Programming Assignment 2:

Constant Propagation and Worklist Solver

Course “Static Program Analysis” @Nanjing University
Assignments Designed by Tian Tan and Yue Li
Due: 23:00, Sunday, October 17, 2021

1 Assignment Objectives

- Implement a constant propagation for Java.
- Implement a generic worklist solver, which will be used to solve the data-flow problem you defined, i.e., constant propagation.

In this programming assignment, you will implement the key parts of a constant propagation and a worklist solver on top of Tai-e. We introduce a lot of information in this document which is necessary for implementing a working constant propagation and worklist solver. Please read the document thoroughly.

2 Implementing Constant Propagation

2.1 Scope

In this assignment, you need to implement the constant propagation for values of `int` type. Note that in Java, actually the values of types `boolean`, `byte`, `char`, and `short` are also represented and computed as `int` values during run time[1], thus your analysis would also be able to handle the values of these types. Other primitive types (`long`, `float`, and `double`) and reference types (class types, array types, etc.) are out of scope.

For statements, as shown in page 247 of slides for Lecture 6, you only need to focus on assign statements whose left-hand side expressions are variables, and right-hand side expressions are:

- Constants, e.g., `x = 1`
- Variables, e.g., `x = y`
- Binary expressions, e.g., `x = a + b`, and `x = a >> b`

Table 1 lists all binary operations (except logical) that you could perform on `int` values in Java[2], and you need to handle all these operators in your assignment.

[1] https://docs.oracle.com/javase/specs/jvms/se11/html/jvms-2.html#jvms-2.11.1-320

[2] https://docs.oracle.com/javase/tutorial/java/nutsandbolts/operators.html

Kinds	Operators
Arithmetic	`+ - * / %`
Condition	`== != < > <= >=`
Shift	`<< >> >>>`
Bitwise	`| & ^`

Table 1. Binary operators for `int` in Java

How About Logical Operators?

We do not list logical operators, i.e., logical AND (`&&`) and OR (`||`) in above table, because in Java, these two operators do not have corresponding instructions in bytecode, and instead, they are implemented as branch statements. For example, such statement

```
a = b || c;
```

will be transformed to following semantically equivalent statements:

```
if (b) {
    t = true; // t is temp variable
} else if (c) {
    t = true;
} else {
    t = false;
}
a = t;
```

As our constant propagation can handle assignments for constants (e.g., `t = true`) and variables (e.g., `a = t`), and branch statements (e.g., `if (b) {…}`), it can handle `&&` and `||` automatically.

For the assign statements (again, whose left-hand side expressions are variables) with other right-hand side expressions, e.g., method calls (`x = m(…)`) or field loads (`x = o.f`), you should give them conservative (maybe imprecise) approximations, e.g., `x` = NAC. You will handle method calls and field loads more precisely in later assignments.

For the other statements that are not mentioned above (e.g., field store `o.f = x` which will be handled after we learn alias analysis), the transfer function is identity function.

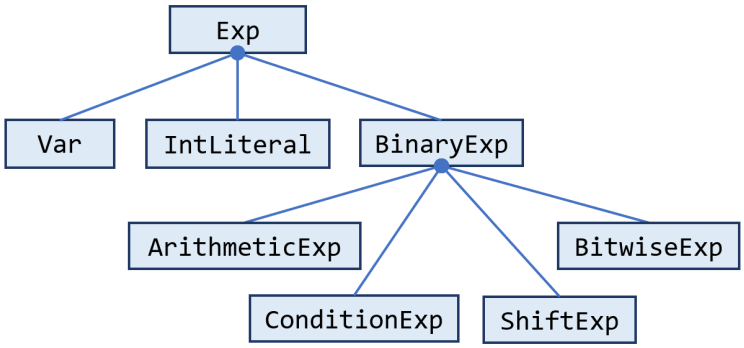
2.2 Tai-e Classes You Need to Know

In this section, we first introduce the IR-related classes (`pascal.taie.ir.*`) and then the analysis-related classes (`pascal.taie.analysis.*`) you need to know for implementing constant propagation.

- `pascal.taie.ir.IR`
  This class is the central data structure of intermediate representation in Tai-e, and

each `IR` instance contains the information for the body of a particular method, such as variables, parameters, statements, etc. You can obtain this information through its APIs, which are all commented in the source code.

- `pascal.taie.ir.exp.Exp`
  You have seen this interface in Assignment 1. In this assignment, you will need to handle more of its subclasses, as shown in this partial class hierarchy:



  Now we introduce the classes in this figure.

- `pascal.taie.ir.exp.Var`
  This class represents the variables in Tai-e's IR.

- `pascal.taie.ir.exp.IntLiteral`
  Following *Java Language Specification*[3], we call constant values *literals* in Tai-e. Each instance of this class represents an integer literal in the program, and you can obtain the `int` value by calling its `getValue()` method.

- `pascal.taie.ir.exp.BinaryExp`
  This class represents binary expressions in the program. It has several subclasses, corresponding to different kinds of binary expressions as shown in Table 1, and each subclass contains an inner enum type[4] which represents the operators supported by the expression class. For example, `ArithmeticExp.Op` represents the operators of `ArithmeticExp` (arithmetic expressions), i.e., `+`, `-`, `*`, `/`, and `%`.

  Note that in Tai-e, both operands of `BinaryExp` are of type `Var`, e.g., statement

  ```
  x = y + 6;
  ```

  will be transformed to

  ```
  %intconst0 = 6;      // %intconst* are temp variables introduced
  x = y + %intconst0; // by Tai-e to hold constant int values
  ```

  in Tai-e's IR. Such design simplifies the implementation of analyses, as you only need to consider one case (i.e., `Var`) for every operand of any `BinaryExp`.

[3] https://docs.oracle.com/javase/specs/jls/se11/html/jls-15.html#jls-15.8.1

[4] https://docs.oracle.com/javase/tutorial/java/javaOO/enum.html

- `pascal.taie.ir.stmt.DefinitionStmt`
  This class is a subclass of `Stmt`, and it represents all definition statements[5] in the program, e.g., `x = y` or `x = m(…)` where `x` is defined. This class is very simple, and you could read its source code and comments to decide how to use it.

- `pascal.taie.analysis.dataflow.analysis.DataflowAnalysis`
  This is the interface of concrete data-flow analyses and will be used by the analysis solver as you have seen in Assignment 1. In this assignment, you also only need to focus on the first 5 APIs, which will be invoked by the worklist solver you write.

- `pascal.taie.analysis.dataflow.analysis.constprop.Value`
  This class represents the lattice values in constant propagation, i.e., (the lattice described in page 238 of slides for Lecture 6). Its code and comments are self-explaining. You should use these static methods to obtain instances of this class:
  - `Value getNAC()`: returns NAC
  - `Value getUndef()`: returns UNDEF
  - `Value makeConstant(int)`: returns a constant for the given integer

- `pascal.taie.analysis.dataflow.analysis.constprop.CPFact`
  This class represents the data facts in constant propagation, i.e., the mapping from variables (`Var`) to their lattice values (`Value`). This class provides various map-related operations, such as query/update key-value mappings, etc., and most of them are inherited from `pascal.taie.analysis.dataflow.fact.MapFact`. The APIs of both classes are commented in the source code, and you should read the source code and decide which APIs to use in this assignment.

- `pascal.taie.analysis.dataflow.analysis.constprop.ConstantPropagation`
  This class implements `DataflowAnalysis` and defines constant propagation. It is incomplete, and you need to finish it as explained in Section 2.3.

2.3 Your Task [Important!]

Your first task is to implement the following APIs of `ConstantPropagation`:

- `CPFact newBoundaryFact(CFG)`
- `CPFact newInitialFact()`
- `void meetInto(CPFact,CPFact)`
- `boolean transferNode(Stmt,CPFact,CPFact)`

You have seen the above four APIs from Assignment 1, which are inherited from `DataflowAnalysis`. Note that when implementing `newBoundaryFact()`, for each

[5] In this assignment, we use two terms *assign statement* and *definition statement* interchangeably.

method being analyzed, you should handle the parameters of the method properly, i.e., initialize their values to NAC (*Question for you: Why do we do this?*).

❖ Hint: As mentioned in Section 2.1, we focus on constant propagation for values of `int` type in this assignment. To achieve this, we provide an auxiliary method `canHoldInt(Var)` in `ConstantPropagation` to judge if a variable can hold values of `int` type, and you should use it to check if a parameter, and also other variables, are in the scope of this assignment.

In addition, you need to implement these two auxiliary methods:

◆ `Value meetValue(Value,Value)`
This corresponds to the meet operator ⊓ defined in page 238 of slides for Lecture 6. You should invoke this method from `meetInto()`.

◆ `Value evaluate(Exp,CPFact)`
This method evaluates the lattice value (`Value`) for a right-hand side expression (`Exp`). You will need to handle three cases in this method as described in page 247 of slides for Lecture 6, and for other cases, it should return NAC (also described in Section 2.1). You should invoke this method from `transferNode()`.

❖ Hints: 1) As in Assignment 1, the design of `meetInto()` might be a bit different from your expectation. To understand this design, please review relevant part in the document for Assignment 1.
2) The evaluation results of condition expressions (e.g., `a == b`) should be represented by 1 (for true) or 0 (for false).
3) For cases of division-by-zero (both `/` and `%`), you should treat its result as UNDEF, e.g., for `x = a / 0`, `x` is UNDEF.

3 Implementing Worklist Solver

3.1 Tai-e Classes You Need to Know

Similar to iterative solver, to implement worklist solver on Tai-e, you need to know `DataflowResult`, `CFG`, and `Solver`, which have been introduced in Assignment 1. Besides, you need to know:

➢ `pascal.taie.analysis.dataflow.solver.WorkListSolver`
This class extends `Solver` and implements worklist algorithm. It is incomplete, and to be finished.

3.2 Your Task [Important!]

Your second task is to finish two APIs of the solver classes mentioned above:

- `Solver.initializeForward(CFG,DataflowResult)`
- `WorkListSolver.doSolveForward(CFG,DataflowResult)`

You only need to focus on forward-related methods as constant propagation is a forward analysis. In `initializeForward()`, you should implement the first three lines in the algorithm in page 258 of slides for Lecture 6. You should implement the main part of worklist algorithm in `doSolveForward()`.

❖ Hints: 1) The worklist algorithm in the slides compares old_OUT and OUT[B] to decide if the successors of a node need to be added to the worklist, which is not very efficient. `DataflowAnalysis.transferNode()` returns whether the transfer changes the OUT fact of the node on each call, and you could leverage this feature to avoid comparing old_OUT and OUT[B].
2) Similar to iterative solver in Assignment 1, do not forget to initialize IN fact of each `Stmt` in `Solver.initializeForward()` (the same initial fact as in OUT).

4 Run and Test Your Implementation

You can run the analysis as described in *Tai-e Manual for Assignments*. Tai-e performs constant propagation for each method of input class, and outputs the analysis results, i.e., the data-flow information (lattice values of variables) in OUT fact of each Stmt:

```
-------------------- <Assign: void assign()> (constprop) --------------------
[0@L4] x = 1; null
[1@L5] x = 2; null
[2@L6] x = 3; null
[3@L7] x = 4; null
[4@L8] y = x; null
[5@L8] return; null
```

The OUT facts are `null` as you have not finished the analysis yet. After you implement the analysis, the output should be:

```
-------------------- <Assign: void assign()> (constprop) --------------------
[0@L4] x = 1; {x=1}
[1@L5] x = 2; {x=2}
[2@L6] x = 3; {x=3}
[3@L7] x = 4; {x=4}
[4@L8] y = x; {x=4, y=4}
[5@L8] return; {x=4, y=4}
```

In addition, Tai-e outputs the control-flow graphs of the methods it analyzes to folder `output/`. The CFGs are stored as .dot files, and can be visualized by Graphviz (https://graphviz.org/download/).

We provide class `pascal.taie.analysis.dataflow.analysis.constprop.CPTest` as the test class for this assignment, and you could use it to test your implementation as described in *Tai-e Manual for Assignments*.

5 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!

6 Submission of Assignment

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

- `ConstantPropagation.java`
- `Solver.java`
- `WorkListSolver.java`

The naming convention your submission is: `<STUDENT_ID>-<NAME>-A2.zip`

Please submit your assignment to 教学立方.

7 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!