Assignment-4

Yulei Sui

University of Technology Sydney, Australia

Assignment 4: Quiz + A Coding Task

- One quiz (10 points)
  - Static symbolic execution
  - Automatic translation from code to Z3 formulas/constraints

Assignment 4: Quiz + A Coding Task

- One quiz (10 points)
  - Static symbolic execution
  - Automatic translation from code to Z3 formulas/constraints
- One coding task (15 points)
  - **Goal:** automatically perform assertion-based verification for code using static symbolic execution.
  - **Specification and code template:** `https://github.com/SVF-tools/Teaching-Software-Verification/tree/main/Assignment-3`
  - **SVF Z3 APIs:** `https://github.com/SVF-tools/Teaching-Software-Verification/wiki/Z3-API`

You are encouraged to finish the quizzes before starting your coding task.

Methods to Be Implemented

You need to implement the following four functions in `Assignment-4.cpp`:

- `SSE::handleNonBranch`
- `SSE::handleCall`
- `SSE::handleRet`
- `SSE::handleBranch`
- The required implementation parts are indicated with TODO comments and you only need to fill up the code template if a method is partially implemented.

In the following slides, we provide several examples to assist your understanding of SSE.

Interprocedural Example

```c
void foo(int* p) {
  *p = 1;
}
int main() {
    int a = 0;
    foo(&a);
    svf_assert(a == 1);
}
```

compile

```
void @foo(i32* %p) {
entry:
  store i32 1, i32* %p
  ret void
}
i32 @main() {
entry:
  %a = alloca i32
  store i32 0, i32* %a
  call void @foo(i32* %a)
  %0 = load i32, i32* %a
  %cmp = icmp eq i32 %0, 1
  call void @svf_assert(i1 zeroext %cmp)
  ret i32 0
}
```

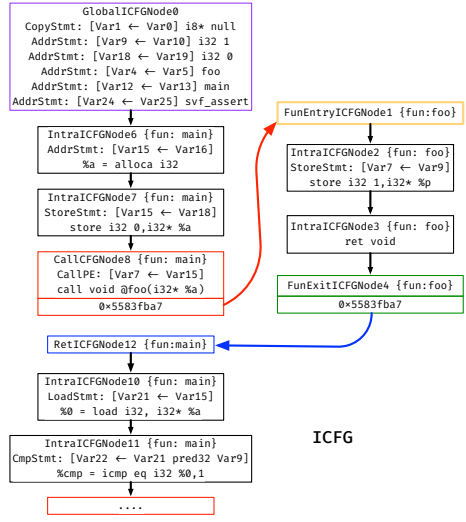
Interprocedural Example

```
void foo(int* p) {
  *p = 1;
}
int main() {
    int a = 0;
    foo(&a);
    svf_assert(a == 1);
}
```

compile

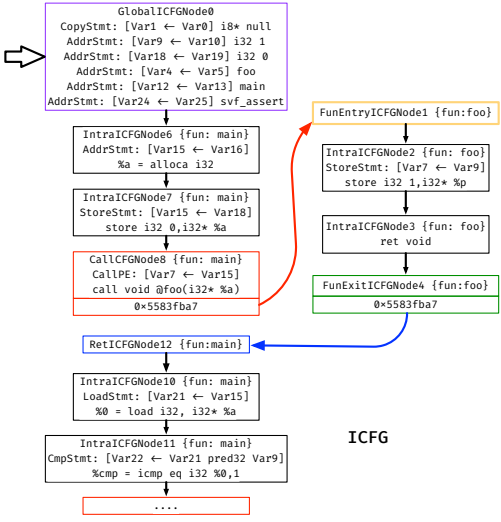
```
void @foo(i32* %p) {
entry:
  store i32 1, i32* %p
  ret void
}
i32 @main() {
entry:
  %a = alloca i32
  store i32 0, i32* %a
  call void @foo(i32* %a)
  %0 = load i32, i32* %a
  %cmp = icmp eq i32 %0, 1
  call void @svf_assert(i1 zeroext %cmp)
  ret i32 0
}
```

SVF



ICFG

Interprocedural Example

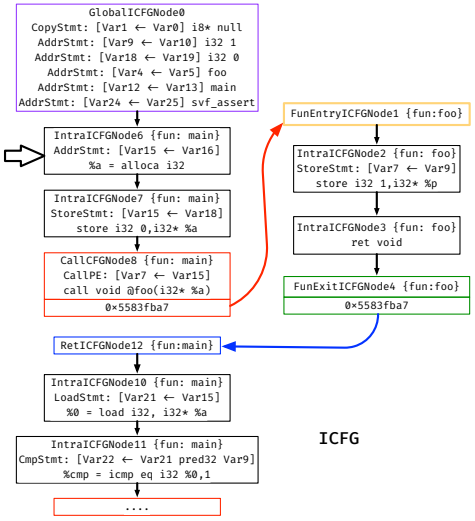


ICFG

```
------------SVFVar and Value------------
ObjVar25 (0x7f000019)    Value: NULL
ObjVar19 (0x7f000013)    Value: 0
ObjVar16 (0x7f000010)    Value: NULL
ObjVar13 (0x7f00000d)    Value: NULL
ObjVar10 (0x7f00000a)    Value: 1
ObjVar5 (0x7f000005)     Value: NULL
ValVar24                 Value: 0x7f000019
ObjVar2 (0x7f000002)     Value: NULL
ObjVar3 (0x7f000003)     Value: NULL
ValVar1                  Value: 2
ValVar0                  Value: 2
ValVar4                  Value: 0x7f000005
ValVar9                  Value: 1
ValVar12                 Value: 0x7f00000d
ValVar18                 Value: 0
                  ...
----------------------------------------
```

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

Interprocedural Example



ICFG

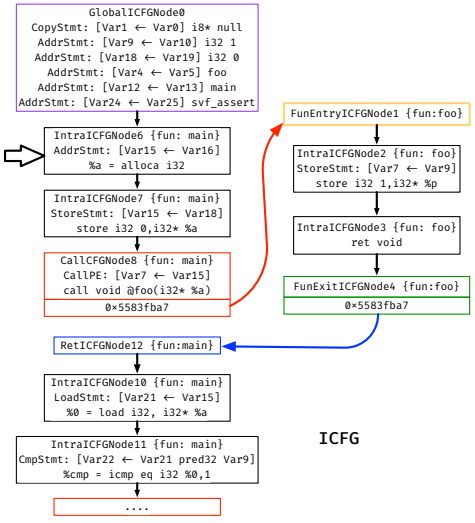
Algorithm 2 `handleIntra(intraEdge)`

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

`HandleNonBranch(intraEdge)`

```
1  dst ← intraEdge.getDstNode(); src ← intraEdge.getSrcNode()
2  foreach stmt ∈ dst.getSVFStmts() do
3      if addr ∈ dyn_cast⟨AddrStmt⟩(stmt) then
4          obj ← getMemObjAddress(addr.getRHSVarID())
5          lhs ← getZ3Expr(addr.getLHSVarID())
6          addToSolver(obj == lhs)
7      else if copy ∈ dyn_cast⟨CopyStmt⟩(stmt) then
8          lhs ← getZ3Expr(copy.getLHSVarID())
9          rhs ← getZ3Expr(copy.getRHSVarID())
10         addToSolver(rhs == lhs)
11     else if load ∈ dyn_cast⟨LoadStmt⟩(stmt) then
12         lhs ← getZ3Expr(load.getLHSVarID())
13         rhs ← getZ3Expr(load.getRHSVarID())
14         addToSolver(lhs == z3Mgr.loadValue(rhs))
       ...
```

Interprocedural Example



ICFG

```
-------------SVFVar and Value-------------
ObjVar25 (0x7f000019)    Value: NULL
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ValVar1                  Value: 2
ValVar0                  Value: 2
ValVar4                  Value: 0x7f000005
ValVar9                  Value: 1
ValVar12                 Value: 0x7f00000d
ValVar18                 Value: 0
+ValVar15               Value:  0x7f000010
                    ...
------------------------------------------
```
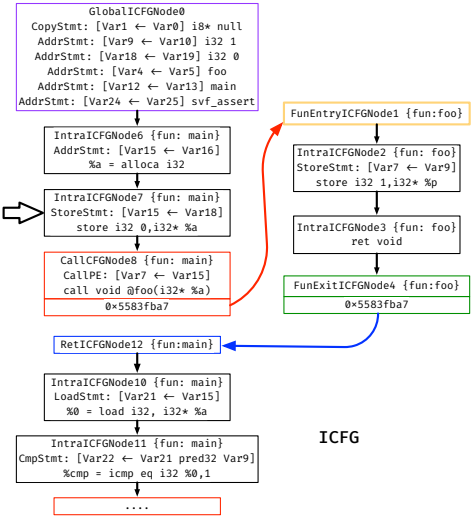

Analyzing IntraICFGNode6 {fun: main}

AddrStmt: [Var14 ← Var15]

%a = alloca i32

Interprocedural Example



ICFG

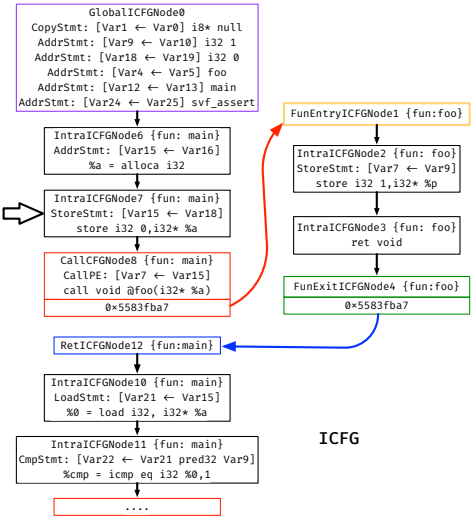
Algorithm 2 `handleIntra(intraEdge)`

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

`HandleNonBranch(intraEdge)`

```
   dst ← intraEdge.getDstNode(); src ← intraEdge.getSrcNode()
   foreach stmt ∈ dst.getSVFStmts() do
11     ...
12     else if load ∈ dyn_cast⟨LoadStmt⟩(stmt) then
13         lhs ← getZ3Expr(load.getLHSVarID())
14         rhs ← getZ3Expr(load.getRHSVarID())
15         addToSolver(lhs == z3Mgr.loadValue(rhs))
16     else if store ∈ dyn_cast⟨StoreStmt⟩(stmt) then
17         lhs ← getZ3Expr(store.getLHSVarID())
18         rhs ← getZ3Expr(store.getRHSVarID())
19         z3Mgr.storeValue(lhs, rhs)
20     else if gep ∈ dyn_cast⟨GepStmt⟩(stmt) then
21         lhs ← getZ3Expr(gep.getLHSVarID())
22         rhs ← getZ3Expr(gep.getRHSVarID())
23         offset = z3Mgr.getGepOffset(gep)
24         gepAddress = z3Mgr.getGepObjAddress(rhs, offset)
25         addToSolver(lhs == gepAddress)
26     ...
```

Interprocedural Example



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ObjVar19 (0x7f000013)    Value: 0
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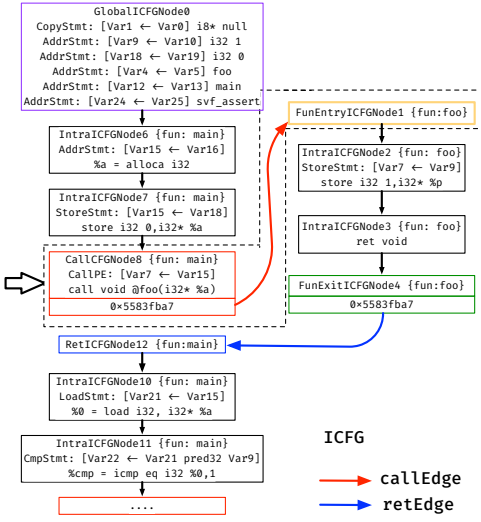
ObjVar5 (0x7f000005)     Value: NULL
ValVar24                 Value: 0x7f000019
ObjVar2 (0x7f000002)     Value: NULL
ValVar15                Value:  0x7f000010
ObjVar3 (0x7f000003)     Value: NULL
ValVar1                  Value: 2
ValVar0                  Value: 2
ValVar4                  Value: 0x7f000005
ValVar9                  Value: 1
ValVar12                 Value: 0x7f00000d
+ValVar18               Value:  0
                    ...
------------------------------------------
```

Analyzing IntraICFGNode6 {fun: main}

StoreStmt: [Var15 ← Var18]

`store i32 0, i32 * %a`

Interprocedural Example

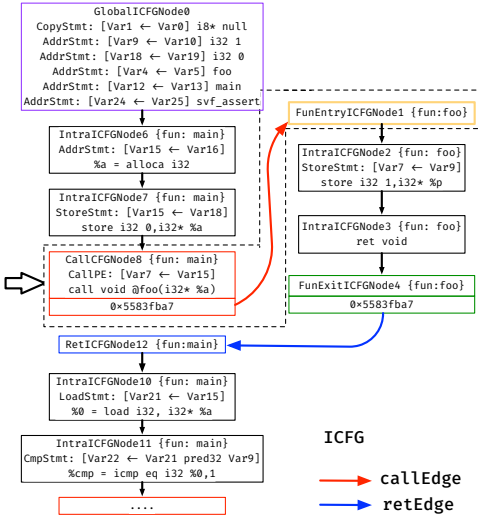


Algorithm 1 Context sensitive control-flow reachability

Input : src : ICFGNode dst : ICFGNode
path : vector⟨ICFGNode⟩ visited : set⟨ICFGNode⟩;

```
1  dfs(path, src, dst)
2    visited.insert(src)
3    path.push_back(src)
4    if src == dst then
5      print path
6    foreach edge ∈ src.getOutEdges() do
7      if edge.dst ∉ visited then
8        if edge.isIntraCFGEdge() then
9          if handleIntra(edge) then
10           dfs(path, edge.dst, dst)
11       else if edge.isCallCFGEdge() then
12         if handleCall(edge) then
13           dfs(path, edge.dst, dst)
14       else if edge.isRetCFGEdge() then
15         if handleRet(edge) then
16           dfs(path, edge.dst, dst)
17   visited.erase(src)
18   path.pop_back(src)
```

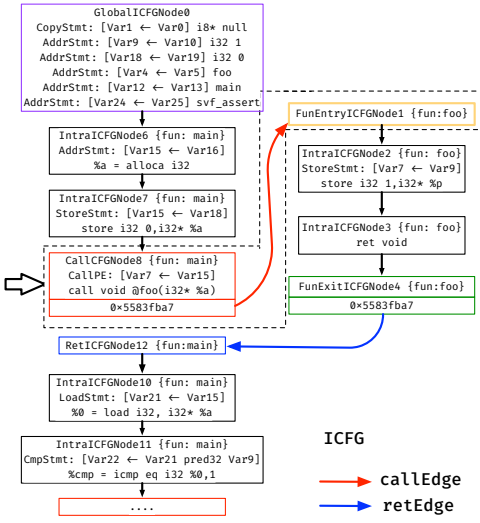
Interprocedural Example

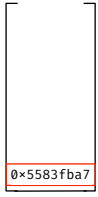


Algorithm 3 `handleCall(callEdge)`

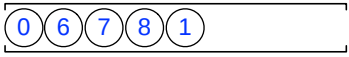
```
1  callNode ← callEdge.getSrcNode();
2  FunEntryNode ←callEdge.getDstNode();
3  callstack.push_back(callNode);
4  getSolver().push();
5  foreach callPE ∈ calledge.getCallPEs() do
6      lhs ← getZ3Expr(callPE.getLHSVarID());
7      rhs ← getZ3Expr(callPE.getRHSVarID());
8      addToSolver(lhs == rhs);
9  return true;
```

Interprocedural Example





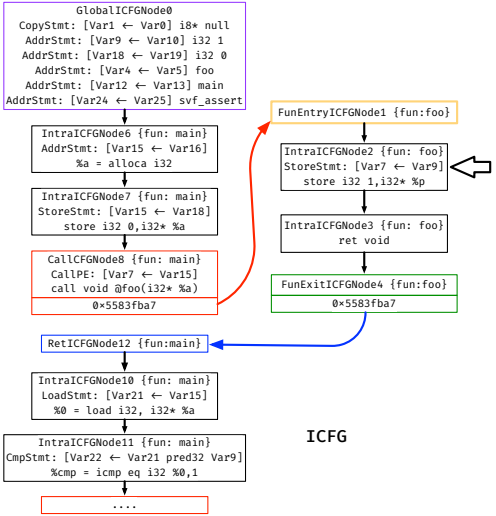
callstack



path (a sequence of ICFGNodes represented by their IDs)

State of callstack after processing call edge between CallCFGNode8 and FunEntryICFGNode1

Interprocedural Example



ICFG

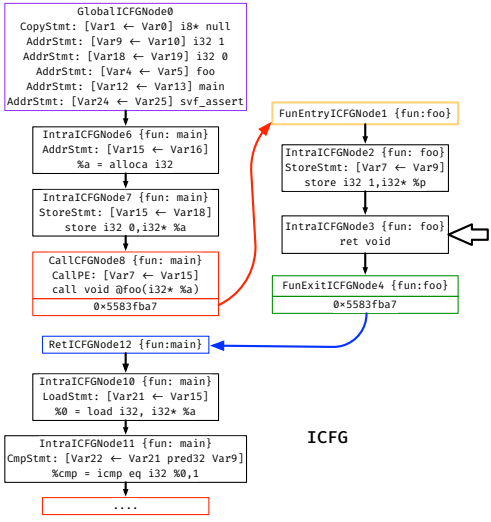
Algorithm 2 handleIntra(intraEdge)

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

HandleNonBranch(intraEdge)

```
   dst ← intraEdge.getDstNode(); src ← intraEdge.getSrcNode()
   foreach stmt ∈ dst.getSVFStmts() do
11     ...
12     else if load ∈ dyn_cast⟨LoadStmt⟩(stmt) then
13         lhs ← getZ3Expr(load.getLHSVarID())
14         rhs ← getZ3Expr(load.getRHSVarID())
15         addToSolver(lhs == z3Mgr.loadValue(rhs))
16     else if store ∈ dyn_cast⟨StoreStmt⟩(stmt) then
17         lhs ← getZ3Expr(store.getLHSVarID())
18         rhs ← getZ3Expr(store.getRHSVarID())
19         z3Mgr.storeValue(lhs, rhs)
20     else if gep ∈ dyn_cast⟨GepStmt⟩(stmt) then
21         lhs ← getZ3Expr(gep.getLHSVarID())
22         rhs ← getZ3Expr(gep.getRHSVarID())
23         offset = z3Mgr.getGepOffset(gep)
24         gepAddress = z3Mgr.getGepObjAddress(rhs, offset)
25         addToSolver(lhs == gepAddress)
26     ...
```

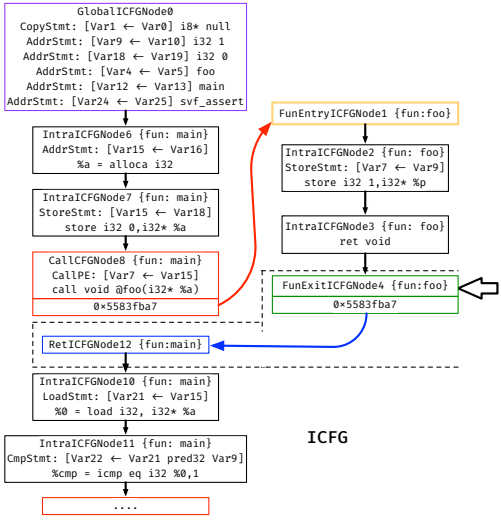
Interprocedural Example



ICFG

`ret void` instruction.
Nothing needs to be done.
Continue.

Interprocedural Example

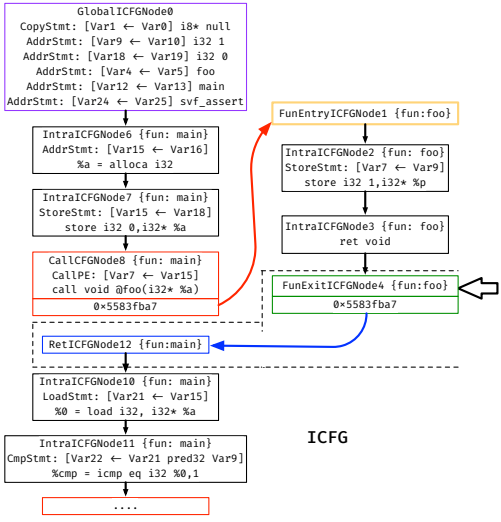


Algorithm 1 Context sensitive control-flow reachability

Input : src : ICFGNode dst : ICFGNode
path : vector⟨ICFGNode⟩ visited : set⟨ICFGNode⟩;

```
1  dfs(path, src, dst)
2    visited.insert(src)
3    path.push_back(src)
4    if src == dst then
5      print path
6    foreach edge ∈ src.getOutEdges() do
7      if edge.dst ∉ visited then
8        if edge.isIntraCFGEdge() then
9          if handleIntra(edge) then
10           dfs(path, edge.dst, dst)
11       else if edge.isCallCFGEdge() then
12         if handleCall(edge) then
13           dfs(path, edge.dst, dst)
14       else if edge.isRetCFGEdge() then
15         if handleRet(edge) then
16           dfs(path, edge.dst, dst)
17
18   visited.erase(src)
19   path.pop_back(src)
```

Interprocedural Example

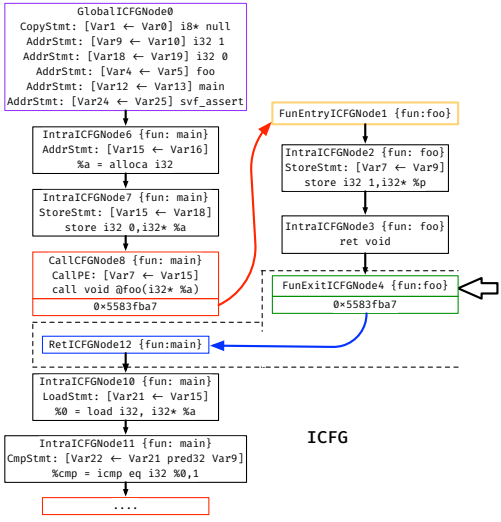


ICFG

Algorithm 4 `handleRet(retEdge)`

```
1  retNode ← retEdge.getDstNode();
2  rhs(getCtx());
3  lhs(getCtx());
4  if retPE = retEdge.getRetPE() then
5      rhs ← getEvalExpr(getZ3Expr(retPE.getRHSVarID()));
6      lhs ← getZ3Expr(retPE.getLHSVarID());
7  if callstack ≠ ∅ then
8      if callstack.back() == getCallICFGNode(retNode) then
9          callstack.pop_back();
10         getSolver().pop();
11     else
12         return false;
13 if retEdge.getRetPE() then
14     addToSolver(lhs == rhs);
15 return true;
```

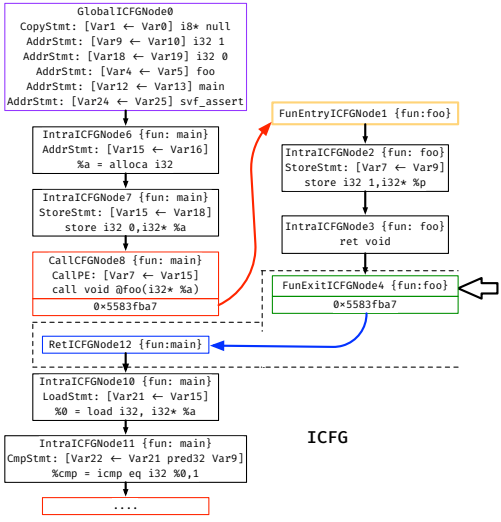
Interprocedural Example

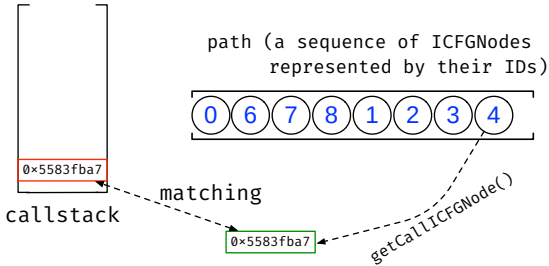


Algorithm 4 `handleRet(retEdge)`

```
1  retNode ← retEdge.getDstNode();
2  rhs(getCtx());
3  lhs(getCtx());
4  if retPE = retEdge.getRetPE() then
5      rhs ← getEvalExpr(getZ3Expr(retPE.getRHSVarID()));
6      lhs ← getZ3Expr(retPE.getLHSVarID());
7  if callstack ≠ ∅ then
8      if callstack.back() == getCallICFGNode(retNode) then
9          callstack.pop_back();
10         getSolver().pop();
11     else
12         return false;
13 if retEdge.getRetPE() then
14     addToSolver(lhs == rhs);
15 return true;
```

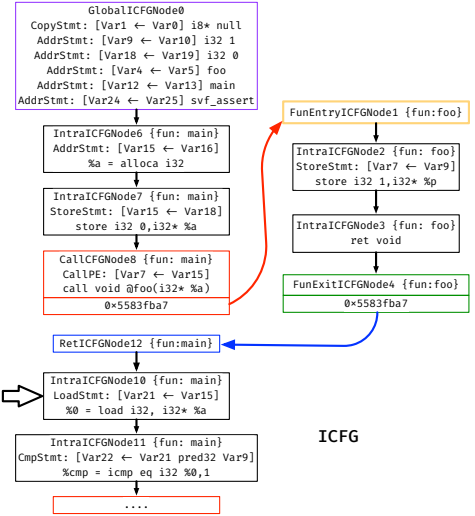
Interprocedural Example





State of callstack while processing return edge from FunExitICFGNode4 to RetICFGNode12

Interprocedural Example



ICFG

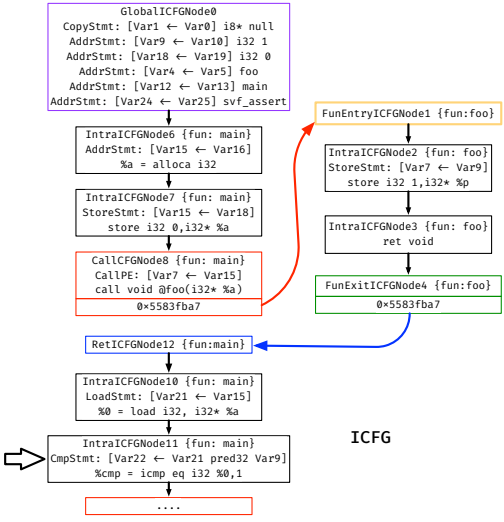
Algorithm 2 `handleIntra(intraEdge)`

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

`HandleNonBranch(intraEdge)`

```
   dst ← intraEdge.getDstNode(); src ← intraEdge.getSrcNode()
   foreach stmt ∈ dst.getSVFStmts() do
   ...
11     else if load ∈ dyn_cast⟨LoadStmt⟩(stmt) then
12         lhs ← getZ3Expr(load.getLHSVarID())
13         rhs ← getZ3Expr(load.getRHSVarID())
14         addToSolver(lhs == z3Mgr.loadValue(rhs))
15     else if store ∈ dyn_cast⟨StoreStmt⟩(stmt) then
16         lhs ← getZ3Expr(store.getLHSVarID())
17         rhs ← getZ3Expr(store.getRHSVarID())
18         z3Mgr.storeValue(lhs, rhs)
19     else if gep ∈ dyn_cast⟨GepStmt⟩(stmt) then
20         lhs ← getZ3Expr(gep.getLHSVarID())
21         rhs ← getZ3Expr(gep.getRHSVarID())
22         offset = z3Mgr.getGepOffset(gep)
23         gepAddress = z3Mgr.getGepObjAddress(rhs, offset)
24         addToSolver(lhs == gepAddress)
   ...
```

Interprocedural Example



ICFG

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ValVar21                 Value: 1
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ValVar1                  Value: 2
ValVar0                  Value: 2
ValVar4                  Value: 0x7f000005
ValVar9                  Value: 1
ValVar12                 Value: 0x7f00000d
ValVar18                 Value: 0
-----------------------------------------
```

The assertion is successfully verified!!

START: 0 → 6 → 7 → 8 → 1 → 2 → 3 → 4 → 12 → 10 → 11 → … → *END*

Branch Example

```c
int main(){
    int x = 1, y = 1;
    int a = 1, b = 2;
    if (a > b) {
        y++;
    } else {
        x++;
        svf_assert (x == 2);
    }
    return 0;
}
```



```
i32 @main() {
entry:
  %cmp = icmp sgt i32 1, 2
  br i1 %cmp, label %if.then, label %if.else
if.then:
  %inc = add nsw i32 1, 1
  br label %if.end
if.else:
  %inc1 = add nsw i32 1, 1
  %cmp2 = icmp eq i32 %inc1, 2
  call void @svf_assert(i1 zeroext %cmp2)
  br label %if.end
if.end:
ret i32 0
}
```

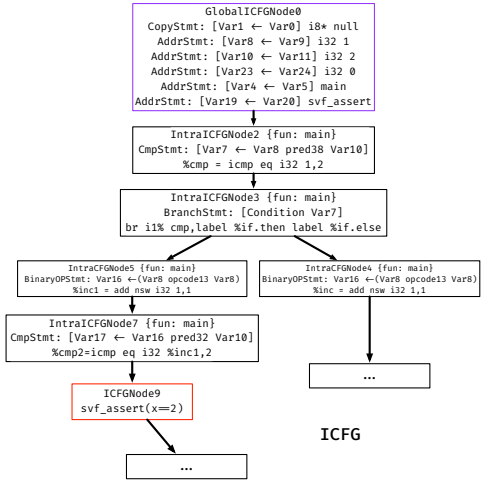
Branch Example

```
int main(){
    int x = 1, y = 1;
    int a = 1, b = 2;
    if (a > b) {
        y++;
    } else {
        x++;
        svf_assert (x == 2);
    }
    return 0;
}
```

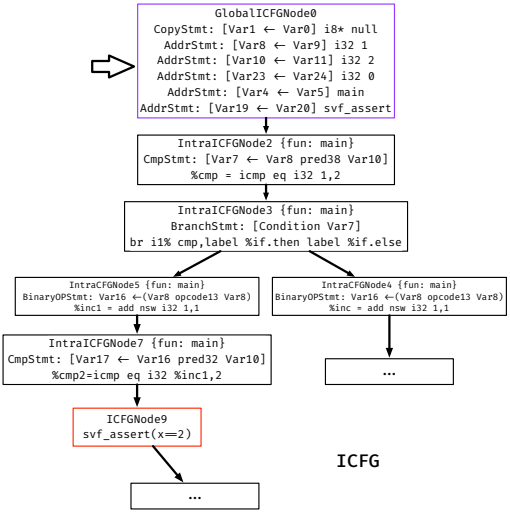
compile

```
i32 @main() {
entry:
  %cmp = icmp sgt i32 1, 2
  br i1 %cmp, label %if.then, label %if.else
if.then:
  %inc = add nsw i32 1, 1
  br label %if.end
if.else:
  %inc1 = add nsw i32 1, 1
  %cmp2 = icmp eq i32 %inc1, 2
  call void @svf_assert(i1 zeroext %cmp2)
  br label %if.end
if.end:
ret i32 0
}
```

SVF



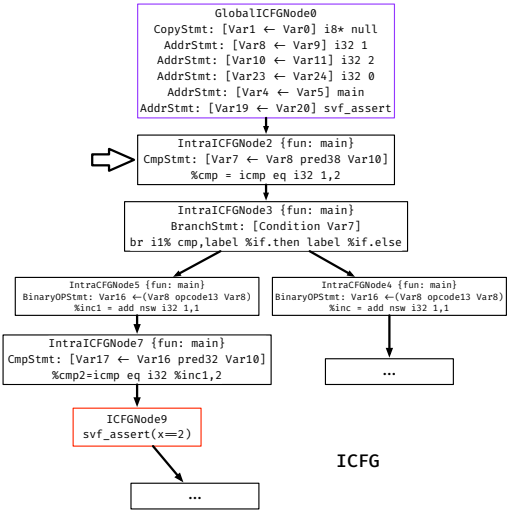
Branch Example




```
-------------SVFVar and Value-------------
ObjVar20 (0x7f000014)    Value: NULL
ObjVar24 (0x7f000018)    Value: 0
ObjVar11 (0x7f00000b)    Value: 2
ObjVar9 (0x7f000009)     Value: 1
ObjVar5 (0x7f000005)     Value: NULL
ValVar19                 Value: 0x7f000014
ValVar23                 Value: 0
ObjVar2 (0x7f000002)     Value: NULL
ObjVar3 (0x7f000003)     Value: NULL
ValVar1                  Value: 3
ValVar0                  Value: 3
ValVar4                  Value: 0x7f000005
ValVar8                  Value: 1
ValVar10                 Value: 2
                  ...
-----------------------------------------
```

The values of Z3 expressions for each SVFVar after analyzing `GlobalICFGNode0`

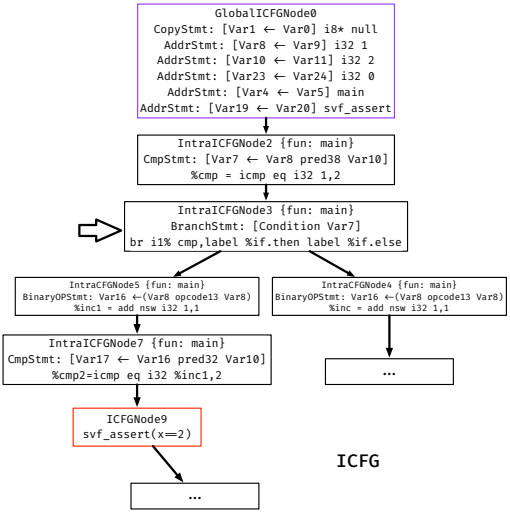
Branch Example




```
## Analyzing IntraICFGNode2 {fun: main}
CmpStmt: [Var7 <-- (Var8 predicate38 Var10)]
   %cmp = icmp sgt i32 1, 2
==> (not (<= ValVar8 ValVar10))
==> (= ValVar7 0)
                    ...
```

Code for handling `CmpStmt` has been implemented in the HandleNonBranch() function.

Branch Example



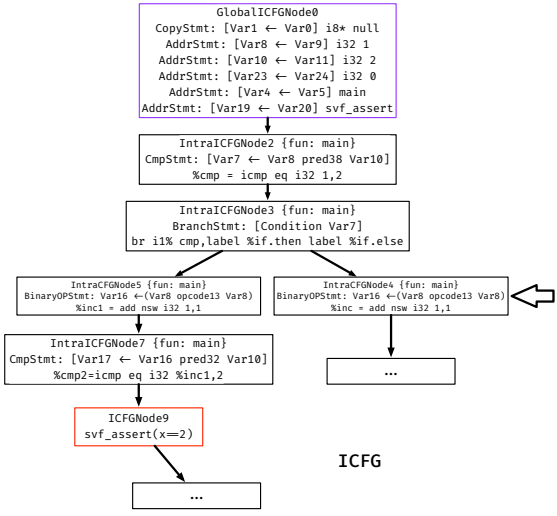
Algorithm 2 `handleIntra(intraEdge)`

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

`handleBranch(intraEdge)`

```
1   cond = intraEdge.getCondition()
2   successorVal = intraEdge.getSuccessorCondValue()
3   res = getEvalExpr(cond == suc)
4  if res.is_false() then
5      addToSolver(cond! = suc)
6      return false
7  else if res.is_true() then
8      addToSolver(cond == suc)
9      return true
10 else
11     return true
```

Branch Example



ICFG

```
------------SVFVar and Value------------
ObjVar20 (0x7f000014)    Value: NULL
ObjVar24 (0x7f000018)    Value: 0
ObjVar11 (0x7f00000b)    Value: 2
ObjVar9 (0x7f000009)     Value: 1
ObjVar5 (0x7f000005)     Value: NULL
ValVar19                 Value: 0x7f000014
ValVar23                 Value: 0
ObjVar2 (0x7f000002)     Value: NULL
ObjVar3 (0x7f000003)     Value: NULL
ValVar1                  Value: 3
ValVar0                  Value: 3
ValVar4                  Value: 0x7f000005
ValVar8                  Value: 1
ValVar10                 Value: 2
ValVar7                  Value: 0
                  ...
----------------------------------------
```

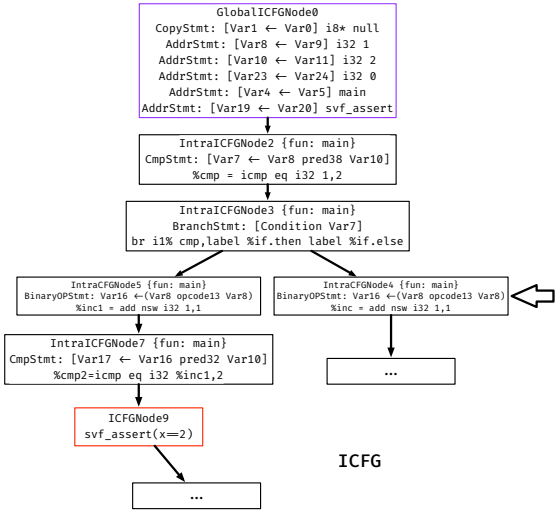
Branch IntraCFGEdge: [ICFGNode4 ← ICFGNode3]

branchCondition: %cmp = icmp sgt i32 1, 2

(= ValVar7 1)

This conditional ICFGEdge is **infeasible**!!

Branch Example

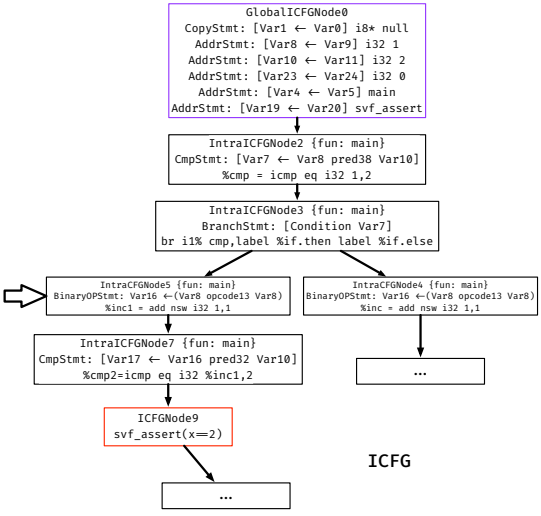


Algorithm 1 Context sensitive control-flow reachability

Input : src : ICFGNode dst : ICFGNode
path : vector⟨ICFGNode⟩ visited : set⟨ICFGNode⟩;

```
1  dfs(path, src, dst)
2    visited.insert(src)
3    path.push_back(src)
4    if src == dst then
5      print path
6    foreach edge ∈ src.getOutEdges() do
7      if edge.dst ∉ visited then
8        if edge.isIntraCFGEdge() then
9          if handleIntra(edge) then
10           dfs(path, edge.dst, dst)
11       else if edge.isCallCFGEdge() then
12         if handleCall(edge) then
13           dfs(path, edge.dst, dst)
14       else if edge.isRetCFGEdge() then
15         if handleRet(edge) then
16           dfs(path, edge.dst, dst)
17   visited.erase(src)
18   path.pop_back(src)
```

Branch Example



ICFG

```
------------SVFVar and Value------------
ObjVar20 (0x7f000014)    Value: NULL
ObjVar24 (0x7f000018)    Value: 0
ObjVar11 (0x7f00000b)    Value: 2
ObjVar9 (0x7f000009)     Value: 1
ObjVar5 (0x7f000005)     Value: NULL
ValVar19                 Value: 0x7f000014
ValVar23                 Value: 0
ObjVar2 (0x7f000002)     Value: NULL
ObjVar3 (0x7f000003)     Value: NULL
ValVar1                  Value: 3
ValVar0                  Value: 3
ValVar4                  Value: 0x7f000005
ValVar8                  Value: 1
ValVar10                 Value: 2
ValVar7                  Value: 0
                  ...
----------------------------------------
```

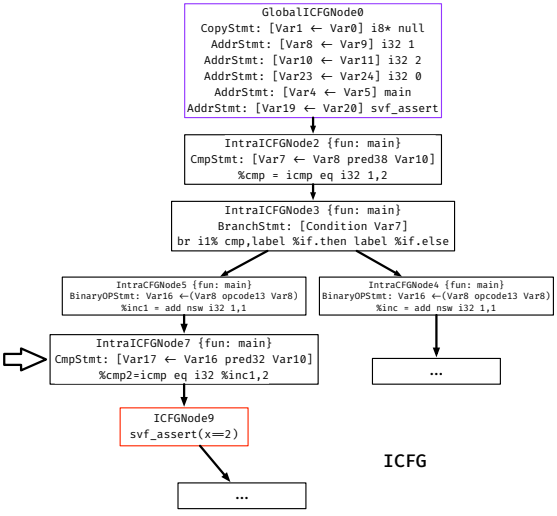
Branch IntraCFGEdge: [ICFGNode5 ← ICFGNode3]

branchCondition: %cmp = icmp sgt i32 1, 2

(= ValVar7 0)

This conditional ICFGEdge is **feasible**!!

Branch Example

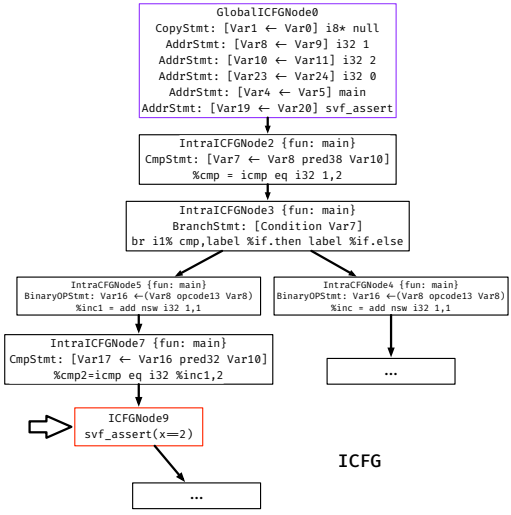



```
-------------SVFVar and Value-------------
ObjVar20 (0x7f000014)    Value: NULL
ObjVar24 (0x7f000018)     Value: 0
ObjVar11 (0x7f00000b)    Value: 2
ObjVar9 (0x7f000009)     Value: 1
ObjVar5 (0x7f000005)     Value: NULL
ValVar19                 Value: 0x7f000014
ValVar23                 Value: 0
ValVar17                 Value: 1
ObjVar2 (0x7f000002)     Value: NULL
ObjVar3 (0x7f000003)     Value: NULL
ValVar16                 Value: 2
ValVar1                  Value: 3
ValVar0                  Value: 3
ValVar4                  Value: 0x7f000005
ValVar8                  Value: 1
ValVar10                 Value: 2
ValVar7                  Value: 0
                  ...
-----------------------------------------
```

Analyzing IntraICFGNode7 fun: main

CmpStmt: [Var17 ← (Var16 predicate32 Var10)]

Branch Example



The assertion is successfully verified!!

START: $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 5 \rightarrow 7 \rightarrow 9 \rightarrow$ *END*