Abstract Pathfinder

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ABSTRACT

We present Abstract Pathfinder, an extension to the Java Pathfinder (JPF) verification tool-set that supports data abstraction to reduce the large data domains of a Java program to small, finite abstract domains, making the program more amenable to verification. We use data abstraction to compute an over-approximation of the original program in such a way that if a (safety) property is true in the abstracted program the property is also true in the original program. Our approach enhances JPF with an abstract interpreter and abstract state-matching mechanisms, together with a library of abstractions from which the user can pick which abstractions to use for a particular application. We discuss the details of our implementation together with some preliminary experiments with analyzing multi-threaded Java programs, where Abstract Pathfinder achieves significant time and memory savings as compared with plain JPF.

Categories and Subject Descriptors
D.2.4 [Software Engineering]: Software/Program Verification

General Terms
Verification

Keywords
Java Pathfinder, state space traversal, abstraction

1. INTRODUCTION

Exhaustive state space traversal techniques such as model checking are popular approaches to program verification and bug finding. Model checking is useful especially for analysing multi-threaded programs. Tools using this approach check all interleavings of program threads for property violations (errors). An example of such a tool is Java Pathfinder (JPF) [8] which targets Java bytecode programs.

The core of JPF is a special Java virtual machine that supports backtracking, state matching, and non-determinism in both data and scheduling decisions. JPF constructs the program state space on-the-fly during the execution of the program in the special virtual machine. A transition in the state space is a sequence of bytecode instructions executed by a single thread, where the first instruction in the sequence represents a non-deterministic choice corresponding to a thread context switch. At every transition boundary, JPF saves the current JVM state (the program state) in a serialized form for the purpose of backtracking and state matching. The complete JVM state includes all heap objects, stacks of all threads and all static data. Changes of the JVM state are performed inside the interpreter of bytecode instructions, which too is a part of JPF.

Plain JPF contains a concrete interpreter, which models faithfully all Java bytecode instructions and keeps concrete values of program variables. We say that plain JPF performs concrete execution of instructions during the state space traversal.

The main drawback of JPF with respect to practical usefulness is that it performs an exhaustive traversal which is prone to state explosion. Although JPF supports many optimizations, including partial order reduction and other symmetry reductions, checking of all thread interleavings with concrete execution is time-consuming and requires a lot of memory.

A possible solution is to use data abstraction to reduce the large domains of selected program variables to smaller domains and make program verification via state space traversal more feasible. Consider the example in Figure 1. It is a simple variant of the classic producer – consumer problem with a shared object of the Data class. The safety property of interest is absence of data races. Plain JPF would explore the program behavior for all possible values of the variable remaining, i.e. all integer values between 0 and 1000000, and the program state space would therefore be very large.

One can use the signs abstraction on the variable remaining to replace the large domain of the Java int type with a small finite domain \{POS, ZERO, NEG\}, which only encodes the sign of variable remaining, while abstracting away the actual value. Consequently, all program states that differ only in the value of the variable would be collapsed to three different states with the corresponding abstract values. The state space explored by JPF with such an abstraction would therefore be much smaller, reducing the time needed to verify the given safety property, while all program behaviors would be still analyzed.

1.1 Contribution

A lot of work has been done in data abstraction (e.g., predicate abstraction [1,2,6]), but only few approaches target Java. A notable exception is the Bandera toolset [4]. It performs finite state abstraction of a given Java program by the means of a source-to-source transformation based on the specific data abstractions selected (and defined) by the user.

In this paper, we present Abstract Pathfinder – an extension for
2. ABSTRACT MODEL CHECKING WITH JAVA PATHFINDER

The main general benefit of abstract model checking is better performance and scalability. The abstract domains are typically defined as much smaller than the ranges of concrete types, so that state space of the abstract program is much smaller than the state space of the original program, and therefore Abstract Pathfinder has to explore much less states to cover all program behaviors than in the case of the plain JPF and the original program.

3. SUPPORTED ABSTRACTIONS

Abstract Pathfinder provides an extensible library of abstractions for numeric data types of Java. The current version of the library contains the following abstractions: signs, evenness, and two variants of an interval abstraction.

3.1 Signs

The domain of the signs abstraction is the set \{POS, ZERO, NEG\}, whose elements express the fact that a value is positive, zero, or negative, respectively. A value in the original concrete program is mapped to one element of the abstract domain. Figure 2 shows an abstraction function for values of the Java type int.

```
signs abstract(int v) {
    if (v > 0) return POS;
    if (v == 0) return ZERO;
    if (v < 0) return NEG;
}
```

Figure 2: Signs — abstraction function

The result of an arithmetic operation over two values such that at least one is abstract can be any subset of the abstract domain.
4. IMPLEMENTATION

MIN preserves concrete values in the interval \( \text{long} \) for integer values and floating-point values (i.e., for constants and greater than the fact that a value is less than is the set domain for given two integer or floating-point values parameterized with two user-defined values.

3.3 Intervals with non-zero decimal part. The basic interval abstraction is defined as follows. The abstract domain of the evenness abstraction is the set \{ ODD, EVEN \}, whose elements represent odd and even values, respectively. This abstraction can be used only for integer values (constants and program variables of Java types such as \text{int} \) and \text{long} \), as the concepts of oddity and evenness do not make sense for floating-point values.

3.2 Evenness

The domain of the evenness abstraction is the set \{ ODD, EVEN \}, whose elements represent odd and even values, respectively. This abstraction can be used only for integer values (constants and program variables of Java types such as \text{int} \) and \text{long} \), as the concepts of oddity and evenness do not make sense for floating-point values.

3.3 Intervals

We support two variants of the interval abstraction. Both are parameterized with two user-defined values MIN and MAX.

The second variant of the interval abstraction is more precise as it preserves concrete values in the interval \{ MIN, MAX \}. The abstract domain for two integer values MIN and MAX is the set \{ LESS, MIN, MIN+1, \ldots, MAX-1, MAX, GREATER \}. Note, however, that this abstraction is intended for use with small intervals.

Other abstractions can be defined similarly.

4. IMPLEMENTATION

We implemented Abstract Pathfinder as a JPF project extension. The project has the following components:

- Generic Abstraction and AbstractionBoolean classes. All the data abstractions are sub-classes of the Abstraction class.
- Library of abstractions.
- Abstract interpreter for all the numeric bytecodes. JPF’s attribute mechanism is used for storing and propagating abstract values. It includes an AbstractInstructionFactory.
- FocusAbstractChoiceGenerator for implementing non-deterministic choice among multiple abstract values.
- AbstractSerializer for abstract state matching.
- AbstractListener for printing the results.

We describe some of these components in more detail below.

4.1 The Abstraction class

Every abstraction must be implemented as a subclass of the Abstraction class that is used in the abstract interpreter of bytecode instructions (see Figure 4). The generic Abstraction class contains skeleton implementations of abstraction functions and helper methods for construction and processing of sets of abstract values, and it also defines several methods for which each particular abstraction must provide a custom implementation; the AbstractBoolean class contains a generic abstraction for boolean values. Abstract Pathfinder allows the user to pick specific abstractions from the library that are then used for a particular application. A new abstraction can be easily added to the library by extending the constructor of the AbstractInstructionFactory class with the abstraction’s initialization code.

4.2 The Abstract Interpreter

The abstract interpreter redefines mostly bytecode instructions that perform arithmetic operations for all the primitive types. It operates upon the abstract values if they are available, and falls back to standard concrete interpretations otherwise. Abstract values are stored in attributes for local variables, stack operands, and object fields, and propagated between instructions via attributes. If some program variable has an abstract value then its concrete value is set to 0.

Figure 5 shows the implementation of an abstract interpreter for the IADD bytecode instruction that adds two integer values. Its description follows.

At first, it attempts to retrieve the abstract values of operands from the attributes, and passes them to the respective method of the Abstraction class which performs the actual addition. If the abstract value is not defined for any of the two concrete operands, the standard interpreter is called as a fallback. Finally, the concrete result value 0 is set and the abstract result value is stored as an attribute of the concrete result.

If the result of the arithmetic operation is a set of abstract values (i.e., not a single token), a non-deterministic choice over the values in the result set is created. For this purpose, we introduced a new type of a choice generator that we call focus choice generator. Subsequent behavior of the program is checked for all abstract values in the result set one by one. In each branch, one of the abstract values is stored in the attribute as the actual result of the operation. We note that we made our abstractions as precise as possible, e.g. adding POS and NEG results in a non-deterministic choice between POS, NEG and ZERO, while incrementing NEG results only.
import java.util.Set;

public class Abstraction {
  public Set<Abstraction> get_tokens() {
    throw new RuntimeException("not implemented");
  }

  public int get_num_tokens() {
    throw new RuntimeException("not implemented");
  }

  public boolean isTop = false;

  public boolean isTop() {
    return isTop;
  }

  public Abstraction abstract_map(int v) {
    throw new RuntimeException("not implemented");
  }

  public Abstraction abstract_map(long v) {
    throw new RuntimeException("not implemented");
  }

  // abstract numeric operations
  public static Abstraction _add(int v1, Abstraction abs_v1, int v2, Abstraction abs_v2) {
    Abstraction result = null;
    if (abs_v1 != null) {
      if (abs_v2 != null)
        result = abs_v1._plus(abs_v2);
      else
        result = abs_v1._plus(v2);
    } else if (abs_v2 != null)
      result = abs_v2._plus(v1);
    return result;
  }

  public static Abstraction _mul(int v1, Abstraction abs_v1, int v2, Abstraction abs_v2) {
    ...}

  // abstract comparison operations
  public AbstractBoolean _lt(Abstraction right) {
    throw new RuntimeException("lt not implemented");
  }

  public static Abstraction _add(SystemState ss, KernelState ks, ThreadInfo th) {
    StackFrame sf = th.getTopFrame();
    // retrieve abstract operands stored in the attributes
    Abstraction abs_v1 = (Abstraction) sf.getOperandAttr(0);
    Abstraction abs_v2 = (Abstraction) sf.getOperandAttr(1);
    Abstraction result;
    if (abs_v1 == null && abs_v2 == null) {
      // fall back to a concrete interpretation
      return super.execute(ss, ks, th);
    } else {
      int v1 = th.peek(0);
      int v2 = th.peek(1);
      result = Abstraction.add(v1, abs_v1, v2, abs_v2);
      if (!result.isSingleToken()) {
        // result is a set of abstract values
        ChoiceGenerator cg;
        if (!th.isFirstStepInsn()) {
          // first time seen
          − create choice generator
          int size = result.getNumberOfTokens();
          cg = new FocusAbstractChoiceGenerator(size);
          ss.setNextChoiceGenerator(cg);
          return this;
        } else {
          // make the next choice − return the result
          cg = ss.getChoiceGenerator();
          assert (cg instanceof FocusAbstractChoiceGenerator);
          int key = (Integer) cg.getNextChoice();
          result = result.getToken(key);
        }
      }
      // set the concrete result value to 0
      th.pop();
      th.pop();
      th.push(0, false);
    }
    return getNext(th);
  }
}

Figure 4: Generic Abstraction class

Figure 5: Abstract interpreter for IADD

in a non-deterministic choice between NEG and ZERO (since POS is not possible).

Note that both abstract values and concrete values are passed to
the addition method of the Abstraction class. This is important for
the case when an abstract value is defined only for one operand.
The abstract value of the other (concrete) operand is computed in-
side the addition method.

Use of a custom instruction factory means that Abstract Pathfinder
is not compatible with other JPF extensions that also use custom
bytecode interpreter (factories).

Variables and constant values to be abstracted are marked in the
program code which therefore has to be modified before the use of
Abstract Pathfinder. For example, an initialization expression int x = 10 is replaced with
int x = Debug.makeAbstractInteger(10). In the
future, we will add support for defining abstracted variables in the
.jpf configuration files.

4.3 Abstract State Matching

JPF uses a “serializer” to save the current JVM state into a com-
 pact form for the purpose of state matching. However, the serial-
izer used inplain JPF takes into account only concrete values of
program variables. To perform abstract state matching, we have
implemented a custom serializer that processes also attributes that
represent abstract values in addition to concrete values, and there-
fore enables proper consideration of abstract values in state matching.

```java
int x,y,z;
x = 1; y = -1; z = 0;

// non-deterministic choice
boolean b = Verify.getBoolean();
if (b) {
    v = x + z;
} else {
    b = true;
    v = y + z;
}
L1: // transition break and state matching
println("v is "+v);
```

Figure 6: State matching with abstract values

The program fragment in Figure 6 illustrates the need for a custom serializer that properly considers abstract values. Let \( x, y, \) and \( z \) be program variables for which Abstract Pathfinder uses the signs abstraction. Both branches of the if-else statement are explored because of the non-deterministic choice. The abstract value of \( v \) is POS at the end of the if branch and NEG at the end of the else branch. The concrete value of \( v \), as set by the abstract interpreter of bytecode instructions, is 0 at the end of any branch. The concrete value of \( b \) is true at the end of any branch.

If the serializer from plain JPF is used then the println statement would be reached only once. Concrete values of all program variables are the same after both branches of the if-else statement, and therefore the state space search procedure would see an already visited state upon reaching the location L1 for the second time and backtrack prematurely.

However, the correct behavior is to reach the println statement twice, because the abstract value of \( v \) at the end of the if branch is different from the abstract value at the end of the else branch. If the custom serializer that processes abstract values is used, then the search procedure correctly sees a new state upon reaching L1 for the second time and continues exploration further.

5. EVALUATION

We performed experiments on small examples, including the producer – consumer example, to find how much the use of abstraction reduces the number of states that JPF must explore and its running time. We set the limit on memory usage to 512 MB.

<table>
<thead>
<tr>
<th></th>
<th>Time</th>
<th>Memory</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>plain JPF</td>
<td>&gt; 45 s</td>
<td>&gt; 512 MB</td>
<td>&gt; 141680</td>
</tr>
<tr>
<td>Abstract Pathfinder</td>
<td>1 s</td>
<td>15 MB</td>
<td>155</td>
</tr>
</tbody>
</table>

Table 1: Experiments with producer – consumer

Results in Table 1 show that Abstract Pathfinder achieves significant time and memory savings compared to plain JPF (when using the Signs abstraction). Abstract Pathfinder explores the whole state space of the abstract program in one second, while plain JPF runs out of available memory after 45 seconds and processes much more states up to that point.

6. CONCLUSION

We described here Abstract Pathfinder, a new tool for performing data abstraction for Java programs. We gave the main aspects of its implementation, and provided an overview of the currently supported abstractions. Results of our preliminary experiments are very promising, but much work still has to be done to make Abstract Pathfinder even more useful.

The current version of Abstract Pathfinder allows to use only a single particular abstraction from the library. Our first priority is to add support for simultaneous usage of multiple abstractions. We plan to achieve this by implementing a container abstraction that will associate two or more abstract values with a concrete value.

In the future, we would like to extend the current abstractions such that they can model tricky aspects of numerical data types, such as integer overflows, infinite values, and precision of floating-point values (rounding). We also plan to support other kinds of abstractions, most notably predicate abstraction. We believe that JPF’s symbolic execution framework, a.k.a. Symbolic Pathfinder [7], could be leveraged to build such abstractions automatically. Finally we would also like to extend the tool beyond primitive types, to handle arrays and data structures, in a way similar to shape analysis [3].

7. ACKNOWLEDGMENTS

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8. REFERENCES