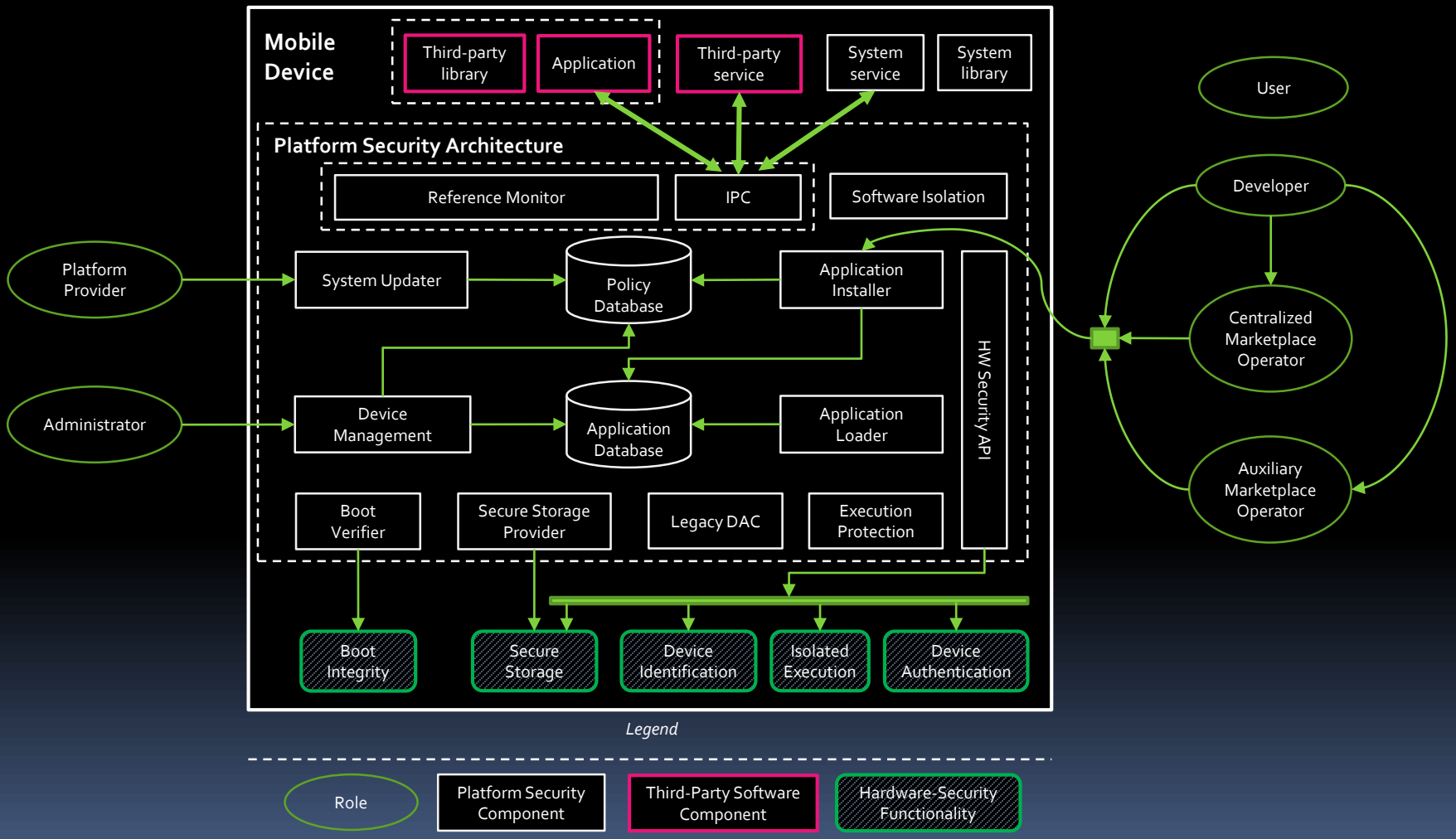
Lecture 2

CASE STUDY: ANDROID OS PLATFORM SECURITY

You will be learning:

- Android as a software platform
  - Internals and surrounding ecosystem
- Security techniques in Android:
  - Application signing
  - Application isolation
  - Permission-based access control
  - Hardware-based security features

Mobile Software platform security



Android in a nutshell

- Linux-based (ARM, x86, x86_64, MIPS)
- Widely used for phones and tablets
  - Wearables, smart TVs, cameras, (handheld) gaming consoles, etc.
- Applications written in Java, Kotlin
  - May include C++ NDK libraries
- Open-source software stack + closed source applications and services

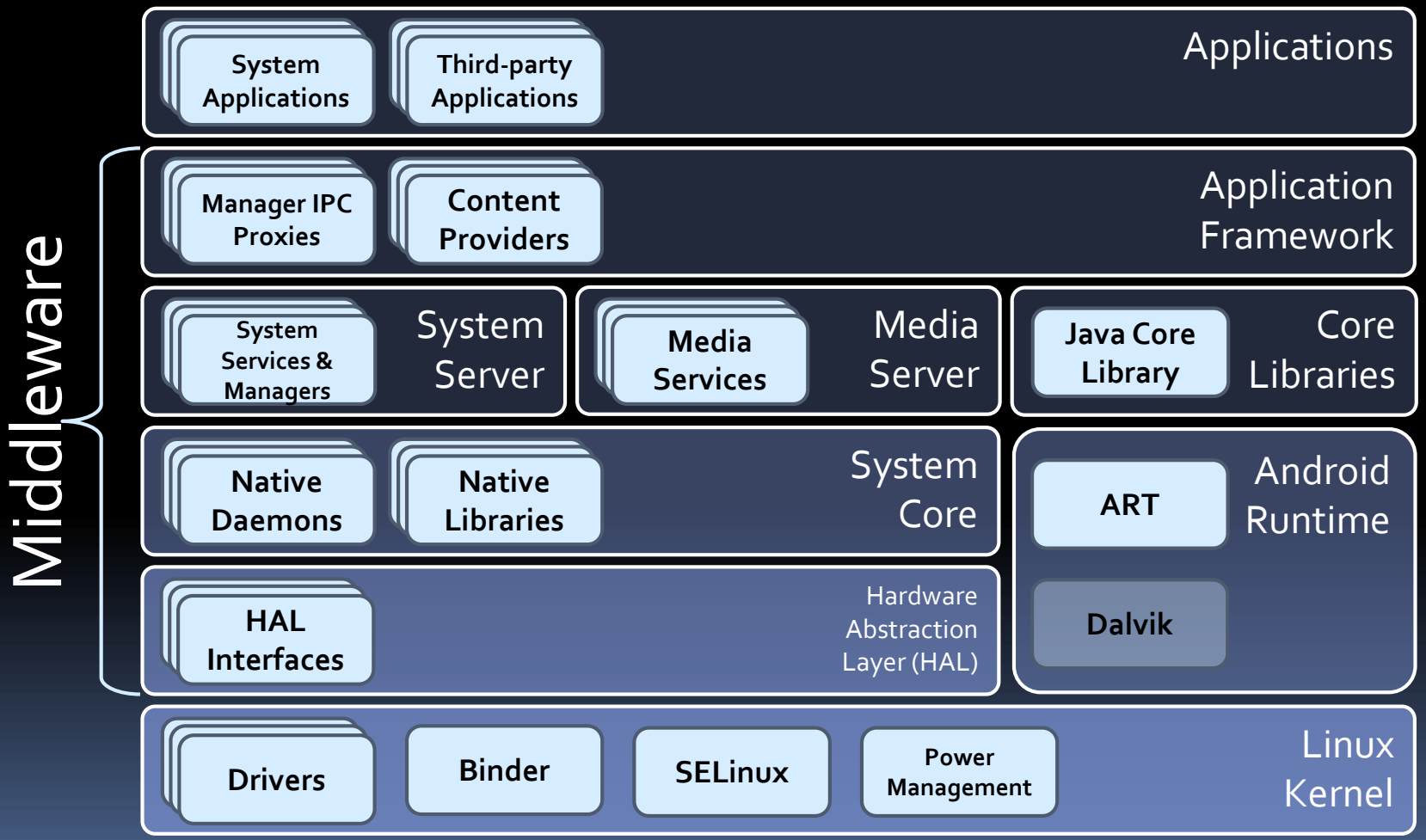
Security goals

- Protect user data
- Protect system resources
- Provide application isolation

On terminology

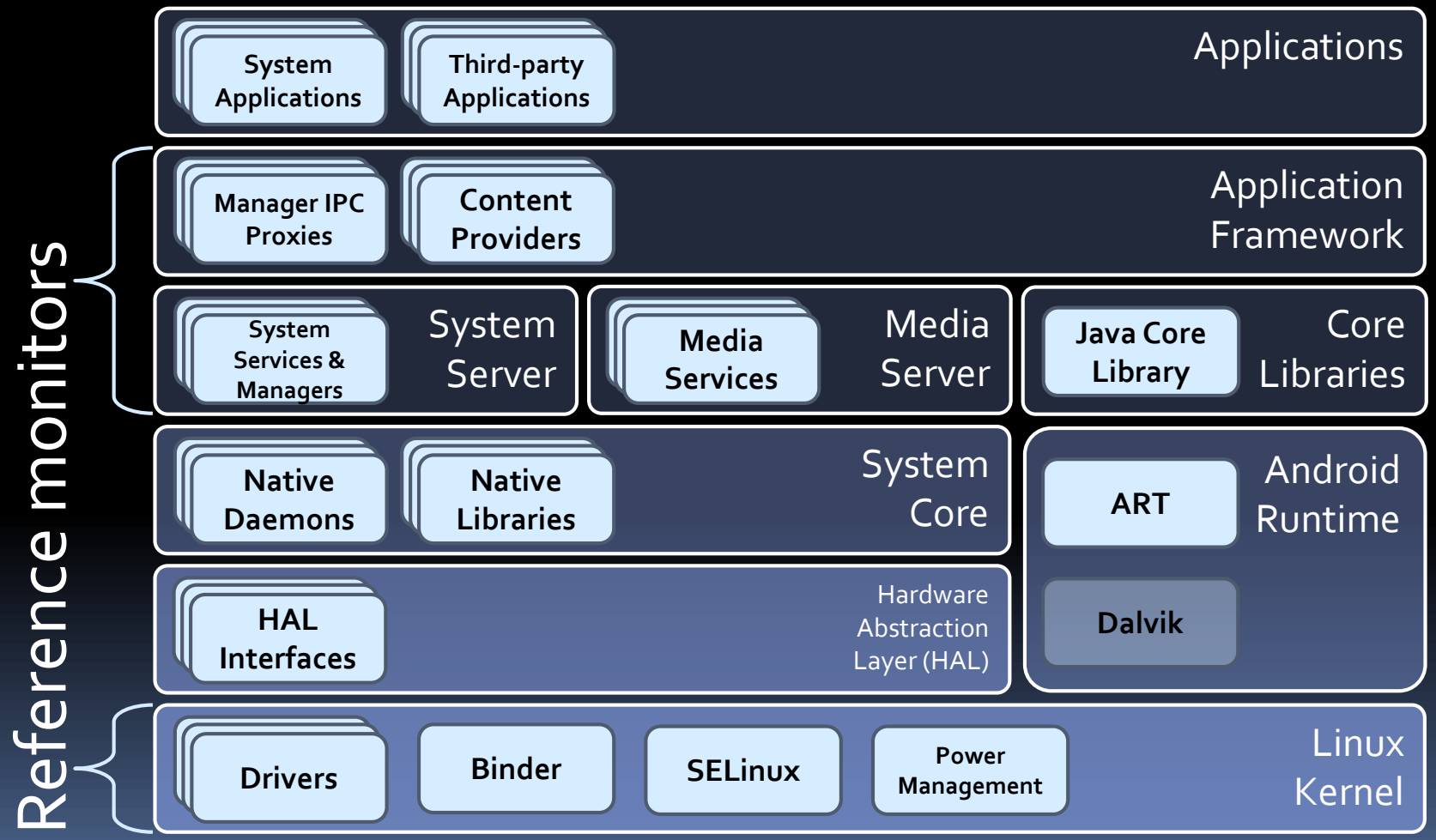
- Linux = the kernel
- “Desktop Linux” ≈ GNU / Linux
- Linux DAC = (Unix) file permissions
- Linux MAC = SELinux
- Permissions = Android app perms. or SELinux

Android Software Stack



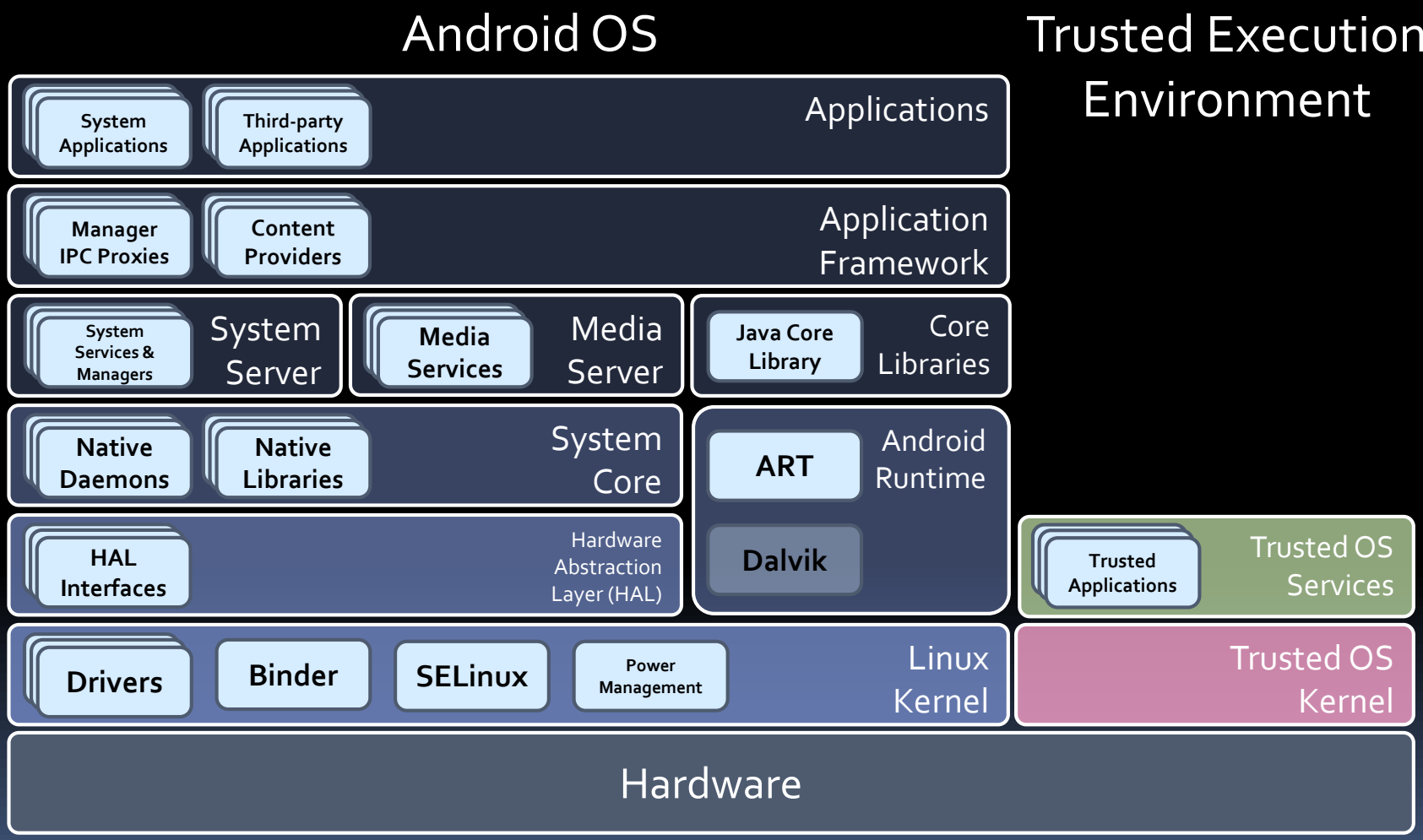
Android Open Source Project. Security. 2015

Android Software Stack



Android Open Source Project. Security. 2015

Android Software Stack



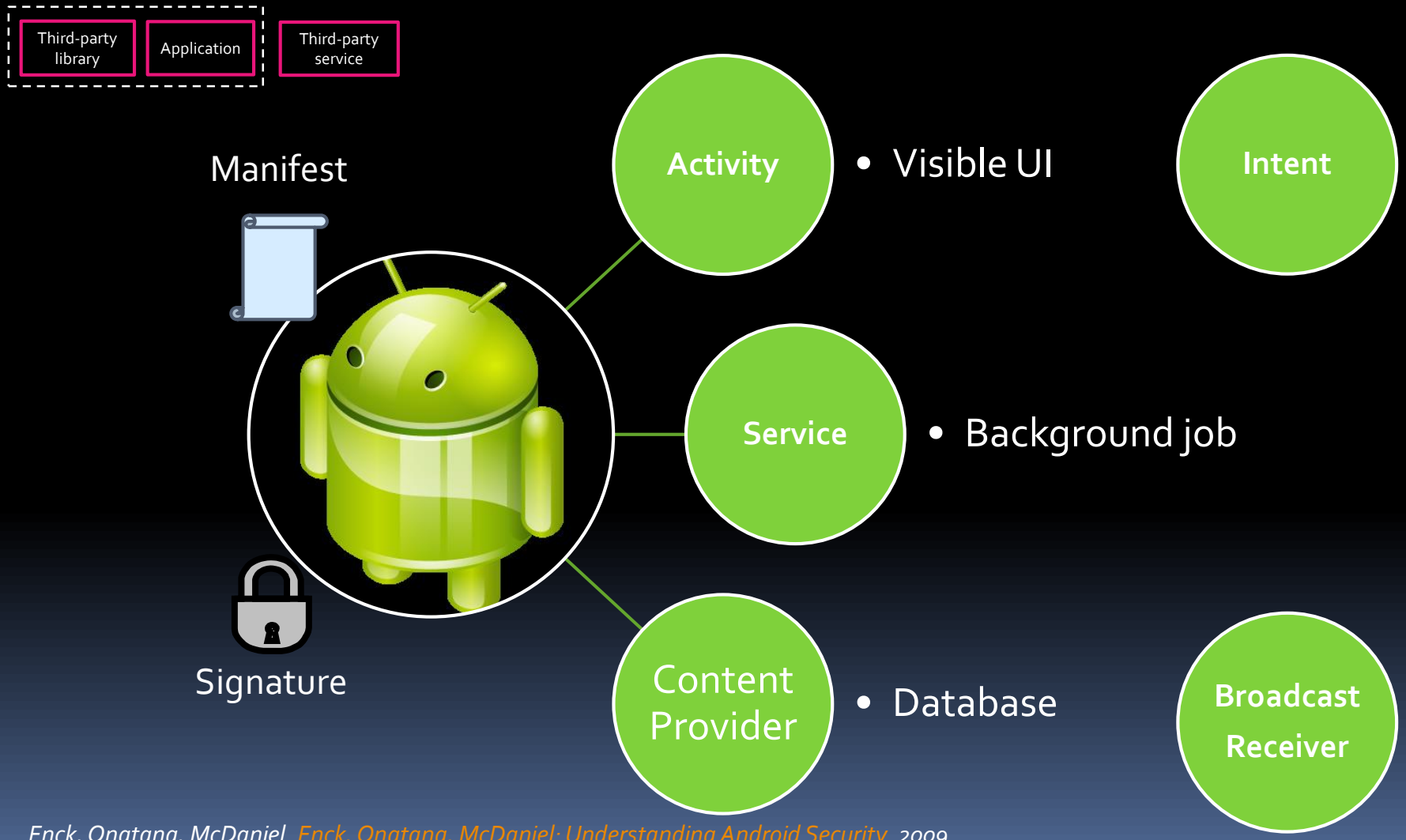
Google. Android for Work Security white paper. 2015

Versions & API Levels

- Confectionary code names for major versions
- API level indicates application framework version

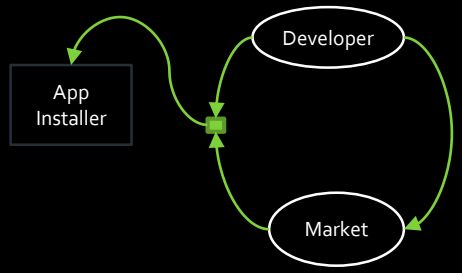
Version	Code name	Release date	API level
9	Pie	Aug 6, 2018	API level 28
8.1.0	Oreo	Dec 5, 2017	API level 27
8.0.0	Oreo	Aug 21, 2017	API level 26
7.1	Nougat	Oct 4, 2016	API level 25
7.0	Nougat	Aug 22, 2016	API level 24
6.0	Marshmallow	Oct 5, 2015	API level 23
…			

Application components



Enck, Ongtang, McDaniel. Enck, Ongtang, McDaniel: Understanding Android Security. 2009
Android Open Source Project. Application Security. 2015

Software distribution



- Apps from multiple sources
  - Google Play
  - Auxiliary marketplaces
  - Sideloading
  - Pre-installed software
- Marketplace services
  - Discovery
  - Purchase & Installation
  - User-submitted ratings / flagging
  - Malware scans (Google Bouncer)
  - Remote application installation & removal

Application signing

- Goal: same-origin policy for apps

Developer signs with private key

Signature verified with developer's public key

Application signing (cont.)

- For application packages (APKs)
  - Self-signed X.509 certificates (no PKI!)
  - Package update requires same certificate
  - Developer manages APK signing key (cannot be recovered)
- For app bundles (AABs)
  - Upload format for compiled sources and resources
  - Defer APK generation and signing to marketplace
  - Google manages APK signing key
  - Developer signs AABs or APKs with upload key (can be reset)

Elenkov. Android's Security Architecture. 2015.
Google Play. Manage your app signing keys. 2018
Android Open Source Project: About Android App Bundles. 2018

APK Signature Scheme

- JAR signing (v1)
  - Individual signature for each integrity protected file
  - Does not protect ZIP metadata
- APK Signature Scheme v2 (since 7.0)
  - Whole-file signature stored in APK Signing Block
- APK Signature Scheme v3 (since 8.0)
  - Adds APK key rotation via proof-of-rotation attribute
  - Old signing certs marked as trusted for granting signature permissions via self-trusted-old-certs attribute

Elenkov. Android's Security Architecture. 2015.
Android Open Source Project: Android Security: Application Signing. 2018

APK Signature Scheme v2 & v3

APK Structure:

For each signer:

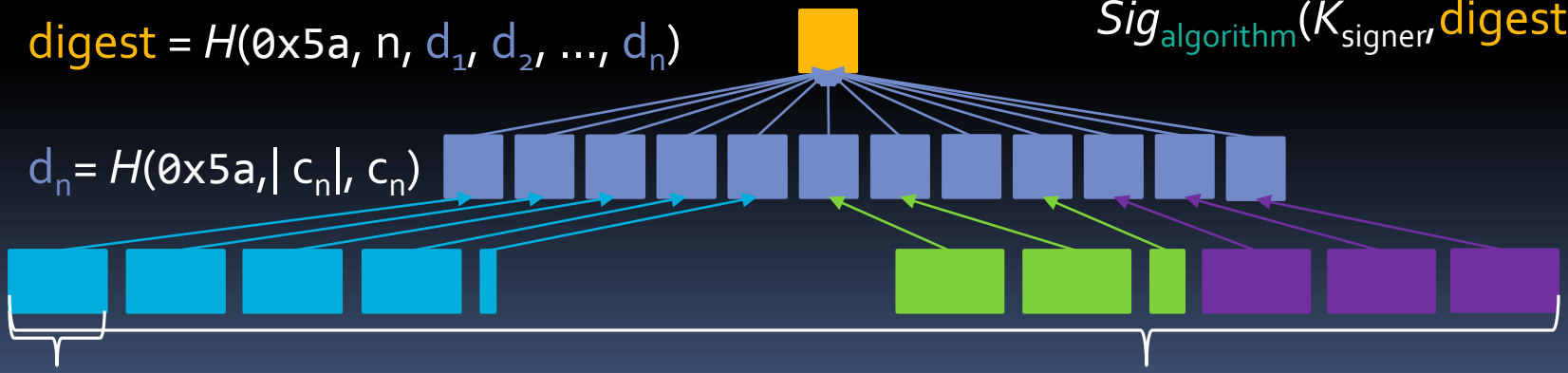
- Signer's identity as X509 certificate chain
- Signature as <algorithm, digest, signature> -tuples
- Additional attributes as <key, value> -pairs

Digest calculated as two-level Merkle tree:

signature = $Sig_{algorithm}(K_{signer}, digest)$

digest = $H(0x5a, n, d_1, d_2, \ldots, d_n)$

$d_n = H(0x5a, |c_n|, c_n)$

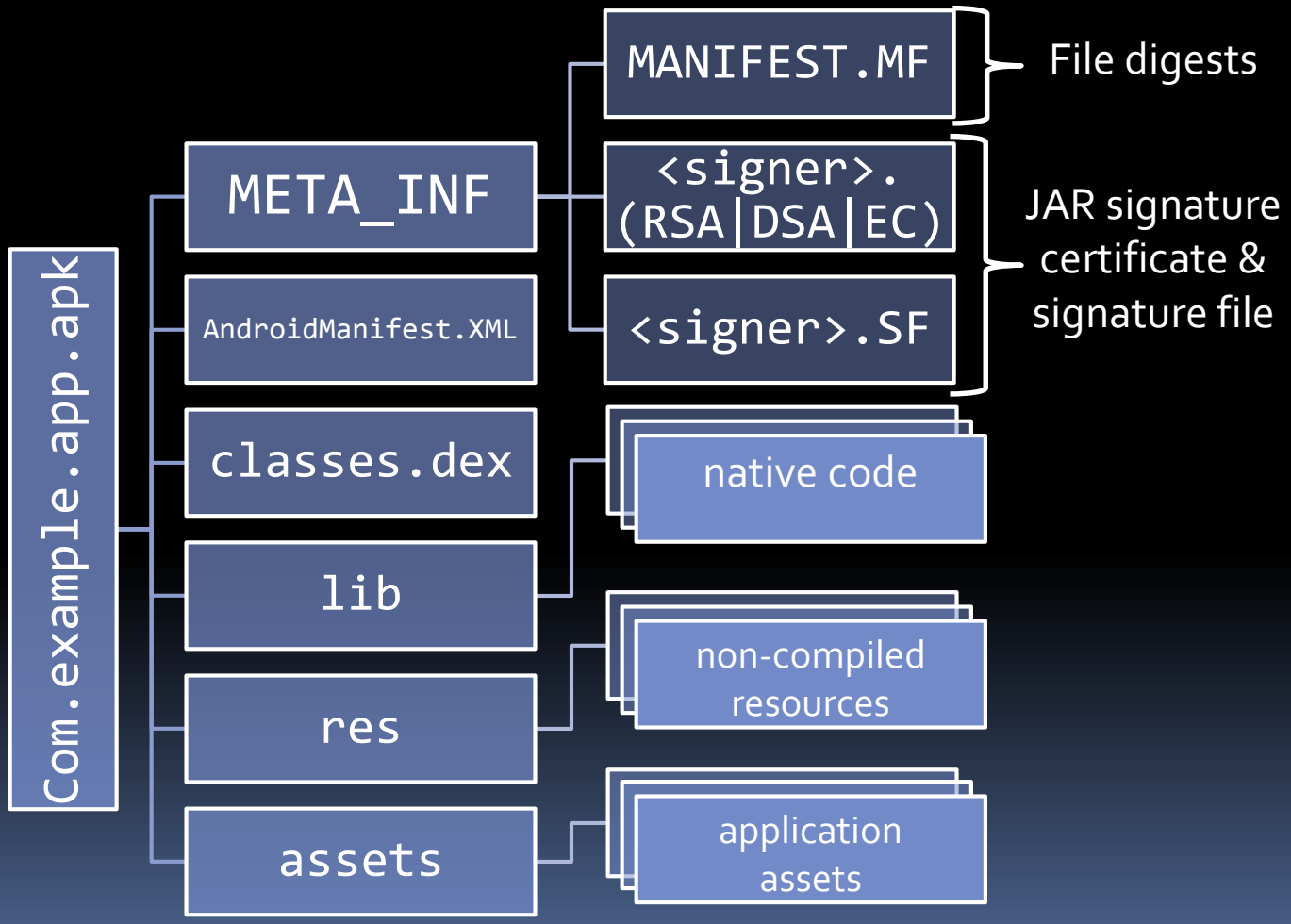


c_i = up to 1MB chunk of ZIP section

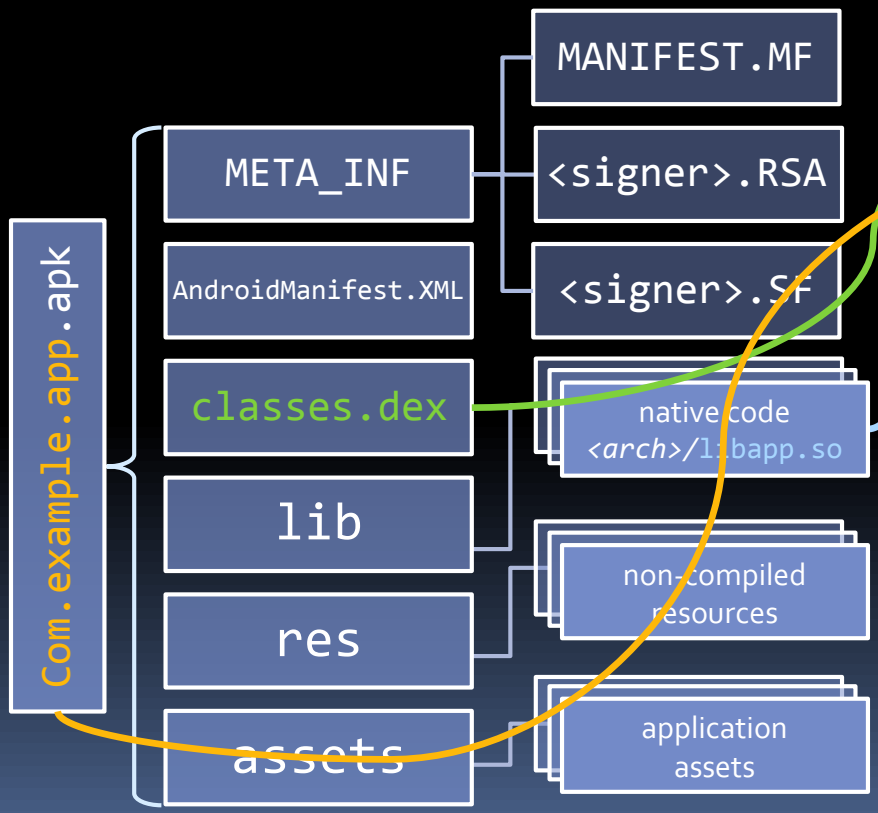
n = number of chunks

Android Open Source Project: APK Signature Scheme v2. 2017

APK Contents



Package Installation



- Code and resources (common)
  - **/data/app/com.example.app/**
    - lib/*<arch>*/libapp.so
    - oat/*<arch>*/base.odex
    - base.apk
- Data (per user)
  - **/data/user/0/com.example.app/**
    - files/
    - databases/
    - shared_prefs/
  - **/data/user/1/com.example.app/**
    - …

Application isolation

- Goal: Applications cannot interfere with one another

Application isolation

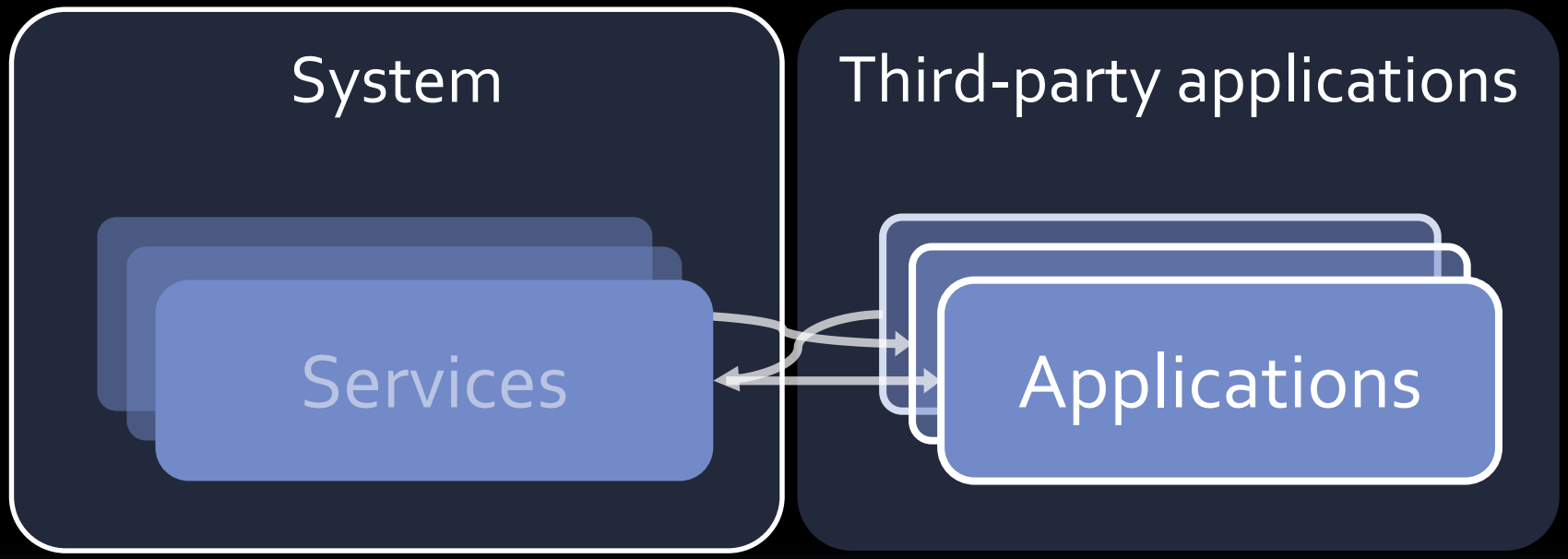
Implementation on Android:

- Kernel: Process & memory protection
- Kernel: Linux DAC
- Kernel: Linux MAC (SELinux)
- Kernel: Seccomp filters for app processes
- Middleware: mediation of Binder IPC
- Applications run in separate ART virtual machine instances

Application Sandbox

- Each application assigned a Unix UID
  - One UID per user per application (since 5.0)
  - UID owns
    - Filesystem resources in `/data/user/<nr>/`
    - `Processes`
    - `Permissions (!)`
- Applications from same developer (= signed with same developer key) may share UID sandbox

Application isolation



- Linux DAC domain (UID)

Rooting

- Rooting applications exploit vulnerabilities in privileged system daemons to obtain shell

- Note: bootloader unlocking intentionally supported by many OEMs
  - e.g. `fastboot oem unlock`

SELinux in Android

- Goal: System services and applications should not be able to deviate from their intended *modus operandi*

SELinux in Android (cont.)

- Implementation on Android:
  - Kernel-level MAC (SELinux) – Policies based on SELinux context
  - Middleware MAC (MMAC) – Policies based on package identity

Smalley, Craig. Smalley, Craig: Security Enhanced (SE) Android. 2013
Android Open Source Project. Security-Enhanced Linux in Android. 2015

SELinux in Android (cont.)

- Enforces MAC even for processes running with root/superuser privileges (since 4.4)
- Blocks many root exploits and misconfigurations
- Can reduce attack surface of kernel exploits by limiting access to vulnerable syscalls
  - 39% of 2016 security issues target kernel as opposed to userspace (up from 9% in 2015)
  - 85% of kernel bugs attributed to device drivers

Smalley, Craig. Smalley, Craig: Security Enhanced (SE) Android.2013
Android Open Source Project. Security-Enhanced Linux in Android. 2015
Van Deer Stoep, Jeff. Android: protecting the kernel. 2016
Google. What's new in Android Security (Google I/O'17). 2017

Skip to App Isolation

SELinux in Android

- Type Enforcement
  - Access Control Policy described as rules on abstract labels
  - System processes (subjects) and system resources (objects) mapped to labels

SELinux in Android

- *Domain* - Label for process(es)
- *Type* - Label for object(s)
- *Class* - Kind of object being accessed
  - (e.g. file, socket)
- *Permission* - Operation being performed
  - (e.g. read, write)

SELinux Project Wiki. ObjectClassesPerms

SELinux rules

- EVERYTHING FORBIDDEN BY DEFAULT!
- ALLOW rules define how subjects may interact with objects
- NEVERALLOW rules prevent specific ALLOW rules from being added to a policy

SELinux rule structure

ALLOW [domain] [type] : [class] { [set of permissions] }

Subject (e.g. process)

Object (resource)

Class of resource (e.g. file, socket, directory)

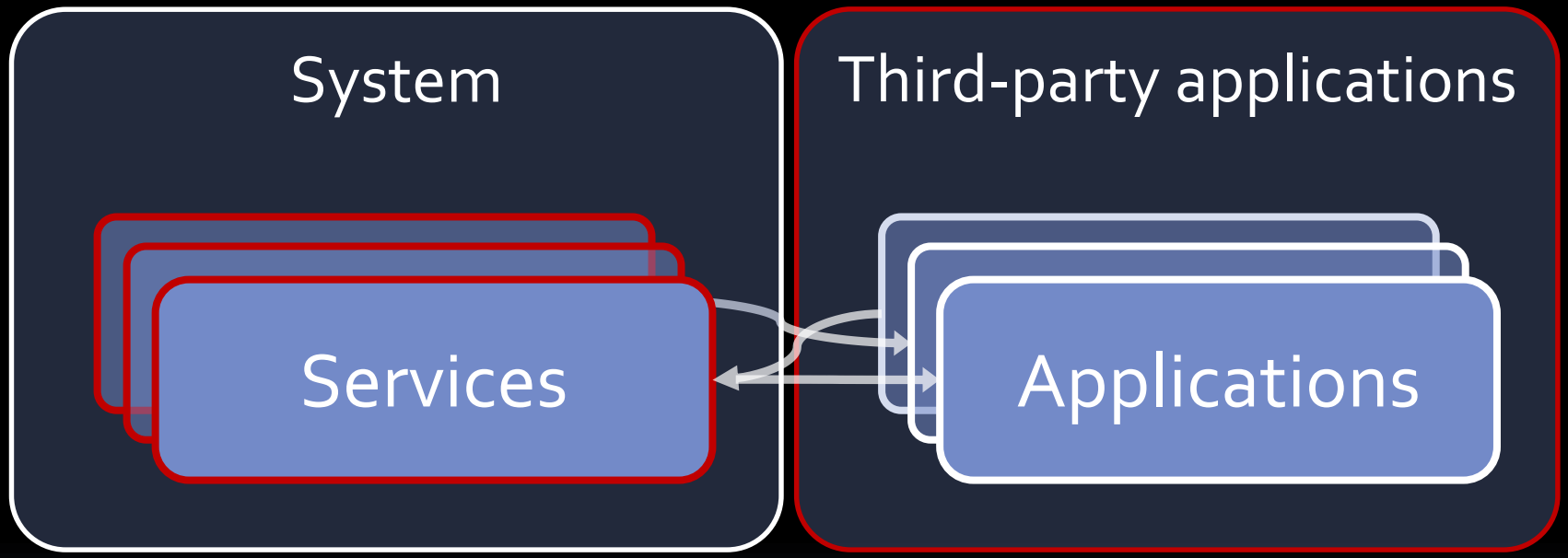
Operations allowed by this rule on the Class

NEVERALLOW [domain] [type] : [class] { [set of permissions] }

SELinux attributes

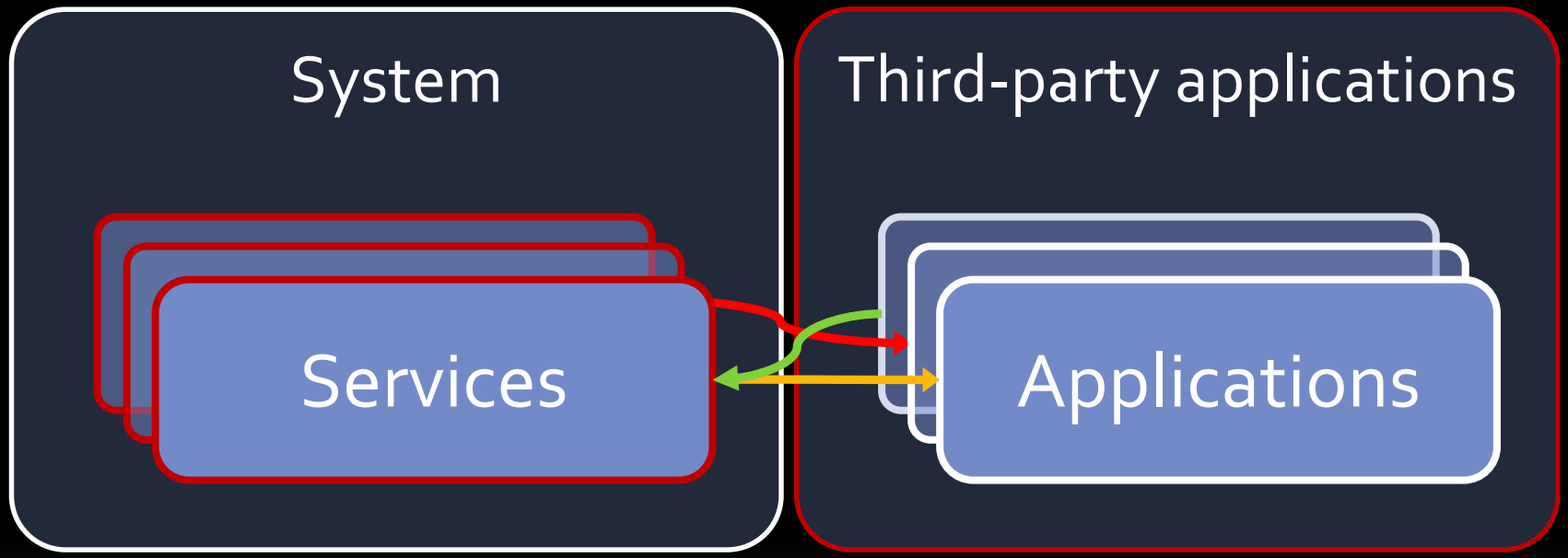
- Attribute
  - Identifier assigned to a group of types
  - Not a type in itself!
  - Used in rules when referring to groups of types
  - Cannot be used to label subjects nor objects
- Used to define behaviour common to multiple types without repeating rules
- Composition of attributes enables modularity

Application isolation (cont.)



- Linux DAC domain (UID)
- Linux MAC domain (SELinux)

Protected APIs



- Unrestricted service calls
- Approval-based service calls
- Restricted service calls

Protected APIs

- Goal: Protect system resources from unauthorized access

Protected APIs (cont.)

- Implementation in Android:
  - Protected APIs for ”risky” actions
  - Permission-based access control

Protected APIs (cont.)

- What kinds of system calls on a smartphone would warrant protecting and why?

Sensitive user data

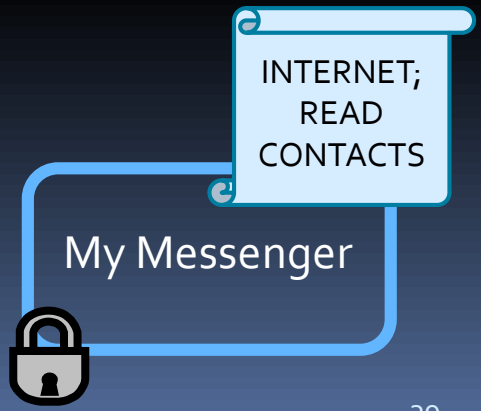
- Subject to permissions checks:
  - Personal information (e.g. contacts)
  - Sensitive input devices (e.g.camera)
    - Location tracking can be manually disabled
  - Actions that cost money (e.g. calls, SMS)
  - Device metadata (e.g. logs)

Access control & permissions

- Goal: Controls application access to protected APIs (and each other)
  - User agency vs. protecting system resources
  - Usability of security features

Permission assignment

- Application declares all permissions in AndroidManifest.xml
- Permissions assigned to application UID
- Some permissions not user-grantable
  - Only available to pre-installed applications



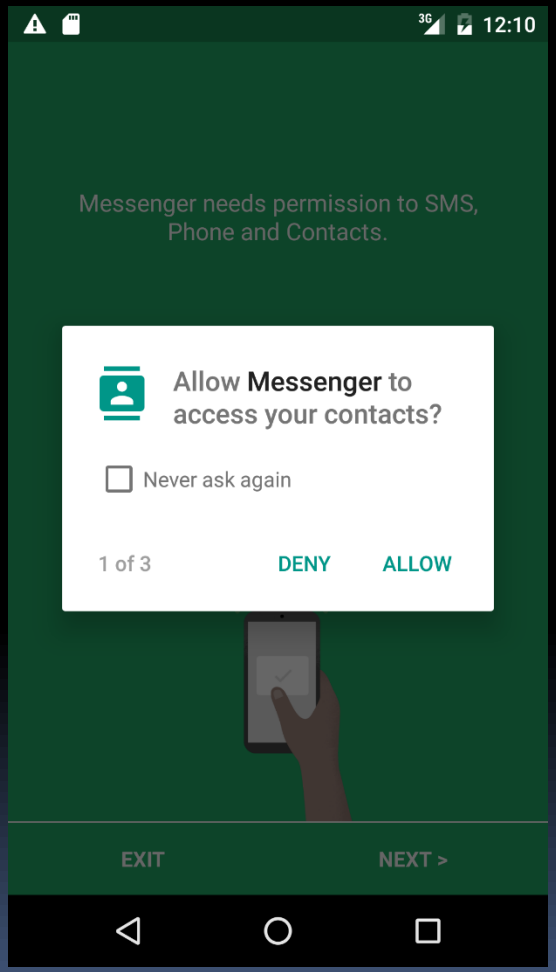
Android permissions

- 4 categories
  - Normal
  - Dangerous
  - Signature
  - Signature | Privileged

Permission assignment

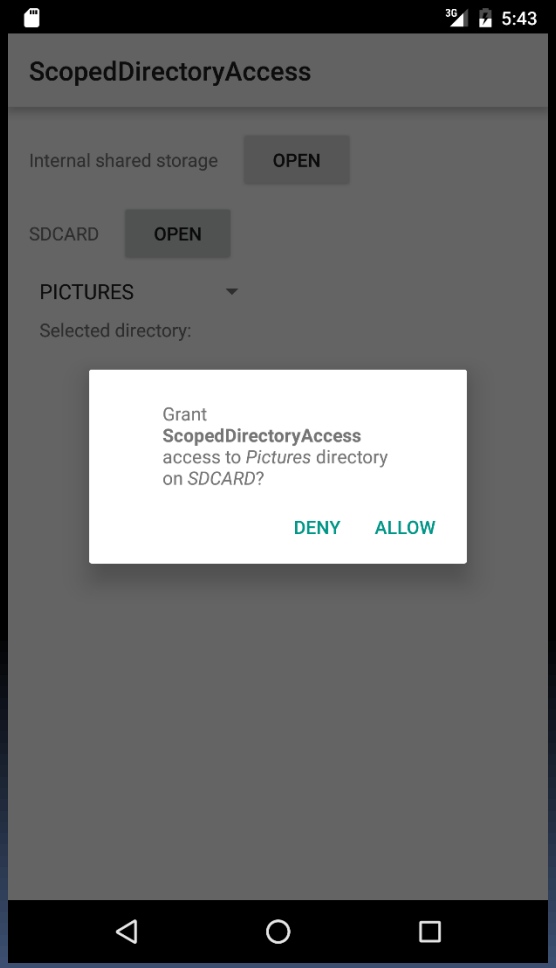
- **Normal** permission granted automatically
- **Dangerous** permissions require user approval at install time (up to 5.1) or run time (since 6.0)
- **Signature** permissions granted if app signature matches the declarer of the permission (or self-trusted-old-certs)
- **Privileged** permissions granted only to system apps
  - Subject to whitelist by PackageManager (since 6.0)

User approval (since 6.0)



- **Dangerous** permissions require user approval at runtime
- If not granted, application continues to run with limited capabilities
- Permission managed per application, per user
  - Stored in /data/system/users/<nr>/ runtime-permissions.xml

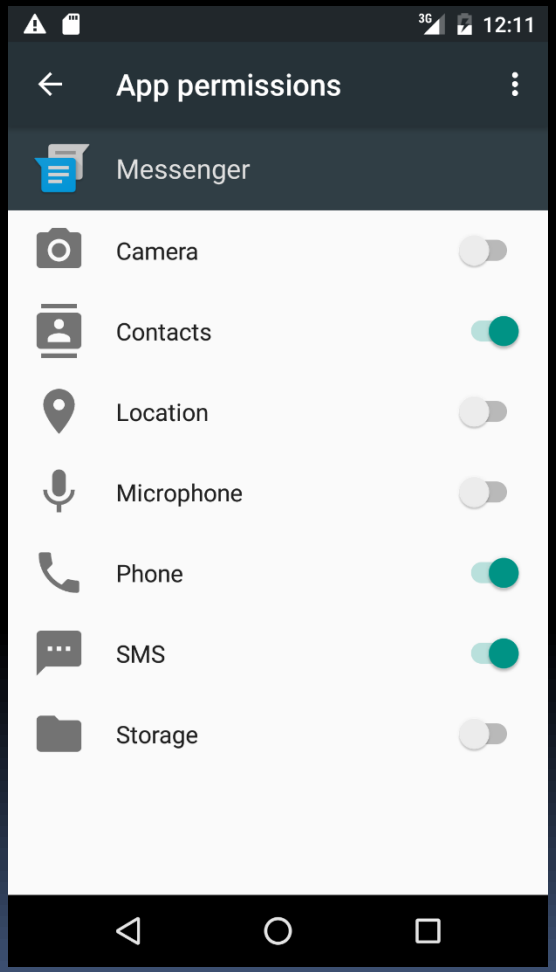
Scoped directory access (since 7.0)



- Allow access to specific shared storage directories

Android Developers. *Using Scoped Directory Access*.

Permission revocation



- May be revoked later from application settings
- Also install-time permissions may be revoked
  - applications may not handle revocation well!

Alternatives to obtaining permissions

- Delegate task to other application using *Intent*, e.g. invoke Camera app using `ACTION_IMAGE_CAPTURE` Intent
  - Caller does not need `CAMERA` permission
  - Caller cannot control the user experience, but does not have to provide UI for task
  - If no default app available, user is prompted to designate the handler

Android Open Source Project. Permissions Best Practices.

Intents

- Messaging object used for Inter-Component Communication (ICC)
  - Recall: activities, services, content providers, broadcast receivers
- Addressing
  - Explicit – fully qualified component name
  - Implicit – Intent filter declared in manifest
    - Provides a mechanism for late binding
- Pending Intents
  - Token-based access control delegation

Binder

- IPC system for object-orientated operating system services (cf. CORBA/COM)
- Most underlying IPC based on Binder
  - Intents & content providers abstractions on top of Binder
  - Cf. local UNIX-domain sockets, signals, filesystem
  - Bionic libc doesn't support System V IPC
- Does not provide mediation by itself
  - Access mediated by system services

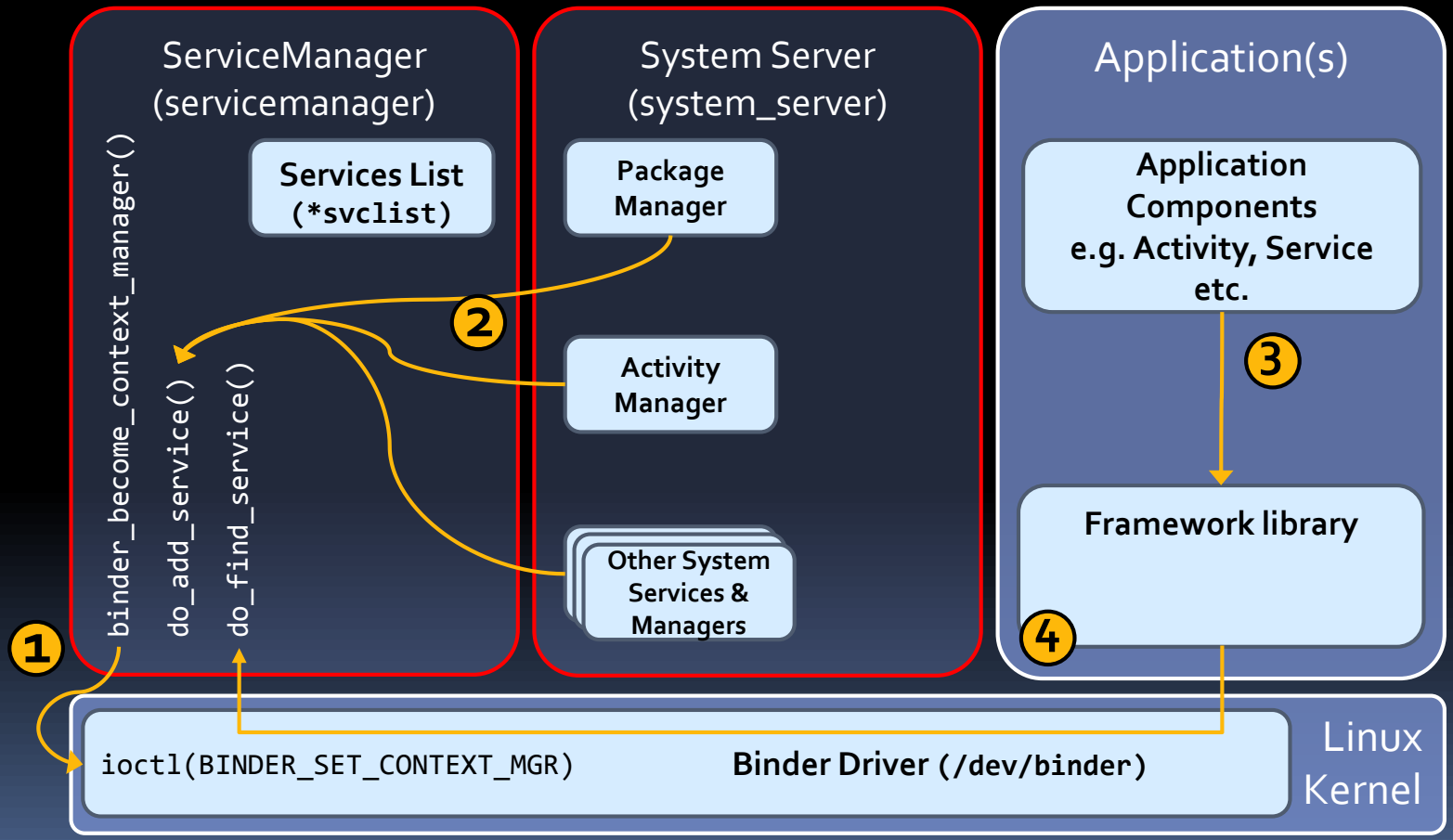
Binder domains (since 8.0)

- Binder traffic split in three domains (contexts)
  - Separate device node and context manager
  - Access to device node restricted by SELinux policy
- Context manager acts as "phonebook" for services available via Binder

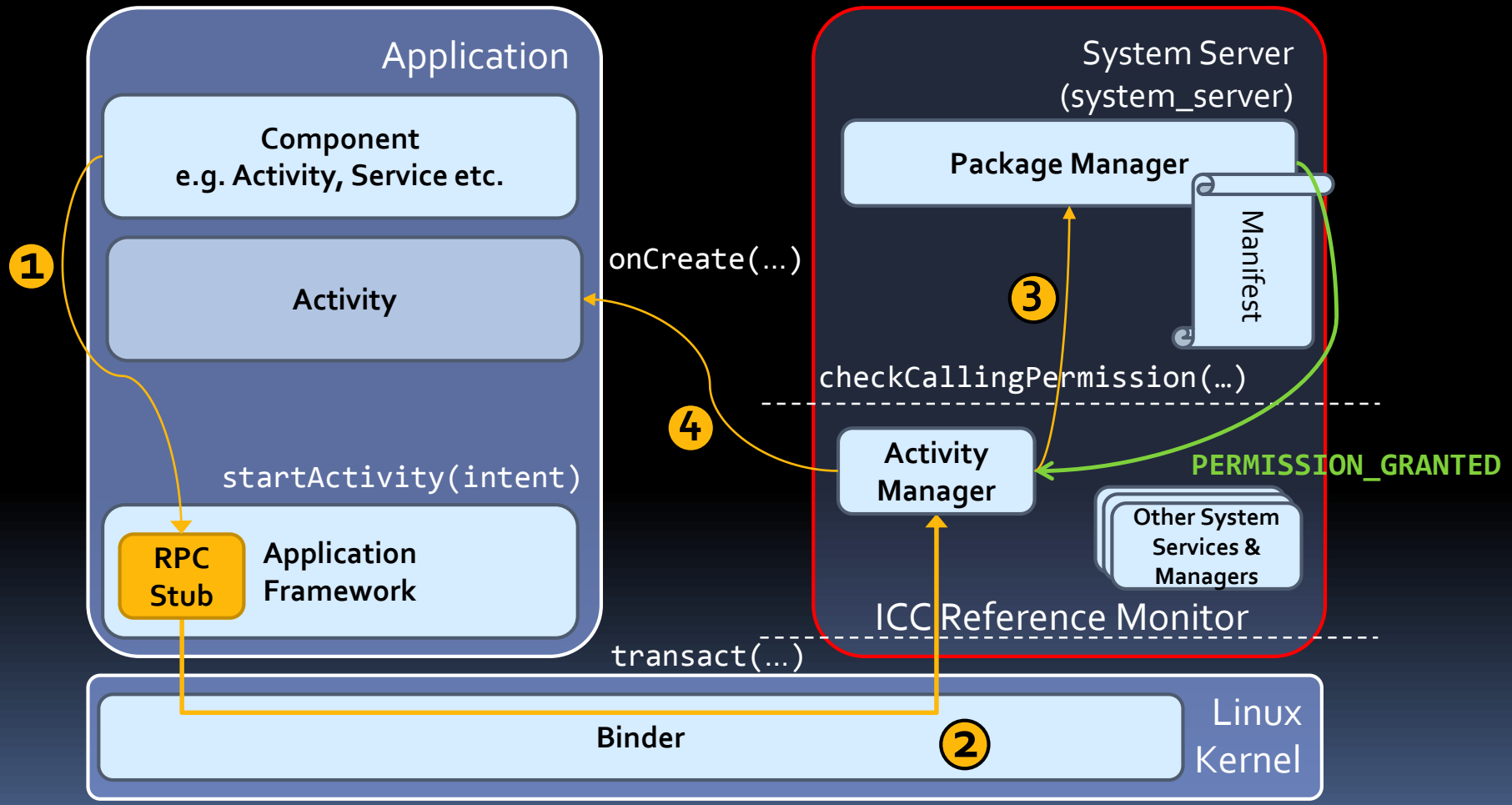
IPC Domain	Manager	Clients
/dev/binder	servicemanager	Framework / app processes
/dev/hwbinder	hwservicemanager	Framework / HAL processes
/dev/vndbinder	vndservicemanager	Framework / vendor processes

Android Open Source Project. Using Binder IPC. 2018

Binder Service Discovery



Starting an Activity



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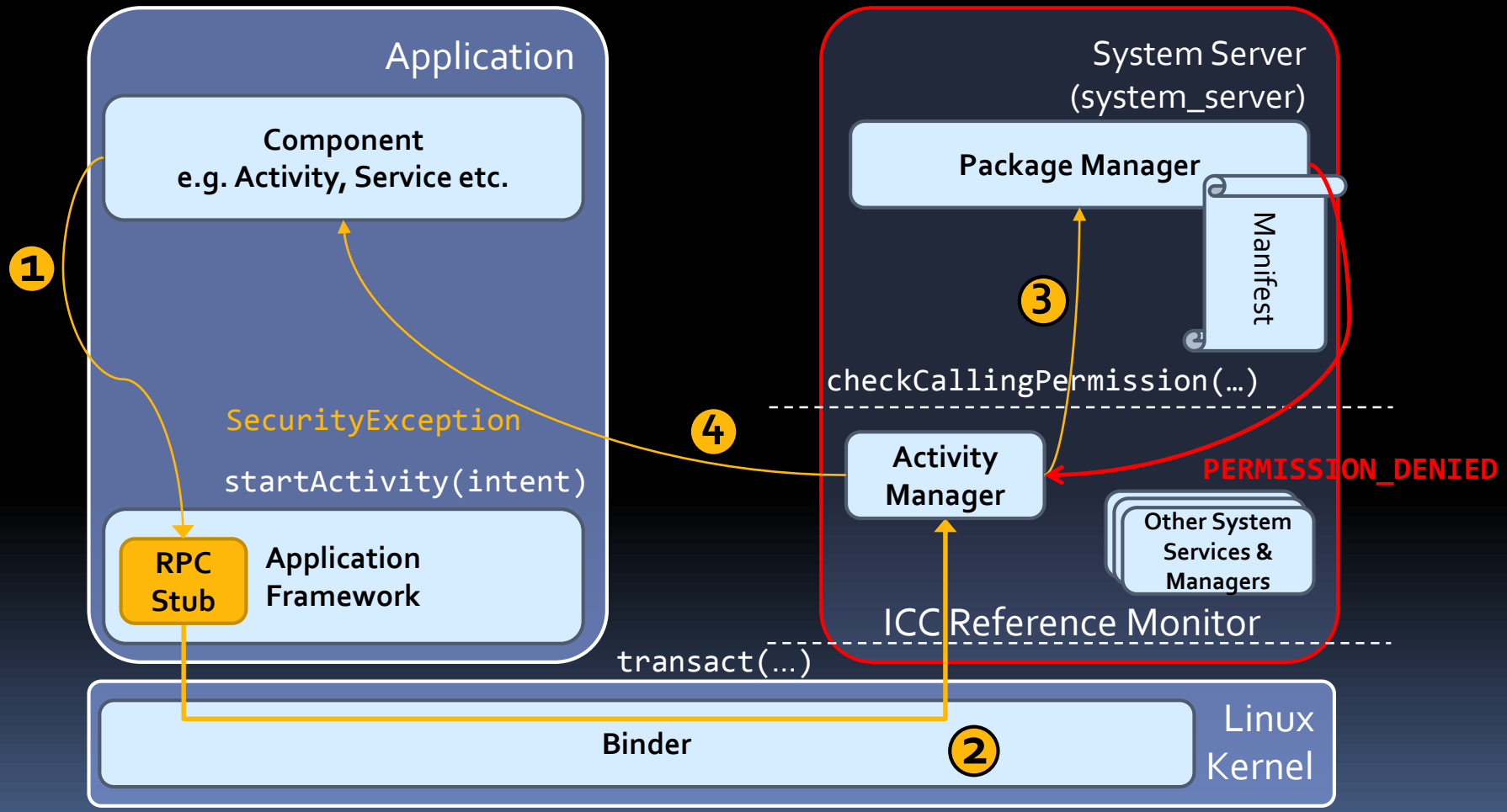


Hardware-based security features

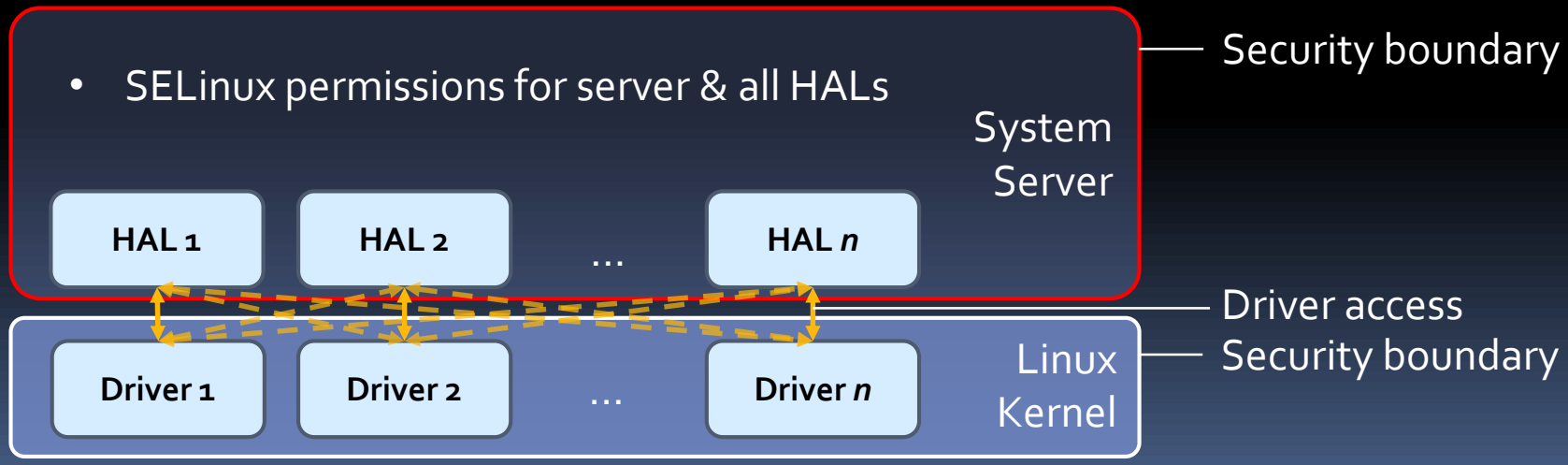
- Goals:
  - Strong but easy to use user authentication
  - Secure storage
  - Platform integrity

Hardware-based security features

- Implementation on Android:
  - Fingerprint / Gatekeeper
  - Keychain / Keystore
  - Full-disk / File-Based encryption
  - Verified boot

Hardware Abstraction Layers

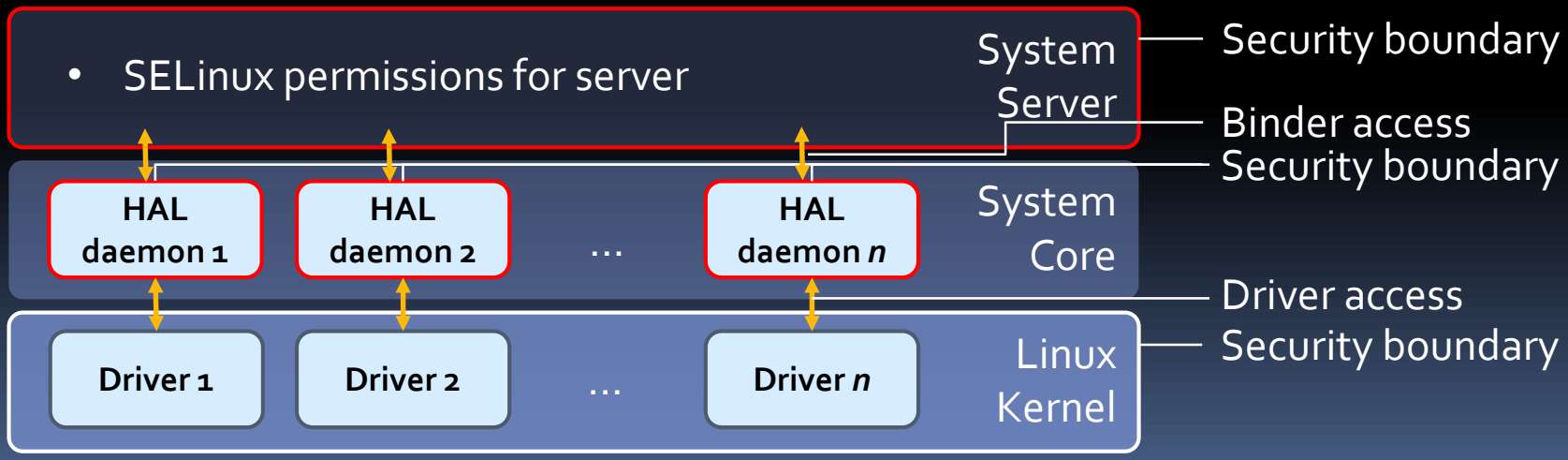
- Interface between device independent code and device-specific hardware implementation
- Prior to 8.0 HALs packaged as shared libraries
  - Run in same security context as client process
  - Process needs all permissions required by HAL



Android Developers Blog. Shut the HAL Up. 2017

Hardware Abstraction Layers

- In 8.0 HALs moved into sandboxed processes
  - HAL processes require only permissions for HAL
  - Increased IPC overhead between client and HAL
  - HAL processes practical after improvements to Binder driver (scatter-gather, fine-grained locking, real-time priority inheritance)



Android Developers Blog. Shut the HAL Up. 2017

Authentication

- Keyguard
  - Pattern
  - PIN / Password
- Gatekeeper HAL (since 6.0)
  - Allows Keyguard to make use of native security features
- Fingerprint HAL (since 6.0)
  - Access to vendor-specific fingerprint hardware

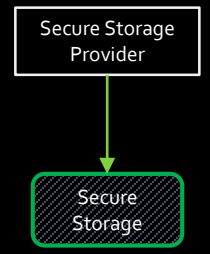
Android Open Source Project. Gatekeeper.
Elenkov. Password storage in Android M. 2015.

Authentication (cont.)

- TrustAgentAPI (since 5.0)
  - Enables services that notify the system about whether they believe the environment of the device to be trusted
- Smart Lock Trust Agent (since 5.0)
  - Trusted Bluetooth device
  - Trusted NFC
  - Trusted place (via geofencing)
  - Facial recognition
  - On-body detection

Elenkov. Dissecting Lollipop's SmartLock. 2014.
Nexus Help: Set up your device for automatic unlock.
Android Developers. Creating and monitoring Geofences.

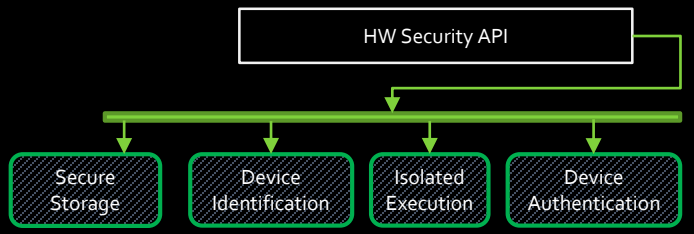
Android Keystore



- Protects cryptographic keys from extraction even if application or OS is compromised
  - KeyChain API for system credentials (since 4.0)
  - KeyStore API (Java CE) for application-bound keys
- Hardware-backed keystore binds keys to device (inc. operating system and patch level of system image)
  - Keys not exposed unencrypted outside secure h/w
  - KeyInfo.isInsideSecureHardware() (since 6.0) indicates if key is stored in hardware keystore
- KeyChain API is used for Wi-Fi and Virtual Private Network (VPN) certificates

Google. Android for Work Security white paper. 2015

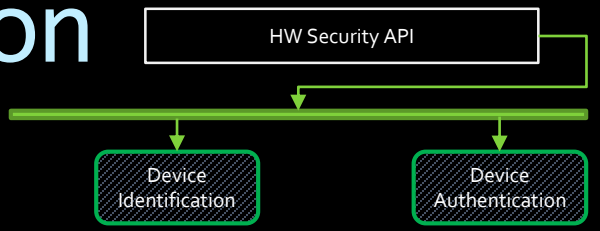
Keymaster



- KeymasterHAL
  - Access to hardware-backed keystore
  - Assymmetric key generation, signing and verification (since 4.1)
  - Binder IKeyStoreInterface (since 4.3)
  - Symmetric key support, access control, public key import and private / symmetric key import (since 6.0)
  - Key attestation (since 7.0)
  - ID attestation (since 8.0)
  - Secure key import (since 9.0)
  - Protected Confirmation (since 9.0)
- Strongbox Keymaster
  - backed by hardware security module with discrete CPU, secure storage, true RNG, tamper protection (since 9.0)

Android Open Source Project. Keymaster. 2018
Elenkov. Keystore redesign in Android M.2015.
Elenkov. Credential storage enhancements in Android 4.3. 2013.
Android Developers. Android 7.0 for Developers. 2016
Android Developers. Key Attestation. 2018
Android Developers. Android 9 features and APIs. 2018

Key / ID attestation

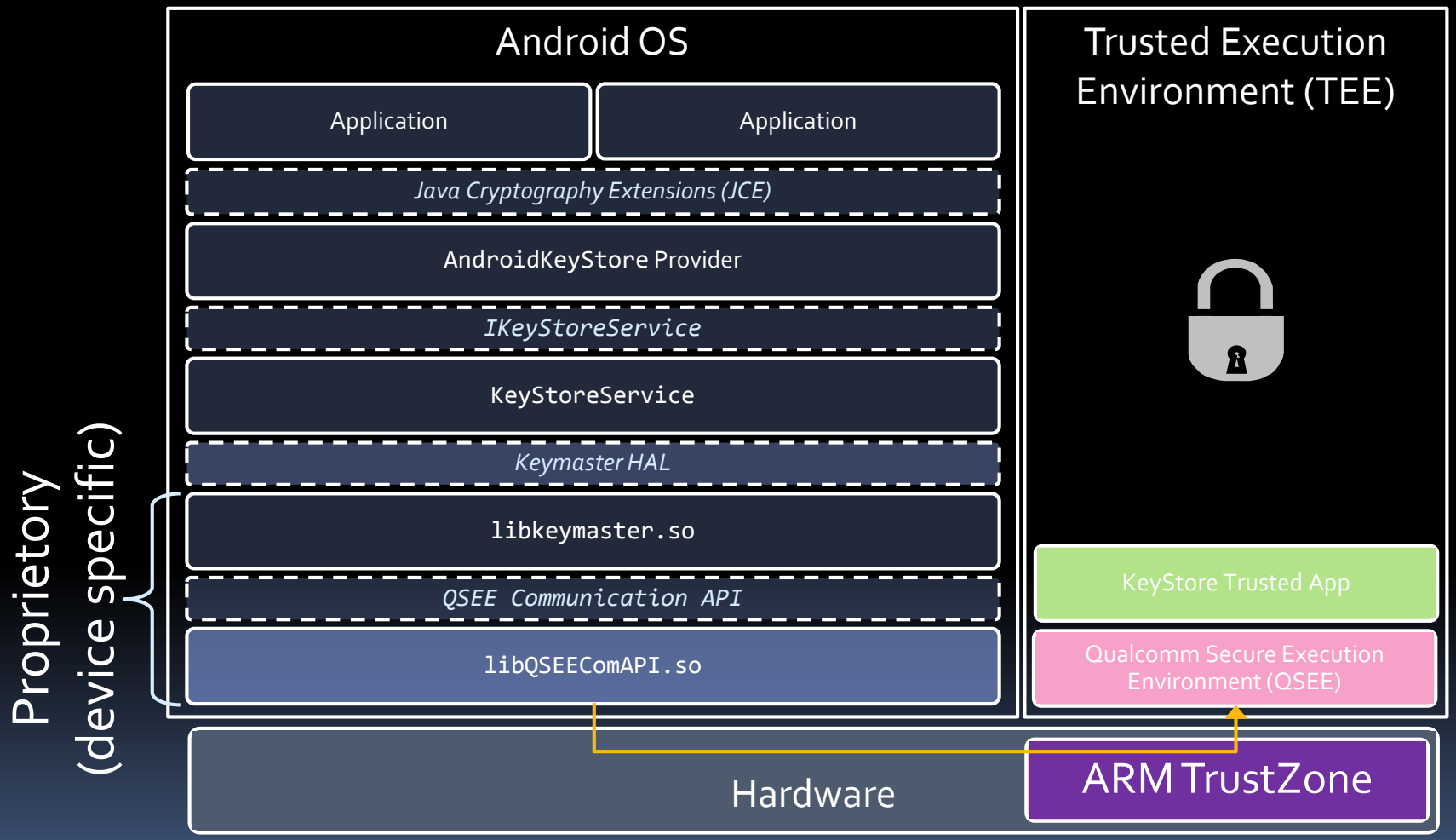


- Signed statement that improves confidence that applications keys stored in hardware-backed keystore
  - attestation certificate chain root cert signed with Google attestation root key
  - accessed via `getCertificateChain()` for KeyStore object's
  - must be validated on separate trusted server!

- ID attestation provides proof of hardware identifiers
  - E.g. brand, manufacturer, model, serial number or IMEI

Android Open Source Project. Key and ID attestation. 2018.
Android Developers. Key and ID attestation. 2018
Android Developers. Verifying hardware-backed key pairs with Key Attestation. 2018

Qualcomm Keymaster architecture



Elenkov. Keystore redesign in Android M.2015.
Elenkov. Credential storage enhancements in Android 4.3. 2013.

Skip to End

Full Disk Encryption

- Block-device encryption based on `dm-crypt`
- Encrypted on first boot (since 5.0)
- AES 128 CBC and ESSIV:SHA256
- DEK encrypted with AES 128
  - KEK derived from user PIN / password / pattern

  + hardware-bound key stored in TEE (since 5.0)
- Crypto acceleration through hardware AES (e.g. `dm-req-crypt`)

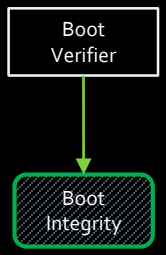
Android Open Source Project. Full Disk Encryption.
Elenkov. Hardware-accelerated disk encryption in Android M. 2015.

File-Based Encryption (since 7.0)

- Direct Boot enables supported apps to operate before user unlocks device
- Two storage locations for data:
  - Credential Encrypted (CE) storage (default) only available after user has unlocked device
  - Device Encrypted (DE) storage available during Direct Boot and after user has unlocked device (requires hardware-backed Keymaster)

Android Open Source Project. File Based Encryption.
Android Developers. Supporting Direct Boot.

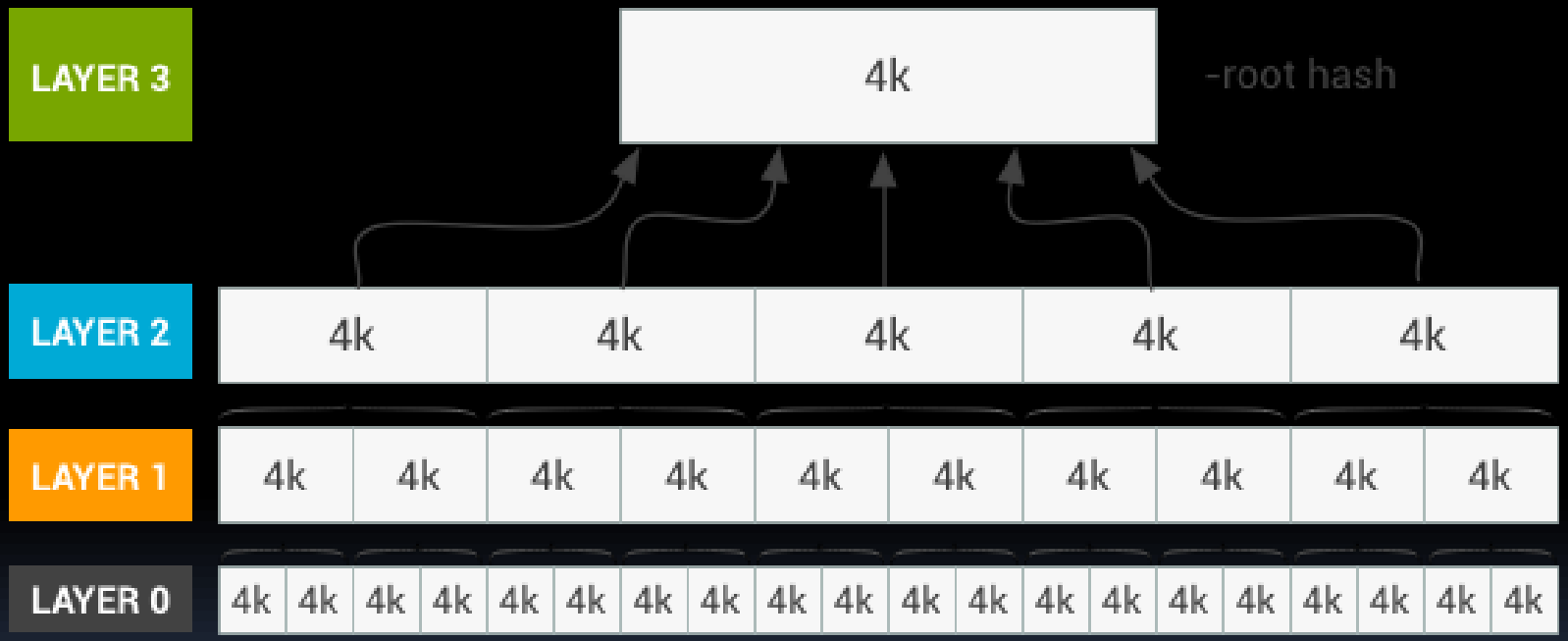
Verified Boot



- Based on `dm-verity` kernel feature
- Calculates SHA256 hash over every 4K block of the system partition block device
  - Hash values stored in hash tree
  - Tree collapsed into a single root hash
- Hashes verified on-demand on disk access
- Signature of the root hash verified with public key included on the boot partition
  - Must be verified externally by the OEM

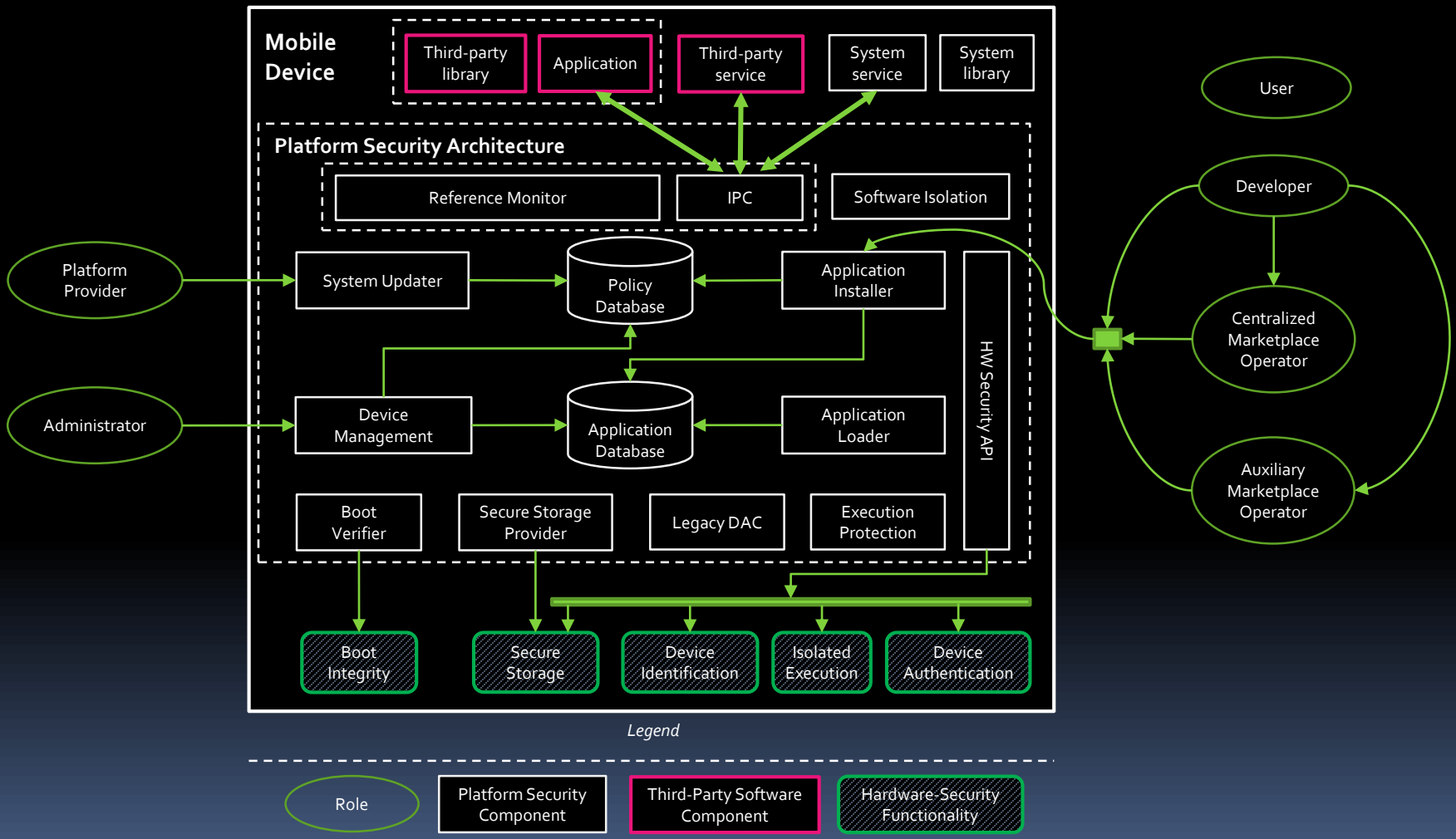
Android Open Source Project. Verified Boot.
Cryptsetup. DMVerity.

Verified Boot Hash Tree



Android Open Source Project. Verified Boot.
Cryptsetup. DMVerity.

Mobile Software platform security



Did you learn:

- Android as a software platform
  - Internals and surrounding ecosystem
- Security techniques in Android:
  - Application signing
  - Application isolation
  - Permission-based access control
  - Hardware-based security features

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Plan for the course

- Lecture 1: Platform security basics
- Lecture 2: Case study – Android OS Platform Security
- Lecture 3: Mobile platform security
- Lecture 4: Hardware security enablers
- Lecture 5: Usability of platform security
- Lecture 6: Summary and outlook
- Lecture 7: SE Android policies
- Lecture 8: Machine learning and security
- Lecture 8: IoT Security