Persistence of Termination for Term Rewriting Systems with Ordered Sorts

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Abstract—A property $P$ is persistent if for any many-sorted term rewriting system $\mathcal{R}$, $\mathcal{R}$ has the property $P$ if and only if term rewriting system $\Theta(\mathcal{R})$, which results from $\mathcal{R}$ by omitting its sort information, has the property $P$. Zantema showed that termination is persistent for term rewriting systems without collapsing or duplicating rules. In this paper, we show that the Zantema’s result can be extended to term rewriting systems on ordered sorts, i.e., termination is persistent for term rewriting systems on ordered sorts without collapsing, decreasing or duplicating rules. Furthermore we give the example as application of this result. Also we obtain that completeness is persistent for this class of term rewriting systems.

Keywords: Theory of computing, Model-based reasoning, term rewriting system, termination

I. INTRODUCTION

Term rewriting systems (TRSs) can offer both flexible computing and effective reasoning with equations and have been widely used as a model of functional and logic programming languages and as a basis of theorem provers, symbolic computation, algebraic specification and verification [4].

A rewrite system is called terminating (strongly normalizing) if there is no infinite rewrite sequence. The notion of termination for rewrite systems corresponds to the existence of answers of computations. So termination is the fundamental notion of term rewriting systems as computation models [7]. It is well-known that termination is undecidable for term rewriting systems in general. However, several sufficient approaches for proving this property have been successfully developed in particular cases.

Zantema [23] introduced the notion of persistence as follows. A property $P$ is persistent if for any many-sorted TRS $\mathcal{R}$, $\mathcal{R}$ has the property $P$ if and only if TRS $\Theta(\mathcal{R})$, which results from $\mathcal{R}$ by omitting its sort information, has the property $P$. Usual many-sorted TRS was extended with ordered sorts by Aoto and Toyama [2]. And it was shown that the persistency of confluence [1] is preserved for this extension in [2]. Zantema [23] showed that termination is persistent for TRSs without collapsing or duplicating rules. Ohsaki and Middeldorp [20] studied the persistence of termination, acyclicity and non-loopingness on equation many-sorted TRSs. Aoto proved that the persistence of termination for TRSs in which all variables are of the same sort [3]. We showed that the persistence of termination for non-overlapping TRSs [11]. Also, we showed that the persistence of termination for locally confluent overlay TRSs [12]. And we showed that the persistence of termination for right-linear overlay TRSSs [13]. Furthermore we showed that the persistence of semi-completeness for TRSs [14].

In this paper, we show that the above Zantema’s result is preserved for Aoto and Toyama’s extension in the subclass of order sorted term rewriting systems.

This research was first appeared in [9] and studied in [10]. Furthermore, Ohsaki [21] studied the case of equational order-sorted TRSs. Their equational order-sorted TRSs [21] were based on order-sorted algebras in [8], [22]. However, our TRSs on ordered sorts are based on Aoto and Toyama [2]. For example, we consider the sorts $\text{Zero}$ and $\text{Nat}$. If $\text{Zero} < \text{Nat}$ then $A_{\text{Zero}} \subset A_{\text{Nat}}$ where $A_{\text{Zero}}$ and $A_{\text{Nat}}$ are order-sorted algebras in equational order-sorted TRSs [21]. However, in our TRSs on ordered sorts we do not consider order-sorted algebras. In our research, if $\text{Zero} < \text{Nat}$ then $T(\text{Zero}) \cap T(\text{Nat}) = \emptyset$ holds where $T(\text{Zero})$ and $T(\text{Nat})$ are sets of terms with sort $\text{Zero}$ and $\text{Nat}$, respectively. So our research does not depend on order-sorted algebras.

In section 2, many-sorted TRS is formulated on ordered sorts. Then, the persistence of termination on ordered sorts is shown in section 3 and 4. The proof is a generalization of a simplified proof of modularity of termination [18]. Furthermore we give the example as application of this result. Also we obtain that completeness is persistent for term rewriting systems on ordered sorts.

II. PRELIMINARIES

We mainly follow basic definitions and basic lemmas in the literature [2].

A. Sorted Term Rewriting Systems

In this subsection, we introduce the basic notions of sorted term rewriting systems. Usual term rewriting systems [4] are considered as special cases of sorted term rewriting systems.

Let $\mathcal{S}$ be a set of sorts and $\mathcal{V}$ be a set of countably infinite sorted variables. We assume that $\mathcal{S}$ is equipped with a well-founded partial ordering $\succ$. We write $b \succeq b'$ if and only if $b \succ b'$ or $b = b'$.

We assume there is a set $\mathcal{F}$ of countably infinite variables of sort $\mathcal{S}$. Let $\mathcal{F}$ be a set of sorted function symbols. We assume that each sorted function symbol $f \in \mathcal{F}$ is given with the sorts of its arguments and the sort of its value, all of which are included in $\mathcal{S}$. We write $f_1 \times \ldots \times b_n \rightarrow b'$ if and only if $f$ takes $n$ arguments of sorts.
A term $x$ that has more occurrences in some variable has more occurrences in $\forall x \in V$ (such that $x$ has an occurrence in $t$).

The set $\mathcal{T}(\forall x \in V)$ is defined as follows: (1) $\forall x \in V \subseteq \mathcal{T}(\forall x \in V)$, (2) $\forall x \in V \subseteq \mathcal{T}(\forall x \in V)$, $b_1 \leq b_2$ (i = 1, ...n) then $f(t_1, ..., t_n) \in \mathcal{T}(\forall x \in V)$. Here $\mathcal{T}(\forall x \in V)$ denotes the set of all terms of sort $b$.

We define the set of all strict sorted terms if (2) is replaced by (2') if $f(b_1 \times ... \times b_n) \rightarrow b'$, $t_1 \in \mathcal{T}(\forall x \in V)$ and $b_1 \leq b_2$ (i = 1, ...n) then $f(t_1, ..., t_n) \in \mathcal{T}(\forall x \in V)$. We write $t \rightarrow b$ if $t$ is of sort $b$. The set of all variables that appear in $t$. $\mathcal{T}(\forall x \in V)$ is an abbreviation as $\mathcal{T}$ and $\forall x \in V$, respectively.

A term rewriting system (TRS, for short) is a pair $\mathcal{S} = (F, V)$ where $F = \{ f \mid f \in \mathcal{T}(\forall x \in V) \}$ is a set of function symbols and variables, respectively, on a trivial set $\{x\}$ of sorts with empty relation on it. Terms built from this language are called unsorted terms.

If some variable has more occurrences in $t$ than it has in $r$ then the rewrite rule $l \rightarrow r$ is said to be duplicating. If $l : b, r : b'$ and $b \rightarrow b'$ then the rewrite rule $l \rightarrow r$ is said to be decreasing.

When $\mathcal{S} = \{x\}$ with an empty relation, $\mathcal{S}$ is called a term rewriting system (TRS, for short). Given an arbitrary STRS $\mathcal{S}$, by identifying each sort with $\ast$, we obviously obtain a TRS $\Theta(\mathcal{S})$ - called the underlying TRS of $\mathcal{S}$.

B. Sorting of Term Rewriting Systems

Aoto and Toyama [1], [2] defined the notion of sort attachment and formulated the notion of persistence using sort attachment. We mainly follow basic definitions in [2] in this subsection.

Let $\mathcal{F}$ and $\mathcal{V}$ be sets of function symbols and variables, respectively, on a trivial set $\{x\}$ of sorts with empty relation on it. Terms built form this language are called unsorted terms. Let $\mathcal{S}$ be another set of sorts with well-founded partial ordering $\succ$ on $\mathcal{F}$ and $\mathcal{V}$ respectively. A term $t$ is said to be well-sorted under $\mathcal{S}$ with sort $b$ (written as $t(b) = b$) if and only if $t \in \mathcal{T}(\mathcal{F}, \mathcal{V})$.

The set of well-sorted terms under $\mathcal{S}$ is denoted by $\mathcal{T}(\mathcal{F}, \mathcal{V})$. The set of well-sorted terms under $\mathcal{S}$ is denoted by $\mathcal{T}(\mathcal{F}, \mathcal{V})$. A STRS $\mathcal{S}$ is defined as follows: It is clear that definition of Zantema [23] and the following definition are equivalent when set of sorts with empty relation on it. Using the sort attachment, persistence can be alternatively formulated as follows. It is clear that definition of Zantema [23] and the following definition are equivalent when set of sorts with empty relation on it.

Definition 2.1: A property $P$ is persistent if and only if for any rewrite rule $l \rightarrow r \in \mathcal{R}$, $l$ and $r$ are strictly well-sorted under $\mathcal{S}$ and $l \rightarrow r$. The set of $\tau$-sorted rewrite rules of $\mathcal{R}$ is denoted by $\mathcal{R}^\tau$. Note that $\mathcal{R}^\tau$ acts on $\mathcal{T}(\mathcal{F}, \mathcal{V})$ whenever $s \rightarrow \mathcal{T}(\mathcal{F}, \mathcal{V})$ is strict. Well-sorted contexts are defined by special constants $\varnothing$,..., Well-sorted terms and contexts are often treated as sorted terms and contexts, respectively.

Let $(\mathcal{F}, \mathcal{R})$ be a TRS. A sort attachment $\tau$ on $\mathcal{S}$ is said to be consistent with $\mathcal{R}$ if and only if for any rewrite rule $l \rightarrow r \in \mathcal{R}$, $l$ and $r$ are strictly well-sorted under $\mathcal{S}$ and $l \rightarrow r$. The set of $\tau$-sorted rewrite rules of $\mathcal{R}$ is denoted by $\mathcal{R}^\tau$. Note that $\mathcal{R}^\tau$ acts on $\mathcal{T}(\mathcal{F}, \mathcal{V})$ whenever $s \rightarrow \mathcal{T}(\mathcal{F}, \mathcal{V})$ is strict. Well-sorted contexts are defined by special constants $\varnothing$,..., Well-sorted terms and contexts are often treated as sorted terms and contexts, respectively.

III. Characterization of Unsorted Terms

In this section we give a characterization of unsorted terms by ordered sorts. The proofs of the following basic lemmas were given by Aoto and Toyama [2].

Definition 3.1: The top sort (under $\tau$) of an unsorted term $t$ is defined as follows:

- $\text{top}(t) = \tau(t)$ if $t \in \mathcal{V}$.
- $\text{top}(t) = b'$ if $t = f(t_1, \ldots, t_n)$ with $f : b_1 \times \ldots \times b_n \rightarrow b'$.
**Definition 3.2:** Let $t = C[t_1, \ldots, t_n]$ ($n \geq 0$) be an unsorted term with $C[1, \ldots] \neq \sqsubseteq$. We write $t = C[t_1, \ldots, t_n]$ if and only if

1. $C:b_1 \times \cdots \times b_n \rightarrow b'$ is a context that is well-ordered under $\tau$.
2. $\text{top}(t_i) \neq b_i$ for all $i = 1, \ldots, n$.

The $t_1, \ldots, t_n$ are to be the principal subterms of $t$. We denote $t = C\langle \langle t_1, \ldots, t_n \rangle \rangle$ if either $t = C[t_1, \ldots, t_n]$ or $C = \sqsubseteq$ and $t_i \in \{t_1, \ldots, t_n\}$. Multi-set $S(t)$ consists of all principal subterms of $t = C[t_1, \ldots, t_n]$.

**Definition 3.3:** Let $t$ be an unsorted term. Rank of $t$ is defined as follows:

- $\text{rank}(t) = 1$ if $t$ is well-sorted term.
- $\text{rank}(t) = 1 + \max\{\text{rank}(t_1), \ldots, \text{rank}(t_n)\}$ if $t = C[t_1, \ldots, t_n]$.

**Definition 3.4:** Let $t$ be an unsorted term. Cap of $t$ is defined as follows:

- $\text{cap}(t) = t$ if $t$ is well-sorted term.
- $\text{cap}(t) = [C[1, \ldots], t]$ if $t = C[t_1, \ldots, t_n]$.

**Definition 3.5:** A rewrite step $s \rightarrow \tau t$ is said to be inner (written as $s \rightarrow^\omega \tau t$) if and only if $s = C[s_1, \ldots, C'[\theta, s_n]] \rightarrow^\omega \tau C'[s_1, \ldots, C'[\theta, \ldots, s_n]] = t$ for some $s_1, \ldots, s_n, l \in r \in \mathcal{R}$, $\theta$ and $C'$, otherwise outer (written as $s \rightarrow \tau t$).

**Definition 3.6:** A rewrite step $s \rightarrow^\omega \tau t$ is said to be vanishing if and only if $s = C[s_1, \ldots, \theta[x]] \rightarrow^\omega \tau \theta(x) = t$ for some $s_1, \ldots, s_n, C$ and $\theta$ such that $C'[\theta] = C[s_1, \ldots, \theta, \ldots, s_n]$.

**Lemma 4.1:** Let $t$ be a strictly well-sorted term. Suppose $t = C[x_1, \ldots, x_n]$ with all variables displayed and $C : b_1 \times \cdots \times b_n \rightarrow b'$. Then for any substitution $\theta$, if $x_i = x_j$ and $\theta(x_i)$ is a principal subterm of $\theta t$ then $\theta(x_j)$ is also a principal subterm of $\theta t$.

**Definition 3.7:** A rewrite rule $l \rightarrow r$ in $\mathcal{R}$ is said to be decreasing if and only if $\text{top}(l) \succ \text{top}(r)$. A rewrite step $s \rightarrow^\omega \tau t$ is said to be decreasing if and only if $\text{top}(s) \succ \text{top}(t)$.

**Definition 3.8:** A rewrite step $s \rightarrow^\omega \tau t$ is said to be destructive at level 1 if and only if $s \rightarrow^\omega \tau t$ is either vanishing or decreasing. The rewrite step $s \rightarrow^\omega \tau t$ is said to be destructive at level $k + 1$ if and only if $s = C[s_1, \ldots, s_j, \ldots, s_n] \rightarrow^* \tau C \langle s_1, \ldots, t_j, \ldots, s_n \rangle = t$ with $s_j \rightarrow^\omega \tau t_j$ destructive at level $k$.

**Lemma 3.9:** If a rewrite step $s \rightarrow^\omega \tau t$ is not vanishing then $\text{top}(s) \succeq \text{top}(t)$. If a rewrite step $s \rightarrow^\omega \tau t$ is not destructive at level 1 then $\text{top}(s) = \text{top}(t)$.

**Definition 3.10:** If $s \rightarrow^\omega \tau t$ then $\text{rank}(s) \geq \text{rank}(t)$. If a rewrite step $s \rightarrow^\omega \tau t$ is vanishing then $\text{rank}(s) > \text{rank}(t)$.

**Definition 3.11:** The grade of $t$ is defined by $\text{grade}(t) = \langle \text{rank}(t), \text{top}(t) \rangle$ where $N$ is the set of all natural numbers. Let $> \succ$ be the lexicographic ordering on $N \times S$ induced from $\succ$ on $N$ and $\succ$ on $S$. The lexicographic ordering $> \succ$ on $N \times S$ is well-founded since orderings $>$ on $N$ and $\succ$ on $S$ are well-founded.

**Lemma 3.12:** If $s \rightarrow^\omega \tau t$ then $\text{grade}(s) \geq \text{grade}(t)$. If a rewrite step $s \rightarrow^\omega \tau t$ is destructive at level 1 then $\text{grade}(s) > \text{grade}(t)$.

**IV. PERSISTENCE OF TERMINATION**

In this section we discuss the persistence of termination for TRSs on ordered sorts and give the example as application of this result. Furthermore we obtain that completeness is persistent for TRS on ordered sorts. We mainly follow the Ohlebusch’s argument in [18].
2. $\text{cap}(s) = \text{cap}(t)$. By lemma 4.4, $S(t) = S(s) \setminus \{s_j\} \cup \{t_j\}$.

- $s_j \rightarrow t_j$ is vanishing. Since $\text{rank}(s_j) > \text{rank}(t_j)$, $\text{grade}(s_j) > \text{grade}(t_j)$ holds.

- $s_j \rightarrow t_j$ is decreasing. Since $\text{rank}(s_j) \geq \text{rank}(t_j)$ and $\text{top}(s_j) > \text{top}(t_j)$, $\text{grade}(s_j) > \text{grade}(t_j)$ holds.

Therefore, $p_s > \text{mut} \ p_t$ holds. □

**Lemma 4.9:** Let $R'$ be a terminating STRS. Let $D = S_0 \rightarrow_{R} s_1 \rightarrow_{R} s_2 \rightarrow_{R} \cdots$ be an infinite rewrite sequence starting from some $t \in S(s_0)$. Since $\text{rank}(t_0) < \text{rank}(s_0)$ this contradicts the minimality of $\text{grade}(D)$.

2. Suppose that there are only finitely many inner rewrite steps in $D$ which are destructive at level 2. Then we can assume that there is no outer rewrite step which is destructive at level 1.

1. Suppose that are only finitely many outer rewrite steps in $D$. Then we can assume that there is no outer rewrite step in $D$ which is destructive at level 2. By lemma 4.5, if $s \rightarrow_{R}^* t$ in $D$ then $\text{cap}(s) \rightarrow_{R} \text{cap}(t)$ and if $s \rightarrow_{R}^* t$ in $D$ then $\text{cap}(s) = \text{cap}(t)$. By the case 1, $R'$ is not terminating. This is contradiction by the assumption.

3. Suppose that there are only finitely many inner rewrite steps in which are applied duplicating rules in $D$. We consider the following cases.

- If $s_j \rightarrow_{R} s_{j+1}$ then $S(s_{j+1}) \subseteq S(s_j)$ since the rewrite step is non-destructive and non-duplicating and lemma 4.3. Then $p_{s_j} > \text{mut} \ p_{s_{j+1}}$ holds.

- If $s_j \rightarrow_{R} s_{j+1}$ is not destructive at level 2 then we have $s_j = C[t_1, \ldots, t_n] \rightarrow_{R} C[t_1, \ldots, t_n] = s_{j+1}$ where $t_k \rightarrow_{R} t_k$. Then $p_{s_j} > \text{mut} \ p_{s_{j+1}}$ holds since $\text{grade}(t_k) > \text{grade}(t_k)$.

- If $s_j \rightarrow_{R} s_{j+1}$ is destructive at level 2 then we have $s_j = C[t_1, \ldots, t_n] \rightarrow_{R} C[t_1, \ldots, t_n] = s_{j+1}$ where $t_k \rightarrow_{R} t_k$. By the well-foundedness of $\text{mut} \ p_{s_{j+1}}$ there are only finitely many inner rewrite steps which are destructive at level 2 in $D$. This contradicts the case 2.

**Lemma 4.10:** Let $R'$ be a terminating STRS. Assume that $R$ is not terminating. Then $R$ has duplicating rules and $R'$ has collapsing or decreasing rules.

**Proof.** By lemma 4.9, it is trivial. □

**Theorem 4.11:** The following statements hold.

1. Termination is a persistent property of TRSs on ordered sorts without collapsing and decreasing rules.

2. Termination is a persistent property of TRSs on ordered sorts without duplicating rules.

**Proof.** By lemma 4.10, it is trivial. □

**Example 4.12:** We show that the following TRS $R$ is terminating using theorem 4.11. To show the termination of the following TRS directly seems difficult form known results (E.g. recursive path ordering [7]). Also, we can not use the modularity results for composable TRSs [17], [19] and hierarchical combinations and hierarchical combinations with common subsystem of TRSs [16], [19]. Furthermore, we can not use the Zantema’s result [23] for proving termination of the following TRS. However, we can show the termination of next TRS using our results in this paper.

$$R = \begin{cases} g(x, B) & (r1) \\ g(x, B) & (r2) \\ g(x, d(z, B)) & (r3) \\ I(A, g(x, d(y, C))) & (r4) \\ I(x, g(x, d(z, z))) & (r5) \\ d(z, A) & (r6) \end{cases}$$

Let $\mathcal{S} = \{0, 1, 2\}$, $\tau = 0 \times 1 \times 2$.

Any well-sorted term in $\mathcal{T}^0$, $\mathcal{T}^1$ and $\mathcal{T}^2$ is terminating, i.e.

- any well-sorted term in $\mathcal{T}^1$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^0$. Then $\mathcal{T}^0$ is the only applicable rule. A TRS $\{r6\}$ is terminating using recursive path ordering. Hence, $t$ is terminating.

- $t \in \mathcal{T}^1$. Then $\mathcal{T}^1$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^2$. Then $\mathcal{T}^2$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^3$. Then $\mathcal{T}^3$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^4$. Then $\mathcal{T}^4$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^5$. Then $\mathcal{T}^5$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^6$. Then $\mathcal{T}^6$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^7$. Then $\mathcal{T}^7$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^8$. Then $\mathcal{T}^8$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^9$. Then $\mathcal{T}^9$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{10}$. Then $\mathcal{T}^{10}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{11}$. Then $\mathcal{T}^{11}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{12}$. Then $\mathcal{T}^{12}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{13}$. Then $\mathcal{T}^{13}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{14}$. Then $\mathcal{T}^{14}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{15}$. Then $\mathcal{T}^{15}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{16}$. Then $\mathcal{T}^{16}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{17}$. Then $\mathcal{T}^{17}$ is terminating. We consider the following cases:

- $t \in \mathcal{T}^{18}$. Then $\mathcal{T}^{18}$ is terminating. We consider the following cases:
V. CONCLUSION AND FUTURE WORK

In this paper, we have shown that the Zantema’s result [23] is preserved for Aoto and Toyama’s extension [2] in the subclass of order sorted term rewriting systems. That is, we have shown that termination is persistent for TRSs on ordered sorts without collapsing, decreasing or duplicating rules. Furthermore, we have given the example as application of our results. Also we obtain the persistence of completeness for TRSs on ordered sorts.

However, the difference between our work and Ohsaki’s work [21] is still unclear. So we consider this point for the future.

REFERENCES