Past-present temporal programs over finite traces

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Abstract. Extensions of Answer Set Programming with language constructs from temporal logics, such as temporal equilibrium logic over finite traces (TEL_f), provide an expressive computational framework for modeling dynamic applications. In this paper, we study the so-called past-present syntactic subclass, which consists of a set of logic programming rules whose body references to the past and head to the present. Such restriction ensures that the past remains independent of the future, which is the case in most dynamic domains. We extend the definitions of completion and loop formulas to the case of past-present formulas, which allows for capturing the temporal stable models of past-present temporal programs by means of an LTL_f expression.

1 Introduction

Reasoning about dynamic scenarios is a central problem in the areas of Knowledge Representation [6] (KR) and Artificial Intelligence (AI). Several formal approaches and systems have emerged to introduce non-monotonic reasoning features in scenarios where the formalisation of time is fundamental [3,4,12,19,24]. In *Answer Set Programming* [7] (ASP), former approaches to temporal reasoning use first-order encodings [20] where the time is represented by means of a variable whose value comes from a finite domain. The main advantage of those approaches is that the computation of answer sets can be achieved via incremental solving [17]. Their downside is that they require an explicit representation of time points.

Temporal Equilibrium Logic [2] (TEL) was proposed as a temporal extension of *Equilibrium Logic* [22] with connectives from *Linear Time Temporal Logic* [23] (LTL). Due to the computational complexity of its satisfiability problem (ExpSpace), finding tractable fragments of TEL with good computational properties have also been a topic in the literature. Within this context, *splittable temporal logic programs* [1] have been proved to be a syntactic fragment of TEL that allows for a reduction to LTL via the use of Loop Formulas [15].

When considering incremental solving, logics on finite traces such as LTL_f [11] have been shown to be more suitable. Accordingly, *Temporal Equilibrium Logic* *on Finite traces* (TEL_f) [9] was created and became the foundations of the temporal ASP solver *telingo* [8].

We present a new syntactic fragment of TEL_f, named *past-present* temporal logic programs. Inspired by Gabbay's seminal paper [16], where the declarative character of past temporal operators is emphasized, this language consists of a set of logic programming rules whose formulas in the head are disjunctions of atoms that reference the present, while in its body we allow for any arbitrary temporal formula without the use of future operators. Such restriction ensures that the past remains independent of the future, which is the case in most dynamic domains, and makes this fragment advantageous for incremental solving.

As a contribution, we study the Lin-Zhao theorem [21] within the context of past-present temporal logic programs. More precisely, we show that when the program is *tight* [13], extending Clark's completion [10,14] to the temporal case suffices to capture the answer sets of a finite past-present program as the LTL_f-models of a corresponding temporal formula. We also show that, when the program is not tight, the use of loop formulas is necessary. To this purpose, we extend the definition of loop formulas to the case of past-present programs and we prove the Lin-Zhao theorem in our setting.

The paper is organised as follows: in Section 2, we review the formal background and we introduce the concept of past-present temporal programs. In Section 3, we extend the completion property to the temporal case. Section 4 is devoted to the introduction of our temporal extension of loop formulas. In section 5, we shows that temporal completion can be captured in the general theory of loop formulas by considering unitary cycles. Finally, in Section 6, we present the conclusions as well as some future research lines.

2 Past-present temporal programs over finite traces

In this section, we introduce the so-called *past-present* temporal logic programs and its semantics based on *Temporal Equilibrium Logic over Finite traces* (TEL_f for short) as in [2]. The syntax of our language is inspired from the pure-past fragment of Linear Time Temporal Logic (LTL) [18], since the only future operators used are *always* and *weak next*.

We start from a given set $\mathcal{A}$ of atoms which we call the *alphabet*. Then, *past temporal formulas* φ are defined by the grammar:

$$\varphi ::= a \mid \bot \mid \neg\varphi \mid \varphi_1 \wedge \varphi_2 \mid \varphi_1 \vee \varphi_2 \mid \bullet\varphi \mid \varphi_1 \,\mathbf{S}\, \varphi_2 \mid \varphi_1 \,\mathbf{T}\, \varphi_2$$

where $a \in \mathcal{A}$ is an atom. The intended meaning of the (modal) temporal operators is as in LTL. $\bullet\varphi$ means that φ is true at the previous time point; $\varphi \,\mathbf{S}\, \psi$ can be read as φ is true since ψ was true and $\varphi \,\mathbf{T}\, \psi$ means that ψ is true since both φ and ψ became true simultaneously or ψ has been true from the beginning.

Given $a \in \mathbb{N}$ and $b \in \mathbb{N}$, we let $[a..b] \stackrel{def}{=} \{i \in \mathbb{N} \mid a \leq i \leq b\}$ and $[a..b) \stackrel{def}{=} \{i \in \mathbb{N} \mid a \leq i < b\}$. A *finite trace* $\mathbf{T}$ of length λ over alphabet $\mathcal{A}$ is a sequence $\mathbf{T} = (T_i)_{i\in[0..\lambda)}$ of sets $T_i \subseteq \mathcal{A}$. To represent a given trace, we write a sequence of sets of atoms concatenated with '$\cdot$'. For instance, the finite trace $\{a\} \cdot \emptyset \cdot \{a\} \cdot \emptyset$ has length 4 and makes a true at even time points and false at odd ones.

A *Here-and-There trace* (for short *HT-trace*) of length λ over alphabet $\mathcal{A}$ is a sequence of pairs $(\langle H_i, T_i \rangle)_{i \in [0..\lambda)}$ with $H_i \subseteq T_i$ for any $i \in [0..\lambda)$. For convenience, we usually represent the HT-trace as the pair $\langle \mathbf{H}, \mathbf{T} \rangle$ of traces $\mathbf{H} = (H_i)_{i \in [0..\lambda)}$ and $\mathbf{T} = (T_i)_{i \in [0..\lambda)}$. Given $\mathbf{M} = \langle \mathbf{H}, \mathbf{T} \rangle$, we also denote its length as $|\mathbf{M}| \stackrel{def}{=} |\mathbf{H}| = |\mathbf{T}| = \lambda$. Note that the two traces $\mathbf{H}$, $\mathbf{T}$ must satisfy a kind of order relation, since $H_i \subseteq T_i$ for each time point i. Formally, we define the ordering $\mathbf{H} \leq \mathbf{T}$ between two traces of the same length λ as $H_i \subseteq T_i$ for each $i \in [0..\lambda)$. Furthermore, we define $\mathbf{H} < \mathbf{T}$ as both $\mathbf{H} \leq \mathbf{T}$ and $\mathbf{H} \neq \mathbf{T}$. Thus, an HT-trace can also be defined as any pair $\langle \mathbf{H}, \mathbf{T} \rangle$ of traces such that $\mathbf{H} \leq \mathbf{T}$. The particular type of HT-traces satisfying $\mathbf{H} = \mathbf{T}$ are called *total*.

An HT-trace $\mathbf{M} = \langle \mathbf{H}, \mathbf{T} \rangle$ of length λ over alphabet $\mathcal{A}$ *satisfies* a past temporal formula φ at time point $k \in [0..\lambda)$, written $\mathbf{M}, k \models \varphi$, if the following conditions hold:

1. $\mathbf{M}, k \models \top$ and $\mathbf{M}, k \not\models \bot$
2. $\mathbf{M}, k \models p$ if $p \in H_k$ for any atom $p \in \mathcal{A}$
3. $\mathbf{M}, k \models \varphi \wedge \psi$ iff $\mathbf{M}, k \models \varphi$ and $\mathbf{M}, k \models \psi$
4. $\mathbf{M}, k \models \varphi \vee \psi$ iff $\mathbf{M}, k \models \varphi$ or $\mathbf{M}, k \models \psi$
5. $\mathbf{M}, k \models \neg\varphi$ iff $\langle \mathbf{T}, \mathbf{T} \rangle, k \not\models \varphi$
6. $\mathbf{M}, k \models \bullet\varphi$ iff $k > 0$ and $\mathbf{M}, k{-}1 \models \varphi$
7. $\mathbf{M}, k \models \varphi \;\mathbf{S}\; \psi$ iff for some $j \in [0..k]$, we have $\mathbf{M}, j \models \psi$ and $\mathbf{M}, i \models \varphi$ for all $i \in (j..k]$
8. $\mathbf{M}, k \models \varphi \;\mathbf{T}\; \psi$ iff for all $j \in [0..k]$, we have $\mathbf{M}, j \models \psi$ or $\mathbf{M}, i \models \varphi$ for some $i \in (j..k]$

A formula φ is a *tautology* (or is *valid*), written $\models \varphi$, iff $\mathbf{M}, k \models \varphi$ for any HT-trace $\mathbf{M}$ and any $k \in [0..\lambda)$. We call the logic induced by the set of all tautologies *Temporal logic of Here-and-There over finite traces* (THT_f for short).

The following equivalences hold in THT_f: 1. $\top \equiv \neg\bot$, 2. $\mathbf{I} \equiv \neg\bullet\top$, 3. $\blacksquare\varphi \equiv \bot \mathbf{T} \varphi$, 4. $\blacklozenge\varphi \equiv \top \mathbf{S} \varphi$, 5. $\widehat{\bullet}\varphi \equiv$

Definition 1 (Past-present Program). *Given alphabet $\mathcal{A}$, the set of* regular literals *is defined as $\{a, \neg a, \mid a \in \mathcal{A}\}$.*

A past-present rule *is either:*

- *an* initial rule *of form* $\quad H \leftarrow B$
- *a* dynamic rule *of form* $\quad \widehat{\circ}\,\square(H \leftarrow B)$
- *a* final rule *of form* $\quad \square(\,\mathbf{F} \rightarrow (\bot \leftarrow B)\,)$

where B is an pure past formula for dynamic rules and $B = b_1 \wedge \cdots \wedge b_n$ with $n \geq 0$ for initial and final rules, the b_i are regular literals, $H = a_1 \vee \cdots \vee a_m$ with $m \geq 0$ and $a_j \in \mathcal{A}$. A past-present program *is a set of past-present rules.* $\square$

We let $I(P)$, $D(P)$, and $F(P)$ stand for the set of all initial, dynamic, and final rules in a past-present program P, respectively. Additionally we refer to H as the *head* of a rule r and to B as the *body* of r. We let $B(r) = B$ and $H(r) = H$

for all types of rules above. For example, let consider the following past-present program P_1:

$$load \leftarrow \tag{1}$$
$$\widehat{\circ}\Box(shoot \vee load \vee unload \leftarrow\ ) \tag{2}$$
$$\widehat{\circ}\Box(dead \leftarrow shoot \wedge \neg unload\, \mathbf{S}\, load) \tag{3}$$
$$\widehat{\circ}\Box(shoot \leftarrow dead) \tag{4}$$
$$\Box(\mathbf{F} \rightarrow (\bot \leftarrow \neg dead)) \tag{5}$$

We get $I(P_1) = \{(1)\}$, $D(P_1) = \{(2),(3),(4)\}$, and $F(P_1) = \{(3)\}$. Rule (1) states that the gun is initially loaded. Rule (2) gives the choice to shoot, load, or unload the gun. Rule (3) states that if the gun is shot while it has been loaded, and not unloaded since, the target is dead. Rule (4) states that if the target is dead, we shoot it again. Rule (5) ensures that the target is dead at the end of the trace.

The satisfaction relation of a past-present rule on an HT-trace $\mathbf{M}$ of length λ and at time point $k \in [0..\lambda)$ is defined below:

- $\mathbf{M}, k \models H \leftarrow B$ iff $\mathbf{M}', k \not\models B$ or $\mathbf{M}', k \models H$, for all $\mathbf{M}' \in \{\mathbf{M}, \langle \mathbf{T}, \mathbf{T}\rangle\}$
- $\mathbf{M}, k \models \widehat{\circ}\,\Box(H \leftarrow B)$ iff $\mathbf{M}', i \not\models B$ or $\mathbf{M}', i \models H$ for all $\mathbf{M}' \in \{\mathbf{M}, \langle \mathbf{T}, \mathbf{T}\rangle\}$ and all $i \in [k+1..\lambda)$
- $\mathbf{M}, k \models \Box(\,\mathbf{F} \rightarrow (\bot \leftarrow B)\,)$ iff $\langle \mathbf{T}, \mathbf{T}\rangle, \lambda - 1 \not\models B$

An HT-trace $\mathbf{M}$ is a *model* of a past-present program P if $\mathbf{M}, 0 \models r$ for all rule $r \in P$. Let P be past-present program. A total HT-trace $\langle \mathbf{T}, \mathbf{T}\rangle$ is a *temporal equilibrium model* of P iff $\langle \mathbf{T}, \mathbf{T}\rangle$ is a *model* of P, and there is no other $\mathbf{H} < \mathbf{T}$ such that $\langle \mathbf{H}, \mathbf{T}\rangle$ is a *model* of P. The trace $\mathbf{T}$ is called a *temporal stable model* (TS-model) of P.

For length $\lambda = 2$, P_1 has a unique TS-model $\{load\} \cdot \{shoot, dead\}$.

3 Temporal completion

In this section, we extend the completion property to the temporal case of past-present programs.

An occurrence of an atom in a formula is *positive* if it is in the antecedent of an even number of implications, negative otherwise. An occurrence of an atom in a formula is *present* if it is not in the scope of $\bullet$ (previous). Given a past-present program P over $\mathcal{A}$, we define its *(positive) dependency graph* $G(P)$ as $(\mathcal{A}, E)$ such that $(a, b) \in E$ if there is a rule $r \in P$ such that $a \in H(r) \cap \mathcal{A}$ and b has positive and present occurence in $B(r)$ that is not in the scope of negation. A nonempty set $L \subseteq \mathcal{A}$ of atoms is called *loop* of P if, for every pair a, b of atoms in L, there exists a path of length > 0 from a to b in $G(P)$ such that all vertices in the path belong to L. We let $L(P)$ denote the set of loops of P.

Due to the structure of past-present programs, dependencies from the future to the past cannot happen, and therefore there can only be loops within a same time point. To reflect this, the definitions above only consider atoms with present occurences. For example, rule $a \leftarrow b \wedge \bullet c$ generates the edge (a, b) but not (a, c).

For P_1, we get for the initial rules $G(I(P_1)) = (\{load, unload, shoot, dead\}, \emptyset)$ whose loops are $L(I(P_1)) = \emptyset$. For the dynamic rules, we get $G(D(P_1)) = (\{load, unload, shoot, dead\}, \{(dead, shoot), (dead, load), (shoot, dead)\})$ and $L(D(P_1)) = \{\{shoot, dead\}\}$.

In the following, $\varphi \rightarrow \psi \stackrel{def}{=} \psi \leftarrow \varphi$ and $\varphi \leftrightarrow \psi \stackrel{def}{=} \varphi \rightarrow \psi \wedge \varphi \leftarrow \psi$.

Definition 2 (Temporal completion). *We define the temporal* completion *formula of an atom a in a past-present program P over $\mathcal{A}$, denoted $CF_P(a)$ as:*

$$\Box\big(a \leftrightarrow \bigvee_{r \in I(P), a \in H(r)} (\mathbf{I} \wedge S(r, a)) \vee \bigvee_{r \in D(P), a \in H(r)} (\neg \mathbf{I} \wedge S(r, a))\big)$$

where $S(r, a) = B(r) \wedge \bigwedge_{p \in H(r) \setminus \{a\}} \neg p$.

The temporal completion *formula of P, denoted $CF(P)$, is*

$$\{CF_P(a) \mid a \in \mathcal{A}\} \cup \{r \mid r \in I(P) \cup D(P), H(r) = \bot\} \cup F(P).$$

A past-present program P is said to be *tight* if $I(P)$ and $D(P)$ do not contain any loop.

Theorem 1. *Let P be a tight past-present program and $\mathbf{T}$ a trace of length λ. Then, $\mathbf{T}$ is a* TS*-model of P iff $\mathbf{T}$ is a LTL$_f$-model of $CF(P)$.* □

The completion of P_1 is

$$CF(P_1) = \left\{ \begin{array}{c} \Box(load \leftrightarrow \mathbf{I} \vee (\neg \mathbf{I} \wedge \neg shoot \wedge \neg unload)), \\ \Box(shoot \leftrightarrow (\neg \mathbf{I} \wedge \neg load \wedge \neg unload)) \vee (\neg \mathbf{I} \wedge dead)), \\ \Box(unload \leftrightarrow (\neg \mathbf{I} \wedge \neg shoot \wedge \neg load)), \\ \Box(dead \leftrightarrow (\neg \mathbf{I} \wedge shoot \wedge \neg unload \, \mathbf{S} \, load)), \\ \Box(\mathbf{F} \rightarrow (\bot \leftarrow \neg dead)) \end{array} \right\}.$$

For $\lambda = 2$, $CF(P_1)$ has a unique LTL$_f$-model $\{load\} \cdot \{shoot, dead\}$, which is identical to the TS-model of P_1. Notice that for this example, the TS-models of the program match the LTL$_f$-models of its completion despite the program not being tight. This is generally not the case. Let P_2 be the program made of the rules (1), (3), (4) and (5). The completion of P_2 is

$$CF(P_2) = \left\{ \begin{array}{l} \Box(load \leftrightarrow \mathbf{I}),\ \Box(shoot \leftrightarrow (\neg \mathbf{I} \wedge dead)),\ \Box(unload \leftrightarrow \bot), \\ \Box(dead \leftrightarrow (\neg \mathbf{I} \wedge shoot \wedge \neg unload \, \mathbf{S} \, load)),\ \Box(\mathbf{F} \rightarrow (\bot \leftarrow \neg dead)) \end{array} \right\}.$$

P_2 does not have any TS-model, but $\{load\} \cdot \{shoot, dead\}$ is a LTL$_f$-model of $CF(P_2)$. Under ASP semantics, it is impossible to derive any element of the loop $\{shoot, dead\}$, as deriving *dead* requires *shoot* to be true, and deriving *shoot* requires *dead* to be true. The completion does not restrict this kind of circular derivation and therefore is insufficient to fully capture ASP semantics.

4 Temporal loop formulas

To restrict circular derivations, Lin and Zhao introduced the concept of loop formulas in [21]. In this section, we extend their work to past-present programs.

Definition 3. *Let φ be a implication-free past-present formula and L a loop. We define the supporting transformation of φ with respect to L as*

$$\begin{aligned}
S_{\bot}(L) &\stackrel{def}{=} \bot \\
S_p(L) &\stackrel{def}{=} \bot \textit{ if } p \in L \text{ ; } p \textit{ otherwise, for any } p \in \mathcal{A} \\
S_{\neg\varphi}(L) &\stackrel{def}{=} \neg\varphi \\
S_{\varphi\wedge\psi}(L) &\stackrel{def}{=} S_\varphi(L) \wedge S_\psi(L) \\
S_{\varphi\vee\psi}(L) &\stackrel{def}{=} S_\varphi(L) \vee S_\psi(L) \\
S_{\bullet\varphi}(L) &\stackrel{def}{=} \bullet\varphi \\
S_{\varphi \mathbf{T} \psi}(L) &\stackrel{def}{=} S_\psi(L) \wedge (S_\varphi(L) \vee \bullet(\varphi \mathbf{T} \psi)) \\
S_{\varphi \mathbf{S} \psi}(L) &\stackrel{def}{=} S_\psi(L) \vee (S_\varphi(L) \wedge \bullet(\varphi \mathbf{S} \psi))
\end{aligned}$$

□

Definition 4 (External support). *Given a past-present program P, the external support formula of a set of atoms $L \subseteq \mathcal{A}$ wrt P, is defined as*

$$ES_P(L) = \bigvee_{r\in P, H(r)\cap L \neq \emptyset} \Big(S_{B(r)}(L) \wedge \bigwedge_{a \in H(r)\setminus L} \neg a\Big)$$

□

For instance, for $L = \{shoot, dead\}$, $ES_{P_2}(L)$ and $ES_{P_1}(L)$ are

$$\begin{aligned}
ES_{P_2}(L) &= S_{dead}(L) \vee S_{shoot\wedge\neg unload \mathbf{S} load}(L) \\
&= S_{dead}(L) \vee (S_{shoot}(L) \wedge S_{\neg unload \mathbf{S} load}(L)) \\
&= S_{dead}(L) \vee (S_{shoot}(L) \wedge S_{\neg unload}(L) \vee \bullet(\neg unload \mathbf{S} load)) \\
&= \bot \vee (\bot \wedge \neg unload \vee \bullet(\neg unload \mathbf{S} load)) = \bot. \\
ES_{P_1}(L) &= S_{dead}(L) \vee S_{shoot\wedge\neg unload \mathbf{S} load}(L) \vee (\neg load \wedge \neg unload) \\
&= \neg load \wedge \neg unload.
\end{aligned}$$

Rule (2) provides an external support for L. The body *dead* of rule (4) is also a support for L, but not external as *dead* belongs to L. The supporting transformation only keeps external supports by removing from the body any positive and present occurence of element of L.

Definition 5 (Loop formulas). *We define the set of loop formulas of a past-present program P over $\mathcal{A}$, denoted $LF(P)$, as:*

$$\bigvee_{a\in L} a \rightarrow ES_{I(P)}(L) \textit{ for any loop } L \textit{ in } I(P)$$

$$\widehat{\circ}\Box\Big(\bigvee_{a\in L} a \rightarrow ES_{D(P)}(L)\Big) \textit{ for any loop } L \textit{ in } D(P)$$

Theorem 2. *Let P be a past-present program and $\mathbf{T}$ a trace of length λ. Then, $\mathbf{T}$ is a* TS*-model of P iff $\mathbf{T}$ is a LTL_f-model of $CF(P) \cup LF(P)$.* $\square$

For our examples, we have that $LF(P_1) = \widehat{\circ}\square(shoot \vee dead \rightarrow \neg load \wedge \neg unload)$ and $LF(P_2) = \widehat{\circ}\square(shoot \vee dead \rightarrow \bot)$. It can be also checked that $\{load\}\cdot\{shoot, dead\}$ satisfies $LF(P_1)$, but not $LF(P_2)$. So, we have that $CF(P_1) \cup LF(P_1)$ has a unique LTL_f-model $\{load\} \cdot \{shoot, dead\}$, while $CF(P_2) \cup LF(P_2)$ has no LTL_f-model, matching the TS-models of the respective programs.

5 Temporal loop formulas with unitary cycles

Ferraris et al. [15] proposed an approach where the computation of the completion can be avoided by considering unitary cycles. In this section, we extend such results for past-present programs. We first redefine loops so that unitary cycles are included.

Definition 6 (Unitary cycle). *A nonempty set $L \subseteq \mathcal{A}$ of atoms is called* loop *of P if, for every pair a, b of atoms in L, there exists a path (possibly of length 0) from a to b in $G(P)$ such that all vertices in the path belong to L.*

With this definition, it is clear that any set consisting of a single atom is a loop. For example, $L(D(P_1)) = \{\{load\}, \{unload\}, \{shoot\}, \{dead\}, \{shoot, dead\}\}$.

Theorem 3. *Let P be a past-present program and $\mathbf{T}$ a trace of length λ. Then, $\mathbf{T}$ is a* TS*-model of P iff $\mathbf{T}$ is a LTL_f-model of $P \cup LF(P)$.*

With unitary cycle, $LF(P_1)$ becomes

$$
\begin{aligned}
load &\rightarrow \top \\
unload &\rightarrow \bot \\
shoot &\rightarrow \bot \\
dead &\rightarrow \bot \\
\widehat{\circ}\square(load &\rightarrow \neg shoot \wedge \neg unload) \\
\widehat{\circ}\square(unload &\rightarrow \neg shoot \wedge \neg load) \\
\widehat{\circ}\square(shoot &\rightarrow (\neg shoot \wedge \neg load) \vee dead) \\
\widehat{\circ}\square(dead &\rightarrow shoot \wedge \neg unload \,\mathbf{S}\, load) \\
\widehat{\circ}\square(shoot \vee dead &\rightarrow \neg load \wedge \neg unload)
\end{aligned}
$$

$P_1 \cup LF(P_1)$ has the same LTL_f-model $CF(P_1) \cup LF(P_1)$, $\{load\}\cdot\{shoot, dead\}$, which is the TS-model of P_1.

6 Conclusion

We have focused on temporal logic programming within the context of Temporal Equilibrium Logic over finite traces. More precisely, we have studied a fragment close to logic programming rules in the spirit of [16]: a past-present temporal logic program consists of a set of rules whose body refers to the past and present while their head refers to the present. This fragment is very interesting for implementation purposes since it can be solved by means of incremental solving techniques as implemented in *telingo*.

Contrary to the propositional case [15], where answer sets of an arbitrary propositional formula can be captured by means of the classical models of another formula ψ, in the temporal case, this is impossible to do the same mapping among the temporal equilibrium models of a formula φ and the LTL models of another formula ψ [5].

In this paper, we show that past-present temporal logic programs can be effectively reduced to LTL formulas by means of completion and loop formulas. More precisely, we extend the definition of completion and temporal loop formulas in the spirit of Lin and Zhao [21] to the temporal case, and we show that for tight past-present programs, the use of completion is sufficient to achieve a reduction to an LTL_f formula. Moreover, when the program is not tight, we also show that the computation of the temporal completion and a finite number of loop formulas suffices to reduce TEL_f to LTL_f.

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A Proofs

Definition 7. *Let* $\langle \mathbf{H}, \mathbf{T} \rangle$ *and* $\langle \mathbf{H}', \mathbf{T} \rangle$ *be two HT-traces of length* λ *and let* $i \in [0..\lambda)$. *We say denote by* $\langle \mathbf{H}, \mathbf{T} \rangle \sim_i \langle \mathbf{H}', \mathbf{T} \rangle$ *the fact for all* $j \in [0..i)$, $H_i = H'_i$.

Proposition 1. *For all HT-traces* $\langle \mathbf{H}, \mathbf{T} \rangle$ *and* $\langle \mathbf{H}', \mathbf{T} \rangle$ *and for all* $i \in [0..\lambda)$, *if* $\langle \mathbf{H}, \mathbf{T} \rangle \sim_i \langle \mathbf{H}', \mathbf{T} \rangle$ *then for all* $j \in [0..i)$ *and for all past formulas* φ, $\langle \mathbf{H}, \mathbf{T} \rangle, j \models \varphi$ *iff* $\langle \mathbf{H}', \mathbf{T} \rangle, j \models \varphi$

Definition 8 ($\mathbf{X}^i$). *Let* $\langle \mathbf{H}, \mathbf{T} \rangle$ *be a HT-trace of length* λ *and* $i \in [0..\lambda)$. *We denote* $\mathbf{X}^i$ *the trace of length* λ *satisfying* $X^i_k = \emptyset$ *for all* $k \in [0..i)$.

Lemma 1. *For all HT-traces* $\langle \mathbf{H}, \mathbf{T} \rangle$ *of length* λ, *for all* $i \in [0..\lambda)$ *and for any past formula* φ, *if each present and positive occurrence of an atom from* X^i_i *in* φ *is in the scope of negation then* $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \varphi$ *iff* $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \models \varphi$.

Proof of Lemma 1. By induction on φ. First, note that for any formula ϕ of the form $\varphi \vee \psi$, $\varphi \wedge \psi$, $\varphi \ \mathsf{T} \ \psi$ or $\varphi \ \mathsf{S} \ \psi$, if all present and positive occurrences of an atom p are in the scope of negation in ϕ, then all present and positive occurrences of p are also in the scope of negation in φ and ψ.

- case $\bot$: clearly, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \bot$ and $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \not\models \bot$.
- case p: we consider two cases. If $p \notin X^i_i$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \models p$ iff $p \in H_i$, iff $p \in H_i \setminus X_i$, iff $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \models p$.
  If $p \in X^i_i$, then p has a present and positive occurence in φ, which is not in the scope of negation. Therefore, the lemma automatically holds.
- case $\neg\varphi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \neg\varphi$ iff $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models \varphi$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \neg\varphi$ (because of persistency).
- case $\bullet\varphi$:
  - if $i = 0$, then $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \bullet\varphi$ and $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \not\models \bullet\varphi$.
  - if $i > 0$, then $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \bullet\varphi$ iff $\langle \mathbf{H}, \mathbf{T} \rangle, i-1 \models \varphi$. Let X^{i-1} be such that $X^{i-1}_{i-1} = \emptyset$. Then, we can apply the induction hypothesis, so $\langle \mathbf{H}, \mathbf{T} \rangle, i-1 \models \varphi$ iff (IH) $\langle \mathbf{H} \setminus \mathbf{X}^{i-1}, \mathbf{T} \rangle, i-1 \models \varphi$. Since $\langle \mathbf{H} \setminus \mathbf{X}^{i-1}, \mathbf{T} \rangle \sim_i \langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle$ (Proposition 1) then $\langle \mathbf{H} \setminus \mathbf{X}^{i-1}, \mathbf{T} \rangle, i-1 \models \varphi$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i-1 \models \varphi$, iff $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \models \bullet\varphi$.
- case $\varphi \vee \psi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \varphi \vee \psi$ iff $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \varphi$ or $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \psi$. Since all positive and present occurences of atoms from X^i_i in φ and ψ are in the scope of negation, we can apply the induction hypothesis to get $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \models \varphi$ or $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \models \psi$. Therefore, $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \models \varphi \vee \psi$.

- case $\varphi \wedge \psi$: Similar as for $\varphi \vee \psi$.
- case $\varphi \mathbf{S} \psi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \varphi \mathbf{S} \psi$ iff for some $j \in [0..i]$, $\langle \mathbf{H}, \mathbf{T} \rangle, j \models \psi$ and $\langle \mathbf{H}, \mathbf{T} \rangle, k \models \varphi$ for all $k \in (j..i]$. By induction we get that iff for some $j \in [0..i]$, $\langle \mathbf{H} \setminus \mathbf{X}^j, \mathbf{T} \rangle, j \models \psi$ and $\langle \mathbf{H} \setminus \mathbf{X}^k, \mathbf{T} \rangle, k \models \varphi$ for all $k \in (j..i]$. Since $\langle \mathbf{H} \setminus \mathbf{X}^t, \mathbf{T} \rangle \sim_t \langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle$ for all $t \in [0..i)$, by Proposition 1 we get that iff for some $j \in [0..i]$, $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, j \models \psi$ and $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, k \models \varphi$ for all $k \in (j..i]$. iff $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \models \varphi \mathbf{S} \psi$.
- case $\varphi \mathbf{T} \psi$: assume by contradiction that $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, i \not\models \varphi \mathbf{T} \psi$. This means that there exist $j \in [0..i]$ such that $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, j \not\models \psi$ and $\langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle, k \not\models \varphi$ for all $k \in (j..i]$. Since $\langle \mathbf{H} \setminus \mathbf{X}^t, \mathbf{T} \rangle \sim_t \langle \mathbf{H} \setminus \mathbf{X}^i, \mathbf{T} \rangle$ for all $t \in [0..i)$, by Proposition 1 we get that there exist $j \in [0..i]$ such that $\langle \mathbf{H} \setminus \mathbf{X}^j, \mathbf{T} \rangle, j \not\models \psi$ and $\langle \mathbf{H} \setminus \mathbf{X}^k, \mathbf{T} \rangle, k \not\models \varphi$ for all $k \in (j..i]$. By induction, there exist $j \in [0..i]$ such that $\langle \mathbf{H}, \mathbf{T} \rangle, j \not\models \psi$ and $\langle \mathbf{H}, \mathbf{T} \rangle, k \not\models \varphi$ for all $k \in (j..i]$ iff $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \varphi \mathbf{T} \psi$: a contradiction.

□

Definition 9. *Let $L \subseteq \mathcal{A}$ and let $\lambda > 0$ and $i \in [0..\lambda)$. By $\mathbf{X}(L)^i$ we mean a trace of length λ satisfying the following conditions:*

1. *$L \subseteq X(L)^i_i \subseteq \mathcal{A}$;*
2. *$X(L)^i_t = \emptyset$ for all $t \in [0..i)$.*

Lemma 2. *Let $\langle \mathbf{H}, \mathbf{T} \rangle$ be a HT-trace of length λ, φ a past formula. Let us consider the set of atoms $L \subseteq \mathcal{A}$. For all $i \in [0..\lambda)$, if each positive occurrence of an atom from $X(L)^i_i \setminus L$ in φ is in the scope of negation, $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_\varphi(L)$ iff $\langle \mathbf{H} \setminus \mathbf{X}(L)^i, \mathbf{T} \rangle, i \models \varphi$.*

Proof of Lemma 2. By induction on φ. First, note that for any formula ϕ of the form $\varphi \vee \psi$, $\varphi \wedge \psi$, $\varphi \mathbf{T} \psi$ or $\varphi \mathbf{S} \psi$, if all present and positive occurrences of an atom p are in the scope of negation in ϕ, then all present and positive occurrences of p are also in the scope of negation in φ and ψ.

- case $\bot$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \bot$ and $\langle \mathbf{H} \setminus \mathbf{X}(L)^i, \mathbf{T} \rangle, i \not\models \bot$.
- case $p \notin L$: we consider the following two cases
  - If $p \notin L$, $S_p(L) = p$ and, by definition, $p \notin X(L)^i_i$. Therefore, $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_p(L)$ iff $\langle \mathbf{H}, \mathbf{T} \rangle, i \models p$, iff $p \in H_i$ iff $p \in H_i \setminus X(L)^i_i$, iff $\langle \mathbf{H} \setminus \mathbf{X}(L)^i, \mathbf{T} \rangle, i \models p$.
  - If $p \in L$ then $p \notin X(L)^i_i \setminus L$ and $S_p(L) = \bot$. Therefore, we get that $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models S_p(L)$ and $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \not\models p$.
- case $\neg\varphi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\neg\varphi}(L)$ iff $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \neg\varphi$, iff $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models \varphi$, iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \neg\varphi$.
- case $\bullet\varphi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\bullet\varphi}(L)$ iff $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \bullet\varphi$.
  - If $i = 0$, then both $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \not\models \bullet\varphi$ and $\langle \mathbf{H} \setminus \mathbf{X}(L)^0, \mathbf{T} \rangle, 0 \not\models \bullet\varphi$.
  - If $i > 0$, then $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \bullet\varphi$ iff $\langle \mathbf{H}, \mathbf{T} \rangle, i-1 \models \varphi$. By definition, $X(L)^i_j = \emptyset$ for $j \in [0..i)$ so by Lemma 1, $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i-1 \models \varphi$, iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \bullet\varphi$.

– case $\varphi \wedge \psi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\varphi\wedge\psi}(L)$
iff $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\varphi}(L)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\psi}(L)$,
iff (IH) $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \varphi$ and $\langle \mathbf{H} \setminus \mathbf{X}^i(X), \mathbf{T} \rangle, i \models \psi$,
iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \varphi \wedge \psi$.
– case $\varphi \vee \psi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\varphi\vee\psi}(L)$
iff $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\varphi}(L)$ or $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\psi}(L)$,
iff (IH) $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \varphi$ or $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \psi$,
iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \varphi \vee \psi$.
– case $\varphi \,\mathsf{S}\, \psi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\varphi \mathsf{S} \psi}(L)$ iff
  1. $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\psi}(L)$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \psi$ (IH) or
  2. $\langle \mathbf{H}, \mathbf{T} \rangle, i \models S_{\varphi}(L)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \bullet(\varphi \mathsf{S} \psi)$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \varphi$ (IH) and $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \bullet(\varphi \mathsf{S} \psi)$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \varphi$ and $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \bullet(\varphi \,\mathsf{S}\, \psi)$

From the previous items we conclude iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \psi \vee (\varphi \wedge \bullet\,(\varphi \,\mathsf{S}\, \psi))$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \models \varphi \,\mathsf{S}\, \psi$.
– case $\varphi \,\mathsf{T}\, \psi$: $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models S_{\varphi \mathsf{T} \psi}(L)$ iff
  1. $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models S_{\psi}(L)$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \not\models \psi$ (IH) or
  2. $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models S_{\varphi}(L)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \bullet(\varphi \mathsf{T} \psi)$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \not\models \varphi$ (IH) and $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \bullet(\varphi \mathsf{T} \psi)$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \not\models \varphi$ and $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \not\models \bullet(\varphi \,\mathsf{T}\, \psi)$

From the previous items we conclude iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \not\models \psi \wedge (\varphi \vee \bullet\,(\varphi \,\mathsf{T}\, \psi))$ iff $\langle \mathbf{H} \setminus \mathbf{X}^i(L), \mathbf{T} \rangle, i \not\models \varphi \,\mathsf{T}\, \psi$.

□

Proof of Theorem 1. From left to right, let us assume towards a contradiction that $\mathbf{T}$ is a temporal answer set of P, but $\mathbf{T}$ is not an LTL$_f$-model of $CF(P)$. By construction, if $\mathbf{T}$ is a temporal answer set of P then $\mathbf{T}$ is an LTL$_f$ model of P so $\mathbf{T}, 0 \models P$. Therefore, $\mathbf{T}, 0 \models r$, for all $r \in P$ such that $H(r) = \bot$ and $\mathbf{T}, 0 \models r$ for all $r \in F(P)$. Since $\mathbf{T}, 0 \not\models CF(P)$, there exists $a \in \mathcal{A}$ such that

$$\mathbf{T}, 0 \not\models \Box\big(a \leftrightarrow \bigvee_{r \in I(P), a \in H(r)} (\mathsf{I} \wedge S(r,a)) \vee \bigvee_{r \in D(P), a \in H(r)} (\neg \mathsf{I} \wedge S(r,a))\big)$$

So, there exists $i \in [0..\lambda)$ such that

$$\mathbf{T}, i \not\models a \leftrightarrow \bigvee_{r \in I(P), a \in H(r)} (\mathsf{I} \wedge S(r,a)) \vee \bigvee_{r \in D(P), a \in H(r)} (\neg \mathsf{I} \wedge S(r,a))$$

We consider two cases:

1. $\mathbf{T}, i \models a$ and $\mathbf{T}, i \not\models \bigvee_{r \in I(P), a \in H(r)} (\mathsf{I} \wedge S(r,a)) \vee \bigvee_{r \in D(P), a \in H(r)} (\neg \mathsf{I} \wedge S(r,a))$:
   – If $i = 0$ then we get that for all $r \in I(P)$, if $a \in H(r)$ then $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models S(r,a)$. Therefore, for all $r \in I(P)$, if $a \in H(r)$ then $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models \S(r,a)$. Let $\mathbf{H}$ be a trace of length λ such that $H_0 = T_0 \setminus \{a\}$ and $H_i = T_i$ for $i \in [1..\lambda)$. Clearly, $\mathbf{H} < \mathbf{T}$. We show a contradiction by proving that $\langle \mathbf{H}, \mathbf{T} \rangle \models P$:

(a) $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models I(P)$: note that $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models B(r) \to H(r)$ for all $r \in I(P)$, iff for any $r \in I(P)$, $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models B(r)$ or $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models H(r)$. If $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models B(r)$ then, by persistence, $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \not\models B(r)$, and $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models B(r) \to H(r)$. If $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models B(r)$, then $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models H(r)$. There are two cases.
   - Case $a \notin H(r)$: $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models H(r)$ so there is some $p \in H(r)$ such that $p \in T_0$ and $p \neq a$. Then, $p \in H_0$, $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models H(r)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models r$.
   - Case $a \in H(r)$: We know that $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models B(r) \wedge \bigwedge_{p \in H(r) \setminus \{a\}} \neg p$. Since, by assumption, $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models B(r)$, it follows $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models \bigwedge_{p \in H(r) \setminus \{a\}} \neg p$ Therefore, there is $p \in H(r) \setminus \{a\}$ such that $p \in T_0$. Then $p \in H_0$, $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models H(r)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models r$.

   As r is chosen arbitrarily, $\langle \mathbf{H}, \mathbf{T} \rangle \models I(P)$.

(b) $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models D(P)$: $\langle \mathbf{T}, \mathbf{T} \rangle \models D(P)$, then $\langle \mathbf{T}, \mathbf{T} \rangle, i \models B(r) \to H(r)$ for all $r \in D(P)$ and $i \in [1..\lambda)$. Then, for any $r \in D(P)$ and $i \in [1..\lambda)$, $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models B(r)$ or $\langle \mathbf{T}, \mathbf{T} \rangle, i \models H(r)$. If $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models B(r)$ then, by persistence, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$, and $\langle \mathbf{H}, \mathbf{T} \rangle, i \models r$. If, $\langle \mathbf{T}, \mathbf{T} \rangle, i \models H(r)$, there is some $p \in H(r)$ such that $p \in T_i$. $H_i = T_i$, so $p \in H_i$ and $\langle \mathbf{H}, \mathbf{T} \rangle, i \models H(r)$. Then $\langle \mathbf{H}, \mathbf{T} \rangle, i \models r$. As r and i are chosen arbitrarily, $\langle \mathbf{H}, \mathbf{T} \rangle \models D(P)$.

(c) $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models F(P)$: final rules are constraints, so $\langle \mathbf{T}, \mathbf{T} \rangle \models F(P)$ implies $\langle \mathbf{H}, \mathbf{T} \rangle \models F(P)$.

We showed that $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models P$: a contradiction.

– If $i > 0$: we follow a very similar reasoning as for the case $i = 0$.

2. $\mathbf{T}, i \not\models a$ but $\mathbf{T}, i \models \bigvee_{r \in I(P), a \in H(r)} (\mathbf{I} \wedge S(r, a)) \vee \bigvee_{r \in D(P), a \in H(r)} (\neg \mathbf{I} \wedge S(r, a))$: again, we consider two cases here
   – there exists $r \in I(P), a \in H(r)$ and $\mathbf{T}, i \models \mathbf{I} \wedge S(r, a)$: in this case, it follows that $i = 0$, so $\mathbf{T}, 0 \models a$ and $\mathbf{T}, 0 \models S(r, a)$. Therefore, $\mathbf{T}, 0 \models B(r)$. Since $\mathbf{T}, 0 \models r$ and $\mathbf{T}, 0 \models B(r)$ then $\mathbf{T}, 0 \models p$ for some $p \in H(r)$, which contradicts $\mathbf{T}, 0 \not\models a$ and $\mathbf{T}, 0 \models \neg q$ for all $p \in H(r) \setminus \{a\}$.
   – there exists $r \in D(P), a \in H(r)$ and $\mathbf{T}, i \models \neg \mathbf{I} \wedge S(r, a)$: in this case we conclude that $i > 0$ and so $\mathbf{T}, i \models a$ and $\mathbf{T}, i \models S(r, a)$. Therefore, $\mathbf{T}, i \models B(r)$. Since $\mathbf{T}, 0 \models r$ and $\mathbf{T}, i \models B(r)$ then $\mathbf{T}, i \models q$ for some $q \in H(r)$. However, from $\mathbf{T}, i \models S(r, a)$ and $\mathbf{T}, i \not\models a$ we conclude that $\mathbf{T}, i \not\models p$ for all $p \in H(r)$: a contradiction.

For the converse direction, assume, again, by contradiction that $\langle \mathbf{T}, \mathbf{T} \rangle$ is not a TEL_f model of P. We consider two cases:

1. $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models P$. Therefore, there exists $r \in P$ such that $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models r$. Clearly, r cannot be a constraint, otherwise we would already reach a contradiction. We still have to check two cases:
   – If $r \in I(P)$, then $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models B(r)$ and $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models H(r)$. Take any $a \in H(r)$. It follows that $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models \mathbf{I} \wedge S(r, a)$. so $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models CF_P(a)$: a contradiction.
   – If $r \in D(P)$ we follow a similar reasoning as for the previous case.

2. $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models P$ but $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models P$ for some $\mathbf{H} < \mathbf{T}$. By definition, there exists $i \geq 0$ such that $H_i \subset T_i$. Let us take the smallest i satisfying this property. Therefore, $H_j = T_j$ for all $j \in [0..i)$. .Moreover, Let us take $a \in T_i \setminus H_i$ and let us proceed depending on the value of i

   – If $i > 0$ and $a \in T_i$ then $\langle \mathbf{T}, \mathbf{T} \rangle, i \models CF_P(a)$ then there exists $r \in D(P)$ such that $\langle \mathbf{T}, \mathbf{T} \rangle, i \models S(r, a)$. Therefore $H(t) \setminus \{a\} \cup T_i = 0$ Since $a \notin H_i$ then $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models H(r)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$.
     At this point of the proof we have that $\langle \mathbf{T}, \mathbf{T} \rangle, i \models B(r)$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$ and $T_j \setminus H_j = \emptyset$ for any $j < i$. By Lemma 1, there must be some $b \in T_i \setminus H_i$ with a present and positive occurence in $B(r)$ that is not in the scope of negation. Then, for any $a \in T_i \setminus H_i$, there is some $b \in T_i \setminus H_i$ such that $(a, b) \in G(D(P))$. P is tight, so $G(D(P))$ is acyclic. Then, there is a topological ordering of the nodes in $G(D(P))$, and therefore of the atoms in $T_i \setminus H_i$, such that if $a, b \in T_i \setminus H_i$ and $(a, b) \in G(D(P))$, then a appears before b in the topoligical ordering. Then, there is no outgoing edge from the last node in the ordering, which contradict the fact that, for any $a \in T_i \setminus H_i$, there is some $b \in T_i \setminus H_i$ such that $(a, b) \in G(D(P))$.

   – If $i = 0$ we proceed as in the previous case.

□

Proof of Theorem 2.

We first prove that if $\mathbf{T}$ is a temporal answer set of P, then $\mathbf{T}$ is a LTL$_f$-model of $CF(P)$ and $LF(P)$. The proof for $CF(P)$ is the same as for Theorem 1. Remains to prove that $\mathbf{T}$ is a LTL$_f$-model of $LF(P)$. Assume by contradiction that $\langle \mathbf{T}, \mathbf{T} \rangle \not\models LF(P)$. Two different cases must be considered:

– there is a loop L in $G(D(P))$ such that $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models \bigvee_{a \in L} a \rightarrow ES_{D(P)}(L)$ for some $i \in [1..\lambda)$, or
– there is a loop L in $G(I(P))$ such that $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \not\models \bigvee_{a \in L} a \rightarrow ES_{I(P)}(L)$.

For the first case, let $\mathbf{H}$ be a trace of length λ such that $H_i = T_i \setminus L$ and $H_k = T_k$ otherwise. We show that $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models P$, which will contradict the hypothesis $\mathbf{T}$ is a TEL$_f$-model of P:

1. $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models I(P)$: follows from $\langle \mathbf{T}, \mathbf{T} \rangle \models I(P)$ by Lemma 1 as $T_0 \setminus H_0 = \emptyset$.
2. $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models F(P)$: follows from $\langle \mathbf{T}, \mathbf{T} \rangle \models F(P)$ as rules in $F(P)$ are constraints.
3. $\langle \mathbf{H}, \mathbf{T} \rangle, 0 \models D(P)$: $\langle \mathbf{T}, \mathbf{T} \rangle, 0 \models D(P)$ since $\mathbf{T}$ is a TEL$_f$-model of P. Therefore, $\langle \mathbf{T}, \mathbf{T} \rangle, k \models r$ for all $k \in [1..\lambda)$ and for all $r \in D(P)$. Then, $\langle \mathbf{T}, \mathbf{T} \rangle, k \not\models B(r)$ or $\langle \mathbf{T}, \mathbf{T} \rangle, k \models H(r)$. If $\langle \mathbf{T}, \mathbf{T} \rangle, k \not\models B(r)$, by persistence, $\langle \mathbf{H}, \mathbf{T} \rangle, k \not\models B(r)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, k \models r$. If $\langle \mathbf{T}, \mathbf{T} \rangle, k \models B(r)$, then $\langle \mathbf{T}, \mathbf{T} \rangle, k \models H(r)$.
   In the case $k \neq i$, $H_k = T_k$ and $\langle \mathbf{T}, \mathbf{T} \rangle, k \models H(r)$ imply $\langle \mathbf{H}, \mathbf{T} \rangle, k \models H(r)$.In the case $k = i$, we have two cases.
   – if $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models S_{B(r)}(L)$, then, as $(T_i \setminus H_i) \setminus L = \emptyset$ and $T_k \setminus H_k = \emptyset$ for $k < i$, by Lemma 2, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$. So $\langle \mathbf{H}, \mathbf{T} \rangle, i \models r$.

– if $\langle \mathbf{T}, \mathbf{T} \rangle, i \models S_{B(r)}(L)$ and $H(r) \cap L = \emptyset$ then $\langle \mathbf{H}, \mathbf{T} \rangle, i \models H(r)$ follows from $\langle \mathbf{T}, \mathbf{T} \rangle, i \models H(r)$ and $\langle \mathbf{H}, \mathbf{T} \rangle, i \models r$.
– if $\langle \mathbf{T}, \mathbf{T} \rangle, i \models S_{B(r)}(L)$ and $H(r) \cap L = \emptyset$ then
  - if there is some $p \in H(r) \setminus L$ such that $p \in T_i$, then $p \in H_i$. So $\langle \mathbf{H}, \mathbf{T} \rangle, i \models H(r)$ and then $\langle \mathbf{H}, \mathbf{T} \rangle, i \models r$.
  - if there is no $p \in H(r) \setminus L$ such that $p \in T_i$, then $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \setminus L} \neg p$. As we also have $\langle \mathbf{T}, \mathbf{T} \rangle, i \models S_{B(r)}(L)$, $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigvee_{a \in L} a \rightarrow ES_{D(P)}(L)$, which contradict our hypothesis.

The proof of the second case follows a similar reasoning as for the first one.

Next, we prove that if $\mathbf{T}$ is a LTL$_f$-model of $CF(P)$ and $LF(P)$, then $\mathbf{T}$ is a TEL$_f$-model of P. The proof for $\langle \mathbf{T}, \mathbf{T} \rangle \models P$ is the same as for Theorem 1. Remains to prove that there is no $\mathbf{H} < \mathbf{T}$ such that $\langle \mathbf{H}, \mathbf{T} \rangle \models P$.

Let assume that there exists such a trace $\mathbf{H}$, and let i be the smallest time point such that $H_i \subset T_i$. Therefore, $H_k = T_k$ for all $k \in [0..i)$.

– If $i > 0$: Let $a \in T_i \setminus H_i$. $\langle \mathbf{T}, \mathbf{T} \rangle \models CF(P)$, so $\langle \mathbf{T}, \mathbf{T} \rangle, i \models a \leftrightarrow \bigvee_{r \in D(P), a \in H(r)} (B(r) \wedge \bigwedge_{p \in H(r) \setminus \{a\}} \neg p)$. As $a \in T_i$, there is some rule $r \in D(P)$ such that $a \in H(r)$, $\langle \mathbf{T}, \mathbf{T} \rangle, i \models B(r)$, and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \setminus \{a\}} \neg p$. $\langle \mathbf{H}, \mathbf{T} \rangle \models P$, so $\langle \mathbf{H}, \mathbf{T} \rangle, i \models B(r) \rightarrow a \vee \bigvee_{p \in H(r) \setminus \{a\}} p$. Then, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$ or $\langle \mathbf{H}, \mathbf{T} \rangle, i \models a$ or $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \bigvee_{p \in H(r) \setminus \{a\}} p$. As $a \notin H_i$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models a$. As $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \setminus \{a\}} \neg p$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \bigvee_{p \in H(r) \setminus \{a\}} p$. So, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$.
  $\langle \mathbf{T}, \mathbf{T} \rangle, i \models B(r)$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$ and $T_j \setminus H_j = \emptyset$ for $j < i$, so, by Lemma 1, there must be some $b \in T_i \setminus H_i$ with a present and positive occurence in $B(r)$ that is not in the scope of negation. Therefore, for any $a \in T_i \setminus H_i$, there is some $b \in T_i \setminus H_i$ such that $(a, b) \in G(D(P))$. It implies a loop L in $D(P)$, with $L \subseteq T_i \setminus H_i$.
  The strongly connected components (SCC) of the dependency graph of $D(P)$ over $T_i \setminus H_i$ form a directed acyclic graph, so there is some SCC L, such that, for any $a \in L$, there is no $b \in (T_i \setminus H_i) \setminus L$ such that $(a, b) \in G(D(P))$.
  For any $a \in T_i \setminus H_i$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$, for all $r \in D(P)$ such that $a \in H(r)$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \setminus \{a\}} \neg p$. So $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$, for all $r \in D(P)$ such that $L \cap H(r) \neq \emptyset$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \setminus L} \neg p$. Let $\mathbf{X}$ be a trace of length λ with $X_i = L$ and $X_j = \emptyset$ for $j \neq i$. For any $a \in L$ there is no $b \in (T_i \setminus H_i) \setminus L$ such that $(a, b) \in G(D(P))$, so all positive and present occurences of atoms from L in $B(r)$ are in the scope of negation. Then, we can apply Lemma 1, and get that $\langle \mathbf{T} \setminus \mathbf{X}, \mathbf{T} \rangle, i \not\models B(r)$, for all $r \in D(P)$ such that $L \cap H(r) \neq \emptyset$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \setminus L} \neg p$. Then, as $X_i \setminus L = \emptyset$, by Lemma 2, $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models S_{B(r)}(L)$, for all $r \in D(P)$ such that $L \cap H(r) \neq \emptyset$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \setminus L} \neg p$. So, $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models \bigvee_{a \in L} a \rightarrow ES_{D(P)}(L)$, and then $\langle \mathbf{T}, \mathbf{T} \rangle \not\models LF(P)$. Contradiction.

– Case $i = 0$: we reach a contradiction in a similar way as above.

□

Proof of Theorem 3.

We first prove that if $\mathbf{T}$ is a temporal answer set of P, then $\mathbf{T}$ is a LTL$_f$-model of $P \cup LF(P)$. $\mathbf{T}$ is a temporal answer set of P, so $\mathbf{T}$ is a LTL$_f$-model of P. We can show that $\mathbf{T}$ is a LTL$_f$-model of $LF(P)$ the same way as for Theorem 2.

Next, we prove that if $\mathbf{T}$ is a LTL$_f$-model of $P \cup LF(P)$, then $\mathbf{T}$ is a temporal answer set of P. It amounts to showing that there is no $\mathbf{H} < \mathbf{T}$ such that $\langle \mathbf{H}, \mathbf{T} \rangle \models P$. Let assume that there is such a trace $\mathbf{H}$, and let i be the smallest time point such that $H_i \subset T_i$.

1. If $i > 0$, Let $a \in T_i \backslash H_i$. $\langle \mathbf{T}, \mathbf{T} \rangle \models LF(P)$, so $\langle \mathbf{T}, \mathbf{T} \rangle, i \models a \leftrightarrow \bigvee_{r \in D(P), a \in H(r)} (S_{B(r)}(a) \wedge \bigwedge_{p \in H(r) \backslash \{a\}} \neg p)$. As $a \in T_i$, there exists $r \in D(P)$ such that $a \in H(r)$, $\langle \mathbf{T}, \mathbf{T} \rangle, i \models S_{B(r)}(a)$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \backslash \{a\}} \neg p$. $\langle \mathbf{H}, \mathbf{T} \rangle \models P$, so $\langle \mathbf{H}, \mathbf{T} \rangle, i \models B(r) \rightarrow a \vee \bigvee_{p \in H(r) \backslash \{a\}} p$. Then, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$ or $\langle \mathbf{H}, \mathbf{T} \rangle, i \models a$ or $\langle \mathbf{H}, \mathbf{T} \rangle, i \models \bigvee_{p \in H(r) \backslash \{a\}} p$. As $a \notin H_i$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models a$. As $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \backslash \{a\}} \neg p$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models \bigvee_{p \in H(r) \backslash \{a\}} p$. So, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$.
   $\langle \mathbf{T}, \mathbf{T} \rangle, i \models S_{B(r)}(a)$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$ and $T_j \setminus H_j = \emptyset$ for $j < i$, so, by Lemma 2, there must be some $b \in T_i \setminus H_i$ with a present and positive occurence in $B(r)$ that is not in the scope of negation. Therefore, for any $a \in T_i \setminus H_i$, there is some $b \in T_i \setminus H_i$ such that $(a, b) \in G(D(P))$. It implies a loop L in $D(P)$, with $L \subseteq T_i \setminus H_i$.
   The strongly connected components (SCC) of the dependency graph of $D(P)$ over $T_i \backslash H_i$ form a directed acyclic graph, so there is some SCC L, such that, for any $a \in L$, there is no $b \in (T_i \setminus H_i) \setminus L$ such that $(a, b) \in G(D(P))$.
   For any $a \in T_i \setminus H_i$, $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$, for all $r \in D(P)$ such that $a \in H(r)$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \backslash \{a\}} \neg p$. So $\langle \mathbf{H}, \mathbf{T} \rangle, i \not\models B(r)$, for all $r \in D(P)$ such that $L \cap H(r) \neq \emptyset$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \backslash L} \neg p$. Let $\mathbf{X}$ be a trace of length λ with $X_i = L$ and $X_j = \emptyset$ for $j \neq i$. For any $a \in L$ there is no $b \in (T_i \setminus H_i) \setminus L$ such that $(a, b) \in G(D(P))$, so all positive and present occurences of atoms from L in $B(r)$ are in the scope of negation. Then, we can apply Lemma 1, and get that $\langle \mathbf{T} \setminus \mathbf{X}, \mathbf{T} \rangle, i \not\models B(r)$, for all $r \in D(P)$ such that $L \cap H(r) \neq \emptyset$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \backslash L} \neg p$. Then, as $X_i \setminus L = \emptyset$, by Lemma 2, $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models S_{B(r)}(L)$, for all $r \in D(P)$ such that $L \cap H(r) \neq \emptyset$ and $\langle \mathbf{T}, \mathbf{T} \rangle, i \models \bigwedge_{p \in H(r) \backslash L} \neg p$. So, $\langle \mathbf{T}, \mathbf{T} \rangle, i \not\models \bigvee_{a \in L} a \rightarrow ES_{D(P)}(L)$, and then $\langle \mathbf{T}, \mathbf{T} \rangle \not\models LF(P)$: a contradiction.

2. For the case when $i = 0$ we reach a contradiction in a similar way as above.

$\square$