

Around dot depth two

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Abstract. It is known that the languages definable by formulae of the logics $FO^2[<, S]$, $\Delta_2[<, S]$, $LTL[F, P, X, Y]$ are exactly the variety $DA * D$. Automata for this class are not known, nor is its precise placement within the dot-depth hierarchy of starfree languages. It is easy to argue that $\Delta_2[<, S]$ is included in $\Delta_3[<]$; in this paper we show that it is incomparable with $\mathcal{B}(\Sigma_2)[<]$, the boolean combination of $\Sigma_2[<]$ formulae. Using ideas from Straubing’s “delay theorem”, we extend our earlier work [LPS08] to propose partially-ordered two-way deterministic finite automata with look-around (*po2dla*) and a new interval temporal logic called LITL and show that they also characterize the variety $DA * D$. We give effective reductions from LITL to equivalent *po2dla* and from *po2dla* to equivalent $FO^2[<, S]$. The *po2dla* automata admit efficient operations of boolean closure and the language non-emptiness of *po2dla* is NP-complete. Using this, we show that satisfiability of LITL remains NP-complete assuming a fixed look-around length. (Recall that for $LTL[F, X]$, it is PSPACE-hard.)

A rich set of correspondences has been worked out between diverse mechanisms for defining the first-order definable word languages and their subclasses (a recent survey is [DGK08]). In the following, CFA refers to counter-free automata, SFRE to star-free regular expressions and Ap refers to the variety of aperiodic monoids [Pin86].

$$CFA \equiv SFRE \equiv Ap \equiv FO[<] \equiv LTL[U, S] \equiv ITL$$

Further, Thomas showed [Tho82] that by restricting the quantifier-alternation depth in the $FO[<]$ formulae a strict dot-depth hierarchy of star-free languages is obtained, see the paper by Pin and Weil [PW97] for details. For example, $\mathcal{B}(\Sigma_2)[<]$ is the class of languages defined by the boolean combination of $\Sigma_2[<]$ formulae, which are the ones which have one block of existential quantifiers followed by one block of universal quantifiers followed by a quantifierless formula.

For the FO formulations below, given an alphabet A and $a \in A$, the unary predicate $Q_a(x)$ holds iff the letter at position x is a . The binary predicate $S(x, y)$ denotes the successor relation on positions, and $<$ is, as usual, its transitive closure.

Example 1. Let $A = \{a, b\}$ be the alphabet described by $\phi_A \stackrel{\text{def}}{=} \forall x. Q_a(x) \vee Q_b(x)$, which will be an additional conjunct below, not explicitly mentioned.

- $\phi_1 \stackrel{\text{def}}{=} \exists x \exists y. S(x, y) \wedge Q_a(x) \wedge Q_a(y)$ is a $\mathcal{B}(\Sigma_1)[S]$ formula defining $L_1 = A^*aaA^*$.
- $\phi_2 \stackrel{\text{def}}{=} \exists x \exists y. Q_a(x) \wedge Q_a(y) \wedge \forall z. (x < z \supset y \leq z)$ is a $\Sigma_2[<]$ formula defining L_1 .

- Let $\phi_3 \stackrel{\text{def}}{=} (\forall x. \text{first}(x) \supset Q_a(x)) \wedge (\forall x. \text{last}(x) \supset Q_b(x)) \wedge$
 $(\forall x, y. ((x < y) \wedge Q_a(x) \wedge Q_a(y) \supset \exists z. x < z \wedge z < y \wedge Q_b(z))) \wedge$
 $(\forall x, y. ((x < y) \wedge Q_b(x) \wedge Q_b(y) \supset \exists z. x < z \wedge z < y \wedge Q_a(z)))$

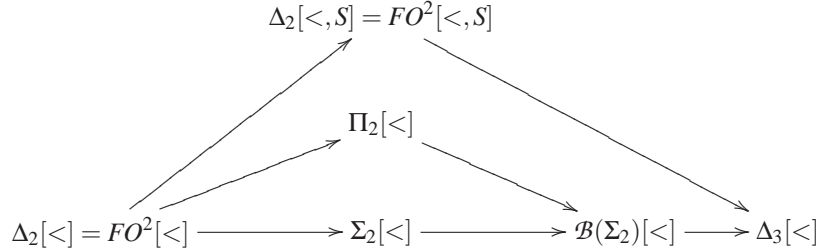
Then, ϕ_3 is a $\Pi_2[<]$ formula defining the language $L_2 = (ab)^*$. \square

More recently, Thérien and Wilke [TW98] showed that the 2-variable fragment $FO^2[<]$ [Mor75] (where only two variables occur, quantified any number of times), is expressively equivalent to the unambiguous languages and variety DA of Schützenberger [Sch76,TT02] and the subset $\Delta_2[<]$ in the dot-depth hierarchy. Etessami, Vardi and Wilke [EVW02] identified the unary temporal logic $LTL[F, P]$ and Schwentick, Thérien and Vollmer [STV02] identified partially-ordered 2-way deterministic finite automata (these are also called linear [LT00]) as equivalent formalisms. In [LPS08], we added to these correspondences a “deterministic” interval temporal logic called $UITL$. The papers [TW98, EVW02] also characterized $FO^2[<, S]$, which can define languages not definable in the logic $FO^2[<]$ such as those in Example 1. For a detailed study of these logics, see the recent papers of Weis and Immerman [WI07], and of Kufleitner and Weil [KW09].

$$PO2DFA \equiv UL \equiv DA \equiv FO^2[<] \equiv \Delta_2[<] \equiv LTL[F, P] \equiv UITL$$

$$DA * D \equiv FO^2[<, S] \equiv \Delta_2[<, S] \equiv LTL[F, P, X, Y]$$

It is clear that $\Delta_2[<, S] \subseteq \Delta_3[<]$ since successor can be defined using $<$ and one quantifier. In this paper we provide an automaton characterization and an interval logic characterization for this class of languages, and we separate it from $\mathcal{B}(\Sigma_2)[<]$, the languages defined by the boolean combination of $\Sigma_2[<]$ formulae. This also shows that $FO^2[<, S]$ is a *proper* subset of $\Delta_3[<]$, as diagrammatically depicted below.



Our automaton and logic characterizations are based on Rhodes expansions [Til76]; the two-sided variant below is inspired by Straubing’s theorem $DA * D \equiv DA * LI$ [Str85].

Definition 1. Let A be a finite alphabet, $A' = A \cup \{\triangleright, \triangleleft\}$ be its extension with two end-markers $\triangleright, \triangleleft \notin A$, and $A_d^p = (A')^{2d+1}$ the alphabet whose letters are actually words of length $2d + 1$ over A . Let $w = w_1 w_2 \dots w_n$ be a given word, where $w_i \in A$ is a letter. Let $\text{around}_d(w, i) = w_{i-d} \dots w_i \dots w_{i+d}$ denote the two-sided d -lookaround string at position i . Note that if the position i is near one of the endpoints then $\text{around}_d(w, i)$ is padded by repeating the endmarker at that end. We define the **Rhodes-Straubing d -expansion** of w (and for a language L pointwise) for $d \geq 1$ to be $w_d^p = u_1 u_2 \dots u_n$, where each $u_i = \text{around}_d(w, i)$. This is a word over A_d^p . When $d = 0$ we let w_0^p be w . For example, $(abcab)_2^p$ is $(\triangleright \triangleright abc)(\triangleright abca)(abcab)(bcab\triangleleft)(cab\triangleleft\triangleleft)$. \square

Straubing’s delay theorem shows that a language, or in our context a formula ϕ of $FO^2[<, S]$, can be seen as a formula ϕ' of $FO^2[<]$ over a Rhodes-Straubing d -expansion where d is the number of occurrences of successor predicates in ϕ . Carrying this intuition to automata, we extend *po2dfa* to partially-ordered 2-way deterministic finite state automata with lookahead (*po2dla*) which essentially make transitions on the Rhodes-Straubing expansion of the word. We also extend our unambiguous interval logic *UITL* to an unambiguous interval logic with lookahead called LITL. With some amount of technical hacking, we are able to show that LITL and *po2dla* have the expressive power of $FO^2[<, S]$.

The resulting automata and interval logic have many interesting features. A significant property of *po2dla* is that the boolean operations (including complementation) can be done within *po2dla* with a linear blowup in size. Language emptiness of *po2dla* is NP-complete and inclusion between *po2dla* is CoNP-complete, assuming a fixed lookahead size k .

The logic LITL inherits the desirable properties of its ancestor *UITL* [LPS08]. It admits unique parsability of models and exploiting this we can provide an efficient PTIME reduction from LITL to *po2dla*. This immediately gives us a small model property for the logic. Moreover, given a formula of length n with alphabet size m and lookahead length k , we can show that the satisfiability problem is in nondeterministic time $O((m^k) \times n)$. Assuming fixed lookahead size k , satisfiability is NP-complete. By comparison, the satisfiability of the logic $LTL[F, X]$ is PSPACE-hard, although an action-indexed version was shown NP-complete by Muscholl and Walukiewicz [MW05].

The rest of the paper is organized as follows: the next section defines our automata, Section 2 the logic and the reductions from logic to automata and from automata to $FO^2[<, S]$. Section 3 deals with expressiveness and finally brings us back from $FO^2[<, S]$ to our logic.

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1 Partially-ordered two-way DFA with look-around

Fix an alphabet A and its extension $A' = A \cup \{\triangleright, \triangleleft\}$ with two endmarkers $\triangleright, \triangleleft \notin A$. Given $w \in A^*$, let $dom(w) = \{1, \dots, |w|\}$. In recognizing w , the two-way automaton actually scans the string $w' = \triangleright w \triangleleft$ with letters \triangleright and \triangleleft at positions 0 and $|w| + 1$ respectively. Thus, $dom(w') = \{0, \dots, |w| + 1\}$.

Let $a \in A'$ and let $u, v \in A^*$. We shall consider **patterns** of the form $u\underline{a}v$ with an underlined distinguished position. Given a pattern $u\underline{a}v$ and a word w' , a position $i \in dom(w')$ matches the pattern, denoted $(w'[*], i, [*] = u\underline{a}v)$, if the letter in w' at position i is a and this is followed by the string v (forward lookahead) and also this a is preceded

by the string u (backward lookahead). Formally, $(w'[* , i , *] = u\bar{a}v)$ iff $w'[i] = a$ and $\forall k \in \text{dom}(v). i+k \in \text{dom}(w') \wedge w'[i+k] = v[k]$ and $\forall k \in \text{dom}(u). i-k \in \text{dom}(w') \wedge w'[i-k] = u[k]$. (When clear from the context, $u\bar{a}v$ will be written as uav).

For a string u , let $\text{Pre}(u)$ and $\text{Suf}(u)$ be the set of all prefixes and suffixes (respectively) of u . Given two patterns $u_1\bar{a}_1v_1$ and $u_2\bar{a}_2v_2$, we say that they are overlapping iff (i) $a_1 = a_2$, (ii) $u_1 \in \text{Suf}(u_2)$ or $u_2 \in \text{Suf}(u_1)$, and (iii) $v_1 \in \text{Pre}(v_2)$ or $v_2 \in \text{Pre}(v_1)$.

1.1 Automaton Definition

Partially ordered two-way DFA were introduced by Schwentick, Thérien and Vollmer [STV02] to characterize the unambiguous languages. We present a generalization with forward and backward lookahead. The transitions of the automaton are labelled by patterns over the alphabet, instead of letters. There is a default else transition associated with each state which is taken if no other transition is applicable. This makes our automata total.

Definition 2. A *partially ordered 2DFA (po2dla) with lookahead size k over A'* is a tuple $M = (Q, \leq, \delta, s, t, r)$ where (Q, \leq) is a finite partial order of states with distinct start, accept and reject states s, t and r where r and t are the only minimal elements of the poset and s is the only maximal element. Let \mathcal{P} be the set of all patterns with a maximum lookahead of size k , i.e. the set of all $u\bar{a}v$ such that $u, v \in A^*$, $a \in A'$ and $|u|, |v| \leq k$. The transition function δ has two types of transitions: the matching transitions form a partial function $\delta_m : (Q \setminus \{t, r\} \times \mathcal{P}) \rightarrow (Q \times \{L, R, X\})$ where the first component q' of $\delta_m(q, u)$ satisfies $q' < q$, and the default else transition is a total function $\delta_{else} : (Q \setminus \{t, r\}) \rightarrow (Q \times \{L, R\})$ where the first component q' satisfies $q' \leq q$.

Further, for determinism we have that, for all $q \in Q$, and $u_1\bar{a}_1v_1, u_2\bar{a}_2v_2 \in \mathcal{P}$, if $\delta_m(q, u_1\bar{a}_1v_1) = q_1$ and $\delta_m(q, u_2\bar{a}_2v_2) = q_2$ such that $q_1 \neq q_2$, then $u_1\bar{a}_1v_1$ and $u_2\bar{a}_2v_2$ are not overlapping. To ensure that the head of the automaton does not "fall beyond" the end-markers, we have an additional syntactic condition:

$$\forall q \in Q \setminus \{t, r\}. \exists q', q'' \in Q. \delta_m(q, \triangleright) = (q', R) \text{ and } \delta_m(q'', \triangleleft) = (q'', L). \quad \square$$

A configuration of automaton M running on word w' is a pair (q, p) with $q \in Q$, $p \in \text{dom}(w')$. The automaton in a configuration (q, p) takes the unique δ_m transition from q , whose label is matched at the position p . If such a transition does not exist, then the automaton takes the default transition δ_{else} where it must change position.

Run The run of the automaton M on a word w' and starting at a position p_0 , is a sequence of state-position configurations $(q_0, p_0), (q_1, p_1) \dots (q_n, p_n)$, where

- $q_0 = s$ and $q_n \in \{t, r\}$. The run is accepting if $q_n = t$ and rejecting if $q_n = r$.
- For all $i \geq 0$, if there exists (unique) $u\bar{a}v$ such that $\delta_m(q_i, u\bar{a}v) = (q', d)$ for some (q', d) and $(w'[* , i , *] = u\bar{a}v)$, then (a) $q_{i+1} = q'$ and (b) $p_{i+1} = p_i + 1$ if $d = R$, $p_{i+1} = p_i - 1$ if $d = L$ and $p_{i+1} = p_i$ if $d = X$.
- Otherwise, $q_{i+1} = q'$, where $\delta_{else}(q_i) = (q', d)$, and $p_{i+1} = p_i + 1$ if $d = R$ and $p_{i+1} = p_i - 1$ otherwise.

The outcome of the run is given by the total function $[[M]]$ such that for any $w \in A^*$ and $i \in \text{dom}(w')$ is given by $[[M]](w, i) = (q_n, p_n)$, the final configuration of the run. A word w is accepted by M if the unique run of M on $w' = \triangleright w \triangleleft$ starting at position 1 is accepting. The language $\mathcal{L}(M) \subseteq A^*$ is the set of words accepted by M . \square

Since the states of M are partially ordered, the only loops allowed are self-loops on the default else transitions. During a sequence of such self-loop transitions the automaton moves in the same direction. Moreover, the automaton must change state on reaching an endmarker. So, because of the partial order, a *po2dla* cannot loop infinitely: it has at most $|Q| - 1$ reversals and all its runs are bounded by length $|Q| \times |w|$. Since δ_{else} is a total function, the automaton always has a terminating run on every word: hence the automaton is complete.

Example 2. Figure 1 gives the *po2dla* for the languages $(ab)^*$ and A^*aaA^* . The default else transitions are shown with just a direction. In the automaton \mathcal{A}_1 , two consecutive a 's or b 's lead to rejection from state s_1 , and in state s_2 which is reached at the end of the word, we check that it ends with b .

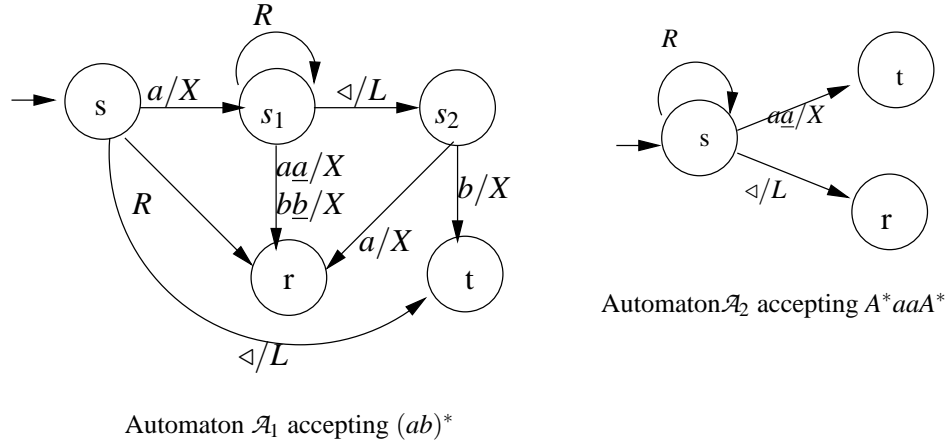


Fig. 1

Proposition 1. *The po2dla are closed under sequential composition and Boolean operations, constructible with automata of linear size (number of states).*

The proofs follow our earlier paper [LPS08]. Just as we have there, the automata can be described by a syntax of **extended turtle expressions** going beyond those of Schwentick, Thérien and Vollmer [STV02]. We omit these because of lack of space.

1.2 Small model property and decision problems

We let $INTV(w) = \{[i, j] \mid i, j \in \text{dom}(w), i \leq j\}$ be the set of intervals over w , and $w[i, j]$ (or $w, [i, j]$ in the next section) denote the factor of w corresponding to the interval $[i, j]$.

We will extend this notation to open and semi-open intervals as usual, as well as to their unions.

Consider a *po2dla* M over an alphabet A with n states and a maximum lookahead of k . Recall that $A' = A \cup \{\triangleright, \triangleleft\}$ and for $w \in A^*$ we have $w' = \triangleright w \triangleleft$. Recall also the definition of $\text{around}_d(w, i)$ given in Definition 1. When clear from the context, we will abbreviate this by $\text{around}(w, i)$ or $\text{around}(i)$.

Lemma 1 (Membership). *Given a word $w \in A^*$, checking whether $w \in L(M)$ can be carried out by simulating the automaton in deterministic time $O(mnk)$ where m is the number of states of M , n is the length of the word w' and k is the lookahead size.*

Proof. Lookahead is handled by maintaining an array of length $2k + 1$ storing the factor around the current head position. Note that there can be at most $m - 1$ reversals in the *po2dla*. The algorithm requires space $\log m + \log n + (2k + 1) \log |A'|$. \square

Now consider the unique run of M accepting w . We say that a position $p \in \text{dom}(w')$ is purely-self-looping (PSL) if for all configurations of the form (q, p) in the run having position p , the (unique) enabled transition of M is the *self-looping else transition* (which does not result in change of state).

Call an interval $[m_1, m_2] \in \text{INTV}(w)$ a tunnel if all $j \in [m_1, m_2]$ are purely-self-looping (PSL) and $\text{around}(w', m_1) = \text{around}(w', m_2)$. If the automaton makes a right move at position m_1 , it continues moving right without change of state till it reaches m_2 ; and similarly for a left move at m_2 . The following lemma is a direct result of the above and the fact that $\text{around}(m_1) = \text{around}(m_2)$.

Lemma 2. *Given w' and a tunnel $[m_1, m_2]$, let $v' = w'[0, m_1][m_2, |w'|]$ be the word obtained by replacing the tunnel by its last letter. Then, $w \in L(M)$ iff $v \in L(M)$. \square*

From the above lemma, it is clear that every tunnel in word w' can be collapsed into a single letter preserving membership. Thus, in a word without tunnels, there can be a consecutive sequence of PSL positions which has length at most $|A'|^{2k+1}$ (the number of distinct $\text{around}(i)$). Every such sequence must be separated by a non-PSL position. There can be at most $n - 1$ non-PSL positions in a run since there can be at most $n - 1$ state changing transitions in an n state *po2dla*. Hence, we get the following theorem.

Theorem 1 (Small model). *If $L(M) \neq \emptyset$ then there exists a word $w \in L(M)$ of length at most $(|A'|^{2k+1} + 1)(n - 1)$. \square*

Corollary 1. *Assuming lookahead k to be constant, the language non-emptiness of *po2dla* is NP-complete and the language inclusion of *po2dla* is CoNP-complete.*

Proof. The technique is to guess the member word of size $(|A'|^{2k+1} + 1)(n - 1)$ non-deterministically, and to use the PTIME membership checking algorithm on this. Thus, non-emptiness is in NP. The non-emptiness problem for *po2dfa* is shown to be NP-hard [SP09]. Since *po2dla* are extension of *po2dfa*, we conclude that their non-emptiness problem is NP-complete. We also conclude that the language inclusion problem is CoNP-complete as intersection and complementation of *po2dla* cause only linear blowup in the automaton size, and $L_1 \subseteq L_2$ iff $L_1 \cap \overline{L_2} = \emptyset$. \square

2 Logic LITL

Interval temporal logic is based on a *chop* operator which divides an interval into two. Although this yields succinct formulae, the complexity of satisfiability is nonelementary. We proposed unambiguous interval temporal logic [LPS08] replacing chops by marked chop operators F_a and L_a , dividing a given interval at the first/last occurrence of the letter a . Satisfiability of *UITL* is NP-complete. Here we have a simple generalization, chopping an interval at the first/last occurrence of a given pattern $u\underline{a}v$.

Fix an alphabet A . Let $a \in A$ and $u, v \in A^*$. Let D, D_1, D_2 range over formulas in LITL. The abstract syntax of LITL is given below. Here \top denotes the formula *true*.

$$\top \mid pt \mid D_1 \vee D_2 \mid \neg D \mid D_1 F_{u\underline{a}v} D_2 \mid D_1 L_{u\underline{a}v} D_2 \mid \oplus D \mid \ominus D$$

The satisfaction of a formula D is defined over intervals of a word model w as follows. As usual, $w \models D$ iff $w, [1, |w|] \models D$ and $L(D) \stackrel{\text{def}}{=} \{w \mid w \models D\}$ is the language defined by D . The derived operators $\wedge, \supset, \Leftrightarrow$ have their usual definitions.

$$\begin{aligned} w, [i, j] \models pt & \text{ iff } i = j \\ w, [i, j] \models D_1 F_{u\underline{a}v} D_2 & \text{ iff for some } k : k \in [i, j]. (w[*], k, [*] = u\underline{a}v) \text{ and} \\ & \text{ for all } m : i \leq m < k. \neg(w[*], m, [*] = u\underline{a}v) \text{ and} \\ & w, [i, k] \models D_1 \text{ and } w, [k, j] \models D_2 \\ w, [i, j] \models D_1 L_{u\underline{a}v} D_2 & \text{ iff for some } k : k \in [i, j]. (w[*], k, [*] = u\underline{a}v) \text{ and} \\ & \text{ for all } m : k < m \leq j. \neg(w[*], m, [*] = u\underline{a}v) \text{ and} \\ & w, [i, k] \models D_1 \text{ and } w, [k, j] \models D_2 \\ w, [i, j] \models \oplus D & \text{ iff } i < j \text{ and } w, [i+1, j] \models D \\ w, [i, j] \models \ominus D & \text{ iff } i < j \text{ and } w, [i, j-1] \models D \end{aligned}$$

Example 3. The LITL formula $\top F_{aa} \top$ precisely specifies the language $A^* aa A^*$. The formula $(pt F_a \top) \wedge (\top L_b pt) \wedge \neg(\top F_{aa} \top) \wedge \neg(\top F_{bb} \top)$ specifies the language $(ab)^+$ over alphabet $\{a, b\}$. The first and the second conjunct state that the word begins with a and it ends with b . The last two conjuncts state that subwords aa or bb do not occur within the word.

2.1 Unique parsability and reduction to automata

As for its ancestor *UITL* [LPS08], every word model of a *LITL* formula can be uniquely parsed. Fix an LITL formula ϕ . Consider its subformula ψ occurring in context λ ; we denote this by $\phi = \lambda(\psi)$. For any $w \in A^+$, we can uniquely determine if ψ is *relevant* in determining truth of ϕ over w . Moreover, if relevant, we can uniquely assign an interval $Intv_w(\psi)$ such that the truth value of ψ only over this interval is relevant in determining the truth of ϕ over w . The interval $Intv_w(\psi)$ actually depends only on the context λ and not on ψ . Moreover, it is possible to construct *po2dla* $\mathcal{L}(\psi)$ and $\mathcal{R}(\psi)$ which accept at the left and right interval boundaries of $Intv_w(\psi)$ respectively if the subformula is relevant. Using these automata, we can further construct an automaton $M(\psi)$ which accepts if ψ is relevant and it evaluates to true on $Intv_w(\psi)$. Exploiting this unique parsability, the following theorem can be established as a straightforward generalization of the similar theorem for logic *UITL* [LPS08].

Theorem 2. For any $D \in \text{LITL}$ we can effectively construct a *po2dla* $M(D)$ in polynomial time such that $w \in \mathcal{L}(D) \Leftrightarrow w \in \mathcal{L}(M(D))$. The size $|M(D)| = O(|D|^2)$.

Proof (sketch). The construction of $M(D)$ is inductive and proceeds bottom-up on the structure of D . Consider $D = \psi_1 F_{uav} \psi_2$. The corresponding *po2dla* $M(D)$ first moves to the left boundary of $\text{Int}_{v,w}(D)$, then it checks in a single pass (moving in one direction only), for the existence of first uav , and also checks whether it lies within the right boundary of the interval $\text{Int}_{v,w}(\psi)$. It then invokes the automata $M(\psi_1)$ and $M(\psi_2)$ in sequence. The details of the construction can be found in the full paper. \square

Decision problems. The above translation gives a PTIME reduction from LITL formula of size n to a language equivalent automaton of size (i.e. number of states) $O(n^2)$. Moreover, the lookaround size in automaton is at most the pattern size in the LITL formula. Combining this with NP-complete non-emptiness checking of *po2dla*, we conclude that satisfiability of LITL is NP-complete assuming a fixed lookaround size. Our previous paper [LPS08] gave a LOGDCFL procedure for checking membership for logic *UITL*. This procedure extends to logic LITL with the same complexity.

2.2 From *po2dla* to $FO^2[<, S]$

In this section, we outline a language preserving translation from *po2dla* to $FO^2[<, S]$. Essentially the automaton is a dag with self-loops added on some nodes. For each progress edge $e = (p, \alpha, q, \text{dir})$, $p \neq q$, we define $FO^2[<, S]$ formulae $At_e(x)$ and $After_e(x)$ with one free variable x . These formulae satisfy the lemma below. By substituting these formulae as we go along the dag, we get a formula for the words accepted.

Lemma 3. – $\triangleright w \triangleleft i \models At_e(x)$ iff there exists a partial run of M (starting with $(s, 1)$) which ends in configuration (p, i) and $(w[*], i, *) = \alpha$.
– $\triangleright w \triangleleft i \models After_e(x)$ iff there exists a partial run ending with last two configurations $(p, j)(q, i)$ where the last edge of the automaton taken is e .

Construction. It is easy to construct $After_e(x)$ given $At_e(x)$. For edge $e = (p, \alpha, q, \text{dir})$ we have $After_e(x) \stackrel{\text{def}}{=} \exists y. S(x, y) \wedge At_e(y)$ if $\text{dir} = L$; $After_e(x) \stackrel{\text{def}}{=} \exists y. S(y, x) \wedge At_e(y)$ if $\text{dir} = R$; and $After_e(x) \stackrel{\text{def}}{=} At_e(x)$ if $\text{dir} = X$.

Given α , there is a $FO^2[<, S]$ formula $\alpha(x)$ stating that the position x matches α . E.g. $dabc(x) \stackrel{\text{def}}{=} b(x) \wedge (\exists y. S(y, x) \wedge a(y) \wedge (\exists x. S(x, y) \wedge d(x))) \wedge (\exists y. S(x, y) \wedge c(y))$.

Now we give the construction of $At_e(x)$, by induction on the depth of the edge. Consider an edge $e = (p, \alpha, q, \text{dir})$ where the labels of other progress edges from state p are $\alpha_1, \dots, \alpha_k$. Let the incoming progress edges to p be e_1, \dots, e_r . We consider here the case that $\delta_{else}(p) = (p, R)$, i.e. a self-loop scanning rightwards. The case $\delta_{else}(p) = (p, L)$ is symmetric.

$$At_e(x) \stackrel{\text{def}}{=} \alpha(x) \wedge \bigvee_{e_i \in \{e_1, \dots, e_r\}} [(\exists y. y \leq x \wedge After_{e_i}(y)) \wedge (\forall y. y < x \Rightarrow ((\neg \alpha(y) \wedge \neg \alpha_1(y) \wedge \dots \wedge \neg \alpha_k(y)) \vee (\exists x. y < x \wedge After_{e_i}(x))))]$$

For the start state s we assume that there is a dummy incoming edge e_{init} such that $After_{e_{init}}(x)$ is a formula which holds exactly at position 1 in w . The formula $\phi(M)$ for the whole automaton M is the disjunction of the formulae $At_{e_i}(x)$ for each incoming edge e_i to the accepting state t . Note that the size of $\phi(M)$ is exponential in size of M .

Theorem 3. *Every poddla can be effectively reduced to a language equivalent formula of $FO^2[<, S]$ of exponential size.*

Hence, using Theorem 2, every LITL formula can be effectively reduced to a language equivalent $FO^2[<, S]$ formula, but a direct quadratic translation from LITL to $FO^2[<, S]$ generalizing the one in [Shah07] can also be worked out. In this paper, Theorem 5 will show that we can go from $FO^2[<, S]$ to LITL.

3 Games and expressiveness

We now investigate the expressiveness of $FO^2[<, S]$ with respect to the dot-depth hierarchy. Since a successor predicate can be replaced by $<$ with an additional nesting of a quantifier, we get that $FO^2[<, S] \subseteq \Delta_3[<]$.

Theorem 4. (i) $\Pi_2[<] \not\subseteq FO^2[<, S]$
(ii) $\Sigma_2[<] \not\subseteq FO^2[<, S]$
(iii) $FO^2[<, S] \not\subseteq \mathcal{B}(\Sigma_2)[<]$

To prove the above results, we use Ehrenfeucht-Fraïssé games [Fra50,Ehr61]. The signature has unary predicates Q_a, Q_b, Q_c and $<$ and S are the binary predicates, with their usual definitions. Let Sig be a signature, and u, v be two word structures over Sig . An EF game $G(u, v, p, r)$ is a game played by 2 players, the *Spoiler* and *Duplicator*, over the word models u, v . A play of the game has r rounds with each player playing p pebbles. The pebbles are colored with p different colors, each player having exactly one pebble of each color.

In each round the *Spoiler* picks (any) one of the words, and places his p pebbles on it. The *Duplicator* then places his corresponding p pebbles on the other word. *Duplicator* wins the game if at the end of r rounds there exists a partial isomorphism between the pebble positions, with respect to all the relations of Sig . Note that this can only happen if each of the intermediate configurations is also a partial isomorphism. Weis and Immerman [WI07] proved the following version of the Ehrenfeucht-Fraïssé theorem.

Definition 3. *Two words u, v are said to be r - $FO^2[<, S]$ equivalent if for any $FO^2[<, S]$ formula ϕ with quantifier depth $\leq r$, $u \models \phi \Leftrightarrow v \models \phi$, and p - $\mathcal{B}(\Sigma_2)[<]$ equivalent if for any $\mathcal{B}(\Sigma_2)[<]$ formula ϕ with $\leq p$ variables, $u \models \phi \Leftrightarrow v \models \phi$.*

Lemma 4. (a) *Two word models u, v over the signature $[<, S]$ are r - $FO^2[<, S]$ equivalent iff for the game $G(u, v, 2, r)$, the *Duplicator* always has a winning strategy.*
(b) *Two word models u, v over the signature $[<]$ are p - $\mathcal{B}(\Sigma_2)[<]$ equivalent iff for the game $G(u, v, p, 2)$, the *Duplicator* always has a winning strategy.*

Proof (of Theorem 4). We note that since $FO^2[<,S]$ is a boolean closed logic, (i) of the theorem will imply (ii) (or vice versa). We consider words over the alphabet $A = \{a, b, c\}$ described by a conjunct $\phi_A = \forall x(Q_a(x) \vee Q_b(x) \vee Q_c(x))$.

(i) We consider the language $(ac^*bc^*)^*$. This language may be expressed by the conjuncts below giving a $\Pi_2[<]$ formula:

$$\begin{aligned} &\forall x(\forall y(y < x \Rightarrow x = y)) \Rightarrow Q_a(x) \\ &\forall x\exists y(Q_b(y) \wedge (x > y \Rightarrow Q_c(x))) \\ &\forall x\forall y((Q_a(x) \wedge Q_a(y) \wedge x < y) \Rightarrow (\exists z.(x < z < y \wedge Q_b(z)))) \text{ and} \\ &\forall x\forall y((Q_b(x) \wedge Q_b(y) \wedge x < y) \Rightarrow (\exists z.(x < z < y \wedge Q_a(z)))) \end{aligned}$$

For some $r > 0$, consider two word models over the signature $[<,S]$:

$$u : (ac^rbc^r)^{2r}, \text{ and } v : (ac^rbc^r)^rbc^r(ac^rbc^r)^r$$

Here, $u \in (ac^*bc^*)^*$ and $v \notin (ac^*bc^*)^*$. We can show that for any 2-pebble, r -round EF game $G(u, v, 2, r)$, the *Duplicator* always has a winning strategy, and hence u, v are r - $FO^2[<,S]$ equivalent. This is evident from the observation that the two b 's in v that do not have an a between them are separated by r c 's and hence can be duplicated by the r^{th} bc^r in u . It is straightforward to see that any of the moves on a 's or b 's by the *Spoiler* can be duplicated in the other word. So the language $(ac^*bc^*)^*$ cannot be expressed in $FO^2[<,S]$.

(iii) We show that the language given by the LITL formula $(\neg(\top F_{bb} \top))F_{aa} \top$ is not definable in $\mathcal{B}(\Sigma_2)[<]$. Over the signature $[<]$, we first claim that no formula using less than p variables can distinguish in one round between the words $u_1 = (ab)^pbb(ab)^paa(ab)^p$ and $v_1 = (ab)^paa(ab)^pbb(ab)^p$. This is because any subsequence of length p in one word can be matched in the other word.

Now consider the pair of words $u_2 = u_1^p$ and $v_2 = v_1^p$ formed by taking p copies of the earlier ones. Now any placement of p pebbles in one word can be matched in the other word so that the subwords of length at most $p - 2$ between any two pebbles (or a pebble and an end of the word) are the same. This means that *Duplicator* has a winning strategy for the second round as well.

Since for every p , the first word u_2 is not in the language given by $(\neg(\top F_{bb} \top))F_{aa} \top$ and the second word v_2 is in the language, this shows that any $\mathcal{B}(\Sigma_2)[<]$ formula (using, say, p variables) fails to define the language. \square

3.1 Using unambiguity on Rhodes-Straubing expansions

We now show that the expressiveness of $FO^2[<,S]$ is no more than that of LITL. Since the proofs of the lemmas are refinements of those in [TW98], they are omitted here. Let RS_d be the set of all words obtained as Rhodes-Straubing d -expansions (see Definition 1) of words over A , i.e. let $RS_d = (A^*)^p_d$. Our use of it is reminiscent of the rôle of Dyck languages in CFLs.

Lemma 5. *If a language L is defined by an $FO^2[<,S]$ sentence with at most r quantifier alternations and upto d successor formulas, then its d -expansion L^p_d is the intersection of RS_d with a language definable by a sentence of $FO^2[<]$ with at most r quantifier alternations.*

The letters occurring in a word x (more generally, in a set of words) are called its content. We will use $\|x\|$ to denote the size of the content of x . If the letter a is in $\|x\|$,

the left a -chop of x is vaw where $x = v_1av_2$ and a is not in the content of v_1 (not in the content of v_2 , respectively, for a right a -chop).

Definition 4 (Thérien and Wilke). Let $n \geq \|x, y\|$. Any two words x and y are said to be $n, 0$ -equivalent. Two words x and y are $n, k + 1$ -equivalent if they have the same content and for every letter a in the content, if their left a -chops are x_1ax_2, y_1ay_2 respectively, then x_1 and y_1 are $n - 1, k + 1$ -equivalent and x_2 and y_2 are n, k -equivalent, as well as a symmetric condition for right chops. The n, k -choppable languages are those which are a union of n, k -equivalence classes. The **unambiguously choppable** languages are those which are n, k -choppable for some $n, k > 0$.

The next result combines the earlier proposition with the result of Thérien and Wilke [TW98] that an $FO^2[<]$ -definable language is unambiguously choppable.

Corollary 2. If a language L is defined by an $FO^2[<, S]$ sentence with upto d successor formulas, then its d -expansion L_d^p is the intersection of RS_d with an unambiguously choppable language.

We now traverse the path back to our logic LITL.

Theorem 5. The languages defined by sentences of $FO^2[<, S]$ can be defined in LITL.

Proof. From Corollary 2, we know that for an $FO^2[<, S]$ -definable language L (using d successors) over the alphabet A , its Rhodes-Straubing d -expansion $L^p \subseteq RS_d$ is unambiguously choppable over the alphabet $(A')^{2d+1}$. We construct LITL formulae for $\{w \mid w^p \in C^p\}$ and for each n, k -equivalence class $C^p \subseteq L^p$, by induction on n and k . Taking the disjunction of the formulae for the finitely many equivalence classes saturating L^p gives an LITL formula for L .

For the base case, an $n, 0$ -equivalence class determines a content B of letters over $(A')^{2d+1}$. The language recognized by words which map to this equivalence class is B^* , defined by the intersection below. Although B^* is a language over $(A')^{2d+1}$, the LITL formula is over the alphabet A since existence of a letter uav in w^p is equivalent to validating $w \models trueF_{uav}true$.

- For lookarounds $uav \in (A')^{2d+1} \setminus B$ without padding, the conjunct is $\neg(trueF_{uav}true)$.
- For $\triangleright^i uav \in (A')^{2d+1} \setminus B$ where $i > 0$ and $|u| < d$, the conjunct is $\neg(ptF_{uav}true)$.
- For $uav \triangleleft^i \in (A')^{2d+1} \setminus B$ where $i > 0$ and $|v| < d$, the conjunct is $\neg(trueF_{uav}pt)$.

For the induction step, an $n, k + 1$ -equivalence class determines a content B as well as a set of left and right α -chops for $\alpha \in B$. The required formula for an $n, k + 1$ -equivalence class is given by the intersection below.

- formulae $D_1F_\alpha D_2$ ($D'_1L_\alpha D'_2$, respectively) and all allowed left (right, resp.) α -chops, where the lookarounds α range over the content, as well as
- negations of such formulae for the α -chops in $(A')^{2d+1}$ which are not allowed.

The formulae D_1, D_2, D'_1, D'_2 for n, k -classes over content B and for $n - 1, k + 1$ -classes over content $B \setminus \{\alpha\}$ are obtained from the induction hypothesis. Consider for instance that $x^p = v^p\alpha w^p$ is a left α -chop over a Rhodes-Straubing expansion. The induction hypothesis gives us $v \models D_1$ and $w \models D_2$ and so we have $x \models D_1F_\alpha D_2$ using α as a lookaround rather than a letter. \square

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