CSC 591
Systems Attacks and Defences

Symbolic Execution

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Let’s find some bugs

- We have a potentially vulnerable program
- The program has some inputs which can be controlled by the attacker
- What should we do as developers?
  - Add checks (assertions)
  - Write tests
  - Make sure the checks do not fail

- Is this enough?

Concrete Execution

```
void foo(int x, int y) {
    int z = 0;
    if (x > y) {
        z = x;
    }
    else {
        z = y;
    }
    if (z < x) {
        assert false;
    }
}
```

x=0, y=0

False

z = 0

False

// not reached

Concrete Execution

```
void foo(int x, int y) {
    int z = 0;
    if (x > y) {
        z = x;
    }
    else {
        z = y;
    }
    if (z < x) {
        assert false;
    }
}
```

x=1, y=0

True

z = 1

False

// not reached

Pros/Cons

- Testing intended functionality
- Testing for known bugs
- Unintended functionality
- Unknown bugs
- Complete coverage

Can we automate this part?

Symbolic Execution

```
void foo(int x, int y) {
    int z = 0;
    if (x > y) {
        z = x;
    }
    else {
        z = y;
    }
    if (z < x) {
        assert false;
    }
}
```

x=α, y=β

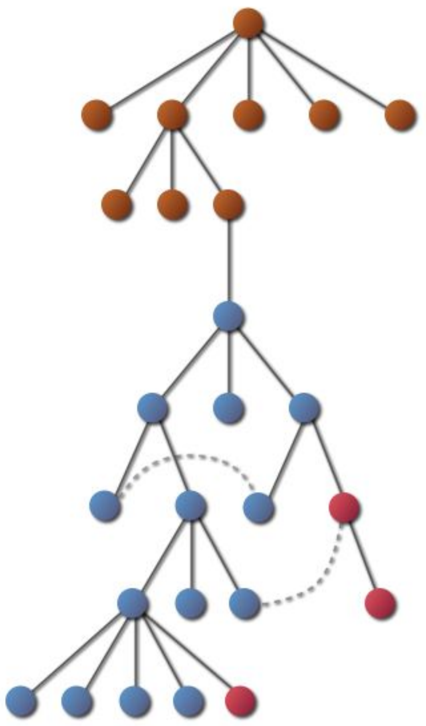
z = α, α > β

z = β, α <= β

1. α < α -> False
2. β < α, α <= β, False

Feasible and Infeasible Paths

- A path is a particular route in the control-flow graph of the program
- A **feasible** path is the path covered for a particular input
- An **infeasible** path is the path that no input can cover



Infeasible Paths

- Dead code => infeasible path
- Infeasible path !=> dead code

- It is normal in a large program to have a large number of infeasible paths

- This makes automatic testing based on the input to the program incredibly hard

Constrains

- $\alpha > \beta \land \alpha + \beta <= 10$

- α, β are called **free variables**
- Solution: a set of variable assignments that makes the constraint satisfiable
- $\{\alpha = 3, \beta = 2\}$ is a solution
- $\{\alpha = 6, \beta = 5\}$ is not a solution

- Decision procedure: is the constraint satisfiable?
- Constraint solver: if is satisfiable, find assignments
- Undecidable problem

Symbolic Execution

- Execute the program differently, “symbols” as input
- Take all feasible paths
- Program state is different:
  - No stack/heap
  - Symbolic values for memory locations
  - Path condition
- Path condition: input constraints so that a certain path is feasible
- A solution to a path condition is a test input that covers the desired path

History of Symbolic Execution

James C. King

Symbolic execution and program testing

Communications of the ACM

(July 1976)

Why are we talking about it now?

- Computation intensive
  - Too many paths
  - Program state grows a lot
  - Constraint solver is computationally expensive, but we need to identify the feasible paths

- Powerful computers
- Better constraint solvers

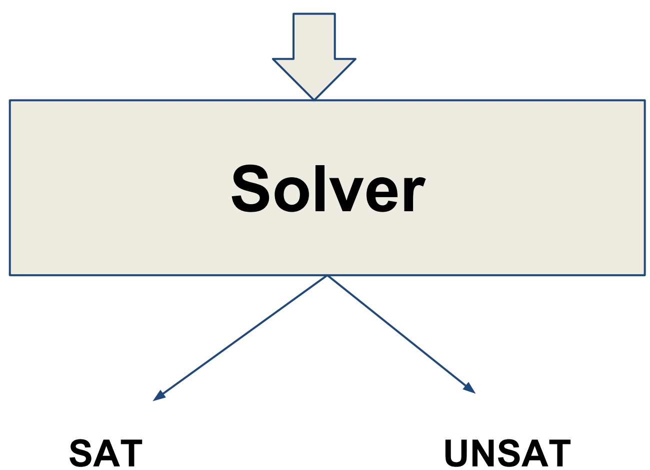
Symbolic Execution Tools

- KLEE
  - Open source symbolic executor
  - Runs on top of LLVM
  - Has found lots of problems in open-source software
- SAGE
  - Microsoft internal tool
  - Symbolic execution to find bugs in file parsers - E.g., JPEG, DOCX, PPT, etc
  - Cluster of n machines continuously running SAGE

Constraint Solver

- Boolean **SAT**isfiability Problem
- Find values that satisfy a boolean formula
- NP-Complete

$$(I1 \lor I2 \lor x2) \land (\neg x2 \lor I3 \lor x3)$$



SMT Solvers

- Satisfiability modulo theories
- SAT, but with binary variables replaced by predicates over a suitable set of non-binary variables

3x + 2y - z >= 4

$$(\sin(x)^3 = \cos(\log(y) \cdot x) \vee b \vee -x^2 \geq 2.3y) \wedge \left(\neg b \vee y < -34.4 \vee \exp(x) > \frac{y}{x}\right)$$

Popular SMT solvers

- Z3 - developed at Microsoft Research
  - https://github.com/Z3Prover/z3
- Yices - developed at SRI
  - http://yices.csl.sri.com/
- STP - developed by Vijay Ganesh, now @ Waterloo
  - http://stp.github.io/
- CVC3 - developed primarily at NYU
  - http://www.cs.nyu.edu/acsys/cvc3/

Forking Execution

- What to do when we reach a branching point?
  - Follow both paths (condition satisfied and negation)
- State explosion *really* fast (exponential)
  - Loops on symbolic variables are problematic
- How can we do this more efficiently?
  - Prune paths by following only feasible ones
  - Concolic execution: run the program concretely and assist the execution with symbolic execution by changing the path conditions

Static analysis

- It will terminate, even if the whole program is taken into account
- Approximation is the key
  - Let's assume every path is feasible
- False alarms
- Less accurate

Symbolic search

- We have to decide on a strategy
  - Depth-first search (DFS)
  - Breadth-first search (BFS)

- Potential drawbacks
  - No smart choices
  - DFS can get easily stuck in one part of the program
    - Literally on a loop
  - BFS is a better choice
    - Harder to implement (think about concolic execution)

Search strategies

- Focus on the paths that matter
  - Assertion failures
  - Time bound
  - Vulnerable functions (like strcmp)

- Improve coverage
  - Program execution as a DAG
    - Nodes = program states
    - Edge(n1, n2) = can transition from n1 to state n2
  - Graph exploration algorithm

Randomness

- In the beginning we know nothing, how do we start?
- Ideas
  - Pick next path at random
  - Randomly restart search
  - Choose randomly among equal priority paths

- But then how do we reproduce our analysis?
  - Pseudo-randomness
  - Record the seed
  - Otherwise bugs can disappear on reruns

Coverage-guided heuristics

- Let's visit statements that we haven't seen before
- Approach
  - Score of statement = # visits
  - Pick the next statement with the lowest score
- Pros
  - Errors are often in hard-to-reach parts of the program
  - This strategy tries to reach everywhere.
- Cons
  - Maybe never be able to get to a statement if proper precondition not set up

Generational search

- Hybrid of BFS and coverage-guided
  - Generation 0: pick one program at random, run to completion
  - Generation 1: take paths from gen 0; negate one branch condition on a path to yield a new path prefix; find a solution for that prefix; then take the resulting path
  - Generation n: similar, but branching off gen n-1
- Also uses a coverage heuristic to pick priority

Path-based search limited

```
int counter = 0, values = 0;
for (i = 0; i<100; i++) {
  if (input[i] == 'B') {
    counter++;
    values += 2;
  }
}
assert(counter != 75);
```

- 2^{100} possible execution paths
- Hard to find the bug
  - $\binom{100}{75} \approx 2^{78}$ paths reach buggy line of code
  - Pr(finding bug) = $2^{78} / 2^{100} = 2^{-22}$

Libraries and native code

- Execution of a program is not solely contained on the program's code
  - Libraries, system calls, assembly code
- We could extend the symbolic execution to those parts
  - Pull in the library and symbolically execute it
  - If library is complicated, then our program state will grow too large
  - Replace the library with a simpler version (libc -> newlib)
- Model the code of the external dependencies

Concolic Execution

- Dynamic symbolic execution
- Concrete execution of the program with assistance by symbolic execution

- Instrument the program
  - Keep a shadow state with symbolic variables
  - Start with a concrete execution that sets an initial path

- Follow one path and use symbolic execution to determine the next one
  - Negate a condition
  - Inputs are concrete values

Concretization

- Use symbolic execution as guidance
  - But replace symbolic variables with concrete values that satisfy the path condition
- This way the program is actually executed
  - Abstract parts that are not in the code (system calls)
  - No symbolic-ness at such calls (we lose information)
- Very useful when conditions get too complex for SMT solver

Conclusion

- Symbolic execution is very powerful and productive
- Not very practical as programs grow large
  - Limited by the power of the constraint solver
  - Bound by the infeasible paths number
- Promising research area!

Your Security Zen

Vizio smart TVs spied on millions of users without their consent

Vizio's smart TVs captured "information about video displayed on the smart TV, including video from consumer cable, broadband, set-top box, DVD, over-the-air broadcasts, and streaming devices" since February 2014.

Source: https://www.helpnetsecurity.com/2017/02/07/vizio-smart-tvs-spied/