CS451 – Software Analysis

Lecture 15

Symbolic Execution

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Overview

- Symbolic execution tracks metadata about a program's state
  - Exactly as we do with taint analysis
- In taint analysis we can reason if specific data that is processed in taint sinks comes from taint sources
- In symbolic execution we can reason about which specific input can drive a program to a specific state
- As it holds with taint analysis, symbolic execution can happen at the source or binary level

Applications

- Creation of inputs that reach specific code states
- Increase code coverage
  - In software testing, or fuzzing if we test for security vulnerabilities, we need to artificially create inputs
  - These inputs should exercise as much of the analyzed code as possible
- Programs that are dynamically analyzed
  - Computing the right payload is not trivial
- Symbolic execution is powerful, but can can face scalability issues, when the program's size is increased

Symbolic vs concrete execution

- When we run or analyze a program, we use concrete values
  - These values taken from the input initialize and set variables of the program, again, with concrete values
  - The memory of the process is filled in with specific data
- In symbolic execution, the program is *emulated* with symbolic values instead of concrete ones
- Symbolic execution at the binary level implies that certain memory cells or h/w registers contain symbolic information

Symbolic state

- Symbolic execution replaces concrete values with symbols (α_i, $i \in N$) that represent a range of concrete values
- The symbolic execution engine constantly computes
  - A set of symbolic expressions
  - A set of path constraints

Symbolic expression

- A symbolic expression φ_j, with i ∈ N, corresponds either to a symbolic value, α_i, or to some mathematical combination of symbolic expressions, such as: $\varphi_3 = \varphi_1 + \varphi_2$
- The symbolic execution engine maintains a store, σ, with all symbolic expressions

Path constraint

- The path constraint encodes the limitations imposed on the symbolic expressions by the branches taken during execution
- For example, if the symbolic execution takes a branch if (x < 5) and x is mapped to φ_1, then we have a path constraint: $\varphi_1 < 5$
- All path constraints are stored in π

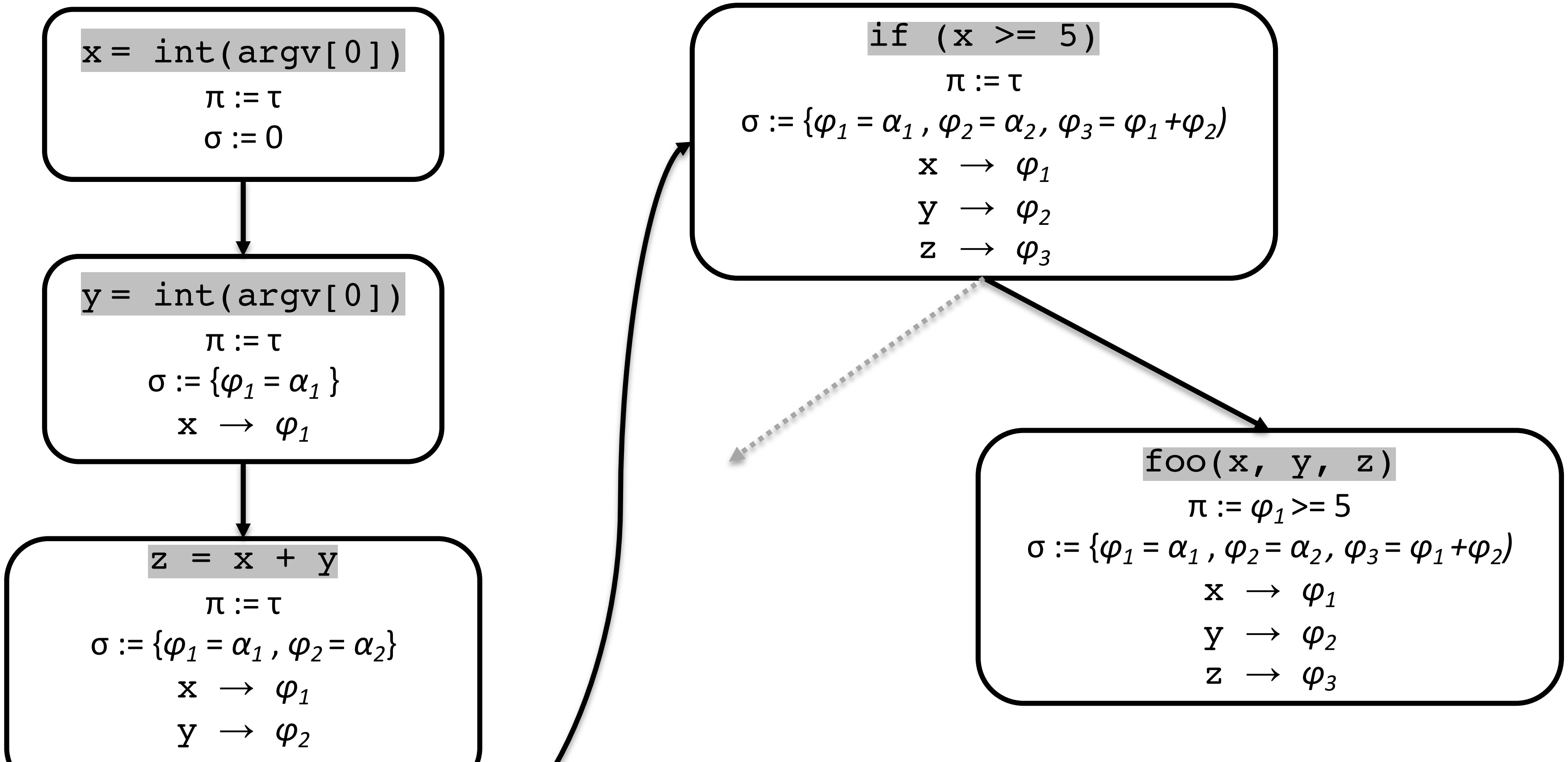
Example

```
x = int(argv[0])
y = int(argv[1])
z = x + y

if (x >= 5)
  foo(x, y, z)
  y = y + z
  if (y < x)
    baz(x, y, z)
  else
    qux(x, y ,z)
else
   bar(x, y, z)
```

What kind of inputs do we need to reach the call of foo() or bar()?

Executing the program symbolically



Solution: x = 5 and y = 0

Variants and limitations

- There are different types of symbolic execution engines, which can be used for building analysis tools and other applications
- Static vs dynamic
  - The engine may emulate the program statically or actually executing it dynamically (concolic execution)
- Online vs offline
  - The engine may explore multiple paths in parallel or not
- Symbolic state
  - Which parts of the program are represented symbolically and which are not
- Path coverage
  - Which (and how many) program paths the engine explores

Static symbolic execution

- Symbolic execution can be performed statically by emulating all branches symbolically
- Advantages
  - The analysis can be applied on any code, even on code that runs on a different architecture
- Disadvantages
  - Hard to emulate all branches and to emulate parts outside of your control (kernel, third-party library)
  - *Effect modelling* tries to model the behavior of a part you do not control, but it is hard in practice (you need to model the network, the filesystem, etc.)
  - *Direct external interactions* may actually perform the call, but again if multiple calls need to be performed the case becomes complex

Dynamic symbolic execution

- Dynamic symbolic execution or *concolic execution* runs the program with concrete values but keeps a symbolic state
  - Symbolic state is tracked using metadata, as we do with taint analysis
- Does not explore multiple paths in parallel, but only a single path with a concrete value
  - To explore different paths, it flips path constraints and uses the constraint solver to compute concrete inputs that lead to an alternative branch
- Much scalable compared to static symbolic execution
  - No need to maintain state for parallel paths
  - Supports external interactions
- Code coverage is based on concrete values and may be low

Online vs offline

- Online symbolic execution explores multiple paths in parallel, while offline explores only a given path
  - Usually, static symbolic execution is online and dynamic symbolic execution is offline, but there are variants
- Online has the advantage of not running the same code multiple times, however the needed symbolic state can be significant

Symbolic state

- Many frameworks allow to define which parts of the memory is going to be treated as symbolic and which as concrete
  – This approach is more scalable and the constraints can be much easier to solve
- Some engines make memory accessing also symbolic
  – Fully symbolic memory attempts to model all the outcomes of a memory load/store operation (e.g., if you read from an array a[i], where you know i is unsigned and i <5, you are going to read all elements a[0]..a[4])
  – Address concretization attempts to put concrete bounds in cases of unbound memory accessing

Path coverage

- Exploring *all* possible paths can lead to the *path explosion problem*
- Focus on specific paths using heuristics
  - A bug finding tool may focus on sensitive parts, such as loops indexing buffers
- Use a DFS approach to explore each path deeply before moving to another one
  - Sometimes problems arise in deeply nested code
- Concolic execution explores one path at a time
  - You need to restart the program with a different input to explore more paths
  - You can use snapshots for avoiding a complete restart

Increasing scalability

- Simplifying constraints
  - Limiting the number of symbolic variables, by selecting the interesting ones (not an easy problem, sometimes taint analysis can help)
  - Limiting the number of symbolic operations (e.g., if you are interested in an indirect branch that involves %rax, then you can execute symbolically only the operations that contribute to the value of %rax)
  - Simplifying symbolic memory
- Avoiding the constraint solver