Attacking Samsung Galaxy A* Boot Chain, and Beyond

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Damiano Melotti
Raphaël Neveu
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Quarkslab

Who we are

- Maxime Rossi Bellom @max_r_b
- Security researcher and R&D leader @ Quarkslab
- Working on mobile and embedded software security

- Gabrielle Viala @pwissenlit
- Security researcher and R&D leader @ Quarkslab
- Playing with low-level stuff

- Damiano Melotti @DamianoMelotti
- Ex security researcher @ Quarkslab
- Interested in low-level mobile security and fuzzing

- Raphaël Neveu
- Security researcher @ Quarkslab
- Working on low-level mobile security

Dissecting the Modern Android Data Encryption Scheme

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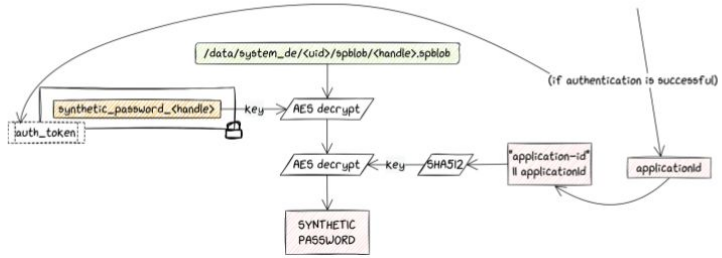
Bruteforce of the password

1. pwd = generate new password
2. token = **scrypt**(pwd, R, N, P, Salt)
3. Application_id = token || Prehashed value
4. Key = **SHA512**("application_id" || application_id)
5. **AES_Decrypt**(value_from_keymaster, key)

```
$ python3 bruteforce-tee.py
workers will cycle through the last 5 chars
Found it: 1234
the plaintext is '1234'
Done in 18.031058311462402s
Throughput: 1478.448992816657 tries/s
```


Attacking SP derivation

- Need to target the TEE
- Two alternatives
  - Keymaster TA (accessing the first AES key)
  - **Gatekeeper TA** (validating credentials and minting auth tokens)



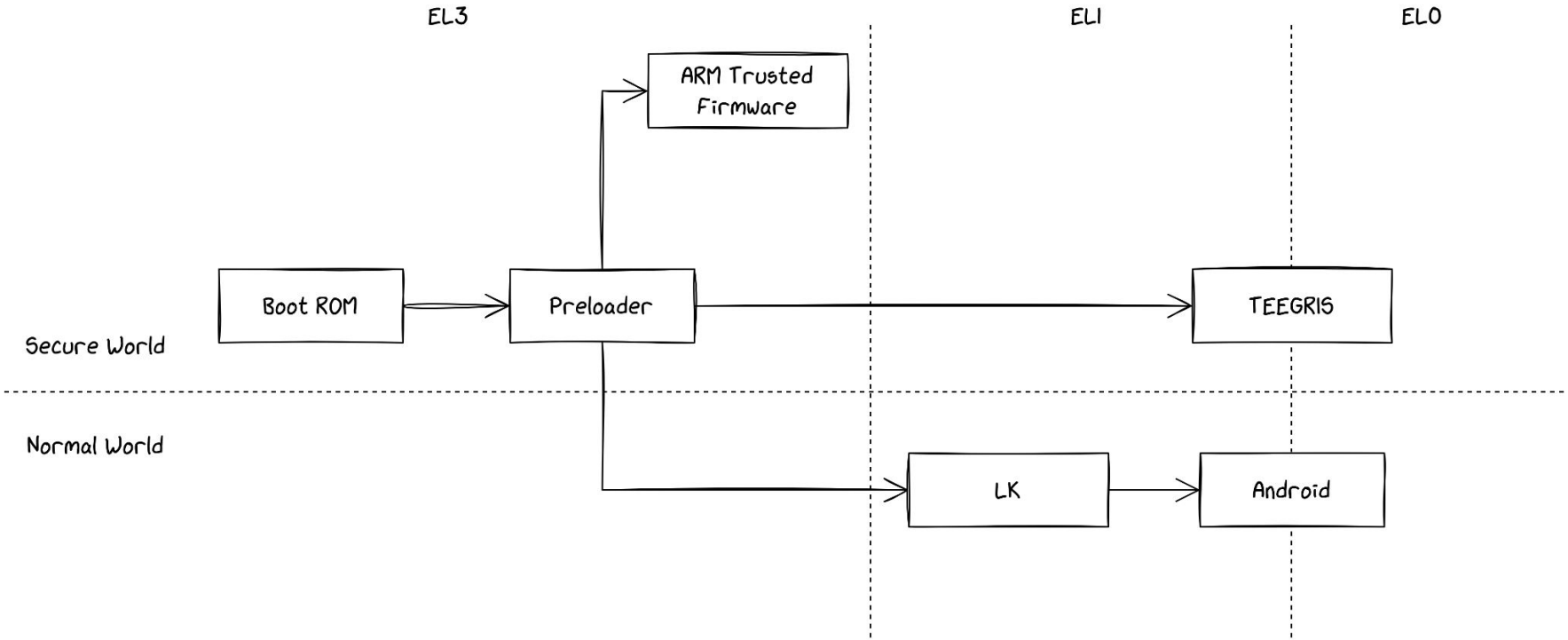

```
Preloader -     HW version:             0x0
Preloader -     WDT:                    0x10007000
Preloader -     Uart:                   0x11002000
Preloader -     Brom payload addr:      0x100a00
Preloader -     DA payload addr:        0x201000
Preloader -     CQ_DMA addr:            0x10212000
Preloader -     Var1:                   0x25
Preloader - Disabling Watchdog...
Preloader - HW code:                    0x707
Preloader - Target config:              0xe5
Preloader -     SBC enabled:            True
Preloader -     SLA enabled:            False
Preloader -     DAA enabled:            True
Preloader -     SWJTAG enabled:         True
Preloader -     EPP_PARAM at 0x600 after EMMC_BOOT/SDMMC_BOOT:  False
Preloader -     Root cert required:     False
Preloader -     Mem read auth:          True
Preloader -     Mem write auth:         True
Preloader -     Cmd 0xC8 blocked:       True
Preloader - Get Target info
Preloader - BROM mode detected.
Preloader -     HW subcode:             0x8a00
Preloader -     HW Ver:                 0xca00
Preloader -     SW Ver:                 0x0
Preloader - ME_ID:                      34C0B89C3AC60179BFB7015S591927F9
Preloader - SOC_ID:                     8EDADE25C1C71F2C4BC41DE3D879F3DC0D2348AC1C0CBFE8DCDF336568D3F18D
PLTools - Loading payload from mt6768_payload.bin, 0x264 bytes
PLTools - Kamakiri / DA Run
Kamakiri - Trying kamakiri2..
Kamakiri - Done sending payload...
PLTools - Successfully sent payload: /home/maxime/tools/mtkclient/mtkclient/payloads/mt6768_payload.bin
Port - Device detected :)
Main - Connected to device, loading
Main - Using custom preloader : preloader_k69v1_64_titan_buffalo.bin
Mtk - Valid preloader detected.
Mtk - Patched "seclib_sec_usbdl_enabled" in preloader
Mtk - Patched "sec_img_auth" in preloader
Mtk - Patched "get_vfy_policy" in preloader
Main - Sent preloader to 0x201000, length 0x3ff24
Preloader - Jumping to 0x201000
Preloader - Jumping to 0x201000: ok.
Main - PL Jumped to daaddr 0x201000.
Main - Keep pressed power button to boot.
[+] Waiting for device to boot
```

Our Device

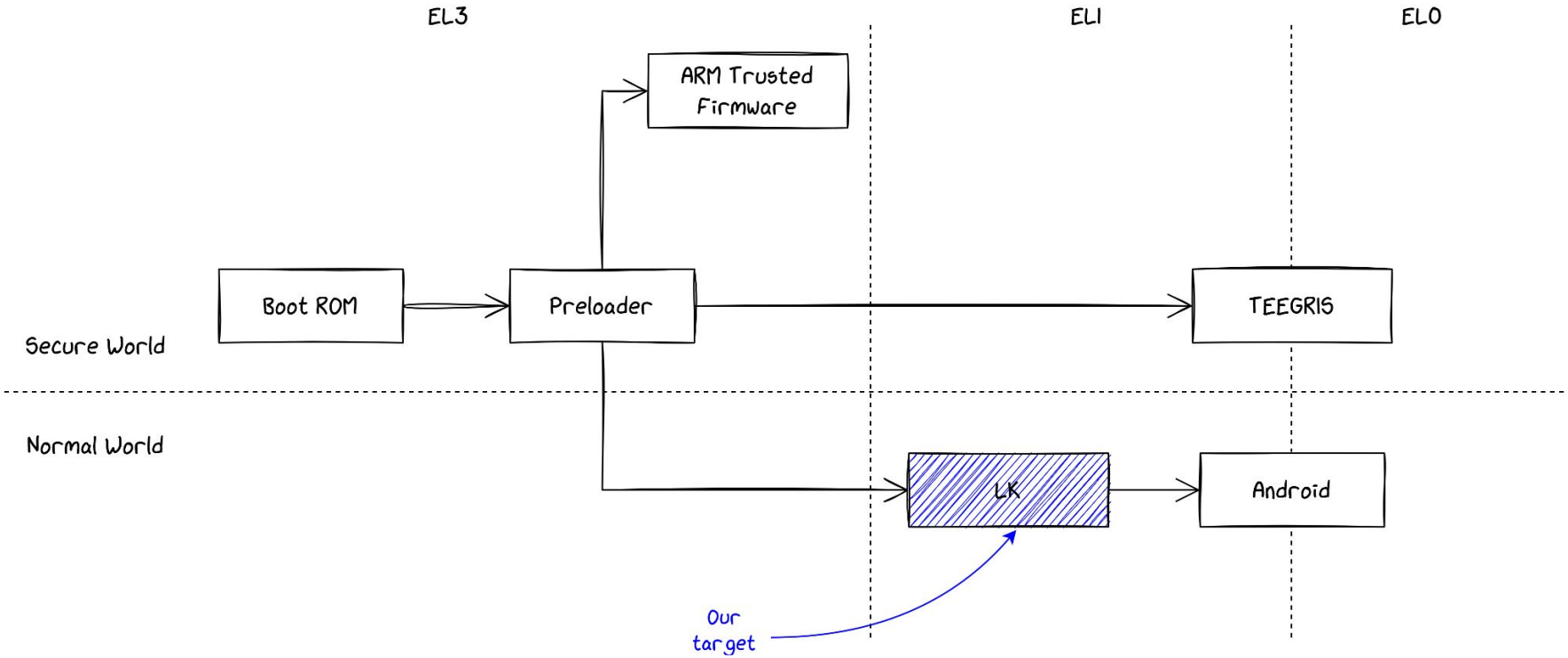
- Samsung Galaxy A225F
  - Cheap (~300€)
  - Mediatek SoC MT6769V
  - Main OS: Android
  - Mix of Mediatek and Samsung code
  - Trustzone OS: TEEGRIS
  - Secure Boot Bypass using MTKClient[1]
    - ➜ making debugging easier

[1]: https://github.com/bkerler/mtkclient

Mediatek Secure Boot Process



Mediatek Secure Boot Process



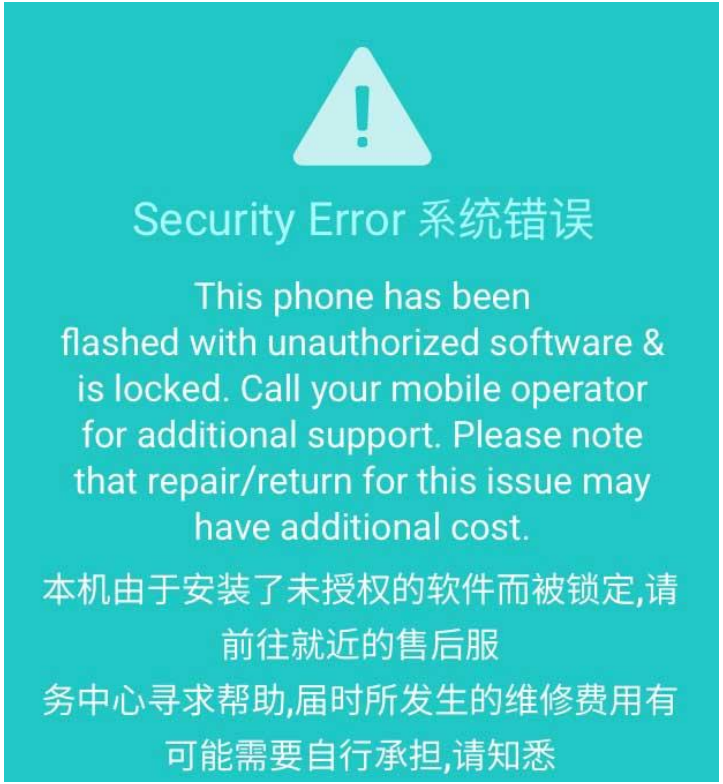
Little Kernel (LK)

- Open-source OS[2]
- Common as bootloader in the Android world
- Allows to boot Android or other modes (Recovery)
- Implements **A**ndroid **V**erified **B**oot v2
  - Verification of Android images
  - Involving boot and vbmeta partitions
  - Anti-rollback

[2]: https://github.com/littlekernel/lk

Little Kernel by Samsung

- Samsung modified LK to include:
  - The Odin recovery protocol
  - Knox Security Bit
  - Etc...
  - And a JPEG parser/renderer
- This version is closed source



Why Targeting the JPEG Loader/Parser

- JPEGs are placed in a TAR archive in the *up_param* partition
- The archive is signed… but the signature is not checked at boot

  ❗ Anyone able to write the flash can modify these JPEGs
- Parsing JPEG is known to be hard (cf. LogoFail[3])

[3]: https://www.binarly.io/blog/inside-the-logofail-poc-from-integer-overflow-to-arbitrary-code-execution

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How are these JPEGs loaded by LK?

[3]: https://www.binarly.io/blog/inside-the-logofail-poc-from-integer-overflow-to-arbitrary-code-execution

Heap Overflow in JPEG Loading

```
_JPEG_BUF = alloc(0x100000);
if (_JPEG_BUF == 0) {
  log("%s: img buf alloc fail\n","drawimg");
  uVar2 = 0xffffffff;
}
else {
  memset(_JPEG_BUF,0,0x100000);
  iVar1 = read_jpeg_file(file_name,_JPEG_BUF,0);
  if (iVar1 == 0) {
    log("%s: read %s from up_param as 0, size\n","drawimg",file_name);
    uVar2 = 0xffffffff;
  }
// ...

pimage(*(undefined4 *)(&DAT_4c5107fc + param_1 * 0x3c),
   *(undefined4 *)(&DAT_4c510800 + param_1 * 0x3c),
   0x2d0,0x640,1,_JPEG_BUF,iVar1);
```

Heap Overflow in JPEG Loading

Heap allocation of constant size for the buffer

```
_JPEG_BUF = alloc(0x100000);
if (_JPEG_BUF == 0) {
  log("%s: img buf alloc fail\n","drawimg");
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}
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  if (iVar1 == 0) {
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  }
// ...

pimage(*(undefined4 *)(&DAT_4c5107fc + param_1 * 0x3c),
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```

Heap Overflow in JPEG Loading

Read the JPEG in the buffer

```
_JPEG_BUF = alloc(0x100000);
if (_JPEG_BUF == 0) {
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  uVar2 = 0xffffffff;
}
else {
  memset(_JPEG_BUF,0,0x100000);
  iVar1 = read_jpeg_file(file_name,_JPEG_BUF,0);
  if (iVar1 == 0) {
    log("%s: read %s from up_param as 0, size\n","drawimg",file_name);
    uVar2 = 0xffffffff;
  }
// ...

pimage(*(undefined4 *)(&DAT_4c5107fc + param_1 * 0x3c),
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Heap Overflow in JPEG Loading

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    uVar2 = 0xffffffff;
  }
// ...

pimage(*(undefined4 *)(&DAT_4c5107fc + param_1 * 0x3c),
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   0x2d0,0x640,1,_JPEG_BUF,iVar1);
```
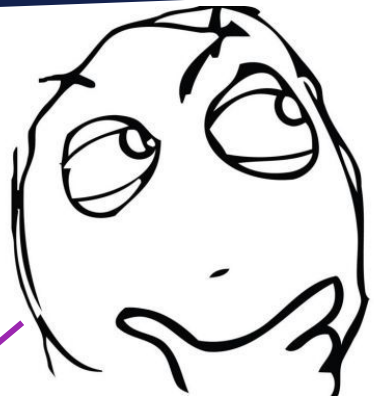

Parse and render the JPEG

Heap Overflow in JPEG Loading



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```

Heap Overflow in JPEG Loading

- `read_jpeg_file` takes a size as 3rd argument
- It triggers an error if the file does not fit the size provided

```
file_size = string_to_int(tar_header_file.size,0,8);
if (size != 0 && size < file_size) {
    file_size = print("read fail! (%d < %d)\n",size,file_size,size);
    return file_size;
}
iVar1 = read(data_addr,index + 1,file_size,outbuf);
```

Heap Overflow in JPEG Loading

- `read_jpeg_file` takes a size as 3rd argument
- It triggers an error if the file does not fit the size provided

  👉 Unless the size provided is 0...

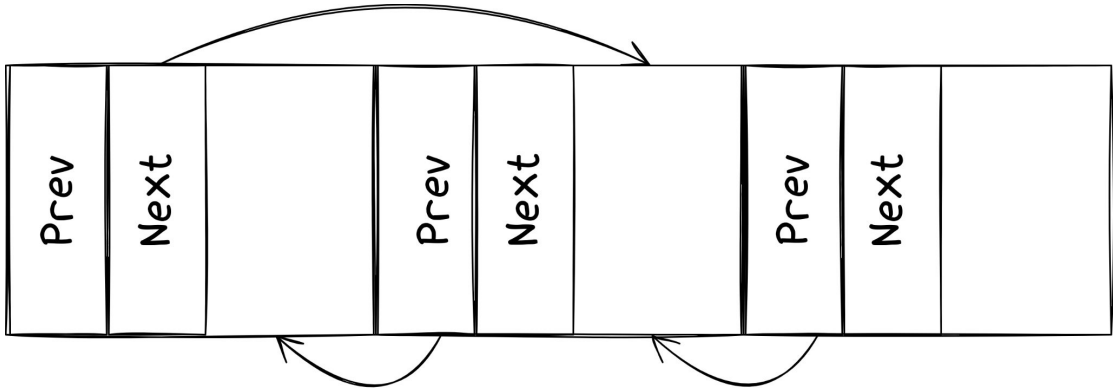
```
file_size = string_to_int(tar_header_file.size,0,8);
if (size != 0 && size < file_size) {
    file_size = print("read fail! (%d < %d)\n",size,file_size,size);
    return file_size;
}
iVar1 = read(data_addr,index + 1,file_size,outbuf);
```

Is it exploitable?

Exploiting a Heap Overflow in Little Kernel

- The heap algorithm is *miniheap*
  - It relies on a doubly linked list
- Chunks are in a unique memory pool
  - An overflow may overwrite the metadata of next chunk

```
struct free_chunk_head {
    struct free_chunk_head *prev;
    struct free_chunk_head *next;
    size_t len;
}
```



From Heap Overflow to Arbitrary Write

- After allocation, a chunk is removed from the free list
- `next` and `prev` are dereferenced to change the corresponding nodes

  ⇒ Controlling a free chunk leads to a write-what-where

```
node->next->prev = node->prev;
node->prev->next = node->next;
node->prev = node->next = 0;
```

From Heap Overflow to Arbitrary Write

- After allocation, a chunk is removed from the free list
- `next` and `prev` are dereferenced to change the corresponding nodes

  ⇒ Controlling a free chunk leads to a write-what-where

  ❗ Both values must writable addresses

```
node->next->prev = node->prev;
node->prev->next = node->next;
node->prev = node->next = 0;
```

From Arbitrary Write to Code Execution

Important details about LK

- ❌ No ASLR
- ❌ No canaries
- ❌ No bounds checks in the heap algorithm
- ❌ Heap is executable!

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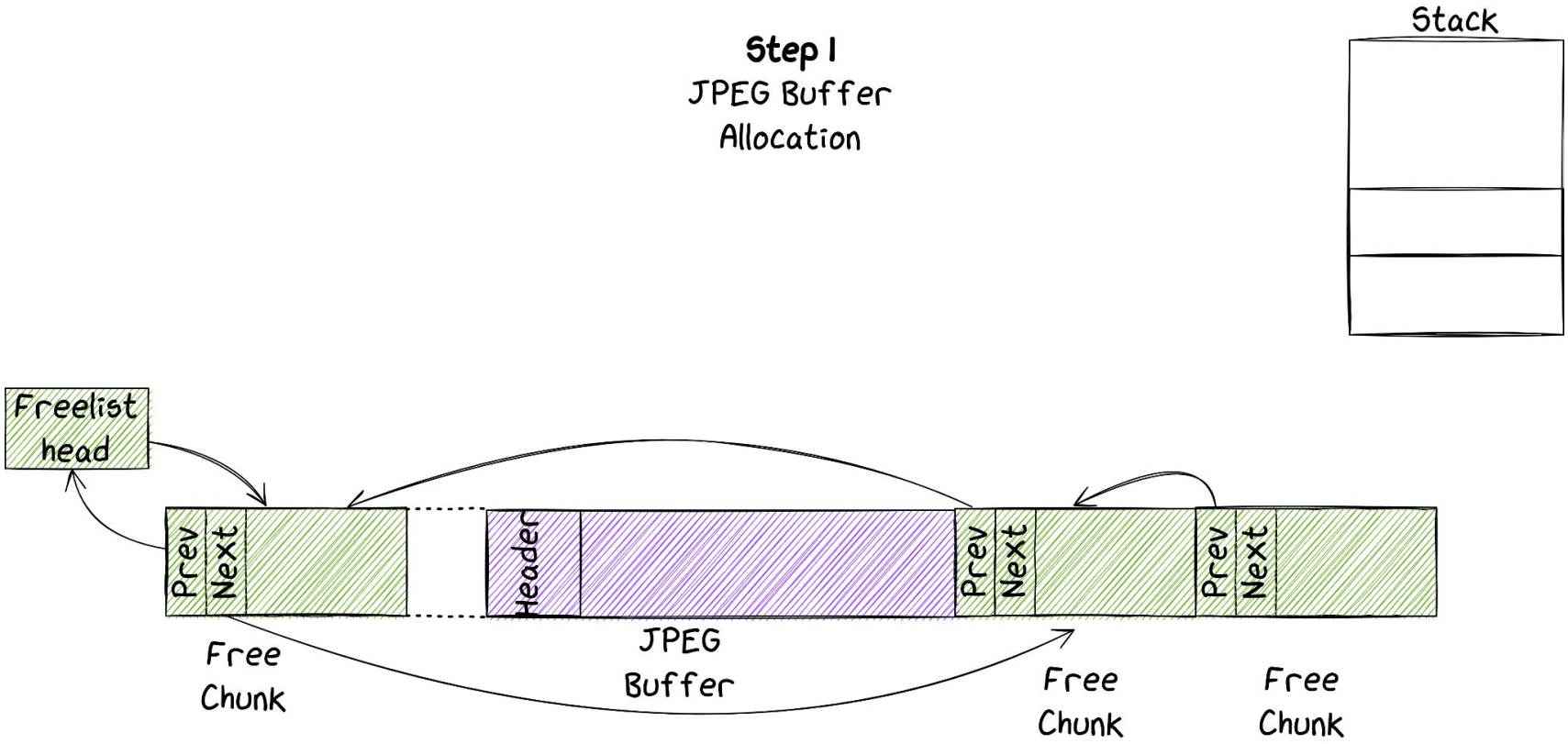
Exploit strategy becomes simple:

1. Overwrite a pointer that the code will jump to
   👉 the return address in the stack
2. Make it point to a shellcode in our JPEG buffer

Exploiting a Heap Overflow in Little Kernel



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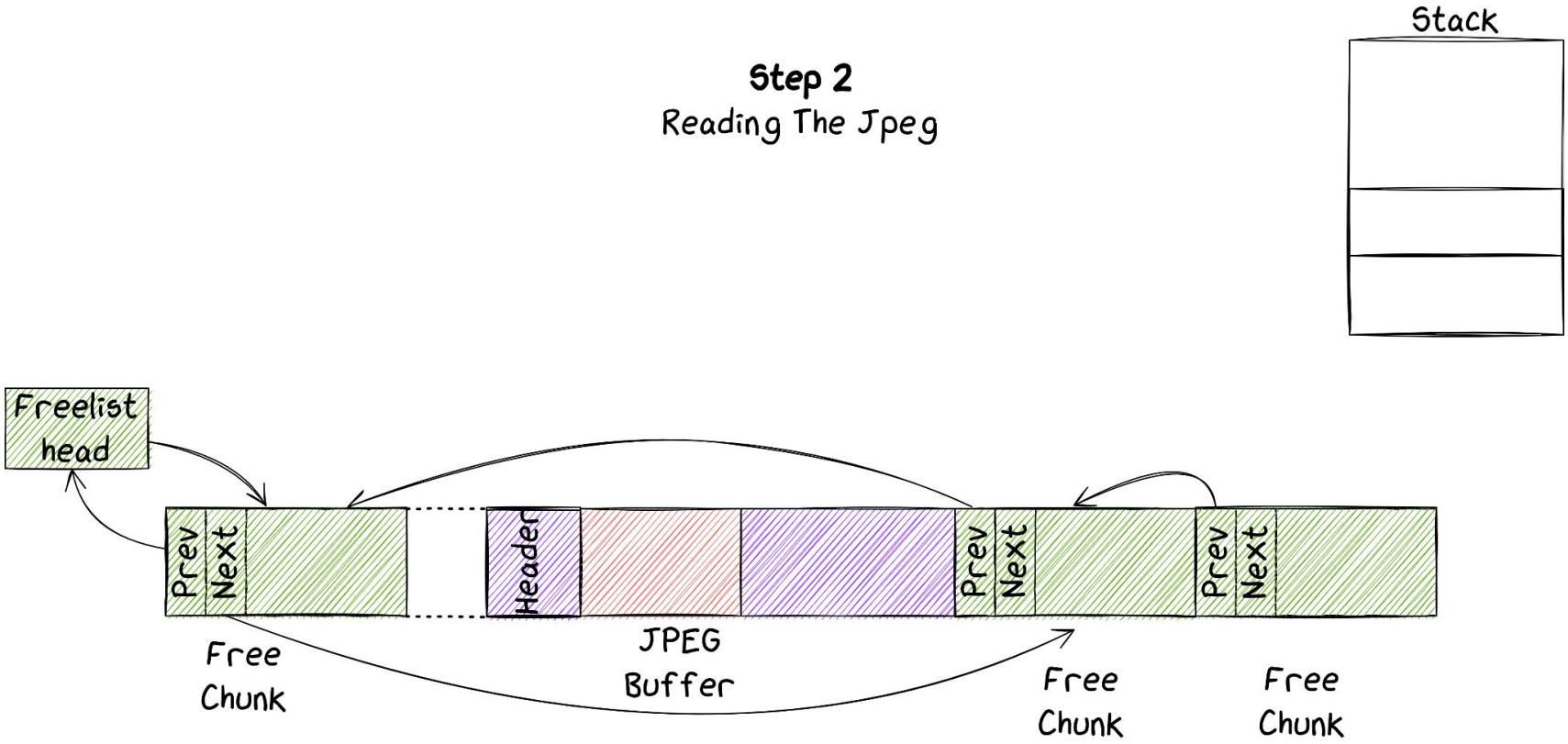

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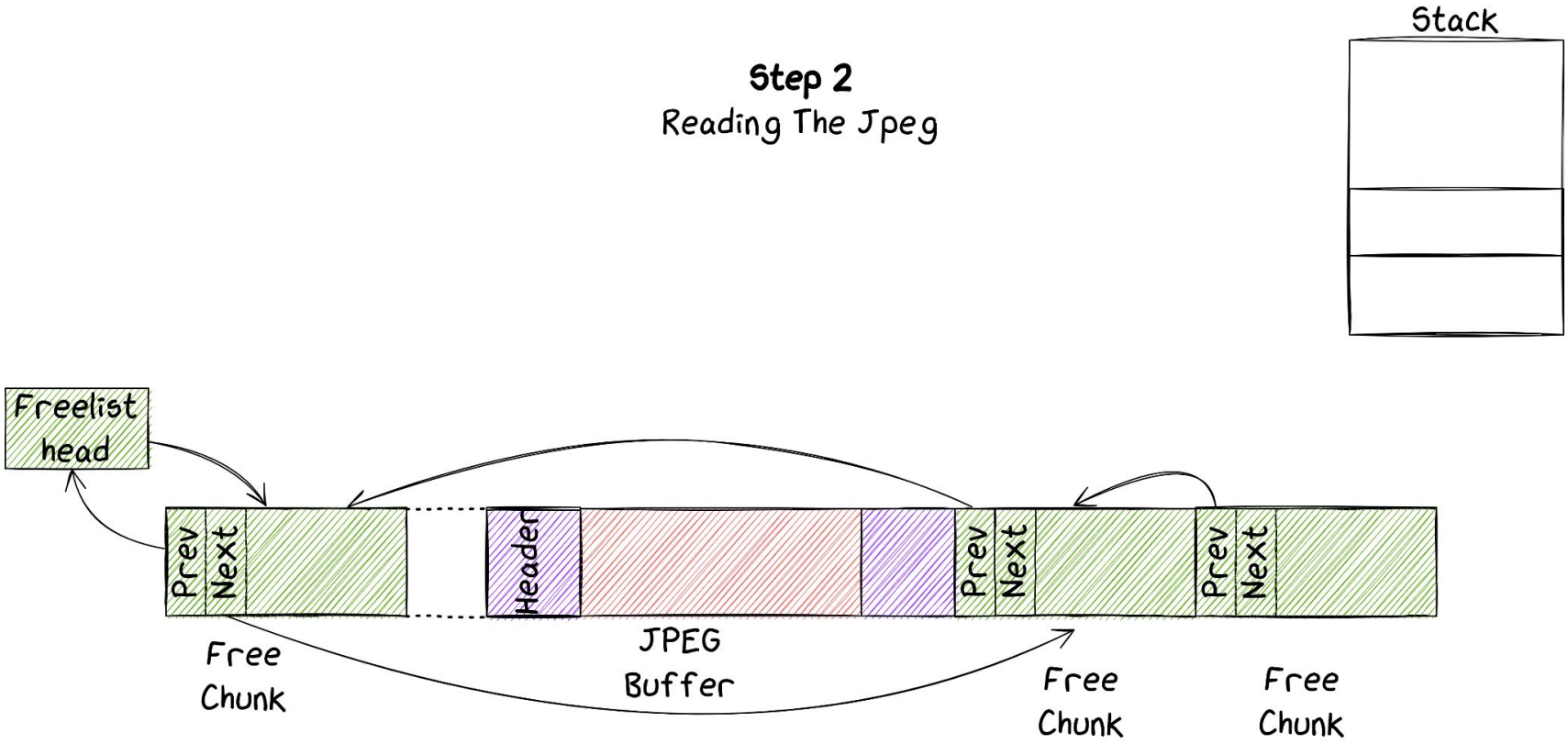

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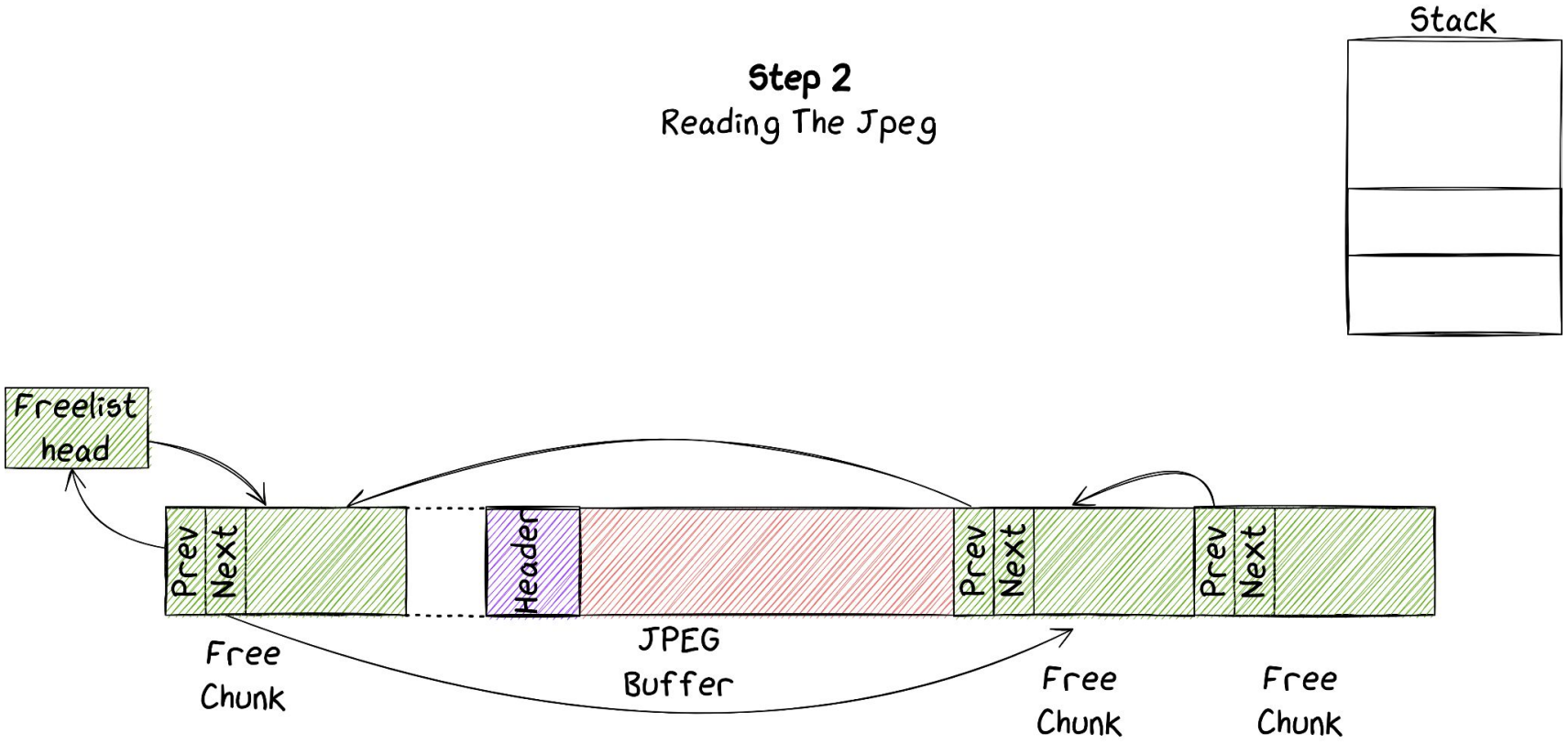

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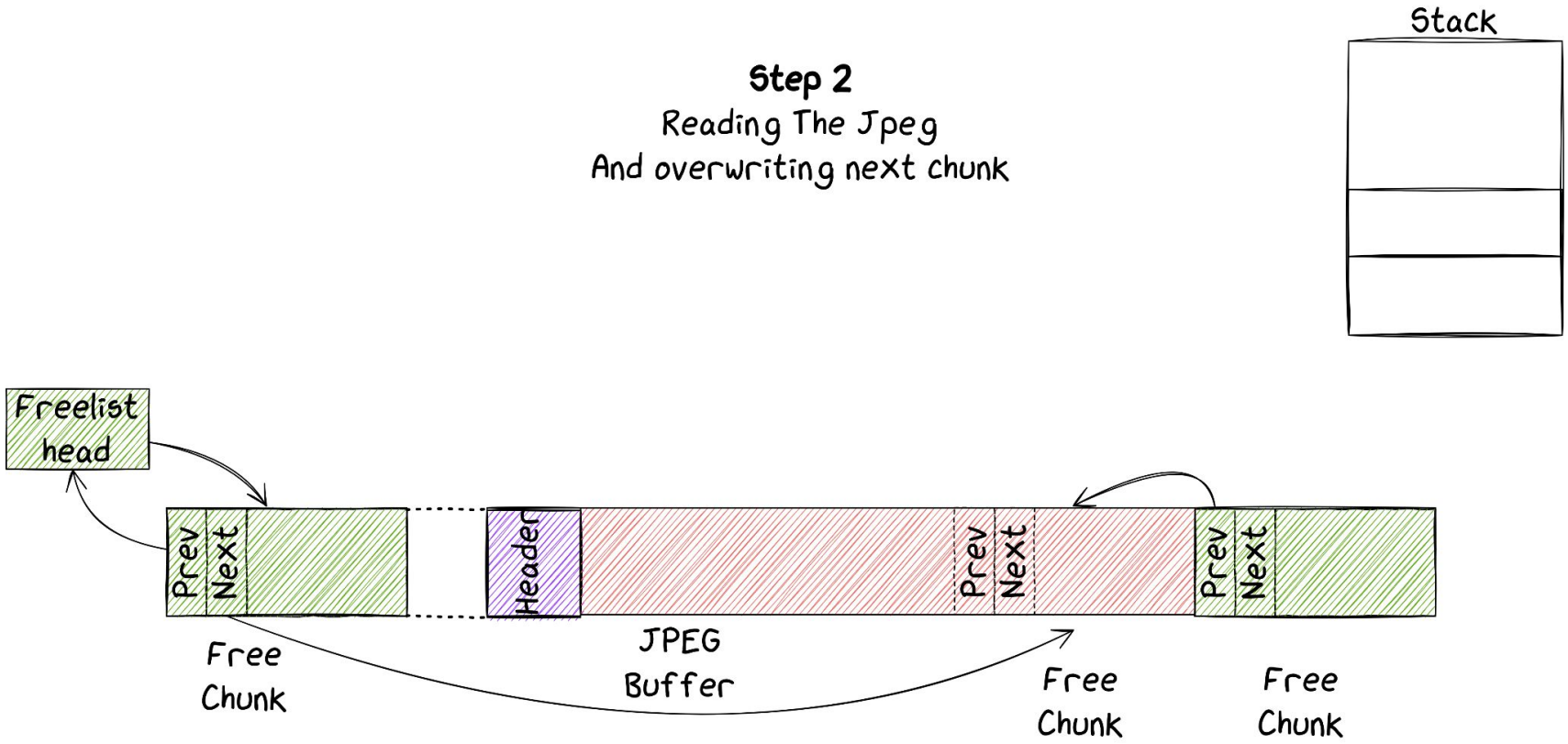
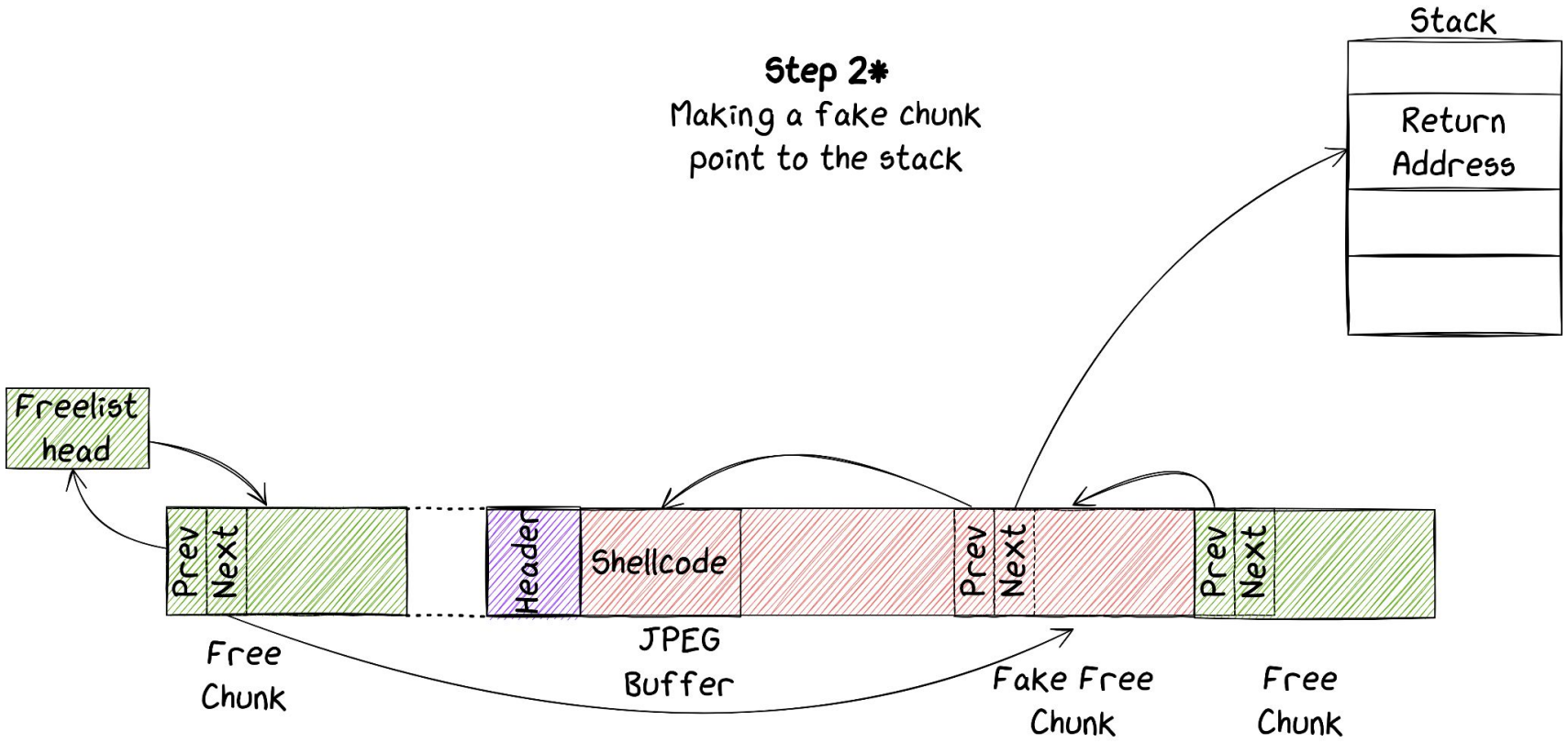


Exploiting a Heap Overflow in Little Kernel



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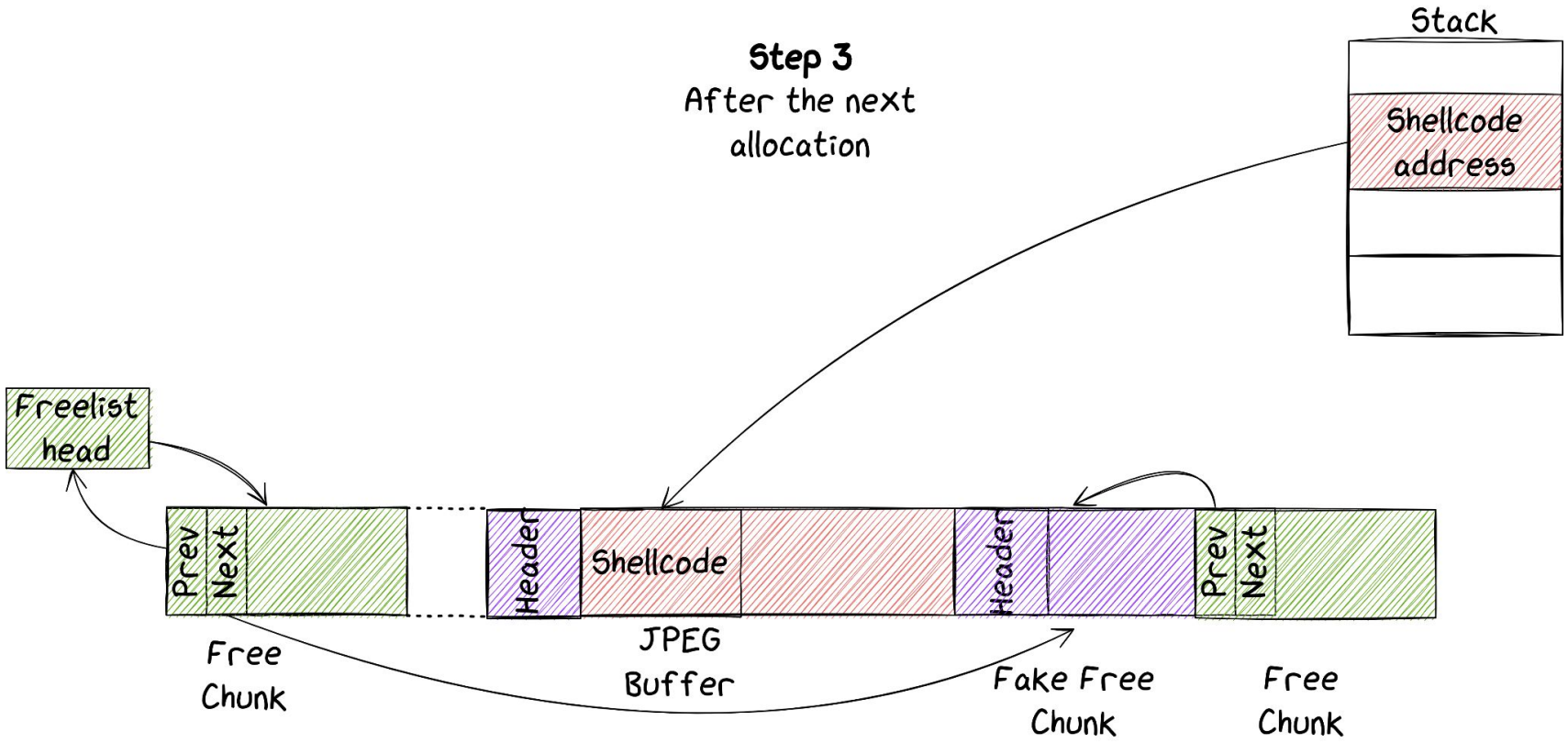


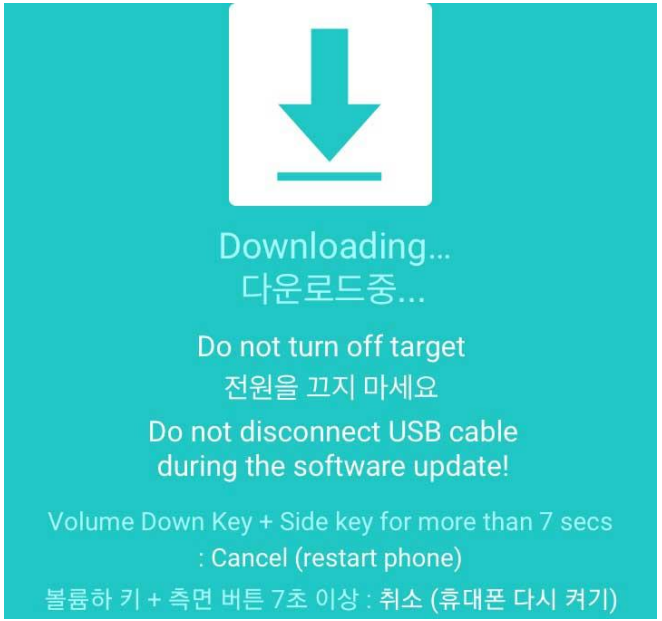
To sum-up

- SVE-2023-2079/CVE-2024-20832
  - ✅ Leads to code execution
  - ✅ Persistent (it survives reboots and factory reset)
  - ✅ Gives full control over Normal World EL1/0
  - ✅ Impacts Samsung devices based on Mediatek SoCs
    - Including those for which MTKClient does not work
  - ❌ Requires to flash the *up_param* partition

How to write our JPEGs in the up_param partition?

Odin: Samsung's recovery protocol

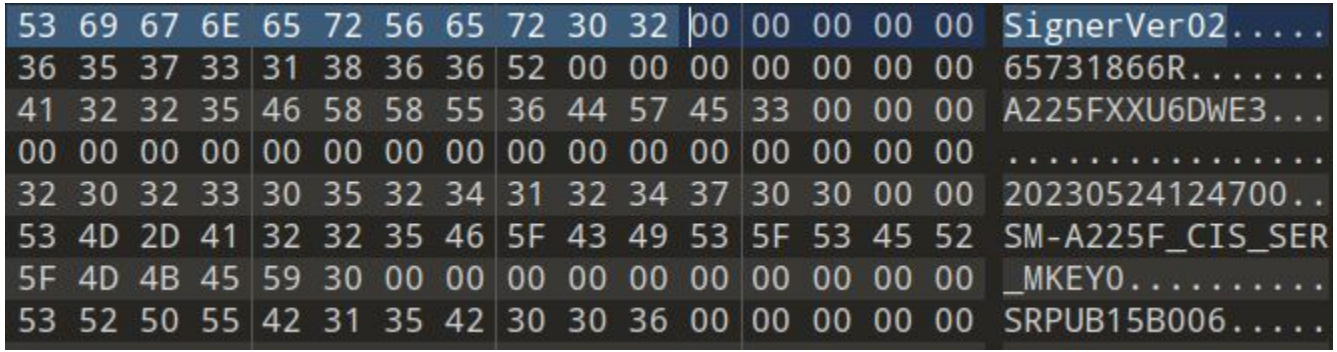
- Odin is implemented in LK
- It is available through the *Download Mode*
  - It allows to flash partitions over USB
- The Odin official client is closed source
- There is an open-source client: Heimdall[4]



[4]: https://github.com/Benjamin-Dobell/Heimdall

Odin: Samsung's recovery protocol

- Images are authenticated and contain a footer signature
- Two internal structures indicate which partitions to flash
  - The *Partition Information Table* (PIT)
  - A global structure indicating which partitions to authenticate



Odin: Partition Information Table

- PIT is retrieved statically from the eMMC
- It indicates where partitions are stored
  - Memory type, block count, etc
- A partition not present in PIT can't be flashed
- PIT can be updated, but requires a signed image

```
--- Entry #1 ---
Binary Type: 0 (AP)
Device Type: 2 (MMC)
Identifier: 70
Attributes: Read/Write
Update Attributes: 1
Block Size/Offset: 0
Block Count: 34
Partition Name: pgpt
…
```

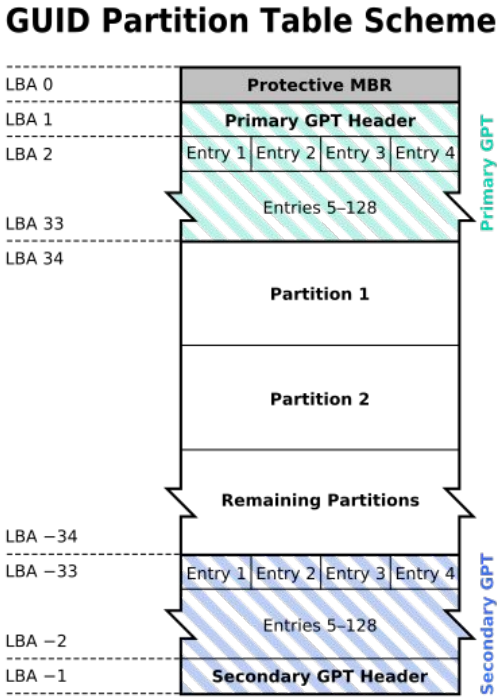
Odin: Image Authentication

- A global array indicates how an image should be authenticated
- An image not present in this array will not be authenticated
  - (Except for some specific images)
- Comparing this array with PIT gives a set of images flashable without authentication

md5hdr, **md_udc**, **pgpt**, **sgpt**, and **vbmeta_vendor**

GPT: GUID Partition Table

- **pgpt** points to the Primary GPT Header
- **sgpt** points to the Secondary GPT Header
- Similarly to the PIT, it describes the partitions
  - (Names, sizes, addresses, etc)
- Any GPT can be flashed through Odin
  - ❗ No authentication required



Source: https://en.wikipedia.org/wiki/GUID_Partition_Table

GPT vs PIT

- **PIT** and **GPT** are used for the same thing: to describe partitions
- **PIT** is mainly used for Samsung features in LK
  - Odin, JPEGs loading, etc
- And **GPT** is used the rest of the time

❗ We can't just rename a partition to *up_param* to flash our JPEGs

PIT Loading

```
pit_address = 0x4400;
exist = get_part_table("pit");
if (exist == 0) {
  pit_address = get_partition_offset("pit");
}
type = storage(3);
iVar1 = storage_read(type,0x4000,(int)pit_address,
                     (int)((ulonglong)pit_address >> 0x20),
                     &ODIN_TEMP_BUF_PIT,0x4000);
```

PIT Loading

PIT default address

```
pit_address = 0x4400;
exist = get_part_table("pit");
if (exist == 0) {
  pit_address = get_partition_offset("pit");
}
type = storage(3);
iVar1 = storage_read(type,0x4000,(int)pit_address,
                     (int)((ulonglong)pit_address >> 0x20),
                     &ODIN_TEMP_BUF_PIT,0x4000);
```

PIT Loading

PIT default address

Check for pit partition
And use it if it exists

```
pit_address = 0x4400;
exist = get_part_table("pit");
if (exist == 0) {
  pit_address = get_partition_offset("pit");
}
type = storage(3);
iVar1 = storage_read(type,0x4000,(int)pit_address,
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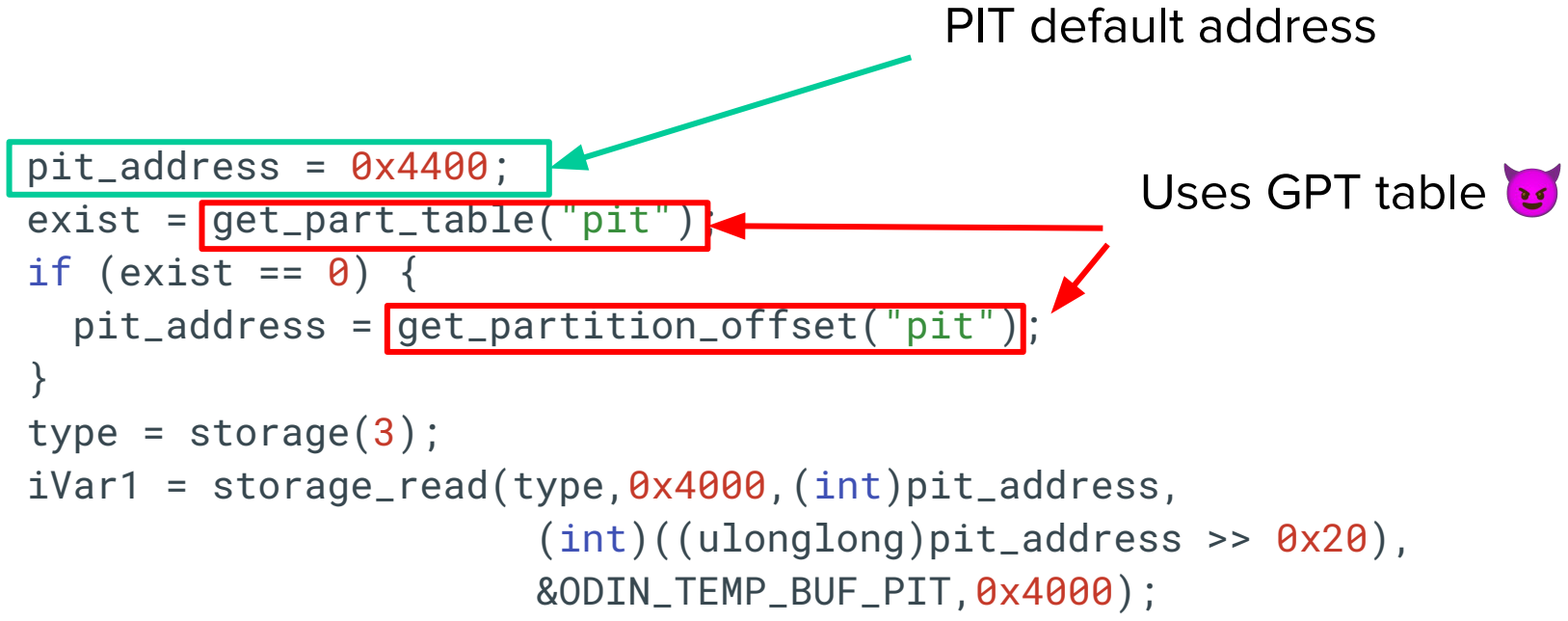
```

PIT Loading


PIT default address
Uses GPT table 😈
pit_address = 0x4400;
exist = get_part_table("pit");
if (exist == 0) {
pit_address = get_partition_offset("pit");
}
type = storage(3);
iVar1 = storage_read(type,0x4000,(int)pit_address,
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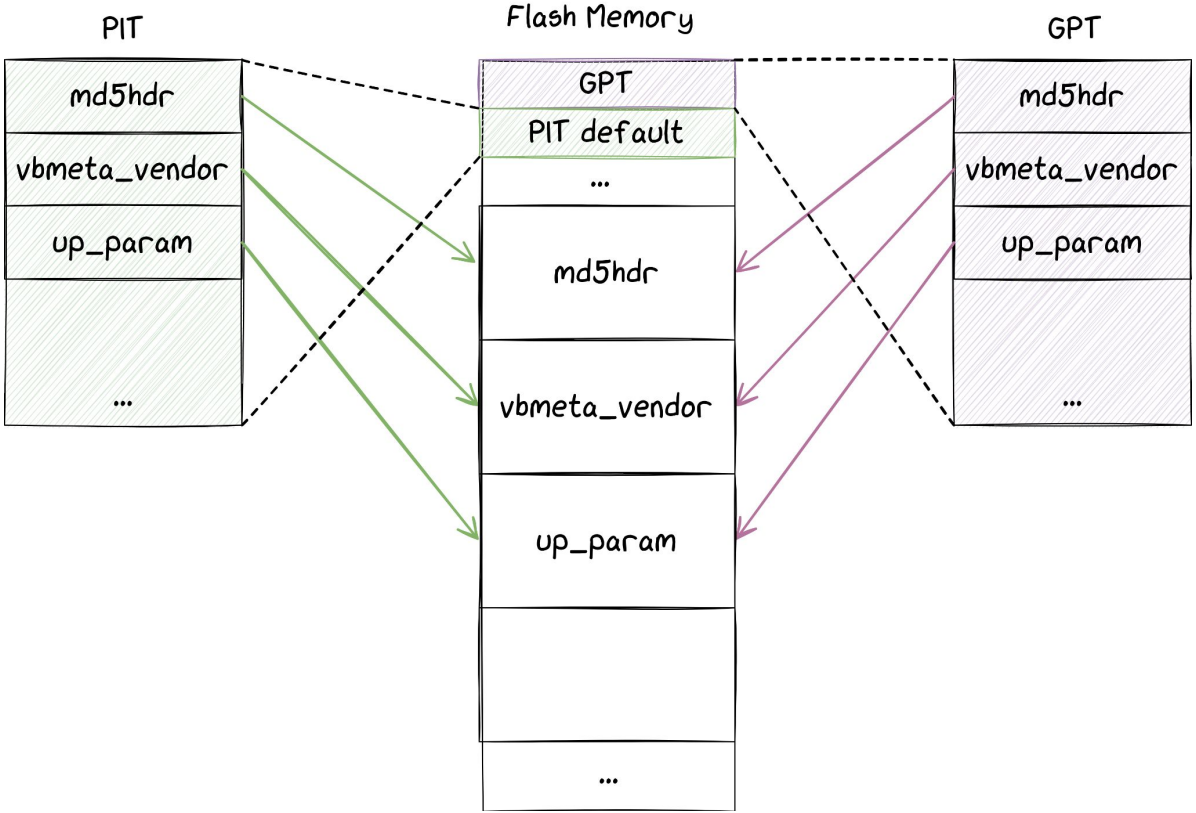
Strategy to Bypass Odin Authentication



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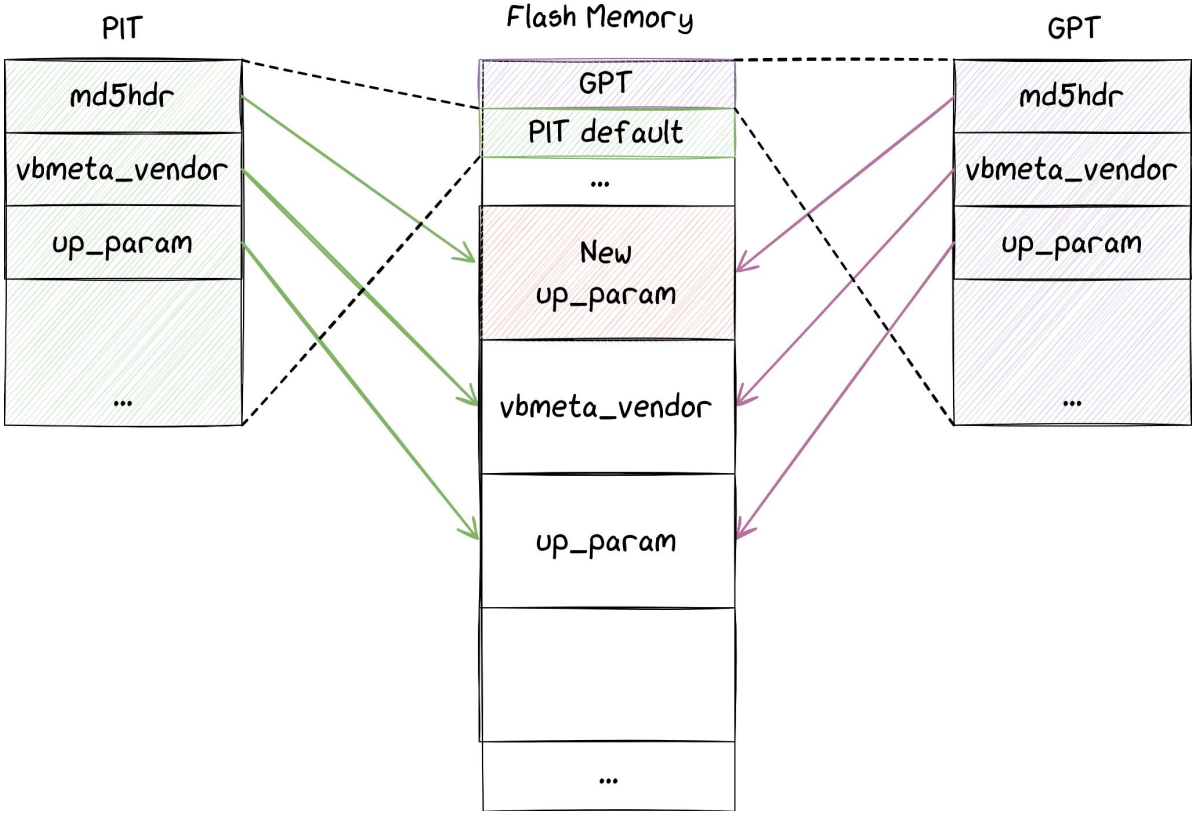

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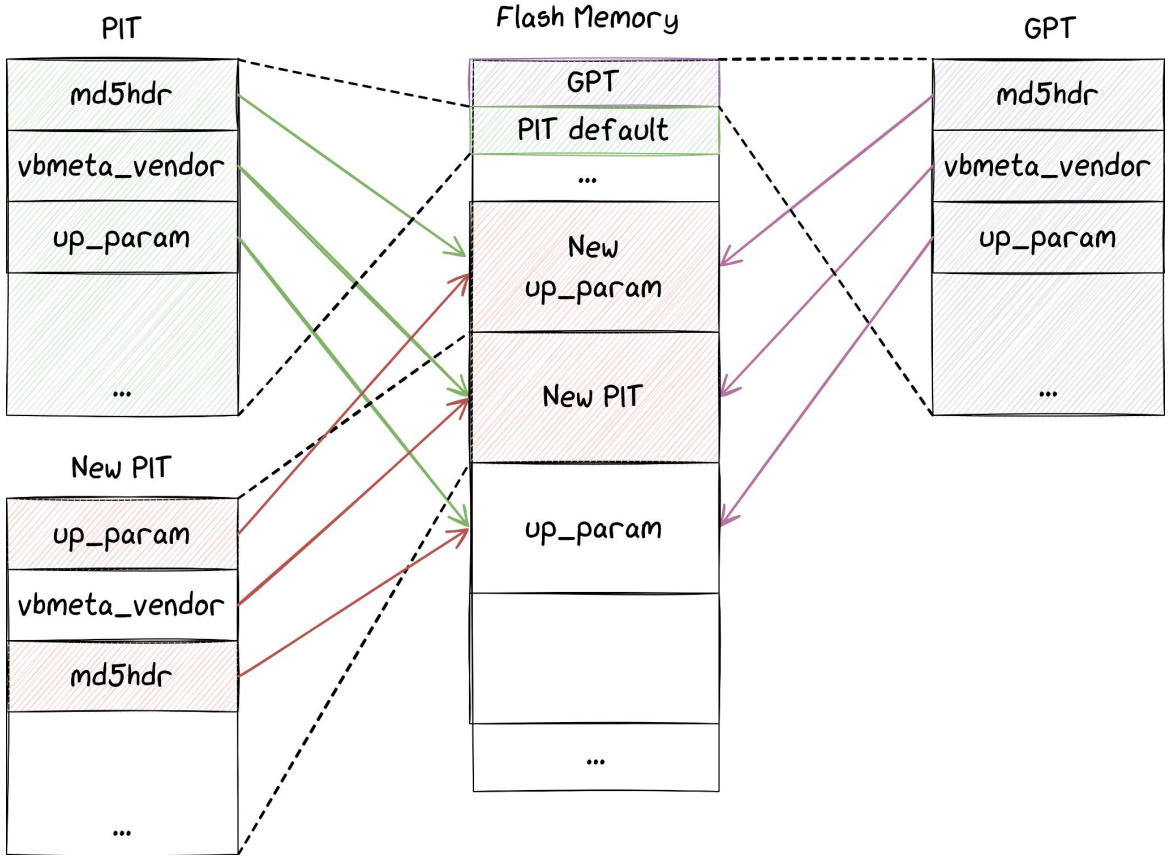

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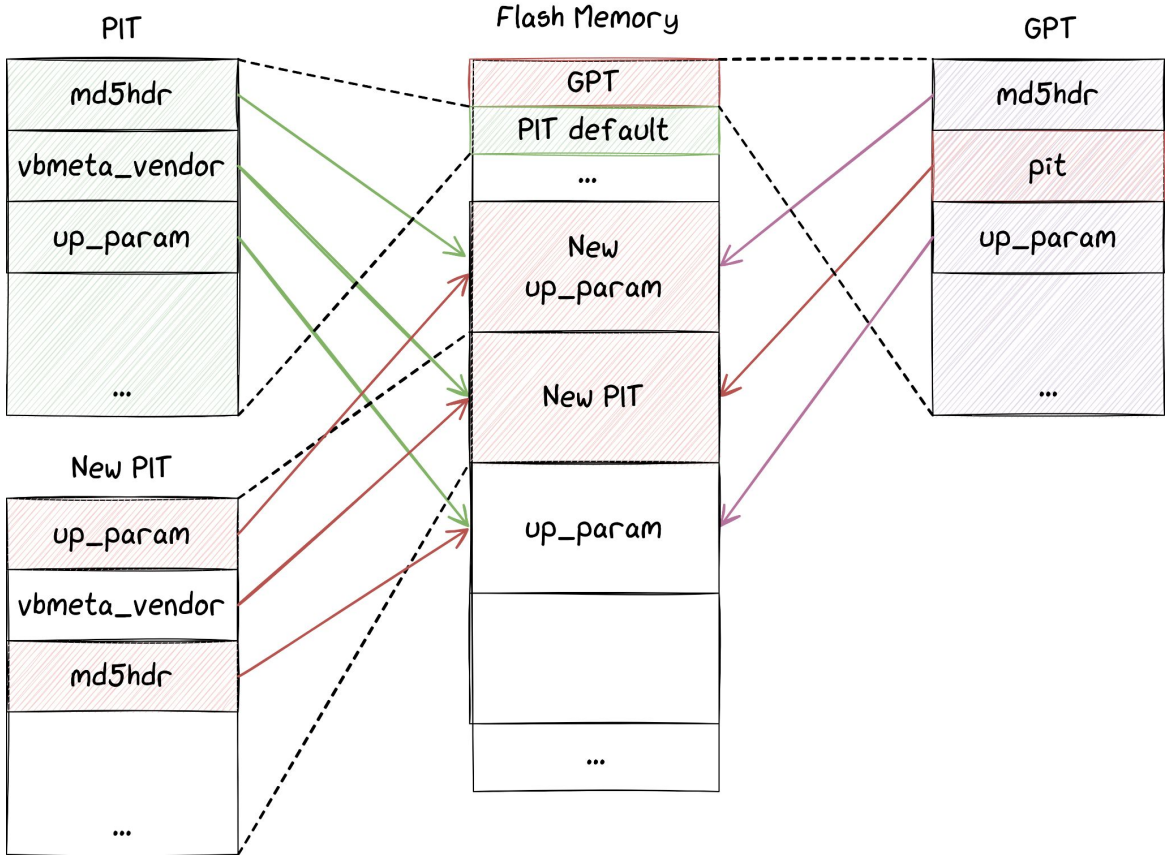

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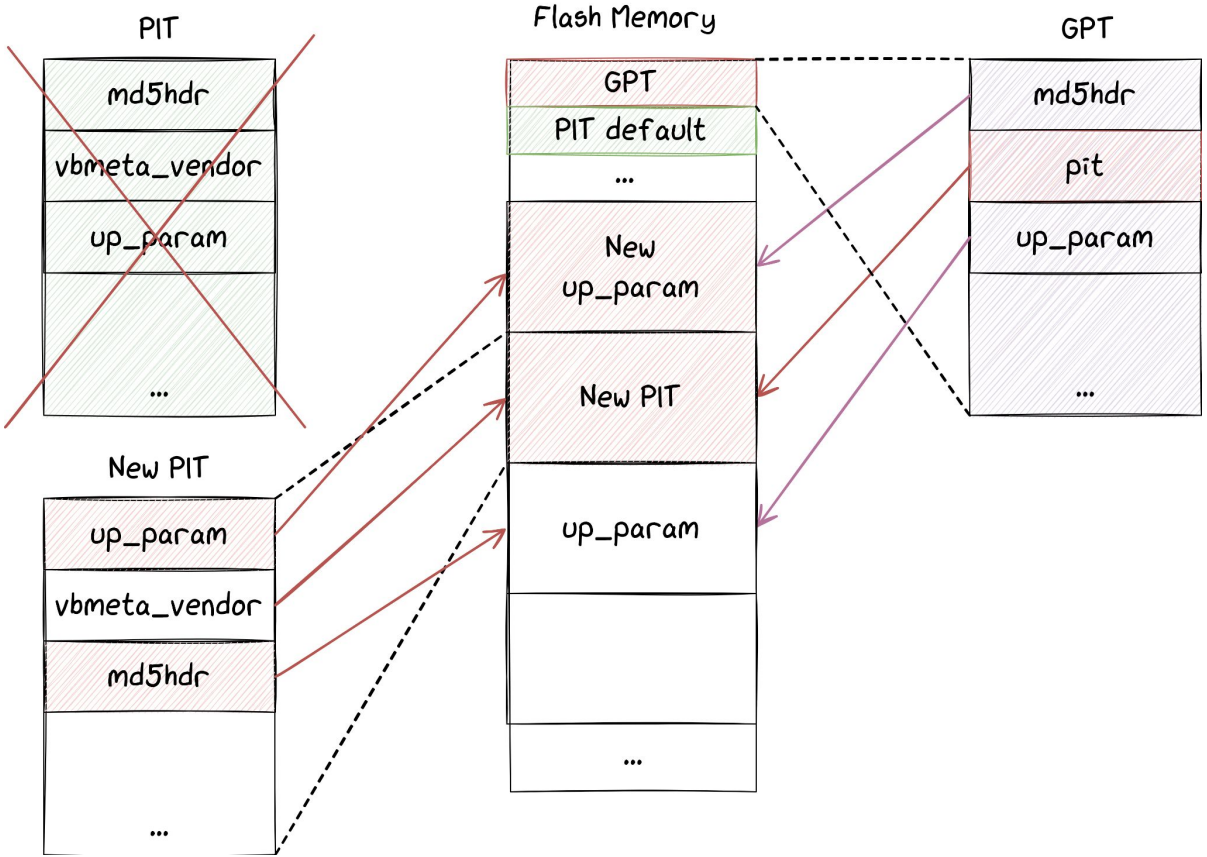
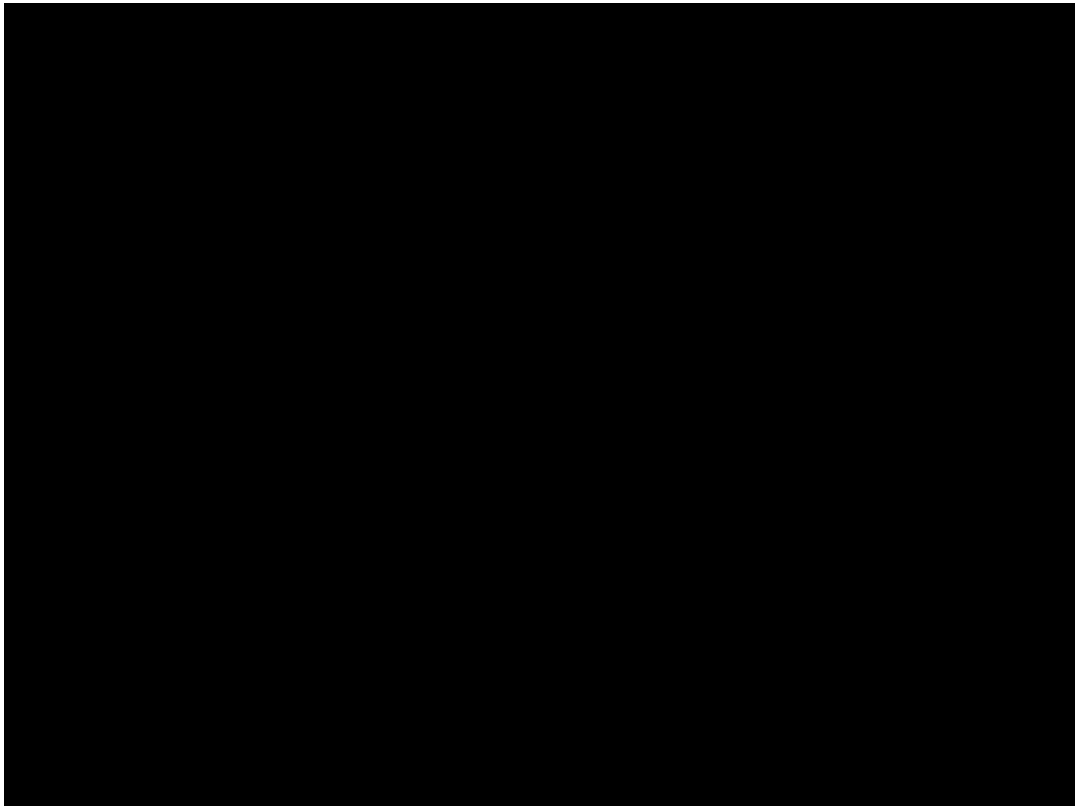


To sum up

- SVE-2024-0234/CVE-2024-20865
  - ✅ Can bypass authentication in Odin
  - ✅ We can flash anything in the eMMC
  - ✅ Including our *up_param* partition
  - ✅ Seems to impact most Samsung using Mediatek SoCs

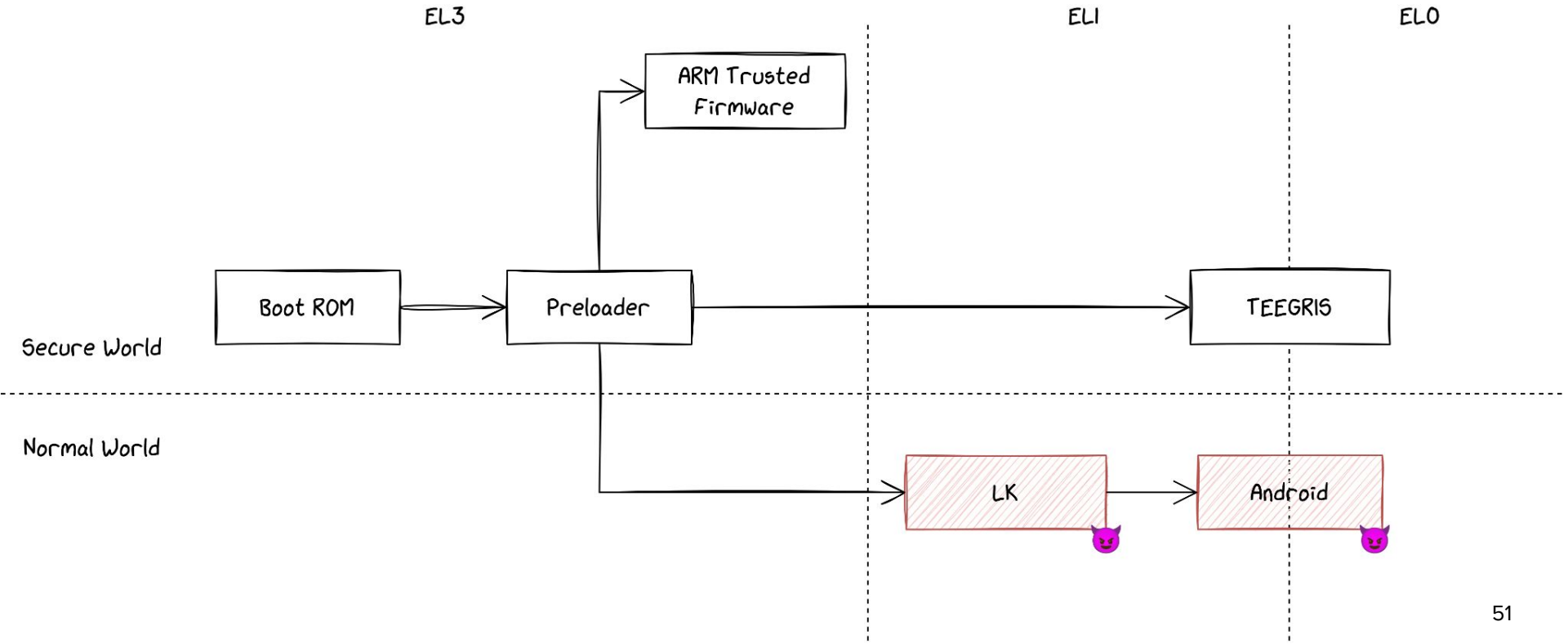
Chaining Everything Together



To Conclude

- Chain based on 2 vulnerabilities
  - ✅ Leads to code execution in LK
  - ✅ Persistent (it survives reboots and factory reset)
  - ✅ Impacts Samsung devices based on Mediatek SoCs
    - Including those for which MTKClient does not work
  - ✅ Can be triggered over USB thanks to Odin authentication bypass
  - ✅ Gives full control over Normal World EL1/0
  - ❌ Still no access to secrets stored in Secure World

Targeting ARM Trusted Firmware



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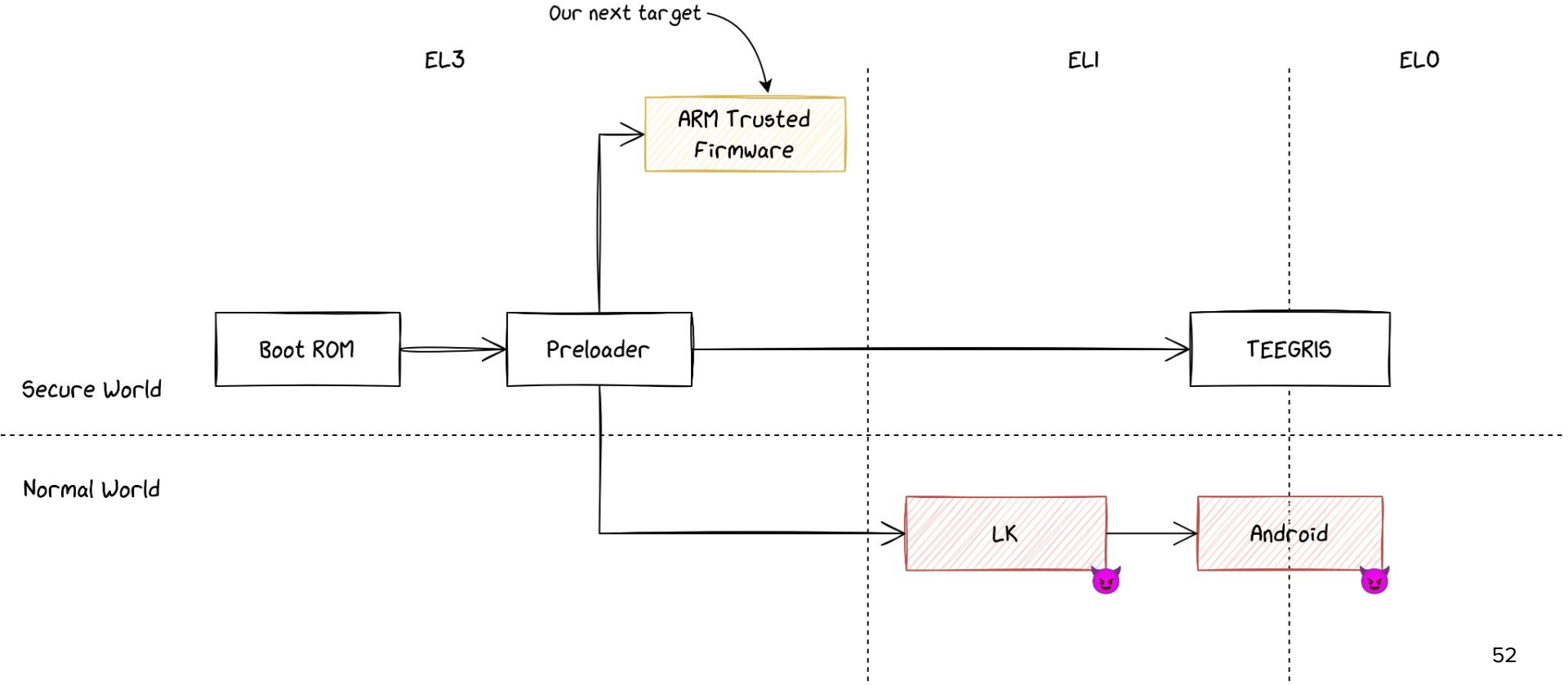
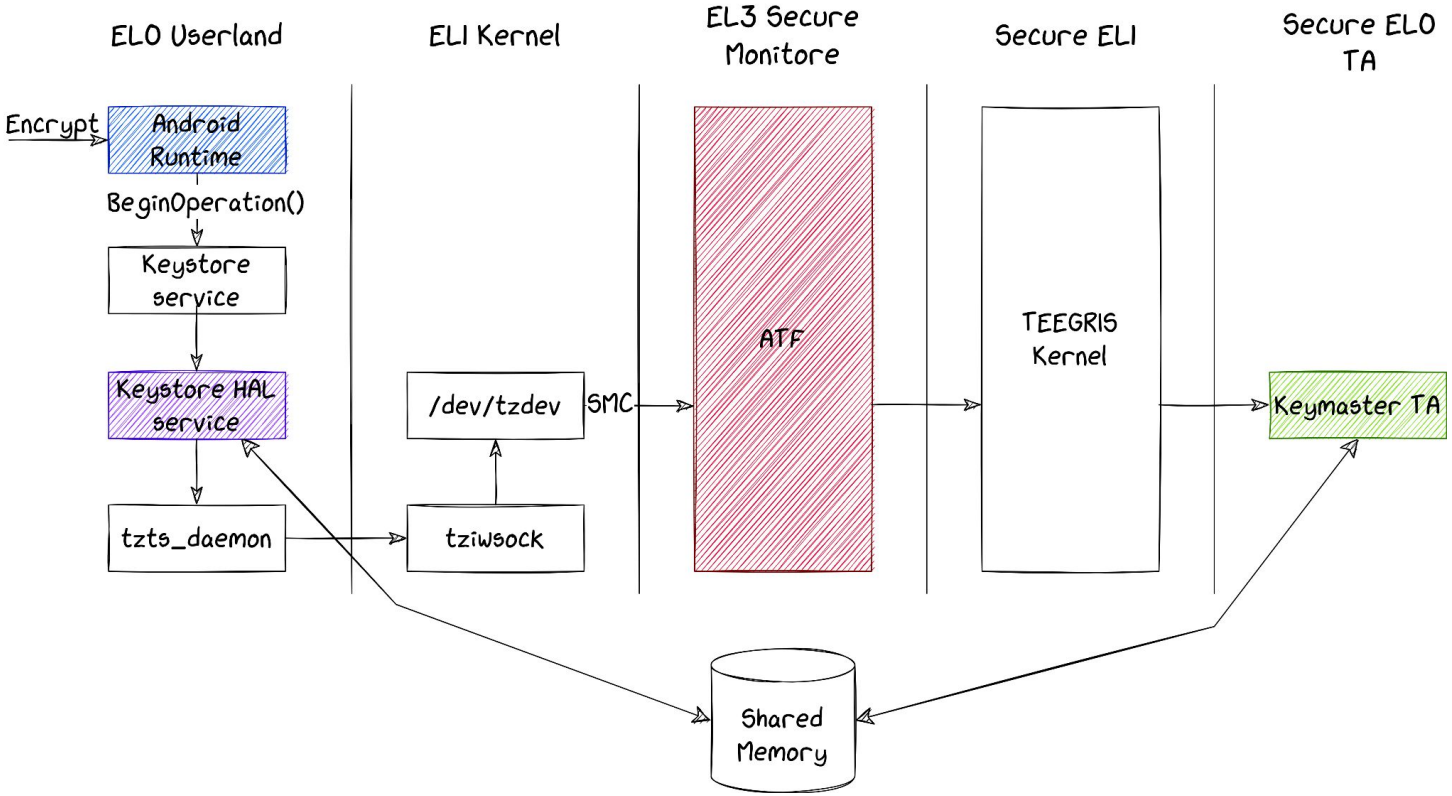


Communication between NSW and SW

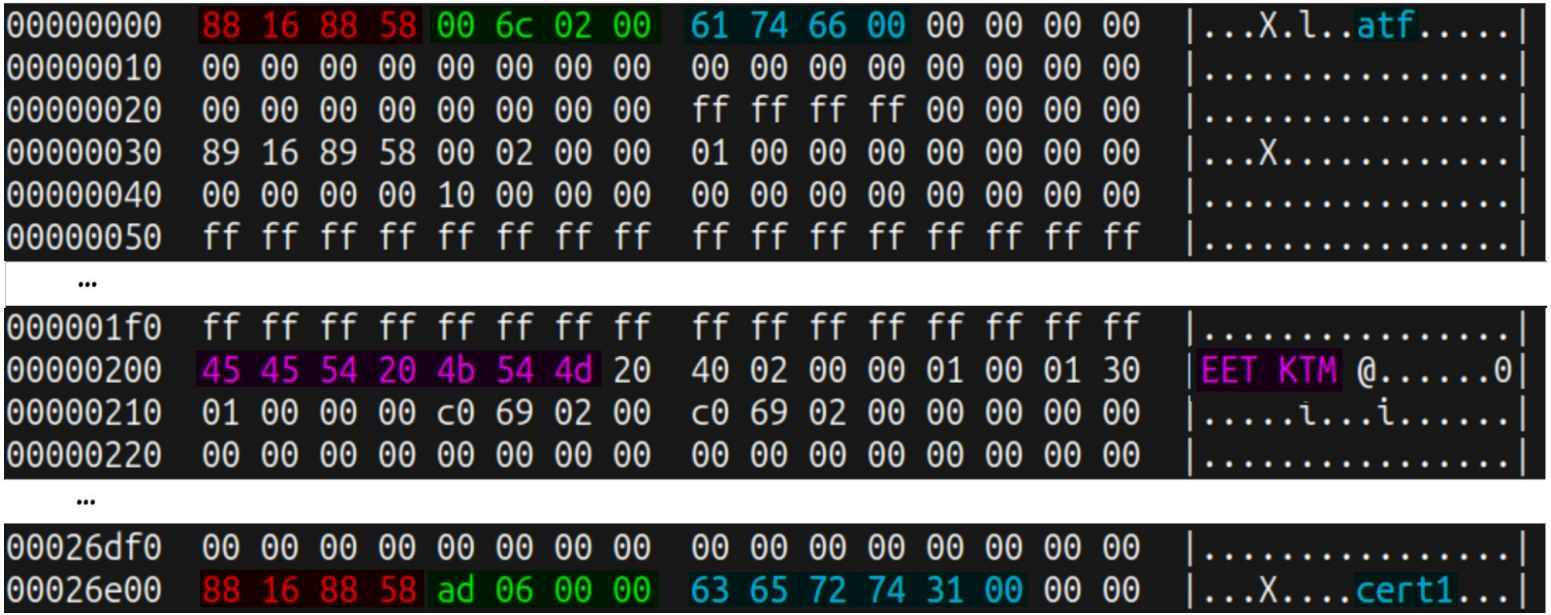


Vulnerability Research on ATF

- Motivation:
  - Highest privilege level → A bug here can be devastating
  - Reachable from Normal World through SMCs
- Code is simple
- Interacts a lot with HW through unknown registers
  - Fuzzing not particularly interesting in this case
- Our approach: focus on static analysis

Extracting ATF

- Inside an Android ROM Image:
  - `tee-verified.img`: **ATF**, `TEEGRIS kernel`, `userboot.so`…



SMC Handlers

```
if ((is_secure & 1) == 0) {
  puVar1 = mediatek_plat_sip_handler_secure(smc_id,arg1,arg2,arg3
                ,arg4,arg5,output);
  return puVar1;
}
[...]
if ((origin < 2) && (IN_BOOTLOADER == 0)) {
  puVar1 = mediatek_plat_sip_handler_kernel(smc_id,arg1,arg2,arg3
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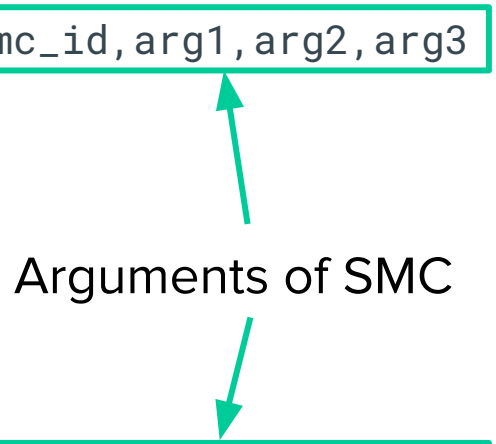

Leaking from Virtual Address Space

```
uint* global_array = (uint *)0x4ce2f578;
[...]
if (smcid == 0x82000526) {
    out_value = global_array[arg1 * 4];
    goto exit;
}
[...]
    output[2] = out_value;
    output[1] = arg1;
    *output = 0;
    return output;
```

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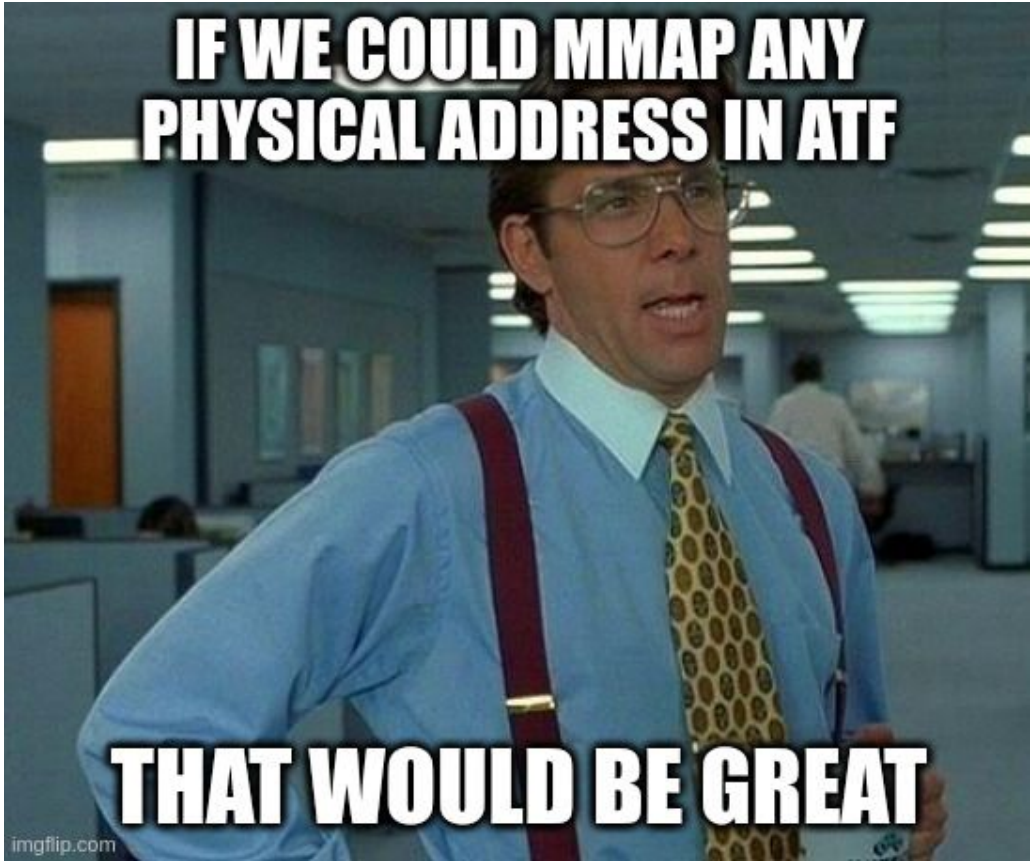
```

Fully controlled by attacker... And never checked

SVE-2023-2215 (CVE-2024-20820)

- In `mediatek_plat_sip_handler_kernel`, reachable from Linux Kernel
- To exploit it, send the SMC `0x82000526` with
  - `(`**`arbitrary_address`**` - 0x4ce2f578) / 4`
- Bug introduced by Samsung only in some devices (including A225F)
- It leaks 4 bytes from ATF virtual address space
  - We can read all the internal data of ATF
  - But we can't leak anything from other SW components

SVE-2023-2215 (CVE-2024-20820)



Mapping Any Physical Address in ATF

SMC `0x8200022A` calls function `spm_actions`

```
if (smc_id == 0x8200022a) {
    spm_actions(arg1,arg2,arg3);
```

Mapping Any Physical Address in ATF

SMC `0x8200022A` calls function `spm_actions`

```
undefined * spm_actions(ulong cmdid,undefined *addr,ulong size) {
    switch(cmdid & 0xffffffff) {
[...]
      case 1:
        if (size < 0x100001) {
            mmap_wrap(addr,size);
[...]
}
```

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And still no checks on the address

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[...]
}
```

Physical Address

And still no checks on the address

CVE-2024-20021

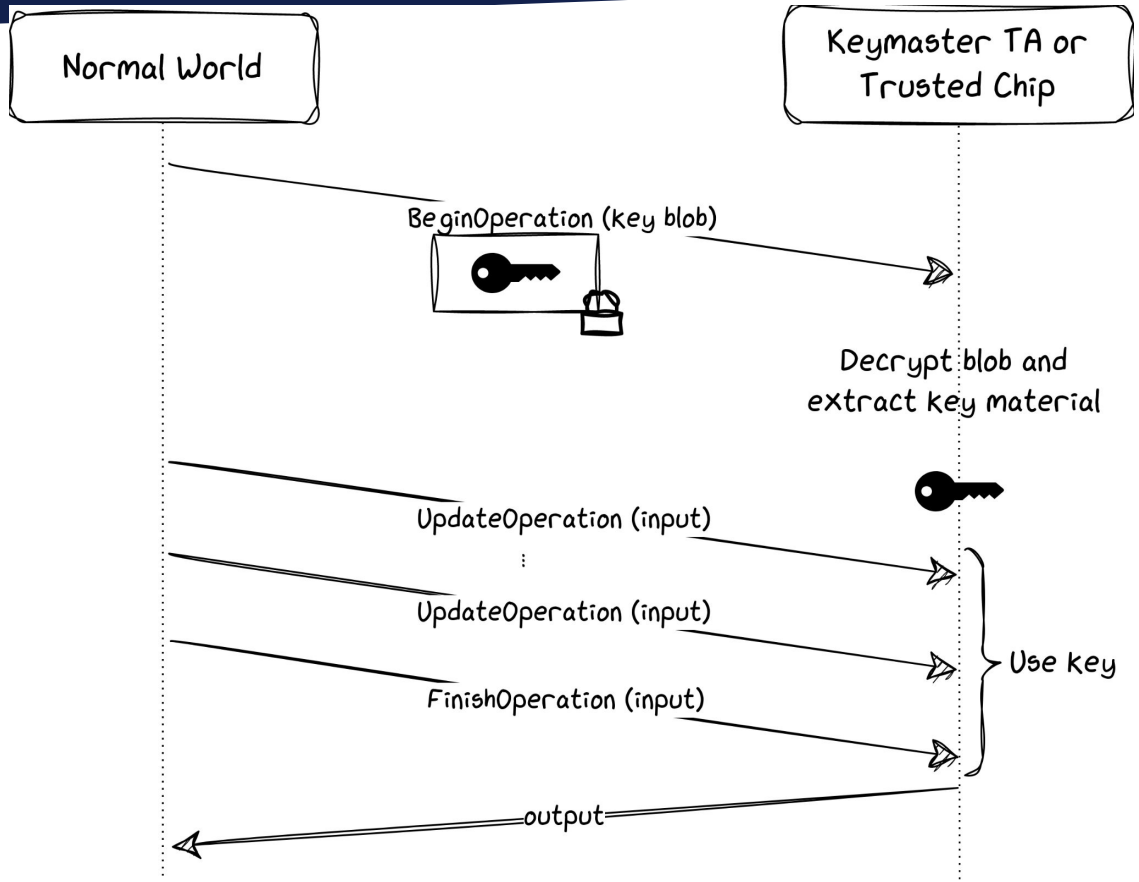
- Also in `mediatek_plat_sip_handler_kernel`
- Will `mmap` with physical base address to the same virtual address
  - ... however we can't `munmap`
    - So we are limited to 8 consecutive `mmaps`
    - Meaning we can leak up to **8MB** of data
- Introduced by Mediatek (impacts plenty of Mediatek SoCs)
- Chained to our leak, we can read everything in Secure World
  - Including TEEGRIS

Can we use this vulnerability to leak Keystore keys?

Android Keystore system

- Key storage and crypto services
- Keys are stored as encrypted *key blobs*
- Three protection levels:
  - Software only
  - TEE (default)
  - Hardware-backed (StrongBox)
- Raw key should never leave protected environment

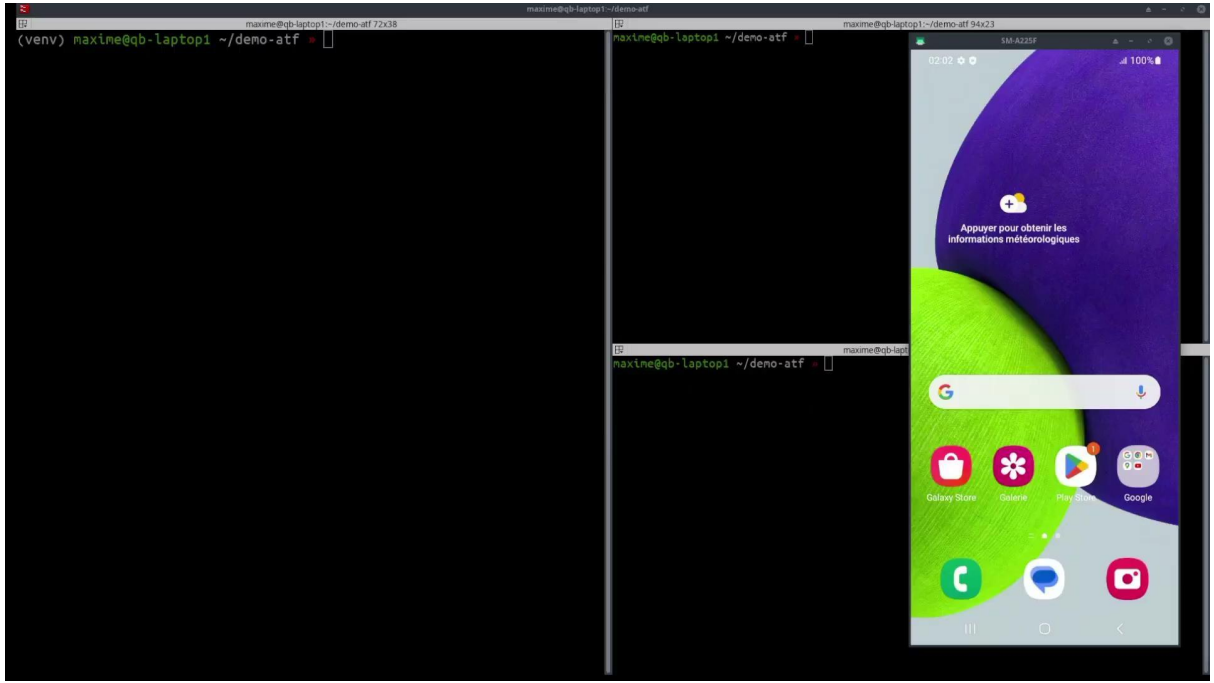
Android Keystore system



Our PoC

1. **Import** a key into the Android Keystore
2. **Encrypt** using that key
3. **Stop the execution** after `BeginOperation` is called
    - To makes sure the key stays in memory
4. **Leak** the identified region of memory
5. Try all possible keys from leak to decrypt ciphertext

Demo


maxime@qb-laptop1:~/demo-atf
maxime@qb-laptop1:~/demo-atf 72x38
(venv) maxime@qb-laptop1 ~/demo-atf
maxime@qb-laptop1:~/demo-atf 94x23
maxime@qb-laptop1 ~/demo-atf
maxime@qb-laptop1 ~/demo-atf
SM-A225F
02:02
100%
Appuyer pour obtenir les informations météorologiques
Galaxy Store
Galerie
Play Store
Google

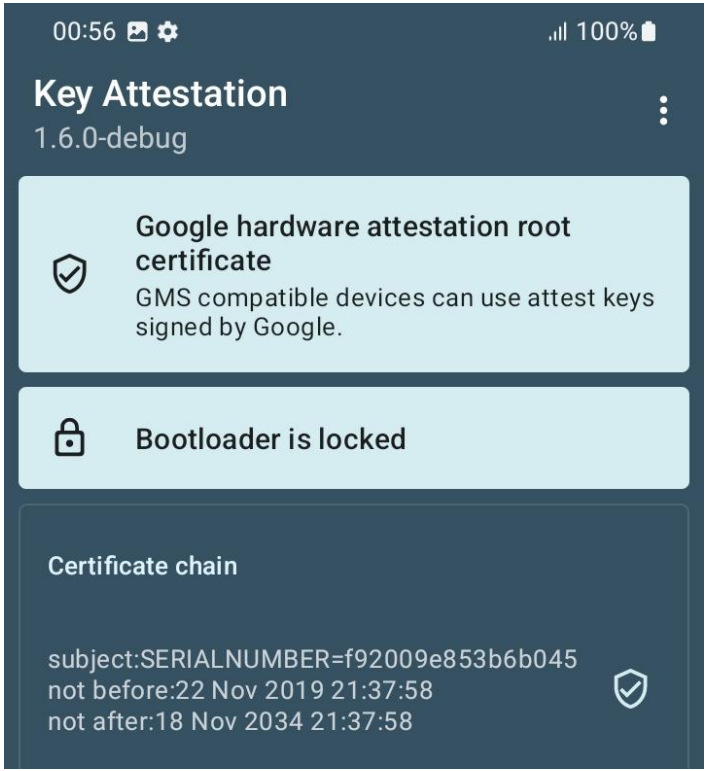
What's next?

Key Attestation

- Proves that a key pair is stored in the secure hardware
  - Trustzone or Security Chip
- Contains information about the device state
  - Such as bootloader locked status and verified boot state
- Used by SafetyNet[5] to tell if a device has been compromised

[5]: https://www.sstic.org/media/SSTIC2022/SSTIC-actes/droidguard_a_deep_dive_into_safetynet/SSTIC2022-Article-droidguard_a_deep_dive_into_safetynet-thomas.pdf

First Key Attestation test

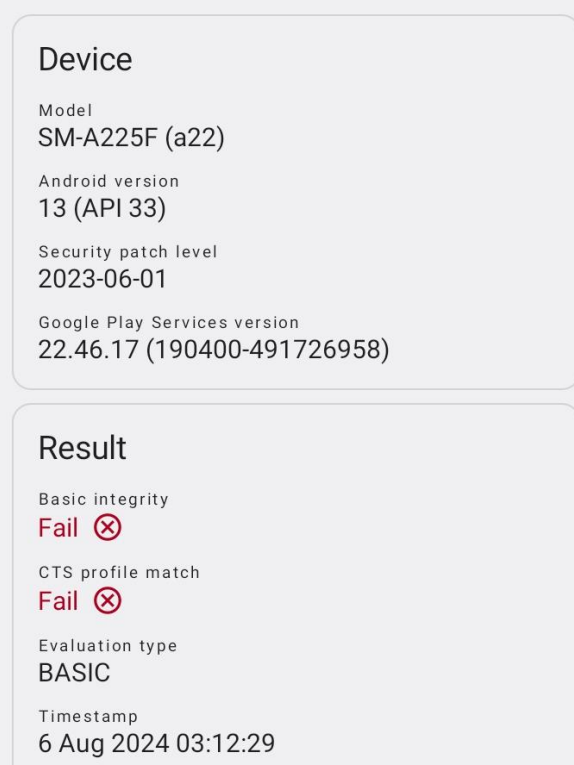


✅ Attestation generated with a demo app[6]

👉 Our exploit seems not detected!

[6]: https://github.com/vvb2060/KeyAttestation

What about SafetyNet?

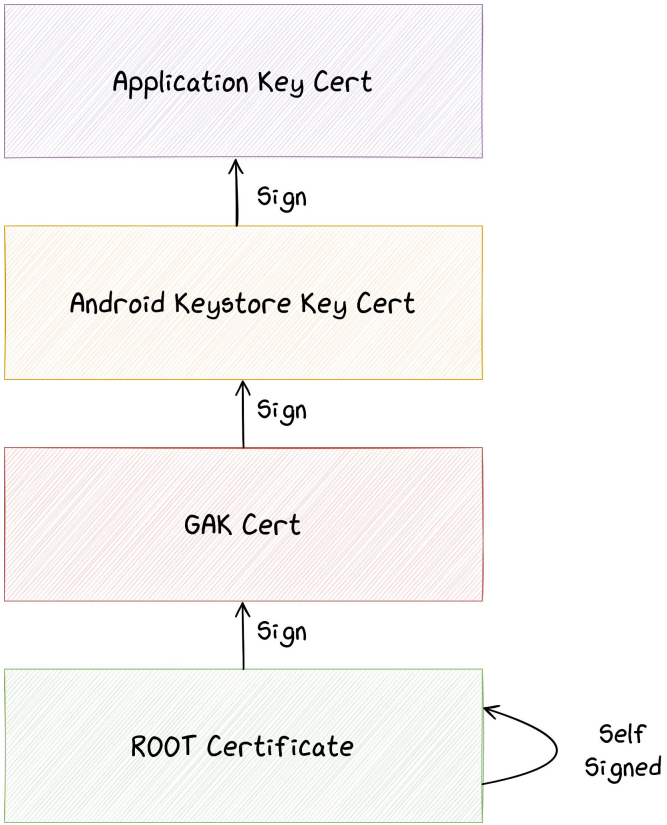


✅ SafetyNet detects the exploit

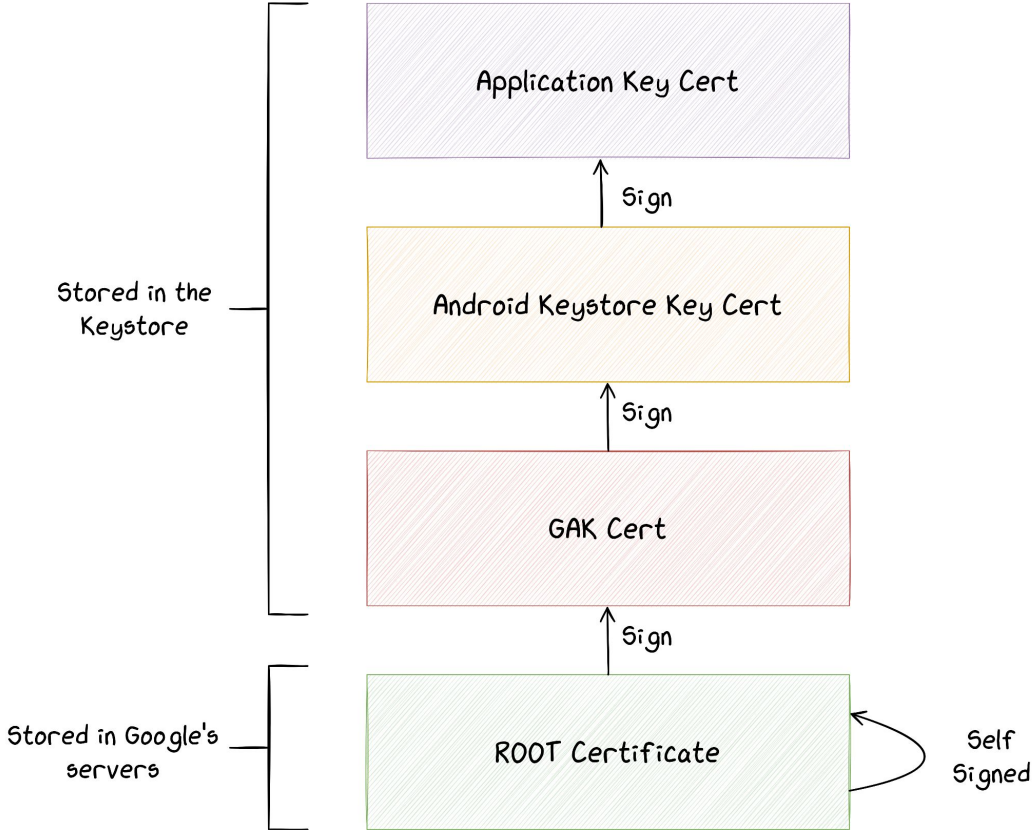
- Possibly through heuristics to detect Magisk

[6]: https://github.com/RikkaW/YASNAC

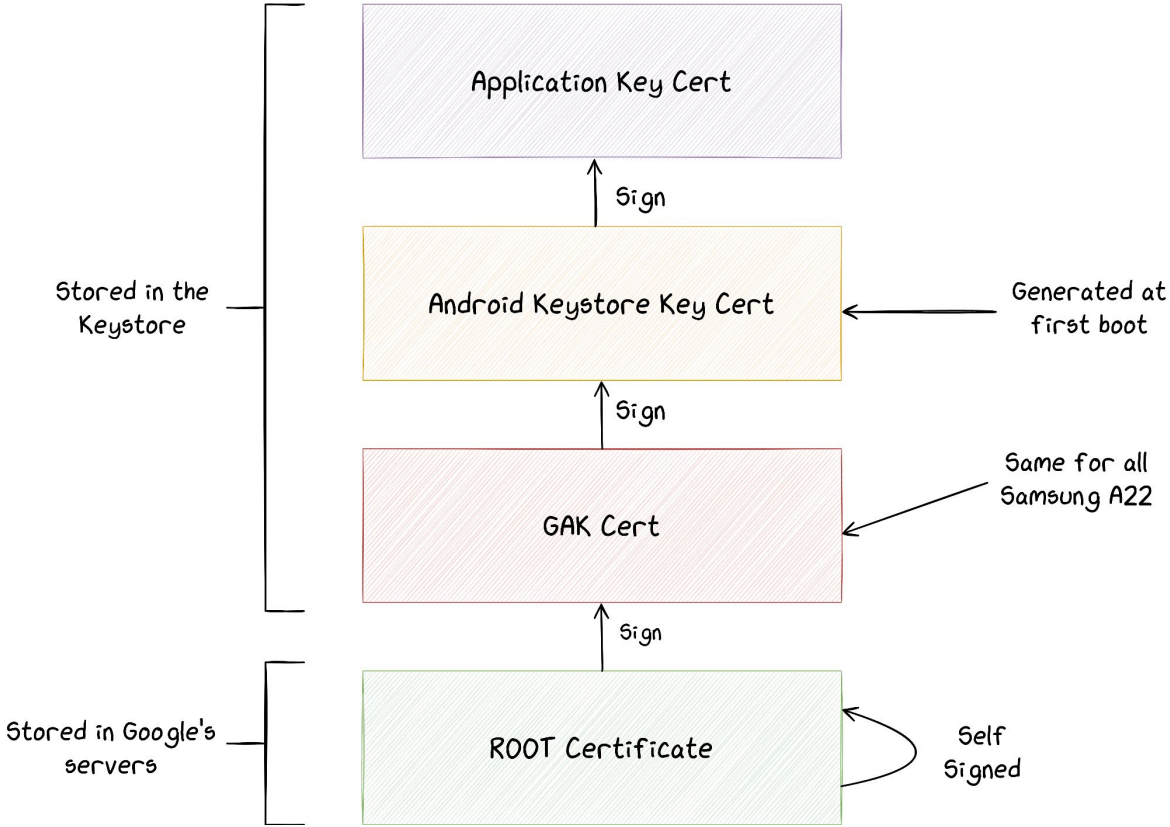
Certificate Chain



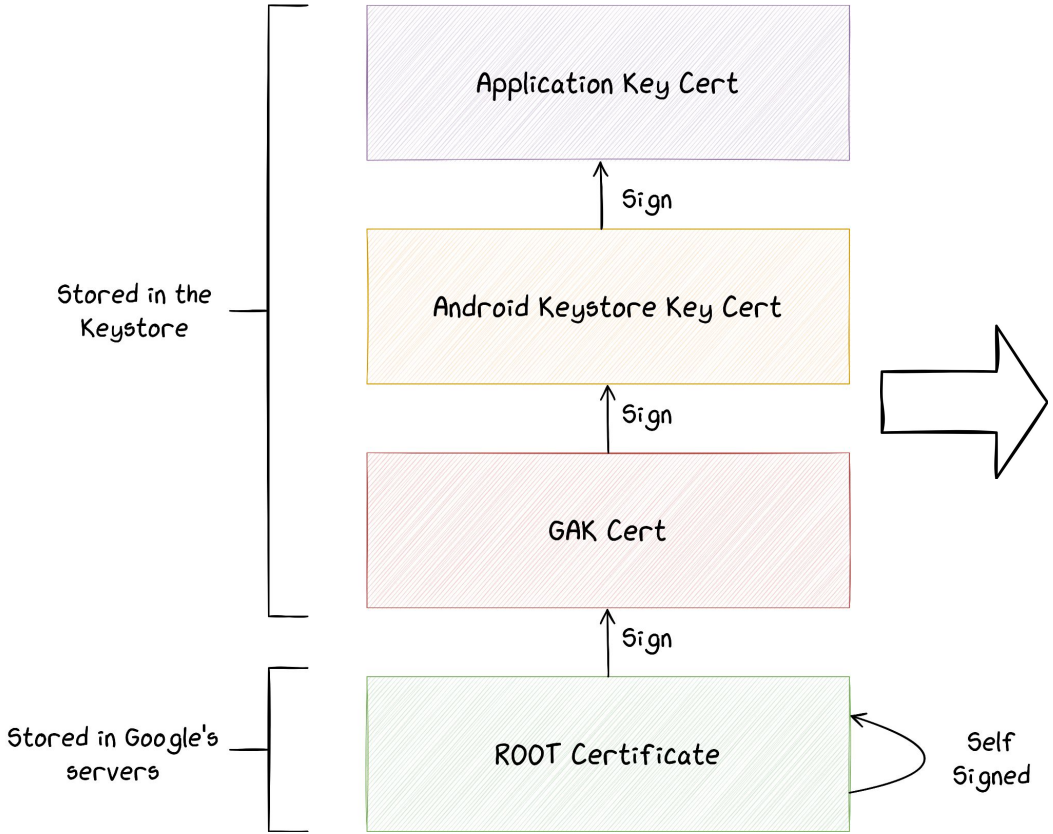
Certificate Chain



Certificate Chain



Certificate Chain



Root of trust
verifiedBootKey:
07EFE057CEBF085AAA79D1FB2090CCCB59
9D6A51B027FEABF123FD78E84D3D63
deviceLocked: true
verifiedBootState: Verified
verifiedBootHash:
E07ADF185A36CE4A2FED204CF9C3103D54
1B7A90305F89785154A460688553E0

OS version
130000

OS patch level
202306

Attestation application ID
Package info 1/1:
io.github.vvb2060.keyattestation (version code 165)

Certificate sha256 digest 1/1:
D8B53693490D6E7467F985165001A547F72
2E75735B34E6AA13BF949F5216F1E

Strategy to leak GAK

- Stored as EKEY in Android Filesystem
  - `/mnt/vendor/efs/DAK/GAK_EC.private`

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1. **Forge a valid** Begin request with GAK keyblob
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4. Try to every possible private keys in the dump
   - By generating the public key out of it

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➜ Still WIP

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Conclusion

- We presented 4 vulnerabilities leading to
  - Authentication bypass in Odin
  - Code execution with persistence in LK
  - Leak of SW memory, including Keystore keys
    - Still unclear if we can leak Attestation Keys
- Impact low/middle end Samsung devices
  - Vulnerabilities are simple, and yet super impactful
  - No mitigations in LK nor ATF
- All the vulnerabilities are now fixed

Thank you!

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@DamianoMelotti
@pwissenlit

contact@quarkslab.com

Quarkslab