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# Android Platform Security

*Mobile Security 2022*

Florian Draschbacher
florian.draschbacher@iaik.tugraz.at

Some slides based on material by **Johannes Feichtner**

# Practicals

- Feedback for assignment 1 soon!
- Start early with assignment 2!
- Any questions? Ask!

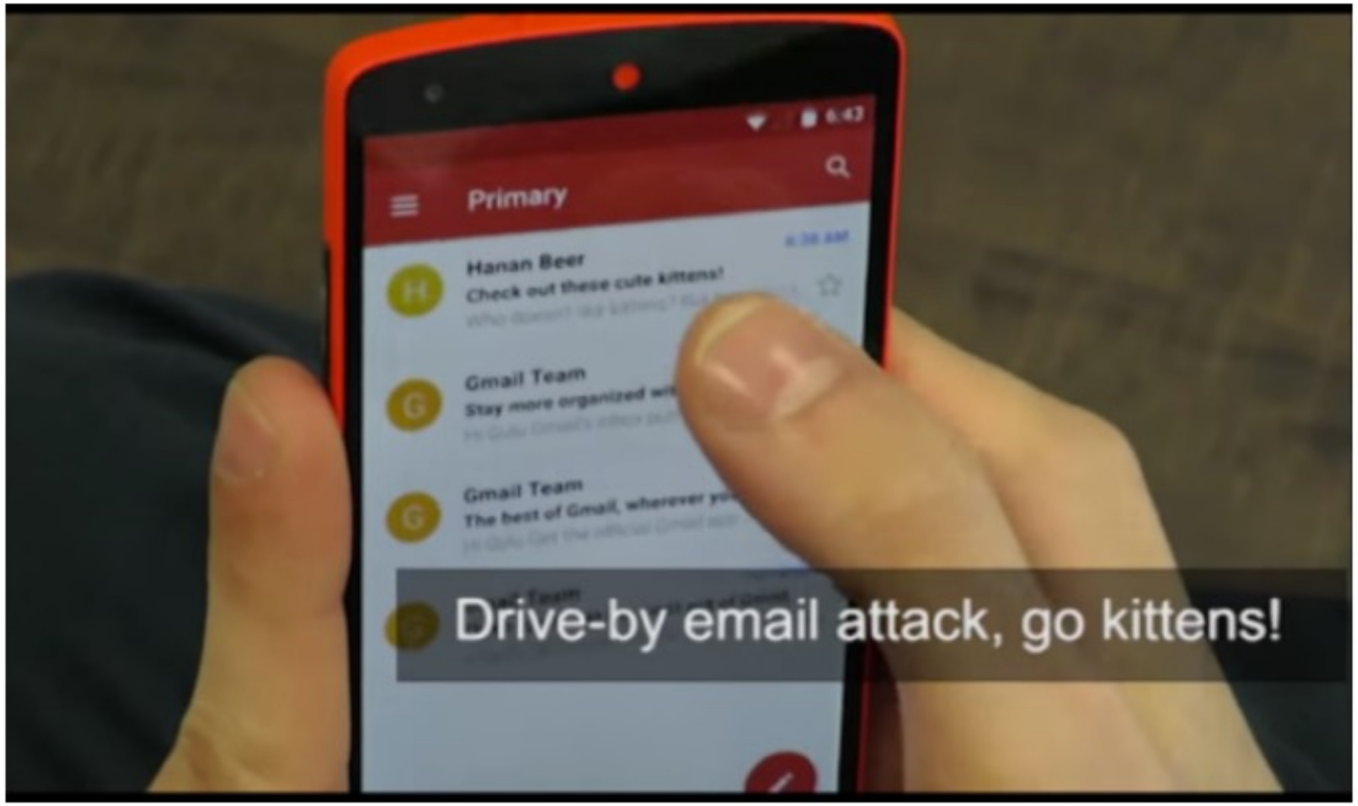
# Outline

- Android Platform Fundamentals
- Low-level System Security
- Encryption System
- Android OS Security
- Key Management
- Rooting

# 275 million Android phones imperiled by new code-execution exploit

Unpatched "Stagefright" vulnerability gives attackers a road map to hijack phones.

DAN GOODIN - 3/18/2016, 9:26 PM




Source: https://goo.gl/9fgYSc

## What?

Bugs in Android's `libstagefright` and `libutils`

## How?

- Attacker embeds shellcode in harmless multimedia file
- Message is downloaded (e.g. via MMS)
- Exploit is executed

## Result

- Attacker can execute any code on remote device

# Serious flaw in WPA2 protocol lets attackers intercept passwords and much more

KRACK attack is especially bad news for Android and Linux users.

DAN GOODIN - 10/16/2017, 6:37 AM

## What?

Android can be tricked into using an <u>all-zero encryption key</u> for WPA/WPA2 WiFi communication

## How?

- Attacker resends message of 4-way handshake to device
- Real encryption key is replaced with zero key

## Result

- Attacker can intercept and manipulate traffic from device

Source: [https://goo.gl/5Ea555](https://goo.gl/5Ea555)

# Billions of devices imperiled by new clickless Bluetooth attack

BlueBorne exploit works against unpatched devices running Android, Linux, or Windows.

DAN GOODIN - 9/12/2017, 3:00 PM

BlueBorne

Source: [https://goo.gl/sDiTuu](https://goo.gl/sDiTuu)

## What?

Implementation flaws in common Bluetooth stacks enable remote code execution

## On Android?

- Device constantly scans for other devices nearby
- Bluetooth implementation runs with privileged permissions and is exploitable (heap overflows)

## Result

- Remote code execution on phone without user noticing

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# Android Platform Fundamentals

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# Android

- Open-Source OS developed mainly by Google
  - Linux kernel: GNU GPLv2, Rest: Apache 2.0
  - Many implementation details can be studied from source code!

- Wide device support
  - CPU architectures, hardware features, …
  - Used by various device manufacturers
  - Proprietary additions, modifications, forks

- Compatibility Test Suite ensures compatibility
  - Requirement for access to Google Mobile Services (Play Store, …)

Source: [source.android.com](source.android.com)

# Android Device Architecture

- Most Android devices feature a main CPU and some secure environment
  - Secure Key Storage
  - Handling biometric unlock (Fingerprint, …)

- ARM TrustZone
  - Secure environment runs in a separate execution environment on main CPU

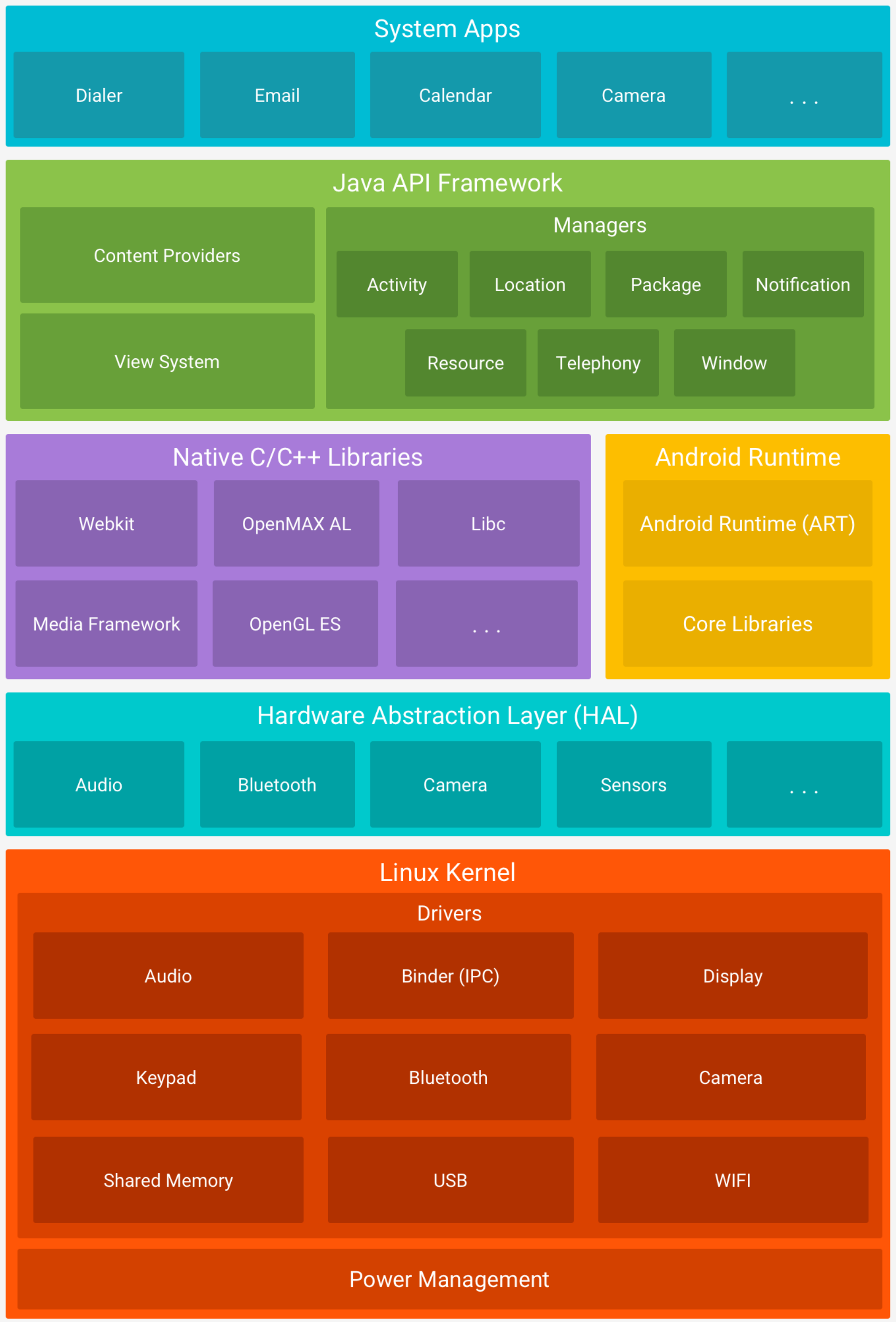
- Secure Element
  - Secure environment runs on a dedicated CPU
  - E.g. Google Titan M2 in Pixel 6 devices

Sources: security.googleblog.com, security.googleblog.com, developer.android.com

# Android System Architecture

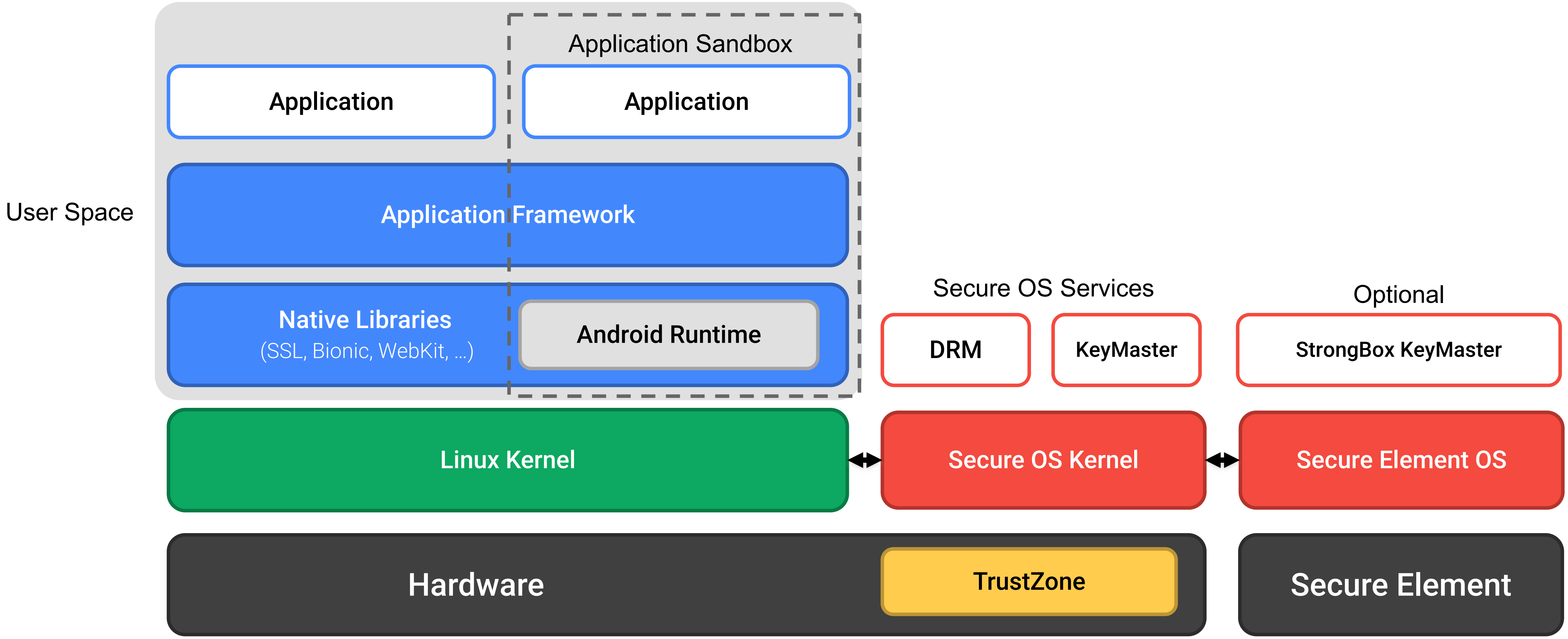
- Linux kernel
  - Device drivers
  - POSIX interface
  - Binder IPC
  - Low Memory Killer

- Userspace
  - HAL (Hardware Abstraction Layer)
  - Android Runtime
  - System Services
  - Application Framework




Picture: android.com / Apache 2.0

# Android Security Architecture

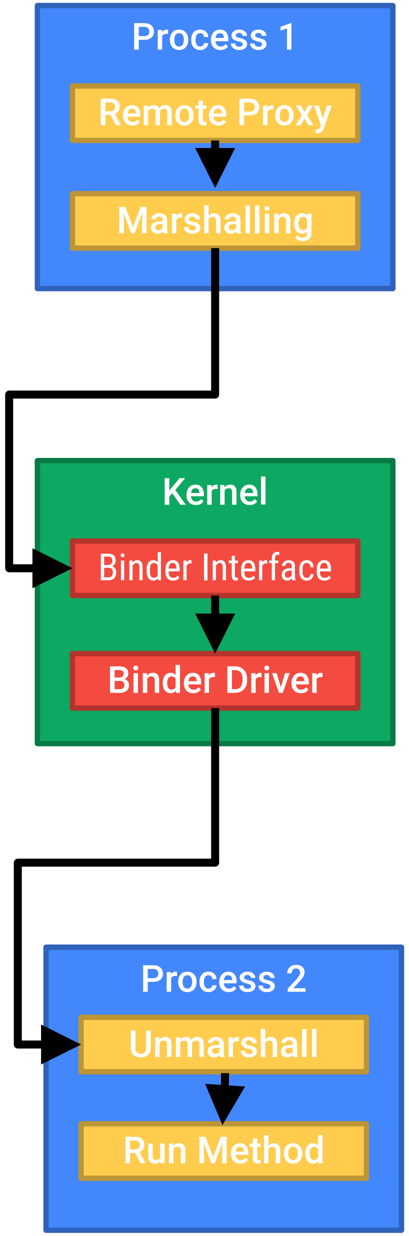


# Binder

## Android-specific implementation of secure and efficient RPC

- Supports passing objects and file descriptors
- Manages memory life cycle of shared objects
- Kernel passes UID of calling process to callee
  - Callee can check permissions of caller
- Proxy and Stub classes can be generated from AIDL
  - Android Interface Definition Language

- `Intent`, `Parcel`, `Service`, `Context.getSystemService()`, ...
  - All based on Binder functionality!

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# Android Fragmentation

- Android is shipped by many different device manufacturers
  - Different CPU architectures, HW peripherals, UI modifications, …
- Releasing OS update for a device used to be time-consuming
  - Obtaining updated firmware from peripheral vendors
  - Porting modifications to new base
- Situation improved with Project Treble (Android 8.0 / 2017)
  - Low-level vendor implementation untouched in Android updates
- Further improvements with Project Mainline (Android 10.0 / 2019)
  - System components can be updated through Google Play

Sources: android-developers.googleblog.com, source.android.com

# Android Fragmentation Today

**More than 20% of devices run an OS release that is older than 4 years!**

The situation is probably not that bad though

## Android Security Updates

Major manufacturers release monthly security updates even after the last Android version update

**Still, many devices run legacy OS versions**

- Particularly cheap devices
- Known vulnerabilities!

| ANDROID PLATFORM VERSION | API LEVEL | CUMULATIVE DISTRIBUTION |
|---|---|---|
| 4.1 Jelly Bean | 16 | |
| 4.2 Jelly Bean | 17 | 99,8% |
| 4.3 Jelly Bean | 18 | 99,5% |
| 4.4 KitKat | 19 | 99,4% |
| 5.0 Lollipop | 21 | 98,0% |
| 5.1 Lollipop | 22 | 97,3% |
| 6.0 Marshmallow | 23 | 94,1% |
| 7.0 Nougat | 24 | 89,0% |
| 7.1 Nougat | 25 | 85,6% |
| 8.0 Oreo | 26 | 82,7% |
| 8.1 Oreo (Aug 2017) | 27 | 78,7% |
| 9.0 Pie | 28 | 69,0% |
| 10. Q | 29 | 50,8% |
| 11. R | 30 | 24,3% |

Source: Android Studio

# Low-Level
# System Security

# Verified Boot

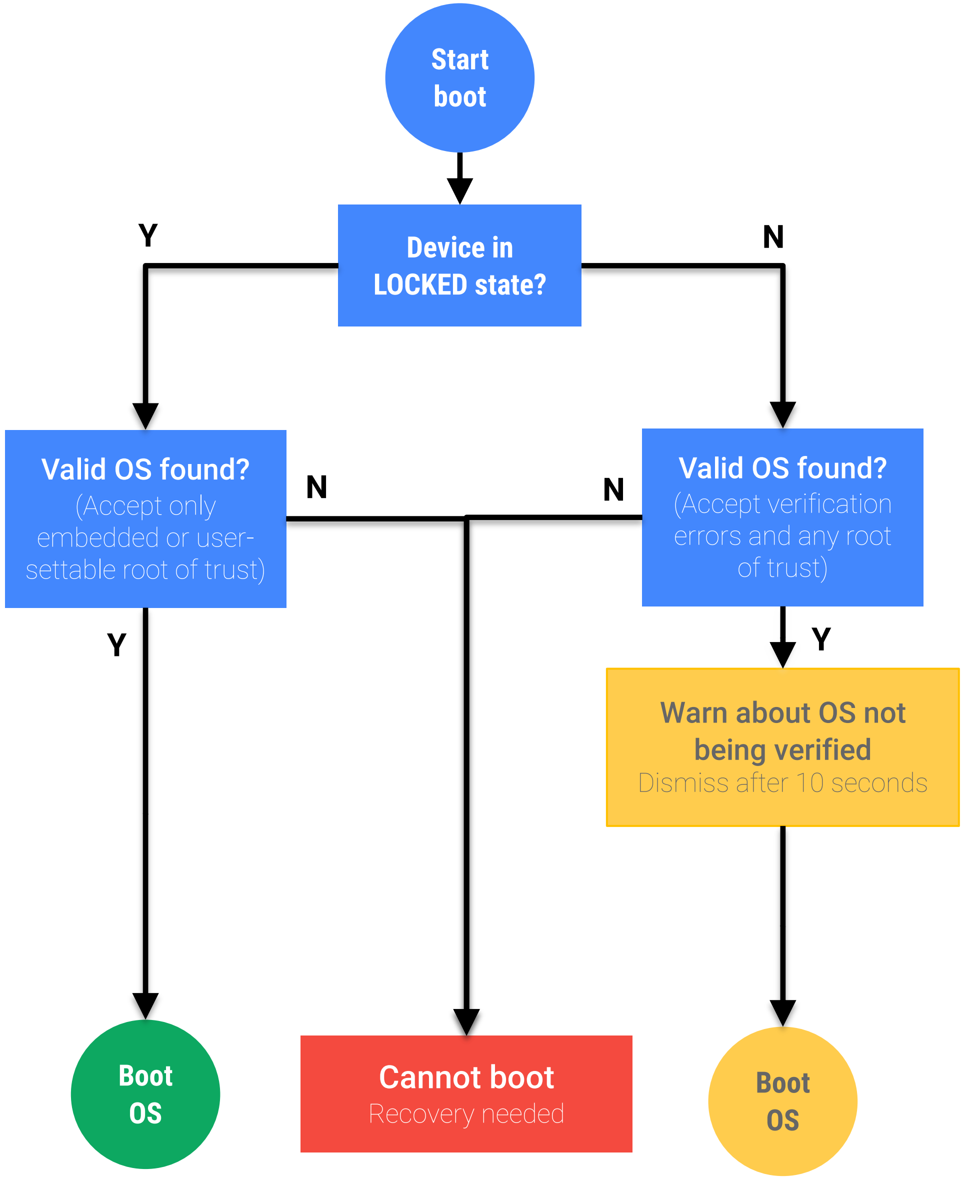
Chain of Trust from lowest-level bootloader to system partition

1. Device vendor embeds Root of Trust certificate in read-only storage
2. Bootloader checks signature of boot partition against Root of Trust
3. Kernel checks signature of system partition

How to efficiently check the signature of the relatively large system partition?

- Use the Device Mapper verity (`dm-verity`) feature in Linux kernel
- Transparent real-time integrity checking of block devices
  → Prevent persistent rootkits

# Verified Boot Flow




## This flow is simplified

- Some devices allow changing Root of Trust
- Additionally: Rollback protection
- dm-verity error may reboot device

## Device / bootloader state

- `LOCKED/UNLOCKED`
- Unlocking effectively disables signature check
- State changes erase all user data

## Boot state

- `GREEN/YELLOW/ORANGE/RED`
- Yellow (Not displayed): Custom Root of Trust
- Only red stops boot

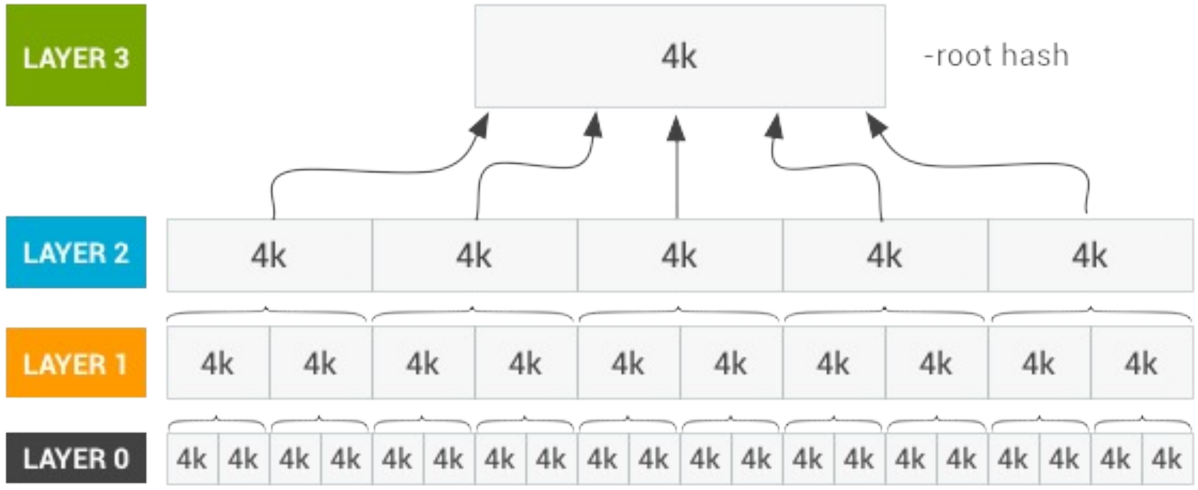
# dm-verity – Insight

**Idea:** Look at block device and storage layer of file system using a hash tree

- Hash values stored in tree of pages
  - Only „root hash" must be trusted to verify rest of tree
- Hash of a page is checked by kernel when it is accessed (always or first time)

- Modification of any 4k-block would change the „root hash"

- Verify signature of „root hash" using public key included on `boot` partition
  → Confirm that device's system partition is unchanged




Picture: source.android.com / Apache 2.0

Source: source.android.com

# dm-verity

## Limitations

- Only applicable to *read-only* partitions
  - *Read-write* partitions would update metadata even when files are only read
  - Any change in FS breaks the tree
    → but useful for /system partition (or where *read-only* is no drawback)

- Need block-based OTA updates Source: source.android.com
  - Consider system partition as a single file („block“)
  - Need to ensure that all devices have same /system partition

# Encryption Systems

# Android Data Encryption Systems

- Full-Disk Encryption (FDE) Android 5.0 - 9.0
  - Encrypts complete user data partition
  - Using key derived from user passcode
  - Passcode must be entered before the device can fully boot

- File-Based Encryption (FBE) Android 7.0+
  - Every file is individually encrypted using different keys
  - If hardware support: Additional encryption of file metadata
  - Device can boot without requiring passcode *(Direct Boot)*
    - Limited context until passcode provided

# File-Based Encryption

## Two Areas

- Device Encrypted (DE)
  - Immediately available after device turn-on
  - *„Direct boot"* mode: Receive phone calls, set alarms, …
- Credential Encrypted (CE)
  - Available after user entered authentication credentials

Keys stored in */data/misc/vold/user_keys*

→ Different subdirectory in **ce** and **de** per Android user id

```
$ ls -R /data/misc/vold/user_keys
+ ce/0/current:
        - encrypted_key
        - keymaster_key_blob
        - salt
        - secdiscardable
        - stretching
        - version
+ de/0:
        - encrypted_key
        - keymaster_key_blob
        - secdiscardable
        - stretching
        - version
```

# File-Based Encryption

The exact encryption process is highly configurable

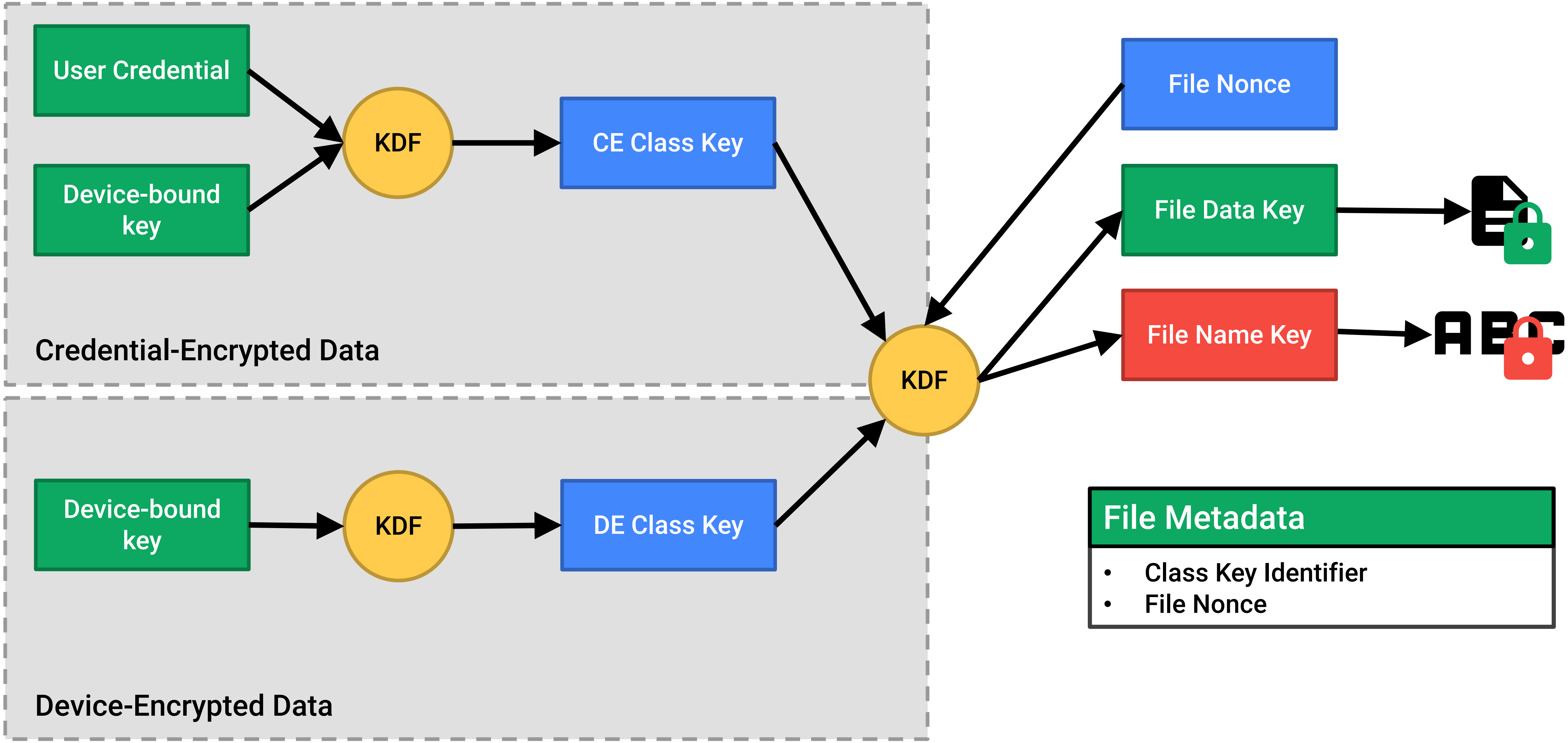
## Core principles

- Lowest-level file encryption is implemented using fscrypt
  - Common Linux kernel API for file encryption across different file systems
  - Encryption metadata stored as FS attributes

- File name and contents encrypted using separate keys
  - Derived from master key and a file-specific nonce

- Master keys here: DE and CE class keys

# File-Based Encryption (Simplified)



# File-Based Encryption: Flaw 1

From Android's developer documentation:

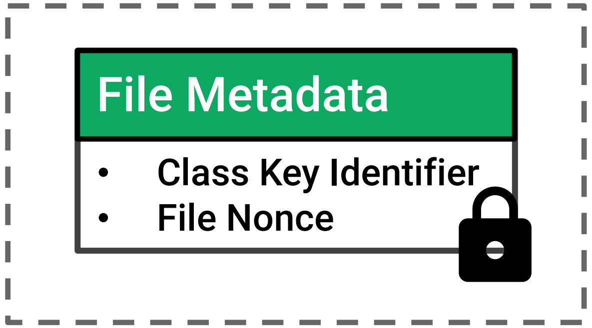
> Credential encrypted storage is only available after the user has successfully unlocked the device, up until when the user restarts the device again. If the user enables the lock screen after unlocking the device, **this doesn't lock credential encrypted storage**.

- CE keys **are not evicted until the next reboot**!
- Protection is only really effective
  - While device is completely shut down
  - Between boot and first unlock

- Key difference to how iOS Data Protection works!

Source: [developer.android.com](developer.android.com)

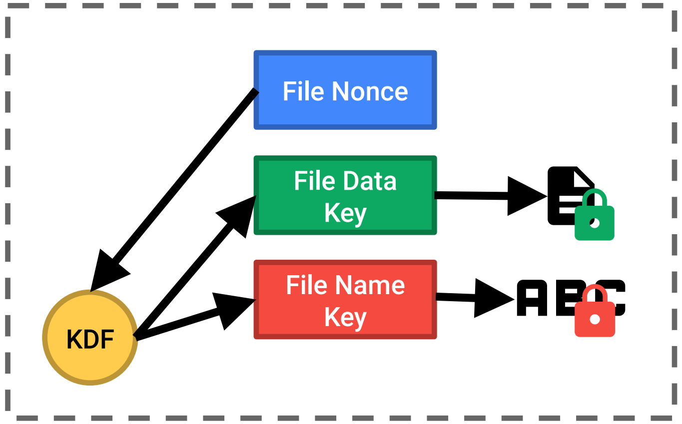
# File-Based Encryption: Flaw 2




- Early implementations: File metadata not encrypted
  - File size, creation and access date

- Solution: **Metadata Encryption** Android 9+
  - Similar scheme as FDE, but only for file system metadata
  - Metadata decrypted at boot time
  - Wrapped key stored on special partition
  - Key protected by TEE, only unlocked if Verified Boot succeeds
  - Mandatory in Android 11 and later

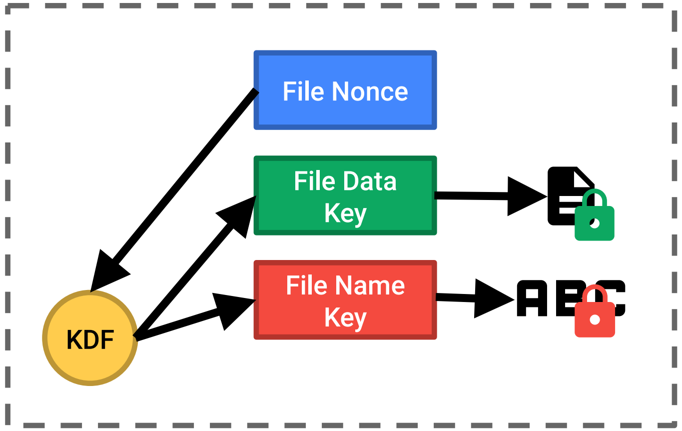
# File-Based Encryption: Flaw 3




- Class keys derived inside TEE
  - ARM TrustZone
  - Device-bound key cannot be extracted
- However, class keys may be processed by the main CPU
  - For deriving file-specific keys in kernel
  - May be compromised by vulnerable kernel
- Solution: Some devices employ Hardware-Wrapped Keys
  - Ephemerally wrap all keys as they pass through CPU
  - Requires inline crypto hardware for storage accesses

Android 11+

# File-Based Encryption: Flaw 4




- Insecure KDF for deriving file keys

$$DEK_f = AES^{ECB}_{nonce_f}(MK)$$

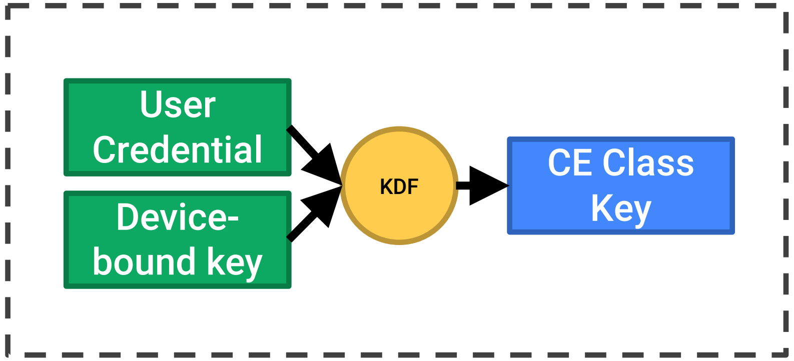
- Which can be inversed as

$$MK = AES^{ECB}_{nonce_f}(DEK_f)$$

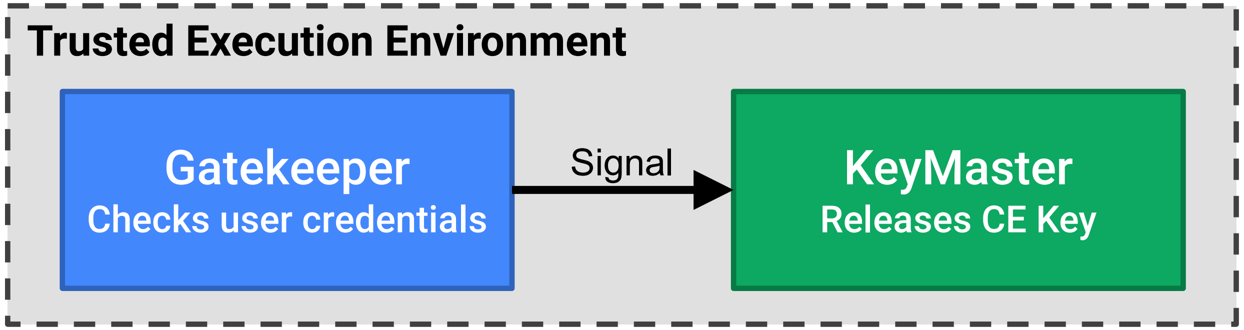
- Attack: Identify and collect all $nonce_f$ and $DEK_f$ from memory dump
  - (Assumes Hardware Key Wrapping is not used)
  - From dump it's not obvious which of the $nonce_f$ and $DEK_f$ belong together
  - Calculate all potential $MK$ candidates
  - If the same potential $MK$ is found for two combinations of $nonce_f$ and $DEK_f$
    - Actual $MK$ found!

Source: [Tobias Groß et al.: One key to rule them all: Recovering the master key from RAM to break Android's file-based encryption]()

# File-Based Encryption: Flaw 5




- In some implementations, the CE key is not cryptographically bound to the user credentials




(Simplified)

- Problem: If vulnerability in TEE found ➔ Release CE key without credentials
- Solution: Ensure there is a cryptographic relation between user credentials and CE Class key (via KDF)

Source: qualcomm.com

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# Android OS Security

# Android Security Model

- Kernel-based application sandbox
  - DAC (UID, GID-based access control) and MAC (SELinux type enforcement)
  - Dedicated, per-application Linux User ID
- Secure IPC (local sockets, Binder, intents)
- Systems running with reduced privileges
- Code signing
  - Application packages (APKs)
  - OS update packages (OTA packages)
- Permissions: System and custom (per app)

# App Sandbox

- Android assigns unique Linux user ID to each application → separate processes

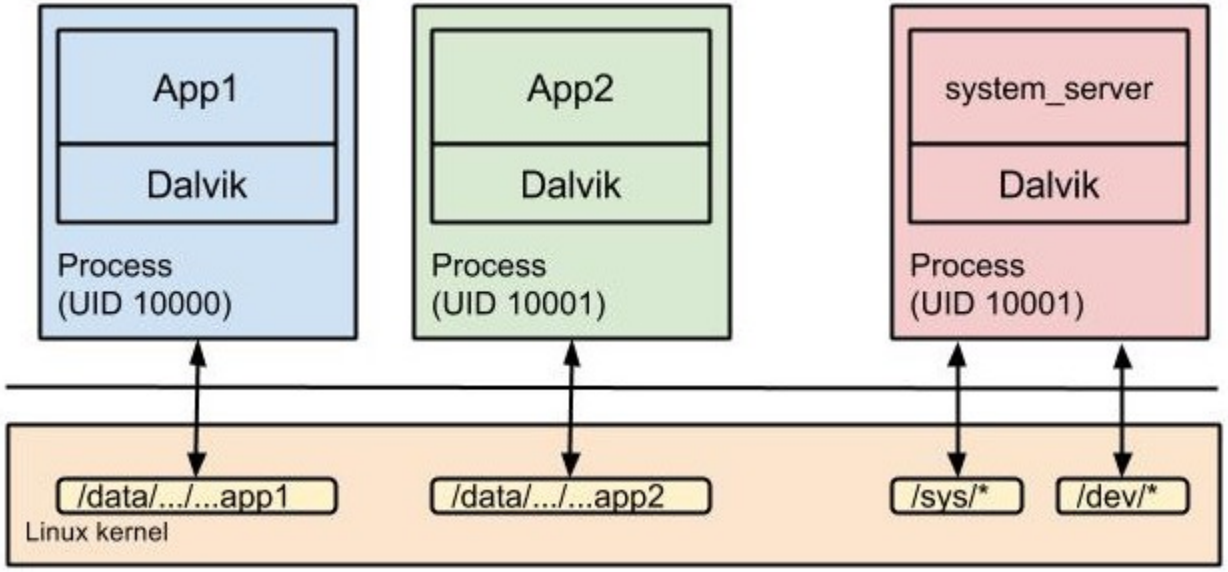
→ Kernel-level application sandbox

- Security enforced at process level through standard Linux facilities (UID, GID)

- Sandbox at kernel level

→ Security model extends to native code and OS applications too

- FS permissions as a mechanism to keep files / folders separate



# App Sandbox

- **Installing new apps**
  - Creates new directory /data/data/<Package name>/
    - E.g. /data/data/com.whatsapp/

```
$ ls -l /data/data/
drwx------  4 u0_a97       u0_a97       4096 2017-01-18 14:27 com.android.calendar
drwx------  6 u0_a120      u0_a120      4096 2017-01-19 12:54 com.android.chrome
...
```

- Accessing other apps‘ directory → needs same UID
  - Apps signed with same developer certificate
  - And explicitly sharing same UID in AndroidManifest.xml

```xml
<manifest xmlns:android="http://schemas.android.com/apk/res/android"
  package="com.android.nfc"
  android:sharedUserId="android.uid.nfc">
```

# SELinux

Security-Enhanced Linux

Mandatory Access Control: Deny any access that is not explicitly allowed

Subjects are unable to modify the policy (cf. Discretionary Access Control!)

- Implemented as **Linux Security Module**: Hooks into kernel syscall code

- **Subject**: A Linux process
- **Object**: A system resource (file, socket, …)
- **Domain**: Label identifying a process or set of processes
- **Modes**: Permissive (only log violations), Enforcing (disallow violations)
- **Policy**: Define allowed operations for a subject/domain and specific object

Source: source.android.com

# SELinux on Android

**Goal**: Limit the power of privilege-escalation attacks

**Example**: If process `netd` (running as root) is compromised, still do not allow it to access files only intended for process `system_server`

- Since Android 5.0: Enforcing Mode
- Harden Android Sandbox
- More than 60 different domains
- Policies improved with every new OS release

Source: [source.android.com](source.android.com)

# SELinux on Android – Sample Rules

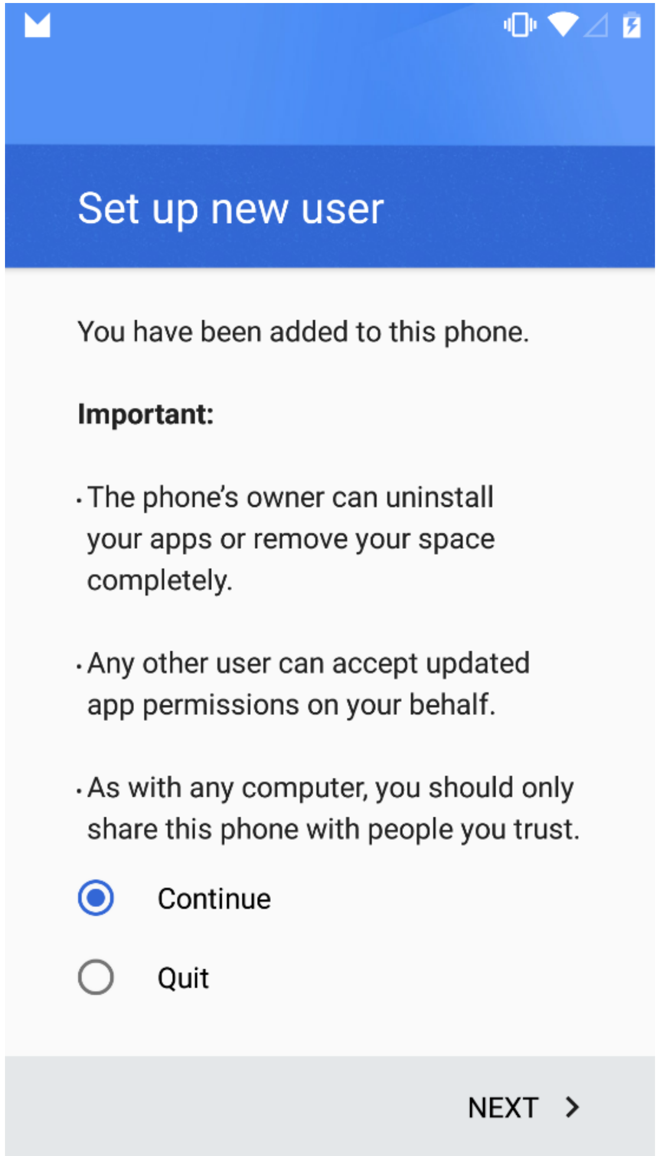
- No unlabeled files
- No ptrace
- No device node creation
- No raw I/O
- No mmap zero
- No mac_override
- No setting security properties
- No access to /data/security and /data/misc/keystore
- No /dev/mem or /dev/kmem access
- No /proc usermode helpers
- No ptrace of init
- No access to generically labeled /dev/block files
- Restrictions on mounting filesystems
- No execute of files from outside of /system
- No access to /data/properties
- No writing to /system or rootfs
- No registering of unknown services
- No entering init domain
- No /sys/kernel/debug read access
- No apps acquiring capabilities
- No raw app access to camera, microphone, NFC, radio, etc.
- No app-generic socket access
- No app/proc access to different security domains
- No access to GPS files
- Cannot disable SELinux

Meanwhile > 250 Rules

# Multi-User support

- Originally for tablets only, now for phones too (> Android 5.0)
- Users isolated by UID / GID and SELinux
- Separate settings & app data directories
  - System directory: /data/system/users/<user ID>/
  - App data directory: /data/user/<user ID>/<pkg name>/
- Apps have different UID and install state for each user
  - App UID: uid = userId * 10000 + (appId % 10000)
  - Shared Apps: Install state in per-user package-restrictions.xml
- External storage isolation

# User Types




- **Primary** user (owner)
  - Full control over device
- **Secondary** users
  - Restricted profile
    - Share apps with primary user
    - Only on tablets
  - Managed profile
    - Separate apps and data but share UI with primary user
    - Managed by Device Policy Client (DPC)
- **Guest** user
  - Temporary, restricted access to device
  - Data (session) can be deleted

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# Key Management

# Android KeyStore

- System-managed, secure cryptographic key store
  - Hardware-backed: Trusted Execution Environment (ARM TEE)
  - Optionally: Additional Secure Element („StrongBox“)
  - Accessible to apps through Java Crypto APIs
  - Import keys, perform crypto operations without exposing key material
  - Strict separation between keys of different applications

- Android OS defines the KeyMaster HAL interface
  - Vendors either provide their own KeyMaster Trusted Application (TA)
  - Or adopt the open-source Trusty OS reference implementation

Source: [source.android.com](source.android.com)

# KeyStore: Access Control

- Developers can limit how a new key may be accessed
  - Limit operations: E.g. only use key for signatures
  - Require user authentication (fingerprint or PIN)
  - Specify key expiration date
  - Request delay between accesses

- Some requirements are only checked in software
  - Depending on implementation

Source: source.android.com

# Key Store: Key Attestation

**Goal**: Cryptographically proof that a particular public key is hardware-backed

i.e. the corresponding private key can not be extracted

- KeyMaster can generate an X.509 certificate chain for the key
  - Also includes information on the device state, key access control, and caller app

- Chain includes device-specific certificate
- Root of chain: Google Hardware Attestation Root certificate

- **Best practice:**
  - Include the attestation certificate chain in communication to backend server
  - Only serve requests if chain successfully validated

Source: developer.android.com

# Key Store: Fingerprint Authentication

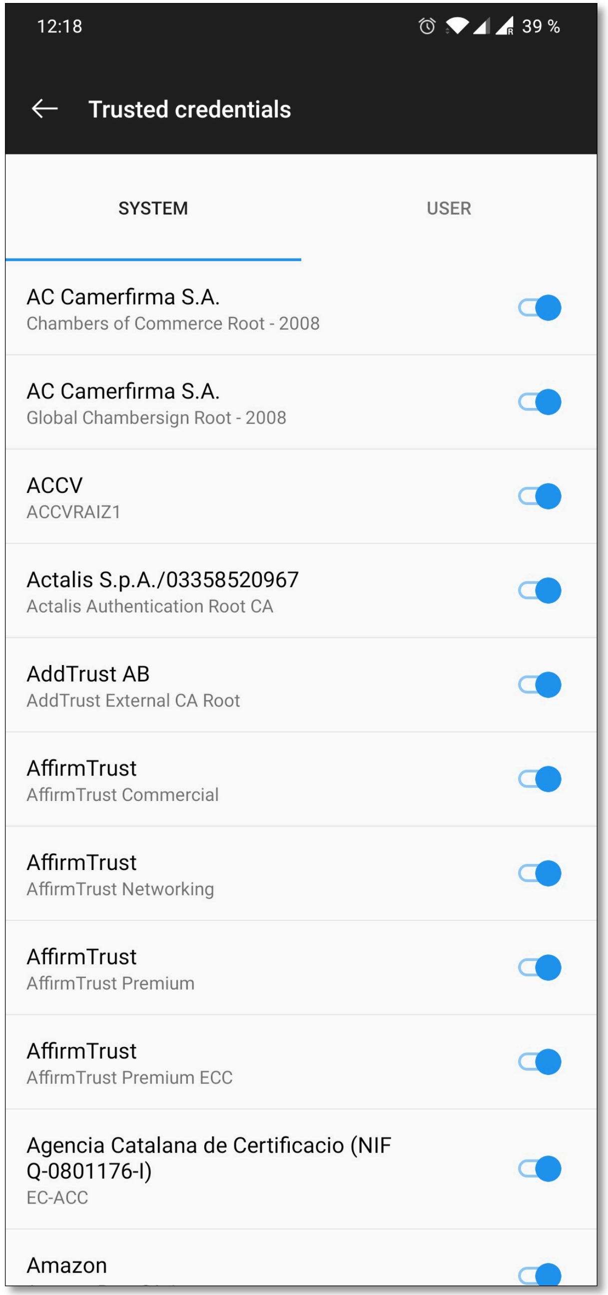
- Developers can require Fingerprint Authentication for sensitive operation
  - E.g. authorizing banking transactions
- Many app developers implement this insecurely

```
BiometricPrompt prompt = new BiometricPrompt.Builder(context).build();
prompt.authenticate(null, executor, new BiometricPrompt.AuthenticationCallback() {
    @Override
    public void onAuthenticationSucceeded(BiometricPrompt.AuthenticationResult result) {
        // Authenticated!?
    }
});
```

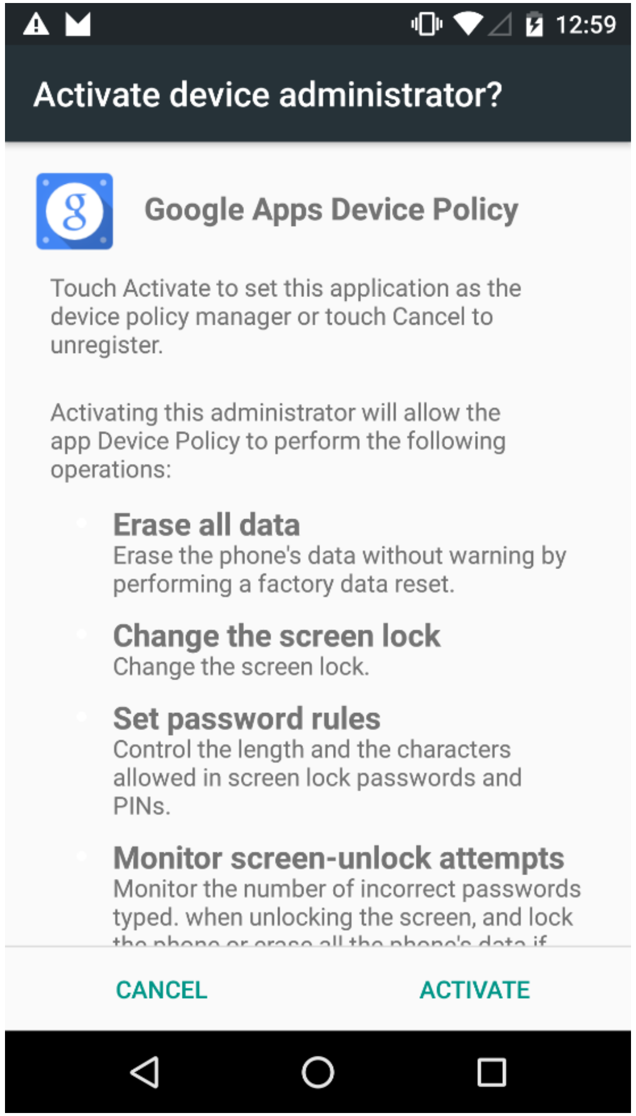
- Root attacker may modify app to just call the success callback
- **Solution**: Use the private key unlocked by the successful authentication
  - Sign server challenge, check on server, ensures TEE was actually involved

# Certificates & PKI

- Android-specific trust store for TLS certificates
- Trust anchors (Root CAs)
  - Pre-installed („system certificates“)
  - User-installed („user certificates“)
- User certificates can be installed, but
  - Must be explicitly confirmed by user
  - May be rejected by individual apps



# MDM




- Device security policy can be set by admin
  - Password / PIN policy
  - Device lock / unlock
  - Storage encryption
  - Camera access
- Needs to be activated by user
- Cannot be directly uninstalled
- May be required to sync account data
  - Microsoft Exchange (EAS)
  - Google Apps

# Rooting

# Android Rooting

Rooting refers to the process of obtaining root permissions – ie. the ability to run code (usually a shell) with **superuser** privileges.

- If bootloader unlockable:
  - Rooting doesn't require any privilege escalation exploits
  - Unlike jailbreaking on iOS
  - Simplest form of rooting: Flashing ROM that contains a su application
- Otherwise: Need privilege escalation exploit
  - "Soft-rooting": Obtain root permission by exploiting vulnerable privileged process
  - Only possible on legacy Android versions
    - SELinux

# Systemless Root

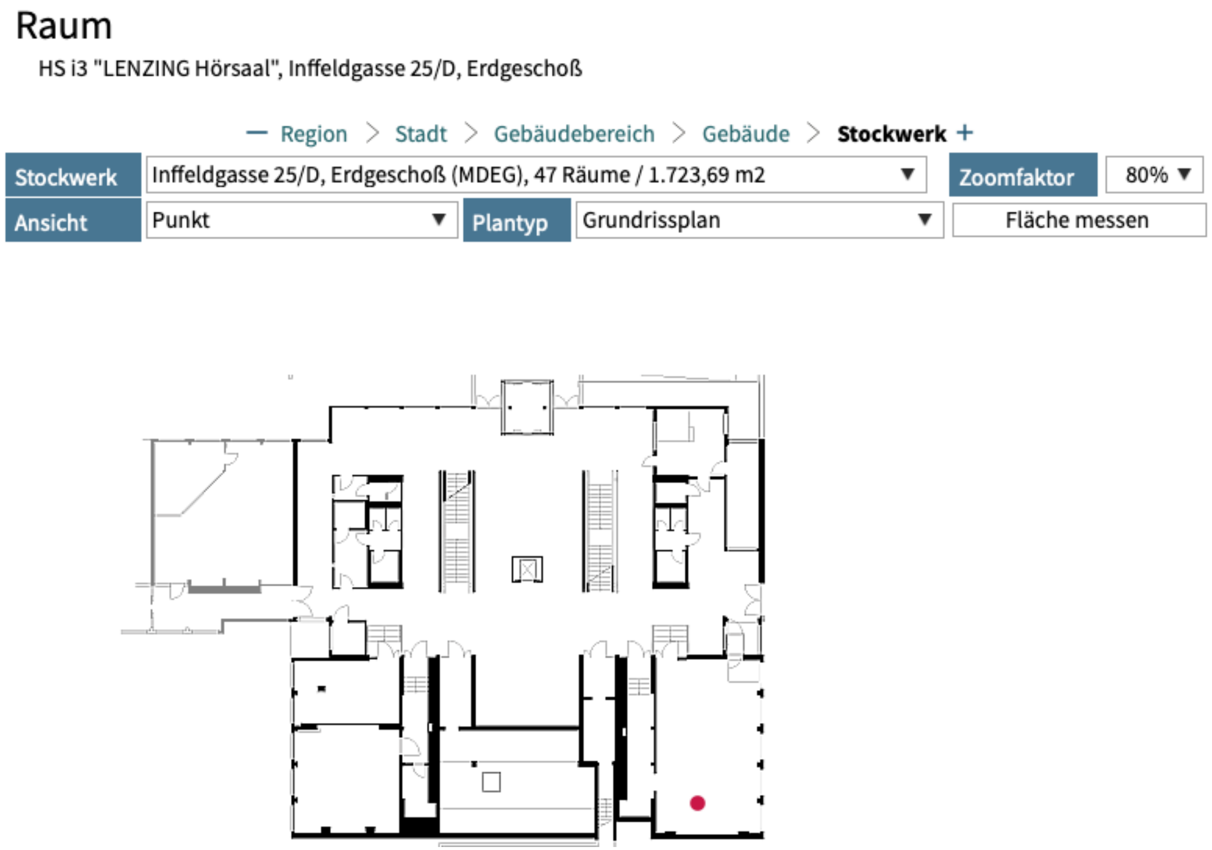
- Problem: SELinux prevents any process from obtaining full root permissions
  – Even processes that run as root are restricted to a subset of capabilities

- Solution: Start superuser daemon before SELinux is fully started
  – Set a custom init program that spawns SU daemon
  – Then hand over to Android's original init program

- This can be accomplished by just modifying the boot partition
  – System partition is untouched: OTA updates can still be installed
    - dm-verity hashes are unaffected
  – Example: Magisk

# Important: One-Time Room Change!

Next week's lecture will be in **Lecture Room i3**!

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# Outlook

- 06.05.2022
  - Application Security on Android
- 13.05.2022
  - Mobile Hardware Security