Termination of Narrowing in Left-Linear Constructor Systems

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Outline

1. introduction
   - narrowing
2. termination of narrowing via termination of rewriting
   - data generators
   - main result
3. automating the termination analysis
   - abstract terms and argument filterings
   - a direct approach to termination analysis
   - a transformational approach
4. the technique in practice
   - the termination tool TNT
   - inference of safe argument filterings
   - some refinements
5. related work
6. conclusions

What is narrowing?

Standard definition of addition (TRS)

$$\begin{array}{rcll} \mathsf{add}(\mathsf{z}, y) & \to & y & (R_1) \\ \mathsf{add}(\mathsf{s}(x), y) & \to & \mathsf{s}(\mathsf{add}(x, y)) & (R_2) \end{array}$$

With **rewriting**: $\mathsf{add}(\mathsf{s}(\mathsf{z}), \mathsf{z}) \to_{R_2} \mathsf{s}(\mathsf{add}(\mathsf{z}, \mathsf{z})) \to_{R_1} \mathsf{s}(\mathsf{z})$

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but also:

$$\begin{tikzcd} \mathsf{add}(x, \mathsf{z}) \arrow[dr, "\text{``guess''}"'] & & \mathsf{s}(\mathsf{add}(y, \mathsf{z})) \arrow[dr, "\text{``guess''}"'] & & \mathsf{s}(\mathsf{z}) \\ & \mathsf{add}(\mathsf{s}(y), \mathsf{z}) \arrow[ur, "R_2"'] & & \mathsf{s}(\mathsf{add}(\mathsf{z}, \mathsf{z})) \arrow[ur, "R_1"'] & \end{tikzcd}$$

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Formal definition

Definition (rewriting)

$\boxed{s \rightarrow_{p,R} s[r\sigma]_p}$ if there are $\left\{ \begin{array}{l} \bullet \text{ a position } p \text{ of } s \\ \bullet \text{ a rule } R = (l \rightarrow r) \text{ in } \mathcal{R} \\ \bullet \text{ a substitution } \sigma \text{ such that } s|_p = l\sigma \end{array} \right.$

$\Downarrow$

Definition (narrowing)

$\boxed{s \rightsquigarrow_{p,R,\sigma} (s[r]_p)\sigma}$ if there are $\left\{ \begin{array}{l} \bullet \text{ a nonvariable position } p \text{ of } s \\ \bullet \text{ a variant } R = (l \rightarrow r) \text{ of a rule in } \mathcal{R} \\ \bullet \text{ a substitution } \sigma \text{ such that } s|_p\sigma = l\sigma \\ \quad [\sigma = \mathrm{mgu}(s|_p, l)] \end{array} \right.$

Some motivation

We want to analyze the termination of narrowing

Why?

- narrowing is relevant in a number of areas: functional logic languages, partial evaluation, protocol verification, type inference, etc
- no termination prover for narrowing

We want to analyze the termination of narrowing by analyzing the termination of rewriting

Why?

- many techniques and tools for rewriting!

Main ideas

- replace logic variables by data generators
- analyze the termination of rewriting with data generators
- adapt direct and transformational approaches

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Termination of narrowing

The termination problem

- given a TRS, are all possible narrowing derivations finite?

Too strong!

$$\mathsf{add}(x,y) \leadsto_{R_2,\{x\mapsto \mathsf{s}(x')\}} \mathsf{add}(x',y) \leadsto_{R_2,\{x'\mapsto \mathsf{s}(x'')\}} \cdots$$

In this work

- given a TRS $\mathcal{R}$ and a set of terms T,
  are all possible narrowing derivations $t_1 \leadsto t_2 \leadsto \ldots$ for $t_1 \in T$ finite?
  (in symbols: T is $\leadsto_{\mathcal{R}}$-terminating)

For instance, $\{\ \mathsf{add}(s,t) \mid s \text{ is ground } \}$ is $\leadsto_{\mathcal{R}}$-terminating

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Theorem

T is $\leadsto_{\mathcal{R}}$-terminating
if $\{t\sigma \mid t \in T \text{ and } t \leadsto^*_\sigma s \text{ in } \mathcal{R}\}$ is finite and $\to_{\mathcal{R}}$-terminating

Drawbacks:

- very difficult to approximate
- sufficient but not necessary:

$$\begin{array}{rcl} \mathsf{f(a)} & \to & \mathsf{b} \\ \mathsf{a} & \to & \mathsf{a} \end{array}$$

The set $\{f(x)\}$ is $\leadsto_{\mathcal{R}}$-terminating
but $\{\mathsf{f(a)}\}$ is finite but not $\to_{\mathcal{R}}$-terminating:

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A first solution

Variables in narrowing can be seen as generators of possibly infinite terms

Therefore
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$$\{t\sigma \mid t \in T \text{ and } \sigma \text{ maps variables to possibly infinite terms }\}$$

Example

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- **however**, if σ maps x to an infinite term of the form $\mathsf{s}(\mathsf{s}(\ldots))$, then the derivation for $\mathsf{add}(x, \mathsf{z})\sigma$ is now infinite:

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Problem

proving that the set

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is $\rightarrow_{\mathcal{R}}$-terminating is often **too strong**...

Example Given the TRS

$$\begin{array}{rcl} \mathsf{a} & \rightarrow & \mathsf{a} \\ \mathsf{f}(x) & \rightarrow & x \end{array}$$

$\mathsf{f}(x)$ is clearly $\rightsquigarrow_{\mathcal{R}}$-terminating
but $\exists\sigma$ such that $\mathsf{f}(x)\sigma$ is not $\rightarrow_{\mathcal{R}}$-terminating (e.g., $\sigma = \{x \mapsto \mathsf{a}\}$)

$\Rightarrow$ an infinite computation $\mathsf{f}(\mathsf{a}) \rightarrow_{\mathcal{R}} \mathsf{f}(\mathsf{a}) \rightarrow_{\mathcal{R}} \ldots$ is introduced by σ !!

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A second solution

$\Rightarrow$ forbid the reduction of redexes introduced by σ...

A second problem...

...this restriction makes the condition unsound!

Example Given the TRS

$$\begin{array}{rcl} \mathsf{a} & \to & \mathsf{a} \\ \mathsf{f}(\mathsf{a}) & \to & \mathsf{c}(\mathsf{b}, \mathsf{b}) \end{array}$$

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  (e.g., $\mathsf{c}(y, \mathsf{f}(y)) \leadsto_{\{y \mapsto \mathsf{a}\}} \mathsf{c}(\mathsf{a}, \mathsf{c}(\mathsf{b}, \mathsf{b})) \leadsto_{id} \mathsf{c}(\mathsf{a}, \mathsf{c}(\mathsf{b}, \mathsf{b})) \leadsto_{id} \ldots$)

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Last Solution

$\Rightarrow$ consider narrowing derivations where terms introduced by instantiation cannot be narrowed!

For instance,

- (innermost) basic narrowing over arbitrary TRSs
- lazy and needed narrowing over left-linear constructor TRSs
- ...

Any narrowing strategy over left-linear constructor TRSs can only introduce constructor substitutions

Termination of narrowing via termination of rewriting

In the following, we consider **left-linear** **constructor** TRSs:

$$\begin{array}{rcl} f_1(t_{11}, \ldots, t_{1m_1}) & \to & r_1 \\ & \ldots & \\ f_n(t_{n1}, \ldots, t_{nm_n}) & \to & r_n \end{array}$$

with

- $f_i(t_{i1}, \ldots, t_{in_i})$ linear (no multiple occurrences of the same variable)
- $t_{i1}, \ldots, t_{in_i}$ constructor terms (no occurrence of $f_1, \ldots, f_n$)

Property variables are bound to (irreducible) constructor terms

$\Downarrow$

Our approach we replace variables by "data generators" that only produce (ground) constructor terms

Data generators [Antoy, Hanus, 2006; de Dios-Castro, López-Fraguas 2006]

For every TRS $\mathcal{R}$, we define $\mathcal{R}_{\mathsf{gen}}$ as $\mathcal{R}$ augmented with

$$\boxed{\mathsf{gen} \;\to\; \mathsf{c}(\overbrace{\mathsf{gen},\ldots,\mathsf{gen}}^{n \textit{ times}})}$$

for all constructor $\mathsf{c}/n \in \mathcal{C},\;\; n \geqslant 0$

E.g., for $\mathcal{C} = \{\mathsf{z}/0, \mathsf{s}/1\}$, we have

$$\mathcal{R}_{\mathsf{gen}} = \mathcal{R} \cup \left\{ \begin{array}{lcl} \mathsf{gen} & \to & \mathsf{z} \\ \mathsf{gen} & \to & \mathsf{s}(\mathsf{gen}) \end{array} \right\}$$

Some notation: $\widehat{t} = t\sigma$, with $\sigma = \{x \mapsto \mathsf{gen} \mid x \in \mathcal{V}ar(t)\}$

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Correctness of data generators [Antoy, Hanus 2006]

Completeness

$$\text{If } s \leadsto_\sigma t \text{ in } \mathcal{R} \quad \text{then} \quad \widehat{s} \rightarrow^*_{\mathsf{gen}} \widehat{s\sigma} \rightarrow \widehat{t} \text{ in } \mathcal{R}_{\mathsf{gen}}$$

Generally unsound

E.g., $\mathsf{add}(\mathsf{gen}, \mathsf{gen}) \rightarrow \mathsf{add}(\mathsf{z}, \mathsf{gen}) \rightarrow \mathsf{gen} \rightarrow \mathsf{s}(\mathsf{gen}) \rightarrow \mathsf{s}(\mathsf{z})$

but

$$\mathsf{add}(x, x) \leadsto_{\{x \mapsto \mathsf{z}\}} \mathsf{z}$$
$$\mathsf{add}(x, x) \leadsto_{\{x \mapsto \mathsf{s}(x')\}} \mathsf{s}(\mathsf{add}(x', \mathsf{s}(x'))) \leadsto_{\{x' \mapsto \mathsf{z}\}} \mathsf{s}(\mathsf{s}(\mathsf{z}))$$
$$\ldots$$

Soundness is preserved for admissible derivations

- a derivation is admissible iff all the occurrences of gen originating from the replacement of the same variable are reduced to the same term

What about termination in $\mathcal{R}_{\text{gen}}$?

Clearly, no term with occurrences of gen terminates!

Fortunately, **relative termination** of $\mathcal{R}_{\text{gen}}$ suffices:

- T is relatively $\mathcal{R}_{\text{gen}}$-terminating to $\mathcal{R}$ if every derivation $t_1 \to t_2 \ldots$ for $t_1 \in T$ contains finitely many $\to_{\mathcal{R}}$ steps

Theorem (termination of narrowing via termination of rewriting)

Let $\mathcal{R}$ be a left-linear constructor TRS
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Proving termination automatically

The problem

Given $\mathcal{R}$ and T,

T is $\leadsto_{\mathcal{R}}$-terminating if $\widehat{T}$ is relatively $\rightarrow_{\mathcal{R}_{\text{gen}}}$-terminating to $\mathcal{R}$

Drawback

- the set T is generally infinite

Solution: use abstract terms

- similar to modes in logic programming
- E.g., $\text{add}(g, v)$ denotes the set of terms $\text{add}(t_1, t_2)$ with
  - t_1 (definitely) **g**round
  - t_2 (possibly) **v**ariable
- concretization funcion γ,

  e.g., $\gamma(\text{add}(g, v)) = \{\text{add}(z, x), \text{add}(z, z), \text{add}(s(z), x), \text{add}(s(z), z), \ldots\}$

Proving termination automatically

The problem

Given $\mathcal{R}$ and T,

T is $\leadsto_{\mathcal{R}}$-terminating if $\widehat{T}$ is relatively $\rightarrow_{\mathcal{R}_{\text{gen}}}$-terminating to $\mathcal{R}$

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- the set T is generally infinite

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Proving termination automatically

The problem (revised)

Given $\mathcal{R}$ and t^α,

$\gamma(t^\alpha)$ is $\leadsto_{\mathcal{R}}$-terminating if $\widehat{\gamma(t^\alpha)}$ is relatively $\rightarrow_{\mathcal{R}_{\mathsf{gen}}}$-terminating to $\mathcal{R}$

Drawback

- checking relative termination requires non-standard techniques

Solution: use argument filterings

- to filter away non-ground arguments of terms
  (equivalently, to filter away occurrences of gen)

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Argument filterings [Kusakari, Nakamura, Toyama 1999]

$\boxed{\pi(\mathsf{f}) \subseteq \{1,\ldots,n\} \text{ for every defined function } \mathsf{f}/n}$

Argument filterings over terms & TRSs:

$$\pi(t) = \begin{cases} x & \text{if } t = x \\ \mathsf{c}(\pi(t_1),\ldots,\pi(t_n)) & \text{if } t = \mathsf{c}(t_1,\ldots,t_n) \\ \mathsf{f}(\pi(t_{i_1}),\ldots,\pi(t_{i_m})) & \text{if } t = \mathsf{f}(t_1,\ldots,t_n) \text{ and } \pi(\mathsf{f}) = \{i_1,\ldots,i_m\} \end{cases}$$

$$\pi(l \to r) \;=\; \pi(l) \to \pi_{\mathsf{rhs}}(r)$$

where $\pi_{\mathsf{rhs}} \approx \pi$ but replaces some extra-variables by a fresh constant $\perp$

From t^α we infer a safe argument filtering π for t^α

- $\pi(t^\alpha) = \mathsf{f}(g,g,\ldots,g)$
- for all $s \leadsto t$, if $\pi(s|_p)$ are ground then $\pi(t|_q)$ are ground too

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Proving termination automatically: approaches

A direct approach

- based on dependency pairs [Arts, Giesl 2000]
- only a slight extension needed

A transformational approach

- based on argument filtering transformation [Kusakari, Nakamura, Toyama 1999]
- no significant extension required

Dependency pairs approach

Dependency pairs $DP(\mathcal{R})$ of a TRS $\mathcal{R}$

$$DP(\mathcal{R}) = \{\ F(s_1,\ldots,s_n) \to G(t_1,\ldots,t_m) \mid \begin{array}{l} f(s_1,\ldots,s_n) \to r \in \mathcal{R} \\ r|_p = g(t_1,\ldots,t_m) \end{array} \}$$

where F, G are tuple symbols

Example

$$\begin{aligned} \mathrm{append}(\mathrm{nil}, y) &\to y \\ \mathrm{append}(\mathrm{cons}(x, xs), y) &\to \mathrm{cons}(x, \mathrm{append}(xs, y)) \\ \mathrm{reverse}(\mathrm{nil}) &\to \mathrm{nil} \\ \mathrm{reverse}(\mathrm{cons}(x, xs)) &\to \mathrm{append}(\mathrm{reverse}(xs), \mathrm{cons}(x, \mathrm{nil})) \end{aligned}$$

$$\mathrm{APPEND}(\mathrm{cons}(x, xs), y) \to \mathrm{APPEND}(xs, y) \quad (1)$$
$$\mathrm{REVERSE}(\mathrm{cons}(x, xs)) \to \mathrm{REVERSE}(xs) \quad (2)$$
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Dependency pairs approach: differences

Definition (chain)

A (possibly infinite) sequence of dependency pairs $s_1 \to t_1$, $s_2 \to t_2, \ldots$ from $DP(\mathcal{R})$ is a $(DP(\mathcal{R}), \mathcal{R}, \pi)$-chain if

- $\exists$ (constructor) substitution σ such that $\widehat{t_i\sigma} \to^*_{\mathcal{R}_{\text{gen}}} \widehat{s_{i+1}\sigma}$ for $i \geqslant 1$
- $\pi(\widehat{s_i\sigma}), \pi(\widehat{t_i\sigma})$ contain no occurrences of gen

Three main extensions w.r.t. the standard notion:

- it is parameterized by π
- variables are replaced by gen and reductions w.r.t. $\mathcal{R}_{\text{gen}}$
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Example

Given the dependency pair

$$\mathsf{APPEND}(\mathsf{cons}(x, xs), y) \to \mathsf{APPEND}(xs, y) \qquad (1)$$

we have an infinite $(DP(\mathcal{R}), \mathcal{R}, \pi)$-chain, (1),(1),. . . , for

$$\pi(\mathsf{append}) = \pi(\mathsf{APPEND}) = \{2\}$$

since there exists $\sigma = \{y \mapsto \mathsf{nil}\}$ such that

$$\begin{array}{ccc} \mathsf{APPEND}(\mathsf{cons}(x, xs), y) & \to & \mathsf{APPEND}(xs, y) \quad (1) \\ \widehat{t\sigma}\uparrow & & \downarrow\widehat{t\sigma} \\ \mathsf{APPEND}(\mathsf{cons}(\mathsf{gen}, \mathsf{gen}), \mathsf{nil}) & \leftarrow & \mathsf{APPEND}(gen, \mathsf{nil}) \end{array}$$

where $\pi(\mathsf{APPEND}(\mathsf{gen}, \mathsf{nil})) = \pi(\mathsf{APPEND}(\mathsf{cons}(\mathsf{gen}, \mathsf{gen}), \mathsf{nil})) \in \mathcal{T}(\mathcal{F})$

(not a chain in the standard framework of rewriting)

Theorem

Let π be a safe argument filtering for t^α in $\mathcal{R}$
If there is no infinite $(DP(\mathcal{R}), \mathcal{R}, \pi)$-chain, then $\gamma(t^\alpha)$ is $\leadsto_{\mathcal{R}}$-terminating

Now, we could follow the standard dependency pair framework...

Argument filtering processor

E.g., we prove the soundness of transforming the DP problem

$$(DP(\mathcal{R}), \mathcal{R}, \pi) \qquad \Longrightarrow \qquad (\pi(DP(\mathcal{R})), \pi(\mathcal{R}), id)$$

where $id(\mathsf{f}) = \{1, \ldots, n\}$ for all f/n occurring in $\pi(\mathcal{R})$

Therefore,

- all DP processors [GTSKF06] for proving the termination of rewriting can also be used for proving the termination of narrowing

Example

$t^\alpha = \mathsf{append}(g, v)$

$\pi = \{\mathsf{append} \mapsto \{1\},\ \mathsf{reverse} \mapsto \{1\}\}$ (π is safe for t^α)

The argument filtering processor returns:

Dependency pairs:

$$\left\{ \begin{array}{rcl} \mathsf{APPEND}(\mathsf{cons}(x, xs)) & \to & \mathsf{APPEND}(xs) \\ \mathsf{REVERSE}(\mathsf{cons}(x, xs)) & \to & \mathsf{REVERSE}(xs) \\ \mathsf{REVERSE}(\mathsf{cons}(x, xs)) & \to & \mathsf{APPEND}(\mathsf{reverse}(xs)) \end{array} \right.$$

Rewrite system:

$$\left\{ \begin{array}{rcl} \mathsf{append}(\mathsf{nil}) & \to & \perp \\ \mathsf{append}(\mathsf{cons}(x, xs)) & \to & \mathsf{cons}(x, \mathsf{append}(xs)) \\ \mathsf{reverse}(\mathsf{nil}) & \to & \mathsf{nil} \\ \mathsf{reverse}(\mathsf{cons}(x, xs)) & \to & \mathsf{append}(\mathsf{reverse}(xs)) \end{array} \right.$$

Argument filtering: $id = \{\mathsf{append} \mapsto \{1\},\ \mathsf{reverse} \mapsto \{1\}\}$

A transformational approach

Our aim

- transform the original TRS $\mathcal{R}$ into a new TRS $\mathcal{R}'$
- narrowing terminates in $\mathcal{R}$ if rewriting terminates in $\mathcal{R}'$

Hence any termination technique for rewrite systems can be used to prove the termination of narrowing

Our transformation is a simplification of the *argument filtering transformation* (AFT) of [Kusakari, Nakamura, Toyama 1999]

The transformation $\mathsf{AFT}_\pi(\mathcal{R})$

for every rule $l \to r$ of the original rewrite system, produce

- a filtered rule $\pi(l) \to \pi_{rhs}(r)$ and
- an additional rule $\pi(l) \to \pi(t)$, for each subterm t of r that is filtered away in $\pi_{rhs}(r)$ and such that $\pi(t)$ is not a constructor term.

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Main result

Theorem

Let π be a safe argument filtering for t^α in $\mathcal{R}$
$\gamma(t^\alpha)$ is $\leadsto_{\mathcal{R}}$-terminating if $\mathsf{AFT}_\pi(\mathcal{R})$ is terminating

Therefore,

- $\mathsf{AFT}_\pi(\mathcal{R})$ can be analyzed using standard techniques and tools for proving the termination of TRSs

  (no data generator is involved in the derivations of $\mathsf{AFT}_\pi(\mathcal{R})$)

Example

$$\begin{aligned}
\mathsf{append}(\mathsf{nil}, y) &\to y \\
\mathsf{append}(\mathsf{cons}(x, xs), y) &\to \mathsf{cons}(x, \mathsf{append}(xs, y)) \\
\mathsf{reverse}(\mathsf{nil}) &\to \mathsf{nil} \\
\mathsf{reverse}(\mathsf{cons}(x, xs)) &\to \mathsf{append}(\mathsf{reverse}(xs), \mathsf{cons}(x, \mathsf{nil}))
\end{aligned}$$

$t^\alpha = \mathsf{append}(g, v)$
$\pi = \{\mathsf{append} \mapsto \{1\},\ \mathsf{reverse} \mapsto \{1\}\}$ (π is safe for t^α)

The transformation $\mathsf{AFT}_\pi(\mathcal{R})$ returns

$$\begin{aligned}
\mathsf{append}(\mathsf{nil}) &\to y \qquad\qquad (y \text{ is an extra variable}) \\
\mathsf{append}(\mathsf{cons}(x, xs)) &\to \mathsf{cons}(x, \mathsf{append}(xs)) \\
\mathsf{reverse}(\mathsf{nil}) &\to \mathsf{nil} \\
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\end{aligned}$$

which is clearly **not** terminating

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$$\begin{aligned} \mathsf{append}(\mathsf{nil}) &\to \cancel{y}\ \ \bot && (\bot \text{ is a fresh constant}) \\ \mathsf{append}(\mathsf{cons}(x, xs)) &\to \mathsf{cons}(x, \mathsf{append}(xs)) \\ \mathsf{reverse}(\mathsf{nil}) &\to \mathsf{nil} \\ \mathsf{reverse}(\mathsf{cons}(x, xs)) &\to \mathsf{append}(\mathsf{reverse}(xs)) \end{aligned}$$

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The termination tool TNT

It takes as input

- a left-linear constructor TRS
- an abstract term

and proceeds as follows:

- infers a safe argument filtering for the abstract term (a binding-time analysis)
- returns a transformed TRS using AFT_π

Website: http://german.dsic.upv.es/filtering.html

The termination of the transformed TRS can be checked with APROVE

[DEMO]

Inference of safe argument filterings

We have adapted a simple **binding-time analysis**

- **binding-times**: definitevely **g**round / possibly **v**ariable

$$g \sqcup g = g \qquad g \sqcup v = v \qquad v \sqcup g = v \qquad v \sqcup v = v$$

$$(g, v, g) \sqcup (g, g, v) = (g, v, v)$$

$$\{\mathsf{f} \mapsto (g, v),\ \mathsf{g} \mapsto (g, v)\} \sqcup \{\mathsf{f} \mapsto (g, g),\ \mathsf{g} \mapsto (v, g)\}$$
$$= \{\mathsf{f} \mapsto (g, v),\ \mathsf{g} \mapsto (v, v)\}$$

- **binding-time environment**: a substitution mapping variables to binding-times
- **division**: a mapping $\mathsf{f}/n \mapsto (m_1, \ldots, m_n)$ for every defined function, where each m_i is a binding-time

Auxiliary functions

$$
\begin{array}{lll}
B_v[[x]]\ \mathrm{g}/n\ \rho & = (\overbrace{g, \ldots, g}^{n\ times}) & (\text{if } x \in \mathcal{V}) \\
B_v[[\mathrm{c}(t_1, \ldots, t_n)]]\ \mathrm{g}/n\ \rho & = B_v[[t_1]]\ \mathrm{g}/n\ \rho \sqcup \ldots \sqcup B_v[[t_n]]\ \mathrm{g}/n\ \rho & (\text{if c} \in \mathcal{C}) \\
B_v[[\mathrm{f}(t_1, \ldots, t_n)]]\ \mathrm{g}/n\ \rho & = bt \sqcup (B_e[[t_1]]\ \rho, \ldots, B_e[[t_n]]\ \rho) & (\text{if f} = \mathrm{g},\ \mathrm{f} \in \mathcal{D}) \\
 & \quad bt & (\text{if f} \neq \mathrm{g},\ \mathrm{f} \in \mathcal{D}) \\
 & \quad \text{where } bt = B_v[[t_1]]\ \mathrm{g}/n\ \rho \sqcup \ldots \sqcup B_v[[t_n]]\ \mathrm{g}/n\ \rho &
\end{array}
$$

$$
\begin{array}{lcll}
B_e[[x]]\ \rho & = & x\rho & (\text{if } x \in \mathcal{V}) \\
B_e[[\mathrm{h}(t_1, \ldots, t_n)]]\ \rho & = & B_e[[t_1]]\ \rho \sqcup \ldots \sqcup B_e[[t_n]]\ \rho & (\text{if h} \in \mathcal{C} \cup \mathcal{D})
\end{array}
$$

Roughly speaking,

- ($B_v[[t]]\ \mathrm{g}/n\ \rho$) returns a sequence of n binding-times that denote the (lub of the) binding-times of the arguments of the calls to g/n that occur in t in the context of the binding-time environment ρ
- ($B_e[[t]]\ \rho$) then returns g if t contains no variable which is bound to v in ρ, and v otherwise

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\begin{array}{lcll}
B_e[[x]]\ \rho & = & x\rho & (\text{if } x \in \mathcal{V}) \\
B_e[[\mathrm{h}(t_1,\ldots,t_n)]]\ \rho & = & B_e[[t_1]]\ \rho \sqcup \ldots \sqcup B_e[[t_n]]\ \rho & (\text{if } \mathrm{h} \in \mathcal{C} \cup \mathcal{D})
\end{array}
$$

Roughly speaking,

- $(B_v[[t]]\ \mathrm{g}/n\ \rho)$ returns a sequence of n binding-times that denote the (lub of the) binding-times of the arguments of the calls to g/n that occur in t in the context of the binding-time environment ρ
- $(B_e[[t]]\ \rho)$ then returns g if t contains no variable which is bound to v in ρ, and v otherwise

BTA algorithm

Given an abstract term $\mathsf{f}_1(m_1, \ldots, m_{n_1})$, the initial division is

$$div_0 = \{\mathsf{f}_1 \mapsto (m_1, \ldots, m_{n_1}),\ \mathsf{f}_2 \mapsto (g, \ldots, g),\ \ \ldots,\ \mathsf{f}_k \mapsto (g, \ldots, g)\}$$

where $\mathsf{f}_1/n_1, \ldots, \mathsf{f}_k/n_k$ are the defined functions of the TRS

Iterative process

$$div_i = \{\mathsf{f}_1 \mapsto b_1,\ \ldots,\ \mathsf{f}_k \mapsto b_k\}$$
$$\Downarrow$$
$$\begin{array}{rl} div_{i+1} = \{ & \mathsf{f}_1 \mapsto b_1 \sqcup B_v[[r_1]]\ \mathsf{f}_1/n_1\ e(b_1, l_1) \sqcup \ldots \sqcup B_v[[r_j]]\ \mathsf{f}_1/n_1\ e(b_j, l_j), \\ & \ldots, \\ & \mathsf{f}_k \mapsto b_k \sqcup B_v[[r_1]]\ \mathsf{f}_k/n_k\ e(b_1, l_1) \sqcup \ldots \sqcup B_v[[r_j]]\ \mathsf{f}_k/n_k\ e(b_j, l_j)\ \} \end{array}$$

where $l_1 \rightarrow r_1, \ldots, l_j \rightarrow r_j$, $j \geq k$, are the rules of the TRS

$$\begin{array}{rcl} e((m_1, \ldots, m_n), \mathsf{f}(t_1, \ldots, t_n)) & = & \{x \mapsto m_1 \mid x \in \mathcal{V}\mathrm{ar}(t_1)\} \\ & \cup & \ldots \\ & \cup & \{x \mapsto m_n \mid x \in \mathcal{V}\mathrm{ar}(t_n)\} \end{array}$$

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When $div_i = div_{i+1}$ (fixpoint), the corresponding safe argument filtering π is obtained as follows:

Given the division

$$\boxed{div = \{\mathsf{f}_1 \mapsto (m^1_1, \ldots, m^1_{n_1}), \ldots, \mathsf{f}_k \mapsto (m^k_1, \ldots, m^k_{n_k})\}}$$

we have

$$\boxed{\pi(div) = \{\mathsf{f}_1 \mapsto \{i \mid m^1_i = g\}, \ldots, \mathsf{f}_k \mapsto \{i \mid m^k_i = g\}\}}$$

$\pi(div)$ is a safe argument filtering since the computed division *div* is *congruent* [JGS93]

Example

$$\begin{array}{rcl} \mathsf{mult}(\mathsf{z}, y) & \to & \mathsf{z} \\ \mathsf{mult}(\mathsf{s}(x), y) & \to & \mathsf{add}(\mathsf{mult}(x, y), y) \end{array} \qquad \begin{array}{rcl} \mathsf{add}(\mathsf{z}, y) & \to & y \\ \mathsf{add}(\mathsf{s}(x), y) & \to & \mathsf{s}(\mathsf{add}(x, y)) \end{array}$$

Given the abstract term $\mathsf{mult}(g, v)$, the associated initial division is

$$div_0 = \{\mathsf{mult} \mapsto (g, v),\ \mathsf{add} \mapsto (g, g)\}$$

The next division, div_1, is obtained from the following expression:

$$\begin{array}{rll} div_1 = \{\mathsf{mult} \mapsto (g, v) & \sqcup & B_v[[\mathsf{z}]]\ \mathsf{mult}/2\ \{y \mapsto v\} \\ & \sqcup & B_v[[\mathsf{add}(\mathsf{mult}(x, y), y)]]\ \mathsf{mult}/2\ \{x \mapsto g,\ y \mapsto v\} \\ & \sqcup & B_v[[y]]\ \mathsf{mult}/2\ \{y \mapsto g\} \\ & \sqcup & B_v[[\mathsf{s}(\mathsf{add}(x, y))]]\ \mathsf{mult}/2\ \{x \mapsto g,\ y \mapsto g\}, \\ \mathsf{add} \mapsto (g, g) & \sqcup & B_v[[\mathsf{z}]]\ \mathsf{add}/2\ \{y \mapsto v\} \\ & \sqcup & B_v[[\mathsf{add}(\mathsf{mult}(x, y), y)]]\ \mathsf{add}/2\ \{x \mapsto g,\ y \mapsto v\} \\ & \sqcup & B_v[[y]]\ \mathsf{add}/2\ \{y \mapsto g\} \\ & \sqcup & B_v[[\mathsf{s}(\mathsf{add}(x, y))]]\ \mathsf{add}/2\ \{x \mapsto g,\ y \mapsto g\} \quad \} \end{array}$$

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Example (cont'd)

Therefore, by evaluating the calls to B_v, we get

$$\boxed{div_1 = \{\mathsf{mult} \mapsto (g, v),\ \mathsf{add} \mapsto (v, v)\}}$$

Note that the change in the binding-times of add comes from the evaluation of

$$B_v[\![\mathsf{add}(\mathsf{mult}(x, y), y)]\!]\ \mathsf{add}/2\ \{x \mapsto g,\ y \mapsto v\}$$

where a call to add appears
(and every argument contains at least one possibly unknown value)

$\Rightarrow$ **If we compute** div_2 **we get** $div_1 = div_2 \Longrightarrow$ div_1 **is a fixpoint**

From this division, the associated safe argument filtering is

$$\boxed{\pi = \{\ \mathsf{mult} \mapsto \{1\},\ \mathsf{add} \mapsto \{\ \}\ \}}$$

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Some refinements

Multiple abstract terms

Consider, e.g.,

$$\begin{array}{rcl} \mathsf{eq}(\mathsf{z},\mathsf{z}) & \to & \mathsf{true} \\ \mathsf{eq}(\mathsf{s}(x),\mathsf{s}(y)) & \to & \mathsf{eq}(x,y) \end{array}$$

and the set

$$T^\alpha = \{\mathsf{eq}(g,v),\ \mathsf{eq}(v,g)\}$$

Here, starting from

$$div_0 = \{\ \mathsf{eq} \mapsto (g,v) \sqcup (v,g)\ \} = \{\ \mathsf{eq} \mapsto (v,v)\ \}$$

is not a good idea . . .

Solution

Lemma

Let $\mathcal{R}$ be a TRS and T^α be a finite set of abstract terms. $\gamma(T^\alpha)$ is $\leadsto_{\mathcal{R}}$-terminating iff $\gamma(t^\alpha)$ is $\leadsto_{\mathcal{R}}$-terminating for all $t^\alpha \in T^\alpha$.

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Some refinements (cont'd)

Non well-moded programs

Consider, e.g.,

$$\begin{array}{rcl} \mathsf{eq}(\mathsf{z},\mathsf{z}) & \rightarrow & \mathsf{true} \\ \mathsf{eq}(\mathsf{s}(x),\mathsf{s}(y)) & \rightarrow & \mathsf{eq}(y,x) \end{array}$$

If we start with

$$\mathsf{eq}(g,v)$$

the only safe argument filtering is

$$\pi = \{\mathsf{eq} \mapsto \{\,\}\}$$

Solution

$$\begin{array}{rcl} \mathsf{eq}_{gg}(\mathsf{z},\mathsf{z}) & \rightarrow & \mathsf{true} \\ \mathsf{eq}_{gg}(\mathsf{s}(x),\mathsf{s}(y)) & \rightarrow & \mathsf{eq}_{gg}(y,x) \\ \mathsf{eq}_{vg}(\mathsf{z},\mathsf{z}) & \rightarrow & \mathsf{true} \\ \mathsf{eq}_{vg}(\mathsf{s}(x),\mathsf{s}(y)) & \rightarrow & \mathsf{eq}_{gv}(y,x) \end{array} \qquad \begin{array}{rcl} \mathsf{eq}_{gv}(\mathsf{z},\mathsf{z}) & \rightarrow & \mathsf{true} \\ \mathsf{eq}_{gv}(\mathsf{s}(x),\mathsf{s}(y)) & \rightarrow & \mathsf{eq}_{vg}(y,x) \\ \mathsf{eq}_{vv}(\mathsf{z},\mathsf{z}) & \rightarrow & \mathsf{true} \\ \mathsf{eq}_{vv}(\mathsf{s}(x),\mathsf{s}(y)) & \rightarrow & \mathsf{eq}_{vv}(y,x) \end{array}$$

Some refinements (cont'd)

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Some refinements (cont'd)

Removing non-reachable functions

Consider, e.g.,

$$\begin{array}{lcl} a & \to & a \\ b & \to & c \\ c & \to & d \end{array}$$

Although narrowing terminates for the abstract term b we get the argument filtering

$$\pi = \{a \mapsto \{\,\},\ b \mapsto \{\,\},\ c \mapsto \{\,\}\}$$

and hence we fail to prove its termination...

Solution

Remove function definitions not reachable from b (i.e., $a \to a$)

Some refinements (cont'd)

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$$\begin{array}{lcl} \mathsf{a} & \to & \mathsf{a} \\ \mathsf{b} & \to & \mathsf{c} \\ \mathsf{c} & \to & \mathsf{d} \end{array}$$

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Remove function definitions not reachable from b (i.e., a $\to$ a)

Related work

Schneider-Kamp *et al* [SKGST07] presented an automated termination analysis for logic programs:

- logic programs are first translated to TRSs
- logic variables are simulated by infinite terms

Main differences:

- data generators (reuse of results relating narrowing and rewriting)
- no transformational approach in [SKGST07]

Nishida and Miura [NM06] adapted the dependency pair method for proving the termination of narrowing:

- direct approach (not based on using generators & rewriting)
- allow extra variables in TRSs
- not comparable

Conclusions

Conclusions

- new techniques for proving the termination of narrowing in left-linear constructor systems
- good potential for reusing existing techniques and tools for rewriting
- first tool for proving the termination of narrowing

Future work

- extension to deal with extra-variables
- application to (offline) partial evaluation

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