Using CLP Simplifications to Improve Java Bytecode Termination Analysis

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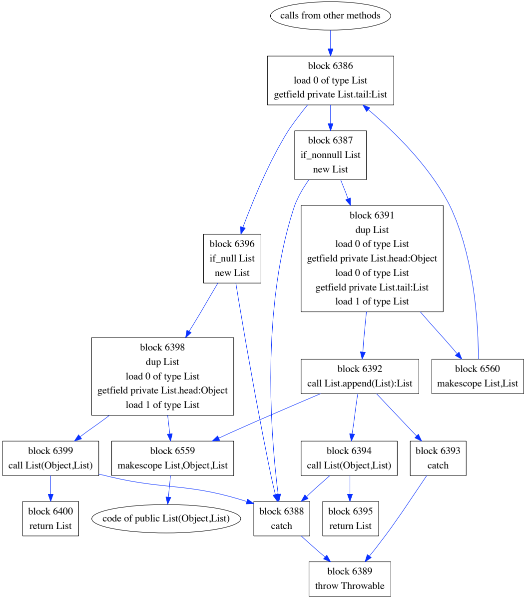
Introduction

JuliaWeb is a termination analyzer for Java Bytecode:
`http://julia.scienze.univr.it/termination`

In this paper:

- we propose a set of simplifications of the *CLP* programs generated by the termination analysis in JuliaWeb;
- we prove those transformations correct w.r.t. termination;
- we experiment with those transformations.

From Java Bytecode to CLP



From Java Bytecode to CLP

Example

```
block6391(IL0,IL1,IS0) :-
    {IS0=OS1, IL1=OS4, IS0=OS0, IL1=OL1, IL0=OL0,
     OS3 >= 0, OS2 >= 0, IL0-OS3 >= 1, IL0-OS2 >= 1},
    block6392(OL0,OL1,OS0,OS1,OS2,OS3,OS4).

block6391(IL0,IL1,IS0) :-
    {IS0=OS1, IL1=OS4, IS0=OS0, IL1=OL1, IL0=OL0,
     OS3 >= 0, OS2 >= 0, IL0-OS3 >= 1, IL0-OS2 >= 1},
    block6560(OL0,OL1,OS0,OS1,OS2,OS3,OS4).
```

- predicates are named `block`*i* or `entry`*j*;
- two arrows connect block 6391 with blocks 6392 and 6560;
- two local variables `L0` and `L1` are in scope: `L0` implements `this` and `L1` `other`;
- at the beginning of block 6391, there is only one stack element `S0`, while there are 5 at its end.

CLP($\mathbb{Z}_{Lin}$): Operational semantics

Let $\vec{m}, \vec{n} \in \mathbb{Z}^*$ and C be the clause

$$p(\vec{i}) \text{ :- } c, q(\vec{o})$$

where c is a linear constraint over the variables $\vec{i} \cup \vec{o}$.

- $q(\vec{n})$ *is derived from* $p(\vec{m})$ using C, written $p(\vec{m}) \rightarrow^C q(\vec{n})$, if there is a solution θ of $c[\vec{i} \mapsto \vec{m}]$ such that $q(\vec{n}) = q(\vec{o})\theta$.
- A *derivation* of $p_0(\vec{n}_0)$ is $p_0(\vec{n}_0) \rightarrow p_1(\vec{n}_1) \rightarrow \cdots \rightarrow p_k(\vec{n}_k)$ such that $p_{i+1}(\vec{n}_{i+1})$ is derived from $p_i(\vec{n}_i)$ for all $0 \leq i < k$.
- A *resolution* is a maximal derivation.

NB: our semantics is *ground* CLP.

CLP($\mathbb{Z}_{Lin}$): Termination

- An entry p *terminates* in a program P if, for every $\vec{n} \in \mathbb{Z}^*$, all resolutions of $p(\vec{n})$ by using the clauses of P, with predicates in the strongly connected component of p, are finite. Otherwise, p *diverges*.
- Let P_1 and P_2 be programs. P_1 *terminates more* than P_2, written $P_1 \sqsupseteq P_2$, if whenever an entry of P_1 terminates in P_1, it also terminates in P_2.
- P_1 and P_2 are *termination-equivalent*, written $P_1 \equiv P_2$, if P_1 terminates more than P_2 and vice versa.

NB: our definition formalizes a *loop-local* notion of termination.

PS1: Removing clauses outside loops

A clause $p(\vec{i})$:- $c, q(\vec{o})$ *occurs in a loop* if p and q belong to the same strongly connected component of predicates.

Proposition

Let P be a program and P_s be the same program deprived of those clauses that do not occur in a loop. Then $P \equiv P_s$.

PS2: Removing clauses by unfolding

If a program contains clauses $p(\vec{m})$:- $c_1, q(\vec{n})$ and $q(\vec{v})$:- $c_2, r(\vec{w})$, we can *unfold* them into the clause $p(\vec{m})$:- $c_1 \wedge c_2 \wedge \vec{n} = \vec{v}, r(\vec{w})$.

Done systematically for all occurrences of q on the right of the clauses of P, and followed by the removal of the clauses defining q, we say that we *unfold q away from P*.

Proposition

Let P be a program and q a non-entry predicate in P with no clause of the form $q(\vec{n})$:- $c, q(\vec{m})$. Let P_s be P where q has been unfolded away. Then $P \equiv P_s$.

PS3: Removing unsupported or subsumed clauses

$p(\vec{i})$:- $c, q(\vec{o})$ is *unsupported* if q is undefined.

$p(\vec{i})$:- $c_1, q(\vec{o})$ *subsumes* $p(\vec{i})$:- $c_2, q(\vec{o})$ if c_1 entails c_2.

Proposition

Let P be a program and P_s be P deprived from unsupported or subsumed clauses. Then $P \equiv P_s$.

Removing variables?

Let c be a constraint:

- $c^v \quad = $ the v*-dedicated part* of $c \quad = \exists_{-\{iv,ov\}}.c$
- $c^{-v} = $ the v*-independent part* of $c = \exists_{\{iv,ov\}}.c$

An operation that removes a variable from a predicate:

$$p(iv_1, \dots, iv_n) \ominus v = \begin{cases} p(iv_1, \dots, iv_{i-1}, iv_{i+1}, \dots, iv_n) & \text{if } v \equiv v_i \\ p(iv_1, \dots, iv_n) & \text{otherwise.} \end{cases}$$

The transformation:

$$Comp^{-v} = \{p(\vec{i}) \ominus v \text{ :- } c^{-v}, q(\vec{o}) \ominus v \mid p(\vec{i}) \text{ :- } c, q(\vec{o}) \in Comp\}$$

removes v from a strongly connected component *Comp*.

Removing variables?

Proposition

Let p_0 be an entry diverging in *Comp*. Then p_0 also diverges in $Comp^{-v}$.

In general, *Comp* is *not* termination-equivalent to $Comp^{-v}$, as shown by the counter-example 4.8 of the paper.

In what follows, we identify two cases where removal of a variable *maintains* termination equivalence. Common condition:

- a variable v is *isolated* in a strongly connected component *Comp* if, for every $p(\vec{i})$:- $c, q(\vec{o}) \in Comp$, $c = c^v \wedge c^{-v}$.

PS4: Removing open variables

- An isolated variable v in a strongly connected component *Comp* is *right-open* if, for every $p(\vec{i})$:- $c, q(\vec{o}) \in Comp$, we have that c^v is either *true* or $iv = ov$, or $ov \geq const$, $ov = const$ or $ov \leq const$ (or equivalent), where *const* is an integer constant. *Left-openness* is defined analogously.

Proposition

Let v be right- or left-open in a strongly connected component *Comp*. If an entry diverges in $Comp^{-v}$ then it diverges in *Comp*.

PS4: Removing open variables

Example

L1 is isolated and right-open in the component:

```
entry3880(IL0,IL1) :-
    {IL1 = OL1, OL0 >= 0, IL0 >= 2, IL0 - OL0 >= 1},
    entry3880(OL0,OL1).
```

Hence L1 can be removed:

```
entry3880(IL0) :-
    {OL0 >= 0, IL0 >= 2, IL0 - OL0 >= 1},
    entry3880(OL0).
```

PS5: Removing uniform variables

- An isolated variable v is *uniform* in a strongly connected component *Comp* if there is $x \in \mathbb{Z}$ such that, for every $p(\vec{i})$:- $c, q(\vec{o}) \in Comp$, the valuation $\{iv \mapsto x, ov \mapsto x\}$ is a solution of c^v.

Property

Let a variable v be uniform in a strongly connected component *Comp*. If an entry diverges in $Comp^{-v}$ then it diverges *Comp*.

PS5: Removing uniform variables

Example

```
block3853(IL0,IL1,IL2) :-
    {IL2 - OL2 = -1, IL1 = OL1, IL0 = OL0, IL1 - IL2 >= 1},
    block3853(OL0,OL1,OL2).
block3853(IL0,IL1,IL2) :-
    {IL2 - OL2 = -1, IL1 = OL1, OL0 = 1, IL1 - IL2 >= 2},
    entry3849(OL0,OL1,OL2).
entry3849(IL0,IL1,IL2) :-
    {IL2 = OL2, IL1 = OL1, IL0 = OL0, IL0 >= 1},
    block3853(OL0,OL1,OL2).
```

L0 is isolated. Taking $x = 1$ shows that L0 is uniform. Hence L0 can be removed.

Experiments

program	meth.	orig	loops	fold	subsum	open	unif
`Ack`	5	7.11	0.21	0.21	0.21	0.21	0.21
precision		5	5	5	5	5	5
`BubbleS`	5	19.07	1.55	0.71	0.71	0.49	0.49
precision		3	4	5	5	5	5
`NQueens`	222	-	210.31	156.32	92.29	47.77	34.34
precision		-	171	171	171	171	171
`JLex`	137	-	228.51	335.85	374.82	121.95	81.21
precision		-	84	87	102	102	102
`Kitten`	947	-	200.39	226.79	152.47	93.70	79.35
precision		-	811	827	827	827	827

Conclusion

We have presented:

- some termination-equivalent simplifications of the CLP programs that are automatically generated during termination analysis of Java bytecode programs;
- some real case of analysis showing that these simplifications decrease the time for building a proof by some order of magnitude.