SCRUTINIZER: Towards Secure Forensics on Compromised TrustZone

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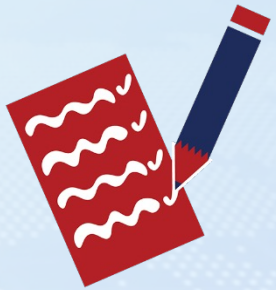
Agenda

- **Background**
- SCRUTINIZER: Towards Secure Forensics on Compromised TrustZone
- Evaluation
- Summary



Trusted Execution Environment (TEE) Protects Data in Use

TEE is a key technology in Confidential Computing; Hardware-assisted security design

Intel SGX/TDX

Keystone

AMD SEV

Arm TrustZone/CCA

TEE has been applied to the computing platforms and commercial products of several companies

Microsoft Azure Cloud

Huawei Cloud

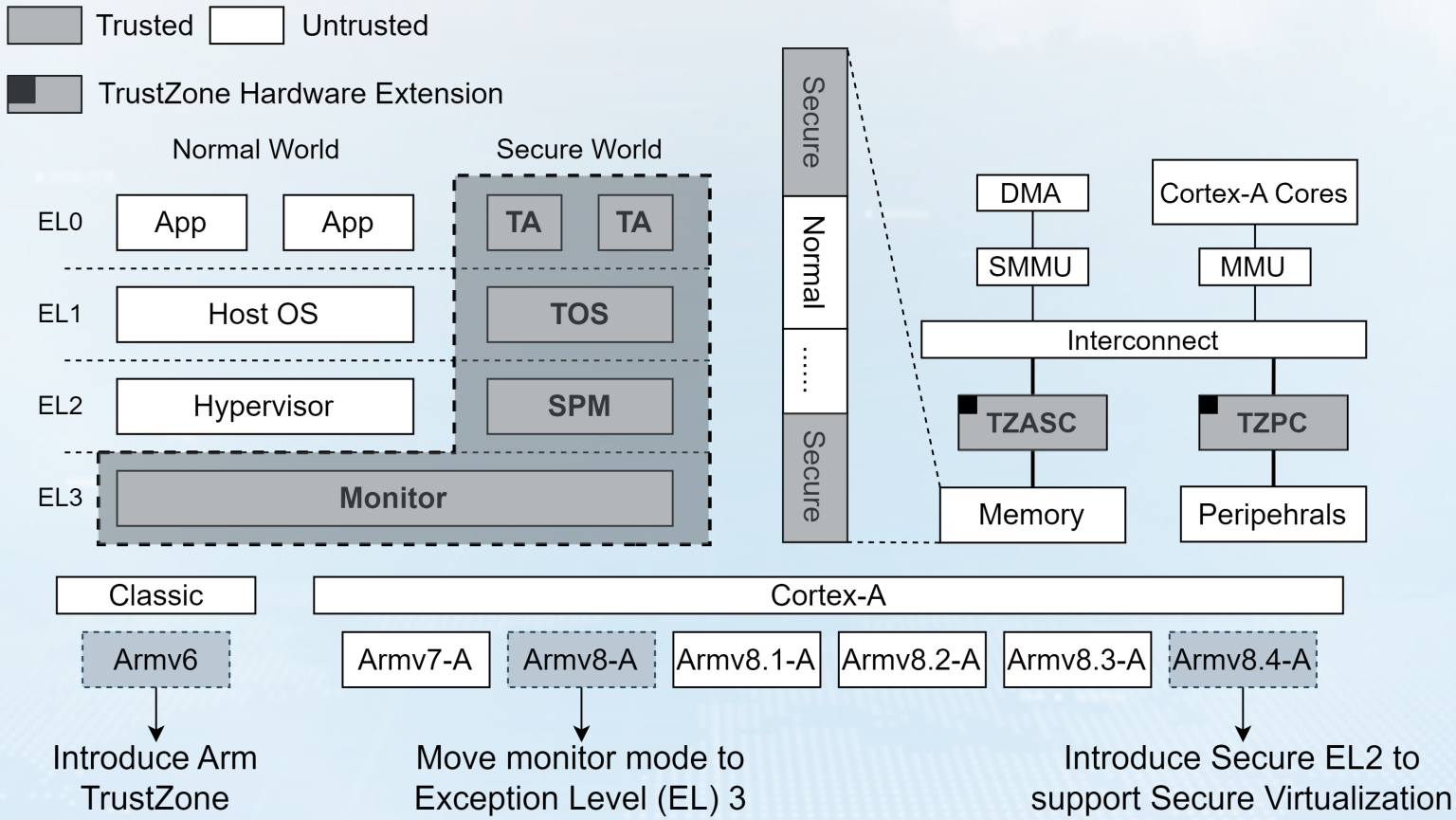
Google Cloud

NVIDIA H100

Ant Occlum

Arm TrustZone TEE

- TrustZone was first introduced in ARMv6 and provides a hardware-based isolation of two execution environments **(Normal World and Secure World)**
- TrustZone ensure isolation two words through hardware extensions (e.g. TZASC and TZPC)
- Since Armv8.4, TrustZone was extended to support virtualization **(Secure EL2)**



TrustZone System is Susceptible to Vulnerabilities

More than 207 vulnerabilities[#] have been identified in Arm **TrustZone system** [*] over the past five years

TEE System	CVE Databases	SVE Databases	Scientific Publications	Miscellaneous Reports	Source Code	Total
Qualcomm TEE	92	-	-	7	-	99
Trustonic TEE	5	17	-	4	-	26
Huawei TEE	3	-	-	1	-	4
Nvidia TEE	10	-	-	-	-	10
Linaro TEE	3	-	-	1	36	40
Other	11	-	15	2	-	28
Total	124	17	15	15	36	207

[#]Sok: Understanding the prevailing security vulnerabilities in trustzone-assisted tee systems. In IEEE SP, 2020

[*] We use 'TrustZone systems' to refer to the software in Secure World, including trusted apps, trusted OS and secure hypervisor (S.EL0 – S.EL2)

Motivation: TrustZone Inspection

More than 207 vulnerabilities have been identified in Arm TrustZone system over the past five years

It's crucial to add extra security forensics* to check TEE systems

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*Capture snapshots of target for backend analysis,
letting the platform owner for incident response or periodic security scans

Existing Approaches Presents Limitations

1. Out-TEE

External methods for TrustZone are **hindered** by TrustZone's protection

2. In-TEE

Internal solutions within Secure World **cannot be isolated** from the compromised TrustZone

3. TZASC

TrustZone hardware features (e.g., **TZASC**) are insufficient to protect a inspection system

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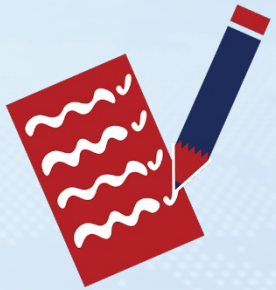
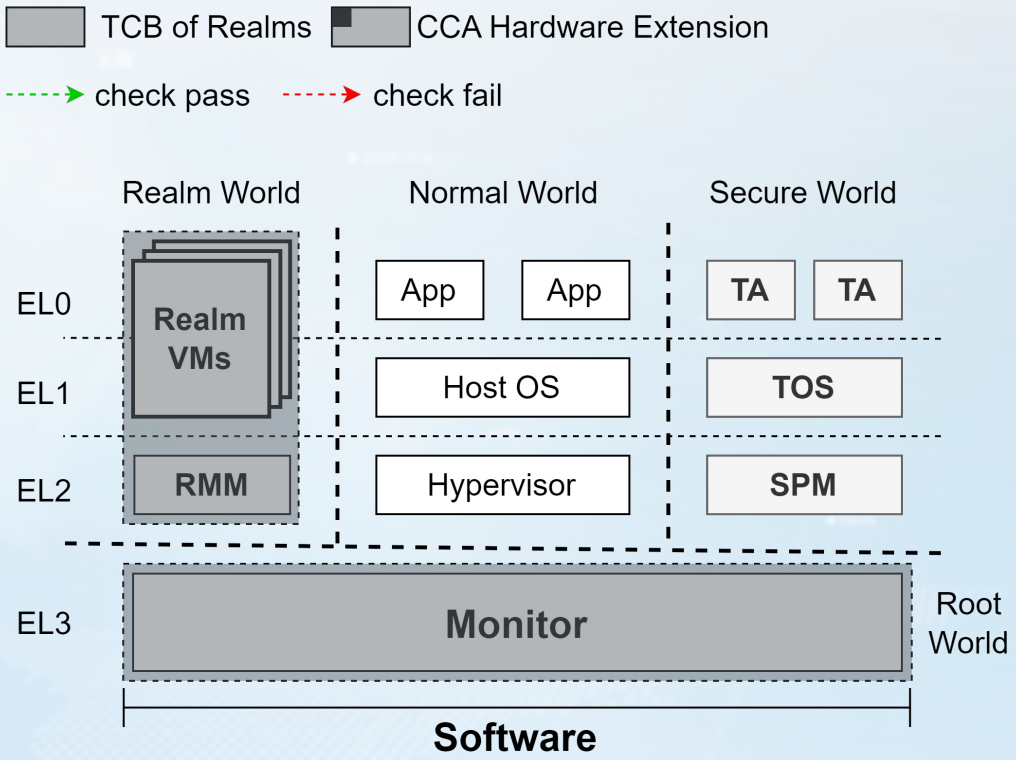
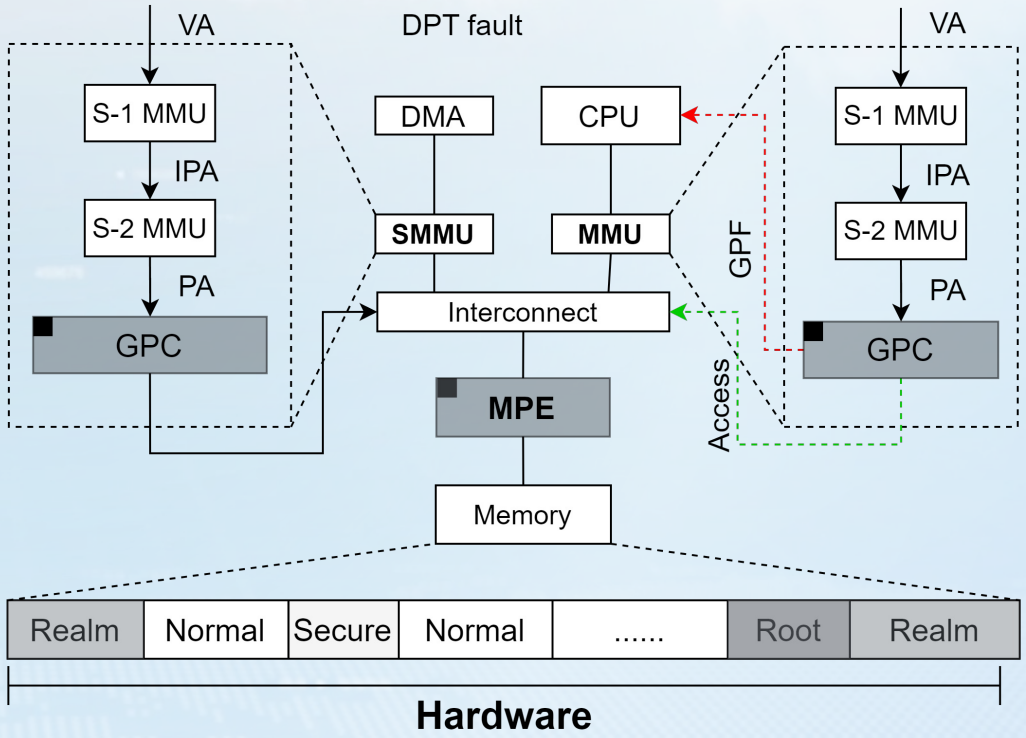


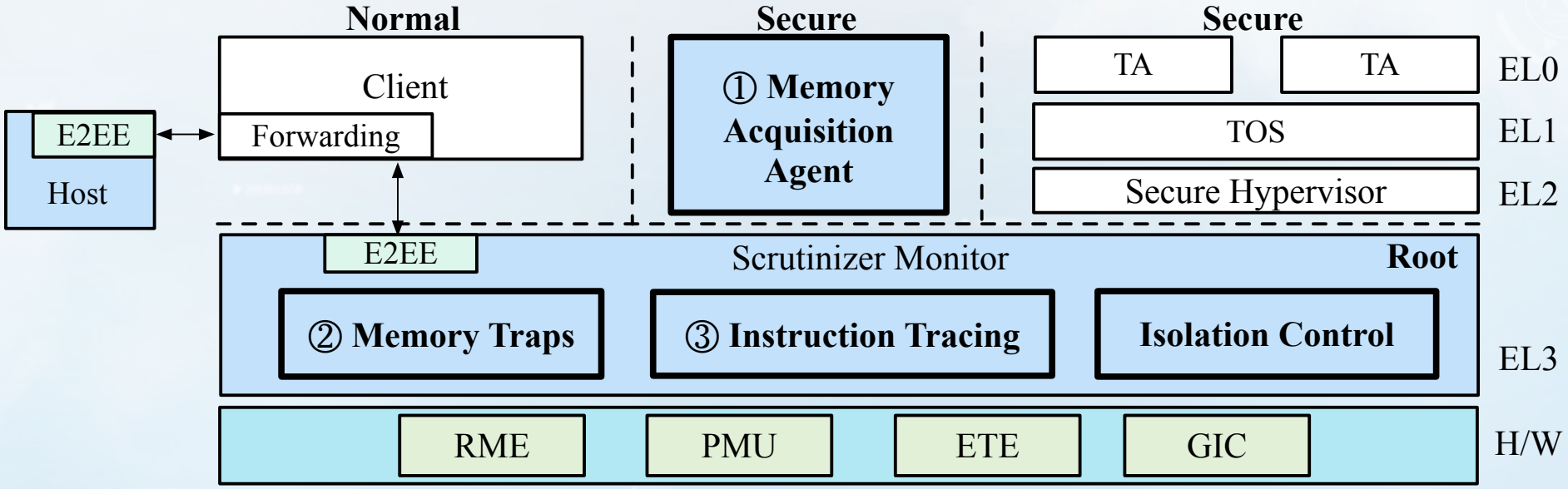
Arm Confidential Compute Architecture (CCA)

- CCA was announced in March 2021 and introduced as supplement to Armv9.2-A
- CCA introduces a set of new hardware features
  - New isolation boundaries for third party confidential computing **(Root and Realm Worlds)**
  - Dynamic assignment of memory to different worlds **(Granule Protection Check, GPC)**





SCRUTINIZER based on **Arm CCA Platform:** Targeting the **TrustZone software** in **Secure World**, including trusted apps, trusted OS and secure hypervisor



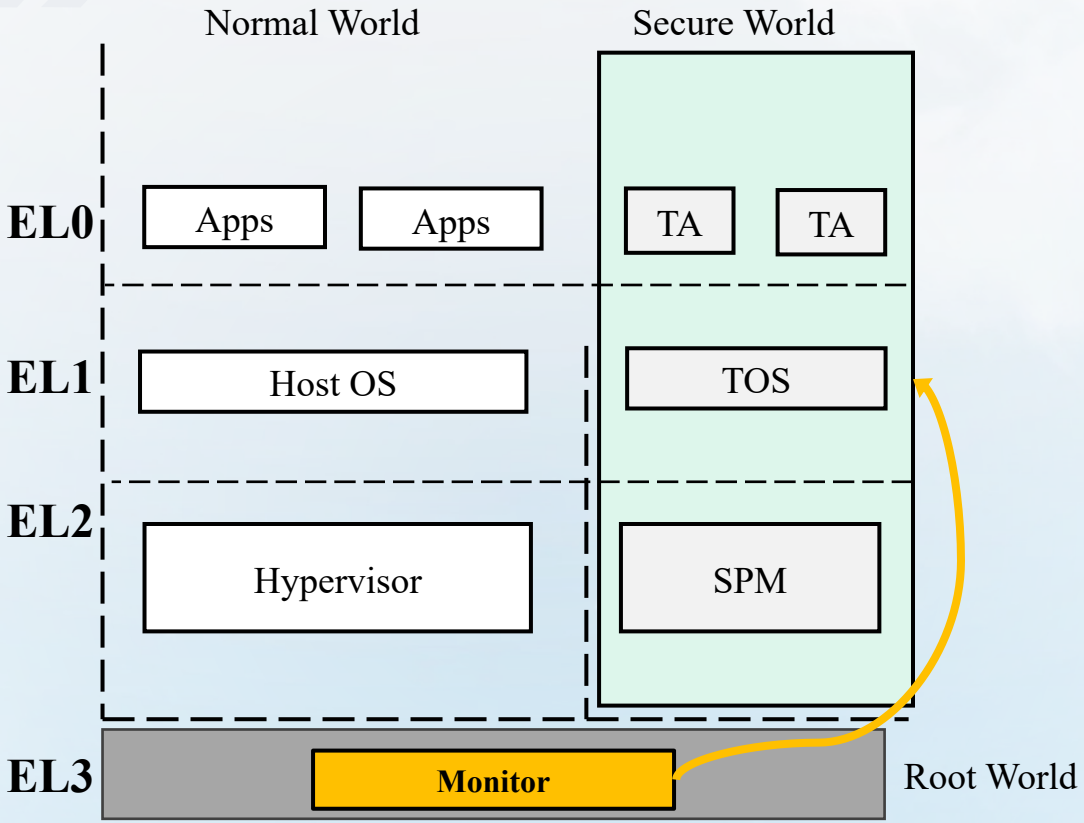
SCRUTINIZER **Monitor** in the EL3 **Root World** protecting the components from compromised TrustZone

- **CCA's RME-based isolation; TCB and performance optimization**

Three **secure forensic functions** with several standard hardware features (**RME, PMU, ETE, GIC**):

- **① Memory Acquisition; ② Memory Access Traps; ③ Instruction Tracing**

Memory Acquisition in Root World?



- Challenge1: Memory acquisition in the Root World **enlarges** the Root World **codebase**
- Challenge2: Acquiring Secure World memory from the Root World is **slower than native access**

Solution1: Memory Acquisition with TCB Optimization

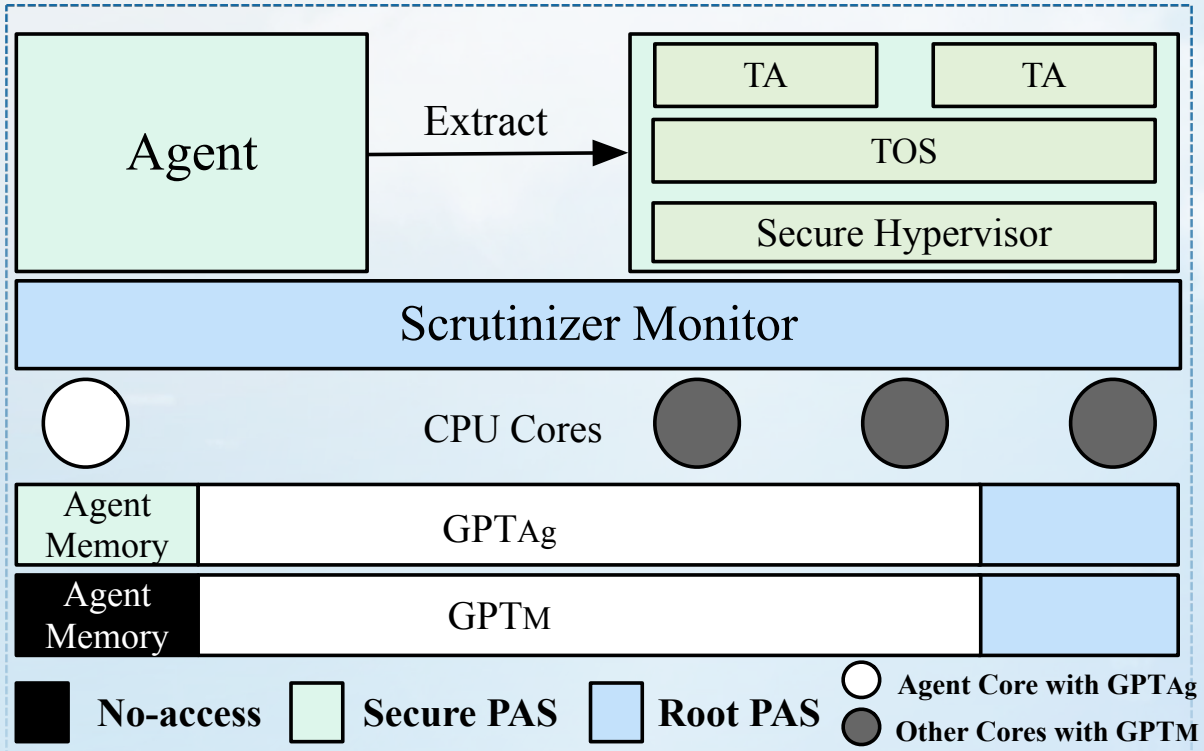
Codebase Reduction Strategy

① **Memory Acquisition Agent: Decouple** the memory acquisition functionality from the **Monitor** and **integrate** it into an **agent**

- ✓ **Reduce the expanded codebase of Monitor and ensure that the Root World's size does not grow with the agent's code**

② **Isolation Control for Agent**: Establish an execution domain **within Secure World** via **dual-GPTs isolation**

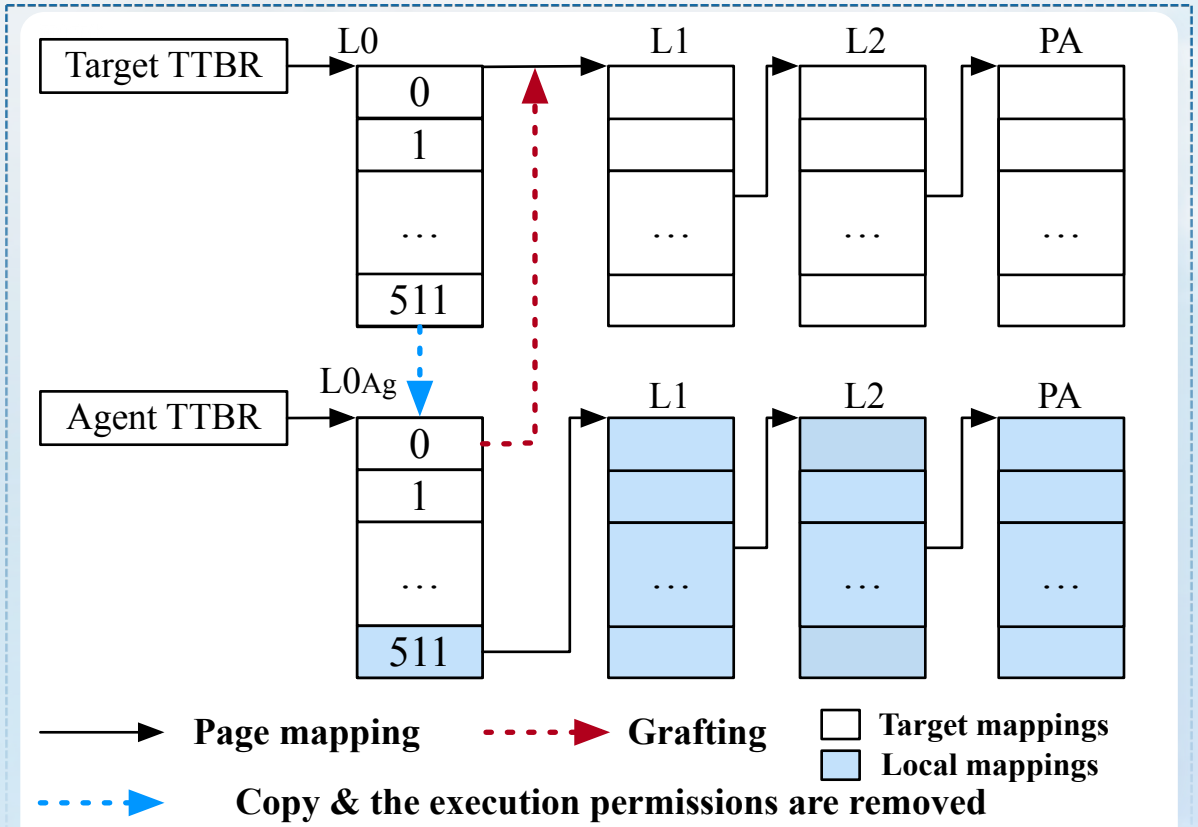
- ✓ **Ensure that the agent executes within Secure World yet remains isolated from compromised TrustZone systems**



Solution2: Memory Acquisition with Performance Optimization

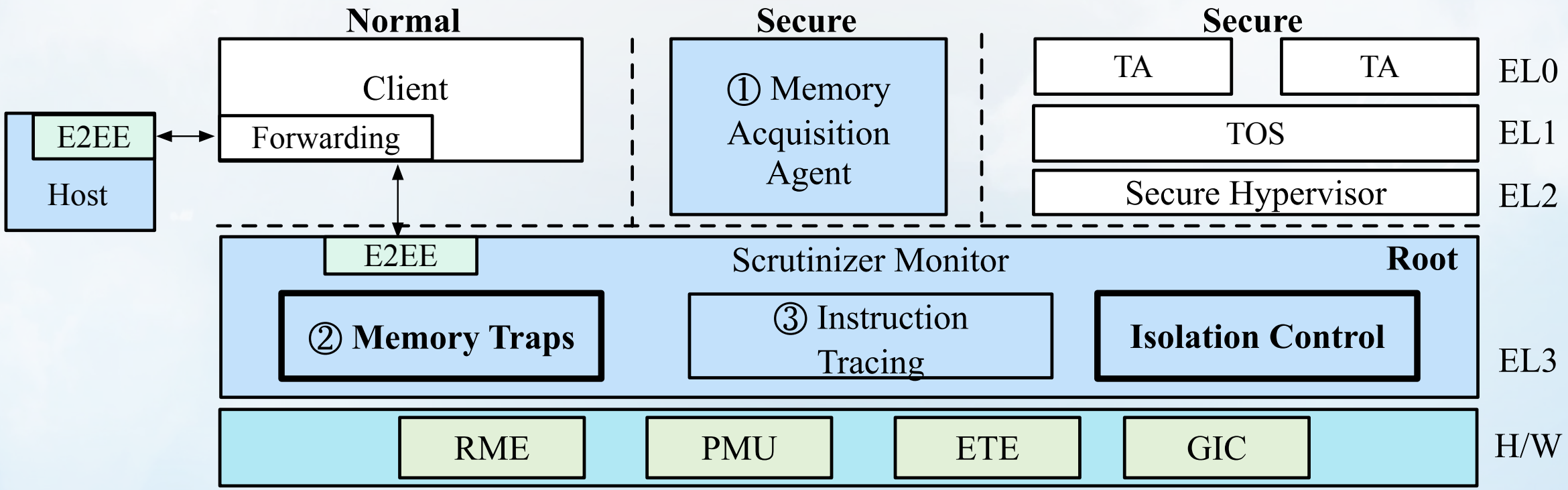
Grafting Mechanism

- Copy the **first-level page table**, i.e., the **target's L0 table**, to the agent's local mappings, and **directly graft the remaining levels**
  - ✓ The **local mappings** are allocated in the agent memory, which is **inaccessible** to TrustZone systems
  - ✓ This enables **efficient access** by the agent to the target memory **without** building **additional operations (VA_TZ → PA_TZ → VA_Ag)**



Since agent run in the Secure EL1/EL2, enabling it to have the capability to directly use the TrustZone virtual address space (VA_TZ) for reading memory (infeasible at EL3 Monitor)

② Memory Access Traps



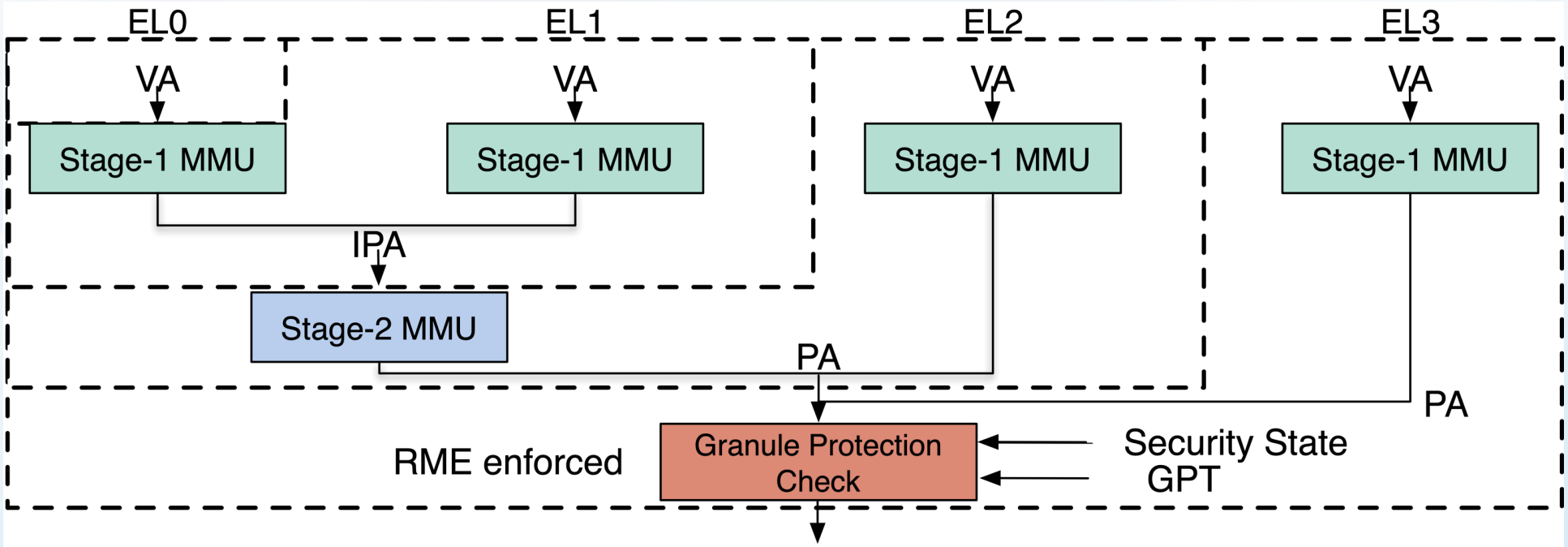
Scrutinizer **monitor** in the EL3 **Root World** protecting the components from compromised TrustZone

- CCA's RME-based isolation; TCB and performance optimization

Three **secure forensic functions** with several standard hardware features (**RME, PMU, ETE, GIC**):

- ① Memory Acquisition; ② **Memory Access Traps**; ③ Instruction Tracing

Secure Memory Access Traps with Platform Compatibility

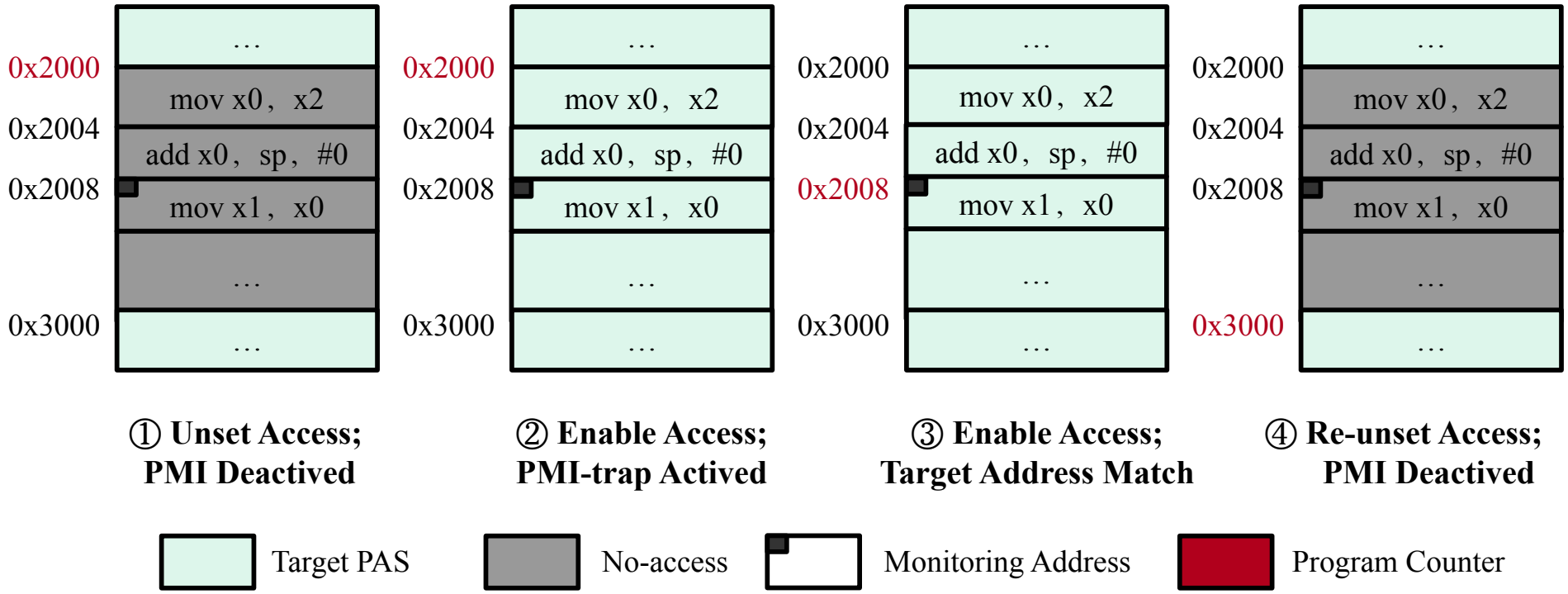


When RME-enforced GPC verification fails, a Granule Protection Fault (GPF) is generated to prevent unauthorized access. This fault can be rerouted to the EL3 Root world.

Challenge of GPC-based Memory Traps

- The granule protection information (GPI) of GPT corresponds to a page (typically 4KB) is coarse
- GPT cannot support page-like permissions, i.e., execution-only or read-only

Solution: Fine-grained Memory Access Traps



- GPT-based security traps (minimum granularity of one page, 4KB)
- Fine-grained improvement: Leverage PMU and GIC hardware features to enhance traps to instruction-level granularity
- Isolation control for PMU and GIC: MMIO isolation and system register restriction

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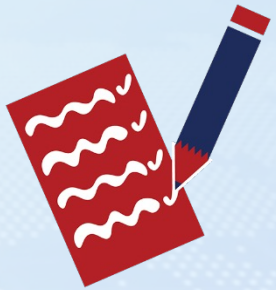


Evaluation

Functional Prototype: Arm FVP Base RevC-2xAEMvA with RME enabled

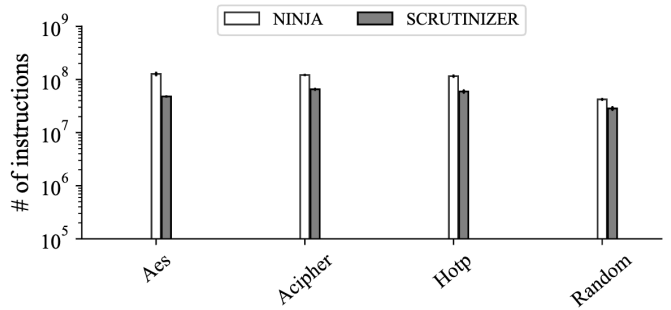
Performance Evaluation based on the Armv8 Juno R2 Board with GPT-analogue + FVP instruction counts

TABLE IV: Acquisition performance comparison in time cost with different memory size.

# of Size	Kernel			Hypervisor		
	Vanilla	SCRUTINIZER	NINJA	Vanilla	SCRUTINIZER	NINJA
4KB	1.63 µs	4.90 µs	27.90 µs	1.60 µs	3.65 µs	27.88 µs
256KB	77.20 µs	82.60 µs	1.76 ms	77.41 µs	81.72 µs	1.76 ms
512KB	142.80 µs	146.20 µs	3.52 ms	135.12 µs	144.80 µs	3.52 ms
1MB	326.60 µs	334.20 µs	7.05 ms	323.61 µs	333.11 µs	7.05 ms
4MB	1.20 ms	1.25 ms	28.21 ms	1.21 ms	1.24 ms	28.20 ms
16MB	5.46 ms	5.51 ms	112.81 ms	5.38 ms	5.46 ms	112.80 ms

Compared to EL3-based memory acquisition (NINJA*), SCRUTINIZER is improved by 20x

SCRUTINIZER's memory trap overhead is reduced by 49.5%



*NINJA: Towards Transparent Tracing and Debugging on ARM, USENIX Security 2017

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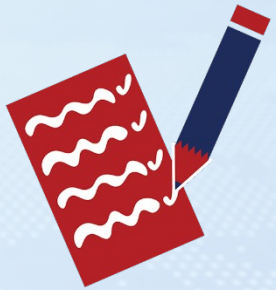

Conclusions

- SCRUTINIZER provides a secure forensics framework for compromised TrustZone
  - Leverage the hardware features of Arm CCA to create an isolated forensic environment
  - Optimize the TCB and performance
  - Ensure platform compatibility

- Source Code
  - https://github.com/Compass-All/SCRUTINIZER