TIMBER-V

Tag-**I**solated **M**emory **B**ringing Fine-grained **E**nclaves to **R**ISC-**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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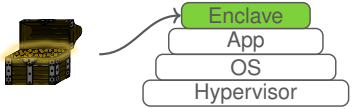

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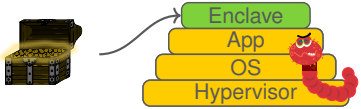

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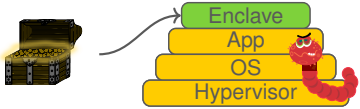

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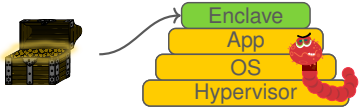

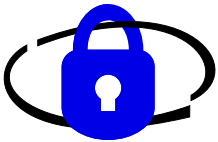

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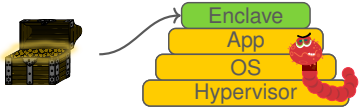

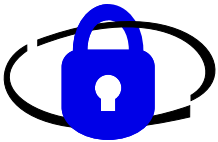

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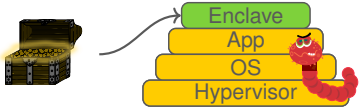

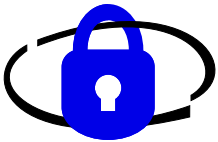

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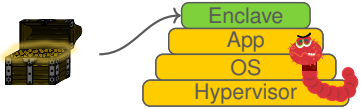

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Background: Enclaves

- Secure execution

Enclave

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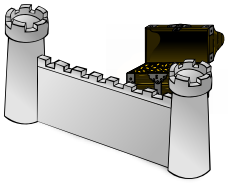
  - Malicious app



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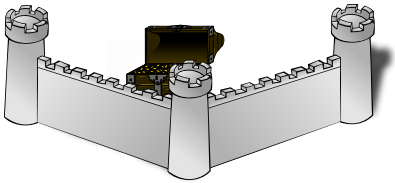

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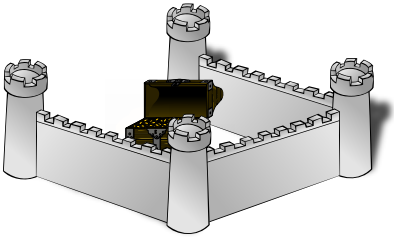

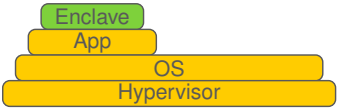

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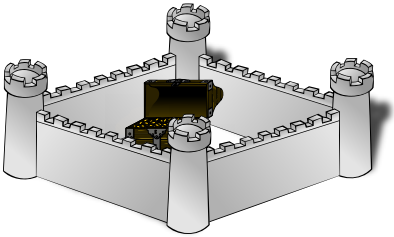
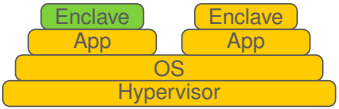
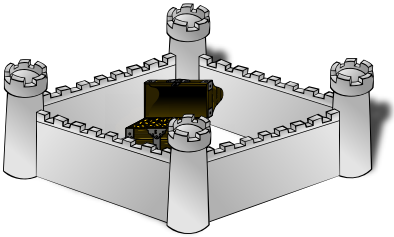




Background: Enclaves

- 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]
  - RISC-V: MultiZone [5], Keystone [6]

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Problems

- Inflexible isolation boundaries
- **Memory fragmentation**

Problem: Memory Fragmentation

Physical memory

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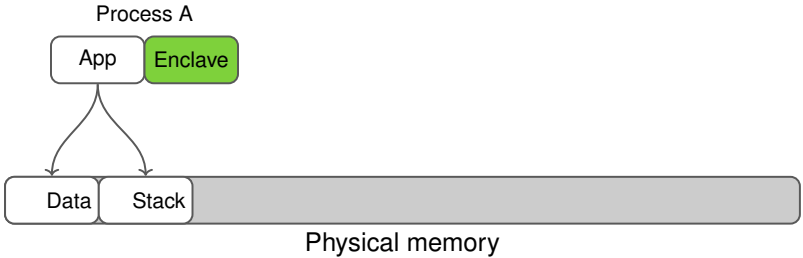

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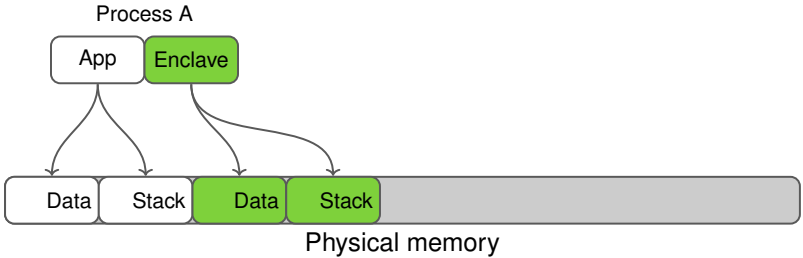

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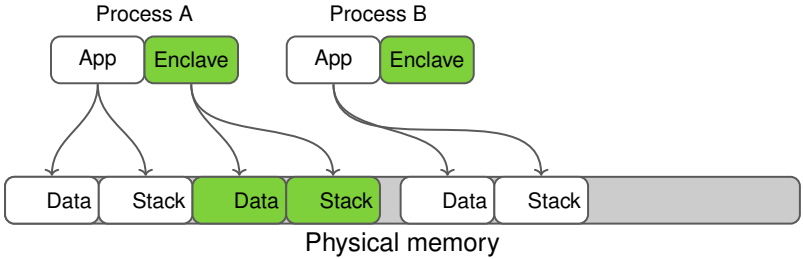

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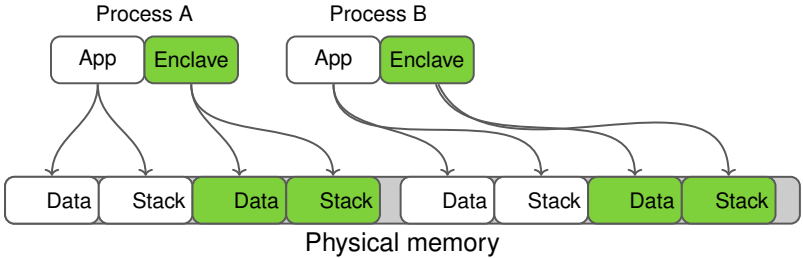

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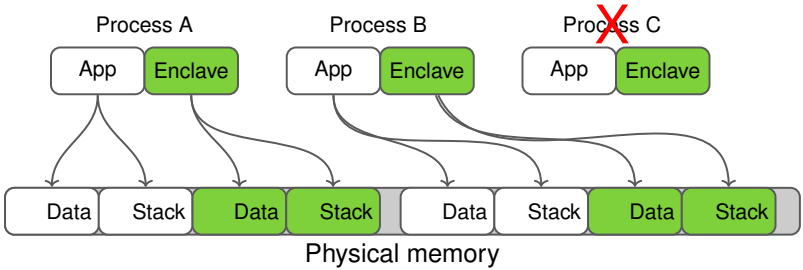

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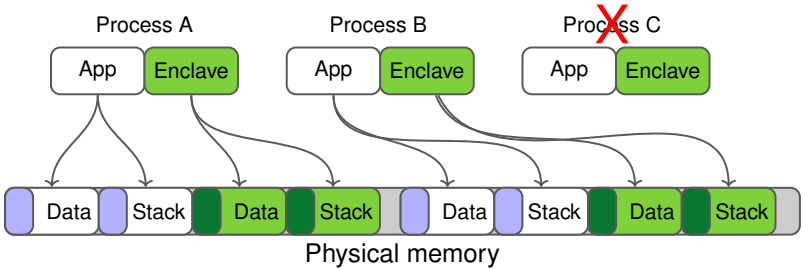

- Bad memory utilization

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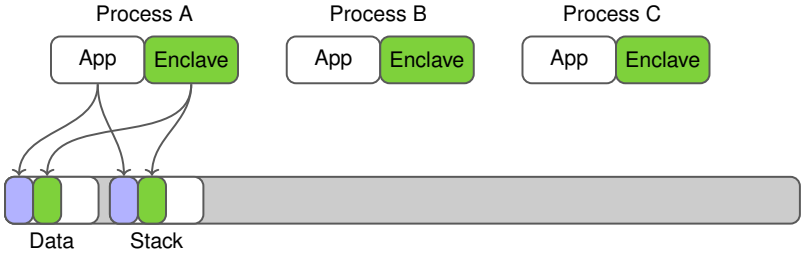

- Bad memory utilization
- We want to interleave memory → Stack sharing

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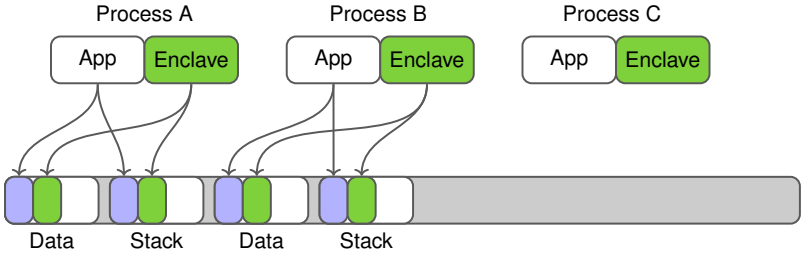

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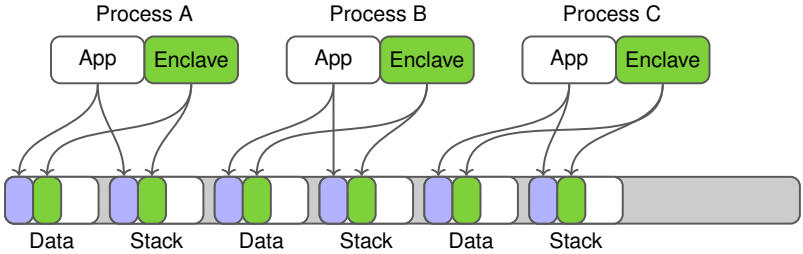

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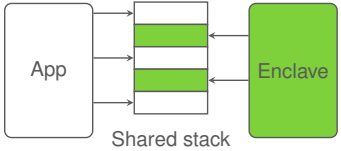
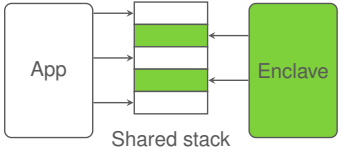


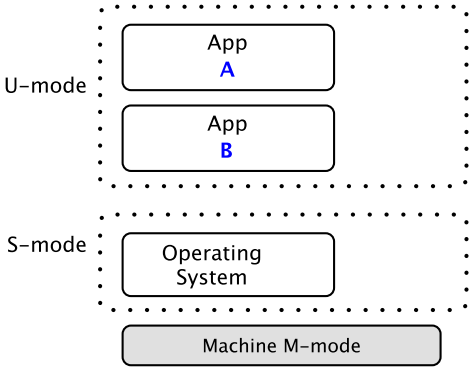
Contributions

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

  ...
- Proof-of-concept



TIMBER-V Overview



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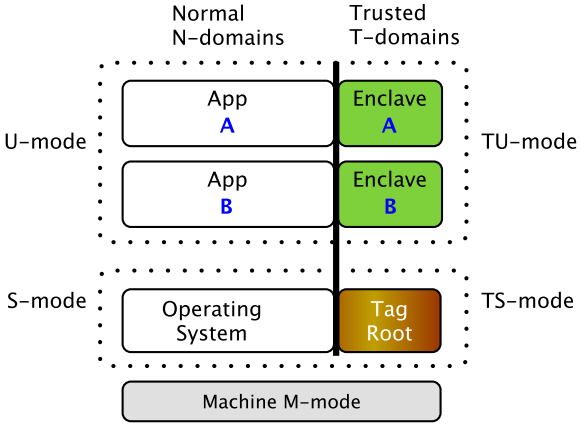

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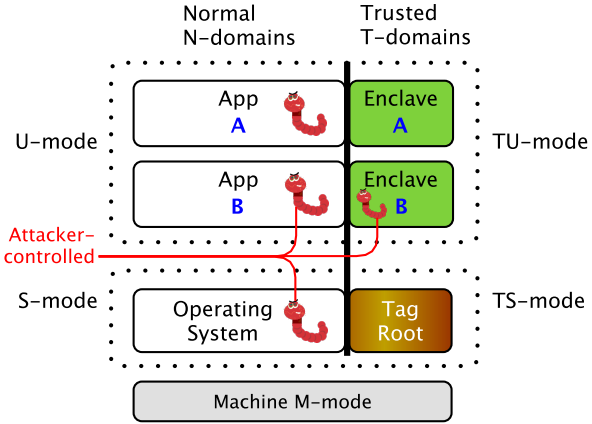


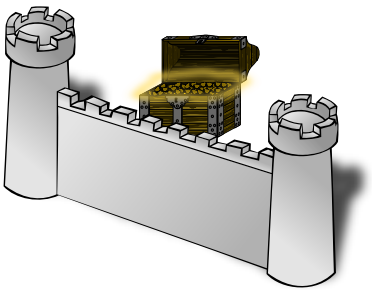
TIMBER-V

Enclave building blocks:

TIMBER-V

Enclave building blocks:

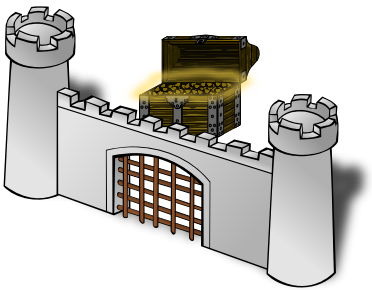
- Memory isolation



TIMBER-V

Enclave building blocks:

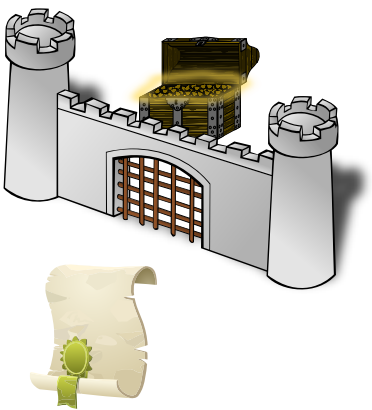
- Memory isolation
- Entry points



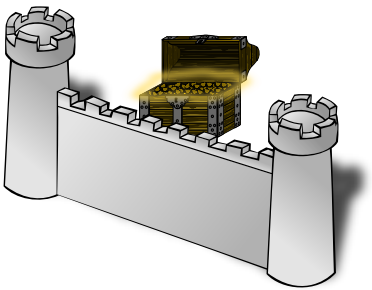
TIMBER-V

Enclave building blocks:

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



TIMBER-V



Enclave building blocks:

- **Memory isolation**
- Entry points
- Attestation, sealing
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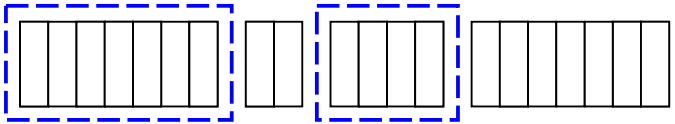
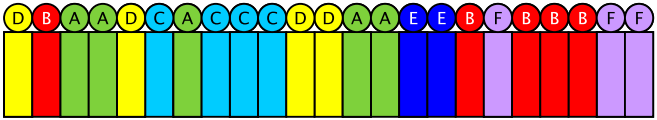
Traditional Memory Protection Unit (MPU)



- MPU regions define application
- Problem: inflexible

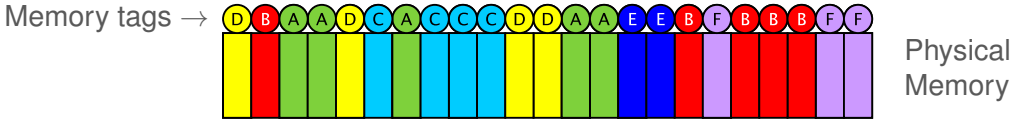
Tagged Memory

Memory tags →



Physical Memory

Tagged Memory



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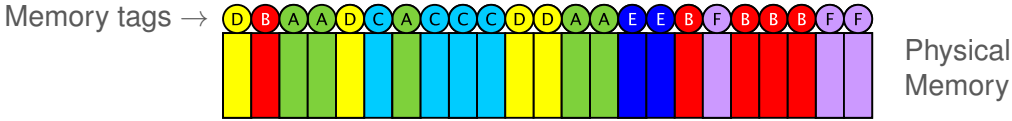
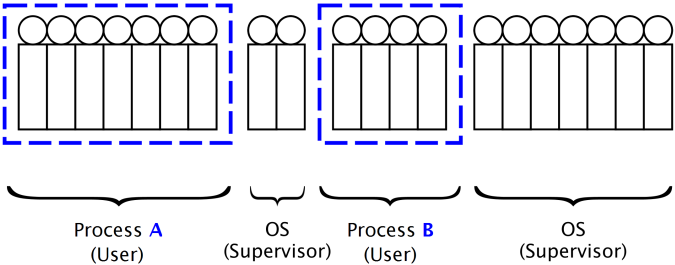


- Memory tags define applications
- Problem: high memory overhead

TIMBER-V: MPU + Tagged Memory



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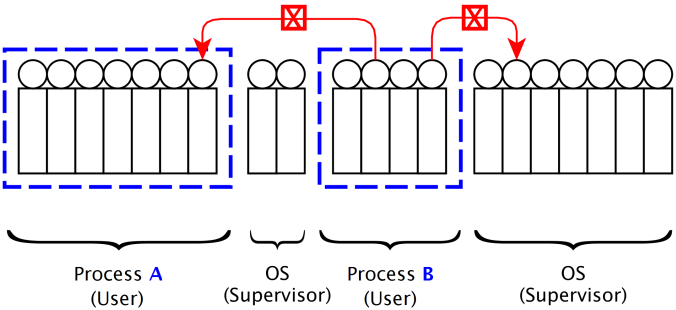

- MPU region defines application
- Application cannot escape

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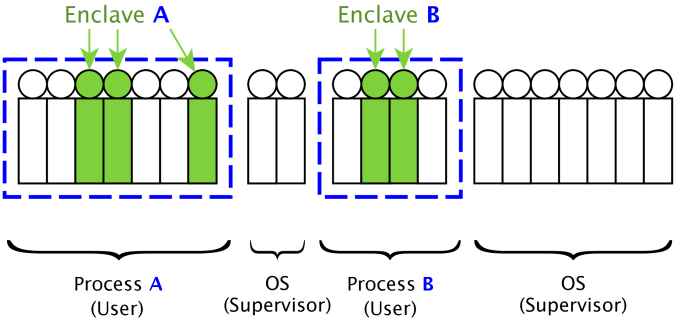

- Memory tag defines enclave

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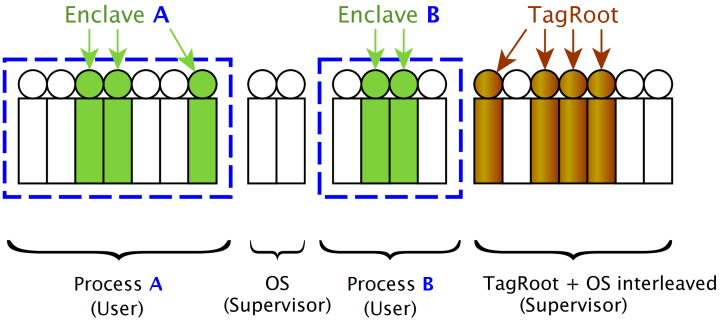
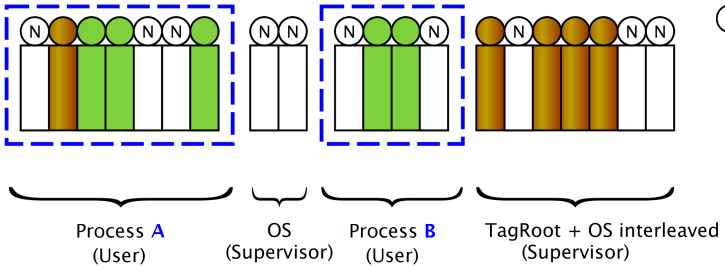


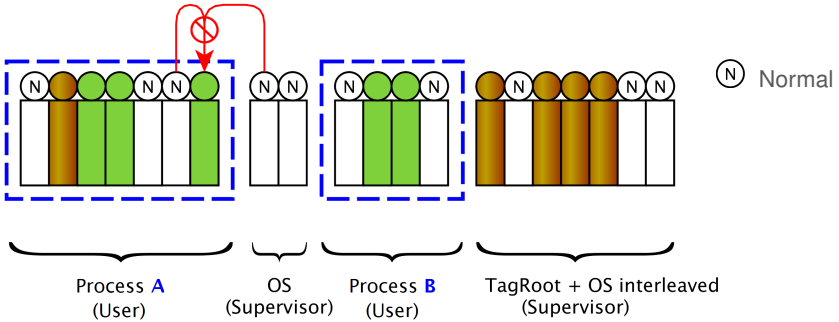
- Memory tag defines enclave
- Memory tag defines TagRoot

TIMBER-V Tag Isolation



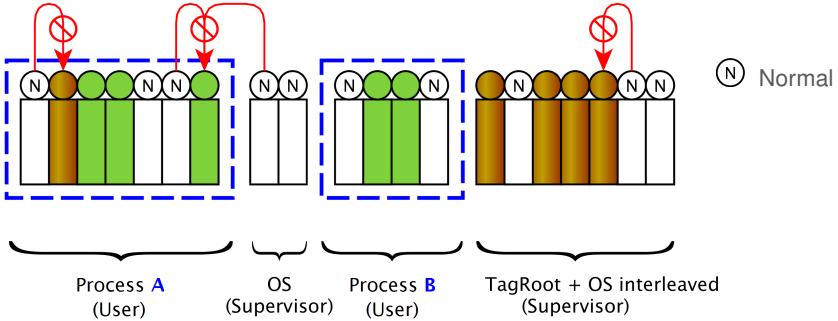
- N Normal memory

TIMBER-V Tag Isolation



- (N) Normal memory
- Cannot access others

TIMBER-V Tag Isolation



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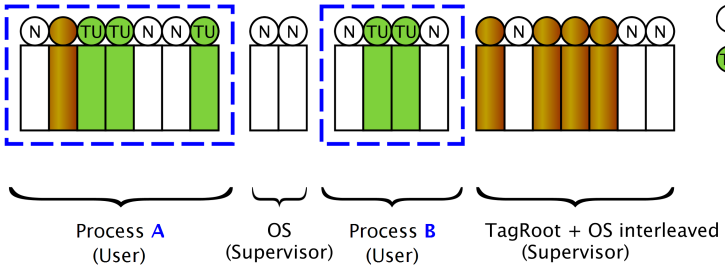

- TU Trusted User memory (enclaves)

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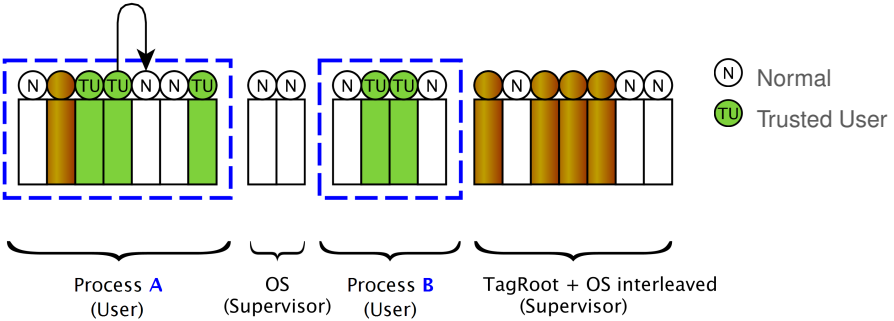

- TU Trusted User memory (enclaves)
- Can access and update normal memory

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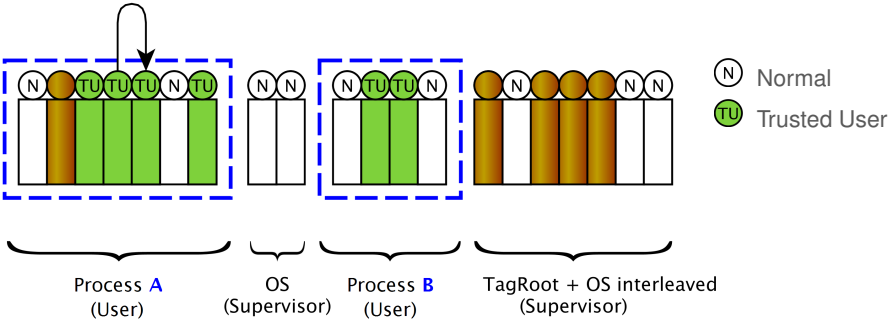

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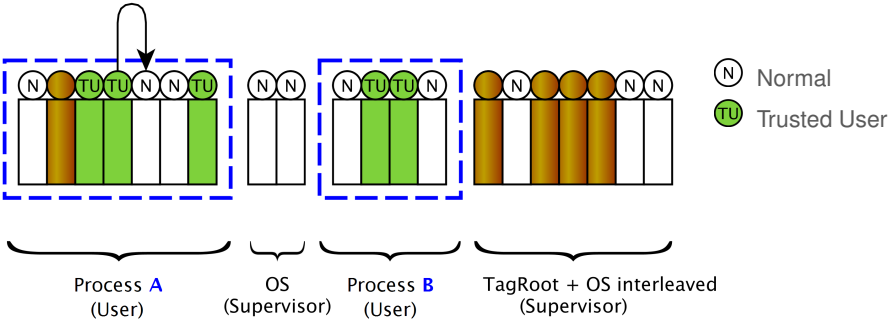
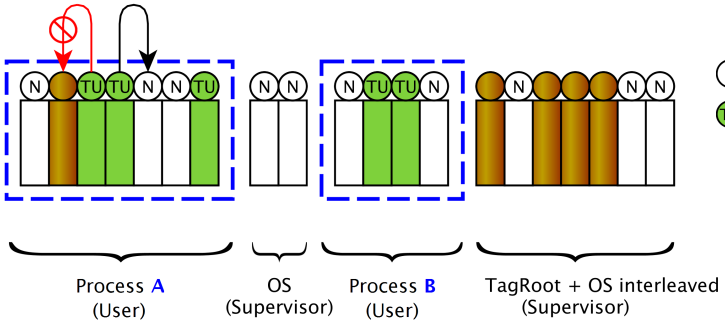
TIMBER-V Tag Isolation



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

TIMBER-V Tag Isolation



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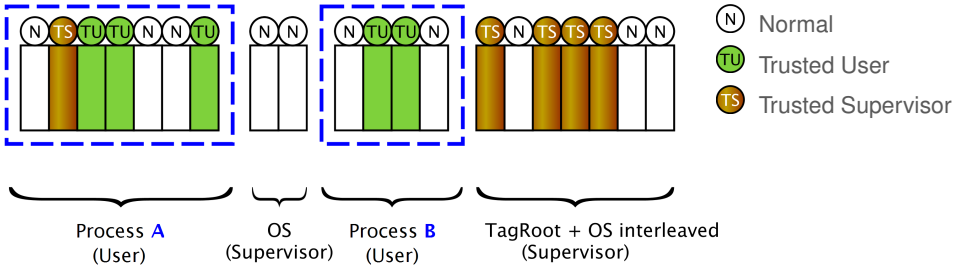
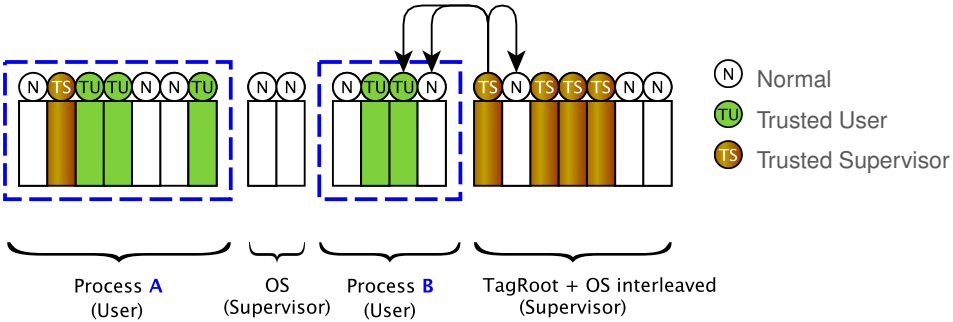


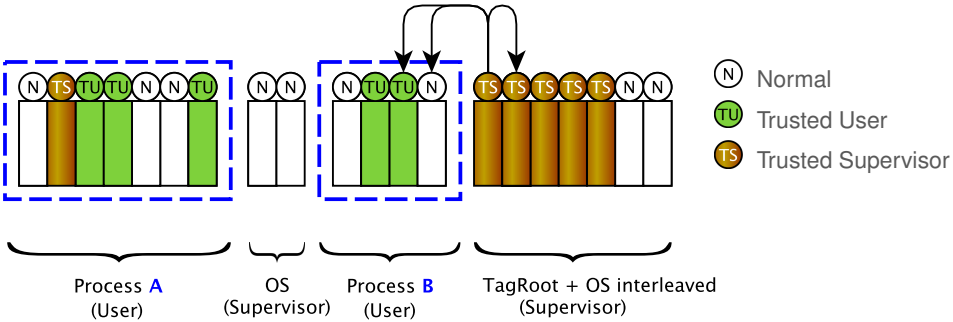
- TS Trusted Supervisor memory (TagRoot)

TIMBER-V Tag Isolation



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

TIMBER-V Tag Isolation



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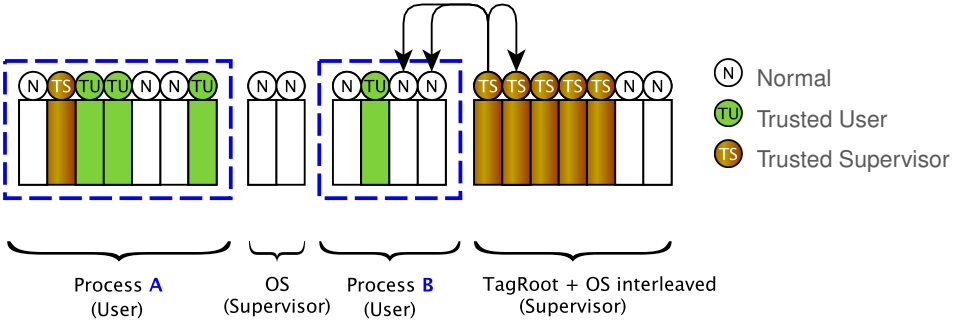

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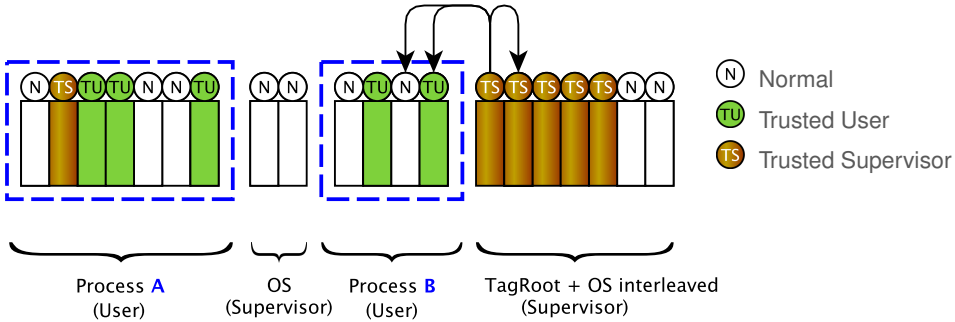

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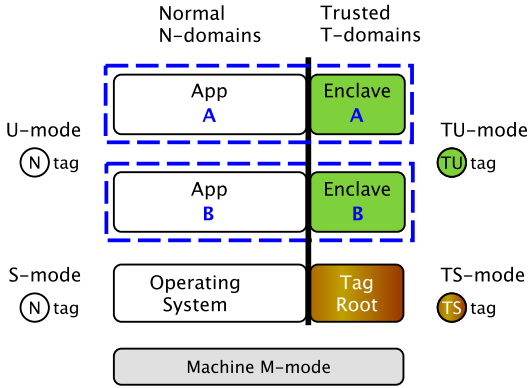
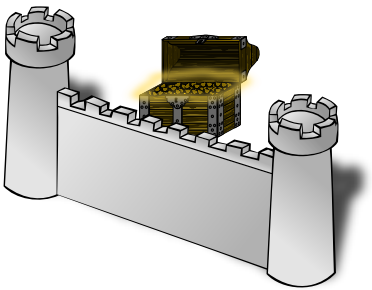
TIMBER-V Memory Isolation



TIMBER-V



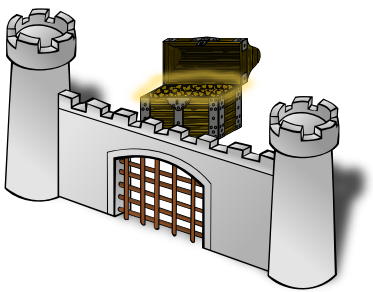
Enclave building blocks:

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

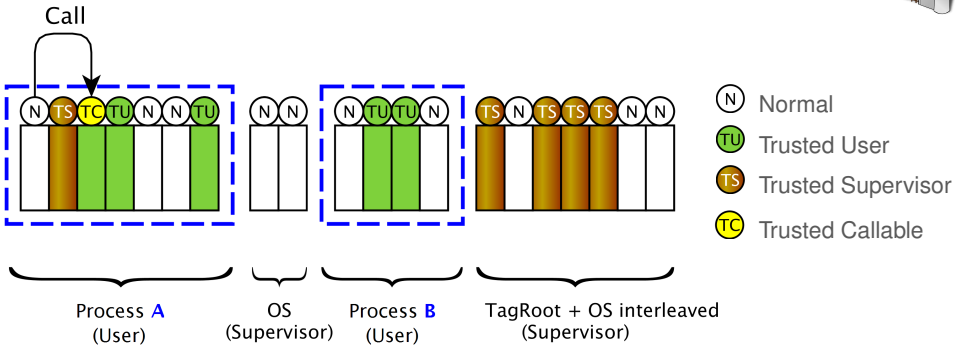
TIMBER-V

Enclave building blocks:

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

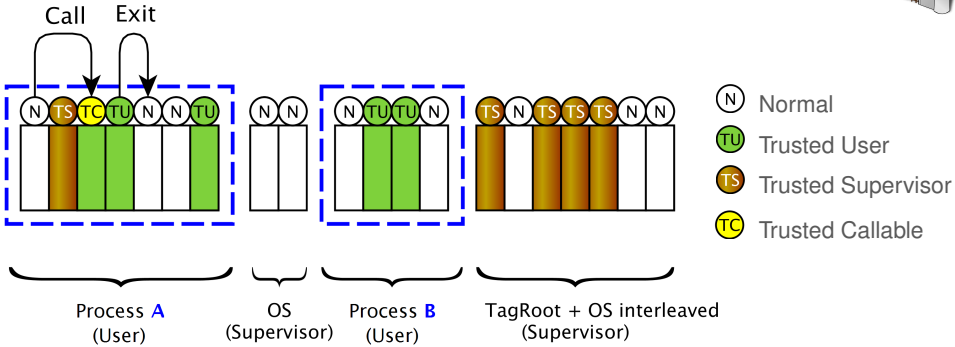


TIMBER-V Entry Points



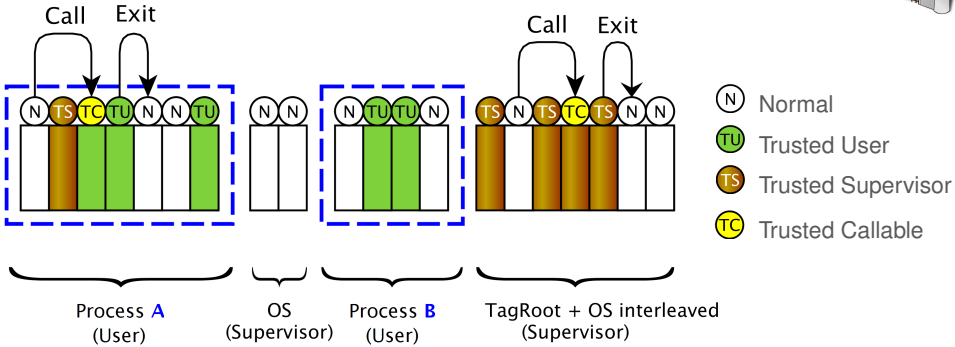
- Enter only at TC Trusted Callable

TIMBER-V Entry Points



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

TIMBER-V Entry Points



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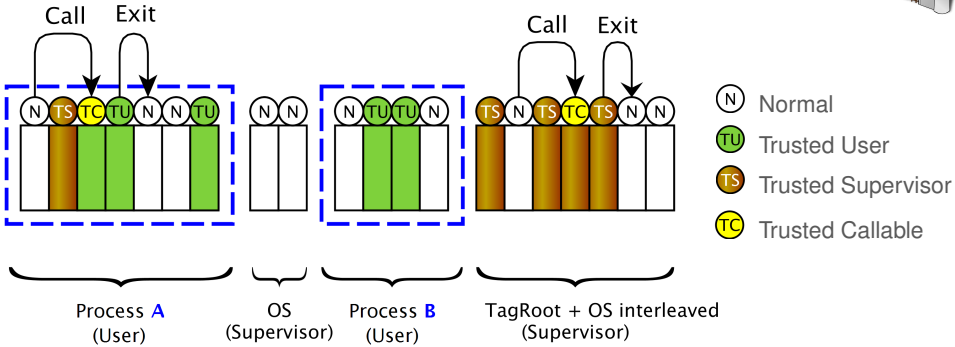
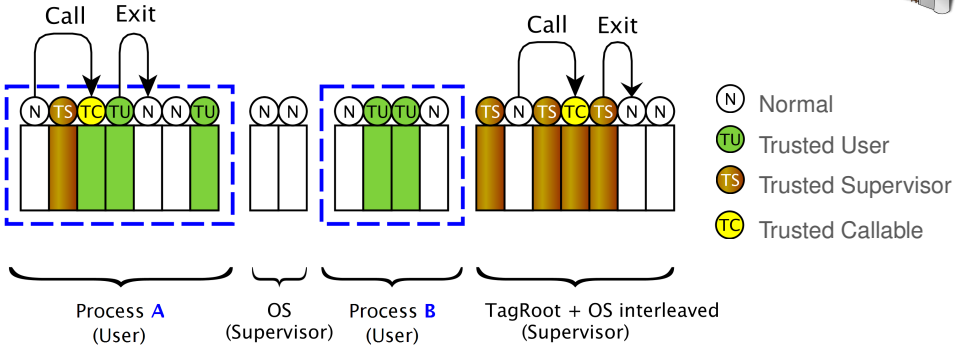


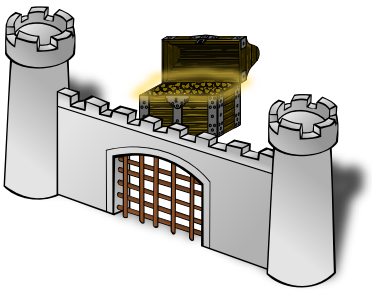
- Four tags → two tag bits only

TIMBER-V Entry Points



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

TIMBER-V



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TIMBER-V

Enclave building blocks:

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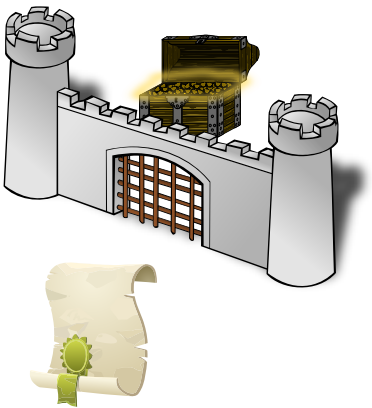
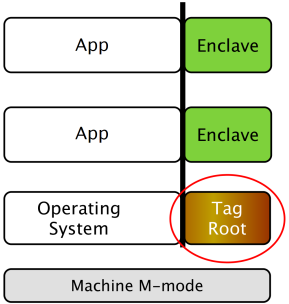


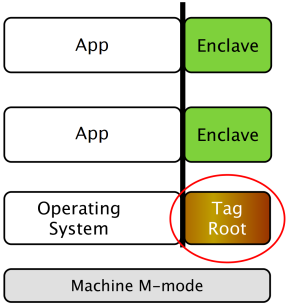
TIMBER-V TagRoot

- Root of trust in privileged software



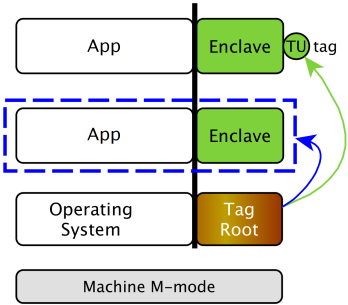
TIMBER-V TagRoot

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



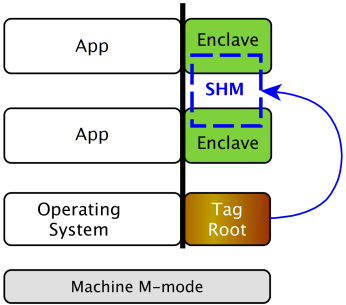
TIMBER-V TagRoot

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



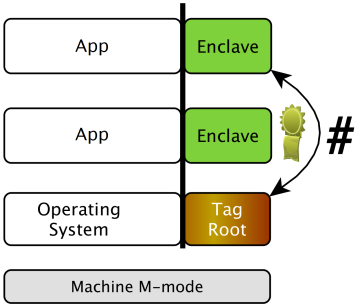
TIMBER-V TagRoot

- 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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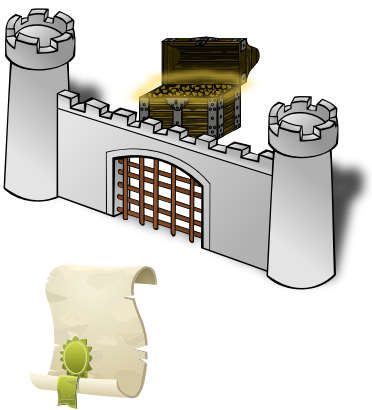
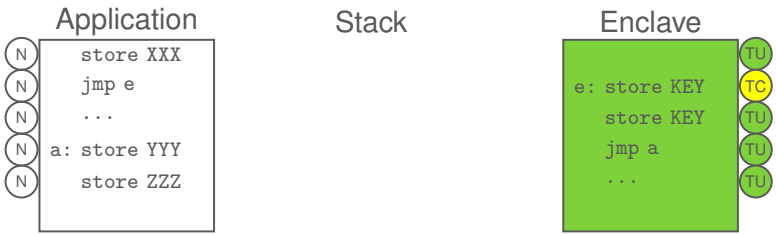
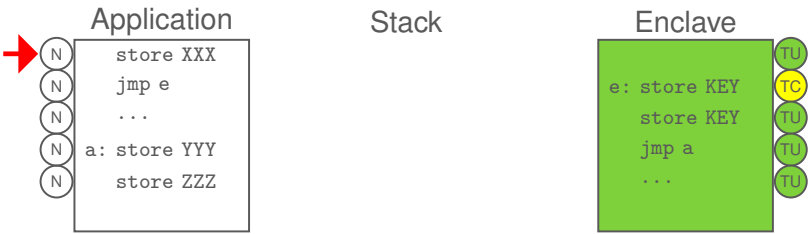


Novel Stack Sharing



- Single stack shared between application and enclave ...

Novel Stack Sharing



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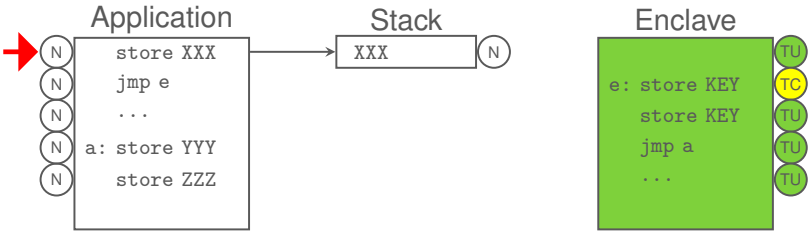

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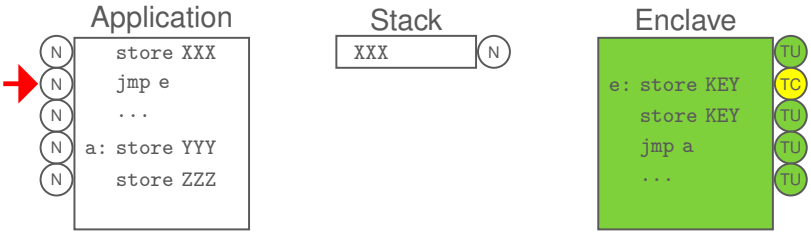

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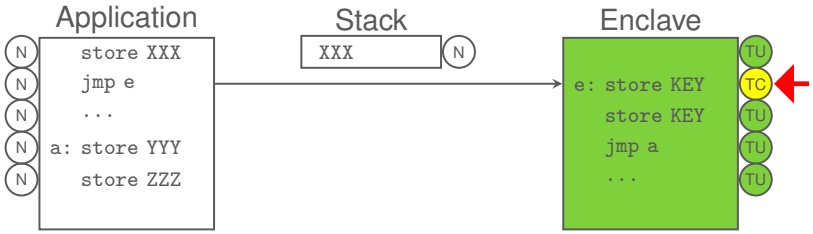

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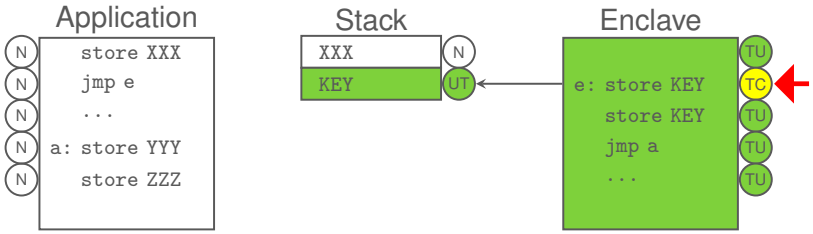

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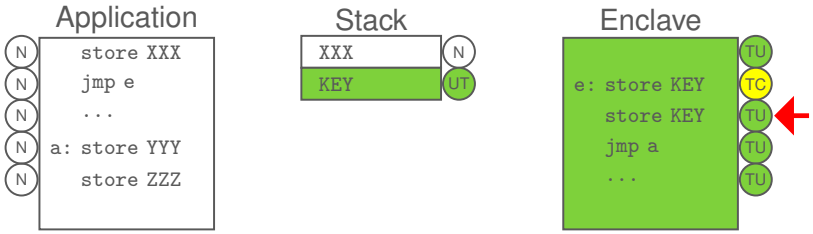

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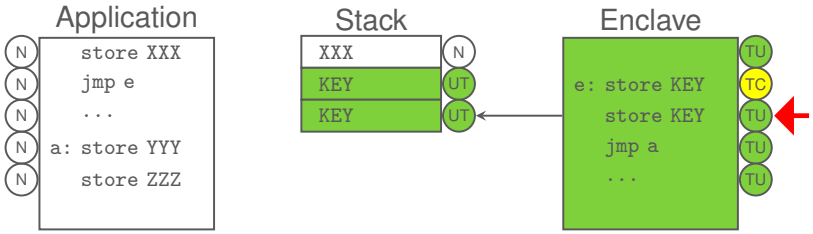

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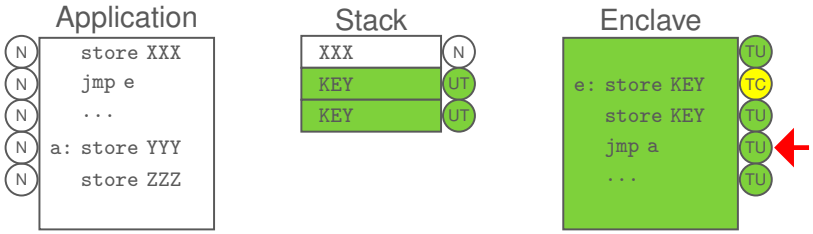

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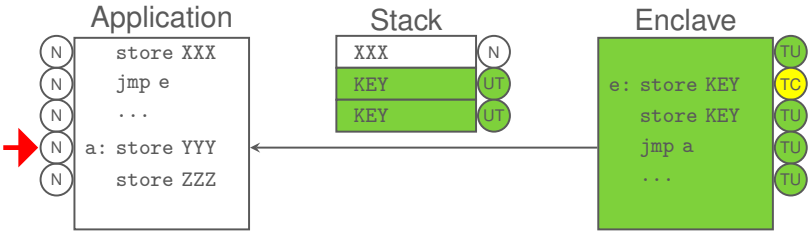

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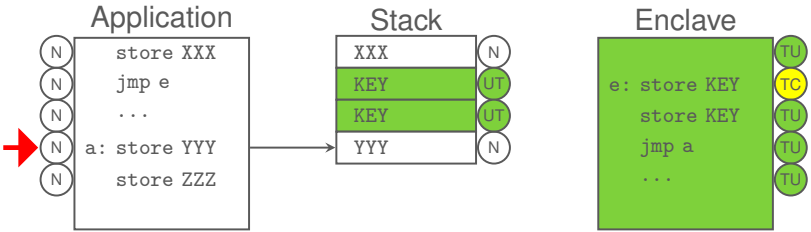

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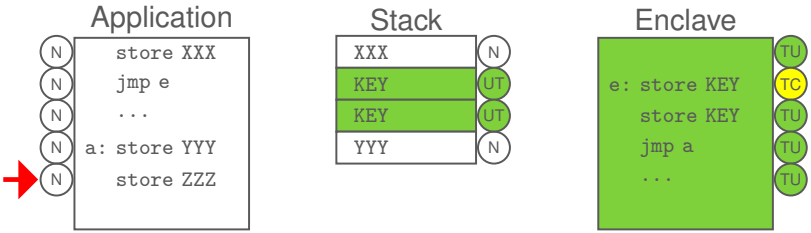

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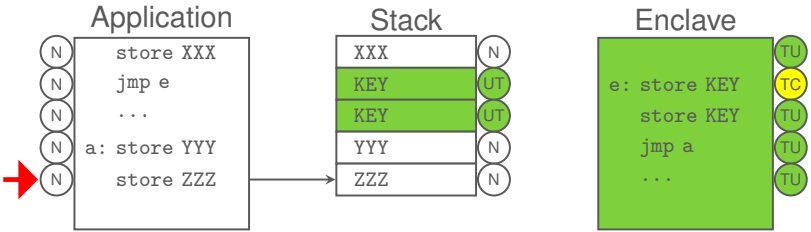

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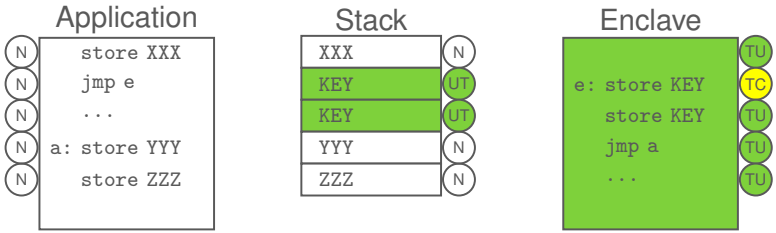
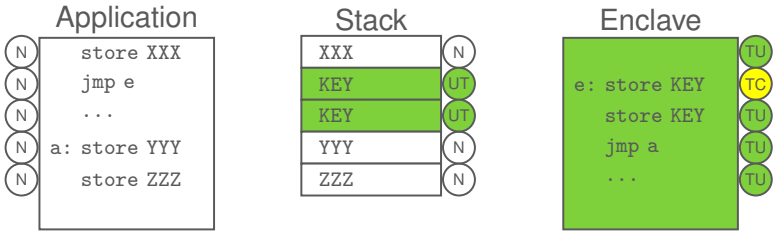


- Single stack shared between application and enclave ...

  ... 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`

TIMBER-V

Tag-**I**solated **M**emory **B**ringing Fine-grained **E**nclaves to **R**ISC-**V**

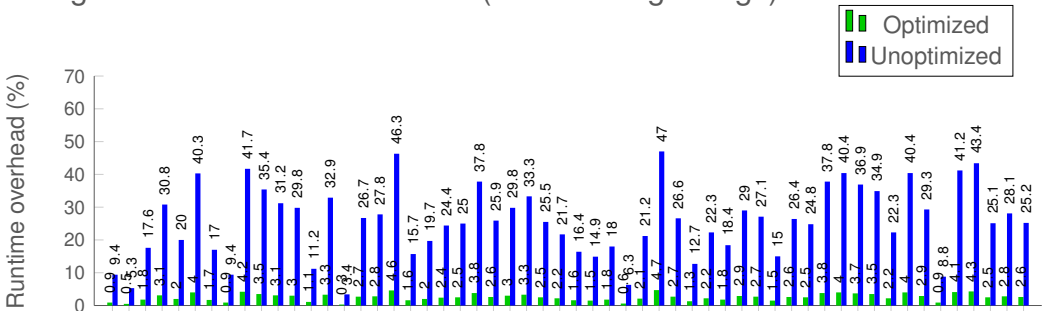
Samuel Weiser* **Mario Werner***
Ferdinand Brasser† **Maja Malenko***
Stefan Mangard* **Ahmad Sadeghi†**
*Graz University of Technology
†TU Darmstadt

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)



References

[1] Franz Ferdinand Brasser, Brahim El Mahjoub, Ahmad-Reza Sadeghi, Christian Wachsmann, and Patrick Koeberl. “TyTAN: tiny trust anchor for tiny devices”. In: Design Automation Conference – DAC’15. ACM, 2015, 34:1–34:6. ISBN: 978-1-4503-3520-1.

[2] Victor Costan, Ilia A. Lebedev, and Srinivas Devadas. “Sanctum: Minimal Hardware Extensions for Strong Software Isolation”. In: USENIX Security’16. USENIX Association, 2016, pp. 857–874.

[3] Karim Eldefrawy, Gene Tsudik, Aurélien Francillon, and Daniele Perito. “SMART: Secure and Minimal Architecture for (Establishing Dynamic) Root of Trust”. In: Network and Distributed System Security Symposium – NDSS’12. The Internet Society, 2012.

[4] Johannes Götzfried, Tilo Müller, Ruan de Clercq, Pieter Maene, Felix C. Freiling, and Ingrid Verbauwhede. “Soteria: Offline Software Protection within Low-cost Embedded Devices”. In: Annual Computer Security Applications Conference – ACSAC’15. ACM, 2015, pp. 241–250. ISBN: 978-1-4503-3682-6.

[5] Hex-Five MultiZone Security - the First Trusted Execution Environment (TEE) For RISC-V. https://hex-five.com/products/ (Accessed 2018/12/10). 2018.

[6] Keystone: Open-source Secure Hardware Enclave. https://keystone-enclave.org/ (Accessed 2018/12/10). 2018.

[7] Patrick Koeberl, Steffen Schulz, Ahmad-Reza Sadeghi, and Vijay Varadharajan. “TrustLite: a security architecture for tiny embedded devices”. In: European Conference on Computer Systems – EUROSYS’14. ACM, 2014, 10:1–10:14. ISBN: 978-1-4503-2704-6.

[8] Joanna Rutkowska. Thoughts on Intel’s upcoming Software Guard Extensions (Part 2). http://theinvisiblethings.blogspot.co.at/2013/09/thoughts-on-intels-upcoming-software.html. (Accessed 2016/10/20). Sept. 2013.

[9] TrustZone Technology for ARMv8-M Architecture. Ref. no. 100690_0200_00_en. https://static.docs.arm.com/100690/0200/armv8m_trustzone_technology_100690_0200.pdf. (Accessed 2018/11/22). 2017.