Programming Assignment 4:

CHA and Interprocedural Constant Propagation

Course "Static Program Analysis" @Nanjing University
Assignments Designed by Tian Tan and Yue Li
Due: 23:00, Thursday, November 4, 2021

1 Assignment Objectives

- Implement a class hierarchy analysis (CHA) for Java.
- Implement an interprocedural constant propagation.
- Implement a worklist solver for interprocedural data-flow analysis.

In this programming assignment, you will implement a CHA-based call graph builder for Java on top of Tai-e. To demonstrate the usefulness of call graph, you will complete an interprocedural constant propagation, which uses the call graph constructed by your analysis. To make interprocedural constant propagation work, you also need to implement a worklist solver that supports interprocedural data-flow analysis (In the lecture, we did not teach you how to implement interprocedural analysis in detail. Don't worry, you will learn it from this assignment).

The scope of this assignment is the same as in Assignment 2, i.e., you still only need to focus on constant propagation for `int` values, and the only difference is that you will handle method calls more precisely in this assignment. If your implementation is correct, you can observe that interprocedural constant propagation achieves better precision than intraprocedural counterpart which treats method calls conservatively.

2 Implementing Class Hierarchy Analysis

In this assignment, you will deal with four kinds of method invocations in Java, i.e., `invokestatic`, `invokespecial`, `invokeinterface`, and `invokevirtual` as explained in Lecture 7. Note that since Java 8, interfaces can also declare non-abstract methods (*default methods*[1]) and since Java 11, `invokeinterface` and `invokevirtual` can call private methods. These new changes complicate the call graph construction. For simplicity, you are not required to handle them in this assignment.

2.1 Tai-e Classes You Need to Know

Some classes used in this assignment have many APIs, thus, to save your effort, we will introduce the APIs of these classes that you may use. Below we present the classes in a

[1] https://docs.oracle.com/javase/tutorial/java/IandI/defaultmethods.html

top-down manner, i.e., we first introduce the key class of call graph construction (`DefaultCallGraph`), and then the other classes it depends on.

- `pascal.taie.analysis.graph.callgraph.DefaultCallGraph`
  This class represents call graph of the program. It provides various APIs (inherited from class `AbstractCallGraph`) to obtain the information of the call graph, and the APIs to modify the call graph, which you may use to build the call graph.
  - `Stream<Invoke> callSitesIn(JMethod)`: returns all call sites in the given method.
  - `boolean contains(JMethod)`: returns whether the call graph contains the given method, i.e., the method is reachable in this call graph.
  - `boolean addReachable(JMethod)`: adds a method to this call graph. After this call, the method becomes reachable in the call graph.
  - `boolean addEdge(Edge<Invoke,JMethod>)`: adds a call edge to this call graph.

- `pascal.taie.analysis.graph.callgraph.CallKind`
  This enumeration type represents the kinds of call graph edges. It defines several constants including `INTERFACE`, `VIRTUAL`, `SPECIAL` and `STATIC`, corresponding to four kinds of invocations in Java we introduced in Lecture 7.

- `pascal.taie.analysis.graph.callgraph.Edge<Invoke,JMethod>`
  This class represents call graph edges. Each edge connects a call site (of type `Invoke`) to a callee method (of type `JMethod`). To construct an `Edge`, you need to provide the `CallKind`, a call site and a callee method to its constructor.

- `pascal.taie.ir.stmt.Invoke` (subclass of `Stmt`)
  This class represents method calls, e.g., `x = o.m(a1,a2,…)`, in the program, and also the call sites in the call graph. It provides APIs to obtain various information of the call site. Specifically, you will use `getMethodRef()` to obtain signature information of the target methods.

- `pascal.taie.ir.proginfo.MethodRef`
  Tai-e's representation to a reference to target method(s) as it appears in a call site. It contains the signature information of the target methods of the call site.
  - `JClass getDeclaringClass()`: returns the declaring class of the method signature (corresponding to class type in page 24 of Lecture 7).
  - `Subsignature getSubsignature()`: returns the subsignature of the callee method(s). We will introduce class `Subsignature` later.

  For `MethodRef`, you should *only* use the above two APIs in this assignment.

- `pascal.taie.language.classes.JMethod`

Tai-e's representation of Java methods. Each instance of `JMethod` corresponds to a method in the program and contains various information about the method.

- `boolean isAbstract()`: if this `JMethod` is an abstract method that has *no* method body, then it returns true; otherwise, it returns false.

➢ `pascal.taie.language.classes.JClass`

Tai-e's representation of Java classes. Each instance of `JClass` corresponds to a class in the program and contains various information about the class.

- `JClass getSuperClass()`: returns the superclass of this class. If this class is the top of class hierarchy, i.e., `java.lang.Object`, null is returned.
- `JMethod getDeclaredMethod(Subsignature)`: returns the method declared in this class with the given subsignature. If no method with the given subsignature can be found, null is returned.
- `boolean isInterface()`: returns whether this class is an interface.

➢ `pascal.taie.language.classes.Subsignature`

Tai-e's representation of subsignature. The subsignature of a method only contains the method name and the descriptor of a method signature as introduced in page 24 of Lecture 7. For example, the subsignature of the following method `foo` is "`T foo(P,Q,R)`" while its signature is "`<C: T foo(P,Q,R)>`".

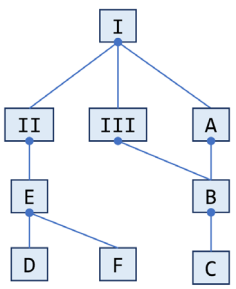
```
class C {
    T foo(P p, Q q, R r) { … }
}
```

➢ `pascal.taie.language.classes.ClassHierarchy`

This class provides class hierarchy information.

- `Collection<JClass> getDirectSubclassesOf(JClass)`: for a given class, returns the classes that directly extend the class.
- `Collection<JClass> getDirectSubinterfacesOf(JClass)`: for a given interface, returns the interfaces that directly extend the interface.
- `Collection<JClass> getDirectImplementorsOf(JClass)`: for a given interface, returns the classes that directly implement the interface.

For example, in this class hierarchy, `I`, `II`, and `III` are interfaces, and the others are classes:



Then we have:

- `getDirectSubclassesOf(A)` = [B]
- `getDirectSubinterfacesOf(I)` = [II, III]
- `getDirectImplementorsOf(II)` = [E]

➢ `pascal.taie.analysis.graph.callgraph.CHABuilder`
This class builds call graph via class hierarchy analysis. It is incomplete, and you need to finish it as explained in Section 2.2.

2.2 Your Task [Important!]

Your first task is to finish class `CHABuilder`. Specifically, you will finish three APIs:

- `JMethod dispatch(JClass,Subsignature)`

  This method implements the Dispatch function given in page 26 of the slides for Lecture 7. If no satisfying method is found, returns null.

- `Set<JMethod> resolve(Invoke)`

  This method implements the Resolve function given in page 33 of the slides for Lecture 7.

  ❖ Hint: you could use method `CallGraphs.getCallKind(Invoke)` to obtain the call kind of a call site.

- `CallGraph<Invoke, JMethod> buildCallGraph(JMethod)`

  This method implements the BuildCallGraph algorithm given in page 52 of the slides for Lecture 7.

We have provided code skeletons for the above three APIs, and your task is to fill the part with comment "`TODO - finish me`".

3 Implementing Interprocedural Constant Propagation

3.1 Edge Transfer

Interprocedural constant propagation is very similar to its intraprocedural counterpart. The main difference between them is that interprocedural constant propagation employs *edge transfer* to handle interprocedural data flows formed by method *calls* and *returns* more precisely.

In classic intraprocedural data-flow analysis, take forward analysis as example, the IN fact of a node is computed by directly meeting the OUT facts of all its predecessors:

$$\mathrm{IN}[B] = \bigcup_{P \text{ a predecessor of } B} \mathrm{OUT}[P]$$

However, in interprocedural data-flow analysis, for a node, we need to first apply an

edge transfer to OUT facts of its predecessors, and then meet the results into its IN fact. For example, in this ICFG fragment discussed in Lecture 7:

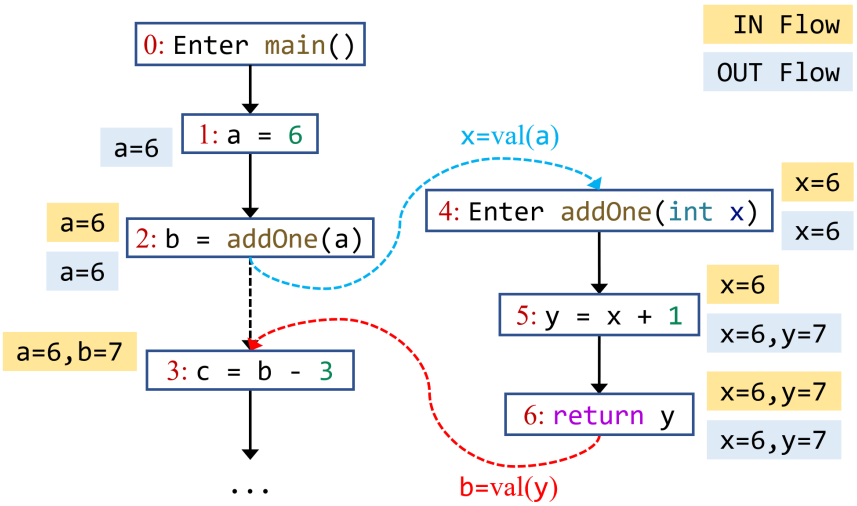


Figure 1. An example of edge transfer.

To compute the IN fact of statement 4, i.e., entry node of method addOne(), we need to apply edge transfer for edge 2→4 to convert the OUT fact of statement 2 (a=6) to x=6, and finally meet x=6 into IN fact of statement 4.

To support edge transfer, we define function *transferEdge*(*edge*, *fact*), which takes an edge (*edge*) on the ICFG and the OUT fact (*fact*) of source node of the edge as inputs, and outputs the resulting fact. Accordingly, the equation for computing IN facts now changes to

$$\text{IN}[B] = \bigcup_{P \text{ a predecessor of } B} \textit{transferEdge}\,(P \rightarrow B, \text{OUT}[P])$$

As we have introduced in Lecture 7, in interprocedural constant propagation, you need to define edge transfer functions for four kinds of ICFG edges, as described below:

- **Normal edge**: the edge transfer function is an identity function, i.e. *transferEdge*(*edge*, *fact*) = *fact*.
- **Call-to-return edge**: for invocation `x = m(…)`, the edge transfer function kills the value of LHS variable, i.e., x, and propagates the values of other variables along the edge. For invocation without LHS variable, e.g., `m(…)`, the edge transfer function is equivalent to an identity function.
- **Call edge**: the edge transfer function passes the values of arguments at a call site to the parameters of its callee(s). Concretely, it obtains the argument values from the OUT fact of the call site, and outputs a fact containing the mapping from parameters of the callee to corresponding values. For example, in Figure 1, *transferEdge*(2→4, {a=6}) = {x=6}. The result of the transfer function should *only* contain the values for parameters of the callee (e.g., x of addOne() in Figure 1).
- **Return edge**: the edge transfer function passes the return values of a callee to the LHS variable of the call site. Concretely, it obtains the returned values from

the OUT fact of the method exit, and outputs a fact containing the mapping from LHS variable of the call site to corresponding value. For example, in Figure 1, *transferEdge*(6 → 3, {x=6,y=7}) = {b=7}. The result of the edge transfer function should *only* contain the value for LHS variable of the call site (e.g., b at statement 3 in Figure 1). If the call site does not have LHS variable, then the transfer function just returns an empty fact.

We will introduce more information about how to implement these edge transfer functions on Tai-e in the following sections.

3.2 Tai-e Classes You Need to Know

- `pascal.taie.analysis.graph.icfg.ICFGEdge`
  This abstract class represents edges in ICFG. It has four subclasses, corresponding to four kinds of ICFG edges:
  - `pascal.taie.analysis.graph.icfg.NormalEdge`
  - `pascal.taie.analysis.graph.icfg.CallToReturnEdge`
  - `pascal.taie.analysis.graph.icfg.CallEdge`
  - `pascal.taie.analysis.graph.icfg.ReturnEdge`

  These classes are simple and commented, and you should read the source code to decide how to use them.

- `pascal.taie.analysis.dataflow.inter.InterDataflowAnalysis`
  This is the interface of concrete interprocedural data-flow analyses. It has 6 APIs. The first 5 APIs are the same as the ones in `DataflowAnalysis`, which you have seen in previous assignments, and the last API, `transferEdge()`, corresponds to the edge transfer function we introduce in Section 3.1. These APIs will be invoked by the interprocedural data-flow analysis solver you will write in this assignment.

- `pascal.taie.analysis.dataflow.inter.AbstractInterDataflowAnalysis`
  This abstract class implements `InterDataflowAnalysis` and provides common functionalities for implementations of `InterDataflowAnalysis`. Specifically, it dispatches different kinds of ICFG nodes/edges to the specific transfer functions, so that the analysis implementations can directly focus on the specific nodes/edges.

- `pascal.taie.analysis.dataflow.inter.InterConstantPropagation`
  This class extends `AbstractInterDataflowAnalysis` and defines inter-procedural constant propagation. It is incomplete, and you need to finish it as explained in Section 3.3.

- `pascal.taie.ir.exp.InvokeExp`
  This class represents invocation expressions in the program. It contains the method reference and arguments of each invocation, and you should read the source code and the comments to decide how to use it.

3.3 Your Task [Important!]

Your second task is to finish the following APIs of `InterConstantPropagation`:

- `boolean transferCallNode(Stmt,CPFact,CPFact)`
- `boolean transferNonCallNode(Stmt,CPFact,CPFact)`
- `CPFact transferNormalEdge(NormalEdge,CPFact)`
- `CPFact transferCallToReturnEdge(CallToReturnEdge,CPFact)`
- `CPFact transferCallEdge(LocalEdge,CPFact)`
- `CPFact transferReturnEdge(LocalEdge,CPFact)`

This class leverages the logic of intraprocedural constant propagation (it holds an object of `ConstantPropagation` in its field `cp`). Thus, to make this class work, you need to finish `ConstantPropagation.java`. You could copy your implementation from previous assignments. Note that you don't need to submit `ConstantPropagation` in this assignment, so that even though your implementation of previous assignments is not entirely correct, it does not affect your score of this assignment.

❖ Hints: 1) When you implement the `transfer*Edge()` methods, you should *not* modify the second parameter, i.e., `OUT` fact of the source node of the edge.
2) As introduced in Assignment 2, you could obtain method parameters from class `IR`. To obtain the `IR` of a method, you could use API `JMethod.getIR()`.

4 Implementing Interprocedural Worklist Solver

4.1 Algorithm

The algorithm of interprocedural worklist solver is almost the same as intraprocedural worklist solver that you have implemented in Assignment 2. There are only two differences between them:

1. As explained in Section 3.1, when computing `IN` fact of a node, interprocedural solver needs to apply edge transfer function (*transferEdge*) to its incoming edges and the `OUT` facts of the predecessors.
2. During initialization, interprocedural solver needs to initialize the `IN`/`OUT` facts of all nodes in the program (i.e., all nodes in the ICFG). It should set boundary fact to only the entry nodes of the entry methods of the ICFG (e.g., the main method). The initial facts of entry nodes of other methods are the same as non-entry nodes.

4.2 Tai-e Classes You Need to Know

➢ `pascal.taie.analysis.dataflow.fact.DataflowResult`
You have seen this class in previous assignments. In this assignment, you will use

a `DataflowResult` object to manages the facts of all nodes in the ICFG. You could get/set IN/OUT facts of nodes in the ICFG through the APIs of this class.

- `pascal.taie.analysis.graph.icfg.ICFG`
  This class represents interprocedural control-flow graph of the program. Similar to `CFG`, it is also iterable, thus you could iterate all nodes of an ICFG via a *for* loop:

  ```
  ICFG icfg = ...;
  for (Node node : icfg) {
      ...
  }
  ```

  For more information about `ICFG`, please read its code and comments.

- `pascal.taie.analysis.dataflow.inter.InterSolver`
  This class is the solver for interprocedural data-flow analysis. It is incomplete, and you need to finish it as explained in Section 4.3.

4.3 Your Task [Important!]

Your final task is to finish two APIs of `InterSolver`:

- `void initialize()`
- `void doSolve()`

Still, you only need to implement a solver for forward analysis as interprocedural constant propagation is forward. You should initialize the IN/OUT facts of ICFG nodes in `initialize()`, and implement the main part of worklist algorithm in `doSolve()`.

Hint: we have setup the analysis to be solved, the ICFG of the program, and the `DataflowResult` object for managing the facts, and stored them in fields `analysis`, `icfg`, and `result` of `InterSolver`, so that you could easily access and manipulate these objects.

5 Run and Test Your Implementation

You can run the analyses as described in *Tai-e Manual for Assignments*. Tai-e first performs CHA to build a call graph for the program, then constructs ICFG based on the call graph, and finally runs interprocedural constant propagation on the ICFG. To help debugging, it outputs the results of both CHA and interprocedural constant propagation:

```
#reachable methods: 0
---------- Reachable methods: ----------

#call graph edges: 0
---------- Call graph edges: ----------
---------------------------------------
```

```
-------------------- <Example: void main(java.lang.String[])> (inter-constprop) --------------------
[0@L5] a = 6; null
[1@L6] temp$1 = invokestatic <Example: int addOne(int)>(a); null
[2@L6] b = temp$1; null
[3@L7] %intconst0 = 3; null
[4@L7] c = b - %intconst0; null
[5@L8] temp$3 = invokestatic <Example: int ten()>(); null
[6@L8] b = temp$3; null
[7@L9] c = a * b; null
[8@L9] return; null

-------------------- <Example: int addOne(int)> (inter-constprop) --------------------
[0@L13] %intconst0 = 1; null
[1@L13] y = x + %intconst0; null
[2@L14] return y; null

-------------------- <Example: int ten()> (inter-constprop) --------------------
[0@L17] temp$0 = 10; null
[1@L18] return temp$0; null
```

The above example has been introduced in Lecture 7. The call graph is empty (0 reachable method) and OUT facts are `null` as you have not finished the analyses yet. After you implement the analyses, the output should be:

```
#reachable methods: 3
---------- Reachable methods: ----------
<Example: int addOne(int)>
<Example: int ten()>
<Example: void main(java.lang.String[])>

#call graph edges: 2
---------- Call graph edges: ----------
<Example: void main(java.lang.String[])>[1@L6] temp$1 = invokestatic <Example: int addOne(int)>(a); -> [<Example: int addOne(int)>]
<Example: void main(java.lang.String[])>[5@L8] temp$3 = invokestatic <Example: int ten()>(); -> [<Example: int ten()>]
----------------------------------------

-------------------- <Example: void main(java.lang.String[])> (inter-constprop) --------------------
[0@L5] a = 6; {a=6}
[1@L6] temp$1 = invokestatic <Example: int addOne(int)>(a); {a=6}
[2@L6] b = temp$1; {a=6, b=7, temp$1=7}
[3@L7] %intconst0 = 3; {%intconst0=3, a=6, b=7, temp$1=7}
[4@L7] c = b - %intconst0; {%intconst0=3, a=6, b=7, c=4, temp$1=7}
[5@L8] temp$3 = invokestatic <Example: int ten()>(); {%intconst0=3, a=6, b=7, c=4, temp$1=7}
[6@L8] b = temp$3; {%intconst0=3, a=6, b=10, c=4, temp$1=7, temp$3=10}
[7@L9] c = a * b; {%intconst0=3, a=6, b=10, c=60, temp$1=7, temp$3=10}
[8@L9] return; {%intconst0=3, a=6, b=10, c=60, temp$1=7, temp$3=10}

-------------------- <Example: int addOne(int)> (inter-constprop) --------------------
[0@L13] %intconst0 = 1; {%intconst0=1, x=6}
[1@L13] y = x + %intconst0; {%intconst0=1, x=6, y=7}
[2@L14] return y; {%intconst0=1, x=6, y=7}

-------------------- <Example: int ten()> (inter-constprop) --------------------
[0@L17] temp$0 = 10; {temp$0=10}
[1@L18] return temp$0; {temp$0=10}
```

In addition, Tai-e outputs the ICFG of the program it analyzes to folder `output/`. The ICFGs are stored as .dot files which can be visualized by Graphviz. Note that each ICFG depends on a call graph, thus if you modify `CHABuilder`, Tai-e may output different ICFGs for the same program.

We provide classes `pascal.taie.analysis.graph.callgraph.cha.CHATest` and `pascal.taie.analysis.dataflow.analysis.constprop.InterCPTest` as the test drivers for CHA and interprocedural constant propagation, and you could use them to test your implementation as described in *Tai-e Manual for Assignments*.

We encourage you to use your implementation of Assignment 2, i.e., intraprocedural constant propagation, to analyze the test cases in this assignment, and observe the precision differences between intra- and inter-procedural analyses.

From this assignment, the analyses you implement are interprocedural analyses, which analyze a program from its entry method, i.e., the *main* method. Hence, if you want to write a test case for your implementation, please make sure that the input class contains a `public static void main(String[])` method.

6 General Requirements

- In this assignment, your only goal is correctness. Efficiency is not your concern.
- **DO NOT** distribute the assignment package to any others.
- Last but not least, do **NOT** plagiarize. The work must be all your own!

7 Submission of Assignment

Your submission should be a zip file, which contains your implementation of

- `CHABuilder.java`
- `InterConstantPropagation.java`
- `InterSolver.java`

The naming convention your submission is: `<STUDENT_ID>-<NAME>-A4.zip`
Please submit your assignment to 教学立方.

8 Grading

The points will be allocated for correctness. We will use your submission to analyze the given test files from the `src/test/resources/` directory, as well as other tests of our own, and compare your output to that of our solution.

Good luck!