

Daniel Leivant
Ruy de Queiroz (Eds.)

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Daniel Leivant
Indiana University
Computer Science Department
Bloomington, IN 47405, USA
E-mail: leivant@cs.indiana.edu

Ruy de Queiroz
Universidade Federal de Pernambuco
Centro de Informatica
Av Prof. Luis Freire, s/n Cidade Universitaria, 50740-540 Recife, PE, Brasil
E-mail: ruy@cin.ufpe.br

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Preface

Welcome to the proceedings of the 14th WoLLIC meeting, which was held in Rio de Janeiro, Brazil, July 2 - 5, 2007. The Workshop on Logic, Language, Information and Computation (WoLLIC) is an annual international forum on inter-disciplinary research involving formal logic, computing and programming theory, and natural language and reasoning. The WoLLIC meetings alternate between Brazil (and Latin America) and other countries, with the aim of fostering interest in applied logic among Latin American scientists and students, and facilitating their interaction with the international applied logic community.

WoLLIC 2007 focused on foundations of computing and programming, novel computation models and paradigms, broad notions of proof and belief, formal methods in software and hardware development; logical approaches to natural language and reasoning; logics of programs, actions and resources; foundational aspects of information organization, search, flow, sharing, and protection. The Program Committee for this meeting, consisting of the 28 colleagues listed here, was designed to promote these inter-disciplinary and cross-disciplinary topics.

Like its predecessors, WoLLIC 2007 included invited talks and tutorials as well as contributed papers. The Program Committee received 52 complete submissions (aside from 15 preliminary abstracts which did not materialize). A thorough review process by the Program Committee, assisted by over 70 external reviewers, led to the acceptance of 21 papers for presentation at the meeting and inclusion in these proceedings. The conference program also included 16 talks and tutorials by 10 prominent invited speakers, who graciously accepted the Program Committee's invitation.

We are sincerely grateful to the many people who enabled the meeting and made it a success: the Program Committee members, for their dedication and hard work over extended periods; the invited speakers, for their time and efforts; the contributors, for submitting excellent work and laboriously refining their papers for the proceedings; the external reviewers, who graciously agreed to selflessly comment on submitted papers, often providing detailed and highly valuable feedback; and the Organizing Committee, whose work over many months made the meeting possible in the first place.

On behalf of the entire WoLLIC community, we would also like to express our gratitude to our institutional sponsors and supporters. WoLLIC 2007 was sponsored by the Association for Symbolic Logic (ASL), the Interest Group in Pure and Applied Logic (IGPL), the European Association for Logic, Language and Information (FoLLI), the European Association for Theoretical Computer Science (EATCS), the Sociedade Brasileira de Computacao (SBC), and the Sociedade Brasileira de Logica (SBL). Generous financial support was provided by the Brazilian government (through CAPES, grant PAEP-0755/06-0), Univ. Fed. Fluminense (UFF), and SBC.

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A Grammatical Representation of Visibly Pushdown Languages

Joachim Baran and Howard Barringer

The University of Manchester, School of Computer Science, Manchester, UK
joachim.baran@cs.manchester.ac.uk, howard.barringer@cs.manchester.ac.uk

Abstract. Model-checking regular properties is well established and a powerful verification technique for regular as well as context-free program behaviours. Recently, through the use of ω -visibly pushdown languages (ω VPLs), defined by ω -visibly pushdown automata, model-checking of properties beyond regular expressiveness was made possible and shown to be still decidable even when the program's model of behaviour is an ω VPL. In this paper, we give a grammatical representation of ω VPLs and the corresponding finite word languages – VPL. From a specification viewpoint, the grammatical representation provides a more natural representation than the automata approach.

1 Introduction

In [AM04], ω -visibly pushdown languages over infinite words (ω VPLs) were introduced as a specialisation of ω -context-free languages (ω CFLs), i.e. they are strictly included in the ω CFLs but more expressive than ω -regular languages (ω RLs). The paper showed that the language inclusion problem is decidable for ω VPLs, and thus, the related model-checking problem is decidable as well. This work was presented in the context of (ω) VPLs¹ being represented as automata and a monadic second-order logic with matching relation.

In this paper, we define a grammatical representation of (ω) VPLs. We also propose that grammars allow us to write more natural specifications than (ω) -visibly pushdown automata ((ω) VPA). Section 2 introduces the formalisms used in this paper. In Section 3 our grammatical representation is presented. Finally, Section 4 concludes our work.

2 Preliminaries

For an arbitrary set X , we write 2^X to denote its power-set. Let Σ denote a finite alphabet over letters a, b, c, \dots , the set of finite (infinite) words over Σ is denoted by Σ^* (Σ^ω). We use ε to denote the empty word. For an arbitrary word $w \in \Sigma^*$ we will write $|w|$ to denote its length. For the empty word ε , we set

¹ Our bracketing of ω abbreviates restating the sentence without the bracketed contents.

$|\varepsilon| = 0$. The concatenation of two words w and w' is denoted by $w \cdot w'$. The length of an infinite word equals the first infinite ordinal ω . Positions in a word w are addressed by natural numbers, where the first index starts at 1. The i -th letter of a word is referred to as $w(i)$. We use a sans-serif font for meta-variables and a (meta)-variable's context is only explicitly stated once.

2.1 Visibly Pushdown Languages

(ω) VPLs are defined over a terminal alphabet of three pairwise disjoint sets Σ_c , Σ_i and Σ_r , which we will use as properties in specifications to denote calls, internal actions and returns respectively. Any call may be matched with a subsequent return, while internal actions must not be matched at all. A formalisation of (ω) VPLs has been given in terms of automata as well as in terms of logic.

Visibly Pushdown Automata. For (ω) VPA, the current input letter determines the actions the automaton can perform.

Definition 1. A visibly pushdown automaton over finite words (VPA) (visibly pushdown automaton over infinite words (ω VPA)) is a sextuple $A = (Q, \Sigma_c \cup \Sigma_i \cup \Sigma_r, \Gamma, \delta, Q', F)$, where Q is a finite set of states $\{p, q, q_0, q_1, \dots\}$, $\Sigma_c, \Sigma_i, \Sigma_r$ are finite sets of terminals representing calls c, c_0, c_1, \dots, c_k , internal actions i, i_0, i_1, \dots, i_l , and returns r, r_0, r_1, \dots, r_m respectively, Γ is a finite set of stack symbols A, B, C, \dots , including the stack bottom marker \perp , δ is a finite set of transition rules between states $p, q \in Q$ for inputs $c \in \Sigma_c$, $i \in \Sigma_i$, or $r \in \Sigma_r$ and stack contents $A, B \in (\Gamma \setminus \{\perp\})$ of the form $p \xrightarrow{c, \kappa/B\kappa} q$ for all $\kappa \in \Gamma$, $p \xrightarrow{i, \kappa/\kappa} q$ for all $\kappa \in \Gamma$, $p \xrightarrow{r, \perp/\perp} q$, or $p \xrightarrow{r, A/\varepsilon} q$, $Q' \subseteq Q$ denotes a non-empty set of designated initial states, $F \subseteq Q$ is the set of final states.

When reading a word w , instantaneous descriptions (q, w, α) are used to describe the current state, the current stack contents and a postfix of w that still has to be processed. The binary move relation \vdash_A determines possible moves an (ω) VPA A can make. Whenever A in \vdash_A is understood from the context, we write \vdash . In the following we use \vdash^* (\vdash^ω) in order to denote a finitely (infinitely) repeated application of \vdash (up to the first infinite ordinal). In conjunction with \vdash^ω , we use Q_{inf} to denote the set of states that appear infinitely often in the resulting sequence.

Definition 2. The language $L(A)$ of a (ω) VPA $A = (Q, \Sigma_c \cup \Sigma_i \cup \Sigma_r, \Gamma, \delta, Q', F)$ is the set of finite (infinite) words that are derivable from any initial state in Q' , i.e. $L(A) = \{w \mid (p, w, \perp) \vdash^* (q, \varepsilon, \gamma) \text{ and } p \in Q' \text{ and } q \in F\}$ ($L(A) = \{w \mid (p, w, \perp) \vdash^\omega (q, \varepsilon, \gamma) \text{ and } p \in Q' \text{ and } Q_{inf} \cap F \neq \emptyset\}$).

In an arbitrary word of the ω VPLs, calls and returns can appear either matched or unmatched. A call automatically matches the next following return, which is not matched by a succeeding call. A call is said to be unmatched, when there are less or equally many returns than calls following it. Unmatched calls cannot

be followed by unmatched returns, but unmatched returns may be followed by unmatched calls.

A word w of the form $c\alpha r$ is called *minimally well-matched*, iff c and r are a matching and α contains no unmatched calls or returns. The set of all minimally well-matched words is denoted by L_{mwm} ([LMS04], p. 412, par. 8). In conjunction with a given ω VPA A , a *summary-edge* is a triple (p, q, f) , $f \in \{0, 1\}$, which abstracts minimally well-matched words that are recognised by A when going from p to q , where on the corresponding run a final state has to be visited ($f = 1$) or not ($f = 0$). The set of words represented by a summary edge is denoted by $L((p, q, f))$.

Definition 3. A pseudo-run of an ω VPA $A = (Q, \Sigma_c \cup \Sigma_i \cup \Sigma_r, \Gamma, \delta, Q', F)$ is an infinite word $w = \alpha_1\alpha_2\alpha_3\ldots$ with $\alpha_i \in (\Sigma_c \cup \Sigma_i \cup \Sigma_r \cup \bigcup_{n=1}^m \{\Omega_n\})$, each Ω_n denotes a non-empty set of summary-edges of the form (p, q, f) with $f \in \{0, 1\}$, in case $\alpha_i = c$, then there is no $\alpha_j = r$ for $i < j$, and there is a word $w' = \beta_1\beta_2\beta_3\ldots$, $w' \in L(A)$, so that either $\alpha_i = \beta_i$, or $\alpha_i = \Omega_k$ and β_i is a minimally well-matched word that is generated due to A moving from state p to q and $(p, q, f) \in \Omega_k$. In case $f = 1$ ($f = 0$), then a final state is (not) on the path from p to q .

According to [AM04], p. 210, par. 6, a non-deterministic Büchi-automaton can be constructed that accepts all pseudo-runs of an arbitrary given ω VPA. For every pseudo-run that is represented by the Büchi-automaton, there exists a corresponding accepting run of the original ω VPA.

Monadic Second-Order Logic with Matched Calls/Returns. A logical representation, $(\omega)\text{MSO}_\mu$, of $(\omega)\text{VPLs}$ was given as an extension of monadic second-order logic (MSO) with a matching relation μ , which matches calls and returns, where the call always has to appear first.

Definition 4. A formula φ is a formula of monadic second-order logic of one successor with call/return matching relation $((\omega)\text{MSO}_\mu)$ over an alphabet $\Sigma_c \cup \Sigma_i \cup \Sigma_r$, iff it is of the form $\varphi \equiv \top$, $\varphi \equiv T_a(i)$, $a \in \Sigma$, $\varphi \equiv i \in X$, $\varphi \equiv i \leq j$, $\varphi \equiv \mu(i, j)$, $\varphi \equiv S(i, j)$, $\varphi \equiv \neg\psi$, $\varphi \equiv \psi_1 \vee \psi_2$, $\varphi \equiv \exists i \psi(i)$, or $\varphi \equiv \exists X \psi(X)$, where ψ , ψ_1 , and ψ_2 are $(\omega)\text{MSO}_\mu$ formula as well, V and W are sets of first-order and second-order variables respectively, and $i, j \in V$, $X \in W$.

We use the standard abbreviations for the truth constant, conjunction and universal quantification. Also, $\forall x(y \leq x \leq z \Rightarrow \varphi)$ is shortened to $\forall x \in [y, z] \varphi$. In order to simplify arithmetic in conjunction with the successor function, we will omit the successor function completely in the following and write $i + 1$ instead of j for which $S(i, j)$ holds. Second-order quantifications $\exists X_1 \exists X_2 \ldots \exists X_k$ are abbreviated in vector notation as $\exists \mathbf{X}$.

We assume the usual semantics for $(\omega)\text{MSO}_\mu$ formulae, where $\mu(i, j)$ is true when $w(i) = c$ and $w(j) = r$ are a matching call/return pair.

Definition 5. The language $\mathcal{L}(\varphi)$ of an $(\omega)\text{MSO}_\mu$ formula φ is the set of finite (infinite) words w for which there is a corresponding model of φ .

2.2 Context-Free Grammars

Definition 6. An (ω) -context-free grammar $((\omega)\text{CFG})$ G over finite words (infinite words) is a quadruple (V, Σ, P, S) (quintuple (V, Σ, P, S, F)), where V is a finite set of non-terminals A, B, \dots , Σ is a finite set of terminals a, b, \dots , V and Σ are disjoint, P is a finite set of productions of the form $V \times (V \cup \Sigma)^*$, and S denotes a designated starting non-terminal $S \in V$ (and $F \subseteq V$ denotes the set of accepting non-terminals).

We will use the notation $A \rightarrow_G \alpha$ for a production (A, α) in G . If G is understood from the context, we write $A \rightarrow \alpha$. We also use \rightarrow_G to denote the derivation relation of G , that determines derivations of sentential forms of G . Again, we drop the sub-script when G is understood from the context. In the following we write $\xrightarrow{*}$ in order to denote a finitely repeated application of \rightarrow while $\xrightarrow{\omega}$ denotes an infinite application of \rightarrow . Similarly to the previously used set Q_{inf} , we use V_{inf} in connection with $\xrightarrow{\omega}$ in order to denote the set of non-terminals that are infinitely often replaced among the sentential forms.

Definition 7. The language $\mathcal{L}(G)$ of an $(\omega)\text{CFG}$ $G = (V, \Sigma, P, S)$ ($G = (V, \Sigma, P, S, F)$) is the set of finite (infinite) words over Σ that are derivable from the initial symbol, i.e. $\mathcal{L}(G) = \{w \mid S \xrightarrow{*} w \text{ and } w \in \Sigma^*\}$ ($\mathcal{L}(G) = \{w \mid S \xrightarrow{\omega} w, w \in \Sigma^\omega \text{ and } V_{inf} \cap F \neq \emptyset\}$).

2.3 Balanced Grammars

Balanced grammars are a specialisation of context-free grammars over finite words [BB02]. Unlike the previous definition of CFGs, balanced grammars are permitted to have an infinite set of productions. This is due to regular expressions over terminals and/or non-terminals in right-hand sides of productions.

Definition 8. A balanced grammar (BG) G over finite words is a quadruple $(V, \underline{\Sigma} \cup \Sigma \cup \overline{\Sigma}, \mathcal{P}, S)$ is a specialisation of a context-free grammar, where $\underline{\Sigma}$ and $\overline{\Sigma}$ are finite sets of terminals $\underline{a}_1, \underline{a}_2, \dots, \underline{a}_k$ and co-terminals $\overline{a}_1, \overline{a}_2, \dots, \overline{a}_k$ respectively, where each terminal \underline{a}_i is associated with its unique counterpart, \overline{a}_i , its co-terminal, and vice versa, Σ is a finite set of intermediate terminals a, b, \dots , the sets $\underline{\Sigma}$, $\overline{\Sigma}$, and Σ are mutually disjoint, \mathcal{P} is a finite or infinite set of productions of the form $V \times \underline{\Sigma}(V \cup \Sigma)^*\overline{\Sigma}$, and S denotes a designated starting non-terminal $S \in V$.

As already pointed out in [BB02], an infinite set of productions does not raise the grammars' expressiveness, but provides a succinct notation. The derivation relation of context-free grammars is still applicable to balanced grammars.

Definition 9. The language $\mathcal{L}(G)$ of a BG $G = (V, \underline{\Sigma} \cup \Sigma \cup \overline{\Sigma}, \mathcal{P}, S)$ is the set of words that are derivable from the initial symbol, i.e. $\mathcal{L}(G) = \{w \mid S \xrightarrow{*} w \text{ and } w \in (\underline{\Sigma} \cup \Sigma \cup \overline{\Sigma})^*\}$.

In the following, we are writing \mathcal{R} to denote an arbitrary regular expression over $V \cup \Sigma$.

3 Grammars for Visibly Pushdown Languages

A grammatical representation of (ω) VPLs is presented, where we take a compositional approach that builds on pseudo-runs and minimally well-matched words. We first state our grammatical representation and then decompose it into two types of grammars. We show their resemblance of pseudo-runs and minimally well-matched words, similar to the approach for (ω) VPAs.

3.1 Quasi Balanced Grammars

In order to simplify our proofs, we give an alternative – but expressively equivalent – definition of BGs, where only a finite number of productions is admitted. We reformulate occurrences of regular expressions \mathcal{R} in terms of production rules $P_{\mathcal{R}}$ and substitute each \mathcal{R} by an initial non-terminal $S_{\mathcal{R}}$ that appears on a left-hand side in $P_{\mathcal{R}}$. Therefore, matchings $\underline{a}\mathcal{R}\bar{a}$ become $\underline{a}S_{\mathcal{R}}\bar{a}$, where the derivation of $S_{\mathcal{R}}$ resembles $L(\mathcal{R})$.

Definition 10. Let $G = (V, \underline{\Sigma} \cup \Sigma \cup \overline{\Sigma}, \mathcal{P}, S)$ denote an arbitrary BG, a quasi balanced grammar (qBG) $G' = (V', \underline{\Sigma}' \cup \Sigma' \cup \overline{\Sigma}', P, S)$ generalises G by having a finite set of productions, where productions are either

- a) in double Greibach normal form $A \rightarrow \underline{a}S_{\mathcal{R}}\bar{a}$, or
- b) of form $A \rightarrow BC$, $A \rightarrow \underline{a}C$, or $A \rightarrow \varepsilon$, where B 's productions are of the form according to a) and C 's productions are of the form according to b).

Lemma 1. For every BG $G = (V, \underline{\Sigma} \cup \Sigma \cup \overline{\Sigma}, \mathcal{P}, S)$ there is a qBG $G' = (V', \underline{\Sigma}' \cup \Sigma' \cup \overline{\Sigma}', P, S)$, such that $L(G) = L(G')$.

3.2 A Grammatical Representation of ω VPLs

Matchings in an ω VPL appear only as finite sub-words in the language, which was utilised in the characterisation of pseudo-runs. Summary-edges reflect sub-words of exactly this form, which are in L_{mwm} . Given an infinite word w , it can be split into sub-words that are either in L_{mwm} or in $\Sigma_c \cup \Sigma_i \cup \Sigma_r$, where no sub-word in Σ_r follows a sub-word in Σ_c . We abbreviate the latter constraint as Σ_c/Σ_r -matching avoiding. Our grammatical representation of ω VPLs utilises Σ_c/Σ_r -matching avoiding ω RGs to describe languages of pseudo-runs. Languages of summary-edges, i.e. languages with words in L_{mwm} , are separately described by qBGs under a special homomorphism. The homomorphism is required to cover matchings of calls c that can match more than one return r , which cannot be reflected as a simple terminal/co-terminal matching \underline{a}/\bar{a} . For example, the matchings c/r_1 and c/r_2 are representable as terminal/co-terminal pairs \underline{a}/\bar{a} and \underline{b}/\bar{b} under the mappings $h(\underline{a}) = h(\underline{b}) = c$, $h(\bar{a}) = r_1$ and $h(\bar{b}) = r_2$. Finally, the amalgamation of Σ_c/Σ_r -matching avoiding ω RGs and qBGs under the aforementioned homomorphism give us a grammatical representation of ω VPLs:

Definition 11. A superficial² ω -regular grammar with injected balanced grammars ($\omega\text{RG}(\text{qBG})+h$) $G = (V, \Sigma_c \cup \Sigma_i \cup \Sigma_r \cup \bigcup_{n=1}^m \{g_n\}, P, S, F, \bigcup_{n=1}^m \{G_n\}, h)$, where

- $\Sigma_c, \Sigma_i, \Sigma_r$ and $\bigcup_{n=1}^m \{g_n\}$ are mutually disjoint,
- G is Σ_c/Σ_r -matching avoiding,
- $G_n = (V_n, \Sigma_n, P_n, S_n)$ is a qBG for $n = 1, 2, \dots, m$,³

is an ωCFG $G' = (V \cup \bigcup_{n=1}^m \{V_n\}, \Sigma \cup \bigcup_{n=1}^m \{\Sigma_n\}, P', S, F)$ with

- disjoint sets V and $\{V_1, V_2, \dots, V_m\}$ as well as Σ and $\{\Sigma_1, \Sigma_2, \dots, \Sigma_m\}$, and
- P' is the smallest set satisfying
 - $A \rightarrow_{G'} aB$ if $A \rightarrow_G aB$, where $a \in (\Sigma_c \cup \Sigma_i \cup \Sigma_r)$, or
 - $A \rightarrow_{G'} S_n B$ if $A \rightarrow_G g_n B$, or
 - $A \rightarrow_{G'} \alpha$ if $A \rightarrow_{G_n} \alpha$,

and h is constrained so that it preserves terminals of the injector grammar, $h(a) = a$ for any $a \in (\Sigma_c \cup \Sigma_i \cup \Sigma_r)$, and for terminals/co-terminals of injected grammars it maps terminals $\underline{a} \in \underline{\Sigma}_n$ to calls $c \in \Sigma_c$, maps co-terminals $\bar{a} \in \bar{\Sigma}_n$ to returns $r \in \Sigma_r$, maps terminals $a \in \Sigma_n$ to internal actions $i \in \Sigma_i$.

In the following, we refer to the homomorphism h under the constraints which are given above as *superficial mapping* h .

Definition 12. The language $\mathcal{L}(G)$ of an $\omega\text{RG}(\text{qBG})+h$ $G = (V, \Sigma_c \cup \Sigma_i \cup \Sigma_r \cup \bigcup_{n=1}^m \{g_n\}, P, S, F, \bigcup_{n=1}^m \{G_n\}, h)$ denotes the set $\{h(w) \mid S \xrightarrow{\omega}_{G'} w \text{ and } w \in (\Sigma \cup \Sigma_1 \cup \Sigma_2 \cup \dots \cup \Sigma_m)^\omega\}$, where G' is the ω -context-free grammar corresponding to G .

Consider an arbitrary $\omega\text{RG}(\text{qBG})+h$ $G = (V, \Sigma_c \cup \Sigma_i \cup \Sigma_r \cup \bigcup_{n=1}^m \{g_n\}, P, S, F, \bigcup_{n=1}^m \{G_n\}, h)$. We call the ωRG $G_\uparrow = (V, \Sigma_c \cup \Sigma_i \cup \Sigma_r \cup \bigcup_{n=1}^m \{g_n\}, P, S, F)$ the *injector grammar* of G , while the qBGs G_1, G_2, \dots, G_m are called *injected grammars* of G .⁴ When G is clear from the context, we just talk about the injector grammar G_\uparrow and the injected grammars G_1, \dots, G_m respectively. The languages associated with these grammars are referred to as injector and injected languages respectively. In fact, injector languages resemble pseudo-runs with pseudo edges g_n , $n = 1 \dots m$, while injected language resemble matchings covered by summary-edges.

3.3 ωVPL and $\omega\text{RL}(\text{qBL})+h$ Coincide

For the equivalence proof of ωVPL s and $\omega\text{RL}(\text{qBL})+h$ s, we first show that minimally well-matched words, as described by summary-edges, can be expressed by

² Superficial – as understood as being on the surface of something.

³ Each Σ_n is a shorthand for $\underline{\Sigma}_n \cup \Sigma_n \cup \bar{\Sigma}_n$.

⁴ This should not be confused with nested words, [AM06], which describe the structure induced by matchings in finite words.