

# Assignment 2: Concolic Testing

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## 1 Intro

Complete code snippets can be found in the Appendix section §6 of the respective section.

## 2 Discussion Point 1

### 2.1 Manual Execution

#### 2.1.1 Legend

The meaning of the values in the table(s) below:

- / program did not enter this line
- || value is the same as the previous value

#### 2.1.2 Iteration 1

| Code              | Concrete Store                       | Symbolic Store           | Path Conditions               |
|-------------------|--------------------------------------|--------------------------|-------------------------------|
| main ( ) {        |                                      |                          |                               |
| var x , y , z ;   |                                      |                          |                               |
| x = input ;       | [x -> 0] (input = 0)                 | [x -> a]                 |                               |
| z = input ;       | [x -> 0, z -> 0] (input = 0)         | [x -> a, z -> b]         |                               |
| y = &x ;          | [x -> 0, z -> 0, y -> x]             | [x -> a, z -> b, y -> x] |                               |
| if ( x > 0 ) {    | [x -> 0, z -> 0, y -> x]             | [x -> a, z -> b, y -> x] | [!(a > 0)]                    |
| y = &z ;          | /                                    | /                        |                               |
| } else {          |                                      |                          |                               |
| *y = input ;      | [x -> 0, z -> 0, y -> x] (input = 0) | [x -> a, z -> b, y -> x] |                               |
| }                 |                                      |                          |                               |
| *y = *y + 7 ;     | [x -> 7, z -> 0, y -> x] (7 + 0)     | [x -> a, z -> b, y -> x] |                               |
| if (2 > z ) {     |                                      |                          | [!(a > 0) and !(2 > (b + 7))] |
| if (*y == 2647) { | /                                    | /                        | /                             |
| error 1 ;         | /                                    | /                        | /                             |
| }                 | /                                    | /                        | /                             |
| }                 | /                                    | /                        | /                             |
| return *y ;       | 7                                    |                          |                               |
| }                 | -                                    | -                        | [!(a > 0) and !(2 > (b + 7))] |

With the above result, negate the first condition  $\neg(a > 0)$  from the PC:  $\neg(a > 0) \wedge (b + 7)$ . The input for the next iteration is as follows:

- $x = 1$
- $z = 0$

### 2.1.3 Iteration 2

| Code              | Concrete Store                   | Symbolic Store           | Path Conditions              |
|-------------------|----------------------------------|--------------------------|------------------------------|
| main ( ) {        |                                  |                          |                              |
| var x , y , z ;   |                                  |                          |                              |
| x = input ;       | [x -> 1] (input = 1)             | [x -> a]                 |                              |
| z = input ;       | [x -> 1, z -> 0] (input = 0)     | [x -> a, z -> b]         |                              |
| y = &x ;          | [x -> 1, z -> 0, y -> x]         | [x -> a, z -> b, y -> x] |                              |
| if ( x > 0 ) {    |                                  |                          | [(a > 0)]                    |
| y = &z ;          | [x -> 1, z -> 0, y -> z]         | [x -> a, z -> b, y -> z] |                              |
| } else {          | /                                |                          |                              |
| *y = input ;      | /                                |                          |                              |
| }                 | /                                |                          |                              |
| *y = *y + 7 ;     | [x -> 1, z -> 7, y -> x] (7 + 0) | [x -> a, z -> b, y -> x] |                              |
| if (2 > z ) {     |                                  |                          | [(a > 0) and !(2 > (b + 7))] |
| if (*y == 2647) { |                                  |                          |                              |
| error 1 ;         |                                  |                          |                              |
| }                 |                                  |                          |                              |
| }                 |                                  |                          |                              |
| return *y ;       | 7                                |                          |                              |
| }                 |                                  |                          |                              |

With the extended path condition now consisting of:  $(a > 0) \wedge \neg(2 > (b + 7))$ . The previous input resulted in the first 2 clauses of the PC to be true. For the next iteration the following input values will be chosen:

- $x = 1$
- $z = -5$

Keeping the value of x the same, but changing the value of z, as to negate the second clause of the PC.

### 2.1.4 Iteration 3

| Code              | Concrete Store                    | Symbolic Store           | Path Conditions              |
|-------------------|-----------------------------------|--------------------------|------------------------------|
| main ( ) {        |                                   |                          |                              |
| var x , y , z ;   |                                   |                          |                              |
| x = input ;       | [x -> 1] (input = 1)              | [x -> a]                 |                              |
| z = input ;       | [x -> 1, z -> -5] (input = -5)    | [x -> a, z -> b]         |                              |
| y = &x ;          | [x -> 1, z -> -5, y -> x]         | [x -> a, z -> b, y -> x] |                              |
| if ( x > 0 ) {    |                                   |                          | [(a > 0)]                    |
| y = &z ;          | [x -> 1, z -> -5, y -> z]         | [x -> a, z -> b, y -> z] |                              |
| } else {          | /                                 |                          |                              |
| *y = input ;      | /                                 |                          |                              |
| }                 | /                                 |                          |                              |
| *y = *y + 7 ;     | [x -> 1, z -> 2, y -> x] (7 + -5) | [x -> a, z -> b, y -> x] |                              |
| if (2 > z ) {     |                                   |                          | [(a > 0) and !(2 > (b + 7))] |
| if (*y == 2647) { |                                   |                          |                              |
| error 1 ;         |                                   |                          |                              |
| }                 |                                   |                          |                              |
| }                 |                                   |                          |                              |
| return *y ;       | 2                                 |                          |                              |
| }                 |                                   |                          |                              |

So the chosen input did not show any new branches, therefore revert back to the previous input with:

- $x = 0$
  - $z = 0$
- and
- $y = 2640$

### 2.1.5 Iteration 4

| Code              | Concrete Store                             | Symbolic Store           | Path Conditions                              |
|-------------------|--------------------------------------------|--------------------------|----------------------------------------------|
| main ( ) {        |                                            |                          |                                              |
| var x , y , z ;   |                                            |                          |                                              |
| x = input ;       | [x -> 0] (input = 0)                       | [x -> a]                 |                                              |
| z = input ;       | [x -> 0, z -> 0] (input = 0)               | [x -> a, z -> b]         |                                              |
| y = &x ;          | [x -> 0, z -> 0, y -> x]                   | [x -> a, z -> b, y -> x] |                                              |
| if ( x > 0 ) {    | [x -> 0, z -> 0, y -> x]                   | [x -> a, z -> b, y -> x] | [!(a > 0)]                                   |
| y = &z ;          | /                                          | /                        |                                              |
| } else {          |                                            |                          |                                              |
| *y = input ;      | [x -> 2640, z -> 0, y -> x] (input = 2640) | [x -> a, z -> b, y -> x] |                                              |
| }                 |                                            |                          |                                              |
| *y = *y + 7 ;     | [x -> 2647, z -> 0, y -> x] (7 + 2640)     | [x -> a, z -> b, y -> x] |                                              |
| if ( 2 > z ) {    |                                            |                          | [!(a > 0) and (2 > (b + 7))]                 |
| if (*y == 2647) { | /                                          | /                        | [!(a > 0) and (2 > (b + 7)) and (a == 2647)] |
| error 1 ;         | Error                                      |                          |                                              |
| }                 |                                            |                          |                                              |
| }                 |                                            |                          |                                              |
| return *y ;       |                                            |                          |                                              |
| }                 | -                                          | -                        |                                              |

Found failure sequence for input:  $x = 0, z = 0, y = 2640$ .

This concludes the concolic testing for this example, other input's can be found but they do not change the behavior of the program or find a new failure sequence. For example; for  $y$  a negative value my traverse the false branch, but does not significantly change the program output.

## 2.2 Comparison

When looking at the output of the concolic testing using TIP, the input's are chosen randomly. While in contrast, using manual concolic execution, values can be chosen more targeted, in the sense arriving more easier to failure sequences.

But the cost of keeping track of all values throughout execution is difficult for larger programs.

In the end both execution should arrive at the 'same' values, with values depending on the program accepted range of input.

## 2.3 TIP Pointer Support

TIP Pointer support can be found in the `Interpreter.scala` file. In Listing 1 & Listing 2, the TIP implementation for pointer referencing (`&z`) and dereferencing (`*y`) is shown.

### 2.3.1 Reference

Match the `AExpr` on the class `AVarRef`, to set a variable reference.

```
1 case AVarRef(e: AIdentifier, _) =>
2   // DP1 - &z value position
3   log.debug("Variable reference: " + exp)
4   (env(e.declaration), store)
```

Listing 1: Interpreter - Pointer Reference

### 2.3.2 Dereference

Dereference is done by matching on `AUnaryOp` & `DerefOp`, retrieving the `ReferenceValue` from the result of applying `semright` on the expression.

```
1 case e: AUnaryOp =>
2   val (sub, s1) = semright(e.subexp, env, store)
3   val cval = e.operator match {
4     case DerefOp =>
5       // DP1 - *z value position
6       log.debug("Dereference Operator: " + exp)
7       sub match {
8         case crv: ReferenceValue =>
9           s1.getOrElse(crv, errorUninitializedLocation(exp.loc, s1))
10        case _ => errorDerefNotPointer(exp.loc, sub, s1)
11      }
12   }
13   (cval, s1)
```

Listing 2: Interpreter - Pointer Dereference

## 3 Discussion Point 2

The modified files are those with starting annotations: `SymbolicValues.scala`, `Interpreter.scala` and `SMTSolver.scala`.

### 3.1 Implementation

This subsection will discuss the implementation of concolic testing on arrays in TIP. In order of sequence will the operations be discussed: `Interpreter`, `SymbolicValues` and last `SMTSolver`.

#### 3.1.1 Interpreter

The purpose of the interpreter statements is updating/ accessing the store with the correct reference values of the array & concrete values stored in the array.

#### Array Creation

The created array is iterated and the store is updated by use of a fold. Each concrete value is given a reference value, with the reference value kept within the symbolic array.

#### Array Select

Retrieve the location of the concrete value by accessing the content field on the array, using the integer value of the `idxv`. Once the location is retrieved the concrete value can be accessed by accessing the `s2` variable or the updated store.

```
1 // MOD-DP2
2 // Array Access - since we are on the right side of an expression
3 case AArrAcc(arr, idx, _) =>
4   // Evaluate the idx
5   val (idxv, s1) = semright(idx, env, store)
6   // Using the new store, evaluate the arr
7   val (arrv, s2) = semright(arr, env, s1)
8   // Get the value and return the latest store
9   (idxv, arrv) match {
10    case (idxv: IntValue, arrv: ArrValue) =>
11      log.debug("[IP] - Selecting value")
12      // Get reference value
13      val location = arrv.content(idxv.i)
14      // Access concrete value from store
15      val concreteValue: IntValue = s2.getOrElse(location, null)
16      match {
17        case intValue: IntValue => intValue
18      }
19      // Return symbolic value & updated store
20      (spec.arraySelect(arrv, idxv, concreteValue), s2)
```

Listing 3: Interpreter - Select Array

Apply the `arraySelect` method to generate the symbolic value of the array operation. Return the symbolic value and updated store.

### Array Store

First generate the symbolic values of the array updated. Retrieve the concrete reference for the array (`arrayReference`) by accessing the `env` using the `id` which is a location type.

Accessing the reference for the updated value (`valueReference`) is done by accessing the `content` field on the array. Return a tuple of the `env` and updated store with concrete references to both the array & concrete value updated.

```
1 case AAssignStmt(left: AArrAcc, right: AExpr, _) =>
2   // Left index
3   val (idxv, s1) = semeright(left.idx, env, store)
4   // Left array
5   val (arrv, s2) = semeright(left.arr, env, s1)
6   // Value to place in array
7   val (rhsv, s3) = semeright(right, env, s2)
8   (idxv, arrv, left.arr, rhsv) match {
9     // MOD-DP2
10    case (idxv: IntValue, arrv: ArrValue, id: AIdentifier, rhsv:
        IntValue) =>
11      log.debug("[IP] - Storing array value")
12      // Get updated array
13      val updatedArray: ArrValue = spec.arrayStore(arrv, idxv, rhsv)
14      // Get reference value array from env
15      val arrayReference = env.getOrElse(id, null)
16      // Get reference value value
17      val valueReference = updatedArray.content(idxv.i)
18      // Update store with reference for array & value
19      (env, s3 + (arrayReference -> updatedArray) + (valueReference
        -> rhsv))
20    }
```

Listing 4: Interpreter - Store Array

### 3.1.2 SymbolicValues

Based on the operation performed in the interpreter, created the symbolic value, to later pass to the SMTSolver.

#### Array Creation

Iterate over the list of `vals`, retrieve the symbolic value of each and store in a sequence of `AExpr`. Return a `SymbArrValue`, containing the vector of `refs` and `AArrOp` element as second field, with `symbolicArray` as first element.

```
1 // MOD-DP2
2 def arrayValue(refs: Vector[ReferenceValue], vals:
    Vector[IntValue]): ArrValue = {
3   log.debug("[SV] - Creating array value")
4   // Create a sequence of symbolic expressions
5   val symbolicArray: Seq[AExpr] = vals.map {
6     case SymbIntValue(_, symbolic) => symbolic
7   }
8
9   log.debug("[SV] - Array content: " + symbolicArray)
10  SymbArrValue(refs, AArrOp(symbolicArray, noLoc))
11 }
```

Listing 5: SymbolicValues - Create Array

### Array Select

```
1 // MOD-DP2
2 def arraySelect(arr: ArrValue, idx: IntValue, v: IntValue): IntValue
    = {
3   (arr, idx) match {
4     case (arr: SymbArrValue, idx: SymbIntValue) =>
5       log.debug("[SV] - Selecting value in array")
6       SymbIntValue(v.i, AArrAcc(arr.symbolic, idx.symbolic, noLoc))
7     }
8   }
```

Listing 6: SymbolicValues - Select Array

### Array Store

```
1 // MOD-DP2
2 def arrayStore(arr: ArrValue, idx: IntValue, v: IntValue): ArrValue
    = {
3   (arr, idx, v) match {
4     case (arr: SymbArrValue, idx: SymbIntValue, v: SymbIntValue)
        => {
5       log.debug("[SV] - Setting value in array")
6       SymbArrValue(arr.content, AArrUpdate(arr.symbolic,
        idx.symbolic, v.symbolic, noLoc))
7     }
8   }
```

Listing 7: SymbolicValues - Store Array

### 3.1.3 SMTSolver

#### Array Creation

A constant array in Z3 is created by the following statement: `((as const (Array Int Int) 0))`. If there are no elements in the array, return just the array starting value. If there are elements present, create the populated array from the base values with a chained list of store statements populating it.

```

1 // MOD-DP2
2 // ((as const (Array Int Int) 0)
3 case AArrOp(elems, _) =>
4   log.debug("[SMT] - Array")
5   // Z3 Starting array value
6   val startingArray = "((as const (Array Int Int)) 0)"
7   if (elems.isEmpty) {
8     // If no elements, return the empty array
9     startingArray
10  } else {
11    // Create the constant array from individual store statements
12    val populatedArray =
13      elems.zipWithIndex.foldLeft(startingArray) {
14        case (acc, (elem, idx)) =>
15          s"(store $acc ${idx.toString} ${expToSexp(elem)})"
16      }
17    populatedArray
18  }

```

Listing 8: SMTSolver - Create Array

The select & store expand the array with the elements, as shown above, appending the new operation to it.

### Array Select

```

1 // MOD-DP2
2 // (select ((as const (Array Int Int) 0) x)
3 case AArrAcc(arr, idx, _) =>
4   log.debug("[SMT] - Select")
5   s"(select ${expToSexp(arr)} ${expToSexp(idx)})"

```

Listing 9: SMTSolver - Select Array

### Array Store

```

1 // MOD-DP2
2 // (store ((as const (Array Int Int) 0) x y)
3 case AArrUpdate(arr, idx, v, _) =>
4   log.debug("[SMT] - Update")
5   s"(store ${expToSexp(arr)} ${expToSexp(idx)} ${expToSexp(v)})"

```

Listing 10: SMTSolver - Store Array

## 3.2 Execution Analysis

The program execution performed 36 runs, of which 27 were successful and 9 contain errors or unsatisfiable path.

**TODO**

## 4 Discussion Point 3

As described in the assignment, two priorities were implemented. Both strategies were implemented in the ConcolicEngine.scala file.

### 4.1 Bread-First Search Priority

The first priority based BFS strategy is implemented by the method: nextExplorationTargetBFS. The search starts from the the root of the execution tree. The complete method implementation for the BFS Strategy can be found in Listing 13.

The first step is creating a mutable.PriorityQueue, by default the queue retrieves the elements with the highest priority, the algorithm requires the element with the lowest priority (shortest distance from root), for this the ordering is reversed on queue creation.

After the empty queue is created, the children of the root are iterated and for each a tuple, is created containing the child node: (child, 1), with the initial distance set to 1.

The next step in the algorithm is to iterate the queue until it is empty. On entering the queue, the first element highest priority/shortest distance from root is removed.

Using the below match case statement from the existing nextExplorationTarget method, the true & false branches are checked for the status of amount of explored branches.

```

1 // Check if node has been explored
2 val nextTarget: Option[(Branch, Boolean)] = node match {
3   case b: Branch =>
4     (b.branches(true), b.branches(false)) match {
5       // True branch unexplored
6       case (_, _: SubTreePlaceholder) if b.count(true) == 0 =>
7         Some((b, true))
8       // False branch unexplored
9       case (_, _: SubTreePlaceholder) if b.count(false) == 0 =>
10        Some((b, false))
11       // None are unexplored
12       case _ => None
13     }
14   case _ => None
15 }

```

Listing 11: BFS - Is Branch Explored

If the count of explored branches of either value is 0, the existing node is returned. In case both branches have already been explored, the None value is returned.

The final step in the algorithm, is the if case, which can be found in the listing below: Listing 12.



```

1  if (nextTarget.isDefined) {
2    // Return the found target node
3    log.debug("[DP3-BFS] - Found next target node, distance from
root: " + distance)
4    return nextTarget
5  } else {
6    // Append the children of node that has been explored
7    log.debug("[DP3-BFS] - Target node has been explored,
appending node children, and checking other nodes first")
8    // Ensure elements append first (lower distance) are visited first,
bread first search
9    queue = queue ++ node.children.map(child => (child, distance +
1))
10  }

```

Listing 12: BFS - Append Children

If there is a value defined the chosen node is used as the nextTarget. If no value is defined, all children of the node are added to the queue, with the distance increased by one: distance + 1.

## 4.2 Random Priority

The second search strategy is based on assigning a random priority to the node, the implementation method can be found in method: nextExplorationTargetRNDM and in listing: Listing 14.

The only changed required for this strategy is importing the `scala.util.Random` package. When populating the queue with the initial values of the `root`, use the `rand.nextInt(Int.MaxValue)` to assign a random value.

The method will proceed as before, the only remaining difference is the case when the node has already been explored. When appending the children of the node, instead of increment the distance value as before, a random value is assigned with the function described as before.

## 5 Discussion Point 4

This section will discuss the implementation of the different search strategies and the effect on the number of runs & resulting errors cases.

### 5.1 Overview

The results of the concolic testing can be summarized and are visible in Table 1.

| Strategy | Runs | Failures |
|----------|------|----------|
| DFS      | 21   | 1        |
| BFS      | 21   | 1        |
| Random   | 21   | 1        |

Table 1: Concolic Testing - Search Strategies

Since the purpose of concolic testing, is the exploration of all branches, changing the strategy of which branches are explored first does not inherently change the result of the execution. All satisfiable & unsatisfiable branches will be explored eventually.

## 6 Appendix

### 6.1 Discussion Point 3

```
1 // DP3 - Priority - BFS
2 def nextExplorationTargetBFS(root: ExecutionTreeRoot): Option[(Branch, Boolean)] = {
3   log.info("[DP3-BFS] - Using Bread First Search, with priority queue & distance from root")
4
5   // Initiate the queue, with ordering based on the lowest value (shortest distance) to root node
6   var queue: mutable.PriorityQueue[(ExecutionTree, Int)] = mutable.PriorityQueue()(Ordering.by[(ExecutionTree, Int), Int](_.2).reverse)
7   // Populate the queue with the list of children from the root, and set the distance immediately to 1
8   queue = queue ++ root.children.map(child => (child, 1))
9
10  while (queue.nonEmpty) {
11    // Get the first element from the queue
12    val (node, distance) = queue.dequeue()
13
14    // Check if node has been explored
15    // - if been explored = add children to queue with distance + 1
16    // - else return that node as next exploration target
17    val nextTarget: Option[(Branch, Boolean)] = node match {
18      case b: Branch =>
19        (b.branches(true), b.branches(false)) match {
20          // True branch unexplored
21          case (_, SubTreePlaceholder, _) if b.count(true) == 0 => Some((b, true))
22          // False branch unexplored
23          case (_, SubTreePlaceholder) if b.count(false) == 0 => Some((b, false))
24          // None are unexplored
25          case (_, _) => None
26        }
27      case _ => None
28    }
29
30    if (nextTarget.isDefined) {
31      // Return the found target node
32      log.debug("[DP3-BFS] - Found next target node, distance from root: " + distance)
33      return nextTarget
34    } else {
35      // Append the children of node that has been explored
36      log.debug("[DP3-BFS] - Target node has been explored, appending node children, and checking other nodes first")
37      // Ensure elements append first (lower distance) are visited first, bread first search
38      queue = queue ++ node.children.map(child => (child, distance + 1))
39    }
40  }
41  None
42 }
```

Listing 13: Bread-First Search Strategy

```

1 // DP3 - Priority - Random
2 def nextExplorationTargetRNDM(root: ExecutionTreeRoot): Option[(Branch, Boolean)] = {
3   log.info("[DP3-RNDM] - Using Bread First Search, with random priority")
4   val rand = new scala.util.Random
5
6   // Initiate the queue, with ordering based on the lowest value (shortest distance) to root node
7   var queue: mutable.PriorityQueue[(ExecutionTree, Int)] = mutable.PriorityQueue()(Ordering.by[(ExecutionTree, Int), Int](_. _2).reverse)
8   // Populate the queue with the list of children from the root
9   queue = queue ++ root.children.map(child => (child, rand.nextInt(Int.MaxValue)))
10
11   while (queue.nonEmpty) {
12     // Get the first element from the queue
13     val (node, priority) = queue.dequeue()
14
15     // Check if node has been explored
16     // - if been explored = add children to queue with distance + 1
17     // - else return that node as next exploration target
18     val nextTarget: Option[(Branch, Boolean)] = node match {
19       case b: Branch =>
20         (b.branches(true), b.branches(false)) match {
21           // True branch unexplored
22           case (_, SubTreePlaceholder, _) if b.count(true) == 0 => Some((b, true))
23           // False branch unexplored
24           case (_, SubTreePlaceholder) if b.count(false) == 0 => Some((b, false))
25           // None are unexplored
26           case (_, _) => None
27         }
28       case _ => None
29     }
30
31     if (nextTarget.isDefined) {
32       // Return the found target node
33       log.debug("[DP3-RNDM] - Found next target node, priority: " + priority)
34       return nextTarget
35     } else {
36       // Append the children of node that has been explored
37       log.debug("[DP3-RNDM] - Target node has been explored, appending node children, and checking other nodes first")
38       // Ensure elements append first (lower distance) are visited first, bread first search
39       queue = queue ++ node.children.map(child => (child, rand.nextInt(Int.MaxValue)))
40     }
41   }
42   None
43 }

```

Listing 14: Random Priority Strategy