Introduction to Fuzzing

What is Fuzzing?

- A form of vulnerability analysis
- Process:
  - Many slightly anomalous test cases are input into the application
  - Application is monitored for any sign of error

Example

Standard HTTP GET request

- § GET /index.html HTTP/1.1

Anomalous requests

- § AAAAAA...AAAA /index.html HTTP/1.1
- § GET ///////index.html HTTP/1.1
- § GET %n%n%n%n%n%n.html HTTP/1.1
- § GET /AAAAAAAAAAAAA.html HTTP/1.1
- § GET /index.html HTTTTTTTTTTTTTP/1.1
- § GET /index.html HTTP/1.1.1.1.1.1.1.1
- § etc...

User Testing vs Fuzzing

- User testing
  - Run program on many **normal** inputs, look for bad things to happen
  - Goal: Prevent **normal users** from encountering errors
- Fuzzing
  - Run program on many **abnormal** inputs, look for bad things to happen
  - Goal: Prevent **attackers** from encountering **exploitable** errors

Types of Fuzzers

- Mutation Based – “Dumb Fuzzing”
  - mutate existing data samples to create test data
- Generation Based – “Smart Fuzzing”
  - define new tests based on models of the input
- Evolutionary
  - Generate inputs based on response from program

Mutation Based Fuzzing

- Little or no knowledge of the structure of the inputs is assumed
- Anomalies are added to existing valid inputs
- Anomalies may be completely random or follow some heuristics
- Requires little to no set up time
- Dependent on the inputs being modified
- May fail for protocols with checksums, those which depend on challenge response, etc.

- Example Tools:
  - Taof, GPF, ProxyFuzz, Peach Fuzzer, etc.

PEACH FUZZER

Mutation Based Example: PDF Fuzzing

- Google .pdf (lots of results)
- Crawl the results and download lots of PDFs

- Use a mutation fuzzer:

1. Grab the PDF file
2. Mutate the file
3. Send the file to the PDF viewer
4. Record if it crashed (and the input that crashed it)

Mutation-based	Super easy to setup and automate +	Little to no protocol knowledge required +	Limited by initial corpus −	May fail for protocols with checksums, or other complexity −

Generation Based Fuzzing

- Test cases are generated from some description of the format: RFC, documentation, etc.
- Anomalies are added to each possible spot in the inputs
- Knowledge of protocol should give better results than random fuzzing
- Can take significant time to set up

- Examples
  - SPIKE, Sulley, Mu-4000, Codenomicon, Peach Fuzzer, etc…

Example Specification for ZIP file

```
<!--  A.  Local file header -->
  <Block name="LocalFileHeader">
    <String name="lfh_Signature" valueType="hex" value="504b0304" token="true" mut
    <Number name="lfh_Ver" size="16" endian="little" signed="false"/>
    ...
    [truncated for space]
    ...
    <Number name="lfh_CompSize" size="32" endian="little" signed="false">
      <Relation type="size" of="lfh_CompData"/>
    </Number>
    <Number name="lfh_DecompSize" size="32" endian="little" signed="false"/>
    <Number name="lfh_FileNameLen" size="16" endian="little" signed="false">
      <Relation type="size" of="lfh_FileName"/>
    </Number>
    <Number name="lfh_ExtraFldLen" size="16" endian="little" signed="false">
      <Relation type="size" of="lfh_FldName"/>
    </Number>
    <String name="lfh_FileName"/>
    <String name="lfh_FldName"/>
    <!--  B.  File data -->
    <Blob name="lfh_CompData"/>
  </Block>
```

Src: http://www.flinkd.org/2011/07/fuzzing-with-peach-part-1/

Mutation vs Generation

Mutation-based	Super easy to setup and automate	Little to no protocol knowledge required	Limited by initial corpus	May fail for protocols with checksums, or other complexity
Generation-based	Writing generator is labor intensive for complex protocols	have to have spec of protocol (frequently not a problem for common ones http, snmp, etc…)	Completeness	Can deal with complex checksums and dependencies

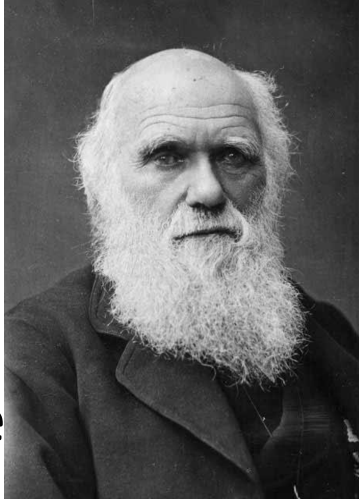
White box vs. black box fuzzing

- Black box fuzzing: sending the malformed input without any verification of the code paths traversed
- White box fuzzing: sending the malformed input and verifying the code paths traversed. Modifying the inputs (via Symbolic Execution) to attempt to cover all code paths

Technique	Effort	Code coverage	Defects Found
black box + mutation	10 min	50%	25%
black box + generation	30 min	80%	50%
white box + mutation	2 hours	80%	50%
white box + generation	2.5 hours	99%	100%

Source: http://msdn.microsoft.com/en-us/library/cc162782.aspx

Evolutionary Fuzzing



- Attempts to generate inputs based on the response of the program
- Autodafe
  - Prioritizes test cases based on which inputs have reached dangerous API functions
- EFS
  - Generates test cases based on code coverage metrics
- AFL
  - Most popular choice in DARPA CGC

Challenges

- Mutation based – can run forever. When do we stop?
- Generation based – stop eventually. Is it enough?
- How to determine if the program did something "bad"?

- These are the standard problems we face in most automated testing.

Code Coverage

- Some of the answers to our problems are found in code coverage
- To determine how well your code was tested, code coverage can give you a metric.
- But it's not perfect (is anything?)
- Code coverage types:
  - Statement coverage – which statements have been executed
  - Branch coverage – which branches have been taken
  - Path coverage – which paths were taken.

Code Coverage - Example

```
if (a > 2)
    a = 2;
if (b > 2)
   b = 2
```

How many test cases for 100% line coverage?
How many test cases for 100% branch coverage?
How many test cases for 100% paths?

Code Coverage Tools

- If you have source: gcov, Bullseye, Emma
- If you don't:
  - Binary instrumentation: PIN, DynamoRIO, QEMU
  - Valgrind : instrumentation framework for building dynamic analysis tools
  - Pai Mei : a reverse engineering framework consisting of multiple extensible components.

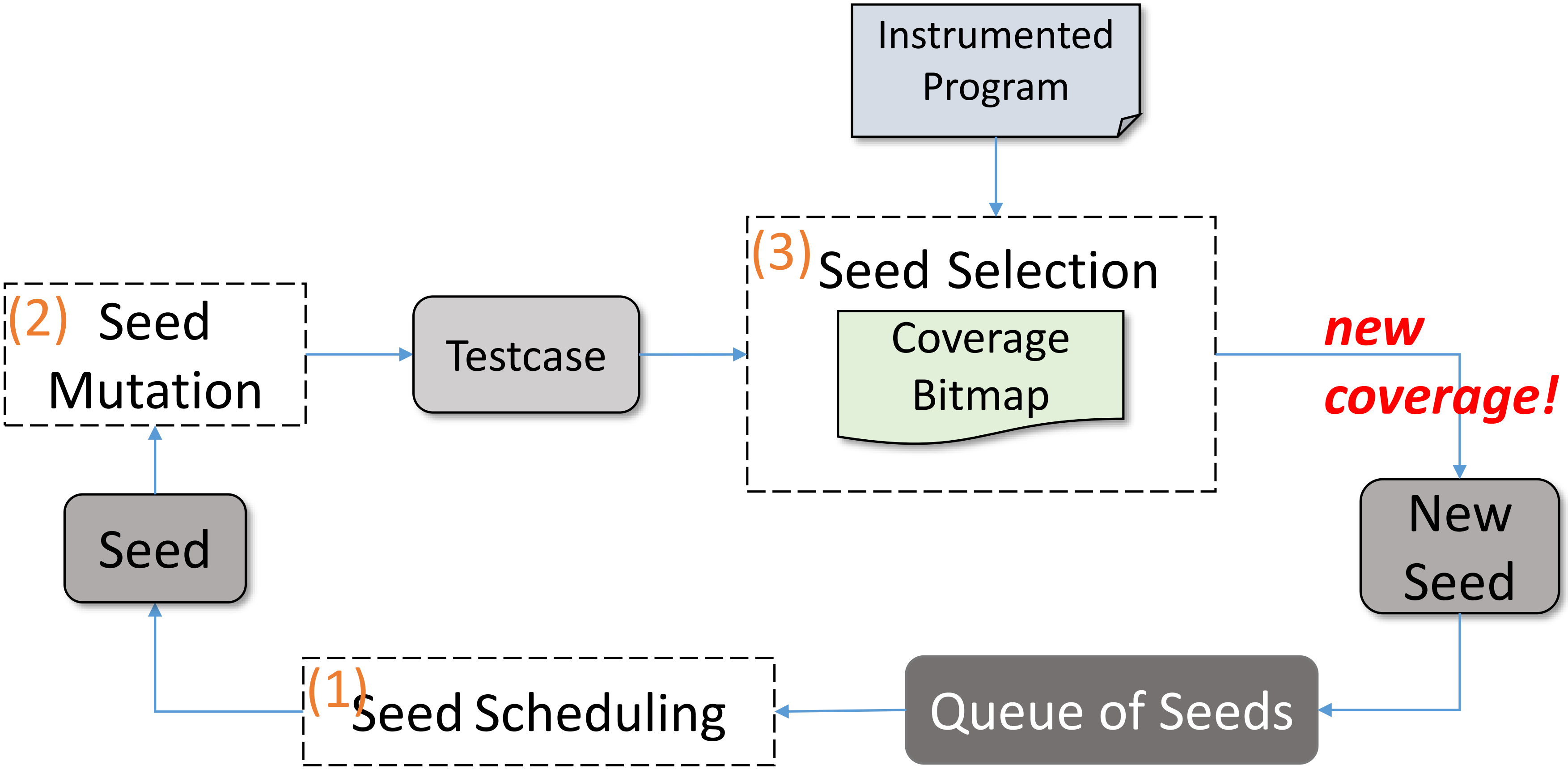
Lots more to discuss on Code Coverage in a Software Engineering class.. but lets move on.

Lessons about Fuzzing

- Protocol knowledge is helpful
  - Generational beats random, better specification make better fuzzers
- Using more fuzzers is better
  - Each one will vary and find different bugs
- The longer you run (typically) the more bugs you'll find
- Guide the process, fix it when it break or fails to reach where you need it to go
- Code coverage can serve as a useful guide

AFL – American Fuzzy Lop

- Fuzzer developed by Michal Zalewski (lcamtuf), Project Zero, Google
  - He's on holiday today ☹
- http://lcamtuf.coredump.cx/afl/


Instrumented Program
(3) Seed Selection
Coverage Bitmap
(2) Seed Mutation
Testcase
new coverage!
Seed
New Seed
(1) Seed Scheduling
Queue of Seeds

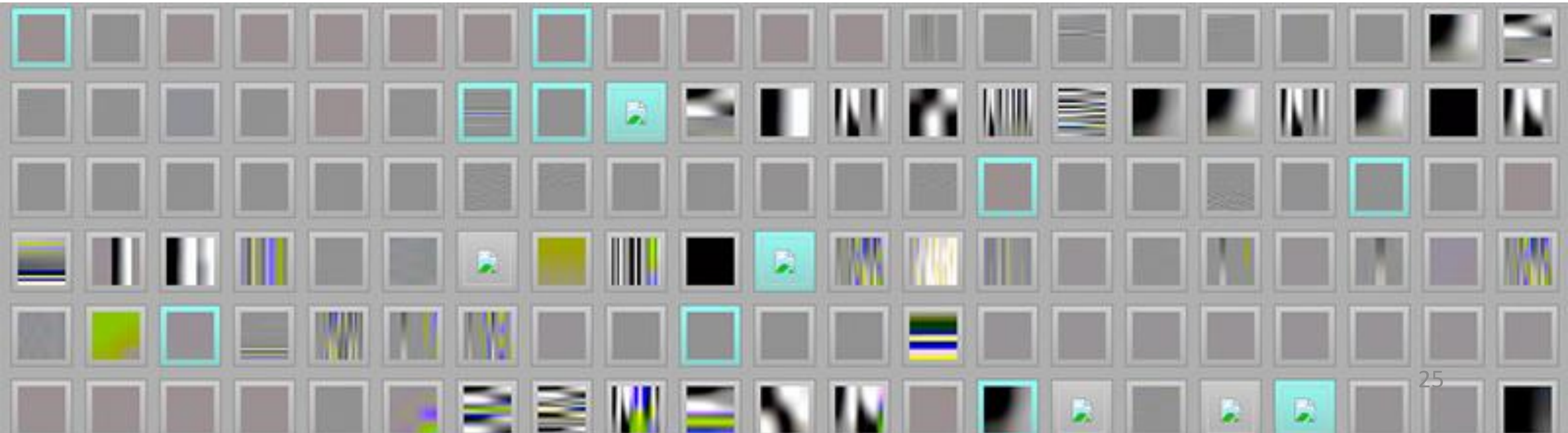
Why use AFL?

It finds bugs

IJG jpeg 1 libjpeg-turbo 1 2 libpng 1 libtiff 1 2 3 4 5 mozjpeg 1 libbpg (1) Mozilla Firefox 1 2 3 4 5 Google Chrome 1 Internet Explorer 1 2 (3) (4) LibreOffice 1 2 3 4 poppler 1 freetype 1 2 GnuTLS 1 GnuPG 1 2 (3) OpenSSH 1 2 3 bash (post-Shellshock) 1 2 tcpdump 1 2 3 4 5 6 7 Adobe Flash / PCRE 1 2 JavaScriptCore 1 2 3 4 pdfium 1 ffmpeg 1 2 3 4 libmatroska 1 libarchive 1 2 3 4 5 6 … wireshark 1 ImageMagick 1 2 3 4 5 6 7 8 … lcms (1) PHP 1 2 lame 1 FLAC audio library 1 2 libsndfile 1 2 3 less / lesspipe 1 2 3 strings (+ related tools) 1 2 3 4 5 6 7 file 1 2 dpkg 1 rcs 1 systemd-resolved 1 2 sqlite 1 2 3 libyaml 1 Info-Zip unzip 1 2 OpenBSD pfctl 1 NetBSD bpf 1 man & mandoc 1 2 3 4 5 … IDA Pro clamav 1 2 libxml2 1 glibc 1 clang / llvm 1 2 3 4 5 6 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 perl 1 2 3 4 5 6 libxmp radare2 1 2 fwknop metacam 1 exifprobe 1 capnproto 1

It's spooky

- Michal gave djpeg (IJG jpeg library) to AFL
- Plus a non-jpeg file as an input
  - $ echo 'hello' >in_dir/hello
- AFL started to produce valid jpeg files after a day or two



More reasons

- It's dead simple
- No configuration of AFL necessary, robust
- It's cutting edge
- It's fast
- Produces very very good input files (corpus) that can be used in other fuzzers
- Many targets that were never touched by AFL (and it will crush them)

You won't believe what you are reading

- Source: http://lcamtuf.coredump.cx/afl/demo/
- afl-generated, minimized image test sets (partial) [...]
- JPEG XR jxrlib 1.1 JxrDecApp[1] IE → Ditched [2]
- [2] Due to the sheer number of exploitable bugs that allow the fuzzer to jump to arbitrary addresses.

When to use AFL

The usual use case

- You have the source code and you compile with gcc or clang
- Your are on 32bit or 64bit on Linux/OSX/BSD
- The to-be-fuzzed code (e.g. parser) reads it's input from stdin or from a file
- The input file is usually only max. 10kb
- This covers *a lot* of Linux libraries

What if something does not apply?

- No source code?
  - Try the experimental QEMU instrumentation
- Not on 32/64 bit?
  - There is an experimental ARM version
- Not reading from stdin or file?
  - Maybe your project has a utility command line tool that does read from file
  - Or you write a wrapper to do it
  - Same if you want to test (parts of) network protocol parsers

How to use AFL

Steps of fuzzing

1. Compile/install AFL (once)
2. Compile target project with AFL
   - afl-gcc / afl-g++ / afl-clang / afl-clang++ / (afl-as)
3. Chose target binary to fuzz in project
   - Chose its command line options to make it run fast
4. Chose valid input files that cover a wide variety of possible input files
   - afl-cmin / (afl-showmap)

Steps of fuzzing

5. Fuzzing
   - afl-fuzz
6. Check how your fuzzer is doing
   - command line UI / afl-whatsup / afl-plot / afl-gotcpu
7. Analyze crashes
   - afl-tmin / triage_crashes.sh / peruvian were rabbit
   - ASAN / valgrind / exploitable gdb plugin / …
8. Have a lot more work than before
   - CVE assignment / responsible disclosure / …

Installing AFL (step 1)

```
#!/bin/bash
#Download & compile new AFL version:
wget http://lcamtuf.coredump.cx/afl.tgz
tar xfz afl.tgz
rm afl.tgz
cd `find . -type d -iname "afl-*"|sort|head -1`
make
echo "Provide sudo password for sudo make install"
sudo make install
```

AFL binaries

```
/opt/afl-1.56b$ ./afl-
afl-as        afl-fuzz     afl-plot
afl-clang     afl-g++      afl-showmap
afl-clang++   afl-gcc      afl-tmin
afl-cmin      afl-gotcpu   afl-whatsup
```

```
/opt/afl-1.56b$ ./afl-gcc
[...]
This is a helper application for afl-fuzz. It serves
as a drop-in replacementfor gcc or clang, letting you
recompile third-party code with the required runtime
instrumentation.
[...]
```

Instrumenting a project (step 2) – example: libtiff from CVS repository

```
/opt/libtiff-cvs-afl$ export CC=afl-gcc
/opt/libtiff-cvs-afl$ export CXX=afl-g++
/opt/libtiff-cvs-afl$ ./configure --disable-shared
/opt/libtiff-cvs-afl$ make clean
/opt/libtiff-cvs-afl$ make
```

Choosing the binary to fuzz (step 3) – they are all waiting for it

```
/opt/libtiff-cvs-afl$ ./tools/
bmp2tiff     fax2tiff    ppm2tiff    raw2tiff
thumbnail    tiff2pdf    tiff2rgba   tiffcp
tiffdither   tiffinfo    tiffset     fax2ps
gif2tiff     pal2rgb     ras2tiff    rgb2ycbcr
tiff2bw      tiff2ps     tiffcmp     tiffcrop
tiffdump     tiffmedian  tiffsplit
```

```
/opt/libtiff-cvs-afl$ ./tools/bmp2tiff
LIBTIFF, Version 4.0.3
Copyright (c) 1988-1996 Sam Leffler
[...]
usage: bmp2tiff [options] input.bmp [input2.bmp ...]
output.tif
```

Chose initial input files (step 4)

```
/opt/libtiff-cvs-afl$ mkdir input_all
/opt/libtiff-cvs-afl$ scp host:/bmps/ input_all/
/opt/libtiff-cvs-afl$ ls -1 input_all |wc –l
886
```

Chose initial input files (step 4)

```
/opt/libtiff-cvs-afl$ afl-cmin -i input_all -o input
-- /opt/libtiff-cvs-afl/tools/bmp2tiff @@ /dev/null
corpus minimization tool for afl-fuzz by
<lcamtuf@google.com>
[*] Testing the target binary...
[+] OK, 191 tuples recorded.
[*] Obtaining traces for input files in
'input_all'...
Processing file 886/886...
[*] Sorting trace sets (this may take a while)...
[+] Found 4612 unique tuples across 886 files.
[*] Finding best candidates for each tuple...
Processing file 886/886...
[*] Sorting candidate list (be patient)...
[*] Processing candidates and writing output files...
Processing tuple 4612/4612...
[+] Narrowed down to 162 files, saved in 'input'.
```

Chose initial input files (step 4)

```
/opt/libtiff-cvs-afl$ ls -1 input |wc -l
162
```

Fuzzing (step 5)

```
/opt/libtiff-cvs-afl$ screen –S fuzzing
/opt/libtiff-cvs-afl$ afl-fuzz -i input –o output --
/opt/libtiff-cvs-afl/tools/bmp2tiff @@ /dev/null
```

How is our fuzzer doing? (step 6)

```
                     american fuzzy lop 1.56b (bmp2tiff)

┌─ process timing ─────────────────────────────────────┬─ overall results ─────┐
│        run time : 0 days, 0 hrs, 2 min, 30 sec       │  cycles done : 0      │
│   last new path : 0 days, 0 hrs, 0 min, 3 sec        │  total paths : 193    │
│ last uniq crash : 0 days, 0 hrs, 0 min, 4 sec        │ uniq crashes : 2      │
│  last uniq hang : 0 days, 0 hrs, 0 min, 1 sec        │   uniq hangs : 15     │
├─ cycle progress ────────────────────┬─ map coverage ─┴───────────────────────┤
│  now processing : 3 (1.55%)         │    map density : 1344 (2.05%)         │
│ paths timed out : 0 (0.00%)         │ count coverage : 3.53 bits/tuple      │
├─ stage progress ────────────────────┼─ findings in depth ────────────────────┤
│  now trying : auto extras (over)    │ favored paths : 68 (35.23%)           │
│ stage execs : 15/72 (20.83%)        │  new edges on : 79 (40.93%)           │
│ total execs : 86.9k                 │ total crashes : 19 (2 unique)         │
│  exec speed : 71.11/sec (slow!)     │   total hangs : 100 (15 unique)       │
├─ fuzzing strategy yields ───────────┴───────────────┬─ path geometry ────────┤
│   bit flips : 12/704, 1/700, 1/692                  │    levels : 2          │
│  byte flips : 0/88, 0/84, 0/76                      │   pending : 190        │
│ arithmetics : 4/4840, 0/4068, 0/2495                │  pend fav : 65         │
│  known ints : 1/404, 1/2333, 2/2842                 │ own finds : 31         │
│  dictionary : 0/0, 0/0, 0/16                        │  imported : n/a        │
│       havoc : 9/65.6k, 0/0                          │  variable : 0          │
│        trim : 8.33%/20, 0.00%                       ├────────────────────────┘
└─────────────────────────────────────────────────────┘          [cpu:316%]
```

How is our fuzzer doing? (step 6)

```
                     american fuzzy lop 1.56b (bmp2tiff)

┌─ process timing ─────────────────────────────────────┬─ overall results ─────┐
│        run time : 0 days, 0 hrs, 13 min, 8 sec       │  cycles done : 0      │
│   last new path : 0 days, 0 hrs, 4 min, 20 sec       │  total paths : 213    │
│ last uniq crash : 0 days, 0 hrs, 4 min, 51 sec       │ uniq crashes : 11     │
│  last uniq hang : 0 days, 0 hrs, 5 min, 18 sec       │   uniq hangs : 44     │
├─ cycle progress ────────────────────┬─ map coverage ─┴───────────────────────┤
│  now processing : 6 (2.82%)         │    map density : 1356 (2.07%)          │
│ paths timed out : 0 (0.00%)         │ count coverage : 3.54 bits/tuple       │
├─ stage progress ────────────────────┼─ findings in depth ────────────────────┤
│  now trying : interest 16/8         │ favored paths : 78 (36.62%)            │
│ stage execs : 1377/1517 (90.77%)    │  new edges on : 85 (39.91%)            │
│ total execs : 123k                  │ total crashes : 48 (11 unique)         │
│  exec speed : 23.04/sec (slow!)     │   total hangs : 557 (44 unique)        │
├─ fuzzing strategy yields ───────────┴───────────────┬─ path geometry ────────┤
│   bit flips : 20/1744, 3/1737, 3/1723               │    levels : 2          │
│  byte flips : 0/218, 0/211, 0/197                   │   pending : 207        │
│ arithmetics : 12/12.0k, 0/10.5k, 0/6002             │  pend fav : 74         │
│  known ints : 0/979, 1/4399, 7/5631                 │ own finds : 51         │
│  dictionary : 0/0, 0/0, 3/217                       │  imported : n/a        │
│       havoc : 12/74.4k, 0/0                         │  variable : 0          │
│        trim : 5.22%/51, 0.00%                       ├────────────────────────┘
└─────────────────────────────────────────────────────┘             [cpu:300%]
```

How is our fuzzer doing? (step 6)

```
                      american fuzzy lop 1.56b (bmp2tiff)

┌─ process timing ─────────────────────────────────────┬─ overall results ─────┐
│        run time : 0 days, 1 hrs, 27 min, 43 sec      │  cycles done : 0      │
│   last new path : 0 days, 0 hrs, 28 min, 27 sec      │  total paths : 281    │
│ last uniq crash : 0 days, 0 hrs, 31 min, 10 sec      │ uniq crashes : 44     │
│  last uniq hang : 0 days, 0 hrs, 29 min, 29 sec      │   uniq hangs : 76     │
├─ cycle progress ───────────────────┬─ map coverage ─┴───────────────────────┤
│  now processing : 57 (20.28%)      │    map density : 1375 (2.10%)          │
│ paths timed out : 0 (0.00%)        │ count coverage : 3.67 bits/tuple       │
├─ stage progress ───────────────────┼─ findings in depth ────────────────────┤
│  now trying : arith 32/8           │ favored paths : 95 (33.81%)            │
│ stage execs : 3480/18.9k (18.37%)  │  new edges on : 104 (37.01%)           │
│ total execs : 938k                 │ total crashes : 427 (44 unique)        │
│  exec speed : 18.23/sec (zzzz...)  │   total hangs : 4681 (76 unique)       │
├─ fuzzing strategy yields ──────────┴─────────────┬─ path geometry ──────────┤
│   bit flips : 40/24.8k, 4/24.7k, 4/24.7k         │    levels : 2            │
│  byte flips : 0/3096, 0/2554, 1/2654             │   pending : 252          │
│ arithmetics : 22/137k, 6/110k, 0/62.2k           │  pend fav : 72           │
│  known ints : 0/10.5k, 6/67.6k, 17/97.3k         │ own finds : 119          │
│  dictionary : 0/0, 0/0, 3/6243                   │  imported : n/a          │
│       havoc : 55/356k, 0/0                       │  variable : 0            │
│        trim : 14.63%/1266, 18.73%                ├──────────────────────────┘
└──────────────────────────────────────────────────┘             [cpu:304%]
```

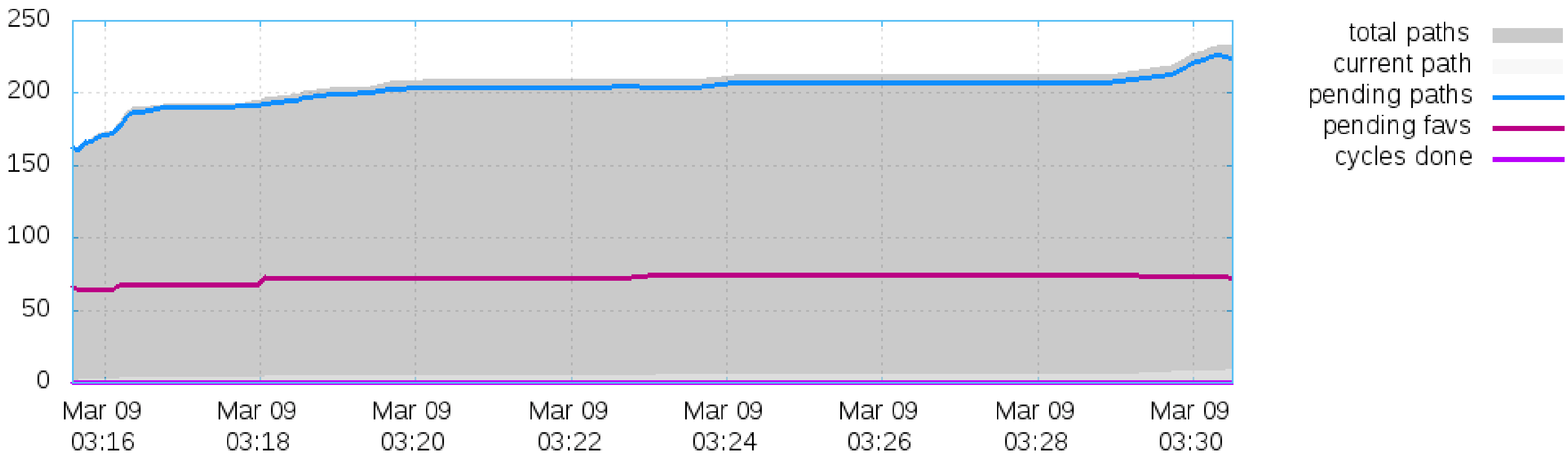
How is our fuzzer doing? (step 6)

```
/opt/libtiff-cvs-afl$ afl-gotcpu
afl-gotcpu 1.56b (Mar  9 2015 02:50:32) by
<lcamtuf@google.com>
[*] Measuring preemption rate (this will take 5.00
sec)...
[+] Busy loop hit 79 times, real = 5001 ms, slice =
2448 ms.
>>> FAIL: Your CPU is overbooked (204%). <<<
```

How is our fuzzer doing? (step 6)

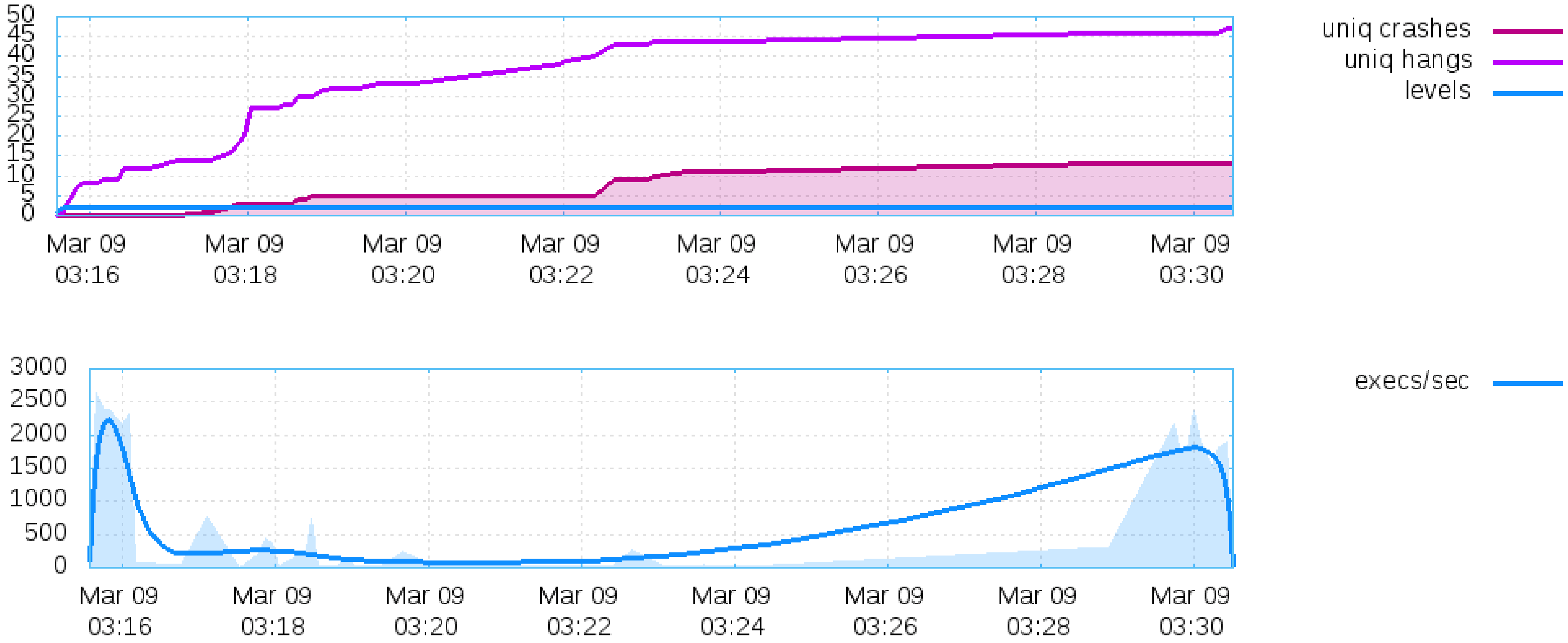
- afl-plot

Banner: bmp2tiff
Directory: output/
Generated on: Mon MÃ¤r 9 04:31:02 CET 2015

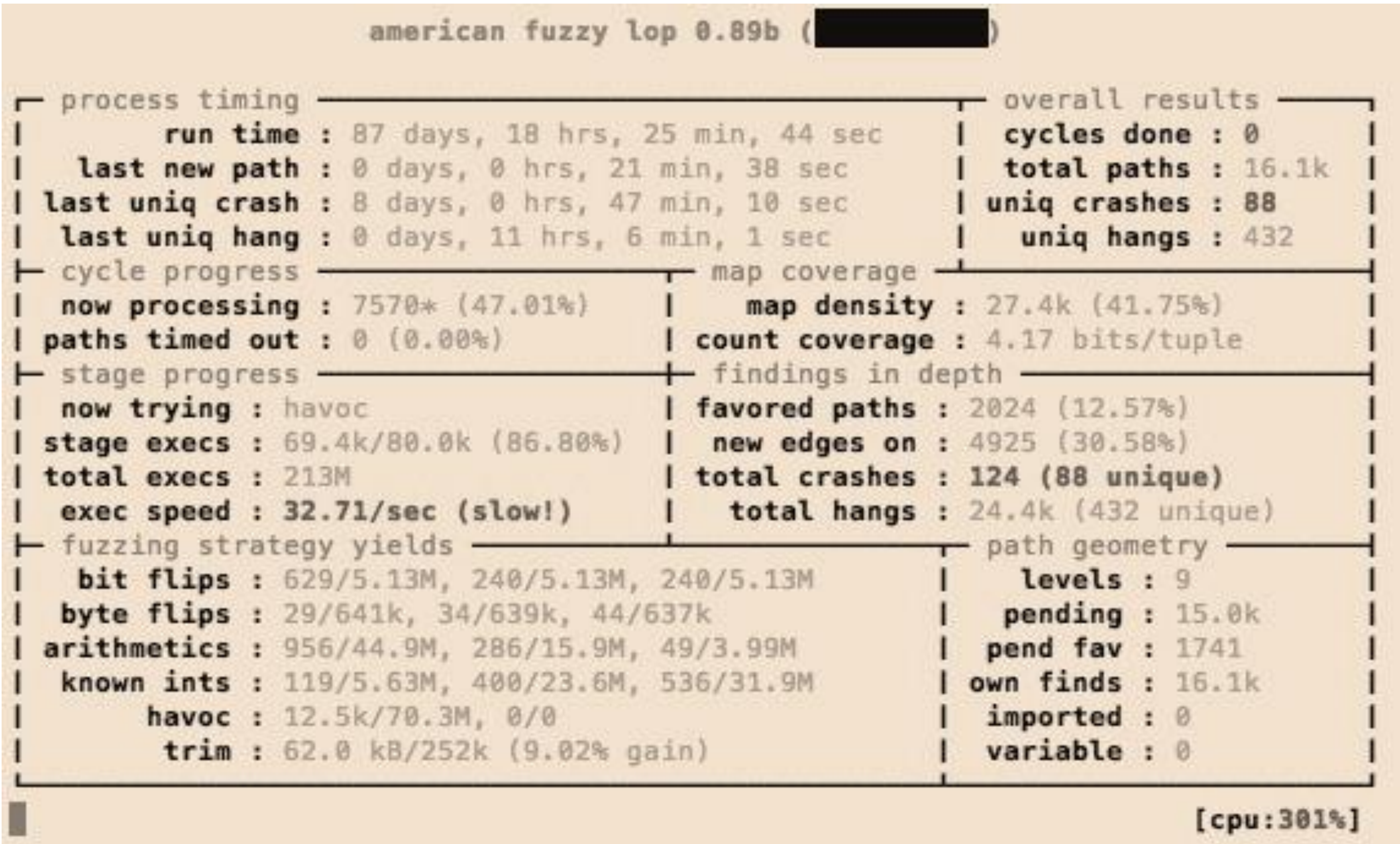


How is our fuzzer doing? (step 6)

- afl-plot



Other examples



Crash analysis (step 7) minimizing crash input

```
/opt/libtiff-cvs-afl$ afl-tmin -i
output/crashes/id\:000000\,sig\:11\,src\:000003\,op\:
int16\,pos\:21\,val\:+1 -o minimized-crash
/opt/libtiff-cvs-afl/tools/bmp2tiff @@ /dev/null
afl-tmin 1.56b (Mar  9 2015 02:50:31) by
<lcamtuf@google.com>
[+] Read 36 bytes from
'output/crashes/id:000000,sig:11,src:000003,op:int16,
pos:21,val:+1'.
[*] Performing dry run (mem limit = 25 MB, timeout =
1000 ms)...
[+] Program exits with a signal, minimizing in crash
mode.
[*] --- Pass #1 ---
[*] Stage #1:  Removing blocks of data...
Block length = 2, remaining size = 36
Block length = 1, remaining size = 34
[...]
```

Crash analysis (step 7) minimizing malicious input

```
/opt/libtiff-cvs-afl$ ls -als
output/crashes/id\:000000\,sig\:11\,src\:000003\,op\:
int16\,pos\:21\,val\:+14 -rw------- 1 user user 36
Mär  9 04:17
output/crashes/id:000000,sig:11,src:000003,op:int16,p
os:21,val:+1

/opt/libtiff-cvs-afl$ ls -als minimized-crash 4 -rw--
----- 1 user user 34 Mär  9 05:51 minimized-crash
```

Crash analysis (step 7) example of manual analysis

```
uncompr_size = width * length;
...
uncomprbuf = (unsigned char *)_TIFFmalloc(uncompr_size);
```

```
(gdb) p width
$70 = 65536
(gdb) p length
$71 = 65544
(gdb) p uncompr_size
$72 = 524288
```

```
524289 is (65536 * 65544) % MAX_INT
```

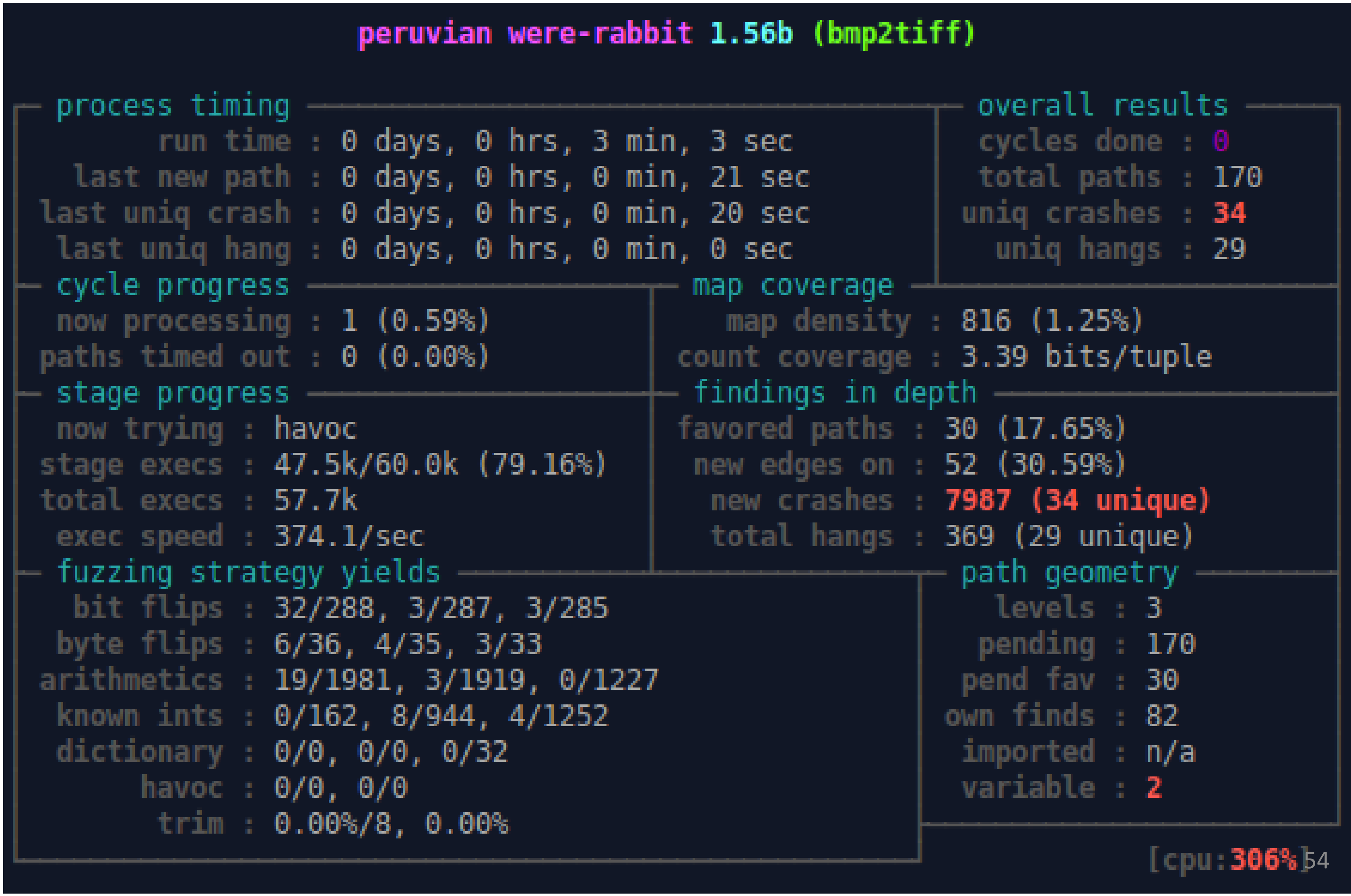
Crash analysis (step 7) peruvian were-rabbit

Crash analysis (step 7)
peruvian were-rabbit

- Using crashes as inputs, mutate them to find different crashes (that AFL considers "unique")

```
/opt/libtiff-cvs-afl$ afl-fuzz -i output/crashes/ -o
peruvian_crashes -C /opt/libtiff-cvs-afl/tools/bmp2tiff
@@ /dev/null
```

Crash analysis (step 7)
peruvian were-rabbit



Research Questions

- What coverage metric should we use?
- Better mutation strategy than random?
- How to make better use of fuzzing and symbolic execution?