Assertion-based Verification Using Static Symbolic Execution

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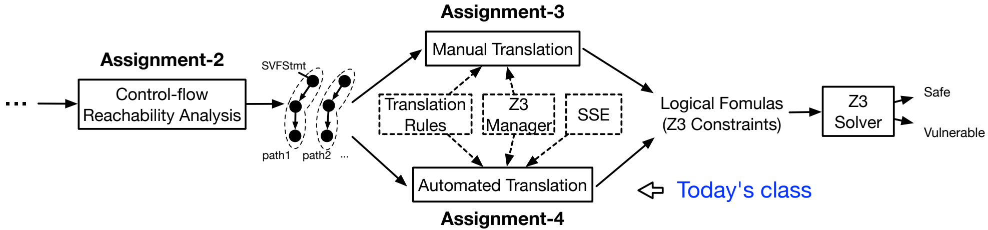
Automated Assertion-based Verification



Today's class

Static Symbolic Execution (SSE)

- An static interpreter follows the program, assuming symbolic values for inputs rather than obtaining actual inputs as normal execution of the program would.
- Automated testing technique that symbolically executes a program.
- Use symbolic execution to explore all program paths to find latent bugs.

Static Symbolic Execution for Assertion-based Verification

- Given a Hoare triple $P \ \{prog\} \ Q$,
  - P represents program inputs,
  - *prog* is the actual source code,
  - Q is the assertion(s) to be verified.
- SSE translates `SVFStmt` of each program path (which ends with an assertion) into a Z3 logical formula.
  - In our project, the path of each loop is bounded once for verification.
- Prove satisfiability of the logic formulas of each program path from the program entry to each assertion on the ICFG.

Driver Program of SSE (What We Have From Assignment 2)

Algorithm 1 Context sensitive control-flow reachability

```
Input : src : ICFGNode   dst : ICFGNode
        path : vector⟨ICFGNode⟩   visited : set⟨ICFGNode⟩;
dfs(path, src, dst)
  visited.insert(src)
  path.push_back(src)
  if src == dst then
    print path
  foreach edge ∈ src.getOutEdges() do
    if edge.dst ∉ visited then
      if edge.isIntraCFGEdge() then
        if handleIntra(edge) then
          dfs(path, edge.dst, dst)
      else if edge.isCallCFGEdge() then
        if handleCall(edge) then
          dfs(path, edge.dst, dst)
      else if edge.isRetCFGEdge() then
        if handleRet(edge) then
          dfs(path, edge.dst, dst)
  visited.erase(src)
  path.pop_back(src)
```

Algorithm 2 handleIntra(intraEdge) (Override in SSE)

```
return true
```

Algorithm 3 handleCall(callEdge) (Override in SSE)

```
callNode ← getSrcNode(callEdge)
callstack.push_back(callNode)
return true
```

Algorithm 4 handleRet(retEdge) (Override in SSE)

```
retNode ← getDstNode(retEdge)
if callstack ≠ ∅ then
  if callstack.back() == getCallICFGNode(retNode) then
    callstack.pop()
    return true
  else
    return false
return true
```

Driver Program of SSE (What We Have From Assignment 2)

Algorithm 1 Context sensitive control-flow reachability

```
Input : src : ICFGNode   dst : ICFGNode
        path : vector⟨ICFGNode⟩   visited : set⟨ICFGNode⟩;
dfs(path, src, dst)
  visited.insert(src)
  path.push_back(src)
  if src == dst then
    print path
  foreach edge ∈ src.getOutEdges() do
    if edge.dst ∉ visited then
      if edge.isIntraCFGEdge() then
        if handleIntra(edge) then
          dfs(path, edge.dst, dst)
      else if edge.isCallCFGEdge() then
        if handleCall(edge) then
          dfs(path, edge.dst, dst)
      else if edge.isRetCFGEdge() then
        if handleRet(edge) then
          dfs(path, edge.dst, dst)
  visited.erase(src)
  path.pop_back(src)
```

Algorithm 2 handleIntra(intraEdge) (Override in SSE)

```
return true
```

Algorithm 3 handleCall(callEdge) (Override in SSE)

```
callNode ← getSrcNode(callEdge)
callstack.push_back(callNode)
return true
```

Algorithm 4 handleRet(retEdge) (Override in SSE)

```
retNode ← getDstNode(retEdge)
if callstack ≠ ∅ then
  if callstack.back() == getCallICFGNode(retNode) then
    callstack.pop()
    return true
  else
    return false
return true
```

Override the above three methods in SSE implementation!

Handle Intra-procedural CFG Edges (handleIntra)

Algorithm 2 handleIntra(intraEdge)

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

handleBranch(intraEdge)

```
cond = intraEdge.getCondition()
successorVal = intraEdge.getSuccessorCondValue()
res = getEvalExpr(cond == successorVal)
if res.is_false() then
    addToSolver(cond! = successorVal)
    return false
else if res.is_true() then
    addToSolver(cond == successorVal)
    return true
else
    return true
```

HandleNonBranch(intraEdge)

```
dst ← intraEdge.getDstNode(); src ← intraEdge.getSrcNode()
foreach stmt ∈ dst.getSVFStmts() do
    if addr ← dyn_cast⟨AddrStmt⟩(stmt) then
        obj ← getMemObjAddress(addr.getRHSVarID())
        lhs ← getZ3Expr(addr.getLHSVarID())
        addToSolver(obj == lhs)
    else if copy ← dyn_cast⟨CopyStmt⟩(stmt) then
        lhs ← getZ3Expr(copy.getLHSVarID())
        rhs ← getZ3Expr(copy.getRHSVarID())
        addToSolver(rhs == lhs)
    else if load ← dyn_cast⟨LoadStmt⟩(stmt) then
        lhs ← getZ3Expr(load.getLHSVarID())
        rhs ← getZ3Expr(load.getRHSVarID())
        addToSolver(lhs == z3Mgr.loadValue(rhs))
    else if store ← dyn_cast⟨StoreStmt⟩(stmt) then
        lhs ← getZ3Expr(store.getLHSVarID())
        rhs ← getZ3Expr(store.getRHSVarID())
        z3Mgr.storeValue(lhs, rhs)
    else if gep ← dyn_cast⟨GepStmt⟩(stmt) then
        lhs ← getZ3Expr(gep.getLHSVarID())
        rhs ← getZ3Expr(gep.getRHSVarID())
        offset ← z3Mgr.getGepOffset(gep)
        gepAddress ← z3Mgr.getGepObjAddress(rhs, offset)
        addToSolver(lhs == gepAddress)
```

Handle Call (`handleCall`) and Return (`handleRet`) CFG Edges

Algorithm 3 `handleCall(callEdge)`

```
  callNode ← callEdge.getSrcNode();
  FunEntryNode ←callEdge.getDstNode();
  callstack.push_back(callNode);
  getSolver().push();
foreach callPE ∈ calledge.getCallPEs() do
    lhs ← getZ3Expr(callPE.getLHSVarID());
    rhs ← getZ3Expr(callPE.getRHSVarID());
    addToSolver(lhs == rhs);
return true;
```

Algorithm 4 `handleRet(retEdge)`

```
retNode ← retEdge.getDstNode();
rhs(getCtx());
lhs(getCtx());
if retPE ← retEdge.getRetPE() then
  rhs ← getEvalExpr(getZ3Expr(retPE.getRHSVarID()));
  lhs ← getZ3Expr(retPE.getLHSVarID());
if callstack ≠ ∅ then
  if callstack.back() == getCallICFGNode(retNode) then
      callstack.pop_back();
      getSolver().pop();
  else
      return false;
if retEdge.getRetPE() then
  addToSolver(lhs == rhs);
return true;
```

Scalar Example

Comparison between the concrete and symbolic states before the assertion.

```
void foo(unsigned x){
    if(x > 10) {
        y = x + 1;
    }
    else {
        y = 10;
    }
assert(y >= x + 1);
}
```

Scalar Example

Comparison between the concrete and symbolic states before the assertion.

```
void foo(unsigned x){
    if(x > 10) {
        y = x + 1;
    }
    else {
        y = 10;
    }
assert(y >= x + 1);
}
```

Concrete Execution
(Concrete states of `x`, `y`)

One execution:
`x` : 20
`y` : 21

Another execution:
`x` : 8
`y` : 10

Scalar Example

Comparison between the concrete and symbolic states before the assertion.

```c
void foo(unsigned x){
    if(x > 10) {
        y = x + 1;
    }
    else {
        y = 10;
    }
assert(y >= x + 1);
}
```

Concrete Execution (Concrete states of `x`, `y`)

One execution:

$\mathtt{x}$: 20

$\mathtt{y}$: 21

Another execution:

$\mathtt{x}$: 8

$\mathtt{y}$: 10

Symbolic Execution (`getZ3Expr(x)` **represents** `x`'s **symbolic state**)

If branch:

$\mathtt{x}$: $\mathtt{getZ3Expr(x)} > 10 \wedge \mathtt{getZ3Expr(x)} < \text{UINT\_MAX})$

$\mathtt{y}$: $\mathtt{getZ3Expr(x)} + 1$

Else branch:

$\mathtt{x}$: $\mathtt{getZ3Expr(x)} > 0 \wedge \mathtt{getZ3Expr(x)} < 10$

$\mathtt{y}$: 10

Scalar Example

Comparison between the concrete and symbolic states before the assertion.

```c
void foo(unsigned x){
    if(x > 10) {
        y = x + 1;
    }
    else {
        y = 10;
    }
assert(y >= x + 1);
}
```

Concrete Execution (Concrete states of x, y)	Symbolic Execution (getZ3Expr(x) **represents** x's **symbolic state**)
One execution:	If branch:
x : 20	x : getZ3Expr(x) $>$ 10 $\wedge$ getZ3Expr(x) $<$ UINT_MAX)
y : 21	y : getZ3Expr(x) + 1
Another execution:	Else branch:
x : 8	x : getZ3Expr(x) $>$ 0 $\wedge$ getZ3Expr(x) $<$ 10
y : 10	y : 10

- Concrete execution: verify the assertion by **exhaustively** finding concrete states of x and y by exercising all possible inputs.
- Symbolic execution: verify the assertion by feeding the symbolic states (**logical formulas**) of x and y into **SMT Solver**.

Memory Operation Example

```
void foo(unsigned x) {
  int* p;
  int y;

  p = malloc(..);
  *p = x + 5;
  y = *p;
  assert(y>5);
}
```

Memory Operation Example

```c
void foo(unsigned x) {
  int* p;
  int y;

  p = malloc(..);
  *p = x + 5;
  y = *p;
  assert(y>5);
}
```

Concrete Execution
(Concrete states)

One execution:

x	:	10
p	:	0x1234
0x1234	:	15
y	:	15

Another execution:

x	:	0
p	:	0x1234
0x1234	:	5
y	:	5

Memory Operation Example

```
void foo(unsigned x) {
 int* p;
 int y;

 p = malloc(..);
 *p = x + 5;
 y = *p;
 assert(y>5);
}
```

Concrete Execution
(Concrete states)

One execution:

x	:	10
p	:	0x1234
0x1234	:	15
y	:	15

Another execution:

x	:	0
p	:	0x1234
0x1234	:	5
y	:	5

Symbolic Execution
(Symbolic states)

x	:	`getZ3Expr(x)`
p	:	0x7f000001 `virtual address from getMemObjAddress("malloc")`
0x7f000001	:	`getZ3Expr(x)` + 5
y	:	`getZ3Expr(x)` + 5

Field Access for Struct and Array Example

```
struct st{
    int a;
    int b;
}
void foo(unsigned x) {
 struct st* p = malloc(..);
 q = &(p->b);
 *q = x;
 assert(*(&p->b) == x);
}
```

Field Access for Struct and Array Example

```
struct st{
    int a;
    int b;
}
void foo(unsigned x) {
 struct st* p = malloc(..);
 q = &(p->b);
 *q = x;
 assert(*(&p->b) == x);
}
```

Concrete Execution
(Concrete states)
One execution:

x	:	10
p	:	0x1234
$\&(p \rightarrow b)$	:	0x1238
q	:	0x1238
0x1238	:	10

Another execution:

x	:	20
p	:	0x1234
$\&(p \rightarrow b)$	:	0x1238
q	:	0x1238
0x1238	:	20

Field Access for Struct and Array Example

```
struct st{
    int a;
    int b;
}
void foo(unsigned x) {
 struct st* p = malloc(..);
 q = &(p->b);
 *q = x;
 assert(*(&p->b) == x);
}
```

Concrete Execution
(Concrete states)
One execution:

x	:	10
p	:	0x1234
$\&(p \rightarrow b)$	:	0x1238
q	:	0x1238
0x1238	:	10

Another execution:

x	:	20
p	:	0x1234
$\&(p \rightarrow b)$	:	0x1238
q	:	0x1238
0x1238	:	20

Symbolic Execution
(Symbolic states)

x	:	`getZ3Expr(x)`
p	:	0x7f000001 `virtual address from getMemObjAddress("malloc")`
$\&(p \rightarrow b)$	:	0x7f000002
q	:	0x7f000002 `field virtual address from getGepObjAddress(base, offset)`
0x7f000002	:	`getZ3Expr(x)`

The virtual address for modeling a field is based on the index of the field offset from the base pointer of a struct (nested struct will be flattened to allow each field to have a unique index)

Call and Return Example

```
1   int foo(int z) {
2       k = z;
3       return k;
4   }
5   int main(unsigned z) {
6     int x;
7     int y;
8     x = foo(3);
9     y = foo(z);
10    assert(x == 3);
11  }
```

Concrete Execution
(Concrete states)

One execution:

`z` : 10
stack push (calling foo at line 8)
`k` : 3
stack pop (returning from foo at line 4)
`x` : 3
stack push (calling foo at line 9)
`k` : 10
stack pop (returning from foo line 4)
`y` : 10

Symbolic Execution
(Symbolic states)

One execution:

`z` : `getZ3Expr(z)`
stack push (calling foo at line 8)
`k` : 3
stack pop (returning from foo at line 4)
`x` : 3
stack push (calling foo at line 9)
`k` : `getZ3Expr(z)`
stack pop (returning from foo line 4)
`y` : `getZ3Expr(z)`

What’s next?

- (1) Understand SSE algorithms in the slides
- (2) Read through Assignment-4.pdf on Canvas to understand some examples for automated code verification.
- (3) Finish the quizzes of Assignment 4 on Canvas
- (4) Implement a automated translation from code to Z3 formulas using `SSE` and `Z3Mgr` i.e., coding task in Assignment 4