

Lab: Z3 Theorem Prover

(Week 4)

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Quiz-1 and Exercise-1 Marks Released

Marks are out and let us go through Quiz-1 questions!

Quiz-2 and Exercise-2

Remember to `git pull` or `docker pull`!

You **MUST** update your code template to the latest version for Lab-Exercise-2. Otherwise, you will not receive marks because Lab-2 and Assignment-2 have been changed to differentiate from previous years.

Quiz-2 and Exercise-2

- Quiz-2 with 25 questions (5 points), **due date: 23:59 Tuesday, Week 7**
 - Logical formula and predicate logic
 - Z3's knowledge and translation rules
- Lab-Exercise-2 (5 points), **due date: 23:59 Tuesday, Week 7**
 - **Goal:** Manually translate code into z3 formulas/constraints and verify the assertions embedded in the code.
 - **Specification:** <https://github.com/SVF-tools/Software-Security-Analysis/wiki/Lab-Exercise-2>
 - **SVF Z3 APIs:** <https://github.com/SVF-tools/Software-Security-Analysis/wiki/SVF-Z3-API>
- Assignment-2 (25 points) will **start from Week 5 and due date: 23:59 Tuesday, Week 8**
 - **Goal:** automatically perform assertion-based verification for code using static symbolic execution.
 - **Specification:** <https://github.com/SVF-tools/Software-Security-Analysis/wiki/Assignment-2>

Intraprocedural Example

```
1 int* p;  
2 int q;  
3 int* r;  
4 int x;  
5 p = malloc(...);  
6 q = 5;  
7 *p = q;  
8 x = *p;  
9 assert(x==10);
```

Source code

```
1 expr p = getZ3Expr("p");  
2 expr q = getZ3Expr("q");  
3 expr r = getZ3Expr("r");  
4 expr x = getZ3Expr("x");  
5 printExprValues();
```

Translation code using Z3Mgr

-----Var and Value-----

nothing printed because
expressions have no value

Output on terminal

Intraprocedural Example

```
1 int* p;  
2 int q;  
3 int* r;  
4 int x;  
5 p = malloc(...);  
6 q = 5;  
7 *p = q;  
8 x = *p;  
9 assert(x==10);
```

Source code

```
1 expr p = getZ3Expr("p");  
2 expr q = getZ3Expr("q");  
3 expr r = getZ3Expr("r");  
4 expr x = getZ3Expr("x");  
5 expr malloc1 = getMemObjAddress("malloc1");  
6 addToSolver(p == malloc1);  
7 printExprValues();
```

Translation code using Z3Mgr

```
-----Var and Value-----  
Var5 (malloc1)   Value: 0x7f000005  
Var1 (p)         Value: 0x7f000005  
-----
```

0x7f000005 (or 2130706437 in decimal)
represents the virtual memory
address of this object
Each ObjVar starts with 0x7f + its ID.

Output on terminal

Intraprocedural Example

```
1 int* p;  
2 int q;  
3 int* r;  
4 int x;  
5 p = malloc(...);  
6 q = 5;  
7 *p = q;  
8 x = *p;  
9 assert(x==10);
```

Source code

```
1 expr p = getZ3Expr("p");  
2 expr q = getZ3Expr("q");  
3 expr r = getZ3Expr("r");  
4 expr x = getZ3Expr("x");  
5 expr malloc1 = getMemObjAddress("malloc1");  
6 addToSolver(p == malloc1);  
7 addToSolver(q == getZ3Expr(5));  
8 storeValue(p, q);  
9 addToSolver(x == loadValue(p));  
10 printExprValues();
```

Translation code using Z3Mgr

```
-----Var and Value-----  
Var5 (malloc1)   Value: 0x7f000005  
Var1 (p)         Value: 0x7f000005  
Var2 (q)         Value: 5  
Var4 (x)         Value: 5  
-----
```

store value of q to address 0x7f000005

load the value from 0x7f000005 to x

Output on terminal

Intraprocedural Example

```
1 int* p;  
2 int q;  
3 int* r;  
4 int x;  
5 p = malloc(...);  
6 q = 5;  
7 *p = q;  
8 x = *p;  
9 assert(x==10);
```

```
1 expr p = getZ3Expr("p");  
2 expr q = getZ3Expr("q");  
3 expr r = getZ3Expr("r");  
4 expr x = getZ3Expr("x");  
5 expr malloc1 = getMemObjAddress("malloc1");  
6 addToSolver(p == malloc1);  
7 addToSolver(q == getZ3Expr(5));  
8 storeValue(p, q);  
9 addToSolver(x == loadValue(p));  
10 printExprValues();  
11  
12 // use checkNegateAssert to unsat of x!=10  
13 // could check sat of x==10 due to  
14 // closed-world program
```

```
-----Var and Value-----  
Var5 (malloc1)   Value: 0x7f000005  
Var1 (p)         Value: 0x7f000005  
Var2 (q)         Value: 5  
Var4 (x)         Value: 5  
  
Assertion failed: (false &&  
"The assertion is unsatisfiable");  
-----
```

Contradictory Z3 constraints!

$x \equiv 5$ contradicts $x \equiv 10$

Source code

Translation code using Z3Mgr

Output on terminal

Intraprocedural Example

```
1 int* p;  
2 int q;  
3 int* r;  
4 int x;  
5 p = malloc(...);  
6 q = 5;  
7 *p = q;  
8 x = *p;  
9 assert(x==10);
```

```
1 expr p = getZ3Expr("p");  
2 expr q = getZ3Expr("q");  
3 expr r = getZ3Expr("r");  
4 expr x = getZ3Expr("x");  
5 expr malloc1 = getMemObjAddress("malloc1");  
6 addToSolver(p == malloc1);  
7 addToSolver(q == getZ3Expr(5));  
8 storeValue(p, q);  
9 addToSolver(x == loadValue(p));  
10 printExprValues();  
11  
12 /// evaluation code as below  
13 std::cout<< getEvalExpr(x == getZ3Expr(10))  
14 << std::endl;
```

```
-----Var and Value-----  
Var5 (malloc1)   Value: 0x7f000005  
Var1 (p)         Value: 0x7f000005  
Var2 (q)         Value: 5  
Var4 (x)         Value: 5  
false  
-----
```

There is no model available (unsat)
when evaluating `x == getZ3Expr(10)`

Source code

Translation code using Z3Mgr

Output on terminal

Interprocedural Example (Call and Return)

```
1 int bar(int a){  
2     int r = a;  
3     return r;  
4 }  
5 void main(){  
6     int p, q;  
7     p = bar(2);  
8     q = bar(3);  
9     assert(p==2)  
10 }
```

Source code

```
1 expr p = getZ3Expr("p");  
2 expr q = getZ3Expr("q");  
3 solver.push();  
4 expr a = getZ3Expr("a");  
5 addToSolver(a == getZ3Expr(2));  
6 solver.check();  
7 expr r = getEvalExpr(a);  
8 printExprValues();  
9 solver.pop();  
10 addToSolver(p == r);
```

Handle first callsite p=bar(2)

Translation code using Z3Mgr

```
-----Var and Value-----  
Var2 (a)           Value: 2  
-----
```

- (1) push the z3 constraints when calling bar and pop when returning from bar
- (2) Expression r is the return value evaluated from a after returning from callee bar

Output on terminal

Interprocedural Example (Call and Return)

```
1 int bar(int a){
2     int r = a;
3     return r;
4 }
5 void main(){
6     int p, q;
7     p = bar(2);
8     q = bar(3);
9     assert(p==2)
10 }
```

Source code

```
1 expr p = getZ3Expr("p");
2 expr q = getZ3Expr("q");
3 solver.push();
4 expr a = getZ3Expr("a");
5 addToSolver(a == getZ3Expr(2));
6 solver.check();
7 expr r = getEvalExpr(a);
8 solver.pop();
9 addToSolver(p == r);
10 printExprValues();
```

Handle first callsite p=bar(2)

Translation code using Z3Mgr

```
-----Var and Value-----
Var1 (p)          Value: 2
-----
```

Now we only have p's value and a is not in the current stack since constraint a == getZ3Expr(2) has been popped

Output on terminal

Interprocedural Example (Call and Return)

```
1 int bar(int a){  
2     int r = a;  
3     return r;  
4 }  
5 void main(){  
6     int p, q;  
7     p = bar(2);  
8     q = bar(3);  
9     assert(p==2)  
10 }
```

```
1 expr p = getZ3Expr("p");  
2 expr q = getZ3Expr("q");  
3 solver.push();  
4 expr a = getZ3Expr("a");  
5 addToSolver(a == getZ3Expr(2));  
6 expr r = getEvalExpr(a);  
7 solver.pop();  
8 addToSolver(p == r);  
9 solver.push();  
10 addToSolver(a == getZ3Expr(3));  
11 r = getEvalExpr(a);  
12 solver.pop();  
13 addToSolver(q == r);  
14 printExprValues();
```

Handle second callsite q=bar(3)

```
-----Var and Value-----  
Var1 (p)          Value: 2  
Var2 (q)          Value: 3  
-----
```

We have two expressions and their values
in main's scope

Source code

Translation code using Z3Mgr

Output on terminal

Bad Interprocedural Example Without push/pop

```
1 int bar(int a){
2     int r = a;
3     return r;
4 }
5 void main(){
6     int p, q;
7     p = bar(2);
8     q = bar(3);
9     assert(p==2)
10 }
```

Source code

```
1 expr p = getZ3Expr("p");
2 expr q = getZ3Expr("q");
3 expr a = getZ3Expr("a");
4 addToSolver(a == getZ3Expr(2));
5 expr r = getEvalExpr(a);
6 addToSolver(p == r);
7 addToSolver(a == getZ3Expr(3));
8 r = getEvalExpr(a);
9 addToSolver(q == r);
10 printExprValues();
```

Translation code using Z3Mgr

```
-----Var and Value-----
Assertion failed: (res!=z3::unsat &&
"unsatisfied constraints! Check your
contradictory constraints added to
the solver")
-----
```

both `a == getZ3Expr(2)` and
`a == getZ3Expr(3)` are added
into the solver in the same scope

Output on terminal

Bad Interprocedural Example Without Evaluating Return

```
1 int bar(int a){
2     int r = a;
3     return r;
4 }
5 void main(){
6     int p, q;
7     p = bar(2);
8     q = bar(3);
9     assert(p==2)
10 }
```

```
1  expr p = getZ3Expr("p");
2  expr q = getZ3Expr("q");
3  expr r = getZ3Expr("r");
4  expr a = getZ3Expr("a");
5  solver.push();
6  addToSolver(a == getZ3Expr(2));
7  addToSolver(r == a); // invalid after pop
8  solver.pop();
9  addToSolver(p == r);
10 printExprValues();
11 solver.push();
12 addToSolver(a == getZ3Expr(3));
13 addToSolver(r == a); // invalid after pop
14 solver.pop();
15 addToSolver(q == r);
16 printExprValues();
```

```
-----Var and Value-----
Var1 (p)          Value: random
Var2 (q)          Value: random
Var3 (r)          Value: random
-----
```

the values of p,q,r are
the same random number

Source code

Translation code using Z3Mgr

Output on terminal

Array and Struct Example

```
1 void main(){
2     int* a;
3     int* x;
4     int y;
5     a = malloc(...);
6     x = &a[2];
7     *x = 3;
8     y = *x;
9     assert(y==3);
10 }
```

Source code

```
1 expr a = getZ3Expr("a");
2 expr x = getZ3Expr("x");
3 expr y = getZ3Expr("y");
4 addToSolver(a == getMemObjAddress("malloc"));
5 addToSolver(x == getGepObjAddress(a,2));
6 storeValue(x, getZ3Expr(3));
7 addToSolver(y == loadValue(x));
8
9 /// print expr values as below
10 printExprValues();
```

Translation code using Z3Mgr

```
-----Var and Value-----
Var1 (a)           Value: 0x7f000004
Var4 (malloc)      Value: 0x7f000004
Var2 (x)           Value: 0x7f000003
Var3 (y)           Value: 0x7f000003
-----
```

getGepObjAddress returns the field address of the aggregate object *a*
The virtual address also in the form of 0x7f... + VarID

Output on terminal

Array and Struct Example

```
1 void main(){
2     int* a;
3     int* x;
4     int y;
5     a = malloc(...);
6     // similar for struct
7     // x=&(a->fld2)
8     x = &a[2];
9     *x = 3;
10    y = *x;
11    assert(y==3);
12 }
```

Source code

```
1 expr a = getZ3Expr("a");
2 expr x = getZ3Expr("x");
3 expr y = getZ3Expr("y");
4 addToSolver(a == getMemObjAddress("malloc"));
5 addToSolver(x == getGepObjAddress(a,2));
6 storeValue(x, getZ3Expr(3));
7 addToSolver(y == loadValue(x));
8
9 /// print expr values as below
10 printExprValues();
```

Translation code using Z3Mgr

```
-----Var and Value-----
Var1 (a)           Value: 0x7f000004
Var4 (malloc)      Value: 0x7f000004
Var2 (x)           Value: 0x7f0001f7
Var3 (y)           Value: 3
-----
```

getEvalExpr retrieve the value
from the expression

Output on terminal

Branch Example

```
1 void main(int argv){
2     int y = 2;
3     if(argv > 2)
4         y = argv;
5
6     // both definitions of y
7     // at lines 2 and 4 go to
8     // this joint point
9     assert(y>=2);
10 }
```

Source code

```
1 expr argv = getZ3Expr("argv");
2 expr y = getZ3Expr("y");
3 // new variable y1 to mimic the phi to merge
4 // two definitions of y at control flow joint point
5 expr y1 = getZ3Expr("y1");
6 expr two = getZ3Expr(2);
7 addToSolver(y == two);
8 addToSolver(y1 == ite(argv > two, argv, y));
9
10 /// expr validation and evaluation as below
11 printExprValues();
12 std::cout<<getEvalExpr(y1 >= two)<<"\n";
```

Translation code using Z3Mgr

```
-----Var and Value-----
Var1 (argv)      Value: 0
Var2 (y)         Value: 2
Var3 (y1)        Value: 2
-----
true
```

Output on terminal