Advanced Systems Security

Fuzz Testing

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Detect Vulnerabilities

• We want to develop techniques to detect vulnerabilities automatically before they are exploited
  ‣ What’s a vulnerability?
  ‣ How to find them?
Vulnerability

• How do you define computer ‘vulnerability’?
Vulnerability

• How do you define computer ‘vulnerability’?
  ‣ Flaw
  ‣ Accessible to adversary
  ‣ Adversary has ability to exploit
One Approach

• Run the program on various inputs
  ‣ See what happens
  ‣ Maybe you will find a flaw

• How should you choose inputs?
Dynamic Analysis Options

• Regression Testing
  ‣ Run program on many normal inputs and look for bad behavior in the responses
    • Typically looking for behavior that differs from expected – e.g., a previous version of the program

• Fuzz Testing
  ‣ Run program on many abnormal inputs and look for bad behavior in the responses
    • Looking for behaviors that may be triggered by adversaries
      ‣ Bad behaviors are typically crashes caused by memory errors
Dynamic Analysis Options

• Why do you think fuzz testing is more appropriate for finding vulnerabilities than regression testing?
Fuzz Testing

• Fuzz Testing
  ‣ Idea proposed by Bart Miller at Wisconsin in 1988

• Problem: People assumed that utility programs could correctly process any input values
  ‣ Available to all

• Result: Found that they could crash 25-33% of UNIX utility programs
Fuzz Testing

• Fuzz Testing
  ‣ Idea proposed by Bart Miller at Wisconsin in 1988

• Approach
  ‣ Generate random inputs
  ‣ Run lots of programs using random inputs
  ‣ Identify crashes of these programs
  ‣ Correlate with the random inputs that caused the crashes

• Problems: Not checking returns, Array indices…
Fuzzing Example

• Fuzz Testing
  ‣ Example

format.c (line 276):
...
while (lastc != '\n') {
    rdc();
}
...

input.c (line 27):
rdc()
{ do { readchar(); } 
     while (lastc == ' ' || lastc == '\t'); return (lastc); }

Challenges

- **Idea**: Search for possibly accessible and exploitable flaws in a program by running the program under a variety of inputs

- **Challenge**: Selecting input values for the program
  - What should be the goals in choosing input values for dynamic analysis?
Challenges

• **Idea**: Search for possibility exploitable flaws in a program by running the program under a variety of inputs

• **Challenge**: Selecting input values for the program
  ‣ What should be the goals in choosing input values for dynamic analysis?
    ‣ *Find all exploitable flaws*
    ‣ *With the fewest possible input values*

• How should these goals impact input choices?
Black Box Fuzzing

• Like Miller – Feed the program random inputs and see if it crashes

• **Pros**: Easy to configure

• **Cons**: May not search efficiently
  ‣ May re-run the same path over again (low coverage)
  ‣ May be very hard to generate inputs for certain paths (checksums, hashes, restrictive conditions)
  ‣ May cause the program to terminate for logical reasons – fail format checks and stop
Black Box Fuzzing

• Example

```c
function( char *name, char *passwd, char *buf )
{
    if ( authenticate_user( name, passwd ) ) {
        if ( check_format( buf ) ) {
            update( buf );
        }
    }
}
```
Mutation-Based Fuzzing

• Supply a well-formed input
  ‣ Generate random changes to that input

• No assumptions about input
  ‣ Only assumes that variants of well-formed input may problematic

• Example: zzuf
  ‣ Reading: The Fuzzing Project Tutorial
Mutation-Based Fuzzing

• Example: zzuf
  ‣ http://sam.zoy.org/zzuf/

• The Fuzzing Project Tutorial
  ‣ zzuf -s 0:1000000 -c -C 0 -q -T 3 objdump -x win9x.exe
  ‣ Fuzzes the program objdump using the sample input win9x.exe
  ‣ Try 1M seed values (-s) from command line (-c) and keep running if crashed (-C 0) with timeout (-T 3)
Mutation-Based Fuzzing

• Easy to setup, and not dependent on program details
• But may be strongly biased by the initial input
• Still prone to some problems
  ‣ May re-run the same path over again (same test)
  ‣ May be very hard to generate inputs for certain paths (checksums, hashes, restrictive conditions)
Generation-Based Fuzzing

• Generational fuzzer generate inputs “from scratch” rather than using an initial input and mutating

• However, to overcome problems of naïve fuzzers they often need a format or protocol spec to start

• Examples include
  › SPIKE, Peach Fuzz

• However format-aware fuzzing is cumbersome, because you'll need a fuzzer specification for every input format you are fuzzing
Generation-Based Fuzzing

• Can be more accurate, but at a cost
  • **Pros**: More complete search
    ‣ Values more specific to the program operation
    ‣ Can account for dependencies between inputs
  • **Cons**: More work
    ‣ Get the specification
    ‣ Write the generator – ad hoc
• Need to do for each program
Grey Box Fuzzing

- Rather than treating the program as a black box, instrument the program to track the paths run
- Save inputs that lead to new paths
  - Associated with the paths they exercise
- Example
  - American Fuzzy Lop (AFL)
- “State of the practice” at this time
AFL

- Provides compiler wrappers for gcc to instrument target program to collect fuzzing stats

- http://lcamtuf.coredump.cx/afl/
AFL Display

• Tracks the execution of the fuzzer

![AFL Display Image]

• Key information are
  ▸ “total paths” – number of different execution paths tried
  ▸ “unique crashes” – number of unique crash locations
AFL Output

• Shows the results of the fuzzer
  ‣ E.g., provides inputs that will cause the crash
• File “fuzzer_stats” provides summary of stats – UI
• File “plot_data” shows the progress of fuzzer
• Directory “queue” shows inputs that led to paths
• Directory “crashes” contains input that caused crash
• Directory “hangs” contains input that caused hang
AFL Operation

• How does AFL work?
  ‣ http://lcamtuf.coredump.cx/afl/technical_details.txt

• The instrumentation captures branch (edge) coverage, along with coarse branch-taken hit counts.
  ‣ cur_location = <COMPILE_TIME_RANDOM>;
  ‣ shared_mem[cur_location ^ prev_location]++;
  ‣ prev_location = cur_location >> 1;

• Record branches taken with low collision rate

• Enables distinguishing unique paths
AFL Operation

- How does AFL work?
  - [http://lcamtuf.coredump.cx/afl/technical_details.txt](http://lcamtuf.coredump.cx/afl/technical_details.txt)

- When a mutated input produces an execution trace containing new tuples, the corresponding input file is preserved and routed for additional processing
  - Otherwise, input is discarded

- Mutated test cases that produced new state transitions are added to the input queue and used as a starting point for future rounds of fuzzing
AFL Operation

• How does AFL work?
  ‣ [Link](http://lcamtuf.coredump.cx/afl/technical_details.txt)

• Fuzzing strategies
  ‣ Highly deterministic at first – bit flips, add/sub integer values, and choose interesting integer values
  ‣ Then, non-deterministic choices – insertions, deletions, and combinations of test cases
Grey Box Fuzzing

• Finds flaws, but still does not understand the program

• **Pros**: Much better than black box testing
  ‣ Essentially no configuration
  ‣ Lots of crashes have been identified

• **Cons**: Still a bit of a stab in the dark
  ‣ May not be able to execute some paths
  ‣ Searches for inputs independently from the program

• Need to improve the effectiveness further
White Box Fuzzing

• Combines test generation with fuzzing
  ‣ Test generation based on static analysis and/or symbolic execution
  ‣ Rather than generating new inputs and hoping that they enable a new path to be executed, compute inputs that will execute a desired path
    • And use them as fuzzing inputs

• Goal: Given a sequential program with a set of input parameters, generate a set of inputs that maximizes code coverage
Helping Fuzzing

• One problem in fuzzing is to generate inputs to cover all paths
  ‣ Can symbolic execution help with this?
  ‣ Driller: Augmenting Fuzzing through Symbolic Execution
    • Slides from Nick Stephens at NDSS 2016
x = int(input())
if x > 10:
    if x < 100:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"

Let's fuzz it!

1 ⇒ "You lose!"
593 ⇒ "You lose!"
183 ⇒ "You lose!"
4 ⇒ "You lose!"
498 ⇒ "You lose!"
48 ⇒ "You win!"
x = int(input())
if x > 10:
    if x^2 == 152399025:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"

Let's fuzz it!

1 ⇒ "You lose!"
593 ⇒ "You lose!"
183 ⇒ "You lose!"
4 ⇒ "You lose!"
498 ⇒ "You lose!"
42 ⇒ "You lose!"
3 ⇒ "You lose!"
......
57 ⇒ "You lose!"
```python
x = input()
if x >= 10:
    if x % 1337 == 0:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```
x = input()
if x >= 10:
    if x % 1337 == 0:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"

1337
Different Approaches

Fuzzing
- Good at finding solutions for general conditions
- Bad at finding solutions for specific conditions

Symbolic Execution
- Good at finding solutions for specific conditions
- Spends too much time iterating over general conditions
Fuzzing vs. Symbolic Exec

```python
x = input()

def recurse(x, depth):
    if depth == 2000:
        return 0
    else:
        r = 0;
        if x[depth] == "B":
            r = 1
        return r + recurse(x[depth], depth)

if recurse(x, 0) == 1:
    print "You win!"
```

```python
x = int(input())
if x >= 10:
    if x^2 == 152399025:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```

Fuzzing Wins

Symbolic Execution Wins
Combining the Two

Control Flow Graph

Test Cases
Combining the Two

“Cheap” fuzzing coverage

Control Flow Graph

Test Cases

“X”

“Y”
Combining the Two

“Cheap” fuzzing coverage

Tracing via Symbolic Execution

Control Flow Graph

Reachable?

Test Cases

“X”

“Y”
Combining the Two

“Cheap” fuzzing coverage

Tracing via Symbolic Execution

New test cases generated

Synthesized!

Test Cases

“X”

“Y”

“MAGIC”

Control Flow Graph
Combining the Two

“Cheap” fuzzing coverage

Tracing via Symbolic Execution

New test cases generated

Towards completer code coverage!

Test Cases

“X”

“Y”

“MAGIC”

“MAGICY”

Control Flow Graph
Combining the Two

“Cheap” fuzzing coverage

Tracing via Symbolic Execution

New test cases generated

Towards complete code coverage!

Test Cases

“X”

“Y”

“MAGIC”

“MAGICY”

Control Flow Graph
Take Away

• Goal is to detect vulnerabilities in our programs before adversaries exploit them

• One approach is dynamic testing of the program
  ‣ Fuzz testing aims to achieve good program coverage with little effort for the programmer
  ‣ Challenge is to generate the right inputs

• Black box (Mutational and generation), Grey box, and White box approaches are being investigated
  ‣ AFL (Grey box) is now commonly used