PartEmu: Enabling Dynamic Analysis of Real-World TrustZone Software Using Emulation

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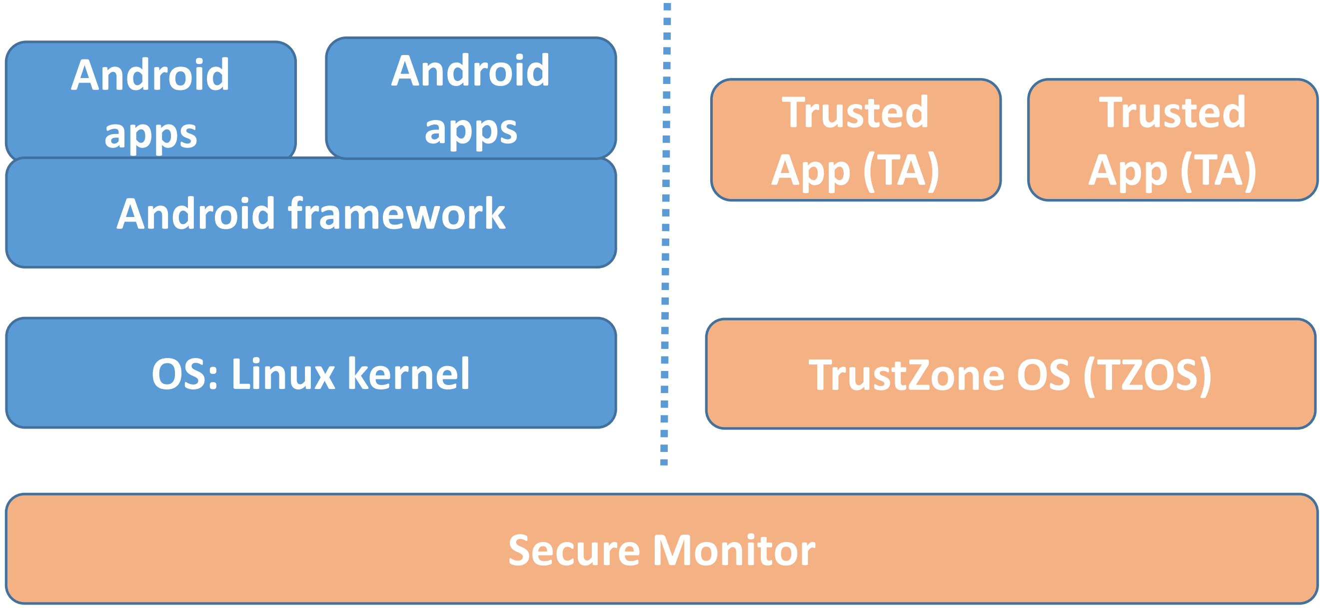
The “Hidden” Software Stack: TrustZone



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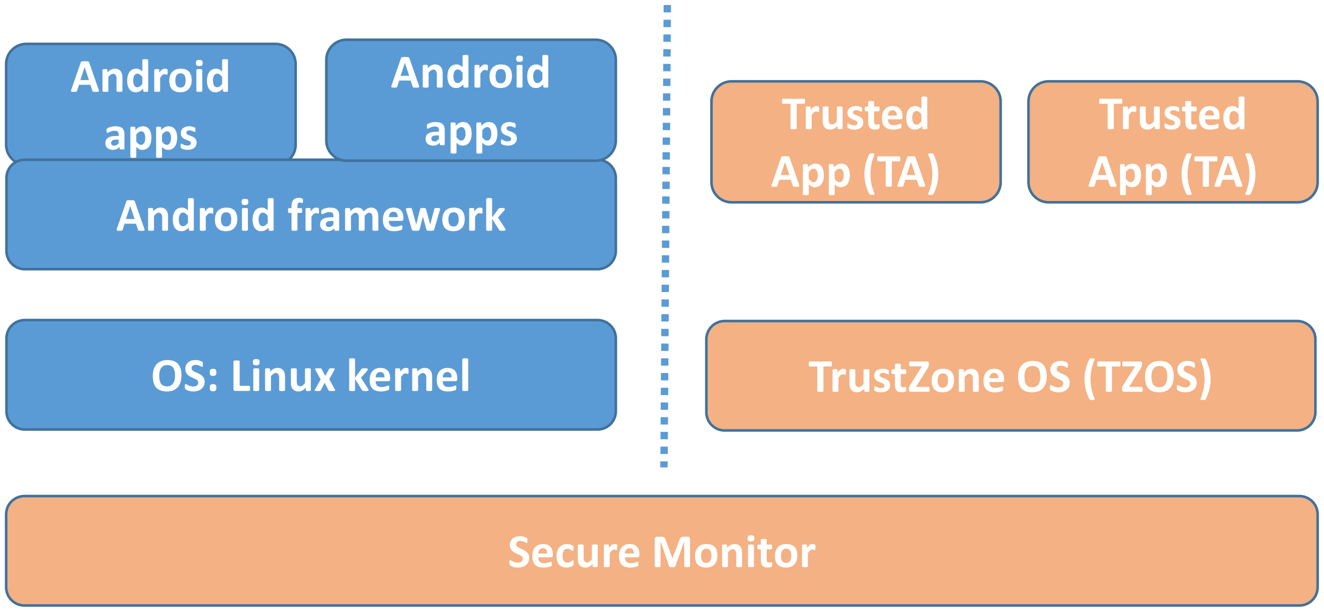

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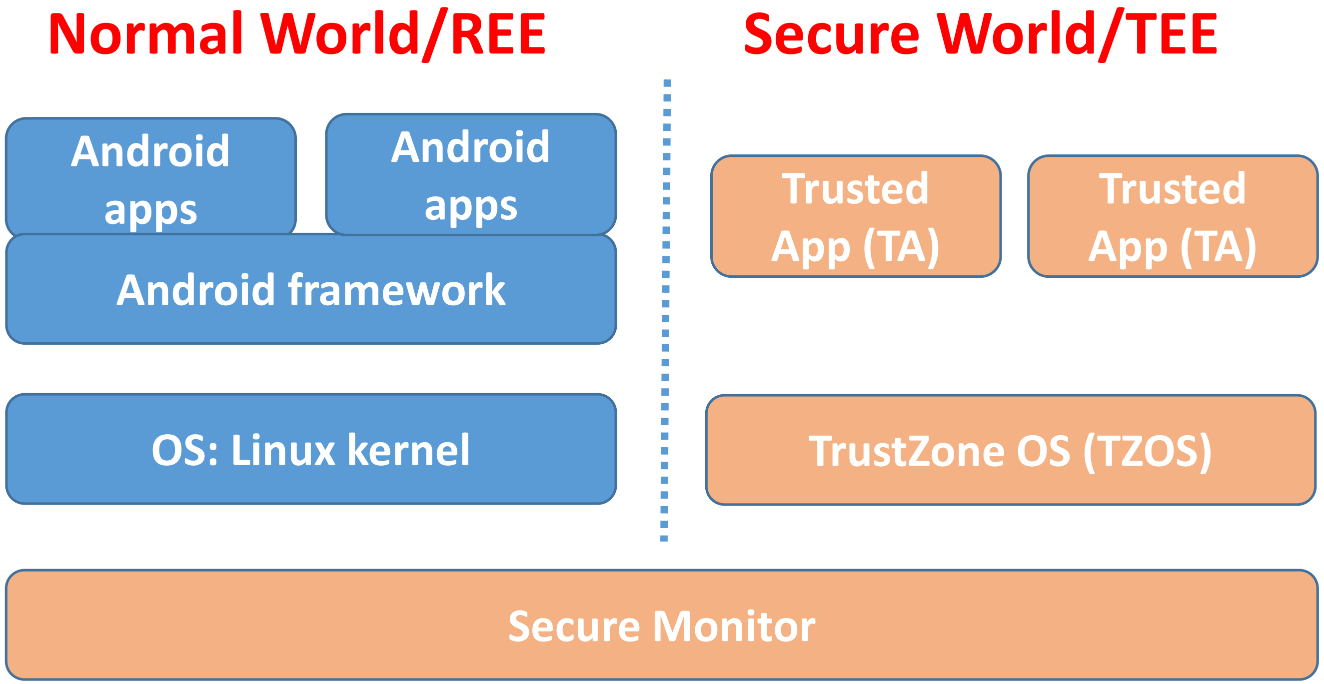

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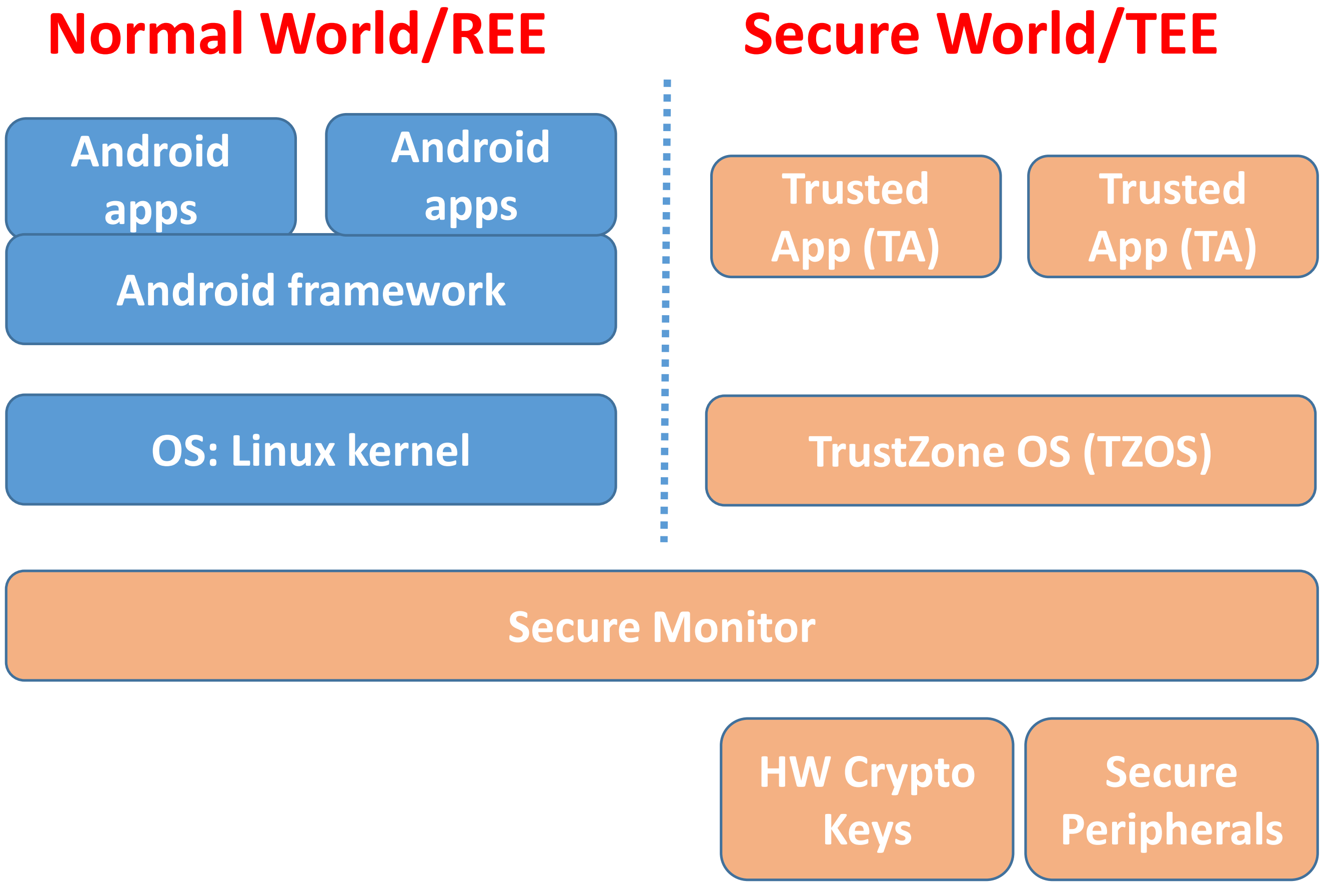

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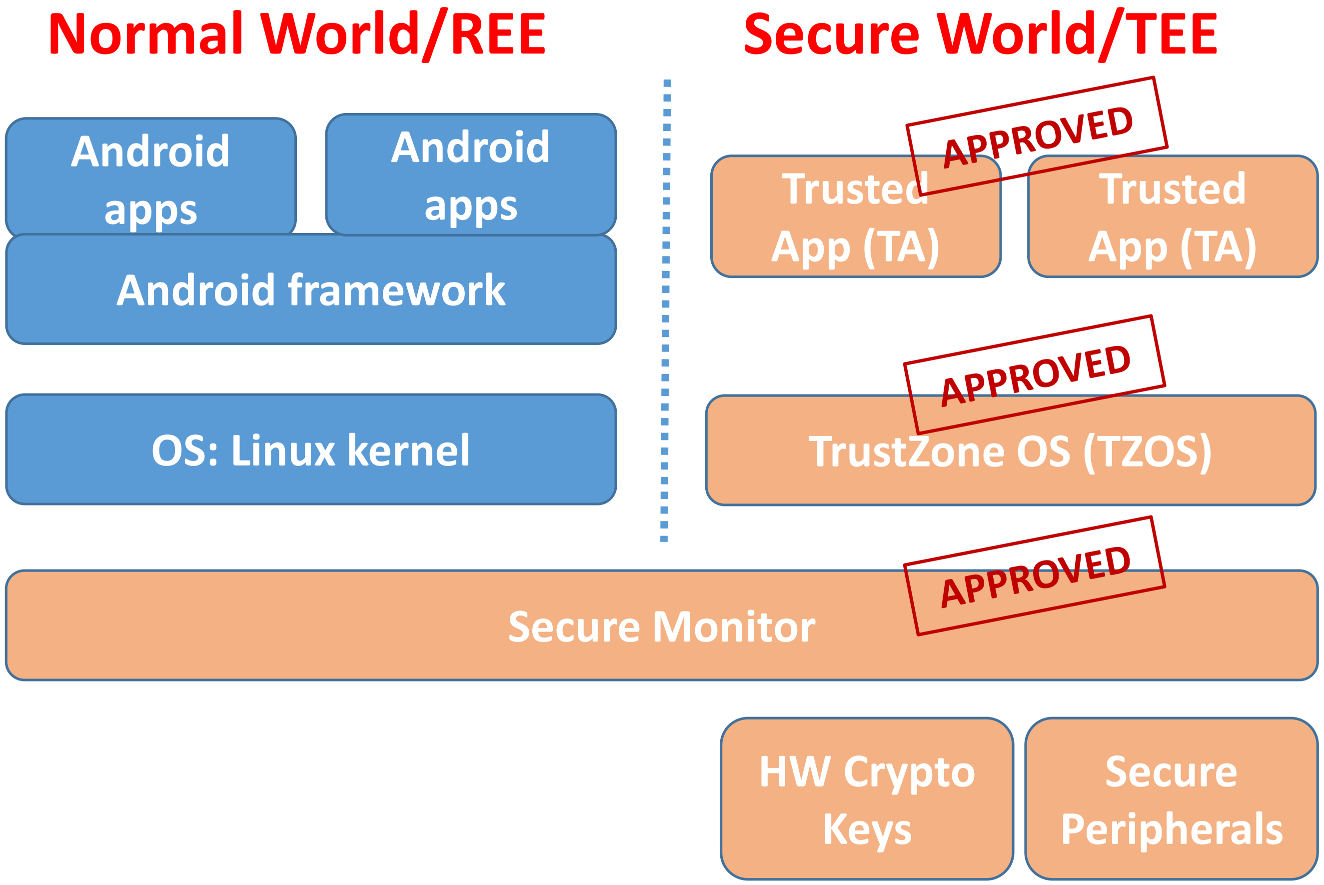


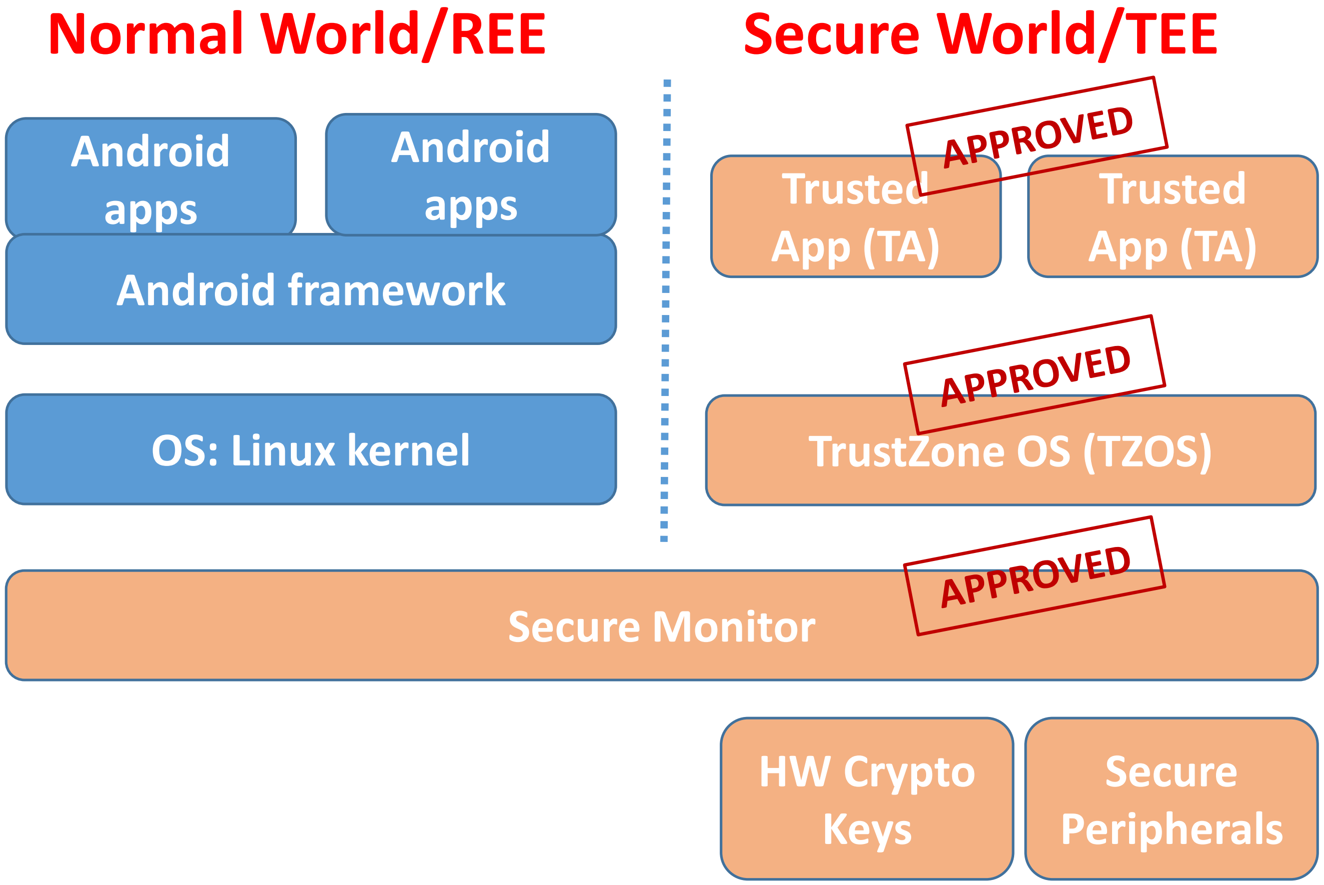
- Separate software stack
  - Trusted applications (TAs)
  - TrustZone OS (TZOS)
  - TEE/REE
- Basis for security: Has access to hardware keys
- Access to TZ locked down: Only signed software can run

Problem: Dynamic analysis of TZ is hard!

Approach

Results: What did we learn?

Problem: Dynamic Analysis of TZ is Hard



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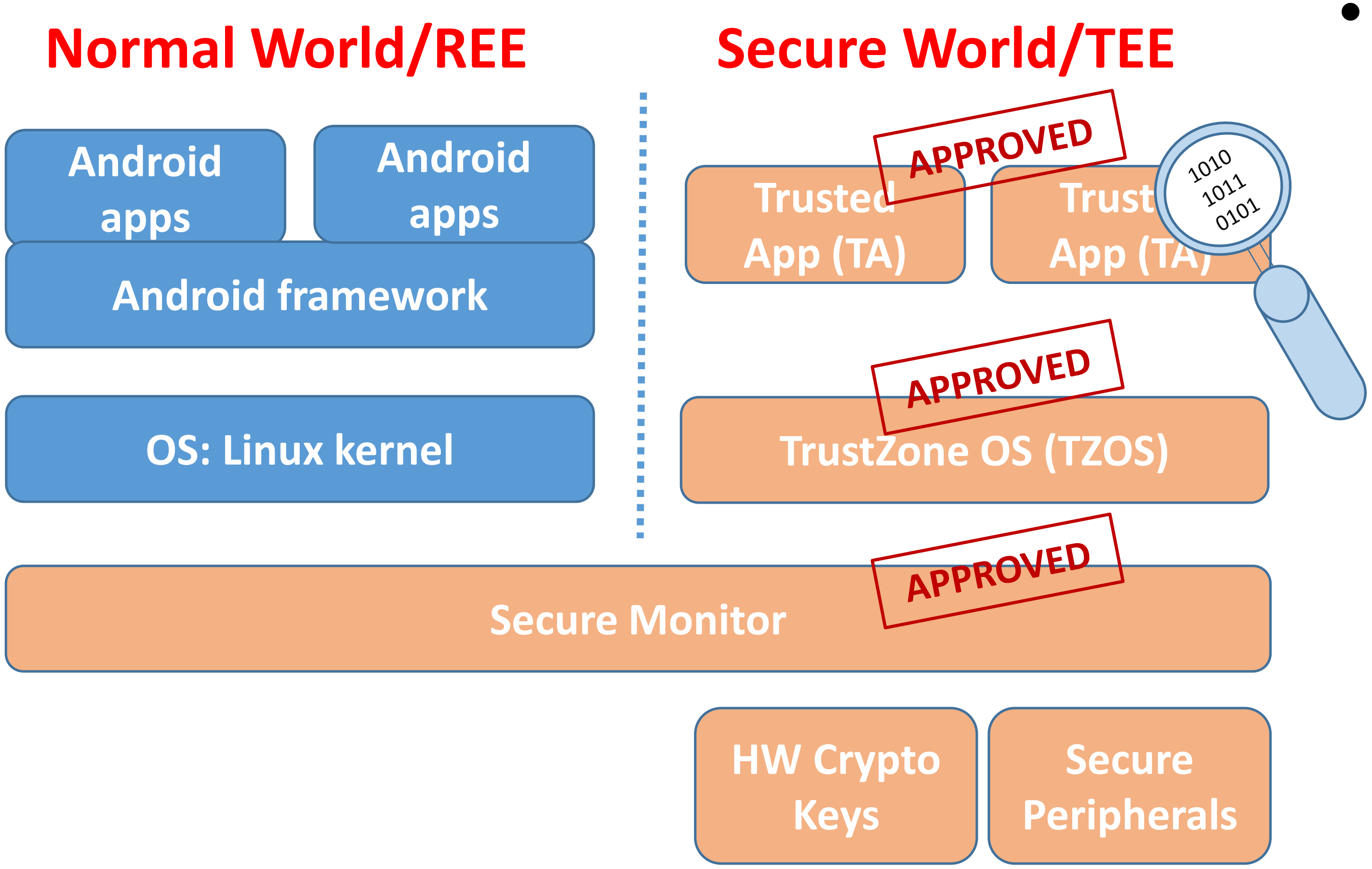

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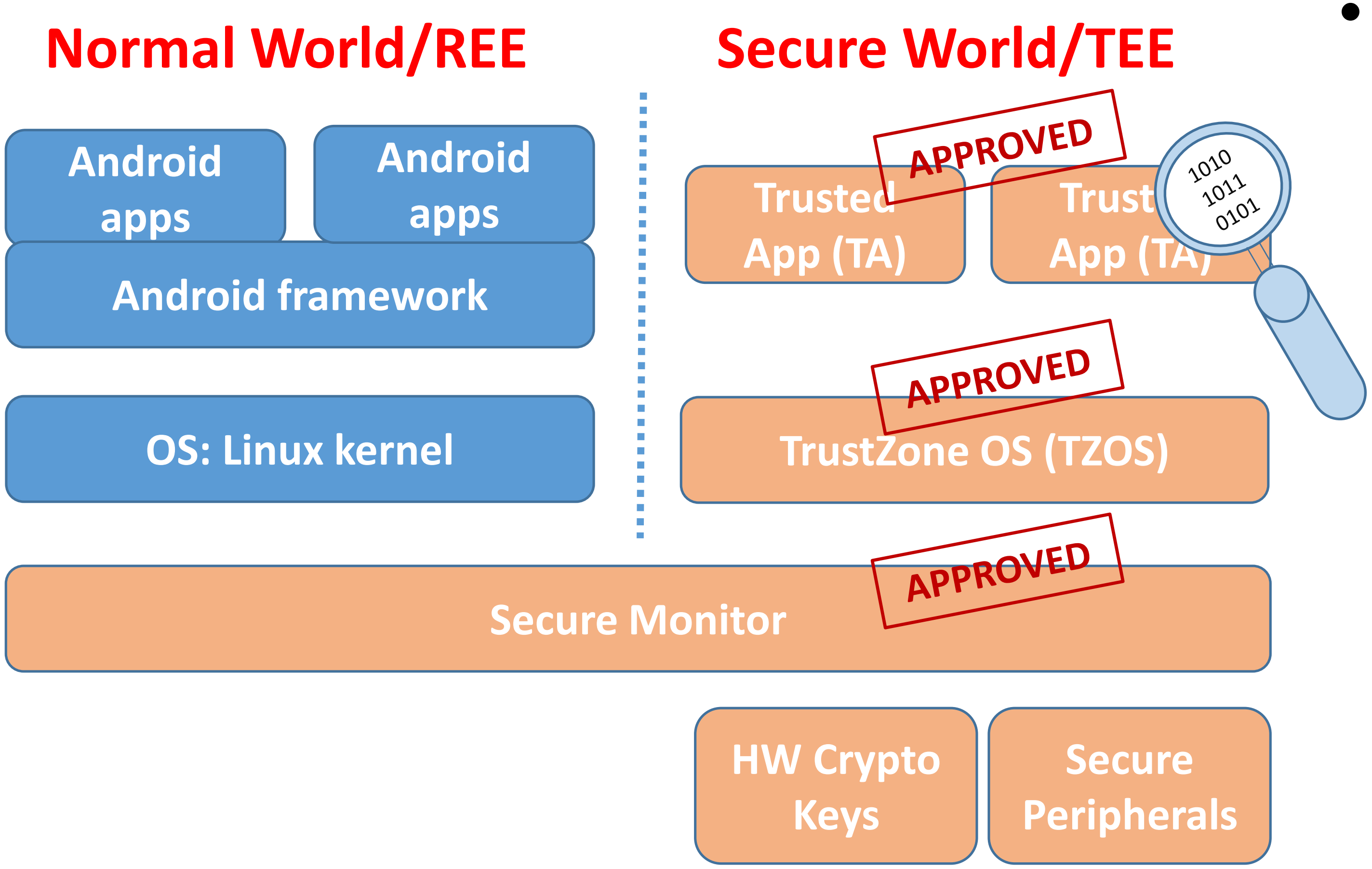

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  - Feedback-driven fuzz testing – needs list of basic blocks covered

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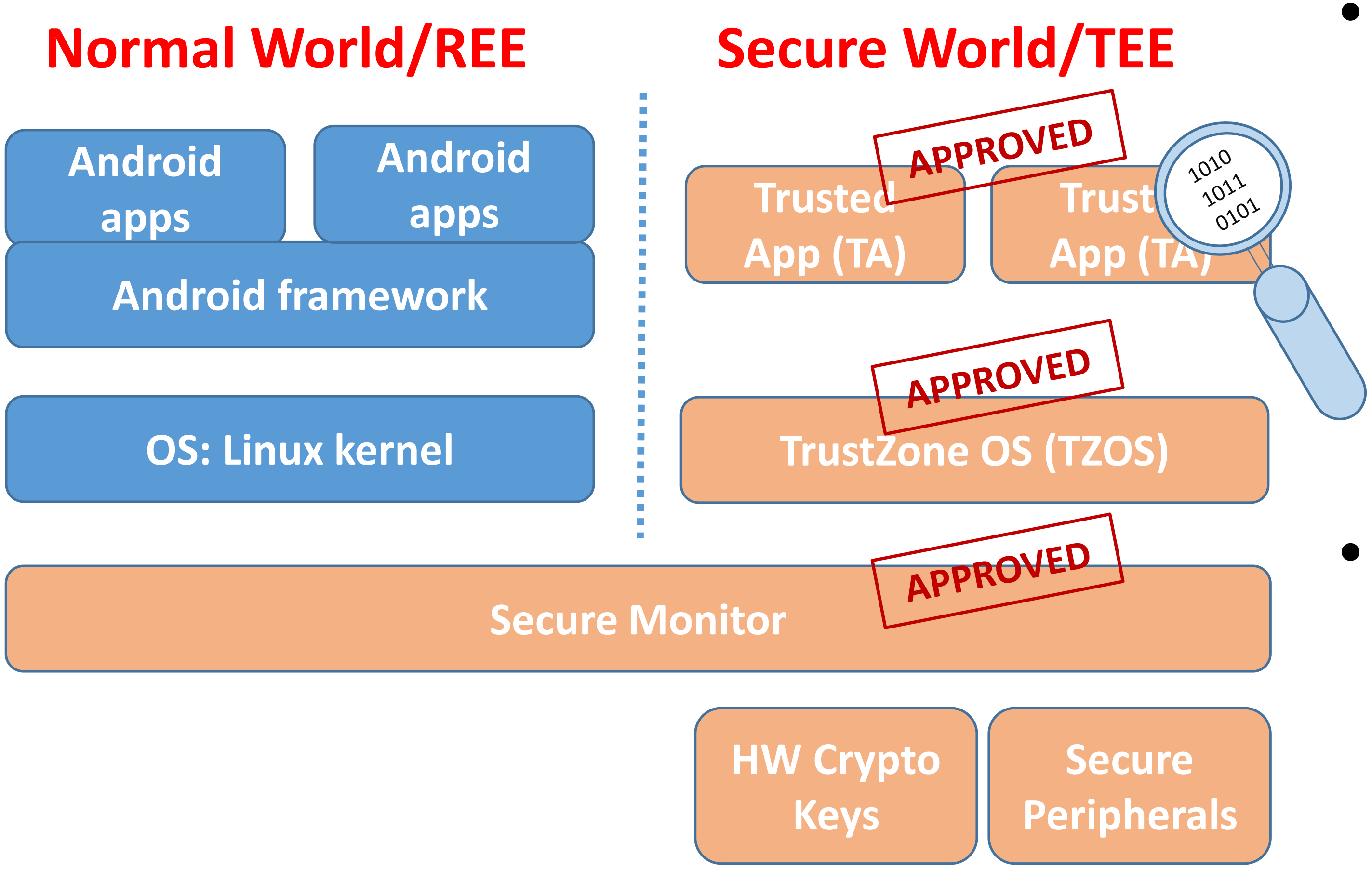
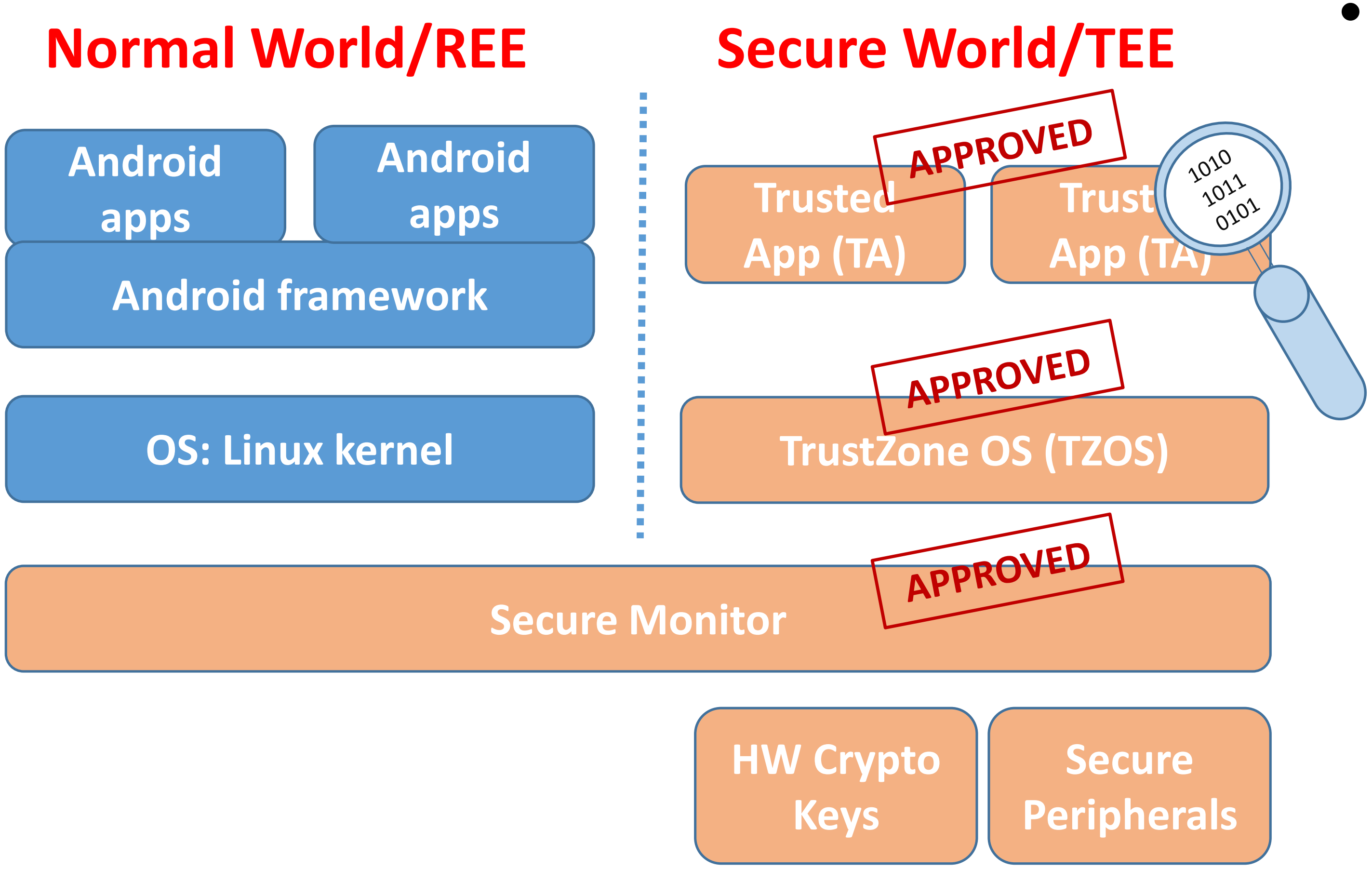


- Dynamic analysis needs ability to monitor target
  - Debugging – needs memory/registers
  - Feedback-driven fuzz testing – needs list of basic blocks covered
- However, cannot instrument TZ software or monitor TZ memory due to signing!

Problem: Dynamic Analysis of TZ is Hard



- Prior dynamic analysis approaches limited!
  - TA/TZOS binary reverse engineering
  - Fuzz testing without feedback

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- We build an emulator that runs real-world TZOSes and TAs
- Emulation enables dynamic analysis
  - Allows introspection and monitoring of TZ execution
- We support four widely-used real-world TZOSes:
  - Qualcomm’s QSEE
  - Trustonic’s Kinibi
  - Samsung’s TEEGRIS
  - Linaro’s OP-TEE

Problem: Dynamic analysis of TZ is hard!

Approach: How did we run TZ in an emulator?

Results: What did we learn?

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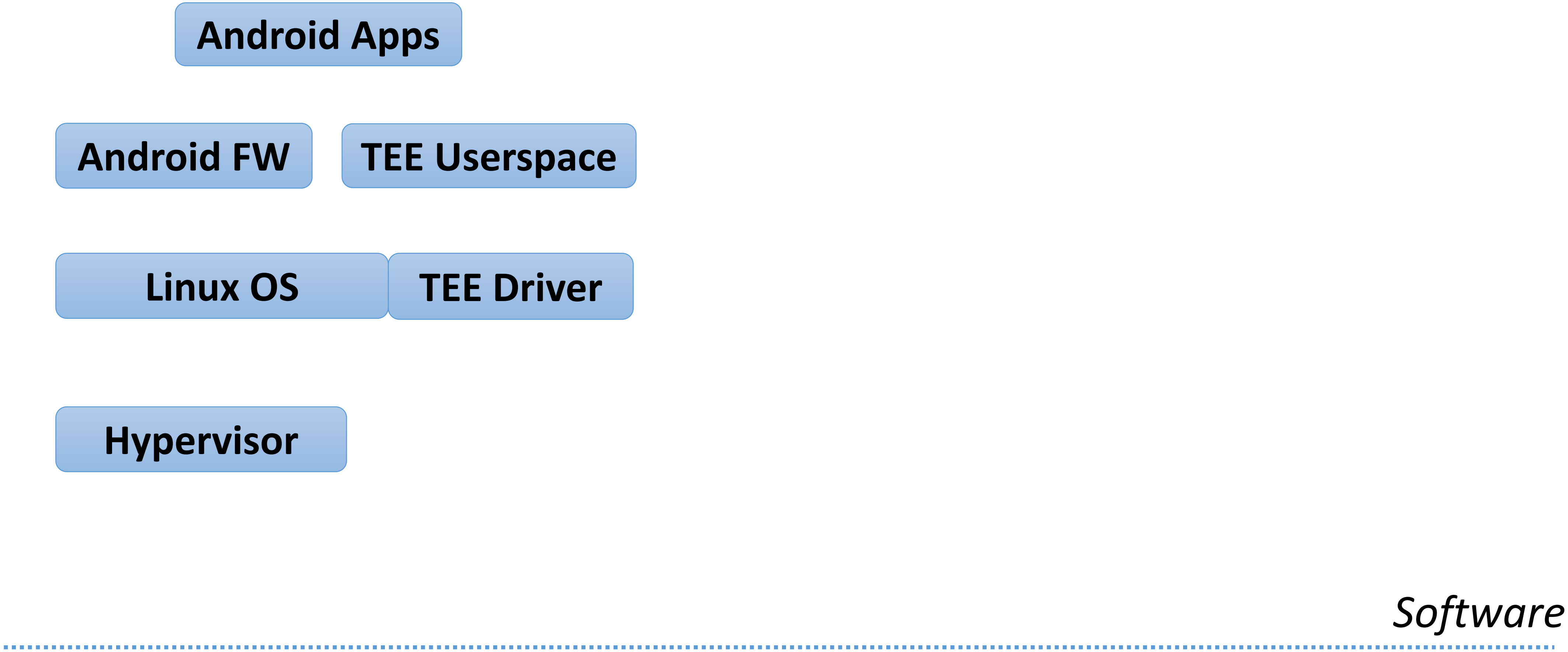

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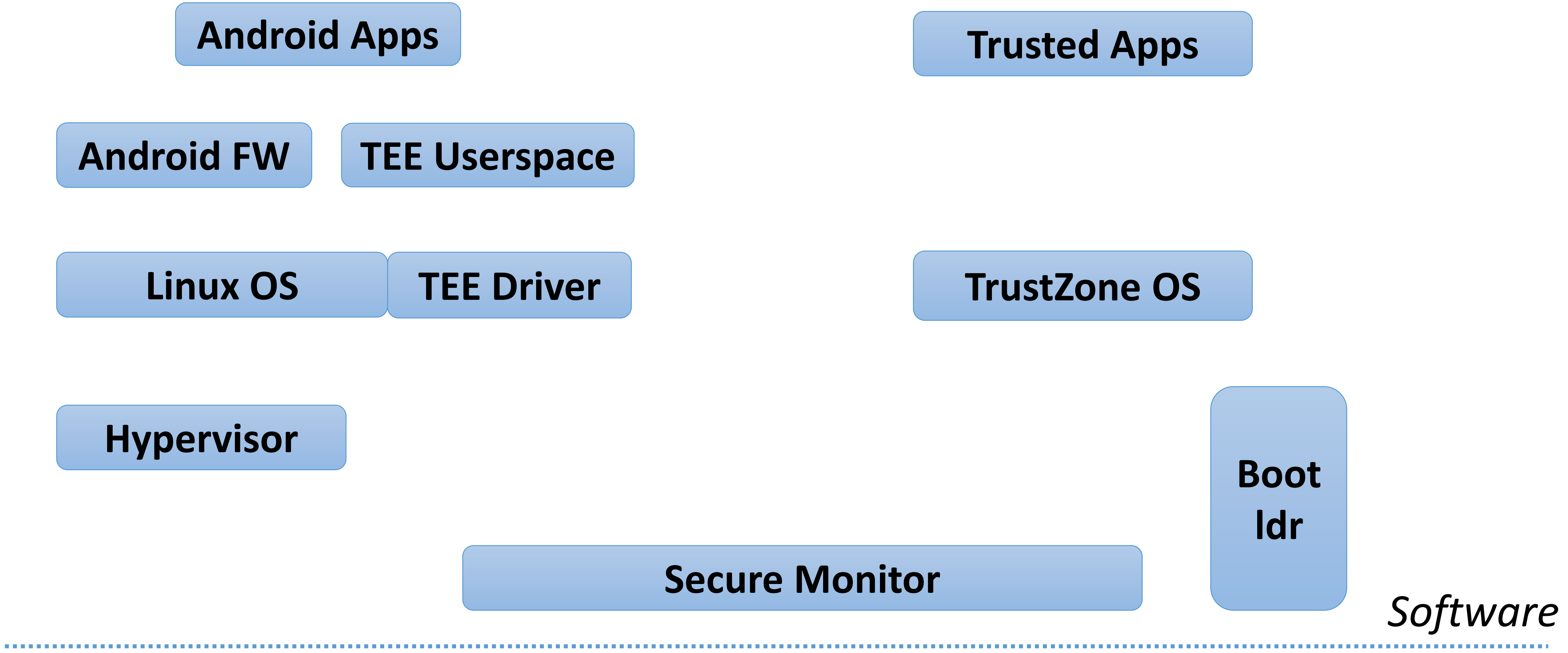

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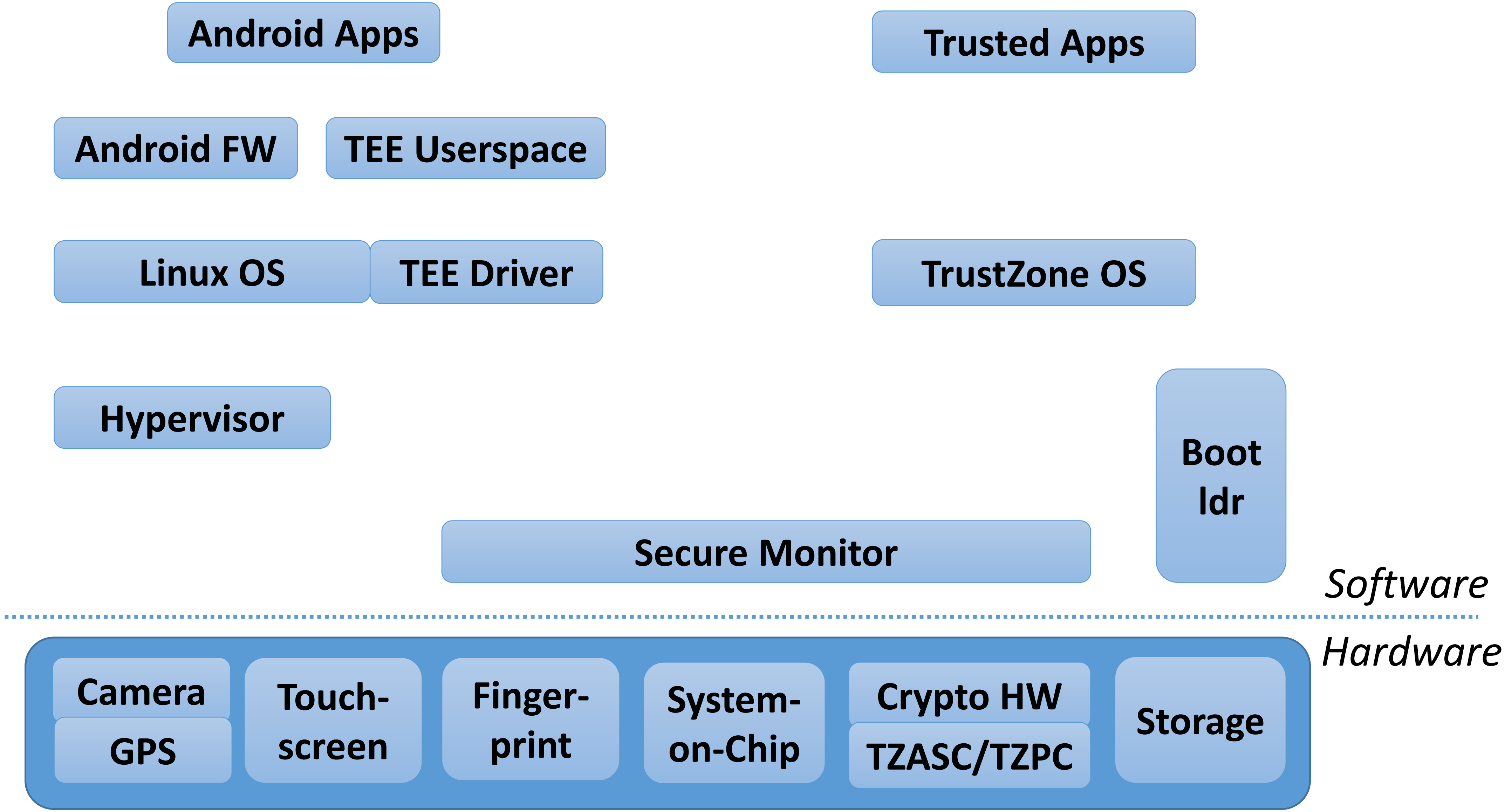

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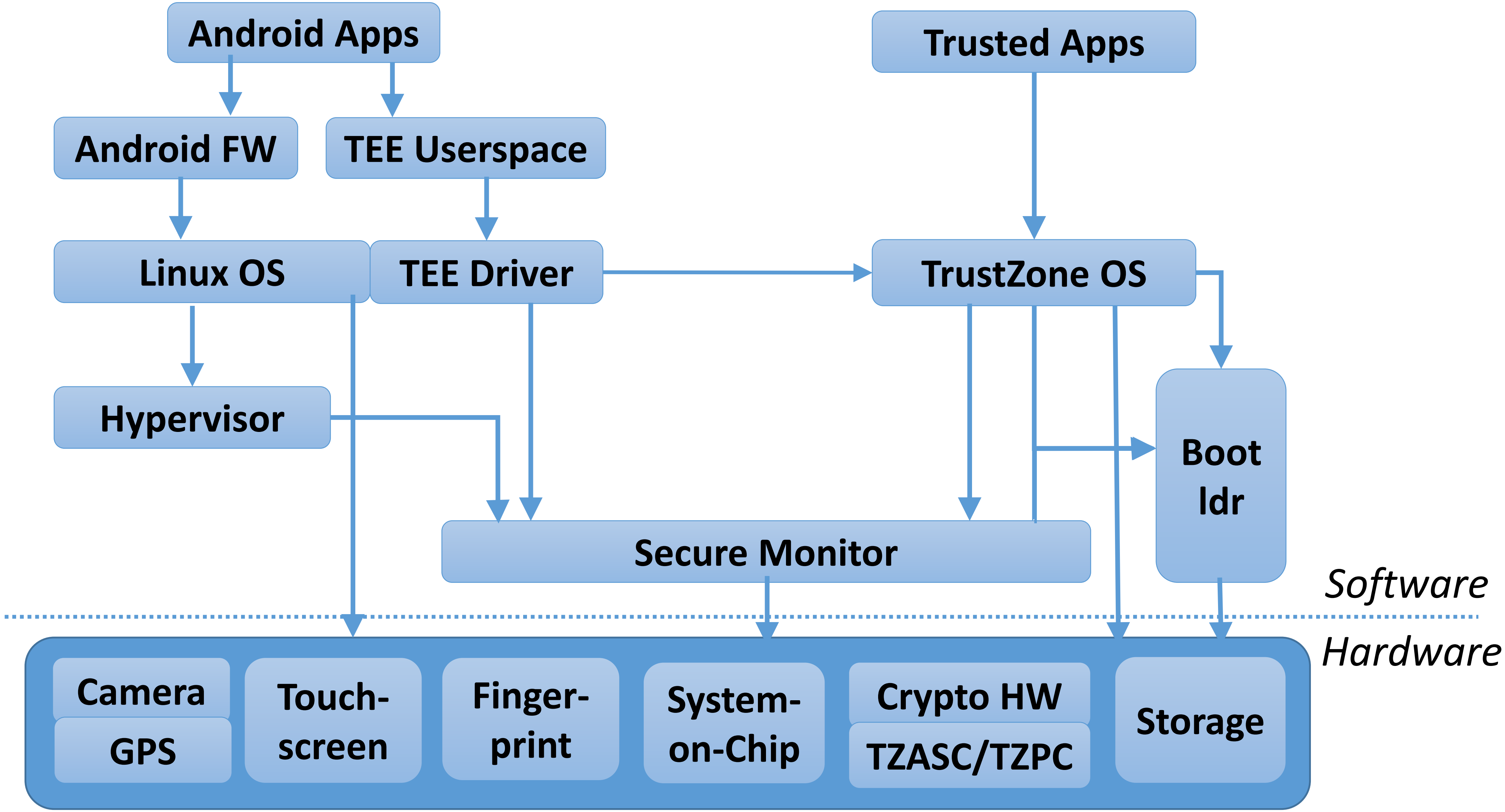
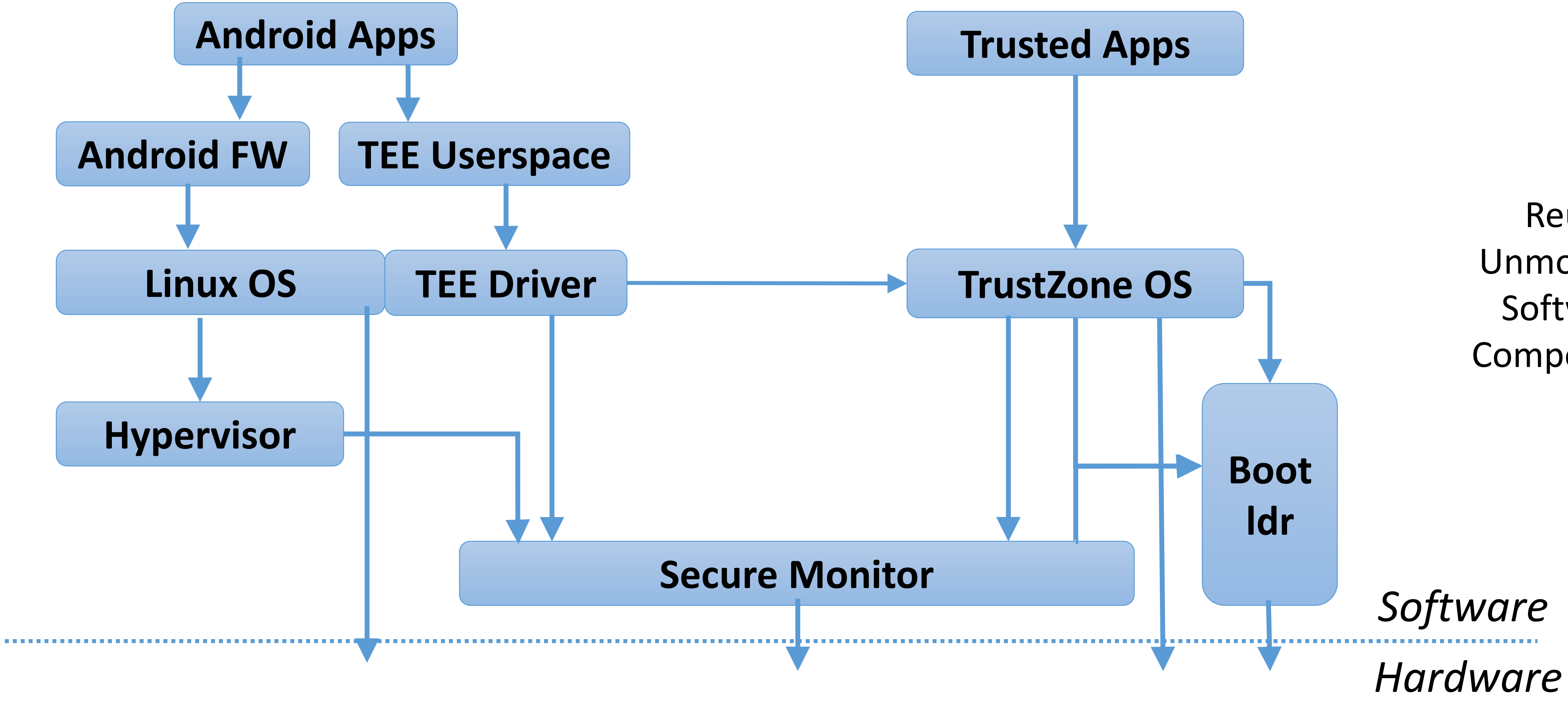


Traditional Approach: Emulate all HW



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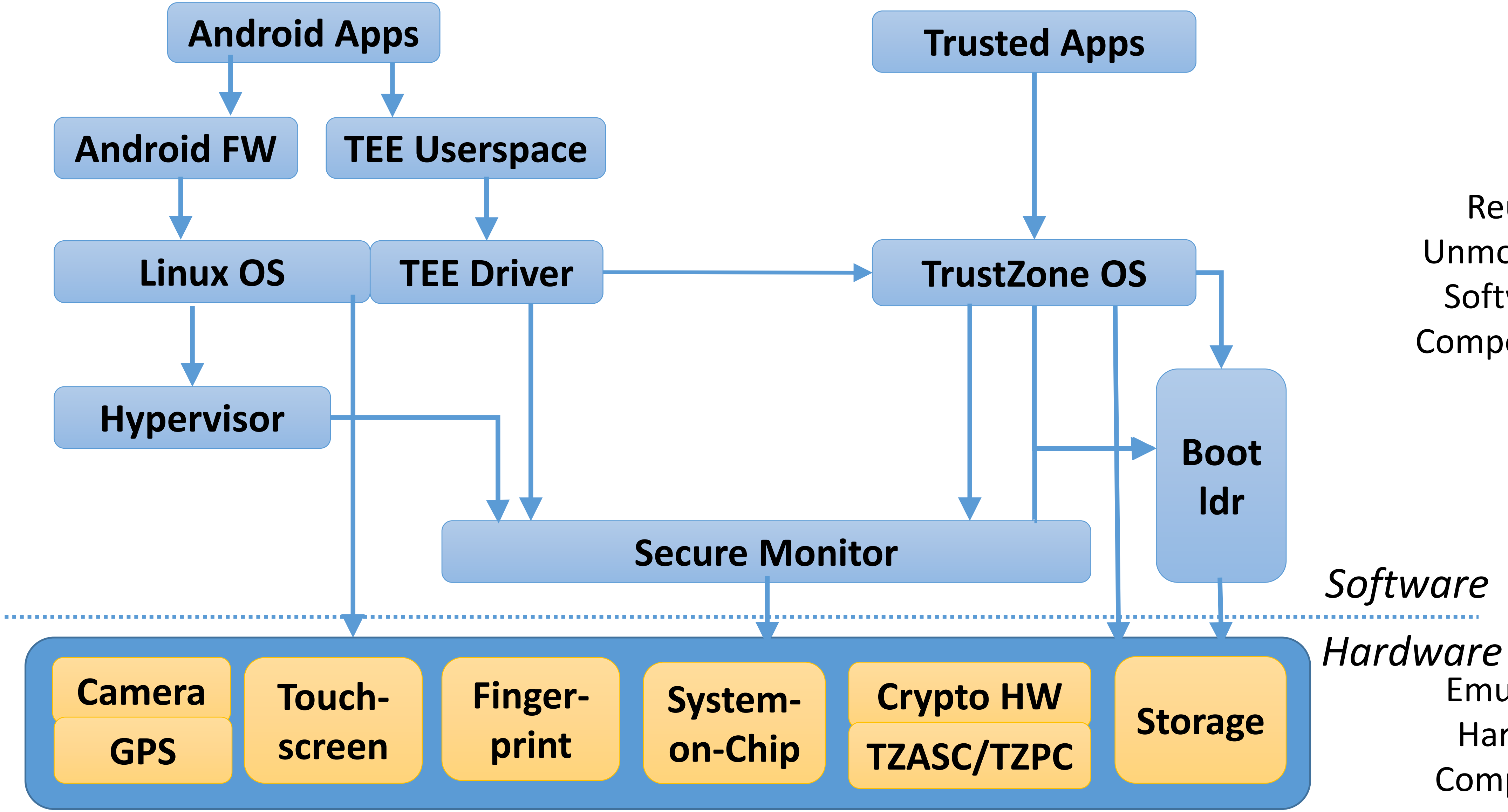

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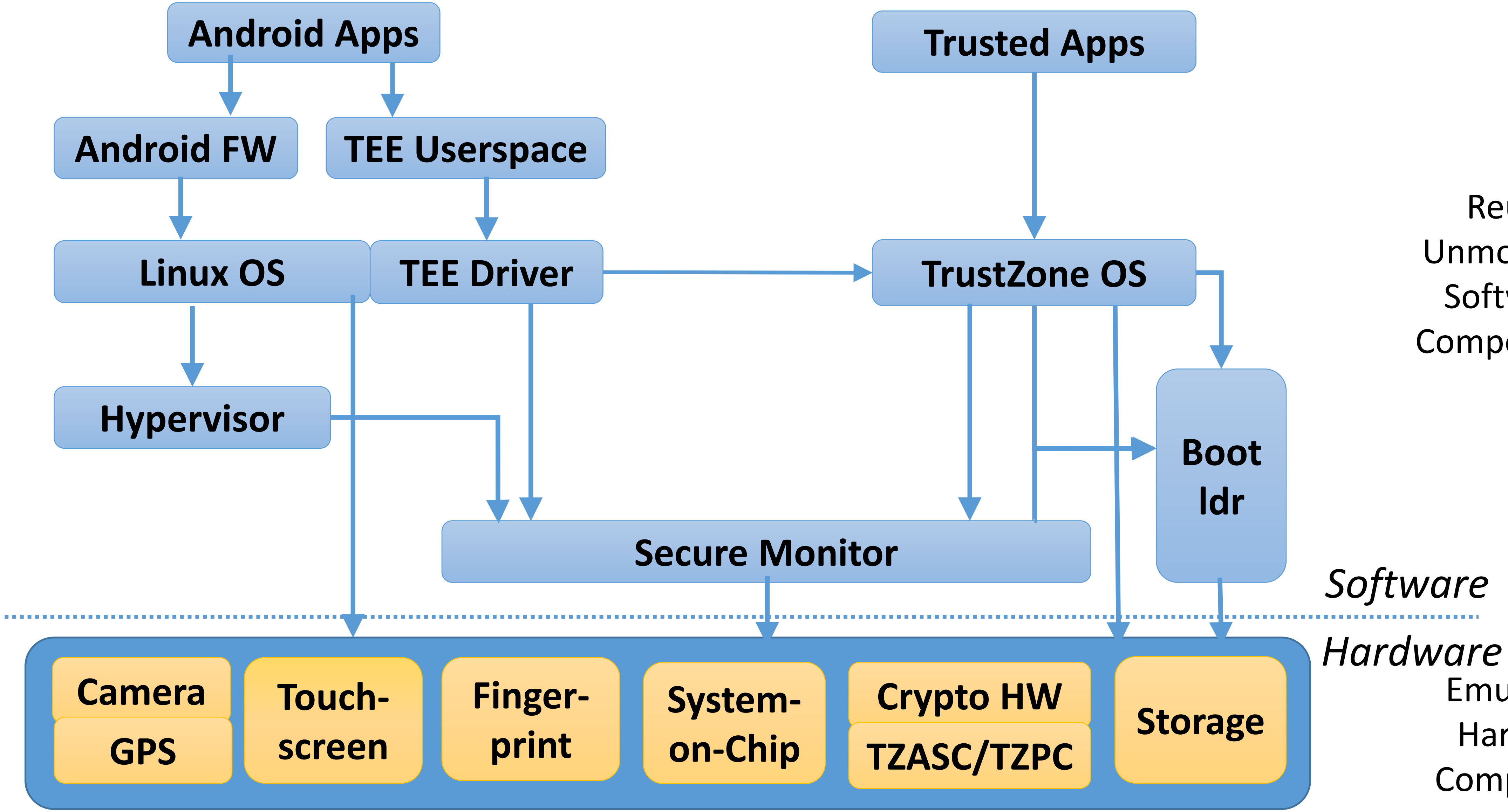

Reuse Unmodified Software Components

Emulate All Hardware Components

Impractical to emulate all hardware

Our Approach: Emulate Subset of HW and SW

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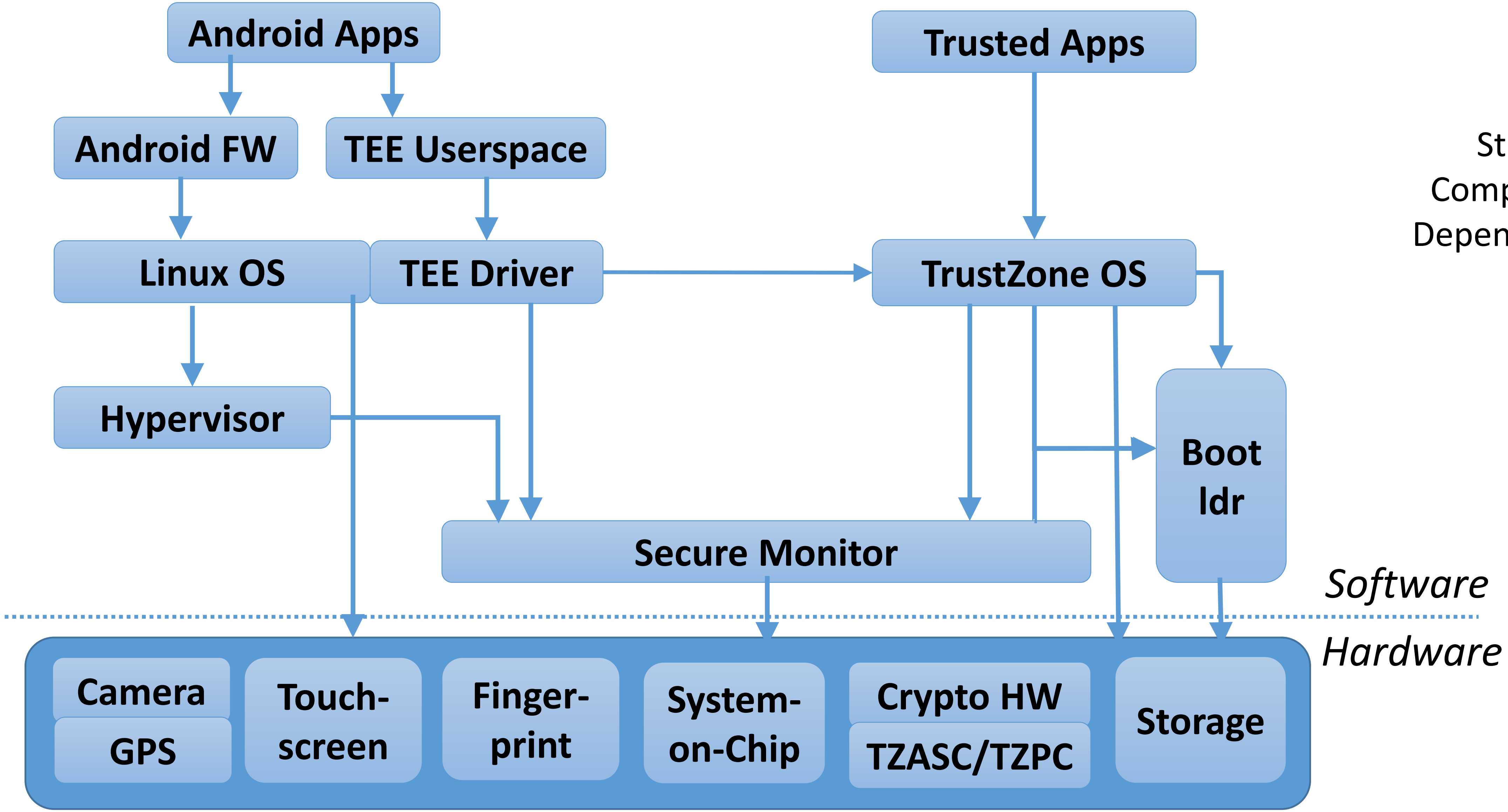

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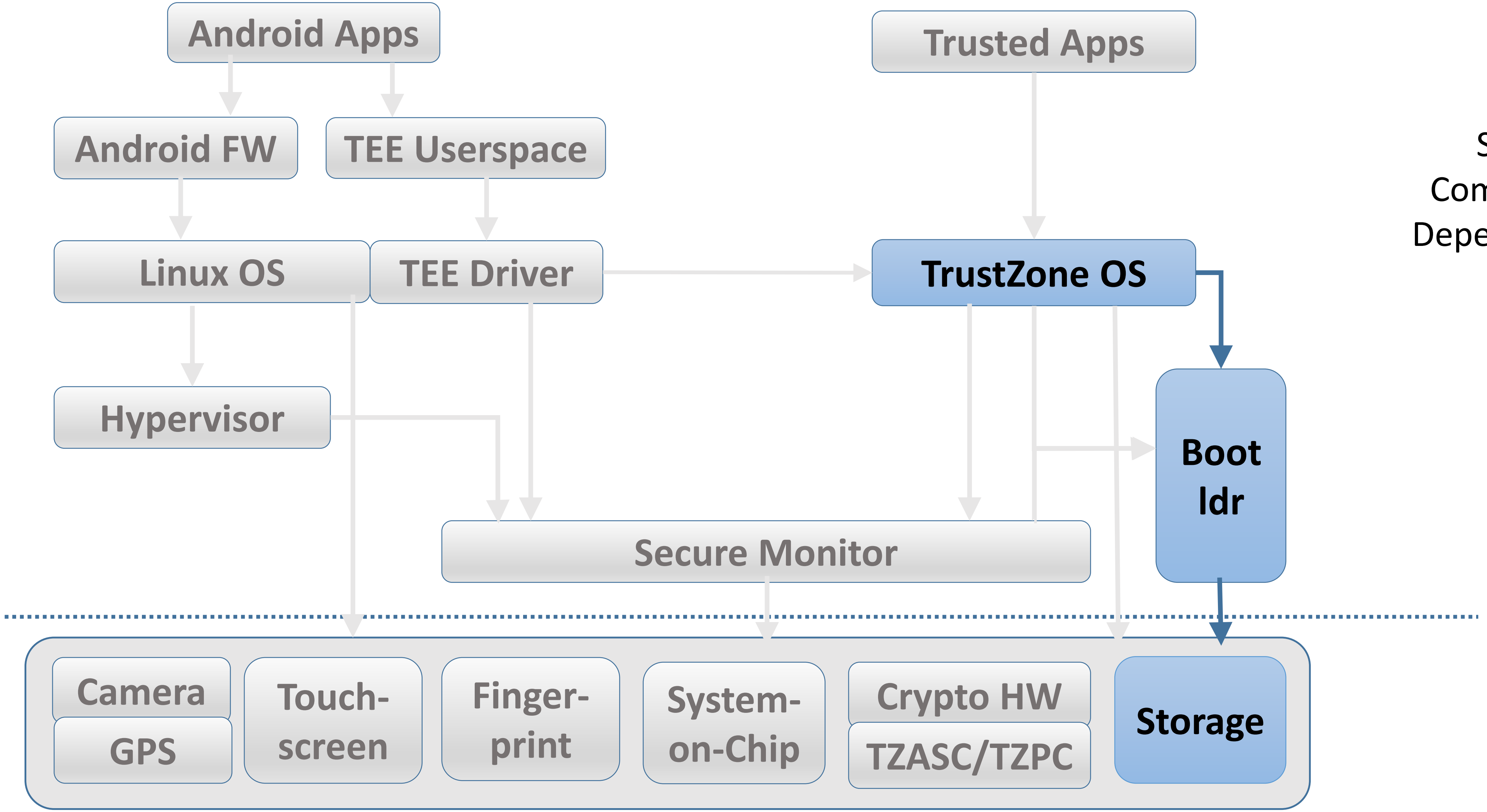

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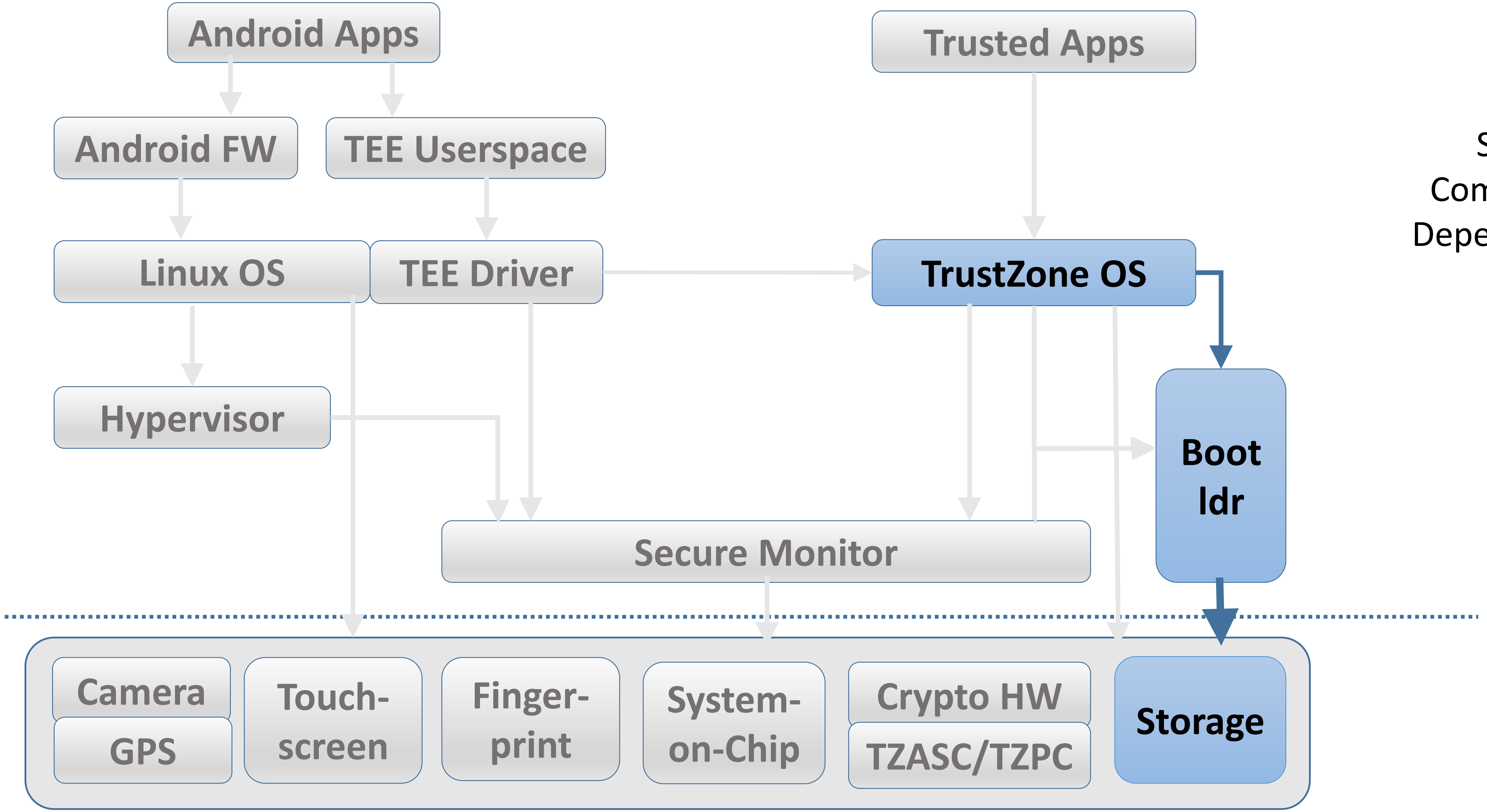

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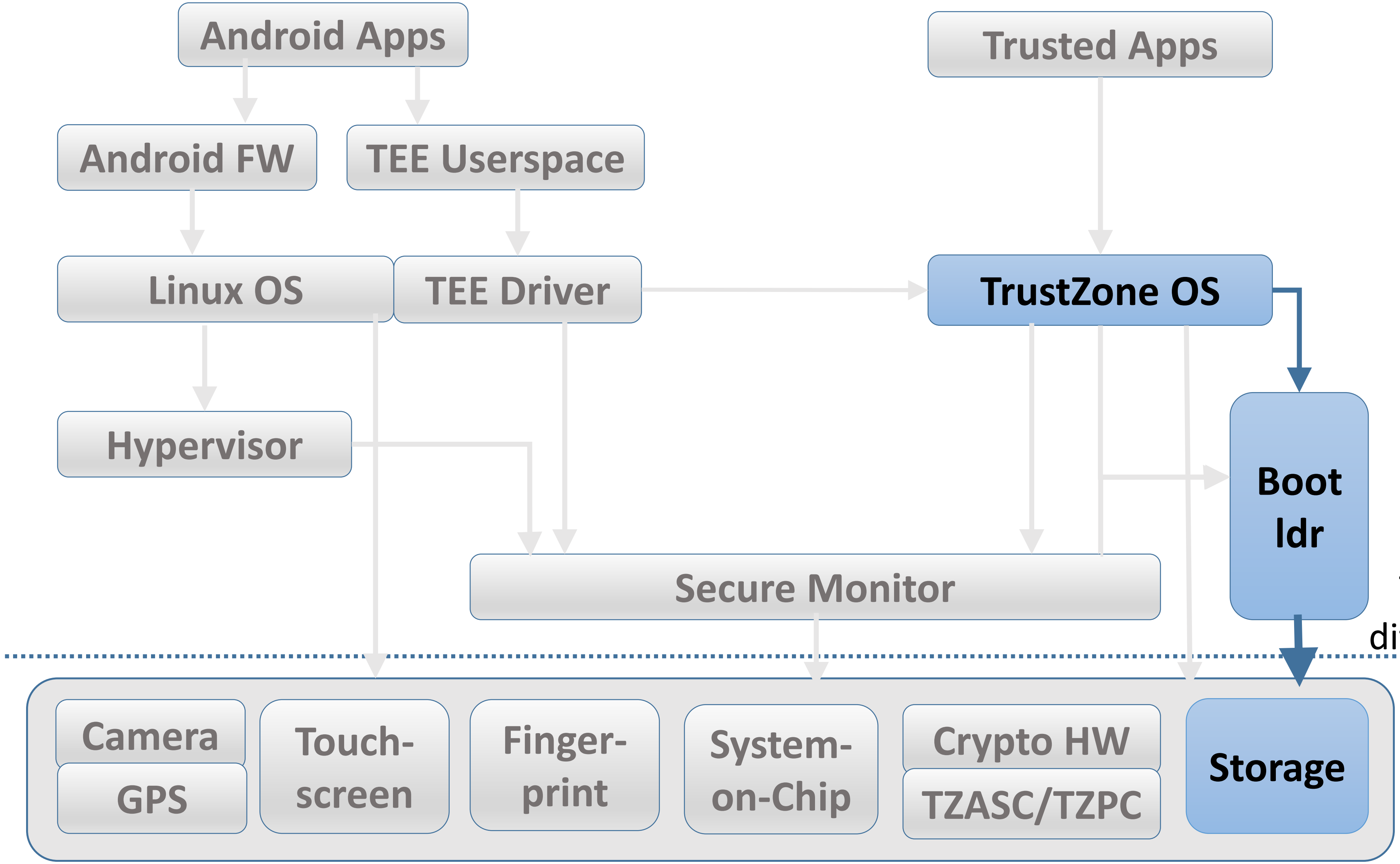

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Tighty coupled, difficult to emulate dependency

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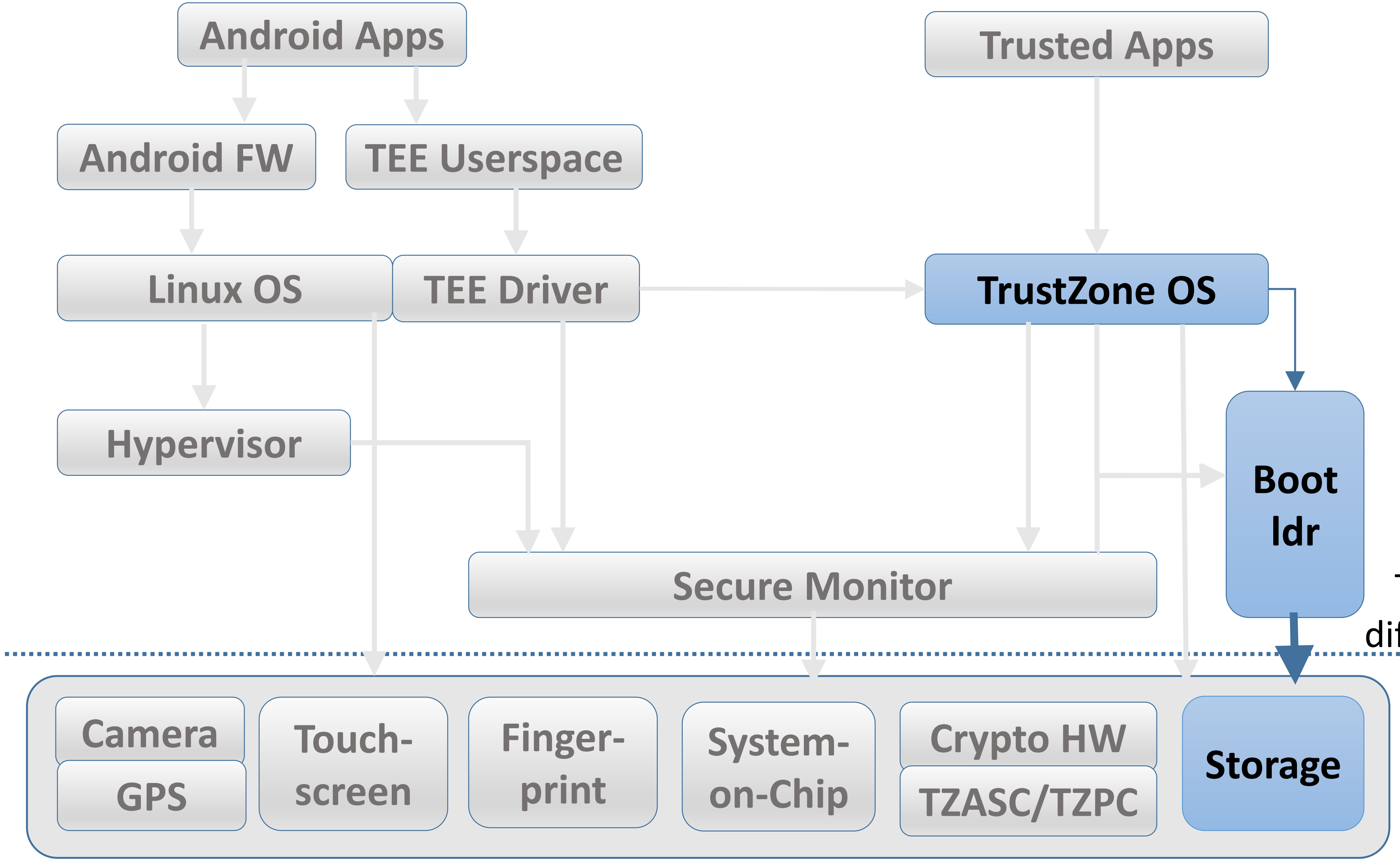

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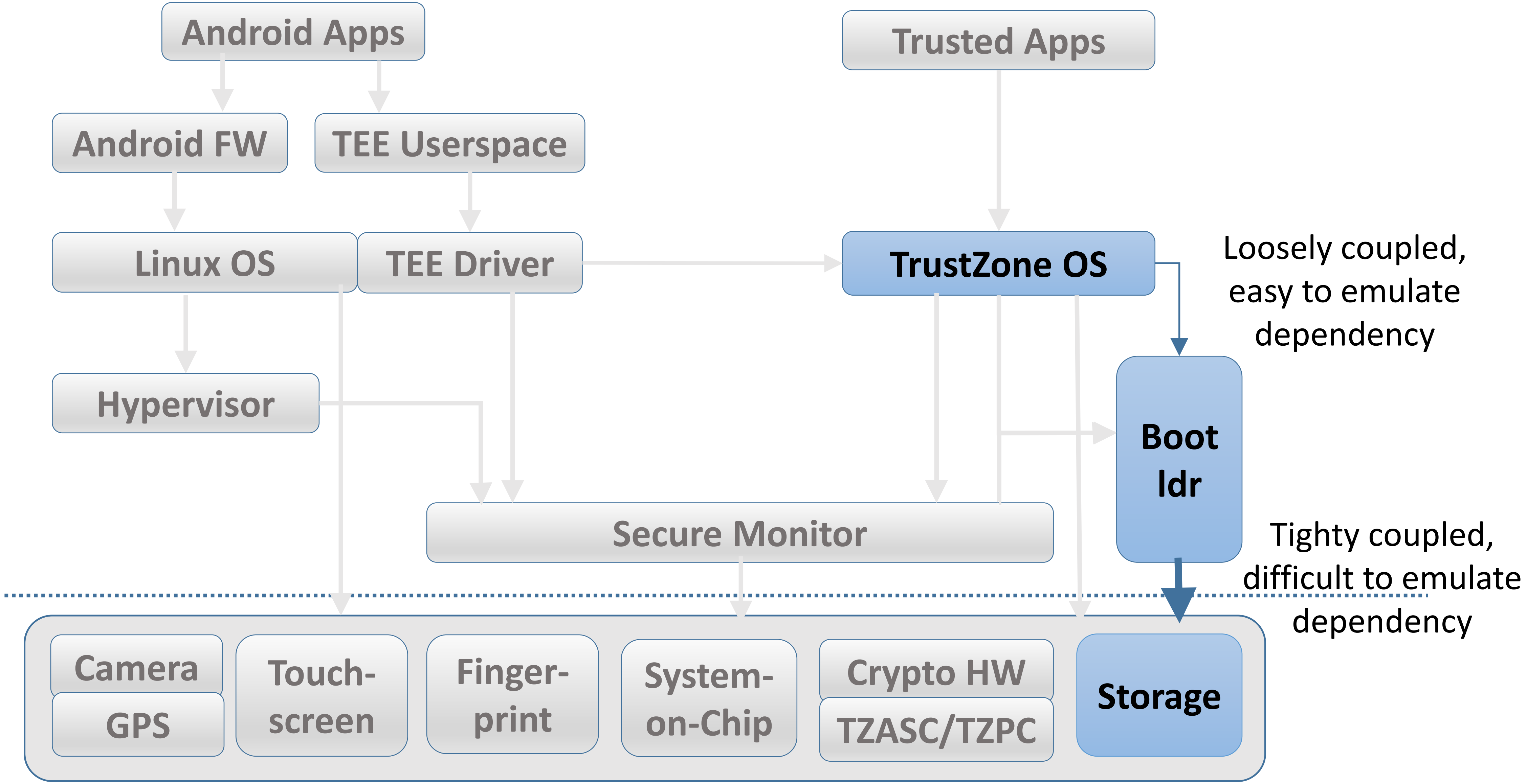

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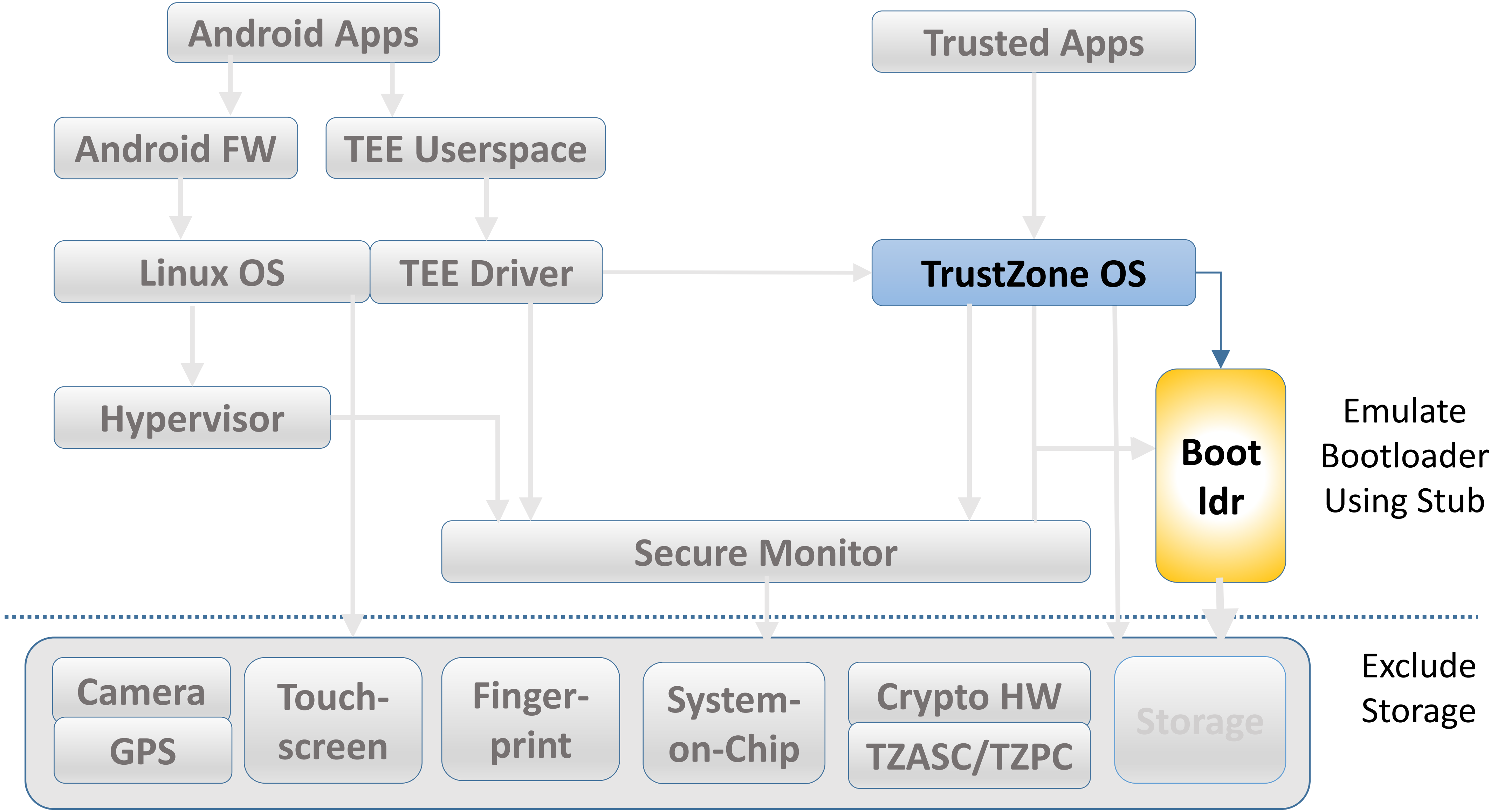

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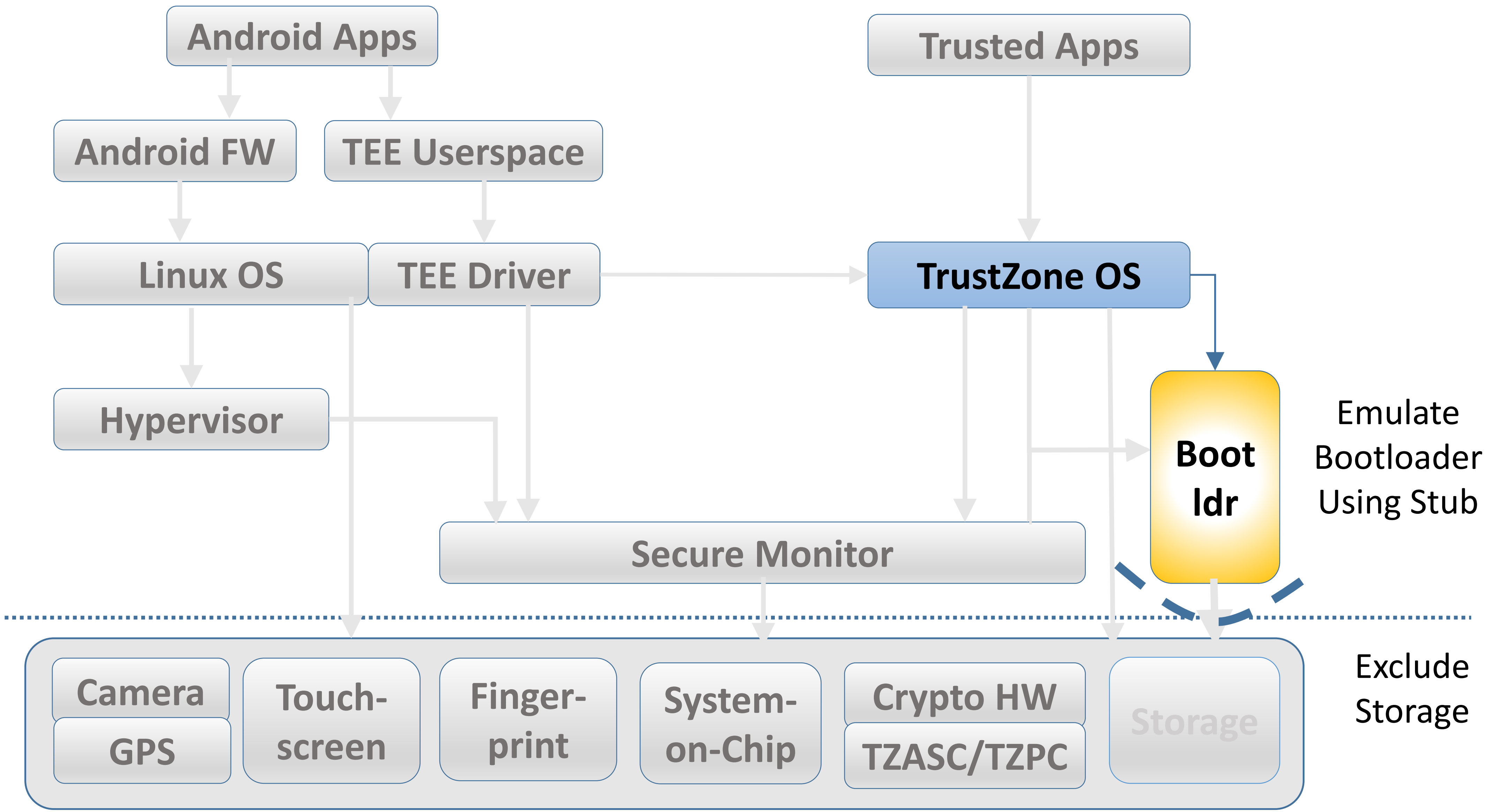

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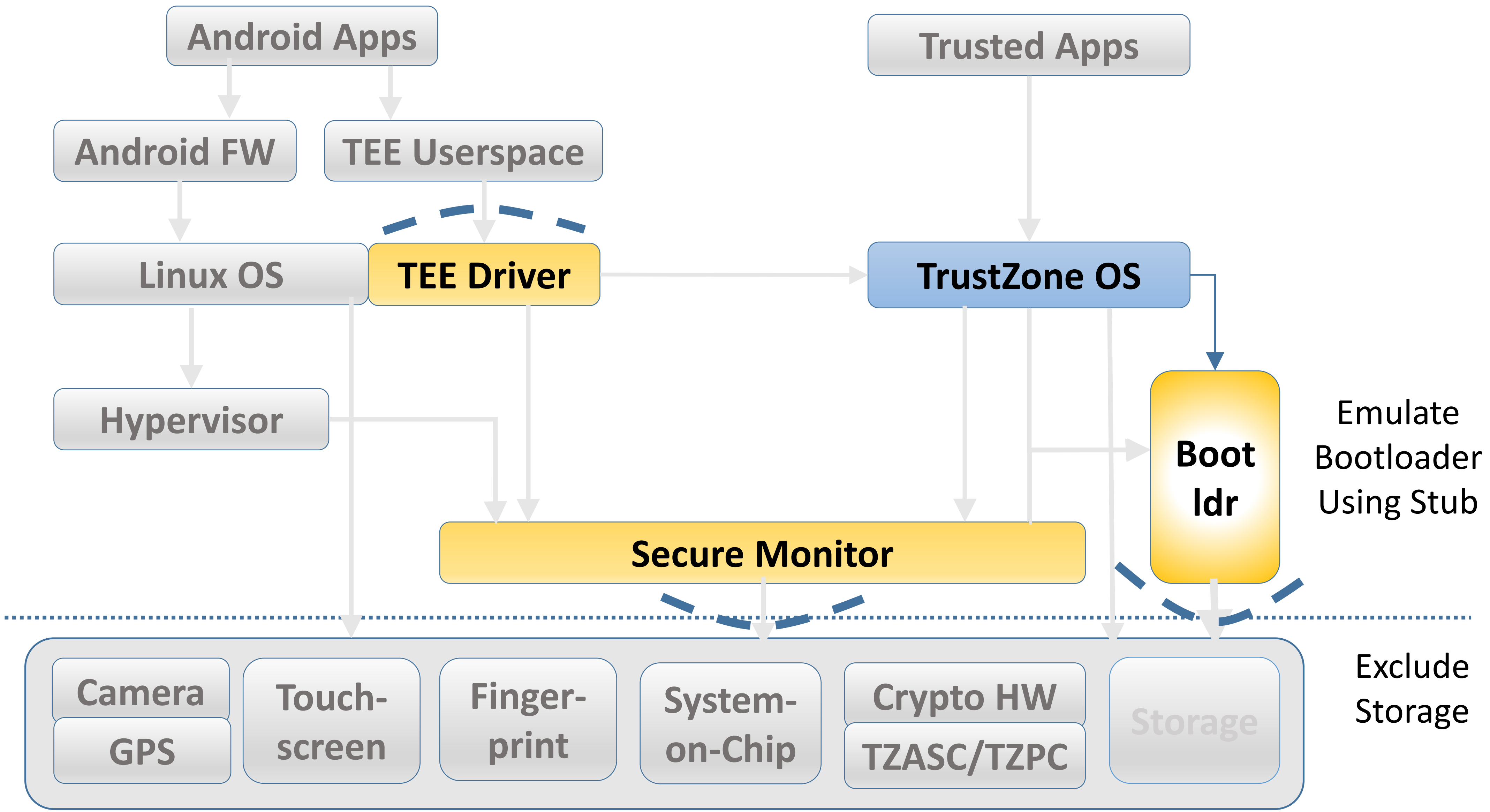

Emulation Effort Feasible Using Patterns

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- Patterns to Emulate Hardware (MMIO Loads and Stores)

```
# Constant read (CONSTANT_READ_REG)
v = read(CONSTANT_READ_REG);
if (v != VALID_VALUE)
    fail();

# Read-write (READ_WRITE_REG)
write(READ_WRITE_REG, v1);
v2 = read(READ_WRITE_REG);
if (v2 != v1)
    fail();

# Increment (INCR_REG)
v = read(INCR_REG);
if (read(INCR_REG) < v)
    fail();

# Poll (POLL_REG)
while (read(POLL_REG) != READY);
```

```
# Random (RAND_REG)
v1 = read(RAND_REG)
v2 = read(RAND_REG)
if (v1 == v2)
    fail();

# Shadow (SHADOW_REG1, SHADOW_REG2)
# Commit (COMMIT_REG)
# Target (TARGET_REG1, TARGET_REG2)
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v3 = read(TARGET_REG1)
v4 = read(TARGET_REG2)
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Constants	Low	13	8	2	3
Any value	Low	1	3	0	0
Simple value	Low	2	1	14	2
Complex values	High	2	1[note a]	0	0
Total	-	**18**	**13**	**16**	**5**
Emulated Secure Monitor Calls[note b]					
Return simple value	Low	0	-	3	-
Return constant	Low	1	-	5	-
Store/retrieve values	Low	1	-	2	-
Control transfer	High	3	-	2	-
Total	-	**5**	**-**	**12**	**-**

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Implementation

QEMU

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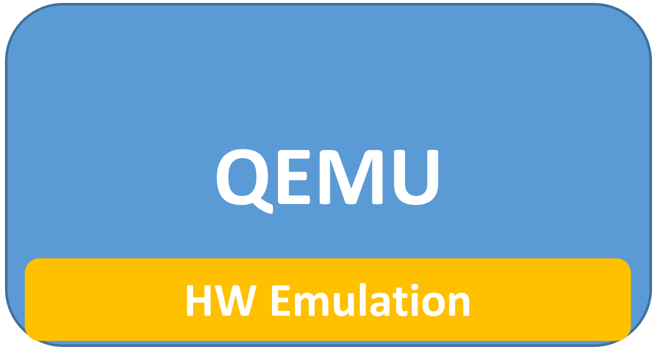

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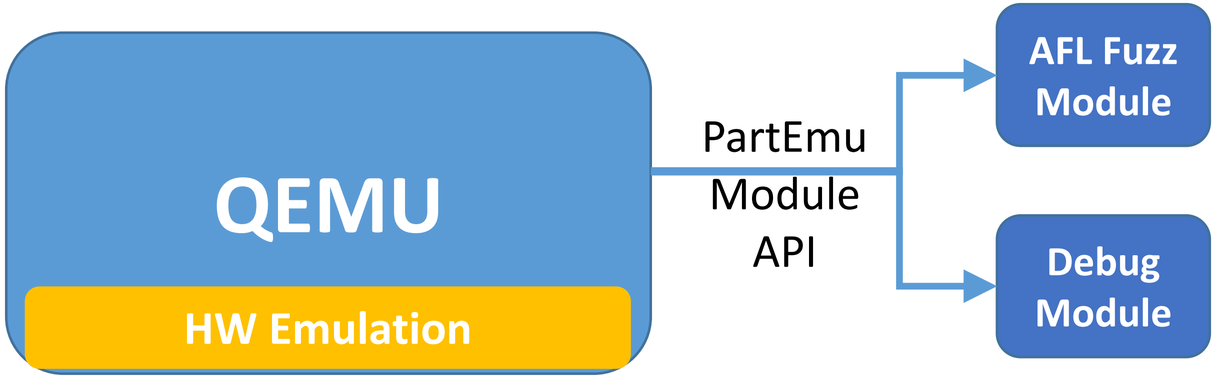

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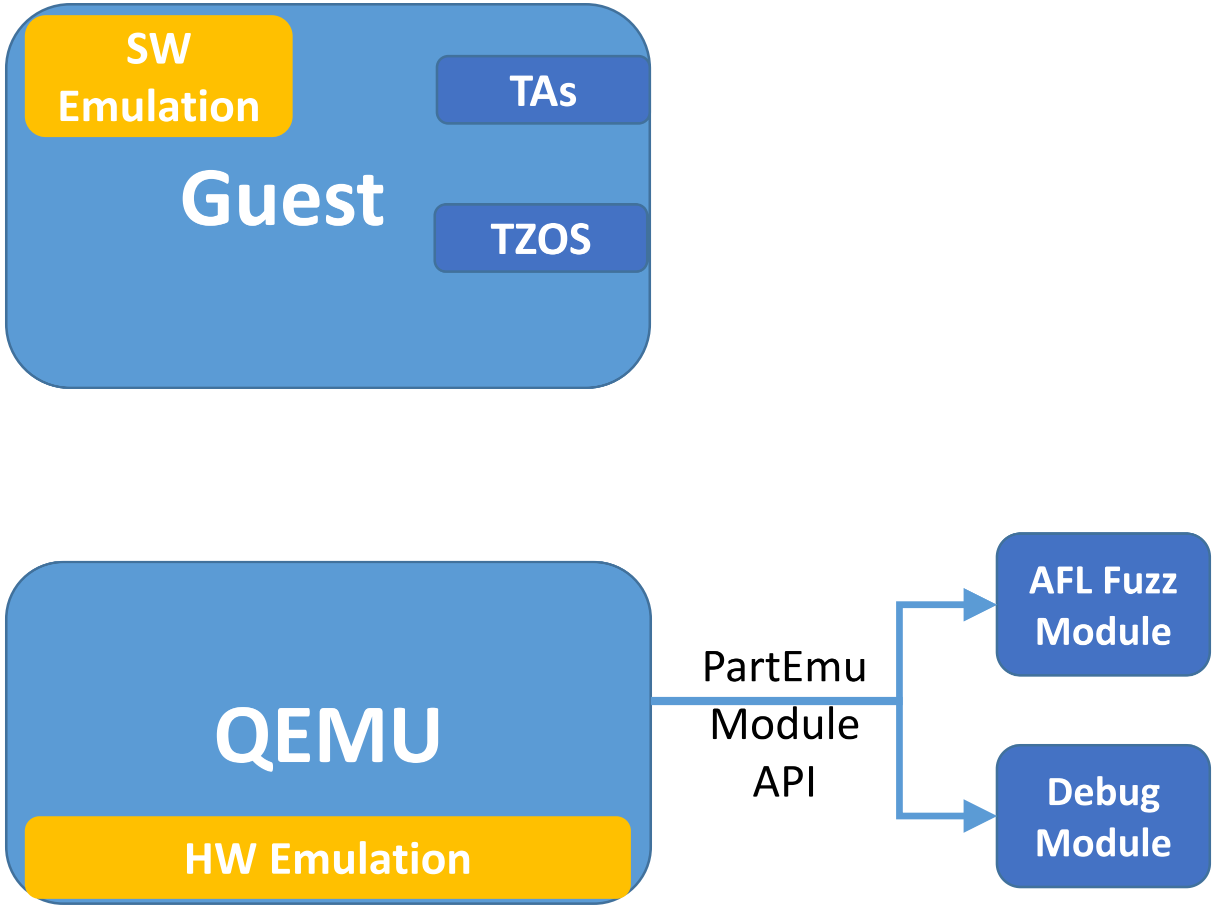

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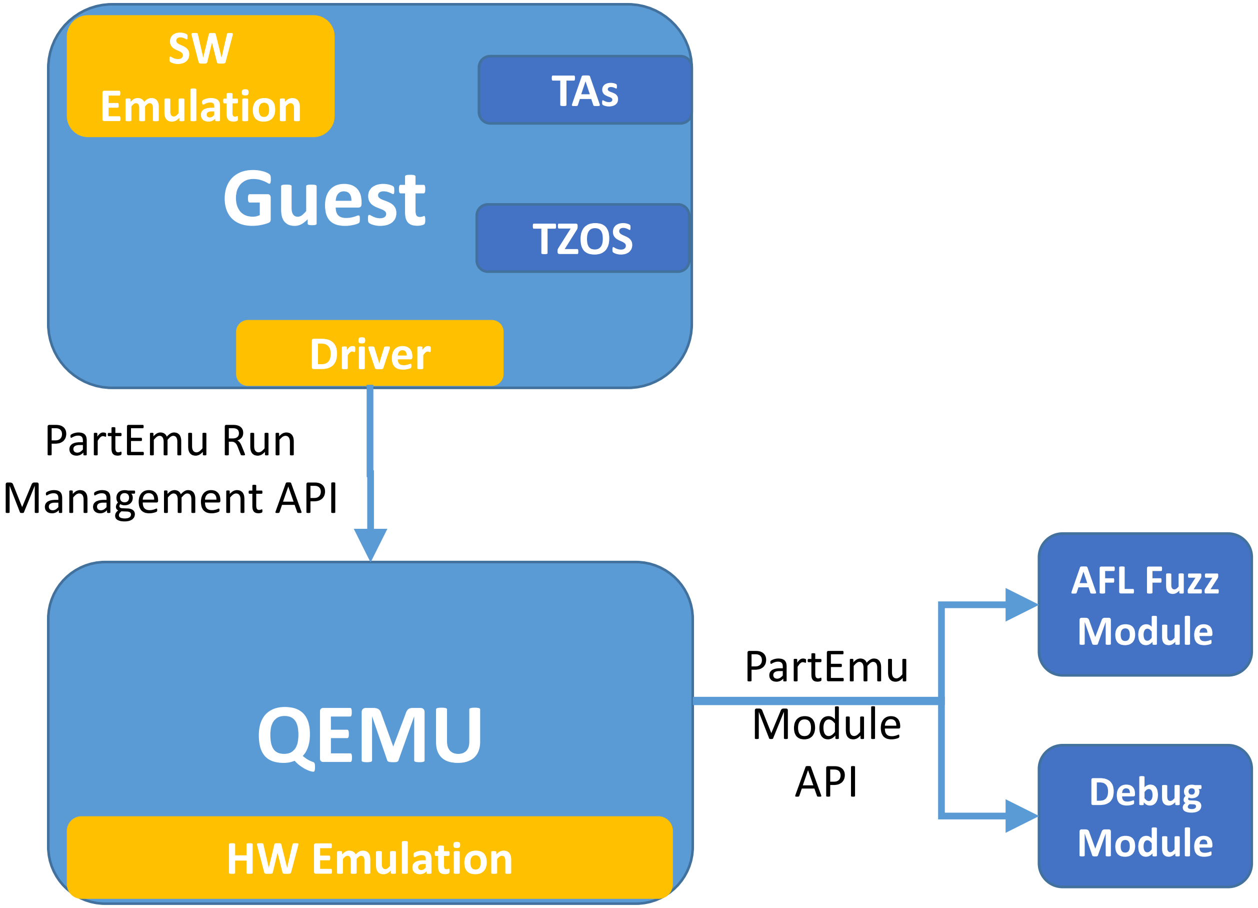

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Fuzz Testing TAs Using AFL

16 Firmware Images

Fuzz Testing TAs Using AFL

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12 Smartphone / IoT vendors

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12 Smartphone / IoT vendors

196 Unique TAs

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196 Unique TAs

AFL Crashed **48** TAs

Fuzz Testing TAs Using AFL

16 Firmware Images	**12** Smartphone / IoT vendors	**196** Unique TAs	AFL Crashed **48** TAs

- Found TZ-specific coding anti-patterns that led to crashes

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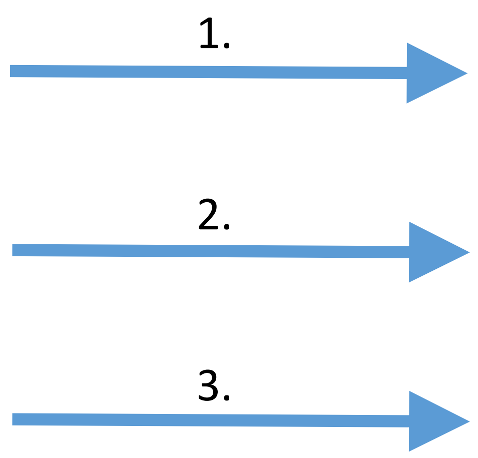


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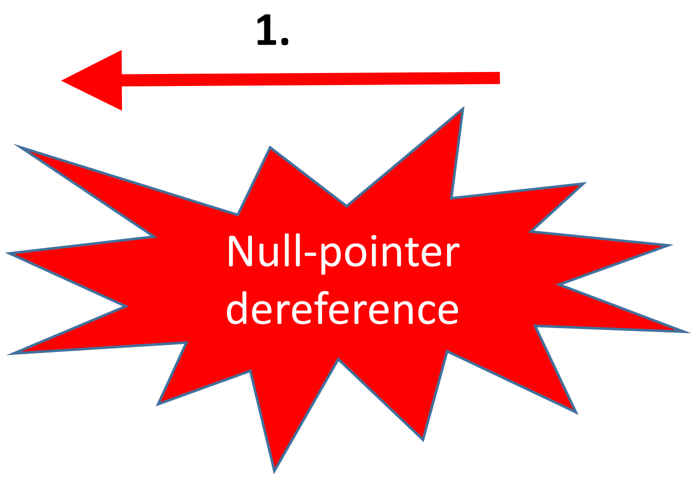

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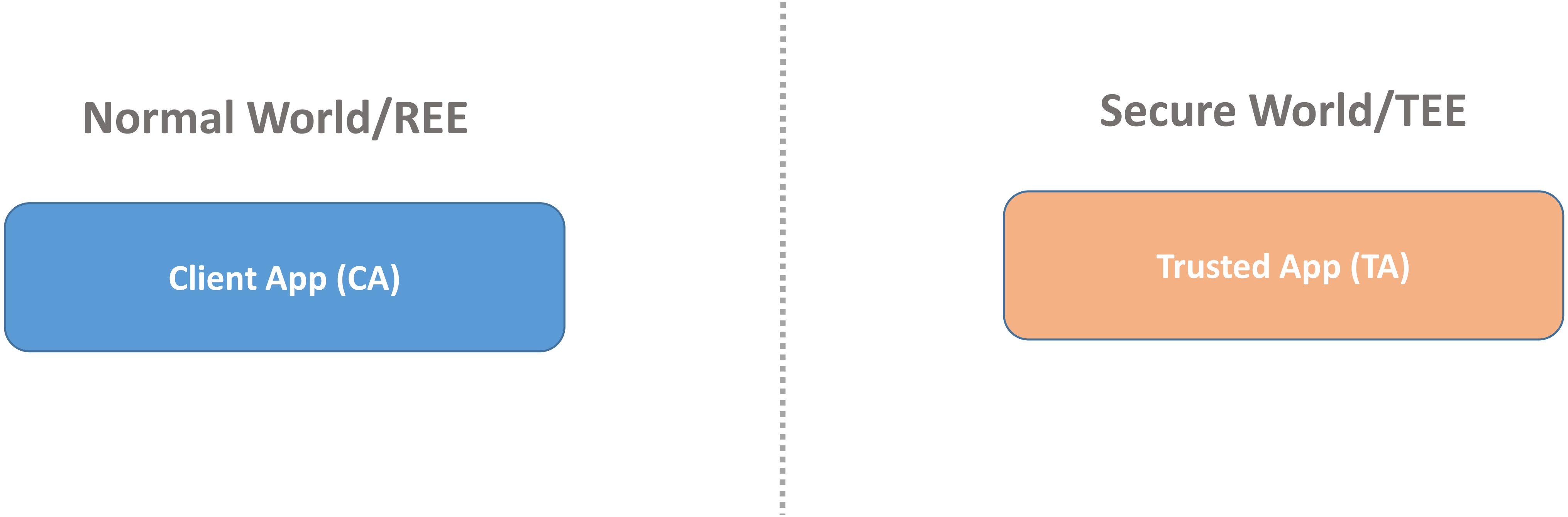
Null-pointer dereference

TA should properly handle any sequence of requests from CA

Anti-Pattern 2: Unvalidated Normal-World Pointers



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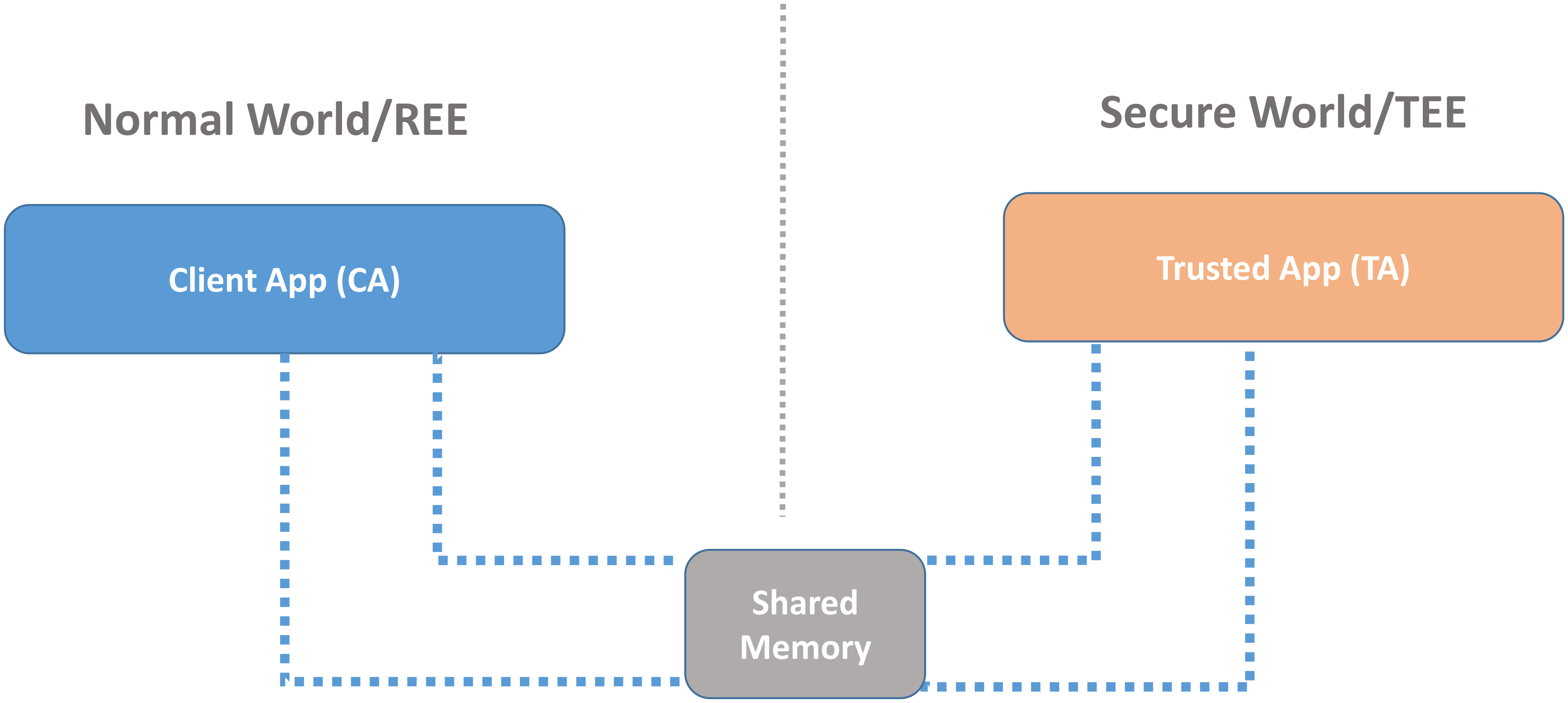

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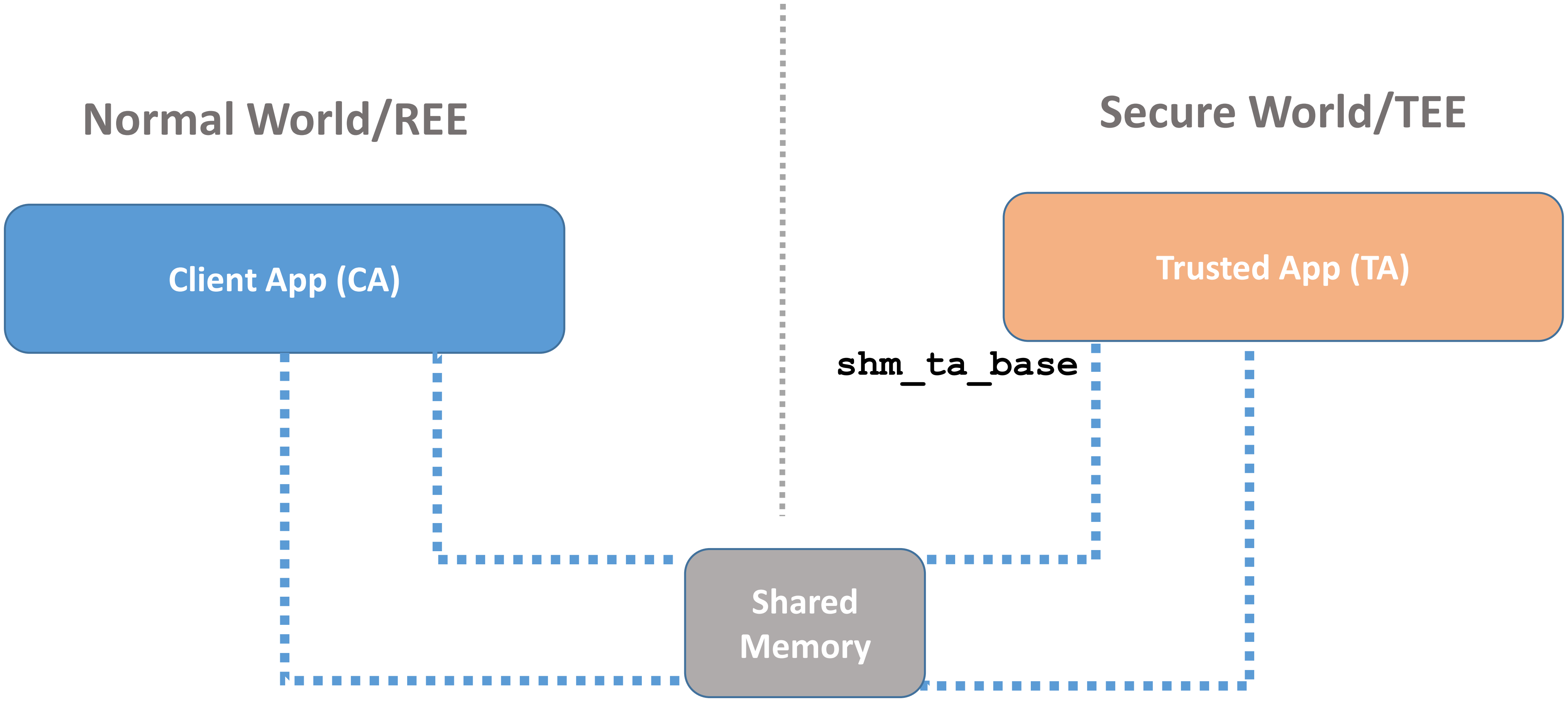

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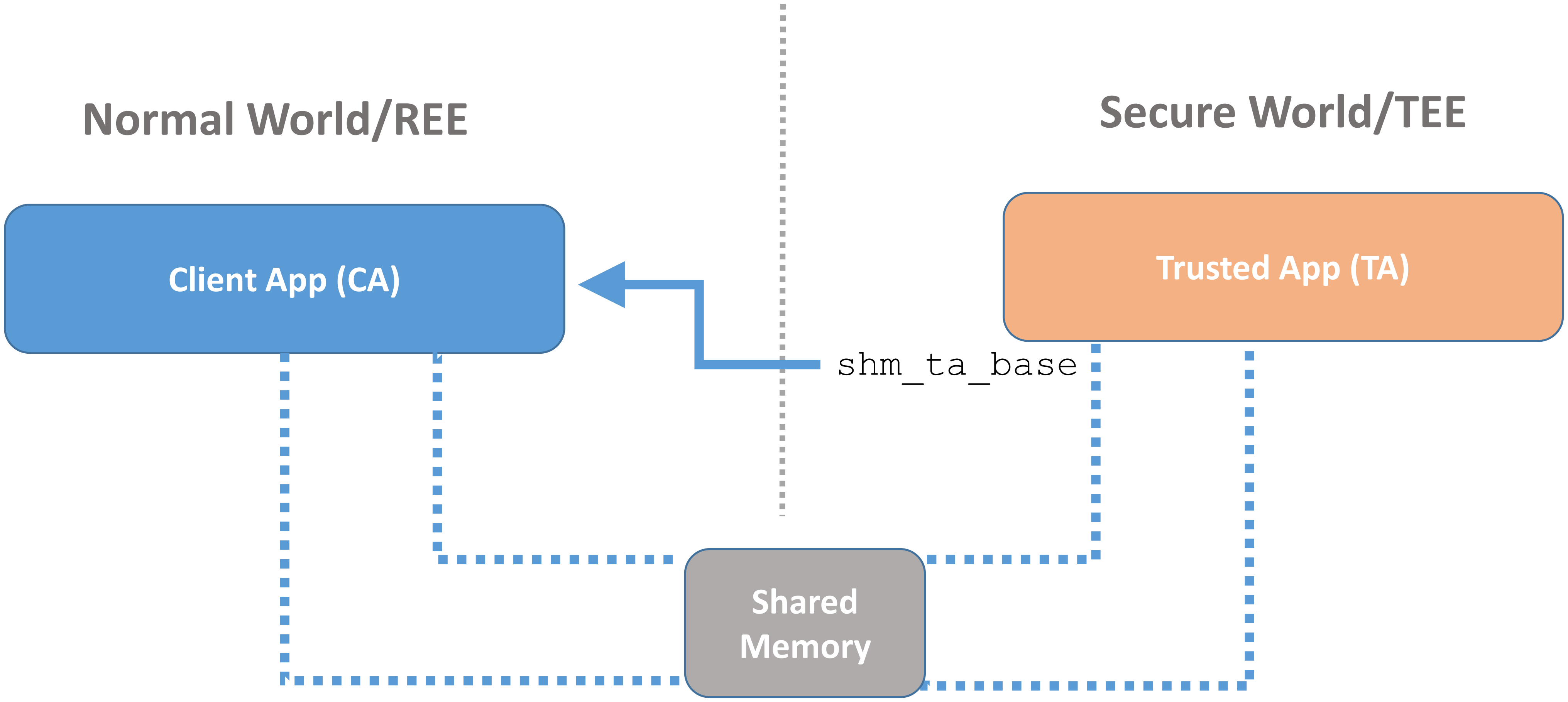

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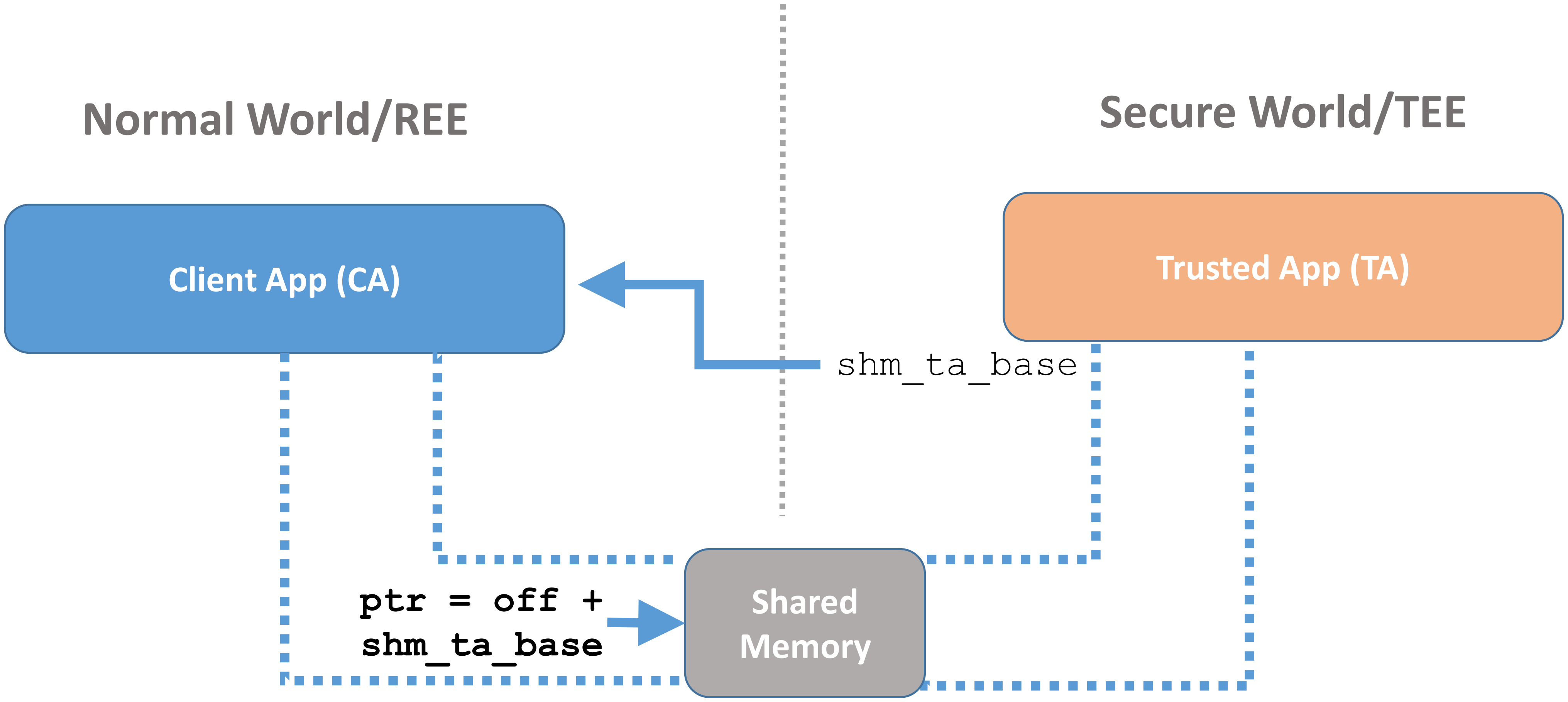

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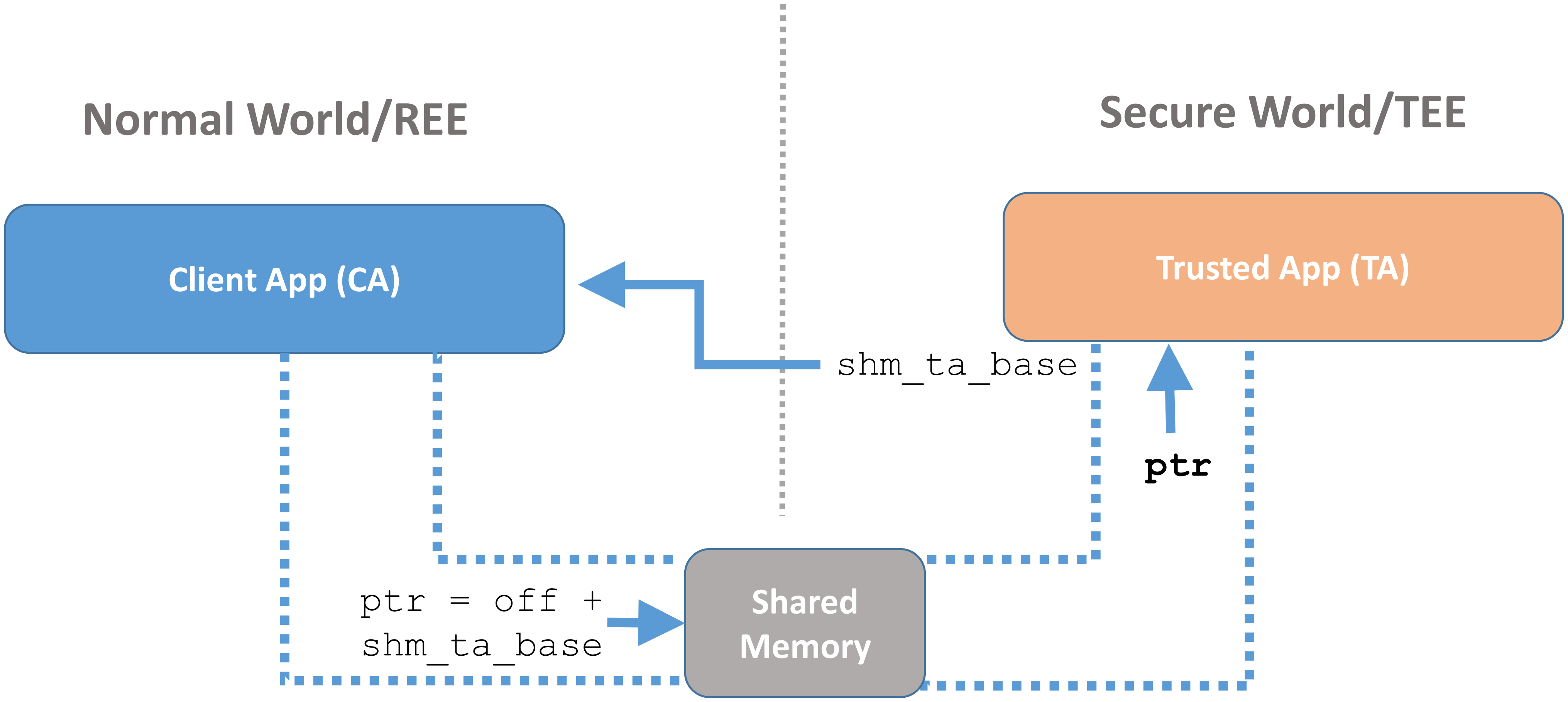

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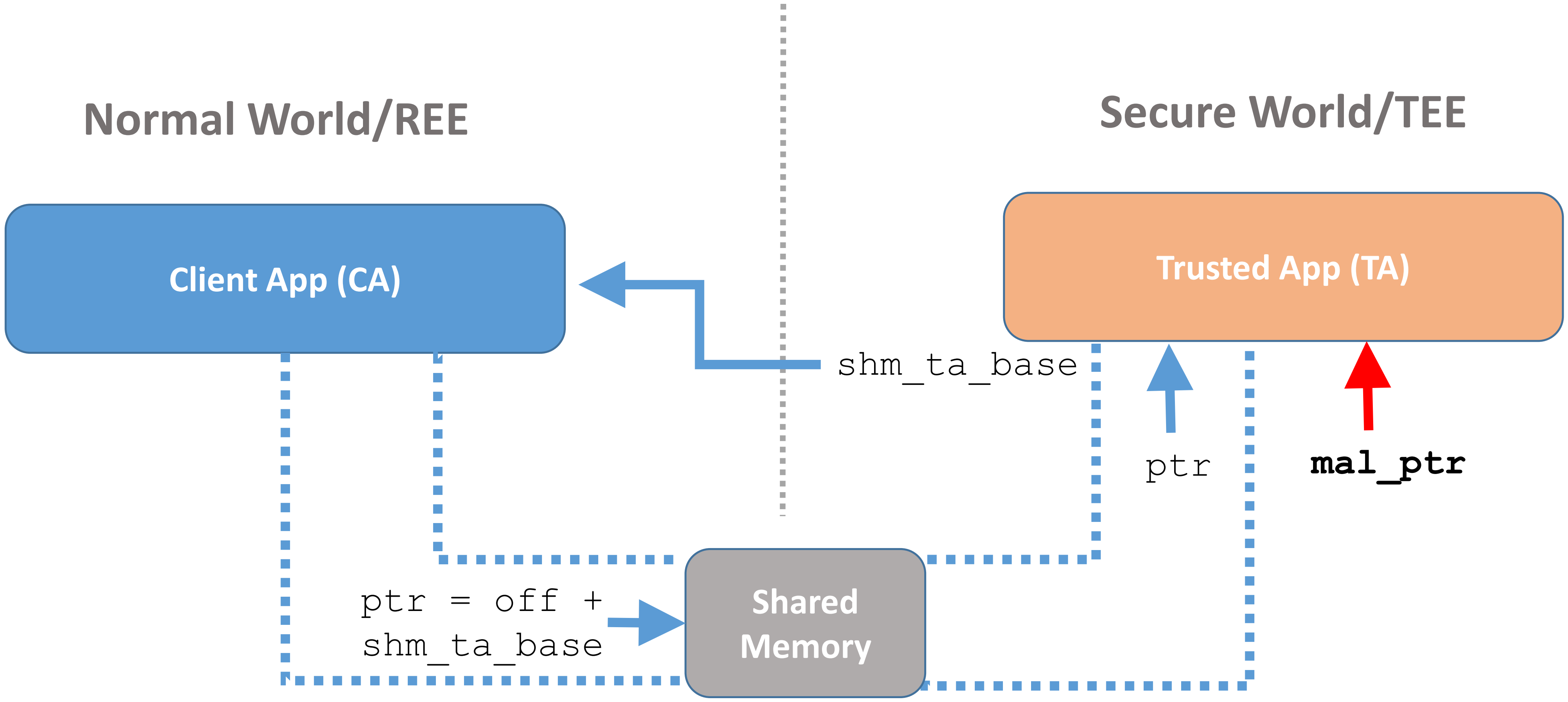

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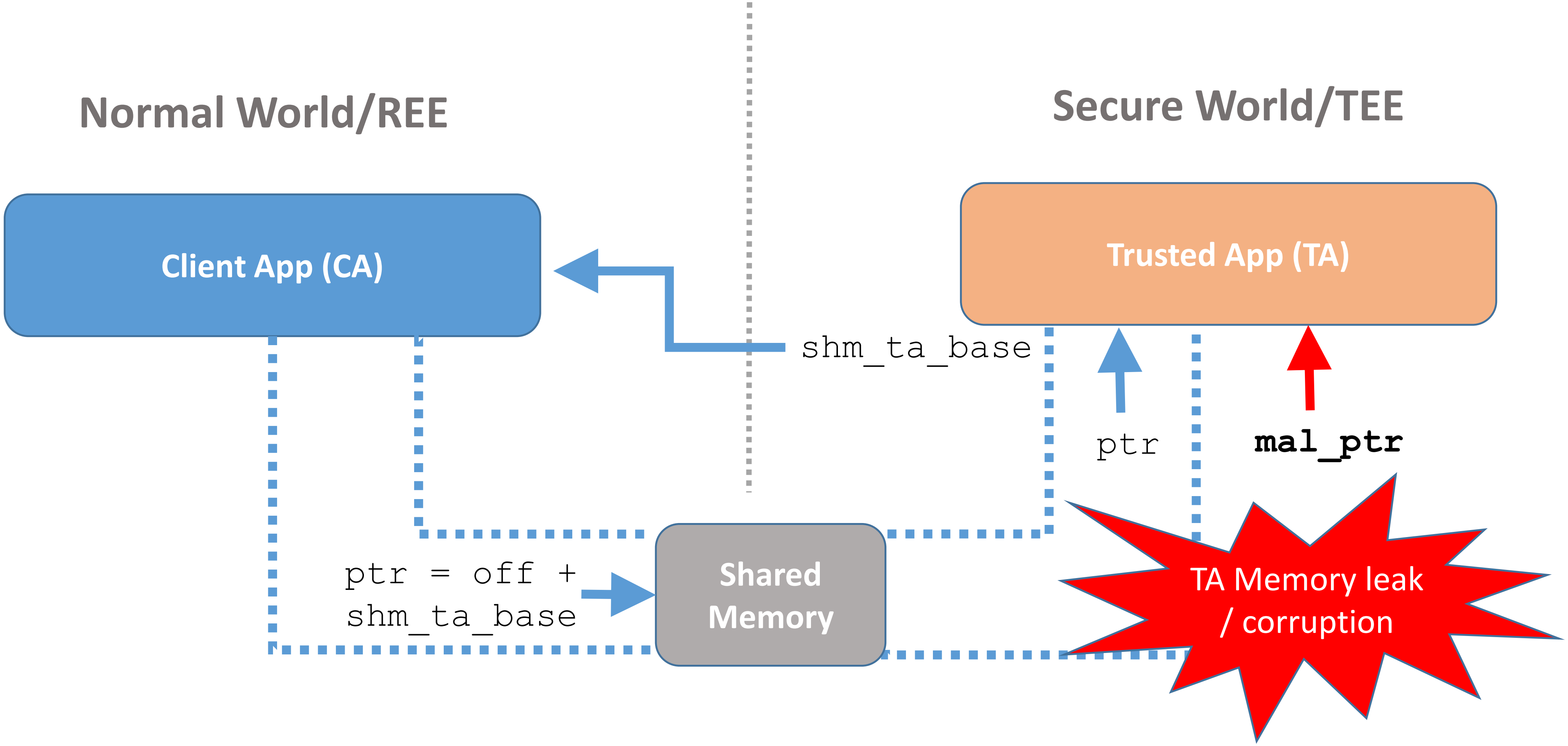

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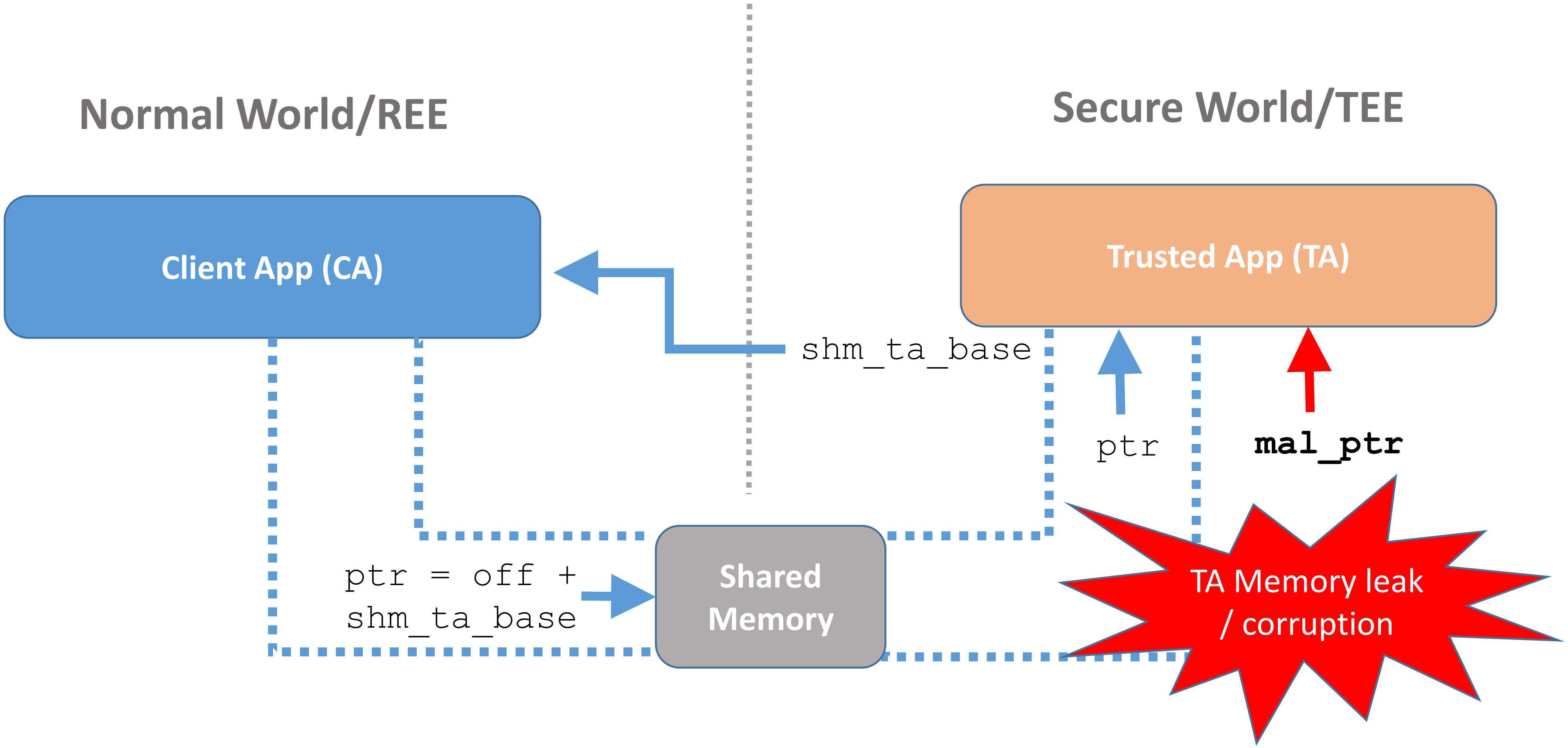

TA should check that CA-supplied pointers point to shared memory

Anti-Pattern 3: Unvalidated Parameter Types

- GlobalPlatform TEE API allows 4 parameters in TA calls
  - Each parameter can be either a value or a pointer to a buffer

```
TEE_Result TA_InvokeCommandEntryPoint(void *session, uint32_t cmd,
       uint32_t paramTypes, TEE_Params params[4])
{
       // Use params[0] as a buffer
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       switch (request_ptr->request) {
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TA Memory leak / corruption

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- We identified vulnerability patterns unique to TA development
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Thank you!