Software Security

Fuzzing (continued)

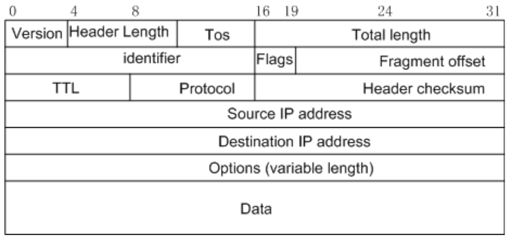
Erik Poll

Radboud Universiteit Nijmegen

Last week

1. Totally dumb fuzzing - generate random (long) inputs
2. Mutation-based - apply random mutations to valid inputs
   - Eg OCPP
   - Tools: Radamsa, zzuf, ...
3. Generation-based aka grammar-based
   - Eg GSM
   - Pro: can reach ‘deeper’ bugs than 1 & 2 ☺
   - Con: but lots of work to construct fuzzer or grammar ☹
   - Tools: Boofuzz, SNOOZE, SPIKE, Peach, Sulley, antiparser, Netzob, ..

Less shallow



This week: more advanced forms of fuzzing

1. Basic fuzzing with random/long inputs
2. 'Dumb' mutational fuzzing

   example: OCPP
3. Generational fuzzing aka grammar-based fuzzing

   example: GSM
4. Whitebox fuzzing with SAGE

   using symbolic execution
5. Code-coverage guided evolutionary fuzzing with `afl`

   aka grey box fuzzing or 'smart' mutational fuzzing

Whitebox fuzzing with SAGE

Whitebox fuzzing using symbolic execution

- **The central problem with fuzzing: how can we generate inputs that trigger interesting code executions?**

  Eg fuzzing the procedure below is unlikely to hit the error case

```
int foo(int x) {
    y = x+3;
    if (y==13) abort(); // error
}
```

- **The idea behind whitebox fuzzing: if we know the code, then by analysing the code we can find interesting input values to try.**

- **SAGE from Microsoft Research that uses symbolic execution of x86 binaries to generate test cases.**

```
m(int x,y){
    x = x + y;
    y = y - x;
    if (2*y > 8) { ...
                 }
    else if (3*x < 10){ ...
                      }
    }
```

Can you provide values for `x` *and* `y` *that will trigger execution of the two if-branches?*

Symbolic execution

```
m(int x,y){
   x = x + y;
   y = y – x;
   if (2*y > 8) { ...
                }
   else if (3*x < 10){ ...
   }                       }
```

Suppose `x` *=* *N* *and* `y` *=* *M.*

`x` *becomes* *N+M*

`y` *becomes* *M - (N+M) = -N*

if-branch taken if $2 * -N > 8$, *i.e.* $N < -4$

Aka the path condition

2nd if-branch taken if
$N \geq -4$ *AND* $3 * (M+N) < 10$

Given a set of constraints, an SMT solver (Yikes, Z3, ...) produces values that satisfy it, or proves that it are not satisfiable.

This generates test data (i) *automatically* and (ii) *with good coverage*

- **SMT solvers can also be used for static analyses as in PREfast, or more generally, for program verification**

Symbolic execution for test generation

- Symbolic execution can be used to automatically generate test cases with good coverage
- Basic idea instead of giving variables concrete values (say `42`), variables are given symbolic values (say α or N), and program is executed with these symbolic values to see when certain program points are reached
- *Downsides of symbolic execution?*
  - Very expensive (in time & space)
  - Things explode if there are loops or recursion, or if you make heavy use of the heap
  - You cannot pass symbolic values as input to some APIs, system calls, I/O peripherals, ...

SAGE mitigates these by using a *single concrete execution* to obtain *symbolic constraints* to generate *many* test inputs for *many* execution paths

SAGE example

Example program

```
void top(char input[4]) {
    int cnt = 0;
    if (input[0] == 'b') cnt++;
    if (input[1] == 'a') cnt++;
    if (input[2] == 'd') cnt++;
    if (input[3] == '!') cnt++;
    if (cnt >= 3) crash();
}
```

What would be interesting test cases?

Do you think a fuzzer could find them?

How could you find them?

SAGE example

Example program

```
void top(char input[4]) {
    int cnt = 0;
    if (input[0] == 'b') cnt++;
    if (input[1] == 'a') cnt++;
    if (input[2] == 'd') cnt++;
    if (input[3] == '!') cnt++;
    if (cnt >= 3) crash();
}
```

path contraints:

$i_0 \neq$ 'b'

$i_1 \neq$ 'a'

$i_2 \neq$ 'd'

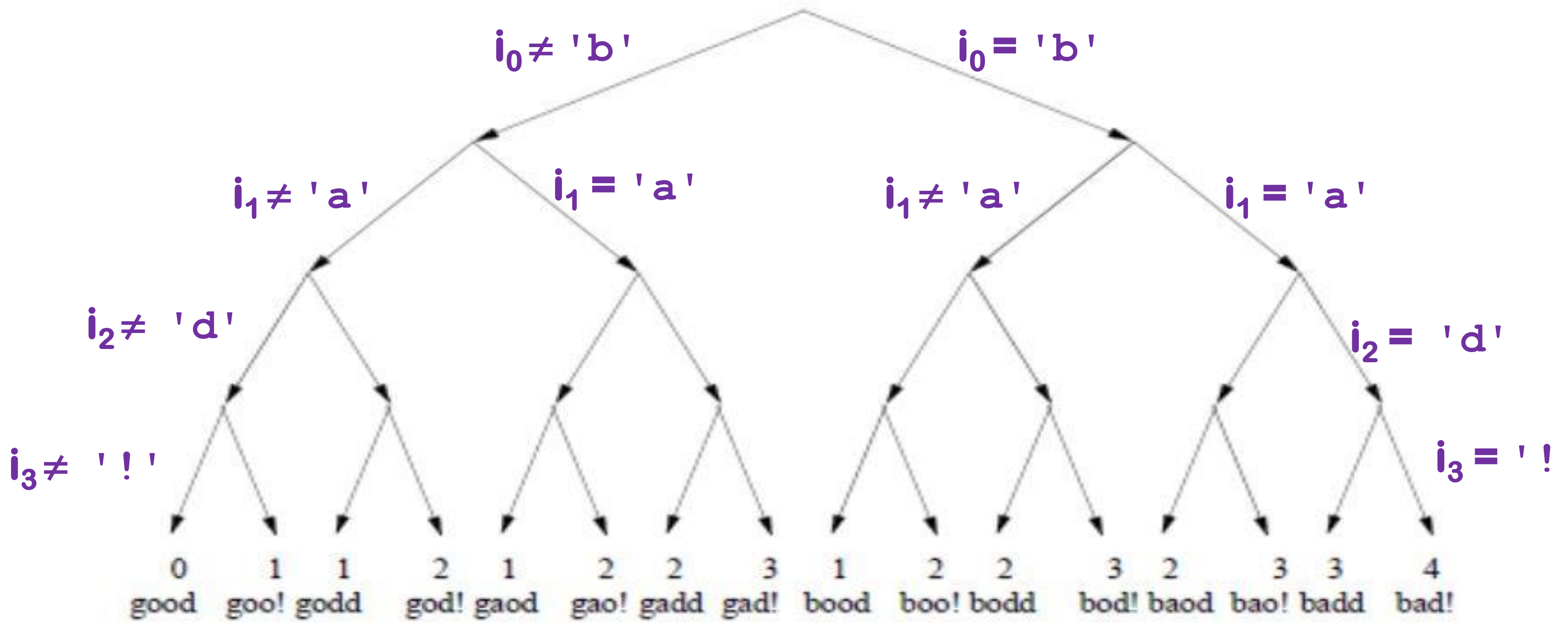
$i_3 \neq$ '!'

SAGE executes the code for some concrete `input`, say `'good'`

It then collects *path constraints* for an arbitrary symbolic input of the form $i_0i_1i_2i_3$

Search space for interesting inputs

Based on this *one* execution, combining the 4 constraints found & their negations, yields $2^4 = 16$ test cases



Note: the initial execution with the input 'good' was not very interesting, but some of these others are

SAGE success

SAGE was very successful at uncovering security bugs, eg

Microsoft Security Bulletin MS07-017 aka CVE-2007-0038: Critical

Vulnerabilities in GDI Could Allow Remote Code Execution

Stack-based buffer overflow in the animated cursor code in Windows ... allows remote attackers to execute arbitrary code ... via a large length value in the second (or later) `anih` block of a RIFF .ANI, cur, or .ico file, which results in memory corruption when processing cursors, animated cursors, and icons

Root cause: vulnerablity in PARSING of RIFF .ANI, cur, and ico-formats.

NB SAGE automatically generates inputs triggering this bug *without* knowing these formats

[Godefroid et al., *SAGE: Whitebox Fuzzing for Security Testing*, ACM Queue 2012]

[Patrice Godefroid, *Fuzzing: Hack, Art, and Science*, Communications of the ACM, 2020]

Coverage-guided evolutionary fuzzing with `afl`

(American Fuzzy Lop)

Evolutionary Fuzzing

Use evolution:

- try random input mutations, and
- observe the effect on some form of coverage, and
- let only the interesting mutations evolve further
  - where "interesting" = resulting in 'new' execution paths

Aka coverage-guided evolutionary greybox fuzzing,

but terminology is a bit messy/non-standard

alf: observing jumps to find interesting inputs/input changes

input

code

line	instruction
1	**JMP 6**
2	..
3	..
4	..
5	**JZ (Jump If Zero) 7**
6	..
7	*arraycopy (dst, input[i..j]);*
8	
9	..
10	**JCXZ 2**
11	..
12	..
13	*println (part of input);*
14	..
15	**JNE 103131**
16	..
17	

afl bitmap `shared_mem`

	1	2	3	4	5	6	7	8	9	10	11	12
1						☑[1]						
2												
3												
4												
5							☑[3]					
6												
7												
8												
9												
10		☑[2]										
11												
12												
13												
14												
15												

afl [http://lcamtuf.coredump.cx/afl]

- Code instrumented to observe execution paths:
  - if source code is available, by using modified compiler
  - if source code is not available, by running code in an emulator
- Code coverage represented as a 64KB bitmap:
  each control flow jumps is mapped to a change in this bitmap
  - different executions could result in same bitmap, but chance is small
- Mutation strategies include: bit flips, incrementing/decrementing integers, using pre-defined interesting values (eg. 0, -1, MAX_INT,....) or user-supplied dictionary, deleting/combining/zeroing input blocks, ...
- The fuzzer forks the SUT to speed up the fuzzing
- Big win: no need to specify the input format, but still good coverage

afl's instrumentation of compiled code

Code is injected at every branch point in the code

```
cur_location = <SOME_RANDOM_NUMBER_FOR_THIS_CODE_BLOCK>;
shared_mem[cur_location ^ prev_location]++;
prev_location = cur_location >> 1;
```

where `shared_mem` is a 64 KB memory region

Intuition: for every jump from L_1 to L_2 a different byte in `shared_mem` is changed (increased).

Which byte is determined by random values chosen at compile time inserted at source and destination of every jump

```
                 american fuzzy lop 2.52b (dnsmasq)

┌─ process timing ─────────────────────────────────────┬─ overall results ─────┐
│        run time : 0 days, 20 hrs, 31 min, 27 sec      │  cycles done : 3      │
│   last new path : 0 days, 0 hrs, 48 min, 28 sec       │  total paths : 3409   │
│ last uniq crash : 0 days, 2 hrs, 22 min, 39 sec       │ uniq crashes : 12     │
│  last uniq hang : none seen yet                       │   uniq hangs : 0      │
├─ cycle progress ────────────────────┬─ map coverage ─┴───────────────────────┤
│  now processing : 3138* (92.05%)    │    map density : 0.34% / 4.51%         │
│ paths timed out : 0 (0.00%)         │ count coverage : 2.92 bits/tuple       │
├─ stage progress ────────────────────┼─ findings in depth ────────────────────┤
│  now trying : user extras (insert)  │ favored paths : 686 (20.12%)           │
│ stage execs : 509k/1.38M (36.79%)   │  new edges on : 1022 (29.98%)          │
│ total execs : 29.4M                 │ total crashes : 363 (12 unique)        │
│  exec speed : 464.9/sec             │  total tmouts : 54 (18 unique)         │
├─ fuzzing strategy yields ───────────┴───────────────┬─ path geometry ────────┤
│   bit flips : 151/1.22M, 104/1.22M, 47/1.22M         │    levels : 17         │
│  byte flips : 0/152k, 2/61.4k, 4/59.8k               │   pending : 2326       │
│ arithmetics : 133/3.47M, 0/1.04M, 0/286k             │  pend fav : 7          │
│  known ints : 32/264k, 29/1.62M, 10/2.55M            │ own finds : 1887       │
│  dictionary : 103/2.43M, 48/5.49M, 176/1.58M         │  imported : n/a        │
│       havoc : 1060/6.14M, 0/0                        │ stability : 100.00%    │
│        trim : 40.91%/56.3k, 58.16%                   ├────────────────────────┘
^C────────────────────────────────────────────────────┘          [cpu000:150%]

+++ Testing aborted by user +++
[+] We're done here. Have a nice day!
```

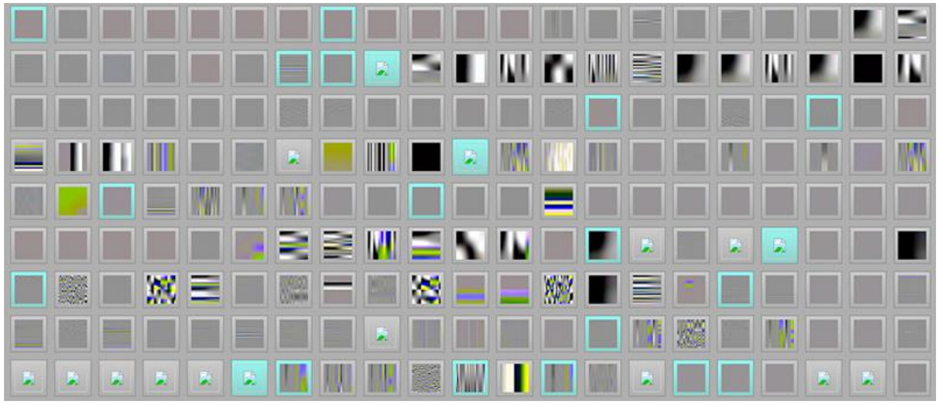
Cool example: learning the JPG file format

Fuzzing a program that expects a JPG as input, starting with 'hello world' as initial test input, afl can learn to produce legal JPG files

along the way producing/discovering error messages such as

- `Not a JPEG file: starts with 0x68 0x65`
- `Not a JPEG file: starts with 0xff 0x65`
- `Premature end of JPEG file`
- `Invalid JPEG file structure: two SOI markers`
- `Quantization table 0x0e was not defined`

and then JPGs like

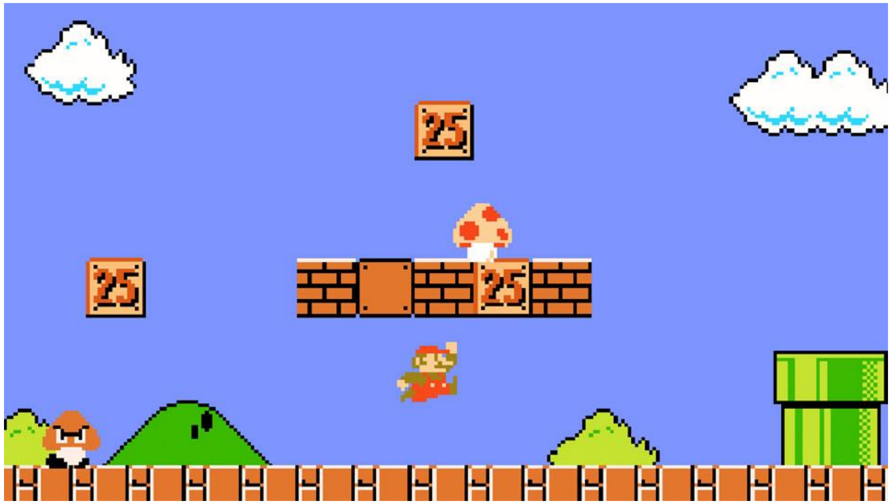


[Source http://lcamtuf.blogspot.nl/2014/11/pulling-jpegs-out-of-thin-air.html]

Other strategies in evolutionary fuzzing

Instead of maximizing path/code coverage, we can also let inputs evolve to maximize some other variable or property

- **Code may need to instrumented to let fuzzer observe that property**



Eg the x-coordinate of Super Mario

[Aschermann et al., *IJON: Exploring Deep State Spaces via Fuzzing,* IEEE S&P 2020]

https://www.youtube.com/watch?v=3PyhXlHDkNI

Conclusions

- Fuzzing is great technique to find (a certain class of) security flaws!
- If you ever write or use C(++) code, you should fuzz it.
- Challenge: getting good coverage fuzzing without too much effort

  Successful approaches include

  – White-box fuzzing based on symbolic execution with SAGE
  – Evolutionary fuzzing aka coverage guided greybox fuzzing with `afl`
- *Does fuzzing makes sense for code in other programming languages?*

  Yes, even if the kind of bugs found may have lower security impact.
- A more ambitious generation of tools not only tries to find security flaws, but also to then build exploits, eg. `angr`

To read (see links on the course page)

- Michal Zawleski, technical white paper for afl
- Patrice Godefroid, *Fuzzing: Hack, Art, and Science*, CACM 2020

Fuzzing web-applications

- *How could a fuzzer detect SQL injections or XSS weaknesses?*
  - For SQL injection: monitor database for error messages
  - For XSS, see if the website echoes HTML tags in user input
- There are various tools to fuzz web-applications: Spike proxy, HP Webinspect, AppScan, WebScarab, Wapiti, w3af, RFuzz, WSFuzzer, SPI Fuzzer Burp, Mutilidae, ...
- Some fuzzers crawl a website, generating traffic themselves, other fuzzers modify traffic generated by some other means.
- *Can we expect false positives/negatives?*
  - false negatives due to test cases not hitting the vulnerable cases
  - false positives & negatives due to incorrect test oracle, eg
    - for SQL injection: not recognizing some SQL database errors (false neg)
    - for XSS: signaling quoted echoed response as XSS (false pos)