ESPRESSIF DevCon24

Trusted Execution Environment (TEE) on ESP32-C6

Enhanced Security for RISC-V SoCs

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CONTENTS

Speaker Intro

We are a part of the Security Team, and we work on building and maintaining the Security features supported in ESP-IDF and elsewhere.

Among other things, we work on support for cryptographic peripherals such as AES, RSA, Key Manager, flash encryption and secure boot.

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Senior Software Engineer

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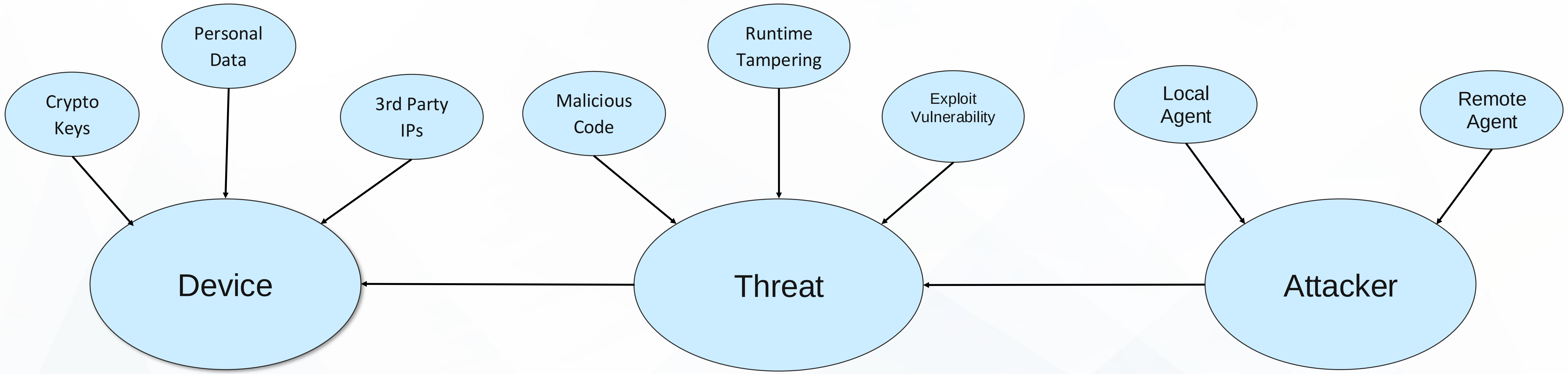
Embedded Software Engineer

01 Trusted Execution Environment (TEE)

Introduction: The Why and the What

Introduction: Why TEE?

A device's Security Model is derived from its Threat Model



Introduction: Why TEE?

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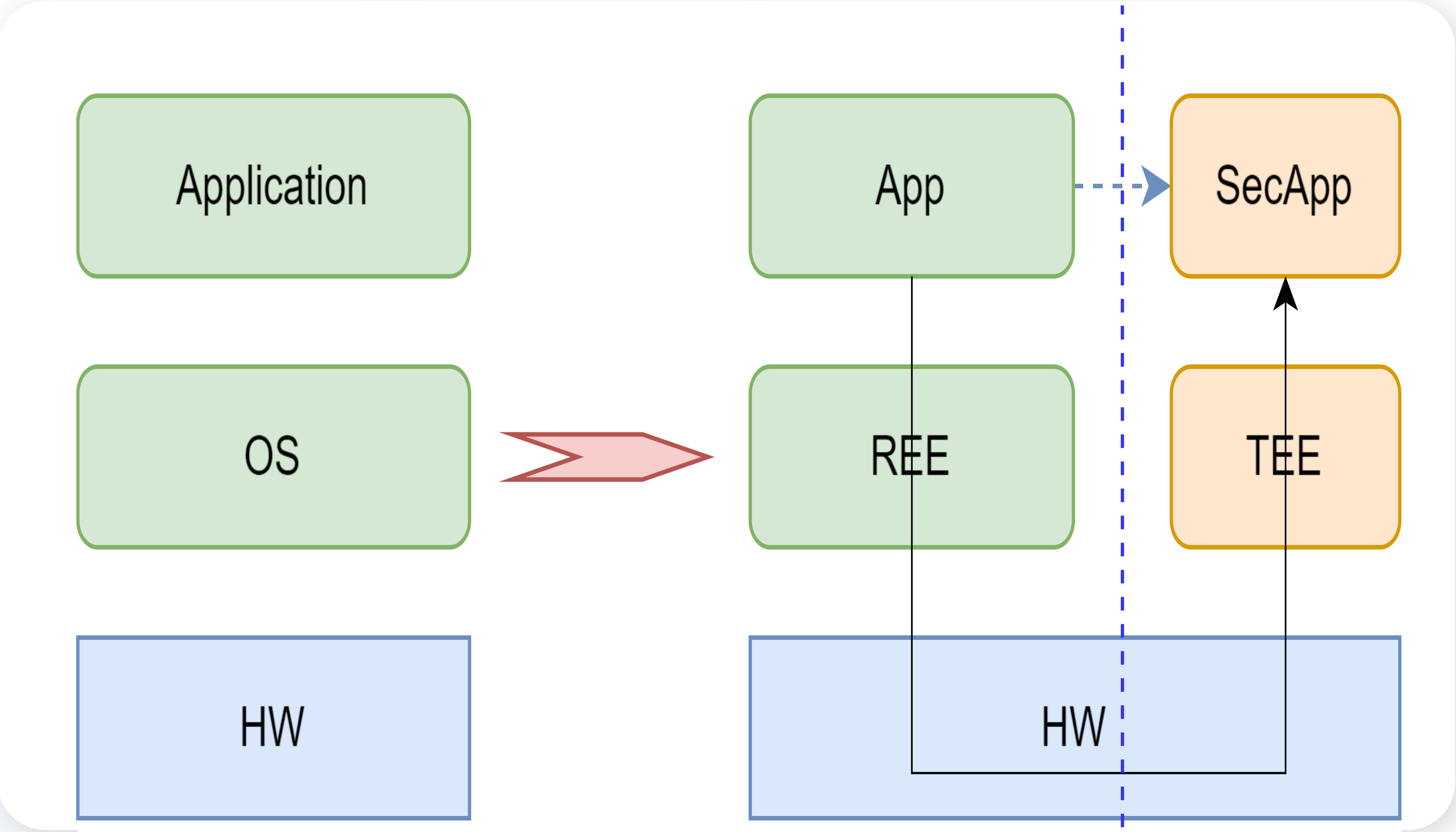
> A device's Security Model is derived from its Threat Model

- Threat Mitigation
  - Reduce the attack surface by isolating security-sensitive system assets from the rest of the system
  - Confidentiality of the data, Authenticity and Integrity of execution environment
  - No primary focus on invasive or non-invasive hardware attacks

Introduction - What is TEE

H/W-Defined, S/W-Implemented Isolation Mechanism

- Isolates security-sensitive hardware and software resources from the rest of the system, forming a parallel execution environment (TEE)
- TEE provides runtime security for these hardware and software resources, protecting them from the rest of the system
- Establishes a clear and well-defined interface between the two environments

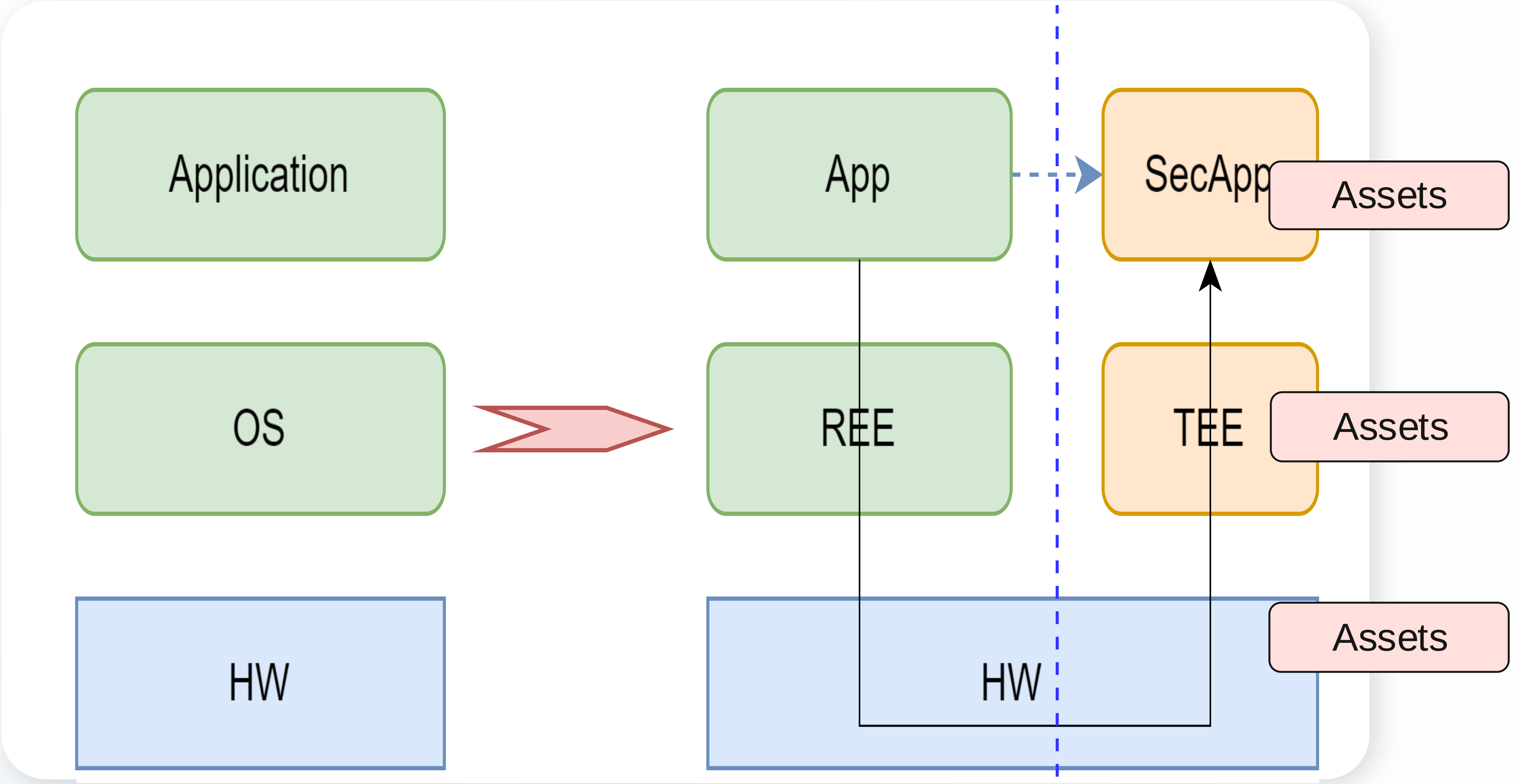


Introduction - What is TEE

Real world example

Assets : Cryptographic key, Secure Application, Crypto HW

- Crypto key generate or provision
- Use in challenge response protocol
- Secure communication

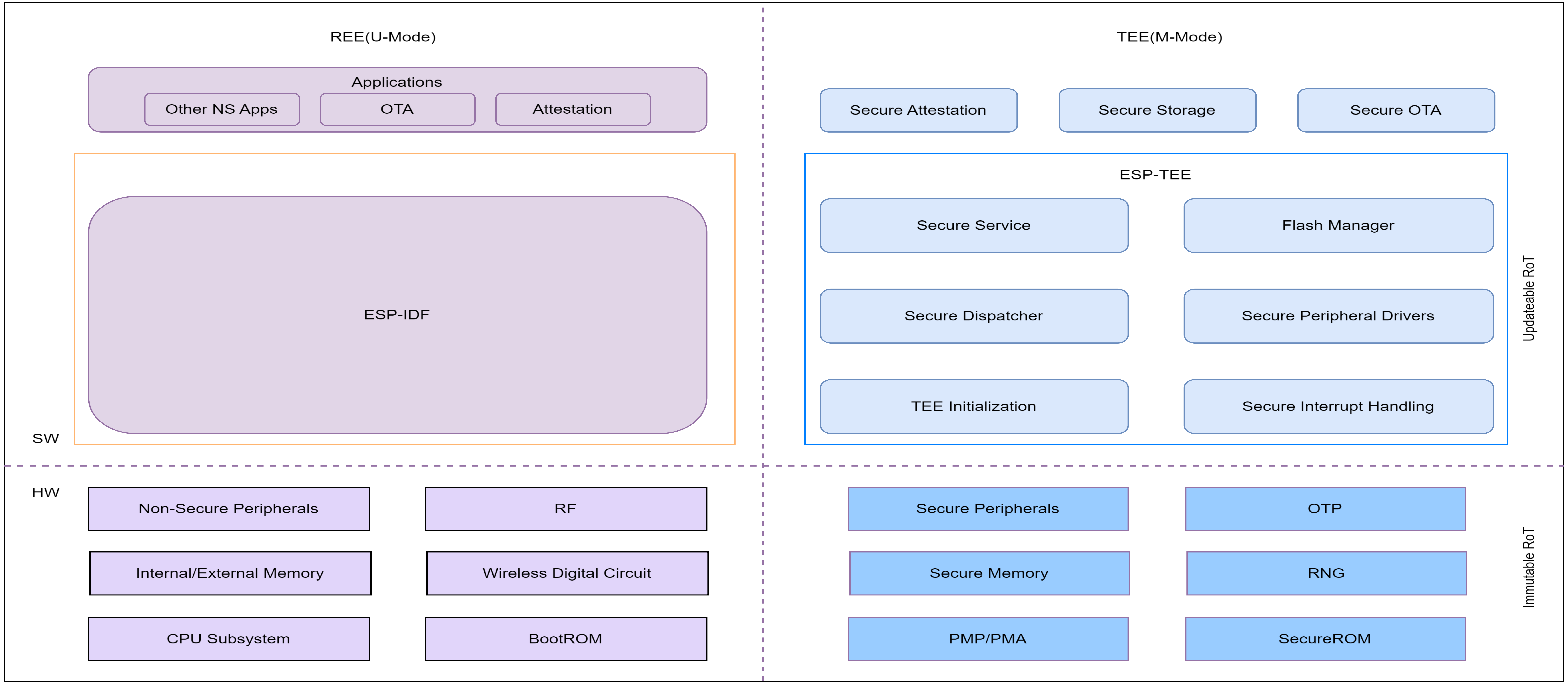


- Enhance system security, implementation completely defined by system requirement.
- Requires for various certification and regulation.

02 ESP-TEE: Architecture

TEE on the ESP32-C6 SoCs

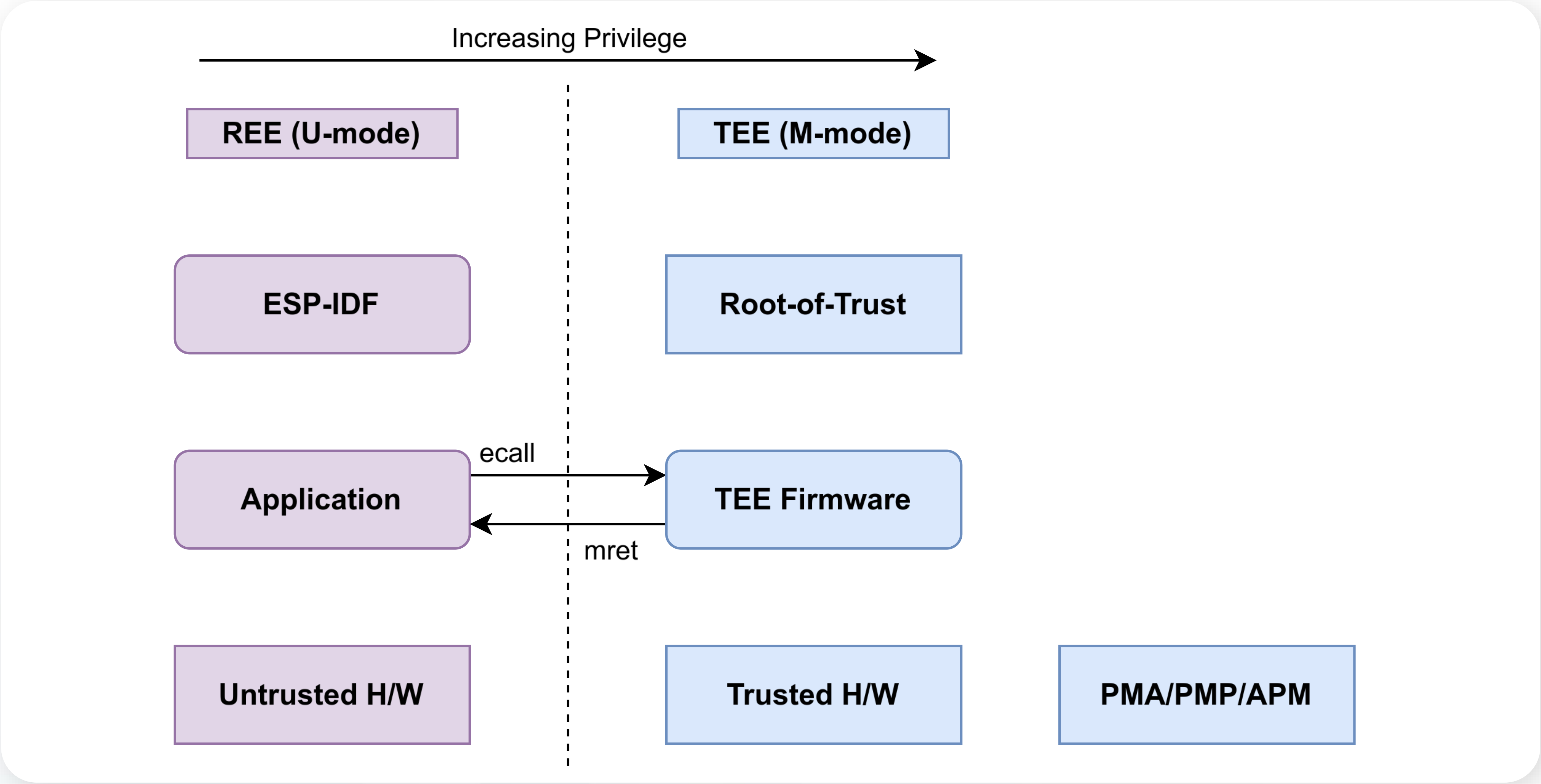
TEE on ESP SoCs: ESP-TEE



ESP-TEE: Architecture

Hardware Components (Immutable Root-of-Trust)

- ESP-TEE uses RISC-V ISA security features to achieve TEE/REE isolation
- Requires RISC-V M and U Privilege modes
  - M-Mode: Higher privilege mode host TEE firmware
  - U-Mode: Lower privilege mode host ESP-IDF and untrusted HW
- PMP/PMA to manage physical memory access
  - Default M –Mode have full access and U-Mode none
  - M-Mode configure PMP and PMA for selective memory access by U-Mode
- PMS: APM+TEE(hardware peripheral)
  - Complement PMP/PMA to manage the physical memory
- Root Of Trust: ROM, eFuse, Crypto HW, Isolation HW (APM), Secure memory



ESP-TEE: Architecture

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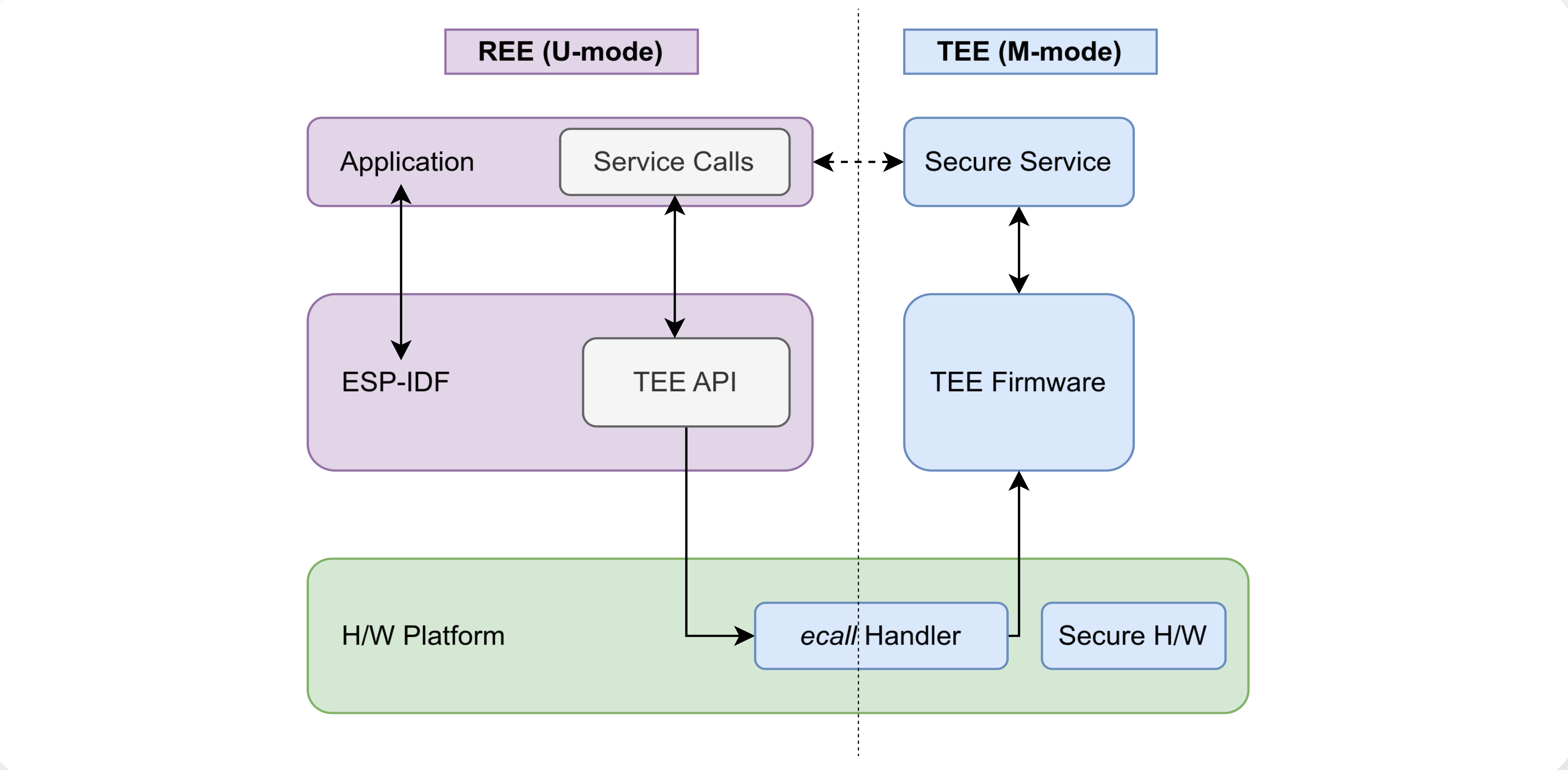
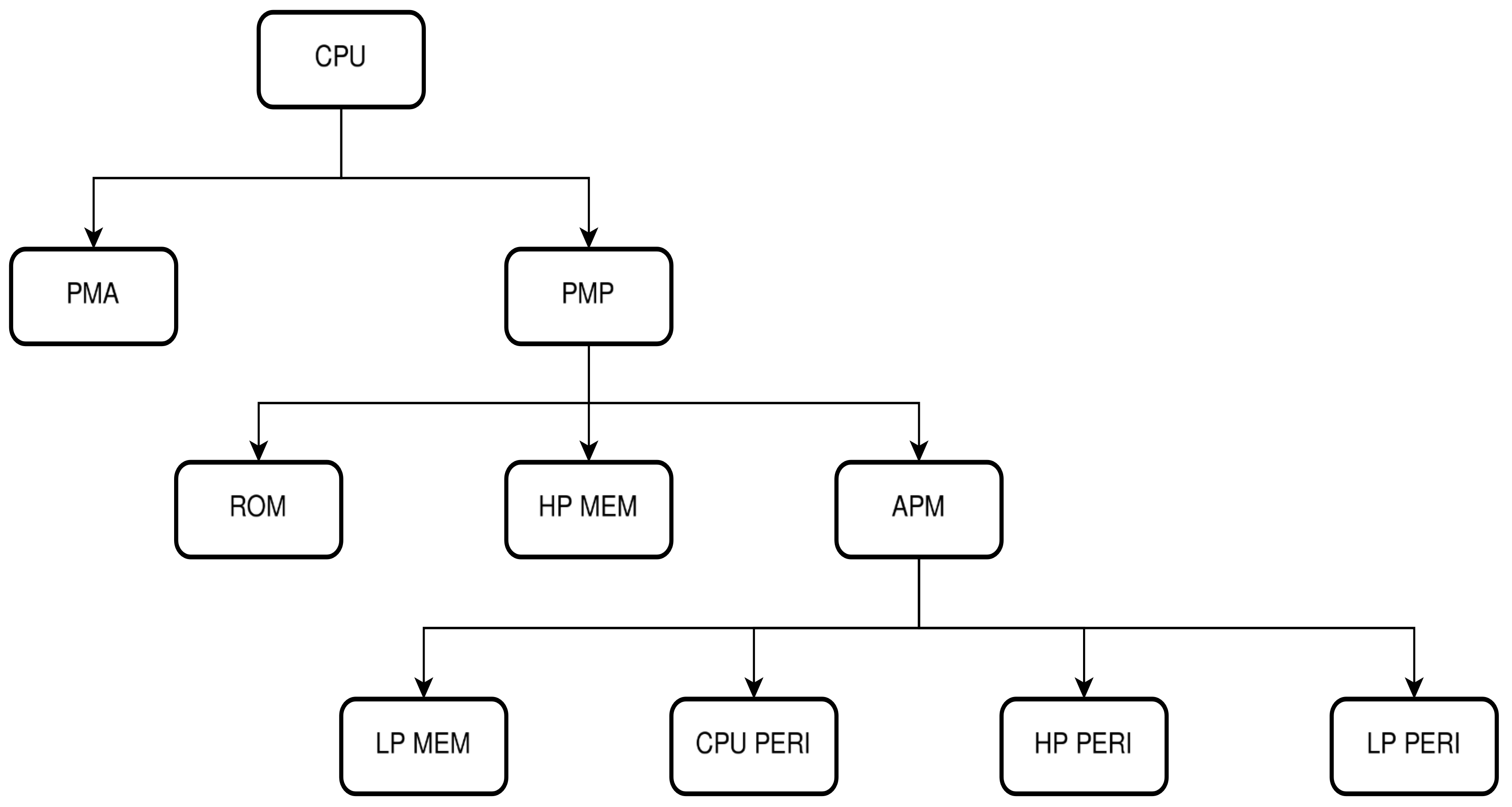
Software Components (Updatable Root-of-Trust)

- TEE firmware include various internal components responsible for -
  - Secure configuration to achieve isolation
  - TEE initialization for secure services, interrupt and exception handling
- Includes Basic Secure Services, Crypto API and other secure HW abstraction which are used to implements use case based Secure Services (Attestation, OTA, Secure Storage etc.)
- Provide TEE interface API to REE to invoke secure service into TEE
- Uses RISC-V Environment call (ecall) to transition between TEE and REE



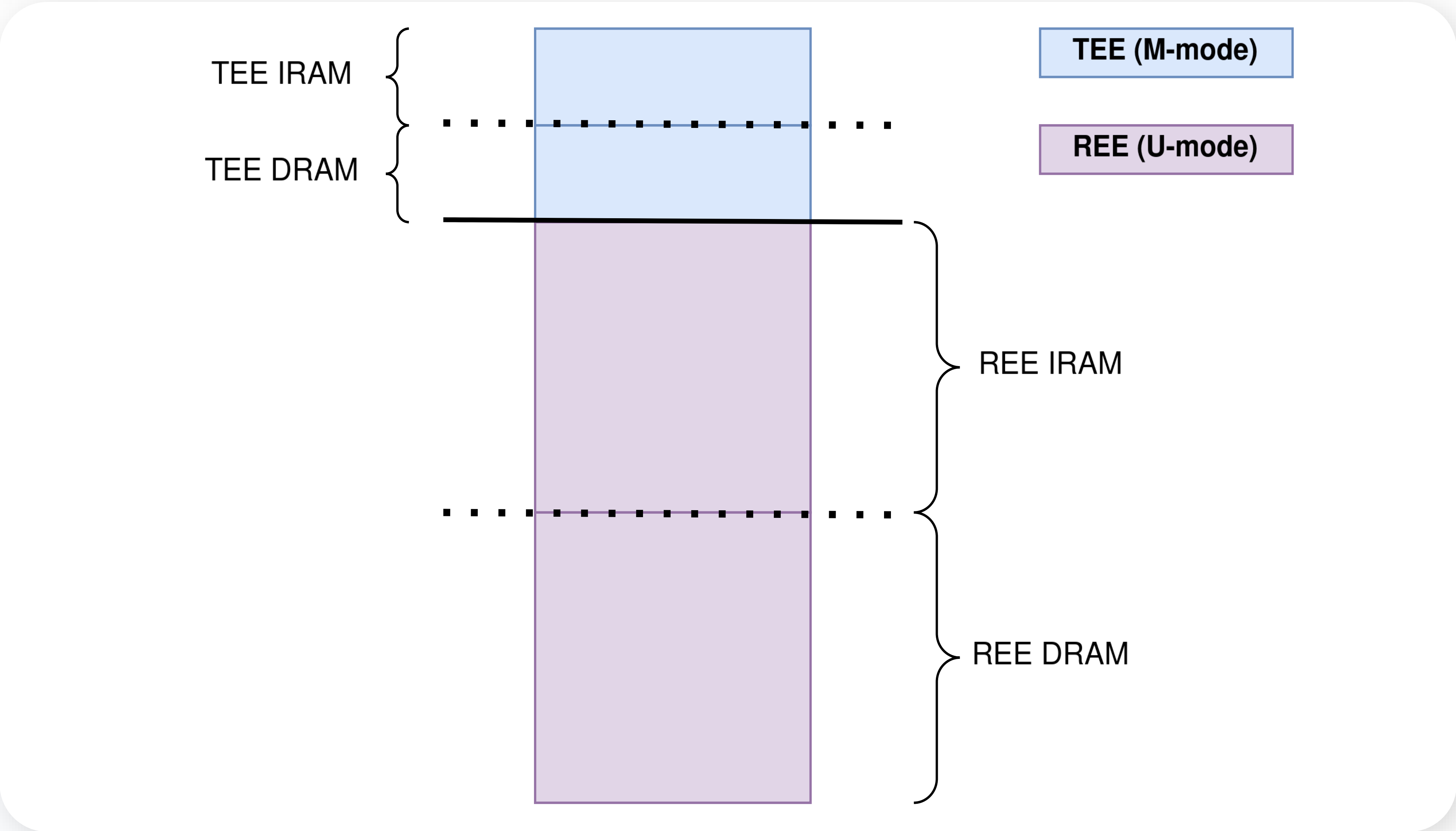
ESP-TEE: Architecture



Resource Isolation

- Isolation between TEE and REE is established during TEE initialization.
- RISC-V primitives like PMP, PMA, and proprietary hardware peripheral APM are used for this isolation.
- PMP, PMA configuration and the APM peripheral (protected by PMP) are modifiable only in M-Mode.
- All configurations are locked and remain so until the next reset.

ESP-TEE: Architecture

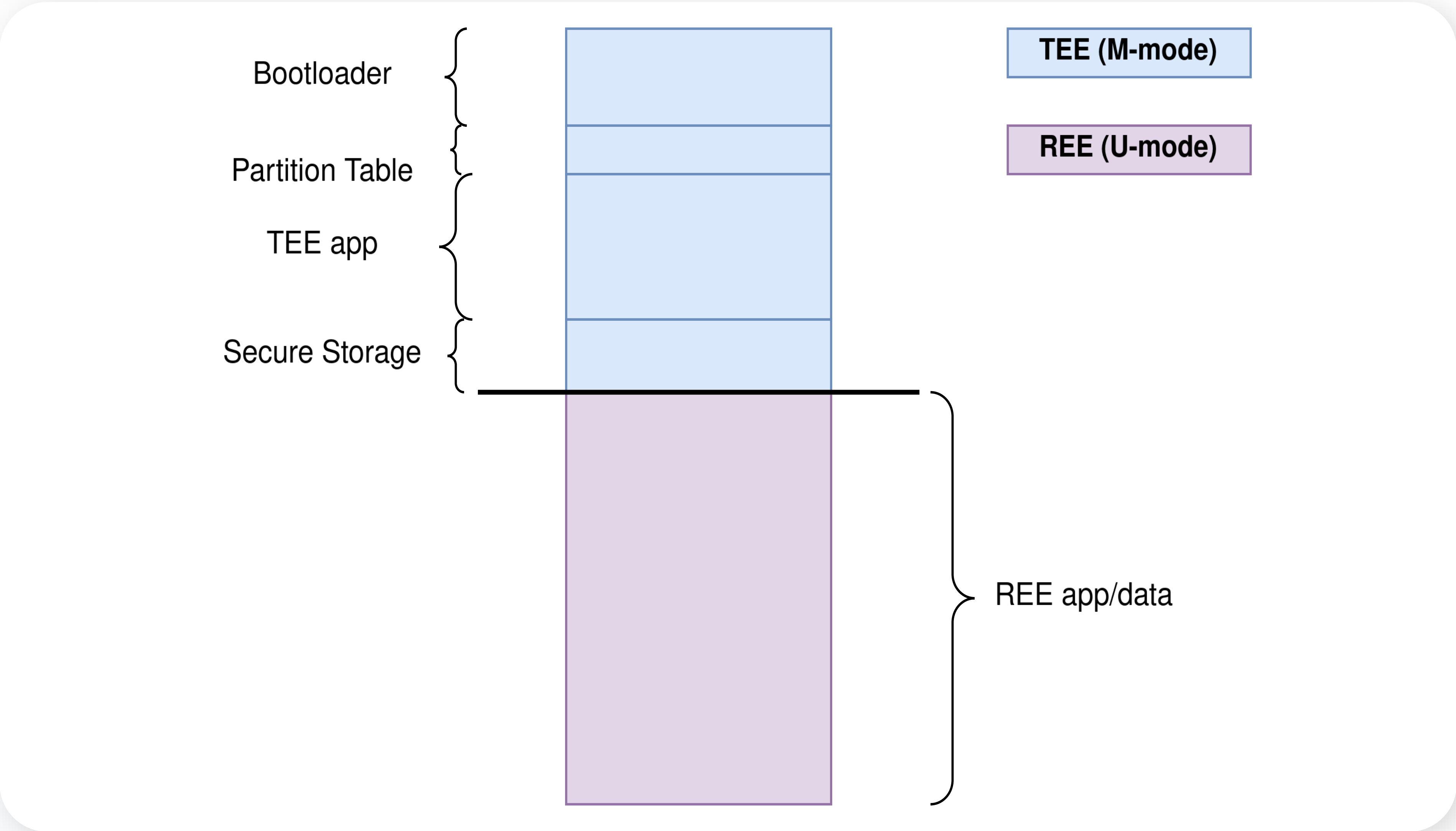


Internal SRAM

Internal Memory (SRAM)

- A memory region is reserved for the TEE starting from the beginning of the HP SRAM
- Permission management is done by PMP for all regions (TEE I/DRAM and REE I/DRAM)
- TEE region is further divided into IRAM (text – RX) and DRAM (data – RW) sections using PMA

ESP-TEE: Architecture



External Flash

External Memory (Flash)

- Designated partitions in the external flash are reserved for the TEE – XIP execution, secure storage, and OTA data
- Access through cache protected using PMP
- Physical Access protected using APM

Peripherals

- AES, SHA, eFuse and Interrupt Controller are protected from REE access using APM

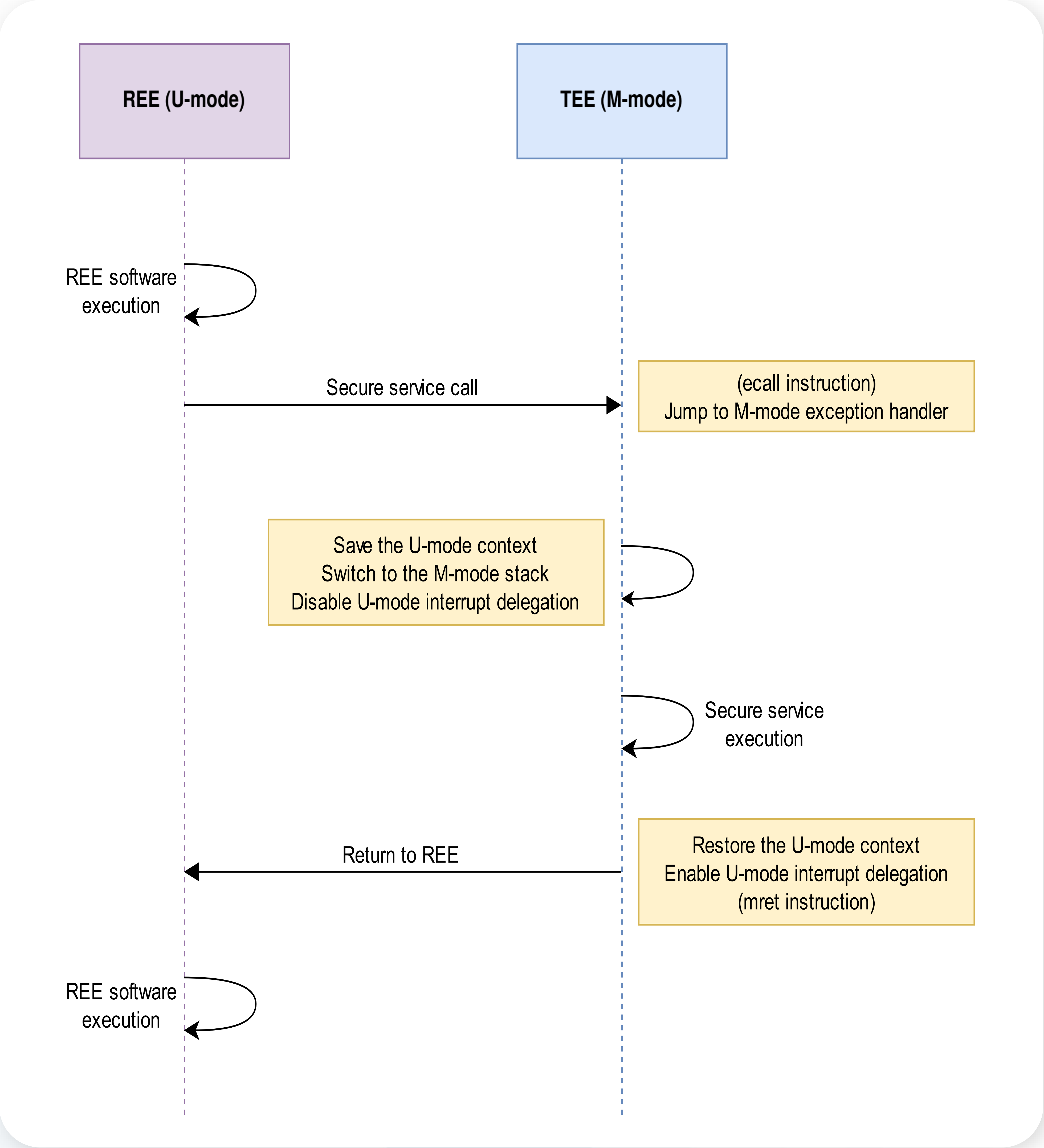
03

ESP-TEE: Internals

TEE Firmware and Secure Services

ESP-TEE: Secure Services

- Secure Service Call Table
  - Indexed list of all secure services provided by TEE – shared with the REE
- Service Dispatcher
  - Entry point to the TEE for any secure service call from REE
  - Parses the input arguments and passes execution control to the appropriate service



ESP-TEE: Secure Services

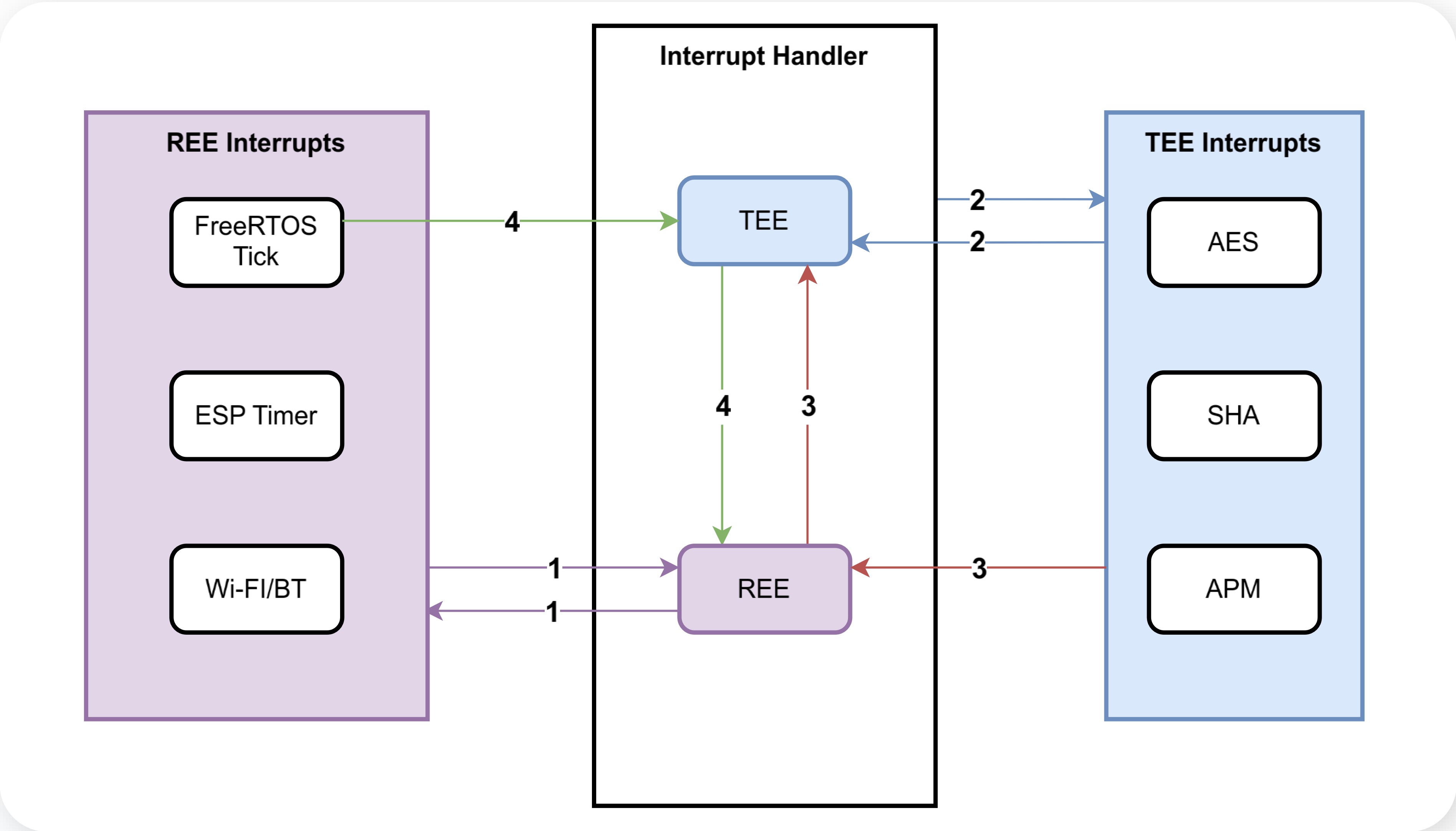
ESP-IDF Secure Services

- Basic secure services included in the TEE firmware, providing routine functionalities to the REE
- E.g., CryptoAPI services (AES/SHA), interrupt matrix and eFuse access

Custom Secure Services

- Optional secure services included as configurable TEE features
- Users can also define their own services as required
- E.g., Secure Storage, Secure OTA, and Attestation (included by default with ESP-TEE)

ESP-TEE: Interrupts

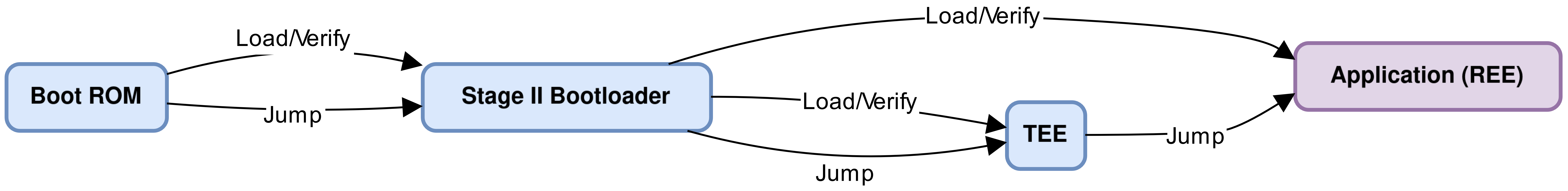


Interrupt Handling

- Separate vector tables for TEE (`mtvec`) and REE (`utvec`)
- Secure interrupt sources are protected from REE
- REE interrupts are delegated to REE when CPU is in REE (`mideleg`)
- Four interrupt handling scenarios
    1. REE interrupts in REE
    2. TEE interrupts in TEE
    3. TEE interrupts in REE
    4. REE interrupts in TEE

ESP-TEE: Boot Sequence

- After a reset, the Boot ROM loads the stage II bootloader, which then loads the TEE and application images from the boot device.
- Control is passed to the TEE, which sets up memory, interrupts, and peripheral access, before switching to the REE in U-mode to run the application.



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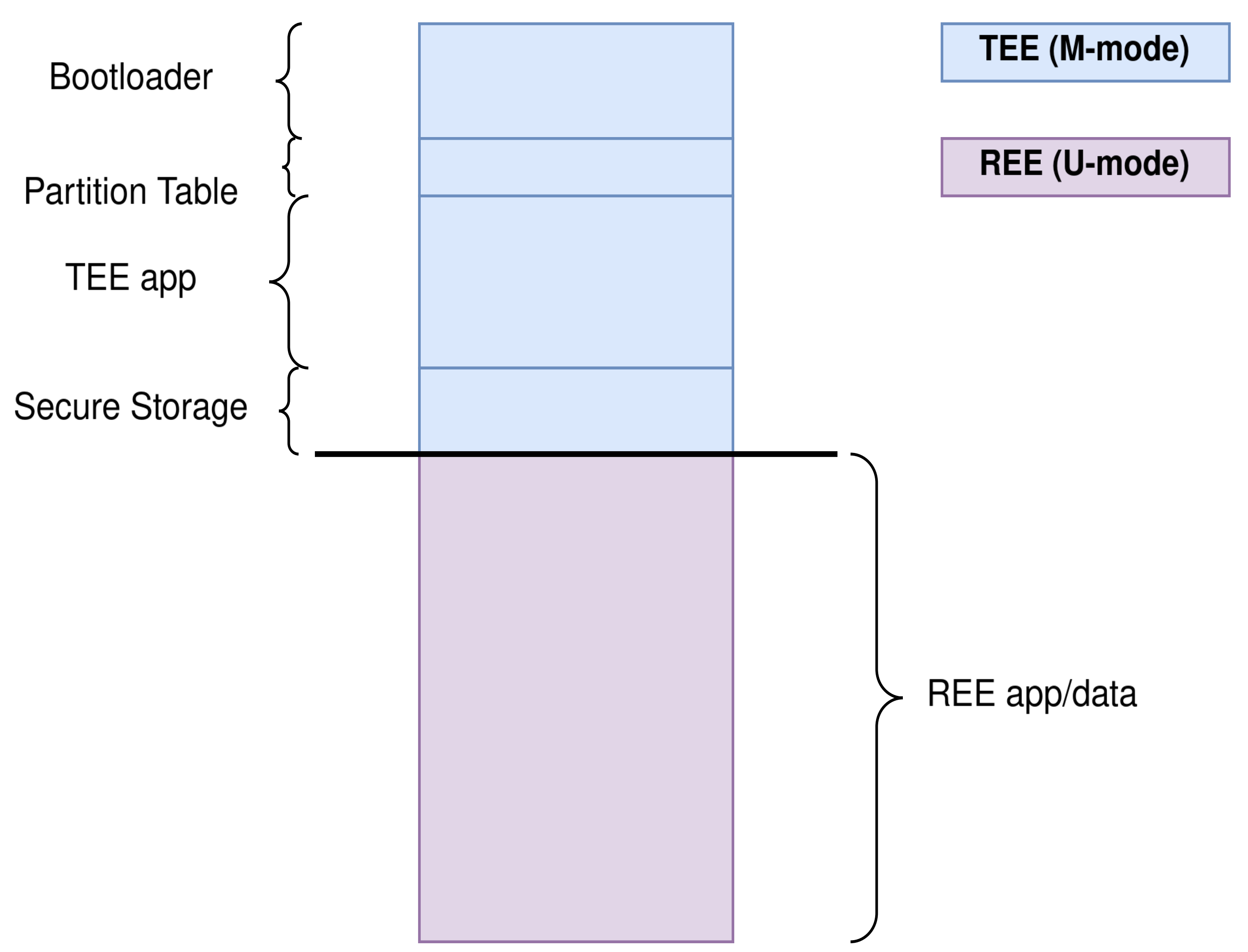
ESP-TEE: Use Cases

Practical applications of TEE

ESP-TEE: Secure Storage



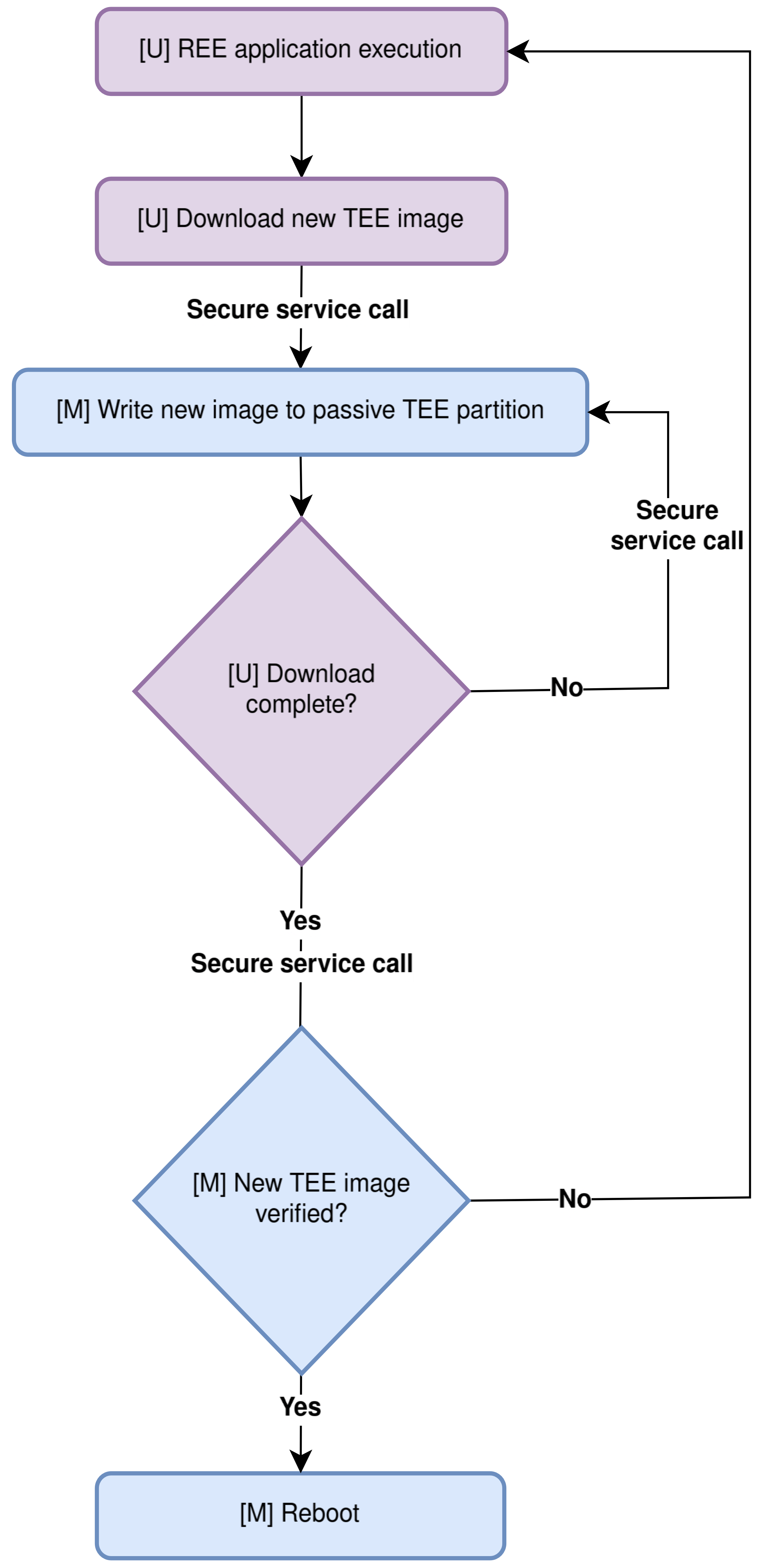
Persistent Storage for Sensitive Information

- Utilizes a dedicated external flash partition
- Encrypted with AES-256-GCM scheme with device-specific key (eFuse)
- Data and encryption key are inaccessible to the REE

Key Management

- Supports storage of ECDSA secp256r1 key pairs (14 slots)
- Interface to the REE for securely signing messages in the TEE using the above key material

ESP-TEE: OTA Updates



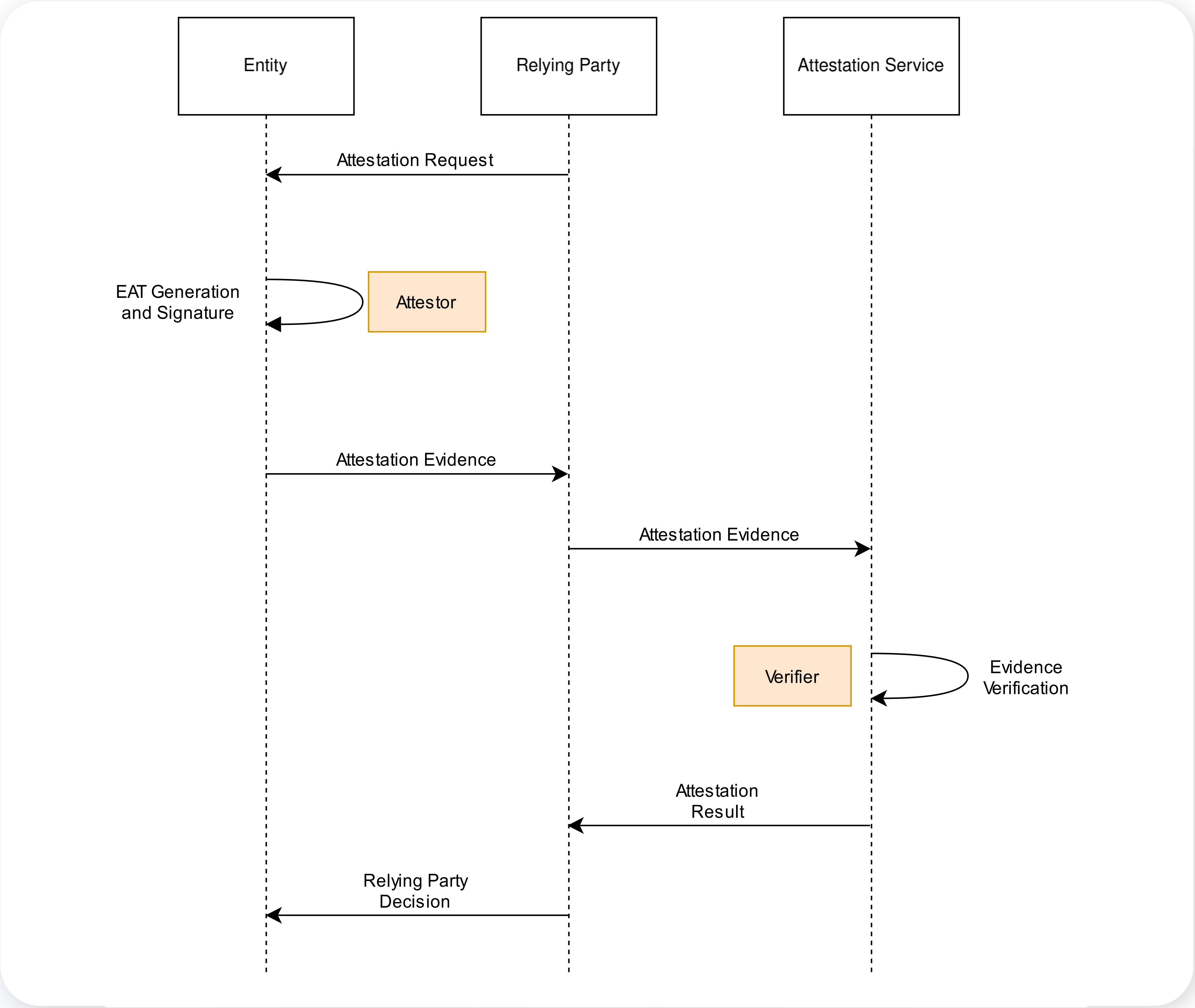
Securely manage TEE OTA updates

- Two TEE OTA app and one TEE OTA data partition entries are required
- Support for TEE app rollback
- Compatible with Secure Boot

ESP-TEE: Attestation

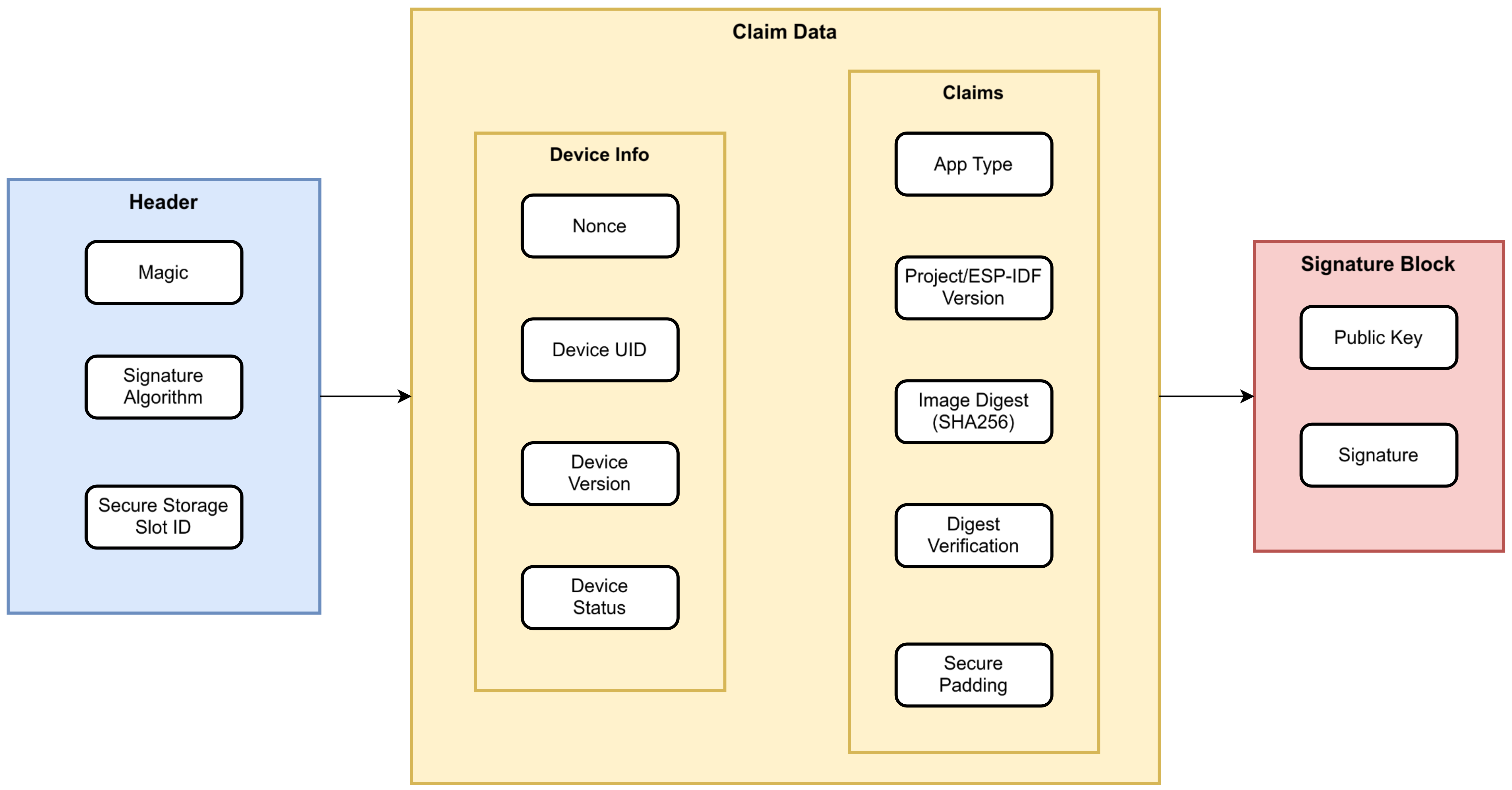
- Mechanism enabling a device to make claims about its identity and security status
- Useful for manufacturers and cloud service providers for device assurance and trust

- Entity Attestation Token (EAT)
  - Cryptographically signed small data blob containing device claims, defined in JSON format
  - Claims: Device ID, Software version, Hardware version, etc.



ESP-TEE: Attestation

- REE interface to securely generate and return an EAT from TEE
- EAT signed using an ECDSA secp256r1 key-pair from the given TEE secure storage slot
- Supported Claims for all firmware images (Bootloader, active TEE and REE app)
  - Project and ESP-IDF version
  - Image Digest (SHA256)
  - Public key corresponding to the signing private key (from secure storage)
  - ECDSA signature of the EAT



ESP-TEE: How to Use It

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Migration of Existing Projects

- Enable the TEE Kconfig option
- Partition Table needs to be updated
- TEE firmware generation handled by the build system
- Reference examples will be provided for all the current use cases

Performance and Resource Impact

01

64 KB SRAM reserved for TEE (configurable)

02

~280KB external flash for TEE (use case dependent)

03

CPU cycles overhead: Service Call

Entry: 778 (4.86 µs @ 160 MHz)

Exit: 365 (2.28 µs @ 160 MHz)

Future Work

01

ESP-TEE Beta version will release soon

02

Support for other RISC-V SoCs in plans

03

Certification and Regulatory Compliance (E.g., PSA L2)

04

Optimize performance and resource impact

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Thanks for watching !