Towards Infinite-State Verification and Planning with Linear Temporal Logic Modulo Theories

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Abstract

In this extended abstract, we discuss about *Linear Temporal Logic Modulo Theories over finite traces* ($\mathsf{LTL}_\mathsf{f}^{\mathsf{MT}}$), a temporal logic that we recently introduced with the goal of providing an equilibrium between generality of the formalism and decidability of the logic. After recalling its distinguishing features, we discuss some future applications.

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Category Extended Abstract

1 Overview

Linear Temporal Logic (LTL) [11] is arguably the most common language for the specification of system properties in the field of *formal verification*. In recent years, its *finite-traces* counterpart, LTL_f [4], also took traction in the field of *artificial intelligence*, where reasoning about a finite execution (*e.g.* in planning) is more natural. These formalisms are *propositional logics*, and are therefore suitable to specify and reason about *finite-state* systems. However, many complex scenarios, for example involving arithmetic constraints, complex data types, or relational databases, require to go beyond finite-state systems.

Here, we discuss our take on the problem of specifying and reasoning about infinite-state systems. To this aim, we recently introduced LTL_f *Modulo Theories* ($\mathsf{LTL}_\mathsf{f}^{\mathsf{MT}}$) [6], an extension of LTL_f where propositions are replaced by first-order formulas interpreted over arbitrary theories, similarly to how *satisfiability modulo theories* (SMT) [1] extends the classic Boolean satisfiability problem, and where first-order variables referring to different time points can be compared.

$\mathsf{LTL}_\mathsf{f}^{\mathsf{MT}}$ is, in general, undecidable, but for decidable underlying theories it is *semi-decidable*[1], with an effective semi-decision procedure based on the encoding of a tree-shaped tableau system into first-order logic, handled directly by off-the-shelf SMT solvers. The technique is implemented in the BLACK[2] temporal reasoning framework [7, 8], providing interesting performance. This puts this approach in contrast with other previous studies of first-order extensions of LTL: on one hand, such extensions have been thoroughly studied only from a theoretical perspective, without providing practical reasoning tools [9]; on the other hand, other practice-oriented approaches resulted in efficient tools for ad-hoc extensions (*e.g.* [3]), but difficult to extend or generalize. In contrast, our framework provides a most

[1] This would not be true if we interpreted the logic over *infinite traces* instead.

general and theoretically well-founded ground which can also lead to effective reasoning tools. We discuss here future applications of these framework in the context of formal verification and artificial intelligence.

2 Applications

The first-order setting of $\mathsf{LTL}_\mathsf{f}^\mathsf{MT}$ naturally allows one to specify and reason about structured and complex scenarios. An important use case is that of *data-aware* systems, *i.e.* systems that manipulate unbounded data. Such data can come from numeric variables, or other kinds of unbounded data types. In the most general setting, data comes from *relational databases*, which are naturally grounded in first-order logic and are therefore perfectly suitable to be modeled in $\mathsf{LTL}_\mathsf{f}^\mathsf{MT}$, including relations with primary and foreign key constraints, and many other features.

These considerations lead to the definition of *knowledge-base-driven systems* (KDS), a kind of transition system whose behavior depends on the content of a mutable relational data store, that is updated by the transitions of the system. Work defining and studying KDSs is under review. This concept is of uttermost generality, potentially subsuming many different approaches found in the literature [2, 5], while still being directly handled by the BLACK solver.

On the other hand, inspired by the tight relationship between LTL satisfiability and *classical planning* [10], the same framework can be adapted to approach *data-aware planning problems*, a scenario still unexplored in the planning literature. In such problems, the agent is required to reason about actions whose preconditions depend on the content of an unbounded relational data store, and whose effects update such data store. These kind of planning problems could find applications in a wide range of scenarios such as planning for data warehouses, business process management, and ontology-driven systems.

The $\mathsf{LTL}_\mathsf{f}^\mathsf{MT}$ framework is still in its infancy, and interesting developments are on its path.

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