Static and Dynamic Analysis for Vulnerability Detection

Vulnerability Analysis

Buggy Program

Vulnerability Analysis

Warnings Generated

- **Programmer checks the program, and corrects the 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 being identified by the analysis
- **Complete:** A technique that is guaranteed to be free of false positives
- **Sound:** A technique that is guaranteed to detect all vulnerabilities (i.e., no FNs)
- Note: A technique cannot be sound and complete, since most program properties are undecidable in general.
- *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**
  - 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

BlackBoxFuzzing
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

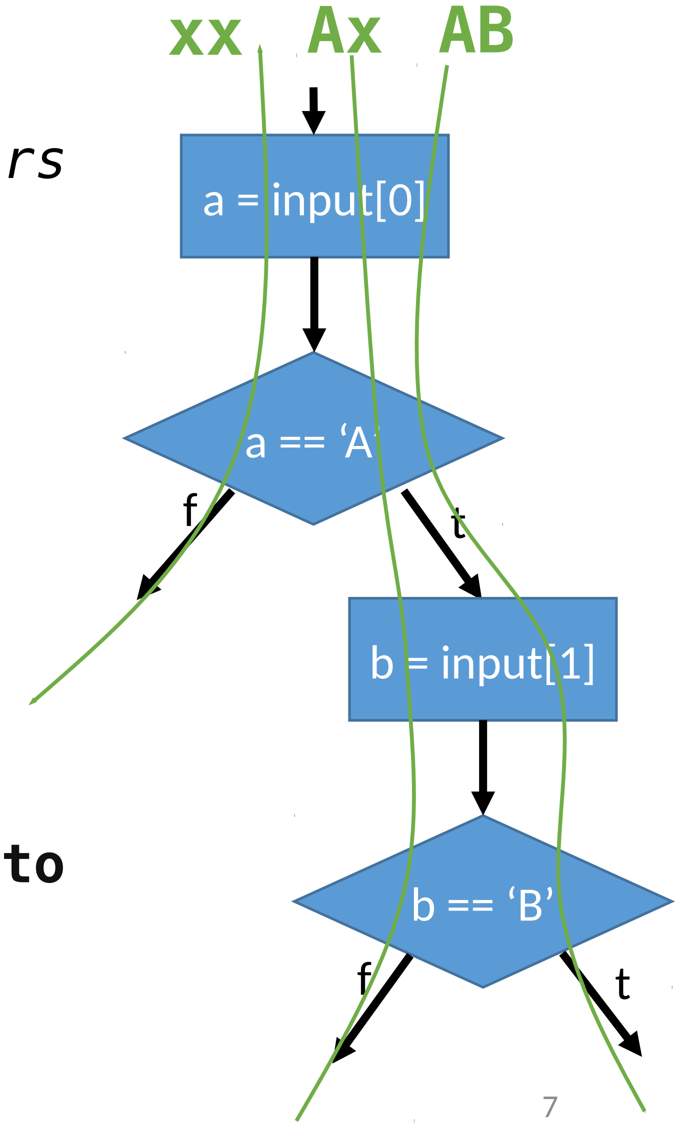
◆ Blind search: a successful mutation does not help subsequent search in any way

Coverage guided fuzzing

```
CoverageGuidedFuzzing
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.



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**
  - Take into account the number of times a statement (or edge) is executed. Variant: use log(count) instead of exact count.
- **Path coverage**
  - Similar, but applies to a full execution path
  - Note: number of possible execution paths can be extremely large, or even be infinite, so it is not used.

Coverage metric

2^{100} paths!

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

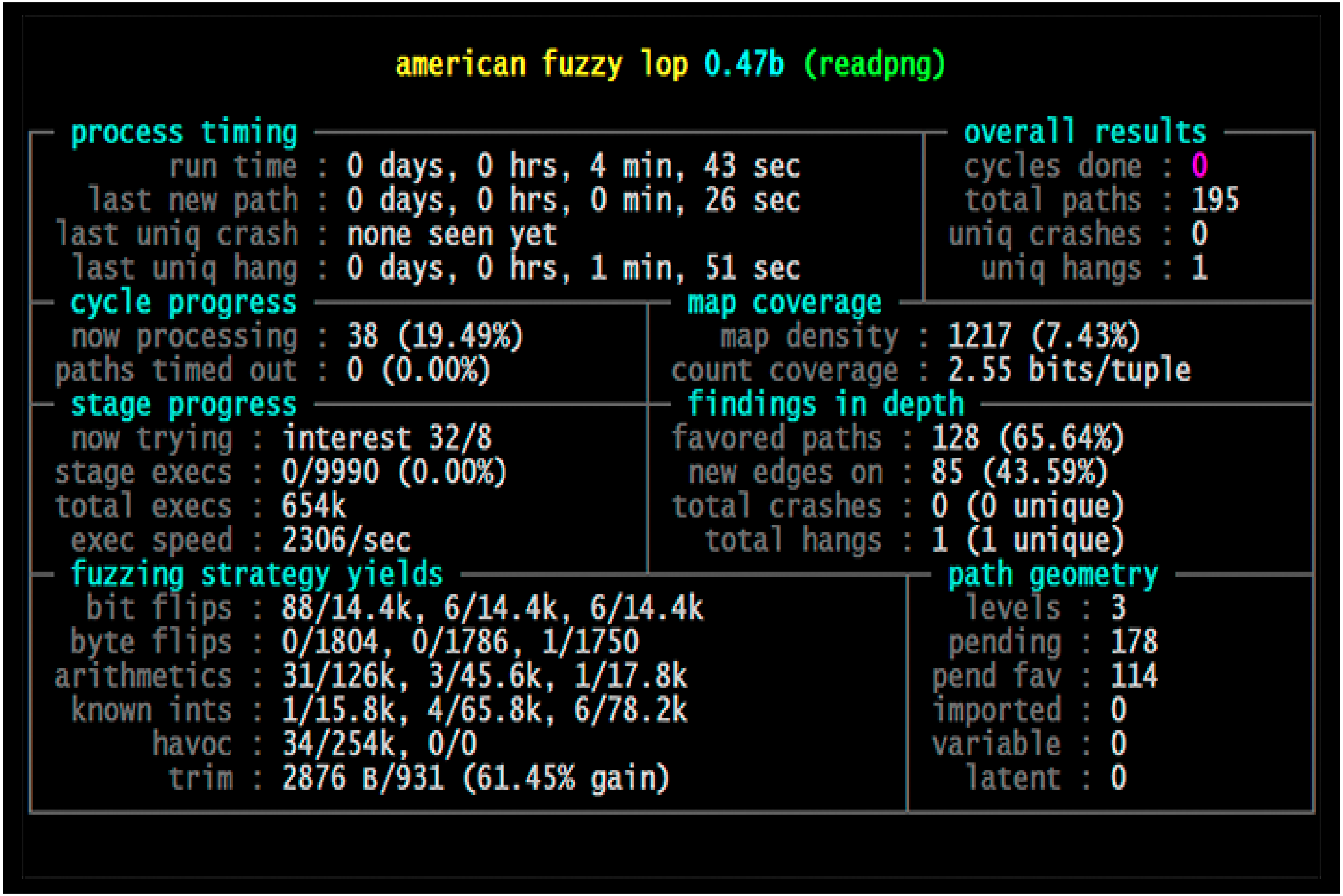
Coverage metric

```c
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: // Wrong command, lose.
  }
  if (maze[y][x] != ' ') // Lose.
  if (maze[y][x] == '#') // Win!
  ...
}
```

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

Winning input: **DDDDRRRRUULUURRRRDDDDRRUUUU**

AFL – state-of-the-art fuzzing



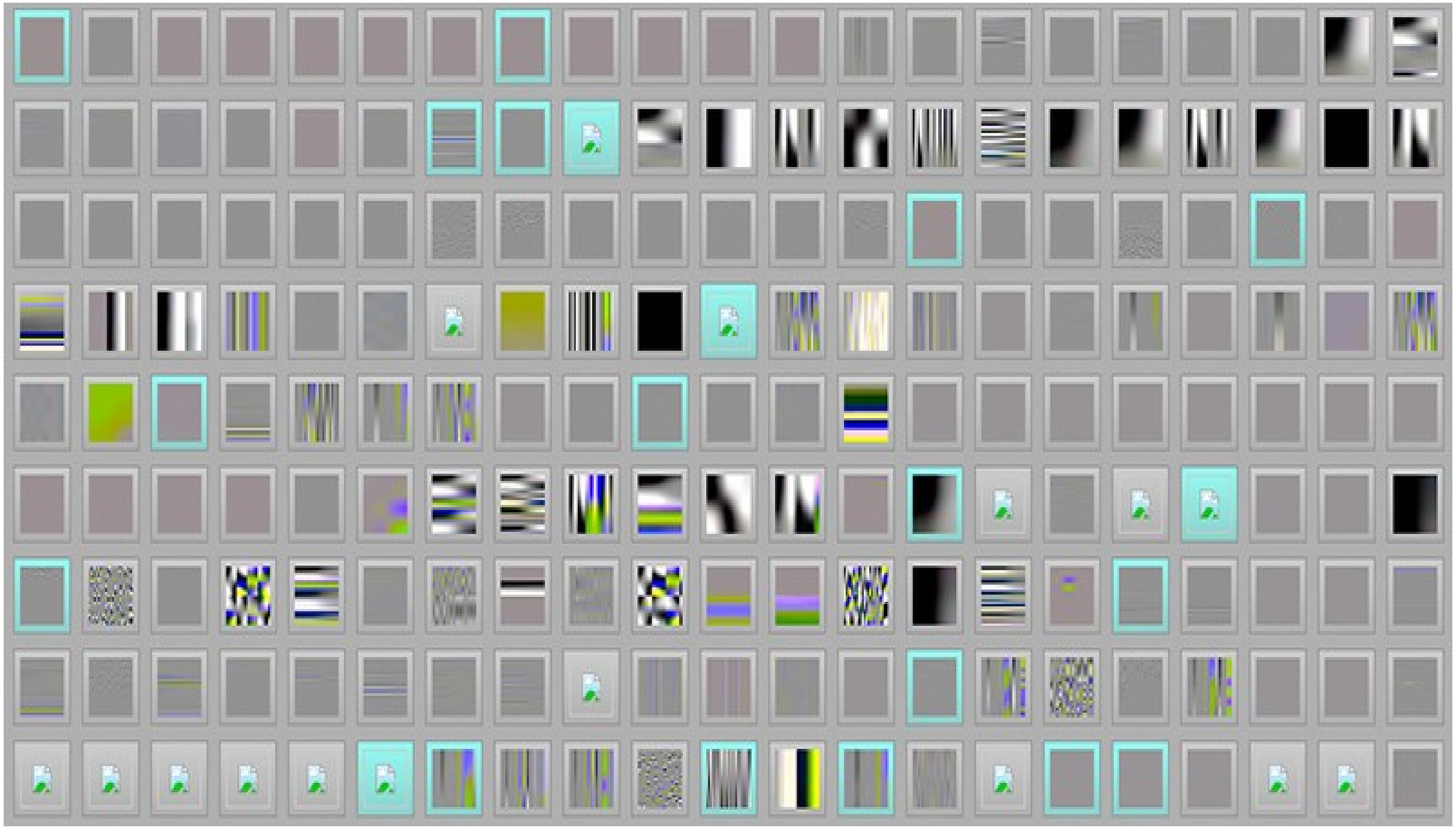
```
                    american fuzzy lop 0.47b (readpng)

┌─ 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], mozjpeg [1], PHP [1, 2, 3, 4, 5], Mozilla Firefox [1, 2, 3, 4], Internet Explorer [1, 2, 3, 4], Apple Safari [1], Adobe Flash / PCRE [1, 2, 3, 4], sqlite [1, 2, 3, 4...], OpenSSL [1, 2, 3, 4, 5, 6, 7], LibreOffice [1, 2, 3, 4], poppler [1], freetype [1, 2], GnuTLS [1], GnuPG [1, 2, 3, 4], OpenSSH [1, 2, 3], PuTTY [1, 2], ntpd [1], nginx [1, 2, 3], bash (post-Shellshock) [1, 2], tcpdump [1, 2, 3, 4, 5, 6, 7, 8, 9], JavaScriptCore [1, 2, 3, 4], pdfium [1, 2], ffmpeg [1, 2, 3, 4, 5], libmatroska [1], libarchive [1, 2, 3, 4, 5, 6, ...], wireshark [1, 2, 3], ImageMagick [1, 2, 3, 4, 5, 6, 7, 8, 9, ...], BIND [1, 2, 3, ...], QEMU [1, 2], lcms [1], Oracle BerkeleyDB [1, 2], Android / libstagefright [1, 2], iOS / ImageIO [1], FLAC audio library [1, 2], libsndfile [1, 2, 3, 4], less / lesspipe [1, 2, 3], strings (+ related tools) [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], man & mandoc [1, 2, 3, 4, 5, ...], IDA Pro [reported by authors], clamav [1, 2, 3, 4, 5], 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], wavpack [1], redis / lua-cmsgpack [1], taglib [1, 2, 3], privoxy [1, 2, 3], perl [1, 2, 3, 4, 5, 6, 7...], libxmp, radare2 [1, 2], SleuthKit [1], fwknop [reported by author], X.Org [1, 2], exifprobe [1], jhead [?], capnproto [1], Xerces-C [1, 2, 3], metacam [1], djvulibre [1], exiv [1], Linux btrfs [1, 2, 3, 4, 6, 7, 8], Knot DNS [1], curl [1, 2], wpa_supplicant [1], libde265 [reported by author], dnsmasq [1], libbpg (1), lame [1], libwmf [1], uudecode [1], MuPDF [1], imlib2 [1], libraw [1], libbson [1], libsass [1], yara [1, 2, 3, 4], W3C tidy-html5 [1], VLC [1], FreeBSD syscons [1, 2, 3], John the Ripper [1, 2], screen [1, 2, 3], tmux [1, 2], mosh [1], UPX [1], indent [1], openjpeg [1], MMIX [1], OpenMPT [1, 2], rxvt [1, 2], dhcpcd [1], Mozilla NSS [1], Nettle [1], 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]

JPEGs out of thin air



Fuzzing: strength and weaknesses

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

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

Dynamic symbolic execution (DSE)

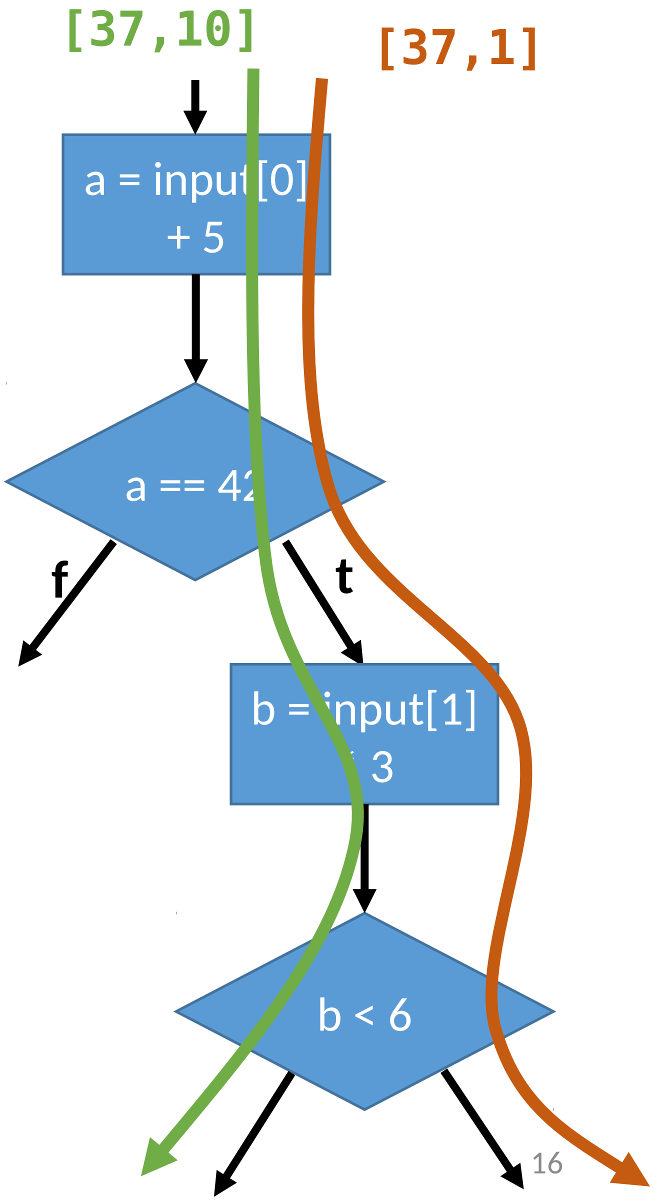
```
DynamicSymbolicExecution
Input:  initial test suite TestSuite
Output: bug triggering inputs Crashers

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
```

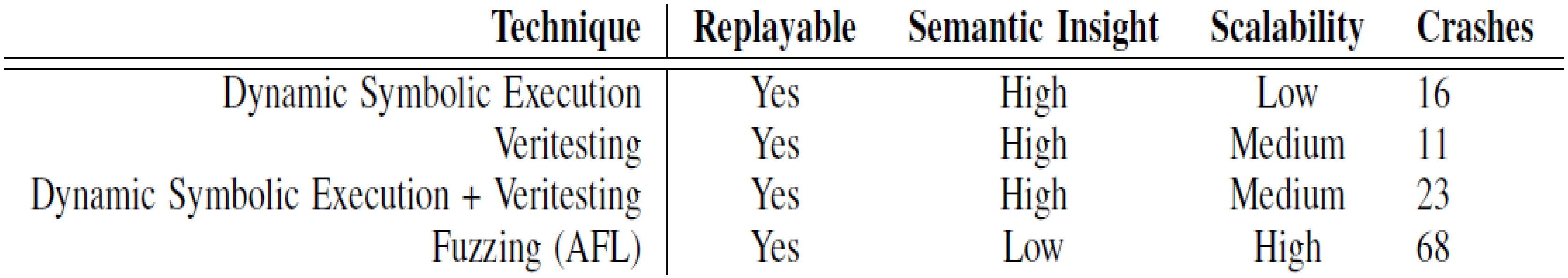


Constraint solvers (SAT/SMT)

- Complete solvers (most used)
  - Complete = always returns an answer (*given enough time*)
  - **Backtracking** based algorithms
  - Typically based on Conflict-Driven Clause Learning (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.”* **ANGR** Study (The Art of War) [Oakland’16]

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