Static and Dynamic Analysis for Vulnerability Detection

Vulnerability Analysis

- 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.

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

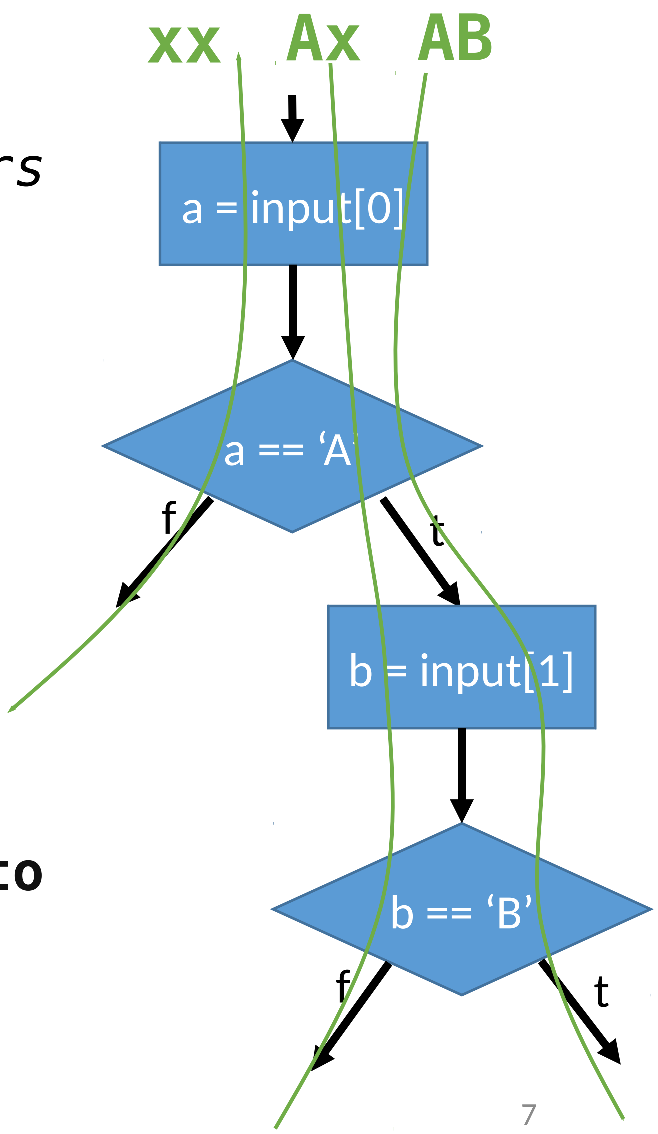
- Blind search: a successful mutation does not help subsequent search in any way

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


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

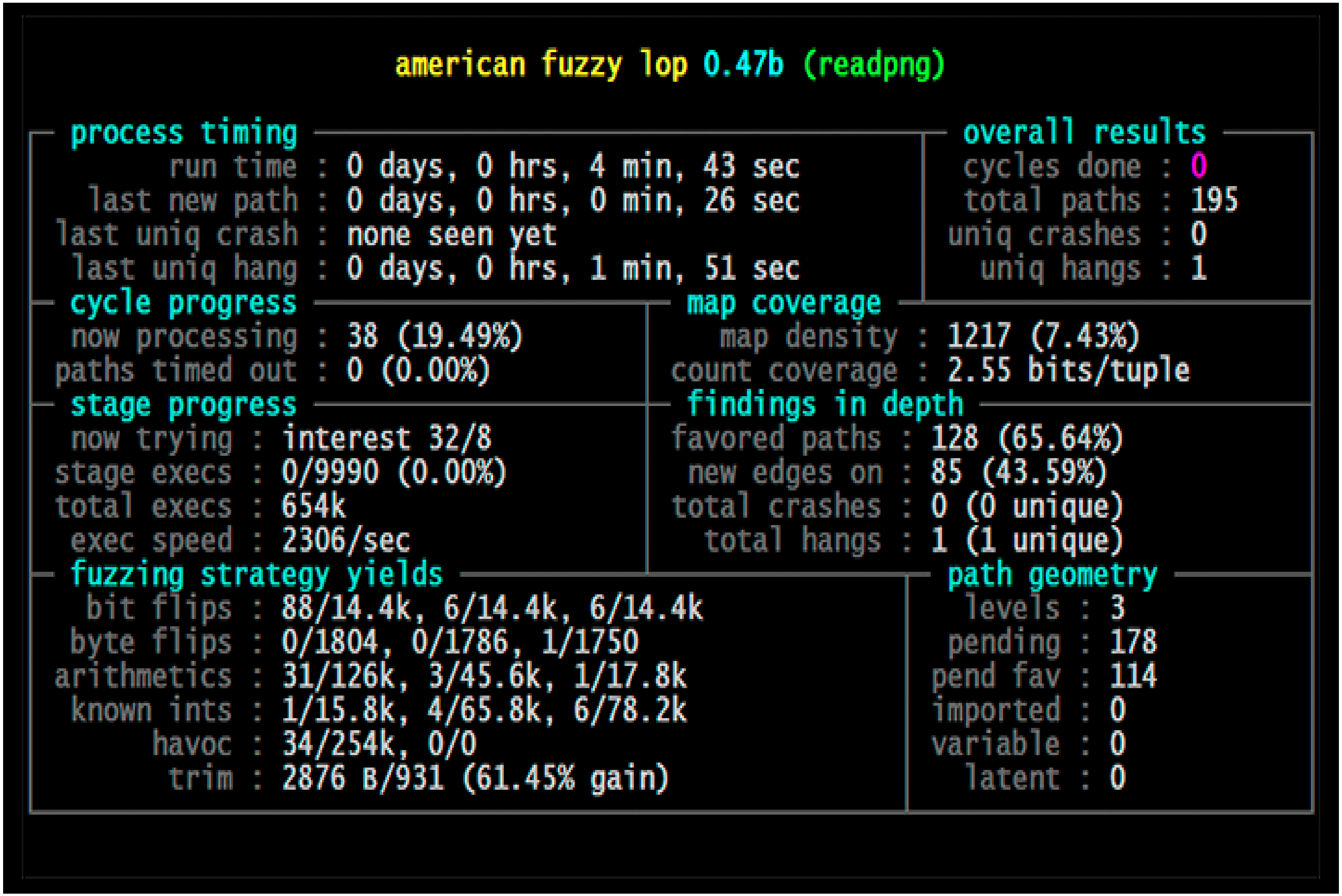
Coverage metric

```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**

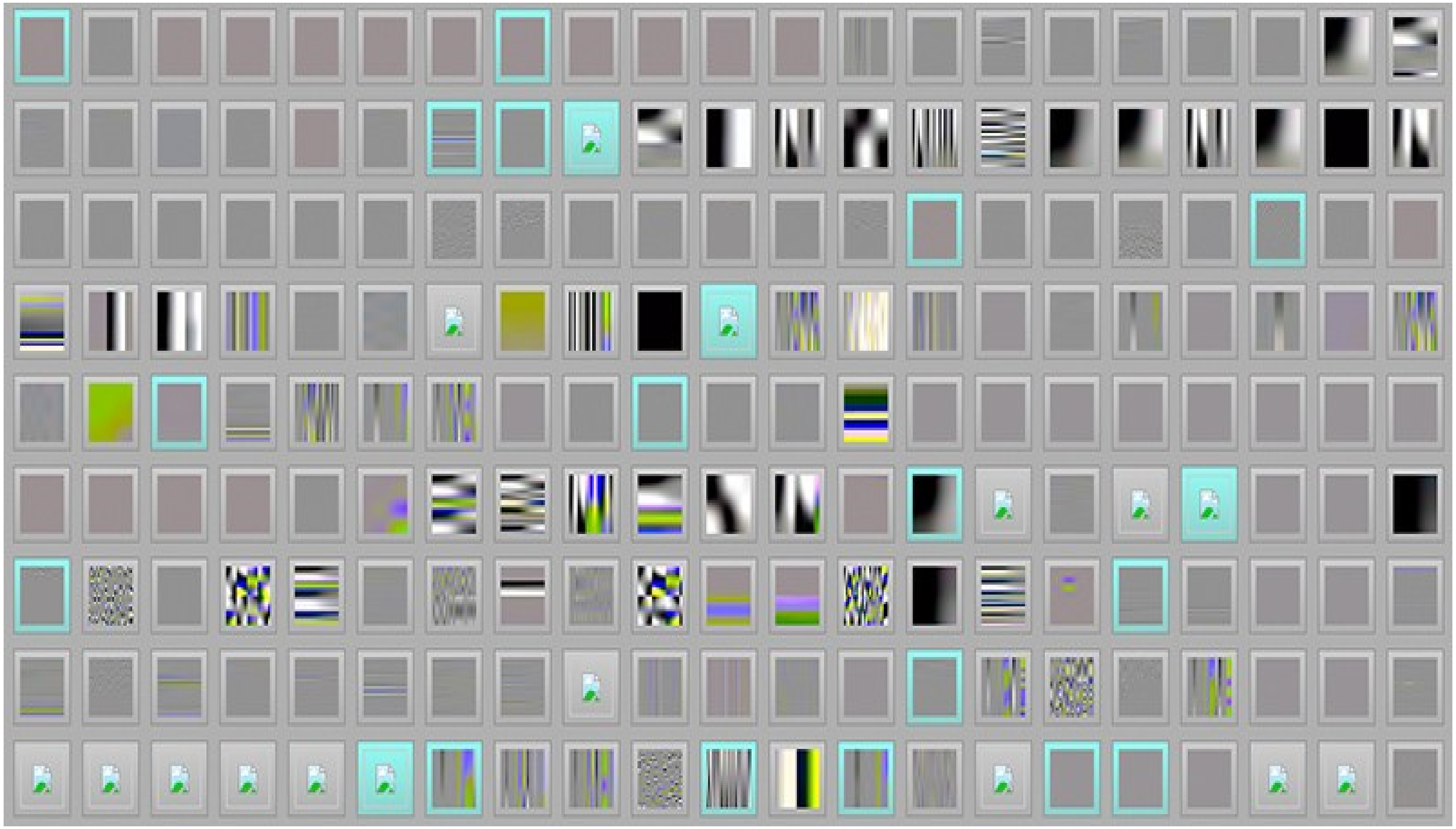
AFL – state-of-the-art fuzzing



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)

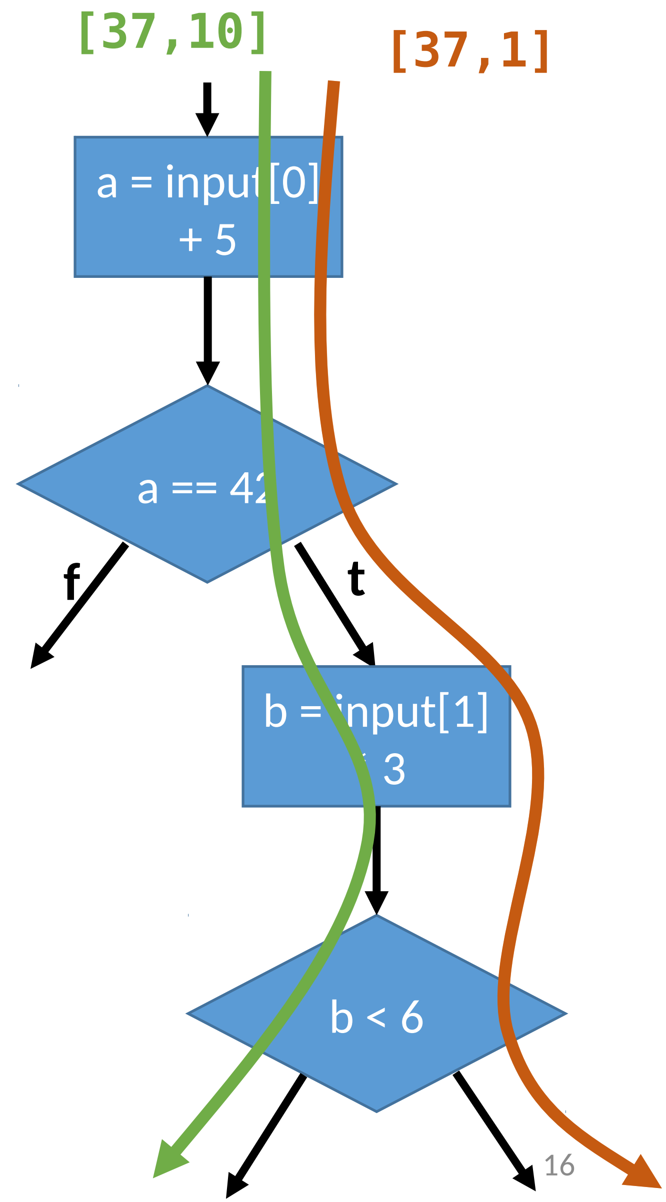
```
DynamicSymbolicExecution
Input:  initial test suite TestSuite
Output: bug triggering inputs Crashers

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