Relative Match-Bounds for Complexity Analysis

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Overview

Definition

$\rightarrow^*_{\mathcal{R}}(L) = \{t \mid \exists s \in L\colon s \rightarrow^*_{\mathcal{R}} t\}$

Definition

$\to_{\mathcal{R}}^*(L) = \{t \mid \exists s \in L\colon s \to_{\mathcal{R}}^* t\}$

Definition

- $\mathsf{lift}_c(f) = f_c$
- $\mathsf{base}(f_c) = f$
- $\mathsf{height}(f_c) = c$

Definition

- relative TRS $\mathcal{R}/\mathcal{S}$ is pair of TRSs
- $\rightarrow_{\mathcal{R}/\mathcal{S}} = \rightarrow^*_{\mathcal{S}} \cdot \rightarrow_{\mathcal{R}} \cdot \rightarrow^*_{\mathcal{S}}$
- relative TRS is terminating if $\rightarrow_{\mathcal{R}/\mathcal{S}}$ is terminating

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Definition

- $\mathsf{dl}_L(t, \to) = \max\{n \mid \exists u \colon t \to^n u, t \in L\}$
- $\mathsf{cp}_L(n, \to) = \max\{\mathsf{dl}_L(t, \to) \mid t \in L, |t| \leqslant n\}$

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$\rightarrow$ has linear complexity on L if $\mathsf{cp}_L(n, \rightarrow)$ is bounded by linear polynomial

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prove linear complexity of TRS $\mathcal{R}$ using match-bounds

1. transform $\mathcal{R}$ into an enriched system that simulates the original derivations

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2. search for an upper bound on the labels that can occur in derivations

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$$\mathsf{match}(\mathcal{R}) = \{l' \to \mathsf{lift}_c(r) \mid \mathsf{base}(l') \to r \in \mathcal{R}\}$$

where $c = 1 + \min\{\mathsf{height}(l'(p)) \mid p \in \mathcal{P}\mathsf{os}_{\mathcal{F}}(\mathsf{base}(l'))\}$

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Example

$$\mathsf{aabb} \to \mathsf{bbbaaa}$$

$\mathsf{match}(\mathcal{R})$

$$\begin{aligned} \mathsf{a}_0\mathsf{a}_0\mathsf{b}_0\mathsf{b}_0 &\to \mathsf{b}_1\mathsf{b}_1\mathsf{b}_1\mathsf{a}_1\mathsf{a}_1\mathsf{a}_1 \\ \mathsf{a}_0\mathsf{a}_3\mathsf{b}_0\mathsf{b}_1 &\to \mathsf{b}_1\mathsf{b}_1\mathsf{b}_1\mathsf{a}_1\mathsf{a}_1\mathsf{a}_1 \\ \mathsf{a}_1\mathsf{a}_2\mathsf{b}_5\mathsf{b}_1 &\to \mathsf{b}_2\mathsf{b}_2\mathsf{b}_2\mathsf{a}_2\mathsf{a}_2\mathsf{a}_2 \\ &\vdots \end{aligned}$$

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a TRS $\mathcal{R}$ is called match-bounded for a language L if there exists a $c \in \mathbb{N}$ such that the maximal height of function symbols occurring in terms in $\to^*_{\mathsf{match}(\mathcal{R})}(\mathsf{lift}_0(L))$ is at most c

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Theorem (Geser *et al.* (RTA 2005))

if $\mathcal{R}$ is linear and match-bounded for L then

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Theorem (Zankl and Korp (RTA 2010))

if a term t is terminating with respect to $\mathcal{R}$ then

$$\max\{\mathcal{O}(\mathsf{dl}_L(t, \to_{\{s_i \to t_i\}/\mathcal{S}_{s_i \to t_i}}))\} = \mathcal{O}(\mathsf{dl}_L(t, \to_{\mathcal{R}}))$$

where $\mathcal{R} = \{s_1 \to t_1, \ldots, s_n \to t_n\}$

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$$\mathcal{R} \quad \mathsf{rev}(x) \to \mathsf{rev}'(x, \mathsf{nil}) \qquad \mathsf{rev}'(\mathsf{nil}, y) \to y$$
$$\mathcal{S} \quad \mathsf{rev}'(\mathsf{cons}(x, y), z) \to \mathsf{rev}'(y, \mathsf{cons}(x, z))$$

$$\mathsf{match}(\mathcal{R}) \quad \begin{array}{ll} \mathsf{rev}_0(x) \to \mathsf{rev}'_1(x, \mathsf{nil}_1) & \mathsf{rev}'_0(\mathsf{nil}_0, y) \to y \\ \mathsf{rev}_1(x) \to \mathsf{rev}'_2(x, \mathsf{nil}_2) & \mathsf{rev}'_2(\mathsf{nil}_4, y) \to y \\ \mathsf{rev}_2(x) \to \mathsf{rev}'_3(x, \mathsf{nil}_3) & \cdots \end{array}$$

$$\mathsf{match}^1(\mathcal{S}) \quad \begin{array}{l} \mathsf{rev}'_0(\mathsf{cons}_0(x, y), z) \to \mathsf{rev}'_1(y, \mathsf{cons}_1(x, z)) \\ \mathsf{rev}'_1(\mathsf{cons}_0(x, y), z) \to \mathsf{rev}'_1(y, \mathsf{cons}_1(x, z)) \\ \mathsf{rev}'_3(\mathsf{cons}_5(x, y), z) \to \mathsf{rev}'_1(y, \mathsf{cons}_1(x, z)) \\ \cdots \end{array}$$

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- $\mathcal{R}/\mathcal{S}$ is relative match-bounded by 1; can be easily shown by constructing a tree automaton with 7 transitions and 1 state
- $\mathcal{R}/\mathcal{S}$ is terminating and $\to_{\mathcal{R}/\mathcal{S}}$ has linear complexity
- $\mathcal{R} \cup \mathcal{S}$ is not match-bounded because $\to_{\mathcal{R}\cup\mathcal{S}}$ has quadratic complexity

Definition

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$$\text{match-RT}^c(\mathcal{S}) = \{l' \to \text{lift}_d(r) \mid \text{base}(l') \to r \in \mathcal{R}\}$$

where

- $d = \min\{c, \text{height}(l'(\epsilon))\}$ if $\|\text{base}(l')\| \geqslant \|r\|$ and $\text{lift}_{\text{height}(l'(\epsilon))}(\text{base}(l')) = l'$
- $d = \min\{c, 1 + \text{height}(l'(p)) \mid p \in \mathcal{P}\text{os}_{\mathcal{F}}(\text{base}(l'))\}$ otherwise

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Definition

enrichment $\text{match-RT}^c(\mathcal{R}, s \to t, \mathcal{S})$ is defined as the relative TRS $\text{match}(s \to t)/\text{match-RT}^c(\mathcal{S}_{s \to t})$ where $\mathcal{S}_{s \to t} = (\mathcal{R} \cup \mathcal{S}) \setminus \{s \to t\}$

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match($s \to t$)

$$\mathsf{rev}_0(x) \to \mathsf{rev}'_1(x, \mathsf{nil}_1)$$
$$\mathsf{rev}_1(x) \to \mathsf{rev}'_2(x, \mathsf{nil}_2)$$
$$\dots$$

match-RT$^1(\mathcal{S}_{s \to t})$

$$\begin{aligned}
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\mathsf{rev}'_3(\mathsf{cons}_5(x, y), z) &\to \mathsf{rev}'_1(y, \mathsf{cons}_1(x, z)) \\
\mathsf{rev}'_0(\mathsf{nil}_0, y) &\to y \\
&\dots
\end{aligned}$$

$$\text{match-RT}^1(\mathcal{R}, s \to t, \mathcal{S}) = \text{match}(s \to t)/\text{match-RT}^1(\mathcal{S}_{s \to t})$$

Definition

a relative TRS $\mathcal{R}/\mathcal{S}$ is called match-RT-bounded for a rewrite rule $s \rightarrow t$ and a language L if there exists a $c \in \mathbb{N}$ such that the maximal height of function symbols occurring in terms belonging to $\rightarrow^*_{\text{match-RT}^c(\mathcal{R}, s \rightarrow t, \mathcal{S})}(\text{lift}_0(L))$ is at most c

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Theorem

if $\mathcal{R}/\mathcal{S}$ is linear and match-RT-bounded for $s \to t$ and L then

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- $\mathcal{R}/\mathcal{S}$ is match-RT-bounded for $s \to t = \mathsf{rev}(x) \to \mathsf{rev}'(x, \mathsf{nil})$ by 1; can be easily shown by constructing a tree automaton with 7 transitions and 1 state

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- $\{s \to t\}/\mathcal{S}_{s \to t}$ is terminating and $\to_{\{s \to t\}/\mathcal{S}_{s \to t}}$ has linear complexity
- match-RT-boundedness for $s' \to t' = \mathsf{rev}'(\mathsf{nil}, y) \to y$ yields that $\mathcal{R}/\mathcal{S}$ is terminating and $\to_{\mathcal{R}/\mathcal{S}}$ has linear complexity: $\max\{\mathcal{O}(\to_{\{s \to t\}/\mathcal{S}_{s \to t}}), \mathcal{O}(\to_{\{s' \to t'\}/\mathcal{S}_{s' \to t'}})\} = \mathcal{O}(\to_{\mathcal{R}/\mathcal{S}})$

Overview

Experimental Results with CaT (TPDB 7.2)

		derivational	
	pm	bpm	bprm
# successes	170	270	277
# linear	38	171	179
# quadratic	110	85	84
# cubic	22	14	14
average time (ms)	519	2349	4206

- b match-bounds
- p strongly linear interpretations
- m matrix interpretations of dimension two and three
- r match-RT-bounds

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		derivational		runtime	
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# successes	170	270	277	921	928
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# quadratic	110	85	84	13	11
# cubic	22	14	14	1	1
average time (ms)	519	2349	4206	284	397

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- new version uses upper bounds and a slightly modified enrichment to treat length-preserving and length-decreasing rewrite rules
- latter one is especially adapted to prove complexity bounds of single rewrite rules