S C I E N C E ▪ T E C H N O L O G Y ▪ P A S S I O N

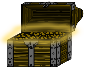
TIMBER-V

Tag-Isolated Memory Bringing Fine-grained Enclaves to RISC-V

Samuel Weiser[*] Mario Werner[*]
Ferdinand Brasser[†] Maja Malenko[*]
Stefan Mangard[*] Ahmad Sadeghi[†]
[*]Graz University of Technology
[†]TU Darmstadt

Motivation

- Goal: Protect sensitive code and data



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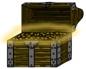

App
OS
Hypervisor

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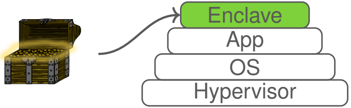

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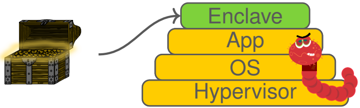
- Goal: Protect sensitive code and data from malicious software



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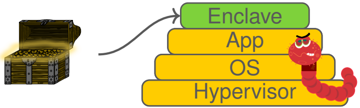

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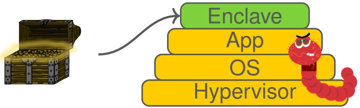

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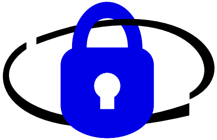
  - Hardware backdoors? [8]



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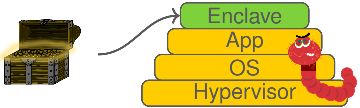

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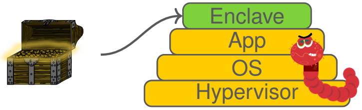
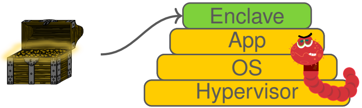


RISC-V®

Motivation



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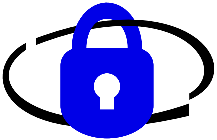
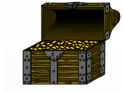


- RISC-V is completely open
  - **Bring SGX features to embedded RISC-V** (embedded = ARM Cortex-M)

Background: Enclaves

- Secure execution



Background: Enclaves

- Secure execution
- Protect against all other software
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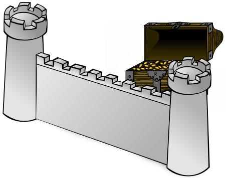

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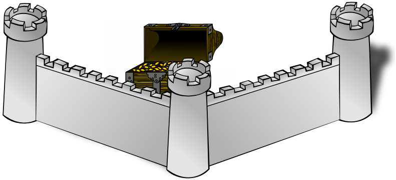

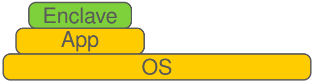

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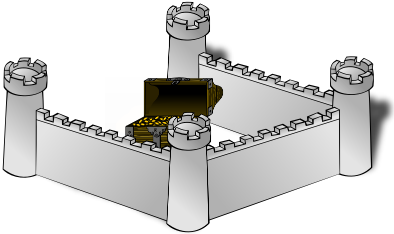

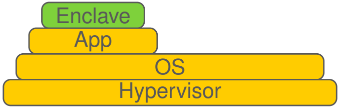

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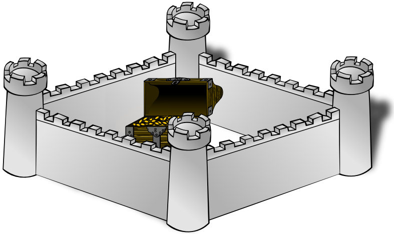
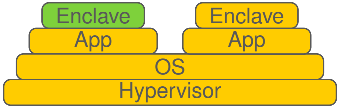
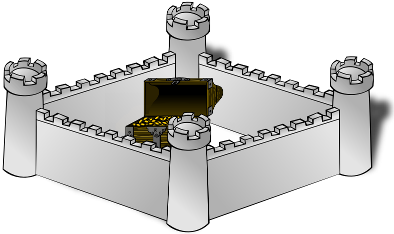
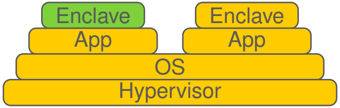




Background: Enclaves

- Secure execution
- Protect against all other software
    - Malicious app
    - Malicious OS
    - Malicious hypervisor
    - Malicious enclaves
- Minimal trust (enclave + HW)





Related Work - Secure Execution

- ”Large”: Sanctum (RISC-V) [2]
- ”Embedded”: [3, 4, 7, 1, 9]
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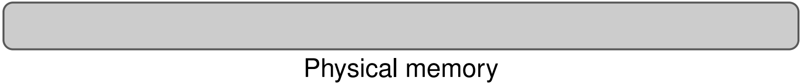
Problems

- Inflexible isolation boundaries
- **Memory fragmentation**

Problem: Memory Fragmentation



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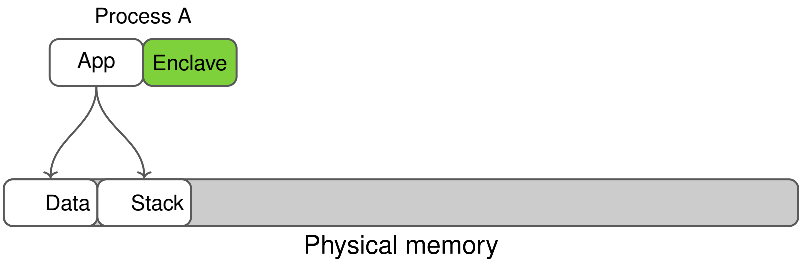

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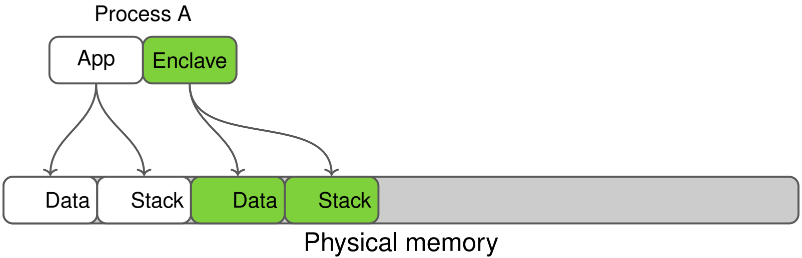

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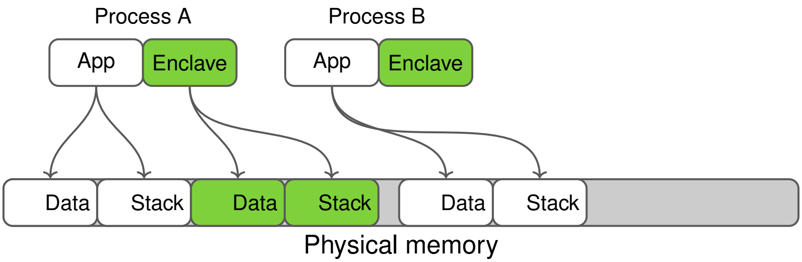

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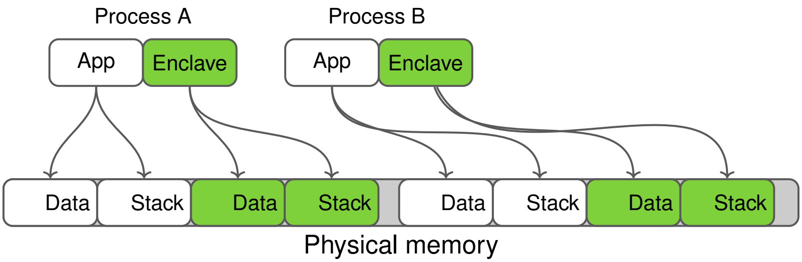

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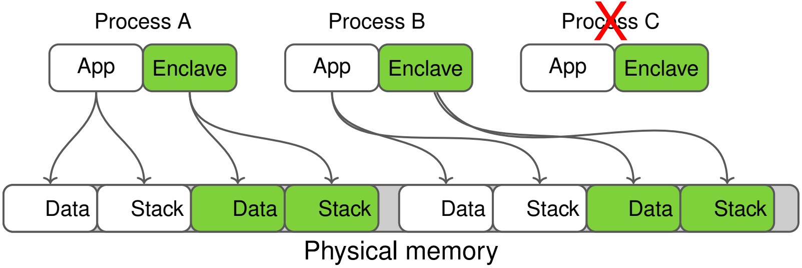

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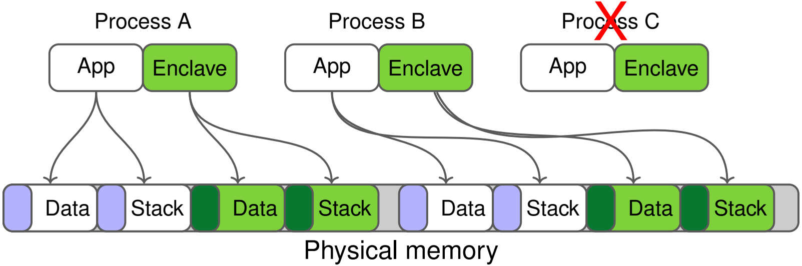
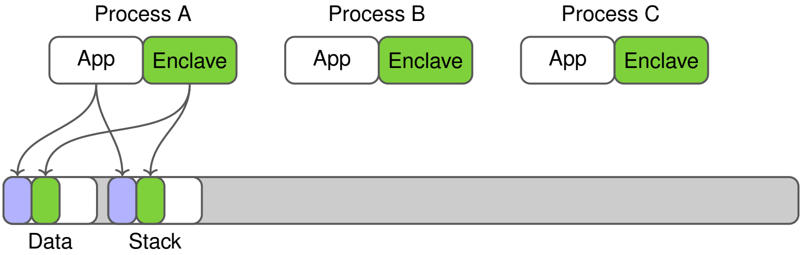


- Bad memory utilization

Problem: Memory Fragmentation



- Bad memory utilization
- We want to interleave memory → Stack sharing

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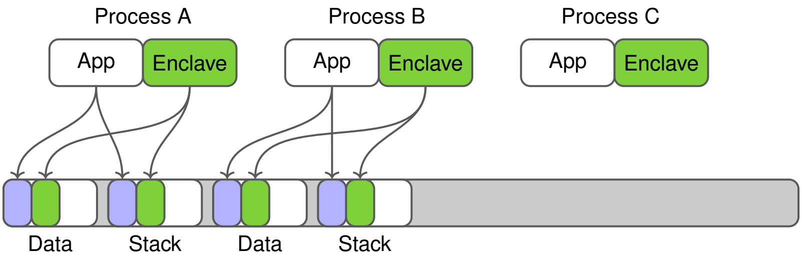

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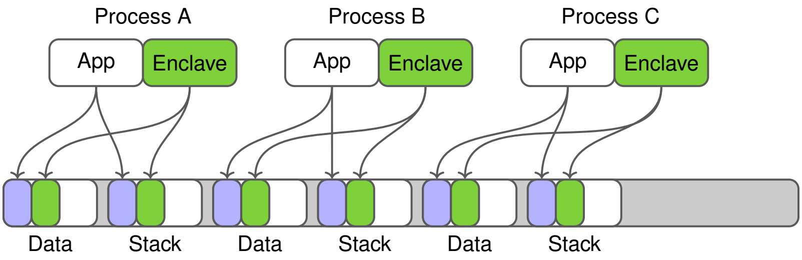

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Contributions

- TIMBER-V: Enclaves from tagged memory for embedded RISC-V

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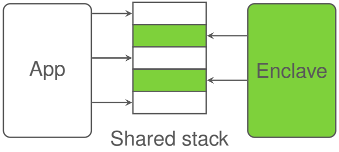
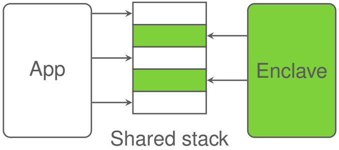


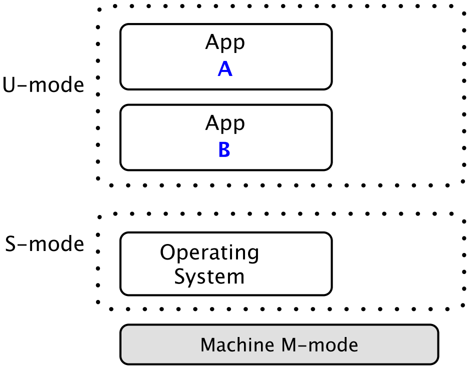
Contributions

- TIMBER-V: Enclaves from tagged memory for embedded RISC-V
- Novel stack sharing
- Fast shared enclave memory

  ...
- Proof-of-concept



TIMBER-V Overview



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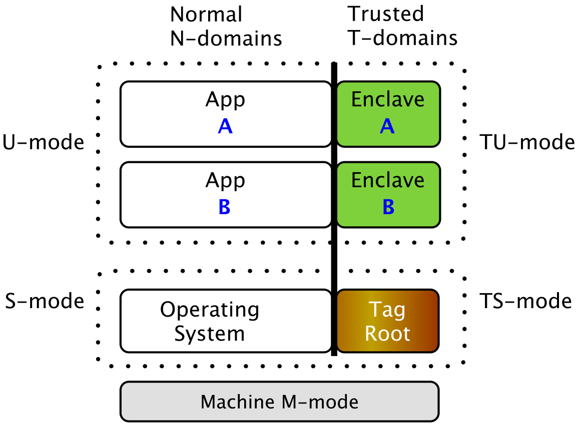

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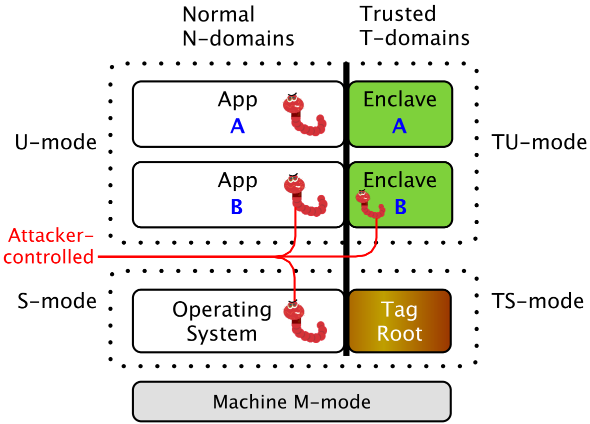

TIMBER-V

Enclave building blocks:

TIMBER-V

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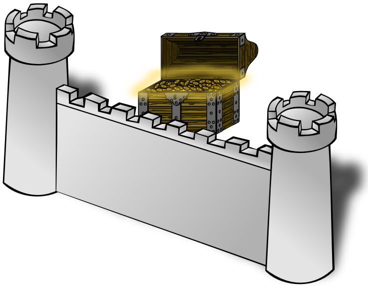
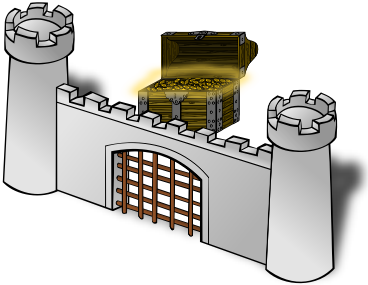
- Memory isolation



TIMBER-V

Enclave building blocks:

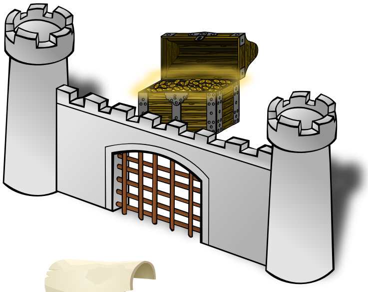
- Memory isolation
- Entry points



TIMBER-V

Enclave building blocks:

- Memory isolation
- Entry points
- Attestation, sealing
- Inter-enclave communication



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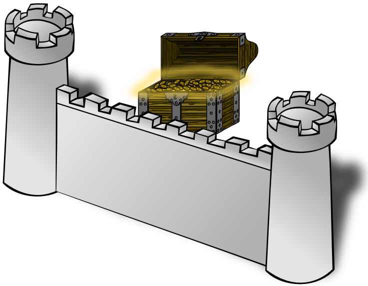
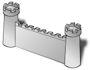
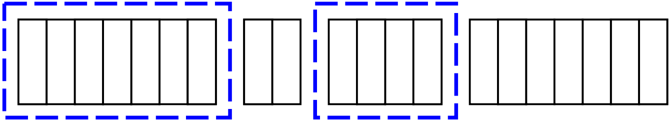


Traditional Memory Protection Unit (MPU)

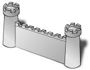




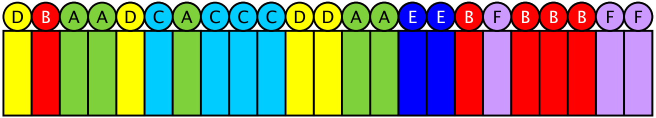
Physical
Memory

- MPU regions define application
- Problem: inflexible

Tagged Memory



Memory tags →



Physical
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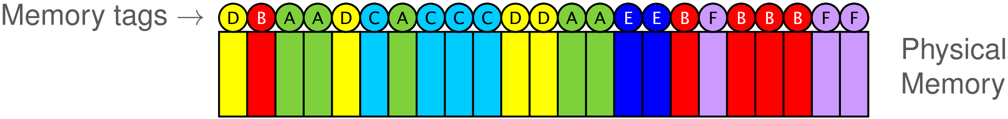
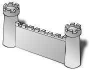
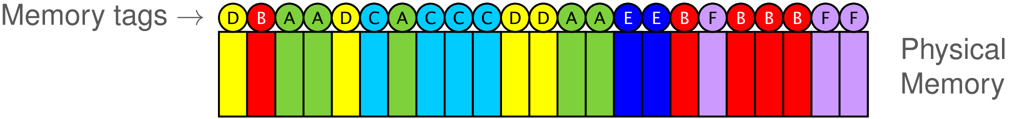


- Memory tags define applications

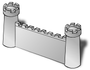
Tagged Memory

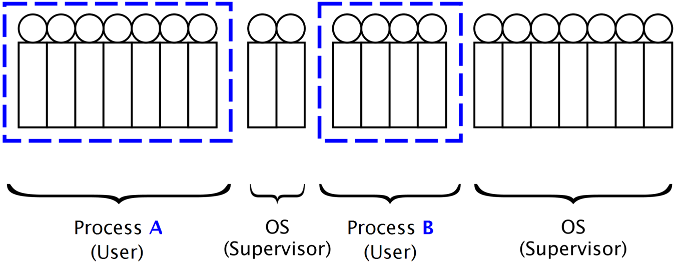




- Memory tags define applications
- Problem: high memory overhead

TIMBER-V: MPU + Tagged Memory





- MPU region defines application

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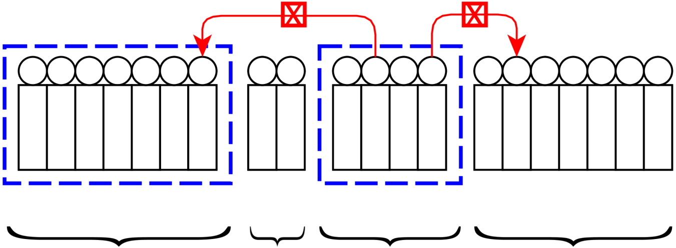
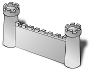
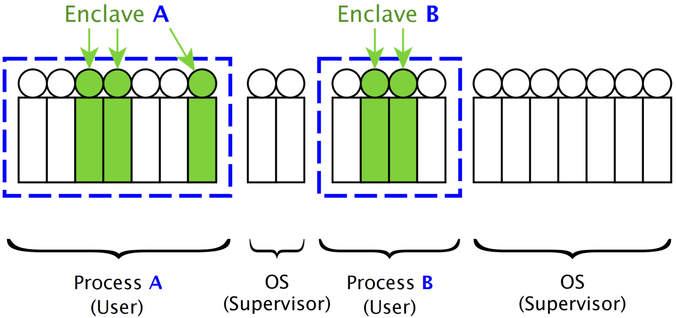


- MPU region defines application
- Application cannot escape

TIMBER-V: MPU + Tagged Memory





- Memory tag defines enclave

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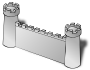
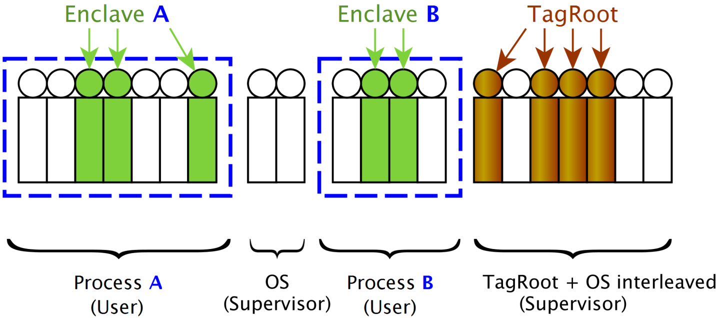
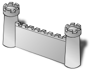
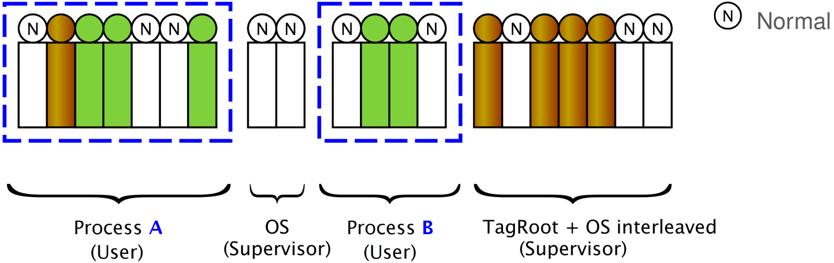




- Memory tag defines enclave
- Memory tag defines TagRoot

TIMBER-V Tag Isolation





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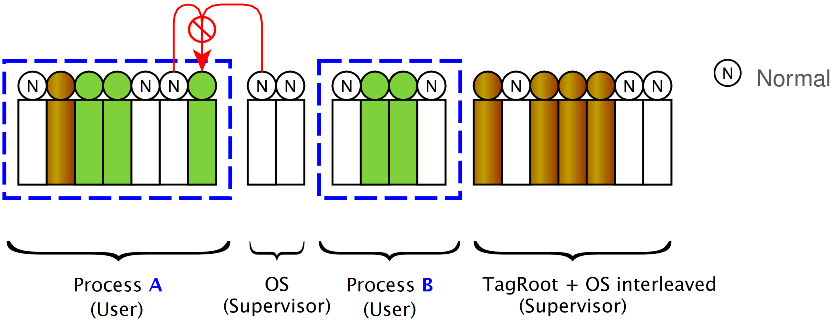
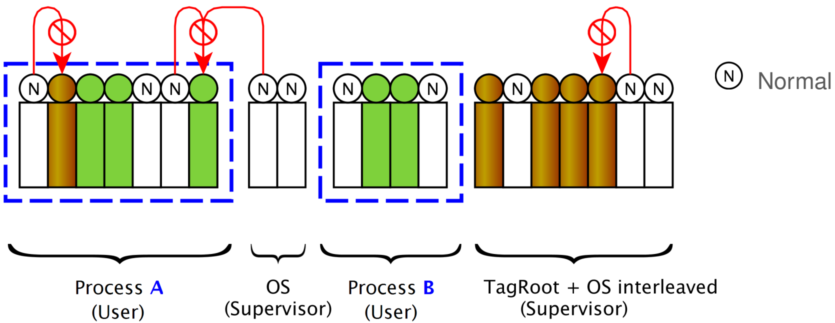


- N Normal memory
- Cannot access others

TIMBER-V Tag Isolation



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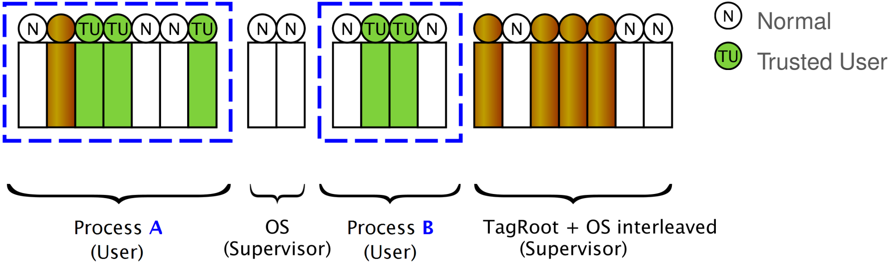

- TU Trusted User memory (enclaves)

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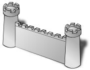

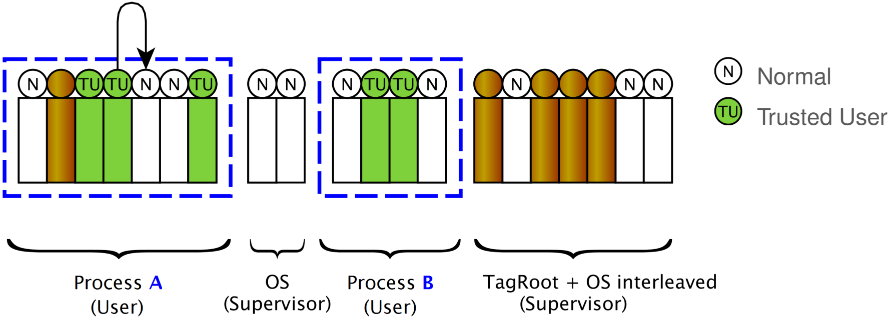

- TU Trusted User memory (enclaves)
- Can access and update normal memory

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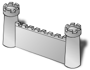

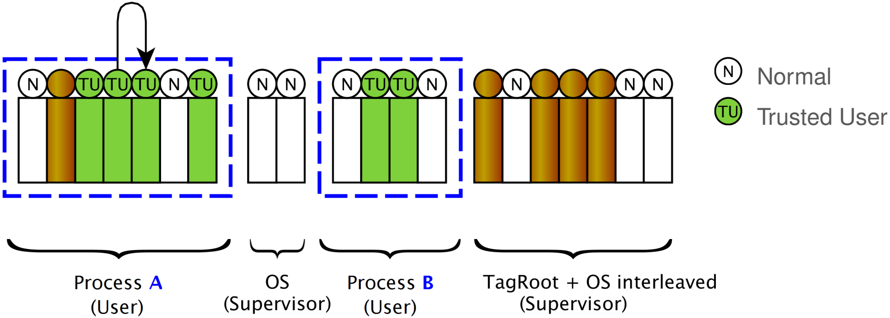

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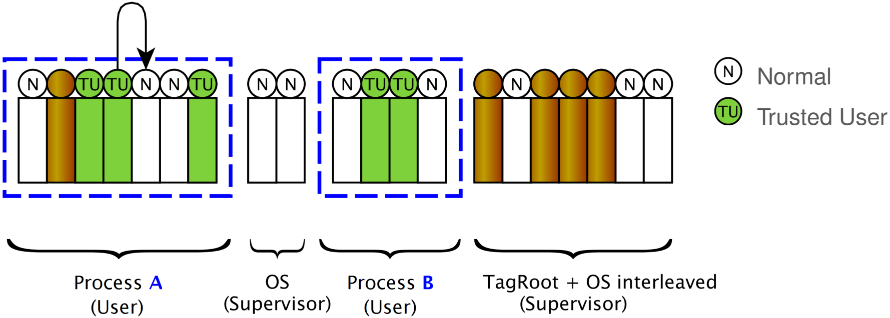
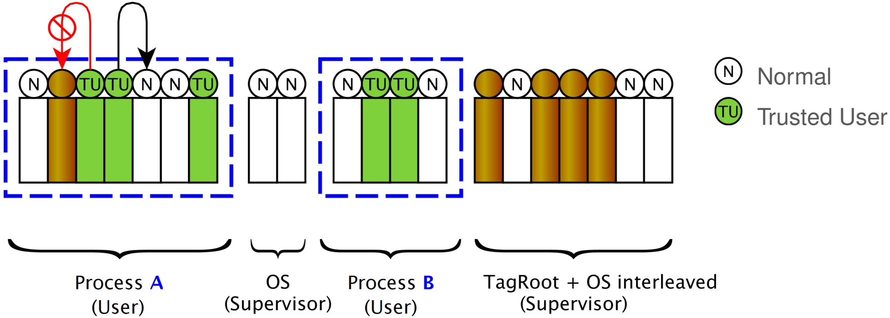
TIMBER-V Tag Isolation



- TU Trusted User memory (enclaves)
- Can access and update normal memory

TIMBER-V Tag Isolation



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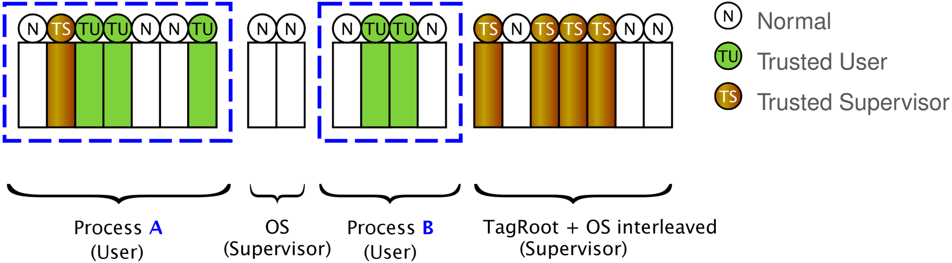
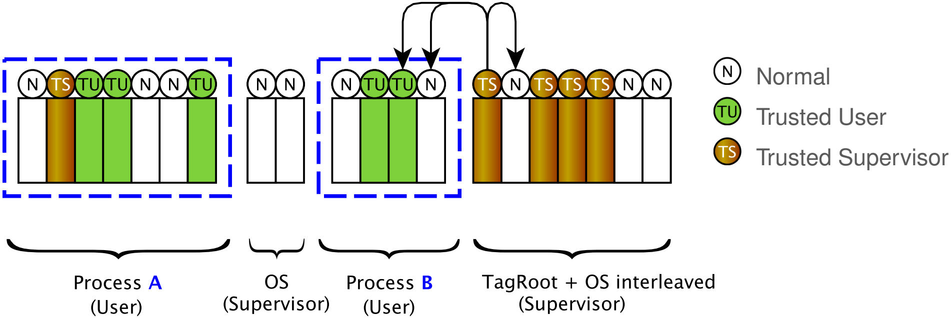
TIMBER-V Tag Isolation



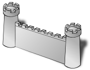
- TS Trusted Supervisor memory (TagRoot)

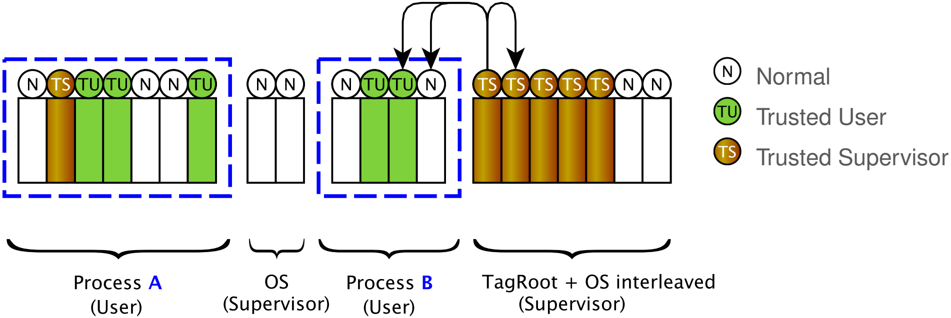
TIMBER-V Tag Isolation



- TS Trusted Supervisor memory (TagRoot)
- Can access and update any tag

TIMBER-V Tag Isolation





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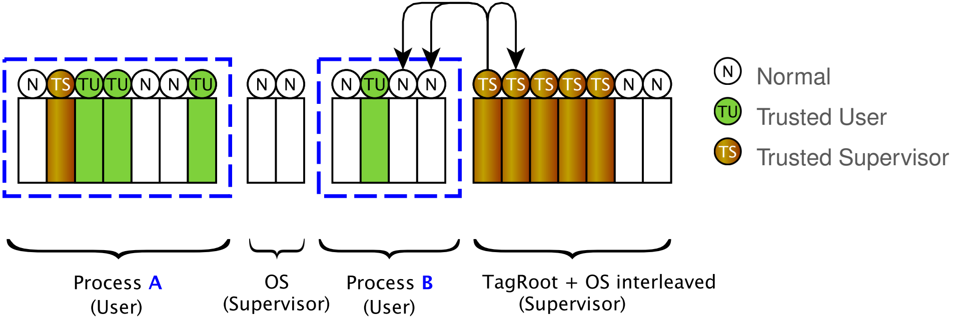

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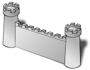

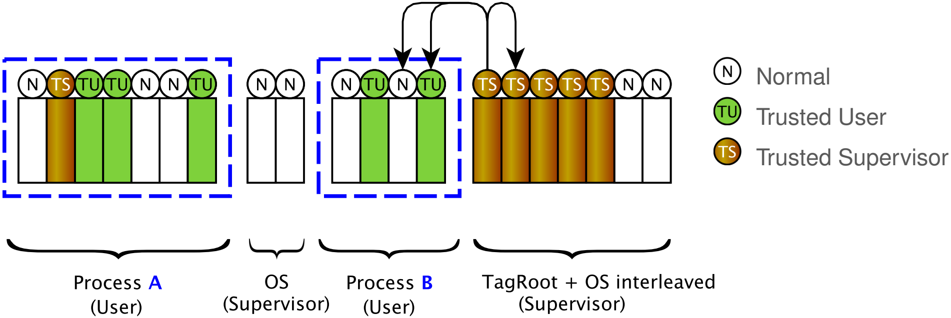

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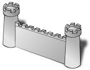
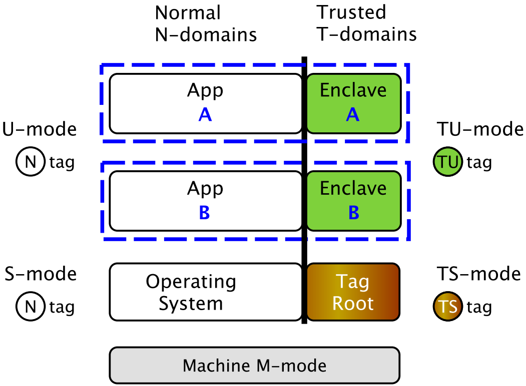
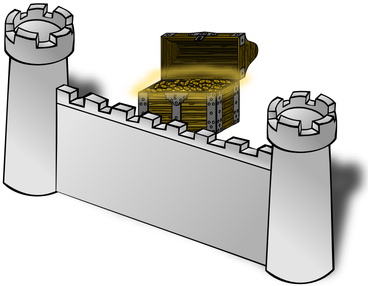
TIMBER-V Memory Isolation





TIMBER-V



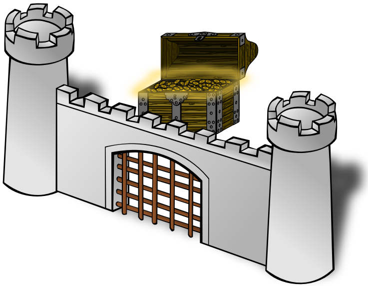
Enclave building blocks:

- ✓ Memory isolation
- Entry points
- Attestation, sealing
- Inter-enclave communication

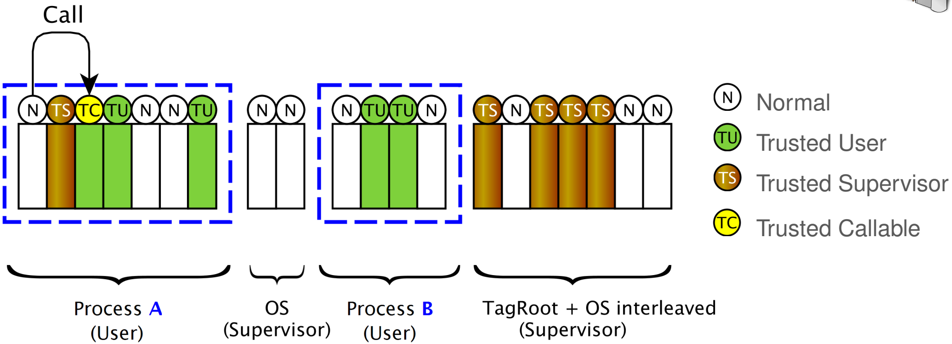
TIMBER-V

Enclave building blocks:

- ✓ Memory isolation
- **Entry points**
- Attestation, sealing
- Inter-enclave communication

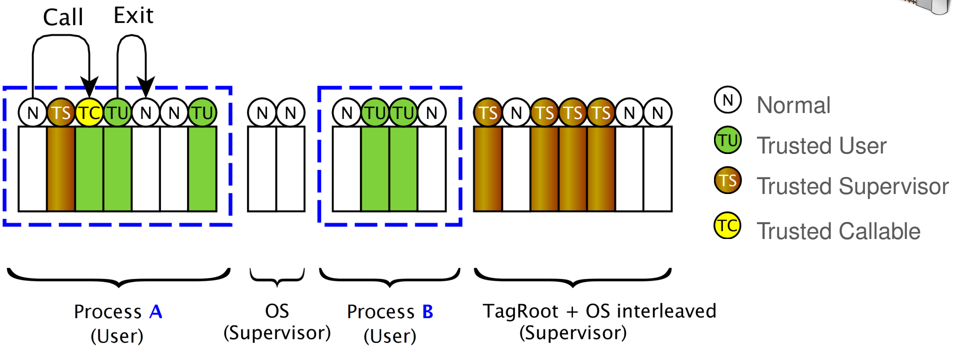


TIMBER-V Entry Points



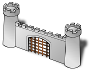
- Enter only at TC Trusted Callable

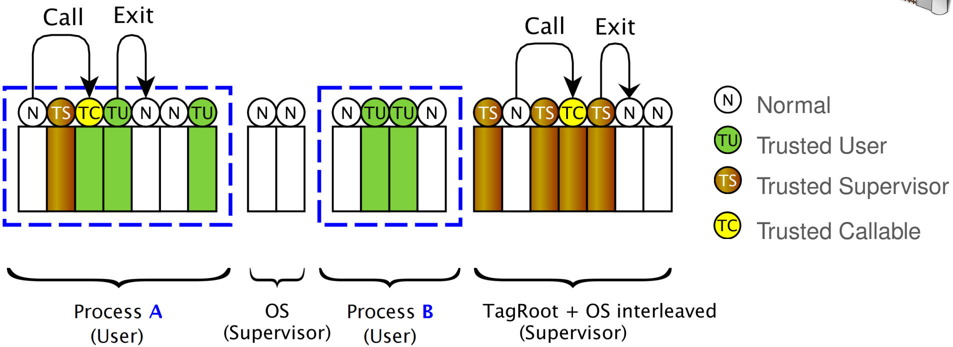
TIMBER-V Entry Points



- Enter only at TC Trusted Callable
- Zero runtime overhead (ordinary `jmp`)

TIMBER-V Entry Points





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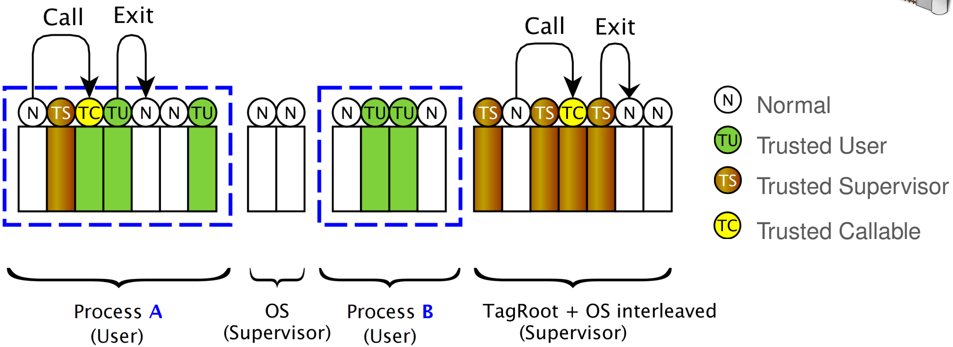
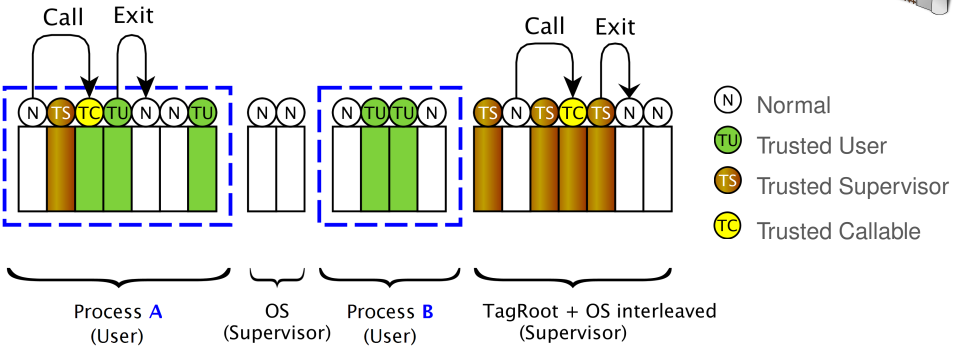


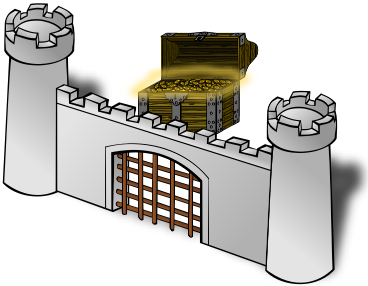
- Four tags $\rightarrow$ two tag bits only

TIMBER-V Entry Points



- Four tags $\rightarrow$ two tag bits only
- For 32-bit system +6.25% memory overhead

TIMBER-V



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TIMBER-V

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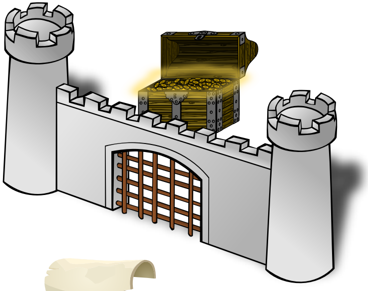
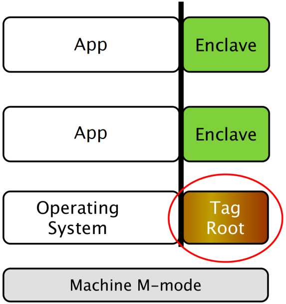


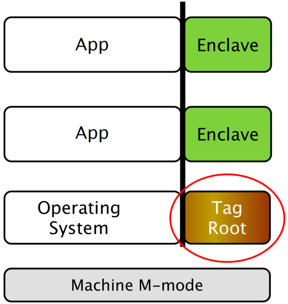
TIMBER-V TagRoot

- Root of trust in privileged software



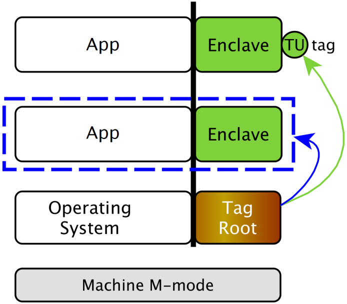
TIMBER-V TagRoot

- Root of trust in privileged software
- Supports SGX and TrustZone model



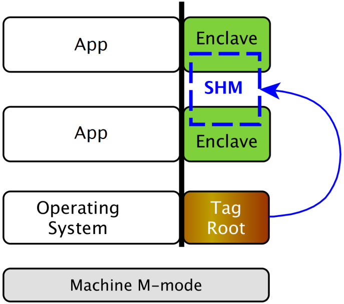
TIMBER-V TagRoot

- Root of trust in privileged software
- Supports SGX and TrustZone model
- Enclave management



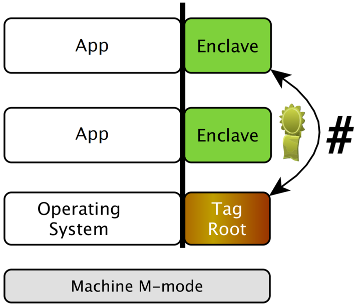
TIMBER-V TagRoot

- Root of trust in privileged software
- Supports SGX and TrustZone model
- Enclave management
- Inter-enclave communication
  - Fast shared memory
  - Mutual authentication
  - Implicit local attestation



TIMBER-V TagRoot

- Root of trust in privileged software
- Supports SGX and TrustZone model
- Enclave management
- Inter-enclave communication
    - Fast shared memory
    - Mutual authentication
    - Implicit local attestation
- Sealing (like SGX)



TIMBER-V

Enclave building blocks:

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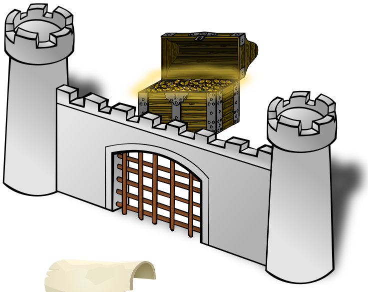
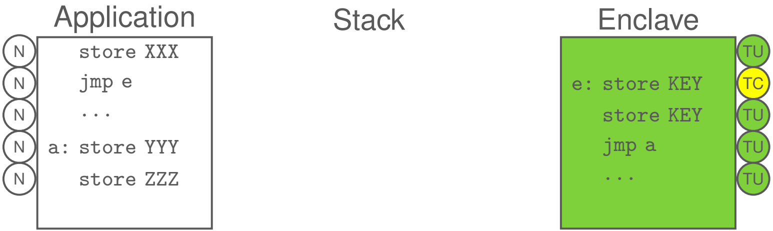
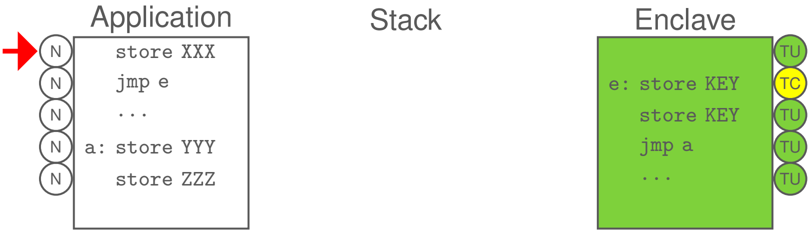


Novel Stack Sharing



- Single stack shared between application and enclave ...

Novel Stack Sharing



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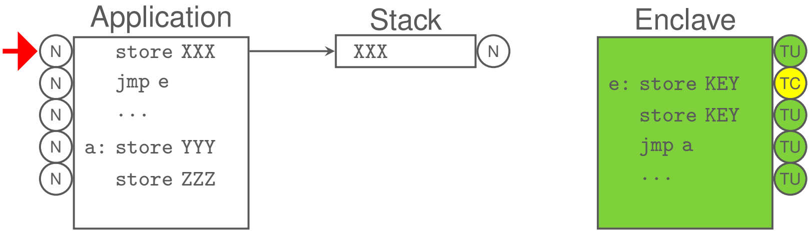

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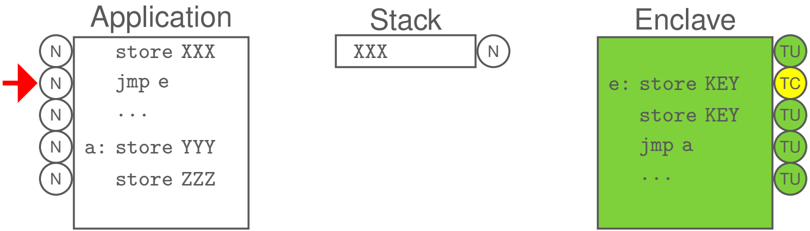

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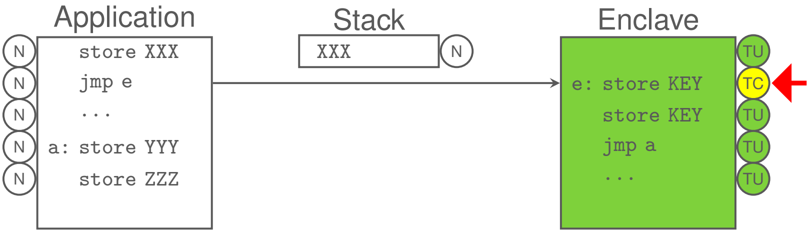

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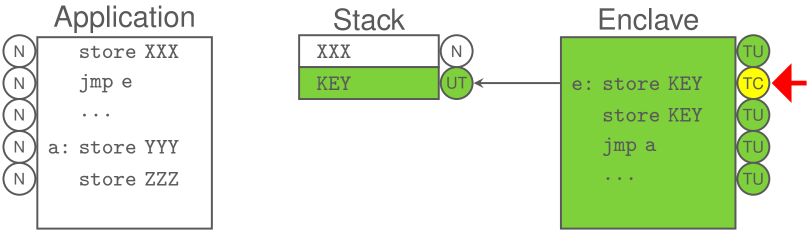

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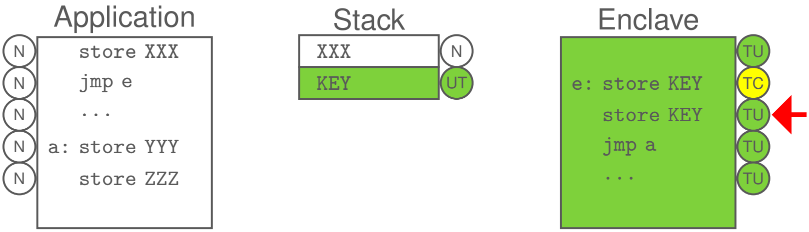

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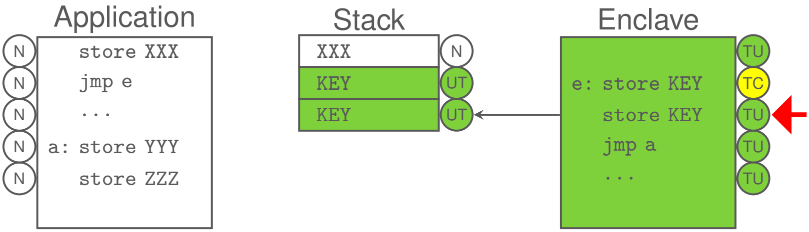

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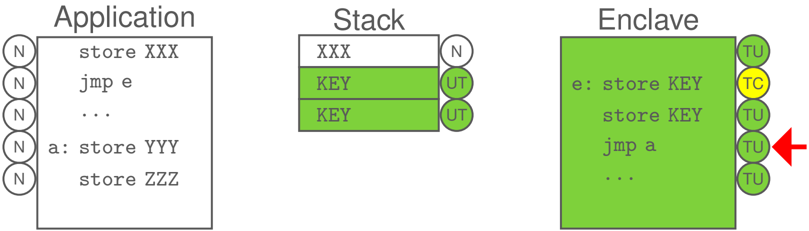

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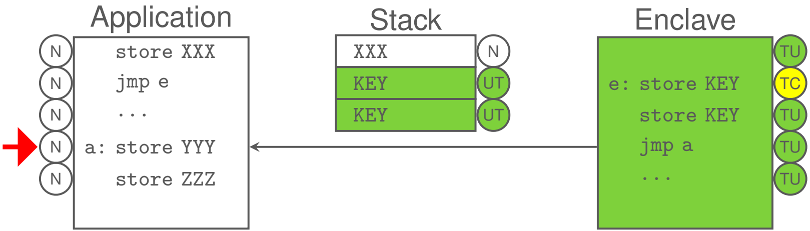

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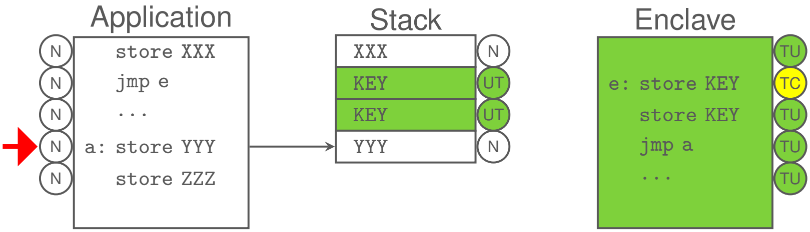

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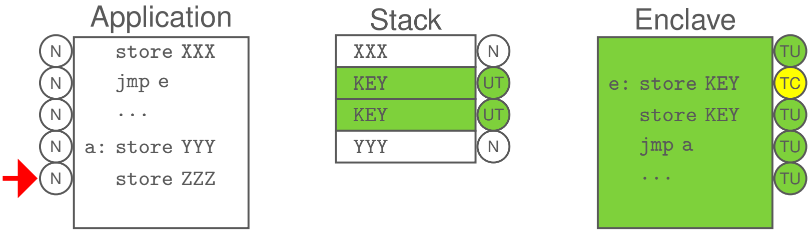

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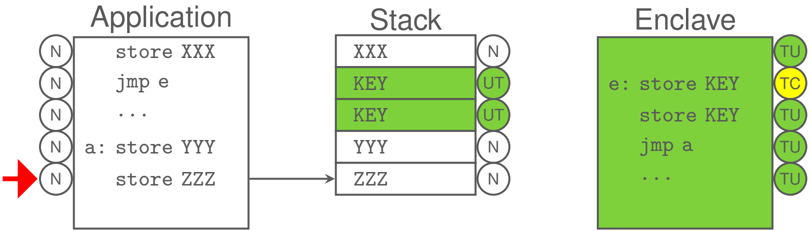

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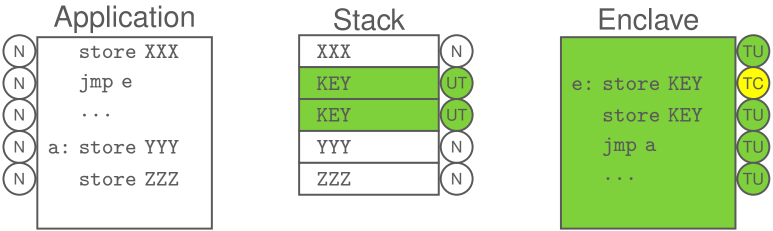
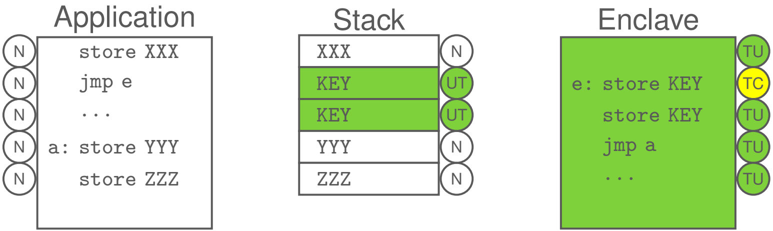


- Single stack shared between application and enclave ...

  ... and between TagRoot!

Novel Stack Sharing



- Single stack shared between application and enclave ...
  ... and between TagRoot!
- Heap sharing quite similar

Key Insights

- Build enclaves with tagged memory
  - Fine granularity and high flexibility
- Combination with MPU allows tiny 2-bit tags
- Reduced memory fragmentation
  - Shared stacks, heaps ...

!

Proof-of-Concept

- Integration in ISA simulator (Spike)
- Full TagRoot implementation
- FreeRTOS integration
- Gnu GCC support
- Benchmarks (Coremark, Beebs)
- Open source: `github.com/IAIK/timber-v`

TU Graz

TIMBER-V

Tag-Isolated Memory Bringing Fine-grained Enclaves to RISC-V

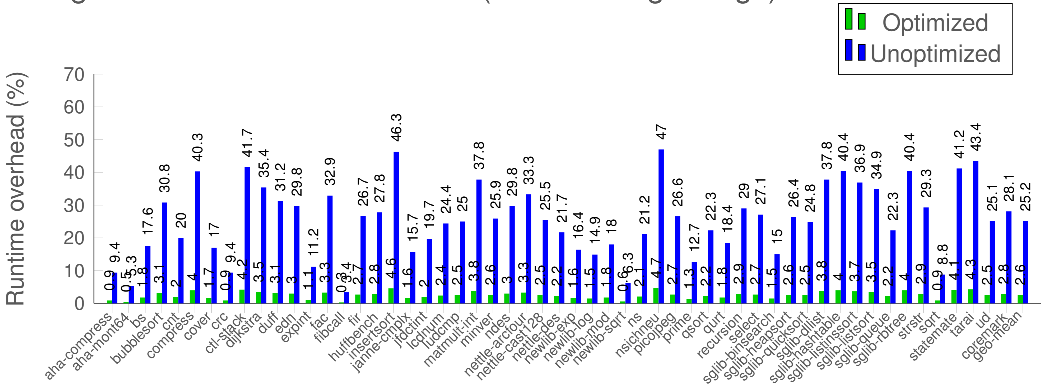
Samuel Weiser[*] Mario Werner[*]
Ferdinand Brasser[†] Maja Malenko[*]
Stefan Mangard[*] Ahmad Sadeghi[†]
[*]Graz University of Technology
[†]TU Darmstadt

Bonus: New Instructions

	RISC-V	TIMBER-V	Arguments
Load	lb,lbu	lbct,lbuct	etag ← check for expected memory tag
	lh,lhu	lhct,lhuct	etag (fault on mismatch)
	lw	lwct	etag
		ltt	etag ← load and test tag w.o. fault
Store	sb	sbct	etag,ntag ← also store new memory tag
	sh	shct	etag,ntag
	sw	swct	etag,ntag

Bonus: TIMBER-V Overhead Estimate

Average overhead: 25.2% vs 2.6% (with caching of tags)



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