CSC2/455 Software Analysis and Improvement
Symbolic Execution

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URCS

Outline

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Concrete Execution

- When programs run, every value they encounter is *concrete*
- We don't use concrete executions for analyses that must hold over all executions
    - A run is only one sample
- Static analysis results hold over all possible executions
    - Compromise: (Sound) approximations of values and paths
    - Will never claim a property is true when it isn't
    - May claim a property is false when it is in fact true
- What if we "approximate" values by symbols?
    - Symbolic Execution

Symbolic Execution

- Originated in the 1970s
  - See King, "Symbolic Execution and Testing", CACM 1976
- Resurgence in the last two decades
  - Underpinned by SMT solvers
- Closely related to Model Checking

Symbolic Execution Engines (or Symbolic Virtual Machines)

- Two main components of symbolic execution
  - A symbolic store (i.e. memory)
  - A symbolic path condition (a boolean formula that represents, in some ways, the symbolic program counter)
- Many symbolic execution engines available
  - Angr (for binary analysis)
  - KLEE (for analyzing C programs, but also LLVM bitcode)
  - Manticore (for analyzing Ethereum contracts, Linux binaries, Webassembly)

An example

```
def min(a, b):
   if a < b:
      x = a
   else
      x = a

   assert x == a or x == b
   assert x <= a and x <= b
```

In the program above, normally `a` and `b` have concrete values.

Let's make them symbolic:

- `a` $= \alpha$
- `b` $= \beta$
- Let $m(x)$ represent the memory store, retrieving the value for variable x

Symbolically Executing `min`

```
def min(a, b):
```

- At entry:
  - $m = \{\mathsf{a} \mapsto \alpha, \mathsf{b} \mapsto \beta\}$
  - $\pi = \text{true}$

Symbolically Executing `min`, contd.

```
if(a < b):
   x = a
```

- Just before `x = a`:
  - $m = \{\mathtt{a} \mapsto \alpha, \mathtt{b} \mapsto \beta\}$
  - $\pi = \alpha < \beta$
- After `x = a`:
  - $m = \{\mathtt{a} \mapsto \alpha, \mathtt{b} \mapsto \beta, \mathtt{x} \mapsto \alpha\}$
  - $\pi = \alpha < \beta$

Symbolically Executing `min`, contd.

```
else:
   x = a
```

- Just before `x = a`:
  - $m = \{\mathtt{a} \mapsto \alpha, \mathtt{b} \mapsto \beta\}$
  - $\pi = \neg(\alpha < \beta)$
- After `x = a`:
  - $m = \{\mathtt{a} \mapsto \alpha, \mathtt{b} \mapsto \beta, \mathtt{x} \mapsto \alpha\}$
  - $\pi = \neg(\alpha < \beta)$
- We have two path conditions now, one for the true part and one for the false part
  - The program has "forked"

Symbolically executing the true path

```
assert x == a or x == b
assert x <= a and x <= b
```

- Here:
  - $\pi = \alpha < \beta$
  - $m = \{\mathtt{a} \mapsto \alpha, \mathtt{b} \mapsto \beta, \mathtt{x} \mapsto \alpha\}$
- The symbolic conditions are (after substituting symbolic values from the store):
  - Prove $(\alpha = \alpha \vee \alpha = \beta)$ is always true when $(\alpha < \beta)$
  - Prove $(\alpha \leq \alpha \wedge \alpha \leq \beta)$ is always true when $(\alpha < \beta)$
- I.e. the following are UNSAT
  - $\alpha \neq \alpha \wedge \alpha \neq \beta \wedge \alpha < \beta$
  - $(\alpha > \alpha \vee \alpha > \beta) \wedge \alpha < \beta$

Symbolically executing the false path

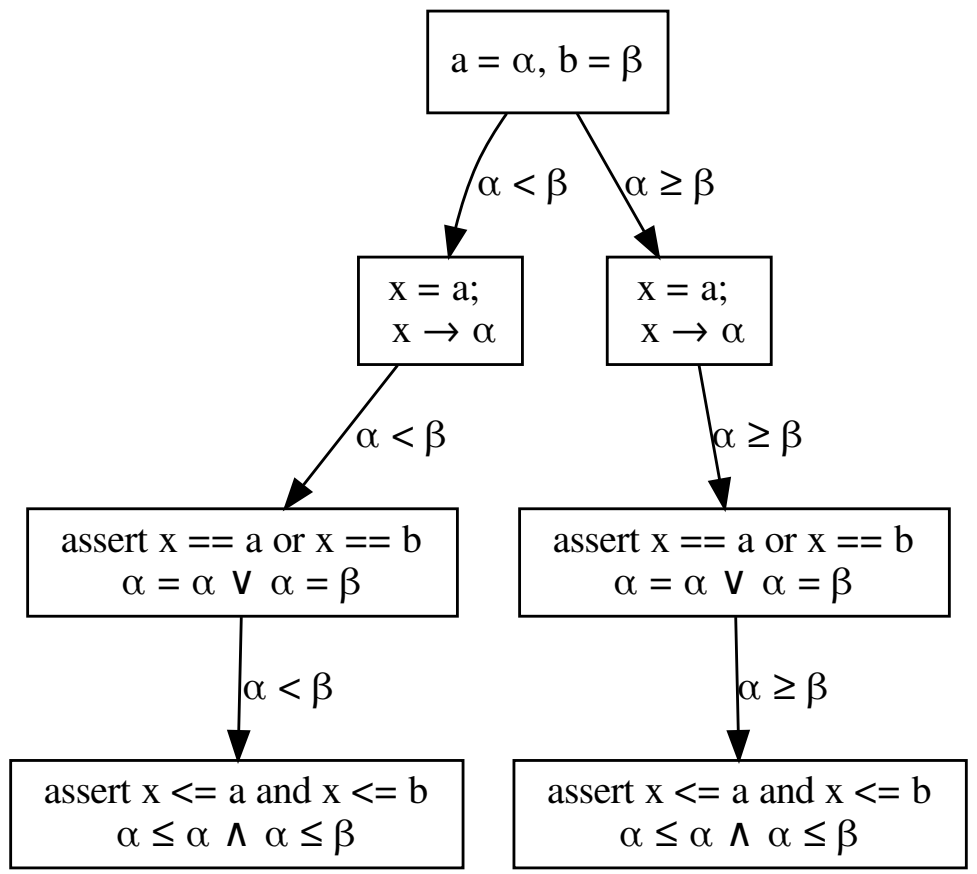
```
assert x == a or x == b
assert x <= a and x <= b
```

- Here:
  - $\pi = \neg(\alpha < \beta)$
  - $m = \{\mathtt{a} \mapsto \alpha, \mathtt{b} \mapsto \beta, \mathtt{x} \mapsto \alpha\}$
- The symbolic conditions are (after substituting symbolic values from the store):
  - Prove $(\alpha = \alpha \vee \alpha = \beta)$ is always true when $\neg(\alpha < \beta)$
  - Prove $(\alpha \leq \alpha \wedge \alpha \leq \beta)$ is always true when $\neg(\alpha < \beta)$
- I.e. the following are UNSAT
  - $\alpha \neq \alpha \wedge \alpha \neq \beta \wedge \alpha \geq \beta$
  - $(\alpha > \alpha \vee \alpha > \beta) \wedge \alpha \geq \beta$, but this not unsat!

The Symbolic Execution Graph

The Symbolic Execution Engine explores a graph:

- Nodes are program statements
- Edges are labeled with path conditions



Another example

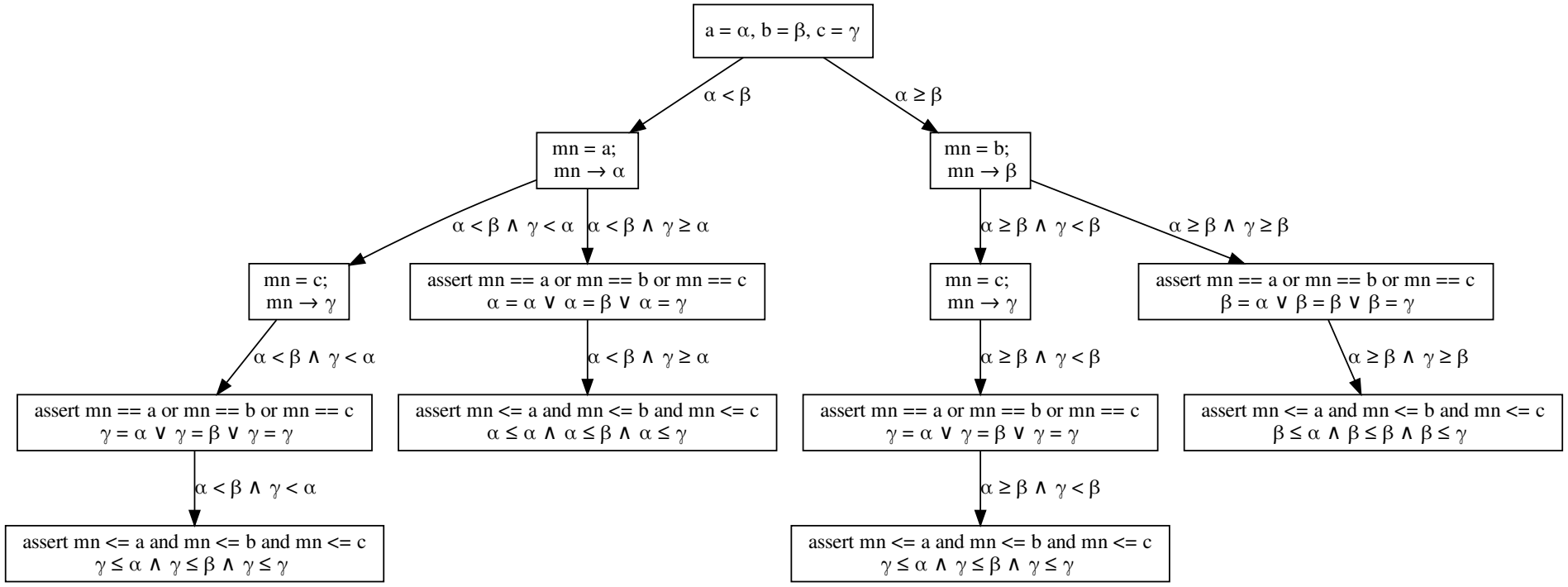
```
def min3(a, b, c):
   if a < b:
      mn = c

      if c < a:
         mn = c
   else:
      mn = b

      if c < b:
         mn = c

   assert mn == a or mn == b or mn == c
   assert mn <= a and mn <= b and mn <= c
```

Symbolic Execution



- You can reach the assert statements under four different path conditions
- Each conditional doubles the number of paths

Symbolic Execution: Expressions

```
y = 1
x = x + y
z = x * 3
```

- $y \mapsto 1$
- $x \mapsto \alpha_x + 1$ (where $m(x) = \alpha_x$)
- $z \mapsto (\alpha_x + 1) \times 3$

Symbolic Execution: Loops

```
i = 0
j = k
while i < 3:
   k = k + 1
   i = i + 1

assert k - j >= 3
```

- Each iteration adds to the path condition
  - $\pi_0 = 0 < 3$, $\pi_1 = 0 < 3 \wedge 1 < 3$, ...,
    $\pi_4 = 0 < 3 \wedge 1 < 3 \cdots \wedge 4 < 3$
- For the assert statement, the path conditions are negations:
  - $\pi'_0 = \neg(0 < 3)$ (this is false, no further exploration)
  - $\pi'_1 = \neg(0 < 3 \wedge 1 < 3)$ (this is false, no further exploration)
  - $\pi'_4 = \neg(0 < 3 \wedge 0 < 3 \cdots \wedge 4 < 3)$ (this is true)
- For π'_4, the store is $\{i \mapsto 3, k \mapsto \kappa + 3, j \mapsto \kappa\}$
  - (assume $k = \kappa$ initially)

Infinite/Symbolic loops

- When it cannot be proved that a path condition is false, the symbolic execution engine must continue exploring it
- This leads to a "state space explosion"

Non-basic Ideas

- Change path exploration
  - Don't use depth-first search
  - Random paths
  - etc.
- Concretize values
  - A mix of symbolic and concrete values ("concolic" execution)
  - May underapproximate paths executed
- Usually justified by noting we're looking for an executable path containing a bug
  - I.e. not trying to prove absence of bugs
- Merging states
- Lots of other "tricks"

Implementing A Symbolic Execution Engine

- Ball and Daniel, Deconstructing Dynamic Symbolic Execution
  - `https://www.github.com/thomasjball/PyExZ3/`
  - for Python, in Python

Outline

EXE and KLEE

- Cadar, Ganesh, Dill, and Engler, EXE: Automatically Generating Inputs of Death, CCS 2006
  - "This paper presents EXE, an effective bug-finding tool that automatically generates inputs that crash real code..."
- Cadar, Dunbar, and Engler, KLEE: unassisted and automatic generation of high-coverage tests for complex systems programs, OSDI 2008
  - "We also used KLEE as a bug finding tool, applying it to 452 applications (over 430K total lines of code), where it found 56 serious bugs, including three in COREUTILS that had been missed for over 15 years."
  - "We used KLEE to cross-check purportedly identical BUSYBOX and COREUTILS utilities, finding functional correctness errors and a myriad of inconsistencies"
- See also the CACM paper referenced earlier by these authors

Using KLEE

- Download and compile from the KLEE website
  - Build Instructions
- Then, use LLVM to generate bitcode

Example

```
#include <klee/klee.h>
#include <assert.h>

int min3(int a, int b, int c) {
  int mn;
  if(a < b) {
    mn = a;
    if(c < a)
      mn = c;
  }
  else {
    mn = b;
    if(c < b)
      mn = c;
  }

  return mn;
}

int main() {
  int a, b, c;
  klee_make_symbolic(&a, sizeof(a), "a");
  klee_make_symbolic(&b, sizeof(b), "b");
  klee_make_symbolic(&c, sizeof(c), "c");
  return min3(a, b, c);
}
```

Executing KLEE

```
$ klee min3.bc
KLEE: output directory is "/src/klee-out-2"
KLEE: Using Z3 solver backend

KLEE: done: total instructions = 63
KLEE: done: completed paths = 4
KLEE: done: generated tests = 4
```

KLEE Test Cases

```
$ ktest-tool klee-last/test00000?.ktest

object 0: name: 'a'
object 0: int : 0

object 1: name: 'b'
object 1: uint: 0

object 2: name: 'c'
object 2: int : 0
```

- a = 0, b = 1, c = 0
- a = 1073741824, b = 1, c = 0
- a = 1, b = 2, c = 0

Adding asserts (and a bug!)

```
#include <klee/klee.h>
#include <assert.h>

int min3(int a, int b, int c) {
  int mn;
  if(a < b) {
    mn = a;
    if(c < a)
      mn = c;
  }
  else {
    mn = b;
    if(c < b)
      mn = b;
  }

  assert(mn == a || mn == b || mn == c);
  assert(mn <= a && mn <= b && mn <= c);

  return mn;
}

int main() {
  int a, b, c;
  klee_make_symbolic(&a, sizeof(a), "a");
  klee_make_symbolic(&b, sizeof(b), "b");
  klee_make_symbolic(&c, sizeof(c), "c");
  return min3(a, b, c);
}
```

Running KLEE

```
KLEE: output directory is "src/klee-out-10"
KLEE: Using Z3 solver backend
KLEE: ERROR: min3asserts.c:18: ASSERTION FAIL: mn <= a && mn <= b && mn <= c
KLEE: NOTE: now ignoring this error at this location

KLEE: done: total instructions = 169
KLEE: done: completed paths = 6
KLEE: done: generated tests = 5
```

- `a = 1, b = 1, c = 0`

KLEE on Coreutils

- See tutorial: `https://klee.github.io/tutorials/testing-coreutils/`

Outline

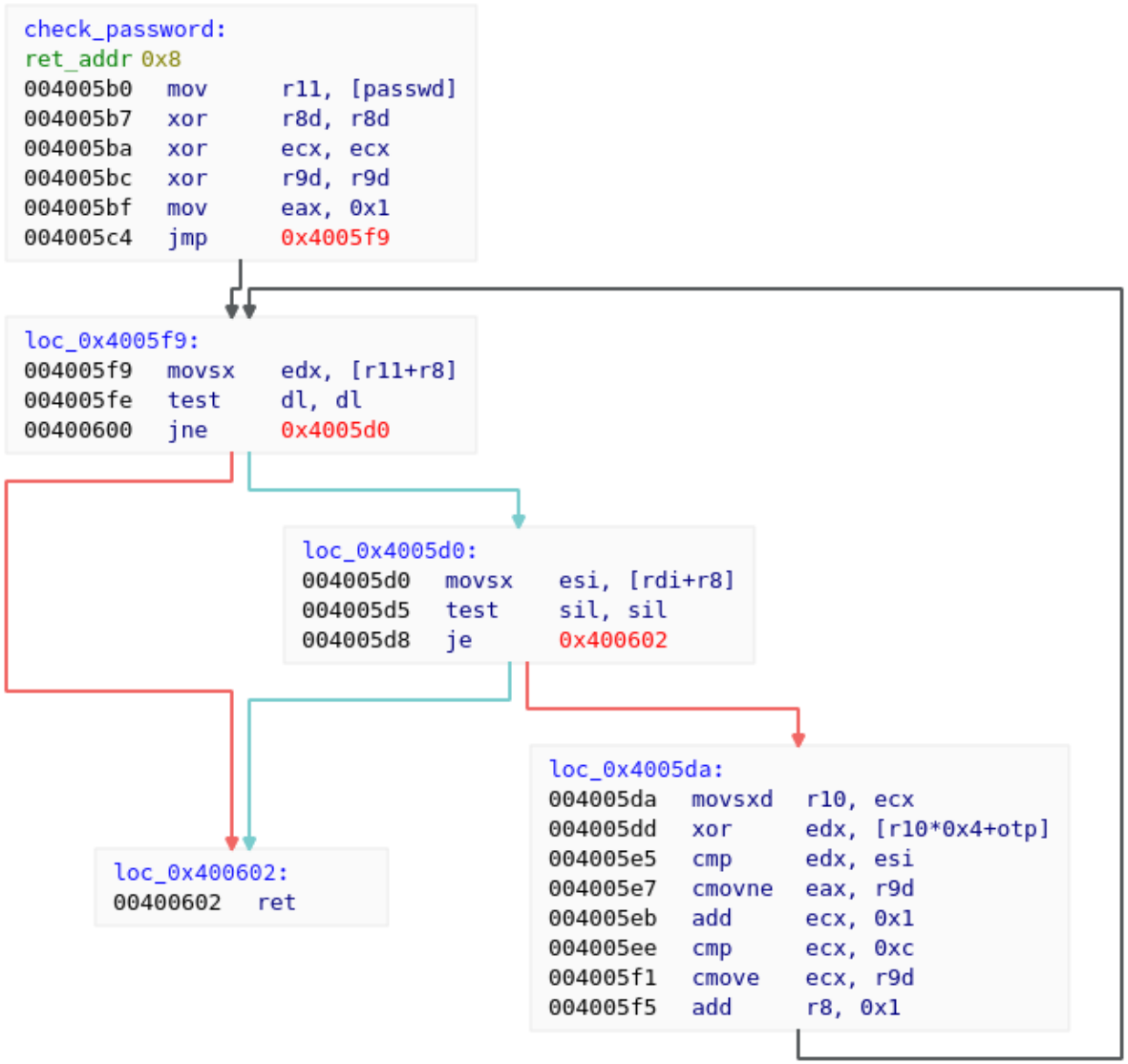
Binary Analysis

- Angr is a symbolic execution engine for x86-64 code
- It is used from within Python3
    - Very easy to install
- Angr is a very programmable symbolic execution engine

Exploring `crackme`

- In a Mission (Not So) Impossible scenario, we have a binary `crackme`, which can only be unlocked using a password
- The password is in the binary, but it is encrypted
- Can we figure it out?

Control Flow Graph



Loading `crackme`

```
proj = angr.Project(args.binary, auto_load_libs=False)
cfg = proj.analyses.CFG()

cpfn = find_function("check_password", cfg)
s = proj.factory.blank_state(addr=cpfn.addr)
```

- This creates an Angr project, by loading the binary, and finding the address of `check_password` in it
- Then we create a blank symbolic state, with program counter at the entry to `check_password`

Symbolically Executing `crackme`

```
simgr = proj.factory.simulation_manager(s)
simgr.explore(find=0x400602, num_find = 20)
```

- We start symbolic execution and explore all states until we reach a state where the PC is 0x400602
  - The is the return address
- Angr returns the first state it finds, but we ask for more (up to 20)

Results

```
(Pdb) simgr.found
[<SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>,
 <SimState @ 0x400602>]
```

- There are thirteen states that exit the function

Examining states

Which basic blocks were executed?

```
(Pdb) simgr.found[0].history.bbl_addrs.hardcopy
[0x4005b0, 0x4005f9, 0x4005d0]
```

What was the (symbolic) return value?

```
(Pdb) simgr.found[1].history.bbl_addrs.hardcopy
[0x4005b0, 0x4005f9, 0x4005d0, 0x4005da, 0x4005d0]

(Pdb) simgr.found[1].regs.eax
<BV32 if mem_ffffffffffff000_13_8{UNINITIALIZED} == 72 &&
 mem_ffffffffffff000_13_8{UNINITIALIZED}[7:7] == 0 then
 0x1 else 0x0>
```

- This is a symbolic if-then-else expression
  - eax contains 1 or 0
  - if the expression involving memory is true
  - (the memory address contains 72)

What was the (symbolic) return value? (2)

```
(Pdb) simgr.found[2].history.bbl_addrs.hardcopy
[0x4005b0, 0x4005f9, 0x4005d0, 0x4005da, 0x4005d0, 0x4005da, 0x4005

(Pdb) simgr.found[2].regs.eax
<BV32 if mem_ffffffffffff001_14_8{UNINITIALIZED} == 101 &&
   mem_ffffffffffff001_14_8{UNINITIALIZED}[7:7] == 0 then
   (if mem_ffffffffffff000_13_8{UNINITIALIZED} == 72 &&
     mem_ffffffffffff000_13_8{UNINITIALIZED}[7:7] == 0
     then 0x1 else 0x0)
   else 0x0>
```

- This is still a symbolic if-then-else expression
  - eax contains 1 or 0 ultimately
  - if the expression involving memory is true
  - (the memory address contains 72 and the address adjacent contains 101)
  - 'He'

Solving for the password

```
(Pdb) simgr.found[12].solver.add(simgr.found[12].regs.eax == 1)
```

- We're adding a constraint that on exit `eax` is 1
  - Presumably, indicating successful match
- We then ask the solver to solve the symbol in `rsi`
  - `rsi` held the characters of the password during comparison
  - This returns 0x21, i.e. 33, i.e. '!'
- But it also concretizes the memory

Looking at the concretized memory

```
(Pdb) simgr.found[12].solver.eval(simgr.found[12].regs.rdi)
0xfffffffffffff000
(Pdb) simgr.found[12].solver.eval(simgr.found[12].memory.load(
        simgr.found[12].regs.rdi, 12), cast_to=bytes)
b'Hello,World!'
```

Why did this function exit 13 times?

```
int check_password(const char *u) {
  int i = 0;
  int j = 0;
  int succ = 1;

  while(passwd[i] != '\0' && *u != '\0') {
    if((passwd[i] ^ otp[j]) != *u) {
      succ = 0;
    }

    i++;
    u++;
    j++;
    if(j == n_otp) j = 0;
  }

  return succ;
}
```

Postscript

- Symbolic Execution can be a powerful analysis tool
  - Used alone or in conjunction with other tools
- Try out the tools we talked about today!