

Introduction to Fuzzing

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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



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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 HTTTTTTTTTTTTTTP/1.1
- § GET /index.html HTTP/1.1.1.1.1.1.1.1
- § etc...

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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

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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

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Fuzzing

- Automatically generate random test cases
- Application is monitored for errors
- Inputs are generally either
 - files (.pdf, png, .wav, .mpg)
 - network based (http, SOAP, SNMP)



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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.



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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
	+	+	-	-

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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...



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Example Specification for ZIP file

```









1  <!-- A. Local file header -->
2  <Block name="LocalFileHeader">
3    <String name="lfh_Signature" valueType="hex" value="504b0304" token="true" mut
4    <Number name="lfh_Ver" size="16" endian="little" signed="false"/>
5    ...
6    [truncated for space]
7    ...
8    <Number name="lfh_CompSize" size="32" endian="little" signed="false">
9      <Relation type="size" of="lfh_CompData"/>
10   </Number>
11   <Number name="lfh_DecompSize" size="32" endian="little" signed="false"/>
12   <Number name="lfh_FileNameLen" size="16" endian="little" signed="false">
13     <Relation type="size" of="lfh_FileName"/>
14   </Number>
15   <Number name="lfh_ExtraFldLen" size="16" endian="little" signed="false">
16     <Relation type="size" of="lfh_FldName"/>
17   </Number>
18   <String name="lfh_FileName"/>
19   <String name="lfh_FldName"/>
20   <!-- B. File data -->
21   <Blob name="lfh_CompData"/>
22 </Block>

```

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

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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 

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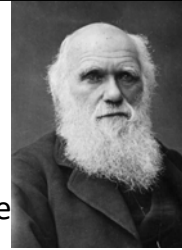
White box vs. black box fuzzing

- **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>
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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

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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.

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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.

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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?

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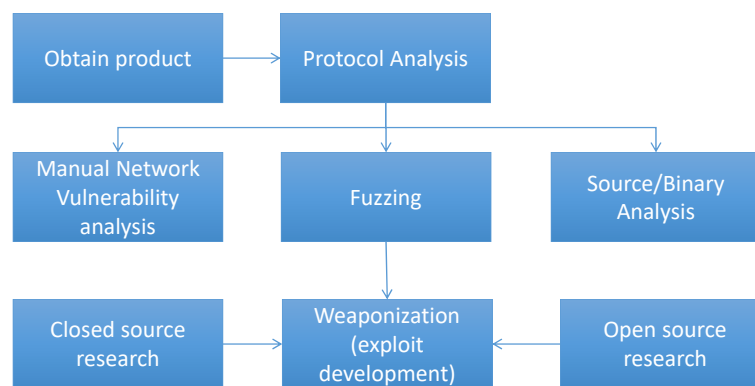
Code Coverage Tools

- 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.

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The Attacker Plan



But... why do it?

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Last step...Sell it!

- Market for 0-Days ~\$10K-100K



The Bug Bounty List

Welcome to Bugcrowd's community powered list of bug bounty programs

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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

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AFL – American Fuzzy Lop

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

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Why use AFL?

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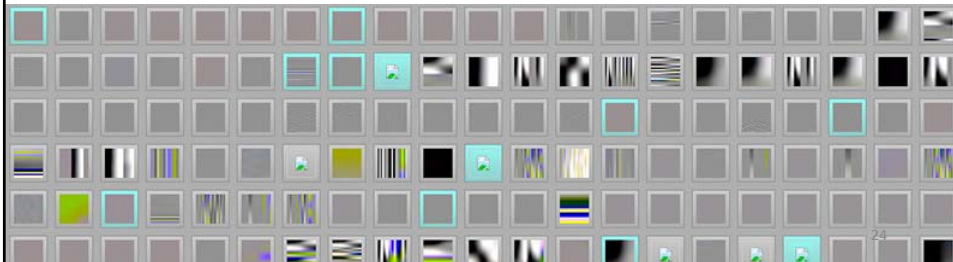
It finds bugs

[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⁾
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[7](#) [8](#) ... [lcms](#) ⁽¹⁾ [PHP](#) [1](#) [2](#) [lame](#) [1](#) [FLAC audio library](#) [1](#) [2](#) [libsndfile](#) [1](#) [2](#) [3](#) [less /](#)
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[exifprobe](#) [1](#) [capnproto](#) [1](#)

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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)

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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 JxrDecApp¹ IE → Ditched ²
- ² Due to the sheer number of exploitable bugs that allow the fuzzer to jump to arbitrary addresses.

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When to use AFL

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The usual use case

- You have the source code and you compile with gcc or clang
- You 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

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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

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How to use AFL

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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)

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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 / ...

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Installing AFL (step 1)

```
#!/bin/bash
#Download & compile new AFL version:
wget http://lcamtuf.coredump.cx/afl.tgz
tar xzf 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
```

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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 replacement for gcc or clang, letting you recompile third-party code with the required runtime instrumentation.

```
[...]
```

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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
```

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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
```

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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 -l input_all |wc -l
886
```

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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'. 38
```

Chose initial input files (step 4)

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

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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
```

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How is our fuzzer doing? (step

6)

```

american fuzzy lop 1.56b (bmp2tiff)

process timing
  run time : 0 days, 0 hrs, 2 min, 30 sec
  last new path : 0 days, 0 hrs, 0 min, 3 sec
  last uniq crash : 0 days, 0 hrs, 0 min, 4 sec
  last uniq hang : 0 days, 0 hrs, 0 min, 1 sec
cycle progress
  now processing : 3 (1.55%)
  paths timed out : 0 (0.00%)
stage progress
  now trying : auto extras (over)
  stage execs : 15/72 (20.83%)
  total execs : 86.9k
  exec speed : 71.11/sec (slow!)
fuzzing strategy yields
  bit flips : 12/704, 1/700, 1/692
  byte flips : 0/88, 0/84, 0/76
  arithmetics : 4/4840, 0/4068, 0/2495
  known ints : 1/404, 1/2333, 2/2842
  dictionary : 0/0, 0/0, 0/16
  havoc : 9/65.6k, 0/0
  trim : 8.33%/20, 0.00%

overall results
  cycles done : 0
  total paths : 193
  uniq crashes : 2
  uniq hangs : 15

map coverage
  map density : 1344 (2.05%)
  count coverage : 3.53 bits/tuple
findings in depth
  favored paths : 68 (35.23%)
  new edges on : 79 (40.93%)
  total crashes : 19 (2 unique)
  total hangs : 100 (15 unique)

path geometry
  levels : 2
  pending : 190
  pend fav : 65
  own finds : 31
  imported : n/a
  variable : 0

[cpu:310%]

```

How is our fuzzer doing? (step

6)

```

american fuzzy lop 1.56b (bmp2tiff)

process timing
  run time : 0 days, 0 hrs, 13 min, 8 sec
  last new path : 0 days, 0 hrs, 4 min, 20 sec
  last uniq crash : 0 days, 0 hrs, 4 min, 51 sec
  last uniq hang : 0 days, 0 hrs, 5 min, 18 sec
cycle progress
  now processing : 6 (2.82%)
  paths timed out : 0 (0.00%)
stage progress
  now trying : interest 16/8
  stage execs : 1377/1517 (90.77%)
  total execs : 123k
  exec speed : 23.04/sec (slow!)
fuzzing strategy yields
  bit flips : 20/1744, 3/1737, 3/1723
  byte flips : 0/218, 0/211, 0/197
  arithmetics : 12/12.0k, 0/10.5k, 0/6002
  known ints : 0/979, 1/4399, 7/5631
  dictionary : 0/0, 0/0, 3/217
  havoc : 12/74.4k, 0/0
  trim : 5.22%/51, 0.00%

overall results
  cycles done : 0
  total paths : 213
  uniq crashes : 11
  uniq hangs : 44

map coverage
  map density : 1356 (2.07%)
  count coverage : 3.54 bits/tuple
findings in depth
  favored paths : 78 (36.62%)
  new edges on : 85 (39.91%)
  total crashes : 48 (11 unique)
  total hangs : 557 (44 unique)

path geometry
  levels : 2
  pending : 207
  pend fav : 74
  own finds : 51
  imported : n/a
  variable : 0

[cpu:300%]

```

How is our fuzzer doing? (step

6)

```

american fuzzy lop 1.56b (bmp2tiff)

process timing
  run time : 0 days, 1 hrs, 27 min, 43 sec
  last new path : 0 days, 0 hrs, 28 min, 27 sec
  last uniq crash : 0 days, 0 hrs, 31 min, 10 sec
  last uniq hang : 0 days, 0 hrs, 29 min, 29 sec
overall results
  cycles done : 0
  total paths : 281
  uniq crashes : 44
  uniq hangs : 76

cycle progress
  now processing : 57 (20.28%)
  paths timed out : 0 (0.00%)
map coverage
  map density : 1375 (2.10%)
  count coverage : 3.67 bits/tuple

stage progress
  now trying : arith 32/8
  stage execs : 3480/18.9k (18.37%)
  total execs : 938k
  exec speed : 18.23/sec (zzzz...)
findings in depth
  favored paths : 95 (33.81%)
  new edges on : 104 (37.01%)
  total crashes : 427 (44 unique)
  total hangs : 4681 (76 unique)

fuzzing strategy yields
  bit flips : 40/24.8k, 4/24.7k, 4/24.7k
  byte flips : 0/3096, 0/2554, 1/2654
  arithmetics : 22/137k, 6/110k, 0/62.2k
  known ints : 0/10.5k, 6/67.6k, 17/97.3k
  dictionary : 0/0, 0/0, 3/6243
  havoc : 55/356k, 0/0
  trim : 14.63%/1266, 18.73%
path geometry
  levels : 2
  pending : 252
  pend fav : 72
  own finds : 119
  imported : n/a
  variable : 0

[cpu:304%]
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```

How is our fuzzer doing? (step

6)

```

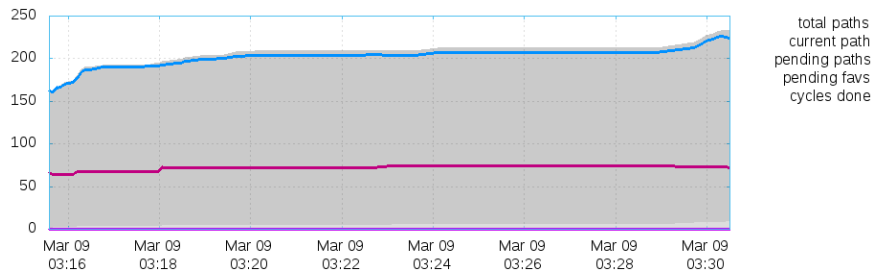
/opt/libtiff-cvs-afl$ afl-gotcpu
afl-gotcpu 1.56b (Mar  9 2015 02:50:32) by
<lcantuf@google.com>
[*] Measuring preemption rate (this will take 5.00
sec)...
[+] Busy loop hit 79 times, real = 5001 ms, slice =
2448 ms.
>>> FAIL: Your CPU is overbooked (204%). <<<

```

How is our fuzzer doing? (step 6)

- afl-plot

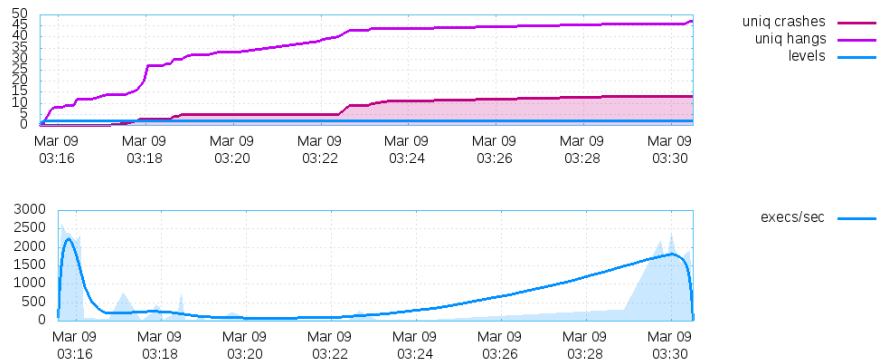
Banner: bmp2tiff
Directory: output/
Generated on: Mon Mar 9 04:31:02 CET 2015



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How is our fuzzer doing? (step 6)

- afl-plot



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Other examples

```

american fuzzy lop 0.89b (██████████)
┌── process timing ───────────────────────────────────────────────────────────┐
│ run time : 87 days, 18 hrs, 25 min, 44 sec │
│ last new path : 0 days, 0 hrs, 21 min, 38 sec │
│ last uniq crash : 8 days, 0 hrs, 47 min, 10 sec │
│ last uniq hang : 0 days, 11 hrs, 6 min, 1 sec │
└── overall results ───────────────────────────────────────────────────────────┘
│ cycles done : 0 │
│ total paths : 16.1k │
│ uniq crashes : 88 │
│ uniq hangs : 432 │
┌── cycle progress ───────────────────────────────────────────────────────────┐
│ now processing : 7570* (47.01%) │
│ paths timed out : 0 (0.00%) │
└── map coverage ───────────────────────────────────────────────────────────┘
│ map density : 27.4k (41.75%) │
│ count coverage : 4.17 bits/tuple │
┌── stage progress ───────────────────────────────────────────────────────────┐
│ now trying : havoc │
│ stage execs : 69.4k/80.0k (86.80%) │
│ total execs : 213M │
│ exec speed : 32.71/sec (slow!) │
└── findings in depth ─────────────────────────────────────────────────────────┘
│ favored paths : 2024 (12.57%) │
│ new edges on : 4925 (30.58%) │
│ total crashes : 124 (88 unique) │
│ total hangs : 24.4k (432 unique) │
┌── fuzzing strategy yields ───────────────────────────────────────────────────┐
│ bit flips : 629/5.13M, 240/5.13M, 240/5.13M │
│ byte flips : 29/641k, 34/639k, 44/637k │
│ arithmetics : 956/44.9M, 286/15.9M, 49/3.99M │
│ known ints : 119/5.63M, 400/23.6M, 536/31.9M │
│ havoc : 12.5k/70.3M, 0/0 │
│ trim : 62.0 kB/252k (9.02% gain) │
└── path geometry ───────────────────────────────────────────────────────────┘
│ levels : 9 │
│ pending : 15.0k │
│ pend fav : 1741 │
│ own finds : 16.1k │
│ imported : 0 │
│ variable : 0 │
┌────────────────────────────────────────────────────────────────────────────────┐
│ [cpu:301%] │
└────────────────────────────────────────────────────────────────────────────────┘

```

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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
[...]
```

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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

```

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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

```

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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
```

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Crash analysis (step 7) peruvian were-rabbit

```

peruvian were-rabbit 1.56b (bmp2tiff)
-----
process timing
  run time : 0 days, 0 hrs, 3 min, 3 sec
  last new path : 0 days, 0 hrs, 0 min, 21 sec
  last uniq crash : 0 days, 0 hrs, 0 min, 20 sec
  last uniq hang : 0 days, 0 hrs, 0 min, 0 sec
-----
cycle progress
  now processing : 1 (0.59%)
  paths timed out : 0 (0.00%)
-----
stage progress
  now trying : havoc
  stage execs : 47.5k/60.0k (79.16%)
  total execs : 57.7k
  exec speed : 374.1/sec
-----
fuzzing strategy yields
  bit flips : 32/288, 3/287, 3/285
  byte flips : 6/36, 4/35, 3/33
  arithmetics : 19/1981, 3/1919, 0/1227
  known ints : 0/162, 8/944, 4/1252
  dictionary : 0/0, 0/0, 0/32
  havoc : 0/0, 0/0
  trim : 0.00%/8, 0.00%
-----
overall results
  cycles done : 0
  total paths : 170
  uniq crashes : 34
  uniq hangs : 29
-----
map coverage
  map density : 816 (1.25%)
  count coverage : 3.39 bits/tuple
-----
findings in depth
  favored paths : 30 (17.65%)
  new edges on : 52 (30.59%)
  new crashes : 7987 (34 unique)
  total hangs : 369 (29 unique)
-----
path geometry
  levels : 3
  pending : 170
  pend fav : 30
  own finds : 82
  imported : n/a
  variable : 2
-----
[cpu:306%]b3

```