Principles of Staged Static+Dynamic Partial Analysis

29th Static Analysis Symposium

Aditya Anand and Manas Thakur

Indian Institute of Technology Mandi

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Introduction

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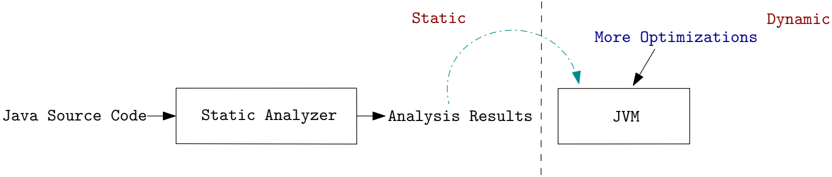
- Performing precise program-analysis during JIT Compilation – highly inefficient.
- Most JIT compilers sacrifice precision for efficiency.
- **Can we use static analysis to impart precision in JIT analyses?**

Using Static Analysis Results in JIT Compilers



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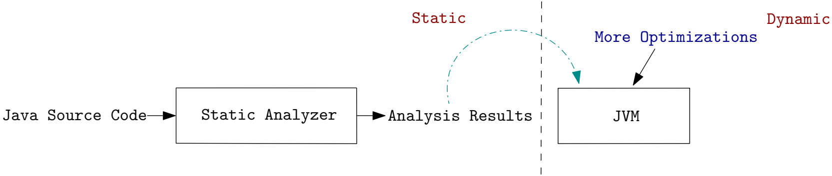

- ❖ Challenge:
  - ✧ Library code needed to perform whole-program analysis.

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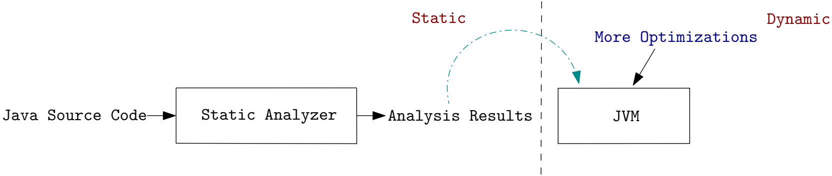


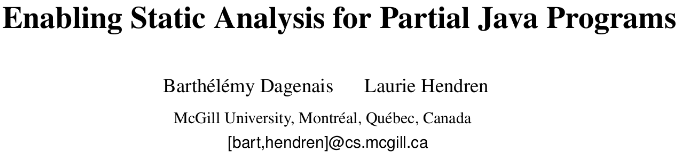
❖ Challenge:

- ✧ Library code needed to perform whole-program analysis.
- ✧ Imprecise results due to conservative assumptions.

Partial Program Analysis

Partial Program Analysis

- Proposed: OOPSLA 2008



Enabling Static Analysis for Partial Java Programs

Barthélémy Dagenais Laurie Hendren

McGill University, Montréal, Québec, Canada
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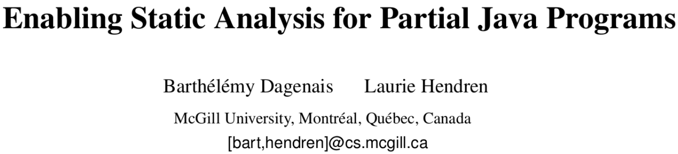

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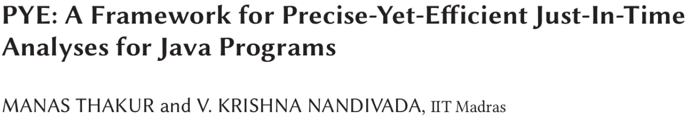
- ❖ Applied to JIT compilers: TOPLAS 2019



PYE: A Framework for Precise-Yet-Efficient Just-In-Time Analyses for Java Programs

MANAS THAKUR and V. KRISHNA NANDIVADA, IIT Madras

PYE Framework and Conditional Values

"Precise-Yet-Efficient" framework generates highly precise analysis results for JIT compilers at a very low cost:

- ❖ Offloads expensive analysis to static compiler (javac) and generates *conditional values*.
- ❖ JIT component evaluates the conditional values at run-time and generates final analysis result.

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- JIT component evaluates the conditional values at run-time and generates final analysis result.

- Essentially, conditional values for a program element enlist the dependencies of that element.

Dependencies in form of Conditional Values

```
class A {
   void foo(B b) {
      A a1 = new A(); // Object O3
      A a2 = new A(); // Object O4
      a1.bar(a2);
      L l1 = new L(); // Object O6
      l1.lib(a2); }
   void  bar(A p1) {
      // no assignment to p1
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```
class L {
   // A library class
   void lib(A r1) {
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- Conditional values for object O_4 (for escape analysis):

$$\begin{aligned} g_{\texttt{A.foo}}(O_4) = \{&\langle\langle \texttt{A.bar}, \texttt{p1}\rangle, D, D\rangle, \langle\langle \texttt{L.lib}, \texttt{r1}\rangle, D, D\rangle, \\ &\langle\langle \texttt{A.bar}, \texttt{p1}\rangle, E, E\rangle, \langle\langle \texttt{L.lib}, \texttt{r1}\rangle, E, E\rangle\} \end{aligned} \tag{1}$$

Partial Result

$$[\![g_{\texttt{A.foo}}(O_4)]\!] = \ \sqcap_{ea} \{D, \langle\langle \texttt{L.lib}, \texttt{r1}\rangle, D, D\rangle, D, \langle\langle \texttt{L.lib}, \texttt{r1}\rangle, E, E\rangle\}$$

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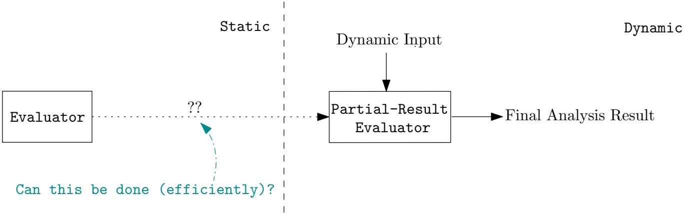

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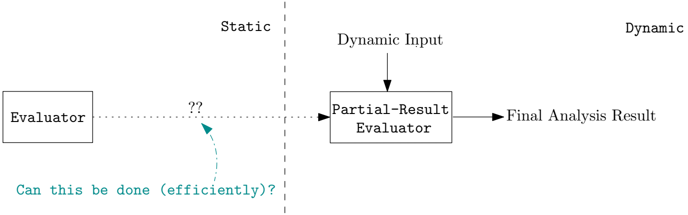

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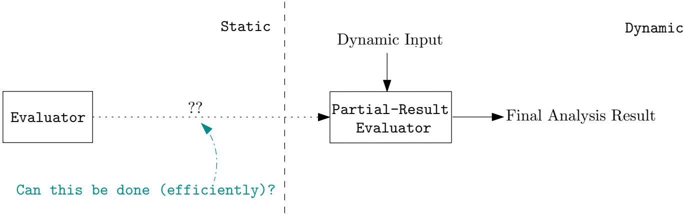
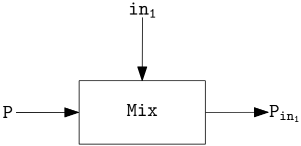


- Does the precision of staged analysis remain same as whole-program analysis? What about its efficiency?

Partial Evaluation

Partial evaluation [Jones 1996] specializes a given program with its statically available inputs. The resultant partially evaluated program can later be executed with the dynamic inputs to generate the final output.



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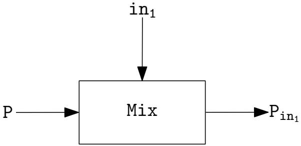

- Advantage: The specialized program $\mathtt{P}_{\mathtt{in}_1}$ often executes faster compared to executing the original program $\mathtt{P}$ provided both static and dynamic inputs together.

Futamura Projections

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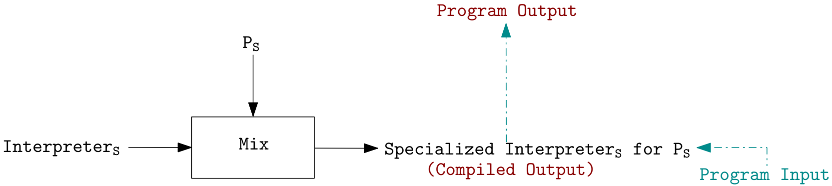

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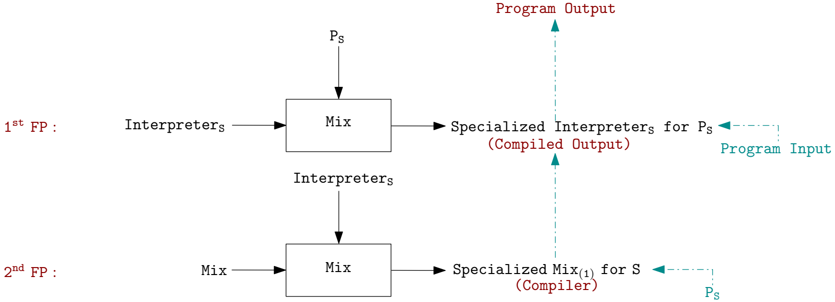

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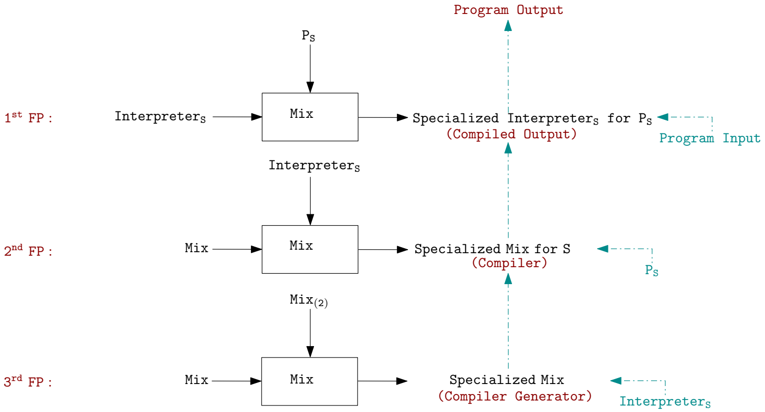

Modeling Partial Analysis based on Partial Evaluation

Mapped Notation

Source Program → $g_m(x)$ (Conditional Values)

Static Inputs → S_x (Resolved Values)

Runtime Inputs → D_x (Unresolved Values)

Evaluator → $\mathtt{CEval}_{\psi}$

Language for Conditional Values

- Conditional Values:

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```
<Start>      ::=  <ProgElem> :  <CV>*
<ProgElem>   ::=  <Class> <Method> <Type> <Ref> <Fields>
<CV>         ::=  <ProgElem> <DepVal> <ResVal>
<Type>       ::=  LOCAL | PARM | ARG | RETVAL | FIELD
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- Updated Conditional Values:

$$\begin{aligned} \langle \texttt{A foo LOCAL 4}\ \langle\texttt{nil}\rangle\rangle : \{&\langle\langle \texttt{A bar PARM 1}\langle\texttt{nil}\rangle\rangle\ \texttt{D D}\rangle, \langle\langle \texttt{L lib RETVAL 1}\langle\texttt{nil}\rangle\ \texttt{D D}\rangle\}, \\ \{&\langle\langle \texttt{A bar PARM 1}\langle\texttt{nil}\rangle\rangle\ \texttt{E E}\rangle, \langle\langle \texttt{L lib RETVAL 1}\langle\texttt{nil}\rangle\ \texttt{E E}\rangle\} \end{aligned}$$

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❖ Tagged Conditional Values:

$\langle$`A foo LOCAL 4` $\langle$`nil`$\rangle\rangle$:

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(a)

```
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<TaggedCV>   ::=   <Tag> <CV>
<Tag>        ::=   STATIC | DYNAMIC
```

(b)

Conditional Value Evaluator

```
Procedure CEval($g_m(x)$, $\texttt{IN}_{g_m(x)}$)
    Initialize a list $L$ of statically known dependencies.
    foreach $d \in \texttt{IN}_{g_m(x)}$ do
        Add $d$ to $L$.
        Add the transitive dependencies of $d$ to $L$.
    Form strongly connected components (SCCs) in the list $L$.
    repeat
        foreach strongly connected component $S$ formed above do
            if $\nexists e \in S$ s.t. $e$ depends on another SCC then
                $\forall e \in S$, resolve $e$ to $\perp$.
            Take a meet of the resolved values in each SCC
    until fixed point;
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- Evaluated Conditional Values:

$$= \sqcap_{ea} \{\langle\langle \texttt{DYNAMIC L lib RETVAL 1}\langle\texttt{nil}\rangle\ \texttt{D D}\rangle, \langle\langle \texttt{DYNAMIC L lib RETVAL 1}\langle\texttt{nil}\rangle\ \texttt{E E}\rangle\}$$

AM Projections

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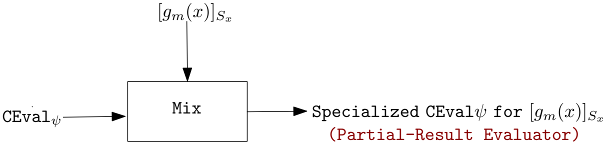
- Specialize the evaluator with the partial result.



$[g_m(x)]_{S_x}$

`CEval`$_\psi$

`Mix`

`Specialized CEval`ψ `for` $[g_m(x)]_{S_x}$

`(Partial-Result Evaluator)`

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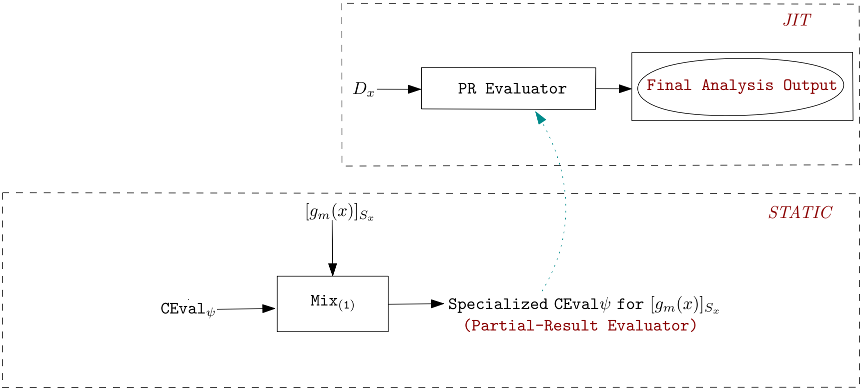


JIT

D_x PR Evaluator Final Analysis Output

STATIC

$[g_m(x)]_{S_x}$

$\texttt{CEval}_{\psi}$ $\texttt{Mix}_{(1)}$ Specialized CEvalψ for $[g_m(x)]_{S_x}$
(Partial-Result Evaluator)

Generated Partial Result Evaluator

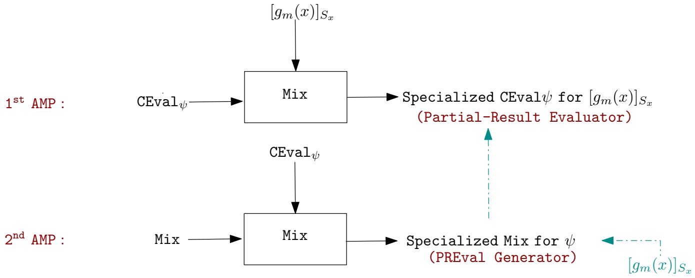
```
class PartialResultEvaluator {
   public static void main(String[] args) {
      // Read the values for dynamic dependencies
      x1 = Resolved value of <L.lib, r1> // first dependence
      x2 = Resolved value of <L.lib, r1> // second dependence
      res = x1 ⊓_ea x2
      print(res);
   }
}
```

Figure: Schema of the partial-result evaluator emitted for $g_{\texttt{A.foo}}(O_4)$.

- Can be placed in any VM to obtain the final analysis result for O_4.

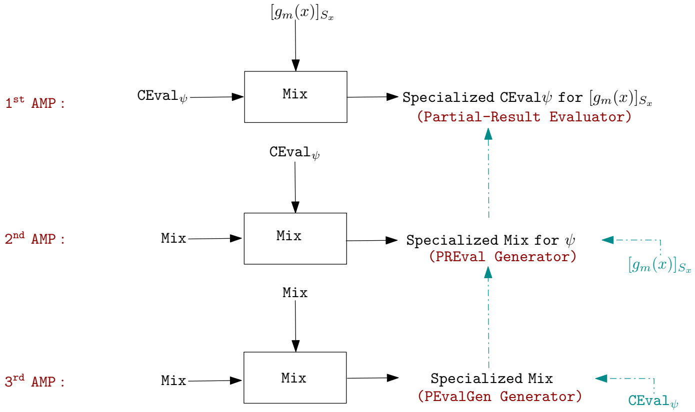
2^{nd} AM Projection

❖ Specialize Mix with the conditional-value evaluator.



3^{rd} AM Projection

- Specialize Mix with Mix.



Efficiency, Correctness and Precision of Staging

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- Lemma 1. Statically available Input

If the set of statically available dependencies is empty, then the specialization performed by the first AM projection for a conditional-value evaluator can be seen in same light as the specialization performed by the first Futamura projection for a program interpreter.

Efficiency, Correctness and Precision of Staging

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- Lemma 2. Maximal Specialization

Partial evaluation of a program with a statically available input implies that the program is specialized to the extent possible (that is, maximally specialized) with respect to that input.

Efficiency, Correctness and Precision of Staging

- Theorem 1. Efficiency

For a given program element and its statically available dependencies, the partial-result evaluator obtained by the first AM projection is maximal in terms of the conditional-value evaluation that can be performed statically.

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For a given program element and its statically available dependencies, the partial-result evaluator obtained by the first AM projection is maximal in terms of the conditional-value evaluation that can be performed statically.

- Theorem 2. Precision and Correctness

For any program element, the analysis results generated by a whole-program analysis and by the corresponding staged analysis are the same.

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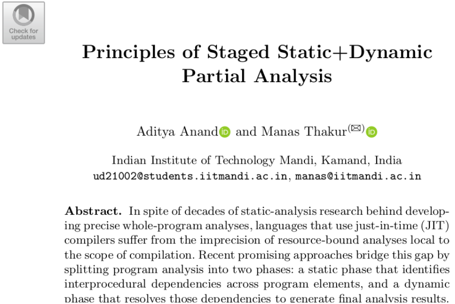

Principles of Staged Static+Dynamic Partial Analysis

Aditya Anand and Manas Thakur(✉)

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Abstract. In spite of decades of static-analysis research behind developing precise whole-program analyses, languages that use just-in-time (JIT) compilers suffer from the imprecision of resource-bound analyses local to the scope of compilation. Recent promising approaches bridge this gap by splitting program analysis into two phases: a static phase that identifies interprocedural dependencies across program elements, and a dynamic phase that resolves those dependencies to generate final analysis results.

Conclusion

- Formalized the theory of staged static+dynamic partial analysis based on the theory of partial evaluation.

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- Projections for efficiently generating the evaluators (and their generators) for partial results.

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Thank You!