Nested Enclave: Supporting Fine-grained Hierarchical Isolation with SGX

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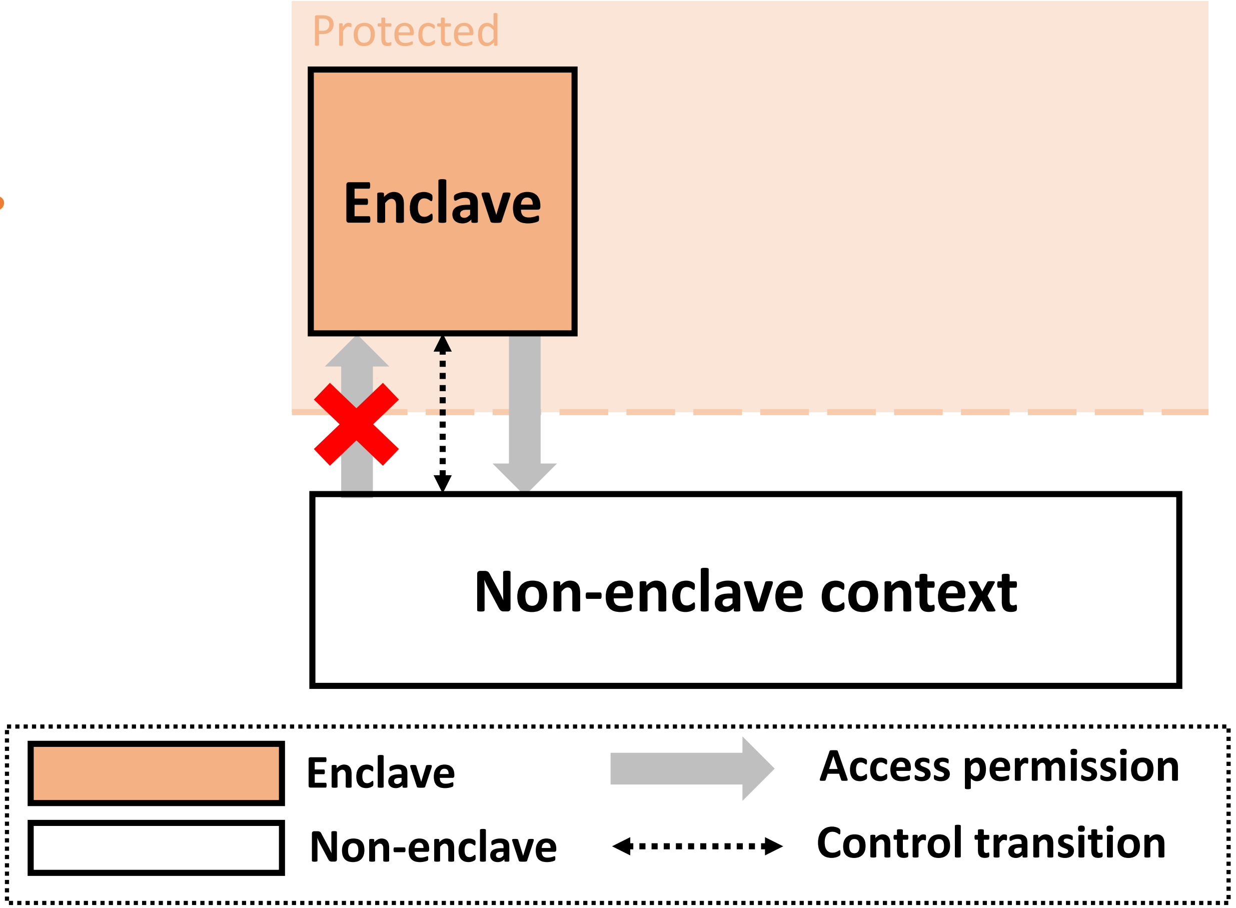
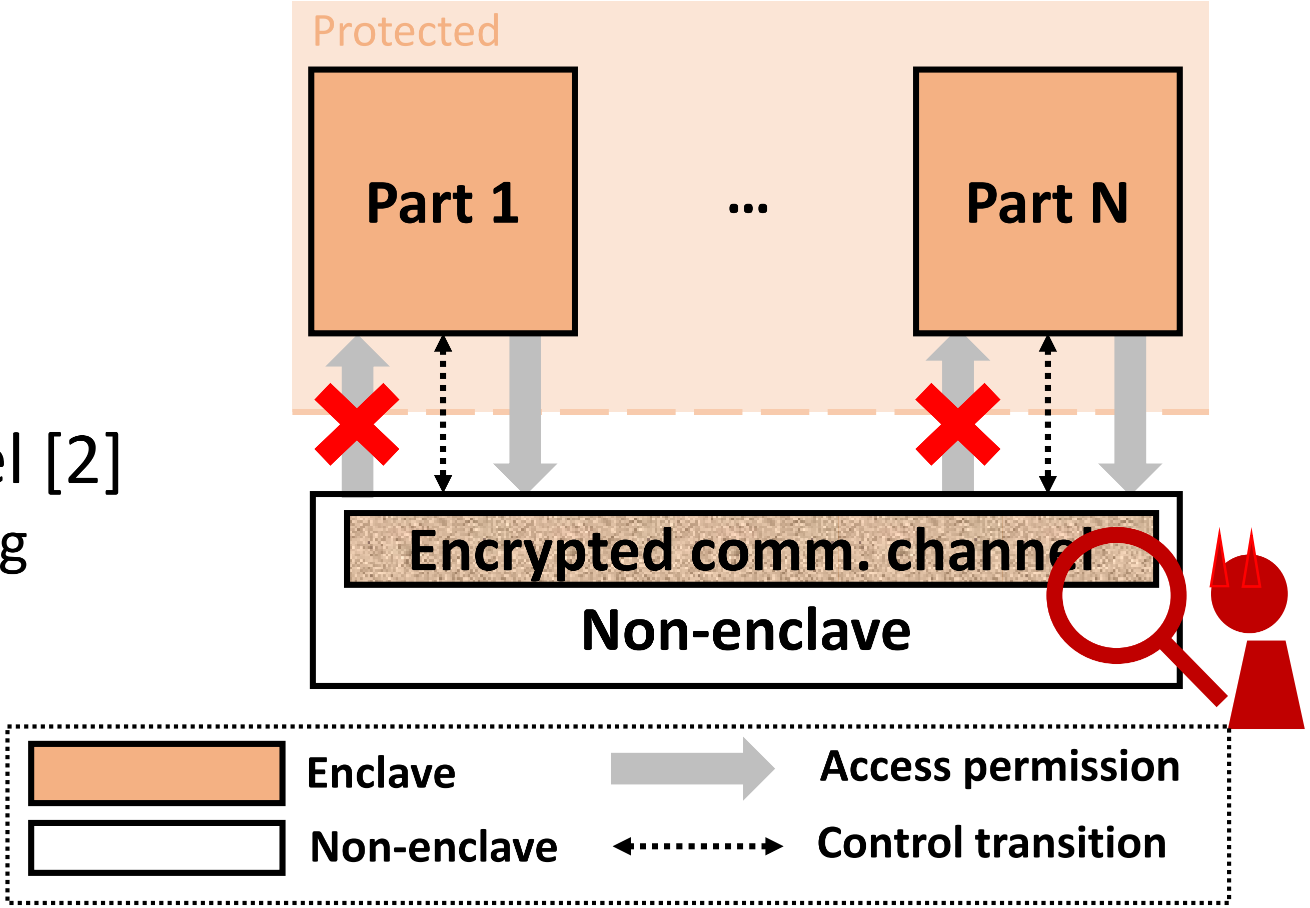
SGX Trusted Execution Environment

- Intel SGX
  - Provides trusted execution environments (TEE) called *Enclave*
  - Protected from malicious privileged SW
  - Guarantee confidentiality and integrity
  - **Monolithic design**



Need for Extension

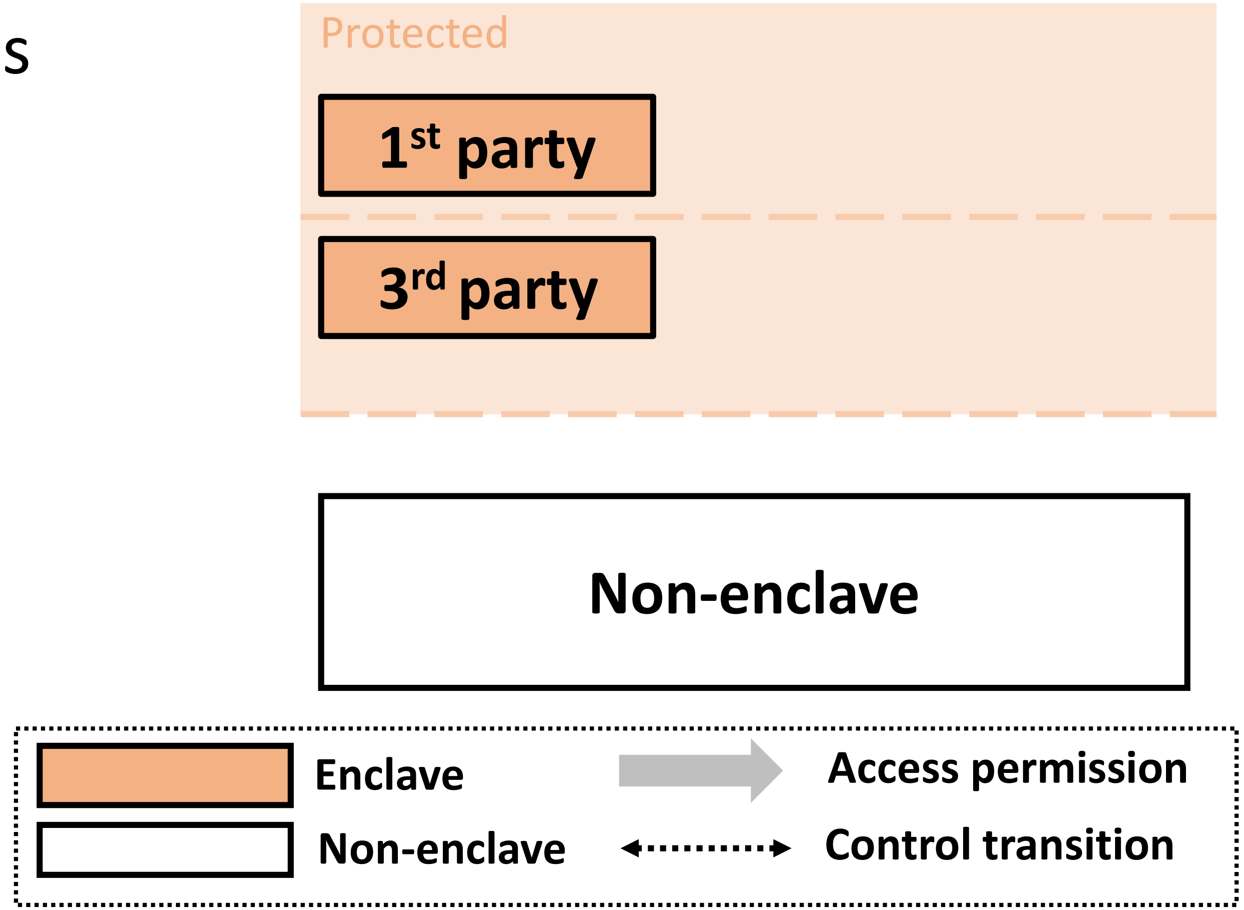
- Mutually distrustful parties [1]
  - Multiple parties are involved for building an application
  - Use multiple enclaves
- Exposed communication channel [2]
  - Must protect against eavesdropping
  - Must detect silent drops



[1] Ryoan: A Distributed Sandbox for Untrusted Computation on Secret Data [2] PANOPLY: Low-TCB Linux Applications with SGX Enclaves

Multi-level Security [3]

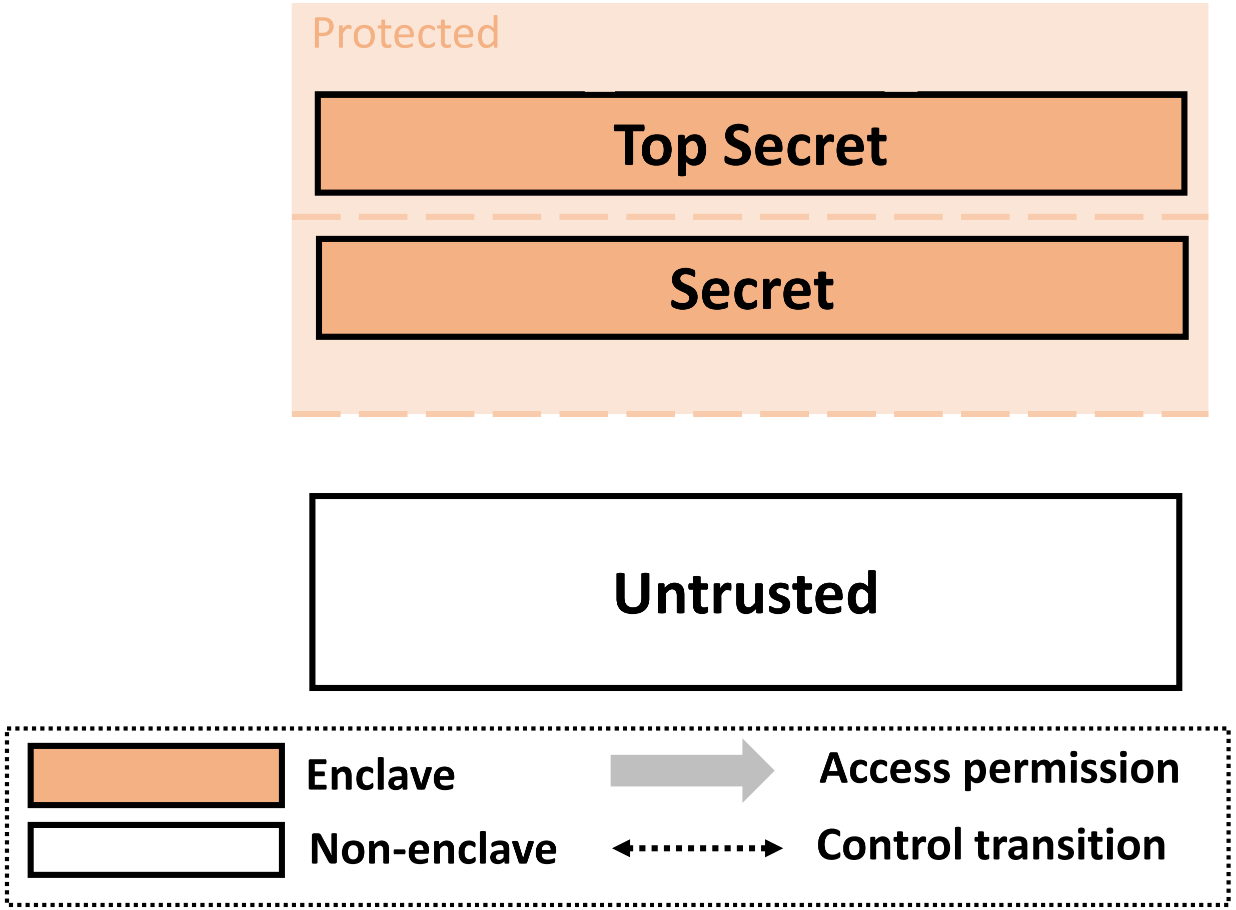
- Applications need multiple levels of security
  - Top secret / Secret
  - 1st party app / 3rd party library



[3] Secure Computer Systems: Mathematical Foundations

Compartmentalization

- Compartmentalization
  - Isolated peer compartments



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Compartmentalization

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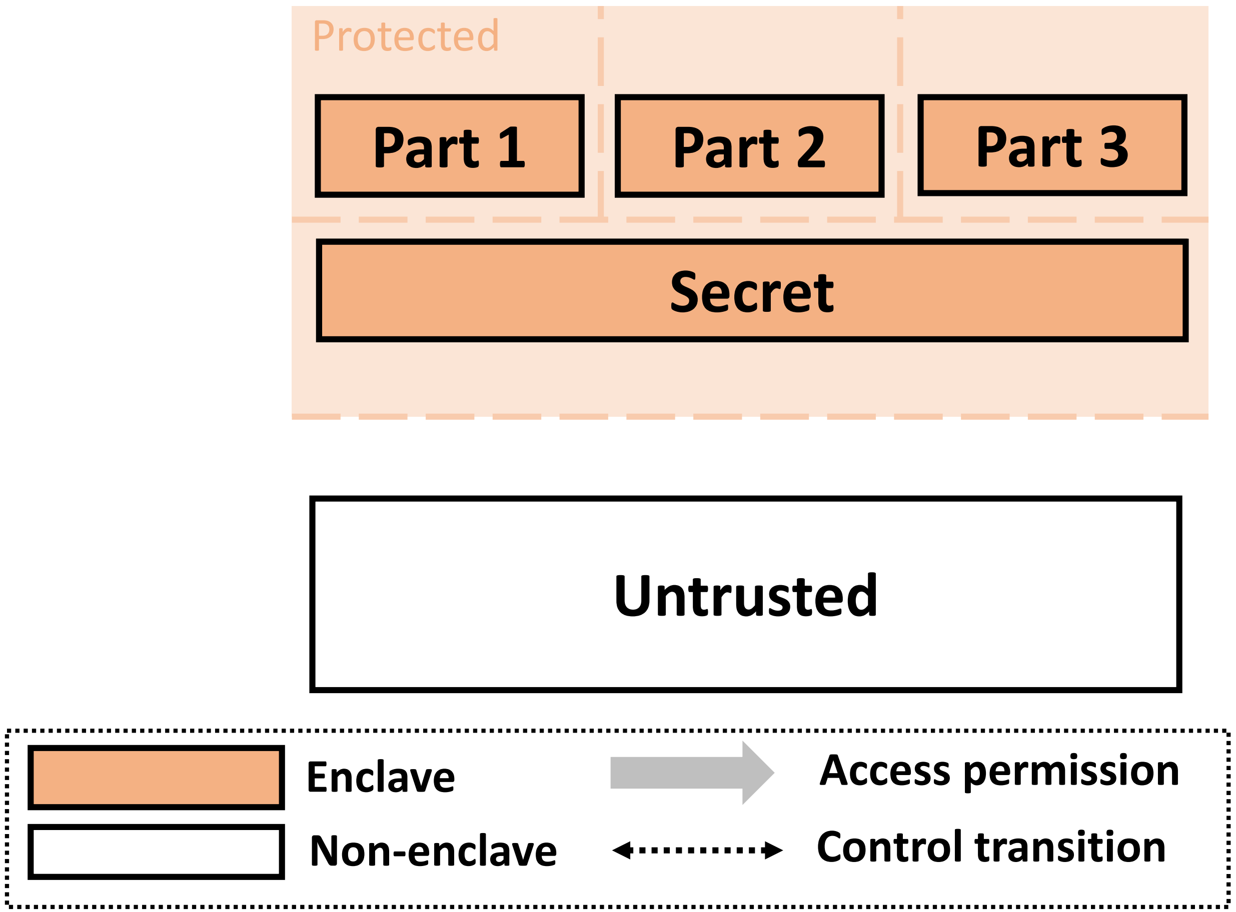
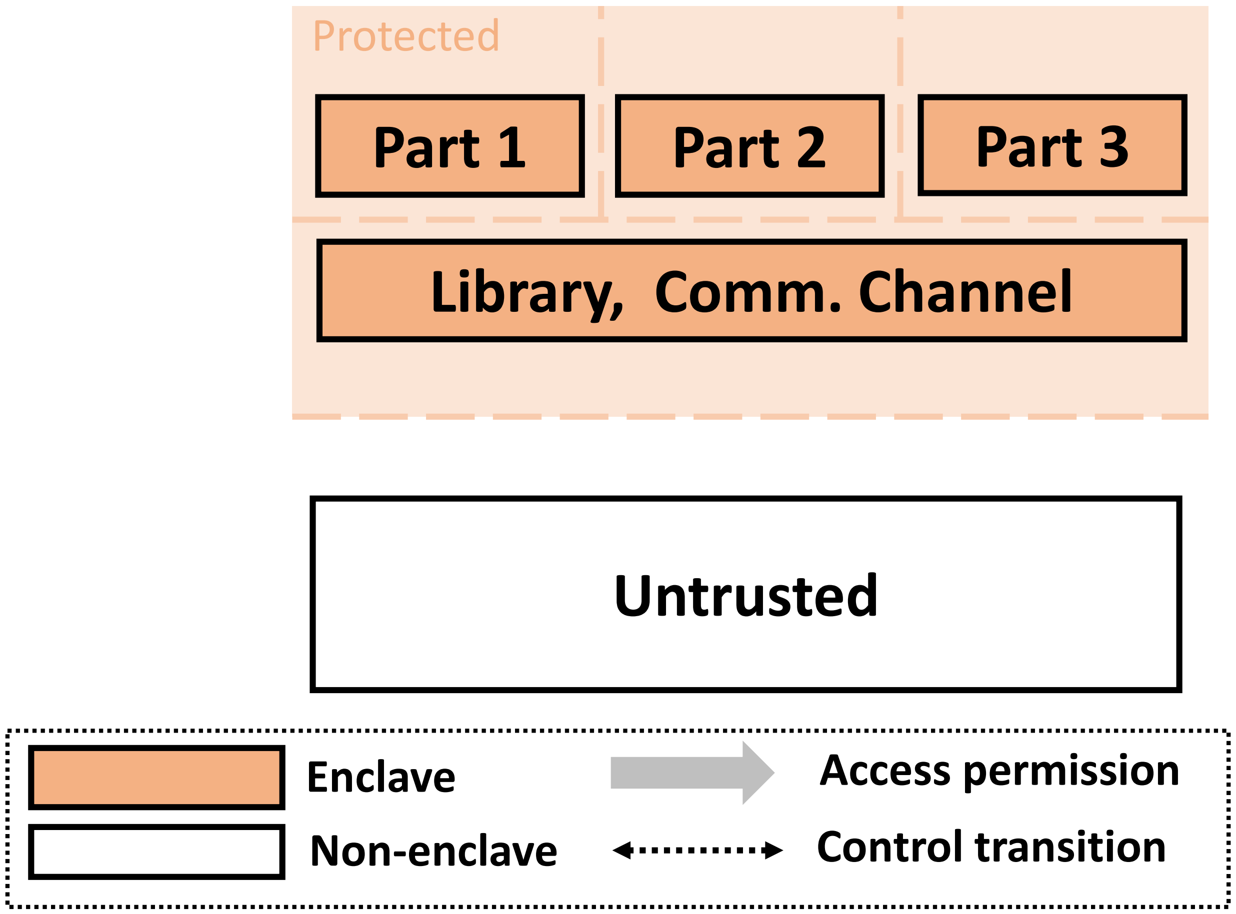


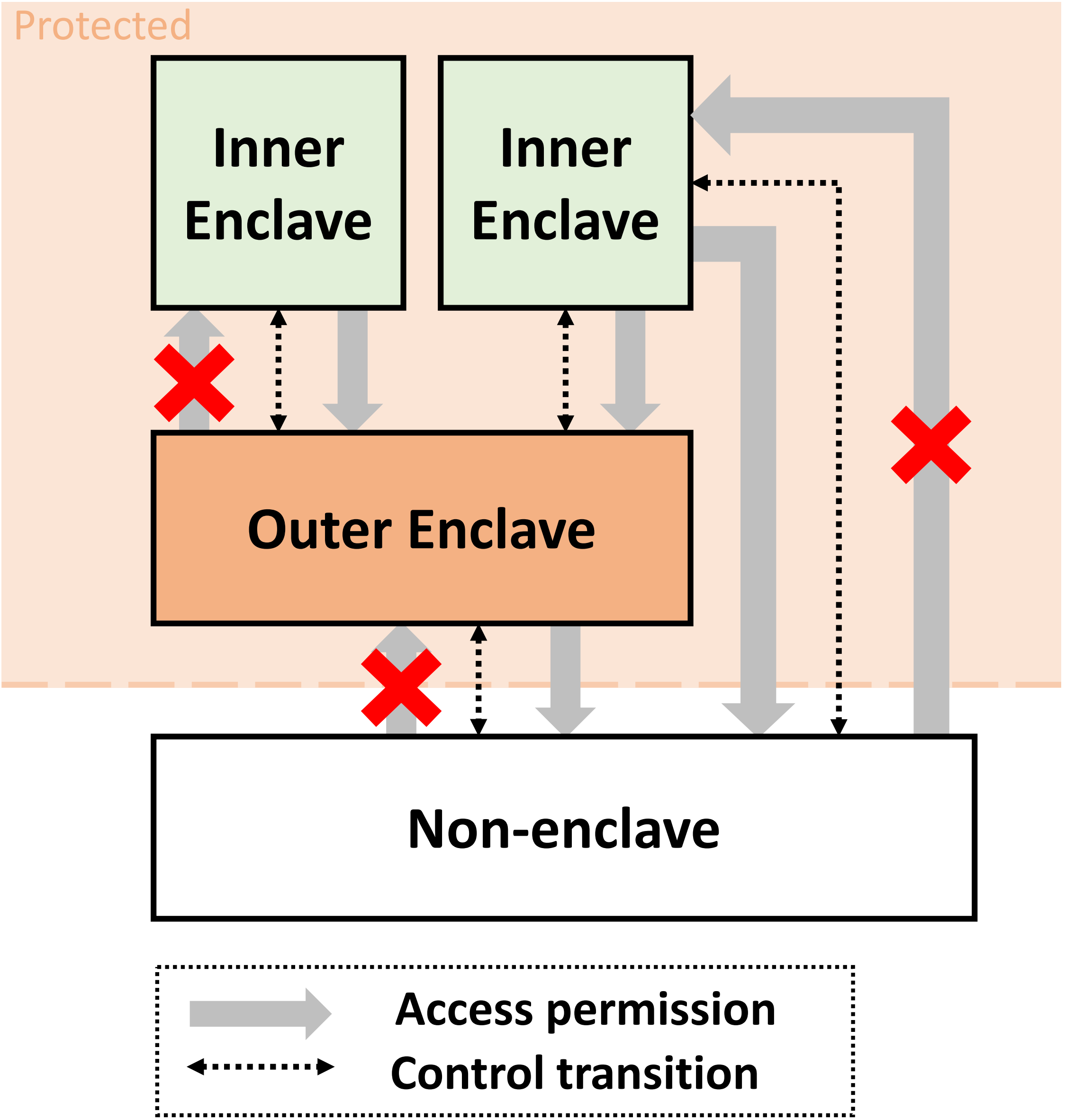
Compartmentalization

- Compartmentalization
  - Isolated peer compartments
- Sharing lower compartment
  - Shared library
  - Communication channel



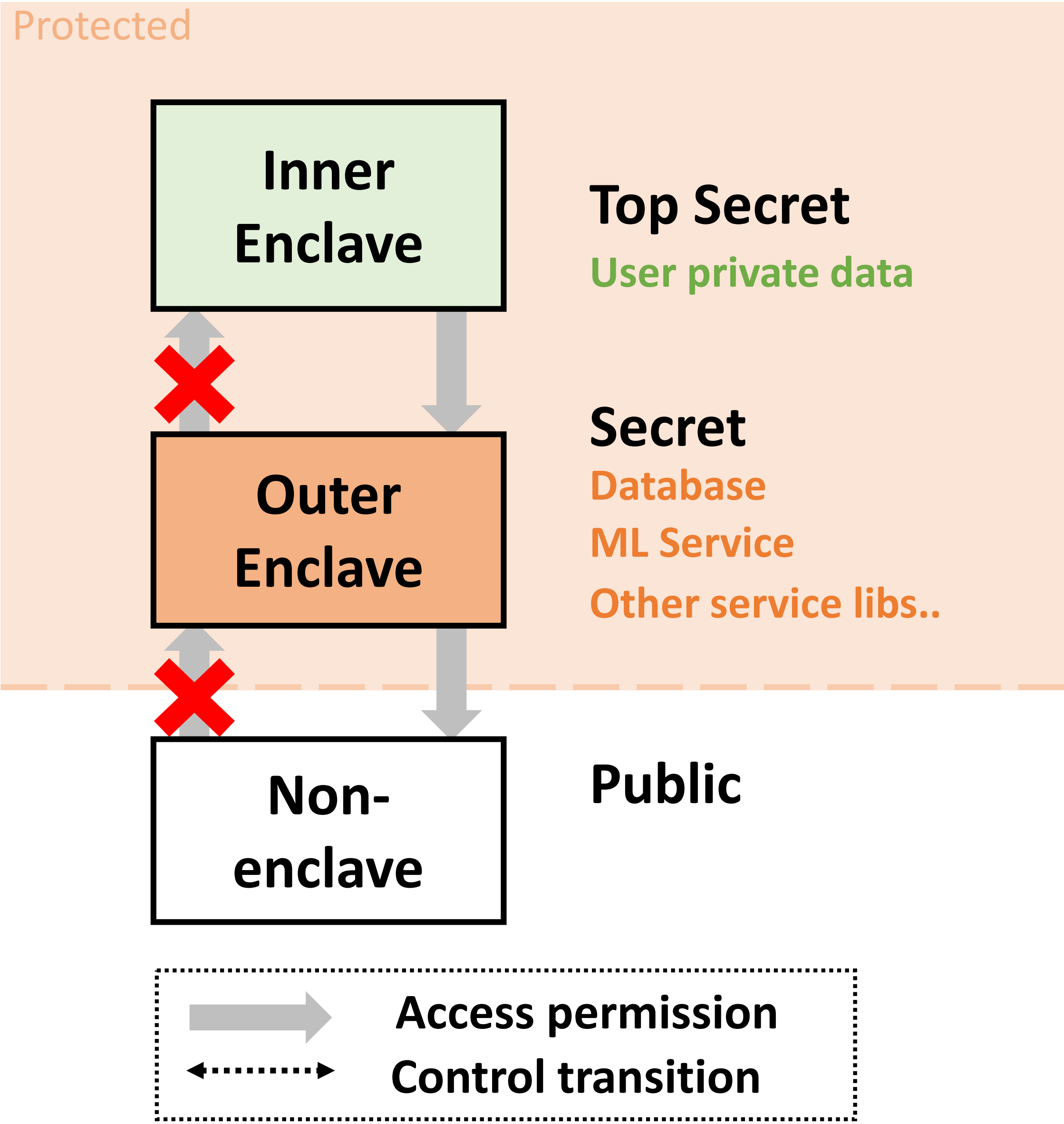
Nested Enclave

- Nested enclave is hardware extension to SGX
  - Inner Enclave
  - Outer Enclave



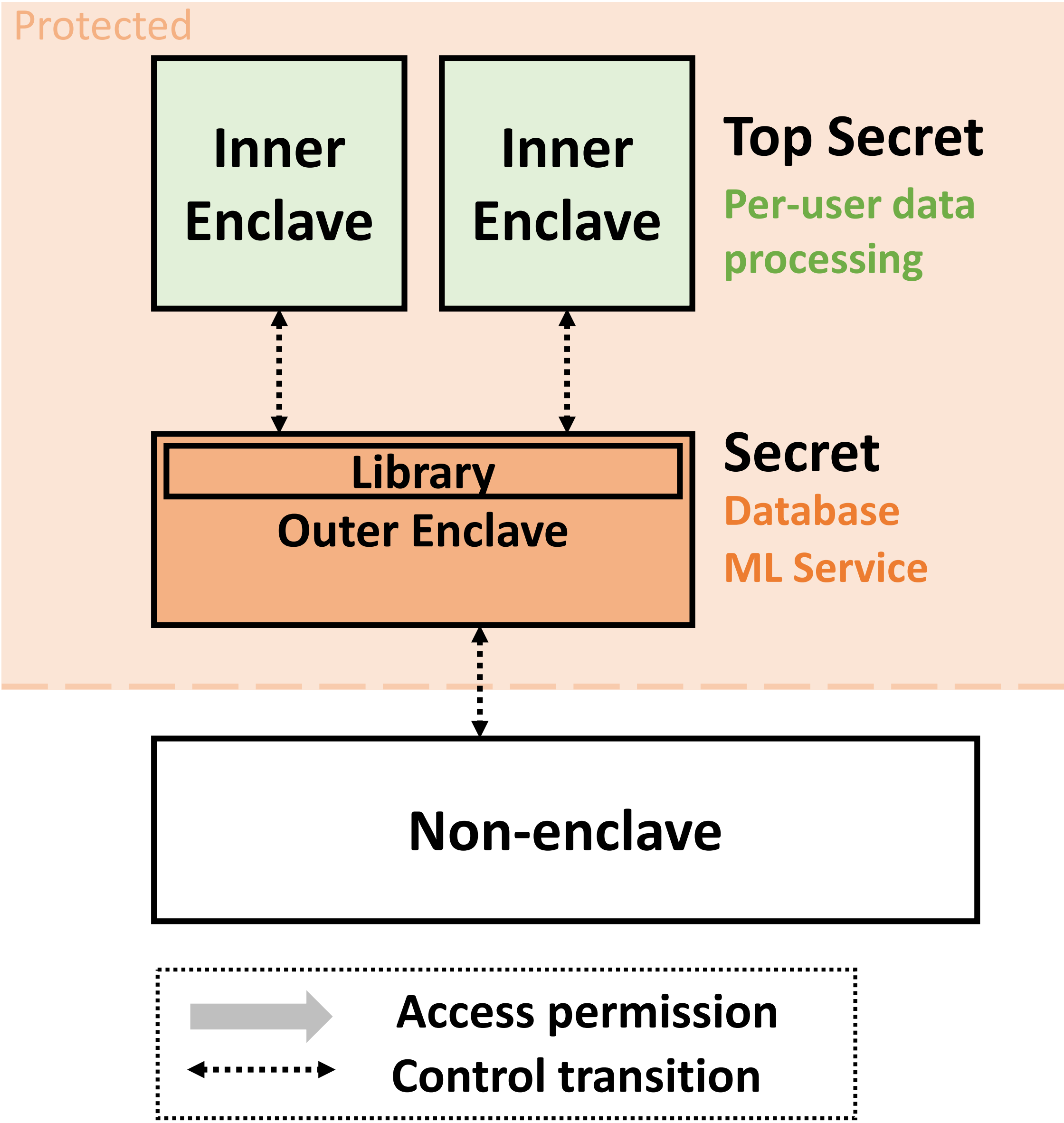
New semantics

- Hierarchical Isolation
  - Non-enclave context doesn't have access permission to both enclaves
  - Outer enclave doesn't have access permission to inner enclaves
  - Inner enclave has access permission to lower levels
- Supporting multi-level security



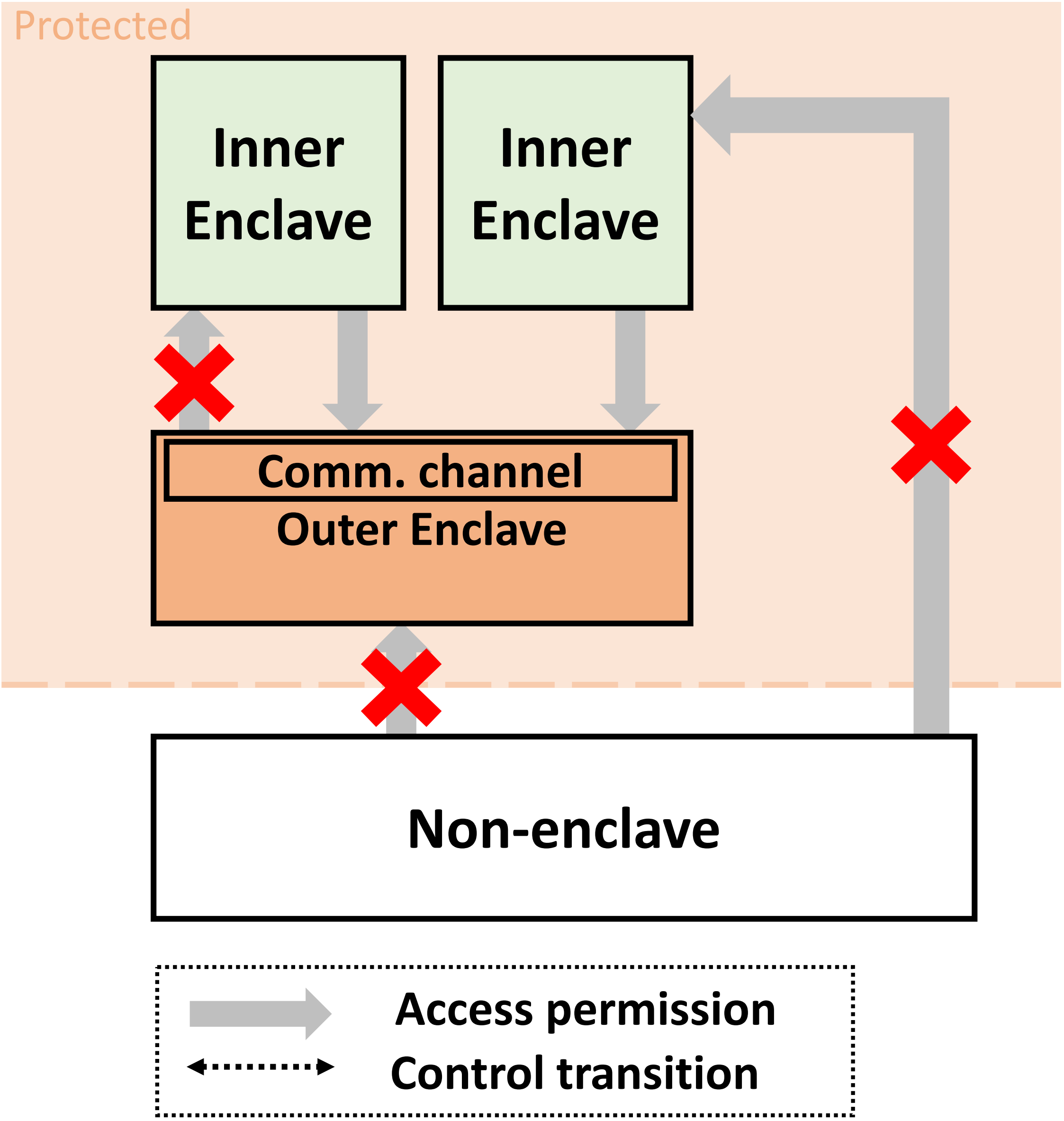
New semantics (Cont'd)

- Compartmentalization
  - Isolation among Inner Enclaves
- Shared library with Outer Enclave
  - Reduced total memory usage
  - Inner enclave is protected from shared library



New semantics (Cont'd)

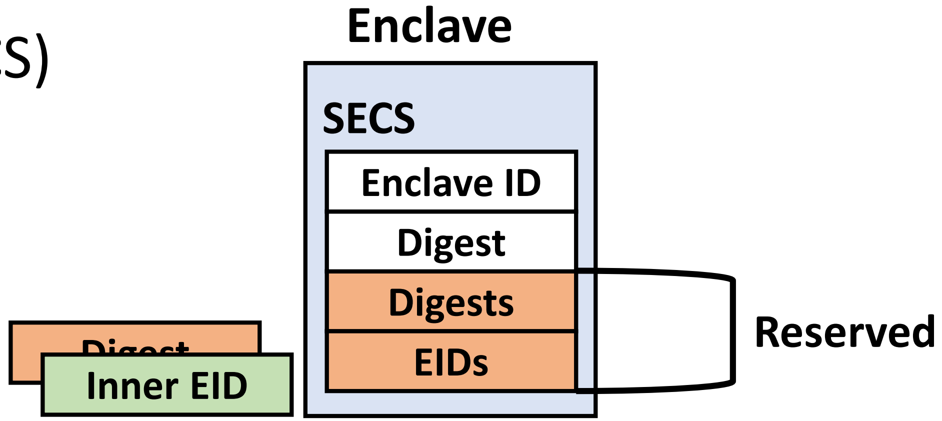
- Secure communication channel in outer enclave
  - Hardware based protection via Memory Encryption Engine (MEE)
- Faster communication through caches
  - No encryption for data in caches
  - Enables faster data transfer [4]



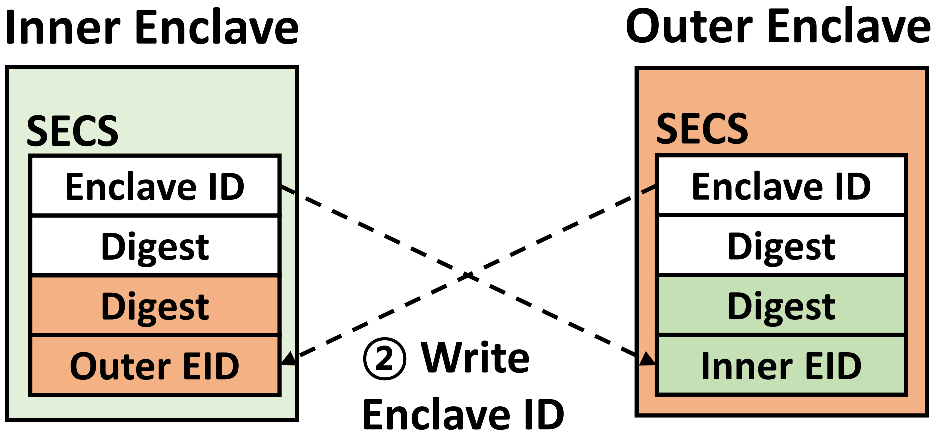
[4] The multikernel: a new OS architecture for scalable multicore systems

States and Association

- SGX Enclave Control Structure (SECS)
  - The state of an enclave
  - Use reserved fields to contain
    - Inner or outer enclave's digest
    - Inner or outer enclave's ID (EID)



- Association of inner-outer enclaves
  - Attest the pair enclave with digest
  - Write verified Enclave ID (EID) in SECS

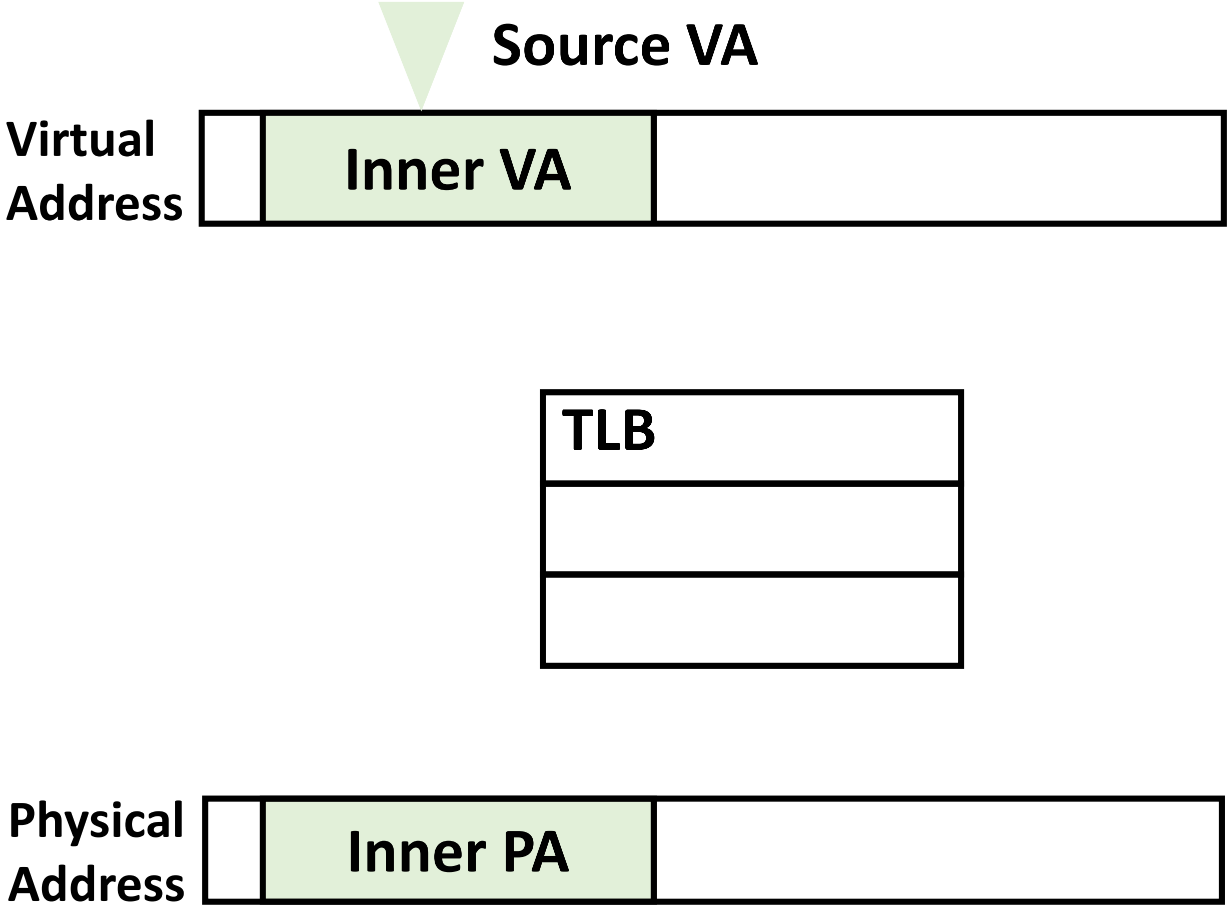


Memory Access Validation

- SGX validates memory access during TLB miss handling
- *EPCM (Enclave Page Cache Map)* in SGX:
  - Meta data for each physical frame
  - Owner EID, VPN (virtual page number), etc

- Invariant for security: TLB must contain only validated translation
- Cases
  - (A) Inner enclave accesses its enclave region
  - (B) Inner enclave accesses its outer enclave region
  - Others

Access Validation (A)



(A) Inner enclave accesses its enclave region

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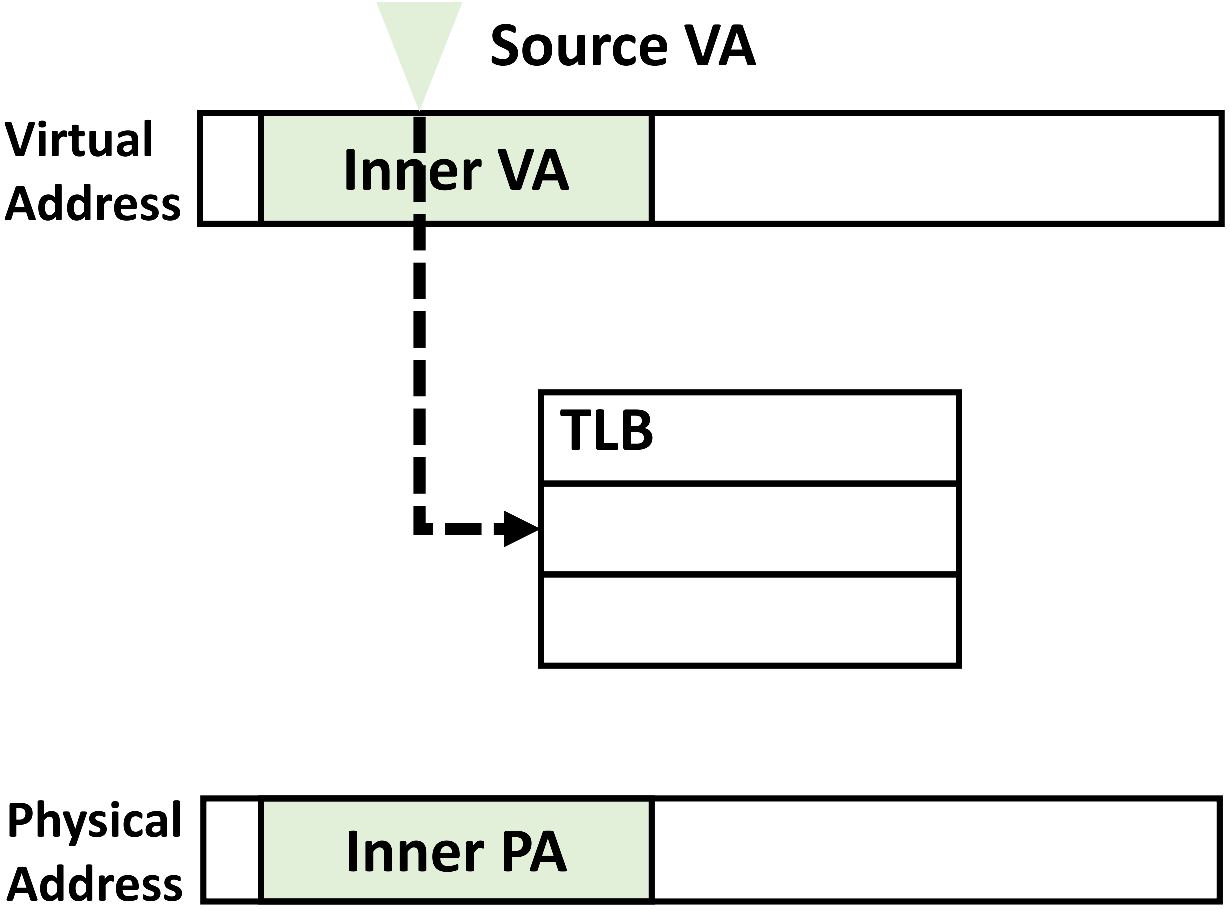

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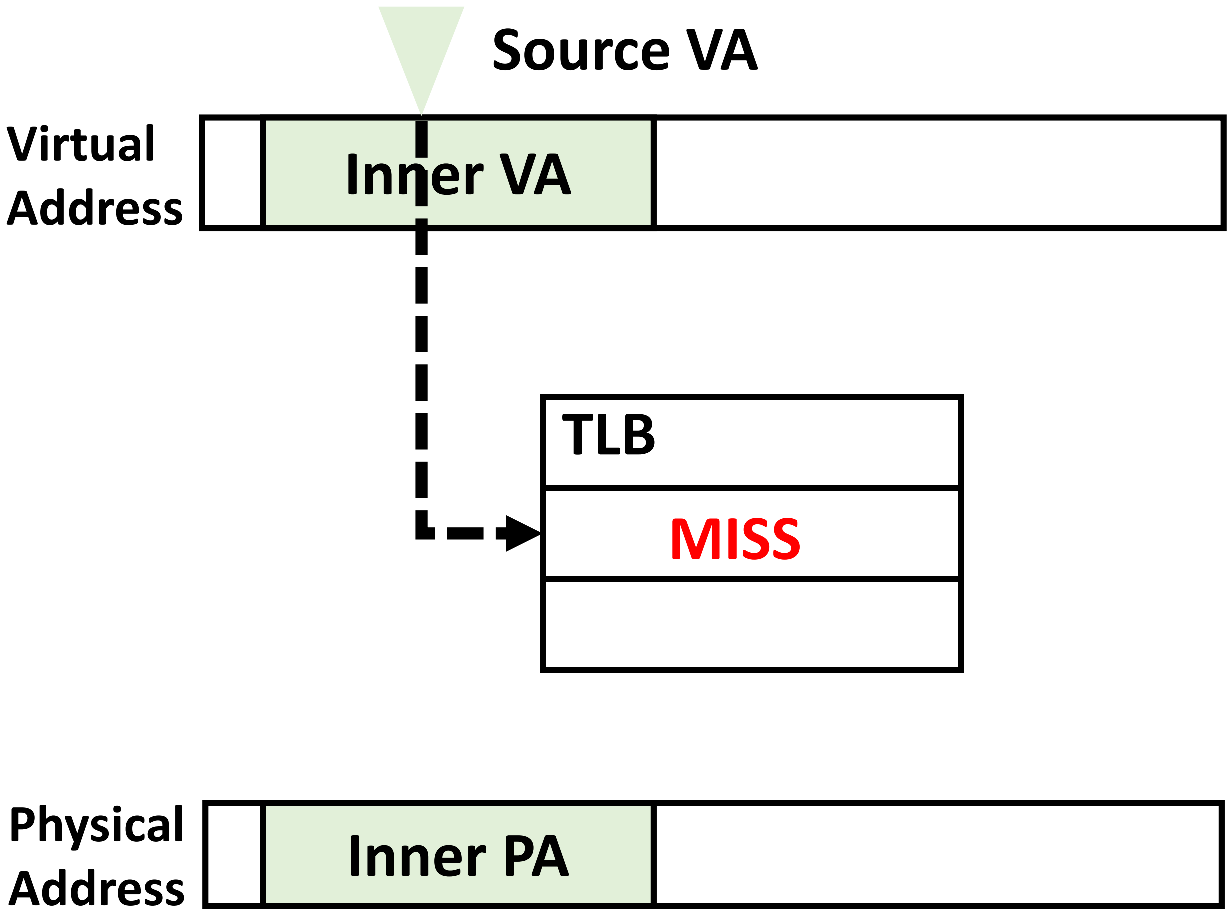

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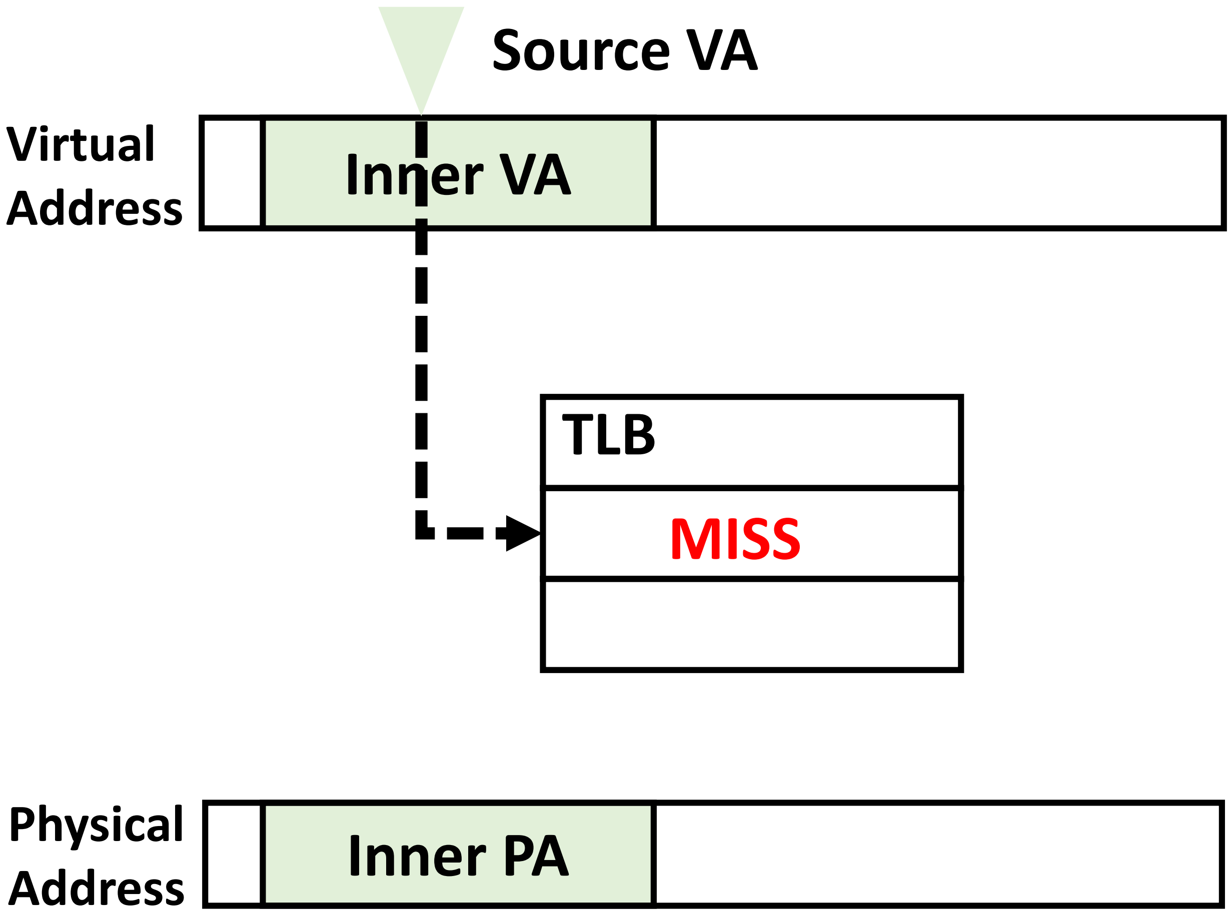
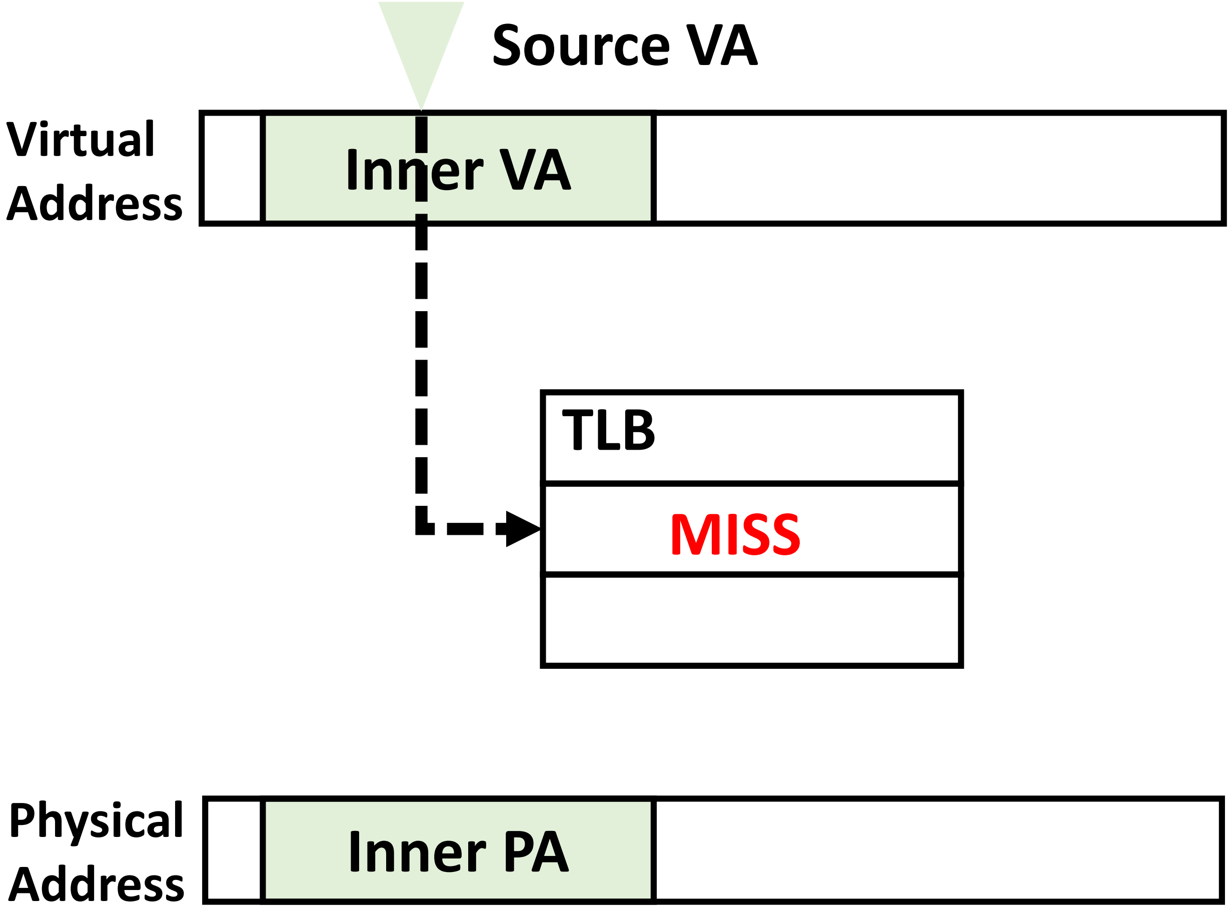


(A) Inner enclave accesses its enclave region

(1) Target PA is Enclave PA?
(2) Check EPCM
- Correct VPN?
- (Owner EID == current EID) || (Owner EID == Outer EID)

Access Validation (A)



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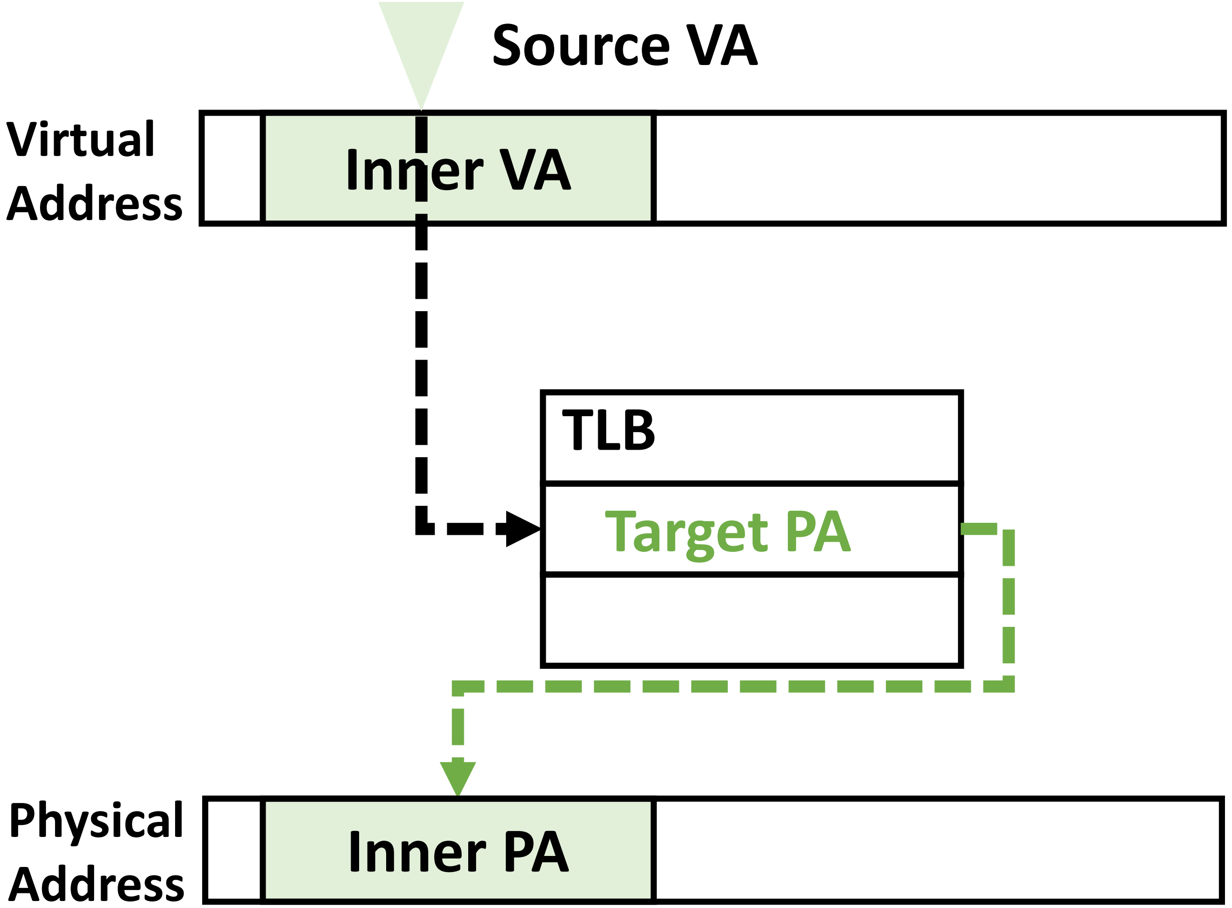
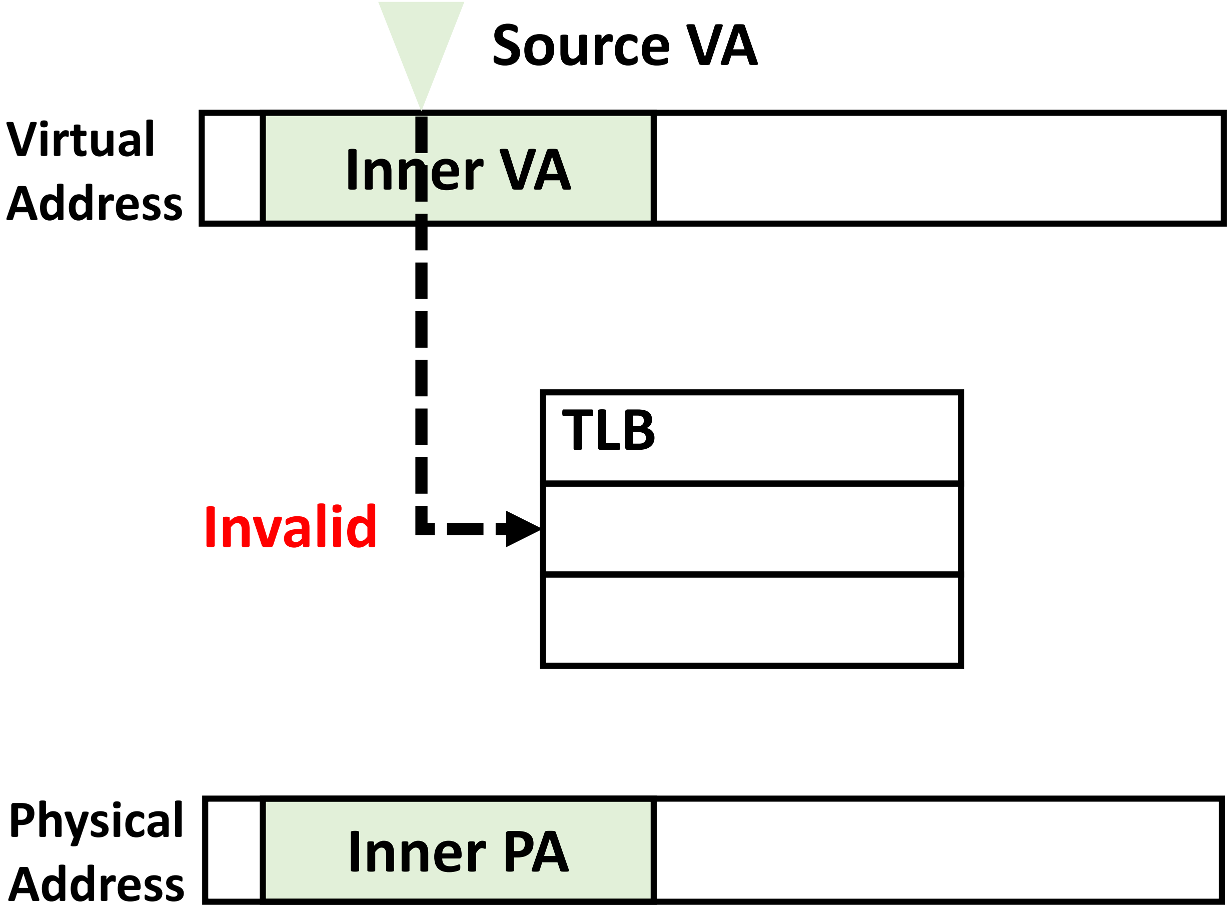


(A) Inner enclave accesses its enclave region

(1) Target PA is Enclave PA?
(2) Check EPCM
- **Correct VPN?**
- **(Owner EID == current EID)**
  || (Owner EID == Outer EID)

YES => Insert TLB entry

Access Validation (A)



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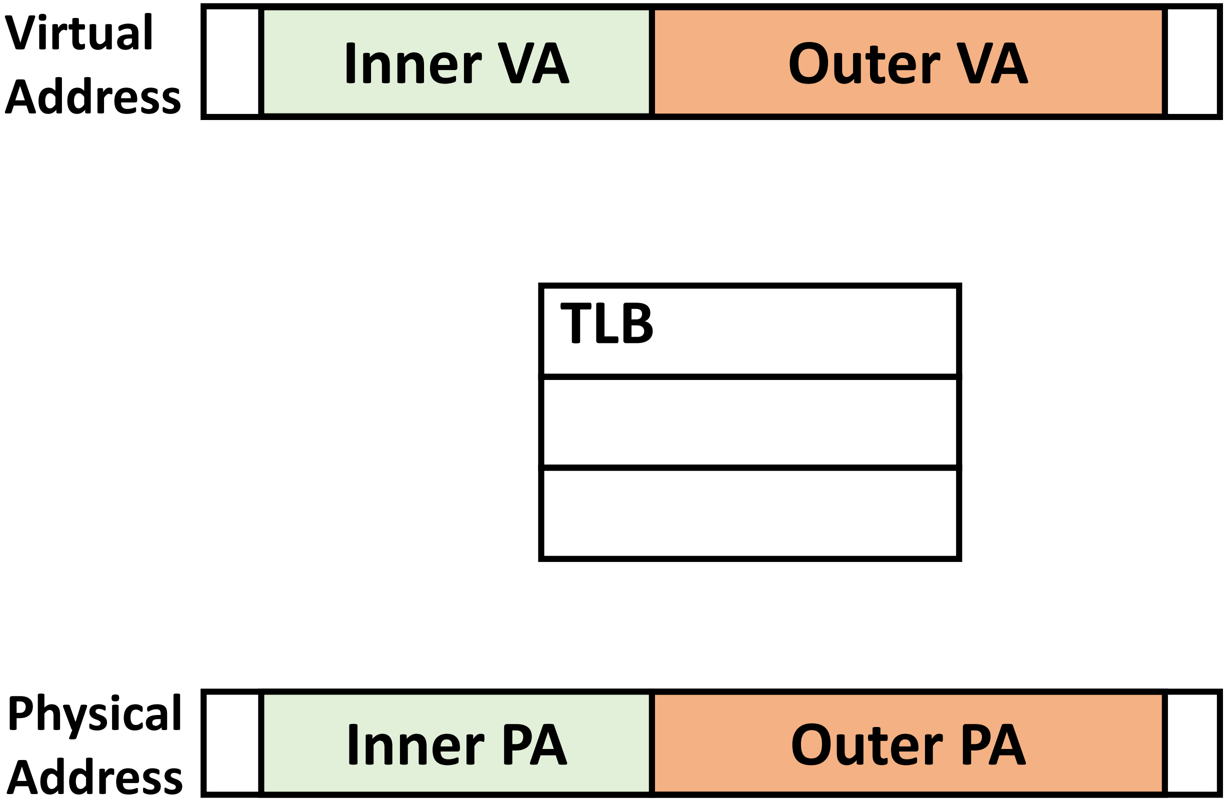
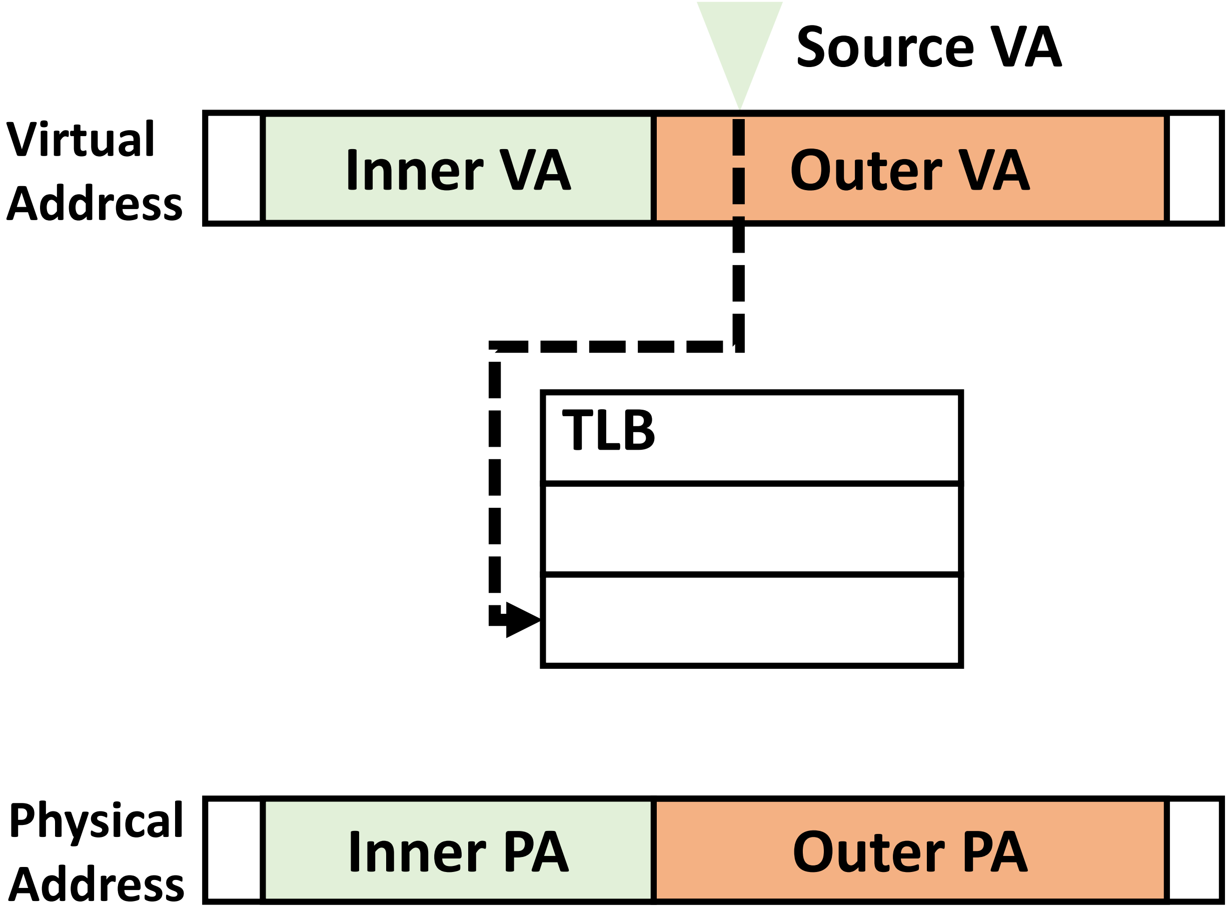
YES => Insert TLB entry
No => Invalid

Access Validation (B)

(B) Inner enclave accesses its outer enclave region



Access Validation (B)



(B) Inner enclave accesses its outer enclave region

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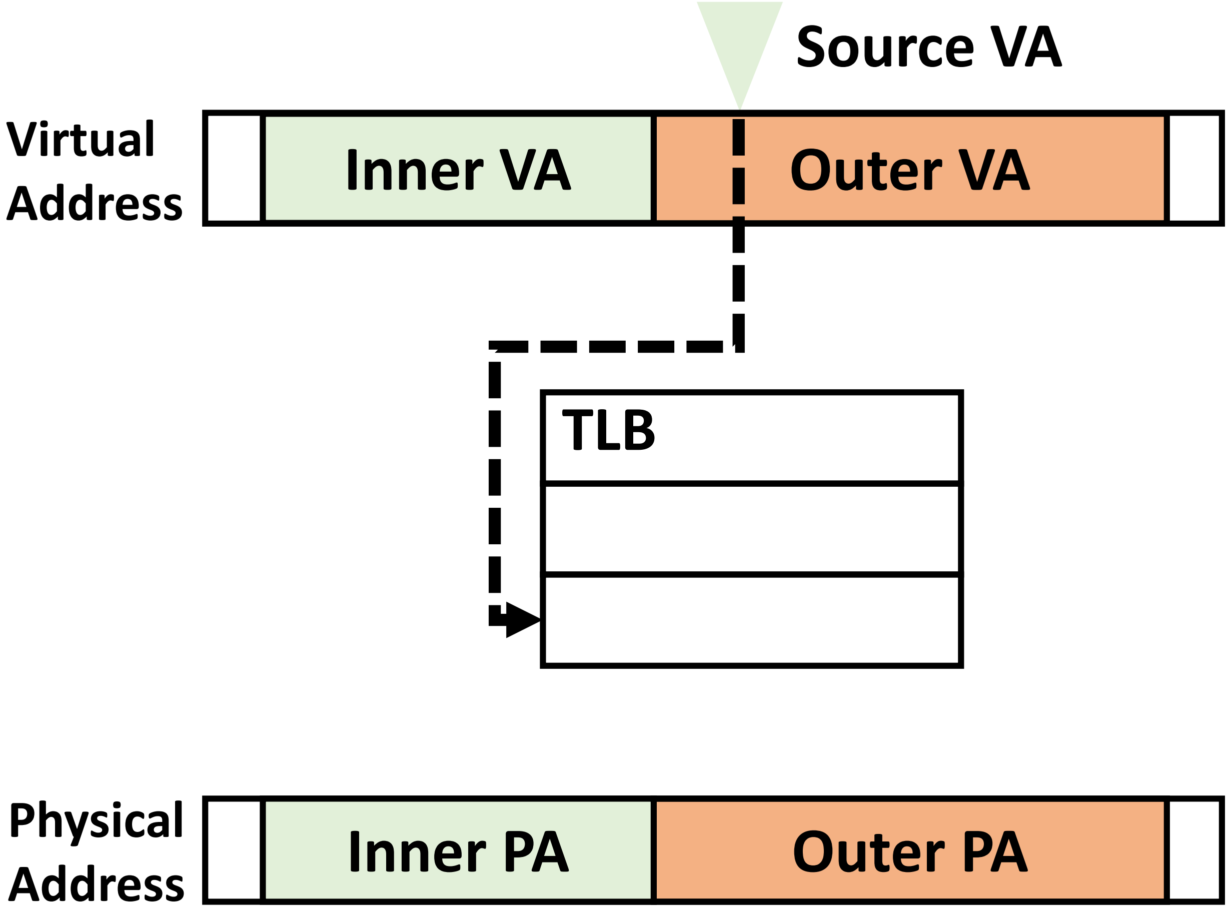
Access Validation (B)



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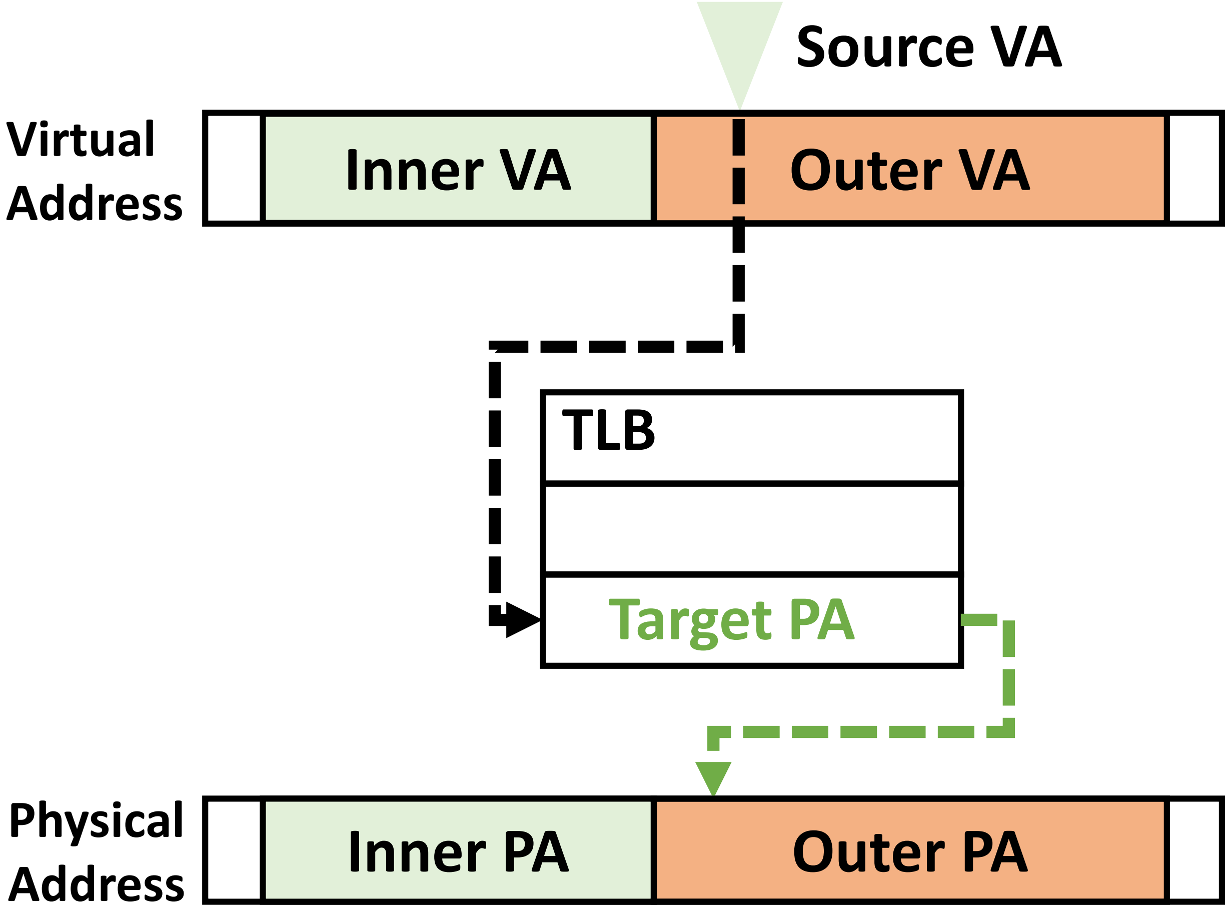

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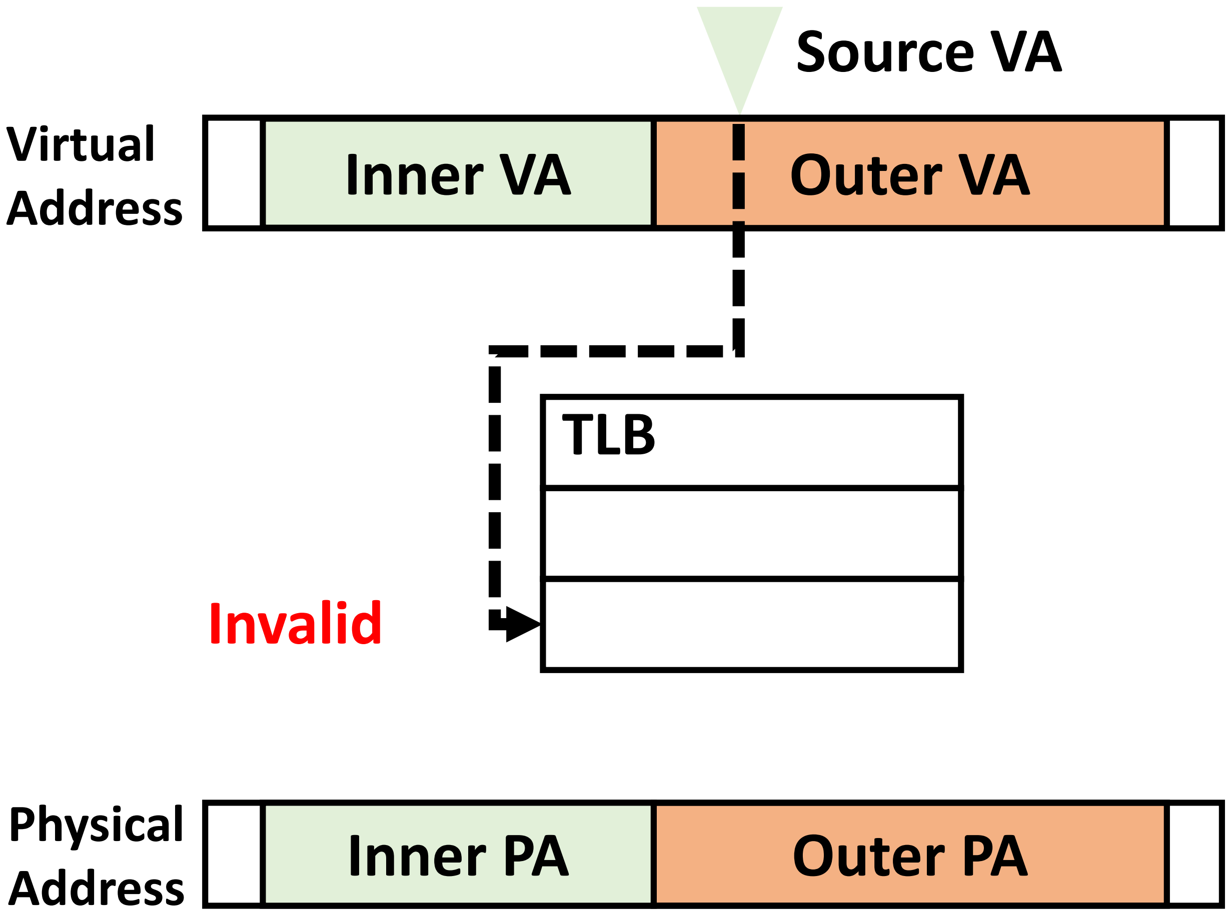

(B) Inner enclave accesses its outer enclave region

(1) Target PA is Enclave PA?
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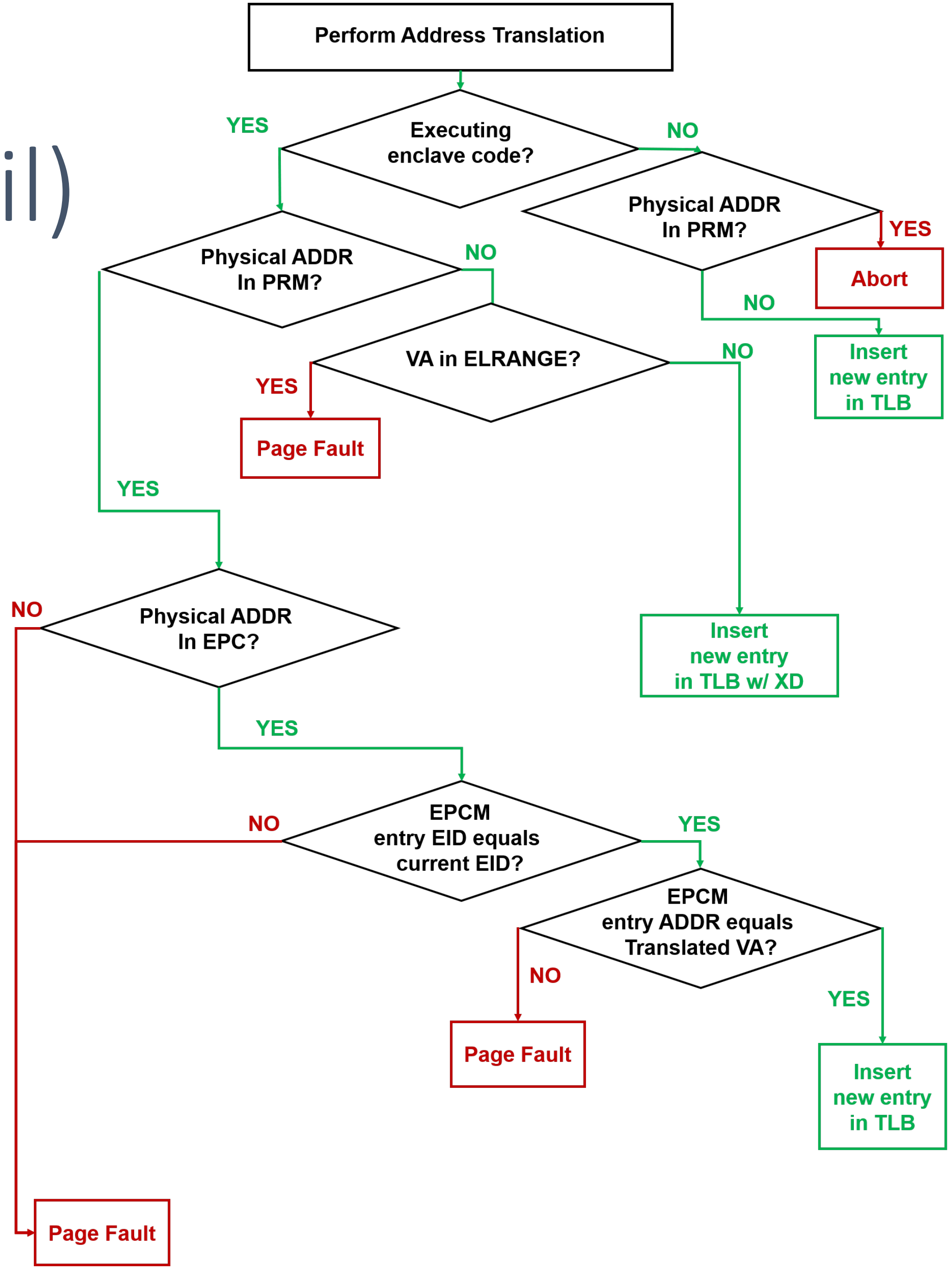
YES => Insert TLB entry
No => Invalid

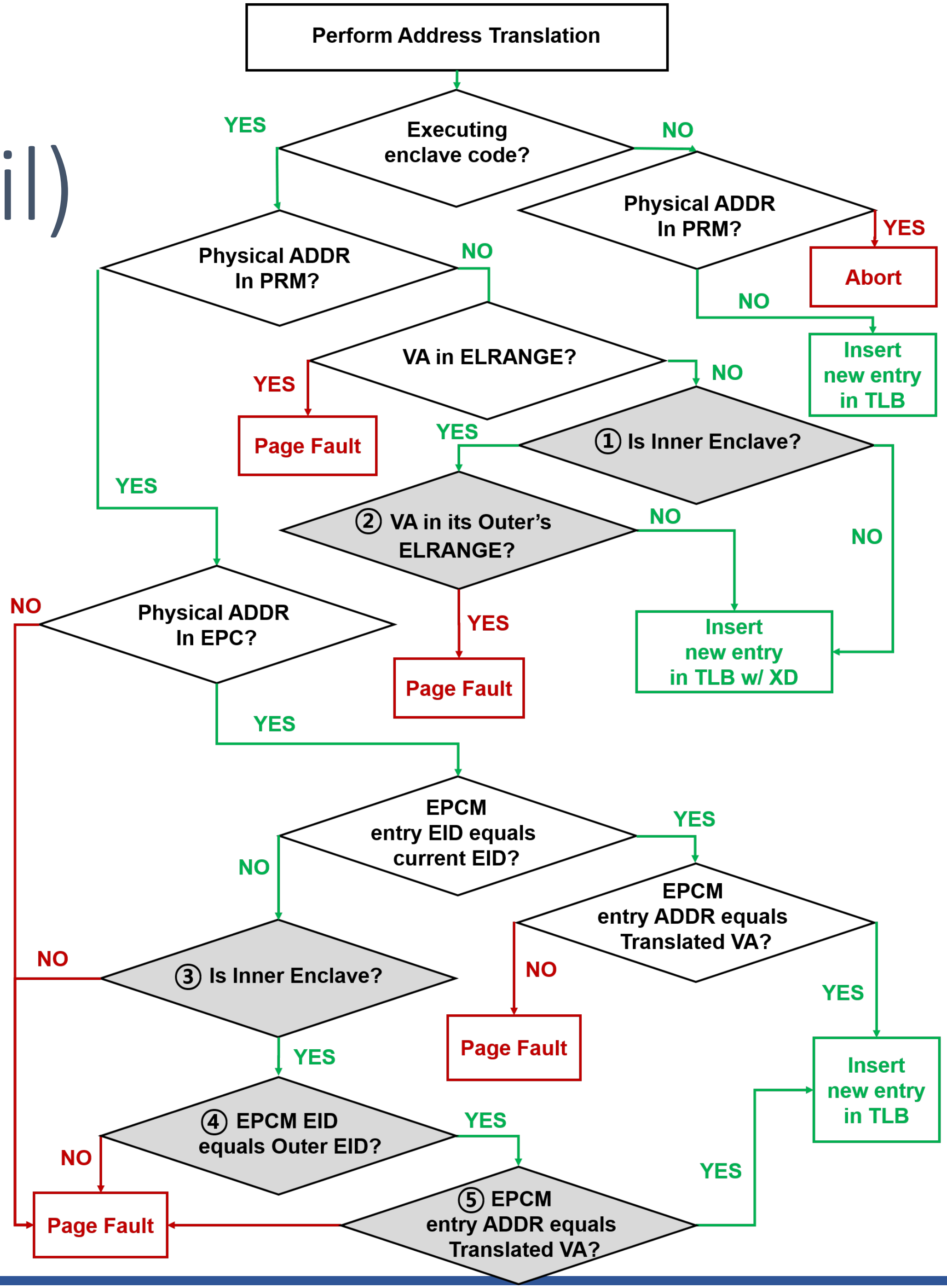
Access Validation (detail)



[4] Intel SGX Explained.

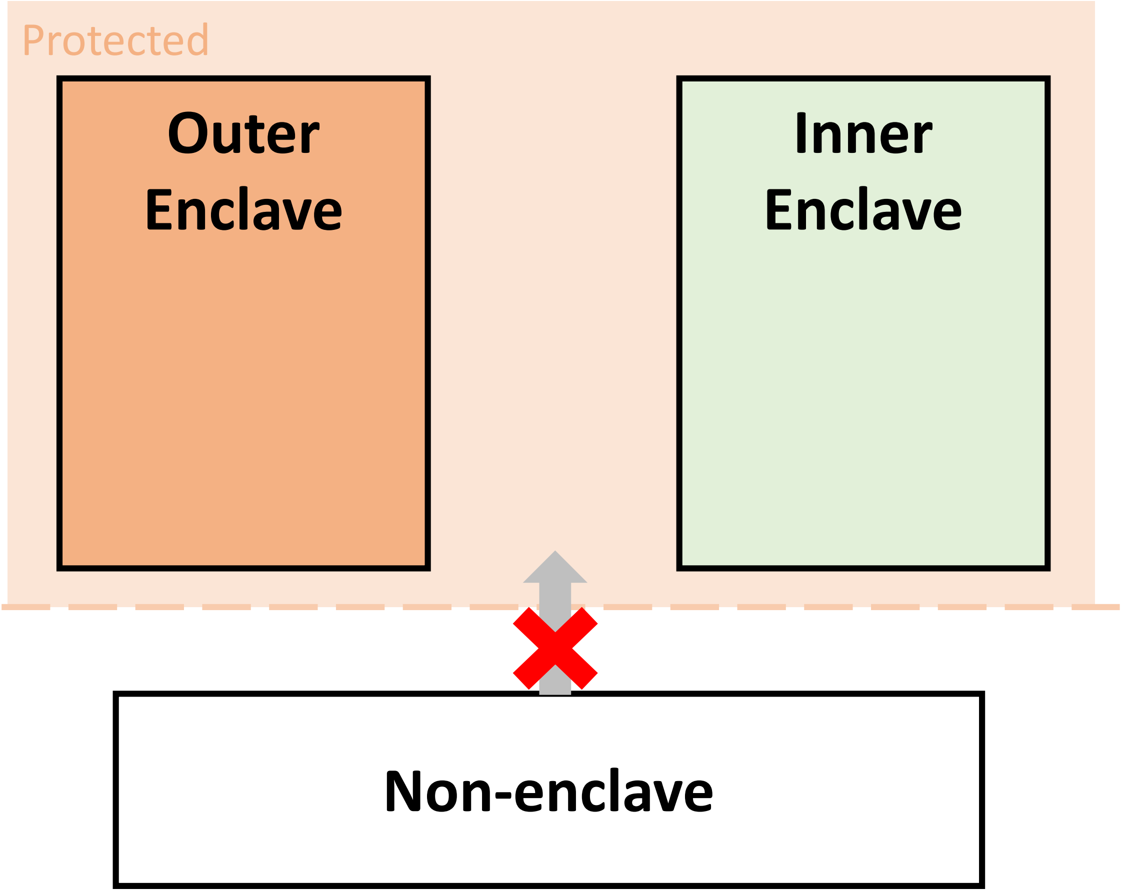
Access Validation (detail)

- Modifications are marked in grey



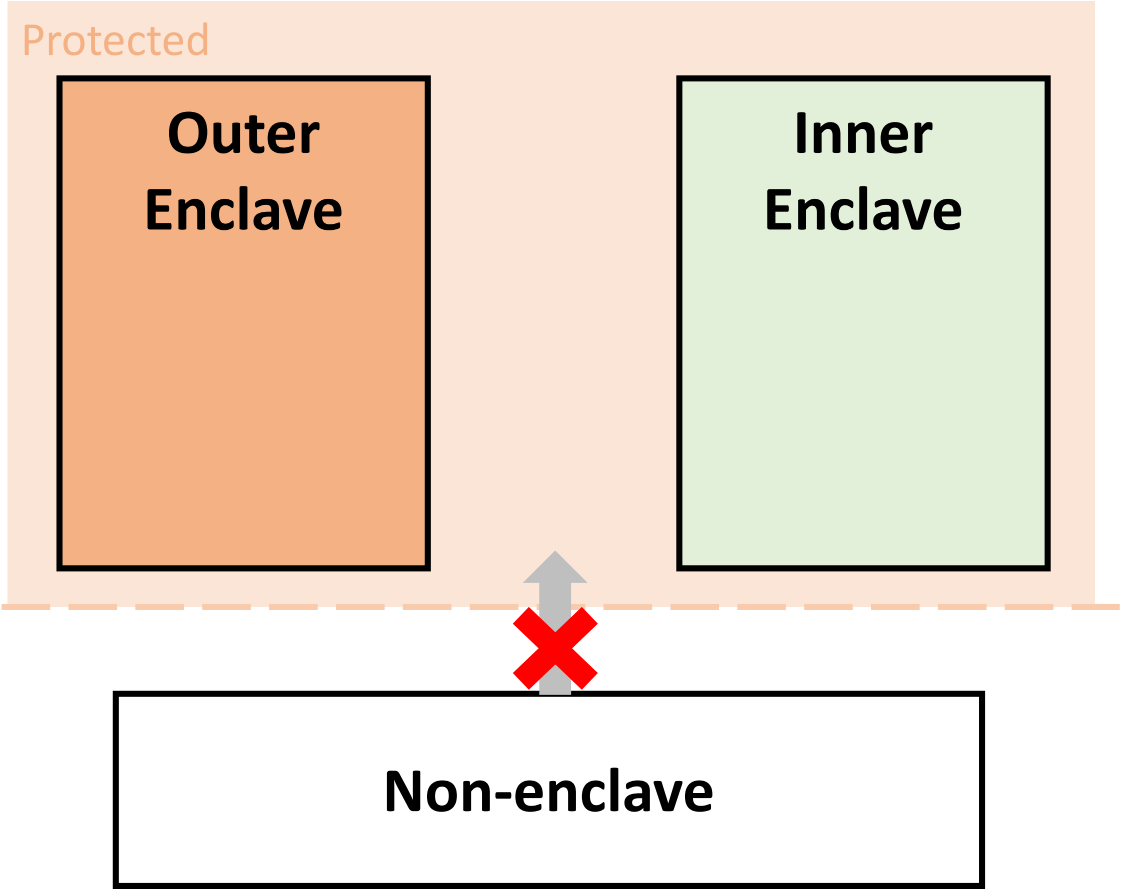
[4] Intel SGX Explained.

Secure Transition



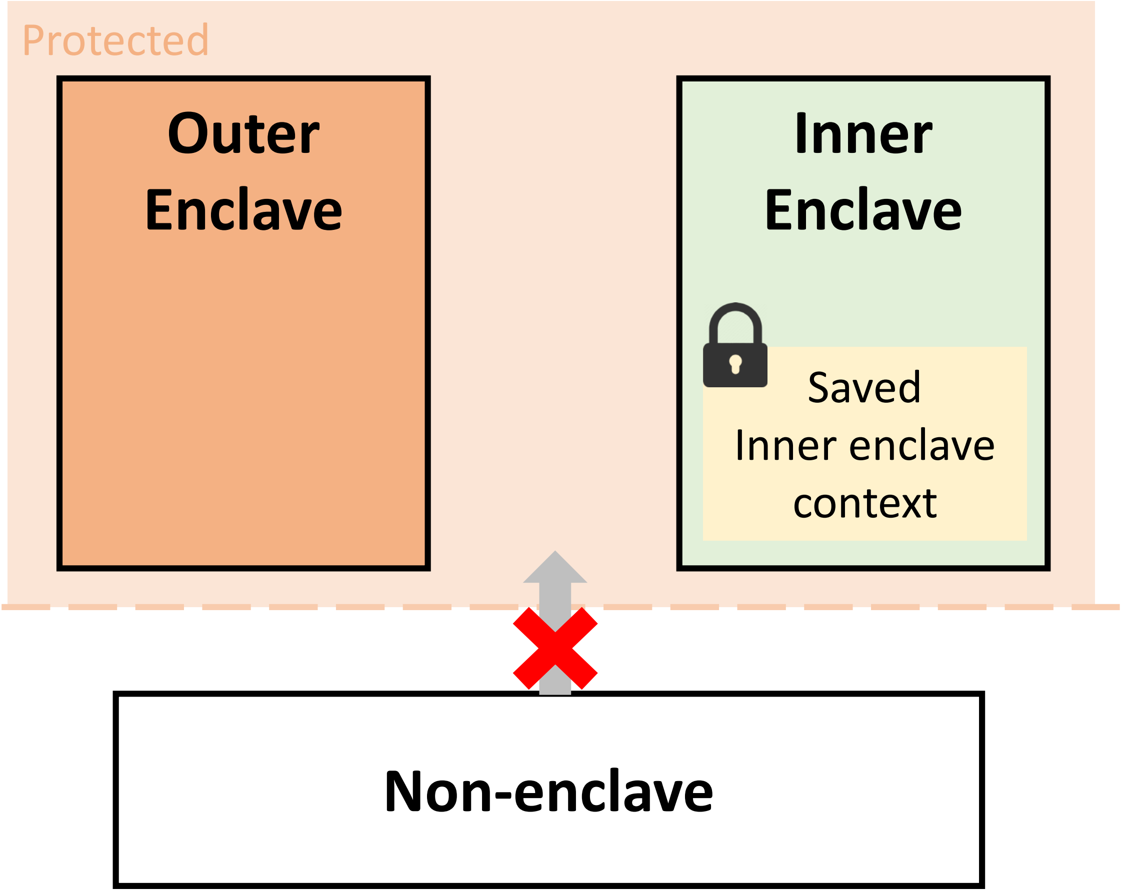
Secure Transition

- Direct transition between inner and outer enclaves



Secure Transition

- Direct transition between inner and outer enclaves
- Transition between Inner and outer enclaves
    - Save running context



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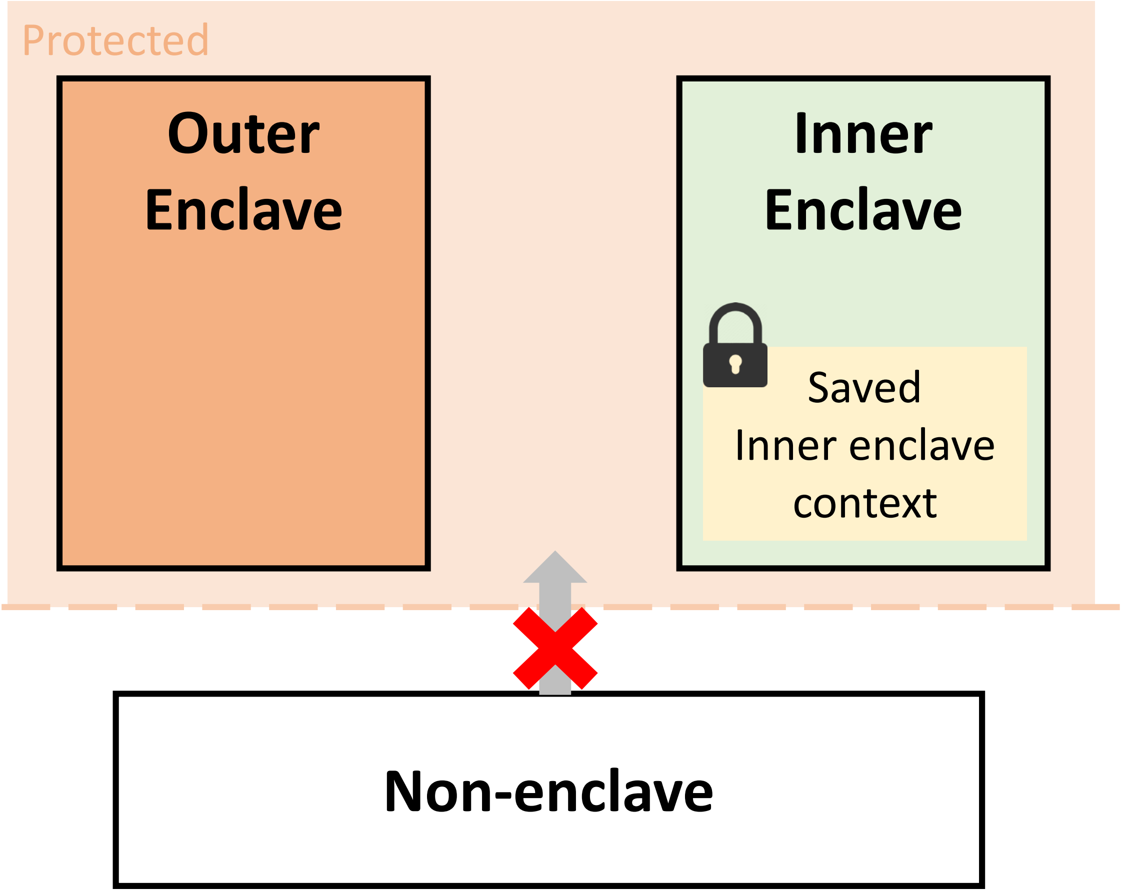
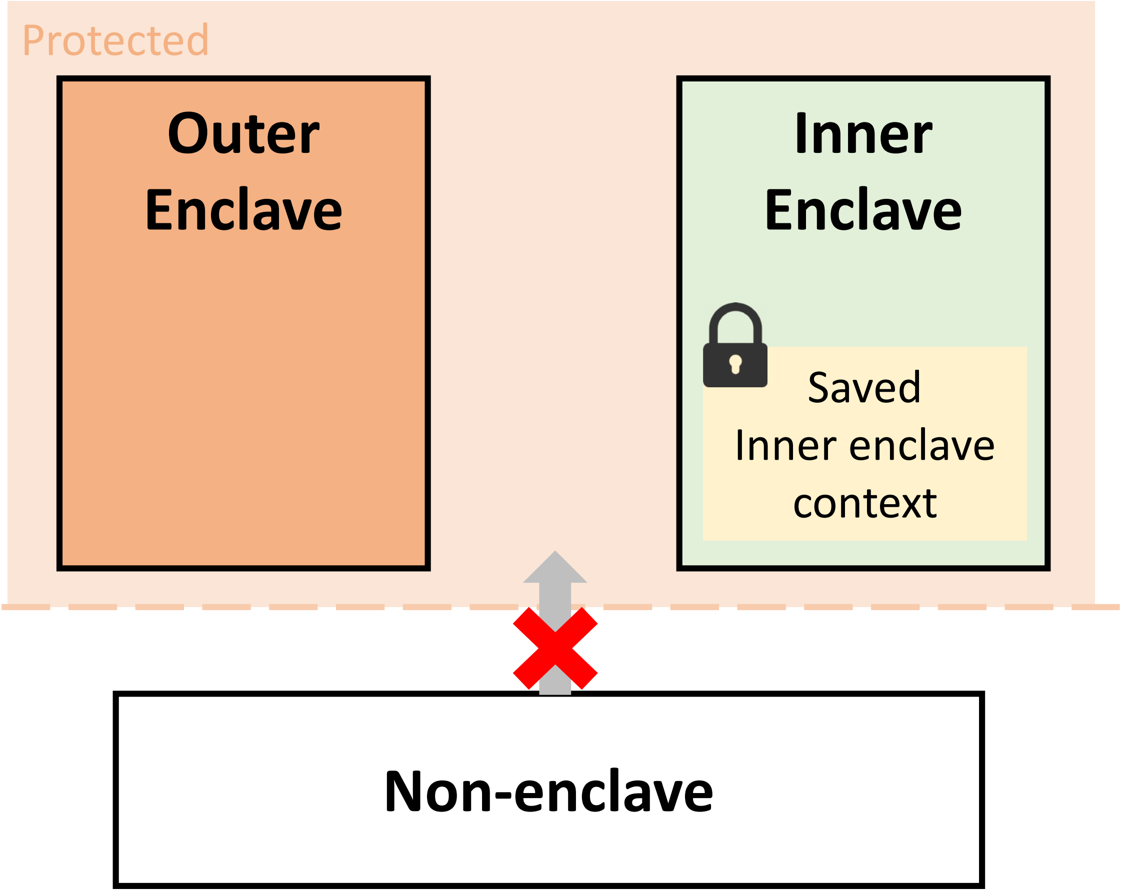
Secure Transition

- Direct transition between inner and outer enclaves
- Transition between Inner and outer enclaves
  - Save running context
  - Flush flags, register, and TLB



Secure Transition

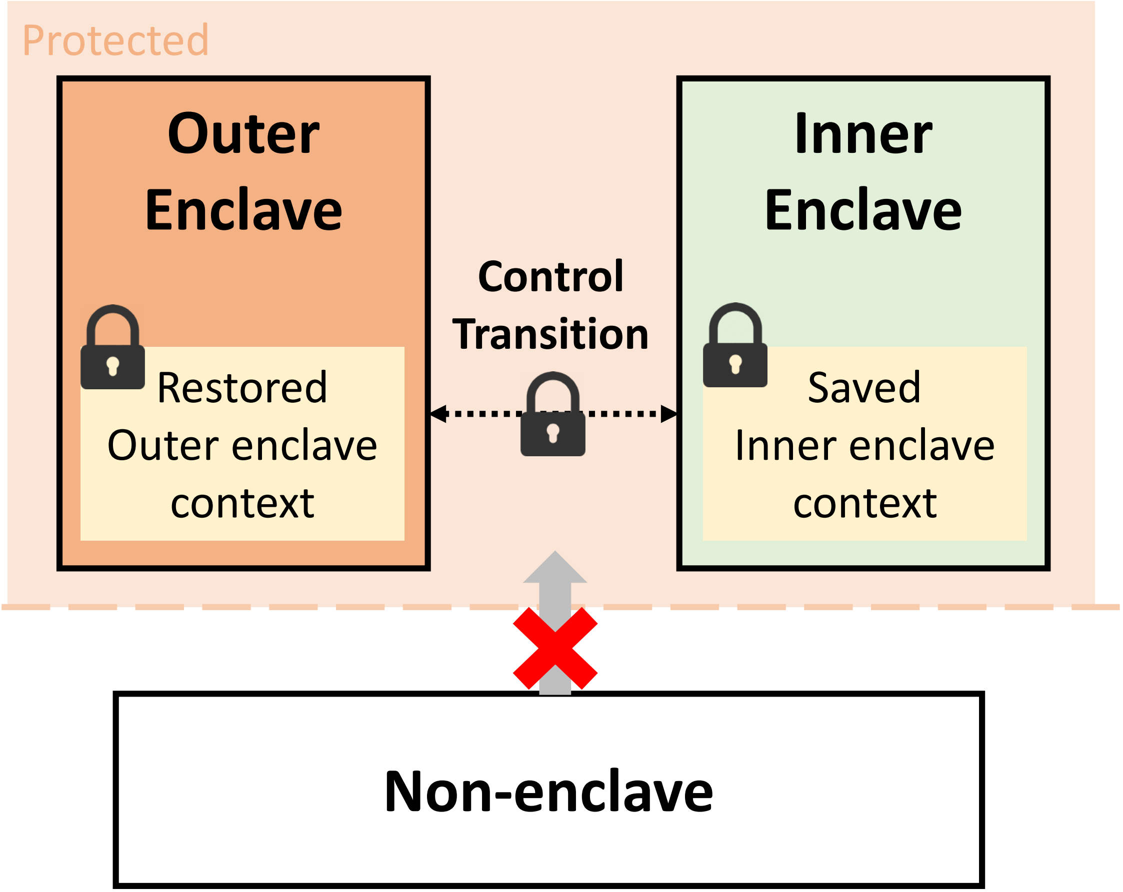
- Direct transition between inner and outer enclaves
- Transition between Inner and outer enclaves
  - Save running context
  - Flush flags, register, and TLB
  - Check & sanitize parameters



Secure Transition

- Direct transition between inner and outer enclaves

- Transition between Inner and outer enclaves
  - Save running context
  - Flush flags, register, and TLB
  - Check & sanitize parameters
  - Restore target context if exists



Evaluation Methodology

Implementation

- New instructions to SDK emulation
  - NEENTER, NEEXIT, NASSO, NEREPORT
- APIs
  - Nested ecall/ocall
  - Association

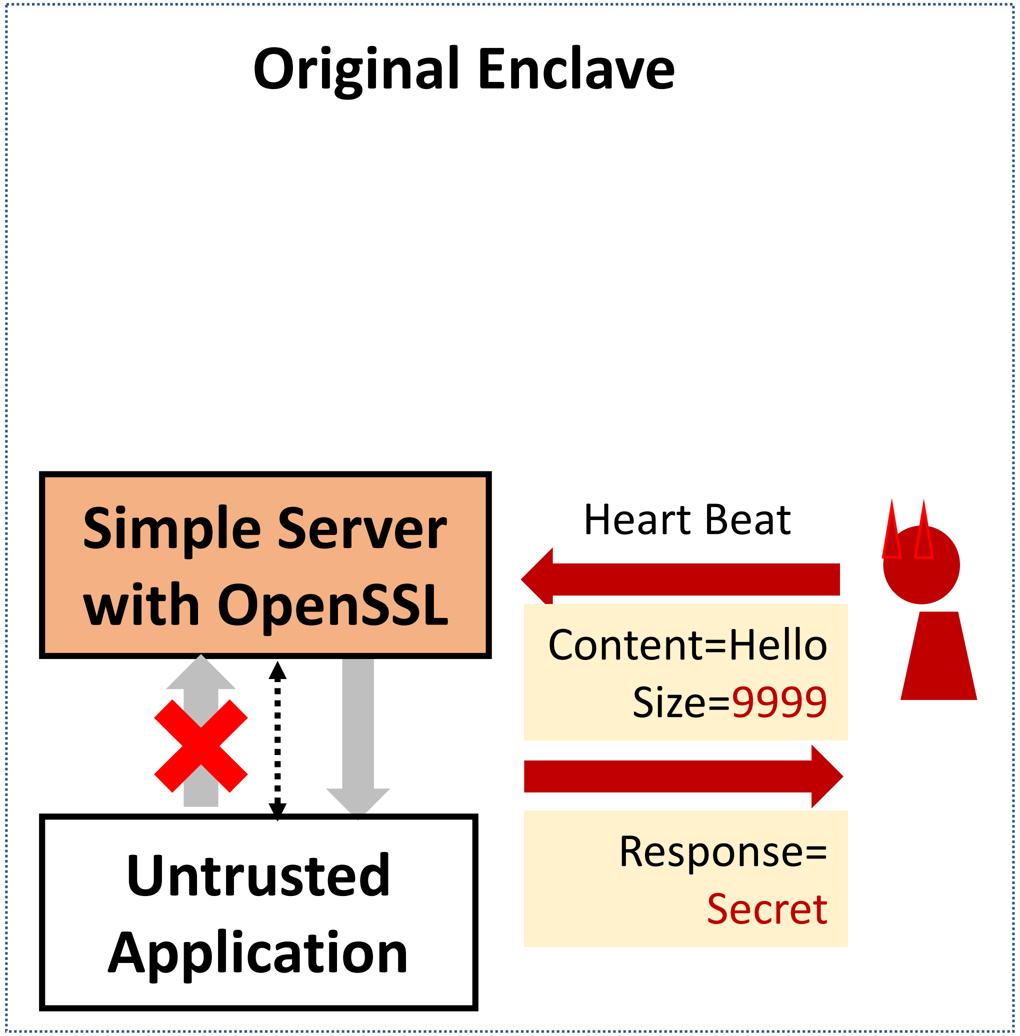
Application porting

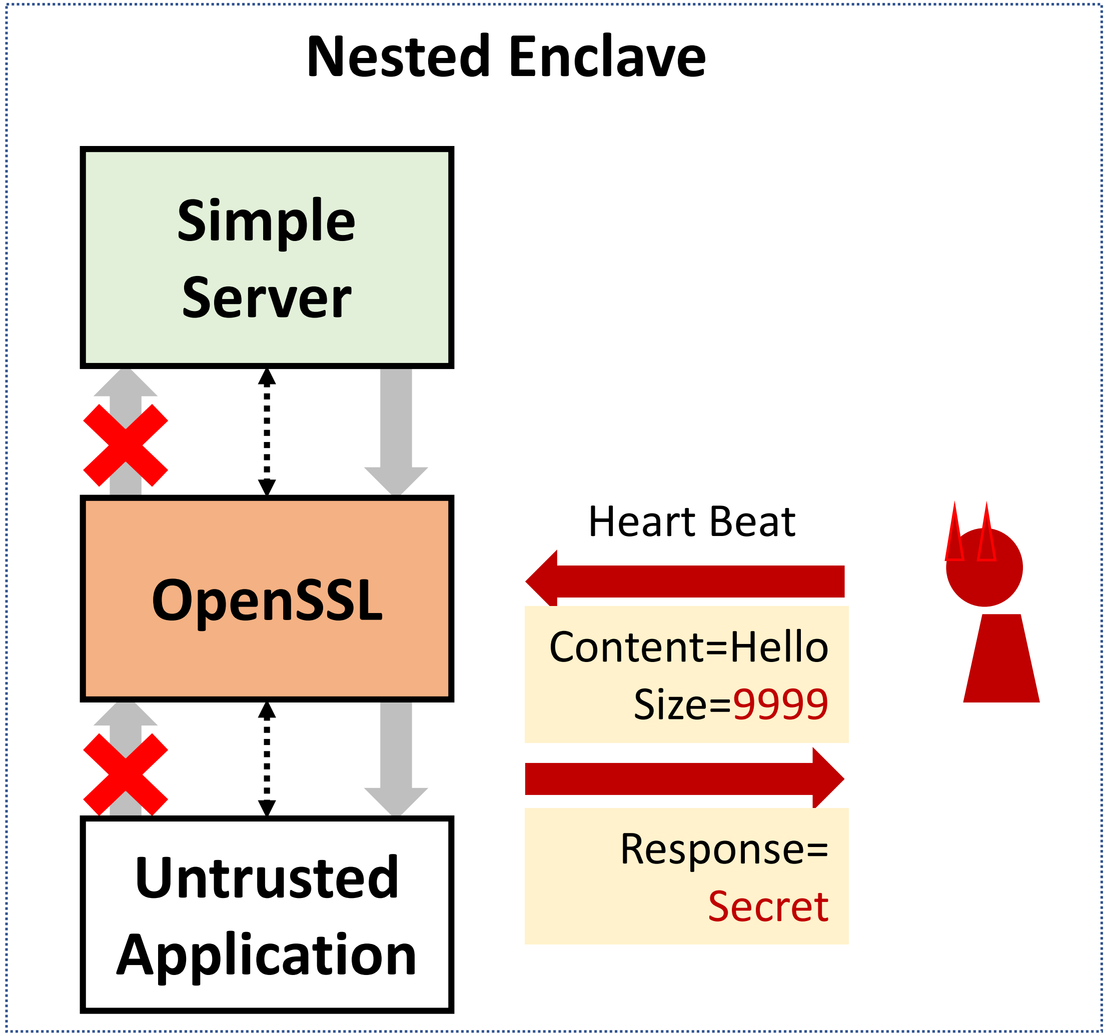
- Echo server with OpenSSL
- Query server with SQLite
- LibSVM (training, prediction)

Evaluation Environment

- Intel i7-7700 64 GB DRAM
- Ubuntu 16.04, Linux kernel 4.13.0.
- Intel SGX SDK / driver v1.9

CASE 1: Heartbleed Attack



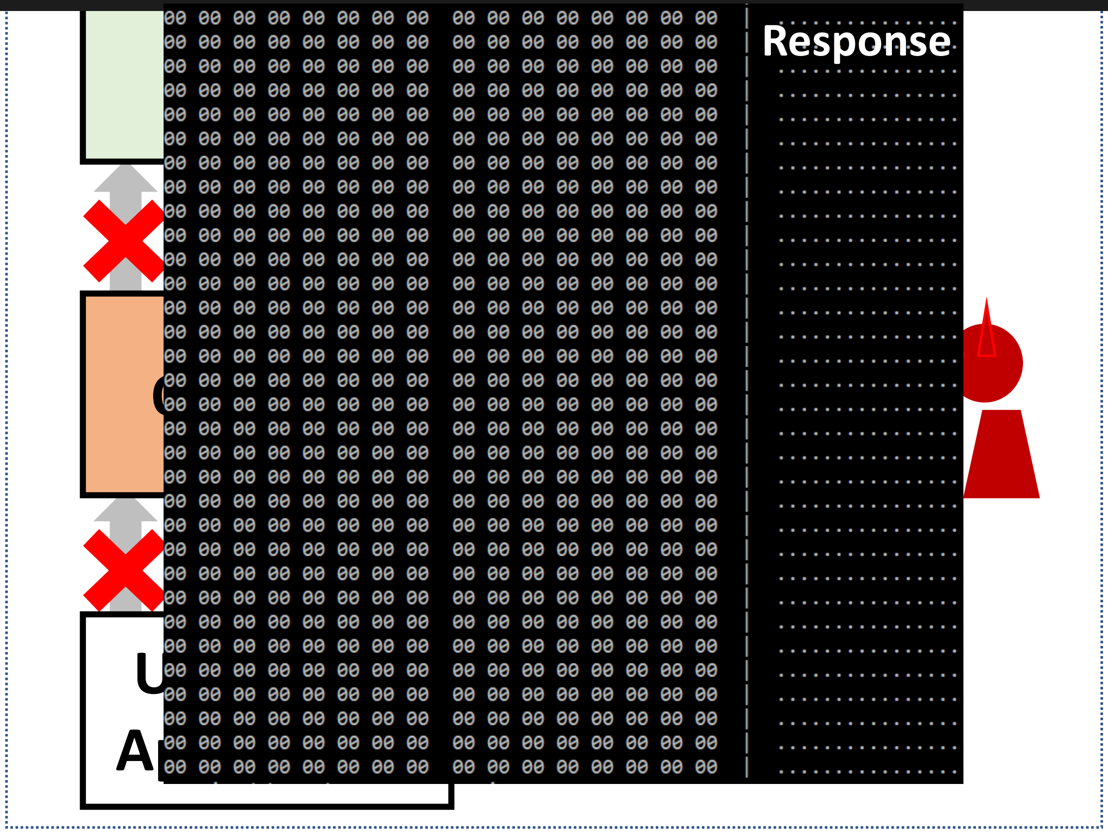


CASE 1: Heartbleed Attack

In Simple Server

```
void info_leak()
{
    char *secret;
    int size = 0x8000;

    secret = (char *) malloc (size);
    for (int i = 0; (i + 1) * 0x100 < size; i++)
        strlcpy (secret + i * 0x100, "ID=admin;PASSWORD=admin_secure_password_1337;EX=deadbeef;TOPSECRET=THISISACONFIDENTIALSTRING;INFO=YOUCANNOTREADITBECAUSEIFREEITAFTERUSETHIS;", 0x100);
    printf ("secret's address: %p, size: %x\n", secret, size);
    free(secret);
}
```



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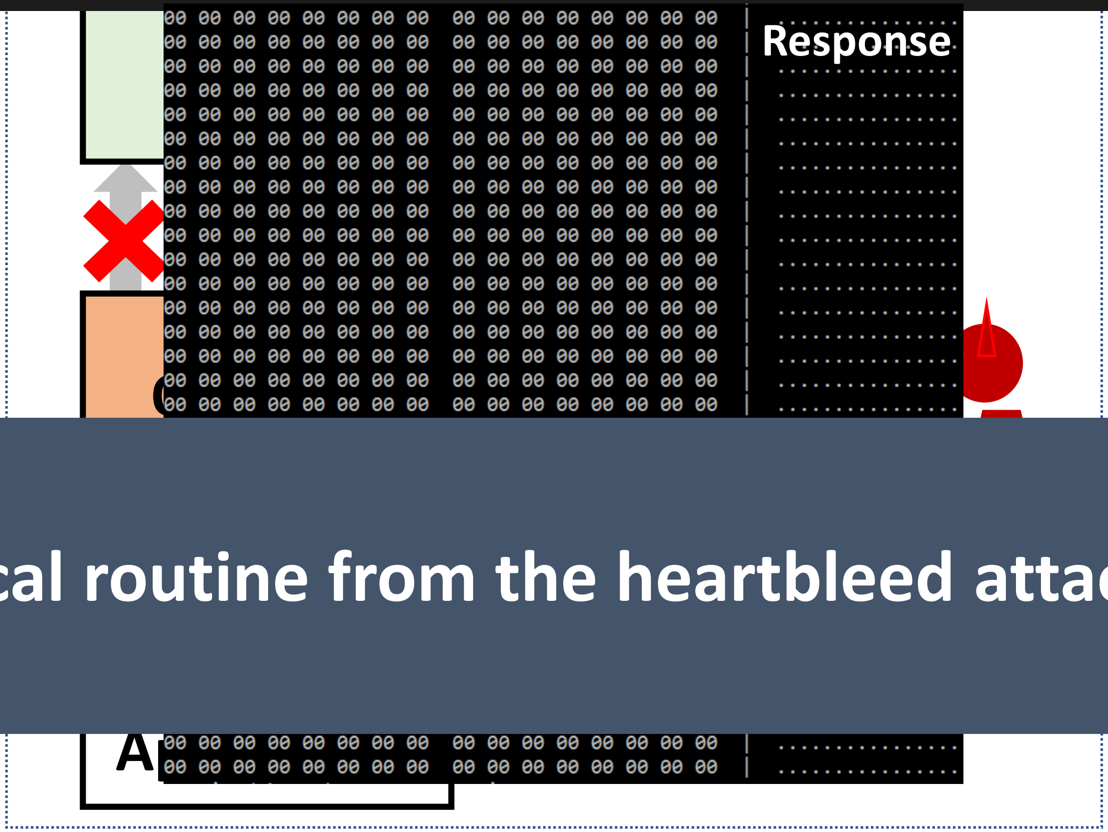
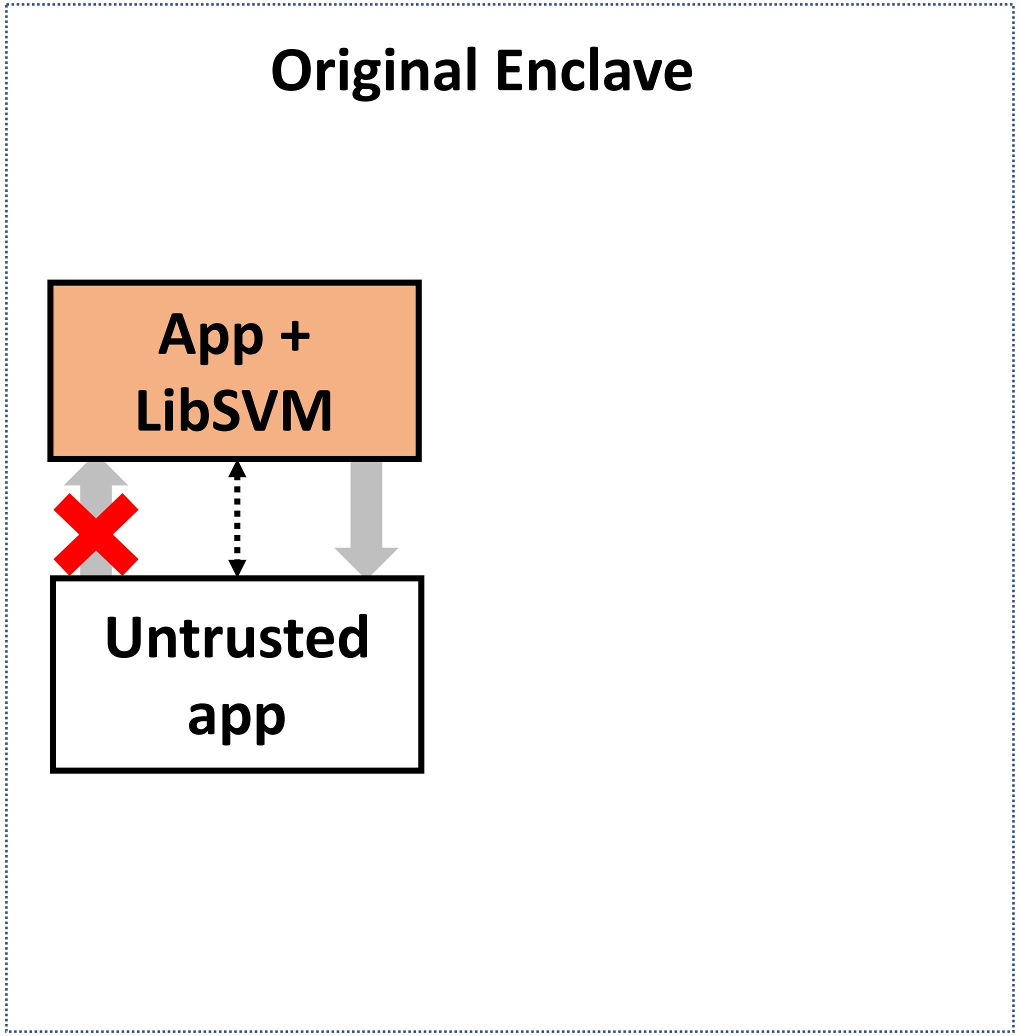
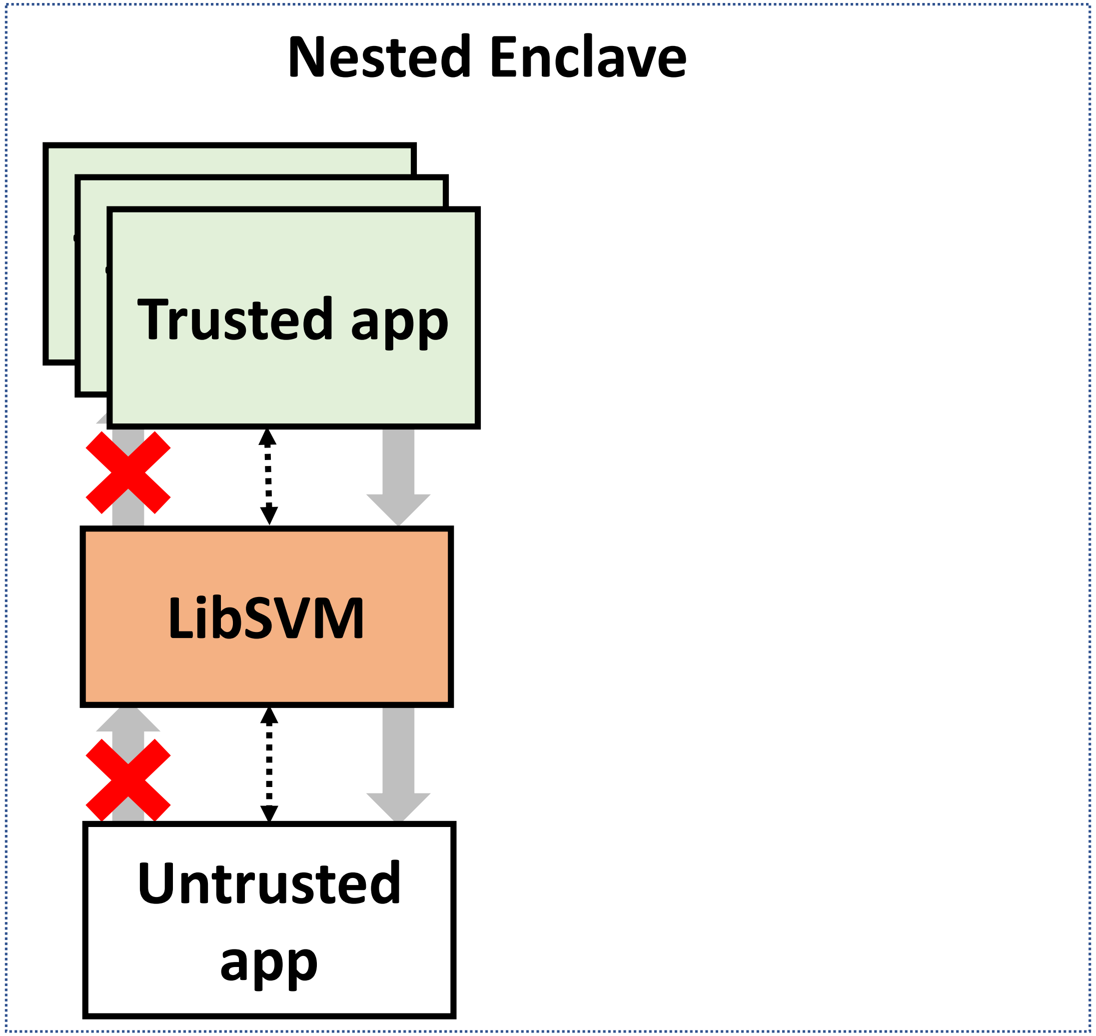


Nested enclave protects the critical routine from the heartbleed attack

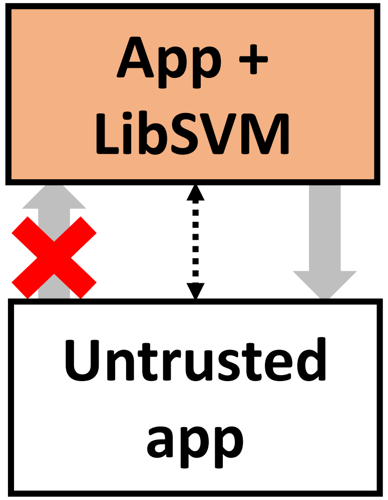
CASE 2: Machine Learning as a Service





CASE 2: Machine Learning as a Service

Original Enclave

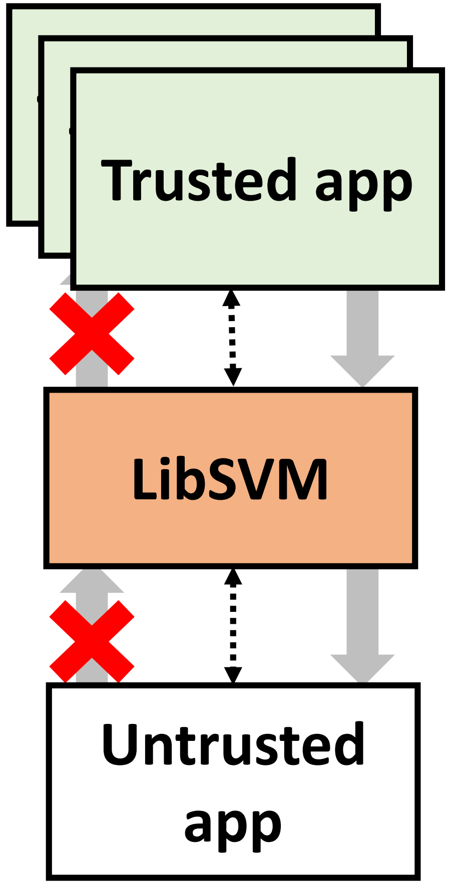


Single enclave:
Private processing+
ML library

User Private Data
- Patient info
- Account info

Data for ML
- X-ray pic
- DNA sequence
- Email …

Nested Enclave



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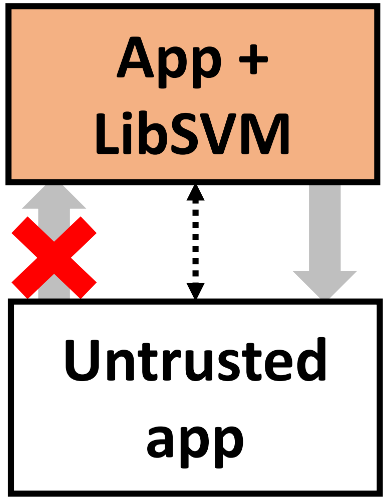

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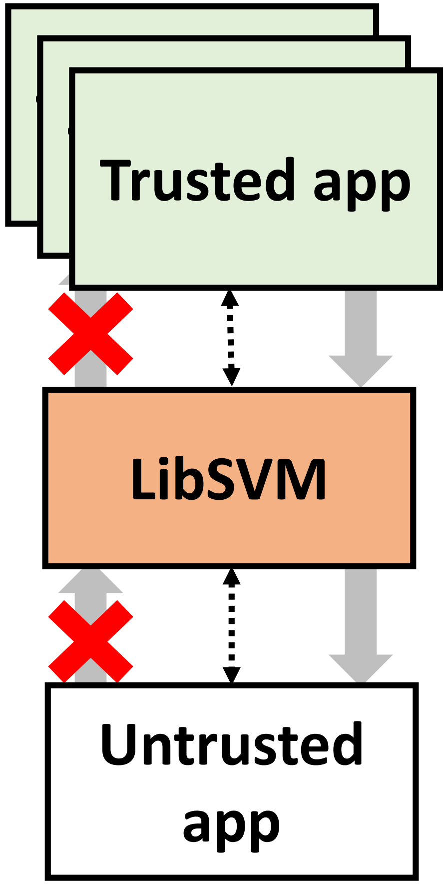


Per-user inner enclave

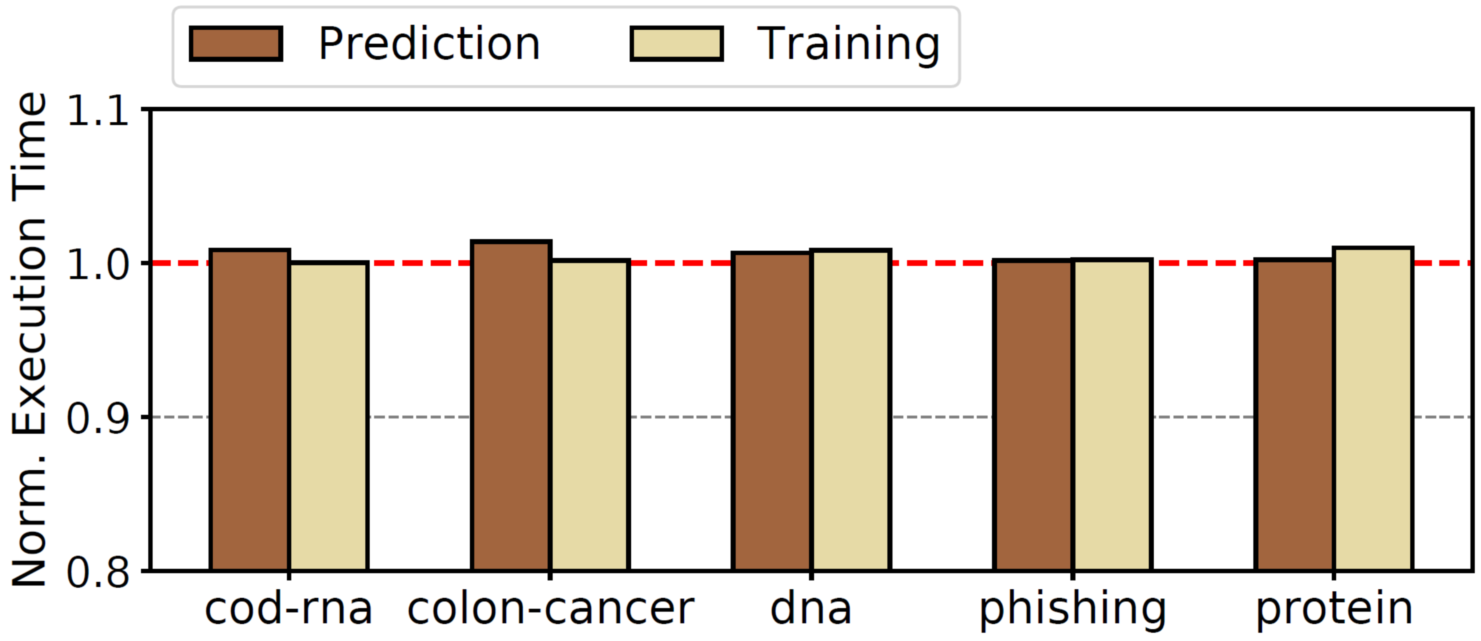
User Private Data
- Patient info
- Account info

Outer enclave: ML library

Data for ML
- X-ray pic
- DNA sequence
- Email …

CASE 2: Machine Learning as a Service

- **Normalized execution time to the original enclave**
- **Overhead is relatively small (< 2%)**



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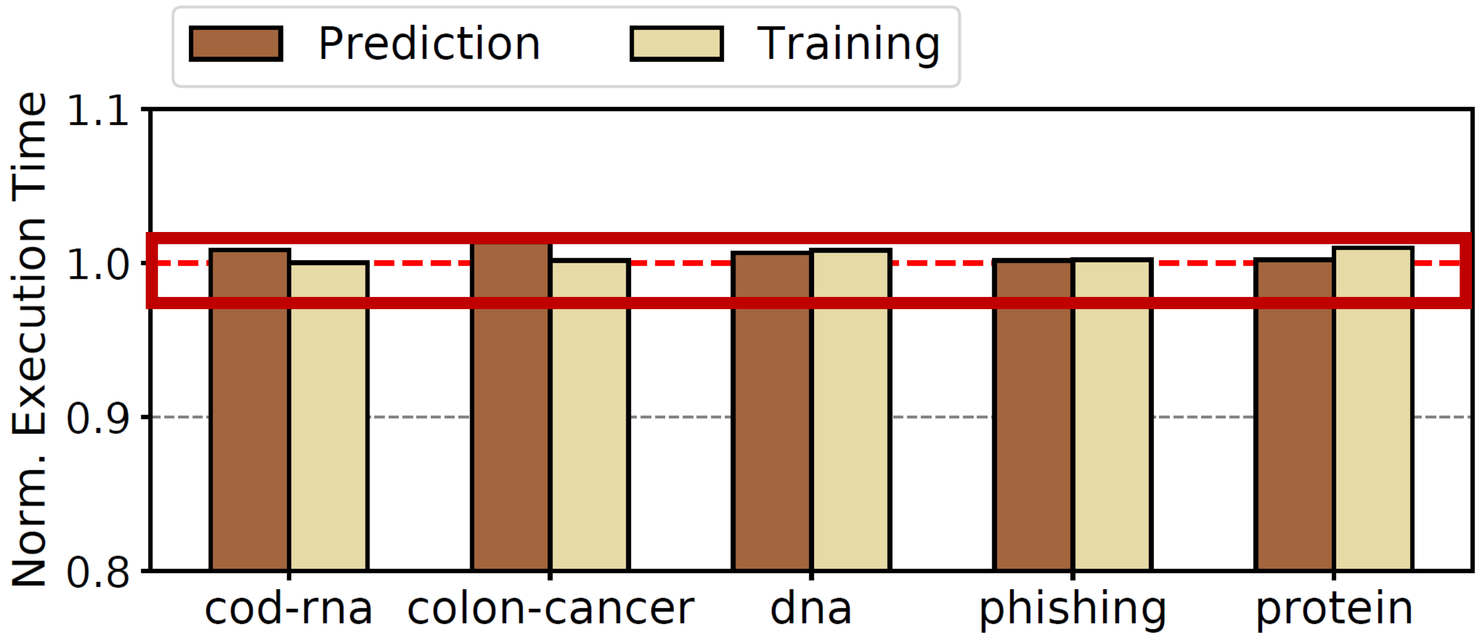

More case studies in paper..

- Library sharing and time to loading enclaves
- Shared SQLite server
- Communication with intra- vs inter enclave channels

Porting effort

Name	Modification	Modified LOC	Original
Echo server	C/C++ code	34	883
	EDL	10	28
	SGX-OpenSSL	0	507k
SVM-predict	C/C++ code	27	208
	EDL	10	49
	SGX-LibSVM	0	152k
SVM-train	C/C++ code	24	333
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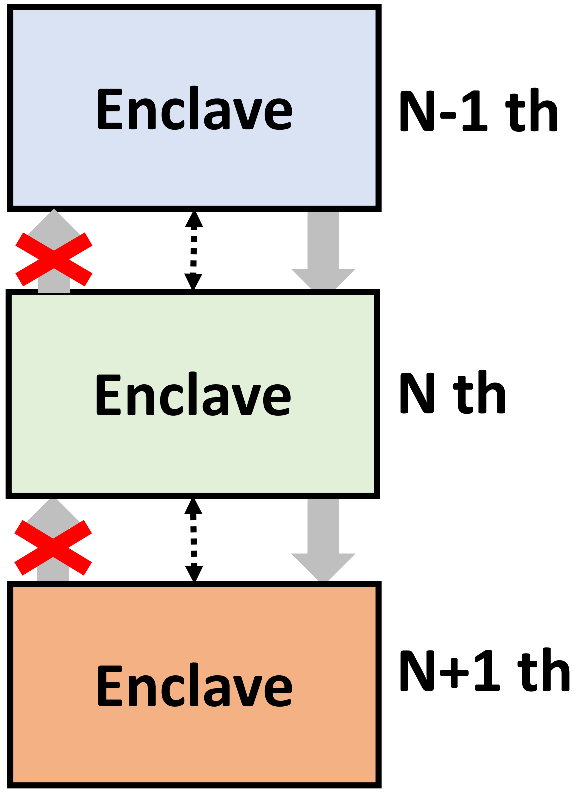
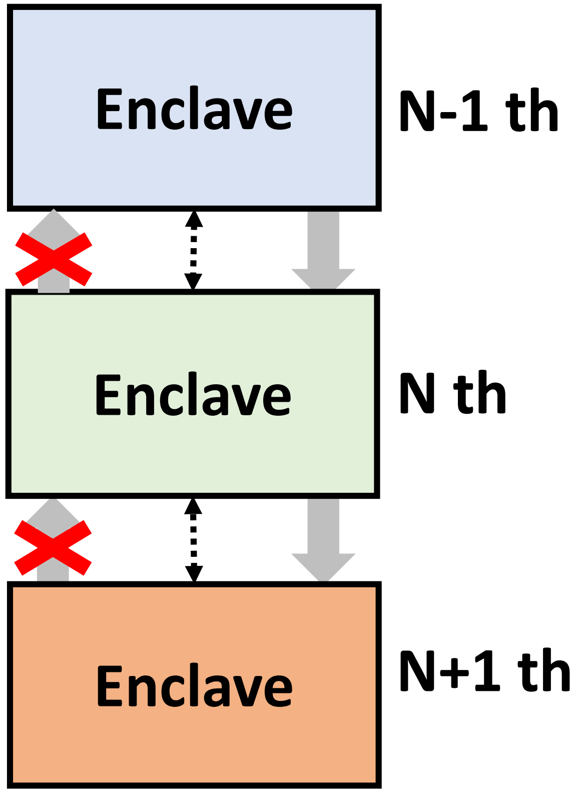
N-depth nesting

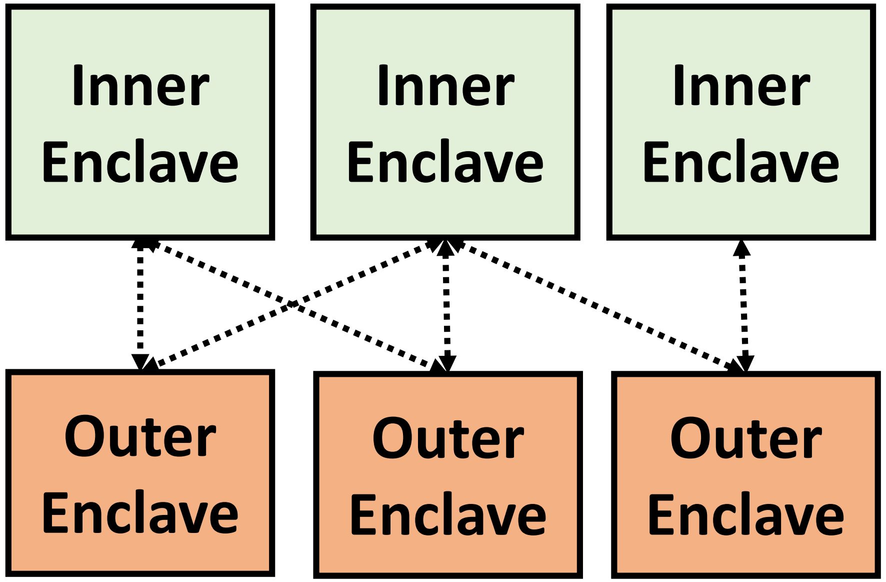


Extending Nested Enclave

N-depth nesting



N to M relation



Conclusion

- A new extension to the trusted execution environments for supporting multi-level security within TEE.
- The required hardware and software extensions for the nested enclave are small.
- Case studies on the nested enclave emulation framework.

Thank you