

Symbolic Execution

Theory, Limitations, Tests, Concolic Testing

YEGOR BUGAYENKO

Lecture #8 out of 10

90 minutes

The slidedeck was presented by the author in this [YouTube Video](#)

All visual and text materials presented in this slidedeck are either originally made by the author or taken from public Internet sources, such as websites. Copyright belongs to their respected authors.



In Theory

In Practice

Test Case Generation

Concolic Testing

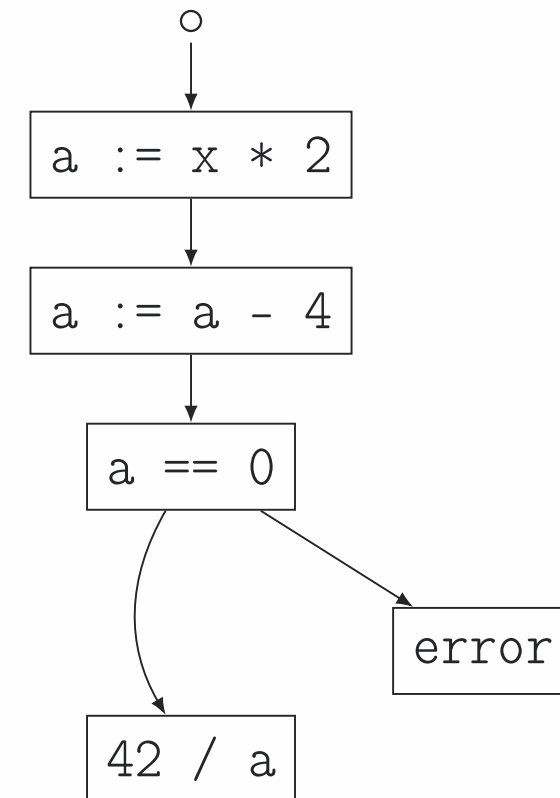
Further Reading/Watching

Chapter #1:

In Theory

Control Flow Graph

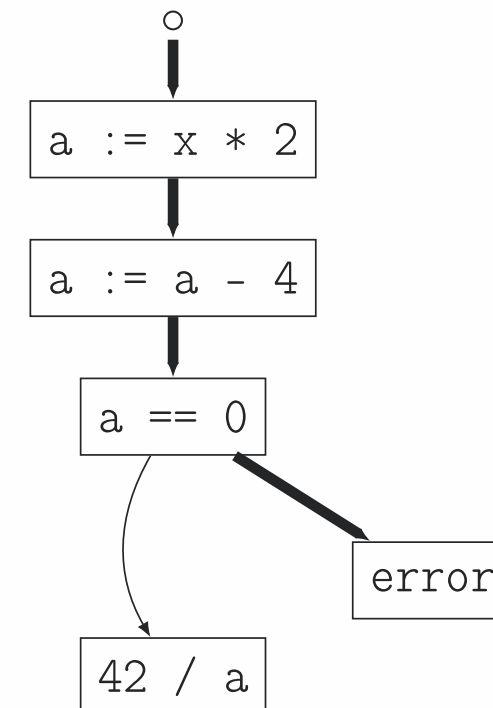
```
int f(int x) {  
    int a = x * 2;  
    a = a - 4;  
    if (a == 0)  
        error("Div by zero!");  
    return 42 / a;  
}
```



Path Feasibility

A path is feasible if there exists an input \mathcal{I} to the program that covers the path; i.e., when program is executed with \mathcal{I} as input, the path is taken.

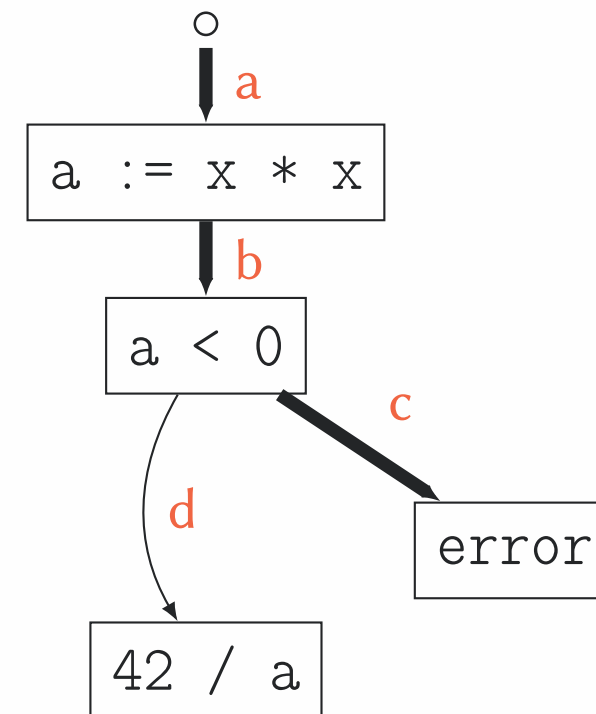
```
int f(int x) {  
    int a = x * 2;  
    a = a - 4;  
    if (a == 0)  
        error("Div by zero!");  
    return 42 / a;  
}
```



Infeasible Path

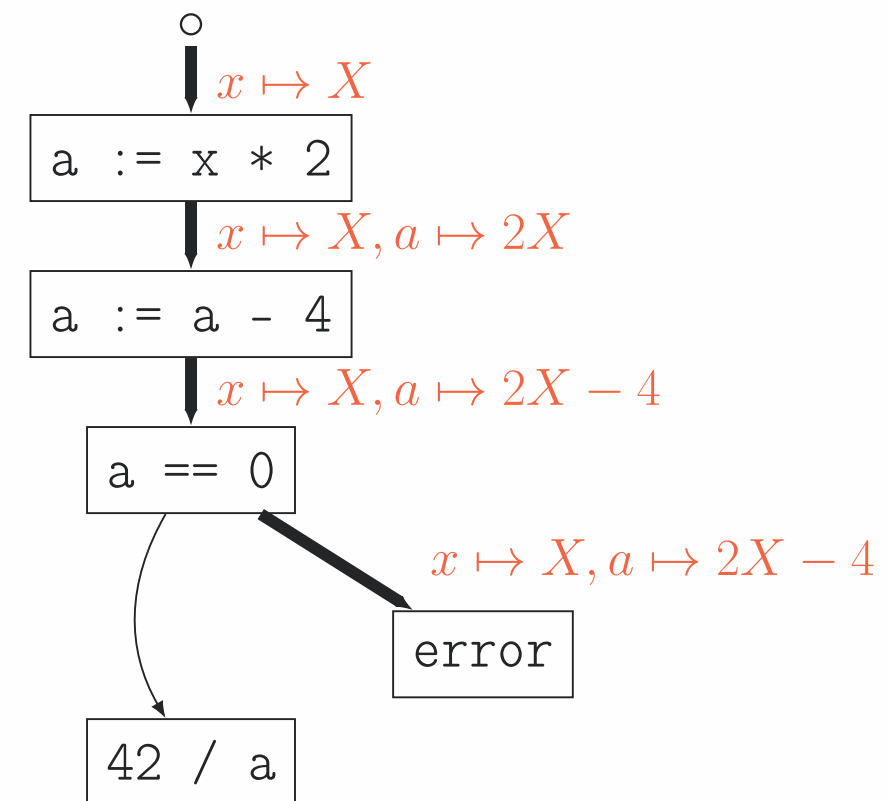
A path is infeasible if there exists no input \mathcal{I} that covers the path.

```
int f(int x) {  
  int a = x * x;  
  if (a < 0)  
    error("Too small!");  
  return 42 / a;  
}
```



Symbols

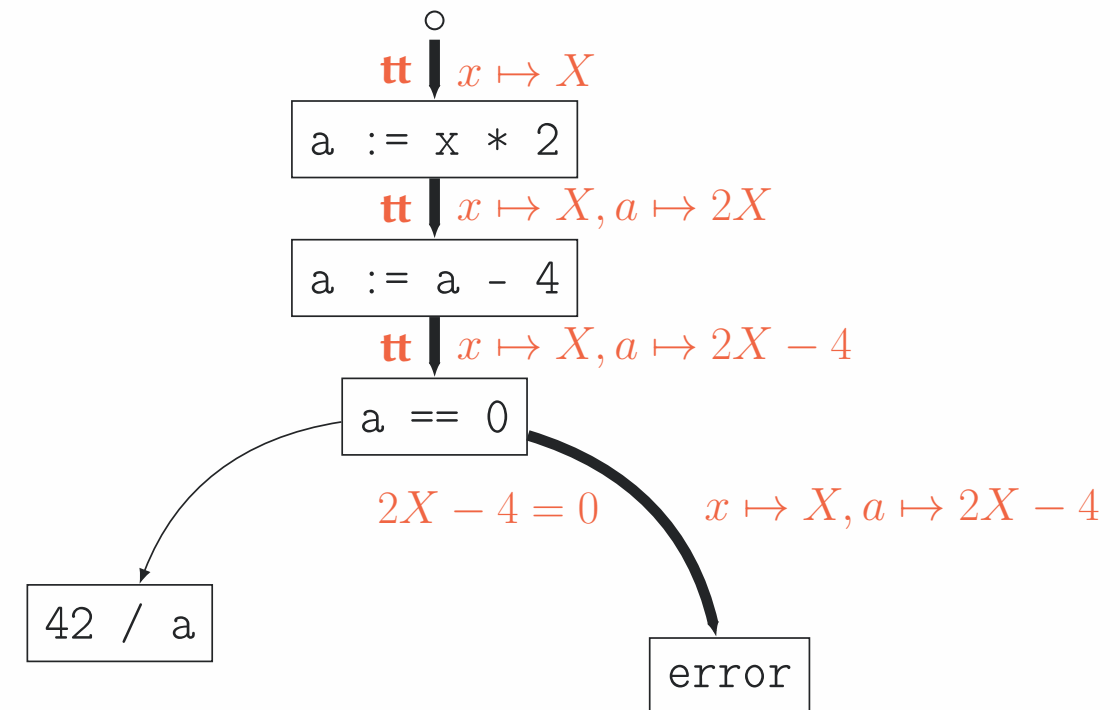
```
int f(int x) {  
  int a = x * 2;  
  a = a - 4;  
  if (a == 0)  
    error("Div by zero!");  
  return 42 / a;  
}
```



Path Conditions

Path condition is a condition on the input symbols such that if a path is feasible its path-condition is satisfiable.

```
int f(int x) {
  int a = x * 2;
  a = a - 4;
  if (a == 0)
    error("Div by zero!");
  return 42 / a;
}
```



Constraint Solver

A constraint solver is a tool that finds satisfying assignments for a constraint, if it is satisfiable.

A solution of the constraint is a set of assignments, one for each free variable that makes the constraint satisfiable.

Constraint:

$$x \mapsto X, a \mapsto 2X - 4$$
$$2X - 4 = 0$$

Solution:

$$X = 2$$

Chapter #2:

In Practice

SAT Solvers

SAT solver is a computer program which aims to solve the Boolean satisfiability problem: whether the variables of a given Boolean formula can be consistently replaced by the values TRUE or FALSE in such a way that the formula evaluates to TRUE.

Examples:

$$a \wedge b \rightarrow \dots$$

$$a \wedge b \wedge \neg a \rightarrow \dots$$

$$a \vee b \vee \neg a \rightarrow \dots$$

$$a \wedge (\mathbf{ff} \vee \mathbf{tt}) \rightarrow \dots$$

All expressions are in Boolean logic.

SMT Solvers

SMT solver is a computer program which aims to solve the satisfiability modulo theories: determine whether a mathematical formula is satisfiable.

Examples:

$$a < 5 \wedge a > 3 \rightarrow \dots$$

$$a < 5 \wedge f(a) > 42 \rightarrow \dots$$

$$a < 5 \vee a > 10 \vee \neg a \rightarrow \dots$$

$$a \wedge \mathbf{ff} \wedge x = 7 \rightarrow \dots$$

SMT solvers: Z3, cvc5, Yices, and many more...

Unsolvable Constraints

Symbolic execution cannot handle unsolvable or almost unsolvable constraints.

```
void enter(String p) {  
    int h = sha256(p);  
    if (!h.endsWith("68f728")) {  
        error("Access denied!");  
    }  
    // You are welcome!  
}
```

Path constraint:

$$p \mapsto P$$
$$H \mapsto \text{sha256}(P)$$
$$\text{endsWith}(H) = \mathbf{tt}$$

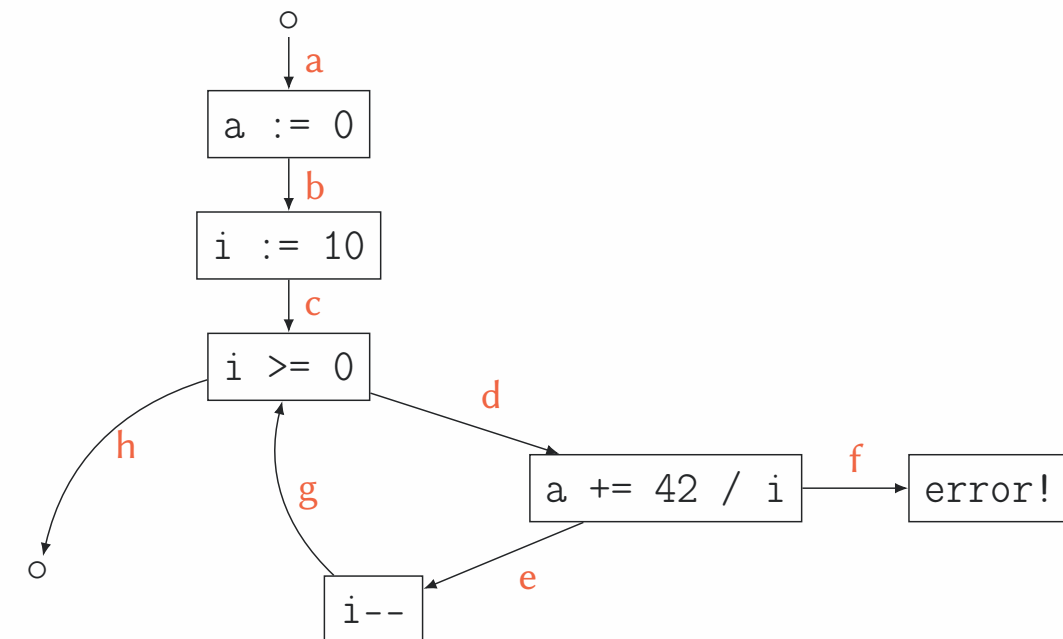
Path Explosion

Path explosion refers to the fact that the number of control-flow paths in a program grows exponentially with an increase in program size and can even be infinite in the case of programs with unbounded loop iterations.

```
int a = 0;
for (int i = 10; i >= 0; i--) {
    a += 42 / i;
}
```

Path:

(a, b, c, d, e, g, d, e, g, d, e, g, d, ..., e, g, d, f)




Clang Tidy vs. ChatGPT

```

/code/tmp/cpp$ cat a.cpp
int f() {
    int a = 0;
    for (int i = 3; i >= 0; i--) {
        a += 42 / i;
    }
    return a;
}
/code/tmp/cpp$ clang-tidy a.cpp --
1 warning generated.
/code/tmp/cpp/a.cpp:4:13: warning: Division by zero [clang-analyzer-core.DivideZero]
    a += 42 / i;
               ^
/code/tmp/cpp/a.cpp:3:3: note: Loop condition is true.
Entering loop body
    for (int i = 3; i >= 0; i--) {
    ^
/code/tmp/cpp/a.cpp:3:3: note: Loop condition is true.
Entering loop body
/code/tmp/cpp/a.cpp:3:3: note: Loop condition is true.
Entering loop body
/code/tmp/cpp/a.cpp:3:27: note: The value 0 is assigned
to 'i'
    for (int i = 3; i >= 0; i--) {
                          ^
/code/tmp/cpp/a.cpp:3:3: note: Loop condition is true.
Entering loop body
    for (int i = 3; i >= 0; i--) {
    ^
/code/tmp/cpp/a.cpp:4:13: note: Division by zero
    a += 42 / i;
               ^

```




Do you see any problems with this C++ code:

```

int a = 0;
for (int i = 10; i >= 0; i--) {
    a += 42 / i;
}

```



There is a problem with this code.

The loop condition is `i >= 0`, which means the loop will run 11 times (i.e., for `i` values of 10, 9, 8, ..., 0). When `i` reaches 0, the expression `42 / i` will cause a division by zero error, which is undefined behavior in C++.

To fix this issue, you can change the loop condition to `i > 0` instead of `i >= 0`. This will ensure that the loop runs only 10 times, for `i` values of 10, 9, 8, ..., 1.

Here's the corrected code:

```

css
Copy code

int a = 0;
for (int i = 10; i > 0; i--) {
    a += 42 / i;
}

```

This code will execute without any issues and will correctly calculate the sum of the expression `42 / i` for `i` values of 10, 9, 8, ..., 1.

Clang Static Analyzer

```
$ cat a.cpp
int main() {
    int a = 0;
    for (int i = 10; i >= 0; i--) {
        a += 42 / i;
    }
    return a;
}
$ clang-tidy a.cpp --
$ clang --analyze -Xclang -analyzer-constraints=z3 \
-Xclang -analyzer-max-loop -Xclang 5 a.cpp
$ clang --analyze -Xclang -analyzer-constraints=z3 \
-Xclang -analyzer-max-loop -Xclang 15 a.cpp
a.cpp:4:13: warning: Division by zero [core.DivideZero]
    a += 42 / i;
           ~~~~
1 warning generated.
```


Chapter #3:

Test Case Generation

Symbolic Input

```
#include <climits>
#include "stdlib.h"
int f(int x) {
    int a = x * 2;
    a = a - 4;
    if (a == 0)
        exit(-1);
    return 42 / a;
}
int main(int argc, char** argv) {
    int x = atoi(argv[1]);
    return f(x);
}
```

```
#include <climits>
#include "stdlib.h"
#include "klee/klee.h"
int f(int x) {
    int a = x * 2;
    a = a - 4;
    if (a == 0)
        exit(-1);
    return 42 / a;
}
int main(int argc, char** argv) {
    int x;
    klee_make_symbolic(&x, sizeof(x), "x");
    return f(x);
}
```

Compile to LLVM Bitcode

```
$ clang -I /opt/homebrew/Cellar/klee/2.3\_4/include -c -g \  
-emit-llvm -O0 -Xclang -disable-O0-optnone a.cpp
```

```
$ klee a.bc
```

```
KLEE: output directory is "/code/tmp/cpp/klee-out-2"
```

```
KLEE: Using STP solver backend
```

```
KLEE: done: total instructions = 38
```

```
KLEE: done: completed paths = 2
```

```
KLEE: done: partially completed paths = 0
```

```
KLEE: done: generated tests = 2
```

```
$ ls -al klee-out-0/*.ktest
```

```
-rw-r--r--  1 yb  staff   46 Apr  7 17:30 test000001.ktest
```

```
-rw-r--r--  1 yb  staff   46 Apr  7 17:30 test000002.ktest
```

```
$ llvm-bcanalyzer --dump a.bc
```

```
...
```

Test Cases

```
#include <climits>
#include "stdlib.h"
#include "klee/klee.h"
int f(int x) {
    int a = x * 2;
    a = a - 4;
    if (a == 0)
        exit(-1);
    return 42 / a;
}
int main(int argc, char** argv) {
    int x;
    klee_make_symbolic(&x, sizeof(x), "x");
    return f(x);
}
```

```
$ ktest-tool klee-last/test000001.ktest
ktest file : 'klee-last/test000001.ktest'
args       : ['a.bc']
num objects: 1
object 0: name: 'x'
object 0: size: 4
object 0: data: b'\x02\x00\x00\x00'
object 0: hex : 0x02000000
object 0: int : 2
object 0: uint: 2
object 0: text: ....
```

```
$ ktest-tool klee-last/test000002.ktest
ktest file : 'klee-last/test000002.ktest'
args       : ['a.bc']
num objects: 1
object 0: name: 'x'
object 0: size: 4
object 0: data: b'\x00\x00\x00\x00'
object 0: hex : 0x00000000
object 0: int : 0
object 0: uint: 0
object 0: text: ....
```

Replaying Test Cases

```
$ export LD_LIBRARY_PATH=/opt/homebrew/Cellar/keel/2.3_4/lib:$LD_LIBRARY_PATH
```

```
$ clang -I /opt/homebrew/Cellar/keel/2.3_4/include -L/opt/homebrew/Cellar/keel/2.3_4/lib \
-lkeelRuntest -Xclang -disable-00-optnone a.cpp
```

```
$ KTEST_FILE=keel-last/test000001.ktest ./a.out ; echo $?
255
```

```
$ KTEST_FILE=keel-last/test000002.ktest ./a.out ; echo $?
246
```

Chapter #4:

Concolic Testing

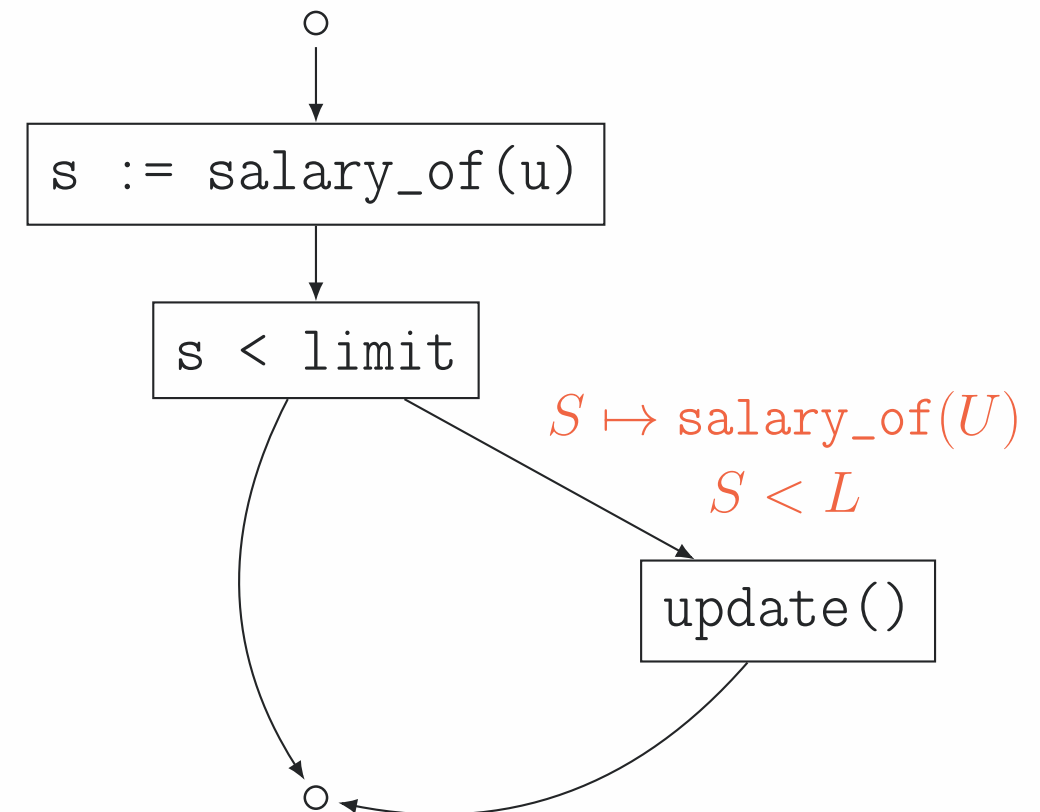
Motivating Example

```
enum user { Viki, Peter, Jeff, Sarah };
```

```
int salary_of(user u) { ... }
```

```
void raise(user u, int limit) {  
    int s = salary_of(u);  
    if (s < limit)  
        update(u, limit);  
}
```

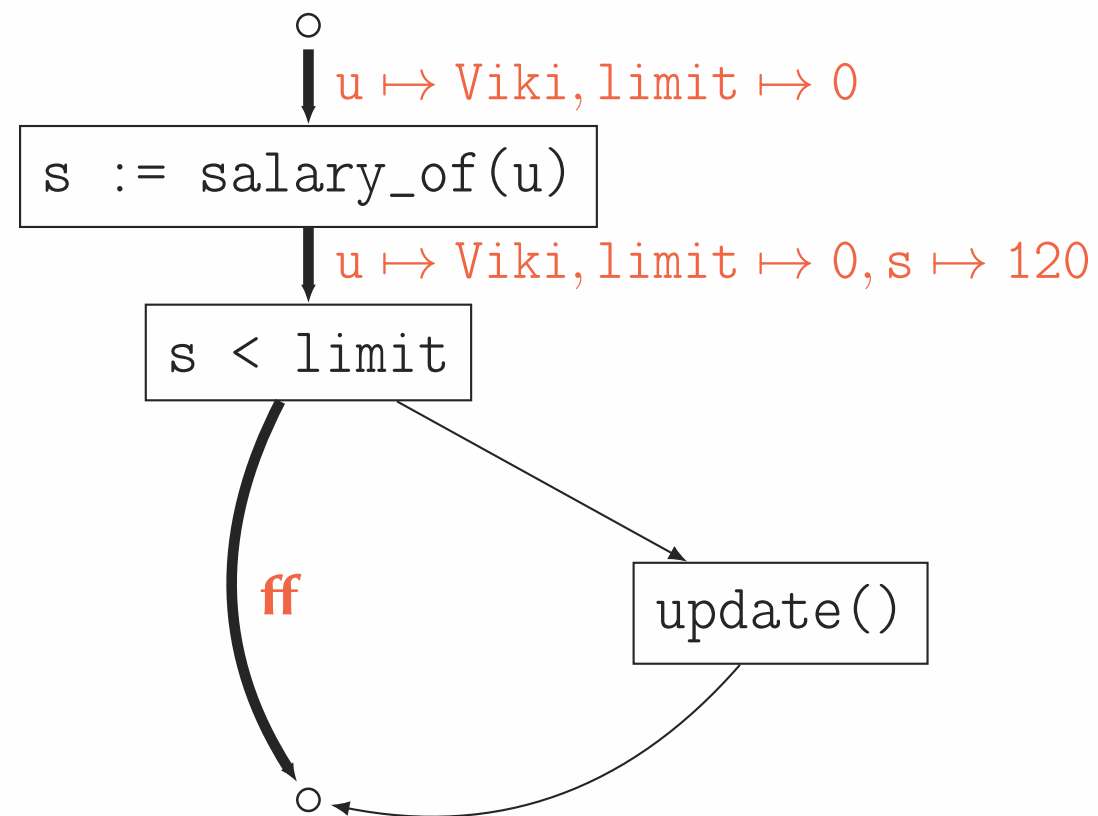
```
// Viki    120  
// Peter   180  
// Jeff    50  
// Sarah   70
```



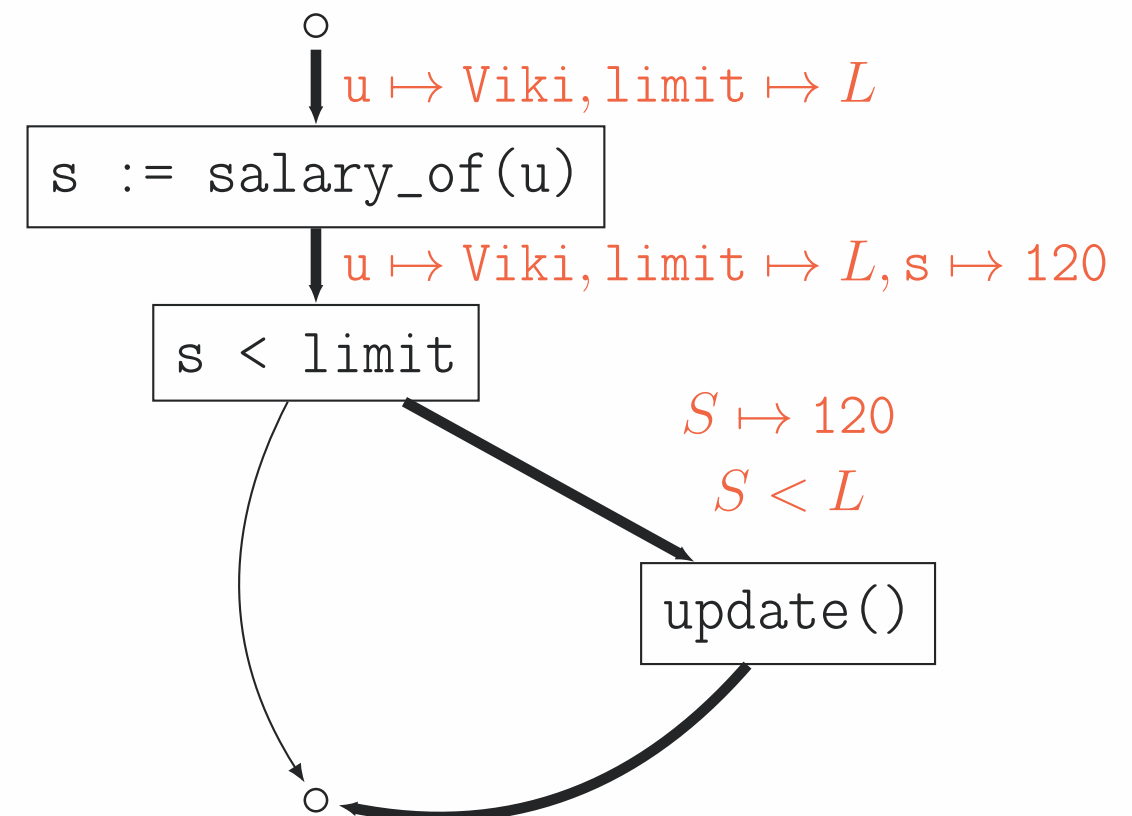
How to find test values of `u` and `limit` for `raise()`? It's impossible :(

Two Steps

1. Concrete (w/random input):



2. Symbolic (w/neglected condition):



Chapter #5:

Further Reading/Watching

Check this GitHub repo: [ksluckow/awesome-symbolic-execution](https://github.com/ksluckow/awesome-symbolic-execution)