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$ with no formulas $\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{X}\varphi$.

Example 3 (Crossing road (cont.)). *Returning to our example, it is easy to check that* $(P_{croos}, w_0) \models \langle\!\langle v_1\rangle\!\rangle^{rat}\mathsf{X}\neg crash$ *that is, agent* v_1 *has a rational strategy to avoid a collision. However, the agent* v_1 *has no rational strategy to ensure to eventually cross the street, that is,* $(P_{croos}, w_0) \not\models \langle\!\langle v_1\rangle\!\rangle^{rat}\top\mathsf{U}c_1$.

5 TREE-LIKE MODEL PROPERTY AND EMBEDDING

In this section we first state the tree-like model property for the language $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$. Thanks to it, we will provide a polynomial embedding of the R-ATL-language into the ATL-language which also offers a polynomial embedding of the R-CL-language into the CL-language. Thanks to the embedding we will be able to provide tight complexity results for satisfiability checking for the two languages $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$ and $\mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$.

5.1 Tree-Like Model Property

Let $\mathcal{R}^*$, $\mathcal{R}^-$ and $\mathcal{R}^+$ be, respectively, the reflexive and transitive closure, the inverse, and the transitive closure of $\mathcal{R} = \bigcup_{\delta \in \mathbb{JACT}} \mathcal{R}_\delta$.

Definition 8. *Let* $M = (W, \mathbb{ACT}, \mathit{TRel}, \mathcal{V})$ *be a CGS. We say that:*

- *M has a unique root iff there is a unique* $w_0 \in W$ *(called the* root*), such that, for every* $v \in W$, $w_0\mathcal{R}^*v$;
- *M has unique predecessors iff for every* $v \neq w_0$*, the cardinality of* $\mathcal{R}^-(v)$ *is at most one;*
- *M has no cycles iff* $\mathcal{R}^+$ *is irreflexive;*
- *M is tree-like iff it has a unique root, unique predecessors and no cycles;*
- *M is joint action disjoint iff for every* $w \in W$ *and for every* $\delta, \delta' \in \mathbb{JACT}$*, if* $\delta \neq \delta'$ *then* $\mathcal{R}_\delta(w) \cap \mathcal{R}_{\delta'}(w) = \emptyset$.

The property of "having stable preferences" defined in Definition 6 and the properties of "having unique root", "having unique predecessors", "having no cycles", "being tree-like" and "being joint action disjoint" defined in Definition 8 are abbreviated *sp*, *ur*, *up*, *nc*, *tr* and *ad*. The properties defined in Definition 8 naturally extend to CGSPs: the CGSP $P = (M, \Omega_M)$ satisfies one of these properties if the underlying CGS M satisfies it. For every $X \subseteq \{sp, ur, up, nc, tr, ad\}$, the class of CGS satisfying the properties in X is denoted by $\mathbf{CP}^X$. By $\mathbf{CP}^\emptyset$, we denote the class of all CGSP.

The following Lemma 1 is a tree-like model property for the language $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$. The proof of the lemma is given in Appendix A [32] The proof relies on a three-step transformation. First, we transform a CGSP into a CGSP with joint action disjointness by constructing one copy of a state for each possible joint action. Second, we transform the resulting CGSP with joint action disjointness into a CGSP with joint action disjointness, unique predecessor and no cycles. This second transformation associates every state of the original CGSP to a finite path. Third, we generate the submodel from the point of evaluation of the original model to guarantee unique rootness.

Lemma 1. *Let* $\varphi \in \mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$*. Then,*

- φ *is satisfiable for the class* $\mathbf{CP}^\emptyset$ *iff* φ *is satisfiable for the class* $\mathbf{CP}^{\{tr,ad\}}$,
- φ *is satisfiable for the class* $\mathbf{CP}^{\{sp\}}$ *iff* φ *is satisfiable for the class* $\mathbf{CP}^{\{sp,tr,ad\}}$.

5.2 Embedding

Let us consider the following translation $tr : \mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT}) \longrightarrow \mathcal{L}_{\text{ATL}}(\mathbb{P}^+, \mathbb{AGT})$ with $\mathbb{P}^+ = \mathbb{P} \cup \{rat_i : i \in \mathbb{AGT}\}$:

$$\begin{aligned}
tr(p) &= p,\\
tr(\neg\varphi) &= \neg tr(\varphi),\\
tr(\varphi \wedge \psi) &= tr(\varphi) \wedge tr(\psi),\\
tr(\langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi) &= \langle\!\langle C \rangle\!\rangle \mathsf{X}\, tr(\varphi),\\
tr(\langle\!\langle C \rangle\!\rangle \mathsf{G}\varphi) &= \langle\!\langle C \rangle\!\rangle \mathsf{G}\, tr(\varphi),\\
tr\big(\langle\!\langle C \rangle\!\rangle (\varphi \,\mathsf{U}\, \psi)\big) &= \langle\!\langle C \rangle\!\rangle \big(tr(\varphi) \,\mathsf{U}\, tr(\psi)\big),\\
tr(\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi) &= \langle\!\langle C \rangle\!\rangle \mathsf{X}\big(rat_C \wedge tr(\varphi)\big),\\
tr(\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}\varphi) &= \langle\!\langle C \rangle\!\rangle \mathsf{G}\big(rat_C \wedge tr(\varphi)\big),\\
tr\big(\langle\!\langle C \rangle\!\rangle^{rat} (\varphi \,\mathsf{U}\, \psi)\big) &= \langle\!\langle C \rangle\!\rangle \big((rat_C \wedge tr(\varphi)) \,\mathsf{U}\, (rat_C \wedge tr(\psi))\big),
\end{aligned}$$

with $rat_C \stackrel{\text{def}}{=} \bigwedge_{i \in \mathbb{AGT}} rat_i$ and the special atomic formula rat_i standing for "agent i is rational".

The idea of the translation is to transform a rational capability operator into its ordinary capability counterpart using the special atomic formulas rat_i. Specifically, the fact that a coalition C has a rational strategy to ensure a given outcome is translated into the fact that the coalition C has a strategy to force the outcome by ensuring that all its members are rational. As the following theorem highlights, satisfiability of R-ATL-formulas is reducible to satisfiability of ATL-formulas using the translation tr. The proof of the theorem is given in Appendix B [32]. The proof relies on a non-trivial construction which transforms a tree-like CGSP into a new tree-like CGSP in which an atomic formula of type rat_i matches the computations that are generated by a non-dominated strategy of agent i. The assumption of stable preferences is essential to guarantee that this matching exists.

Theorem 1. *Let $\varphi \in \mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$. Then, φ is satisfiable for the class $\mathbf{CP}^{\{sp\}}$ iff $\big(\bigwedge_{i \in \mathbb{AGT}} \langle\!\langle \{i\} \rangle\!\rangle \mathsf{G} rat_i\big) \wedge tr(\varphi)$ is satisfiable for the class $\mathbf{CP}^{\{sp\}}$.*

As the following theorem highlights, if we restrict to the language $\mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$ the translation tr also provides an embedding for the general class $\mathbf{CP}$. The proof of Theorem 2 is a straightforward adaptation of the proof of Theorem 1. Instead of matching an atomic formula rat_i with a computation, for every state in a tree-like CGSP we match rat_i with a successor of this state along a computation generated by a non-dominated strategy of agent i. The assumption of stable preferences is no longer required since the translation of formula $\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi$ only refers to the truth values of atoms rat_i in the next state.

Theorem 2. *Let $\varphi \in \mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$. Then, φ is satisfiable for the class $\mathbf{CP}$ iff $\big(\bigwedge_{i \in \mathbb{AGT}} \langle\!\langle \{i\} \rangle\!\rangle \mathsf{X} rat_i\big) \wedge tr(\varphi)$ is satisfiable for the class $\mathbf{CP}$.*

The following complexity result is a direct corollary of Theorems 1 and 2, the fact that the size of $tr(\varphi)$ is polynomial in the size of the input formula φ and the fact that satisfiability checking for ATL is Exptime-complete [43] and satisfiability checking for CL is Pspace-complete [41].

Corollary 1. *Checking satisfiability of formulas in the language $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$ relative to the class $\mathbf{CP}^{\{sp\}}$ is Exptime-complete. It is Pspace-complete relative to both classes $\mathbf{CP}$ and $\mathbf{CP}^{\{sp\}}$, when restricting to the fragment $\mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$.*

Before concluding this section, we would like to highlight the fact that the translation tr from the language $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$ to the language $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}^+, \mathbb{AGT})$ is adequate for the stable preference semantics only. It does not work for the general class $\mathbf{CP}$. To see this, it is sufficient to observe that, on the one hand, the following formula is valid for the general class $\mathbf{CP}$:

$$\varphi_{C,p} =_{def} \langle\!\langle C \rangle\!\rangle \mathsf{G}(rat_C \wedge p) \rightarrow \langle\!\langle C \rangle\!\rangle \mathsf{X} \langle\!\langle C \rangle\!\rangle \mathsf{G}(rat_C \wedge p).$$

Indeed, $\varphi_{C,p}$ is a basic validity of ATL. Moreover, we have

$$tr\big(\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p \rightarrow \langle\!\langle C \rangle\!\rangle \mathsf{X} \langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p\big) = \varphi_{C,p}.$$

But, on the other hand, the formula $\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p \rightarrow \langle\!\langle C \rangle\!\rangle \mathsf{X} \langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p$ is not valid for the class $\mathbf{CP}$, which is the same thing as saying that $\neg\big(\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p \rightarrow \langle\!\langle C \rangle\!\rangle \mathsf{X} \langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p\big)$ is satisfiable for $\mathbf{CP}$. A countermodel for this formula is given in Appendix C [32].

Thus, there is no analog of Theorem 1 for the class $\mathbf{CP}$ since there exists a formula φ (i.e., $\neg\big(\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p \rightarrow \langle\!\langle C \rangle\!\rangle \mathsf{X} \langle\!\langle C \rangle\!\rangle^{rat} \mathsf{G}p\big)$) which is satisfiable for $\mathbf{CP}$ and, at the same time, $\big(\bigwedge_{i \in \mathbb{AGT}} \langle\!\langle \{i\} \rangle\!\rangle \mathsf{G} rat_i\big) \wedge tr(\varphi)$ is not satisfiable for $\mathbf{CP}$ since $\neg tr(\varphi)$ (i.e., $\neg\neg\varphi_{C,p}$ which is equivalent to $\varphi_{C,p}$) is valid for $\mathbf{CP}$.

6 AXIOMATIZATION FOR R-CL

In this section, we first introduce an axiomatic system for R-CL and then show its soundness and completeness.

Definition 9 (Axiomatic system for R-CL). *The axiomatic system for R-CL consists of the following axioms:*

All tautologies of propositional logic	$(\top)$
$\neg\langle\!\langle C \rangle\!\rangle \mathsf{X}\bot$	(A-NAAA)
$\langle\!\langle \emptyset \rangle\!\rangle^{rat} \mathsf{X}\varphi \leftrightarrow \langle\!\langle \emptyset \rangle\!\rangle \mathsf{X}\varphi$	(A-NP$_\emptyset$)
$\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi \rightarrow \langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi$	(A-MR)
$\langle\!\langle \emptyset \rangle\!\rangle \mathsf{X}(\varphi \rightarrow \psi) \rightarrow (\langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi \rightarrow \langle\!\langle C \rangle\!\rangle \mathsf{X}\psi)$	(A-MG0)
$\langle\!\langle \emptyset \rangle\!\rangle^{rat} \mathsf{X}(\varphi \rightarrow \psi) \rightarrow (\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi \rightarrow \langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\psi)$	(A-MG1)
$\langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi \rightarrow \langle\!\langle C' \rangle\!\rangle \mathsf{X}\varphi$, *for* $C \subseteq C'$	(A-MC0)
$\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi \rightarrow \langle\!\langle C' \rangle\!\rangle^{rat} \mathsf{X}\varphi$, *for* $C \subseteq C'$	(A-MC1)
$\langle\!\langle C \rangle\!\rangle \mathsf{X}\top$	(A-NCS)
$(\langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi \wedge \langle\!\langle C' \rangle\!\rangle \mathsf{X}\psi) \rightarrow \langle\!\langle C \cup C' \rangle\!\rangle \mathsf{X}(\varphi \wedge \psi)$, *for* $C \cap C' = \emptyset$	(A-Sup0)
$(\langle\!\langle C \rangle\!\rangle^{rat} \mathsf{X}\varphi \wedge \langle\!\langle C' \rangle\!\rangle^{rat} \mathsf{X}\psi) \rightarrow \langle\!\langle C \cup C' \rangle\!\rangle^{rat} \mathsf{X}(\varphi \wedge \psi)$, *for* $C \cap C' = \emptyset$	(A-Sup1)
$\langle\!\langle C \rangle\!\rangle \mathsf{X}(\varphi \vee \psi) \rightarrow (\langle\!\langle C \rangle\!\rangle \mathsf{X}\varphi \vee \langle\!\langle \mathbb{AGT} \rangle\!\rangle \mathsf{X}\psi)$	(A-Cro)
$\langle\!\langle \mathbb{AGT} \rangle\!\rangle^{rat} \mathsf{X}(\varphi \vee \psi) \rightarrow (\langle\!\langle \mathbb{AGT} \rangle\!\rangle^{rat} \mathsf{X}\varphi \vee \langle\!\langle \mathbb{AGT} \rangle\!\rangle^{rat} \mathsf{X}\psi)$	(A-DGRC)

and the following rules of inference:

$$\frac{\varphi, \varphi \rightarrow \psi}{\psi} \qquad \text{(MP)}$$

$$\frac{\varphi}{\langle\!\langle \emptyset \rangle\!\rangle \mathsf{X}\varphi} \qquad \text{(N)}$$

The names of axioms and inference rules reflect their intuitions. Axiom A-NAAA is called *no absurd available action* and its intuition is that a coalition's available joint action cannot ensure a logically absurd result. Axiom $\texttt{A-NP}_{\emptyset}$ is called *no preference for empty coalition*. As the empty coalition has no preference, its rational capability coincides with its ordinary capability. Axiom A-MR is called *monotonicity of rational capability*: if an outcome can be ensured by a coalition in a rational way then it can be ordinarily ensured by the coalition. Axiom A-MG0 captures *monotonicity of goals*. Axiom A-MG1 is its rational counterpart, namely, *monotonicity of goals under rationality*. Their intuition is that ordinary and rational capabilities are monotonic with respect to goals. Similarly, Axiom A-MC0 and A-MC1 capture, respectively, *monotonicity of coalitions* and *monotonicity of coalitions under rationality*: ordinary and rational capability are monotonic with respect to coalitions. Axiom A-NCS captures *non-empty choice set*, namely, the fact that a coalition has always an available joint action. Axiom A-Sup0 and Axiom A-Sup1 capture, respectively, *superadditivity* and *superadditivity under rationality*. Axiom A-Cro is the so-called *crown* axiom: it was called this way in [20] since it corresponds to the fact that the effectivity function of a game is a crown. Axiom A-DGRC captures *determinism of the grand coalition's rational collective choice*. The inference rules are *modus ponens* (MP) and *necessitation for the empty coalition* (N). Note that $\langle\!\langle\emptyset\rangle\!\rangle\mathsf{X}$ is a normal modal operator because of the validity-preserving rule of inference N and the fact that the following formula is valid:

$$\langle\!\langle\emptyset\rangle\!\rangle\mathsf{X}(\varphi \rightarrow \psi) \rightarrow (\langle\!\langle\emptyset\rangle\!\rangle\mathsf{X}\varphi \rightarrow \langle\!\langle\emptyset\rangle\!\rangle\mathsf{X}\psi),$$

which is an instance of Axiom A-MG0.

The style of our axiomatic system differs from CL's [41]. We want to get the axiomatization as close as possible to the semantics by having as many correspondences as possible between axioms and semantic constraints. In particular, we have the following correspondences: Axiom A-NCS corresponds to Constraint C3 in Definition 1; Axioms A-Sup0 and A-Sup1 correspond to Constraint C2; Axioms A-Cro and A-DGRC correspond to Constraint C1.

In Appendix D [32], we show that the axiomatic system of CL is derivable from R-CL. Note that $\neg\langle\!\langle\emptyset\rangle\!\rangle\mathsf{X}\neg\varphi \rightarrow \langle\!\langle\mathbb{AGT}\rangle\!\rangle\mathsf{X}\varphi$ is an axiom of CL. However, by Fact 2 whose proof is given in Appendix C [32], $\neg\langle\!\langle\emptyset\rangle\!\rangle^{rat}\mathsf{X}\neg\varphi \rightarrow \langle\!\langle\mathbb{AGT}\rangle\!\rangle^{rat}\mathsf{X}\varphi$ is not valid. So, the logic for the fragment of R-CL only containing rational capability operators is substantially different from CL.

Fact 2. *The following two formulas are not valid for the class* **CP**:

$$\neg\langle\!\langle\emptyset\rangle\!\rangle^{rat}\mathsf{X}\neg\varphi \rightarrow \langle\!\langle\mathbb{AGT}\rangle\!\rangle^{rat}\mathsf{X}\varphi \qquad (\mathtt{Max}_{\mathbb{AGT}}1)$$

$$\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{X}(\varphi \vee \psi) \rightarrow (\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{X}\varphi \vee \langle\!\langle\mathbb{AGT}\rangle\!\rangle^{rat}\mathsf{X}\psi) \qquad (\mathtt{Cro1})$$

As usual, for every $\varphi \in \mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$, we write $\vdash \varphi$ to mean that φ is deducible in R-CL, that is, there is a sequence of formulas $(\varphi_1, \dots, \varphi_m)$ such that:

- $\varphi_m = \varphi$, and
- for every $1 \leq k \leq m$, either φ_k is an instance of one of the axiom schema of R-CL or there are formulas $\varphi_{k_1}, \dots, \varphi_{k_t}$ such that $k_1, \dots, k_t < k$ and $\frac{\varphi_{k_1}, \dots, \varphi_{k_t}}{\varphi_k}$ is an instance of some inference rule of R-CL.

We are going to prove soundness and completeness of the logic R-CL relative to the model class **CP**. So, in the rest of this section, when talking about validity of a formula $\varphi \in \mathcal{L}_{\text{R-CL}}(\mathbb{P}, \mathbb{AGT})$ we mean validity of φ relative to the class **CP**.

Our completeness proof for R-CL differs from Pauly's one for CL [41]. It is structured in four parts: an induction on the modal degree of formulas, the normal form (Lemma 2), the downward validity (Lemma 3), and the upward derivability (Lemma 4). Before introducing them, we need to introduce some preliminary notions.

Definition 10 (Literal). *A propositional literal is either p or $\neg p$ for any $p \in \mathbb{P}$. A modal R-CL-literal is a formula of type $\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{X}\varphi$ or $\neg\langle\!\langle C\rangle\!\rangle^{rat}\mathsf{X}\varphi$, for any coalition C and $\varphi \in \mathcal{L}_{R\text{-}CL}(\mathbb{P}, \mathbb{AGT})$.*

The following definition introduces the notion of standard R-CL disjunction.

Definition 11 (Standard R-CL disjunction). *A formula of type*

$$\chi \vee \Big(\big(\bigwedge_{x \in \mathbb{X}} \langle\!\langle C_x\rangle\!\rangle\mathsf{X}\psi_x \wedge \bigwedge_{x \in \mathbb{X}^{rat}} \langle\!\langle C_x\rangle\!\rangle^{rat}\mathsf{X}\psi_x \big) \rightarrow \big(\bigvee_{y \in \mathbb{Y}} \langle\!\langle C_y\rangle\!\rangle\mathsf{X}\psi_y \vee \bigvee_{y \in \mathbb{Y}^{rat}} \langle\!\langle C_y\rangle\!\rangle^{rat}\mathsf{X}\psi_y \big) \Big)$$

is called standard R-CL disjunction, where $\mathbb{X}$, $\mathbb{X}^{rat}$, $\mathbb{Y}$ and $\mathbb{Y}^{rat}$ are four finite and pairwise disjoint sets of indices, χ is a disjunction of propositional literals, C_x is a coalition and $\psi_x \in \mathcal{L}_{R\text{-}CL}(\mathbb{P}, \mathbb{AGT})$ for each $x \in \mathbb{X} \cup \mathbb{X}^{rat} \cup \mathbb{Y} \cup \mathbb{Y}^{rat}$.

The following is a normal form lemma for the logic R-CL. It is proved in a way analogous to the normal form lemma for propositional logic.

Lemma 2 (Normal form). *Any formula $\varphi \in \mathcal{L}_{R\text{-}CL}(\mathbb{P}, \mathbb{AGT})$ is equivalent to a conjunction of standard R-CL disjunctions whose modal degrees are not higher than the modal degree of φ. This equivalence is both valid and derivable.*

Let

$$\chi \vee \Big(\big(\bigwedge_{x \in \mathbb{X}} \langle\!\langle C_x\rangle\!\rangle\mathsf{X}\psi_x \wedge \bigwedge_{x \in \mathbb{X}^{rat}} \langle\!\langle C_x\rangle\!\rangle^{rat}\mathsf{X}\psi_x \big) \rightarrow \big(\bigvee_{y \in \mathbb{Y}} \langle\!\langle C_y\rangle\!\rangle\mathsf{X}\psi_y \vee \bigvee_{y \in \mathbb{Y}^{rat}} \langle\!\langle C_y\rangle\!\rangle^{rat}\mathsf{X}\psi_y \big) \Big)$$

be a standard R-CL disjunction. The following definition introduces its sets of basic indices. They will be used to state the downward validity lemma and the upward derivability lemma.

Definition 12 (Basic indices). *Define $X_0 = \{x \in \mathbb{X} \mid C_x = \emptyset\}$, $Y_0 = \{y \in \mathbb{Y} \mid C_y = \mathbb{AGT}\}$ and $Y_1 = \{y \in \mathbb{Y}^{rat} \mid C_y = \mathbb{AGT}\}$.*

The last definition we need is that of neat set of indices.

Definition 13 (Neatness). *For any $X \subseteq \mathbb{X} \cup \mathbb{X}^{rat}$, we say X is neat iff for all $x, x' \in X$, if $x \neq x'$, then $C_x \cap C_{x'} = \emptyset$.*

The following is our downward validity lemma. Its proof is in Appendix E [32].

Lemma 3 (Downward validity). *Let $\varphi = \chi \vee \big((\bigwedge_{x \in \mathbb{X}} \langle\!\langle C_x\rangle\!\rangle\mathsf{X}\psi_x \wedge \bigwedge_{x \in \mathbb{X}^{rat}} \langle\!\langle C_x\rangle\!\rangle^{rat}\mathsf{X}\psi_x) \rightarrow (\bigvee_{y \in \mathbb{Y}} \langle\!\langle C_y\rangle\!\rangle\mathsf{X}\psi_y \vee \bigvee_{y \in \mathbb{Y}^{rat}} \langle\!\langle C_y\rangle\!\rangle^{rat}\mathsf{X}\psi_y) \big)$ be a standard R-CL disjunction. If φ is valid then following validity-reduction condition is satisfied:*

- *χ is valid, or*

- *there is $X \subseteq \mathbb{X}$ and $X' \subseteq \mathbb{X}^{rat}$ such that $X \cup X'$ is neat and one of the following conditions are met:*
  - *there is $y \in \mathbb{Y}$ such that $\bigcup_{x \in X \cup X'} C_x \subseteq C_y$ and $\bigwedge_{x \in X \cup X'} \psi_x \to (\psi_y \vee \bigvee_{y' \in Y_0} \psi_{y'})$ is valid;*
  - *there is $y \in \mathbb{Y}^{rat}$ such that $\bigcup_{x \in X'} C_x \subseteq C_y$ and $\bigwedge_{x \in X_0 \cup X'} \psi_x \to (\psi_y \vee \bigvee_{y' \in Y_0} \psi_{y'})$ is valid;*
  - *$\bigwedge_{x \in X_0 \cup X'} \psi_x \to \bigvee_{y \in Y_0 \cup Y_1} \psi_y$ is valid.*

The following is our upward derivability lemma. Its proof is in Appendix F [32].

Lemma 4 (Upward derivability). *Let $\varphi = \chi \vee ((\bigwedge_{i \in \mathbb{X}} \langle\langle C_x \rangle\rangle \mathsf{X} \psi_x \wedge \bigwedge_{i \in \mathbb{X}^{rat}} \langle\langle C_x \rangle\rangle^{rat} \mathsf{X} \psi_x) \to (\bigvee_{j \in \mathbb{Y}} \langle\langle C_y \rangle\rangle \mathsf{X} \psi_y \vee \bigvee_{j \in \mathbb{Y}^{rat}} \langle\langle C_y \rangle\rangle^{rat} \mathsf{X} \psi_y))$ be a standard R-CL disjunction. If φ is valid then following derivability-reduction condition is satisfied:*

- *$\vdash \chi$, or*
- *there is $X \subseteq \mathbb{X}$ and $X' \subseteq \mathbb{X}^{rat}$ such that $X \cup X'$ is neat and one of the following conditions are met:*
  - *there is $y \in \mathbb{Y}$ such that $\bigcup_{x \in X \cup X'} C_x \subseteq C_y$ and $\vdash \bigwedge_{x \in X \cup X'} \psi_x \to (\psi_y \vee \bigvee_{y' \in Y_0} \psi_{y'})$;*
  - *there is $y \in \mathbb{Y}^{rat}$ such that $\bigcup_{x \in X'} C_x \subseteq C_y$ and $\vdash \bigwedge_{x \in X_0 \cup X'} \psi_x \to (\psi_y \vee \bigvee_{y' \in Y_0} \psi_{y'})$;*
  - *$\vdash \bigwedge_{x \in X_0 \cup X'} \psi_x \to \bigvee_{y \in Y_0 \cup Y_1} \psi_y$.*

The following is the culminating result of this section: the logic R-CL is sound and complete for the model class **CP**.

We show Theorem 3 by induction on modal degrees of formulas. The inductive hypothesis ensures that the validity-reduction condition of a formula implies its derivability-reduction condition. The complete proof is given in Appendix G [32].

Theorem 3. *Let $\varphi \in \mathcal{L}_{R\text{-}CL}(\mathbb{P}, \mathbb{AGT})$. Then, φ is valid if and only if $\vdash \varphi$.*

7 MODEL CHECKING

The global model checking problem for R-ATL consists of computing, for a given CGSP P, and a formula φ, all the states in which φ holds in P, formally $\{w \in W : (P, w) \models \varphi\}$. In this section, we consider this problem relative to a subclass of CGSP in which preferences are short-sighted.

Definition 14 (Short-sighted preferences). *Let (M, Ω_M) be a CGSP with $M = (W, \mathbb{ACT}, TRel, \mathcal{V})$ a CGS. We say that M has short-sighted preferences if the following condition holds:*

(SSP) $\forall i \in \mathbb{AGT}, \forall w \in W, \forall \lambda, \lambda' \in Comp_{M,w}$ *if* $\lambda(1) = \lambda'(1)$ *then* $\lambda' \approx_{i,w} \lambda$,

where $\lambda' \approx_{i,w} \lambda$ iff $\lambda' \preceq_{i,w} \lambda$ and $\lambda \preceq_{i,w} \lambda'$.

The short-sighted preference condition means that an agent is indifferent between computations that are equal until the next state. Notice that if a CGSP M has both stable and short-sighted preferences in the sense of Definitions 6 and 14 then the following holds:

$$\forall i \in \mathbb{AGT}, \forall v \in W, \text{ if } v \in \mathcal{R}(w_0) \text{ then } \forall \lambda, \lambda' \in Comp_{M,v}, \lambda' \approx_{i,v} \lambda.$$

This means that under stable and short-sighted preferences only the successor states of the initial state w_0 affect an agent's preferences since from the next state on an agent has complete indifference between computations.

The reason why we verify properties relative to CGSPs with short-sighted preferences is to have an efficient model-checking procedure. Indeed, verifying properties with respect to the general class of CGSPs would make model checking exponential since we would need to compute dominance by alternating between sets of strategies of exponential size (similar to [4]).

The proof of Theorem 4 is given in Appendix H [32]. The lower-bound follows from the model checking of ATL [2]. For the upper bound, we first define agents' preference relation in state w over the successors of w. This allows us to define the notion of agents' dominated actions at a given state w. We then reinterpret the rational strategic modalities $\langle\langle C \rangle\rangle^{rat} \mathsf{X}$, $\langle\langle C \rangle\rangle^{rat} \mathsf{G}$, and $\langle\langle C \rangle\rangle^{rat}\ \mathsf{U}$ over dominated actions instead of dominated strategies, which is equivalent for the case of GCSP with short-sighted preferences. Then, we extend the model-checking algorithm for ATL to include the modalities $\langle\langle C \rangle\rangle^{rat} \mathsf{X}$, $\langle\langle C \rangle\rangle^{rat} \mathsf{G}$, and $\langle\langle C \rangle\rangle^{rat}\ \mathsf{U}$. The resulting algorithm, provided in Appendix H, runs in polynomial time.

Theorem 4. *The global model checking problem for R-ATL over GCSP with short-sighted preferences is* Ptime*-complete.*

8 CONCLUSION

We have proposed a novel semantic analysis of preferences in concurrent games and used our semantics based on CGS with preferences to define a new family of ATL and CL languages distinguishing the notion of ordinary capability from the notion of *rational* capability. We have provided a variety of proof-theoretic and complexity results for our languages with an emphasis on both satisfiability checking and model checking.

Directions of future work are manifold. Some proof-theoretic aspects remain to be explored and complexity results to be proved. Future work will be devoted to i) axiomatizing the full logic R-ATL relative to class **CP** and to class $\mathbf{CP}^{\{sp\}}$, ii) studying complexity of satisfiability checking for the language $\mathcal{L}_{\text{R-ATL}}(\mathbb{P}, \mathbb{AGT})$ relative to the general class **CP**. In our running example, the joint strategy in which both agents cross the road is not dominated. This is because preferences are defined for individual agents rather than coalitions. Following previous work on group preference logic [33] and judgment aggregation [6, 22], we plan to extend our framework with the notion of group preferences resulting from the aggregation of individual preferences. We also intend to investigate levels of rationality, where agents assume minimal rationality of their opponents, allowing for iterated strong dominance [9, 34]. Last but not least, we plan to consider an epistemic extension of our semantics and languages to be able to model concurrent games with imperfect information and an agent's knowledge of its rational capability.

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