

Code Verification Using Symbolic Execution

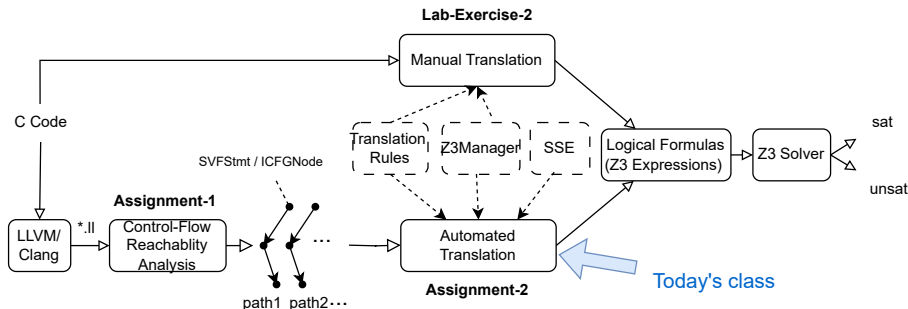
(Week 7)

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Code Verification Using Static Symbolic Execution



- We will detail the algorithms of translating branches and calls/returns.
- We will showcase branches and interprocedural examples.

Translate Branches and Calls/Returns

Algorithm 1: `translatePath(path)`

```
1 foreach edge ∈ path do
2   if intra ← dyn_cast<Intra>(edge) then
3     if handleIntra(intra) == false then
4       return false
5   else if call ← dyn_cast<CallEdge>(edge) then
6     handleCall(call)
7   else if ret ← dyn_cast<RetEdge>(edge) then
8     handleRet(ret)
9   return true
```

Algorithm 2: `handleIntra(intraEdge)`

```
1 if intraEdge.getCondition() then
2   if !handleBranch(intraEdge) then
3     return false;
4   else
5     return handleNonBranch(intraEdge);
6 else
7   return handleNonBranch(intraEdge);
```

Algorithm 3: `handleCall(callEdge)`

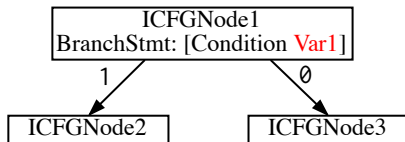
```
1 // Your code starts here ..;
2
3 // For each CallPE lhs = rhs:
4 // (1) Retrieve two z3 expressions  $\langle [c], rhs \rangle$  and  $\langle [c'], lhs \rangle$  under contexts  $c$  (caller's context) and  $c'$  (callee's context); Note that pushCallingCtx will make  $c$  become  $c'$ .
5 // (2) Add  $\langle [c], rhs \rangle \equiv \langle [c'], lhs \rangle$  into the solver.
```

Algorithm 4: `handleRet(retEdge)`

```
1 // Your code starts here ..;
2
3 // For each RetPE lhs = rhs:
4 // (1) Retrieve two z3 expressions  $\langle [c'], rhs \rangle$  and  $\langle [c], lhs \rangle$  under contexts  $c$  (caller's context) and  $c'$  (callee's context); Note that popCallingCtx will make  $c'$  become  $c$ .
5 // (2) Add  $\langle [c'], rhs \rangle \equiv \langle [c], lhs \rangle$  into the solver.
```

getCondition() and getSuccessorCondValue()

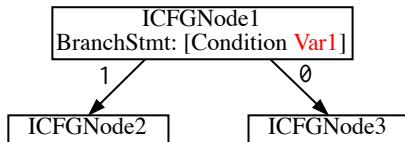
Given a if/else branch on the ICFG as the following:



- `edge → getCondition()` returns the branch condition (of type `SVFValue*` which is a **boolean** (for if/else) or a **numeric** (for switch).
 - `edge → getCondition()` returns `nullptr` if this `IntraCFGEde` is not a branch.
- Given the condition value, you could obtain the ID of the corresponding `SVFVar` (`Var1`) via `edge → getCondition() → getId()`.

getCondition() and getSuccessorCondValue()

Given a if/else branch on the ICFG as the following:



- `edge` \rightarrow `getSuccessorCondValue()` returns the actual condition `succCondValue`, whose value is either 1 (for if branch to execute) or 0 (for the else branch to execute).
 - For example, the `succCondValue` is 1 on the edge from ICFGNode1 to ICFGNode2, and 0 on the edge from ICFGNode1 to ICFGNode3.
- When evaluating the feasibility of a branch edge (e.g., ICFGNode1 to ICFGNode2) given an ICFG path, check `sat` of `Var1 == succCondValue` against the solver's existing constraints.

Example 4: Branches

```
1 void main(int x){  
2     int y;  
3     if(x > 10) {  
4         y = x + 1;  
5     }  
6     else {  
7         y = 10;  
8     }  
9     svf_assert(y >= x + 1);  
10 }
```

Source code

```
1 define void @main(i32 %x) #0 {  
2 entry:  
3     %cmp = icmp ugt i32 %x, 10  
4     br i1 %cmp, label %if.then, label %if.else  
5  
6 if.then:  
7     %add = add i32 %x, 1  
8     br label %if.end  
9  
10 if.else:  
11     br label %if.end  
12  
13 if.end: = %if.else, %if.then  
14     %y.0 = phi i32 [%add, %if.then], [10, %if.else]  
15     %add1 = add i32 %x, 1  
16     %cmp2 = icmp uge i32 %y.0, %add1  
17     call void @svf_assert(i1 zeroext %cmp2)  
18     ret void  
19 }
```

LLVM IR

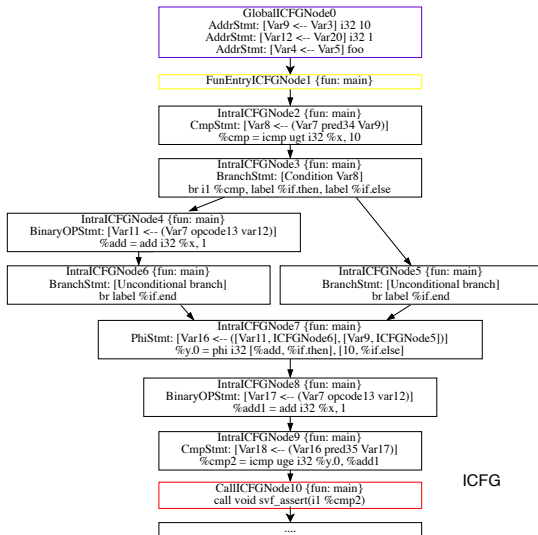
Example 4: Branches

```
1 define void @main(i32 %x) #0 {  
2 entry:  
3   %cmp = icmp ugt i32 %x, 10  
4   br i1 %cmp, label %if.then, label %if.else  
5  
6 if.then:  
7   %add = add i32 %x, 1  
8   br label %if.end  
9  
10 if.else:  
11   br label %if.end  
12  
13 if.end: = %if.else, %if.then  
14   %y.0 = phi i32 [%add, %if.then], [10, %if.else]  
15   %add1 = add i32 %x, 1  
16   %cmp2 = icmp uge i32 %y.0, %add1  
17   call void @svf_assert(i1 zeroext %cmp2)  
18   ret void  
19 }
```

LLVM IR

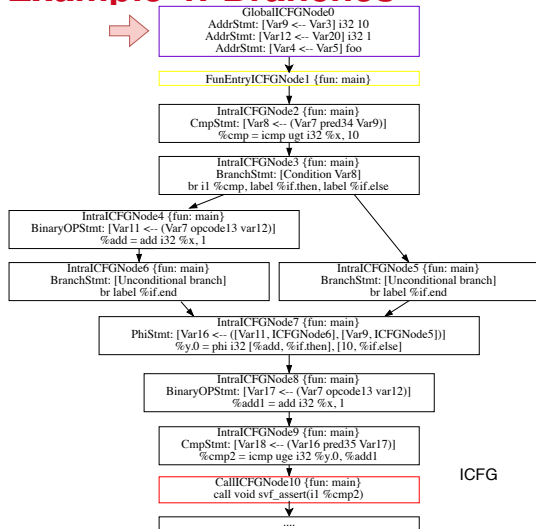
Two ICFG paths:

- *if.then* branch:
0 → 1 → 2 → 3 → 4 → 6 → 7 → 8 → 9 → *svf_assert*
- *if.else* branch:
0 → 1 → 2 → 3 → 5 → 7 → 8 → 9 → *svf_assert*



ICFG

Example 4: Branches



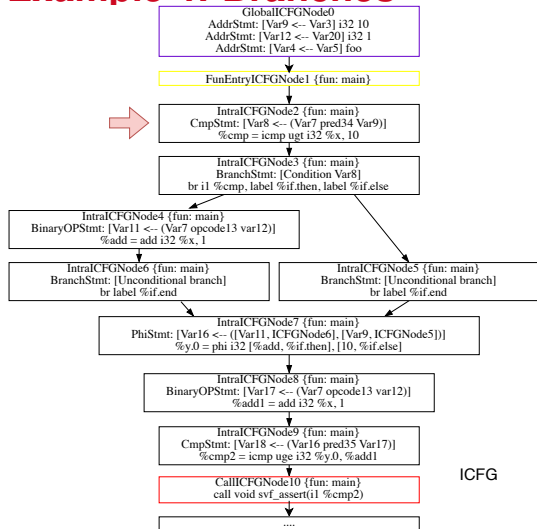
Verifying ICFG path: 0 → 1 → 2 → 3 → 4 →
6 → 7 → 8 → 9 → *svf_assert* (if.then branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
...	

ICFG

Example 4: Branches



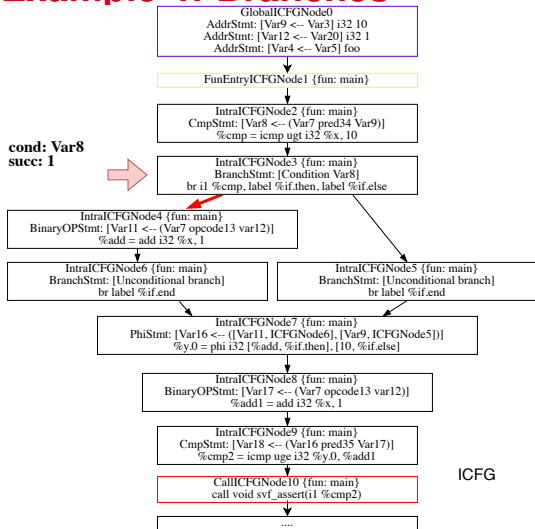
Verifying ICFG path: 0 → 1 → 2 → 3 → 4 →
6 → 7 → 8 → 9 → *svf_assert* (if.then branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 11
ValVar8	Value: 1
...	

ICFG

Example 4: Branches



Algorithm 5: 3 handleIntra(intraEdge)

```

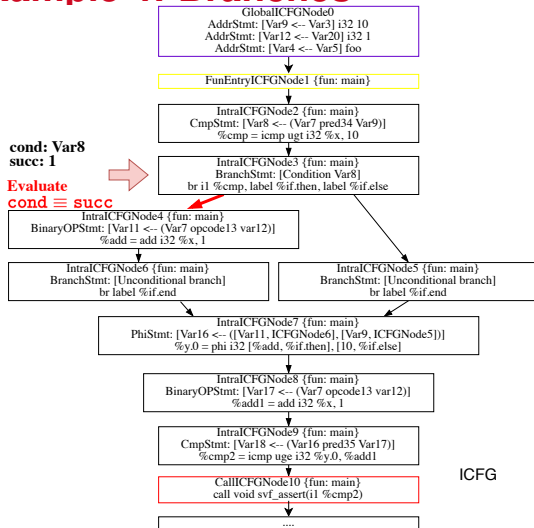
2 if intraEdge.getCondition() &&
   !handleBranch(intraEdge) then
4   return false;
6 else
8   handleNonBranch(edge);
    
```

Algorithm 6: handleBranch(intraEdge)

```

1 cond = ... // Retrieve branch condition boolean var;
2 succ = ... // Edge's succ condition value (0 or 1);
3 // Evaluate path feasibility;
4 // The current path/edge is feasible if 'cond' and
  'succ' have the same value, when evaluated in the
  solver; otherwise this branch edge is infeasible;
5 if the brach edge is infeasible then
6   return false;
7 else
8   // add (cond==succ) to solver if it holds;
9   return true;
    
```

Example 4: Branches



Algorithm 7: 3 handleIntra(intraEdge)

```

2 if intraEdge.getCondition() &&
   !handleBranch(intraEdge) then
4   | return false;
6 else
8   | handleNonBranch(edge);
  
```

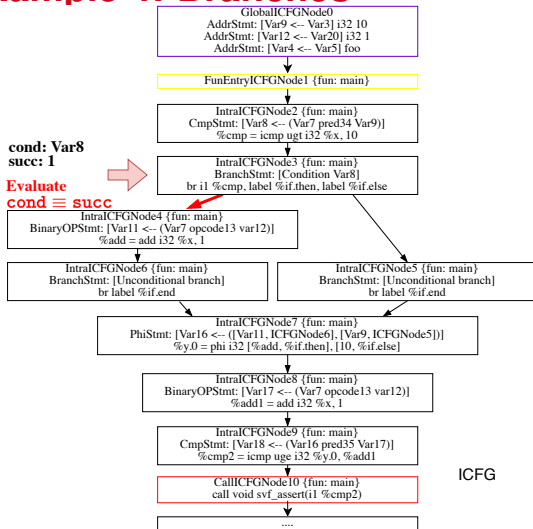
Algorithm 8: handleBranch(intraEdge)

```

1 cond = ... // Retrieve branch condition boolean var;
2 succ = ... // Edge's succ condition value (0 or 1);
3 // Evaluate path feasibility;
4 // The current path/edge is feasible if 'cond' and
  'succ' have the same value, when evaluated in the
  solver; otherwise this branch edge is infeasible;
5 if the brach edge is infeasible then
6   | return false;
7 else
8   // add (cond≡succ) to solver if it holds;
9   | return true;
  
```

Note: getSolver().push() creates a new stack frame for maintaining the newly added Z3 constraints.

Example 4: Branches



ICFG

Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow$
 $6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$ (if.then branch)

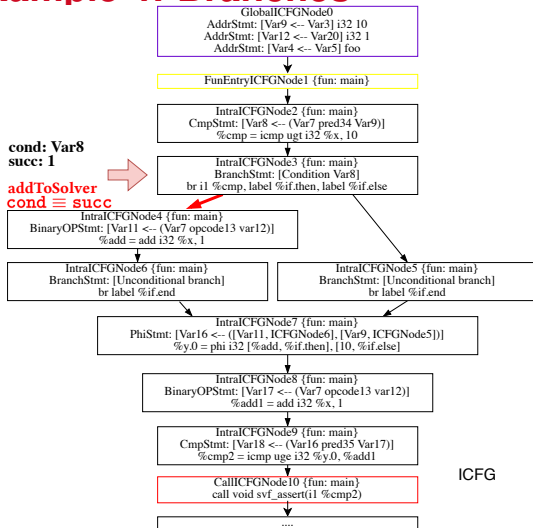
ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 \rightarrow 4	

The constraint $\text{Var8} \equiv 1$ is evaluated to be SAT.

The conditional ICFGEde [ICFGNode3 \rightarrow ICFGNode4] is feasible.

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 11
ValVar8	Value: 1
...	

Example 4: Branches



Algorithm 9: 3 handleIntra(intraEdge)

```

1 if intraEdge.getCondition() &&
  !handleBranch(intraEdge) then
2   return false;
3 else
4   handleNonBranch(edge);
  
```

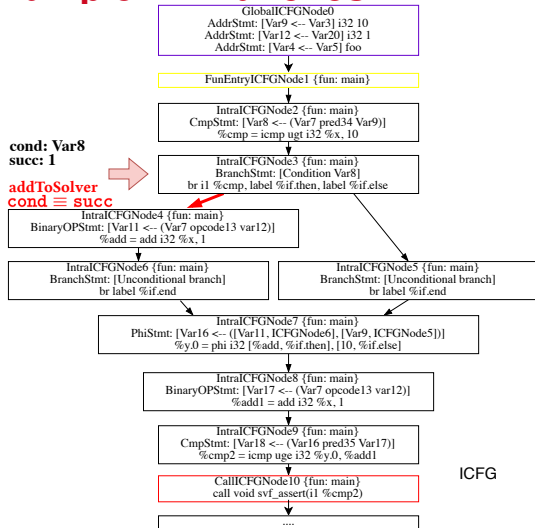
Algorithm 10: handleBranch(intraEdge)

```

1 cond = ... // Retrieve branch condition boolean var;
2 succ = ... // Edge's succ condition value (0 or 1);
3 // Evaluate path feasibility;
4 // The current path/edge is feasible if 'cond' and
  'succ' have the same value, when evaluated in the
  solver; otherwise this branch edge is infeasible;
5 if the brach edge is infeasible then
6   return false;
7 else
8   // add (cond≡succ) to solver if it holds;
9   return true;
  
```

Note: res is sat, so the conditional ICFGEdge
[ICFGNode4 ← ICFGNode3] is **feasible!!**

Example 4: Branches



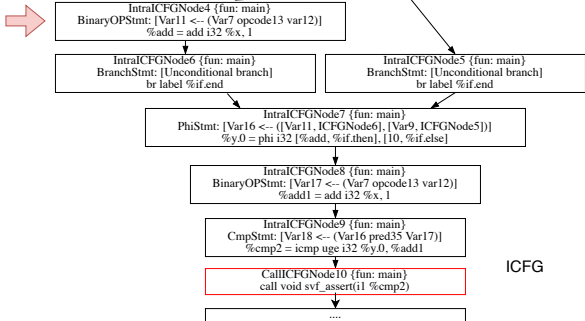
Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert}$ (if.then branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 \rightarrow 4	$\wedge \text{Var8} \equiv 1$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 11
ValVar8	Value: 1
...	

ICFG

Example 4: Branches

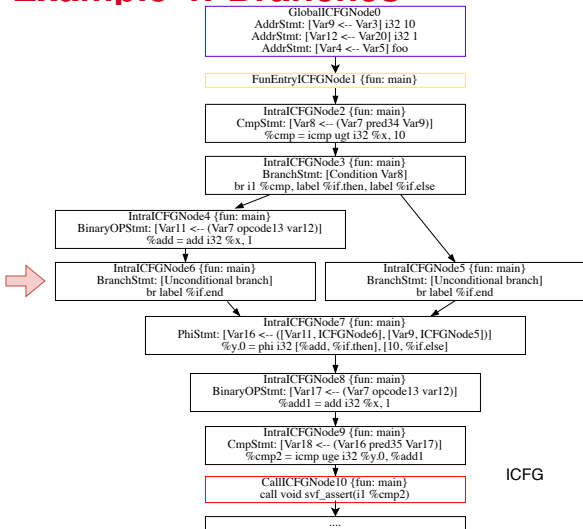


Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert}$ (if.then branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 \rightarrow 4	$\wedge \text{Var8} \equiv 1$
ICFGNode 4	$\wedge \text{Var11} \equiv \text{Var7} + \text{Var12}$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 11
ValVar8	Value: 1
ValVar11	Value: 12
...	

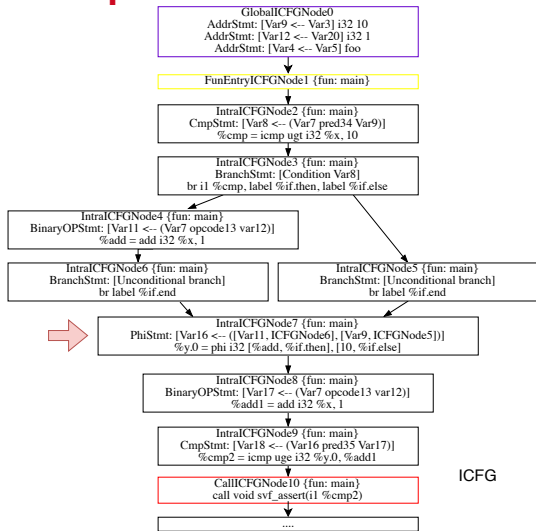
Example 4: Branches



Algorithm 11: 3 `handleIntra(intraEdge)`

```
2 if intraEdge.getCondition() &&
   !handleBranch(intraEdge) then
4   return false;
6 else
8   handleNonBranch(edge);
```


Example 4: Branches



Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert}$ (if.then branch)

Algorithm 12: 3 handlePhi(edge)

```

1 res ← getZ3Expr(phi.getResID());
2 opINodeFound ← false;
3 for i ← 0 to phi.getOpVarNum() - 1 do
4   if edge.srcNode() postdominates phi.getOpICFGNode(i)
   then
5     ope ← getZ3Expr(phi.getOpVar(i).getId());
6     addToSolver(res == ope);
7     opINodeFound ← true;
  
```

Given $\text{Var16} \leftarrow ([\text{Var11}, \text{ICFGNode6}], [\text{Var9}, \text{ICFGNode5}])$, only $\text{Var16} \equiv \text{Var11}$ holds as we traverse the if.then branch from ICFGNode6, where Var11's definition originates

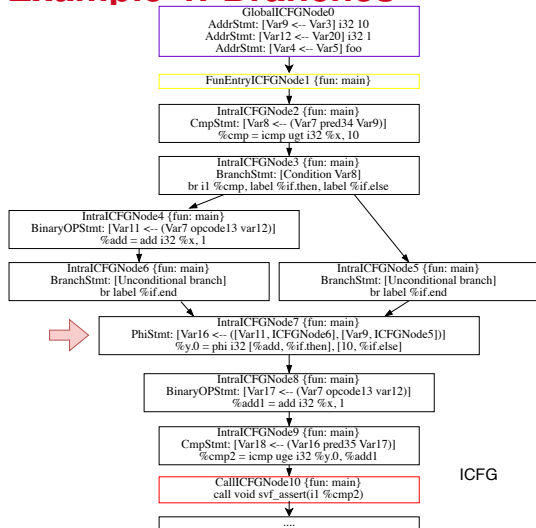
$\text{edge.srcNode}()$: ICFGNode6

$\text{phi.getOpICFGNode}(i)$: ICFGNode where i -th

phi operand var's definition originates.

ICFGNode m postdominates n : if all paths to the graph's exit starting at n must go through m (a node postdominates itself).

Example 4: Branches



Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow$

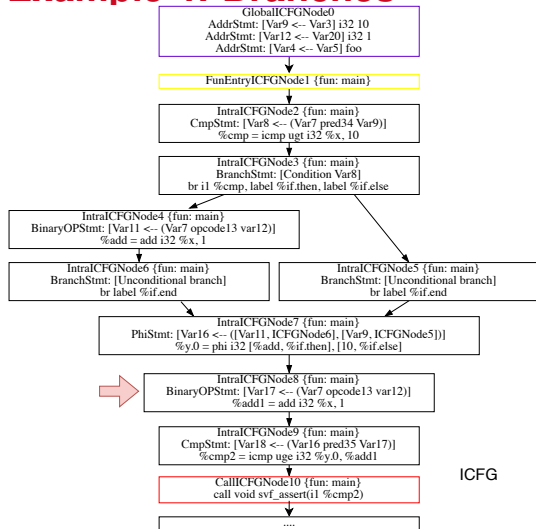
$6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$ (if.then branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var9 \equiv 10 \wedge Var12 \equiv 1 \wedge Var4 \equiv 0x7f000005$
ICFGNode 2	$\wedge Var8 \equiv ite(Var7 > Var9, 1, 0)$
ICFGEde 3 \rightarrow 4	$\wedge Var8 \equiv 1$
ICFGNode 4	$\wedge Var11 \equiv Var7 + Var12$
ICFGNode 7	$\wedge Var16 \equiv Var11$

-----SVFVar and Value-----	
...	
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 11
ValVar8	Value: 1
ValVar11	Value: 12
ValVar16	Value: 12
...	

ICFG

Example 4: Branches



ICFG

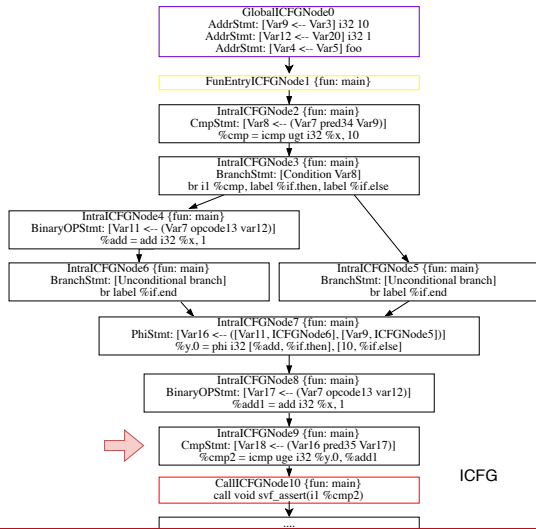
Verifying ICFG path: 0 → 1 → 2 → 3 → 4 →

6 → 7 → 8 → 9 → *svf_assert* (if.then branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 → 4	$\wedge \text{Var8} \equiv 1$
ICFGNode 4	$\wedge \text{Var11} \equiv \text{Var7} + \text{Var12}$
ICFGNode 7	$\wedge \text{Var16} \equiv \text{Var11}$
ICFGNode 8	$\wedge \text{Var17} \equiv \text{Var7} + \text{Var12}$

-----SVFVar and Value-----	
...	
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 11
ValVar8	Value: 1
ValVar11	Value: 12
ValVar16	Value: 12
ValVar17	Value: 12
...	

Example 4: Branches



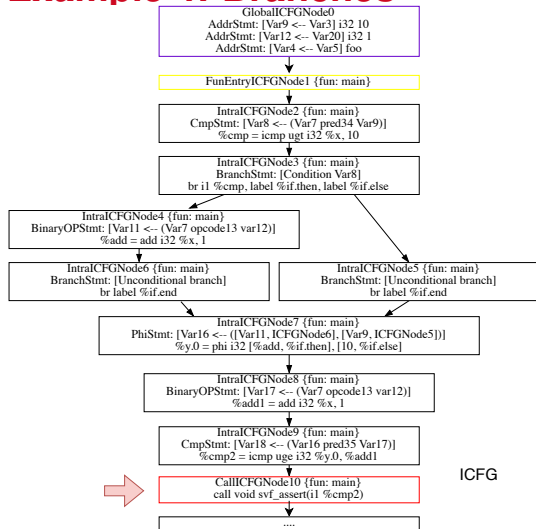
Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow$

$6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$ (if.then branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var9 \equiv 10 \wedge Var12 \equiv 1 \wedge Var4 \equiv 0x7f000005$
ICFGNode 2	$\wedge Var8 \equiv ite(Var7 > Var9, 1, 0)$
ICFGEde 3 \rightarrow 4	$\wedge Var8 \equiv 1$
ICFGNode 4	$\wedge Var11 \equiv Var7 + Var12$
ICFGNode 7	$\wedge Var16 \equiv Var11$
ICFGNode 8	$\wedge Var17 \equiv Var7 + Var12$
ICFGNode 9	$\wedge Var18 \equiv ite(Var16 \geq Var17, 1, 0)$

-----SVFVar and Value-----	
...	
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 11
ValVar8	Value: 1
ValVar11	Value: 12
ValVar16	Value: 12
ValVar17	Value: 12
ValVar18	Value: 1
...	

Example 4: Branches

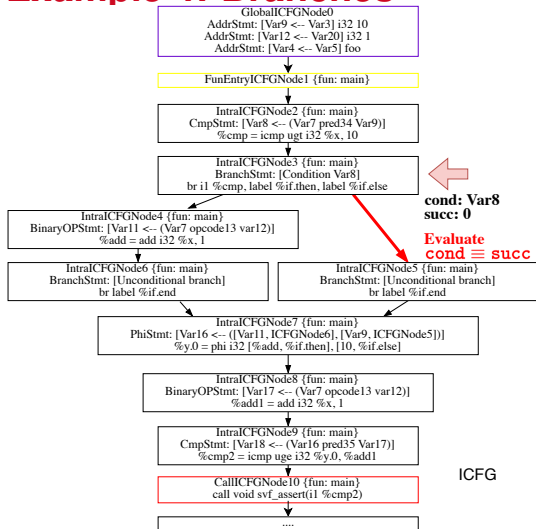


Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow$
 $6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert (if.then branch)}$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 \rightarrow 4	$\wedge \text{Var8} \equiv 1$
ICFGNode 4	$\wedge \text{Var11} \equiv \text{Var7} + \text{Var12}$
ICFGNode 7	$\wedge \text{Var16} \equiv \text{Var11}$
ICFGNode 8	$\wedge \text{Var17} \equiv \text{Var7} + \text{Var12}$
ICFGNode 9	$\wedge \text{Var18} \equiv \text{ite}(\text{Var16} \geq \text{Var17}, 1, 0)$
ICFGNode 10	$\wedge \text{Var18} \equiv 0$ (negation of the assert condition)

Solver yields **UNSAT** (i.e., no counter example),
 therefore, the assertion is successfully verified!!

Example 4: Branches



Algorithm 13: 3 handleIntra(intraEdge)

```

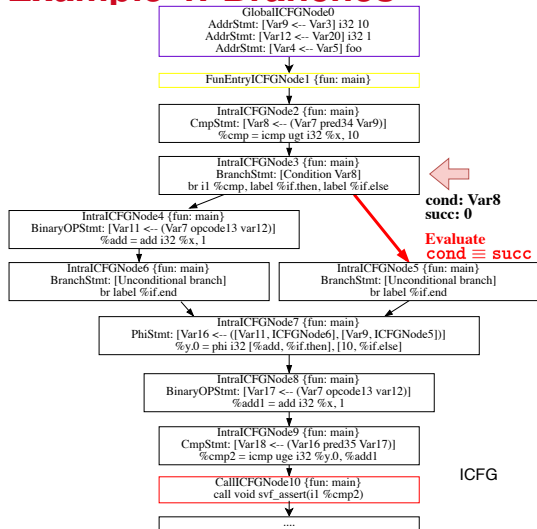
2 if intraEdge.getCondition() &&
   !handleBranch(intraEdge) then
4   return false;
6 else
8   handleNonBranch(edge);
  
```

Algorithm 14: handleBranch(intraEdge)

```

1 cond = ... // Retrieve branch condition boolean var;
2 succ = ... // Edge's succ condition value (0 or 1);
3 // Evaluate path feasibility;
4 // The current path/edge is feasible if 'cond' and
  'succ' have the same value, when evaluated in the
  solver; otherwise this branch edge is infeasible;
5 if the brach edge is infeasible then
6   return false;
7 else
8   // add (cond≡succ) to solver if it holds;
9   return true;
  
```

Example 4: Branches



Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 5 \rightarrow$

$7 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert}$ (if.else branch)

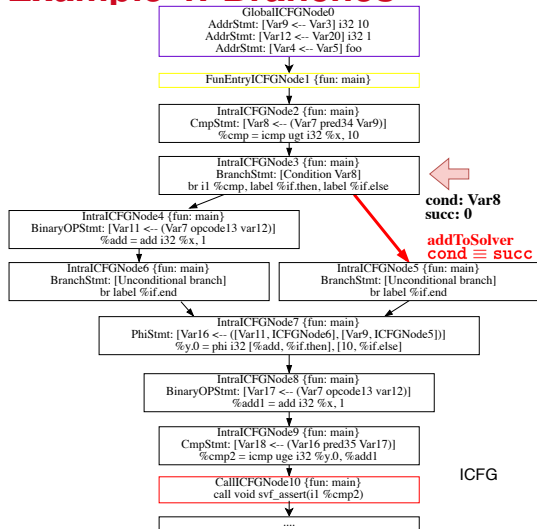
ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$ $\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGNode 2	
ICFGEde 3 \rightarrow 5	

The constraint $\text{Var8} \equiv 0$ is evaluated to be SAT

The conditional ICFGEde [ICFGNode3 \rightarrow ICFGNode5] is feasible.

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 10
ValVar8	Value: 0
...	

Example 4: Branches



Algorithm 15: 3 handleIntra(intraEdge)

```

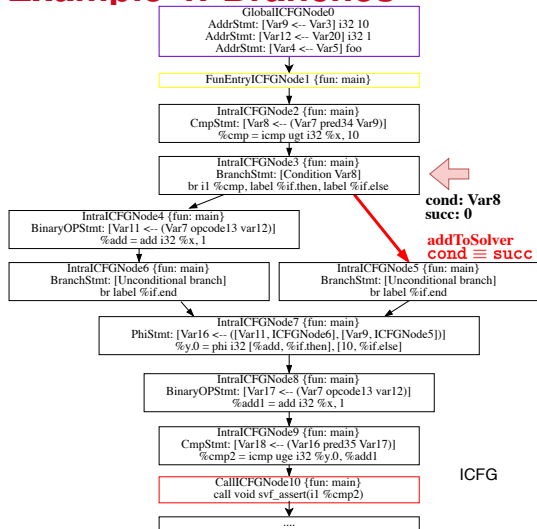
2 if intraEdge.getCondition() &&
   !handleBranch(intraEdge) then
4   return false;
6 else
8   handleNonBranch(edge);
  
```

Algorithm 16: handleBranch(intraEdge)

```

1 cond = ... // Retrieve branch condition boolean var;
2 succ = ... // Edge's succ condition value (0 or 1);
3 // Evaluate path feasibility;
4 // The current path/edge is feasible if 'cond' and
  'succ' have the same value, when evaluated in the
  solver; otherwise this branch edge is infeasible;
5 if the brach edge is infeasible then
6   return false;
7 else
8   // add (cond≡succ) to solver if it holds;
9   return true;
  
```


Example 4: Branches



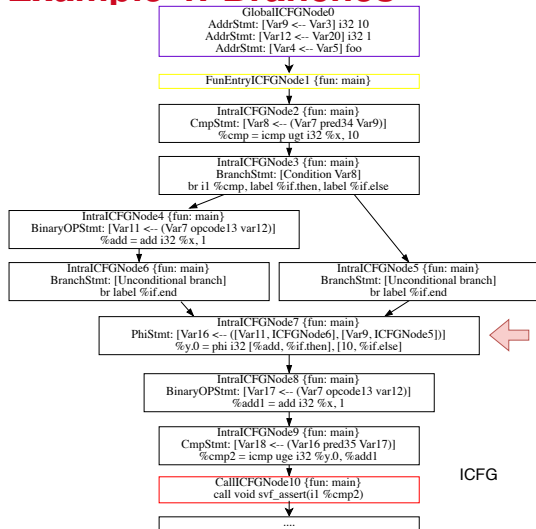
Verifying ICFG path: 0 → 1 → 2 → 3 → 5 →
7 → 8 → 9 → *svf_assert* (if.else branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 → 5	$\wedge \text{Var8} \equiv 0$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 10
ValVar8	Value: 0
...	

ICFG

Example 4: Branches



Verifying ICFG path: 0 → 1 → 2 → 3 → 5 →

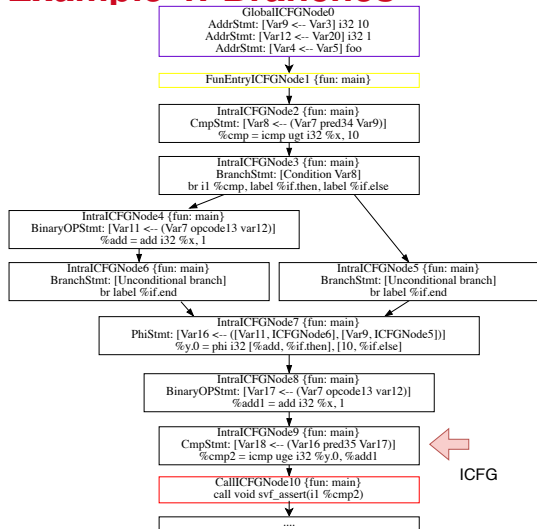
7 → 8 → 9 → *svf_assert* (if.else branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 → 5	$\wedge \text{Var8} \equiv 0$
ICFGNode 7	$\wedge \text{Var16} \equiv \text{Var9}$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 10
ValVar8	Value: 0
ValVar16	Value: 10
...	

ICFG

Example 4: Branches



Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 5 \rightarrow$

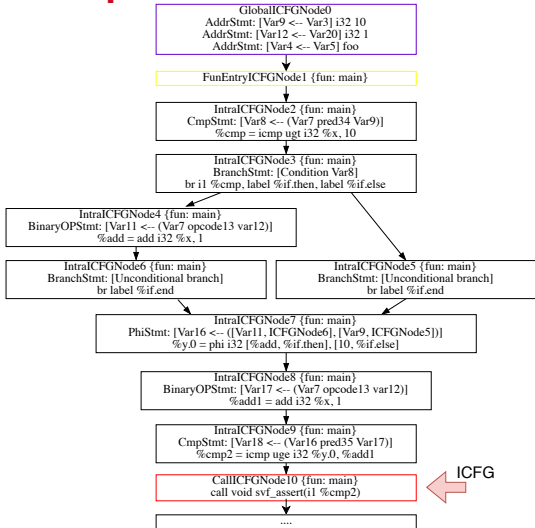
$7 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert (if.else branch)}$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 \rightarrow 5	$\wedge \text{Var8} \equiv 0$
ICFGNode 7	$\wedge \text{Var16} \equiv \text{Var9}$
ICFGNode 8	$\wedge \text{Var17} \equiv \text{Var7} + \text{Var12}$
ICFGNode 9	$\wedge \text{Var18} \equiv \text{ite}(\text{Var16} \geq \text{Var17}, 1, 0)$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ValVar4	Value: 0x7f000005
ValVar9	Value: 10
ValVar12	Value: 1
ValVar7	Value: 10
ValVar8	Value: 0
ValVar16	Value: 10
ValVar17	Value: 11
ValVar18	Value: 0
...	

ICFG

Example 4: Branches



Verifying ICFG path: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 5 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert}$ (if.else branch)

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var9} \equiv 10 \wedge \text{Var12} \equiv 1 \wedge \text{Var4} \equiv 0x7f000005$
ICFGNode 2	$\wedge \text{Var8} \equiv \text{ite}(\text{Var7} > \text{Var9}, 1, 0)$
ICFGEde 3 \rightarrow 5	$\wedge \text{Var8} \equiv 0$
ICFGNode 7	$\wedge \text{Var16} \equiv \text{Var9}$
ICFGNode 8	$\wedge \text{Var17} \equiv \text{Var7} + \text{Var12}$
ICFGNode 9	$\wedge \text{Var18} \equiv \text{ite}(\text{Var16} \geq \text{Var17}, 1, 0)$
ICFGNode 10	$\wedge \text{Var18} \equiv 0$ (negation of the assert condition)

Solver yields **SAT**, a counterexample exists:
(Var16 \equiv 10 \wedge Var17 \equiv 11).

The assertion is violated and fails!

Example 5: Interprocedural

```
1 int foo(int p) {  
2     return p;  
3 }  
4 int main(int argc) {  
5     int x;  
6     int y;  
7     x = foo(3); //ctx:[ $\ell_7$ ]  
8     y = foo(argc); //ctx:[ $\ell_8$ ]  
9     svf_assert(y == argc);  
10 }
```

[ℓ_7]: calling context of foo at ℓ_7

[ℓ_8]: calling context of foo at ℓ_8

Example 5: Interprocedural

```
1 int foo(int p) {  
2     return p;  
3 }  
4 int main(int argc) {  
5     int x;  
6     int y;  
7     x = foo(3); //ctx:[ $\ell_7$ ]  
8     y = foo(argc); //ctx:[ $\ell_8$ ]  
9     svf_assert(y == argc);  
10 }
```

[ℓ_7]: calling context of foo at ℓ_7

[ℓ_8]: calling context of foo at ℓ_8

Concrete Execution
(Concrete states)

One execution:

argc : 0

push calling context (calling foo at ℓ_7)

p : 3

calling context pop (returning from foo at ℓ_2)

x : 3

push calling context (calling foo at ℓ_8)

p : 0

pop calling context (returning from foo ℓ_2)

y : 0

Example 5: Interprocedural

```
1 int foo(int p) {  
2     return p;  
3 }  
4 int main(int argc) {  
5     int x;  
6     int y;  
7     x = foo(3); //ctx:[ $\ell_7$ ]  
8     y = foo(argc); //ctx:[ $\ell_8$ ]  
9     svf_assert(y == argc);  
10 }
```

[ℓ_7]: calling context of foo at ℓ_7

[ℓ_8]: calling context of foo at ℓ_8

Concrete Execution
(Concrete states)

One execution:

```
argc  : 0  
push calling context (calling foo at  $\ell_7$ )  
    p  : 3  
calling context pop (returning from foo at  $\ell_2$ )  
    x  : 3  
push calling context (calling foo at  $\ell_8$ )  
    p  : 0  
pop calling context (returning from foo  $\ell_2$ )  
    y  : 0
```

Symbolic Execution
(Symbolic states)

```
argc  : getZ3Expr(argc)  
push abstract calling context (current ctx:[ $\ell_7$ ])  
     $\langle [\ell_7], p \rangle$  : 3  
    x  : getZ3Expr( $\langle [\ell_7], p \rangle$ )  
pop abstract calling context (current ctx:[ ])   
push abstract calling context (current ctx:[ $\ell_8$ ])  
     $\langle [\ell_8], p \rangle$  : getZ3Expr(argc)  
    y  : getZ3Expr( $\langle [\ell_8], p \rangle$ )  
pop abstract calling context (current ctx:[ ])
```

Example 5: Interprocedural

```

1  int foo(int p) {
2      return p;
3  }
4  int main(int argc) {
5      int x;
6      int y;
7      x = foo(3); //ctx:[ℓ7]
8      y = foo(argc); //ctx:[ℓ8]
9      svf_assert(y == argc);
10 }

```

[ℓ₇]: calling context of foo at ℓ₇

[ℓ₈]: calling context of foo at ℓ₈

Concrete Execution
(Concrete states)

One execution:

```

argc  : 0
push calling context (calling foo at ℓ7)
  p    : 3
calling context pop (returning from foo at ℓ2)
  x    : 3
push calling context (calling foo at ℓ8)
  p    : 0
pop calling context (returning from foo ℓ2)
  y    : 0

```

Symbolic Execution
(Symbolic states)

```

argc  : getZ3Expr(argc)
push abstract calling context (current ctx:[ℓ7])
  ⟨[ℓ7], p⟩ : 3
  x        : getZ3Expr(⟨[ℓ7], p⟩)
pop abstract calling context (current ctx:[ ])
push abstract calling context (current ctx:[ℓ8])
  ⟨[ℓ8], p⟩ : getZ3Expr(argc)
  y        : getZ3Expr(⟨[ℓ8], p⟩)
pop abstract calling context (current ctx:[ ])

```

Checking non-existence of counterexamples:

$\psi(N_1) \wedge \psi(N_2) \wedge \dots \psi(N_i) \wedge \neg\psi(Q)$	Satisfiability	Counterexample
$\langle [ℓ_7], p \rangle \equiv 3 \wedge x \equiv \langle [ℓ_7], p \rangle \wedge \langle [ℓ_8], p \rangle \equiv \text{argc} \wedge y \equiv \langle [ℓ_7], p \rangle \wedge y \neq \text{argc}$	unsat	\emptyset

foo's argument p needs to be **differentiated and renamed** as $\langle [ℓ_7], p \rangle$ and $\langle [ℓ_8], p \rangle$ due to two calling contexts, [ℓ₇] and [ℓ₈] to mimic the runtime call stack which holds the local variable p.

Example 5: Interprocedural

SSE::getZ3Expr(SVFVarID) in Assignment-2

- Get an Z3 expression based on SVFVarID and the current calling context callingCtx
- callingCtx is maintained per ICFG path by calling SSE::pushCallingCtx and SSE::popCallingCtx when handling CallCFGEdge and RetCFGEdge.

```
1 z3::expr SSE::getZ3Expr(NodeID idx) const {  
2     return z3Mgr->getZ3Expr(idx, callingCtx);  
3 }
```

Example 5: Interprocedural

```
1 int foo(int p) {  
2     return p;  
3 }  
4 int main(int argc) {  
5     int x;  
6     int y;  
7     x = foo(3);  
8     y = foo(argc);  
9     svf_assert(y == argc);  
10 }
```

Source code

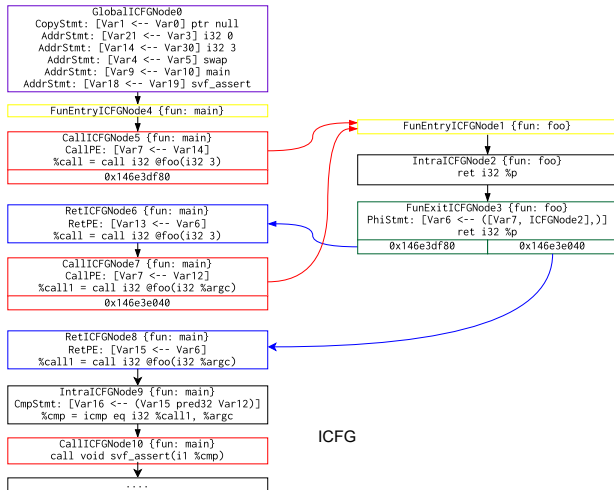
```
1 define i32 @foo(i32 %p) #0 {  
2 entry:  
3     ret i32 %p  
4 }  
5  
6 define i32 @main(i32 %argc) #0 {  
7 entry:  
8     %call = call i32 @foo(i32 3)  
9     %call1 = call i32 @foo(i32 %argc)  
10    %cmp = icmp eq i32 %call1, %argc  
11    call void @svf_assert(i1 zeroext %cmp)  
12    ret i32 0  
13 }
```

LLVM IR

Example 5: Interprocedural

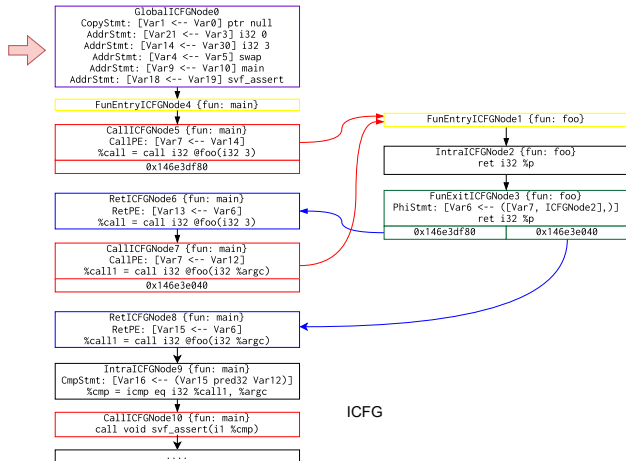
```
1 define i32 @foo(i32 %p) #0 {  
2 entry:  
3   ret i32 %p  
4 }  
5  
6 define i32 @main(i32 %argc) #0 {  
7 entry:  
8   %call = call i32 @foo(i32 3)  
9   %call1 = call i32 @foo(i32 %argc)  
10  %cmp = icmp eq i32 %call1, %argc  
11  call void @svf_assert(i1 zeroext %cmp)  
12  ret i32 0  
13 }
```

LLVM IR



ICFG

Example 5: Interprocedural



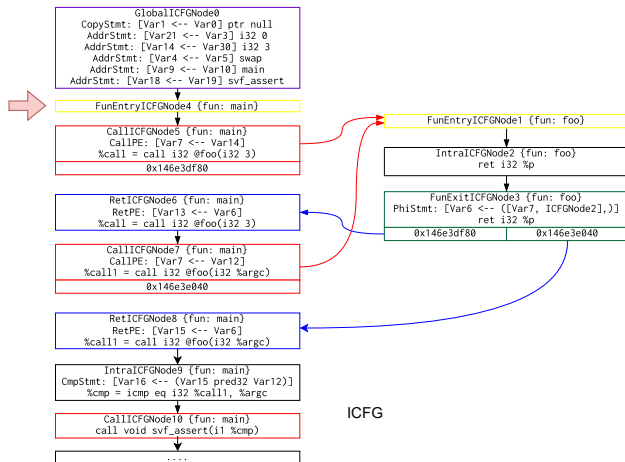
Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var21 \equiv 0 \wedge Var14 \equiv 3 \wedge \dots$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ObjVar10 (0x7f00000a)	Value: NULL
ObjVar19 (0x7f000013)	Value: NULL
ValVar0	Value: NULL
ValVar1	Value: NULL
ValVar21	Value: 0
ValVar14	Value: 3
ValVar4	Value: 0x7f000005
ValVar9	Value: 0x7f00000e
ValVar18	Value: 0x7f00001d
...	

The values of Z3 expressions for each SVFVar after analyzing GlobalICFGNode0 (use printExprValues() to print SVFVars and their values)

Example 5: Interprocedural



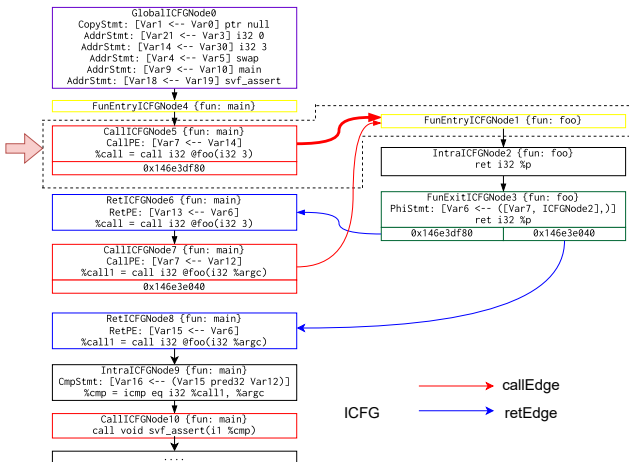
Algorithm 17: 2 `translatePath(path)`

```

2  foreach edge ∈ path do
4    if IntraEdge ← dyn_cast<IntraCFGEdge>(edge)
       then
6      if handleIntra(IntraEdge) == false then
8        return false;
10   else if CallEdge ← dyn_cast<CallCFGEdge>(edge)
       then
12     handleCall(CallEdge);
14   else if RetEdge ← dyn_cast<RetCFGEdge>(edge)
       then
16     handleRet(RetEdge);
18   else
20     assert(false && "what other edges we have?");
21   return true;

```

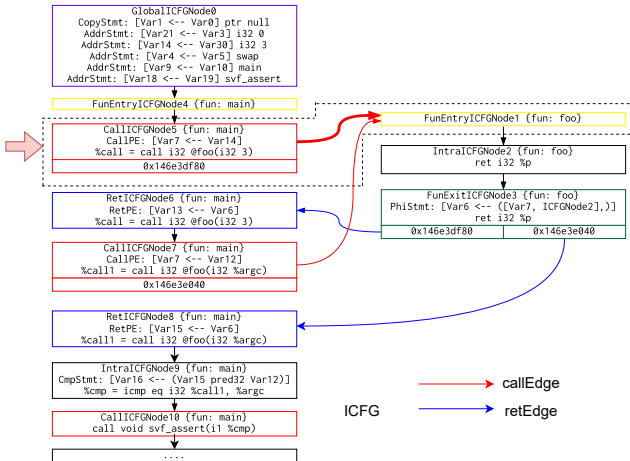
Example 5: Interprocedural



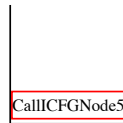
Algorithm 18: `handleCall(callEdge)`

- 1 // (1) For each CallPE lhs = rhs: retrieve rhs expr $\langle [c], \text{rhs} \rangle$ under callingCtx c (caller's context)
- 2 // (2) pushCallingCtx using current calliste ICFGNode; Note that pushCallingCtx will make c become c'. ;
- 3 // (3) For each CallPE lhs = rhs: retrieve lhs expr $\langle [c'], \text{lhs} \rangle$ under callingCtx c' (callee's context) ;
- 4 // (4) For each CallPE lhs = rhs: add $\langle [c], \text{rhs} \rangle \equiv \langle [c'], \text{lhs} \rangle$ into the solver.
- 5 return true;

Example 5: Interprocedural



Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

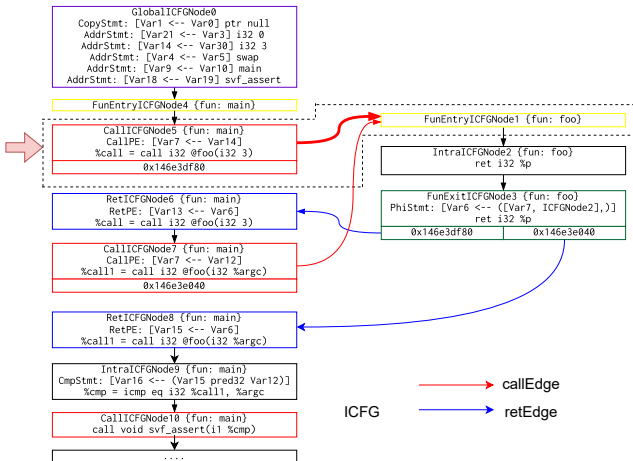


Calling Context

After processing the call edge

$CallICFGNode5 \rightarrow FunEntryICFGNode1$

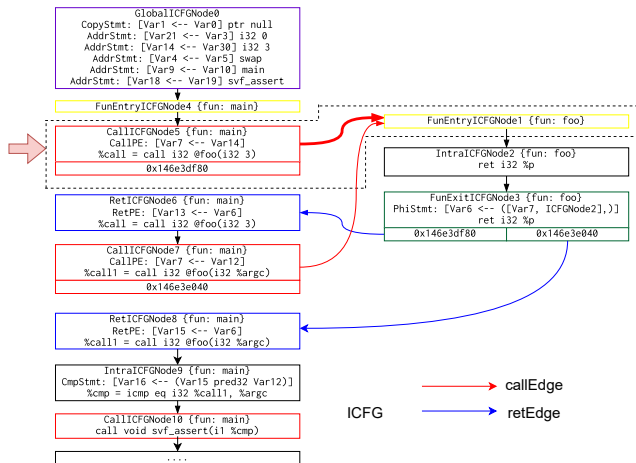
Example 5: Interprocedural



Algorithm 19: `handleCall(callEdge)`

- 1 // (1) For each CallPE lhs = rhs: retrieve rhs expr $\langle [c], \text{rhs} \rangle$ under callingCtx c (caller's context)
- 2 // (2) pushCallingCtx using current calliste ICFGNode; Note that pushCallingCtx will make c become c'. ;
- 3 // (3) For each CallPE lhs = rhs: retrieve lhs expr $\langle [c'], \text{lhs} \rangle$ under callingCtx c' (callee's context) ;
- 4 // (4) For each CallPE lhs = rhs: add $\langle [c], \text{rhs} \rangle \equiv \langle [c'], \text{lhs} \rangle$ into the solver.
- 5 return true;

Example 5: Interprocedural



Verifying ICFG path: 0 → 4 → 5 → 1 → 2 → 3 →

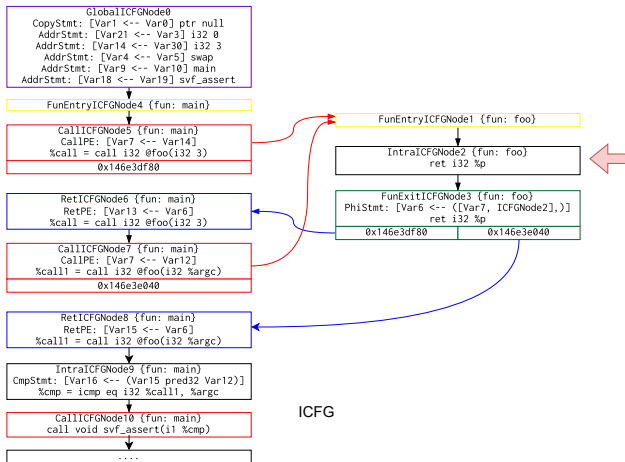
6 → 7 → 1 → 2 → 3 → 8 → 9 → svf_assert

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	Var21 ≡ 0 ∧ Var14 ≡ 3 ∧ ...
ICFGNode 5	∧ ⟨[ICFGNode5], Var7⟩ ≡ Var14

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ObjVar10 (0x7f00000a)	Value: NULL
ObjVar19 (0x7f000013)	Value: NULL
ValVar0	Value: NULL
ValVar1	Value: NULL
ValVar21	Value: 0
ValVar14	Value: 3
ValVar4	Value: 0x7f000005
ValVar9	Value: 0x7f00000e
ValVar18	Value: 0x7f00001d
ValVar7	Value: 3
...	

Note: SVFVar and Value table is printed under the calling context [CallICFGNode5]

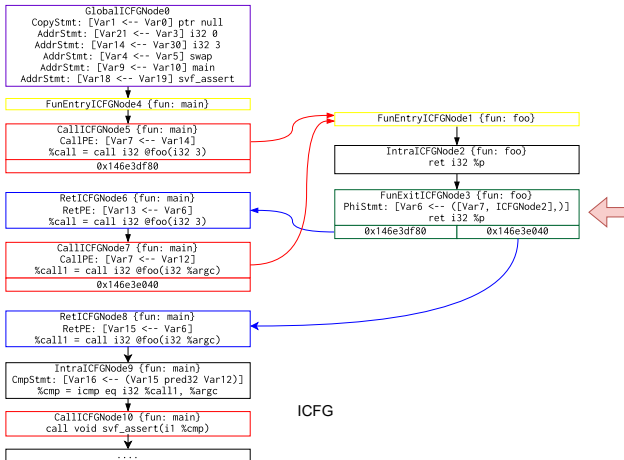
Example 5: Interprocedural



Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow \textcolor{blue}{2} \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert}$

ret i32 %p instruction.
Nothing needs to be done.

Example 5: Interprocedural



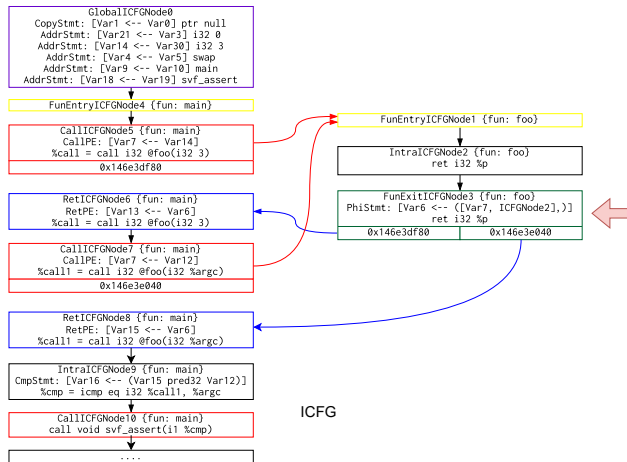
Algorithm 20: 3 handlePhi(edge)

```

1 res ← getZ3Expr(phi.getResID());
2 opINodeFound ← false;
3 for i ← 0 to phi.getOpVarNum() - 1 do
4   if edge.srcNode() postdominates
     phi.getOpICFGNode(i) then
5     ope ← getZ3Expr(phi.getOpVar(i).getId());
6     addToSolver(res == ope);
7     opINodeFound ← true;

```

Example 5: Interprocedural



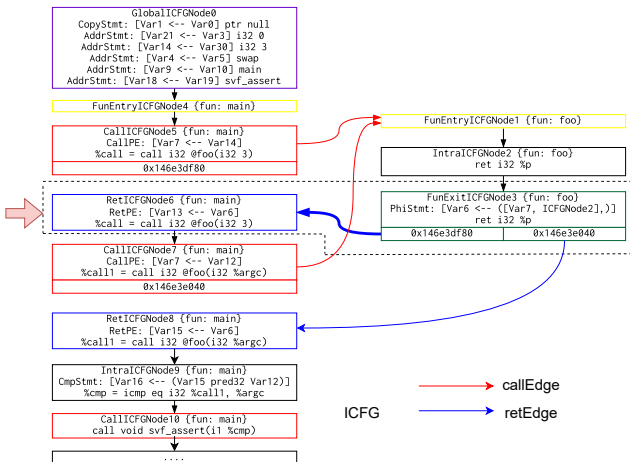
Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var21 \equiv 0 \wedge Var14 \equiv 3 \wedge \dots$
ICFGNode 5	$\wedge \langle [ICFGNode5], Var7 \rangle \equiv Var14$
ICFGNode 3	$\wedge \langle [ICFGNode5], Var6 \rangle \equiv \langle [ICFGNode5], Var7 \rangle$

-----SVFVar and Value-----	
ObjVar5 (0x7f000005)	Value: NULL
ObjVar10 (0x7f00000a)	Value: NULL
ObjVar19 (0x7f000013)	Value: NULL
ValVar0	Value: NULL
ValVar1	Value: NULL
ValVar21	Value: 0
ValVar14	Value: 3
ValVar4	Value: 0x7f000005
ValVar9	Value: 0x7f00000e
ValVar18	Value: 0x7f00001d
ValVar7	Value: 3
ValVar6	Value: 3
...	

Note: SVFVar and Value table is printed under the calling context [CallICFGNode5]

Example 5: Interprocedural

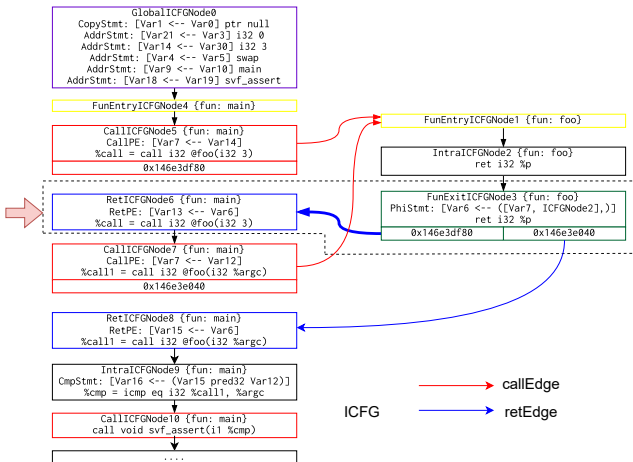


Algorithm 21: `handleRet`(retEdge)

- 1 // (1) For each RetPE lhs = rhs: retrieve rhs
expr $\langle [c'], \text{rhs} \rangle$ under callingCtx c' (callee's context);
- 2 // (2) popCallingCtx(); This will make c' become c (caller's context)
- 3 // (3) For each RetPE lhs = rhs: retrieve lhs
expr $\langle [c], \text{lhs} \rangle$ under callingCtx c (caller's context)
- 4 // (4) Add $\langle [c'], \text{rhs} \rangle \equiv \langle [c], \text{lhs} \rangle$ into the solver.
- 5 return true;

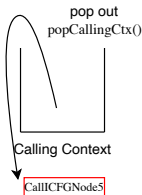
Note: `retPE.getRHSVarID()` returns `ValVar6`
`getZ3Expr(ValVar6)` binds `ValVar6` with the current callingCtx [ICFGNode5] and returns the Z3 expression for [ICFGNode5], `Var6`

Example 5: Interprocedural



Algorithm 22: `handleRet`(retEdge)

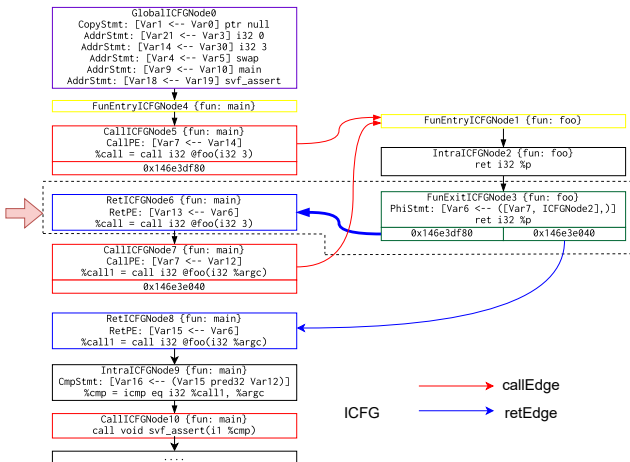
- 1 // (1) For each RetPE lhs = rhs: retrieve rhs expr $\langle [c'], \text{rhs} \rangle$ under callingCtx c' (callee's context);
- 2 // (2) popCallingCtx(); This will make c' become c (caller's context)
- 3 // (3) For each RetPE lhs = rhs: retrieve lhs expr $\langle [c], \text{lhs} \rangle$ under callingCtx c (caller's context)
- 4 // (4) Add $\langle [c'], \text{rhs} \rangle \equiv \langle [c], \text{lhs} \rangle$ into the solver.
- 5 return true;



After processing the return edge

`FunExitICFGNode3` \rightarrow `RetICFGNode6`

Example 5: Interprocedural



Algorithm 23: **handleRet**(retEdge)

- 1 // (1) For each RetPE lhs = rhs: retrieve rhs
expr $\langle [c'], \text{rhs} \rangle$ under callingCtx c' (callee's context);
- 2 // (2) popCallingCtx(); This will make c' become c (caller's context)
- 3 // (3) For each RetPE lhs = rhs: retrieve lhs
expr $\langle [c], \text{lhs} \rangle$ under callingCtx c (caller's context)
- 4 // (4) Add $\langle [c'], \text{rhs} \rangle \equiv \langle [c], \text{lhs} \rangle$ into the solver.
- 5 return true;

Example 5: Interprocedural

```
GlobalICFGNode0
CopyStmt: [Var1 <-- Var0] ptr null
AddrStmt: [Var21 <-- Var3] i32 0
AddrStmt: [Var14 <-- Var30] i32 3
AddrStmt: [Var4 <-- Var5] swap
AddrStmt: [Var9 <-- Var10] main
AddrStmt: [Var18 <-- Var19] svf_assert
```

```
FunEntryICFGNode4 {fun: main}
```

```
CallICFGNode5 {fun: main}
CallPE: [Var7 <-- Var14]
%call = call i32 @foo(i32 3)
0x146e3df80
```

```
RetICFGNode6 {fun: main}
RetPE: [Var13 <-- Var6]
%call = call i32 @foo(i32 3)
```

```
CallICFGNode7 {fun: main}
CallPE: [Var7 <-- Var12]
%call1 = call i32 @foo(i32 %argc)
0x146e3e040
```

```
RetICFGNode8 {fun: main}
RetPE: [Var15 <-- Var6]
%call1 = call i32 @foo(i32 %argc)
```

```
IntraICFGNode9 {fun: main}
CmpStmt: [Var16 <-- (Var15 pred32 Var12)]
%cmp = icmp eq i32 %call1, %argc
```

```
CallICFGNode10 {fun: main}
call void svf_assert(i1 %cmp)
```

```
....
```

```
FunEntryICFGNode1 {fun: foo}
```

```
IntraICFGNode2 {fun: foo}
ret i32 %p
```

```
FunExitICFGNode3 {fun: foo}
PhiStmt: [Var6 <-- ([Var7, ICFGNode2],)]
ret i32 %p
0x146e3df80 0x146e3e040
```

ICFG

→ callEdge

→ retEdge

Verifying ICFG path: 0 → 4 → 5 → 1 → 2 → 3 →

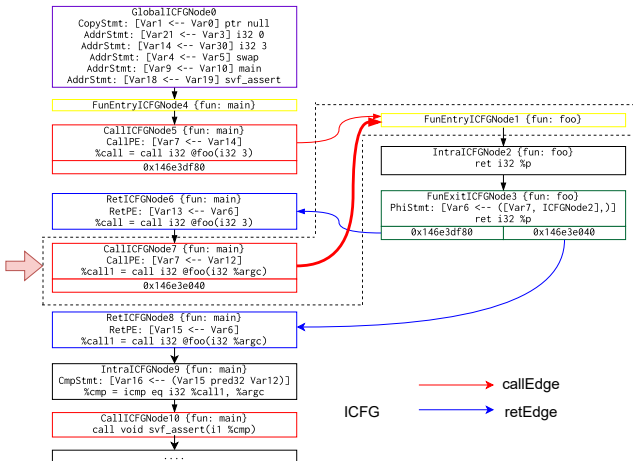
6 → 7 → 1 → 2 → 3 → 8 → 9 → svf_assert

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	Var21 ≡ 0 ∧ Var14 ≡ 3 ∧ ...
ICFGNode 5	∧ ([ICFGNode5], Var7) ≡ Var14
ICFGNode 3	∧ ([ICFGNode5], Var6) ≡ ([ICFGNode5], Var7)
ICFGNode 6	∧ Var13 ≡ ([ICFGNode5], Var6)

-----SVFVar and Value-----

```
ObjVar5 (0x7f000005) Value: NULL
ObjVar10 (0x7f00000a) Value: NULL
ObjVar19 (0x7f000013) Value: NULL
ValVar0 Value: NULL
ValVar1 Value: NULL
ValVar21 Value: 0
ValVar14 Value: 3
ValVar4 Value: 0x7f000005
ValVar9 Value: 0x7f00000e
ValVar18 Value: 0x7f00001d
ValVar13 Value: 3
...
```

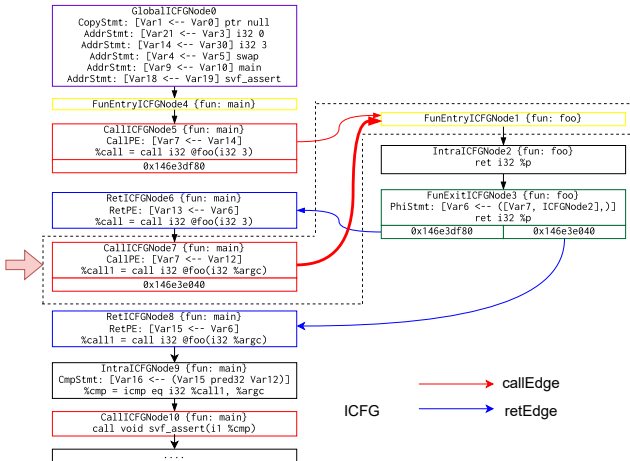

Example 5: Interprocedural



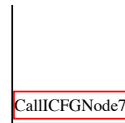
Algorithm 24: `handleCall(callEdge)`

- 1 // (1) For each CallPE lhs = rhs: retrieve rhs expr $\langle [c], \text{rhs} \rangle$ under callingCtx c (caller's context)
- 2 // (2) pushCallingCtx using current calliste ICFGNode; Note that pushCallingCtx will make c become c'. ;
- 3 // (3) For each CallPE lhs = rhs: retrieve lhs expr $\langle [c'], \text{lhs} \rangle$ under callingCtx c' (callee's context) ;
- 4 // (4) For each CallPE lhs = rhs: add $\langle [c], \text{rhs} \rangle \equiv \langle [c'], \text{lhs} \rangle$ into the solver.
- 5 return true;

Example 5: Interprocedural



Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

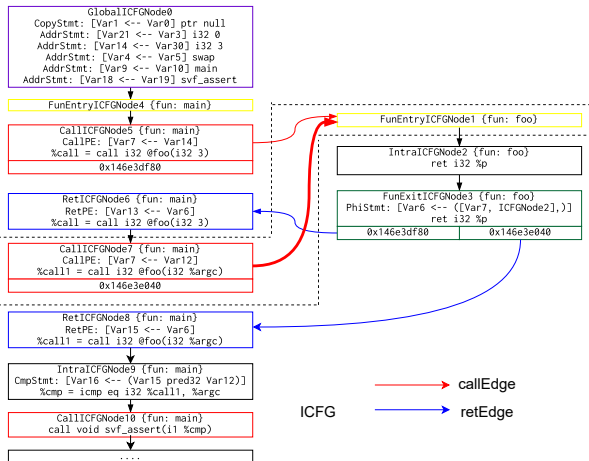


Calling Context

After processing the call edge

CallICFGNode7 → FunEntryICFGNode

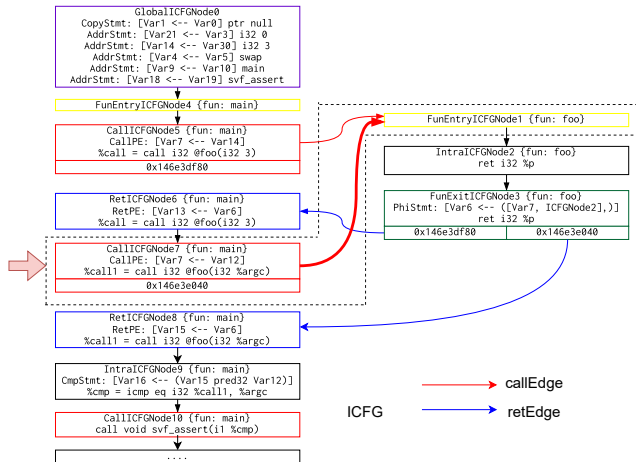
Example 5: Interprocedural



Algorithm 25: `handleCall(callEdge)`

- 1 // (1) For each CallPE lhs = rhs: retrieve rhs
expr $\langle [c], \text{rhs} \rangle$ under callingCtx c (caller's
context)
- 2 // (2) pushCallingCtx using current calliste
ICFGNode; Note that pushCallingCtx will make c
become c'. ;
- 3 // (3) For each CallPE lhs = rhs: retrieve lhs
expr $\langle [c'], \text{lhs} \rangle$ under callingCtx c' (callee's
context) ;
- 4 // (4) For each CallPE lhs = rhs: add
 $\langle [c], \text{rhs} \rangle \equiv \langle [c'], \text{lhs} \rangle$ into the solver.
- 5 return true;

Example 5: Interprocedural



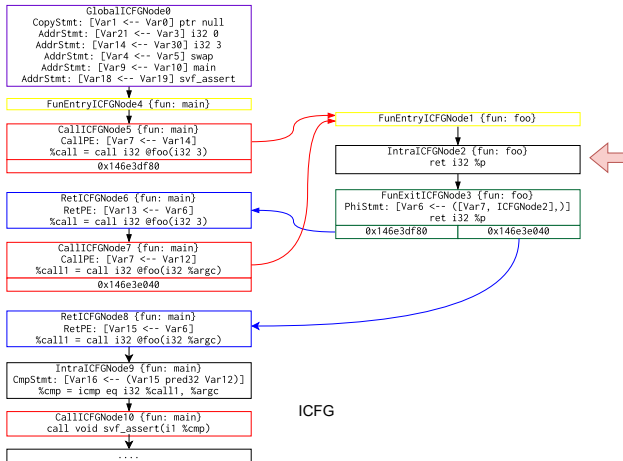
Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var21 \equiv 0 \wedge Var14 \equiv 3 \wedge \dots$
ICFGNode 5	$\wedge \langle [ICFGNode5], Var7 \rangle \equiv Var14$
ICFGNode 3	$\wedge \langle [ICFGNode5], Var6 \rangle \equiv \langle [ICFGNode5], Var7 \rangle$
ICFGNode 6	$\wedge Var13 \equiv \langle [ICFGNode5], Var6 \rangle$
ICFGNode 7	$\wedge \langle [ICFGNode7], Var7 \rangle \equiv Var12$

-----SVFVar and Value-----		
ValVar21	...	Value: 0
ValVar14	...	Value: 3
ValVar13	...	Value: 3
ValVar12	...	Value: 0
ValVar7	...	Value: 0
	...	

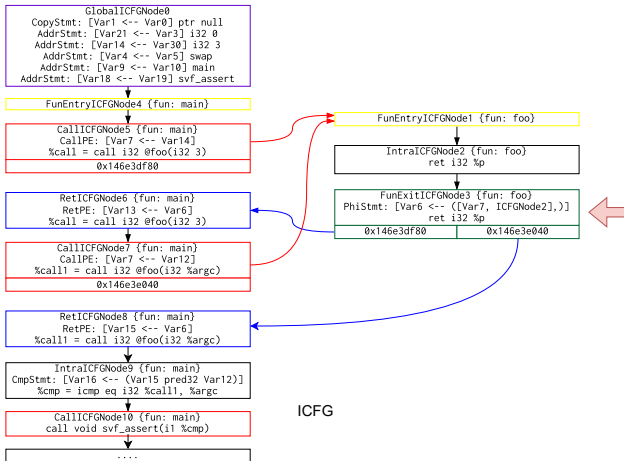
Note: SVFVars and their values in table are under the calling context [CallICFGNode7].
ValVar12 is uninitialized, thus evaluated as 0.

Example 5: Interprocedural



Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$
 $ret\ i32\ \%p$ instruction.
Nothing needs to be done.

Example 5: Interprocedural



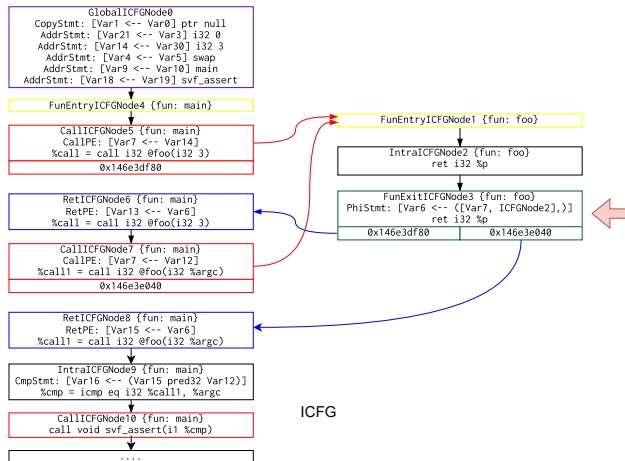
Algorithm 26: 3 handlePhi(edge)

```

1 res ← getZ3Expr(phi.getResID());
2 opINodeFound ← false;
3 for i ← 0 to phi.getOpVarNum() - 1 do
4   if edge.srcNode() postdominates
     phi.getOpICFGNode(i) then
5     ope ← getZ3Expr(phi.getOpVar(i).getId());
6     addToSolver(res == ope);
7     opINodeFound ← true;

```

Example 5: Interprocedural



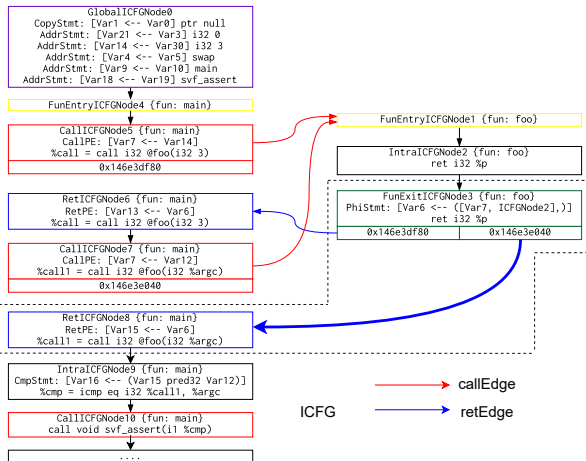
Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var21 \equiv 0 \wedge Var14 \equiv 3 \wedge \dots$
ICFGNode 5	$\wedge \langle [ICFGNode5], Var7 \rangle \equiv Var14$
ICFGNode 3	$\wedge \langle [ICFGNode5], Var6 \rangle \equiv \langle [ICFGNode5], Var7 \rangle$
ICFGNode 6	$\wedge Var13 \equiv \langle [ICFGNode5], Var6 \rangle$
ICFGNode 7	$\wedge \langle [ICFGNode7], Var7 \rangle \equiv Var12$
ICFGNode 3	$\wedge \langle [ICFGNode7], Var6 \rangle \equiv \langle [ICFGNode7], Var7 \rangle$

-----SVFVar and Value-----		
	...	
ValVar21	...	Value: 0
ValVar14	...	Value: 3
	...	
ValVar13	...	Value: 3
ValVar12	...	Value: 0
ValVar7	...	Value: 0
ValVar6	...	Value: 0
	...	

Note: SVFVars and their values in table are under the calling context [CallICFGNode7].

Example 5: Interprocedural

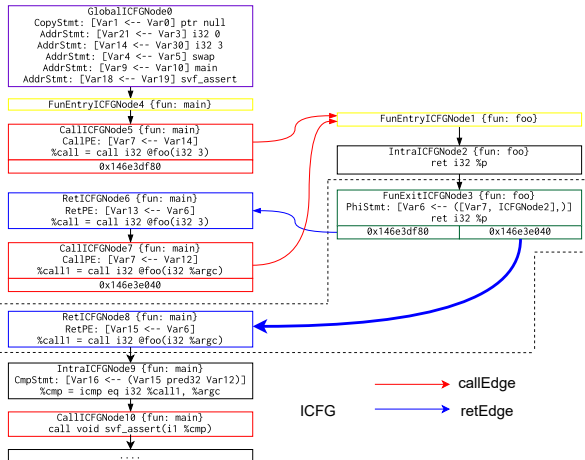


Algorithm 27: `handleRet`(retEdge)

- 1 // (1) For each RetPE lhs = rhs: retrieve rhs
expr $\langle [c'], \text{rhs} \rangle$ under callingCtx c' (callee's context);
- 2 // (2) popCallingCtx(); This will make c' become c (caller's context)
- 3 // (3) For each RetPE lhs = rhs: retrieve lhs
expr $\langle [c], \text{lhs} \rangle$ under callingCtx c (caller's context)
- 4 // (4) Add $\langle [c'], \text{rhs} \rangle \equiv \langle [c], \text{lhs} \rangle$ into the solver.
- 5 return true;

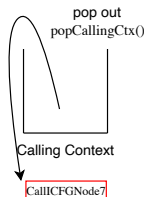
Note: `retPE.getRHSVarID()` returns `ValVar6`
`getZ3Expr(ValVar6)` binds `ValVar6` with the current callingCtx [`ICFGNode7`] and returns the Z3 expression for $\langle [ICFGNode7], \text{Var6} \rangle$

Example 5: Interprocedural



Algorithm 28: `handleRet`(retEdge)

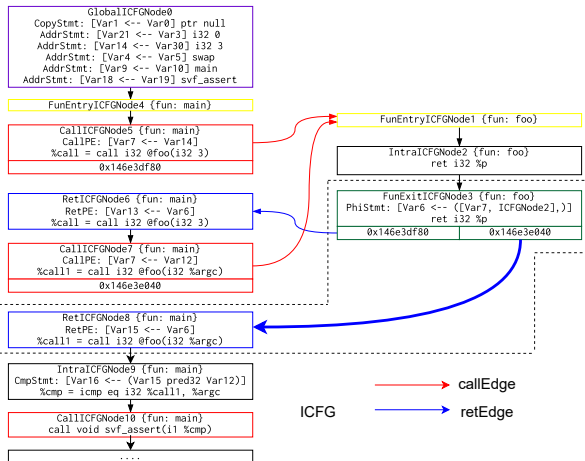
- 1 // (1) For each RetPE lhs = rhs: retrieve rhs expr $\langle [c'], \text{rhs} \rangle$ under callingCtx c' (callee's context);
- 2 // (2) `popCallingCtx()`; This will make c' become c (caller's context)
- 3 // (3) For each RetPE lhs = rhs: retrieve lhs expr $\langle [c], \text{lhs} \rangle$ under callingCtx c (caller's context)
- 4 // (4) Add $\langle [c'], \text{rhs} \rangle \equiv \langle [c], \text{lhs} \rangle$ into the solver.
- 5 return true;



After processing the return edge

FunExitICFGNode3 → RetICFGNode8

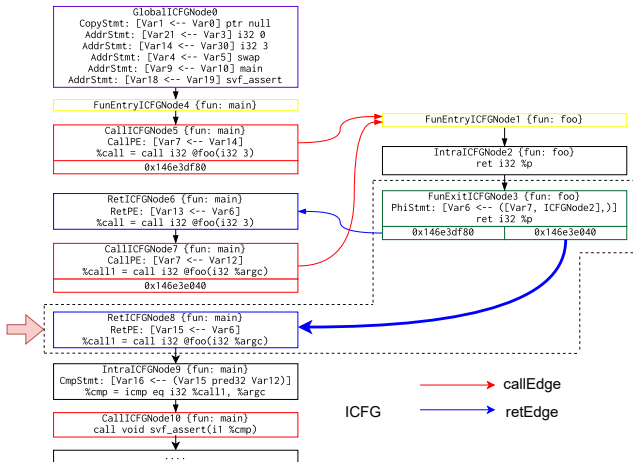
Example 5: Interprocedural



Algorithm 29: **handleRet**(retEdge)

- 1 // (1) For each RetPE lhs = rhs: retrieve rhs
expr $\langle [c'], \text{rhs} \rangle$ under callingCtx c' (callee's
context);
- 2 // (2) popCallingCtx(); This will make c' become
c (caller's context)
- 3 // (3) For each RetPE lhs = rhs: retrieve lhs
expr $\langle [c], \text{lhs} \rangle$ under callingCtx c (caller's
context)
- 4 // (4) Add $\langle [c'], \text{rhs} \rangle \equiv \langle [c], \text{lhs} \rangle$ into the solver.
- 5 return true;

Example 5: Interprocedural



Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var21 \equiv 0 \wedge Var14 \equiv 3 \wedge \dots$
ICFGNode 5	$\wedge \langle [ICFGNode5], Var7 \rangle \equiv Var14$
ICFGNode 3	$\wedge \langle [ICFGNode5], Var6 \rangle \equiv \langle [ICFGNode5], Var7 \rangle$
ICFGNode 6	$\wedge Var13 \equiv \langle [ICFGNode5], Var6 \rangle$
ICFGNode 7	$\wedge \langle [ICFGNode7], Var7 \rangle \equiv Var12$
ICFGNode 3	$\wedge \langle [ICFGNode7], Var6 \rangle \equiv \langle [ICFGNode7], Var7 \rangle$
ICFGNode 8	$\wedge Var15 \equiv \langle [ICFGNode7], Var6 \rangle$

-----SVFVar and Value-----		
ValVar21	...	Value: 0
ValVar14	...	Value: 3
ValVar13	...	Value: 3
ValVar12	...	Value: 0
ValVar15	...	Value: 0
	...	

Example 5: Interprocedural

```
GlobalICFGNode0
CopyStmt: [Var1 <-- Var0] ptr null
AddrStmt: [Var21 <-- Var3] i32 0
AddrStmt: [Var14 <-- Var30] i32 3
AddrStmt: [Var4 <-- Var5] swap
AddrStmt: [Var9 <-- Var10] main
AddrStmt: [Var18 <-- Var19] svf_assert
```

```
FunEntryICFGNode4 {fun: main}
```

```
CallICFGNode5 {fun: main}
CallPE: [Var7 <-- Var14]
%call = call i32 @foo(i32 3)
0x146e3df80
```

```
RetICFGNode6 {fun: main}
RetPE: [Var13 <-- Var6]
%call = call i32 @foo(i32 3)
```

```
CallICFGNode7 {fun: main}
CallPE: [Var7 <-- Var12]
%call1 = call i32 @foo(i32 %argc)
0x146e3e040
```

```
RetICFGNode8 {fun: main}
RetPE: [Var15 <-- Var6]
%call1 = call i32 @foo(i32 %argc)
```

```
IntraICFGNode9 {fun: main}
CmpStmt: [Var16 <-- (Var15 pred32 Var12)]
%cmp = icmp eq i32 %call1, %argc
```

```
CallICFGNode10 {fun: main}
call void svf_assert(i1 %cmp)
```



ICFG

```
FunEntryICFGNode1 {fun: foo}
```

```
IntraICFGNode2 {fun: foo}
ret i32 %p
```

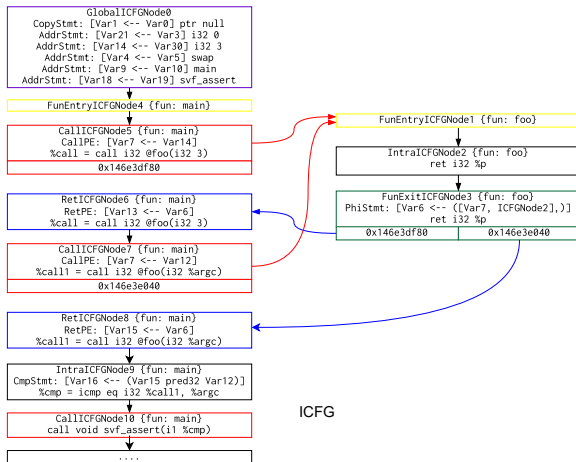
```
FunExitICFGNode3 {fun: foo}
PhiStmt: [Var6 <-- ([Var7, ICFGNode2],)]
ret i32 %p
0x146e3df80 0x146e3e040
```

Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow svf_assert$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$Var21 \equiv 0 \wedge Var14 \equiv 3 \wedge \dots$
ICFGNode 5	$\wedge \langle [ICFGNode5], Var7 \rangle \equiv Var14$
ICFGNode 3	$\wedge \langle [ICFGNode5], Var6 \rangle \equiv \langle [ICFGNode5], Var7 \rangle$
ICFGNode 6	$\wedge Var13 \equiv \langle [ICFGNode5], Var6 \rangle$
ICFGNode 7	$\wedge \langle [ICFGNode7], Var7 \rangle \equiv Var12$
ICFGNode 3	$\wedge \langle [ICFGNode7], Var6 \rangle \equiv \langle [ICFGNode7], Var7 \rangle$
ICFGNode 8	$\wedge Var15 \equiv \langle [ICFGNode7], Var6 \rangle$
ICFGNode 9	$\wedge Var16 \equiv ite(Var15 \equiv Var12, 1, 0)$

-----SVFVar and Value-----		
ValVar13	...	Value: 3
ValVar12		Value: 0
ValVar15		Value: 0
ValVar16		Value: 1
	...	

Example 5: Interprocedural



Verifying ICFG path: $0 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 7 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 8 \rightarrow 9 \rightarrow \text{svf_assert}$

ICFG Node/Edge	Constraints in the solver
ICFGNode 0	$\text{Var21} \equiv 0 \wedge \text{Var14} \equiv 3 \wedge \dots$
ICFGNode 5	$\wedge \langle [\text{ICFGNode5}], \text{Var7} \rangle \equiv \text{Var14}$
ICFGNode 3	$\wedge \langle [\text{ICFGNode5}], \text{Var6} \rangle \equiv \langle [\text{ICFGNode5}], \text{Var7} \rangle$
ICFGNode 6	$\wedge \text{Var13} \equiv \langle [\text{ICFGNode5}], \text{Var6} \rangle$
ICFGNode 7	$\wedge \langle [\text{ICFGNode7}], \text{Var7} \rangle \equiv \text{Var12}$
ICFGNode 3	$\wedge \langle [\text{ICFGNode7}], \text{Var6} \rangle \equiv \langle [\text{ICFGNode7}], \text{Var7} \rangle$
ICFGNode 8	$\wedge \text{Var15} \equiv \langle [\text{ICFGNode7}], \text{Var6} \rangle$
ICFGNode 9	$\wedge \text{Var16} \equiv \text{ite}(\text{Var15} \equiv \text{Var12}, 1, 0)$
ICFGNode 10	$\wedge \text{Var16} \equiv 0$ (negation of the assert condition)

Solver yields **UNSAT**, meaning no counter example.
The assertion is verified successfully!!

What's next?

- (1) Understand SSE algorithms and examples in the slides
- (2) Finish implementing the automated translation from code to Z3 formulas using SSE and Z3SSEMgr in Assignment 2