Fuzzing closed source applications

Introduction

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    - CanSecWest, DeepSec, 31C3, Hacktivity, BSides Vienna, Ruxcon, ToorCon, NorthSec, IT-SeCX, QuBit, DSS ITSEC, ZeroNights, Owasp Chapter, …
    - Topics: EMET, Application Whitelisting, Hacking Kerio Firewalls, Fuzzing Mimikatz, …

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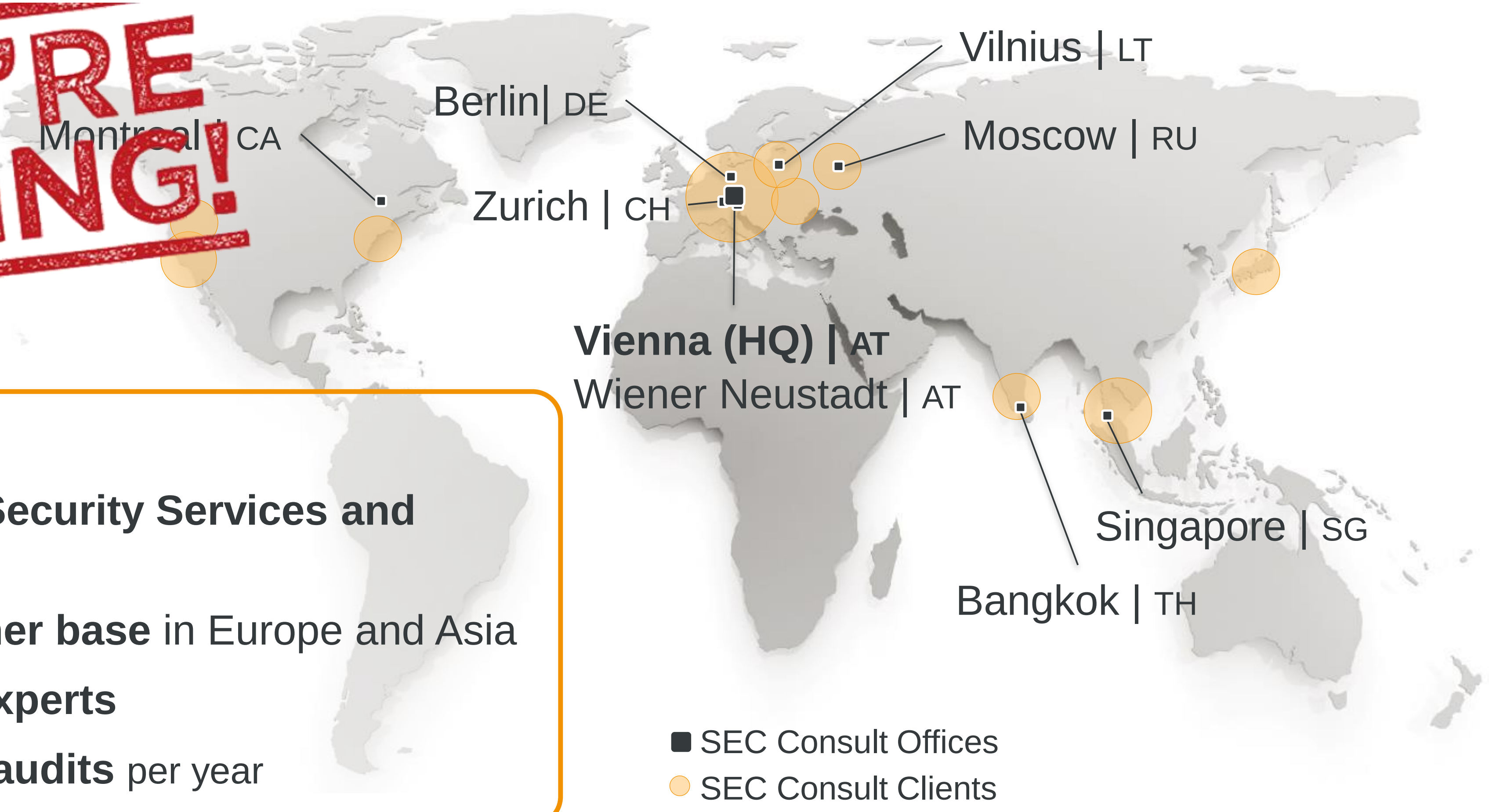
WE'RE HIRING!



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Feedback-based Fuzzing

Feedback based fuzzing

➔ **Consider this pseudocode**

```
if(read_line_from_user () == "command") {
    if(read_line_from_user() == "subcommand") {
        if(read_line_from_user() == "trigger") {
            //buffer_overflow here
        }
    }
}
```

Feedback based fuzzing

➔ **Input „command\n“results in the orange code-coverage output**

```
if(read_line_from_user () == "command") {
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```

Feedback based fuzzing

➔ **Same for „command\nsubcommand\n“**

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```

Feedback based fuzzing

➔ **And so on…**

```
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```

Methods to measure code-coverage

1. Instrumentation during compilation (source code available; gcc or llvm → AFL)

American Fuzzy Lop - AFL

- **One of the most famous file-format fuzzers**
  - Developed by Michal Zalewski

- Instruments application during compile time (GCC or LLVM)
  - Binary-only targets can be emulated / instrumented with qemu
  - Forks exist for PIN, DynamoRio, DynInst, syzygy, IntelPT, …
  - Simple to use!
  - Good designed! (very fast & good heuristics)

- Strategy:
  1. Start with a small min-set of input sample files
  2. Mutate “random” input file from queue like a dumb fuzzer
  3. If mutated file reaches new path(s), add it to queue

Feedback based fuzzing

- **Just use afl-gcc instead of gcc…**

```
user-VirtualBox# afl-gcc -o test2 test.c
afl-cc 2.35b by <lcamtuf@google.com>
afl-as 2.35b by <lcamtuf@google.com>
[+] Instrumented 6 locations (64-bit, non-hardened mode, ratio 100%).
user-VirtualBox# ./test2 1
Test2

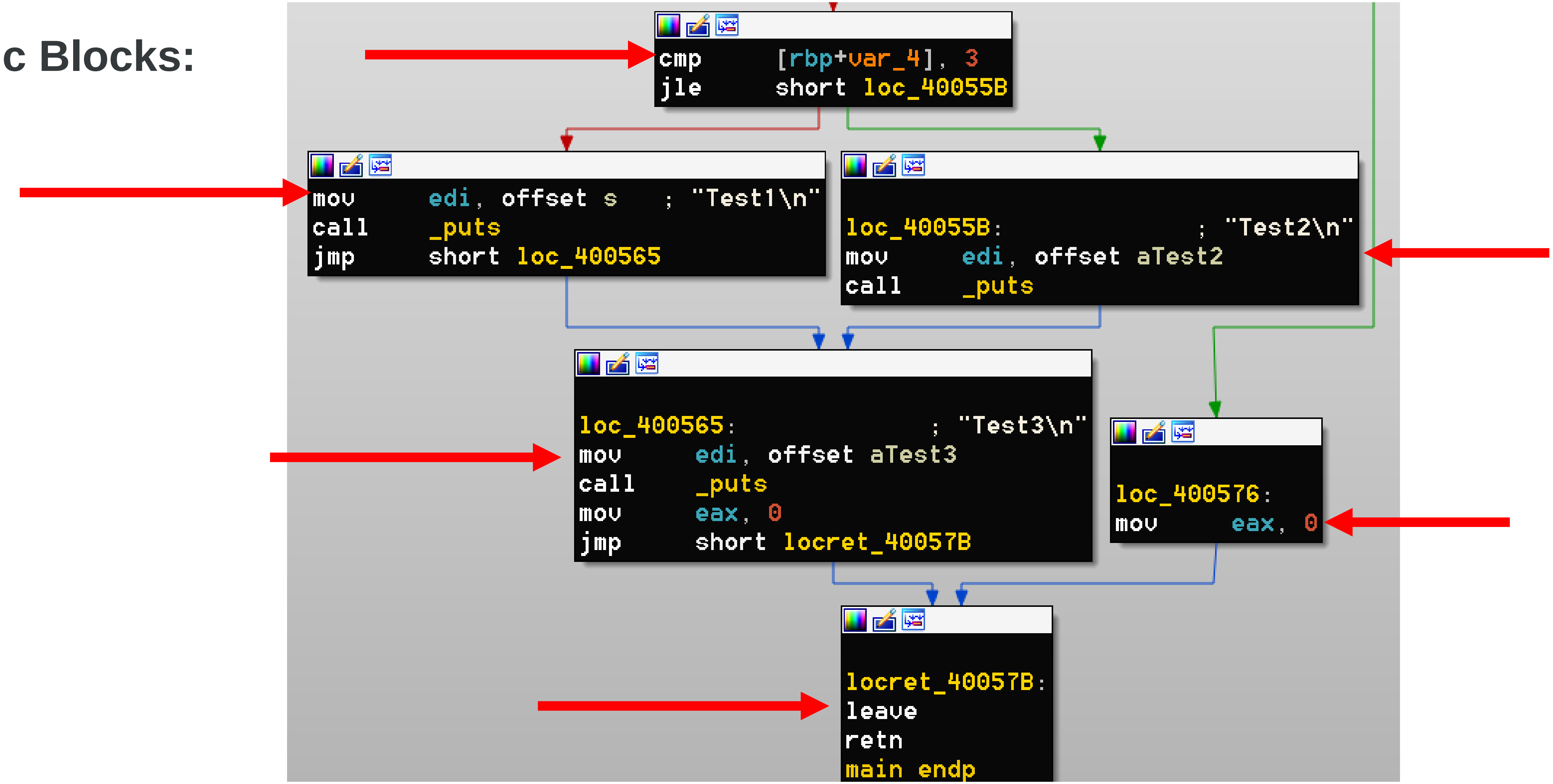
Test3

user-VirtualBox# ./test2 1 2 3 4 5
Test1

Test3
```

Feedback based fuzzing

- **Basic Blocks:**



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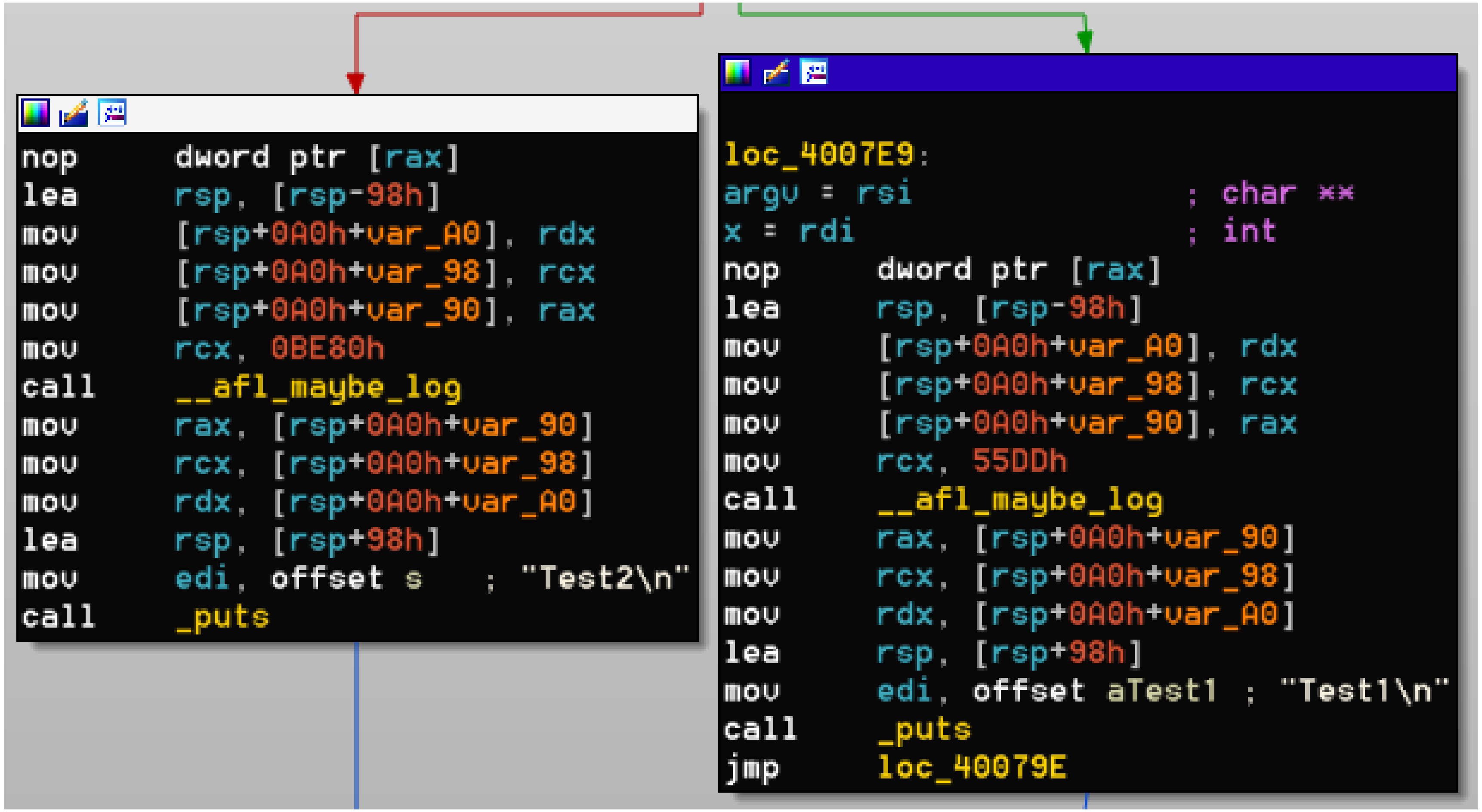
Feedback based fuzzing

- **Result:**

Store old register values

Instrumentation

Restore old register values



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American Fuzzy Lop - AFL

- Instrumentation tracks **edge coverage**, injected code at every basic block:

```
cur_location = <compile_time_random_value>;
bitmap[(cur_location ^ prev_location) % BITMAP_SIZE]++;
prev_location = cur_location >> 1;
```

➔ AFL can distinguish between

  - A->B->C->D->E (tuples: AB, BC, CD, DE)
  - A->B->D->C->E (tuples: AB, BD, DC, CE)

American Fuzzy Lop - AFL

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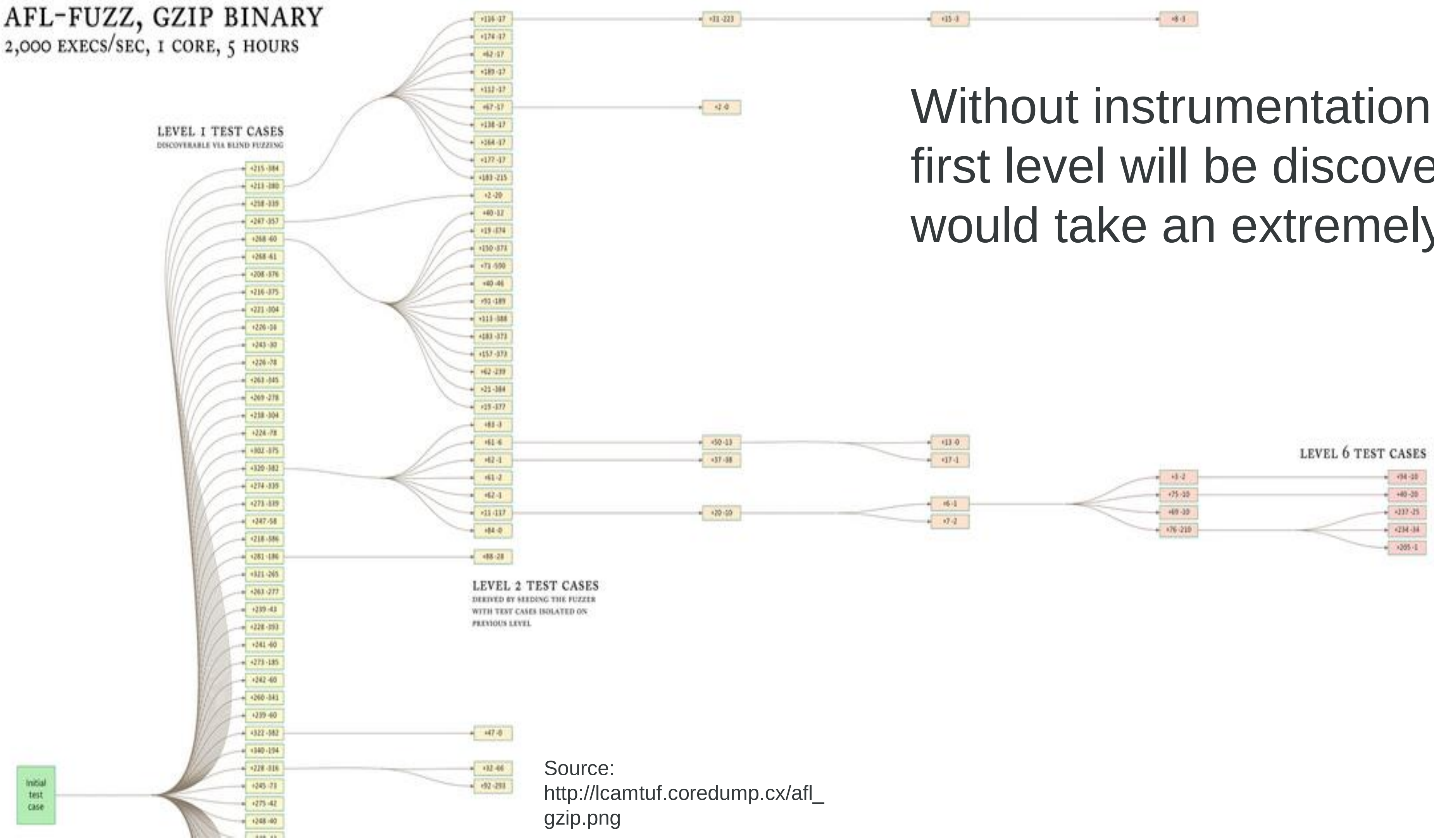
  - A->B->C->D->E (tuples: AB, BC, CD, DE)
  - A->B->D->C->E (tuples: AB, BD, DC, CE)

➔ Without shifting A->B and B->A are indistinguishable

American Fuzzy Lop - AFL



Without instrumentation just the first level will be discovered (or it would take an extremely long time)

Source: http://lcamtuf.coredump.cx/afl_gzip.png

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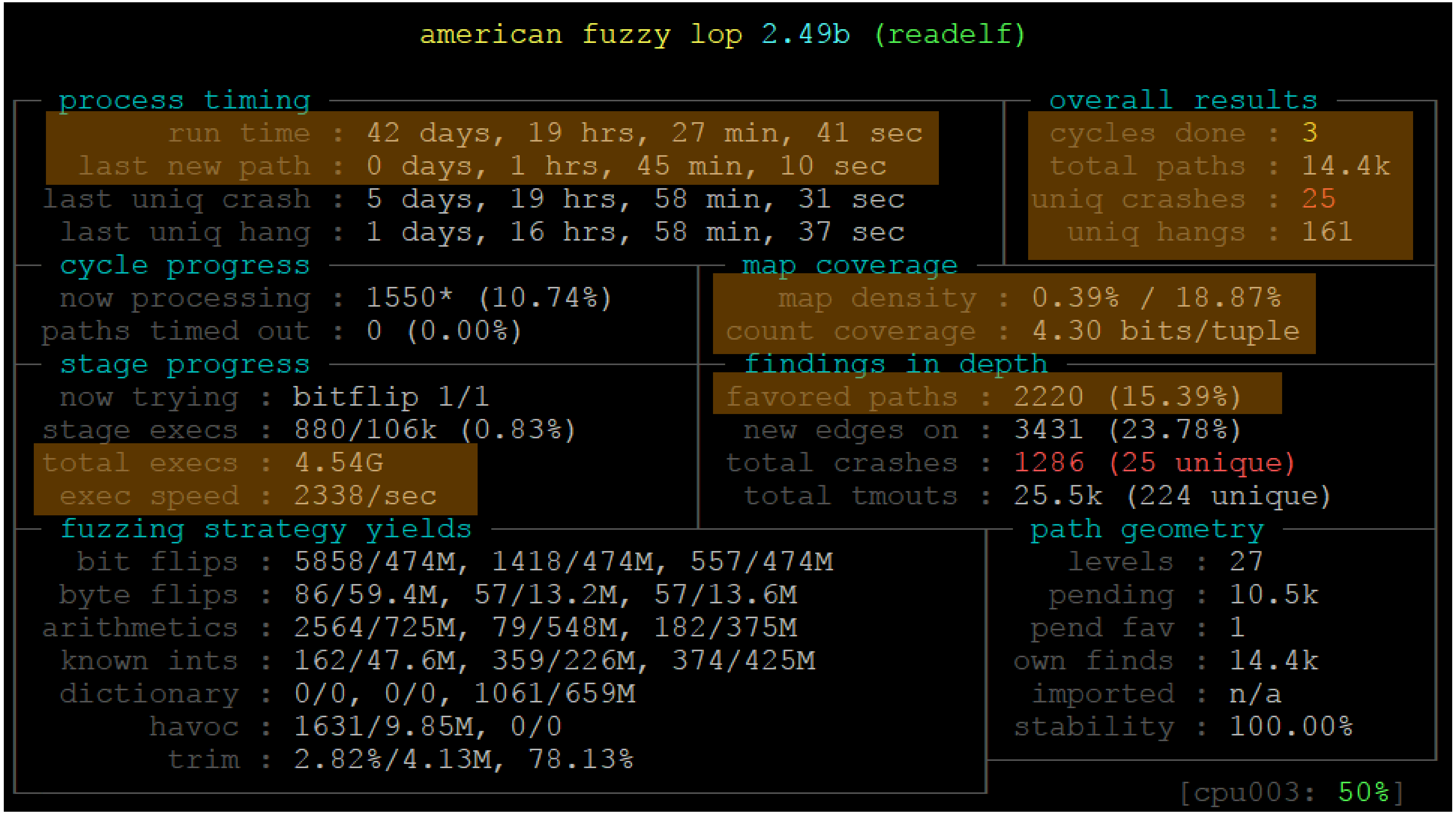
American Fuzzy Lop - AFL



Corpus Distillation

- We can either start fuzzing with an empty input folder or with downloaded / generated input files

- **Empty file:**
    - Let AFL identify the complete format (unknown target binaries)
    - Can be very slow

- **Downloaded sample files:**
    - Much faster because AFL doesn‘t have to find the file format structure itself
    - Bing API to crawl the web (Hint: Don‘t use DNS of your provider …)
    - Other good sources: Unit-tests, bug report pages, …
    - Problem: Many sample files execute the same code ➔ **Corpus Distillation**

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American Fuzzy Lop - AFL

Steps for fuzzing with AFL:

1. Remove input files with same functinality:
   Hint: Call it after tmin again (cmin is a heuristic)
   ```
   ./afl-cmin -i testcase_dir -o testcase_out_dir
   /path/to/tested/program [...program's cmdline...]
   ```

2. Reduce file size of input files:
   ```
   ./afl-tmin -i testcase_file -o testcase_out_file
   /path/to/tested/program [...program's cmdline...]
   ```

3. Start fuzzing:
   ```
   ./afl-fuzz -i testcase_dir -o findings_dir /path/to/tested/program
   [...program's cmdline...] @@
   ```

AFL with CVE-2009-0385 (FFMPEG)

- AFL input with invalid 4xm file (strk chunk changed to strj)

```
30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  000000000000vtrkD...0000000000000000000000000
30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  000000..00..00000000000000000000000000000000
30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  000000000000000000000000000000000000000000000
30 30 73 74  72 6A 28 00  00 00 00 00  00 00 00 00  00 00 30 30  000G000000000000000000000000strj(...........00
00 00 30 00  00 00 4C 49  53 54 30 30  30 30 4D 4F  56 49 4C 49  0000000000000000000...."0..0...LIST0000MOVILI
```

- AFL still finds the vulnerability!
  - Level 1 identifies correct “strk” chunk
  - Level 2 based on level 1 output AFL finds the vulnerability (triggered by 0xffffffff)

```
30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  000000..00..00000000000000000000000000000000
30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  30 30 30 30  000000000000000000000000000000000000000000000
30 30 73 74  72 6B 28 00  00 00 FF FF  FF FF 00 00  00 00 30 30  000G000000000000000000000000strk(...........00
00 00 30 00  00 00 4C 49  53 54 30 30  30 30 4D 4F  56 49 4C 49  0000000000000000000...."0..0...LIST0000MOVILI
```

LibFuzzer

- **LibFuzzer – Similar concept to AFL but in-memory fuzzing**
  - Requires LLVM SanitizerCoverage + writing small fuzzer-functions
  - LibFuzzer is more the Fuzzer for developers
  - AFL fuzzes the execution path of a binary (no modification required)
  - LibFuzzer fuzzes the execution path of a specific function (minimal code modifications required)
    - Fuzz function1 which processes data format 1 → Corpus 1
    - Fuzz function2 which processes data format 2 → Corpus 2
    - AFL can be also do in-memory fuzzing (persistent mode)

- Highly recommended tutorial: http://tutorial.libfuzzer.info

Methods to measure code-coverage

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4. Dynamic instrumentation of compiled application (no source code required; tools: DynamoRio, PIN, Valgrind, Frida, …)

Dynamic Instrumentation Frameworks

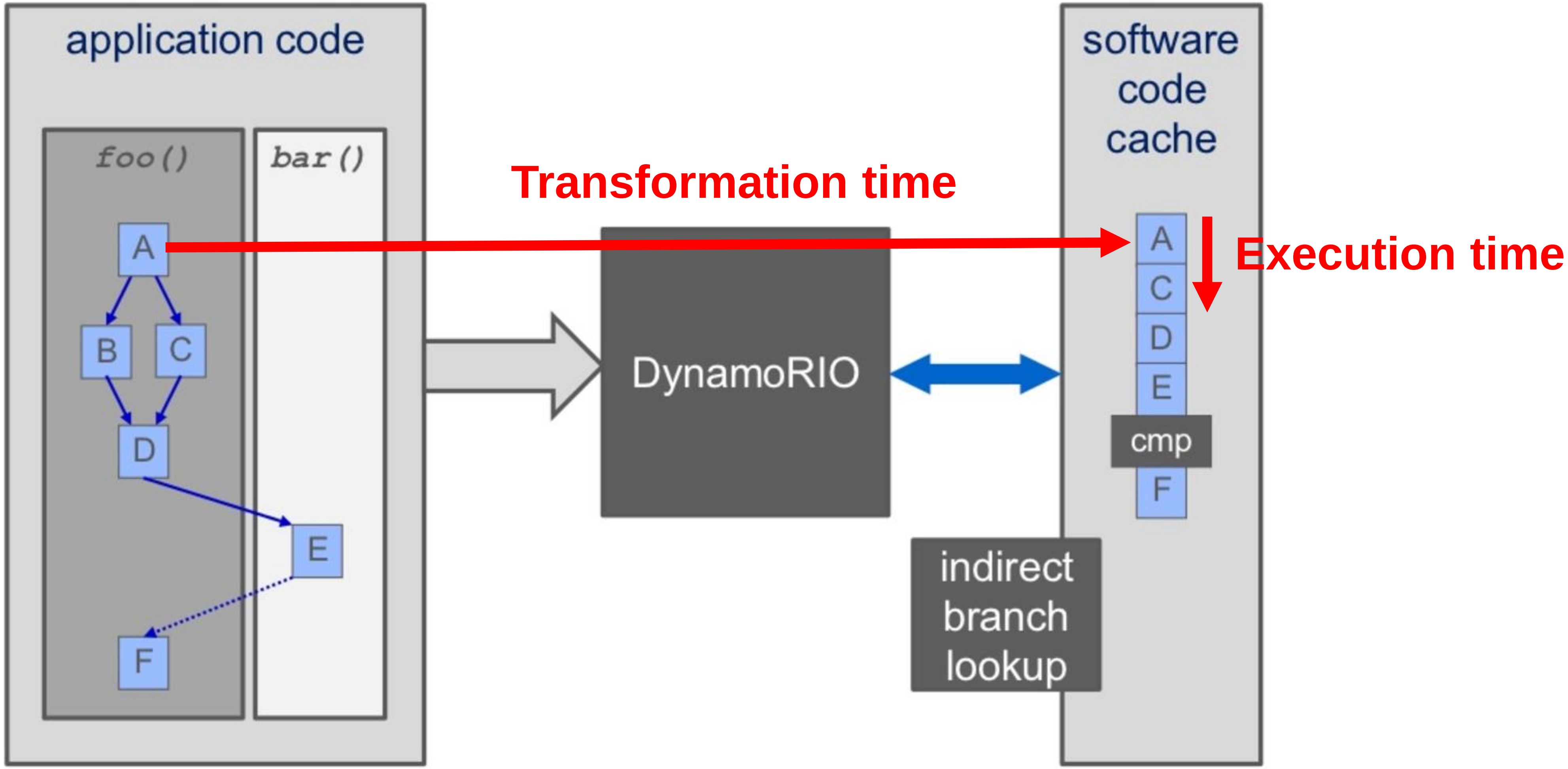
- **Dynamic runtime manipulation** of instructions of a running application!

- Many default tools are shipped with these frameworks
    - drrun.exe –t drcov -- calc.exe
    - drrun.exe –t my_tool.dll -- calc.exe
    - pin -t inscount.so -- /bin/ls

- Register callbacks, which are trigger at specific events
    - new basic block / instruction
    - load of module, exit of process, …

- At callback (e.g. new basic block), we can further add instructions
    - Transformation time (Instrumentation Function): Analyzing a BB the first time (called once)
    - Execution time (Analysis Function): Executed always before instruction gets executed

DynamoRIO



Source: The DynamoRIO Dynamic Tool Platform, Derek Bruening, Google

DynamoRIO

- **Example:** Start Adobe Reader, load PDF file, exit Adobe Reader, extract coverage data (Processing 25 PDFs with one single CPU core)

- Runtime without DynamoRio: ~30-40 seconds

- BasicBlock coverage (no hit count): 105 seconds
  - Instrumentation only during transformation into code cache (transformation time)

- BasicBlock coverage (hit count): 165 seconds
  - Instrumentation on basic block level (execution time)

- Edge coverage (hit count): 246 seconds
  - Instrumentation on basic block level (many instructions required to save and restore required registers for instrumentation code) (execution time)

DynamoRio vs PIN

- **PIN** is another dynamic instrumentation framework (older)
- Currently more people use PIN (➔ more examples are available)
- DynamoRio is noticeable faster than PIN
- But PIN is more reliable
    - DynamoRio can’t start Encase Imager, PIN can
    - DynamoRio can’t start CS GO, PIN can
    - During client writing I noticed several strange behaviors of DynamoRio

WinAFL

- **WinAFL - AFL for Windows**
  - Download: https://github.com/ivanfratric/winafl
  - Developed by Ivan Fratric

- Two modes:
  - DynamoRio: Source code not required
  - Syzygy: Source code required
  - Alternative: You can easily modify WinAFL to use PIN on Windows

- Windows does not use COW (Copy-on-Write) and therefore fork-like mechanisms are not efficient on Windows!
  - On Linux AFL heavily uses a fork-server
  - On Windows WinAFL heavily uses in-memory fuzzing

WinAFL

How to select a target function

The target function should do these things during its lifetime:

1. Open the input file. This needs to happen withing the target function so that you can read a new input file for each iteration as the input file is rewritten between target function runs).
2. Parse it (so that you can measure coverage of file parsing)
3. Close the input file. This is important because if the input file is not closed WinAFL won't be able to rewrite it.
4. Return normally (So that WinAFL can "catch" this return and redirect execution. "returning" via ExitProcess() and such won't work)

Source: https://github.com/ivanfratric/winafl FAQ

WinAFL

GUI Applications

```
Q: Can I fuzz GUI apps with WinAFL
A: Yes, provided that
 - There is a target function that behaves as explained in "How to select
   a target function"
 - The target function is reachable without user interaction
 - The target function runs and returns without user interaction
 If these conditions are not satisfied, you might need to make custom changes
 to WinAFL and/or your target.
```

Source: https://github.com/ivanfratric/winafl FAQ

AutoIt can easily solve this problem

DynamoRio / PIN to change instruction ptr

AutoIt

```
#include <AutoItConstants.au3>

Run("notepad.exe")
Local $hWand = WinWait("[CLASS:Notepad]", "", 10)
ControlSend($hWand, "", "Edit1", "Hello World")
WinClose($hWand)
ControlClick("[CLASS:#32770]", "", "Button3")
WinSetState("[CLASS:Notepad]", "", @SW_MAXIMIZE)
MouseMove(14,31)
MouseClick($MOUSE_CLICK_LEFT)
MouseMove(85,209)
MouseClick($MOUSE_CLICK_LEFT)
ControlClick("[CLASS:#32770]", "", "Button2")
```

AutoIt

- **Another use case: Popup Killer**
  - During fuzzing applications often spawn error message; popup killer closes them
  - Another implementation can be found in CERT Basic Fuzzing Framework (BFF) Windows Setup files (C++ code to monitor for message box events)

```
#include <MsgBoxConstants.au3>
While 1
  Local $aList = WinList()
  ; $aList[0][0] number elements
  ; $aList[x][0] => title ; $aList[x][1] => handle
  For $i = 1 To $aList[0][0]
    If StringCompare($aList[$i][0], "Engine Error") == 0 Then
      ControlClick($aList[$i][1], "", "Button2", "left", 2)
    EndIf
  Next
  sleep(500) ; 500 ms
WEnd
```

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2. Emulation of binary (e.g. with qemu)
3. Writing own debugger and set breakpoints on every basicblock (slow, but useful in some situations)
4. Dynamic instrumentation of compiled application (no source code required; tools: DynamoRio, PIN, Valgrind, Frida, …)
5. Static instrumentation via static binary rewriting (Talos fork of AFL which uses DynInst framework – AFL-dyninst, should be fastest possibility if source code is not available but it's not 100% reliable and currently Linux only); **WinAFL in syzygy mode is very useful on Windows if source-code is available!**

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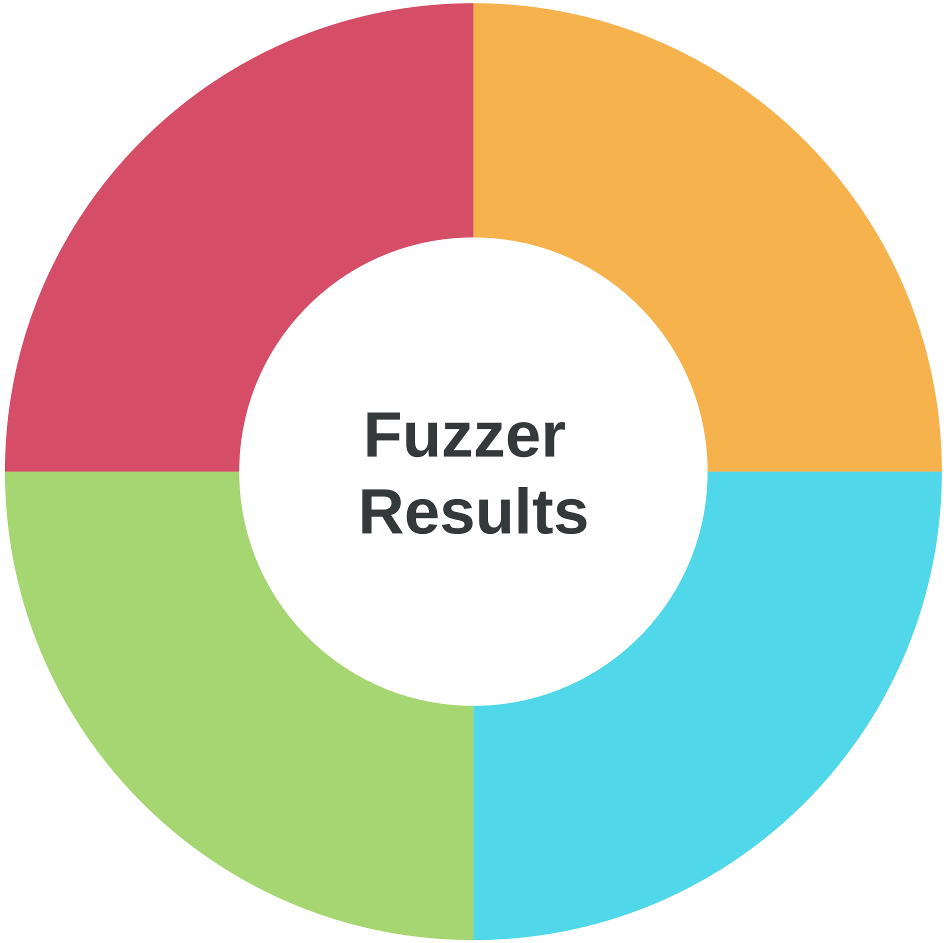
6. Use of hardware features
    - IntelPT (Processor Tracing); available since 6th Intel-Core generation (~2015)
    - WindowsIntelPT (from Talos) or kAFL

Areas which influent fuzzer results

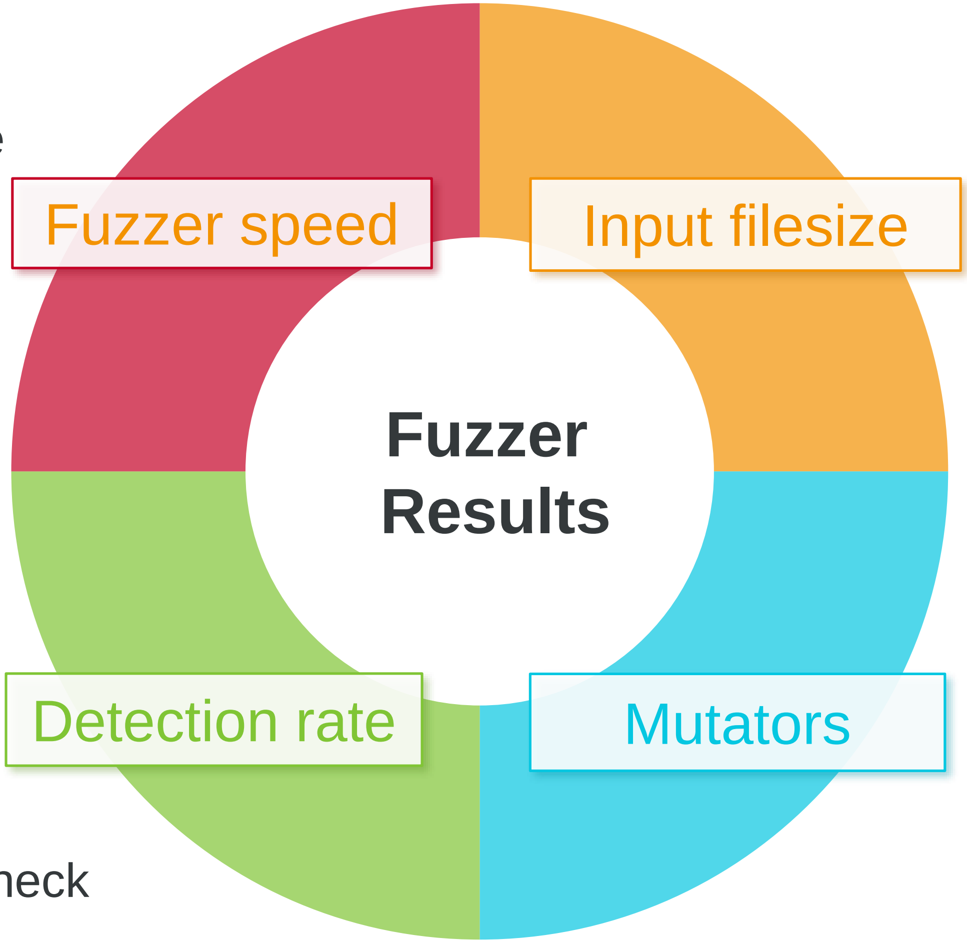
Areas which influence fuzzing results



Overview: Areas which influence fuzzing results

Fork-server
Faster instrumentation code
Static vs. Dynamic Instrumentation
In-memory fuzzing
No process switches
…

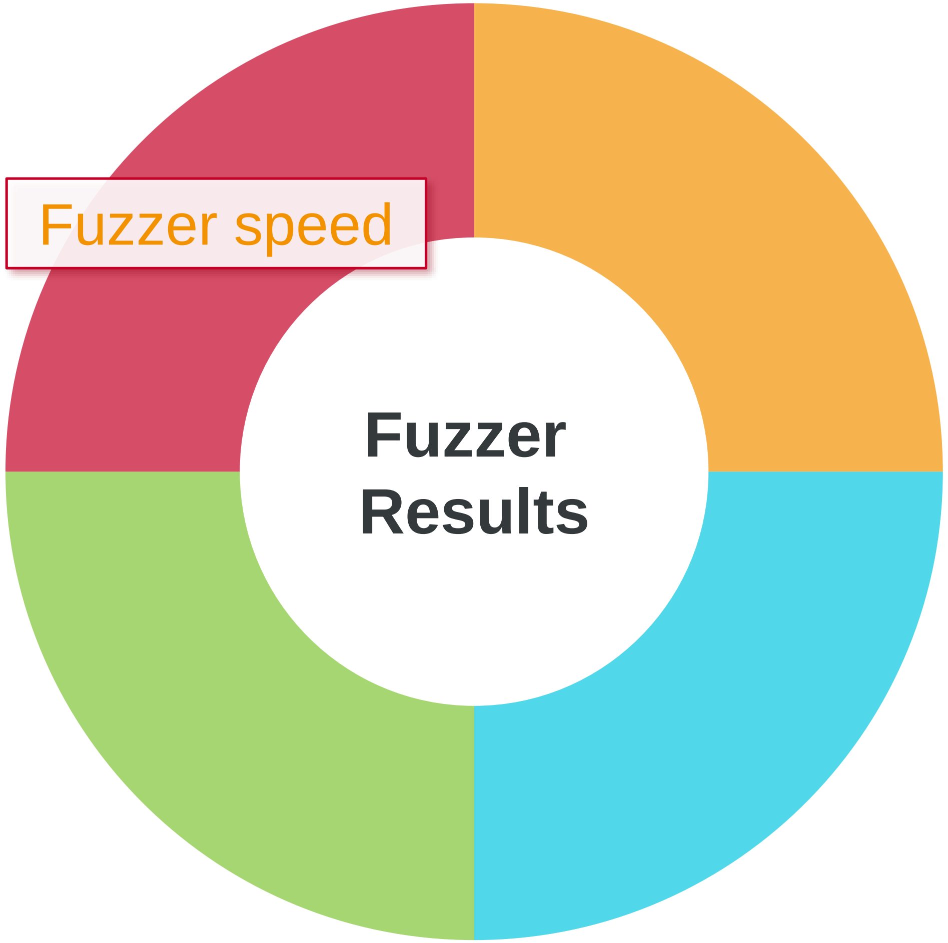
AFL-tmin & AFL-cmin
Heat maps via Taint Analysis and Shadow Memory
…



Page heap / Heap libs
Sanitizers (ASAN, MSAN, SyzyASan, DrMemory, ..)
Dangling Pointer Check
Writeable Format Strings Check
…

Application aware mutators
Generated dictionaries
Append vs. Modify mode
Grammar-based mutators
Use of feedback from application
…

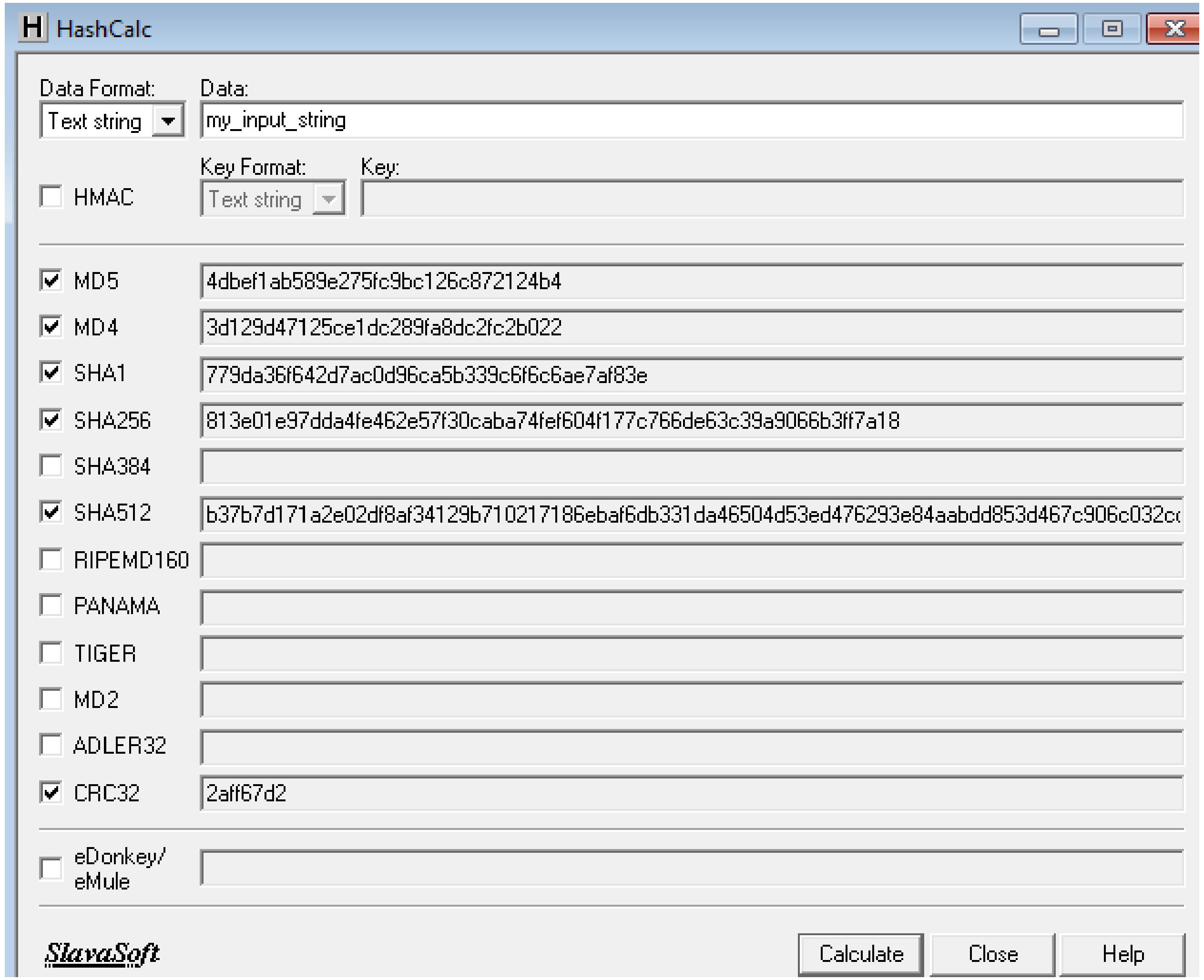
Areas which influence fuzzing results



Fuzzer Speed

1. Fork Server
2. Deferred Fork Server
3. Persistent Mode (in-memory fuzzing)
4. Prevent process switches (between target application and the Fuzzer) by injecting the Fuzzer code into the target process
5. Modify the input in-memory instead of on-disk
6. Use a RAM Disk
7. Remove slow API calls

GUI automation – Example HashCalc



Question 1:
What is the maximum MD5 fuzzing speed with GUI automation?

Question 2:
How many MD5 hashes can you calculate on a CPU per second?

GUI automation

- **HashCalc.exe MD5 fuzzing**
- GUI automation with AutoIt: ~**3 exec / sec**
- In-Memory with debugger: **~750 exec / sec**
- In-Memory with DynamoRio (no instr.): **~200 000 exec / sec**

WinAFL

- **How to find the target function without source code?**

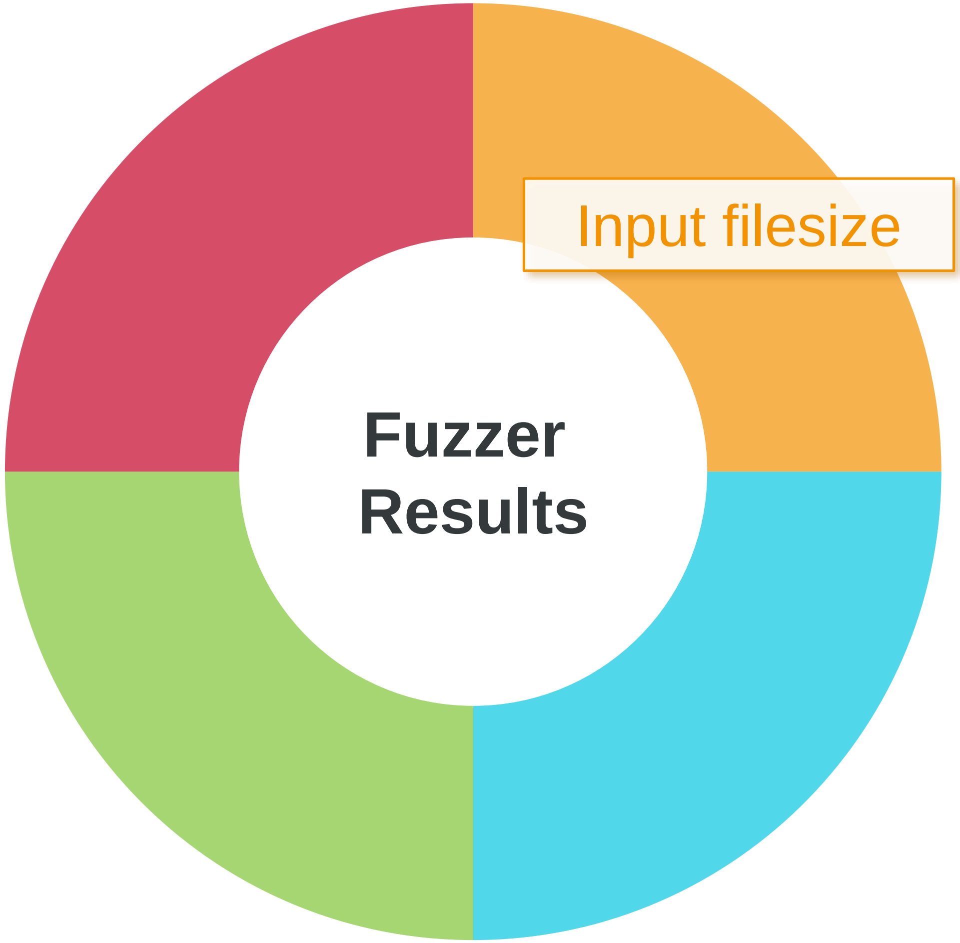
1. Measure code coverage (drrun –t drcov) in two program invocations, one should trigger the function, one not. Then substract both traces (IDA Pro lighthouse)

2. Log all calls and returns together with register and stack values to a logfile. Then search for the correct input / output combination (IDA Pro funcap or a simple DynamoRio / PIN tool)

3. Place memory breakpoints on the input

4. Use a taint engine (see later)

Areas which influence fuzzing results



Input file size

- **The input file size is extremely important!**

- Smaller files
  - Have a higher likelihood to change the correct bit / byte during fuzzing
  - Are faster processed by deterministic fuzzing
  - Are faster loaded by the target application

- AFL ships with two utilities
  - AFL-cmin: Reduce number of files with same functionality
  - AFL-tmin: Reduce file size of an input file
    - Uses a “fuzzer” approach and heuristics
    - Runtime depends on file size
    - Problems with file offsets

Input file size

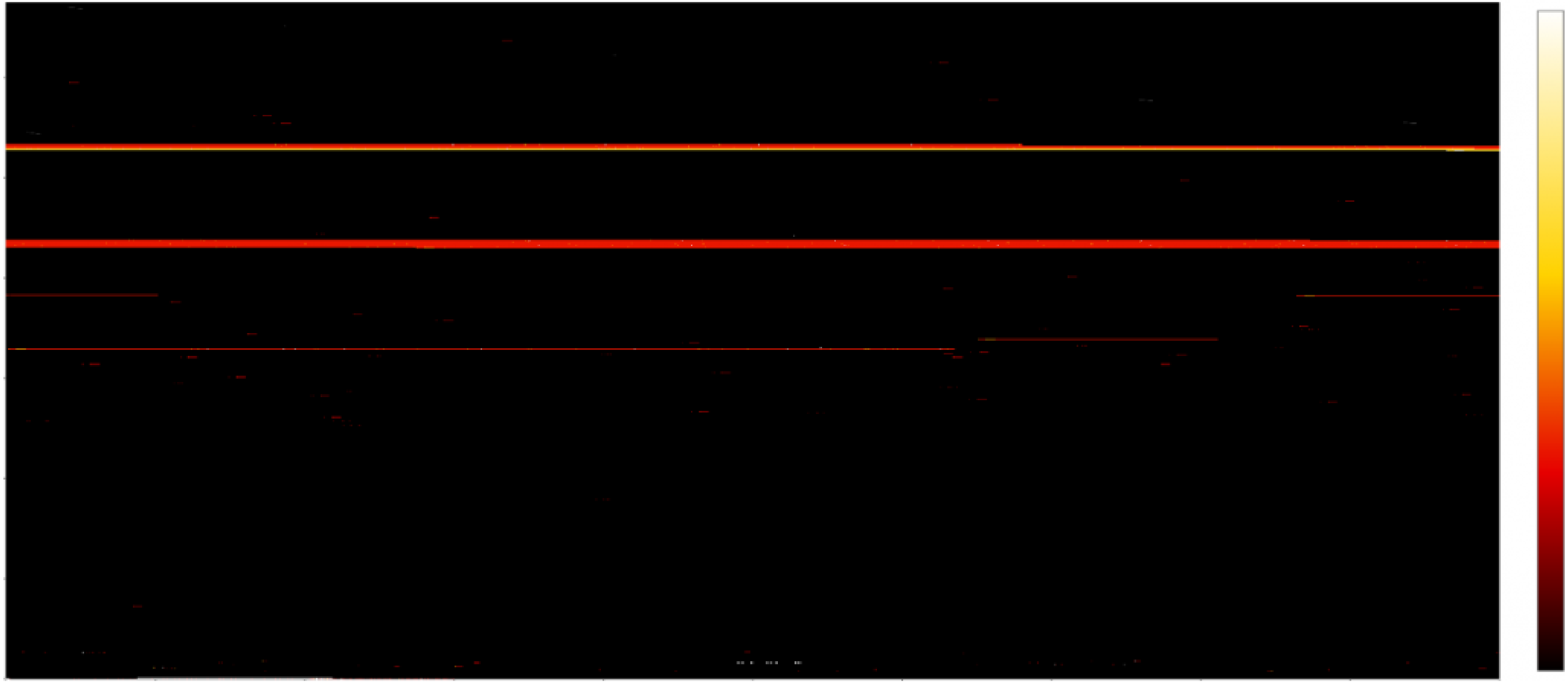
- **Example: Fuzzing mimikatz**

- Initial memory dump: **27 004 528 Byte**
- Memory dump which I fuzzed: **2 234 Byte**

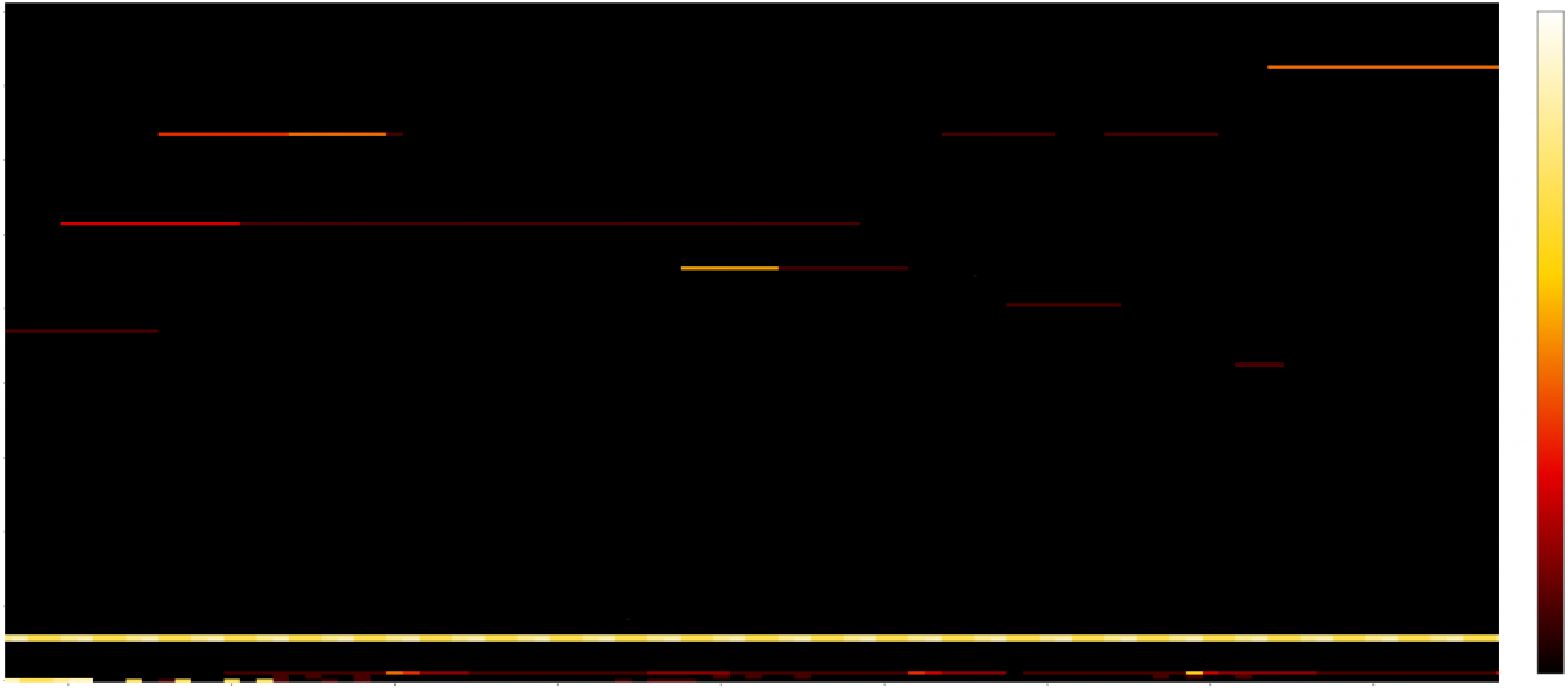
➔ **I'm approximately 12 000 times faster with this setup…**

  - You would need 12 000 CPU cores to get the same result in the same time as my fuzzing setup with one CPU core
  - Or with the same number of CPU cores you need 12 000 days (~33 years) to get the same result as I within one day
  - In reality it's even worse, since you have to do everything again for every queue entry (exponential)

Heat map of the memory dump (mimikatz access)

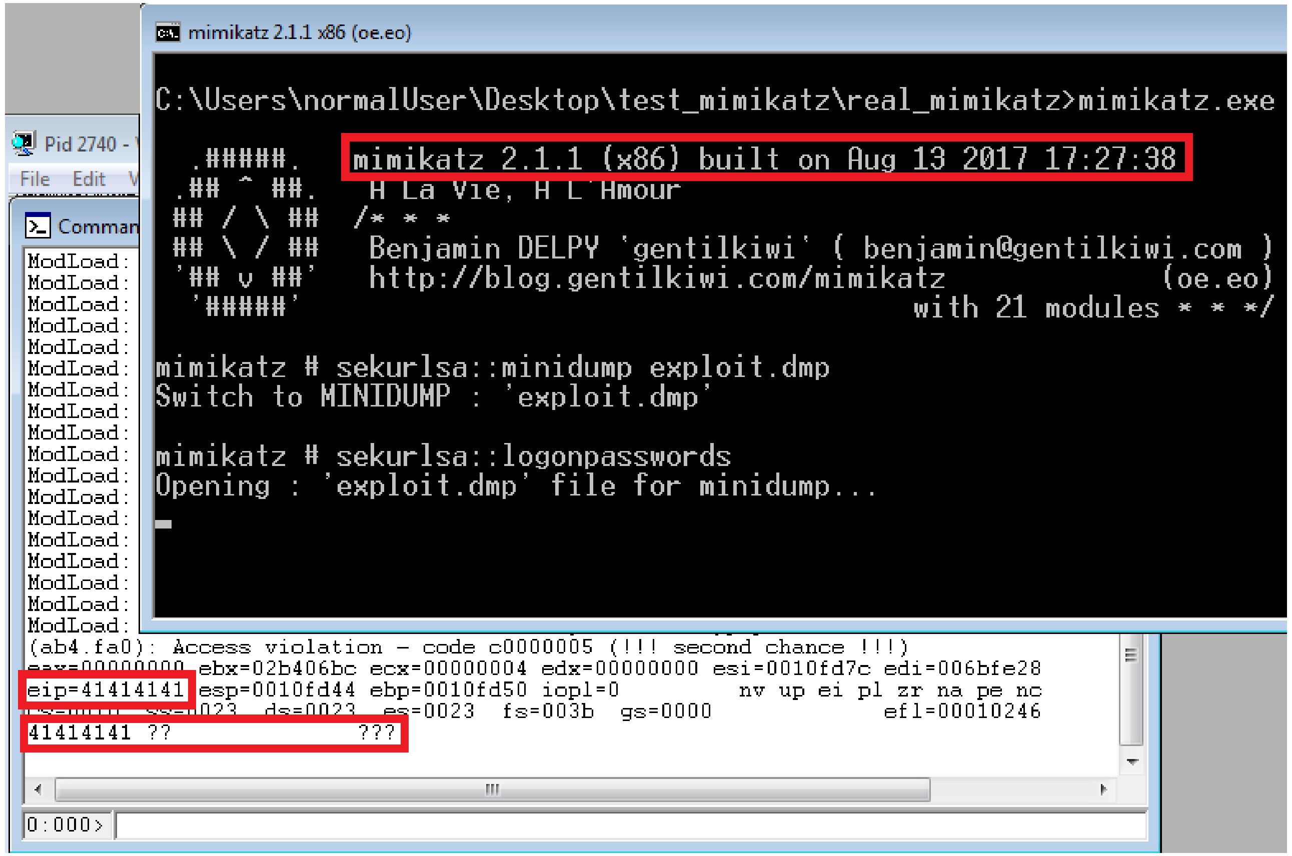


Heat map of the memory dump (mimikatz access) - Zoomed



Fuzzing and exploiting mimikatz

See below link for in-depth discussion how I fuzzed mimikatz with WinAFL:
https://www.sec-consult.com/en/blog/2017/09/hack-the-hacker-fuzzing-mimikatz-on-windows-with-winafl-heatmaps-0day/index.html



Creation of heatmaps

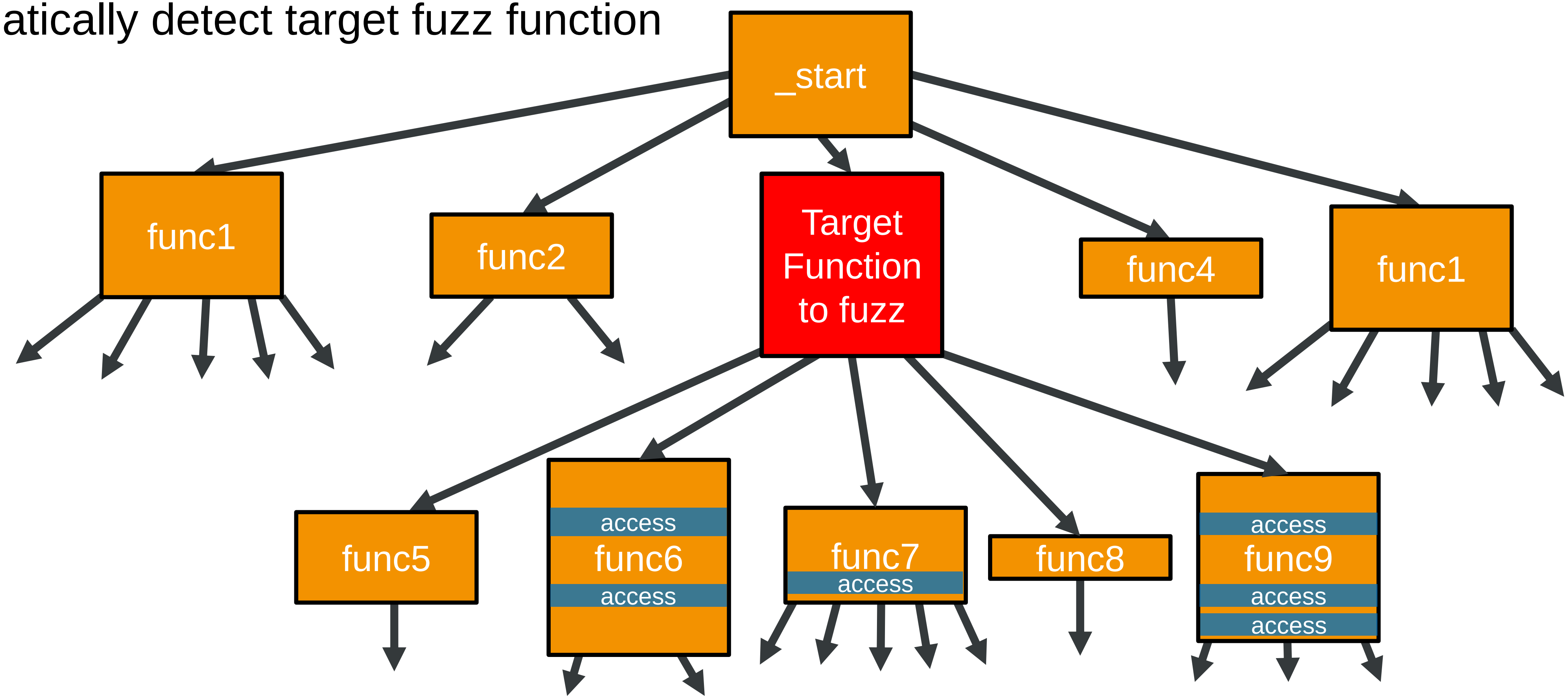
- For mimikatz I used a WinAppDbg script to extract file access information
  - Very slow approach because of the Debugger
  - Can't follow all memory copies ➔ Hitcounts are not 100% correct

- Better approach: Use dynamic instrumentation / emulation
  - libdft
  - Triton
  - Panda
  - Manticore
  - Own PIN / DynamoRio tool

Combine Call-Graph with Taint-Analysis

➔ We can write a DynamoRio/PIN tool which tracks calls and taint status

➔ Automatically detect target fuzz function



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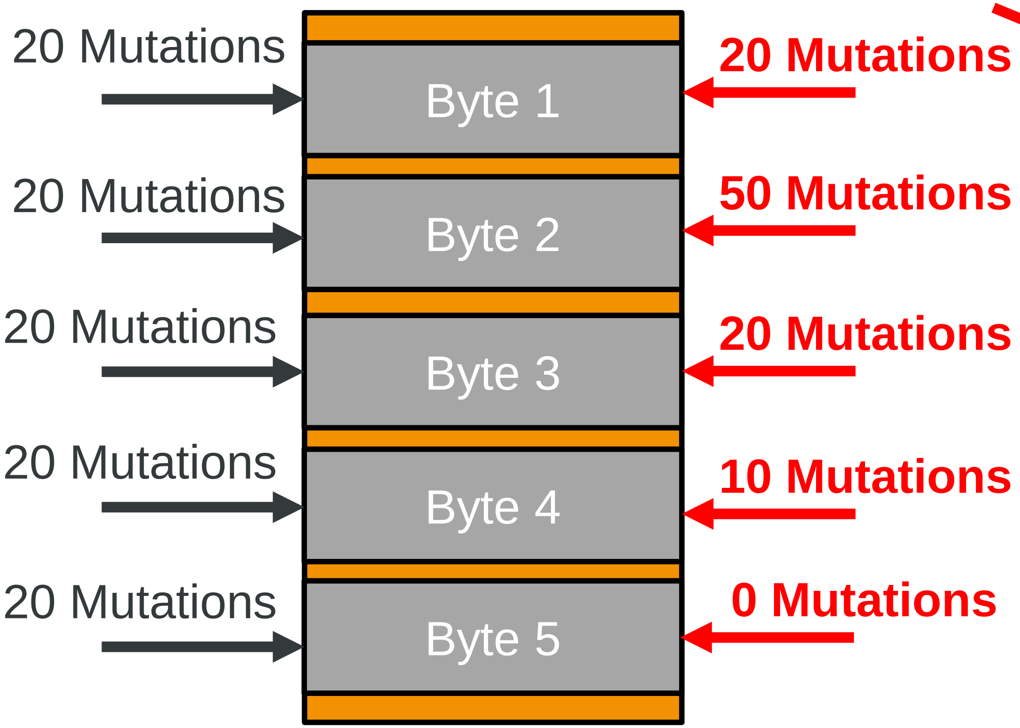
Fuzzing with taint analysis

1. Typically byte-modifications are uniform distributed over the input file
2. With taint analysis we can distribute it uniform over the tainted instructions!

If this sets EFLAGS and can change a cc jump, it should give an extra boost…

Maybe don‘t fuzz this at all X2 is maybe a copy / search function



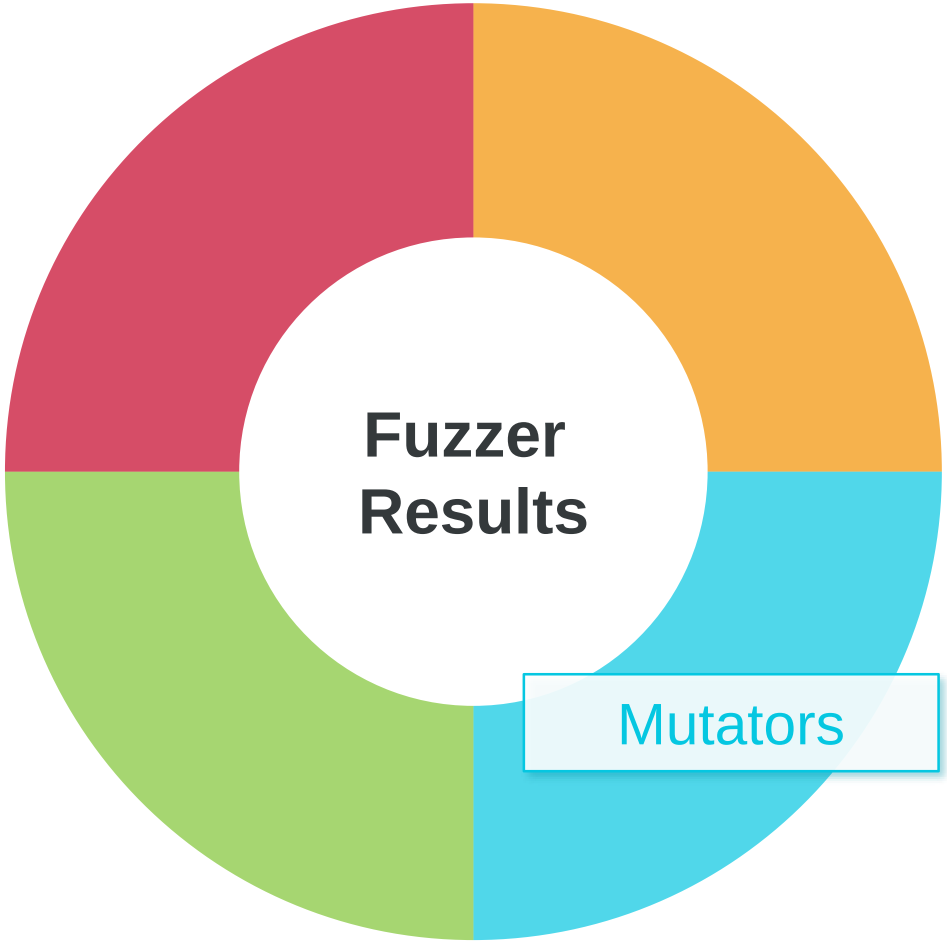
Instruction X1: Read byte 2
Instruction X2: Read byte 1,2,3,4
Instruction X3: Read byte 2
Instruction X4: Read byte 1,2
Instruction X5: Read byte 2,3

Byte 1 read by 2 instructions	2/10 = 20%
Byte 2 read by 5 instructions	5/10 = 50%
Byte 3 read by 2 instructions	2/10 = 20%
Byte 4 read by 1 instruction	1/10 = 10%
Byte 5 read by 0 instructions	0/10 = 0%

The power of dynamic instrumentation frameworks

- ➔ Automatically detect target fuzz function
- ➔ Taint engine can be used on first fuzz iteration ➔ All writes can be logged with the address to revert the memory state for new fuzz iterations
- ➔ Enable taint engine logging only for new code coverage ➔ Automatically detect which bytes make the new input unique and focus on fuzzing them!
- ➔ Call-instruction logging can be used to find interesting functions
  - Malloc / Free functions (to automatically change to own heap implementation)
    - Own heap allocator can free all chunks allocated in a fuzz iteration ➔ No mem leaks
    - Better vulnerability detection (see later slides)
  - Compare functions ➔ Return the comparison value to the fuzzer
  - Checksum functions ➔ Automatically “remove” checksum code
  - Error-handling functions
- ➔ Focus fuzzing on promising bytes

Areas which influence fuzzing results



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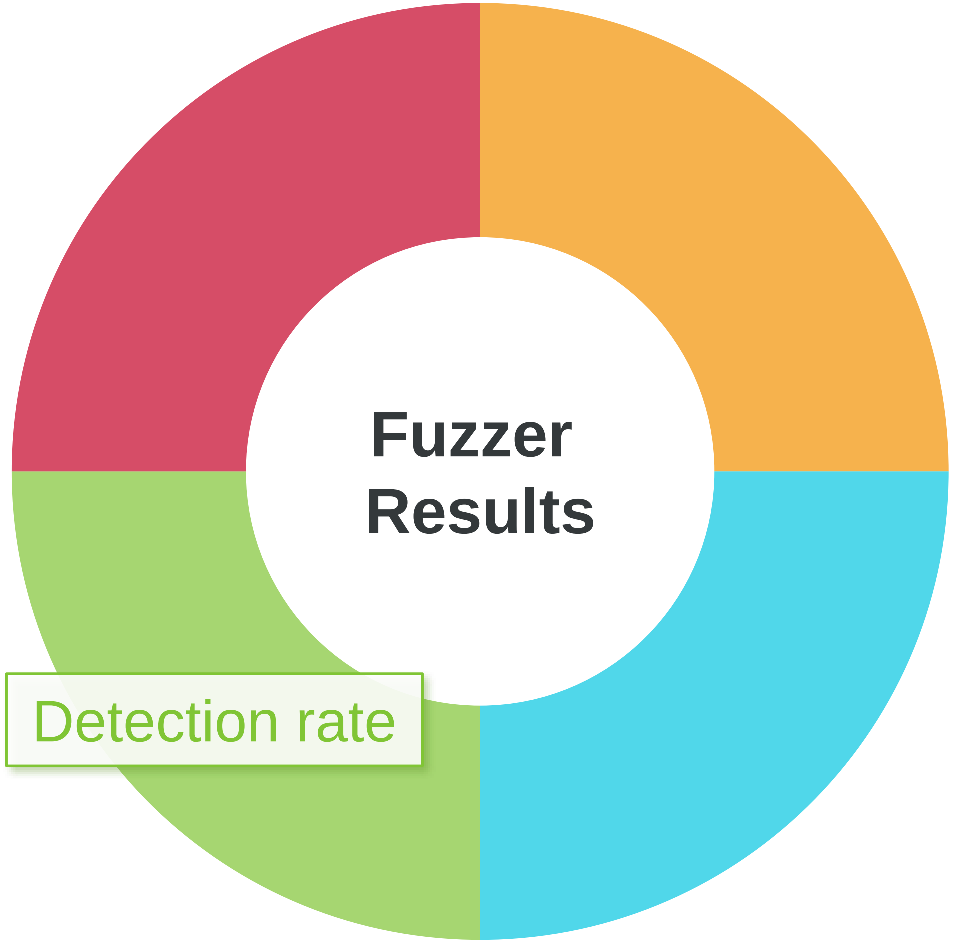
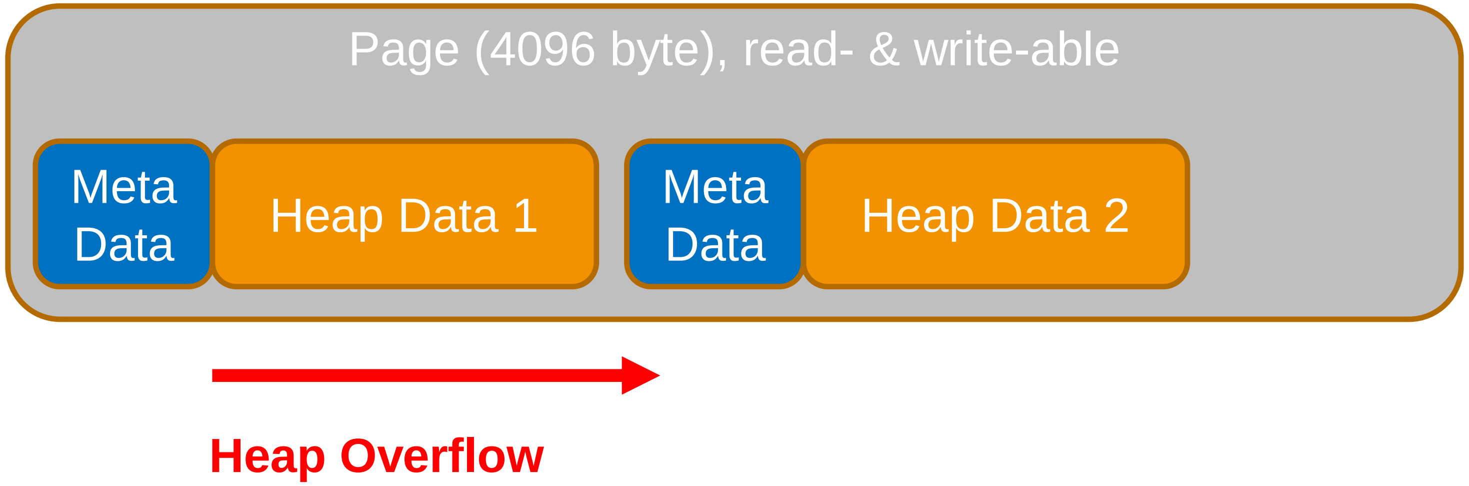
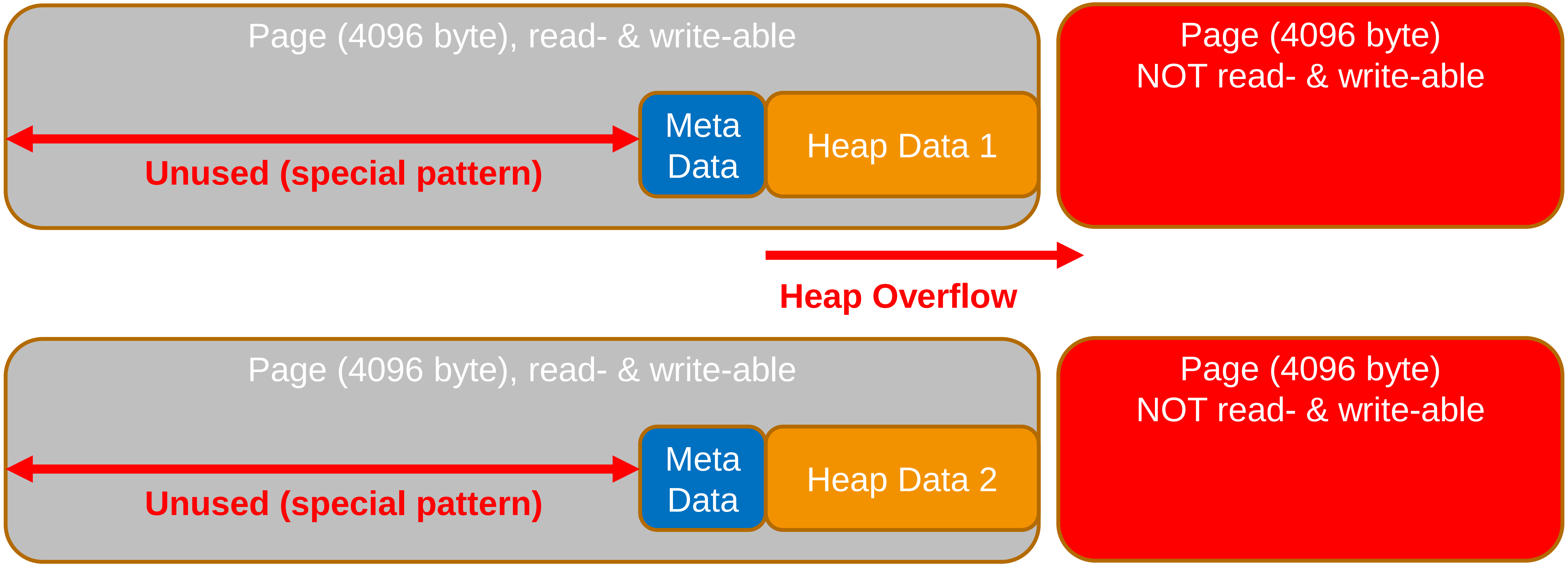


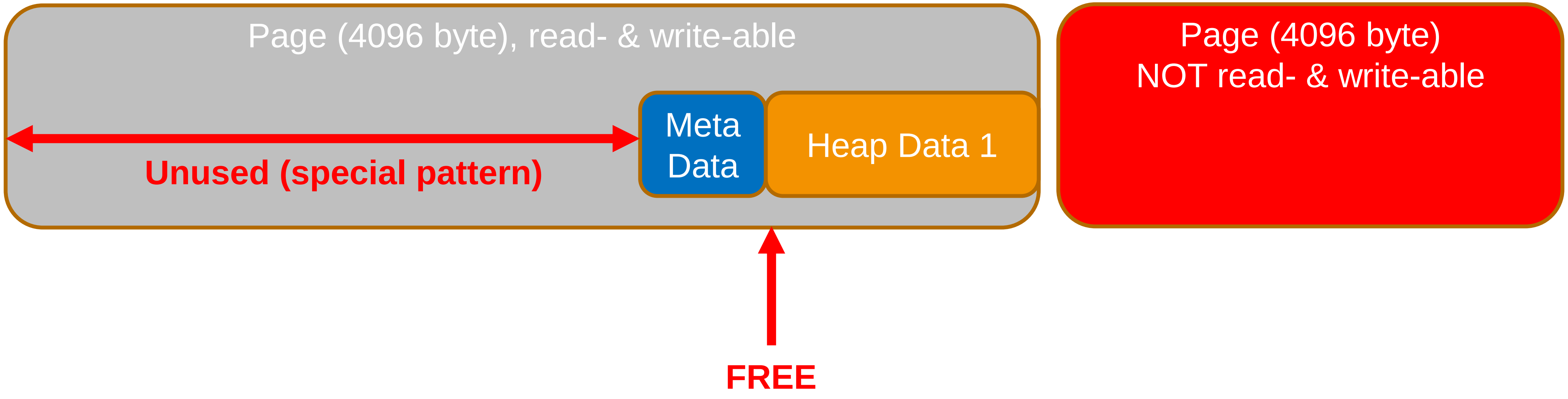
Heap Overflow Detection



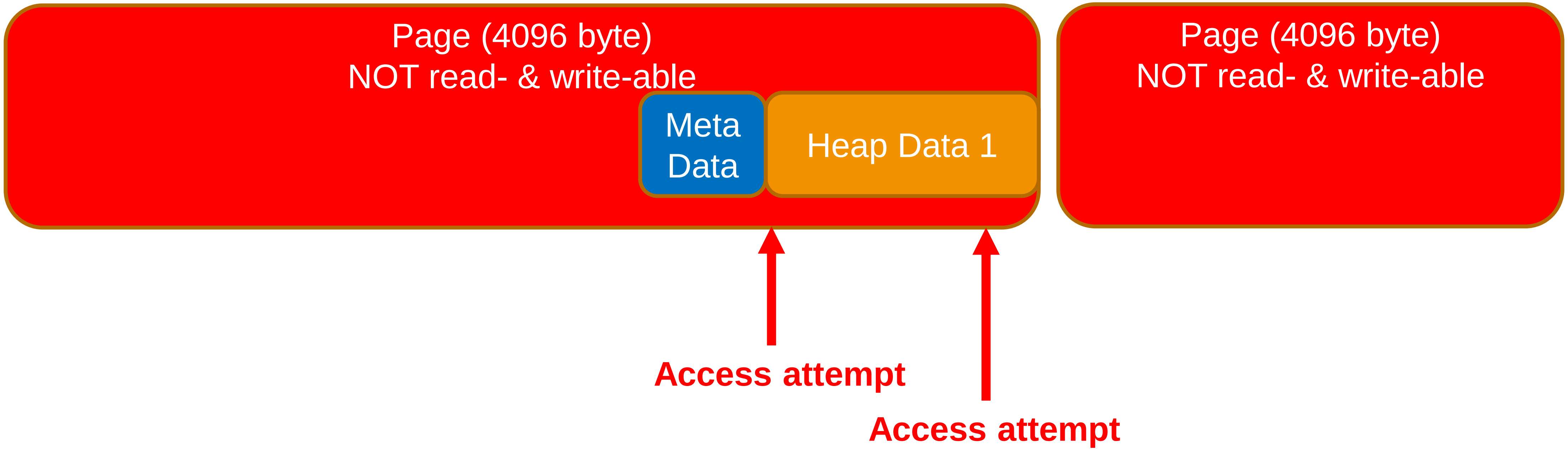
Heap Overflow Detection



Use-After-Free Detection



Use-After-Free Detection



Heap Library

- **Libdislocator** (shipped with AFL)
- https://github.com/DhavalKapil/libdheap
- AFL_HARDEN=1 make (Fortify Source & Stack Cookies)
- On Windows: **Page heap with Application Verifier**
- **Own heap allocator** which checks after free() all memory locations for a dangling pointer!
    - Detect Use-After-Free at free and not at use step
    - Concept similar to MemGC protection from Edge

Detecting not crashing vulnerabilities

- **LLVM has many useful sanitizers!**
  - Address-Sanitizer (ASAN)
    - -fsanitize=address
    - Out-of-bounds access (Heap, stack, globals), Use-After-Free, …
  - Memory-Sanitizer (MSAN)
    - -fsanitize=memory
    - Uninitialized memory use
  - UndefinedBehaviorSanitizer (UBSAN)
    - -fsanitize=undefined
    - Catch undefined behavior (Misaligned pointer, signed integer overflow, …)

- **DrMemory (based on DynamoRio) if source code is not available**

➔ <u>Use sanitizers during development !!!</u>

Detecting not crashing vulnerabilities

- **During corpus generation don’t use sanitizers ➔** performance
  - After we have a good corpus, start fuzzing it with sanitizers / injected libraries
  - I prefer heap libraries because they are faster and run after the first fuzzing session the corpus against binaries with sanitizers for some days
  - I don’t use heap libraries for the master fuzzer (deterministic fuzzing must be fast)

- AFL performance example; one core; no in-memory fuzzing:
  - x64 binary: 1400 exec / sec
  - x86 binary: 1200 exec / sec
  - x86 hardened binary: 1150 exec / sec
  - x86 hardened binary + libdislocator: 600 exec / sec
  - x86 binary with Address Sanitizer: 200 exec / sec

Rules for fuzzing

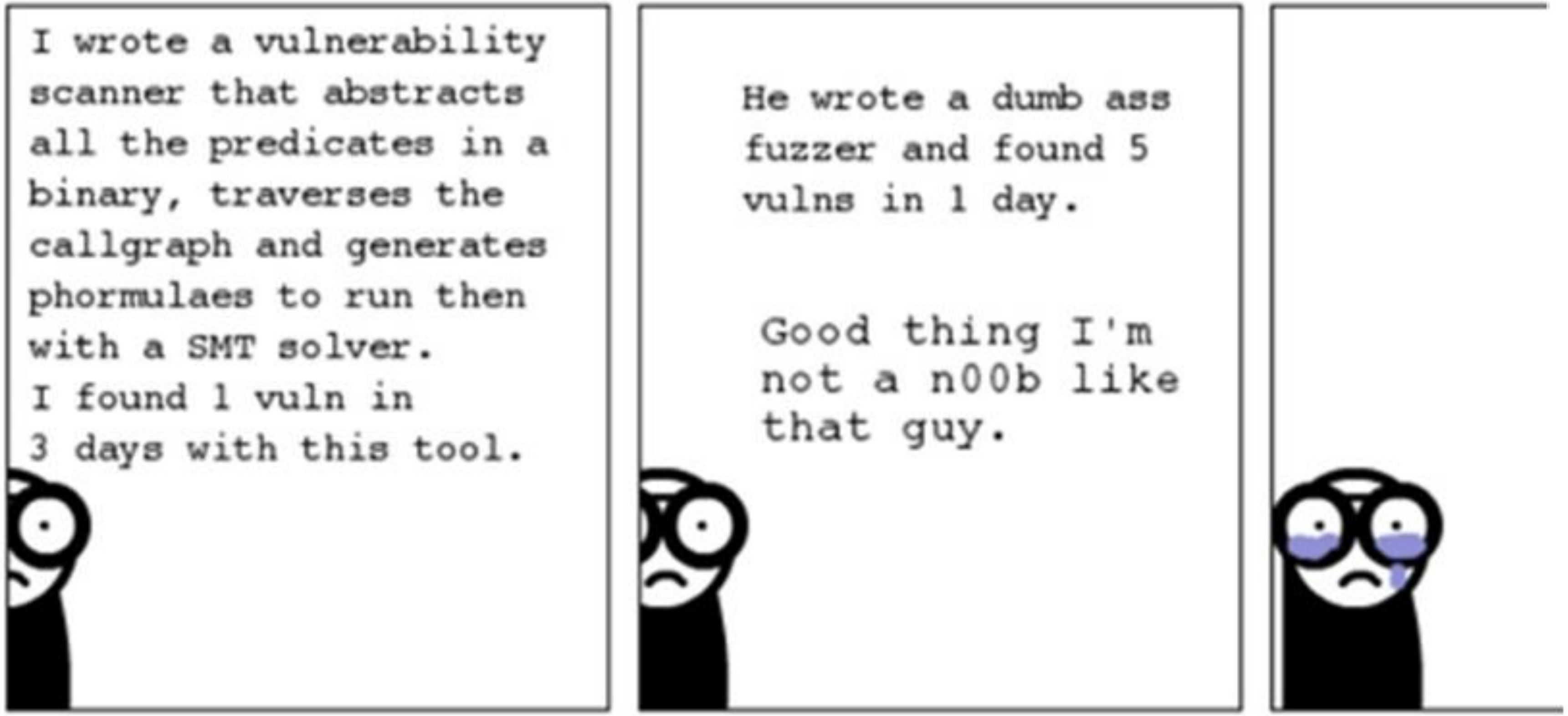
Fuzzing rules

1. Start fuzzing!
2. Start with simple fuzzing, during fuzzing add more logic to the next fuzzer version
3. Use Code/Edge Coverage Feedback
4. Create a good input corpus (via download or feedback)
5. Minimize the number of sample files and the file size
6. Use sanitizers / heap libraries during fuzzing (not for corpus generation)
7. Modify the mutation engine to fit your input data
8. Skip the “initialization code” during fuzzing (fork-server, persistent mode, …)
9. Use wordlists to get a better code coverage
10. Instrument only the code which should be tested
11. Don’t fix checksums inside your Fuzzer, remove them from the target application (faster)
12. Start fuzzing!

A last hint…

Fuzzing can show the presence bugs but <u>can't</u> prove the absence of bugs!

Thank you for your attention!



Source: Twitter

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For any further questions contact **your SEC Consult Expert.**

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