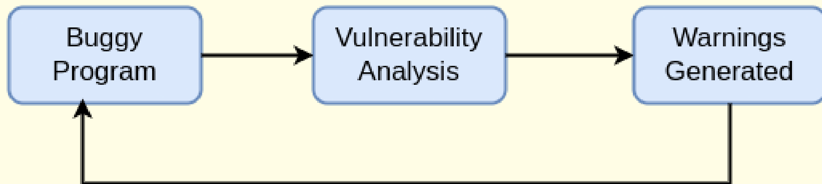
Static and Dynamic Analysis for Vulnerability Detection

Fall 2024

R. Sekar

Vulnerability Analysis

- Programmer checks the program and corrects errors
- Cycle repeated until all relevant bugs are fixed



Terminology

- False Positives: A warning or error is generated, but there is no real vulnerability
- False Negatives: A vulnerability exists, but it is not identified by the analysis
- Complete: A technique guaranteed to be free of false positives
- Sound: A technique guaranteed to detect all vulnerabilities (i.e., no false negatives).
- Note: A technique cannot be both sound and complete since most program properties are undecidable.
- Useful bug-finding tools suffer from both FNs and FPs

Benefits and Drawbacks

- Benefits
  - Does not rely on bugs being exercised: fix the bug before it strikes you.
  - No runtime overhead
  - Leverage programmer knowledge
- Drawbacks
  - Not applicable for operator use
    - May not have source code access
    - May not be able to understand the logic of the program
  - Suffers from false positives
    - A programmer can cope with these, but not an operator

Vulnerability Analysis Techniques

- Static analysis
  - Performed before a program starts execution
  - Works mainly on source code
    - Binary static analysis techniques are rather limited
  - Not very effective in practice, so we won't discuss in depth
- Dynamic analysis
  - Analysis performed by executing the program
  - Key challenge: How to generate input for execution?
  - Two main approaches to overcome challenge
    - Fuzzing: random, black-box testing (primarily)
    - Symbolic execution: systematic technique for generating inputs that exercise "interesting program paths"
    - More of a white-box approach.

Black-Box Fuzzing

Input: initial test suite *TestSuite*

Output: bug triggering inputs *Crashers*

Mutations (helper function)

Input: test input *t*

Output: new test inputs with some bits flipped in *t*

```
while TestSuite not empty:
    t = PickFrom(TestSuite)
    for each m in Mutations(t):
        RunAndCheck(m)
        if Crashes(m):
            add m to Crashers
```

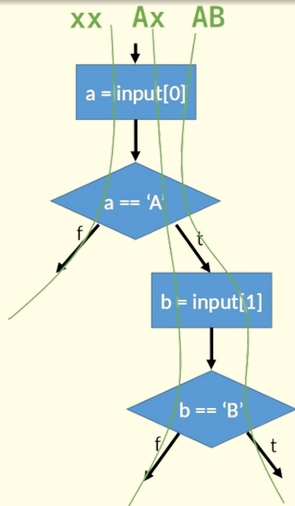
Drawbacks:- A successful mutation does not help subsequent search in any way.

Coverage guided fuzzing

Input: initial test suite *TestSuite*

Output: bug triggering inputs *Crashers*

```
while TestSuite not empty:
    t = PickFrom(TestSuite)
    for each m in Mutations(t):
        RunAndCheck(m)
        if Crashes(m):
            add m to Crashers
        if NewCoverage(m):
            add m to TestSuite
```



Note: A successful mutation feeds into other mutations.

[0] *AFL Fuzzer* by Zalewski '14

Coverage Metrics

- Statement Coverage
  - A statement is covered by a test input if it is executed at least once by the program when processing that input
- Edge (or branch) coverage
  - An edge is covered by a test input if it is taken at least once when processing that input
- Counted coverage
  - Takes into account the number of times a statement (or edge) is executed.
  - Variant: Use log(count) instead of the exact count.

Coverage Metrics

- Path coverage
  - Similar, but applies to a full execution path.
  - Note: The number of possible execution paths can be extremely large, or even infinite, so it is not commonly used.

Coverage Metrics

```
void path_explosion(char *input) {
    int count = 0;
    for (int i = 0; i < 100; i++) {
        if (input[i] == 'A') {
            count++;
}}}
```

Coverage metric

```
int walk_maze(char *steps) {
  int x, y; // Player position.
  for (int i = 0; i < ITERS; i++) {
    switch (steps[i]) {
      case 'U': y--; break;
      case 'D': y++; break;
      case 'L': x--; break;
      case 'R': x++; break;
    default: lose(); // Wrong command, lose.
    }
    if (maze[y][x] == '#') win();  // found treasure!
    if (maze[y][x] != ' ') lose(); // crashed into
        wall
  }
}
```

```
Player position:
(1,4)
Iteration no.: 3
Action: D
+-+---+---+
|X|     |#|
|X| --+ | |
|X|   | | |
|X+-- | | |
|     |   |
+-----+---+
```

AFL - State-of-the-art fuzzing

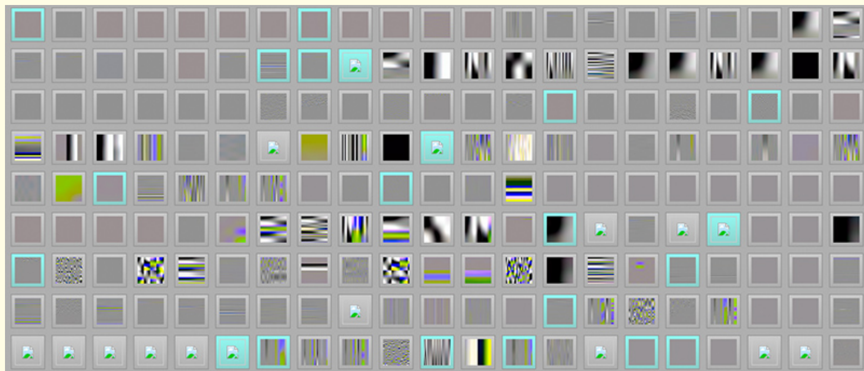
```
                    american fuzzy lop 0.47b (readpng)

- process timing -------------------------------------- overall results -
        run time : 0 days, 0 hrs, 4 min, 43 sec       cycles done : 0
   last new path : 0 days, 0 hrs, 0 min, 26 sec       total paths : 195
 last uniq crash : none seen yet                      uniq crashes : 0
  last uniq hang : 0 days, 0 hrs, 1 min, 51 sec        uniq hangs : 1
- cycle progress ---------------------- map coverage ---------------------
  now processing : 38 (19.49%)            map density : 1217 (7.43%)
 paths timed out : 0 (0.00%)           count coverage : 2.55 bits/tuple
- stage progress ---------------------- findings in depth ----------------
  now trying : interest 32/8           favored paths : 128 (65.64%)
 stage execs : 0/9990 (0.00%)           new edges on : 85 (43.59%)
 total execs : 654k                    total crashes : 0 (0 unique)
  exec speed : 2306/sec                  total hangs : 1 (1 unique)
- fuzzing strategy yields ------------------------- path geometry --------
   bit flips : 88/14.4k, 6/14.4k, 6/14.4k           levels : 3
  byte flips : 0/1804, 0/1786, 1/1750              pending : 178
 arithmetics : 31/126k, 3/45.6k, 1/17.8k          pend fav : 114
  known ints : 1/15.8k, 4/65.8k, 6/78.2k          imported : 0
       havoc : 34/254k, 0/0                       variable : 0
        trim : 2876 B/931 (61.45% gain)             latent : 0
```

Bugs Found by AFL

IJG jpeg [1]
libjpeg-turbo [1 2]
libpng [1]
libtiff [1 2 3 4 5]
PHP [1 2 3 4 5 6 7 8]
Firefox [1 2 3 4]
Explorer [1 2 3 4]
Apple Safari [1]
Adobe Flash [1 2 3 4 5 6 7]
sqlite [1 2 3 4]
OpenSSL [1 2 3 4 5 6 7]
LibreOffice [1 2 3 4]
poppler [1 2]
freetype [1 2]
GnuTLS [1]
GnuPG [1 2 3 4]
OpenSSH [1 2 3 4]
Oracle BerkeleyDB [1 2]
Android/libstage [1 2]
iOS / ImageIO [1]
FLAC audio library [1 2]
libsndfile [1 2 3 4]
less / lesspipe [1 2 3]
strings [1 2 3 4 5 6 7]
file [1 2 3 4]
dpkg [1 2] rcs [1]
systemd-resolved [1 2]
libyaml [1]
Info-Zip unzip [1 2]
libtasn1 [1 2]
OpenBSD pfctl [1]
NetBSD bpf [1]
mandoc [1 2 3 4 5]
clamav [1 2 3 4 5 6]
libxml2 [1 2 4 5 6 7 8 9]
glibc [1]
clang / llvm [1 2 3 4 5 6 7 8]
nasm [1 2]
ctags [1]
mutt [1]
procmail [1]
fontconfig [1]
pdksh [1 2]
Qt [1 2]
wavpack [1 2 3 4]
redis / lua-cmsgpack [1]
taglib [1 2 3]
privoxy [1 2 3]
perl [1 2 3 4 5 6 7...]
radare2 [1 2]
SleuthKit [1]
X.Org [1 2]
exifprobe [1]
capnproto [1]
Xerces-C [1 2 3]
metacam [1]
djvulibre [1]
exiv [1 2]
Linux btrfs [1 2 3 4 6 7 8]
Knot DNS [1]
curl [1 2 3]
wpa_supplicant [1]
dnsmasq [1]
lame [1 2 3 4 5 6]
privoxy [1 2 3]
perl [1 2 3 4 5 6 7...]
MuPDF [1 2 3 4]
imlib2 [1 2 3 4]
libsass [1]
VLC [1 2]
libraw [1]
yara [1 2 3 4]
FreeBSD syscons [1 2 3]
dhcpcd [1]
tmux [1 2]
mbed TLS [1]
Linux netlink [1]
Linux ext4 [1]
Linux xfs [1]
botan [1]
expat [1 2]
Adobe Reader [1]
libav [1]
libical [1]
OpenBSD kernel [1]
collectd [1]
libidn [1 2]
MatrixSSL [1]
jasper [1 2 3 4 5 6 7]
MaraDNS [1]
w3m [1 2 3 4]
Xen [1]
OpenH232 [1]
irssi [1 2 3]
cmark [1]
OpenCV [1]
Malheur [1]
gstreamer [1...]
Tor [1]
gdk-pixbuf [1]
audiofile [1 2 3 4 5 6]
zstd [1]
lz4 [1]
stb [1]
cJSON [1]
libpcre [1 2 3]
MySQL [1]
gnulib [1]
openexr [1]
libmad [1 2]
ettercap [1]
lrzip [1 2 3]
freetds [1...]
Asterisk [1]
ytnef [1 2 3 4]
raptor [1]
mpg123 [1]
Apache httpd [1]
exempi [1 2]
libgmime [1 2 3]
pev [1 2 3 4]
Linux mem mgmt [1]
sleuthkit [1]
Mongoose OS [1]
iOS kernel [1]

JPEGs out of thin air!



Fuzzing: Weaknesses

```
if (input == 0x1badc0de) {
...
}

if (adler32(input) == 0x3eb52a45) {
...
}
```

Dynamic symbolic execution (DSE)

DynamicSymbolicExecution

Input: initial test suite *TestSuite*

Output: bug triggering inputs *Crashers*

```
while TestSuite not empty:
    t = PickFrom(TestSuite)
    for each m in DSENewInputs(t):
        RunAndCheck(m)
        if Crashes(m):
            add m to Crashers
        add m to TestSuite
```

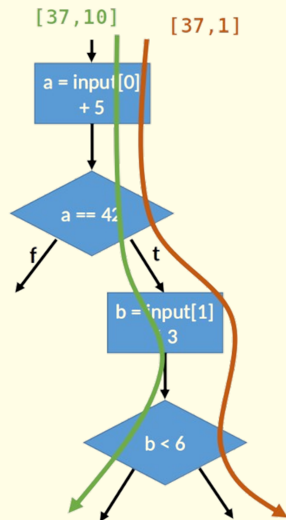
Dynamic symbolic execution

DSENewInputs

Input: test case *t*

Output: new test cases *Children*

```
PC = ExecuteSymbolically(t)
for each condition c in PC:
    NEW_PC = PC[0..i-1] and not c
    new_input = SMTSolve(NEW_PC)
    if new_input != UNSAT:
        add new_input to Children
```



Constraint Solvers(SAT/SMT)

- Complete solvers (most used)
  - Complete = always returns an answer (given enough time)
  - **Backtracking** based algorithm
  - Typically based on Conflict-Driven Clause Learing(CDCL) algorithm
  - e.g., Z3 from Microsoft Research, STP (used by KLEE)
- Incomplete solvers
  - Incomplete = may return "don't know"
  - Trade-off between complexity and the quality of the search
  - Stochastic local search (SLS) based algorithms
  - e.g., SLS-SMT by Frohlich et al. [AAAI'15]
- Note that theoretically complete solvers are indeed incomplete in their practical use, since implementations call the solver, and time out after a specific period.

Fuzzing Vs. DSE

Technique	Replayable	Semantic Insight	Scalability	Crashes
Dynamic Symbolic Execution	Yes	High	Low	16
Veritesting	Yes	High	Medium	11
Dynamic Symbolic Execution + Veritesting	Yes	High	Medium	23
Fuzzing (AFL)	Yes	Low	High	68

"In reality, **fuzzing identified almost three times as many vulnerabilities [as DSE].** *In a sense, this mirrors the recent trends in the security industry:* **symbolic analysis engines** *are criticized as impractical while* **fuzzers** *receive an increasing amount of attention. However, this situation seems at odds with the research directions of recent years, which seem to favor symbolic execution."*

[0] Source:(State of) The Art of War:Offensive Techniques in Binary Analysis

DSE: strength and weaknesses

- Symbolic state maintenance is costly
  - Overhead of executing symbolically can be 1000x [SAGE]
- Constraint solving does not scale well (NP-hard problem)
  - time complexity: complex formulas often time out
- Path condition solved by the solver is not guaranteed to take the targeted path
  - Due to imperfections of the symbolic memory model and environment model
  - Path divergence in 60% of the case [SAGE]
- The probability of a new test case exercising a new path is still much higher than in case of blind fuzzing
- *Tools not user-friendly. Successful use requires a lot of knowledge.*