BootStomp: On the Security of Bootloaders in Mobile Devices

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What is a Bootloader?

What is a Bootloader?

Software module which:

- Initializes the device and its peripherals
- Loads the kernel code from secondary storage
- Jumps to it

We focused on Android bootloaders

Android Bootloaders Overview

- No standard (e.g., ARM gives guidelines)
- Booting through several stages
- Protect integrity of user's device and data:
  - Trusted boot
- Bootloader unlocking

Why attacking bootloaders?

Attacking Bootloaders

An attacker controlling the bootloader might:

- Boot custom Android OS (*bootloader unlocking*)
    - Persistent rootkit
- Brick the device
- In some cases, achieve controls over peripherals

Safety Properties

Integrity of the booting process

- Android OS is verifiably to be in a non-tampered state
- A root process cannot interfere with peripherals setup

Unlocking security mechanism

- A root process cannot unlock the bootloader
- Physical attacker cannot unlock the bootloader

Threat Model

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- Attacker has control over the Android OS
    - Root privileges

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- Attacker has control over the Android OS
  - Root privileges
- If an attacker has root privileges is game over, why even bother?
  - The safety properties should hold anyway

Outline

- Booting Process
- Bootloader Unlocking
- BootStomp
- Evaluation
- Mitigations
- Conclusions

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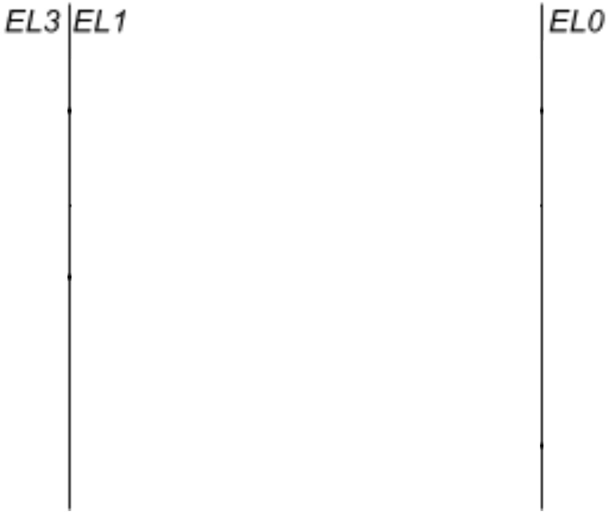
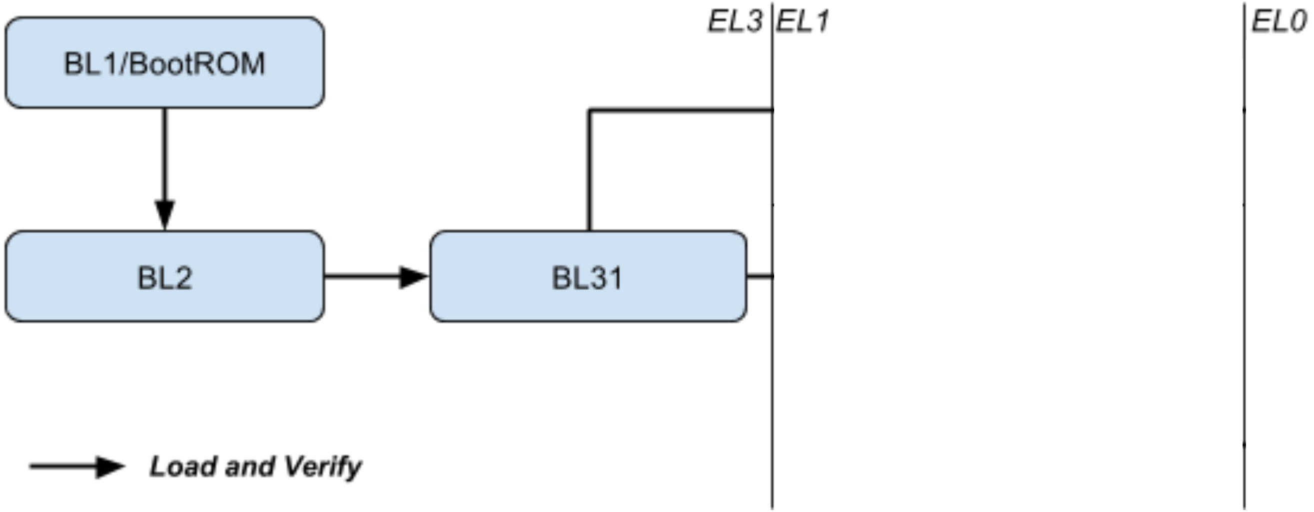
Booting Process

God mode | Kernel mode | User mode



Booting Process

God mode Kernel mode User mode



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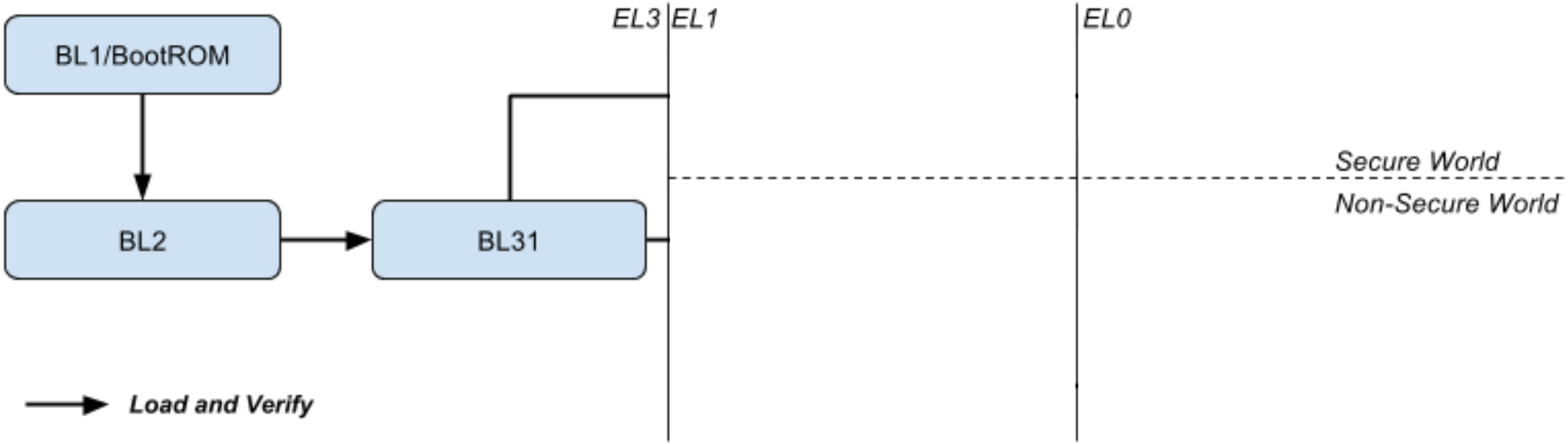

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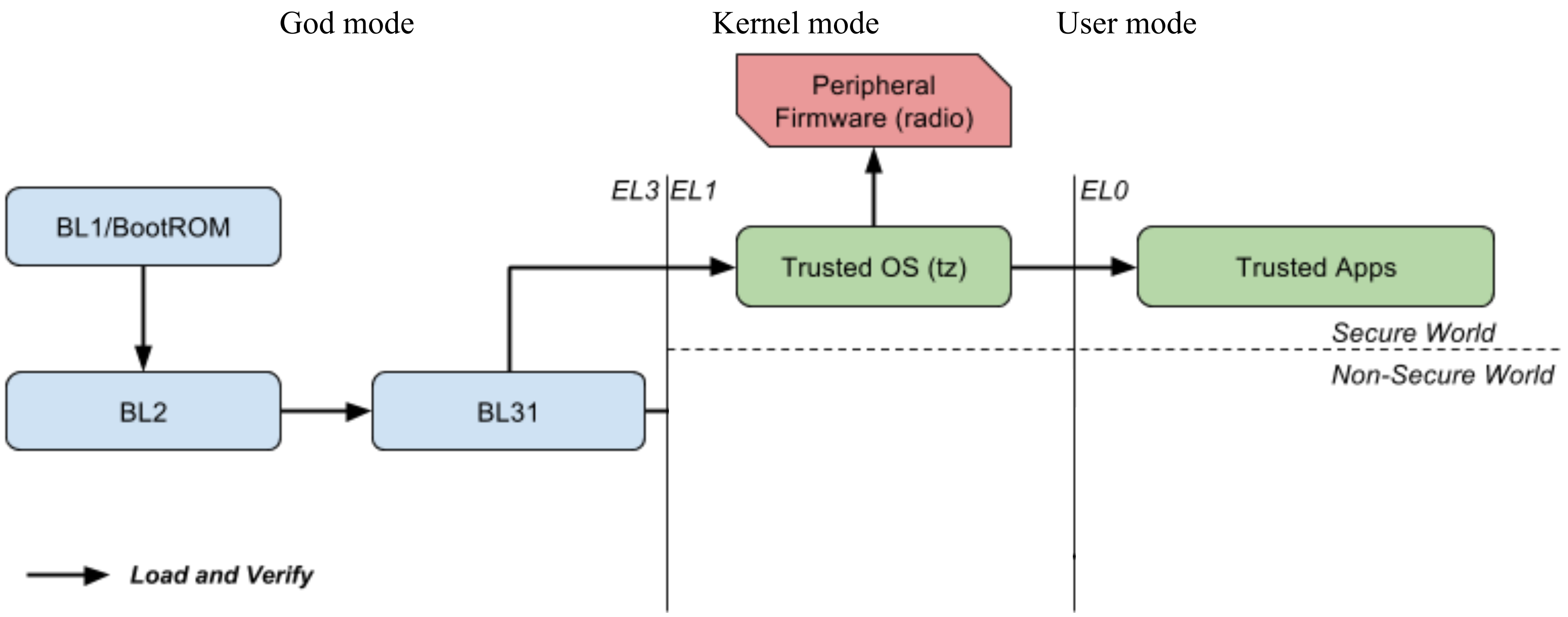
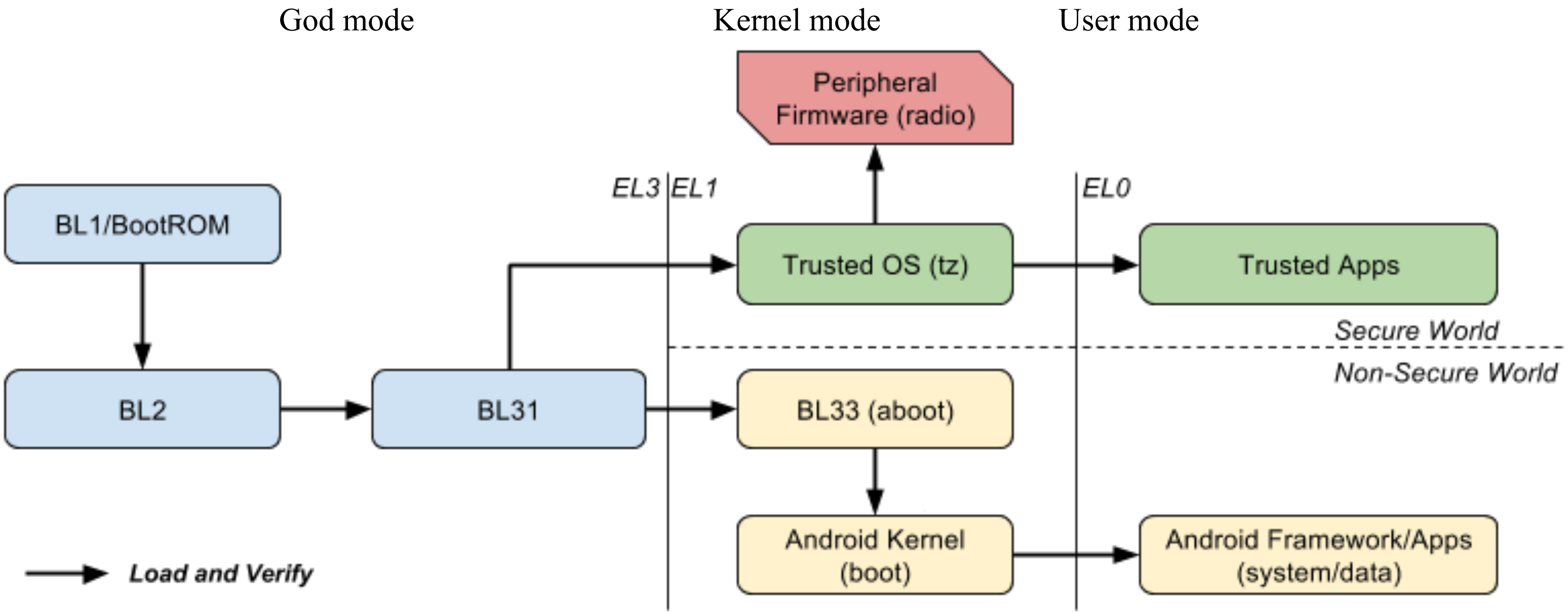


Booting Process



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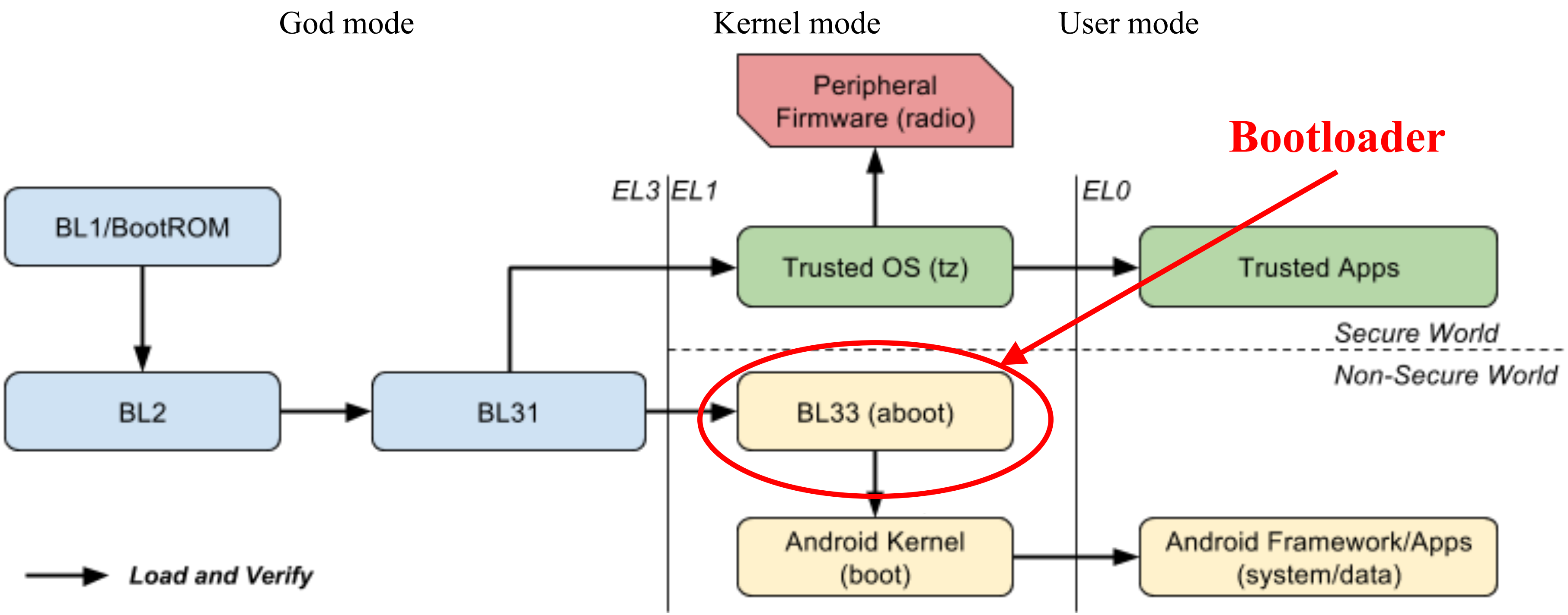

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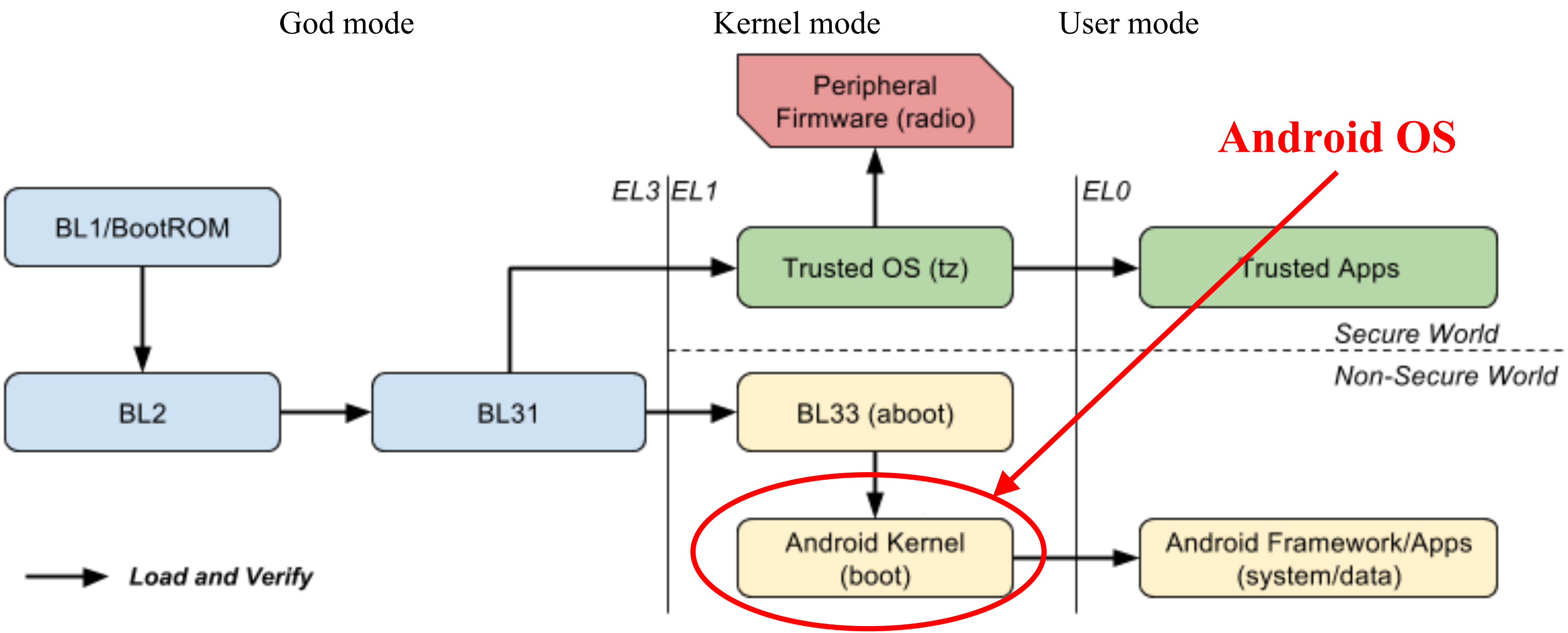

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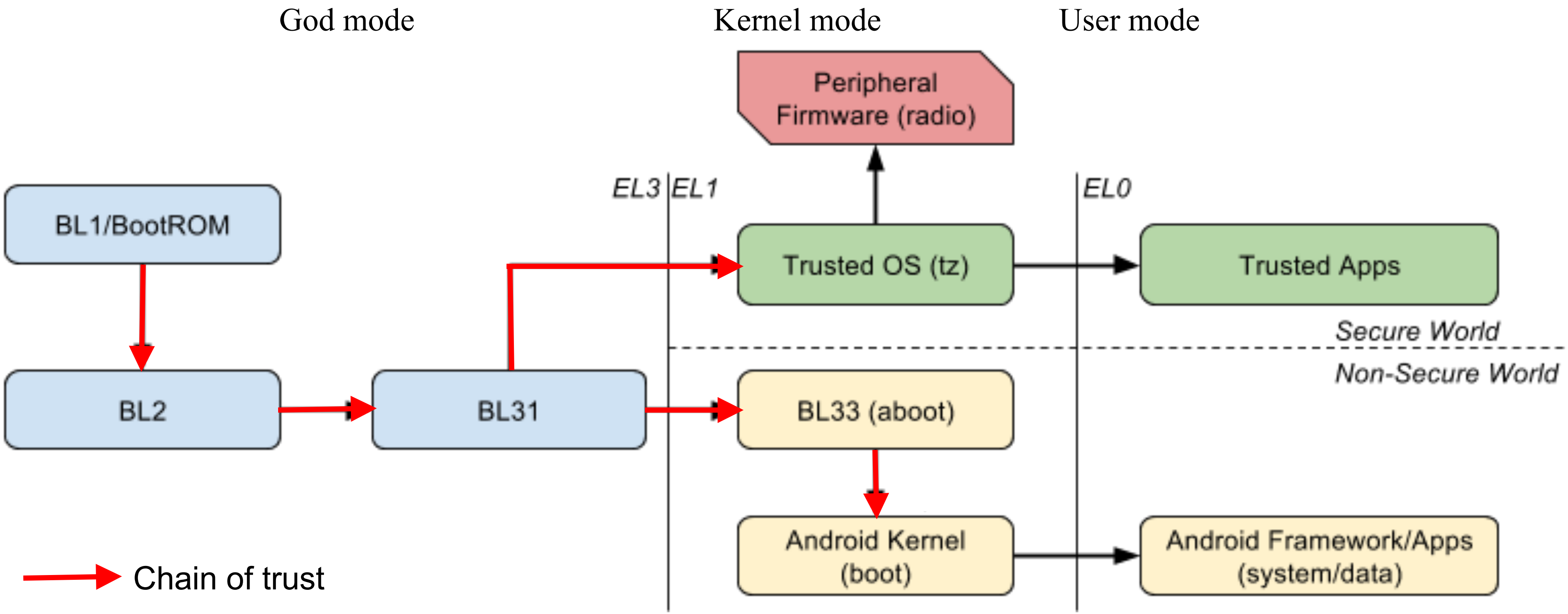

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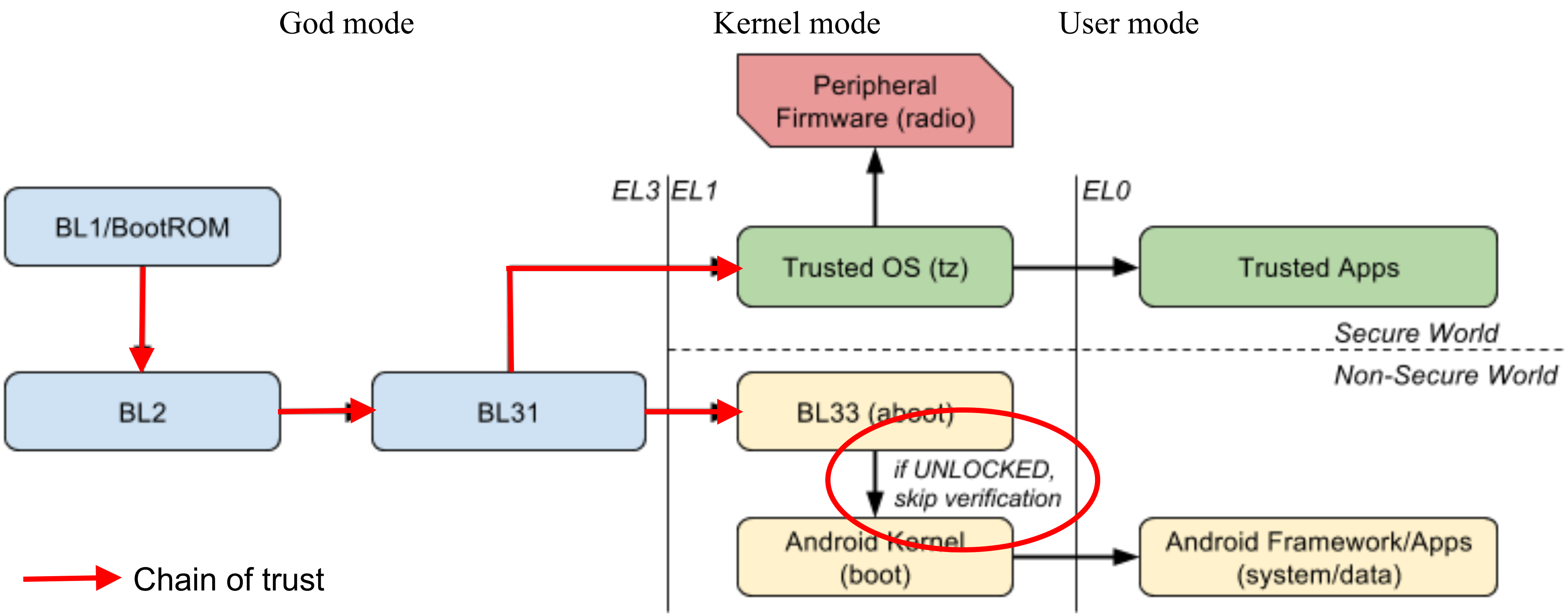

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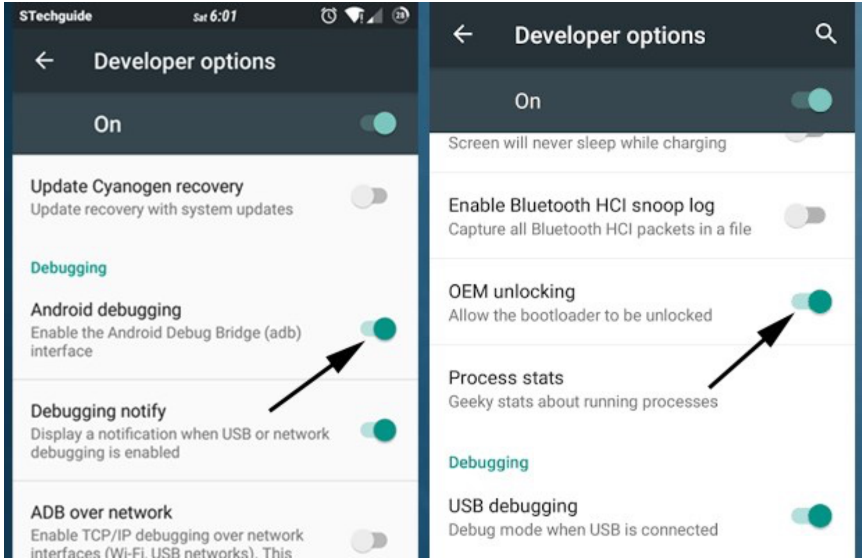
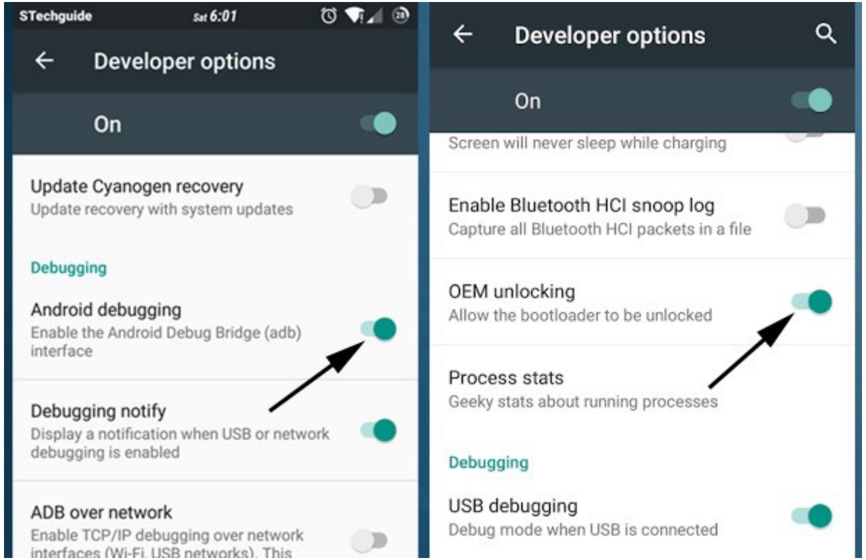
Bootloader Unlocking

Two steps



Bootloader Unlocking

Against an attacker with physical access



Against root process

Bootloader Unlocking

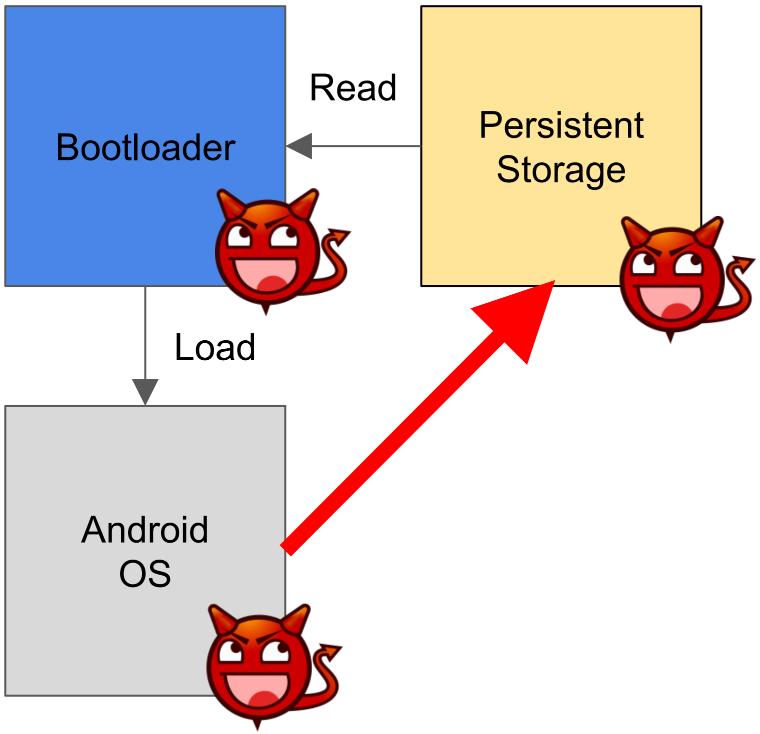
The unlocking state (*device's security state*) saved on persistent storage

- It should be writable only by high privileged components (e.g., bootloader or secure OS)

Can a compromised Android OS affect the booting process?

Can a compromised Android OS affect the booting process?

Yes!


Bootloader
Read
Persistent Storage
Load
Android OS

We need a tool to automatically verify

the safety properties

Towards a Bootloader Analyzer

Bootloaders are hard to analyze:

- The source code is hardly available

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Bootloaders are hard to analyze:

- The source code is hardly available → Binary (blob)
- Dynamic execution is impractical → Hardware is required
- Execute before the Android OS → Known library/syscall are not in use
    - There is no memcpy!

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BootStomp: A Bootloader Analyzer

Automatic static binary tool for finding security vulnerabilities in bootloaders

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Automatic static binary tool for finding security vulnerabilities in bootloaders

- Determine whether **attacker-controlled data** can influence the bootloader intended behavior

- Traceable output
    - Verify generated alerts

BootStomp: A Bootloader Analyzer

BootStomp uses multi-tag taint analysis based on under-constrained dynamic symbolic execution

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BootStomp uses multi-tag taint analysis based on under-constrained dynamic symbolic execution

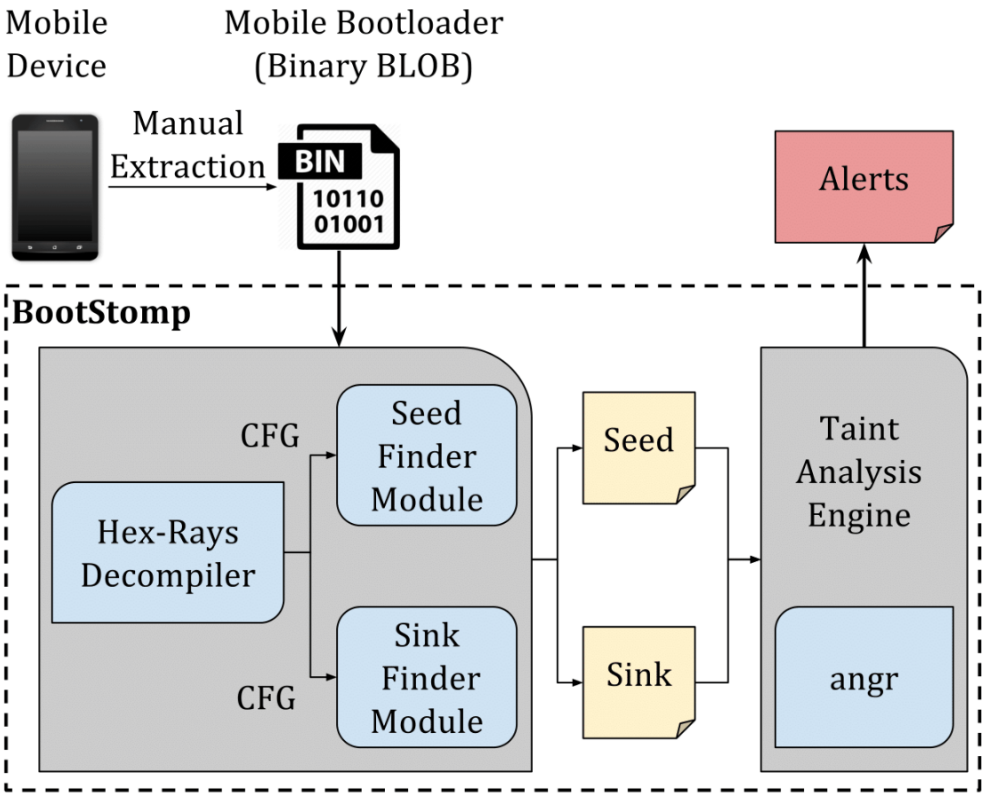
- It uses a **fully symbolic** taint analysis engine to trace attacker-controlled data

BootStomp: A Bootloader Analyzer

BootStomp uses multi-tag taint analysis based on under-constrained dynamic symbolic execution

- Arbitrary memory writes
- Arbitrary memory reads
- Attacker can control loops iterations
- Bypass unlocking mechanism
    - Functions overwriting the security state on persistent storage

BootStomp: A Bootloader Analyzer



BootStomp: A Bootloader Analyzer

BootStomp uses multi-tag taint analysis based on under-constrained dynamic symbolic execution

- Seeds of taint
- Taint propagation and removal
- Sinks of taint
- Taint checking

BootStomp: Seeds of Taint

- Data read from persistent storage
- Data used by the unlocking procedure

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BootStomp must find these functions

BootStomp: Seeds of Taint

Automatic detection of functions:

- Identify the functions based on the “log” strings
- Analysis to identify the arguments to taint

```
LABEL_5:
  v16 = sub_7002D00(a3, v11, v12, 1i64);        // emmc read function
  *v9 = v12 << 9;
  v23 = v16;
  if ( v15[11] )
    sub_70032BC(0xB3u, 8u);
  result = 0i64;
  if ( v23 )
  {
    sub_705F924((__int64)"emmc read error = %d\n", v23, v17, v18, v19, v20, v21, v22, v45);// logging function 1
    sub_7001F04((__int64)"emmc read error = %d\n", v23, v39, v40, v41, v42, v43, v44, v45);// logging function 2
    result = 0xFFFFFFFFi64;
  }
  return result;
}
```

BootStomp: Seeds of Taint

Optionally, provided by the security analyst

- Useful for finding the unlocking function
    - Several do not contain log messages

BootStomp: Taint Propagation and Removal

- Taints are symbolic expressions encoding how the value is computed
- Propagated and removed implicitly during the dynamic symbolic execution traversal

BootStomp: Taint Propagation and Removal

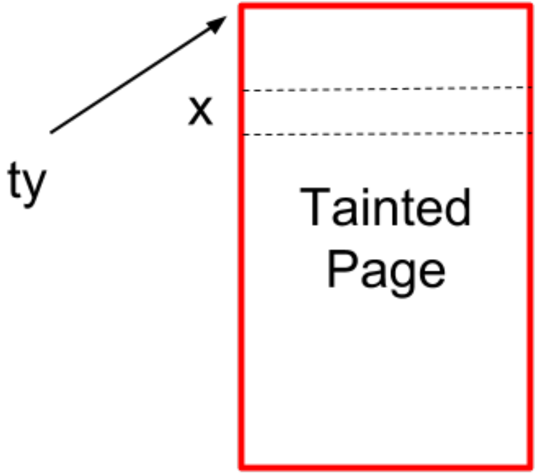
Code

```
ty = seed_func();
x = ty + 5;
....
x = 0xdeadbeef;
```

Symbolic expressions

```
ty = TAINT_ty
x = TAINT_ty + 5
....
x = 0xdeadbeef
```

Memory



BootStomp: Sinks of Taint

- Memcpy-like functions
- Dereference of a tainted variable
- Comparisons of tainted variables in loops’ conditions
- Write to a persistent storage of a tainted variable

BootStomp: Sinks of Taint

- Memcpy-like functions
  - Small functions with loop copying data between two buffers
  - Many callers (a threshold is used)
- Dereference of a tainted variable
- Comparisons of tainted variables in loops’ conditions
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- Memcpy-like functions
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BootStomp: Taint Checking

- An alert is raised when a tainted variable:
  - Reaches a memcpy-like function
  - Gets dereferenced
  - Can control the number of iterations of a loop
  - Gets written to a persistent storage

BootStomp: Taint Checking

- An alert is raised when a tainted variable:
  - Reaches a memcpy-like function
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  - Can control the number of iterations of a loop
  - Gets written to a persistent storage
- A traceable output is produced

Limitation: Path Explosion Problem

- Limited function traversal

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  - Tainted arguments and call stack size < threshold ?

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- Limited function traversal
  - Tainted arguments and call stack size < threshold ?
    - Yes → step into
    - No → step over

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- Limited function traversal
- Limited loop iterations
    - Threshold used

Limitation: Path Explosion Problem

- Limited function traversal
- Limited loop iterations
- Timeout

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- Booting Process
- Unlocking Mechanism
- BootStomp
- **Evaluation**
- Mitigations
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BootStomp has been evaluated against 4 different bootloaders

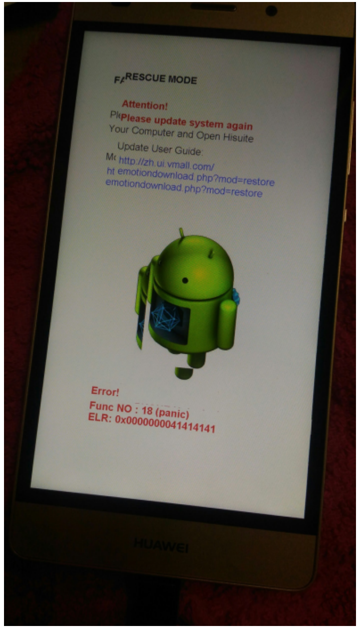
Evaluation: Bugs

Bootloader	Total Alerts	Bugs
Qualcomm (Latest)	4	0
Qualcomm (Old)	8	1 (already known)
NVIDIA	7	1
HiSilicon	17	5
MediaTek	-	-
Total	**36**	**7 (6 0days)**

(Further details in the paper)

Ok good, but how bad are them?

Evaluation: Bugs



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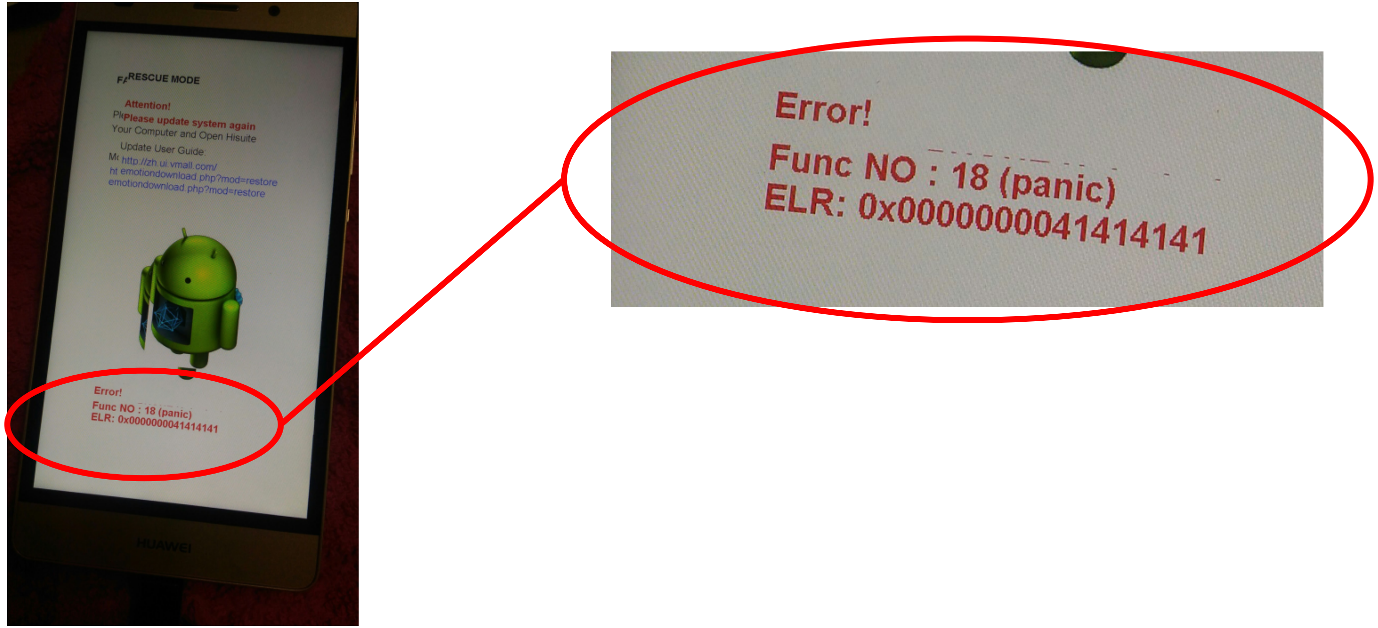

Evaluation: Bugs

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- A lot! Example: some bootloaders work in EL3

Evaluation: Unlocking Bypass

Bootloader	Writes to flash?	Potentially vulnerable?
Qualcomm (Latest)	**6**	**YES***
Qualcomm (Old)	**4**	**YES***
NVIDIA	9	NO
HiSilicon	**17**	**YES***
MediaTek	1	NO

*(**Yes** means BootStomp found a write to a persistent storage)*

Bootloader Unlocking Bypass

```
memcpy(&expected_digest, &from_flash, 32);
    compute_sha(oem_key, input_len, &key_digest);
    if (memcmp(&key_digest, &expected_digest, 32) )
    {
            // Log the result
            return 1;
}

hash_func("bonaciao", &key_digest, &hash_output);
    if (write_to_flash(hash_output, 16) & 0x80000000) )
    {
        // Log the result
            return 0;
    }
```

Overview

- Booting Process
- Unlocking Mechanism
- BootStomp
- Evaluation
- **Mitigations**
- Conclusions

Mitigations

- Google approach
    - The key used to encrypt/decrypt user data contains the security state (locked/unlock)

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- Our proposal
  - Security state stored in the eMMC's *Replay Protected Memory Block* (RPMB)
    - Modify the trusted OS to allow **only** the bootloader to modify it

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Responsible Disclosure

All bugs reported, acknowledged and already fixed

Conclusions

- ✓ First study to explore Android bootloaders
- ✓ Automated technique to analyze bootloaders with traceable alerts
- ✓ Found 6 zero days in various bootloaders
- ✓ https://github.com/ucsb-seclab/bootstomp

That’s All

Questions?

Buffer overflow

```
// oem_get_info function

 oem_read(block, block_len);
buf =  malloc(block[0]); // size block

// .. additional code ..
number_or_blocks = block[1];
block_id = block[2];

if (number_of_blocks == 1 || block_id == number_of_blocks) {
              return;
}

memcpy(buf + off, block[3], 0x300);
```

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If the bootloader only loads the Android O.S., how can an attacker harm the device?

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Bootloaders are very diverse

BL33 in practice

Qualcomm and NVIDIA’s:

- BL33 conforms very closely to Google’s Verified Boot guidelines,
- BL33 runs in EL1

BL33 in practice

Qualcomm and NVIDIA’s

Huawei HiSilicon:

- BL33 is also responsible for initializing modem and peripherals
- BL33 runs in EL3.

BL33 in practice

Qualcomm and NVIDIA's

Huawei HiSilicon

MediaTek:

- BL33 is also responsible for initializing modem
- BL33 runs in EL1