

Past and Future of *DL-Lite*

A. Artale,¹ R. Kontchakov,² V. Ryzhikov¹ and M. Zakharyashev²

¹Faculty of Computer Science
Free University of Bozen-Bolzano, Italy
{artale, ryzhikov}@inf.unibz.it

²Department of Computer Science and Information Systems
Birkbeck College London, UK
{roman, michael}@dcs.bbk.ac.uk

Abstract

We design minimal temporal description logics that are capable of expressing various aspects of temporal conceptual data models and investigate their computational complexity. We show that, depending on the required types of temporal and atemporal constraints, the satisfiability problem for temporal knowledge bases in the resulting logics can be NLOGSPACE-, NP- and PSPACE-complete, as well as undecidable.

Introduction

Conceptual data modelling formalisms such as the Entity-Relationship model (ER) and Unified Modelling Language (UML) have become a *de facto* standard in database design by providing visual means to describe application domains in a declarative and reusable way. On the other hand, both ER and UML turned out to be closely connected with description logics (DLs) developed in the area of knowledge representation, underpinned by formal semantics and thus capable of providing services for effective reasoning over conceptual models; see, e.g., (Berardi, Calvanese, & De Giacomo 2005; Artale *et al.* 2007b).

Temporal conceptual data models (Gregersen & Jensen 1999; Spaccapietra, Parent, & Zimanyi 2006) have been introduced in the context of temporal databases (Jensen & Snodgrass 2000; Date, Darwen, & Lorentzos 2002; Chomicki & Toman 2009). In this case, apart from the ‘classical’ constructs—such as inheritance between classes and relationships, attributes, cardinality constraints restricting participation in relationships, and disjointness and covering constraints—temporal constructs are used to capture the temporal behaviour of various components of conceptual schemas. Such constructs can be grouped into three categories. *Timestamping constraints* discriminate between those classes, relationships and attributes that change over time and those that are time-invariant (Theodoulidis, Loucopoulos, & Wangler 1991; Gregersen & Jensen 1999; Finger & McBrien 2000; Artale & Franconi 2009; Spaccapietra, Parent, & Zimanyi 2006). *Evolution constraints* control how the domain elements evolve over time by ‘migrating’ from one class to another (Hall & Gupta 1991; Mendelzon, Milo, & Waller 1994; Su 1997; Spaccapietra, Parent, & Zimanyi 2006; Artale, Parent, & Spaccapietra 2007). We distinguish between *qualitative* evolution con-

straints describing generic temporal behaviour, and *quantitative* ones specifying the exact time of migration. *Temporal cardinality constraints* restrict the number of times an instance of a class participates in a relationship. *Snapshot cardinality constraints* do it at each moment of time, while *lifespans* cardinality constraints impose restrictions over the entire existence of the instance as a member of the class (Touzovitch 1991; McBrien, Seltveit, & Wangler 1992).

Temporal conceptual data models (TCMs) can be encoded in various temporal description logics (TDLs), which have been designed and investigated since the seminal paper (Schild 1993) with the aim of understanding the computational price of introducing a temporal dimension in DLs; see (Lutz, Wolter, & Zakharyashev 2008) for a recent survey. A general conclusion one can draw from the obtained results is that—as far as there is nontrivial interaction between the temporal and DL components—TDLs based on full-fledged DLs like \mathcal{ALC} turn out to be too complex for effective reasoning (see the end of this section for details).

The aim of this paper is to tailor ‘minimal’ TDLs that are capable of representing various aspects of TCMs and investigate their computational behaviour. First of all, as the DL component we choose the ‘light-weight’ *DL-Lite* logic $DL-Lite_{bool}^N$, which was shown to be adequate for capturing conceptual models without relationship inheritance¹ (Artale *et al.* 2007b), and its fragment $DL-Lite_{core}^N$ with most primitive concept inclusions, which are nevertheless enough to represent almost all types of constraints (apart from covering). To discuss our choice of the temporal constructs, consider a toy TCM describing a company.

For the timestamping constraint ‘employee is a *snapshot class*’ (according to the standard TCM terminology, such a class never changes in time) one can use the TDL axiom $\text{Employee} \sqsubseteq \boxtimes \text{Employee}$ with the temporal operator \boxtimes ‘always.’ Similarly, the constraint ‘manager is a *temporary class*’ in the sense that each of its instances must leave the class, an axiom $\text{Manager} \sqsubseteq \diamond \neg \text{Manager}$ is required, where \diamond stands for ‘some time.’ Both of these axioms are regarded as *global*, that is, applicable to all moments of time. Note that to express \diamond using more standard temporal constructs, we need both ‘some time in the past’

¹The extension of $DL-Lite_{bool}^N$ with relationship inclusions regains the full expressive power of \mathcal{ALC} .

\diamond_P and ‘some time in the future’ \diamond_F . To capture a snapshot n -ary relationship, one can reify it into a snapshot class with n auxiliary *rigid*—that is, time-independent—roles; for a temporary relationship, the reifying class should be temporary and the roles *local* (Artale, Lutz, & Toman 2007; Artale *et al.* 2007c).

The qualitative evolution constraints ‘each manager was once an employee’ and ‘a manager will always remain a manager’ can be expressed as $\text{Manager} \sqsubseteq \diamond_P \text{Employee}$ and $\text{Manager} \sqsubseteq \square_F \text{Manager}$, while ‘an approved project keeps its status until a later date when it starts’ requires the ‘until’ operator: $\text{ApprovedProject} \sqsubseteq \text{ApprovedProject } \mathcal{U} \text{Project}$. The quantitative evolution constraint ‘each project must be finished in 3 years’ is expressed using the next-time operator \circ_F : $\text{Project} \sqsubseteq \circ_F \circ_F \circ_F \text{FinishedProject}$.

The snapshot cardinality constraint ‘an employee can work on at most 2 projects at each moment of time’ can be expressed by the (global) axiom $\text{Employee} \sqsubseteq \leq 2 \text{worksOn}$, while the lifespan constraints like ‘over the whole career, an employee can work on at most 5 projects’ require temporal operators on roles: $\text{Employee} \sqsubseteq \leq 5 \diamond \text{worksOn}$. Note that ‘temporalised’ roles of the form $\diamond R$ and $\boxtimes R$ are rigid.

Finally, to represent a temporal database instance of a TCM, we use assertions like $\circ_P \text{Manager}(\text{bob})$ for ‘Bob was a manager last year’ and $\circ_F \text{manages}(\text{bob}, \text{cronos})$ for ‘Bob will manage project Cronos next year.’ As usual, n -ary tables are represented via reification.

These considerations lead us to TDLs based on the DLs $DL\text{-Lite}_{bool}^N$ and $DL\text{-Lite}_{core}^N$ and interpreted over the flow of time $(\mathbb{Z}, <)$, in which (1) the future and past temporal operators can be applied to concepts; (2) roles can be declared local or rigid; (3) the ‘undirected’ temporal operators ‘always’ and ‘some time’ can be applied to roles; (4) the concept inclusions (TBox axioms) are global and the database (ABox) assertions are specified to hold at particular moments of time.

Unfortunately, and to our surprise, the most expressive TDL based on $DL\text{-Lite}_{bool}^N$ and featuring all of (1)–(4) turns out to be undecidable. As follows from the proof of Theorem 5 below, it is a subtle interaction of functionality constraints on temporalised roles with the next-time operator and full Booleans on concepts that causes undecidability. This ‘negative’ result motivates consideration of various fragments of our full TDL by restricting not only the DL but also the temporal component. The table below illustrates the expressive power of the resulting fragments in the context of TCMs. We also note that both $DL\text{-Lite}_{bool}^N$ and $DL\text{-Lite}_{core}^N$ with global axioms can capture snapshot cardinality constraints, while lifespan cardinality constraints require temporalised roles of the form $\diamond R$.

concept temporal operators	timestamping	evolution	
		qualitative	quantitative
\mathcal{U}/\mathcal{S}	+	+	+
$\square_{F/P}, \circ_{F/P}$	+	+	+
$\square_{F/P}$	+	+	–
$\boxtimes, \circ_{F/P}$	+	–	+
\boxtimes	+	–	–

The next table summarises the complexity results ob-

tained in this paper for satisfiability of temporal knowledge bases formulated in our TDLs.

concept temporal operators	local & rigid roles only		temporalised roles
	$DL\text{-Lite}_{bool}^N$	$DL\text{-Lite}_{core}^N$	$DL\text{-Lite}_{bool}^N$
\mathcal{U}/\mathcal{S}	PSPACE Thm. 1	PSPACE (Artale <i>et al.</i> 2009b)	undec. Thm. 5
$\square_{F/P}, \circ_{F/P}$	PSPACE Thm. 2 (ii)	NP Thm. 3	undec. Thm. 5
$\square_{F/P}$	NP Thm. 2 (i)	NP (Artale <i>et al.</i> 2009b)	?
$\boxtimes, \circ_{F/P}$	PSPACE Thm. 2 (ii)	NP Thm. 3	undec. Thm. 5
\boxtimes	NP Thm. 2 (i)	NLOGSPACE Thm. 4	NP Thm. 6

Apart from the undecidability result of Theorem 5 discussed above, quite surprising is NP-completeness of the temporal extension of $DL\text{-Lite}_{core}^N$ with the operators \square_F and \circ_F (and their past counterparts) on concepts provided by Theorem 3. Indeed, if full Booleans are available, even the propositional temporal logic with these operators is PSPACE-complete. Moreover, if the ‘until’ operator \mathcal{U} is available in the temporal component, disjunction is expressible even with $DL\text{-Lite}_{core}^N$ as the underlying DL and the logic becomes PSPACE-complete again (Artale *et al.* 2009b). In all other cases, the complexity of TDL reasoning coincides with the maximal complexity of reasoning in the component logics (despite nontrivial interaction between them, as none of our TDLs is a fusion of its components). It is also of interest to observe the dramatic increase of complexity caused by the addition of \circ_F to the logic in the lower right corner of the table (from NP-completeness to undecidability).

To put this paper in the more general context of temporal description logics, we note first that our TDLs extend those in (Artale *et al.* 2009b) with the past-time operators \mathcal{S} , \square_P , \diamond_P , \circ_P over \mathbb{Z} (which are essential for capturing timestamping constraints), universal modalities \boxtimes and \diamond , and temporalised roles. Temporal operators on $DL\text{-Lite}$ axioms and concepts in the presence of rigid roles were investigated in (Artale *et al.* 2007c), where it was shown that the resulting temporalisations of $DL\text{-Lite}_{bool}^N$ and $DL\text{-Lite}_{horn}^N$ are EXPSpace-complete. Temporal extensions of the standard DL \mathcal{ALC} feature the following computational behaviour: \mathcal{ALC} with temporal operators on axioms, rigid concepts and roles is 2EXPTIME-complete (Baader, Ghilardi, & Lutz 2008). It is EXPSpace-complete if temporal operators on concepts and axioms are allowed but no rigid or temporalised roles are available (Gabbay *et al.* 2003), and EXPTIME-complete if the language allows only temporalised concepts and global axioms (Schild 1993; Artale *et al.* 2002). Finally, the ‘undirected’ temporal operators \boxtimes and \diamond on concepts and roles together with global axioms result in a 2EXPTIME-complete extension of \mathcal{ALC} (Artale, Lutz, & Toman 2007).

The paper is organised as follows. In the next section, we define the logic $T_{\mathcal{U}\mathcal{S}}DL\text{-Lite}_{bool}^N$ together with its fragments and obtain tight complexity results for the second column of the table above. Then we analyse $DL\text{-Lite}_{core}^N$ and its fragments to fill in the third column. Finally, we show that, when coupled with quantitative evolution constraints, temporalised roles cause undecidability in the case of $DL\text{-Lite}_{bool}^N$, while when combined with the universal

modalities, they do not increase complexity.

$T_{USDL-Lite}_{bool}^N$

First we define our basic temporal extension $T_{USDL-Lite}_{bool}^N$ of the description logic $DL-Lite_{bool}^N$ (Artale *et al.* 2007a; 2009a), which, in turn, extends $DL-Lite_{\sqcap, \mathcal{F}}$ (Calvanese *et al.* 2007) with full Booleans over concepts and cardinality restrictions over roles.

The language of $T_{USDL-Lite}_{bool}^N$ contains *object names* a_0, a_1, \dots , *concept names* A_0, A_1, \dots , *local role names* P_0, P_1, \dots and *rigid role names* G_0, G_1, \dots . *Roles* R , *basic concepts* B and *concepts* C are defined as follows:

$$S ::= P_i \mid G_i, \quad R ::= S \mid S^-,$$

$$B ::= \perp \mid A_i \mid \geq q R,$$

$$C ::= B \mid \neg C \mid C_1 \sqcap C_2 \mid C_1 \mathcal{U} C_2 \mid C_1 \mathcal{S} C_2,$$

where $q \geq 1$ is a natural number (the results obtained below do not depend on whether q is given in unary or binary).

A $T_{USDL-Lite}_{bool}^N$ *interpretation* is a function \mathcal{I} on the integers \mathbb{Z} (the intended flow of time):

$$\mathcal{I}(n) = (\Delta^{\mathcal{I}}, a_0^{\mathcal{I}}, \dots, A_0^{\mathcal{I}(n)}, \dots, P_0^{\mathcal{I}(n)}, \dots, G_0^{\mathcal{I}(n)}, \dots),$$

where $\Delta^{\mathcal{I}}$ is a nonempty set, the (constant) domain of \mathcal{I} , $a_i^{\mathcal{I}} \in \Delta^{\mathcal{I}}$, $A_i^{\mathcal{I}(n)} \subseteq \Delta^{\mathcal{I}}$ and $P_i^{\mathcal{I}(n)}, G_i^{\mathcal{I}(n)} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$ with $G_i^{\mathcal{I}(n)} = G_i^{\mathcal{I}(m)}$, for $i \in \mathbb{N}$ and $n, m \in \mathbb{Z}$. We adopt the unique name assumption according to which $a_i^{\mathcal{I}} \neq a_j^{\mathcal{I}}$, for $i \neq j$, although our complexity results would not change if we dropped it, apart from the NLOGSPACE bound of Theorem 4, which would increase to NP (Artale *et al.* 2009a). The role and concept constructs are interpreted in \mathcal{I} as follows:

$$(S^-)^{\mathcal{I}(n)} = \{(y, x) \mid (x, y) \in S^{\mathcal{I}(n)}\},$$

$$\perp^{\mathcal{I}(n)} = \emptyset, \quad (\neg C)^{\mathcal{I}(n)} = \Delta^{\mathcal{I}} \setminus C^{\mathcal{I}(n)},$$

$$(C_1 \sqcap C_2)^{\mathcal{I}(n)} = C_1^{\mathcal{I}(n)} \cap C_2^{\mathcal{I}(n)},$$

$$(\geq q R)^{\mathcal{I}(n)} = \{x \mid \#\{y \mid (x, y) \in R^{\mathcal{I}(n)}\} \geq q\},$$

$$(C_1 \mathcal{U} C_2)^{\mathcal{I}(n)} = \bigcup_{k > n} (C_2^{\mathcal{I}(k)} \cap \bigcap_{n < m < k} C_1^{\mathcal{I}(m)}),$$

$$(C_1 \mathcal{S} C_2)^{\mathcal{I}(n)} = \bigcup_{k < n} (C_2^{\mathcal{I}(k)} \cap \bigcap_{n > m > k} C_1^{\mathcal{I}(m)}).$$

Note that our *until* and *since* operators are ‘strict’ in the sense they do not include the current moment of time. We also use the temporal operators \diamond_F (‘some time in the future’), \diamond_P (‘some time in the past’), \boxtimes (‘some time’), their duals \square_F , \square_P and \boxtimes , \circ_F (‘next time’) and \circ_P (‘previous time’), which are all expressible by means of \mathcal{U} and \mathcal{S} , e.g.,

$$\diamond_F C = \neg \perp \mathcal{U} C, \quad \square_F C = \neg \diamond_F \neg C, \quad \circ_F C = \perp \mathcal{U} C,$$

$$\boxtimes C = \diamond_F \diamond_P C \quad \text{and} \quad \boxtimes C = \square_F \square_P C.$$

(Other standard abbreviations we use include $C_1 \sqcup C_2$, $\exists R$ and $\top = \neg \perp$.) Apart from full $T_{USDL-Lite}_{bool}^N$, we consider a few of its sublanguages allowing only some of the (definable) temporal operators mentioned above:

- $T_{FPDL-Lite}_{bool}^N$, which allows only $\diamond_F C$, $\diamond_P C$ and their duals (but no $\circ_F C$ or $C_1 \mathcal{U} C_2$), and its extension $T_{FPXDL-Lite}_{bool}^N$ with $\circ_F C$ and $\circ_P C$;

- $T_{UDL-Lite}_{bool}^N$, which allows only $\boxtimes C$ and $\boxtimes C$, and its extension $T_{UXDL-Lite}_{bool}^N$ with $\circ_F C$ and $\circ_P C$.

A *TBox*, \mathcal{T} , in any of our languages \mathcal{L} is a finite set of *concept inclusions* (CIs) of the form $C_1 \sqsubseteq C_2$, where the C_i are \mathcal{L} -concepts. An *ABox*, \mathcal{A} , consists of assertions of the form $\circ^n B(a)$ and $\circ^n S(a, b)$, where B is a basic concept, S a (local or rigid) role name, a, b object names and \circ^n , for $n \in \mathbb{Z}$, is a sequence of n operators \circ_F if $n \geq 0$ and $|n|$ operators \circ_P if $n < 0$. Taken together, the TBox \mathcal{T} and ABox \mathcal{A} form the *knowledge base* (KB) $\mathcal{K} = (\mathcal{T}, \mathcal{A})$ in \mathcal{L} .

The *truth-relation* \models is defined as follows:

$$\mathcal{I} \models C_1 \sqsubseteq C_2 \quad \text{iff} \quad C_1^{\mathcal{I}(n)} \subseteq C_2^{\mathcal{I}(n)} \quad \text{for all } n \in \mathbb{Z},$$

(that is, we interpret concept inclusions globally)

$$\mathcal{I} \models \circ^n B(a) \quad \text{iff} \quad a^{\mathcal{I}} \in B^{\mathcal{I}(n)},$$

$$\mathcal{I} \models \circ^n S(a, b) \quad \text{iff} \quad (a^{\mathcal{I}}, b^{\mathcal{I}}) \in S^{\mathcal{I}(n)}.$$

We call \mathcal{I} a *model* of a KB \mathcal{K} and write $\mathcal{I} \models \mathcal{K}$ if $\mathcal{I} \models \alpha$ for all α in \mathcal{K} . If \mathcal{K} has a model then it is said to be *satisfiable*. A concept C (role R) is *satisfiable* w.r.t. \mathcal{K} if there are a model \mathcal{I} of \mathcal{K} and $n \in \mathbb{Z}$ such that $C^{\mathcal{I}(n)} \neq \emptyset$ (respectively, $R^{\mathcal{I}(n)} \neq \emptyset$). Clearly, the concept and role satisfiability problems are equivalent to KB satisfiability.

Our first result states that, in the worst case, the satisfiability problem for $T_{USDL-Lite}_{bool}^N$ KBs is as complex as satisfiability in propositional temporal logic *LTL*.

Theorem 1. *The satisfiability problem for $T_{USDL-Lite}_{bool}^N$ KBs is PSPACE-complete.*

The proof is by a two-step (non-deterministic polynomial) reduction to *LTL*. First, we reduce satisfiability of a $T_{USDL-Lite}_{bool}^N$ KB $\mathcal{K} = (\mathcal{T}, \mathcal{A})$ to satisfiability in the one-variable first-order temporal logic in a way similar to (Artale *et al.* 2009b). For each basic concept $B (\neq \perp)$, we take a fresh *unary* predicate $B^*(x)$ and encode \mathcal{T} as the formula

$$\mathcal{T}^\dagger = \bigwedge_{C_1 \sqsubseteq C_2 \in \mathcal{T}} \boxtimes \forall x (C_1^*(x) \rightarrow C_2^*(x)),$$

where the C_i^* are the results of replacing each B with $B^*(x)$ (\sqcap with \wedge , etc.). We assume that \mathcal{T} contains CIs of the form $\geq q R \sqsubseteq \geq q' R$, for $\geq q R, \geq q' R$ in \mathcal{T} such that $q > q'$ and there is no q'' with $q > q'' > q'$ and $\geq q'' R$ in \mathcal{T} . We also assume that \mathcal{T} contains $\geq q R \equiv \boxtimes \geq q R$ if $\geq q R$ occurs in \mathcal{T} , for a rigid role R (i.e., for G_i or G_i^-). To take account of the fact that roles are *binary* relations, we add to \mathcal{T}^\dagger the following formula, for each role name S :

$$\varepsilon_S = \boxtimes (\exists x (\exists S)^*(x) \leftrightarrow \exists x (\exists S^-)^*(x))$$

(which says that at each moment of time the domain of S is nonempty iff its range is nonempty). The ABox \mathcal{A} is encoded by the conjunction \mathcal{A}^\dagger of ground atoms of the form $\circ^n B^*(a)$ and $\circ^n (\geq q R)^*(a)$ in the same way as in (Artale *et al.* 2009b). Thus, \mathcal{K} is satisfiable iff the formula

$$\mathcal{K}^\dagger = \mathcal{T}^\dagger \wedge \bigwedge_S \varepsilon_S \wedge \mathcal{A}^\dagger$$

is satisfiable. The second step of our reduction is based on the observation that if \mathcal{K}^\dagger is satisfiable then it can be satisfied in an interpretation such that

(R) if $(\exists S)^*(x)$ is true at some moment (on some domain element) then it is true at all moments of time (perhaps on different domain elements).

Indeed, if \mathcal{K}^\dagger is satisfied in \mathcal{I} then it is satisfied in the disjoint union \mathcal{I}^* of all \mathcal{I}^n , $n \in \mathbb{Z}$, obtained from \mathcal{I} by shifting its time line n moments forward. It follows from **(R)** that \mathcal{K}^\dagger is satisfiable iff there is a set Σ of role names such that

$$\mathcal{K}^{\dagger\Sigma} = \mathcal{T}^\dagger \wedge \bigwedge_{S \in \Sigma} ((\exists S)^*(d_S) \wedge (\exists S^-)^*(d_{S^-})) \wedge \bigwedge_{S \notin \Sigma} \boxtimes \forall x \neg((\exists S)^*(x) \vee (\exists S^-)^*(x)) \wedge \mathcal{A}^\dagger$$

is satisfiable, where the d_S are fresh constants (informally, the roles in Σ are nonempty at some moment, and so can be made always nonempty, whereas all other roles are always empty). Finally, as $\mathcal{K}^{\dagger\Sigma}$ contains no existential quantifiers, it can be regarded as an *LTL*-formula because all the universal quantifiers can be instantiated by all the constants occurring in the formula (i.e., the object names in \mathcal{A} and the d_S , $S \in \Sigma$), which results only in a polynomial blow-up of the formula.

This reduction can also be used to obtain complexity results for the fragments of $T_{US}DL-Lite_{bool}^N$ mentioned above. Using the well-known facts that satisfiability in the fragments of *LTL* with \diamond_F/\diamond_P and with \boxtimes is NP-complete, and that the extension of any of these fragments with \circ_F/\circ_P becomes PSPACE-complete again, we obtain:

Theorem 2. (i) *Satisfiability of $T_{FP}DL-Lite_{bool}^N$ and $T_U DL-Lite_{bool}^N$ KBs is NP-complete.*

(ii) *Satisfiability of $T_{FPX}DL-Lite_{bool}^N$ and $T_{UX}DL-Lite_{bool}^N$ KBs is PSPACE-complete.*

$T_{US}DL-Lite_{core}^N$

To decrease complexity we consider the logic $DL-Lite_{core}^N$ able to capture conceptual models with the exception of sub-relations and covering between entities (Artale *et al.* 2007b). $DL-Lite_{core}^N$ is a fragment of $DL-Lite_{bool}^N$ containing only CIs of the form $B_1 \sqsubseteq B_2$ and $B_1 \sqcap B_2 \sqsubseteq \perp$, where the B_i are basic concepts. Satisfiability of $DL-Lite_{core}^N$ KBs is NLOGSPACE-complete (Artale *et al.* 2009a).

Let $T_{US}DL-Lite_{core}^N$ be the fragment of $T_{US}DL-Lite_{bool}^N$ with CIs of the form $D_1 \sqsubseteq D_2$ and $D_1 \sqcap D_2 \sqsubseteq \perp$, where the D_i are defined by the rule:

$$D ::= B \mid B_1 \mathcal{U} B_2 \mid B_1 \mathcal{S} B_2.$$

By restricting D_1 and D_2 to concepts of the form:

$$D ::= B \mid \diamond_F B \mid \diamond_P B \mid \square_F B \mid \square_P B$$

we obtain $T_{FP}DL-Lite_{core}^N$. These restrictions do not improve the complexity of reasoning: satisfiability of $T_{US}DL-Lite_{core}^N$ KBs is PSPACE-complete, while for $T_{FP}DL-Lite_{core}^N$ it is NP-complete (Artale *et al.* 2009b).

What is really surprising and nontrivial is that the extension of $T_{FP}DL-Lite_{core}^N$ with the next- and previous-time operators does not increase the complexity; cf. Theorem 2 (ii). More formally, define $T_{FPX}DL-Lite_{core}^N$ by restricting D_1 and D_2 to concepts of the form:

$$D ::= B \mid \diamond_F B \mid \diamond_P B \mid \square_F B \mid \square_P B \mid \circ_F B \mid \circ_P B,$$

and let $T_{UX}DL-Lite_{core}^N$ be the logic with the D_i of the form:

$$D ::= B \mid \boxtimes B \mid \boxtimes B \mid \circ_F B \mid \circ_P B.$$

Theorem 3. *Satisfiability for $T_{FPX}DL-Lite_{core}^N$ and $T_{UX}DL-Lite_{core}^N$ KBs is NP-complete.*

In a way similar to the proof of Theorem 1, one can (non-deterministically and polynomially) reduce satisfiability of a $T_{FPX}DL-Lite_{core}^N$ KB to satisfiability of an *LTL*-formula

$$\varphi = \bigwedge_i \boxtimes (E_i \vee E'_i) \wedge \psi,$$

where the E_i and E'_i are of the form p , $\diamond_F p$, $\diamond_P p$, $\square_F p$, $\square_P p$, $\circ_F p$, $\circ_P p$ or a negation thereof, and ψ is a conjunction of formulas of the form $\circ^n p$, p a propositional variable. Let Γ be the set of all subformulas of φ of the form $\diamond_F p$, $\diamond_P p$, $\square_F p$ or $\square_P p$. It should be clear that if φ is satisfied in an interpretation then the flow of time can be partitioned into $|\Gamma| + 1$ intervals $I_0, \dots, I_{|\Gamma|}$ such that, for each $\gamma \in \Gamma$ and each I_i , γ is true at *some* point in I_i iff γ is true at *every* point in I_i . The existence of such intervals can be expressed by certain syntactic conditions on their ‘states,’ the most crucial of which is satisfiability of a formula of the form

$$\chi = \Psi \wedge \square^{\leq m} \Phi \wedge \circ^m (\Psi' \wedge \circ \Psi''),$$

for $\Phi = \bigwedge_i (D_i \vee D'_i)$, with each of the D_i and D'_i being a literal L (a propositional variable or its negation) or $\circ L$, conjunctions Ψ , Ψ' and Ψ'' of literals, and $m \geq 0$, where $\circ^n \Psi$ is the result of attaching n operators \circ to each literal in Ψ and $\square^{\leq m} \Phi = \bigwedge_{0 \leq i \leq m} \circ^i \Phi$. Intuitively, m is the number of distinct states in an interval I_i , Ψ and Ψ' are the first and the last states in I_i , Ψ'' is the first state of the next interval I_{i+1} , and Φ a set of binary clauses that describe possible transitions between the states. For details consult the technical report (Artale *et al.* 2010).

Let $cons_{\Phi}^m(\Psi)$ be the set of all literals L that are true at the moment $m \geq 0$ in every model of $\Psi \wedge \square^{\leq m} \Phi$. As the formula $\Psi \wedge \square^{\leq m} \Phi$ is essentially a 2CNF, one can compute $cons_{\Phi}^m(\Psi)$ inductively as follows:

$$cons_{\Phi}^0(\Psi) = \{L \mid \Phi \cup \Psi \models L\},$$

$$cons_{\Phi}^m(\Psi) = \{L \mid \Phi \models L' \rightarrow \circ L, L' \in cons_{\Phi}^{m-1}(\Psi)\} \cup \{L \mid \Phi \models L\}.$$

Now, for each L , we construct a non-deterministic finite automaton $\mathfrak{A}_L = (Q, Q_0, \sigma, F_L)$ over the alphabet $\{0\}$ that accepts 0^m iff $L \in cons_{\Phi}^m(\Psi)$. Define the states in Q to be all the literals from χ , the set of initial states $Q_0 = cons_{\Phi}^0(\Psi)$, the accepting states $F_L = \{L\}$, and the transition relation

$$\sigma = \{(L'', L') \mid \Phi \models L'' \rightarrow \circ L'\} \cup \{(L', L') \mid \Phi \models L'\}.$$

Then a state L is reachable in m σ -steps from a state in Q_0 iff $L \in cons_{\Phi}^m(\Psi)$, and so the automaton \mathfrak{A}_L is as required. Every such \mathfrak{A}_L can be converted into an equivalent automaton in the Chrobak normal form (Chrobak 1986) using Martinez’s algorithm (To 2009). The automaton in the Chrobak normal form gives rise to M_L -many arithmetic progressions

$$a_1^L + b_1^L \mathbb{N}, \quad \dots, \quad a_{M_L}^L + b_{M_L}^L \mathbb{N},$$

where $a + b\mathbb{N} = \{a + bn \mid n \in \mathbb{N}\}$, such that

(A₁) $M_L, a_i^L, b_i^L \leq |\Phi \cup \Psi|^2$, for $1 \leq i \leq M_L$, and

(A₂) $L \in cons_{\Phi}^m(\Psi)$ iff $m \in \bigcup_{i=1}^{M_L} (a_i^L + b_i^L \mathbb{N})$.

Satisfiability of χ can now be established by a polynomial-time algorithm which checks whether the following three conditions hold:

1. $p, \neg p \in \text{cons}_{\Phi}^n(\Psi)$, for no variable p and no $n \leq m + 1$;
2. $\neg L \in \text{cons}_{\Phi}^m(\Psi)$, for no literal $L \in \Psi'$;
3. $\neg L \in \text{cons}_{\Phi}^{m+1}(\Psi)$, for no literal $L \in \Psi''$.

To verify Condition 1, we check, for each variable p , whether the linear Diophantine equations

$$a_i^p + b_i^p x = a_j^{\neg p} + b_j^{\neg p} y,$$

for $1 \leq i \leq M_p$ and $1 \leq j \leq M_{\neg p}$, have a solution (x_0, y_0) such that $0 \leq a_i^p + b_i^p x_0 \leq m + 1$. Set $a = b_i^p$, $b = -b_j^{\neg p}$ and $c = a_j^{\neg p} - a_i^p$, which gives us the equation $ax + by = c$. If $a \neq 0$ and $b \neq 0$ then, by Bézout's lemma, it has a solution iff c is a multiple of the greatest common divisor d of a and b , which can be checked in polynomial time using the Euclidean algorithm (provided that the numbers are encoded in unary, which can be assumed in view of (\mathbf{A}_1)). Moreover, if the equation has a solution, then the Euclidean algorithm also gives us a pair (u_0, v_0) such that $d = au_0 + bv_0$, in which case all the solutions of the above equation form the set

$$\{((cu_0 + bk)/d, (cv_0 - ak)/d) \mid k \in \mathbb{Z}\}.$$

Thus, it remains to check whether a number between 0 and $m + 1$ is contained in $a_i^p + b_i^p(a_j^{\neg p} - a_i^p)u_0/d + b_i^p b_j^{\neg p}/d\mathbb{N}$. The case $a = 0$ or $b = 0$ is left to the reader.

To verify Condition 2, we check, for each $L \in \Psi'$, whether m belongs to one of $a_i^{-L} + b_i^{-L}\mathbb{N}$, for $1 \leq i \leq M_L$, which can be done in polynomial time. Condition 3 is analogous.

This gives us the NP upper bound for the logics mentioned in Theorem 3. The lower bound can be proved by reduction of the 3-colourability problem to satisfiability of $T_{UX}DL\text{-Lite}_{core}^N$ KBs; see (Artale *et al.* 2009b, Lemma 6).

Theorem 3 shows that $T_{FPX}DL\text{-Lite}_{core}^N$ can be regarded as a good candidate for representing temporal conceptual data models. Although not able to express covering constraints, $T_{FPX}DL\text{-Lite}_{core}^N$ still appears to be a reasonable compromise compared to the full PSPACE-complete logic $T_{FPX}DL\text{-Lite}_{bool}^N$ (cf. Theorem 2 (ii)).

By restricting the temporal constructs to the undirected universal modalities \boxtimes and \diamond , we obtain an even simpler logic:

Theorem 4. *Satisfiability of $T_U DL\text{-Lite}_{core}^N$ KBs is NLOGSPACE-complete.*

The proof of the upper bound is by embedding into the universal Krom fragment of first-order logic.

Logics with Temporalised Roles

As we have seen before, in order to express lifespan cardinalities, temporal operators on roles are required. Modalised roles are known to be ‘dangerous’ and very difficult to deal with when temporalising expressive DLs such as \mathcal{ALC} (Gabbay *et al.* 2003, Section 14.2). To our surprise, even in the case of $DL\text{-Lite}$ temporal operators on roles may cause undecidability. Denote by $T_X^R DL\text{-Lite}_{bool}^N$ the fragment of

$T_{US}DL\text{-Lite}_{bool}^N$ with \circ_F as the only temporal operator over concepts and with roles R of the form

$$R ::= S \mid S^- \mid \diamond R \mid \boxtimes R.$$

The extensions of $\diamond R$ and $\boxtimes R$ in an interpretation \mathcal{I} are defined as follows:

$$(\diamond R)^{\mathcal{I}(n)} = \bigcup_{k \in \mathbb{Z}} R^{\mathcal{I}(k)} \quad \text{and} \quad (\boxtimes R)^{\mathcal{I}(n)} = \bigcap_{k \in \mathbb{Z}} R^{\mathcal{I}(k)}.$$

Theorem 5. *Satisfiability of $T_X^R DL\text{-Lite}_{bool}^N$ KBs is undecidable.*

The proof is by reduction of the $\mathbb{N} \times \mathbb{N}$ -tiling problem; see, e.g., (Börger, Grädel, & Gurevich 1997): given a finite set T of tile types $t = (up(t), down(t), left(t), right(t))$, decide whether T can tile the $\mathbb{N} \times \mathbb{N}$ -grid. We assume that the tiles use k colours numbered from 1 to k .

We construct a $T_X^R DL\text{-Lite}_{bool}^N$ KB \mathcal{K}_T such that \mathcal{K}_T is satisfiable iff T tiles the $\mathbb{N} \times \mathbb{N}$ -grid. The temporal dimension clearly provides us with one of the two axes of the grid. The other axis is constructed from the domain elements: let R be a role such that

$$\geq 2 \diamond R \sqsubseteq \perp \quad \text{and} \quad \geq 2 \diamond R^- \sqsubseteq \perp.$$

In other words, if xRy at some moment of time then there is no $y' \neq y$ with xRy' at any moment of time (and the same for R^-). We can generate an infinite sequence of the domain elements by saying that $\exists R^- \sqcap \circ_F \exists R^-$ is nonempty and

$$\exists R^- \sqcap \circ_F \exists R^- \sqsubseteq \exists R \sqcap \circ_F \exists R.$$

(The reason for generating the R -arrows at two consecutive moments of time will become apparent below.) It should also be noted that the produced sequence may in fact be either a finite loop or an infinite sequence of distinct elements. Now, let t be a fresh concept name for each $t \in T$ and let tile types be disjoint, i.e., $t \sqcap t' \sqsubseteq \perp$ for $t \neq t'$. After the double R -arrows we place the first column of tiles, and every $k + 1$ moments afterwards we place a column of tiles that matches the colours of the previous column:

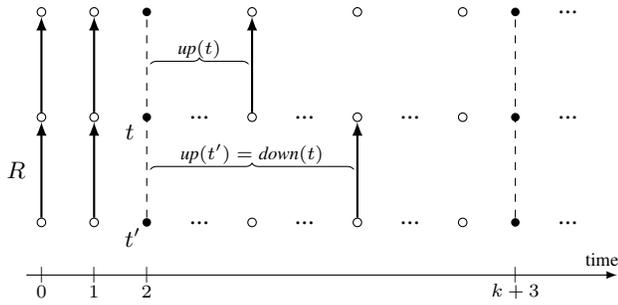
$$\begin{aligned} \exists R^- \sqcap \circ_F \exists R^- &\sqsubseteq \bigsqcup_{t \in T} \circ_F \circ_F t, \\ t &\sqsubseteq \bigsqcup_{right(t)=left(t')} \circ_F^{k+1} t', \quad \text{for each } t \in T. \end{aligned}$$

It remains to ensure that the tiles are arranged in a proper grid and have matching top-bottom colours. It is for this purpose that we have (i) used the double R -arrows to generate the sequence of domain elements and (ii) placed the columns of tiles every $k + 1$ moments of time (not every moment). Consider the following CIs, for $t \in T$:

$$t \sqsubseteq \neg \exists R^- \quad \text{and} \quad t \sqsubseteq \neg \circ_F^i \exists R^-, \quad \text{for } 1 \leq i \leq k, i \neq down(t),$$

$$t \sqsubseteq \circ_F^{up(t)} \exists R.$$

The CIs in first line ensure that between any two tiles $k + 1$ moments apart there may be only one incoming R -arrow. This, in particular, means that after the double R -arrows no other two consecutive R -arrows are possible, and thus the proper $\mathbb{N} \times \mathbb{N}$ -grid is ensured. Moreover, the exact position of the incoming R -arrow is uniquely determined by the *down*-colour of the tile, which in conjunction with the second line guarantees that this colour matches the tile below. The following picture can serve as an illustration of the construction:



Note that the next-time operator \bigcirc_F is heavily used in the encoding above. If we replace it with \diamond and \boxtimes on concepts, then reasoning in the resulting logic $T_U^R DL-Lite_{bool}^N$ becomes decidable:

Theorem 6. *Satisfiability of $T_U^R DL-Lite_{bool}^N$ KBs is NP-complete.*

The proof uses a rather involved quasimodel construction; for details the reader is referred to the technical report (Artale *et al.* 2010).

Conclusion

From the complexity-theoretic point of view, the best candidates for reasoning about TCMs appear to be the TDLs $T_{FPX} DL-Lite_{core}^N$ and $T_{FPX} DL-Lite_{bool}^N$, the former of which is NP-complete and the latter PSPACE-complete. Moreover, we believe that the reduction of $T_{FPX} DL-Lite_{core}^N$ to *LTL* in the proof of Theorem 3 can be done deterministically, in which case one can use standard *LTL* provers for TCM reasoning. We also believe that $T_{FPX} DL-Lite_{core}^N$ extended with temporalised roles can be decidable, which remains one of the most challenging open problems. But it seems to be next to impossible to reason in an effective way about all TCM constraints without any restrictions.

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