Model Checking Coalitional Games with Priced-Resource Agents

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Automated verification of multi-agent systems is a significant topic in the recent literature in artificial intelligence [1]. The need of modeling this kind of systems has inspired logical formalisms, the most famous being the *Alternating-time Temporal Logics* [4] and the *Coalition Logic* (CL) [13, 14], oriented towards the description of collective behaviors.

The idea of such logics is that agents can join together in teams (or coalitions) and share resources to accomplish a task (reach a goal). In particular, Alternating-time Temporal Logics have been introduced in [4], where the full alternating-time temporal language, denoted by ATL^*, has been presented, along with two significant fragments, namely, ATL and ATL^+. These logics are natural specification languages for open system, that is, systems whose behavior depends on the interactions with an external entity, usually called the *environment*.

In [12], Goranko has studied the relationship between the (expressive power of the) two formalisms. In particular, he has shown that CL can be embedded into ATL. Recently these two logics have been used for the verification of multi-agent systems (MAS), where the agents are equipped with a limited amount of resources to reach their goal [2, 3, 6, 7] (more on this in the *Related works* section below).

The framework we present here hinges on these approaches and represents a further step towards the formalization of such complex systems: multi-agent systems in which agents can cooperate to perform a task and are subject to a limited availability of resources, that is an intrinsic feature of most real-world systems. In particular formulae of the formalisms proposed in [2, 3, 6, 7] allow one to assign an endowment of resources to the agents by means of the so-called *team operators* (borrowed from ATL). The problem is then to determine whether the agents in the proponent team have a strategy to carry out the assigned goals with that bounded amount of resources, whatever the agents in the opponent team do. Anyway, the treatment of this boundedness presents some weakness, as we will point out below.

Based on the natural observation that, in order to acquire a resource, there is a price to be paid, usually depending also on the availability of the resource on the market, we propose to consider bounded resources that have each a price to be paid by the agents for their use in reaching the goal. Thus differently from the existing approaches, agents are equipped with an amount of money instead of an endowment of resources. Money is in a sense a meta-resource. On one hand, its introduction is essential to model the natural scenario in which acquiring the resources needed to perform the task, has a price that depends on several factors: on their global availability, on the acting agent, and on the current system state. On the other hand, money has the peculiarity of "measuring" the value of all the resources, thus, it makes sense to consider problems of optimization (e.g., minimization of the amount of money needed to acquire the resources to perform a task).

In the previous approaches the notion of boundedness of resources is somehow weak, in the sense that resource bounds only appear in the formulae and are applied solely to the proponent team, but they are not represented inside the model at all. This means that it is possible to ask whether a team can reach a goal with a given amount of resources, but it is not possible to keep trace of the evolution of the availability of resources in the world (in particular, the resource consumption due to the actions of the opponent is not controlled). For example, consider the formula $\langle\langle A^b\rangle\rangle\Box p$, belonging to the formalism proposed in [3]. Its intuitive semantics is that the team A can guarantee that p always holds, independently from the behavior of the opponent ($\mathcal{AG} \setminus A$), using an amount of resources bounded by b. A model for this formula must contain a loop where the joint actions of agents in the team A do not consume resources, but the joint actions of agents in the opponent team may possibly consume resources, leading to an unlimited consumption of resources. In our opinion, such a behavior is not realistic.

We introduce hence a notion of *global availability* of resources on the market (or in nature) that evolves depending on both proponent and opponent behaviors. Such resources are shared, in the sense that all the agents draw on resources from a shared pool and acquisition of a resource by an agent (independently if the agent belong to the proponent or opponent team) implies that the resources will be available in smaller quantity.

The notion of money used here presents several similarity with the notion of resources used in [3]. Indeed, here money is given to the agents to perform a task (like resources are given to the agents in [3]). Moreover, the consumption of money of the opponent is not controlled (like resource consumption of the opponent in [3]). Money, unlike the other resources, can thus be thought of as a private (non-shared) resource. Additionally, opponent has unlimited economic power, in the sense that opponent's agents are supposed to have enough money to acquire all resources they need (this reflects the choice to not limit the opponent power, as it is usual in game theory, to look for robust strategies of the proponent). Roughly speaking, the opponent can buy everything, except for resources that do not exist anymore.

Another aspect that has not been fully analyzed in the literature is the problem of actions producing resources. On the one hand, in [2, 3], actions can only consume resources; on the other hand, in [7], the authors state that whenever actions can produce resources the model checking problem is undecidable. It can be easily argued that the undecidability comes from the unboundedness production of resources, thus we naturally constrain the way in which actions can produce resources: it is possible for an action to produce a resource in a quantity that is not greater than the amount that has already been consumed so far. Such a notion makes sense as, in practical terms, it allows one to model significant real-world scenarios, such as, acquiring memory by a program, leasing a car during a travel, and, in general, any scenario in which an agent is releasing resources previously acquired.

Finally, we also tackle the problem of coalition formation. How and why agents should aggregate is not a new issue and has been deeply investigated, in past and recent years, in various frameworks, as for example in algorithmic game theory, argumentation settings, and logic-based knowledge representation (see [11, 5]). We face this problem in the setting of priced resource-bounded agents with the goal specified by an ATL formula. In particular we solve the problem of determining the minimal cost coalitions of agents acting in accordance to rules expressed by a priced game arena and satisfying a given formula.

We show that both the model checking problem and the optimal coalition problem are EXPTIME-complete.

Related works. In [2], Alechina et al. introduce the logic RBCL, whose language extends the one of CL with explicit representation of resource bounds. In [3], the same authors propose an analogous extension for ATL, called RB-ATL, and give a model checking procedure that runs in time $O(|\varphi|^{2 \cdot r+1} \times S)$, where φ is the formula to be checked, S is the model, and r is the number of resources. Thus, if the number of resources is treated as constant, the model checking problem for RB-ATL is in PTIME. However, the problem of determining a lower bound to the model checking problem and, in particular, whether a PTIME algorithm exists even if the number of resources is not treated as a constant factor is left open.

In [7], Bulling and Farwer introduce the logics RAL and RAL^*. The former represents a generalization of Alechina et al.'s RB-ATL, the latter is ATL^* extended with bounded resources. The authors study several syntactic and semantic variants of RAL and RAL^* with respect to the (un)decidability of the model checking problem. In particular, while previous approaches only conceive actions *consuming* resources, they introduce the notion of actions *producing* resources. It turned out that such a new notion makes the model checking problem undecidable.

The present work is based on [9, 10], where the logic is introduced and the upper bound (EXPTIME) for the model checking problem is given. Here we complete the complexity characterization of the model checking problem by also showing the EXPTIME-hardness. Finally, it is worth pointing out that a further extension of the logic. based on μ-calculus, is discussed in [8].

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