An Introduction to Fuzzing and a Direct Application to the Real World

Leonardo Galli

flagbot (ctf@vis.ethz.ch)

October 15, 2021

What does this ... have to do with this?

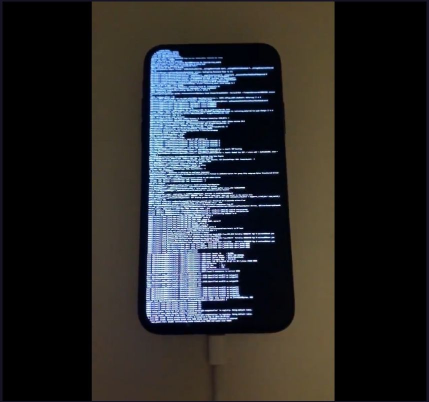

Table of Contents

About Me

- Finished my Bachelor of Computer Science at ETH
- Member of flagbot since over three years
- President of flagbot since over two years
- Lead `organizer` since half a year

Leonardo Galli
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About flagbot

- VIS committee and ETH's Capture the Flag team
  - CTFs are team-based cybersecurity competitions, often involving real-world attacks
- Ranked 1^{st} place in Switzerland in 2019 and 2020[1]
- Playing CTFs on weekends
- Weekly meetings on Monday at 19:00 over Zoom and in person at CAB H52, open to anyone
  - Discussion of challenges and lectures aimed at beginners (recordings available on `flagbot.ch/material`)

Contact: ctf@vis.ethz.ch

More Information: `flagbot.ch`

[1] According to `ctftime.org`

About organizers

- Joint team between flagbot, polygl0ts (EPFL), cr0wn (UK) and secret.club
- Team up together for larger events
- Currently ranked 7th worldwide[2]
- Multiple big wins, such as best European team at DEF CON and #1 at Tencent CTF 2021

```
     ,aooooa,
   ,oY"'  '"Yo,
  ,oY00      Yo,
  oo  ORG     oo
  oo   ANI    oo
  oo   {S|Z}  oo
  oo     ERS  oo
  `ob      00do'
   `oba,  ,ado'
     "YooooY"
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Contact: org@anize.rs
Website: `org.anize.rs`

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Introduction

Motivation

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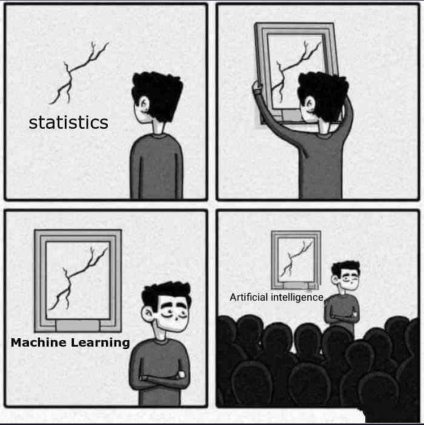

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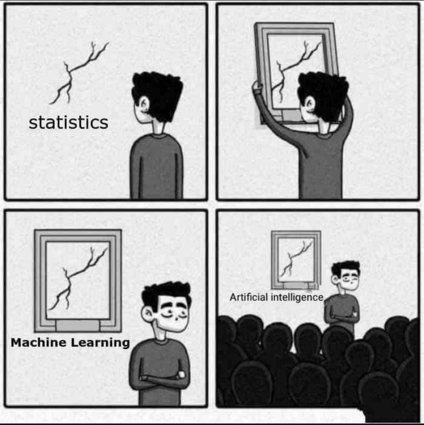

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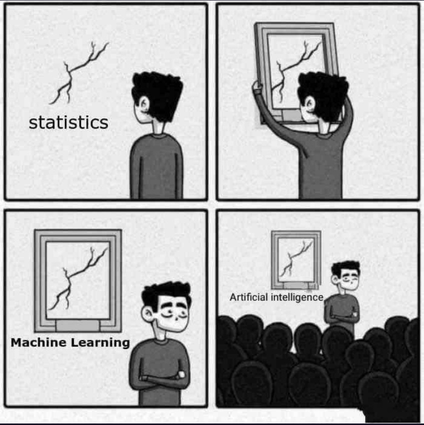

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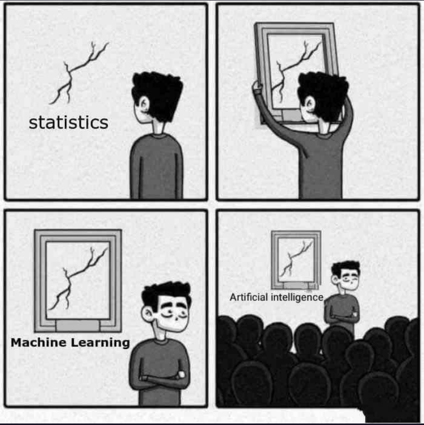

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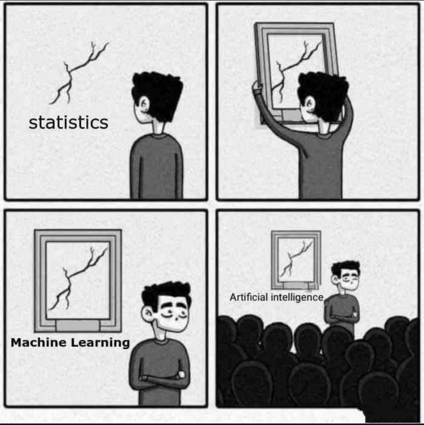
- OSS-Fuzz provides continuous fuzzing for OSS
  - "As of February 2021, 26,000+ bugs found in over 400 open source projects integrated with OSS-Fuzz." [2]



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Fuzzing

Basic Idea

Almost the right kind of fuzzy[3].

[3] Depending on the context.

Basic Idea

- Basic fuzzing loop:

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$\Longrightarrow$ **Any observed crashes indicate presence of bugs**

- Not necessarily any vulnerabilities yet, more on that later

Fuzzing
Types of Fuzzing

Overview

- Fuzzing encompasses broad spectrum of techniques
- Three important ways of categorizing fuzzers

1. How input is generated
   - Mutate existing input
   - Generate from scratch
   - Usually mutation based
2. Awareness of input structure
3. Awareness of application structure

Awareness of Input Structure

- Fuzzing input can be anything, not just text
- Inputs should have certain structures
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- A "dumb" fuzzer does no such thing
- Modern fuzzers usually use a combination of both

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  - Cannot be applied to every application without significant effort

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- Support for most program configurations

Fuzzing
Getting Started with Fuzzing

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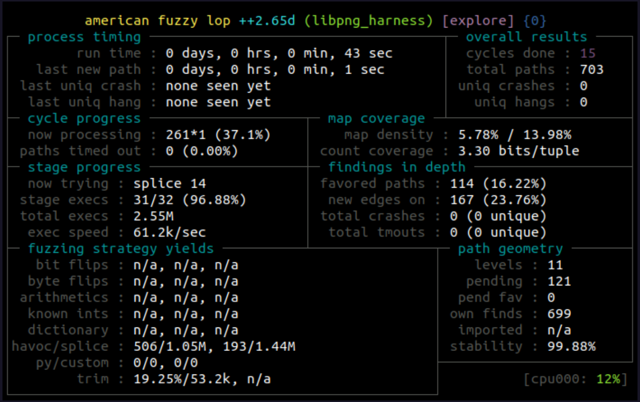
- **Here:** assume AFL++ used

AFL++

- Based on American Fuzzy Lop (AFL)



The famous AFL TUI

AFL++

- Based on American Fuzzy Lop (AFL)
- Most well known coverage-guided grey-box fuzzer

```
         american fuzzy lop ++2.65d (libpng_harness) [explore] {0}
┌─ process timing ────────────────────────────────────┬─ overall results ────┐
│        run time : 0 days, 0 hrs, 0 min, 43 sec      │  cycles done : 15    │
│   last new path : 0 days, 0 hrs, 0 min, 1 sec       │  total paths : 703   │
│ last uniq crash : none seen yet                     │ uniq crashes : 0     │
│  last uniq hang : none seen yet                     │   uniq hangs : 0     │
├─ cycle progress ───────────────────┬─ map coverage ─┴──────────────────────┤
│  now processing : 261*1 (37.1%)    │    map density : 5.78% / 13.98%       │
│ paths timed out : 0 (0.00%)        │ count coverage : 3.30 bits/tuple      │
├─ stage progress ───────────────────┼─ findings in depth ───────────────────┤
│  now trying : splice 14            │ favored paths : 114 (16.22%)          │
│ stage execs : 31/32 (96.88%)       │  new edges on : 167 (23.76%)          │
│ total execs : 2.55M                │ total crashes : 0 (0 unique)          │
│  exec speed : 61.2k/sec            │  total tmouts : 0 (0 unique)          │
├─ fuzzing strategy yields ──────────┴─────────────┬─ path geometry ────────┤
│   bit flips : n/a, n/a, n/a                      │    levels : 11         │
│  byte flips : n/a, n/a, n/a                      │   pending : 121        │
│ arithmetics : n/a, n/a, n/a                      │  pend fav : 0          │
│  known ints : n/a, n/a, n/a                      │ own finds : 699        │
│  dictionary : n/a, n/a, n/a                      │  imported : n/a        │
│havoc/splice : 506/1.05M, 193/1.44M               │ stability : 99.88%     │
│   py/custom : 0/0, 0/0                           ├────────────────────────┘
│        trim : 19.25%/53.2k, n/a                  │          [cpu000: 12%]
└──────────────────────────────────────────────────┘
```

The famous AFL TUI

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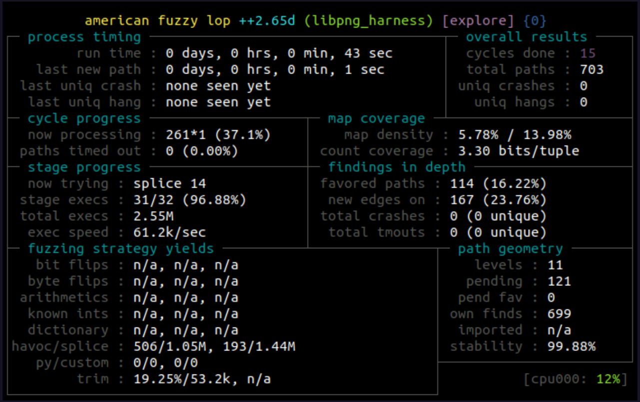
- Based on American Fuzzy Lop (AFL)
- Most well known coverage-guided grey-box fuzzer
- Uses execution tracing, comparison coverage and simple constraint solving to mutate input



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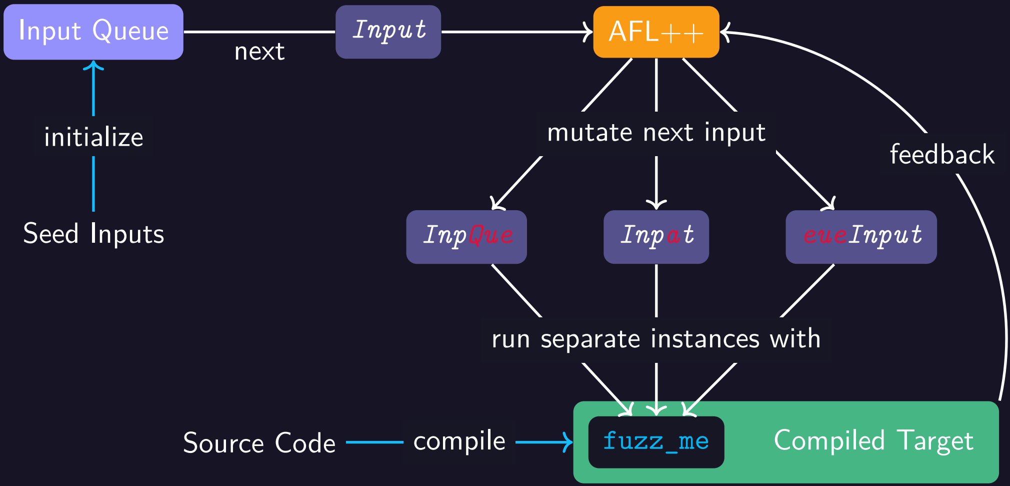
AFL++ Schematic



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  - Wide range, no inputs should be very similar

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  - Complex parsing, many corner cases, etc.
  - Often makes sense to throw fuzzing at only parts of the program
- Remove potentially difficult-to-fuzz features
  - Checksums, cryptography, etc. lead to many invalid inputs
  - Usually also slow down fuzzing
  - Better to fully remove, to speed up fuzzing

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- Sanitizers help by crashing when common security issues occur
  - Increases chances that crashes correspond to vulnerabilities
  - Still not guaranteed, hence manual triaging is always required

Fuzzing

Binary-only Fuzzing

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- **Question:** What if you "lost" access to your source code?[3]

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- **Solution:** Can use tools like RetroWrite to statically rewrite binary with instrumentation
  - Results in faster fuzzing
  - Much more tricky to do
  - Still active area of research

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Fuzzing the iPhone Boot Loader

Motivation

- iPhone security major talking point in the press
  - "Apple Issues Emergency Security Updates to Close a Spyware Flaw" [7]
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$\Longrightarrow$ **Vulnerabilities in the iPhone boot loader are highly sought after.**

- **Goal:** Apply state-of-the-art fuzzing to iPhone boot loader

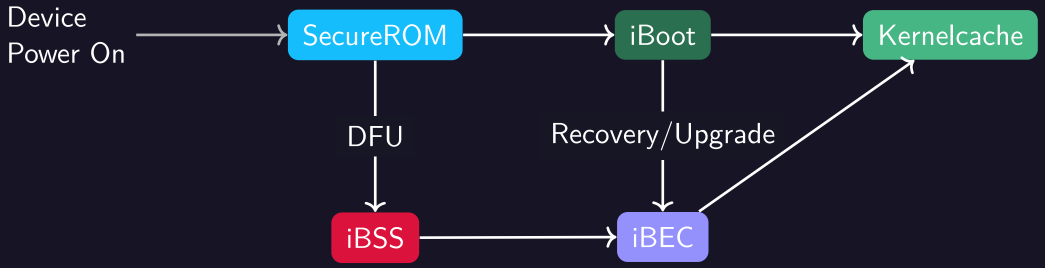
Fuzzing the iPhone Boot Loader

Background

iPhone Boot Sequence

- Boot loader responsible for initializing hardware and setting up everything for the main OS to run
- Consists of multiple stages on iPhones
- Stages form a secure boot chain
  - Every stage loads, verifies and runs next one
  - Verification uses standard X.509 certificate chains, RSA signatures
  - Every stage is stored in a custom format, called IMG4

Schematic Boot Diagram



Schematic view of the iOS boot sequence and its boot loader stages adapted from [5].

Fuzzing the iPhone Boot Loader
Threat Model

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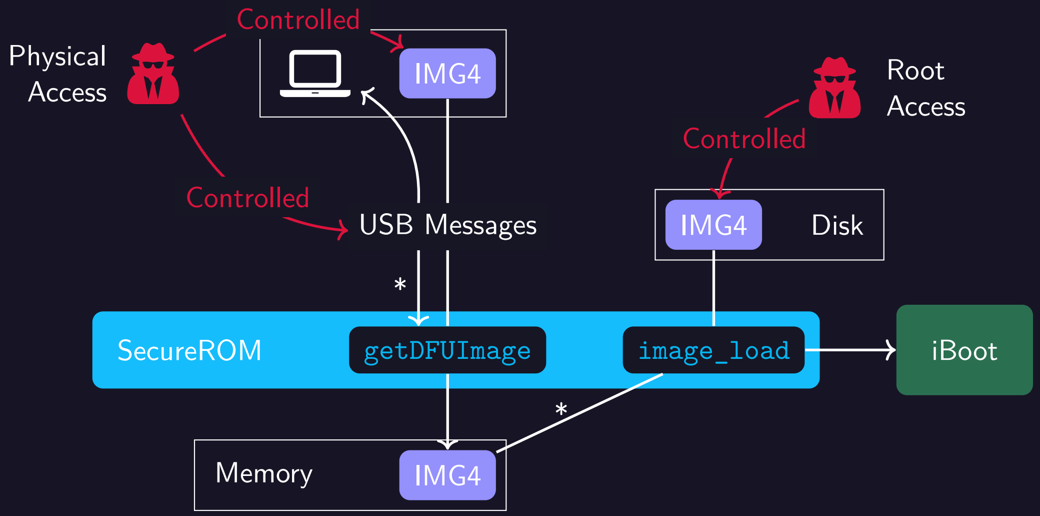
- We assume the physical access threat model

Schematic Threat Model



Fuzzing the iPhone Boot Loader

Building a Fuzzable Binary

Challenges

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- Bare metal or bust

Solution: Static Analysis

```
__int64 sub_100009BCC(char *a1)
{
  sub_1000127BC();
  if (a1 == aKsat || a1 == &unk_19C0107C0)
    sub_100008F90();
  if (*((_QWORD *)a1 + 3) || *((_QWORD *)a1 + 4))
    sub_100009C50(a1 + 24);
  sub_100009C50(a1 + 8);
  v3 = sub_100001C14(a1);
  sub_100012810(v3);
  return sub_10000FEF4(a1);
}
```

Solution: Static Analysis

```c
void task_destroy(struct task *a1)
{
  enter_critical_section();
  if (a1 == &bootstrap_task || a1 == &idle_task)
    panic();
  if (a1->queue_node.prev || a1->queue_node.next)
    list_delete(&a1->queue_node);
  list_delete(&a1->task_list_node);
  arch_task_destroy(a1);
  exit_critical_section();
  heap_free(a1);
}
```

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Solution: Binary Patching

```
// Convert PAC branch to normal branch
r.PatchInstruction("blraaz ").Patch(r.PatchTmpl("blr {{(index .Args 0)}}"))
// Force bzero to never use dca
symb.rom__bzero.PatchOffset(0x18).Patch(r.PatchASM("cmp x2, #0x40000"))
// Override USB driver with custom one
symb.rom_synopsys_otg_controller_init.PatchOffset(0).Patch(
        r.PatchFunctionNoLink("emmutaler_controller_init")
)
// Patch in custom root certificate
certPath := filepath.Join(filepath.Dir(r.inputPath), "..", "certs", "root_ca.der")
certData, _ := os.ReadFile(certPath)
r.RawPatch(symb.rom_root_ca.Start, len(certData),
        fmt.Sprintf(`.incbin "%s"`, certPath))
```

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- **Main idea:** Create normal Linux program calling into SecureROM as necessary.

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- **Main idea:** Create normal Linux program calling into SecureROM as necessary.
- Can use existing fuzzers without modifications
- Functions interesting to fuzz do not need low-level access
- Can fuzz selectively
- Easy to debug without complicated fuzzing harness

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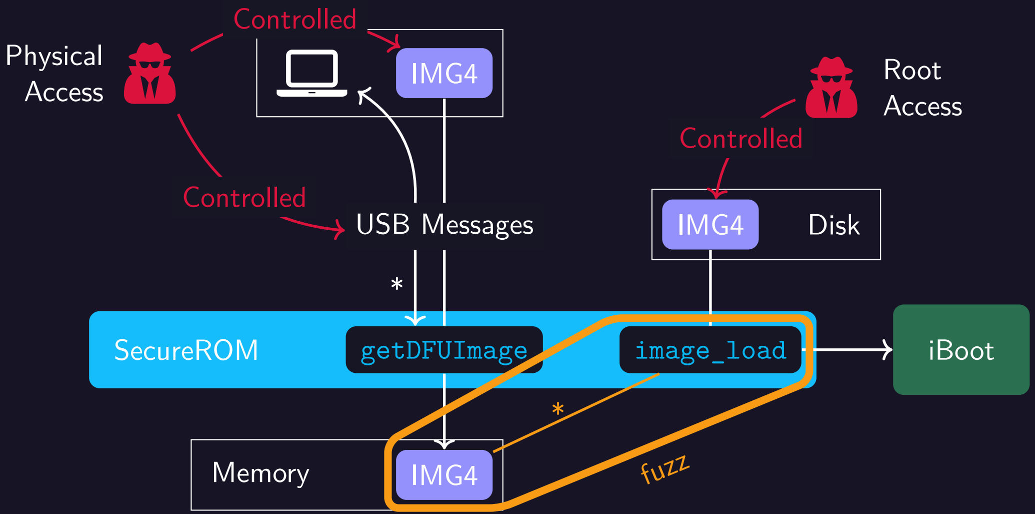
IMG4 Fuzzing



IMG4 Schematic

Schematic view of the high-level fuzzing design for IMG4 parsing.

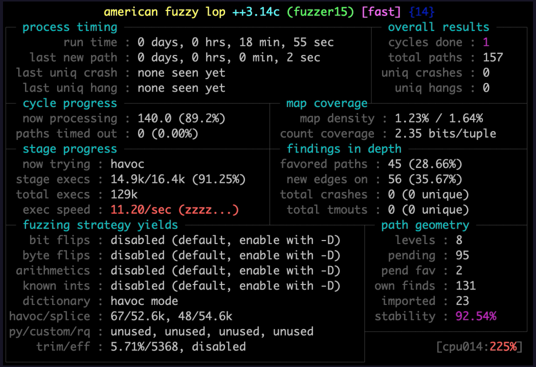
Results

- Ran for one week
- No interesting crashes
- Interesting results with respect to speed

IMG4 Fuzzing
Fuzzing Speed

Fuzzing Speed

- **Problem:** Fuzzing speed is much lower than expected



Fuzzing Speed

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```
─ cycle progress ──────────────────────
  now processing : 140.0 (89.2%)
 paths timed out : 0 (0.00%)
─ stage progress ──────────────────────
  now trying : havoc
 stage execs : 14.9k/16.4k (91.25%)
 total execs : 129k
  exec speed : 11.20/sec (zzzz...)
─ fuzzing strategy yields ─────────────
```

We get it, it is slow

Fuzzing Speed

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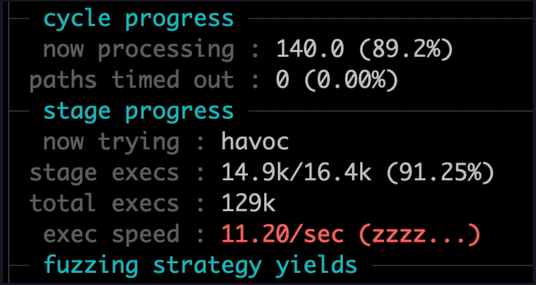
- Multiple factors:
  - Target restarted for every run



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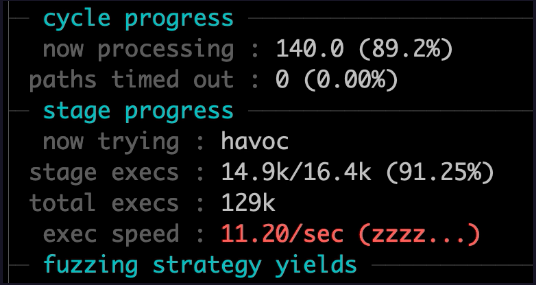

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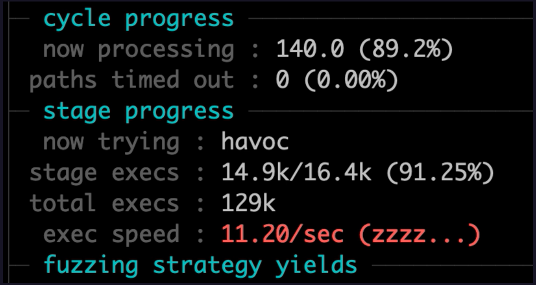

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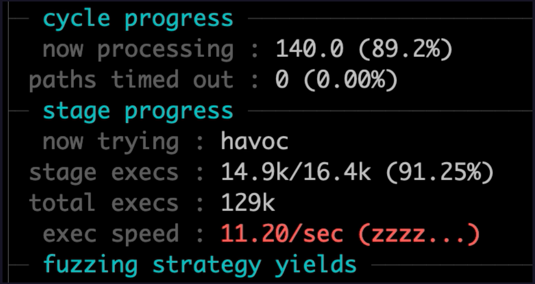
- **Solution:** Use persistent mode for *better* performance



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Persistent Mode

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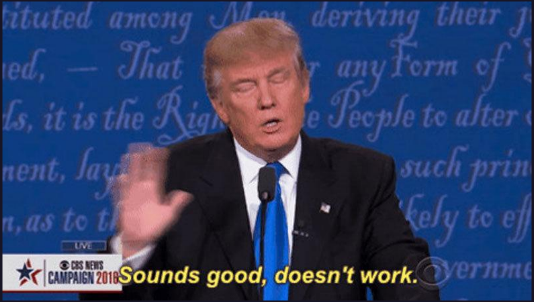

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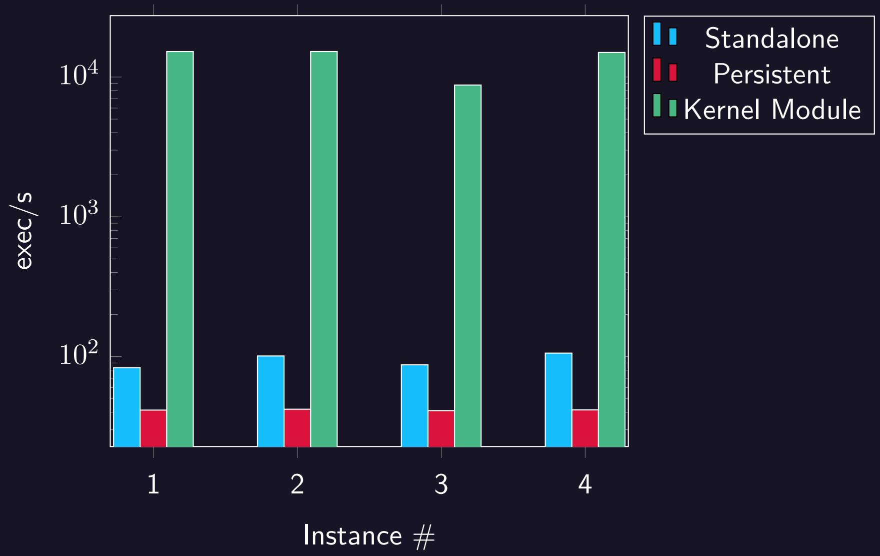
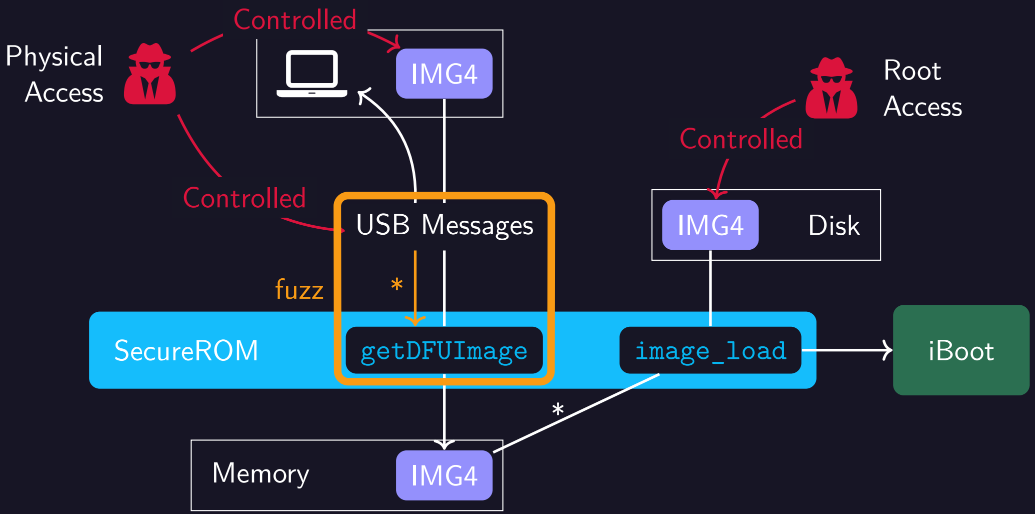
- **Solution:** Use kernel module for copy-on-write snapshotting [10]

IMG4 Fuzzing Speed Results



USB Fuzzing



Controlled
Physical
Access
IMG4
Root
Access
Controlled
Controlled
USB Messages
IMG4
Disk
fuzz
*
SecureROM
getDFUImage
image_load
iBoot
*
Memory
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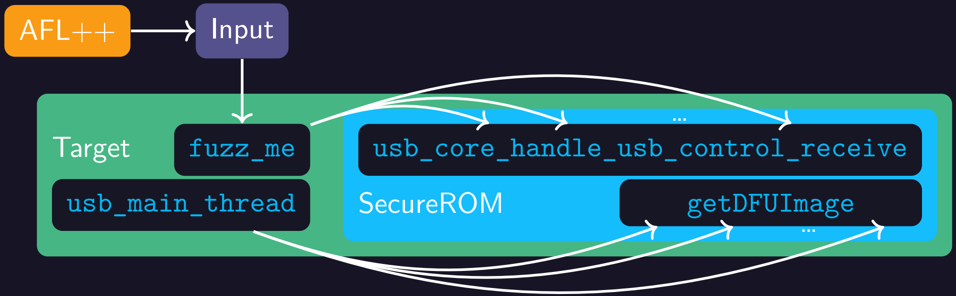
USB Schematic



Schematic view of the high-level fuzzing design for USB messages.

Short Refresher on the Heap

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- `void* ptr = malloc(100)` : allocate 100 bytes
  - Starting at `ptr` , 100 bytes of memory available for anything
  - Usually called dynamically allocated buffer
- `free(ptr)` : release memory previously allocated to be used elsewhere
  - `ptr` should not be used afterwards
  - Needed, since memory management is manual
  - Everything allocated must be freed by programmer

checkm8

Use-After-Free (UAF)

A use-after-free occurs when a pointer to a buffer on the heap is used, after said buffer has already been freed.

- Previously found vulnerability in DFU protocol titled “checkm8” [1]
- Core bug exploited: use-after-free (UAF) in DFU protocol handling
- Before this thesis, iPhone 4S to X were publicly known to exhibit the UAF bug [1].

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- Core bug exploited: use-after-free (UAF) in DFU protocol handling
- Before this thesis, iPhone 4S to X were publicly known to exhibit the UAF bug [1].
- **Goal:** Our fuzzing finds the same UAF bug
- Shows that the fuzzing is successful, since it can find bugs

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Heap Feng Shui [8]

The process of carefully manipulating the heap, allowing exploitation. It is also sometimes called "heap grooming". Usually, it consists of allocating and freeing very specific sizes in a specific order to get the heap into a very specific state.

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- checkm8 performs complicated “heap feng shui” before actual exploit
- Otherwise, exploited buffer is allocated at the same place
- Not exclusive to SecureROM
- **Solution:** Custom allocator tailored to find heap bugs that depend on specific state

USB Fuzzing

Fuzzing-Enabling Thread-safe Allocator (FETA)

FETA Overview

- Drop-in replacement for any code using `malloc` and `free`
- Thread-safe
- Can detect and crash on:
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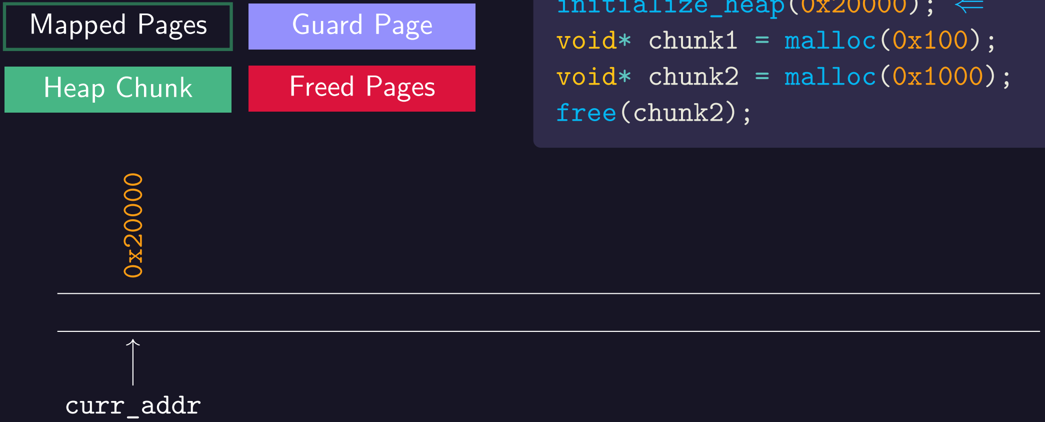
  - **Solution:** "isolate" every heap chunk to its own set of pages

Example Allocations with FETA




```
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Mapped Pages | Guard Page
Heap Chunk | Freed Pages

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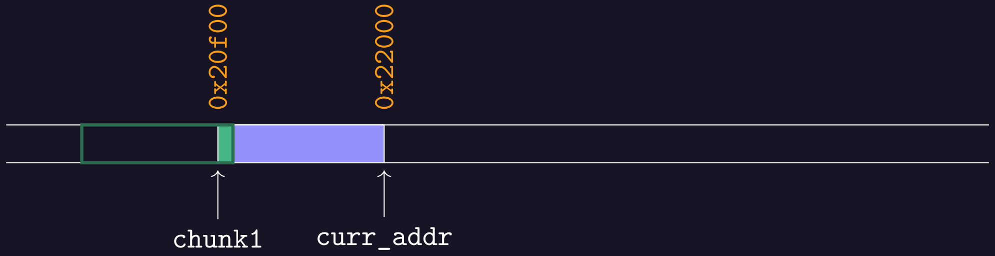

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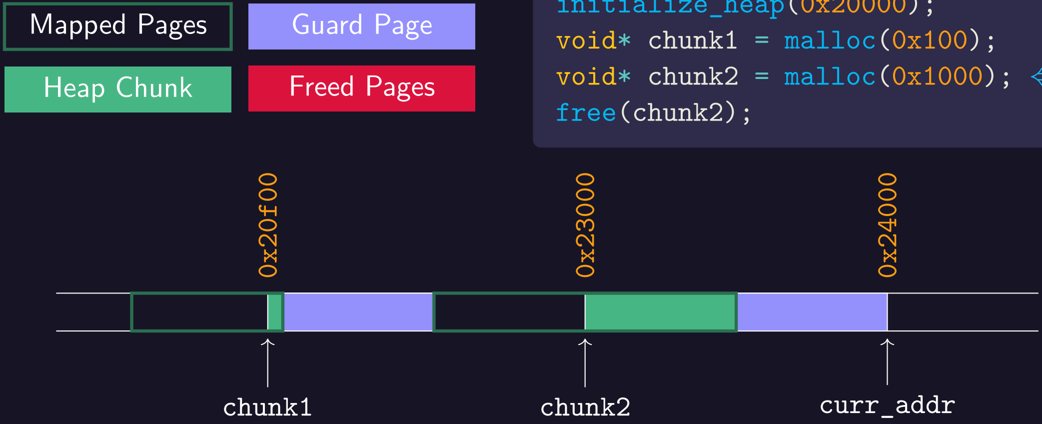


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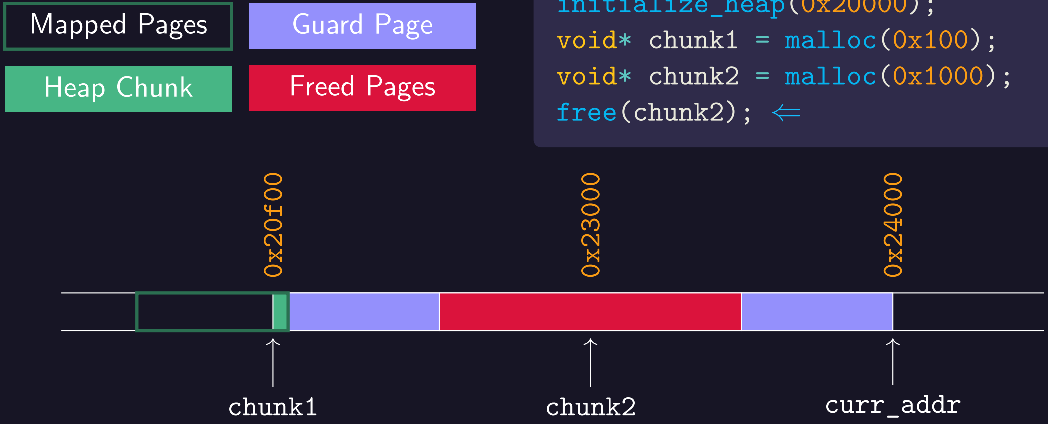


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USB Fuzzing
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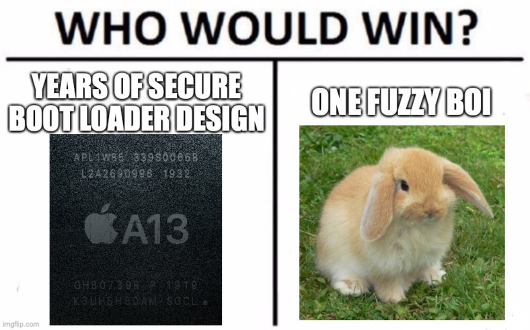

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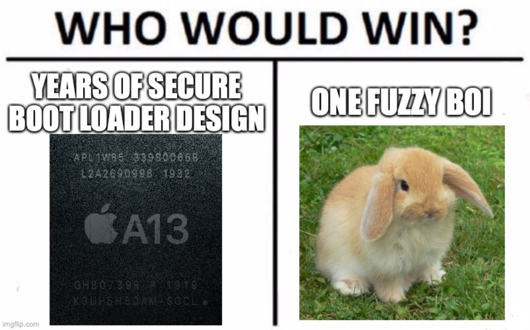

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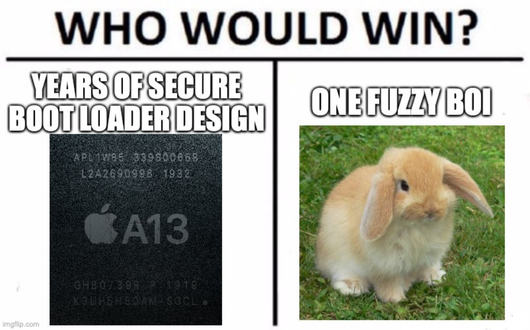

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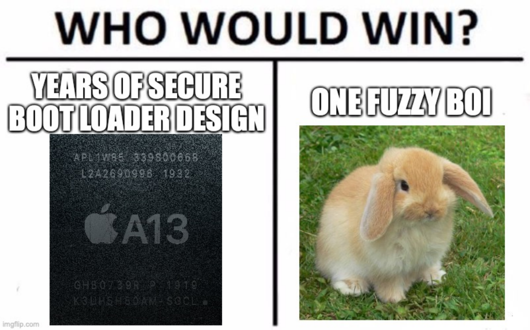

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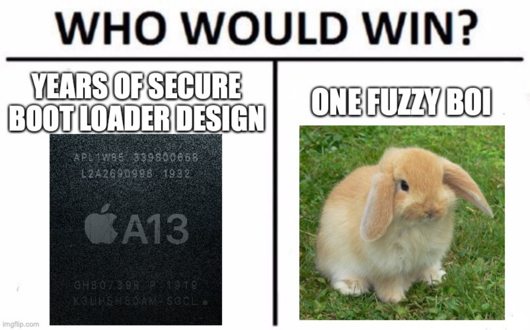
  - Threading library to expose race conditions?



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- FETA performs great and raises interesting questions

Useful Links

Fuzzing

- Fuzzing in Go 1.18: go.dev/blog/fuzz-beta
- AFL++ documentation: aflplus.plus
- Fuzzing-101: github.com/antonio-morales/Fuzzing101
- Awesome Fuzzing Discord: discord.gg/vmAGPuUUvn

Other

- Source code for iPhone boot loader fuzzing: github.com/galli-leo/emmutaler
- flagbot homepage: `flagbot.ch`
- These slides: flagbot.ch/material

Questions?

Bibliography

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