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ABSTRACT. Dynamic topological logics are combinations of topological and temporal modal logics that are used for reasoning about dynamical systems consisting of a topological space and a continuous function on it. Here we partially solve a major open problem in the field by showing (by reduction of the \( \omega \)-reachability problem for lossy channel systems) that the dynamic topological logic over arbitrary topological spaces as well as those over Euclidean spaces \( \mathbb{R}^n \), for each \( n \geq 1 \), are undecidable. Actually, we prove this result for the natural and expressive fragment of the full dynamic topological language where the topological operators cannot be applied to formulas containing the temporal eventuality. Using Kruskal’s tree theorem we also show that the formulas of this fragment that are valid in arbitrary topological spaces with continuous functions are recursively enumerable, which is not the case for spaces with homeomorphisms.

1 Introduction

Dynamic topological logics were introduced in [10, 11, 13, 2] with the aim of logical modelling of and reasoning about the asymptotic properties of iterations of continuous functions on topological spaces, that is, orbits \( \{ f(x), f^2(x), \ldots \} \) of points \( x \) in a topological space under a continuous function \( f \). The full dynamic topological language \( \mathcal{DTL} \) of these logics can be regarded as a natural combination of the standard modal language of \( \mathcal{S}_4 \) (which due to results by McKinsey and Tarski [15] can be considered as the logic of topological spaces) interpreted over topological spaces and the propositional temporal language of \( \mathcal{LTL} \) (which can be used to model iterations) interpreted over \( \langle \mathbb{N}, < \rangle \). For instance, the \( \mathcal{DTL} \)-formulas

\[
\bigcirc \mathbb{I} \varphi \quad \text{and} \quad \mathbb{I} \square f^\varphi
\]

are interpreted in a dynamical system \( \langle T, \mathbb{I}, f \rangle \) (where \( \mathbb{I} \) is the interior operator on the space \( T \) and \( f \) is a continuous function on \( \langle T, \mathbb{I} \rangle \)) under a valuation \( \mathcal{V} \) as, respectively, the sets

\[
f^{-1}(\mathcal{V}(\varphi)) \quad \text{and} \quad \mathbb{I} \bigcap_{n=1}^{\infty} f^{-n}(\mathcal{V}(\varphi))
\]

(\( \mathbb{I} \) denotes the ‘box’ modality of \( \mathcal{S}_4 \)). The available body of knowledge in this area can be roughly classified as follows.

Advances in Modal Logic, Volume 6. © 2006, the authors.
The fragment $\mathcal{DTL}^\circ$ of $\mathcal{DTL}$ with sole temporal operator $\circ$:

- The sets of $\mathcal{DTL}^\circ$-formulas that are valid in dynamic topological systems (DTSs, for short) with homeomorphisms based on (i) arbitrary topological spaces, (ii) Aleksandrov spaces, (iii) the Euclidean spaces $\mathbb{R}^n$, for each $n \geq 1$, coincide, enjoy the finite model property (fmp), are finitely axiomatisable and decidable [2, 13, 12, 8].

- The sets of $\mathcal{DTL}^\circ$-formulas that are valid in DTSs (with continuous functions, not only homeomorphisms) based on (i) topological spaces and (ii) Aleksandrov spaces coincide, enjoy the fmp, are finitely axiomatisable and decidable [2, 12, 5]. A challenging open problem here is to investigate the set of $\mathcal{DTL}^\circ$-formulas that are valid in $\mathbb{R}$.

The fragment $\mathcal{DTL}_0$ of $\mathcal{DTL}$ where no temporal operator can occur in the scope of a topological operator: The logic in this language over arbitrary topological spaces and continuous functions was axiomatised in [12]. It is easy to see, in fact, that this logic is decidable and coincides with the corresponding logics over Aleksandrov spaces and $\mathbb{R}^n$, $n \geq 1$, no matter whether the functions are continuous or homeomorphisms only.

Full $\mathcal{DTL}$:

- The sets of $\mathcal{DTL}$-formulas that are valid in DTSs with homeomorphisms based on (i) topological spaces, (ii) Aleksandrov spaces, (iii) $\mathbb{R}^n$, for each $n \geq 1$, are all pairwise distinct and are not recursively enumerable [8]. It is of interest to note that the logics over (i)–(iii) with finitely many iterations of homeomorphisms coincide, but are still not recursively enumerable [8].

- Only two results have been known for the logics of DTSs with continuous functions. First, the logics over arbitrary and Aleksandrov spaces with finitely many iterations coincide and are decidable, but not in primitive recursive time [7]. Second, the logic over Aleksandrov spaces turns out to be undecidable [9]. The major open problem has been to investigate the computational properties (decidability, axiomatisability, etc.) of the logic over $\mathbb{R}^n$ and arbitrary topological spaces.

In this paper we present a partial solution to this open problem by showing that the logics in question are undecidable.

One key observation that has led to this result was the following fact discovered in [6] (and probably elsewhere) in a somewhat different context: the fragment $\mathcal{DTL}_1$ of $\mathcal{DTL}$, where we are not allowed to apply the topological operators to formulas containing $\Box_f$ or $\Diamond_f$ (as in the latter formula in (1)) but can have $\circ$ in the scope of $\top$, is still expressive enough to encode various undecidable problems. But, on the other hand, it is not sufficiently strong to distinguish between arbitrary and Aleksandrov topological spaces. Clearly, $\mathcal{DTL}_1$ extends both $\mathcal{DTL}^\circ$ and $\mathcal{DTL}_0$. It follows from [8] that the sets of $\mathcal{DTL}_1$-formulas valid in (i) topological spaces, (ii) Aleksandrov spaces,
(iii) \( \mathbb{R}^n \), for each \( n \geq 1 \), with *homeomorphisms* are still not recursively enumerable (even for systems with finitely many iterations).

The first main result of this paper is that the undecidable \( \omega \)-reachability problem for lossy channel systems can be reduced, via \( DTL_1 \)-formulas, to satisfiability in Aleksandrov (and so arbitrary topological) spaces. On the other hand, using Kruskal’s tree theorem, we show that the set of valid \( DTL_1 \)-formulas is recursively enumerable (we actually conjecture that it is finitely axiomatisable). However, it is still an open problem whether the set of all valid \( DTL \)-formulas is axiomatisable.

The second key idea is that the technique of embedding Aleksandrov spaces into \( \mathbb{R} \) from [3] can be used to show that, given an arbitrary \( DTL_1 \)-formula \( \varphi \), one can construct a formula \( \varphi^R \), the *relativisation* of \( \varphi \), such that \( \varphi \) is satisfiable if and only if \( \varphi^R \) is satisfiable in a DTS based on \( \mathbb{R} \).

Therefore, the \( \omega \)-reachability problem is in fact reduced to the satisfiability of relativised \( DTL_1 \)-formulas in Euclidean spaces. For the reader’s convenience we summarise the results discussed above in the table below where merged cells mean that the corresponding logics coincide:

<table>
<thead>
<tr>
<th>language</th>
<th>functions</th>
<th>spaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>( DTL^\circ )</td>
<td>continuous</td>
<td>arbitrary ( \mathbb{R}^n )</td>
</tr>
<tr>
<td>homeomorphisms</td>
<td>fmp, finite axiom. [2, 12, 5]</td>
<td>?</td>
</tr>
<tr>
<td>( DTL_0 )</td>
<td>continuous</td>
<td>arbitrary</td>
</tr>
<tr>
<td>homeomorphisms</td>
<td>decidable, finite axiom. (partly in [12])</td>
<td></td>
</tr>
<tr>
<td>( DTL_1 )</td>
<td>continuous</td>
<td>undecidable, but r.e.</td>
</tr>
<tr>
<td>homeomorphisms</td>
<td>non-r.e. [8]</td>
<td>non-r.e. [8]</td>
</tr>
<tr>
<td>( DTL_1 ) / finite iterations</td>
<td>non-prim. recursive time</td>
<td>non-r.e. [8]</td>
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<tr>
<td>homeomorphisms</td>
<td>non-r.e. [8]</td>
<td>non-r.e. [8]</td>
</tr>
<tr>
<td>( DTL )</td>
<td>continuous</td>
<td>undecidable</td>
</tr>
<tr>
<td>homeomorphisms</td>
<td>non-r.e. [8]</td>
<td>non-r.e. [8]</td>
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2 \( DTL \)

The full language \( DTL \) of *dynamic topological logic* is constructed in the usual way from a countably infinite set \( \{ p_1, p_2, \ldots \} \) of *spatial variables*, the Booleans \( \neg, \land \) (and their standard derivatives \( \lor, \rightarrow \), etc.), the modal (or rather topological) operators \( I \) and \( C \), and the temporal operators \( \square \) (next-time), \( \square_F \) (always in the future) and \( \diamond F \) (eventually). More precisely, \( DTL \)-*formulas* are given by the following definition:

\[
\varphi ::= p_i \mid \neg \varphi \mid \varphi_1 \land \varphi_2 \mid I \varphi \mid \square \varphi \mid \diamond F \varphi.
\]

We use \( C \varphi \) and \( \diamond F \varphi \) as abbreviations for \( \neg I \neg \varphi \) and \( \neg \diamond F \neg \varphi \), respectively.

A *dynamic topological structure* (DTS, for short) is a pair of the form \( \mathfrak{S} = (T, \mathfrak{A}) \), where \( \mathfrak{A} = (T, I) \) is a topological space with the interior operator
\(I\), and \(f : T \to T\) is a continuous function on \(\mathfrak{I}\), that is, \(f^{-1}(A)\) is open whenever \(A \subseteq T\) is open (alternatively, \(f^{-1}(\mathcal{L}A) \subseteq \mathcal{L}f^{-1}(A)\), for all \(A \subseteq T\)).

A \textit{dynamic topological model} (DTM, for short) is a pair \(\mathfrak{M} = (\mathfrak{G}, \mathfrak{V})\), where \(\mathfrak{G}\) is a DTS and \(\mathfrak{V}\) a \textit{valuation} assigning to each variable \(p_i\) a subset \(\mathfrak{V}(p_i)\) of \(T\). The \textit{truth-relation} \((\mathfrak{M}, w) \models \phi\), for \(w \in T\), is defined inductively as follows:

- \((\mathfrak{M}, w) \models p_i\) iff \(w \in \mathfrak{V}(p_i)\),
- \((\mathfrak{M}, w) \models \neg \phi\) iff \((\mathfrak{M}, w) \not\models \phi\),
- \((\mathfrak{M}, w) \models \phi_1 \land \phi_2\) iff \((\mathfrak{M}, w) \models \phi_1\) and \((\mathfrak{M}, w) \models \phi_2\),
- \((\mathfrak{M}, w) \models \Box \phi\) iff \(w \in \mathfrak{I}\{v \in T \mid (\mathfrak{M}, v) \models \phi\}\),
- \((\mathfrak{M}, w) \models \Diamond \phi\) iff \((\mathfrak{M}, f^n(w)) \models \phi\) for all \(n > 0\).

For a class \(\mathcal{K}\) of DTSs, we denote by \(\text{Log} \mathcal{K}\), the \textit{dynamic topological logic of} \(\mathcal{K}\), the set of all \(\mathcal{DTL}\)-formulas \(\phi\) such that \((\mathfrak{M}, w) \models \phi\) for every DTM \(\mathfrak{M}\) based on a DTS from \(\mathcal{K}\) and every point \(w \in \mathfrak{M}\). If we are only interested in the restriction of \(\text{Log} \mathcal{K}\) to a certain fragment \(\mathcal{DTL}_i\) of \(\mathcal{DTL}\), then we write \(\text{Log}_i \mathcal{K}\) for \(\text{Log} \mathcal{K} \cap \mathcal{DTL}_i\).

In this paper, we deal with (i) the class \(\mathcal{T}\) of DTSs based on arbitrary topological spaces, (ii) the classes \(\mathcal{R}^n\) of DTSs based on the Euclidean \(\mathbb{R}^n\), for \(n \geq 1\), and (iii) the class \(\mathcal{A}\) of DTSs based on Aleksandrov spaces. If we restrict these classes to DTSs with homeomorphisms then we write \(\mathcal{T}_h\), \(\mathcal{R}_h^n\), and \(\mathcal{A}_h\), respectively.

We remind the reader that every quasi-order \(\mathfrak{G} = (W, R)\) (\(R\) is a reflexive and transitive relation on \(W\)) gives rise to the topological space \(\mathfrak{I}_\mathfrak{G}\) over \(W\) consisting of all \(R\)-closed subsets of \(W\). In other words, the interior operator \(I_\mathfrak{G}\) on \(\mathfrak{I}_\mathfrak{G}\) can be defined by taking, for every \(X \subseteq W\),

\[
I_\mathfrak{G} X = \{w \in X \mid \forall v \in W \ (w R v \to v \in X)\}.
\]

Such spaces are known as \textit{Aleksandrov spaces}. Alternatively they can be defined as topological spaces where arbitrary (not only finite) intersections of open sets are open; for details see [1, 4]. Clearly, for \(\mathfrak{M} = (\langle \mathfrak{G}, f \rangle, \mathfrak{V})\),

\[
(\mathfrak{M}, w) \models I \phi \iff (\mathfrak{M}, v) \models \phi \text{ for every } v \in W \text{ with } w R v,
\]

It should be also clear that a function \(f : W \to W\) is \textit{continuous} on \(\mathfrak{I}_\mathfrak{G}\) iff

\[
w R v \implies f(w) R f(v),
\]

for all \(w, v \in W\). Such a function \(f\) is called \textit{monotone}. A bijection \(f\) is a \textit{homeomorphism} on \(\mathfrak{I}_\mathfrak{G}\) iff both the implication above and its converse hold.
3 $\mathcal{DTL}_1$

Let us consider now the sublanguage $\mathcal{DTL}_1$ of $\mathcal{DTL}$ where no $\Box_F$ and $\Diamond_F$ can occur in the scope of $I$ ($\bigcirc$ is allowed); more precisely, $\mathcal{DTL}_1$-formulas $\varphi$ are defined as follows:

$$\begin{align*}
\psi & ::= \ p_i \mid \neg \psi \mid \psi_1 \wedge \psi_2 \mid I\psi \mid \bigcirc \psi, \quad (2) \\
\varphi & ::= \ \psi \mid \neg \varphi \mid \varphi_1 \wedge \varphi_2 \mid \Box_F \varphi. \quad (3)
\end{align*}$$

This language turns out to be quite interesting and useful. Note first that the formulas used in the proof of [8, Theorem 9] belong to $\mathcal{DTL}_1$, and so:

**THEOREM 1.** None of the logics $\text{Log}_1 T_h$, $\text{Log}_1 A_h$, $\text{Log}_1 R_n$, for $n \geq 1$, is recursively enumerable.

On the other hand, $\mathcal{DTL}_1$ does not distinguish between arbitrary topological and Aleksandrov spaces and, moreover, enjoys a kind of ‘local finite model property.’ These features of $\mathcal{DTL}_1$ are formulated and proved in Lemmas 2, 5, and 6. They will be heavily used later on in this paper.

**LEMMA 2.** Every satisfiable $\mathcal{DTL}_1$-formula $\varphi$ is satisfiable in a DTM based on an Aleksandrov topological space. Moreover, one can choose a DTM $\mathcal{M}_\Theta$ satisfying $\varphi$ such that $\mathcal{M}_\Theta$ is based on the Aleksandrov space $\mathcal{X}_\Theta$ induced by a quasi-order $\Theta = \langle W, R \rangle$ where,

\[(\text{max})\] for all $x \in W$ and all $\mathcal{DTL}_1$-formulas $\psi$ with $(\mathcal{M}_\Theta, x) \models \psi$, the set $A_{x,\psi} = \{ y \in W \mid xRy \text{ and } (\mathcal{M}_\Theta, y) \models \psi \}$ contains an $R$-maximal point (i.e., a point $z$ such that if $zRz'$ for some $z' \in A_{x,\psi}$ then $z'Rz'$).

To illustrate the idea of the proof suppose that $\varphi$ is satisfied in a DTM $\mathcal{M}$ based on a topological space $\mathcal{X}$. We consider the DTM $\mathcal{M}_\Theta$ based on the Aleksandrov space $\mathcal{X}_\Theta$ of all ultrafilters over $\mathcal{X}$ and show by induction on the formula structure that $\varphi$ is satisfied in $\mathcal{M}$ iff it is satisfied in $\mathcal{M}_\Theta$. There is a subtlety in the proof though: the inductive step for subformulas of the form (2) goes through for all ultrafilters whereas its counterpart for subformulas of the form (3) for principal ultrafilters only. For details see a similar lemma in [7]. It also follows from the proof that the claim of Lemma 2 is true for DTMs with homeomorphisms.

**COROLLARY 3.** $\text{Log}_1 T = \text{Log}_1 A$ and $\text{Log}_1 T_h = \text{Log}_1 A_h$.

It is known [16] that $\text{Log}_1 T \subseteq \text{Log}_1 R^n$, $n \geq 1$, while the question whether the equality $\text{Log}_1 T_h = \text{Log}_1 R^n_h$ holds remains open.

**REMARK 4.** Note that neither equality in the corollary above holds for full $\mathcal{DTL}$. For instance, $\varphi = \Box_F I p \rightarrow I \Box_F p$ is valid in all DTMs based on Aleksandrov spaces (as infinite intersections of open sets are open there). However, $\neg \varphi$ can be satisfied in a DTM $\mathcal{M}$ based on $\mathbb{R}$: if one takes the continuous function $f(x) = 2x$ and $\mathcal{V}(p) = (-1, 1)$ then $\bigcap_{k=1}^{\infty} f^{-k}(I_\mathbb{R} \mathcal{V}(p)) = \{0\}$ but $I_\mathbb{R} \bigcap_{k=1}^{\infty} f^{-k}(\mathcal{V}(p)) = \emptyset$, and so $(\mathcal{M}, 0) \models \neg \varphi$. 

BK: citation added
The following lemma shows that, for $\mathcal{DTL}_1$, DTMs with continuous functions are closely connected to expanding domain product models introduced in [7]:

**LEMMA 5.** Let $\varphi$ be a $\mathcal{DTL}_1$-formula and $\mathfrak{M}$ a DTM based on an Aleksandrov space and satisfying (max) such that $(\mathfrak{M}, x_0) \models \varphi$ for some $x_0$. Then there exist a DTM $\mathfrak{M}^{ep}$ based on the Aleksandrov space induced by a quasi-order $(W^{ep}, R^{ep})$ and a continuous function $f^{ep}$ on it such that $(\mathfrak{M}^{ep}, r_0) \models \varphi$ for some $r_0 \in W^{ep}$ and

$(\text{fin})$ $(W^{ep}, R^{ep})$ is the disjoint union of finite quasi-orders $(W_n^{ep}, R_n^{ep})$, for $n \geq 0$;

$(\text{root})$ for $n \geq 0$, $r_{n+1} = f^{ep}(r_n)$ and $W_n^{ep} = \{ y \in W^{ep} \mid r_n R^{ep} y \}$;

$(\text{inj})$ $f^{ep}$ is injective;

$(\text{size})$ $|W_n^{ep}| \leq ((1 + \ell(\varphi))!)^{n+1}$, for $n \geq 0$, where $\ell(\varphi)$ is the length of $\varphi$.

The proof of this lemma is similar to that of [7, Lemma 2.2].

Before proceeding to Lemma 6, we remind the reader that, for a quasi-order $R$ on $W$, a set $C \subseteq W$ is called a cluster in $(W, R)$ if, for some $x \in W$, $C = \{ y \in W \mid x R y \ & y R x \}$; in this case we also say that $C$ is the cluster generated by $x$ and denote it by $C(x)$. A tree of clusters is a rooted quasi-order $(W, R)$ such that, for all $x, y, z \in W$, if $x R z$ and $y R z$, then $x R y$ or $y R x$. A cluster $C(y)$ is said to be an immediate strict successor of a cluster $C(x)$ if $x R y$, $C(x) \neq C(y)$ and whenever $x R z R y$ then either $C(z) = C(x)$ or $C(z) = C(y)$.

**LEMMA 6.** Let $\varphi$ be a $\mathcal{DTL}_1$-formula satisfiable in a DTM based on an Aleksandrov space and meeting conditions (fin), (root), (inj). Then there exist a recursive function $F(\varphi, n)$ and a DTM $\mathfrak{M}^{ex}$ based on the Aleksandrov space induced by a quasi-order $(W^{ex}, R^{ex})$ and a continuous function $f^{ex}$ on it such that $(\mathfrak{M}^{ex}, r_0) \models \varphi$ for some $r^{ex} \in W^{ex}$, $\mathfrak{M}^{ex}$ satisfies (inj) and

$(\text{tree})$ $(W^{ex}, R^{ex})$ is the disjoint union of finite trees of clusters $(W_n^{ex}, R_n^{ex})$, for $n \geq 0$;

$(\text{top})$ for $n \geq 0$, $y \in W_n^{ex}$, $x \in W_n^{ex}$, with $x R^{ex} f^{ex}(y)$, there is $z \in W_n^{ex}$ such that $z R^{ex} y$ and $f^{ex}(z) = x$; in particular, for all $x, y \in W^{ex}$, $f^{ex}(x) R^{ex} f^{ex}(y)$ implies $x R^{ex} y$;

$(\text{size'})$ $|W_n^{ex}| \leq F(\varphi, n)$.

**Proof.** Let $(\mathfrak{M}, r) \models \varphi$, where $\mathfrak{M} = (\langle \Sigma, f, \Xi \rangle, \Xi)$ is induced by $(W, R)$ and $\mathfrak{M}$ satisfies (fin), (root), (inj). The DTM $\mathfrak{M}^{ex}$ satisfying the conditions of the lemma will be constructed by a kind of ‘unravelling’ $\mathfrak{M}$.
A sequence \( \vec{C} = (C_0, \ldots, C_n) \), \( n \geq 0 \), is called a cluster sequence over \( \langle W, R \rangle \) iff the \( C_i \) are clusters in \( \langle W, R \rangle \) such that \( C_{i+1} \) is an immediate strict successor of \( C_i \). Define a partial order \( \leq \) on cluster sequences by taking

\[
(C_0, \ldots, C_n) \leq (C'_0, \ldots, C'_m) \quad \text{iff} \quad n \leq m \text{ and } C_i = C'_i, \text{ for } 0 \leq i \leq n.
\]

For a point \( x \in W \), let \( T(x) \) be the set of all pairs \( y = \langle \vec{C}, y \rangle \) of cluster sequences \( \vec{C} = (C_0, \ldots, C_n) \) in \( \langle W, R \rangle \) such that \( C_0 = C(x) \) and \( C_n = C(y) \). Such pairs are ordered by the relation

\[
\langle \vec{C}, y \rangle \leq \langle \vec{C}', y' \rangle \quad \text{iff} \quad \vec{C} \leq \vec{C}'.
\]

Clearly, \( \langle T(x), \leq \rangle \) is a tree of clusters, and every \( y \) with \( xRy \) is represented by at least one point \( y \) in this tree. Moreover, for every \( y = \langle \vec{C}, y \rangle \) and \( z \in C(y), T(x) \) contains \( z = \langle \vec{C}, z \rangle \) and both \( y \) and \( z \) are in the same cluster in \( \langle T(x), \leq \rangle \). It should be noted that if \( \langle W, R \rangle \) is a tree of clusters then, for every \( x \in W \), \( T(x, \leq) \) is isomorphic to the quasi-order \( \langle W_x, R_x \rangle \) generated by \( x \).

The new model \( \mathfrak{M}^{ex} \) will be based on the Aleksandrov space induced by a quasi-order on sequences of pairs of the form \( \langle \vec{C}, y \rangle \). We define it inductively: let \( W_0^{ex} = \{ (y) \mid y \in T(r) \} \) (set of sequences of length 1) and

\[
R_0^{ex} = \{ (y, y') \in W_0^{ex} \times W_0^{ex} \mid \, y \leq y' \}.
\]

Suppose that \( \langle W_k^{ex}, R_k^{ex} \rangle, k \geq 0 \), has already been defined. Let \( W_{k+1}^{ex} \) be the union of two sets:

\[
W_{k+1}^{ex} = \bigcup_{(y_0, \ldots, y_k) \in W_k^{ex}} \{ (y_0, \ldots, y_k, f(y_k)) \mid (y_0, \ldots, y_k) \in W_k^{ex} \},
\]

where we write \( f(y_k) \) for \( \langle \vec{C}_k, f(y_k) \rangle \) whenever \( y_k = \langle \vec{C}_k, y_k \rangle \). Note that \( W_{k+1}^{ex} \) contains sequences of length \( k + 2 \) only and, for every sequence \( (y_0, \ldots, y_k) \in W_k^{ex} \) with \( y_k = \langle \vec{C}_k, y_k \rangle \), \( y_k \) indicates the element of \( W \) this sequence represents.

Let \( R_k^{ex} \) be the transitive closure of the union of the following relations:

\[
\{(y_0, \ldots, y_k, f(y_k)), (y_0', \ldots, y_k', f(y_k')) \} \in W_k^{ex} \times W_k^{ex} \mid (y_0, \ldots, y_k) R_k^{ex} (y_0', \ldots, y_k'),
\]

\[
\{(y_0, \ldots, y_k, f(y_k)), (y_0', \ldots, y_k, y) \} \in W_k^{ex} \times X_{k+1}^{ex} \mid y \in T(f(y_k))
\]

\[
\{(y_0, \ldots, y_k, y), (y_0', \ldots, y_k', y') \} \in X_{k+1}^{ex} \times X_{k+1}^{ex} \mid y \leq y'.
\]

Informally, the first relation above states that \( W_k^{ex} \) is an isomorphic copy of \( W_k^{ex} \); the other two relations ‘attach’ a tree to every point \( (y_0, \ldots, y_k, f(y_k)) \) of \( W_k^{ex} \) such that the attachment is an isomorphic copy of the tree generated by \( f(y_k) \) in \( W \). It is readily checked that \( \langle R_{k+1}^{ex}, W_{k+1}^{ex} \rangle \) is a tree of clusters.
The $W_k^{ex}$ are pairwise disjoint. Let $W^{ex} = \bigcup_{k=0}^{\infty} W_k^{ex}$, $R^{ex} = \bigcup_{k=0}^{\infty} R_k^{ex}$, $\Sigma^{ex}$ be the Aleksandrov space induced by $(W^{ex}, R^{ex})$. Define $f^{ex}$ by taking
\[ f^{ex}((y_0, \ldots, y_k)) = (y_0, \ldots, y_k, f(y_k)), \]
for all $(y_0, \ldots, y_k) \in W^{ex}$. Clearly, $f^{ex}$ is monotone, injective and satisfies (top) (in fact, it is a homeomorphism between each pair $W_k^{ex}$ and $W_k^{cl}$).

Finally, define a valuation $\mathcal{V}^{ex}$ by taking, for every variable $p_i$,
\[ \mathcal{V}^{ex}(p_i) = \{ (y_0, \ldots, y_k) \in W^{ex} \mid y_k = \langle \bar{C}_k, y_k \rangle \text{ and } y_k \in \mathcal{V}(p_i) \}. \]
Let $\mathcal{M}^{ex} = \langle (\Sigma^{ex}, f^{ex}), \mathcal{V}^{ex} \rangle$ and $r^{ex} = \langle C(r), r \rangle$. It is not difficult to see that $(\mathcal{M}^{ex}, r^{ex}) \models \varphi$.

We use Lemma 6 and Kruskal’s tree theorem to prove, in a way similar to the proof of [9, Theorem 4], the following (cf. Theorem 1):

**THEOREM 7.** $\text{Log}_T$ is recursively enumerable.

We present here only a sketch of the proof. To apply Kruskal’s tree theorem, we require a representation of the models of Lemma 6 as sequences of labelled trees. This can be achieved in a straightforward way using Hintikka-type structures of the following form. For a $DL$-formula $\varphi$, let $cl\varphi$ be the set of all subformulas of $\varphi$ and their negations. A full $\varphi$-type $t$ is Boolean-closed subset of $cl\varphi$, that is,
- $\neg \psi \in t$ iff $\psi \not\in t$, for every subformula $\psi$ of $\varphi$,
- $\psi_1 \land \psi_2 \in t$ iff $\psi_1, \psi_2 \in t$, for every subformula $\psi_1 \land \psi_2$ of $\varphi$.

A subset $s$ of a $\varphi$-type $t$ is a (simple) $\varphi$-type if it does not contain formulas with occurrences of $\Box_F$ but satisfies the conditions above for all subformulas of $\varphi$ not containing $\Box_F$.

A quasistate $\mathcal{S} = \langle W, R, l \rangle$ is a finite transitive irreflexive tree $\langle W, R \rangle$ with a labelling function $l$ which assigns
- a set $l(x)$ of simple $\varphi$-types to every $x \in W$ that is not the root of $\langle W, R \rangle$ (this set is supposed to encode the cluster represented by $x$),
- a set $l(r) = \{ l^1(r) \} \cup l^2(r)$, where $l^1(r)$ is a full $\varphi$-type and $l^2(r)$ is a set of simple $\varphi$-types, to the root $r$ of $\langle W, R \rangle$

such that the following condition holds for all $\textbf{I} \psi \in \varphi$, $x \in W$, and $t \in l(x)$: we have $\textbf{I} \psi \in t$ iff $\psi \in s$ for every $s \in l(y)$ with $x = y$ or $xRy$.

A sequence $\mathcal{S}_n = \langle W_n, R_n, l_n \rangle$, $n < \omega$, of quasistates is called a quasi-model for $\varphi$ if there are injective maps $f_n : W_n \rightarrow W_{n+1}$ such that
- $(1)$ for all $x, y \in W_n$, $xR_n y$ iff $f_n(x)R_{n+1}f_n(y)$,
- $(2)$ $|\mathcal{S}_n| \leq F(\varphi, n)$, where $F(\varphi, n)$ is the recursive function from Lemma 6,
- $(3)$ $f(r_n) = r_{n+1}$ for the roots $r_n$ and $r_{n+1}$ of $\langle W_n, R_n \rangle$ and $\langle W_{n+1}, R_{n+1} \rangle$, respectively,
LEMMA 8. The proof of the following lemma is easy and left to the reader.

S

orem quasimodel for ϕ

ition of such finite sequences terminates (i.e., there are only finitely many

t

is a quasimodel for ϕ

the conditions above. But then, by Kruskal’s tree theorem, this sequence

Now suppose that the enumeration of such sequences does not terminate

t

• For every □_F ψ ∈ cl ϕ and every n < m, we have ¬□_F ψ ∈ l^1_n(r_n) iff

• Let 0 = k_0 < k_1 < k_2 · · · < k_n ≤ m be the minimal numbers such that

every ¬□_F ψ ∈ l^1_n(r_n) is realised until k_{i+1}. If no ¬□_F ψ exists

in l^1_{k_i}(r_{k_i}), then set k_{i+1} = k_i + 1. Then, if there are m_1, m_2 with

k_i < m_1 < m_2 < k_{i+1} or k_n < m_1 < m_2 < m such that Σ_{m_1} is

embeddable into Σ_{m_2}, then there exists a ¬□_F ψ ∈ l^1_{k_i}(r_{k_i}) which is

realised somewhere in the interval [m_1, m_2).

Now suppose that the enumeration of such sequences does not terminate

(i.e., infinite many such sequences are generated). Then, by König’s

lemma, there exists an infinite sequence whose finite initial segments satisfy

the conditions above. But then, by Kruskal’s tree theorem, this sequence

is a quasimodel for ϕ, and so ϕ is satisfiable. Conversely, if the enumeration

of such finite sequences terminates (i.e., there are only finitely many

(4) ϕ ∈ l^1_0(r_0),

(5) if f_n(x) = y, then for every t ∈ l_n(x) there exists t’ ∈ l_{n+1}(y) such

that for every ϕ ∈ cl ϕ, ϕ ∈ l_{n+1}(y); if x = r_n and

t = l^1_n(r_n), then we can choose t’ = l^1_{n+1}(r_{n+1}),

(6) for every □_F ψ ∈ cl ϕ, ¬□_F ψ ∈ l^1_n(r_n) iff there exists m > n such that

¬ψ ∈ l^1_m(r_m); if m is minimal with this property, then we say that m

realises the eventuality ¬□_F ψ.

The proof of the following lemma is easy and left to the reader.

LEMMA 8. A DT L_1-formula ϕ is satisfiable in a DTM iff there exists a

quasimodel for ϕ.

We remind the reader of the following weak version of Kruskal’s tree the-

orem. An injective function h : (W_1, R_1, l_1) → (W_2, R_2, l_2) between labelled

trees is called an embedding if, for all x, y ∈ W_1, xR_1 y iff h(x)R_2 h(y), and

l_1(x) = l_2(h(x)). We assume that the labels are taken from some finite set.

THEOREM 9 (Kruskal). For any sequence Σ_n, n < ω, of labelled trees,

there exists i < j such that Σ_i is embeddable into Σ_j.

Consider now a quasimodel Σ_n, n < ω, for ϕ. Clearly, if there are i < j

such that Σ_i is embeddable into Σ_j, then the sequence

Σ_0, ..., Σ_{i−1}, Σ_i, Σ_{i+1} ...

is a quasimodel for ϕ as well. Moreover, we can ‘prune’ the quasistates

Σ_j, Σ_{j+1}... in such a way that the bound from (2) above still holds.

Now we can recursively enumerate the DT L_1-formulas ϕ which are not

satisfiable as follows: for every ϕ enumerate all finite sequences Σ_0, ..., Σ_m

such that conditions (1)–(5) above and the following modification of condition

(6) hold:

• For every □_F ψ ∈ cl ϕ and every n < m, we have ¬□_F ψ ∈ l^1_n(r_n) iff

¬□_F ψ ∈ l^1_m(r_m) or there exists k, n < k ≤ m, such that k realises the

eventuality ¬□_F ψ.

• Let 0 = k_0 < k_1 < k_2 · · · < k_n ≤ m be the minimal numbers such that

every ¬□_F ψ ∈ l^1_{k_i}(r_{k_i}) is realised until k_{i+1}. If no ¬□_F ψ exists

in l^1_{k_i}(r_{k_i}), then set k_{i+1} = k_i + 1. Then, if there are m_1, m_2 with

k_i < m_1 < m_2 < k_{i+1} or k_n < m_1 < m_2 < m such that Σ_{m_1} is

embeddable into Σ_{m_2}, then there exists a ¬□_F ψ ∈ l^1_{k_i}(r_{k_i}) which is

realised somewhere in the interval [m_1, m_2).
sequences), then there is no quasimodel for \( \varphi \). Hence \( \varphi \) is not satisfiable. It follows that the non-satisfiable formulas (and therefore the valid formulas) are recursively enumerable.

4 Embedding DTM{\!}s into the real line

THEOREM 10. A DTL\(_1\)-formula \( \varphi \) is satisfiable iff \( \varphi^R \), the relativisation of \( \varphi \), is satisfiable in the DTS \( \langle \langle \mathbb{R}, \mathbb{I}_R \rangle, x \mapsto x + 1 \rangle \), where

\[
\varphi^R = \text{dom} \land \square_R^\top(\text{dom} \rightarrow \circ \text{dom}) \land \varphi_{\text{dom}},
\]

\( \text{dom} \) is a fresh variable, and \( \varphi_{\text{dom}} \) is the result of replacing every occurrence of a subformula of the form \( \top \psi \) in \( \varphi \) with \( \top(\text{dom} \rightarrow \psi) \).

Proof. Suppose that \( \varphi^R \) is satisfied in \( \langle \langle \mathbb{R}, \mathbb{I}_R \rangle, x \mapsto x + 1 \rangle \). Then, by Lemma 2, \( \varphi^R \) is satisfied in a DTM \( \mathcal{M} \) based on an Aleksandrov space. It is readily seen that \( \varphi \) is satisfied in the DTM \( \mathcal{M}' \) obtained from \( \mathcal{M} \) by removing all those points where \( \text{dom} \) is false.

Conversely, suppose that \( \varphi \) is satisfiable. Let \( \mathcal{M}^{ex} = \langle \langle \mathbb{R}^{ex}, f^{ex} \rangle, \mathcal{M}^{ex} \rangle \) be the model provided by Lemma 6 and satisfying \( \varphi \). Our plan is (1) to extend \( \mathcal{M}^{ex} \) to a DTM \( \mathcal{M}^{\top} \) that satisfies \( \varphi^R \) and is based on \( \omega \)-trees of clusters of finite depth, and (2) to embed \( \mathcal{M}^{\top} \) into a model based on \( \langle \langle \mathbb{R}, \mathbb{I}_R \rangle, x \mapsto x + 1 \rangle \).

We remind the reader that a tree of clusters \( \langle W, R \rangle \) is of depth \( n \) if \( n \) is the length of the longest sequence \( C(x_1), \ldots, C(x_n) \) of clusters in \( \langle W, R \rangle \) such that \( C(x_{i+1}) \) is an immediate strict successor of \( C(x_i) \). A cluster \( C \) is called final if it has no strict successor. A tree of clusters is called an \( \omega \)-tree if every non-final cluster has \( \omega \) distinct strict immediate successors.

(1) Fix some \( k \geq 0 \). By (tree), \( \langle W^{ex}_k, R^{ex}_k \rangle \) is a finite tree of clusters. We construct an \( \omega \)-tree of clusters \( \mathcal{G}_k = \langle \hat{W}_k, \hat{R}_k \rangle \) by attaching an \( \omega \)-tree of depth 2 to every cluster in \( \langle W^{ex}_k, R^{ex}_k \rangle \). Let \( \hat{W}_k \) be the union of \( W^{ex}_k \) with \( \{(C(x), n) \mid x \in W^{ex}_k, n \in \mathbb{N}\} \) and \( \hat{R}_k \) the transitive and reflexive closure of

\[
R^{ex}_k \cup \{(x, (C(x), n)) \mid x \in W^{ex}_k, n \in \mathbb{N}\}.
\]

Note that the \( \hat{W}_k \) are pairwise disjoint. Let \( \hat{W} = \bigcup_{k=0}^\infty \hat{W}_k, \hat{R} = \bigcup_{k=0}^\infty \hat{R}_k, \) and let \( \hat{\mathcal{G}} \) be the Aleksandrov space induced by \( \hat{\mathcal{G}} = (\hat{W}, \hat{R}) \).

Define a function \( \hat{f} : \hat{W} \to \hat{W} \) by taking, for all \( x \in W^{ex} \) and \( n \in \mathbb{N} \),

\[
\hat{f}(x) = f^{ex}(x),
\]

\[
\hat{f}((C(x), n)) = \begin{cases} y_m, & \text{if } n < m, \\ (C(f^{ex}(x)), n - m), & \text{otherwise}, \end{cases}
\]

where \( \{y_0, \ldots, y_{m-1}\} \subseteq W^{ex}_{k+1} \setminus \{f(z) \mid z \in W^{ex}_k\} \) and \( C(y_0), \ldots, C(y_{m-1}) \) are all the distinct strict immediate successors of \( C(f^{ex}(x)) \).

\footnote{We write \( \square_R^\top \psi \) for an abbreviation of \( \psi \land \square_R \psi \).}
Clearly, \( \tilde{f} \) is a well-defined function on \( \tilde{\mathcal{W}} \). Informally, (i) each \( x \in W_k^e \) is mapped onto its image \( f^e(x) \); (ii) for each \( x \in W_k^e \), its first \( m \) successors of the form \( (C(x), n) \) from \( \tilde{W}_k \) are mapped onto the roots of the \( m \) distinct trees that are attached to \( C(f^e(x)) \) at step \( k+1 \) and the remaining successors of this sort are simply renumbered. Since every \( \tilde{\mathcal{G}}_{k+1} \) contains an isomorphic copy of \( \tilde{\mathcal{G}}_k \) and in view of (top), the function \( \tilde{f} \) is monotone.

Clearly, \( \varphi^R \) is satisfied in the DTM \( \tilde{\mathcal{M}} \) under the valuation \( \tilde{\mathcal{V}} \) defined by taking \( \mathcal{B}(\text{dom}) = W^e \) and \( \mathcal{B}(p_i) = W^{e}(p_i) \), for every variable \( p_i \) in \( \varphi \).

(2) Next, we require the following generalisation of a result from [3]:

**Lemma 11.** For every open interval \( I \subseteq \mathbb{R} \) and every \( \omega \)-tree of clusters \( \mathcal{G} = \langle W, R \rangle \) of finite depth, there is a surjective open and continuous function \( f^\mathcal{G}_I : I \to \mathcal{T}_\mathcal{G} \). Moreover, for every initial \( \omega \)-subtree \( \mathcal{G}' = \langle W', R' \rangle \) of \( \mathcal{G} \) (where each cluster of \( \mathcal{G}' \) either inherits all strict immediate successors from \( \mathcal{G} \) or none of them) and every point \( z \in I \),

**(cons)** if \( f^\mathcal{G}_I(z) \) is not in a final cluster of \( \mathcal{G}' \), then \( f^\mathcal{G}_I(z) = f^\mathcal{G}'_I(z) \);

**(final)** if \( f^\mathcal{G}_I(z) \) is in a final cluster of \( \mathcal{G}' \), then there is an open interval \( I_z \) with \( z \in I_z \) such that \( f^\mathcal{G}_I(I_z) = \{ y \in W \mid f^\mathcal{G}_I(z) R y \} \).

The above result can be proved by extending [3, Theorem 16] so that in [3, Lemma 15], the enumeration of all countably many immediate strict successors is chosen in such a way that each of them occurs infinitely often in the enumeration.

Thus, Lemma 11 provides us with a surjective open and continuous function \( f_{(0,1)}^{\tilde{\mathcal{G}}_k} : (0,1) \to \tilde{\mathcal{G}}_k \), for each \( k \geq 0 \). Let \( D = \bigcup_{k=0}^{\infty} (k, k+1) \subseteq \mathbb{R} \).

Define a function \( g : D \to \tilde{\mathcal{G}} \) by taking:

\[
g(k+z) = f_{(0,1)}^{\tilde{\mathcal{G}}_k}(z), \quad \text{for all } k \in \mathbb{N} \text{ and } z \in (0,1).
\]

The valuation \( \mathcal{B}^R \) is defined by taking \( \mathcal{B}^R(\text{dom}) = \{ z \in D \mid g(z) \in \tilde{\mathcal{V}}(\text{dom}) \} \) and \( \mathcal{B}^R(p_i) = \{ z \in D \mid g(z) \in \tilde{\mathcal{V}}(p_i) \} \), for every variable \( p_i \) of \( \varphi \).

First, we show that, for all \( z \in \mathbb{R} \),

\[
\text{if } z \in \mathcal{B}^R(\text{dom}) \text{ then } (z+1) \in \mathcal{B}^R(\text{dom}) \text{ and } \tilde{f}(g(z)) = g(z+1). \tag{4}
\]

Indeed, suppose that \( z \in \mathcal{B}^R(\text{dom}) \). Then \( g(z) \in \tilde{\mathcal{V}}(\text{dom}) \) and therefore, \( g(z) \in W_k^e \), for some \( k \geq 0 \). Then \( \tilde{f}(g(z)) \in W_{k+1}^e \subseteq \tilde{\mathcal{B}}(\text{dom}) \). Moreover, by (cons), \( \tilde{f}(g(z)) = g(z+1) \). Hence, \( z+1 \in \mathcal{B}^R(\text{dom}) \). Note that it is essential that \( g(z) \) is not in a final cluster of \( \tilde{\mathcal{G}}_k \); and this is precisely the reason why at step (1) we needed to extend \( \langle W^e, R^e \rangle \) to \( \langle \tilde{W}, \tilde{R} \rangle \) by \( \omega \)-trees of depth 2 (for each final cluster of each \( \tilde{\mathcal{G}}_k \) the attached \( \omega \)-tree of depth 2 provides countably many ‘placeholders’ for the trees that will be attached to this cluster in \( W_{k+1}^e, W_{k+2}^e, \ldots \) note also that these placeholders do not belong to the ‘domain’).
Now, we prove by induction on the construction of subformulas \( \psi \) of \( \varphi^{\text{dom}} \) that, for every \( z \in \mathfrak{V}_R(\text{dom}) \),

\[
g(z) \in \widehat{\mathfrak{F}}(\psi) \iff z \in \mathfrak{V}_R(\psi).
\] (5)

The case of variables follows immediately from the definition and the cases of the Boolean are trivial.

**Case** \( \psi = I(\text{dom} \to \psi') \). Since \( z \in \mathfrak{V}_R(\text{dom}) \), there is \( k \in \mathbb{N} \) such that \( z \in (k, k+1) \). Then

\[
z \in \mathfrak{V}_R(I(\text{dom} \to \psi')) \quad \text{iff} \quad \text{[def. of open set]}
\]

there is an open \( U \subseteq (k, k+1) \) such that

\[
z \in U \quad \text{and} \quad U \subseteq \mathfrak{V}_R(\text{dom} \to \psi')
\] [definition]

there is an open \( U \subseteq (k, k+1) \) such that

\[
z \in U \quad \text{and} \quad U \cap \mathfrak{V}_R(\text{dom}) \subseteq \mathfrak{V}_R(\psi')
\] [IH]

there is an open \( U \subseteq (k, k+1) \) such that

\[
z \in U \quad \text{and} \quad g(U) \cap \widehat{\mathfrak{F}}(\text{dom}) \subseteq \widehat{\mathfrak{F}}(\psi')
\] [V = g(U) \ g open and cont.]

there is an open \( V \subseteq \widehat{W}_k \) such that

\[
g(z) \in V \quad \text{and} \quad V \cap \widehat{\mathfrak{F}}(\text{dom}) \subseteq \widehat{\mathfrak{F}}(\psi')
\] [definition]

\[
g(z) \in \widehat{\mathfrak{F}}(I(\text{dom} \to \psi'))
\]

**Case** \( \psi = \circ \psi' \). Then

\[
z \in \mathfrak{V}_R(\circ \psi') \quad \text{iff} \quad z + 1 \in \mathfrak{V}_R(\psi') \quad \text{iff} \quad \text{[IH]}
\]

\[
g(z + 1) \in \widehat{\mathfrak{F}}(\psi') \quad \text{iff} \quad \text{[(4)]}
\]

\[
g(\widehat{f}(z)) \in \widehat{\mathfrak{F}}(\psi') \quad \text{iff} \quad g(z) \in \widehat{\mathfrak{F}}(\circ \psi').
\]

**Case** \( \psi = \square_F \psi' \) is considered in the same way.

By (4) and (5), \( \varphi^R \) is satisfied in the DTM \( \langle \langle \mathbb{R}, \mathbb{I}_R \rangle, x \mapsto x + 1, \mathfrak{V}_R \rangle \). ■

**Corollary 12.** A DTCL1-formula \( \varphi \) is satisfiable iff \( \varphi^R \) is satisfiable in the DTS \( \langle \langle \mathbb{R}^n, \mathbb{I}_{R^n} \rangle, (x_1, \ldots, x_n) \mapsto (x_1, \ldots, x_{n-1}, x_{n+1}) \rangle, n \geq 1 \).

It should be noted that although the relativisation \( \varphi^R \) is satisfied in a DTS based on an Aleksandrov space iff \( \varphi \) is satisfied in some (in general, different) DTS based on an Aleksandrov space, the analogous statement fails for the Euclidean spaces: \( \varphi \) may not be satisfiable in a DTS based on \( \mathbb{R} \) even if its relativisation \( \varphi^R \) is satisfiable (e.g., a counterexample in [16]). The explanation lies in the variable \( \text{dom} \) which ‘carves’ out of \( \mathbb{R} \) a subspace that topologically resembles an Aleksandrov space.

---

2 For a DTM \( \mathfrak{M} = \langle \mathfrak{F}, \mathfrak{V} \rangle \), we denote by \( \mathfrak{V}(\varphi) \) the set \( \{ w \in \mathfrak{F} | (\mathfrak{M}, w) \models \varphi \} \).
5 Undecidability

As usual, for a finite alphabet \( \Sigma \), the set of all finite words over \( \Sigma \) (including the empty word \( \epsilon \)) is denoted by \( \Sigma^* \) (also called \( \Sigma \)-words). Given a word \( w = a_1 \cdot a_2 \cdot \ldots \cdot a_n \), we denote its length \( n \) by \(|w|\) and refer to its elements using the bracket notation: \( w(i) = a_i \), for \( 1 \leq i \leq n \). For a pair of words \( u \) and \( w \), we say that \( u \) is a subword of \( w \) and write \( u \sqsubseteq w \) if there is a strictly monotone map \( h : \{1, \ldots, |u|\} \to \{1, \ldots, |w|\} \) such that \( u(i) = w(h(i)) \), for every \( i, 1 \leq i \leq |u| \). We also write \( u \sqsubseteq w \) if \( u \sqsubseteq h \ w \) for some \( h \).

A single channel system is a triple \( S = (Q, \Sigma, \Delta) \), where \( Q = \{q_1, \ldots, q_n\} \) is a set of control states, \( \Sigma = \{a_1, \ldots, a_m\} \) is an alphabet of messages and \( \Delta \subseteq Q \times \{?, !\} \times \Sigma \times Q \) is a set of transitions.

A configuration of \( S \) is a pair \( \gamma = \langle q, w \rangle \), where \( q \in Q \) and \( w \in \Sigma^* \). Define a lossy relation and two types of perfect transition relations for \( S \) between configurations by taking:

\[
\begin{align*}
\text{(l)} \quad \langle q, w \rangle &\to_\ell \langle q, w' \rangle \quad \text{iff} \quad w' \sqsubseteq w, \\
\text{(s)} \quad \langle q, w \rangle &\to_\ell \langle q', a \cdot w \rangle, \\
\text{(r)} \quad \langle q, w \cdot a \rangle &\to_\ell \langle q', w \rangle.
\end{align*}
\]

(Here \( \ell \) stands for ‘loose’, \( s \) for ‘send’, and \( r \) for ‘receive.’) Finally, define lossy transition relations for \( S \) as the following compositions:

\[
\begin{align*}
\text{(ls)} \quad \langle q, w \rangle &\to_\ell \langle q', w' \rangle \quad \text{iff} \quad \langle q, w \rangle \to_\ell \langle q', a \cdot w \rangle, \\
\text{(lr)} \quad \langle q, w \cdot a \rangle &\to_\ell \langle q', w \rangle.
\end{align*}
\]

For a binary relation \( \to \) on configurations of \( S \), a sequence \( \gamma_0, \ldots, \gamma_m \) of configurations of \( S \) is called a \( \to \)-computation of \( S \) if \( \gamma_k \to \gamma_{k+1} \), for \( k < m \).

The undecidable ‘master problem’ that will be used to prove the undecidability of the logics under consideration is the \( \omega \)-reachability problem for channel systems: given a channel system \( S = (Q, \Sigma, \Delta) \), two states \( q_0, q_{\text{rec}} \in Q \), and a relation \( \to \) in the interval

\[
\left( \bigcup_{\delta_k \in \Delta} \delta_k \right) \subseteq \to \subseteq \left( \bigcup_{\delta_k \in \Delta} \delta_k \right)
\]

decide whether for every \( n \in \mathbb{N} \) there exists a \( \to \)-computation of \( S \) starting with \( \langle q_0, \epsilon \rangle \) and reaching \( q_{\text{rec}} \) at least \( n \) times. The following lemma can be proved by a reduction of the undecidable boundedness problem for lossy channel systems [14]. The reduction was suggested by Ph. Schnoebelen:

**LEMMA 13.** The \( \omega \)-reachability problem is undecidable.

We are now in a position to prove the main result of the paper:

**THEOREM 14.** None of \( \text{Log}_1 T \) and \( \text{Log}_i R^n \), for \( n \geq 1 \), is decidable.

**Proof.** By Corollary 12, it suffices to consider (the complement of) \( \text{Log}_1 T \).

Given a single channel system \( S = (Q, \Sigma, \Delta) \) and states \( q_0, q_{\text{rec}} \in Q \), we construct a \( DT \mathcal{L}_1 \)-formula \( \varphi_S(q_0, q_{\text{rec}}) \) such that
if \( \varphi_{S,q_0,q_{rec}} \) is satisfiable then, for every \( n \in \mathbb{N} \), there is a lossy computation starting with \( \langle q_0, \epsilon \rangle \) and reaching \( q_{rec} \) at least \( n \) times;

( \iff \) if, for every \( n \in \mathbb{N} \), there is a perfect computation starting with \( \langle q_0, \epsilon \rangle \) and reaching \( q_{rec} \) at least \( n \) times then \( \varphi_{S,q_0,q_{rec}} \) is satisfiable in a DTM.

By Lemma 13 this will imply that \( \text{Log}_1 \mathcal{T} \) is undecidable.

The formula \( \varphi_{S,q_0,q_{rec}} \) is the conjunction of four formulas \( \sigma, \theta_{S,q_0,q_{rec}}, \tau_S \) and \( \rho_{S,q_{rec}} \) and is constructed in four steps (\( \sigma \)), (\( \theta \)), (\( \tau \)) and (\( \rho \)), respectively.

(\( \Rightarrow \)) To explain the meaning of each of the four conjuncts, let us assume that \( \mathcal{M}, x_0 \models \varphi_{S,q_0,q_{rec}} \), for some DTM \( \mathcal{M} = \langle \mathcal{T}, f \rangle \), where \( \mathcal{T} \) is the Aleksandrov topological space induced by a quasi-order \( \langle W, R \rangle \).

For every \( n \geq 0 \), let \( W_n = \{ y \in W \mid f^n(x_0)Ry \} \) and \( R_n = R \cap (W_n \times W_n) \). Clearly, the \( \langle W_n, R_n \rangle \) are quasi-orders. By Lemma 5, we may assume that the \( W_n \) are finite and \( f \) is injective.

(\( \sigma \)) First we introduce a new operator \( S \) (to be interpreted as an almost ‘irreflexive’ diamond in \( \langle W, R \rangle \)). Namely, we fix some fresh variable \( s \) and put, for every \( \mathcal{DL} - \text{formula } \psi \),

\[
S \psi = (s \land \mathcal{C}(\neg s \land \mathcal{C}\psi)) \lor (\neg s \land \mathcal{C}(s \land \mathcal{C}\psi)).
\]

Define new relations \( \overline{R}_n \) on \( W_n, n \geq 0 \), by taking, for all \( x, y \in W_n \),

\[
x \overline{R}_n y \text{ iff } \exists z \in W_n \left( xR_n z R_n y \text{ and } (\mathcal{M}, x) \models s \leftrightarrow (\mathcal{M}, z) \models \neg s \right).
\]

It can be checked that \( \overline{R}_n \) is transitive, \( \overline{R}_n \subseteq R_n \) and, for every \( x \in W_n \),

\[
(\mathcal{M}, x) \models S \psi \text{ iff there is } y \in W_n \text{ such that } x \overline{R}_n y \text{ and } (\mathcal{M}, y) \models \psi.
\]

Let

\[
\sigma = \Box^+_p I(s \leftrightarrow \circleo s).
\]

By the monotonicity of \( f \), if \( (\mathcal{M}, x_0) \models \sigma \) then, for all \( x, y \in W_n \),

\[
\text{if } x \overline{R}_n y \text{ then } f(x) \overline{R}_{n+1} f(y).
\]

(\( \theta \)) Next, we encode infinitely many computations along the orbit of \( x_0 \). Each computation is encoded backwards (from its end to the beginning), and the variable \( m \) delimits computations in the sense that each computation is encoded between two consecutive occurrences of \( m \). For every transition \( \delta_k \in \Delta \), we introduce a fresh variable \( tr\delta_k \) and, for every state \( q_i \in Q \), a
variable $q_i$.\(^3\) Let $\theta_{S,q_0}$ be the conjunction of the following formulas:

$$\bigwedge_{i \neq j} \Box_{F}^{+} (\mathsf{tr} \delta_{i} \land \mathsf{tr} \delta_{j}) \land \bigwedge_{q_i \neq q_j} \Box_{F}^{-} (q_i \land q_j),$$

(8)

$$\bigwedge_{\delta_i \in \Delta} \Box_{F}^{+} (\mathsf{tr} \delta_{k} \rightarrow q_j \land \mathsf{tr} \delta_i),$$

(9)

$$\square_{F}^{+} (\neg m \rightarrow \bigvee_{\delta_i \in \Delta} \mathsf{tr} \delta_i),$$

(10)

$$\square_{F}^{+} (m \rightarrow q_0),$$

(11)

$$m \land \square_{F}^{+} \circ_{F} m,$$

(12)

where $\ast$ denotes either of \{?, !\}. It follows that if $(\mathcal{M}, x_0) \models \theta_{S,q_0}$ then there is an infinite sequence of natural numbers $0 = M_0 < M_1 < \ldots$ such that

$(\mathcal{M}, f^{M_n}(x_0)) \models m,$

for every $n \geq 0$. Let $N_n = M_n - (M_{n-1} + 1)$, for $n > 0$. Clearly, $N_n \geq 1$, for $n > 0$. Let $N_0 = 0$. For every $n \geq 0$, there are also unique sequences

$q^n_0, \ldots, q^n_{N_n}$ and $\delta^n_k, \ldots, \delta^n_{k_{N_n-1}}$

of, respectively, states from $Q$ and transitions from $\Delta$ such that

- $(\mathcal{M}, f^{M_n-j}(x_0)) \models q^n_j$, for each $0 \leq j \leq N_n$,
- $(\mathcal{M}, f^{M_n-j+1}(x_0)) \models \mathsf{tr} \delta^n_{k_j}$, for each $0 \leq j < N_n$,
- $\delta^n_{k_j} = (q^n_j, \ast, a, q^n_{j+1})$ and $q^n_S = q_0$.

($\tau$) Our next step is to encode $\Sigma$-words in the ‘topological dimension.’ For every message $a_i \in \Sigma$, we introduce a fresh variable $a_i$ and let $\lambda = \bigvee_{a_i \in \Sigma} a_i$. Intuitively, $\Sigma$-words are encoded in $\mathcal{R}_k$-connected points of $W_k$. Denote by $\tau_{S}$ the conjunction of the following formulas:

$$\bigwedge_{a_i \neq a_j} \Box_{F}^{+} (a_i \land a_j),$$

(13)

$$\Box_{F}^{+} (\mathsf{I} (\lambda \rightarrow \mathsf{I} \lambda)), \quad \bigwedge_{a_i \in \Sigma} \Box_{F}^{+} (a_i \rightarrow \mathsf{O} (\lambda \rightarrow a_i)),$$

(14)

(15)

$$\mathsf{I} (\lambda \rightarrow \mathsf{I} \neg \lambda), \quad \Box_{F}^{+} (m \rightarrow \mathsf{I} \neg \lambda),$$

(16)

$$\bigwedge_{\delta_k = (q, l, a, q') \in \Delta} \Box_{F}^{+} (\mathsf{tr} \delta_k \rightarrow \mathsf{I} (\lambda \rightarrow \neg \mathsf{S} \mathsf{O} \neg \lambda) \land \mathsf{I} (\lambda \land \mathsf{O} \neg \mathsf{I} \lambda \rightarrow a)), \quad \bigwedge_{\delta_k = (q, l, a, q') \in \Delta} \Box_{F}^{+} (\mathsf{tr} \delta_k \rightarrow \mathsf{I} (\lambda \rightarrow \mathsf{O} \lambda) \land \mathsf{I} (\neg \mathsf{S} \mathsf{I} \lambda \rightarrow \mathsf{O} \mathsf{S} \lambda) \land \mathsf{O} \mathsf{I} (\neg \mathsf{S} \mathsf{I} \lambda \rightarrow a)).$$

(17)

(18)

\(^3\)Note the different font we use to denote these variables: their values will be needed only along the orbit of $x_0$ (in contrast to $s$ and other variables below).
CLAIM 15. Let \( y \in W_n \) be such that \( (\mathfrak{M}, y) \models \lambda \). Then \( y\overline{R}_n y \) does not hold.

**Proof of claim.** Suppose that \( y\overline{R}_n y \). By (16), \( (\mathfrak{M}, f^n(x_0)) \models \neg m \) and thus, by (10), \( (\mathfrak{M}, f^n(x_0)) \models \text{tr}\delta_k \) for some \( \delta_k \in \Delta \). Consider two cases:

(a) if \( \delta_k = (q, ??a, q') \) then \( (\mathfrak{M}, f(y)) \models \lambda \), by the first conjunct of (18);

(b) if \( \delta_k = (q, !, a, q') \) then, as \( y\overline{R}_n y \), we have, by (17), \( (\mathfrak{M}, f(y)) \models \lambda \) again.

By monotonicity of \( f \), we obtain \( f(y) \in W_{n+1} \) and \( f(y)\overline{R}_{n+1} f(y) \); therefore, one can repeat the above step for \( f(y) \). However, this process cannot continue indefinitely since there is \( M_j > n \) such that \( (\mathfrak{M}, f^{M_j}(x_0)) \models m \), and so, by (16), \( (\mathfrak{M}, y) \models \neg \lambda \) for all \( y \in W_{M_j} \).

Say that a finite sequence \( \vec{y} = (y_1, y_2, \ldots, y_k) \) of elements of \( W_n \) with \( y_1\overline{R}_n y_2\overline{R}_n \ldots \) carries the \( \Sigma \)-word \( w \) and write \( \text{val}(\vec{y}) = w \) if \( (\mathfrak{M}, y_i) \models w(i) \), for all \( 1 \leq i \leq |w| \). Note that, by (14), if \( (\mathfrak{M}, y) \models \lambda \) for some \( y \in W_n \) then, for every \( z \in W_n \) with \( y\overline{R}_n z \), we will also have \( (\mathfrak{M}, z) \models \lambda \). Let \( \text{val}(\vec{y}) = \epsilon \) if \( \vec{y} \) is the empty sequence. We say that a sequence \( \vec{y}' = (y'_1, \ldots, y'_i) \) with \( y'_i\overline{R}_n y'_{i+1} \) is an extension of \( \vec{y} = (y_1, \ldots, y_k) \) with \( y_i\overline{R}_n y_{i+1} \) if there is a strictly monotone function \( h : \{1, \ldots, k\} \to \{1, \ldots, r\} \) (i.e., \( h(i) > h(j) \), for \( i > j \)) such that \( y_i = y_{h(i)} \), for \( 1 \leq i \leq k \). A sequence \( \vec{y} = (y_1, \ldots, y_k) \) with \( y_i\overline{R}_n y_{i+1} \) is said to be maximal carrying a \( \Sigma \)-word if no extension of \( \vec{y} \) carries a \( \Sigma \)-word.

Suppose \( (\mathfrak{M}, f^n(x_0)) \models \neg m \). Then, by (10), \( (\mathfrak{M}, f^n(x_0)) \models \text{tr}\delta_k \) for some transition \( \delta_k \in \Delta \). Let \( \vec{y}' = (y_1, \ldots, y_i) \) with \( y_i\overline{R}_n y_{i+1} \) be a maximal sequence carrying a \( \Sigma \)-word and \( \text{val}(\vec{y}') = d_1 \ldots d_r \). First, consider the case when \( \vec{y}' \) is empty. This means that \( (\mathfrak{M}, y) \models \neg \lambda \) for all \( y \in W_n \). Take any maximal sequence \( \vec{y} \) in \( W_{n+1} \) carrying a \( \Sigma \)-word. Clearly, \( \vec{y} \) can be regarded as an extension of \( f(\vec{y}') = \epsilon \) and, as \( \epsilon \) is a subword of any word, we have \( \langle q, \text{val}(\vec{y}) \rangle \overset{\delta_k}{\to}_t \langle q', \epsilon \rangle \), for any transition \( \delta_k = (q, *, a, q') \in \Delta \) (this corresponds to a situation when everything is lost after the transition).

Suppose now that \( \vec{y}' \) is not empty. Let \( f(\vec{y}') = (f(y_1), \ldots, f(y_i)) \). Note that points of this sequence are all distinct since \( f \) is injective. Consider the cases of sending and receiving messages:

**Case \( \delta_k = (q, !, a, q') \).** By the first conjunct of (17), only three subcases are possible:

1. There is no \( m \), \( 1 \leq m \leq l \), such that \( (\mathfrak{M}, y_m) \models \circ \lambda \). Then, by the first conjunct of (17), \( \vec{y}' = (y_1) \) and, by its last conjunct, \( \text{val}(\vec{y}') = a \). Take any maximal sequence \( \vec{y} \) in \( W_{n+1} \) carrying a \( \Sigma \)-word. As \( \vec{y} \) does not contain \( f(y_1) \), it can trivially be regarded as an extension of \( f(\vec{y}') \).

   Thus \( \langle q, \text{val}(\vec{y}) \rangle \overset{\delta_k}{\to}_t \langle q', a \rangle \) (everything but the sent message is lost).

2. Let \( (\mathfrak{M}, y_1) \models \circ \lambda \). Then \( (\mathfrak{M}, f(y_1)) \models \lambda \) and, by (15), \( \text{val}(\vec{y}') = \text{val}(f(\vec{y}')) \). Take any maximal extension \( \vec{y} \) of \( f(\vec{y}') \) carrying a \( \Sigma \)-word. Then \( \text{val}(\vec{y}) \supseteq \text{val}(\vec{y}') \) and \( \langle q, \text{val}(\vec{y}) \rangle \overset{\delta_k}{\to}_t \langle q', \text{val}(\vec{y}') \rangle \) (the sent message is lost; other messages are possibly lost but not completely).
(2) Let \( (\mathcal{M}, y_1) \models \circ \neg 0 \) but \( (\mathcal{M}, y_2) \models \circ \lambda \). By the last conjunct of (17), we have \( (\mathcal{M}, y_1) \models a \) and, by (15), \( \text{val}(\vec{y}') = a \cdot \text{val}(f(\vec{y}')) \). Take any maximal extension \( \vec{y} \) of \( f(\vec{y}') \) carrying a \( \Sigma \)-word. Then we have \( \langle q, \text{val}(\vec{y}) \rangle \xrightarrow{\delta_k} \langle q', \text{val}(\vec{y}') \rangle \) (the sent message is not lost; other messages are possibly lost but not completely).

**Case** \( \delta_k = \langle q, ?, a, q' \rangle \). By the maximality of \( \vec{y} \) and Claim 15, \( (\mathcal{M}, y) \models \lambda \wedge \neg \Sigma \lambda \). Then, by the first and second conjuncts of (18), \( (\mathcal{M}, \vec{y}) \models \lambda \wedge \Sigma \lambda \). By Claim 15, the set \( \{ z \in W_{n+1} \mid f(y)\mathcal{R}_{n+1}z, \ (\mathcal{M}, z) \models \lambda \} \) contains no infinite ascending \( \mathcal{R}_{n+1} \)-chain, and so we can find some \( y \in W_{n+1} \) such that \( f(\vec{y}) \mathcal{R}_{n+1}y \) and \( (\mathcal{M}, y) \models \lambda \wedge \neg \Sigma \lambda \). By the last conjunct of (18), we have \( (\mathcal{M}, y) \models a \). As, by the first conjunct of (18) and (15), \( \text{val}(f(\vec{y}')) = \text{val}(\vec{y}') \), we obtain \( \text{val}(f(\vec{y}')) \cdot y = \text{val}(\vec{y}') \cdot a \). Finally, take any maximal extension \( \vec{y} \) of \( f(\vec{y}') \cdot y \) carrying a \( \Sigma \)-word. Clearly, \( \langle q, \text{val}(\vec{y}) \rangle \xrightarrow{\delta_k} \langle q', \text{val}(\vec{y}') \rangle \).

Now, given \( n \geq 1 \), we can find a lossy computation. Let \( (q_0, \ldots, q_{\Sigma n}) \) and \( (\delta_{\Sigma n}, \ldots, \delta_{\Sigma n-1}) \) be the unique sequences of states and transitions, respectively, defined by the model \( \mathcal{M} \) as described in step (\( \theta \)). We start from the tail: let \( j = N_n \) and take any maximal sequence \( \vec{y}_j \) in \( \mathcal{W}_{M_n-j} \) carrying a \( \Sigma \)-word. We know from the considerations that there is a maximal sequence \( \vec{y}_{j-1} \) in \( \mathcal{W}_{M_n-j-1} \) carrying a \( \Sigma \)-word such that

\[
\langle q_{\Sigma n-1}, \text{val}(\vec{y}_{j-1}) \rangle \xrightarrow{\delta_{\Sigma n}} \langle q_{\Sigma n}, \text{val}(\vec{y}_j) \rangle.
\]

By repeating this procedure sufficiently many times, we arrive at \( \langle q_0, \epsilon \rangle \), where the \( n \)-th computation starts (here we use (11) and (16)).

(\( \rho \)) At the final step we enforce the \( n \)-th computation to visit the state \( q_{\text{rec}} \) at least \( n \) times. We require two fresh variables \( \text{light} \) and \( \text{on} \). Let \( \rho_{\Sigma, q_{\text{rec}}} \) be the conjunction of the following formulas:

\[
\text{light} \wedge \Box_F (m \to I(\text{light} \to \circ \text{light})), \tag{19}
\]

\[
\Box_F I(\text{light} \to \circ \text{light}), \tag{20}
\]

\[
\Box_F (m \to \circ I(\text{light} \to \text{on})), \tag{21}
\]

\[
\Box_F (C(\text{light} \wedge \text{on} \wedge \circ \neg \text{on}) \to q_{\text{rec}}), \tag{22}
\]

\[
\Box_F I((\text{light} \wedge \text{on} \wedge \circ \neg \text{on}) \to \neg S(\text{light} \wedge \text{on} \wedge \circ \neg \text{on})), \tag{23}
\]

\[
\Box_F (m \to I(\text{light} \to \neg \text{on})). \tag{24}
\]

The above conjunction works as follows. By (19), with every start of a computation (i.e., whenever \( m \) is true) a fresh point \( x \) is picked up and the variable \( \text{light} \) is true at it; we say in this case that a new light is created. By (20), \( \text{light} \) is also true at all images \( f'(x) \) of \( x \). At the next iteration, by (21), all lights are switched on, i.e., \( \text{on} \) is true at every point with \( \text{light} \). By (22), whenever a light is switched off the current state of the computation must be \( q_{\text{rec}} \). Finally, by (24), all lights must be switched off at the next
occurrence of \( m \). It should also be noted that, by (19), the root \( x_0 \) is always a light and whenever \( m \) is true (for \( j > 0 \)) a fresh light is created as an \( \overrightarrow{R}_j \)-successor for every existing light. Therefore, after \( k \) occurrences of \( m \) there will be an \( \overrightarrow{R}_j \)-sequence of lights of length \( \geq k \). As, by (23), along every \( \overrightarrow{R}_j \)-sequence only one light may be switched off at a time and, by (23), this may only happen in the state \( q_{\text{rec}} \), the variable \( m \) cannot become true sooner than the computation visits \( q_{\text{rec}} \) at least \( k \) times. This completes the encoding of the \( \omega \)-reachability problem.

\( \implies \) For the converse direction, suppose that, for every \( n \geq 1 \), we have a perfect computation of \( S \) starting with \( \langle q_0, \epsilon \rangle \) and reaching \( q_{\text{rec}} \) at least \( n \) times. Let \( N_n \) be the number of transitions in the \( n \)-th computation; the 0-th computation is considered to be empty and \( N_0 = 0 \). For \( n > 0 \), let \( M_n = \sum_{k=1}^{n}(N_k + 1) \) and \( M_0 = 0 \) (for technical reasons, \( M_{-1} = -1 \)).

Fix \( n \geq 0 \) and consider the \( n \)-th computation:

\[
\langle q_0, \epsilon \rangle \xrightarrow{\delta_{k_0}^n} \langle q_{i_1}, w_1^n \rangle \xrightarrow{\delta_{k_1}^n} \langle q_{i_2}, w_2^n \rangle \xrightarrow{\delta_{k_2}^n} \cdots \xrightarrow{\delta_{k_N}^n} \langle q_{i_N}, w_N^n \rangle.
\]

Let \( H_0^n \) be the number of send (\( ! \)) transitions in the above sequence. Clearly, the number of messages that can be held in the channel during the above computation is bounded by \( H_0^n \).

We inductively define the sequence \((L^n_0, H^n_0), 0 \leq j \leq N_n \) \((w^n_j\) will be written between \( L^n_j \) and \( H^n_j \)). Let \( L^n_0 = H^n_0 \). Suppose \((L^n_{j-1}, H^n_{j-1})\) is defined. Then

\[
(L^n_j, H^n_j) = \begin{cases} (L^n_{j-1}, H^n_{j-1} - 1), & \text{if } \delta_{i_j}^n = \langle q_{i_{j-1}}, \cdot, a, q_{i_j} \rangle, \\ (L^n_{j-1} - 1, H^n_{j-1}), & \text{if } \delta_{i_j}^n = \langle q_{i_{j-1}}, \cdot,!, a, q_{i_j} \rangle. \end{cases}
\]

We are in a position now to define a satisfying model for \( \varphi_{S, q_0, q_{\text{rec}}} \) based on the computations above. First, for each computation number \( n \in \mathbb{N} \) and a step \( j \) in it, \( 0 \leq j \leq N_n \), let

\[
U^n_j = \{0, 1, \ldots, H^n_j\} \times \{0, 1\}
\]

be the chunk of the model required to encode this step of the computation: one extra point \( (0) \) is needed for a light that is created for this computation; moreover, points are duplicated to make the strict modality \( S \) work properly. Note that \( U^n_0 \) is the largest among them and includes all of the \( U^n_j \).

Next, for every \( m \in \mathbb{N} \), let

\[
W_m = \{m\} \times \left[ \bigcup_{n=0}^{M_n < m} \left( \{n\} \times U^n_0 \right) \cup \left( \{n_0\} \times U^n_{M_{n_0} - m} \right) \right],
\]

where \( n_0 \) is such that \( M_{n_0 - 1} < m \leq M_{n_0} \) (i.e., \( n_0 \) is the number of the computation at iteration \( m \) and \( j = M_{n_0} - m \) is the step number inside that computation). Note that the computations are encoded backwards.

Let \( R_m \) be the lexicographic order on \( W_m \), i.e.,

\[(m, n, k, q)R_m(m, n', k', q') \iff n < n' \text{ or } \begin{cases} n = n' \text{ and } (k < k' \text{ or } (k = k' \text{ and } q \leq q')), \end{cases}\]
for all quadruples \((m, n, k, q), (m, n', k', q') \in W_m\) (\(n\) and \(n'\) are for computation numbers, \(k\) and \(k'\) for elements to write words on, and \(q\) and \(q'\) range \(\{0, 1\}\) for duplication). Note that \(r_m = (m, 0, 0, 0)\) is the root of \((W_m, R_m)\).

Let \(W = \bigcup_{m=0}^{\infty} W_m, R = \bigcup_{m=0}^{\infty} R_m\) and let \(\mathcal{T}\) be the Aleksandrov space induced by \((W, R)\). Define \(f\) by taking, for all \((m, n, k, q) \in W, f((m, n, k, q)) = (m + 1, n, k, q)\).

Clearly, \(f\) is monotone on \((W, R)\). Finally, \(\mathfrak{B}\) is defined by taking

\[
\mathfrak{B}(s) = \{(m, n, k, 0) \in W,\}
\]

\[
\mathfrak{B}(m) = \{(m, 0, 0, 0) \in W \mid \exists n \in \mathbb{N} \ C(m; n, 0)\},
\]

\[
\mathfrak{B}(\text{tr} \delta_k) = \{(m, 0, 0, 0) \in W \mid \exists n, j \in \mathbb{N} \ C(m; n, j + 1) \text{ and } \delta^n_j = \delta_k\},
\]

\[
\mathfrak{B}(q_i) = \{(m, 0, 0, 0) \in W \mid \exists n, j \in \mathbb{N} \ C(m; n, j) \text{ and } q^n_j = q_i\},
\]

\[
\mathfrak{B}(a_i) = \{(m, n, k, q) \in W \mid \exists j \in \mathbb{N} \ C(m; n, j) \text{ and } u^n_j(L^n_j + k) = a_i\},
\]

\[
\mathfrak{B}(\text{light}) = \{(m, n, 0, q) \in W\},
\]

\[
\mathfrak{B}(\text{on}) = \{(m, n, 0, q) \in W \mid \exists j \in \mathbb{N} \ C(m; n, j) \text{ and } q_{\text{free}} \text{ occurs } > n \text{ times among } q^n_{0, \ldots, n}\},
\]

where the predicate \(C(m; n, j)\) is true iff \(m = M_n - j\) and \(0 \leq j \leq N_n\).

It can be readily verified that \(((\mathcal{T}, f), \mathfrak{B}), r_0) \models \varphi_{s,q_0,q_{\text{rec}}}.\)

As a consequence we obtain the following

**THEOREM 16.** None of \(\log \mathcal{T}, \log \mathcal{A}, \log \mathcal{R}^n,\) for \(n \geq 1,\) is decidable.

**Acknowledgements.** The work on this paper was partially supported by U.K. EPSRC grants no. GR/S63175/02, ???.

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