Behind the Scenes with iOS Security

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Decrypted Kernel Caches

Component Encryption

iOS 10

User data—No change to encryption

Image3 (pre-iPhone 5S)—iBoot, kernel caches, boot logos no longer encrypted

Image4 kernel caches—No longer encrypted

Changes made as part of wider set of performance optimizations

Encryption for these objects was no longer adding a lot of value

No impact to platform security or encryption of user data

Hardened WebKit JIT Mapping

Hardened WebKit JIT Mapping

Background

Just-in-time compilation is necessary for high-performance JavaScript

iOS normally requires all executable pages to be signed

Code signing policy is relaxed in Safari through `dynamic-codesigning` entitlement to support JIT compilation

Hardened WebKit JIT Mapping

iOS 9

32MB RWX JIT memory region

Write-anywhere primitive sufficient for arbitrary code execution

Attacker can write shell code into JIT region and jump to it without ROP

Hardened WebKit JIT Mapping

Execute-only memory protection

Hardware support introduced in ARMv8

Kernel implementation added in iOS 10

Allows us to emit code containing secret data, not readable within the process

Hardened WebKit JIT Mapping

Split view

Create two virtual mappings to the same physical JIT memory

One executable, one writable

The location of the writable mapping is secret

Hardened WebKit JIT Mapping

Tying it all together

Writable mapping to JIT region is randomly located

Emit specialized `memcpy` with base destination address encoded as immediate values

Make it execute-only

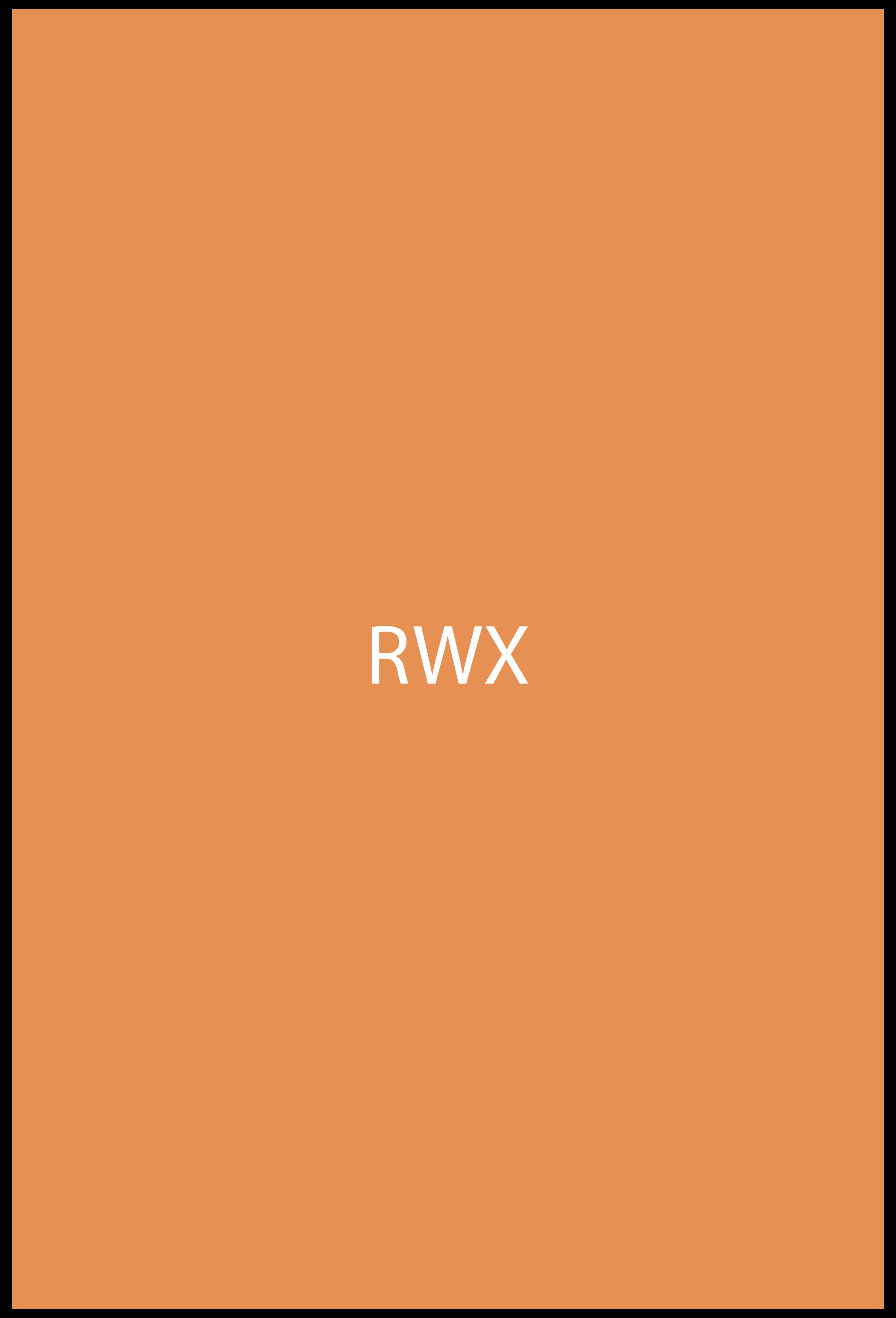
Discard the address of the writable mapping

Use specialized `memcpy` for all JIT write operations

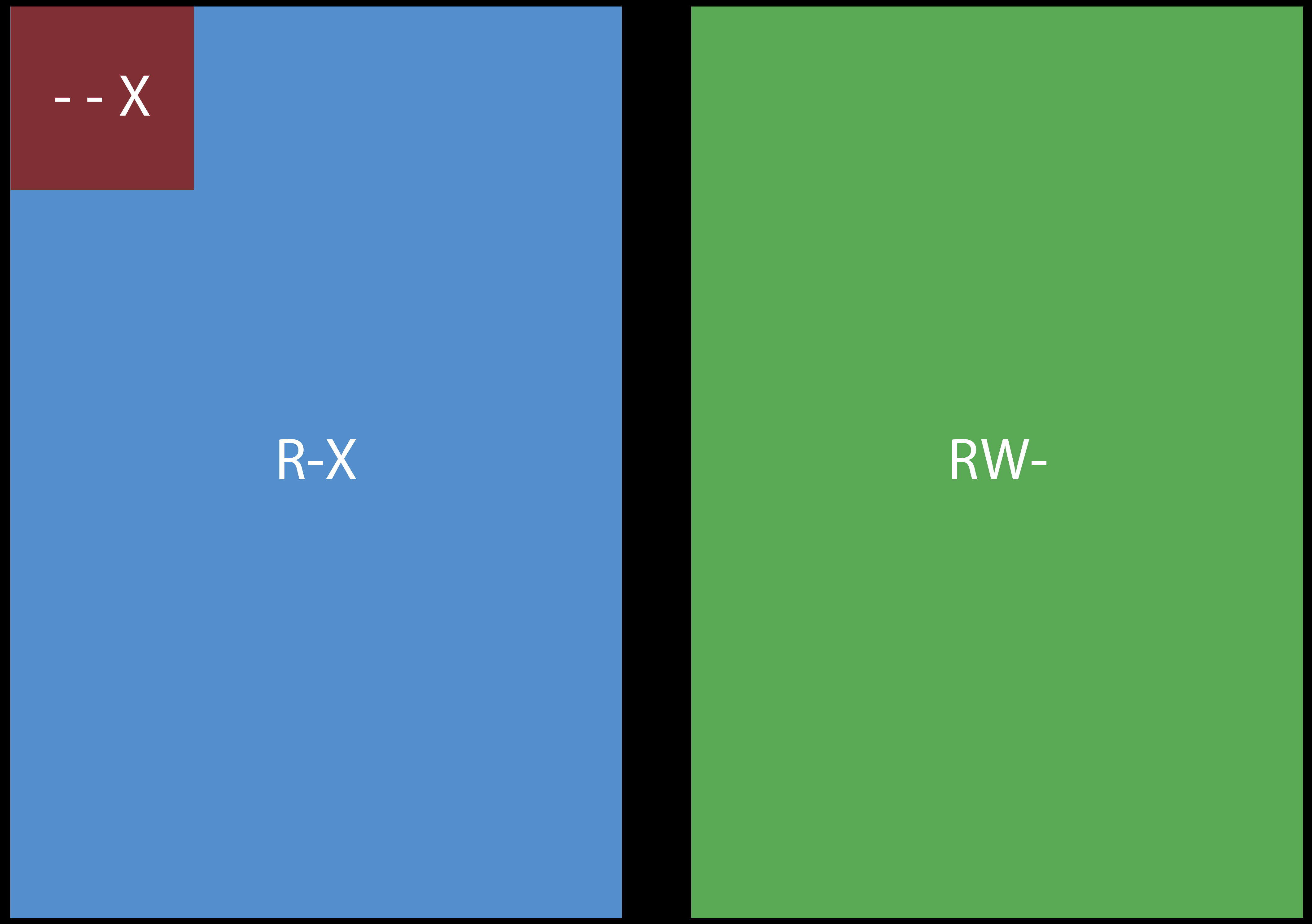
```
void initializeSeparatedWXHeaps(void* stubBase, size_t stubSize, void* jitBase,
size_t jitSize)
{
    mach_vm_address_t writableAddr = 0;

    // 1. Create a second mapping of the JIT region at a random address.
    vm_prot_t cur, max;
    kern_return_t ret = mach_vm_remap(mach_task_self(), &writableAddr, jitSize, 0,
        VM_FLAGS_ANYWHERE | VM_FLAGS_RANDOM_ADDR,
        mach_task_self(), (mach_vm_address_t)jitBase, FALSE,
        &cur, &max, VM_INHERIT_DEFAULT);

    bool remapSucceeded = (ret == KERN_SUCCESS);
    if (!remapSucceeded)
        return;

   // 2. Assemble specialized memcpy function for writing into the JIT region.
    MacroAssemblerCodeRef writeThunk =
jitWriteThunkGenerator(reinterpret_cast<void*>(writableAddr), stubBase, stubSize);

    int result = 0;

#if USE(EXECUTE_ONLY_JIT_WRITE_FUNCTION)
    // 3. Prevent reading the memcpy code we just generated.
    result = mprotect(stubBase, stubSize, VM_PROT_EXECUTE_ONLY);
    RELEASE_ASSERT(!result);
#endif
```

```
    // 4. Prevent writing into the executable JIT mapping.
    result = mprotect(jitBase, jitSize, VM_PROT_READ | VM_PROT_EXECUTE);
    RELEASE_ASSERT(!result);

    // 5. Prevent execution in the writable JIT mapping.
    result = mprotect((void*)writableAddr, jitSize, VM_PROT_READ | VM_PROT_WRITE);
    RELEASE_ASSERT(!result);

    // 6. Zero out writableAddr to avoid leaking the address of the writable mapping.
    memset_s(&writableAddr, sizeof(writableAddr), 0, sizeof(writableAddr));

    jitWriteFunction =
reinterpret_cast<JITWriteFunction>(writeThunk.code().executableAddress());
}
```

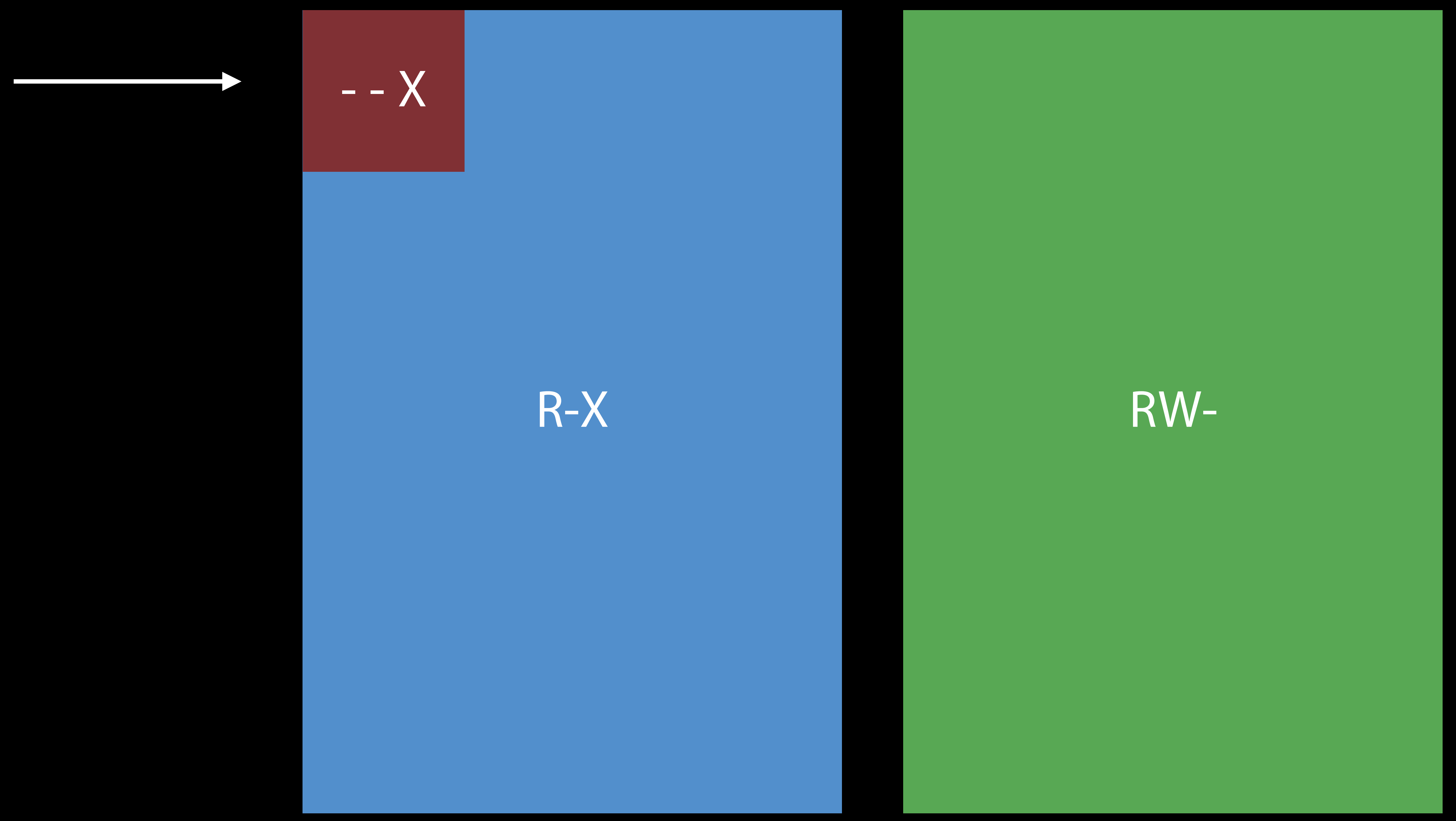
iOS 9



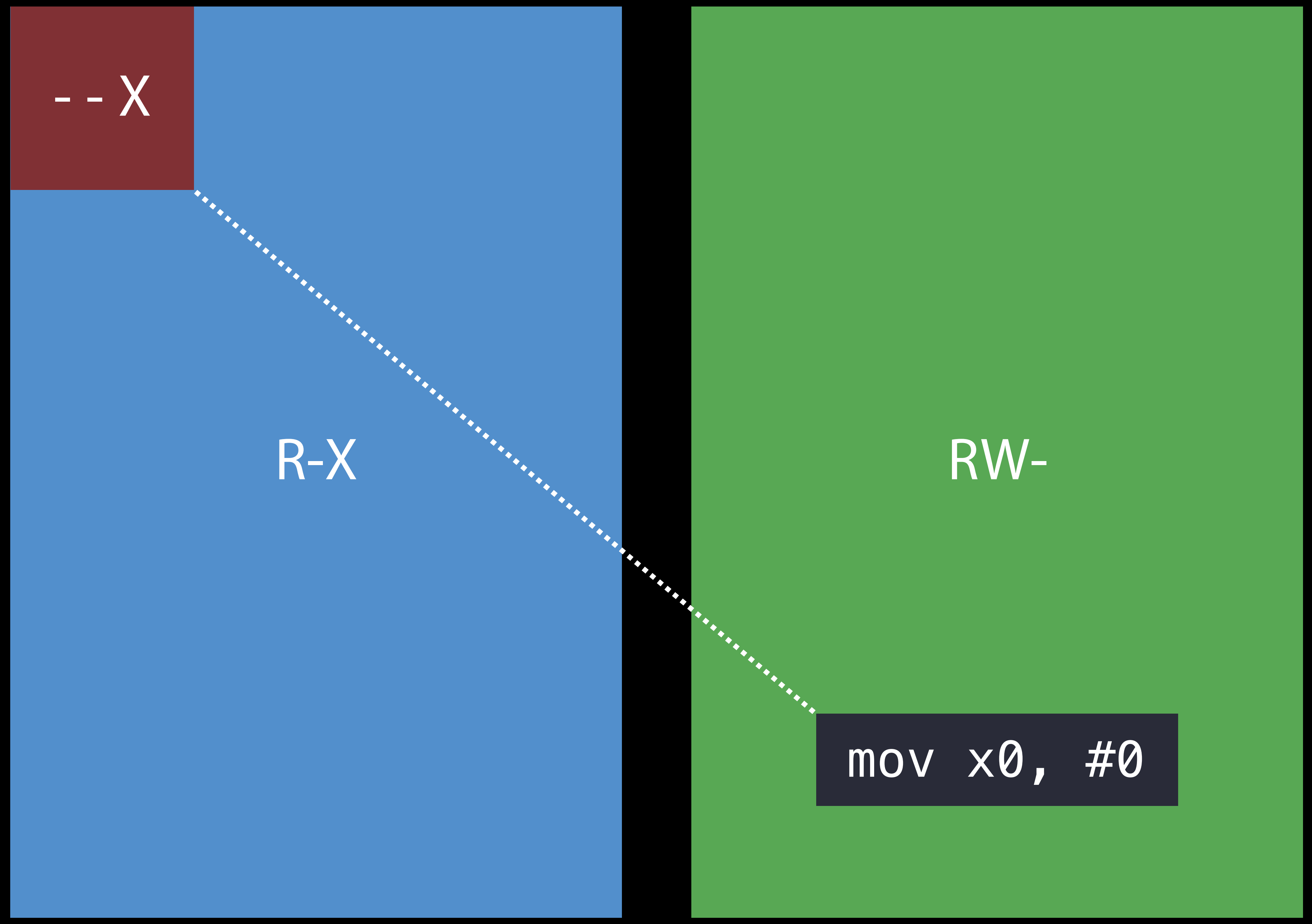
iOS 10



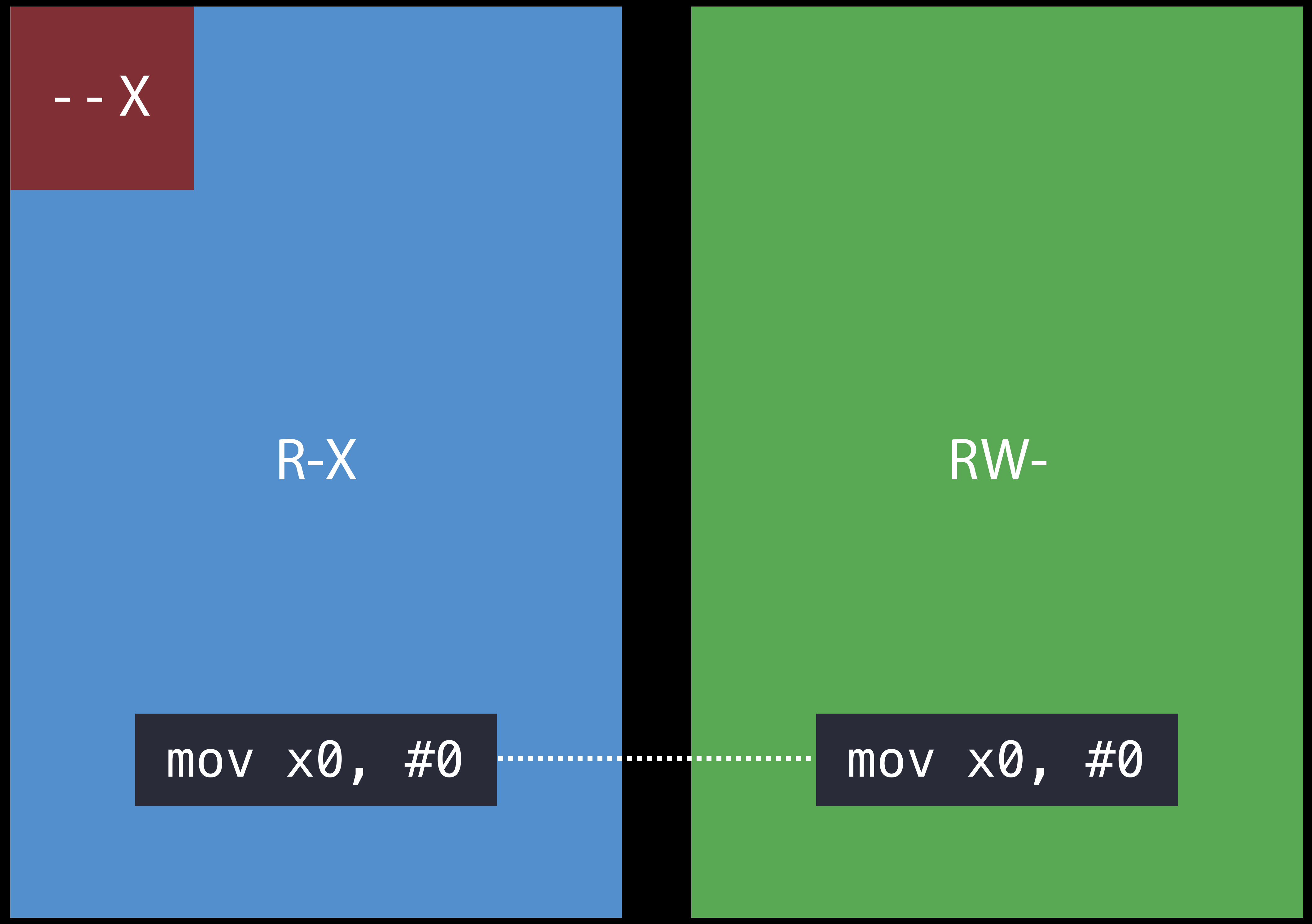
iOS 10



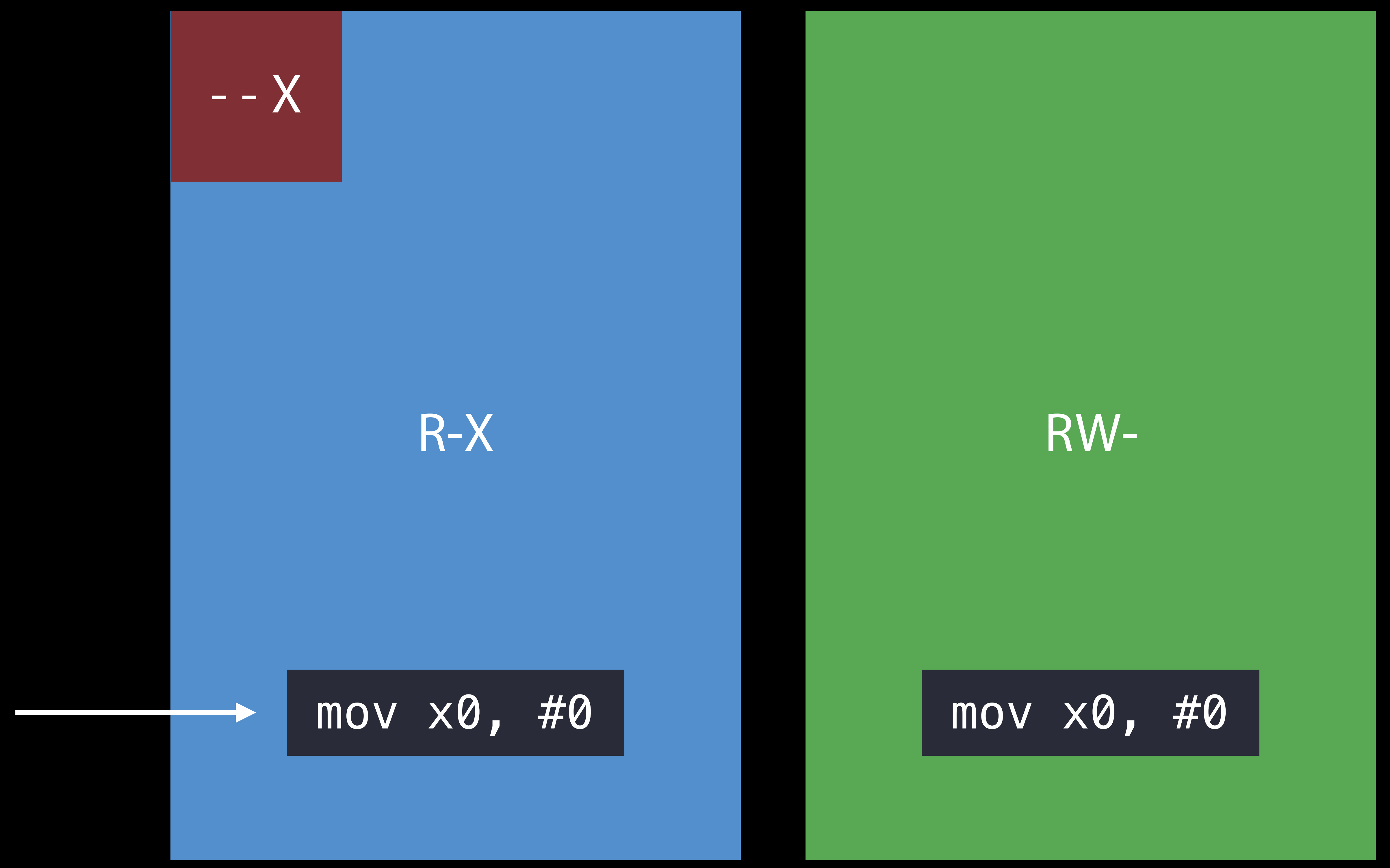
iOS 10



iOS 10



iOS 10



Hardened WebKit JIT Mapping

iOS 10

Write-anywhere primitive now insufficient for arbitrary code execution

Attacker must subvert control flow via ROP or other means or find a way to call execute-only JIT write function

Mitigation increases complexity of exploiting WebKit memory corruption bugs

Data Protection with the Secure Enclave Processor

Data Protection

Goals

User data protected by strong cryptographic master key derived from user passcode

No offline attack on user passcode—Hardware-bound master key derivation

No brute force—Hard limit on number of passcode attempts

Hardware keys for master key derivation not directly exposed to any mutable software

Secure support for alternative unlock mechanisms (Touch ID, Auto Unlock)

Data Protection

Goals—Sidestep AP attack surface

Authentication policy enforcement even under adversarial AP

Master (long-term) key material never exposed to AP

Non-master key material exposed to AP must be ephemeral and session-bound

Secure Enclave Processor

Secure Enclave Processor

Overview

Dedicated SoC core provides trusted environment for handling cryptographic material

Arbitrates all user data access

Hardware accelerators for AES, EC, SHA

Manages its own encrypted memory and communicates with the AP using mailboxes

Factory-paired secure channels to Touch ID sensor and Secure Element

Device UID Key

Background

Each SEP has reference access to a unique private key (UID)

UID generated by SEP itself immediately after fabrication, using its own free-running oscillator TRNG

Available for cryptographic operations via commands exposed by the Secure ROM

No access to UID key material from SEP or other mutable software after fuses blown

User Keybags

Background

Sets of keys generated for each user to protect their data at rest

Keys wrapped by master key derived from user passcode and SEP UID

After 10 incorrect passcode entries, SEP will not process any further attempts

Different policy associated with each keybag key—Usage, availability

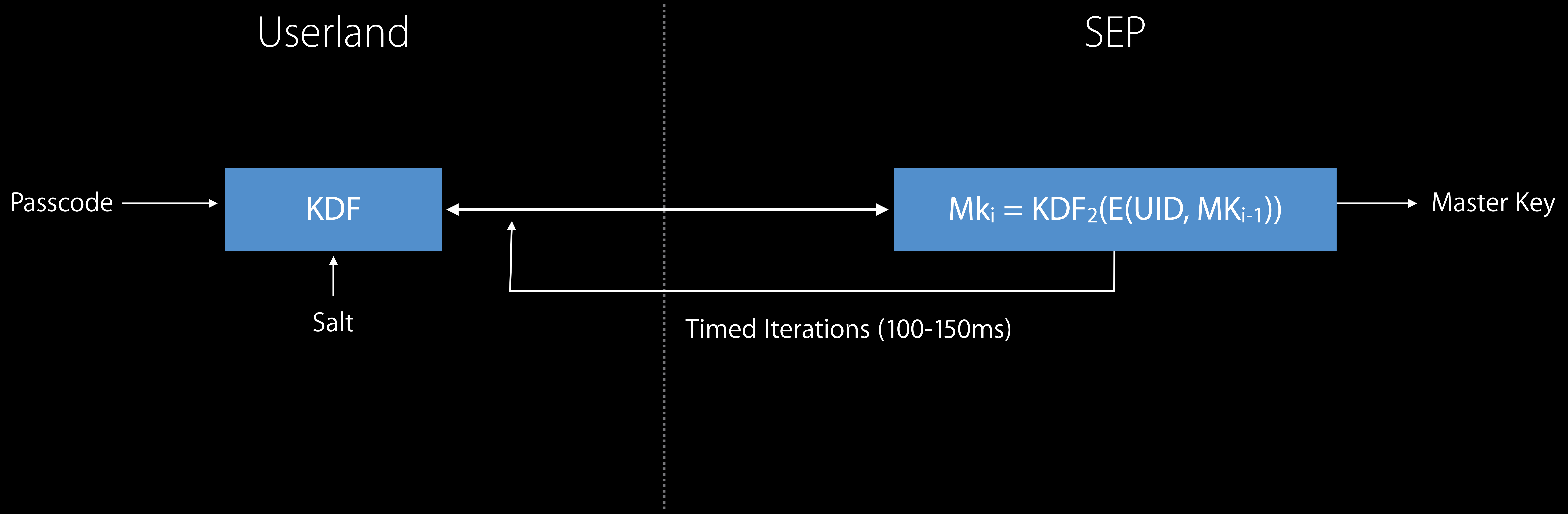
User Keybags

Class keys

Class	Description
A (256-bit AES)	Only available while the device is unlocked
B (Curve 25519)	Public key always available, private key only available when device is unlocked
C (256-bit AES)	Available after the user unlocked the phone at least once after boot
D (256-bit AES)	Always available

```
00000000  44 41 54 41 00 00 05 ca  56 45 52 53 00 00 00 04  |DATA....VERS....|
00000010  00 00 00 04 54 59 50 45  00 00 00 04 00 00 00 00  |....TYPE........|   Keybag version 4
00000020  55 55 49 44 00 00 00 10  4a 99 c1 fd 7e 55 44 43  |UUID....J...~UDC|
00000030  96 96 30 36 42 3a 42 0c  48 4d 43 4b 00 00 00 28  |..06B:B.HMCK...(|
00000040  49 78 be cb 61 71 ed c8  70 4e fc 3d 01 2b 10 bf  |Ix..aq..pN.=.+..|
00000050  4e d4 c4 19 83 dc d1 97  82 3c e1 2f de 9b 51 53  |N........<./..QS|
00000060  d3 d2 be d1 e2 55 ef 40  57 52 41 50 00 00 00 04  |.....U.@WRAP....|
00000070  00 00 00 01 53 41 4c 54  00 00 00 14 7e f0 23 95  |....SALT....~.#.|   KDF Salt
00000080  ee 44 89 d1 c8 47 9a d7  75 2f 07 49 54 74 d0 cc  |.D...G..u/.ITt..|
00000090  49 54 45 52 00 00 00 04  00 00 c3 50 47 52 43 45  |ITER.......PGRCE|   Iteration Count
...
000004e0  47 47 bc 18 6b 92 f3 fa  cc 94 43 4c 41 53 00 00  |GG..k.....CLAS..|
000004f0  00 04 00 00 00 02 57 52  41 50 00 00 00 04 00 00  |......WRAP......|   Key Identifier: Class B
00000500  00 03 4b 54 59 50 00 00  00 04 00 00 00 01 57 50  |..KTYP........WP|   Key Type: Curve25519
00000510  4b 59 00 00 00 28 a2 dd  c7 83 56 45 21 bb 1f 70  |KY...(....VE!..p|   Wrapped Private Key Bytes
00000520  70 07 79 5f 6e ed 42 05  2e a0 2f e2 6f a5 14 4e  |p.y_n.B.../.o..N|
00000530  a2 7f 3c c0 4c 38 bd 5f  1a ce 45 a1 06 ca 50 42  |..<.L8._..E...PB|
00000540  4b 59 00 00 00 20 03 b1  b1 6e aa 7a 59 25 b5 43  |KY... ...n.zY%.C|   Public Key Bytes
00000550  83 7c d1 2c d7 28 f9 d3  48 c1 41 cc 50 47 38 53  |.|.,.(..H.A.PG8S|
00000560  00 ae f7 b5 7b 51 55 55  49 44 00 00 00 10 50 ba  |....{QUUID....P.|
00000570  b5 bc cd cb 42 e6 93 ed  dd 1a 18 3e fb f4 43 4c  |....B......>..CL|
00000580  41 53 00 00 00 04 00 00  00 01 57 52 41 50 00 00  |AS........WRAP..|   Key Identifier: Class A
00000590  00 04 00 00 00 03 4b 54  59 50 00 00 00 04 00 00  |......KTYP......|   Key Type: AES
000005a0  00 00 57 50 4b 59 00 00  00 28 45 9c 2c 38 0c f1  |..WPKY...(E.,8..|   Wrapped Private Key Bytes
000005b0  2a 37 2c 9e 39 b0 90 74  f4 e4 21 f8 b3 c1 48 44  |*7,.9..t..!...HD|
000005c0  eb 36 17 42 16 6b 74 13  15 b2 72 c8 a9 1d 17 f5  |.6.B.kt...r.....|
000005d0  af aa 53 49 47 4e 00 00  00 14 db 7a 1e 3c 39 56  |..SIGN.....z.<9V|
000005e0  b4 f8 70 88 b1 8a c4 cc  4b ea a6 fb df 65        |..p.....K....e|
000005ee
```

Master Key Derivation



Filesystem Data Protection

Overview

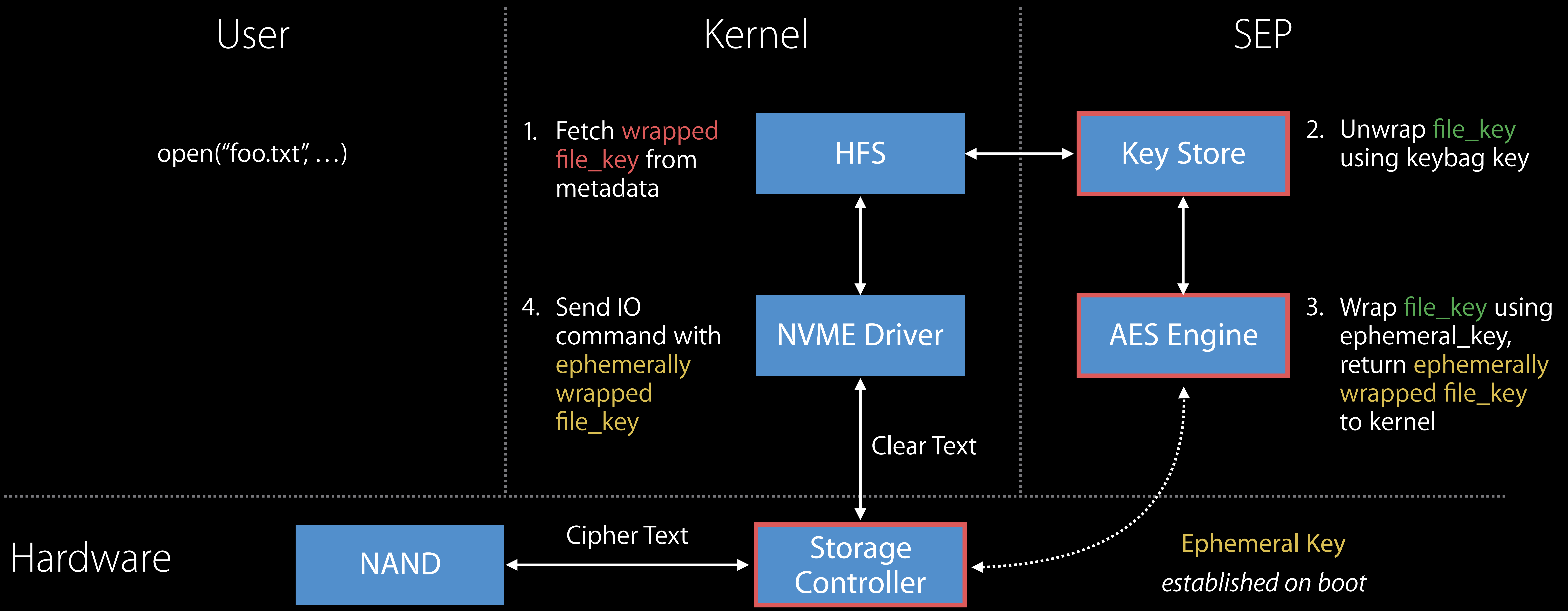
File blocks are encrypted using AES-XTS with 128-bit keys

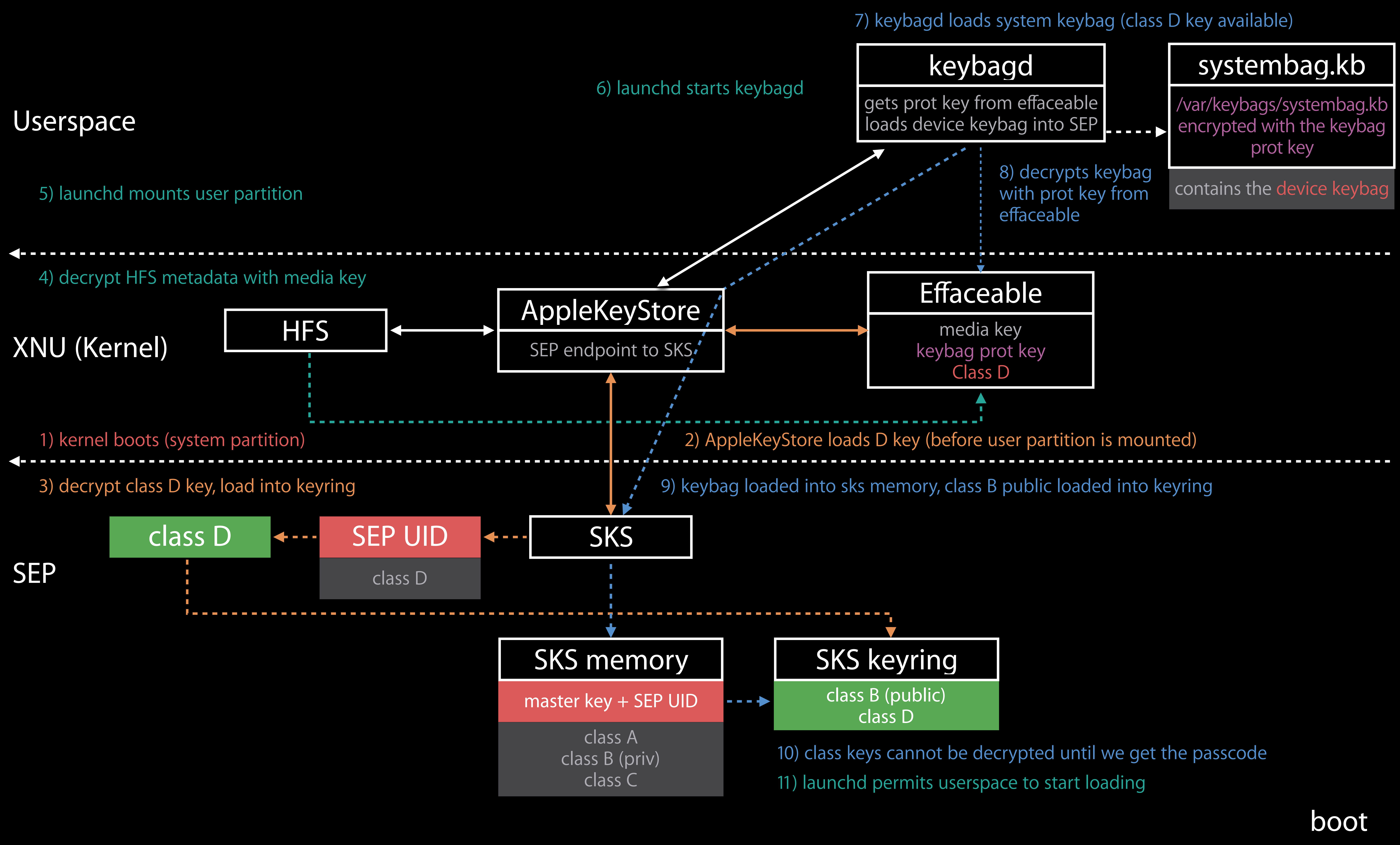
Each file on the user partition is encrypted using a unique random key chosen by SEP

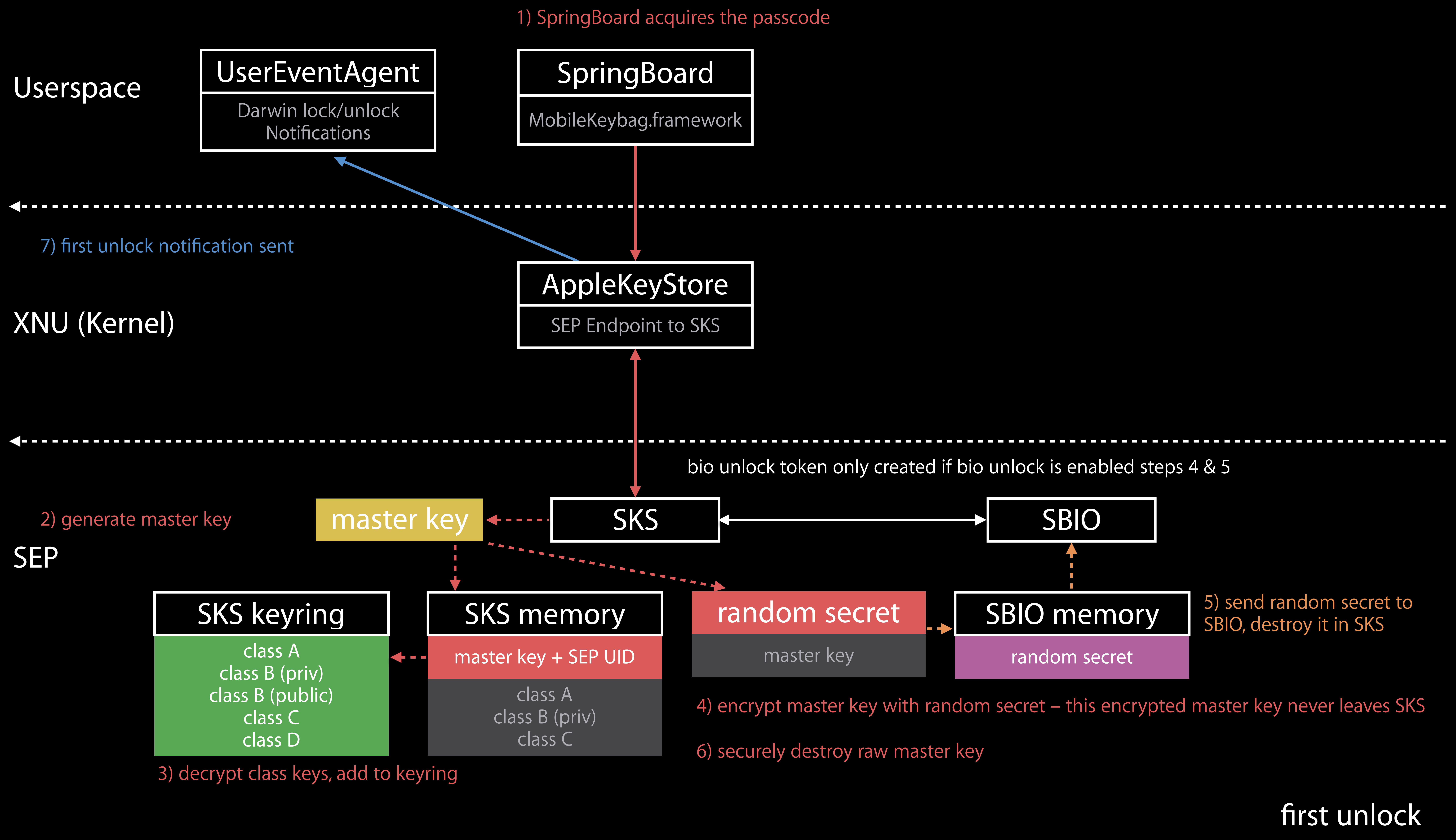
Raw file keys are never exposed to the AP

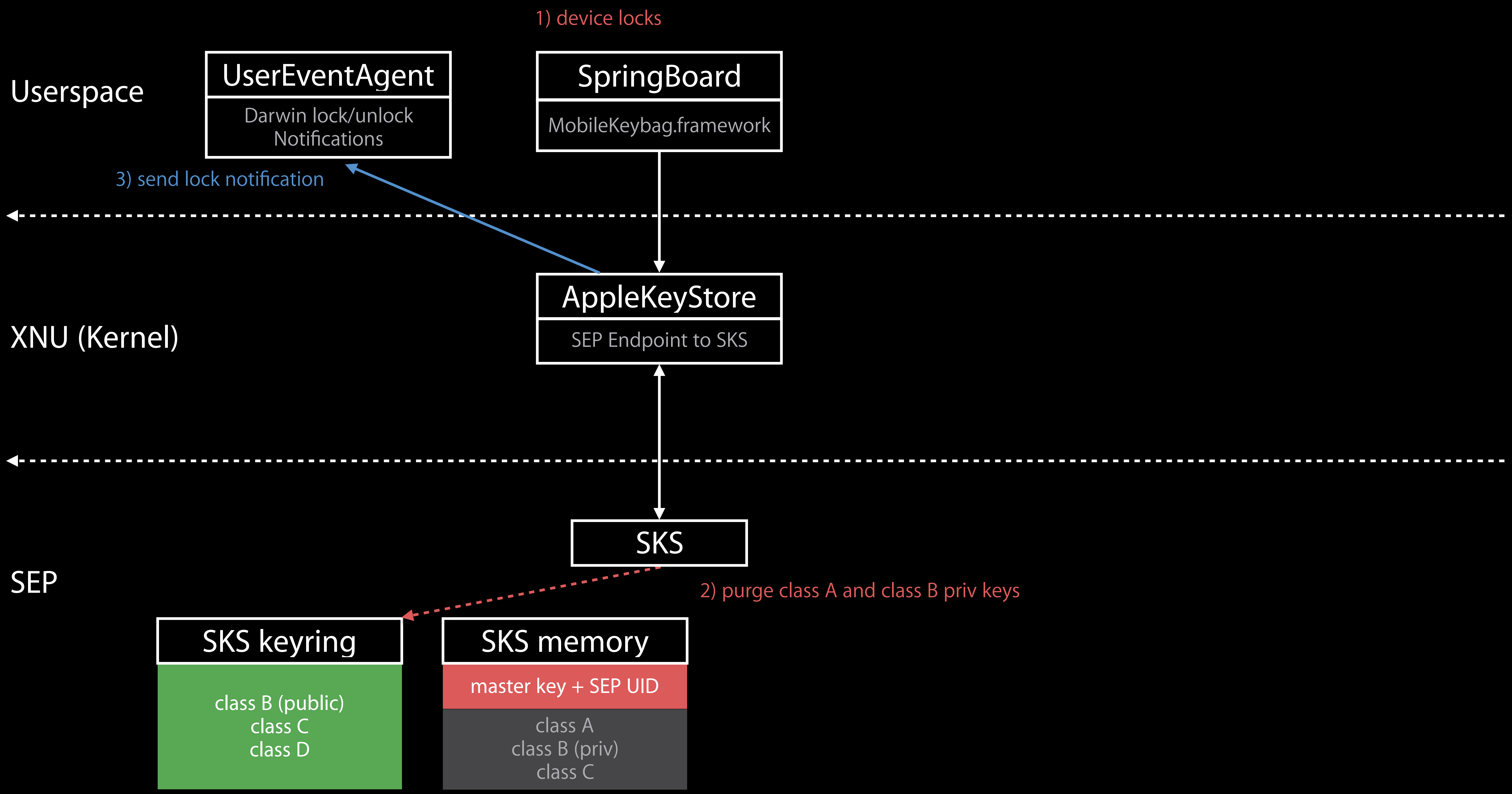
- Wrapped with a key from the user keybag for long-term storage
- Wrapped with an ephemeral key while in use, bound to boot session

Filesystem Data Protection



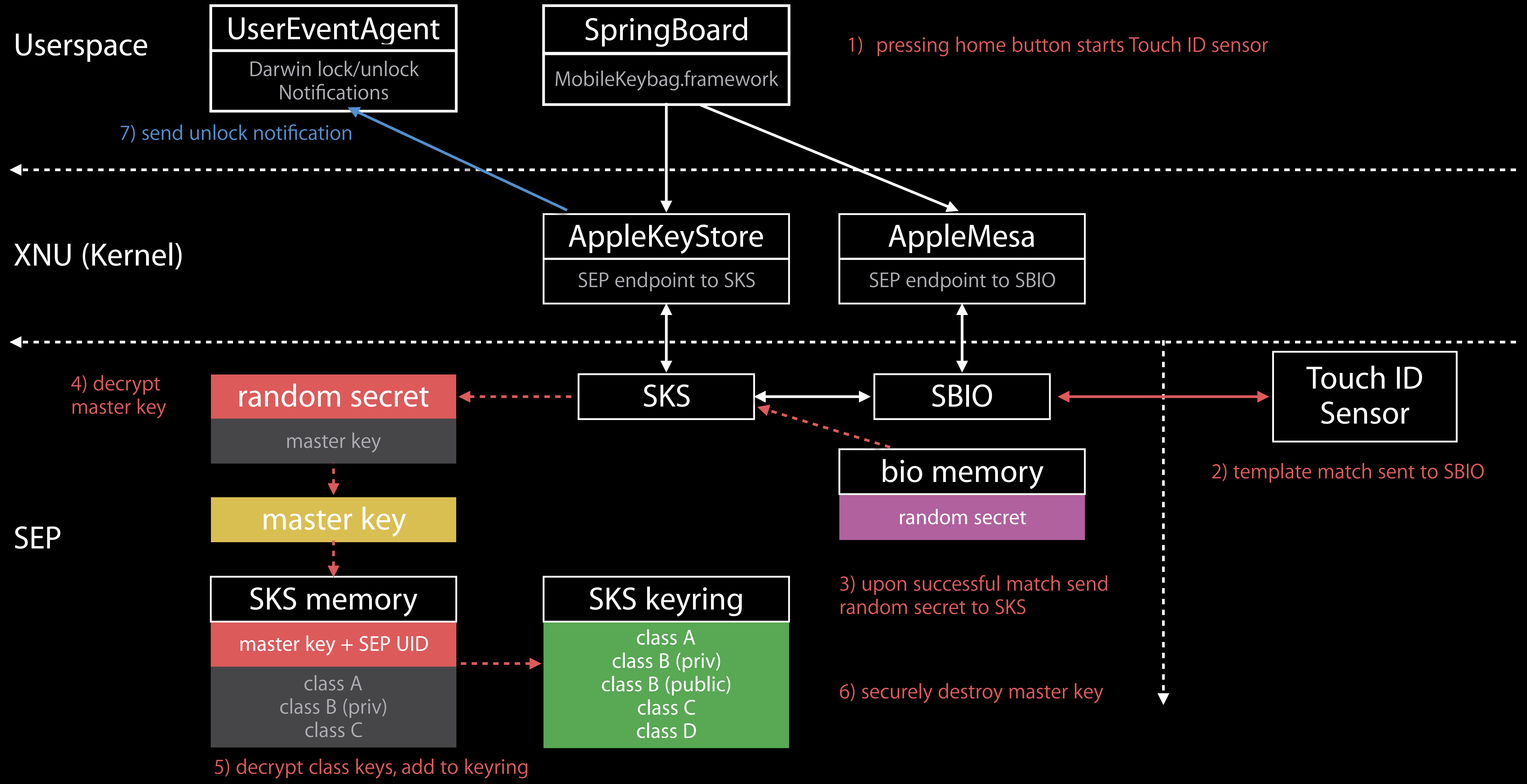

7) keybagd loads system keybag (class D key available)
keybagd
gets prot key from effaceable
loads device keybag into SEP
systembag.kb
/var/keybags/systembag.kb
encrypted with the keybag
prot key
contains the device keybag
6) launchd starts keybagd
Userspace
5) launchd mounts user partition
8) decrypts keybag
with prot key from
effaceable
4) decrypt HFS metadata with media key
HFS
AppleKeyStore
SEP endpoint to SKS
Effaceable
media key
keybag prot key
Class D
XNU (Kernel)
1) kernel boots (system partition)
2) AppleKeyStore loads D key (before user partition is mounted)
3) decrypt class D key, load into keyring
9) keybag loaded into sks memory, class B public loaded into keyring
class D
SEP UID
class D
SKS
SEP
SKS memory
master key + SEP UID
class A
class B (priv)
class C
SKS keyring
class B (public)
class D
10) class keys cannot be decrypted until we get the passcode
11) launchd permits userspace to start loading
boot


1) SpringBoard acquires the passcode
Userspace
UserEventAgent
Darwin lock/unlock Notifications
SpringBoard
MobileKeybag.framework
7) first unlock notification sent
AppleKeyStore
SEP Endpoint to SKS
XNU (Kernel)
bio unlock token only created if bio unlock is enabled steps 4 & 5
2) generate master key
master key
SKS
SBIO
SEP
SKS keyring
class A
class B (priv)
class B (public)
class C
class D
SKS memory
master key + SEP UID
class A
class B (priv)
class C
random secret
master key
SBIO memory
random secret
5) send random secret to SBIO, destroy it in SKS
4) encrypt master key with random secret – this encrypted master key never leaves SKS
6) securely destroy raw master key
3) decrypt class keys, add to keyring
first unlock



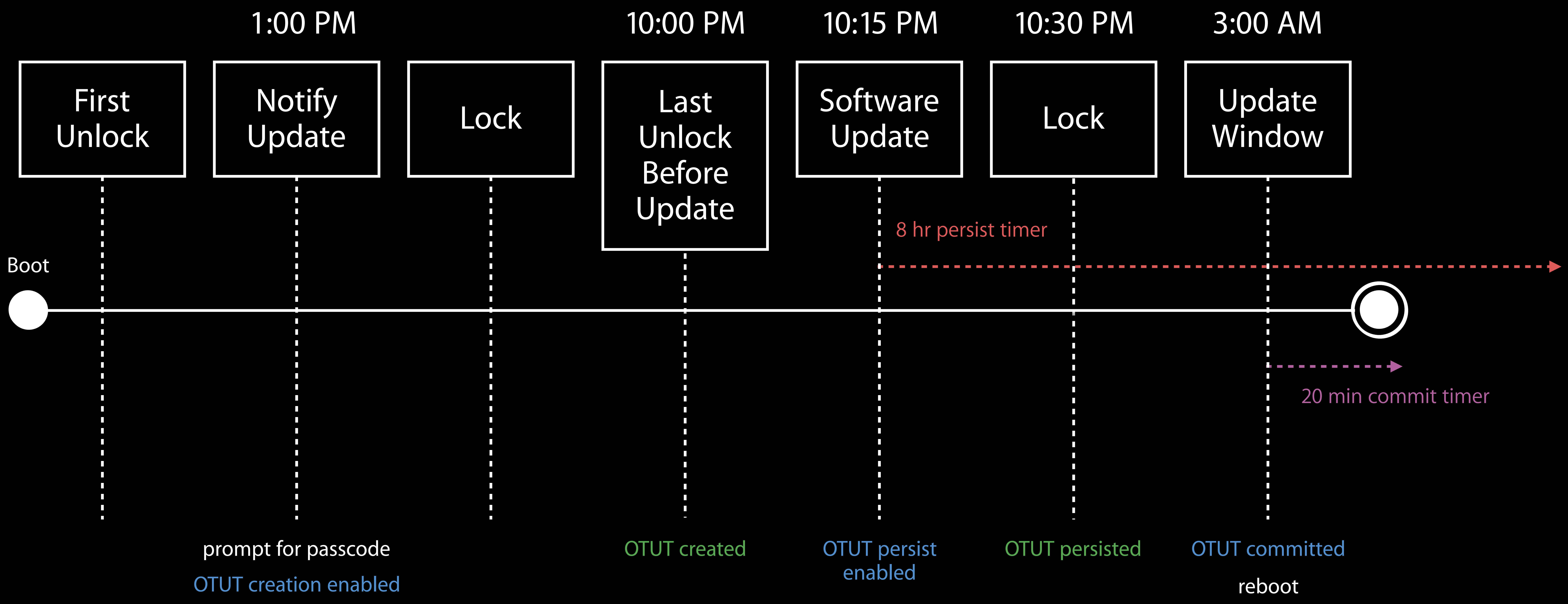
1) device locks
Userspace
UserEventAgent
Darwin lock/unlock Notifications
SpringBoard
MobileKeybag.framework
3) send lock notification
XNU (Kernel)
AppleKeyStore
SEP Endpoint to SKS
SEP
SKS
2) purge class A and class B priv keys
SKS keyring
class B (public)
class C
class D
SKS memory
master key + SEP UID
class A
class B (priv)
class C

lock



Touch ID unlock

Unattended Update—Install Later



SoC Security Mode

Demotion

Production devices can be "demoted" to enable some debugging features like JTAG and loading development software on the AP (but not the SEP)

Requires full OS erase and device explicitly authorized by the personalization server

Forces a different UID on the SEP, no access to existing user data after demotion

SoC mode	AP status	SEP status	SEP UID
Development fused	Development	Development	Development
Production fused	Production	Production	Production
AP demoted	Development	Production	Development

Data Protection

Goals

- User data protected by strong cryptographic master key derived from user passcode
- No offline attack on user passcode—hardware-bound master key derivation
- Hardware keys for master key derivation not directly exposed to any mutable software
- Secure support for alternative unlock mechanisms (Touch ID, Auto Unlock)
- Sidesteps AP attack surface, SEP policy enforced under adversarial AP

Synchronizing Secrets

Synchronizing Secrets

Uses

Passwords and credit card information available on all of a user’s devices

Auto Unlock cryptographic keys shared between Apple Watch and Mac

HomeKit cryptographic keys available on all devices

Synchronizing Secrets

Traditional approaches

Wrap user secrets with strong random key

- User has to take care of a printed “sock drawer key” and enter it on each device
- If printed key is lost, losing devices means loss of secrets

Wrap user secrets with KDF-derived key from their password

- Account provider backend is privileged, can intercept or brute-force account password
- If user resets their account password, must prompt for old password to recover secrets
- Anyone else in possession of wrapped user secrets can launch a brute-force attack

“Humans are incapable of securely storing high-quality cryptographic keys, and they have unacceptable speed and accuracy when performing cryptographic operations.”

C. Kaufman, R. Perlman, M. Speciner

Synchronizing Secrets

Goals—Inspired by Data Protection

Selected user secrets available on all of the user's devices

Synchronization protected with strong cryptographic keys

User can recover secrets even if they lose all their devices

User secrets not exposed to Apple

No brute-force—backend not in a privileged position

iCloud Keychain

Approach

Each device locally generates iCloud Keychain synchronization key pair

User explicitly approves new devices joining the sync circle from a device already in it

Sync circle uses Apple cloud backend for storage and message passing

- No data is accessible to Apple
- Backend not in a privileged position since key pair is strong and random

What if all devices are lost, or need to configure new device without access to old one?

iCloud Keychain Backup

Premise

New credential—iCloud Security Code (commonly device passcode), unknown to Apple

Generate strong random backup (“escrow”) key, wrap with KDF-derived key from iCSC

Back up copy of iCloud Keychain secrets to the Apple cloud, encrypted with escrow key

Send wrapped escrow key to Apple

In case of device loss or new device, user can recover secrets with their iCloud password and the iCSC

Synchronizing Secrets

Goals—Inspired by Data Protection

- ✓ Selected user secrets (passwords, credit cards, …) available on all of the user's devices
- ✓ Synchronization protected with strong cryptographic keys
- ✓ User can recover secrets even if they lose all their devices
- ✓ User secrets not exposed to Apple

Backend not in a privileged position to brute-force keys protecting user secrets

iCloud Keychain Backup

Backend attack surface

In naive implementation, backend could brute force the iCSC to access escrow key

Just like with SEP, need to enforce policy over escrow key

No brute–force—Want hard limit on escrow recovery attempts under adversarial cloud

What if escrow key unwrapping only took place in Hardware Security Modules?

Cloud Key Vault

Overview

HSMs running custom secure code connected to Apple cloud

Key vault fleet operates its own CA, private key never leaves the hardware

Each iOS device hardcodes key vault fleet CA cert

Cloud Key Vault

Unit

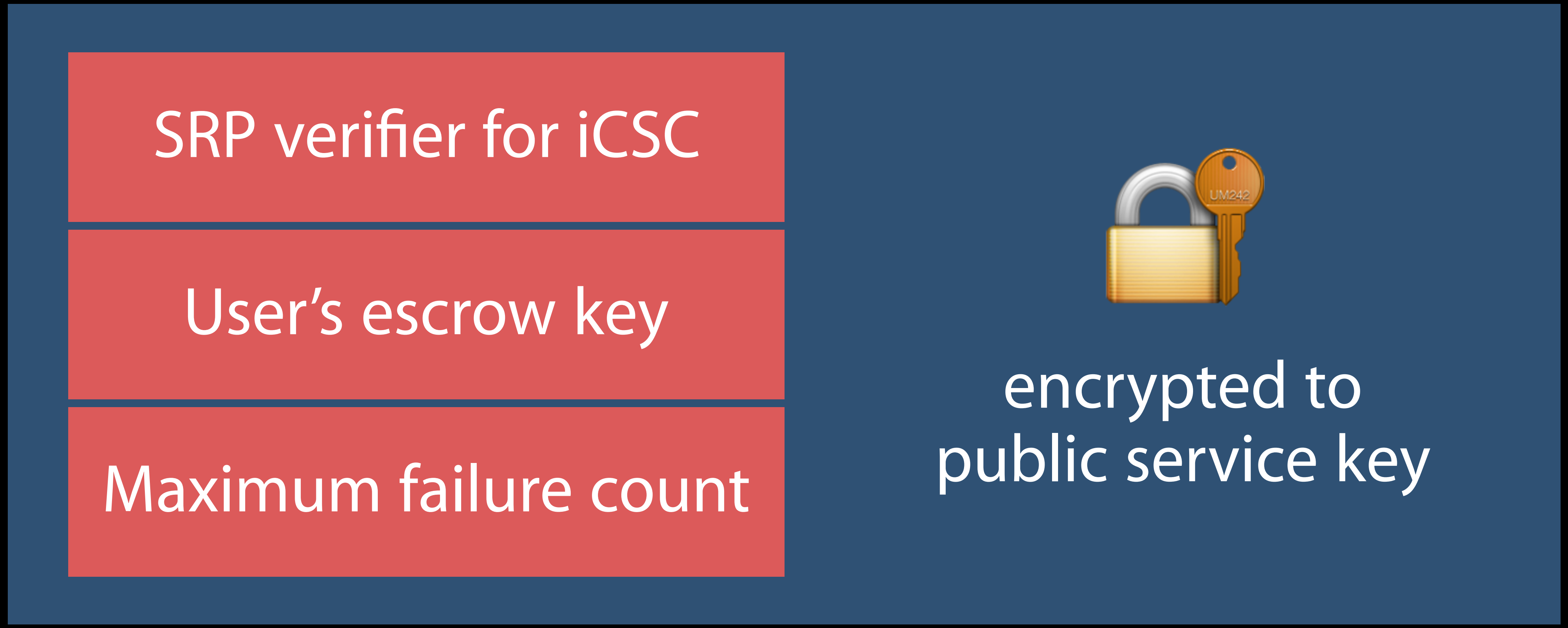
Cloud Key Vault

HSM keys

Key	Description
CSCIK	RSA-2048, allows signing custom secure code to run on the HSM
AK	256-bit for HMAC-SHA-256, to authenticate messages between vault units
CA	RSA-2048, to certify service key (SK)
SK	RSA-2048, allows unwrapping escrow records

Cloud Key Vault

Escrow record generated on iOS device



Cloud Key Vault

Understanding the design

A kind of SEP Data Protection approach for escrow records

Vault service private key material not available to mutable software, just like SEP UID key

User attempting escrow recovery sends previous escrow record, establishes SRP session

Vault unwraps escrow record, SRP with user device against iCSC verifier in the record, return escrow key if successful

If SRP fails due to incorrect iCSC, vault unit bumps a secure counter

- If maximum failure count (10) is exceeded for the record, record is marked terminal

Cloud Key Vault

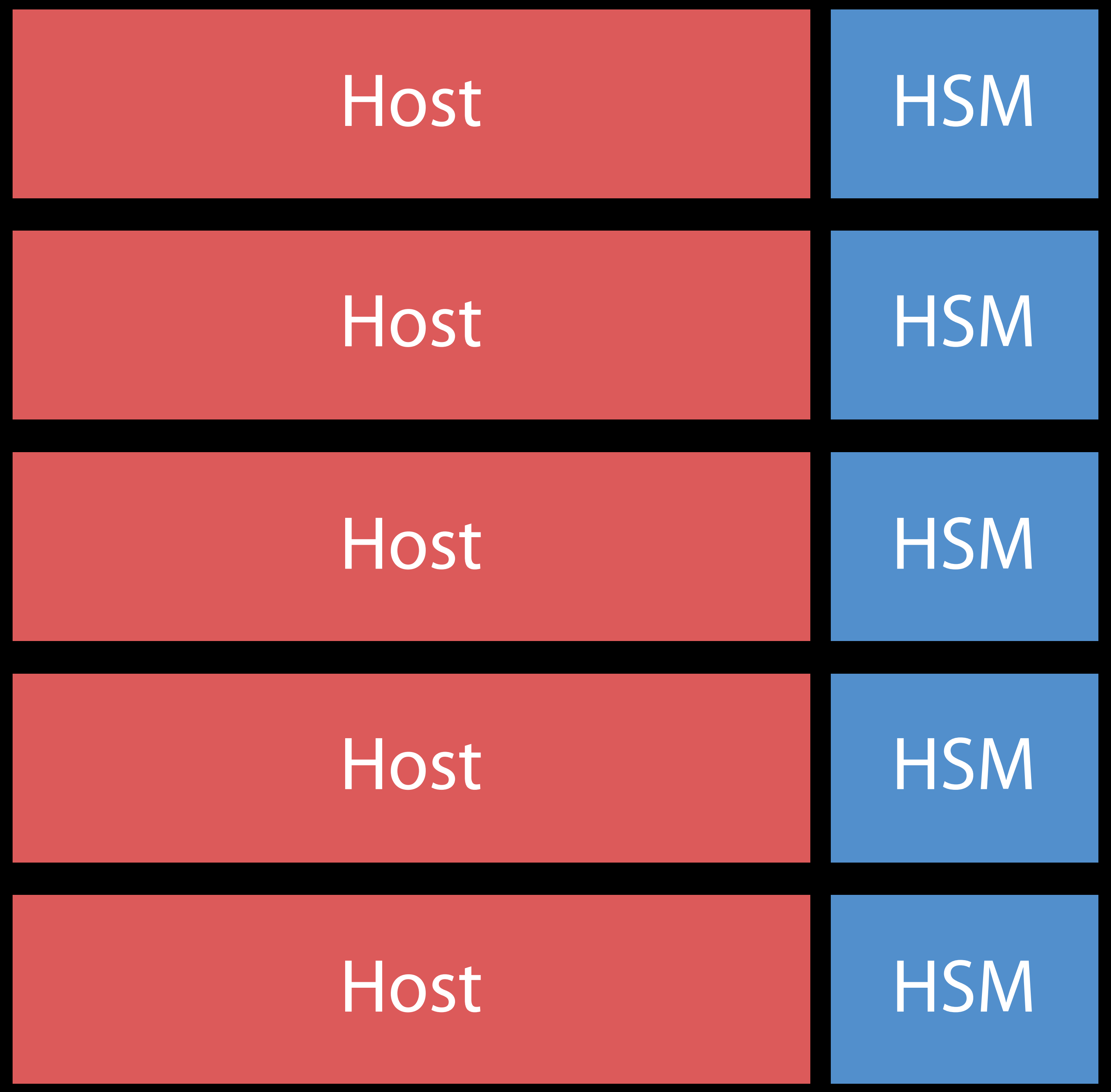
Redundancy and attack surface

Users can’t escrow to only a single vault unit, need redundancy

Escrowing to multiple units means multiplying the maximum failure count providing more opportunity for brute force attack

Cloud Key Vault

Club



Cloud Key Vault

Club

Group of five vault units that share a single SK—Service Key

User generates escrow record for a particular club, certified by the fleet CA

Solves redundancy, but not the brute force limiting problem

Club members would still be subject to partitioning attacks

Cloud Key Vault

Quorum commit

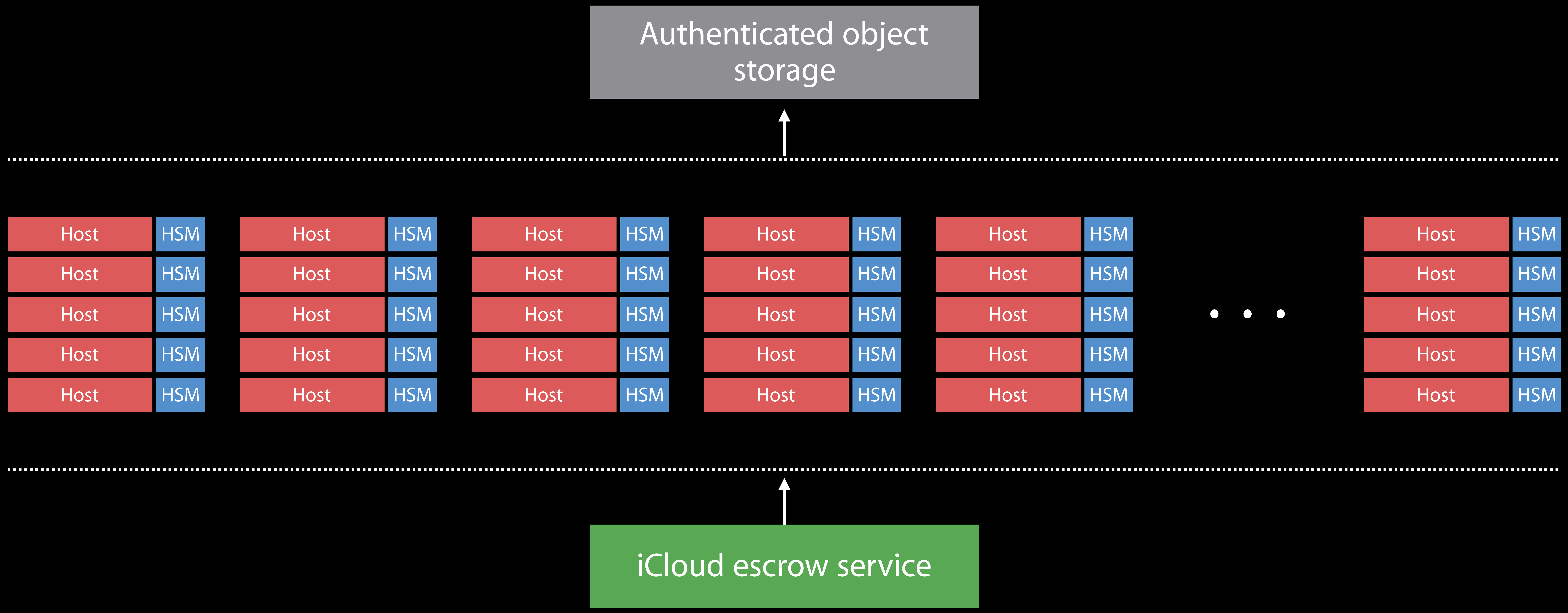
Each club member maintains its own failure count for each escrow record

Escrow recovery prompts a vote, majority quorum required to proceed

Provides redundancy and breaks membership partitioning attacks

Cloud Key Vault

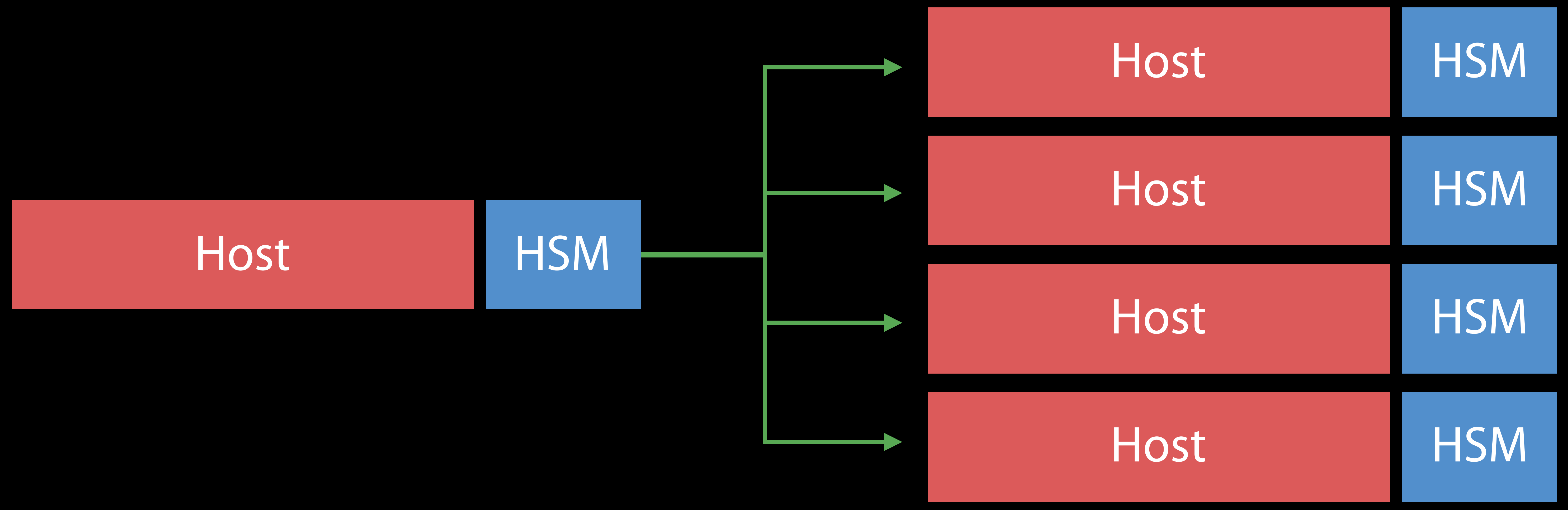
Fleet



Cloud Key Vault

Escrow Recovery Transaction

1. Proposal
2. Vote
3. Schedule
4. Ack
5. Perform
6. Confirm

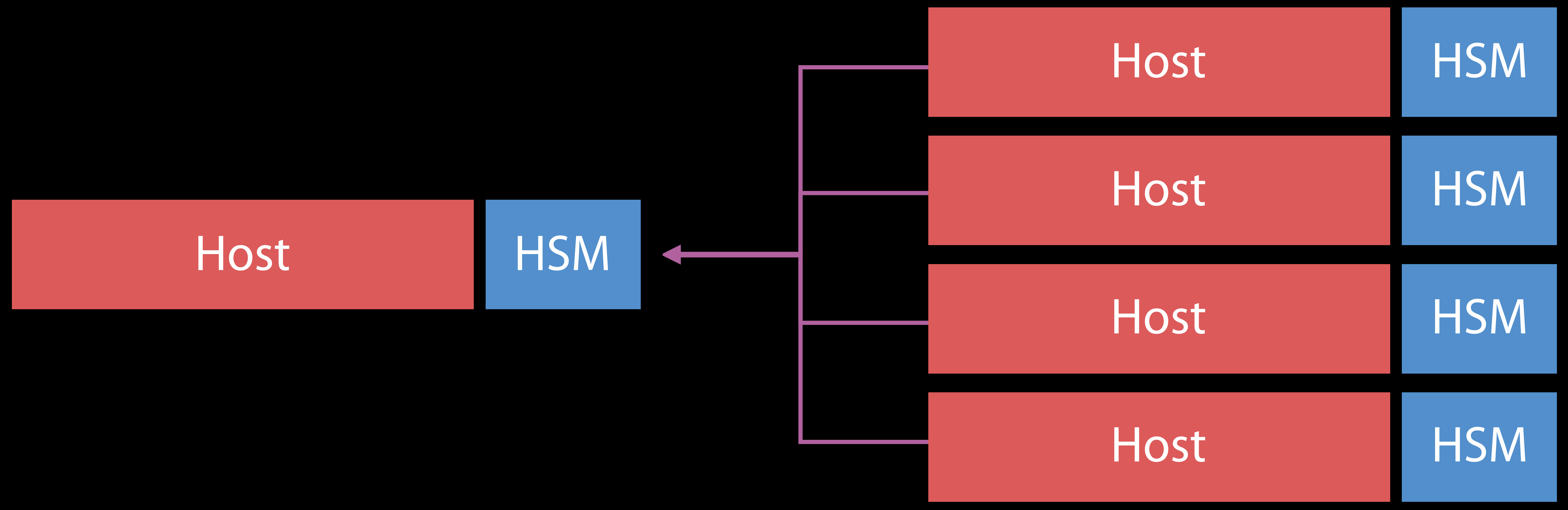


"I propose an update. Please give me your failure count for this record."

Cloud Key Vault

Escrow Recovery Transaction

1. Proposal
2. Vote
3. Schedule
4. Ack
5. Perform
6. Confirm

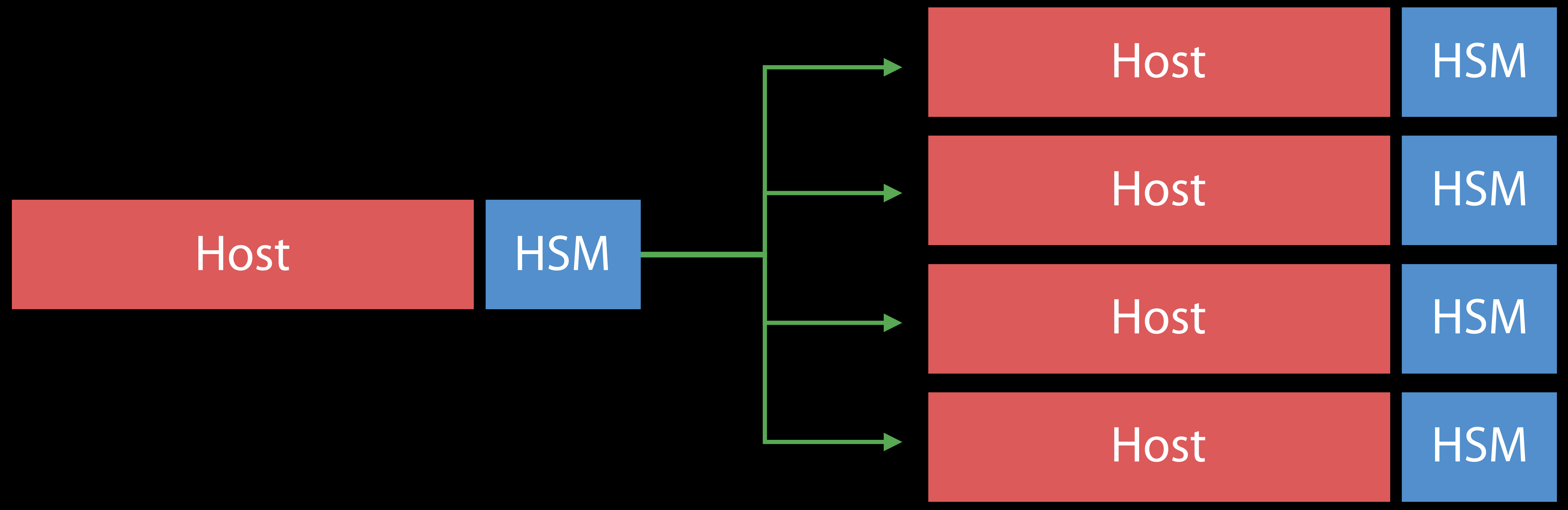


"My counter is 4. I vote yes to update since I'm not in another transaction."

Cloud Key Vault

Escrow Recovery Transaction

1. Proposal
2. Vote
3. Schedule
4. Ack
5. Perform
6. Confirm

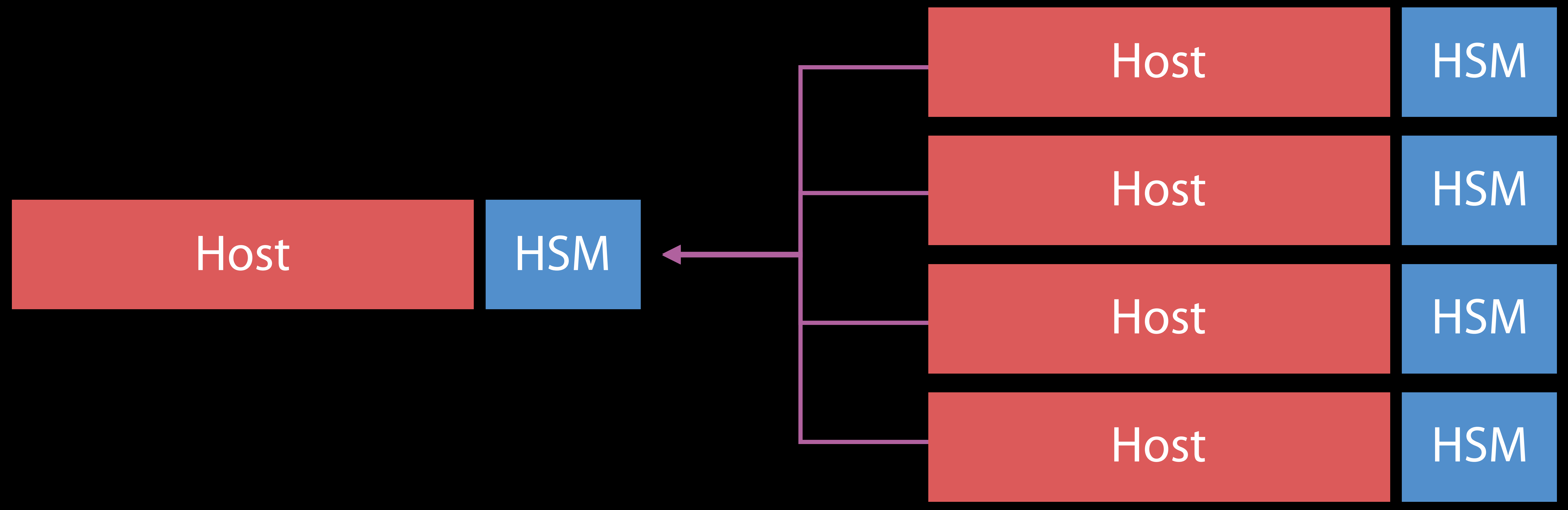


"We have majority quorum and no one's record is terminal, prepare to update failure count to 5."

Cloud Key Vault

Escrow Recovery Transaction

1. Proposal
2. Vote
3. Schedule
4. Ack
5. Perform
6. Confirm

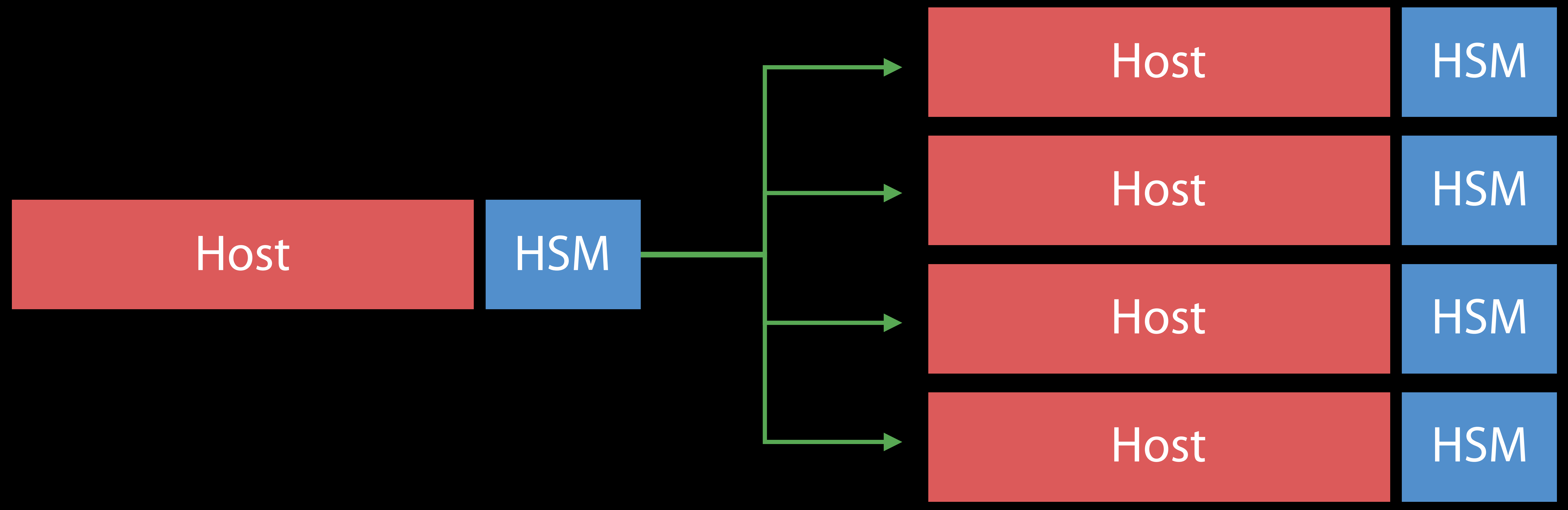


"OK, I've verified majority quorum and stand ready to increase failure count to 5."

Cloud Key Vault

Escrow Recovery Transaction

1. Proposal
2. Vote
3. Schedule
4. Ack
5. Perform
6. Confirm

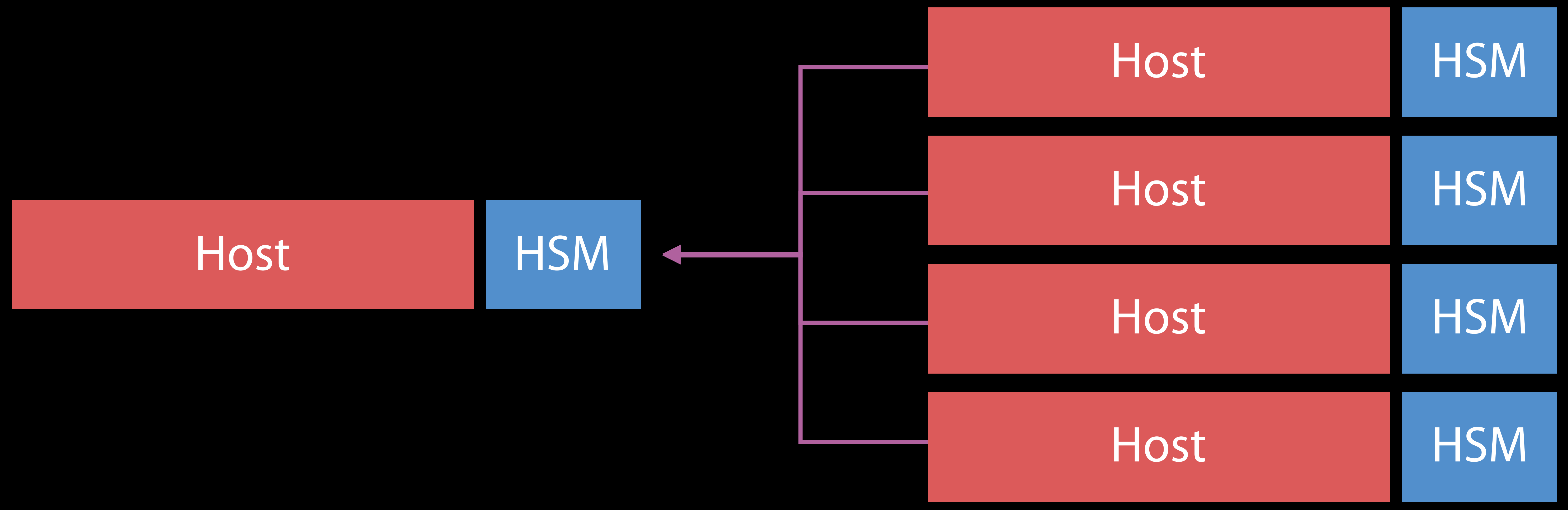


"Please proceed with increasing failure count to 5 for this record."

Cloud Key Vault

Escrow Recovery Transaction

1. Proposal
2. Vote
3. Schedule
4. Ack
5. Perform
6. Confirm



“OK, my failure count is now 5 for this record.”

Cloud Key Vault

Who watches the watchers?

A given vault fleet runs code signed by its CSCIK (custom secure code signing key)

Use of this signing key requires a quorum of physical vault admin smart cards

Admin cards are created in a secure ceremony when fleet is commissioned, stored in separate physical safes in custody of three different organizations at Apple in tamper-proof evidence bags

Cloud Key Vault

Who watches the watchers?

If someone got their hands on all the admin cards…

Couldn’t they sign a malicious custom secure code image that can brute-force iCSC for arbitrary escrow records?

No.

Cloud Key Vault

Before a fleet goes into production

Members of all three admin card-carrying organizations meet in a secure facility

Cross-check serial numbers on evidence bags and on cards

Attestations

- Card carriers present at creation of the admin cards
- No other cards were created
- Evidence bags remained sealed since creation
- Cards present today are the ones originally created

Physical One-Way Hash Function

(We Run the Cards Through a Blender)

Cloud Key Vault

Final attestation

All admin cards originally created are now destroyed

The cards were not used to sign any other custom secure code that can be loaded

No other mechanism is known for changing custom secure code or loading new code

This enables us to make the unequivocal commitment that user secrets are not exposed to Apple

Some News

Apple Security Bounty

Apple Security Bounty

Great help from researchers in improving iOS security all along

iOS security mechanisms continue to get stronger

Feedback from Apple Red Team and external researchers: as iOS security has advanced, increasingly difficult to find the most critical security issues

Apple Security Bounty

Rewards researchers who share critical issues with Apple

We make it a priority to resolve confirmed issues as quickly as possible

Provide public recognition, unless asked otherwise

Initial Categories

Category	Max. Payment
Secure boot firmware components	$200,000
Extraction of confidential material protected by the Secure Enclave Processor	$100,000
Execution of arbitrary code with kernel privileges	$50,000
Unauthorized access to iCloud account data on Apple servers	$50,000
Access from a sandboxed process to user data outside of that sandbox	$25,000

Apple Security Bounty

Payments

We require a clear report and working proof of concept

Vulnerability must affect latest shipping iOS, and where relevant, latest hardware

Exact payment amount determined after review by engineering team, criteria include novelty and likelihood of exposure/degree of user interaction required

Researcher can elect to donate reward to charity of their choice, Apple will consider matching 1:1

Apple Security Bounty

Few dozen initially invited researchers

If vulnerabilities that would be covered under the program are submitted by researchers outside of the program, we will review the submission and, if the work merits it, invite researcher into the program and reward the vulnerability

September

Thank You!

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