The Confluence Problem for Flat TRSs

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Abstract

We prove that confluence is undecidable for flat TRSs. Here, a TRS is flat if the heights of the left and right-hand sides of each rewrite rule are at most one.

1 Introduction

A term rewriting system (TRS) is a set of directed equations (called rewrite rules). A TRS is confluent (Church-Rosser) if any two convertible terms are joinable. Confluence is an important property since it implies the unicity of normal forms [1], and has received much attention so far.

But, confluence is undecidable in general and so even if we restricts to monadic or semi-constructor TRSs [6]. On the other hand, it is known decidable for terminating TRSs [5] and right-ground or variable) TRSs [2]. In particular, confluence is decidable for right-linear shallow TRSs [3], hence we show here that the right-linearity condition is necessary for decidability.

Recently, Jacquemard [4] has reported that confluence is undecidable for flat TRSs. Here, a TRS is flat if the heights of the left and right-hand sides of each rewrite rule are at most one. However, we found that the proof is incorrect. In this paper, we give a correct proof of the undecidability.

2 Preliminaries

We assume that the reader is familiar with standard definitions of rewrite systems [1] and we just recall here the main notations used in this paper.

Let \( \varepsilon \) be the empty sequence. Let \( X \) be a set of variables. Let \( F \) be a finite set of operation symbols graded by an arity function \( \text{ar} : F \to \mathbb{N} (= \{0, 1, 2, \ldots \}) \). \( F_n = \{ f \in F | \text{ar}(f) = n \} \). Let \( T \) be a set of terms built from \( X \) and \( F \) We use \( x \) as a variable, \( f, h \) as function symbols, \( r, s, t \) as terms, \( \theta \) as a substitution. The \textit{height} of a term is defined as follows: \( \text{height}(a) = 0 \) if \( a \) is a variable or a constant and \( \text{height}(f(t_1, \ldots, t_n)) = 1 + \max \{ \text{height}(t_1), \ldots, \text{height}(t_n) \} \) if \( n > 0 \).

A position in a term is expressed by a sequence of positive integers, and positions are partially ordered by the prefix ordering \( \geq \). Let \( s_{tp} \) be the subterm of \( s \) at position \( p \). Let \( s \geq s_{tp} \) if \( t \) is a subterm of \( s \). For position \( p \) and term \( t \), we use \( s[p]_t \) to denote the term obtained from \( s \) by replacing a subterm \( s_{tp} \) by \( t \).

A rewrite rule \( \alpha \rightarrow \beta \) is a directed equation over terms. A TRS \( R \) is a finite set of rewrite rules. A term \( s \) reduces to \( t \) at position \( p \) by a TRS \( R \), denoted \( s \overset{R}{\rightarrow} t \), if \( s[p]_{\alpha \theta} = t_{\beta [\theta]} \) for some rewrite rule \( \alpha \rightarrow \beta \) and substitution \( \theta \). For \( s \overset{R}{\rightarrow} t \), \( p \) and \( R \) may be omitted. Let \( \rightarrow^* \) be \( \rightarrow \cup = \) and \( \rightarrow \) the inverse of \( \rightarrow \). \( s \) and \( t \) are joinable if \( s \rightarrow^* \epsilon \rightarrow^* t \), denoted \( s \downarrow t \). \( t \) is reachable from \( s \) if \( s \rightarrow^* t \). \( r \) is \textit{confluent} on TRS \( R \) if for every \( s \overset{R}{\rightarrow} r \overset{R}{\rightarrow} s^\prime \), \( t \downarrow s^\prime \). A TRS \( R \) is \textit{confluent} if every \( r \) is confluent on \( R \). Let \( \gamma : s_1 \overset{R}{\rightarrow} s_2 \overset{R}{\rightarrow} \cdots \overset{R}{\rightarrow} s_n \) be a rewrite \textit{sequence}. This sequence is abbreviated to \( \gamma : s_1 \rightarrow^* s_n \). \( \gamma \) is called \( p \)-invariant if \( q > p \) for any redex position \( q \) of \( \gamma \), and we write \( \gamma : s_1 \overset{R}{\rightarrow}^* s_n \).

Definition 1 A rule \( \alpha \rightarrow \beta \) is \textit{flat} if \( \text{height}(\alpha) \leq 1 \) and \( \text{height}(\beta) \leq 1 \). A TRS \( R \) is \textit{flat} if every rule in \( R \) is flat.

Definition 2 A \textit{finite automaton} is a 5-tuple \( (Q, \Sigma, \delta, FS, q_0) \) where \( Q \) is a finite set of states, \( \Sigma \) is a finite set of input symbols, \( \delta : Q \times \Sigma \rightarrow Q \) is a function, \( FS \subseteq Q \) is a finite set of final states, and \( q_0 \in Q \) is the initial state.
Let \( \phi \) be a mapping from \( T \) to \( T \). A mapping \( \phi \) can be extended to TRSs as follows: \( \phi(R) = \{ \phi(\alpha) \rightarrow \phi(\beta) \mid \alpha \rightarrow \beta \in R \} \setminus \{ t \rightarrow t \mid t \in T \} \). A mapping \( \phi \) can be extended to substitutions as follows: let \( \phi(\theta) = \{ \pi \rightarrow \phi(\pi) \mid \pi \in \theta \} \). The following lemma holds for \( \phi \).

**Lemma 3** \( R \) is confluent iff there exists a mapping \( \phi : T \rightarrow T \) that satisfies the following conditions (1)--(4).

1. If \( s \rightarrow_R t \) then \( \phi(s) \rightarrow_R^* \phi(t) \).
2. \( \phi(R) \subseteq \phi(R) \).
3. \( t \rightarrow_R^* \phi(t) \).
4. \( \phi(R) \) is confluent.

**Proof** Only if part: Let \( \phi \) be an identity mapping. If part: Let \( s \rightarrow_R t \rightarrow_R t \). By Condition (1), \( \phi(s) \rightarrow_R^* \phi(t) \). By Condition (4), \( \phi(s) \downarrow_R \phi(t) \). By Condition (2), \( \phi(s) \downarrow_R \phi(t) \). By Condition (3), \( s \rightarrow_R^* \phi(s) \) and \( t \rightarrow_R^* \phi(t) \). Thus, \( s \downarrow_R t \).

This lemma is used in Section 4.

### 3 Joinability and reachability for flat TRSs

Jacquemard [4] has reported that reachability and joinability are also undecidable for flat TRSs and the confluence problem is reducible to the reachability one, so that the former is also undecidable. But, we found that the reducibility proof is incorrect and contains some errors not easy to correct. First, we give a more simplified proof of undecidability for joinability and reachability than that given in [4]. Notations used in the proof (but undefined in Section 2) are similar to those of [4].

Let \( P = \{(u_i, v_i) \in \Sigma^+ \times \Sigma^+ \mid 1 \leq i \leq k\} \) be an instance of the Post's Correspondence Problem (PCP). Note that the alphabet \( \Sigma \) is fixed. Let \( l_P = \max_{1 \leq i \leq k}(|u_i|, |v_i|) \). Let \( \lambda \) be a new symbol and \( \Delta = \{1, \cdots, l_P\} \times (\Sigma \cup \{\lambda\})^2 \). We shall use a product operator \( \otimes \) which associates to two words of \( \Sigma^+ \) a word of \( \Delta^* \) as follows:

\[
a_1 \cdots a_n \otimes a'_1 \cdots a'_m = (1, a_1, a'_1) \cdots (l_P, a_n, a'_m),
\]

where \( a_1, \cdots, a_n, a'_1, \cdots, a'_m \in \Sigma, a_i = \lambda \) for all \( i \in \{n + 1, \cdots, l_P\}, \) and \( a'_j = \lambda \) for all \( j \in \{m + 1, \cdots, l_P\} \).

**Example 4** Let \( l_P = 4 \), then \( a \otimes b a b = (1, a, b) (2, a, b) (3, a, b) (4, a, b) \).

Let \( A = (Q_A, \Delta, \delta_A, F_A, q_A) \) and \( B = (Q_B, \Sigma, \delta_B, F_B, q_B) \) be two finite automata recognizing the respective sets \( L(A) = \{ u_i \otimes v_i \mid 1 \leq i \leq k\}^+ \) and \( L(B) = \Sigma^+ \). We may assume that both \( q_A \) and \( q_B \) are non-final. We assume that the automata \( A \) and \( B \) are clean (i.e., any state is reachable from the initial state \( q_A \) or \( q_B \) by some input string).

We assume given 13 disjoint copies of the above signatures, colored with color \( i \in \{0, \cdots, 12\} \): \( \Sigma^{(i)} = \{ a^{(i)} \mid a \in \Sigma \}, Q_A^{(i)} = \{ q \mid q \in Q_A \}, Q_B^{(i)} = \{ q \mid q \in Q_B \}, \Delta^{(i)} = \{ d^{(i)} \mid d \in \Delta \} \). Let \( \Theta^{012} = \Delta^{(0)} \cup \Sigma^{(1)} \cup \Sigma^{(2)} \), \( \Theta^{345} = \Delta^{(3)} \cup \Delta^{(4)} \cup \Sigma^{(5)} \), and \( Q = Q_A^{(0)} \cup Q_A^{(1)} \cup Q_A^{(2)} \cup Q_B^{(0)} \cup Q_B^{(1)} \cup Q_B^{(2)} \). Let \( e \) be a constant. For a ground term \( t \) built with \( \Delta \cup \Sigma \cup \{ e \} \), \( t^{(i)} \) is defined as follows: \( e^{(i)} = e \) and \( (f(t_1))^{(i)} = f^{(i)}(t_1) \) for \( f \in \Delta \cup \Sigma \) and term \( t_1 \).

The following flat TRS \( R_1 \) is defined on an extended signature \( F_0 = Q \cup \{ 0, 1 \}, F_1 = \Theta^{012} \cup \Theta^{345}, F_5 = \{ f \}, \)
and $F_r = \{\mathfrak{g}\}$:

$$T_A^{(6,2)} = \{q^{(i)} \rightarrow a^{(j)}(q^{(i)}) \mid a \in \delta_B(q, a) \} \cup \{q^{(i)} \rightarrow a \mid q \in FS_A\}$$

$$T_B^{(6,2)} = \{q^{(i)} \rightarrow a^{(j)}(q^{(i)}) \mid a \in \delta_B(q, a) \} \cup \{q^{(i)} \rightarrow a \mid q \in FS_B\}$$

$$S^{(6,2)} = \{a^{(i)}(x) \rightarrow a^{(j)}(x) \mid a \in \Sigma\}$$

$$P^{(6,2)} = \{a^{(i)}(x) \rightarrow a^{(j)}(x) \mid d \in \Delta\}$$

$$\Pi_1^{(6,2)} = \{(n, a, a')(x) \rightarrow a^{(i)}(x) \mid n \in \{1, \ldots, l'_B\}, a \in \Sigma, a' \in \Sigma \cup \{\}\}$$

$$\Pi_2^{(6,2)} = \{(n, a, a')(x) \rightarrow a^{(i)}(x) \mid n \in \{1, \ldots, l'_B\}, a \in \Sigma \cup \{\}, a' \in \Sigma\}$$

If $0 \rightarrow_R^{*} 1$ then the rules of $R_1$ are applied as described in the following pic.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 $\rightarrow f$</td>
<td>$q^{(6)}_A, q^{(7)}_A, q^{(8)}_A, q^{(9)}_A, q^{(10)}_B, q^{(11)}_B$</td>
</tr>
<tr>
<td>$f$</td>
<td>$t_3, t_3, t_4, t_4, t_5, t_5$</td>
</tr>
<tr>
<td>$g$</td>
<td>$t_3, t_3, t_4, t_4, t_5, t_5, q^{(12)}_A$</td>
</tr>
<tr>
<td>$P^{(6,2)}$</td>
<td>$\Pi_1^{(6,2)}, \Pi_2^{(6,2)}, P^{(6,2)}$</td>
</tr>
<tr>
<td>$T_A^{(6,2)}$</td>
<td>$T_A^{(6,2)}$</td>
</tr>
</tbody>
</table>

**Definition 5**

1. Let $\rightarrow_R(s) = \{t \mid s \rightarrow_R t\}$. For a set $C \subseteq \{0, \ldots, 12\}$, let $G_C$ be the set of ground terms built with $\varepsilon$ and colored function symbols in $\cup_{i \in C}(\Sigma^{(i)} \cup \Delta^{(i)} \cup Q_A^{(i)} \cup Q_B^{(i)})$.

2. The index of an $i$-colored term built with $\Delta^{(i)} \cup \{\varepsilon\}$ is defined as follows: $\text{index}(\varepsilon) = \varepsilon$ and $\text{index}(n, a, a')^{(i)}(t) = n \cdot \text{index}(t)$.

**Lemma 6** Let $t_0 = ((u_1 \otimes u_1) \cdots (u_m \otimes u_m))(e)^{(0)}$.

1. If $q^{(6)}_A \rightarrow_R^{*} t_0$ then $q^{(6)}_A \rightarrow_R^{*} (q^{(6)}_A \cup P(x, y)) t_0$.

2. If $q^{(9)}_A \rightarrow_R^{*} t_0$ then $q^{(9)}_A \rightarrow_R^{*} (q^{(9)} \cup P(x, y)) t_0$.

**Proof**

1. By the definition of $R_0$, $q^{(6)}_A \rightarrow_R^{*} (q^{(6)}_A \cup P(x, y)) \cup P^{(3,1,1,7)} t_0$, where $\Pi_1^{(3,1,1,7)} = \{(n, a', (3,1,7)) \rightarrow x \mid n \in \{2, \ldots, l'_B\}, a' \in \Sigma \cup \{\}\}$. Note that $\text{index}(t_0) = (1 \cdots l'_B)^m$. In this rewrite sequence, if there is at least one application of some rule of $\Pi_1^{(3,1,1,7)}$, $\text{index}(t_0) = (1 \cdots l'_B)^m$ does not hold, since any rule of $\Pi_1^{(3,1,1,7)}$ cannot delete any symbol of form $(1, a, a')^{(3)}$. Thus, the proposition holds.

2. Similar to (1).

**Lemma 7** $0 \rightarrow_R^{*} 1$ iff PCP has a solution.

**Proof** Only if part: By the definition of $R_1$, $0 \rightarrow_R f(q^{(6)}_A, q^{(7)}_A, q^{(8)}_A, q^{(9)}_A, q^{(10)}_B, q^{(11)}_B) \rightarrow_R^{*} f(t_3, t_3, t_4, t_4, t_5, t_5) \rightarrow_R^{*} g(t_3, t_5, t_4, t_3, t_4, t_5, q^{(12)}_A) \rightarrow_R^{*} g(t_0, t_1, t_5, t_0) \rightarrow_R^{*} 1$. By the definition of $R_0$, $q^{(6)}_A \subseteq G^{(0,1,3,6)} \rightarrow_R^{*} q^{(7)}_A \subseteq G^{(0,1,3,7)} \rightarrow_R^{*} q^{(8)}_A \subseteq G^{(0,2,4,8)} \rightarrow_R^{*} q^{(9)}_A \subseteq G^{(0,2,4,9)} \rightarrow_R^{*} q^{(10)}_B \subseteq G^{(1,2,5,10)}$, and $q^{(11)}_B \subseteq G^{(1,2,5,11)}$. We first show that the following condition (I) holds. (I) $t_i \in G^{(i)}$, $i \in \{0, \ldots, 5\}$. 

Note that $t_3 \in G^{(0,1,3)}$ holds, since $t_3 \rightarrow^*_{R_A} (q_A^{(6)}) \cap \rightarrow^*_{R_B} (q_B^{(7)})$. Similarly, $t_4 \in G^{(0,2,4)}$ and $t_5 \in G^{(1,2,5)}$ hold. Since $t_3 \rightarrow^*_{R_A} t_0$ and $t_4 \rightarrow^*_{R_B} t_0$, we have $t_0 \in G^{(0,1,3)} \cap G^{(0,2,4)} = G^{(0)}$. Similarly, $t_1 \in G^{(1)}$ and $t_2 \in G^{(2)}$ hold. Hence, the condition (I) holds for $i \in \{0,1,2\}$. For $t_3 \in G^{(0,1,3)}$, since $t_3 \rightarrow^*_{R_A} t_0 \in G^{(0)}$ and $t_3 \rightarrow^*_{R_B} t_1 \in G^{(1)}$, $t_3$ cannot contain any symbol in $G^{(0,1,3)}$, so that $t_3 \in G^{(3)}$. Similarly, $t_4 \in G^{(4)}$ and $t_5 \in G^{(5)}$ hold. Hence, (I) holds for $i \in \{3,4,5\}$, as claimed. By (I), we have $t_0 \rightarrow^*_{\Pi_1^{(3,1)}} t_1 \rightarrow^*_{\Pi_1^{(3,1)}} t_5$ and $t_0 \rightarrow^*_{\Pi_2^{(4,2)}} t_2 \rightarrow^*_{\Pi_2^{(4,3)}} t_5$.

By $q_A^{(12)} \rightarrow^*_{R_A} t_0$, $t_0 = (((u_1 \otimes v_1) \cdots (u_m \otimes v_m)(e))^{(0)})$ for some $i_1, \cdots, i_m \in \{1, \cdots, k\}$. Since an initial state $q_A$ is not final, $m \geq 0$ holds. By Lemma 6, $t_0 \rightarrow^*_{R_{1,i_1}} t_0 \rightarrow^*_{R_{1,i_1}} t_4$. Thus, $t_0 = (((u_1 \otimes v_1) \cdots (u_m \otimes v_m)(e))^{(3)}$ and $t_4 = (((u_1 \otimes v_1) \cdots (u_m \otimes v_m)(e))^{(4)}$. By $t_0 \rightarrow^*_{\Pi_1^{(3,1)}} t_1$, $t_1 = (u_1 \cdots u_m(e))^{(1)}$. By $t_4 \rightarrow^*_{\Pi_2^{(4,3)}} t_2, t_2 = (u_1 \cdots u_m(e))^{(2)}$. By $t_1 \rightarrow^*_{\Pi_1^{(3,1)}} t_5 \rightarrow^*_{\Pi_2^{(4,3)}} t_5, t_5 = (u_1 \cdots u_m(e))^{(5)}$. Hence, PCP has a solution.

If part: Let $i_1, \cdots, i_m$ be a solution of PCP, and let $s = ((u_1 \otimes v_1) \cdots (u_m \otimes v_m)(e))^{(0)}$ and $t = u_1 \cdots u_m(e)$. Then, $t = u_1 \cdots u_m(e)$ holds. By the definition of $R_1, 0 \rightarrow f(q_A^{(6)}, q_A^{(6)})^{(7)}(q_A^{(6)})^{(8)}(q_B^{(10)}, q_B^{(12))} \rightarrow f(s^{(3)}, s^{(4)}, t^{(2)}, t^{(0)}) \rightarrow g(s^{(3)}, s^{(4)}, t^{(2)}, t^{(0)})^{(0)}$, $q_A^{(12)} \rightarrow^* g(s^{(0)}, t^{(1)}, t^{(2)}, t^{(0)})^{(0)} \rightarrow 1$. Note that $(1, a')^{(3)}(x) \rightarrow x$ and $(1, a')^{(4)}(x) \rightarrow x$ need not be in $\Pi_1^{(3,1)}$ and $\Pi_2^{(4,2)}$, since $P \subseteq \Sigma^* \times \Sigma^*$. Hence, $0 \rightarrow^*_{R_1} 1$

Since 1 is a normal form, $0 \rightarrow^*_{R_1} 1$ if $0 \not\rightarrow^*_{R_1} 1$. Thus, the following theorem holds.

**Theorem 8** Both joinability and reachability for flat TRSs are undecidable.

## 4 Confluence for flat TRSs

We show that confluence for flat TRSs is undecidable by reduction of the problem of the above section.

Let $\Theta^{12} = \{d_2 \mid d \in \Theta^{012}\}$, where $d_2$ has arity 2. We add TRS $R_1$ in the previous section the following rules:

$$R_2 = R_1 \cup \{e \rightarrow 0 \cup \{d(x) \rightarrow d_2(0, x), d_2(1, x) \rightarrow x \mid d \in \Theta^{012}\}

TRS R_2$ is flat.

First, we show that $0 \rightarrow^*_{R_2} 1$ if $0 \rightarrow^*_{R_1} 1$. For this purpose, we need the following definition and lemma.

**Definition 9** Let $\psi$ be the mapping over ground terms defined as follows.

$$\psi(h(t_1), \cdots, t_n) = \begin{cases} e & \text{if } h \in \{0, 1, f, g\} \\ d(h(t_2)) & \text{if } d \in \Theta^{12} \\ h(\psi(t_1), \cdots, \psi(t_n)) & \text{otherwise} \end{cases}

Let $R'_2 = R_1 \cup \{e \rightarrow 0 \cup \{d(x) \rightarrow d_2(0, x) \mid d \in \Theta^{12}\}

**Lemma 10** For any ground term $s$, if $s \rightarrow R_2 t$ then $\psi(s) \rightarrow^*_{R_2} \psi(t)$.

**Proof** We prove this lemma by induction on the structure of $s$.

**Basis**: If $s \in \{0, 1\}$ then $\psi(s) \rightarrow^*_{R_2} \psi(s)$, since $\psi(0) = 0$ and $\psi(1) = 1$.

**Induction step**: 

- **Case of $s \in \{f(s_1, \cdots, s_n) \in \Theta^{12}\}$**: In this case, $\psi(s) = \psi(t) = e$.
- **Case of $s = d(s_1) \in \{d(s_1) \mid d \in \Theta^{12}\}$**: If $t = d(t_1)$ and $s_1 \rightarrow R_1 t_1$ then $\psi(s) = \psi(t)$ by the induction hypothesis. Otherwise $t = d'(s_1)$, with $d' \in \Theta^{12}$ and $\psi(s) = \psi(t)$ by the induction hypothesis. Otherwise $t = d_2(0, s_1)$ and $\psi(s) = \psi(t) = \psi(t_1)$.
- **Case of $s = d(s_1) \in \{d(s_1) \mid d \in \Theta^{12}\}$**: If $t = d(t_1)$ and $s_1 \rightarrow R_1 t_1$ then $\psi(s) = \psi(t) = \psi(t_1)$ by the induction hypothesis. Otherwise $t = d_2(0, s_1)$ and $\psi(s) = \psi(t) = \psi(t_1)$.

Since 1 appears only in the right-hand side of the rule $g(0, x_1, x_2, x_1, x_2, x_0) \rightarrow 1$, and this contradicts...
the hypothesis that \( \gamma \) is the shortest sequence as above, hence \( d_0(1, x) \rightarrow x \) is not applied in \( \gamma \). Thus, 
\[
 f(q_A^{(6)}, q_A^{(7)}, q_A^{(9)}, q_B^{(10)}, q_B^{(11)}) \rightarrow_{R_2} f(t_3, t_3, t_4, t_5, t_5, t_5, q_A^{(12)}) \rightarrow_{R_3} g(t_3, t_3, t_4, t_5, t_5, t_6, q_B^{(13)}) \rightarrow_{R_4} g(t_6, t_5).
\]

By Lemma 10, 
\[
 f(\psi(t_6), \psi(t_5)) \rightarrow_{R_1} g(\psi(t_6), \psi(t_5), \psi(t_4), \psi(t_3), \psi(t_3), \psi(t_3)),
\]
and 
\[
 g(\psi(t_6), \psi(t_5), \psi(t_4), \psi(t_3), \psi(t_3), \psi(t_3)) \rightarrow_{R_2} \phi(t)
\]

Since \( q \) is an \( R_1 \)-term for every \( q \in Q \), \( 0 \rightarrow_{R_1} \).

If part: Obvious.

Next, we show that \( R_2 \) is confluent iff \( 0 \rightarrow_{R_0} 1 \) by using Lemma 3. Let \( \phi(t) \) be the term obtained from \( t \) by replacing every maximal ground subterm (w.r.t. \( \triangleright_{ub} \)) by \( 1 \). Note that \( \phi(R_0) = P^{(3, 0)} \cup \Pi_1^{(0, 1)} \cup \Pi_2^{(0, 2)} \cup \Sigma^{(0, 1)} \cup \Delta^{(0, 2)} \), \( \phi(R_1) = \phi(R_0) \cup \{ (x_3, x_3, x_4, x_5, x_6) \rightarrow g(x_3, x_3, x_4, x_5, x_3, 1), (x_0, x_1, x_2, x_1, x_2, x_3, x_3, x_3, x_3, x_3, x_3, x_3, x_3) \rightarrow 1 \} \), and \( \phi(R_2) = \{ (d(x) \rightarrow d_2(1, x), d_2(1, x) \rightarrow x \mid d \in \Theta^{012} \} \), and the rules of \( T_A \) and \( T_B \) vanish in \( \phi(R_0) \).

Lemma 12: For any non-constant function symbol \( h \in F \cup \Theta^{012} \), \( h(1, \cdots, 1) \rightarrow_{\phi(R_0)} 1 \).

Proof: For every \( d \in \Theta^{045}, d(1) \rightarrow_{\phi(R_1)} d'(1) \) for some \( d' \in \Theta^{012} \). For every \( d' \in \Theta^{012}, d'(1) \rightarrow_{\phi(R_1)} d'^{(1, 1)}(1) \). For every \( d_2' \in \Theta^{012} \), \( d_2'(1, 1) \rightarrow_{\phi(R_1)} 1 \). Moreover, \( f(1, \cdots, 1) \rightarrow_{\phi(R_1)} g(1, \cdots, 1) \rightarrow_{\phi(R_1)} 1 \). Thus, this lemma holds.

We show now how the hypotheses of Lemma 3 hold for \( R_2 \) and \( \phi \).

Lemma 13: If \( 0 \rightarrow_{R_0} 1 \) then the following propositions hold.

1. If \( s \rightarrow_{R_0} t \) then \( \phi(s) \rightarrow_{\phi(R_0)} \phi(t) \).
2. \( \phi(R_0) \subseteq \phi(R_2) \).
3. \( t \rightarrow_{R_0} \phi(t) \).
4. \( \phi(R_2) \) is confluent.

Proof:

1. By induction on the structure of \( s \). If \( s \) is a ground term then \( \phi(s) = \phi(t) = 1 \). Thus, we assume that \( s \) is not a ground term. Let \( s \rightarrow_{R_0} t \). If \( \varepsilon = \theta \) then \( \phi(s) = \phi(t) = 1 \). Let \( h \in F \cup \Theta^{012} \) and \( s_1, \ldots, s_n, \alpha = (a_1, \ldots, a_n) \) and \( i \in \{ 1, \ldots, n \} \). Since \( R_2 \) is flat, \( a_i \in X \cup F_0 \). \( s \) is not a ground term, \( \phi(s_i) = \phi(a_i) \). If \( s_i \) is not a constant then \( \phi(s_i) = \phi(a_i) \). Similarly, \( \phi(t) = \phi(R_0) \phi(t) \). \( s \) is not a ground term, \( \phi(s_i) = \phi(a_i) \). If \( s_i \) is not a constant then \( \phi(s_i) = \phi(a_i) \). By the induction hypothesis, \( \phi(s_i) \rightarrow_{\phi(R_0)} \phi(t_i) \). \( t \) is not a ground term, \( h(\phi(s_1), \ldots, \phi(s_i), \cdots, \phi(s_n)) = \phi(t) \). If \( t \) is a ground term then \( \phi(s_1), \ldots, \phi(s_i), \cdots, \phi(s_n) = h(1, \cdots, 1) \). By Lemma 12, \( h(1, \cdots, 1) \rightarrow_{\phi(R_0)} 1 \). Thus, \( \phi(s) \rightarrow_{\phi(R_0)} \phi(t) \).

2. Since \( \phi(R_2) \setminus \{ (d(x) \rightarrow d_2(1, x) \mid d \in \Theta^{012} \} \subseteq R_2 \), it suffices to show that \( s = \phi(R_2) \). \( d(1, x) \rightarrow_{\phi(R_1)} d(1, x) \rightarrow_{\phi(R_2)} d(1, x) \).

3. It is true for any ground term, \( t \rightarrow_{\phi(R_2)} 1 \). First, we show that for any \( q \in Q \), \( \exists s \) which does not have function symbols belonging to \( Q \) such that \( q \rightarrow_{\phi(R_2)} s \). Indeed, since both of the automata \( A \) and \( B \) are clean, there exists \( e \in \Delta^{(0)} \cup \Delta^{(4)} \cup \Sigma^{(0)} \) such that \( q \rightarrow_{\phi(R_2)} e \).

Thus, it suffices to show that for any ground term \( t \) which does not have function symbols belonging to \( Q \), \( t \rightarrow_{\phi(R_2)} 1 \) to show this lemma. We show this proposition by induction on the structure of \( t \). Basis case: By \( t \rightarrow_{\phi(R_2)} 0 \rightarrow_{\phi(R_2)} 1 \). Induction step: Let \( t = h(t_1, \ldots, t_n) \) where \( n > 0 \). By induction hypothesis, \( h(t_1, \ldots, t_n) \rightarrow_{\phi(R_2)} 1 \). By Lemma 12, \( (1, \cdots, 1) \rightarrow_{\phi(R_2)} 1 \).

4. We can easily show that \( \phi(R_2) \) is terminating by using a lexicographic path order induced by a precedence greater than the following conditions: for any \( d \in \Theta^{045}, d' \in \Theta^{012}, d' > d\). For \( f > g \). Thus, it suffices to show that every peak of \( \phi(R_2) \) is joinable.

\[
 (n, a, \alpha^{(0)}(x) \rightarrow (n, a, a')^{(3)}(x) \rightarrow a^{(1)}(x)) \text{ is joinable by } (n, a, a')^{(0)}(1, x) \rightarrow x \rightarrow a^{(1)}(1, x) \rightarrow a^{(1)}(x).
\]

\[
 (n, a, a')^{(0)}(x) \rightarrow (n, a, a')^{(3)}(x) \rightarrow x \text{ is joinable by } (n, a, a')^{(0)}(x) \rightarrow (n, a, a')^{(0)}(1, x) \rightarrow x.
\]
\[
(n, a, a')^{(0)}(x) \rightarrow (n, a, a')^{(4)}(x) \rightarrow a'_{2}^{(2)}(1, x) \rightarrow a'_{2}^{(2)}(1, x) \leftarrow a_{2}(x).
\]

\[
(n, a, a')^{(0)}(x) \rightarrow (n, a, a')^{(4)}(x) \rightarrow x \rightarrow a_{2}^{(2)}(1, x) \rightarrow a_{2}^{(2)}(1, x) \leftarrow a_{2}(x).
\]

\[
(n, a, -)^{(0)}(x) \rightarrow (n, a, -)^{(4)}(x) \rightarrow x \rightarrow a_{2}^{(1)}(1, x) \rightarrow a_{2}^{(1)}(1, x) \leftarrow a_{2}(x).
\]

\[
\square
\]

Lemma 14 \( R_{2} \) is confluent iff \( 0 \sim_{R_{2}}^{\mathrm{c}} 1 \).

Proof Only if part: By \((n, -, a')^{(0)}(x) \rightarrow P^{(\mathrm{s}, 0)}(n, -, a')^{(3)}(x) \sim_{\Pi_{1}^{(*.1)}} x,\) confluence ensures that \((n, a, a')^{(0)}(x) \downarrow R_{2} x.\)

Since \( x \) is a normal form, \((n, a, a')^{(0)}(x) \rightarrow a_{2}^{(1)}(1, x) \rightarrow a_{2}^{(1)}(1, x) \leftarrow a_{2}(x).\)

If there exists such \( \gamma, 0 \rightarrow a_{2}(x) \) must hold. If part: By Lemmata 5 and 13.

By Lemmata 7, 11, 14, the following theorem holds.

Theorem 15 Confluence for flat TRSs is undecidable.

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References


