IAIK TU Graz

iOS Platform Security

Mobile Security 2022

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

Outline

- Low-level System Security
- Updates
- Encryption Systems
- Key Management & Passcodes
- Backup

MOTHERBOARD By Joseph Cox Mar 11 2020, 4:46pm

TECH BY VICE

Source: vice.com

We Built a Database of Over 500 iPhones Cops Have Tried to Unlock

"It is the world we are in today, and so have to deal with it," former FBI general counsel Jim Baker said about device encryption.

AO 93 (Rev. 11/13) Search and Seizure Warrant (Page 2)

Return

Case No.:	Date and time warrant executed:	Copy of warrant and inventory left with:
19MJ3553	8/21/2019 2:00pm	

Inventory made in the presence of : BPA-I DAVU SCOTT

Inventory of the property taken and name of any person(s) seized:

LG PHONE ALL INFORMATION WAS EXTRACTED.
BOTH iPHONES WERE SUBMITTED TO RCFL, THE FBI LAB FOR DATA EXTRACTION.

01/29/2019	1:19-sw-05136	USA v. Apple iPhone	District of Colorado	DEA	Drug trafficking	Yes	iPhone 7
01/29/2019	1:19-mj-00048	USA v. Apple Iphone, model A586, Austin Police Department Evidence Tag	Western District of Texas	FBI	Firearms, Drug tr	Yes	iPhone 6
01/30/2019	2:19-mj-00043	USA v. IPHONE IN A TAN GUCCI FABRIC CASE WITH A RED WHITE AND BLUE SNAKE ON IT	District of Maine	FBI	Drug trafficking	Yes	
01/30/2019	2:19-mj-00045	USA v. BLACK IPHONE IN A BLACK CASE et al	District of Maine	DEA	Drug trafficking	Yes	Two iPhones
01/31/2019	1:19-sw-00031	USA v. Red iPhone X, Model Product RED	Eastern District of California	ATF	Drug trafficking, I	Yes	iPhone X
01/31/2019	1:19-sw-00032	USA v. Black iPhone 7, Model A1778, FCC ID: BCG-E3091A	Eastern District of California	ATF	Firearms	Yes	iPhone 7
01/31/2019	1:19-mj-00013	USA v. iPhone X	Western District of North Carol	FBI	Child exploitation	Yes	iPhoneX
01/31/2019	1:19-mj-00016	USA v. Apple iPhone 7 Model A1661	District of New Hampshire	DEA	Drug trafficking		iPhone 7 Plus
02/01/2019	2:19-mj-00280	USA v. Space Gray Apple iPhone 7 Cellular Phone Bearing Model Number A1660 And Contained In A Blue And Gray OtterBox Brand Case	Central District of California			Yes	iPhone 7
02/04/2019	2:19-sw-03014	USA v. In the matter of the search of a gold Apple iPhone, Model A1660, cellular telephone with a cracked screen, and a black Samsung, Model SMB311V, cellular telephone, MEID #A0000047718857	Western District of Missouri	ATF	Drug Trafficking,	Yes	iPhone 7
02/05/2019	6:19-cm-00001	USA v. An Apple iPhone 8 Cellular Telephone	Western District of Arkansas	Social Security A	Embezzlement	Yes	iPhone 8

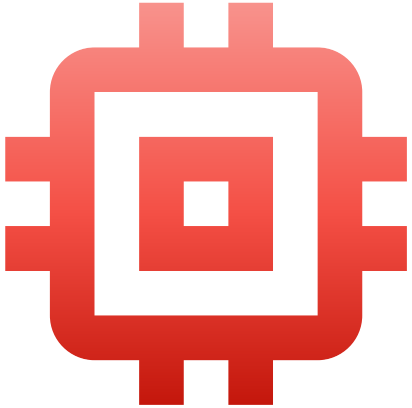
iOS Platform Fundamentals

iOS Device Architecture

- The device is comprised of a main (ARM) CPU and several coprocessors

- Secure Enclave Processor (SEP)
  - Separate processor for cryptographic operations
  - Key storage, management, encryption / decryption
    - Group ID (GID) key shared between SoC family
    - Unique ID (UID) key generated by SEP at factory
  - Securely paired to FaceID and TouchID sensors

- Secure Element
  - Separate chip for Apple Pay and NFC



Picture: Google / Apache 2.0

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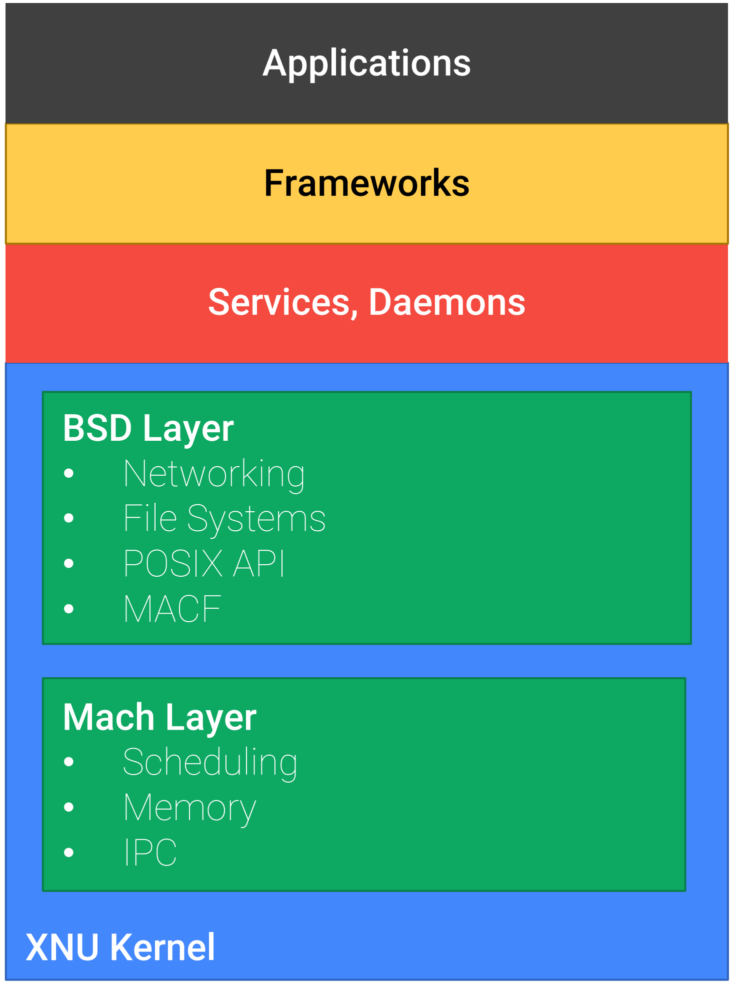
iOS

- XNU Kernel
  - Based on Mach microkernel
  - Added FreeBSD layer for POSIX compatibility
  - IOKit device drivers
  - Shared with macOS
  - Open source!

- Userspace
  - Partly open-source (Darwin)
  - Frameworks (e.g. Cocoa Touch)
  - Daemons, Services, Programs, Apps
    - launchd
    - SpringBoard



Hexley DarwinOS Mascot Copyright 2000 by Jon Hooper. All Rights Reserved.

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Mandatory Access Control Framework (MACF)

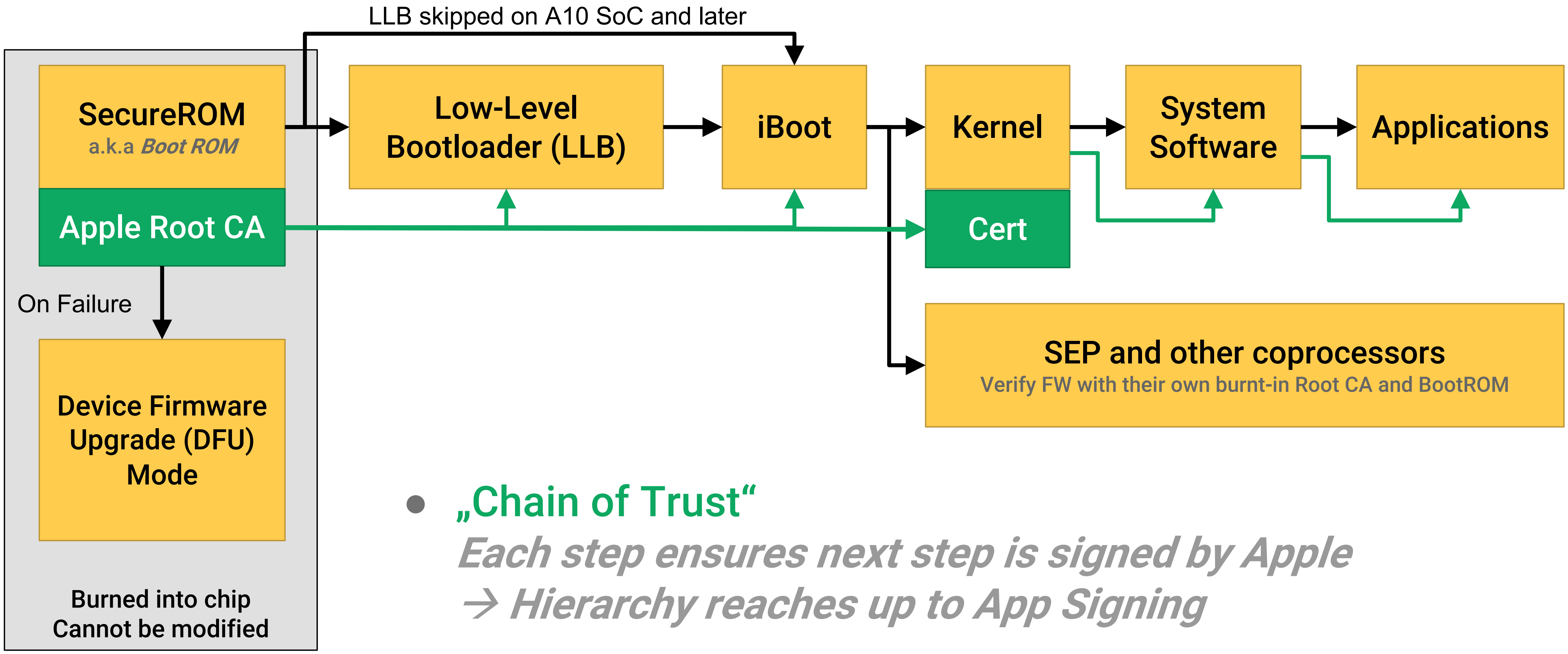
- **MAC extends Discretionary Access Control** (DAC = file permissions)
- **Various hooks scattered throughout syscall implementations in kernel**
- **Hooks call out to Policy Modules for checking if operation permitted**
- **Foundation for central iOS security features**
  - Code Signing Policy Module: AppleMobileFileIntegrity.kext
  - Sandbox Policy Module: Sandbox.kext

Picture: Google / Apache 2.0

Source: J. Levin: "*OS Internals"

Low-Level
System Security

Secure Boot Chain („iBoot Chain“)



- **„Chain of Trust“**
  Each step ensures next step is signed by Apple
  → Hierarchy reaches up to App Signing

- From LLB/iBoot to Applications → can be updated

Sources: J. Levin: "*OS Internals", apple.com

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Secure Boot Chain

Starting with simple boot loader…

- Burnt into hardware: *„Hardware Root of Trust“*
- Prevent tampering of lowest software levels

- Similar (separate) boot process for coprocessors
  - Baseband processor (cellular access)
  - Secure Enclave coprocessor
  - Started by iBoot

→ Error if load / verify next step failed
  - Enter DFU (Recovery mode)
  - Connect to iTunes and restore factory defaults

iOS Downgrades?

Apple prevents them using „*System Software Authorization*“!

- Signatures alone would enable replay attacks

- Online process
  - Device generates nonce *(„anti-replay value“)*
  - Sends Exclusive Chip ID (ECID) + nonce to Apple server
  - Apple generates signature for (OS image + ECID + nonce)
  - Device checks if signature ok, nonce / ECID matches
  - If fine: Install software

- Prevent installation of old OS images by revoking old signatures

Chip Fuse Mode (CPFM)

- A write-only register controls hardware debuggability
  - Burned in factory, enforced by SecureROM
- Two flags: (Production/Development), (Secure/Insecure)
  - Controls CPU and SEP strictness
- Apple-internal development devices:
  - Development: Allow JTAG debug access for CPU
  - Insecure: SEP JTAG + Booting unverified OS image

- Leaked "Dev-Fused" iPhones used by hackers
  - Available from gray market
- 2020: Apple Security Research Device Program
  - Only for high-profile security researchers

Source: twitter.com

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The Prototype iPhones That Hackers Use to Research Apple's Most Sensitive Code

Very few people have heard of them, but "dev-fused" iPhones sold on the grey market are one of the most important tools for the best iOS hackers in the world.

By Lorenzo Franceschi-Bicchierai

March 6, 2019, 7:23pm Share Tweet Snap

Source: vice.com

Sources: J. Levin: "*OS Internals", vice.com

Firmware Encryption

- Firmware is stored on the device in encrypted form
  - Prevent analysis and reverse-engineering
  - Decrypted during boot, using embedded key and IV
    - Wrapped with GID key only available to SEP

→ Access to SEP decryption needed for accessing raw firmware
  - SecureROM exploit
  - SEP exploit
  - Dev-Fused device

Sources: J. Levin: "*OS Internals", theiphonewiki.com

Jailbreak

- Boot chain is an interesting attack target
  - Cut the „Chain of Trust“
  - Modify subsequently loaded components
  - E.g. Remove code signature checks from kernel
- Exploits in LLB, iBoot or kernel
  - Software patchfix possible!
- SecureROM exploits
  - Can not be updated → deploy new chips
  - Checkm8 exploit published in 2019

Source: twitter.com

Secure Enclave

Goals?

- Store and manage sensitive user data
  - Data protection keys
  - Biometric information (FaceID, TouchID)

- Separate from main Application Process (AP ≈ CPU)
  - Even privileged iOS exploits can not access key material

- Enforce strict security policies
  - Prevent brute-force attacks
  - Prevent offline attacks

Secure Enclave Processor (SEP)

Implementation

- Dedicated separate processor core within SoC running its own sepOS
- Transparently encrypted access to external RAM
  - Replay-protected authenticated encryption in hardware!
- AP has no access to SEP memory
- Mailbox interface for exposing services to AP

- Core primitives:
  - Embedded GID and UID keys
  - AES engine hardened against multiple side channel attacks
  - Public Key Accelerator for asymmetric cryptography
  - True Random Number Generator

Source: Mandt et al.: "Demystifying the Secure Enclave Processor", apple.com

TouchID

- Unlock device without having to enter passcode
  - Passcode still required for first unlock after boot
    - And 48 hours after last unlock

- Sensor is securely paired to SEP in factory
  - Establishes a protected communication channel
  - Sensor sends “hash” of fingerprint image to SEP

- Matching fingerprint unlocks access to user data
  - Implemented in SEP

Source: [Ivan Krstic: "Behind the Scenes of iOS Security"]

TouchID (similar procedure also for FaceID)

How does it work?

- Interaction between two programs on SEP
  - SKS: Secure Key Service
  - SBIO: Secure Biometrics

Encrypts user data on device
Details in a few minutes

1. On Code Unlock: SKS derives Master Key (MK) from passcode and UID key
   1. SKS encrypts MK with Random Secret (RS) ➔ Encrypted MK (EMK)
   2. RS sent to SBIO, MK purged from SKS storage
2. On Touch Unlock:
   1. SBIO obtains fingerprint hash from sensor and compares it to registered values
   2. If match: Send RS to SKS
   3. SKS can now decrypt the wrapped MK from the EMK again

Source: Ivan Krstic (Apple): "Behind the Scenes of iOS Security"

Encryption Systems

iOS Data Encryption Systems

- File system encryption
  - Alias: „Full disk encryption“, „Storage encryption“
  - Introduced with iOS 3 and iPhone 3GS
  - Keys were not dependent on passcode, so protection was very limited

- Data Protection
  - Introduced with iOS 4 (2010)
  - Encrypts individual files
  - Improved in newer version (new Protection classes, KeyChain features)

Data Protection

- Upon file creation, a fresh file encryption key is generated — 256-bit AES
- The key is wrapped with 1 of 4 class keys of varying protection
  - Wrapped key and class stored in file metadata
- Class keys are wrapped with SEP UID key and/or user passcode

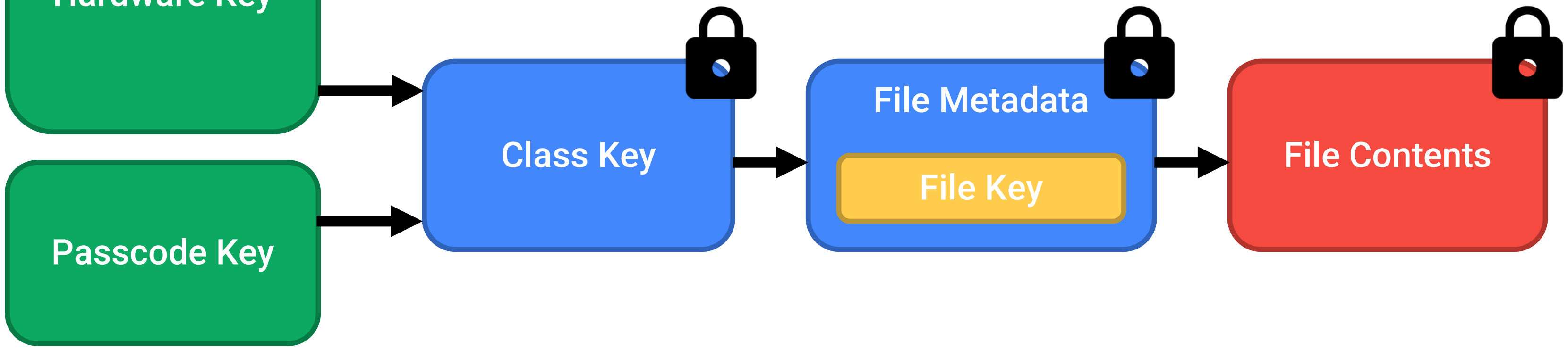
Benefits

- Passcode strength alone depends on user choice
  - Brute-force attacks (offline = on desoldered NAND chip)
- Combined with UID key that never leaves SEP
  - Brute-force attacks have to be carried out on-device!
  - Enforce security policy in SEP
    - Max attempts, delays, …

Data Protection

***Change** file class? Just rewrap file key!*

***Change** passcode? Just rewrap class key!*



Picture: Google / Apache 2.0

Hint: To keep it simple… read from right to left ;)

Source: iOS Security Guide (Q2 / 2019)

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Data Protection Classes (a.k.a. „User Keybag Classes")

Class	Class Key Wrapping	Class Name
A	Passcode + UID	`NSFileProtectionComplete`
Can only be accessed while device is unlocked		
B	Special Case	`NSFileProtectionCompleteUnlessOpen`
Asymmetric Key Pair: Public key always available, Private key only while unlocked (*)		
C	Passcode + UID	`NSFileProtectionCompleteUntilFirstUserAuthentication`
Only accessible after user authenticated once (since last boot)		
D	UID Only	`NSFileProtectionNone`
Always accessible		

(*) Exception for file descriptors acquired already while device unlocked

Sources: J. Levin: "*OS Internals", Ivan Krstic (Apple): "Behind the Scenes of iOS Security"

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Data Protection: Implementation

What happens behind the scenes?

- Passcode-dependant Class keys stored in an encrypted file in device storage
  - „System Key Bag“ file
- Upon boot:
  - SEP loads and decrypts Class D key from Flash (using UID key)
  - System Key Bag sent to SEP, where the class B public key is unwrapped
  - Unwrapped Class Keys are stored in ***SKS Key Ring*** in SEP
- Upon unlock:
  - Remaining class keys unwrapped using Master Key (derived from passcode and UID key)
- Upon lock:
  - Class A and Class B private key removed from ***SKS Key Ring***

Data Protection: Storage Controller

- Hardware assists in hiding class keys from AP

- At boot: SEP generates ephemeral key and sends it to the Storage Controller

- File access:
  - Kernel fetches wrapped file key from metadata and sends it to SEP
  - SEP unwraps key using corresponding class key
  - Rewraps it using ephemeral key and returns result to kernel
  - Kernel sends rewrapped key to Storage Controller to retrieve Flash content

Kernel never gets access to any secret of long-term value!
Ephemerally wrapped key is only valid until reboot

Source: Ivan Krstic (Apple): "Behind the Scenes of iOS Security"

Data Protection – Where is the problem?

- Every new file gets assigned a protection class by an app (!)
  - Handled by the developer!
  - User cannot know which apps encrypt their data and which do not

- Consider the scenario
  - Getting email with PDF attachment (mail app uses data protection)
  - Opening the mail in a PDF reader (not using data protection)

How to find out? → Application Analysis

- Dynamic approach: Monitor live file access using jailbroken device
- Static approach: Look for file API calls + parameters in binary dump

Data Protection – In Practice

```
let fileManager = FileManager.default
fileManager.createDirectory(atPath: folder.path, withIntermediateDirectories: true,
attributes: [FileAttributeKey.protectionKey: FileProtectionType.complete])
…
fileManager.createFile(atPath: databaseKeyURL.path, contents: nil,
attributes: [FileAttributeKey.protectionKey: FileProtectionType.complete])
```

```
let data = Data(count: count)
data.write(to: fullCachePath, options: [.atomic, .completeFileProtection])
```

Since iOS 7 default protection class: *„Protected until first user authentication“*

Effaceable Storage

A section of the Flash storage that can be completely erased

- Note that the process displayed so far is still simplified!
- Complete file system is also encrypted using key stored in effaceable storage
  - "Media Key"
  - Similar to legacy Full Disk Encryption (FDE)
  - Protects file metadata

- System Key Bag file additionally encrypted with key from effaceable storage
  - Yet another key

Source: Ivan Krstic (Apple): "Behind the Scenes of iOS Security"

File System Encryption – Remote Wipe

From the Apple Platform Security Guide (Q1 / 2021):

```
The metadata of all files in the data volume file system are encrypted with a random volume key, which is created when the operating system is first installed or when the device is wiped by a user ... When stored, the encrypted file system key is additionally wrapped by an “effaceable key” ... This key doesn’t provide additional confidentiality of data. Instead, it’s designed to be quickly erased on demand (by the user with the “Erase All Content and Settings” option, or by a user or administrator issuing a remote wipe command from a mobile device management (MDM) solution, Microsoft Exchange ActiveSync, or iCloud). Erasing the key in this manner renders all files cryptographically inaccessible.
```

→ Erase the file system key to avoid further access to any file!

→ Remote Wipe does not actually *delete* the file…

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Key Management
& Passcodes

iOS KeyChain

What for?

Mobile OS needs to handle passwords, login tokens, PINs, certificates, etc

What does it look like?

- 1 SQLite database stored on file system
- Entries can be shared between apps from same developer *(app group)*
- Access from apps using ordinary API
- Protection classes similar to those for files

Side note:

Uninstalling an app does not remove KeyChain data!

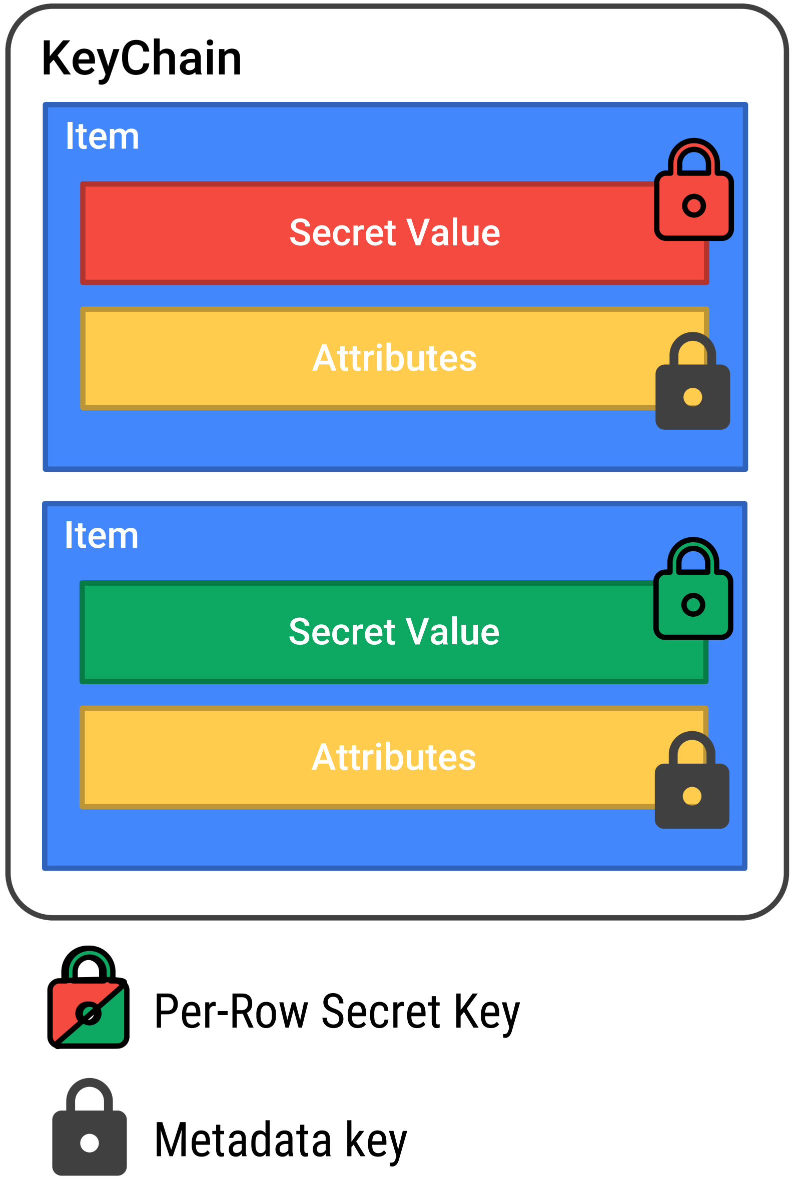
Sources: J. Levin: "*OS Internals", Apple Platform Security Guide (Q2 / 2021)

iOS KeyChain Items

Every entry has…

- Access control list (ACL)
- Key wrapped with protection class key,
- Protection class affiliation
- Attributes describing the entry
- Version number

→ Every aspect is encrypted (AES-256 GCM)!
E.g. also usernames (= attribute), not only passwords!



Source: [Apple Platform Security Guide (Q2 / 2021)]

iOS KeyChain Access Control

Every entry has an Access Control List (ACL) specifying

- **Accessibility**
  - When is item readable?
  - Similar to protection class for Data Protection

- **Authentication**
  - What authentication is needed for access?
  - Confirm user presence through TouchID, FaceID, passcode
  - Ensure TouchID or FaceID enrollment unchanged since entry stored

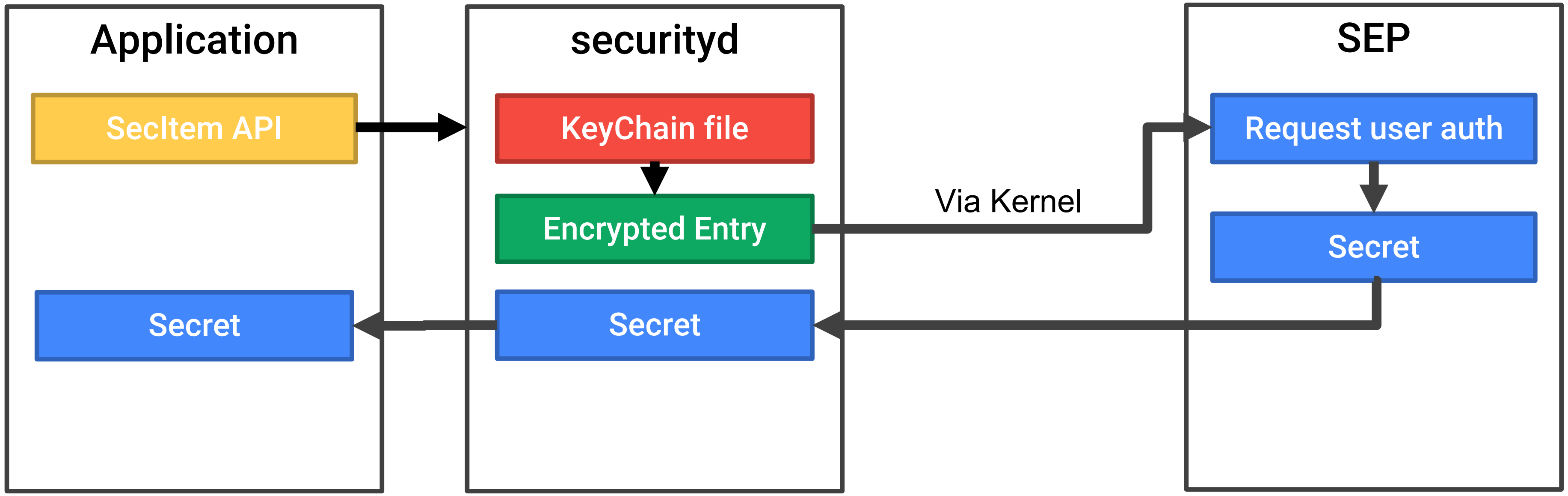
Source: Apple Platform Security Guide (Q2 / 2021)

KeyChain Protection Classes

Secret Availability	Keychain Data Protection
When unlocked	`kSecAttrAccessibleWhenUnlocked`
Protected by user passcode and SEP UID key	
After first unlock	`kSecAttrAccessibleAfterFirstUnlock`
Suitable e.g. for apps that refresh data even while device is locked	
Always	`kSecAttrAccessibleAlways`
Only protected by SEP UID key	
Passcode-enabled	`kSecAttrAccessibleWhenPasscodeSetThisDeviceOnly`
Same as *When unlocked*, except unavailable if no passcode configured	

Source: [Apple Platform Security Guide (Q2 / 2021)]

iOS KeyChain: App Access Workflow



Backups and Sync

Local or Remote Backup

- Local iTunes backups (WiFi or USB cable)
  - Encrypted (AES-256 CBC)
  - Plain
- iCloud backups
  - Sync data to iCloud server
  - Access from other Apple devices

Picture: Google / Apache 2.0

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Keybags on iOS

Keys for file and KeyChain Protection classes are managed in „Keybags“

- System Keybag (= User Keybag)
  - Contains wrapped keys for passcode-dependent protection classes
  - File encrypted with class D key (protected by SEP UID)
  - See Data Protection slides

- Backup Keybag
  - Transferred (exported) system keybag in backups
    - Non-migratory KeyChain entries remain wrapped with SEP UID key
  - Backup encrypted: Key derived from user-specified iTunes password
  - Backup plain: KeyChain still protected by UID-derived key
    → To migrate backup to new device: encrypt the backup!

Sources: P. Teufl et al: "iOS Encryption Systems", Apple Platform Security Guide (Q1 / 2021)

Keybags on iOS Cont'd

- Escrow Keybag
  - Allows iTunes to backup and sync without user passcode!
    - Upon connection, iOS device creates escrow keybag and wraps it with fresh key
    - Key stays on device classified as *Protect Until First User Authentication*
    - Encrypted escrow keybag stored on computer running iTunes
    - iTunes communicates with device to obtain key when needed

Sources: [Apple Platform Security Guide (Q1 / 2021)]

iCloud Keychain

Allows syncing Keychain entries between multiple Apple devices

- Every device generates an iCloud Keychain synchronization key pair
- User approves new device from a device already in this sync cycle
- Apple servers just relay encrypted messages between devices

What if the user loses all their devices?

Source: Ivan Krstic (Apple): "Behind the Scenes of iOS Security"

iCloud Keychain Backup

Only concerns iCloud Keychain backups!
No information available on encryption of full iCloud backups!

- Encrypted using backup („escrow“) key
  - Randomly generated key
  - Wrapped using a key that is derived from iCSC
    → iCSC = iCloud Security Code = User passcode
    - Unknown to Apple!

- iCloud Keychain backup encrypted with escrow key
  - Encrypted backup + wrapped escrow key sent to Apple
  - In case of device loss or new device
    → User can recover secrets with iCloud password and iCSC

- Main problem in practice: iCloud account security

Source: Ivan Krstic (Apple): "Behind the Scenes of iOS Security"

iCloud Keychain Backup

„Who watches the watchers?“ :-)

iCloud backend could brute-force iCSC to access escrow key!

Apple‘s solution: Cloud Key Vault

- Enforce policy over escrow key
  - Want hard limit on escrow recovery attempts under adversarial cloud
  - What if escrow key unwrapping only happens in Hardware Security Modules?

- Cloud Key Vault = HSM running custom secure code
  - Key vault runs own certificate authority
    - Private key never leaves HSM
  - Each iOS device hardcodes key vault CA cert
  - Escrow key wrapped with Cloud Key Vault certificate, unwrapping only in HSM

Source: [Ivan Krstic (Apple): "Behind the Scenes of iOS Security"]

iOS Platform Security

- Low-level System Security
- Updates
- Encryption Systems
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Questions?

Maybe regarding Assignment 1?

Outlook

- 08.04.2022
  - iOS Application Security
- 29.04.2022
  - Android Platform Security