IPADS, Shanghai Jiao Tong University

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vTZ: Virtualizing ARM TrustZone

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ARM

ARM ARM ARM VR

Server SoC
With Virtualization

ARM

Security systems
with TrustZone

OTP

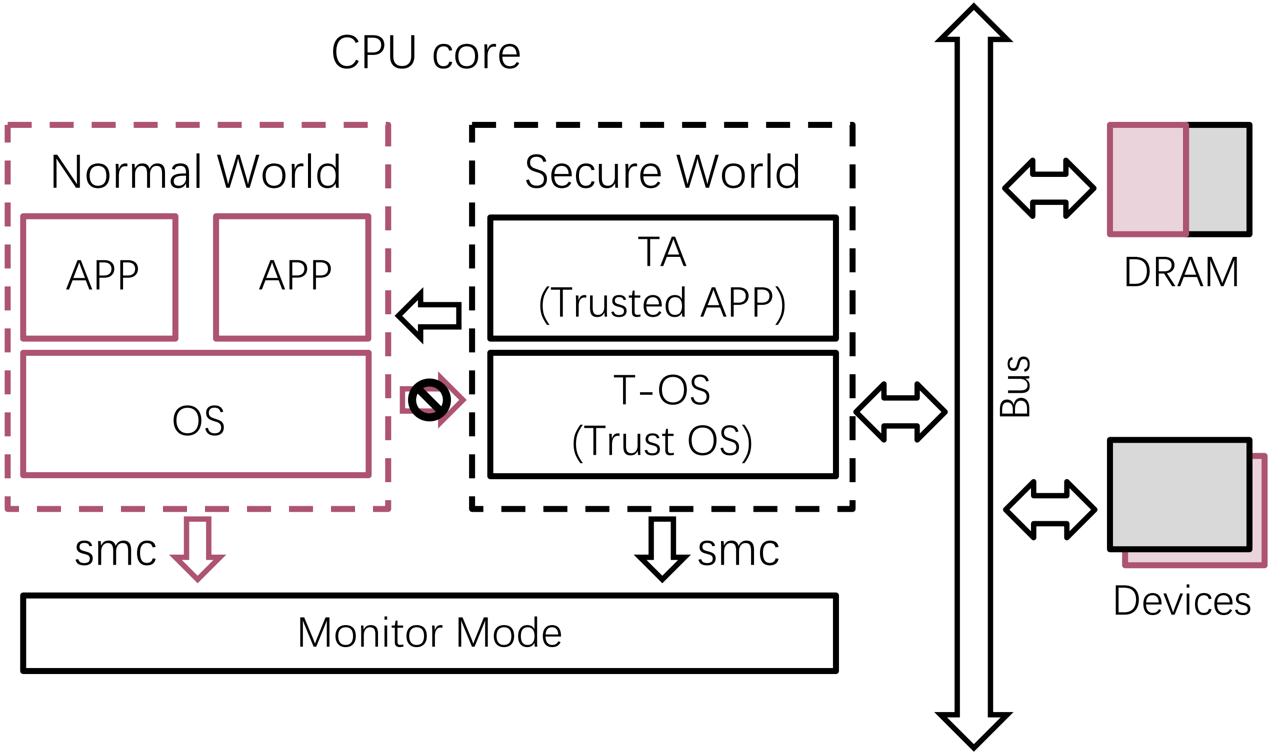
Attested

TrustZone®
System Security by ARM

Pay fTPM

Can VMs use TrustZone?

ARM TrustZone



- Two isolated execution environments
- Different worlds switch to each other by “*smc*” instruction
- Hardware resources can be partitioned into secure/non-secure part dynamically
  - Secure world can access all
  - Normal world can only access non-secure part

TrustZone Usage

- TrustZone on *mobile phone*
  - Secure storage, key protection, kernel integrity checker, malware detector, etc.
- TrustZone on *ARM server*
  - Has similar scenarios and requirements

TrustZone + Virtualization

Requirements	Ideal	Reality
Each guest VM has a secure world	✓	
Guest VM can choose its own trust OS	✓	
Isolation between different guests’ secure worlds	✓	
Hardware resources partition between guest’s normal world and secure world	✓	

TrustZone + Virtualization

Requirements	Ideal	Reality
Each guest VM has a secure world	✓	✗
Guest VM can choose its own trust OS	✓	✗
Isolation between different guests' secure worlds	✓	✗
Hardware resources partition between guest's normal world and secure world	✓	✗

The OS in secure world becomes single point of failure

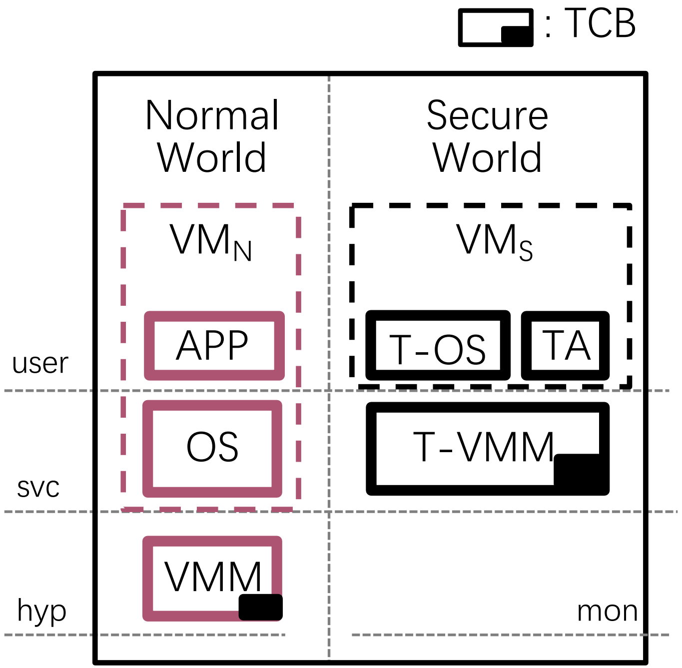
- cve-2015-4421, cve-2015-4422, cve-2015-6639

Goals

- **Multiplexing** the secure world for guest VMs
  - Each guest VM can choose its own trust OS
  - Isolate each guest’s secure world
  - Provide hardware resources partition for each guest
- **Compatibility** for existing software in secure world
  - Provide same functionalities and interfaces with real TrustZone
  - Support existing trust OS
- **Minimizing TCB** of the new architecture

Alternative Designs

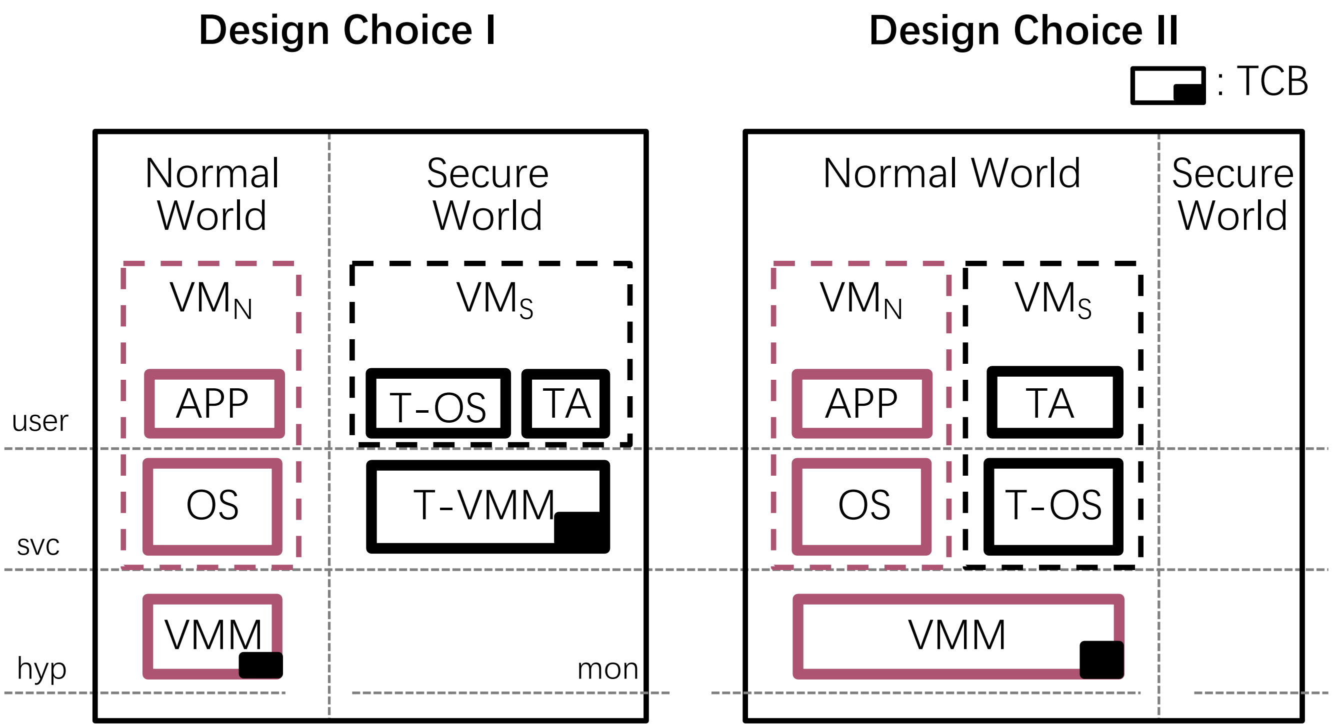
Design Choice I



- Large TCB
- No compatibility
- Bad performance

- T-VMM (trusted VMM) in the secure world
  - Virtualize guest secure world with VM$_S$
- VMM in the normal world
  - Virtualize guest normal world with VM$_N$
- No virtualization extension in secure world
  - Both guest's trust OS and TA run in user mode
  - ARM has virtualization unfriendly instructions
    - Trust OS needs to be modified
- System TCB
  - T-VMM (~10K of LoC)
  - VMM (millions of LoC)

Alternative Designs

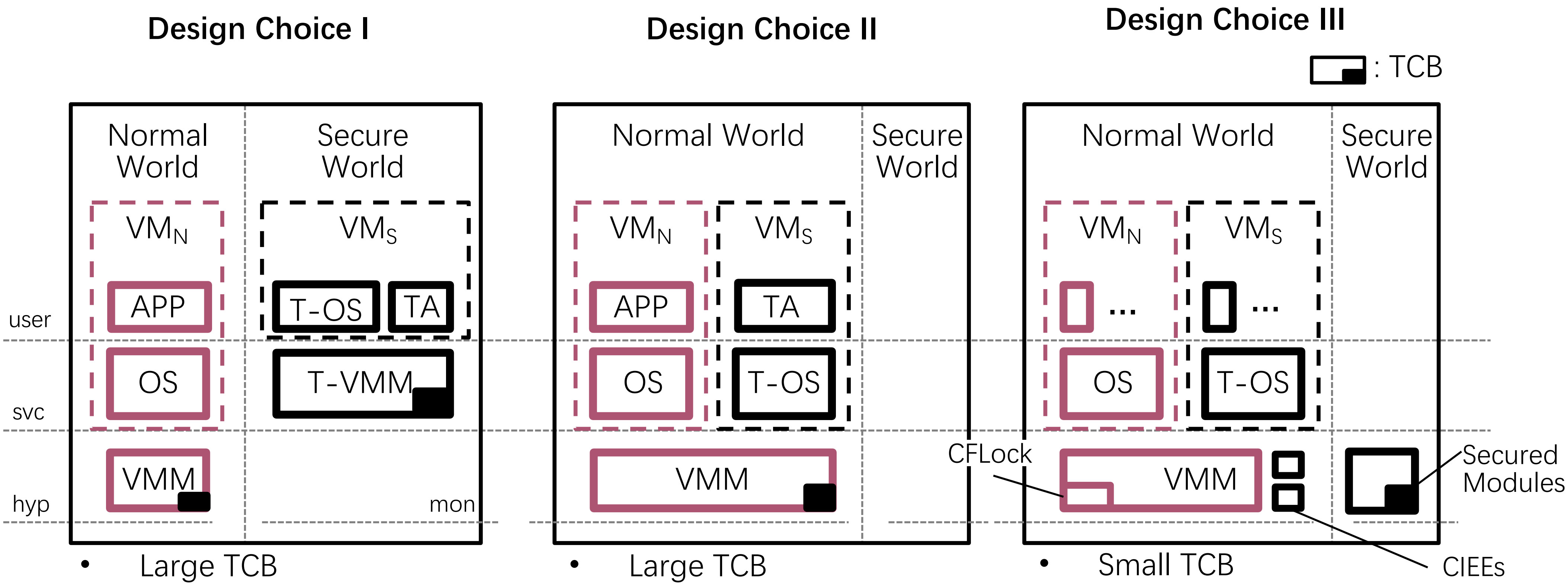


- Large TCB
- No compatibility
- Bad performance

- Large TCB
- Has compatibility
- Good performance

- Virtualize guest secure world in real normal world
- Secure world is not used
- System TCB
  - VMM (millions of LoC)

Alternative Designs



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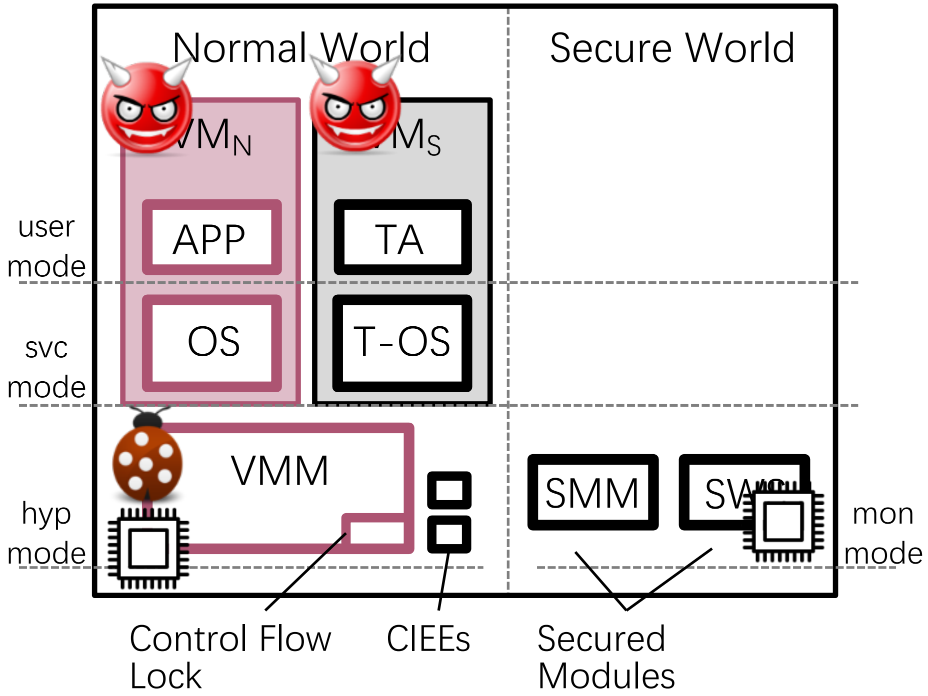
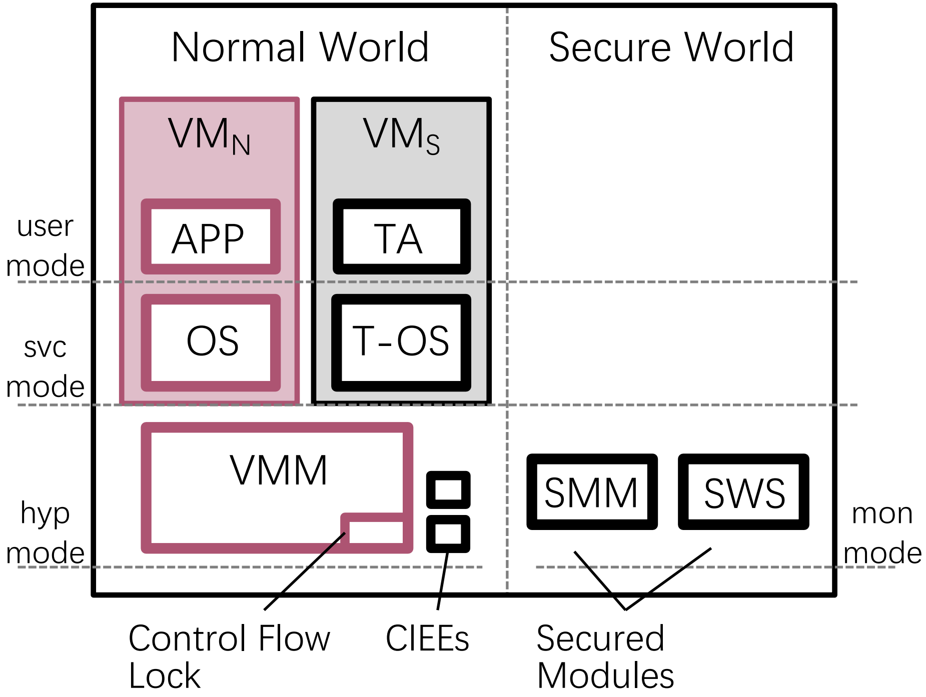
- Has compatibility

Threat Model



- Any guest may be an attacker
- VMM is buggy, can be compromised
- Code integrity is protected during system boot by secure boot technology
- Side-channel attacks and physical attacks are not considered

Overview



- Emulate guest normal world/secure world with different VMs
  - World switching is performed by switching between two VMs
- SMM (Secured Memory Mapping)
  - Memory mapping
- SWS (Secured World Switching)
  - CPU Context
- CIEE (Constrained Isolated Execution Environment)
  - Protect critical logic in hyp mode
- CFLock (Control Flow Lock)

Properties need to be enforced by vTZ

TrustZone Features	System Properties
Secure Boot	SW must boot before NW.
	Boot image of SW must be checked.
	SW cannot be replaced.
CPU States Protection	"smc" must switch to the correct world.
	Protect the integrity of NW CPU states during switching.
	Protect SW CPU states.
Memory Isolation	Only SW can access secure memory.
	Only SW can configure memory partition.
Peripheral Assignment	Secure interrupts must be injected into SW.
	NW cannot access secure peripherals.
	Secure peripherals are trusted for SW
	Only SW can partition interrupt/peripherals.

Properties need to be enforced by vTZ.

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CPU States Protection	**"smc" must switch to the correct world.** Protect the integrity of NW CPU states during switching. Protect SW CPU states.
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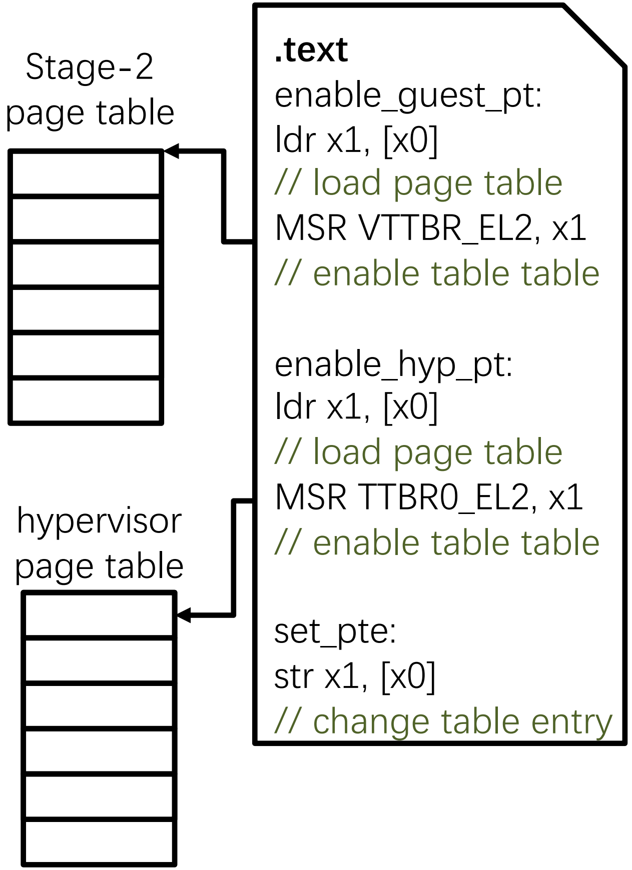
Peripheral Assignment	Secure interrupts must be injected into SW. NW cannot access secure peripherals. Secure peripherals are trusted for SW Only SW can partition interrupt/peripherals.

P1. Only secure world can access secure memory

- Challenge
  - Untrusted VMM controls all memory mappings
  - Map one guest’s secure memory to its normal world or to another guest
  - Map one guest’s secure memory to VMM’s address space
- Solution
  - SMM exclusively controls all memory mappings to physical memory
  - SMM checks memory mappings

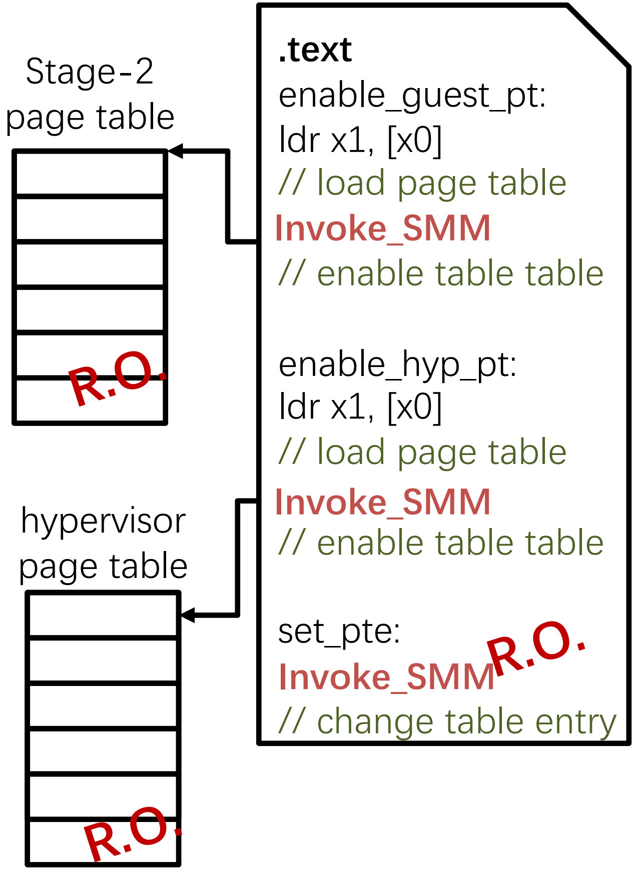
P1. Only secure world can access secure memory

- Two kinds of mappings to the physical memory
  - Stage-2 page table maps guest physical address to physical address
  - Hyp page table maps virtual address to physical address for VMM
- Three ways memory mapping can be modified
  - Enabling a page table
  - Disabling the address translation
  - Changing the entries of page table



SMM (Secured Memory Mapping)

- SMM exclusively controls the mapping
  - Replace all page table maintain instructions
  - Enforce hypervisor's code as read-only (R.O.)
  - Enforce page table as read-only
- SMM enforces memory mapping policy
  - E.g., one guest's secure memory can only be mapped to its own secure world



P1. Only secure world can access the secure memory

P2. “smc” must switch to the correct world

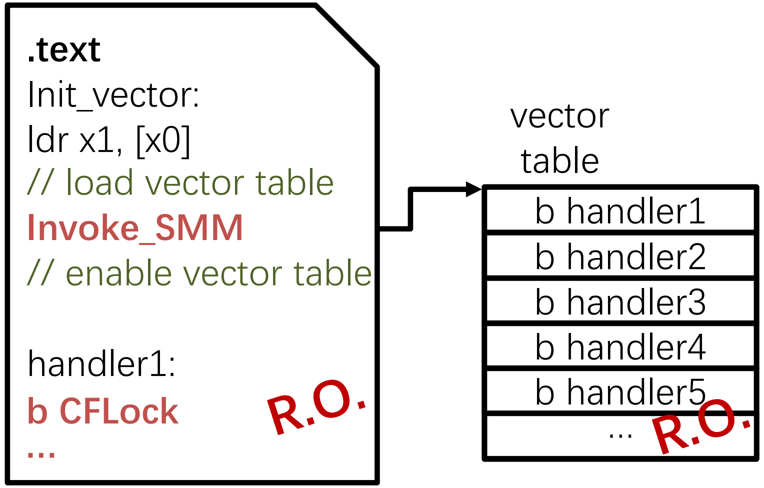
- Challenge
  - Untrusted VMM controls the scheduleing of all VMs
  - “smc” may switch to a malicious VM
  - “smc” may switch to a wrong entry of guest secure world
  - Untrusted VMM may tamper with the CPU context during switching
- Solution
  - SWS hooks all switching between a VM and the VMM
  - SWS checks all switching

SWS (Secured World Switching)

- SWS Interposes switching between a VM and the VMM
  - **VM_exit** is triggered by exception, hooked by CFLock
  - **VM_enter** is performed by special instructions, replacing all of them
    - E.g., *eret*
- SWS binds each guest's secure world and normal world
  - Identify VMs presenting guest's two worlds by VMID

CFLock (Control Flow Lock)

- CFLock: hooks the control flow of exception handling
- Ensure the integrity of vector table containing exception handlers
  - Replace instructions which modify vector table base register
  - Mark vector table as read-only
- Add hook in each exception handler



P2. “smc” must switch to the correct world

- Untrusted VMM registers guest’s two VMs in SWS
  - SWS only allows entering a registered VM
- Untrusted VMM schedules all VMs
- SWS checks all VM_enter / VM_exit operations

P3. Only secure world can partition memory

- Guest configures memory partition in its secure world by accessing a memory partition device (TZASC)
- Challenge
  - There is only one TZASC
  - Cannot control TZASC by the untrusted VMM
- Solution
  - Providing trusted virtual TZASC by “trap and emulate”

P3. Only secure world can partition memory

- **CFLock** traps memory accesses of virtual TZASC
  - Memory mapped device
  - Accessing triggers page fault exception
- **SWS** identifies current VM
  - Only guest secure world can do the partitioning
- Need **an isolated execution environment** to emulate device
  - Reuse some structure of the VMM
  - Protected from VMM
  - Not included in system TCB

P3. Only secure world can partition memory

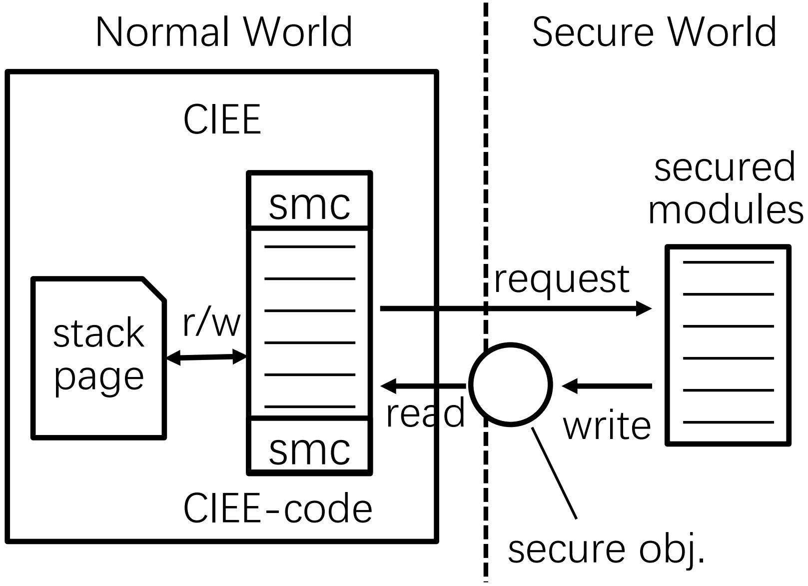
- **CIEE** (Constrained Isolated Execution Environment)
- Protects a piece of code in the hyp mode
- Excluded from system TCB

CIEE (Constrained Isolated Execution Environment)

- Located in the hyp mode
- Prevent against the untrusted VMM
  - Single entry point
  - Run-to-completion
  - No dependence on the hypervisor’s data
  - No data exposure to the hypervisor
  - Unforgeable to the secure world
- Exclude CIEE from system TCB
  - Isolated privilege

CIEE (Constrained Isolated Execution Environment)

- CIEE components
  - CIEE-Code
  - Stack page
  - Secure object
- Enforce five security policies
- Isolated privilege
  - Diff privilege for each CIEE
  - Diff copy of secure obj. for each guest



P3. Only secure world can partition memory

- **CFLock** traps memory accesses of virtual TZASC
  - Memory mapped device
  - Accessing triggers page fault exception
- **SWS** identifies current VM
  - Only guest secure world can do the partitioning
- Emulate TZASC in an **CIEE**

Evaluation

- Can vTZ support existing trust OS?
- How is the performance of server applications on vTZ?
- How is the performance of application with multiple VMs?

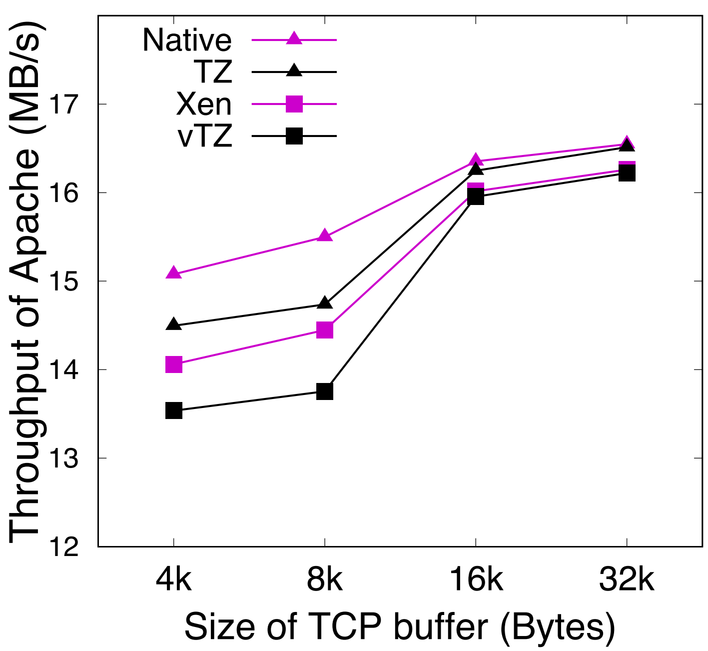
Evaluation

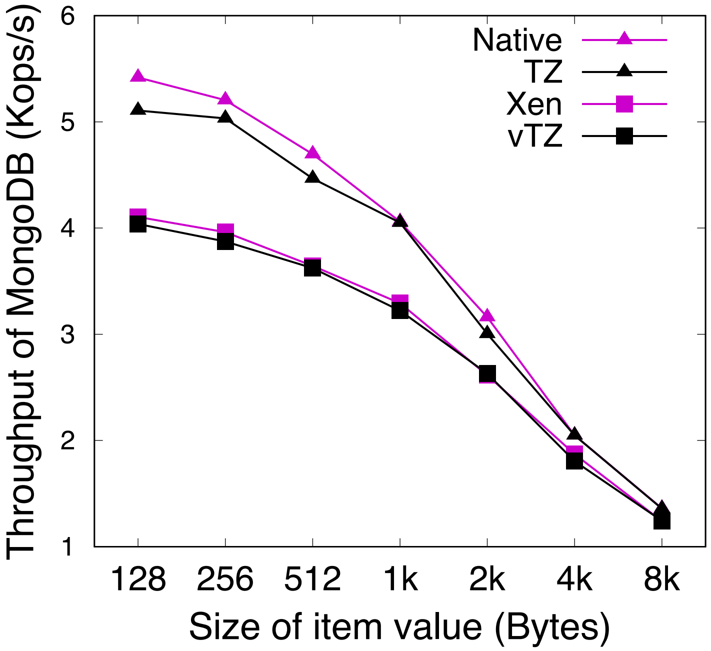
- Hardware platform
  - Hikey (ARMv8) with eight 1.2 GHz cores
  - Exynos (ARMv7) with one 1.7GHz core
- Software environment
  - Xen 4.4 + Linux 4.1

Compatibility

- Port two existing trust OSes on vTZ
  - seL4 [SOSP'2009]
  - OP-TEE [https://github.com/OP-TEE/]
- Porting effort
  - Add description file to describe the device base addresses
    - Base addresses of memory and devices
    - Same as porting an OS on an ARM SoC

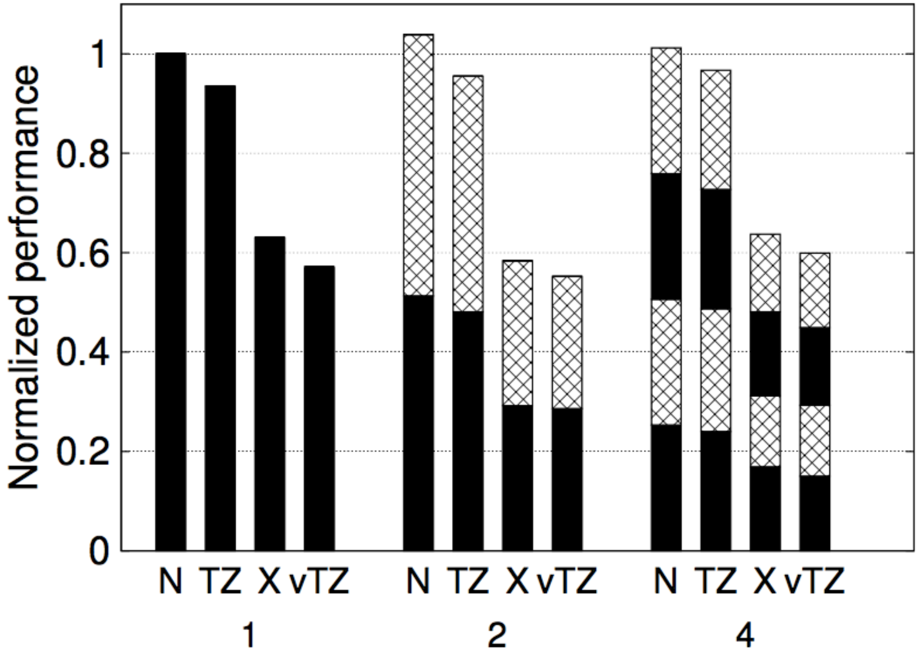
Application Overhead



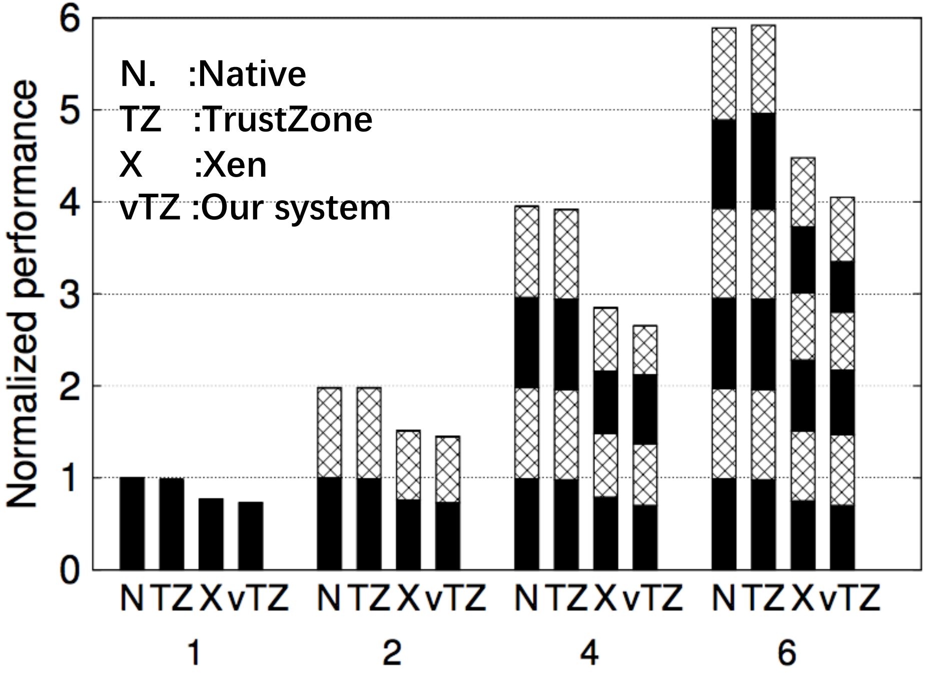


Application Overhead

GoHttps on ARMv7(a) and ARMv8(b) with different VMs.



(a)



(b)

Conclusion

- Analyze security properties of TrustZone
- Combine TrustZone and virtualization to multiplex secure world for each guest
  - **SMM** exclusively controls the memory mapping
  - **CFLock** hooks all exceptions in the hyp mode
  - **SWS** checks all switching between a VM and the VMM
  - **CIEEs** to protect pieces of code in the hyp mode and exclude them from system TCB
- Small system TCB
- Compatible with existing trust OS
  - Porting two trust OSes on vTZ
- Acceptable performance overhead

Thanks

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