Intel® Software Guard Extensions(Intel® SGX)

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Intel Labs
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- The comments and statements are mine and not necessarily Intel’s

- Intel technologies’ features and benefits depend on system configuration and may require enabled hardware, software or service activation. Learn more at intel.com, or from the OEM or retailer.

- No computer system can be absolutely secure.

Outline

- Problem Statement
- Attack Surface and Overview
- Programming environment
  - System programming view
  - Day in the life of an enclave
- SGX Access Control & Off Chip protections
- Attestation and Sealing
- Developing with SGX
- Summary

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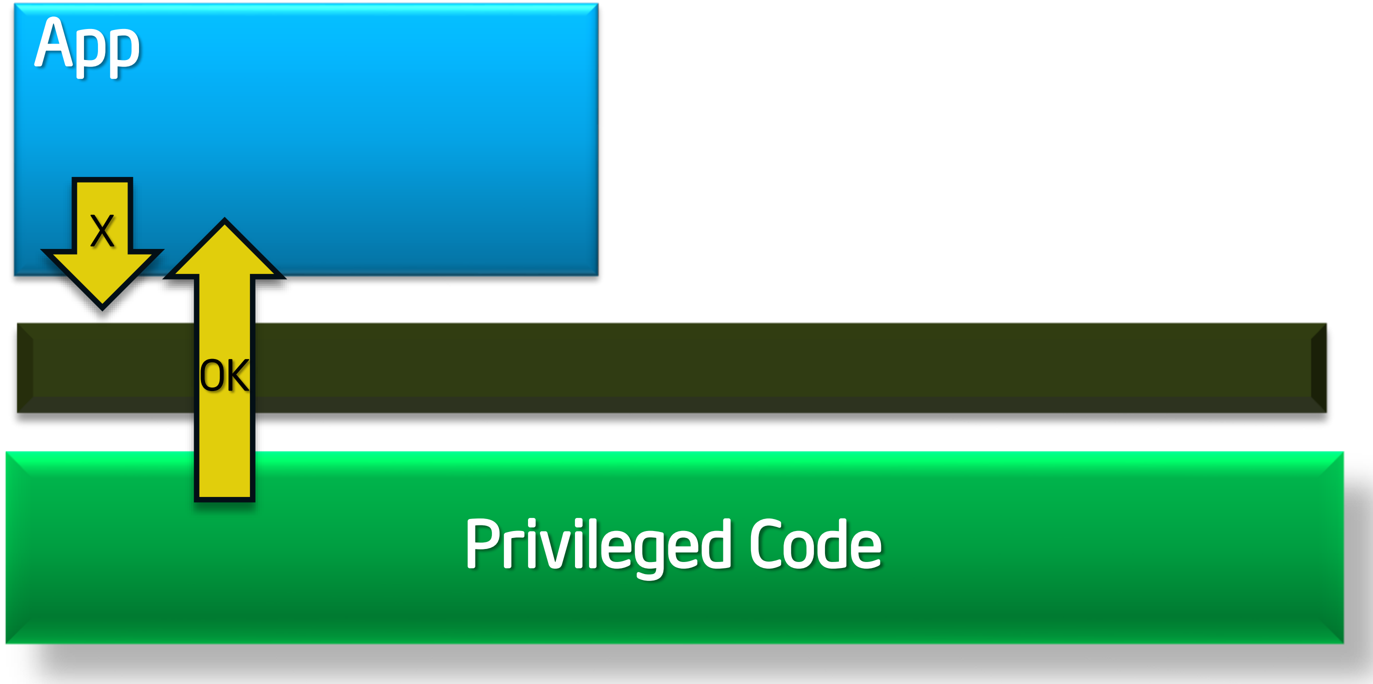
The Basic Issue: Why Aren't Compute Devices Trustworthy?

Protected Mode (rings) protects OS from apps ...



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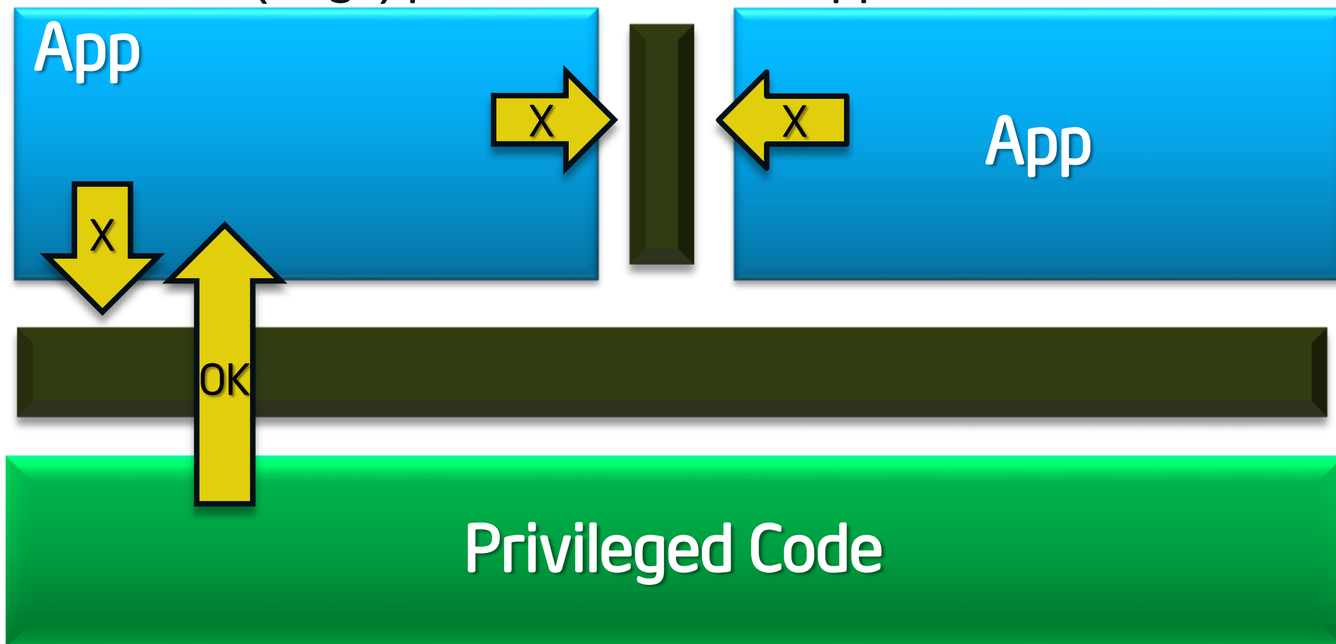

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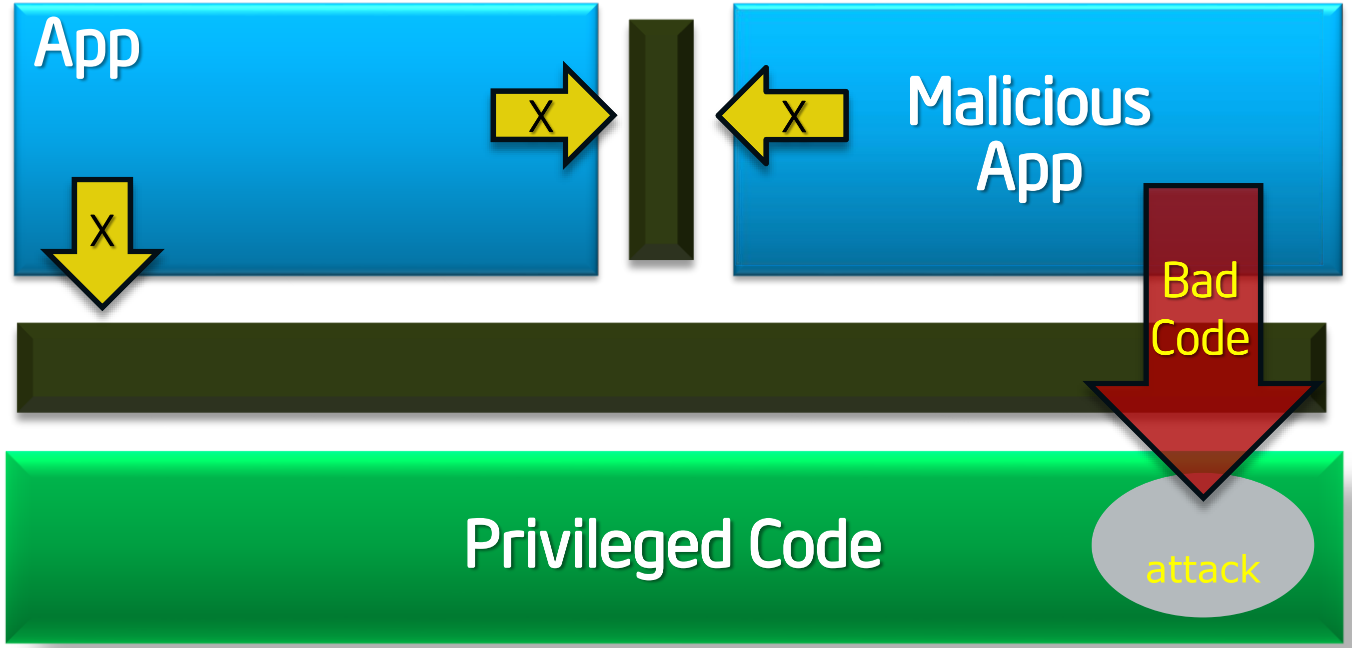

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Apps not protected from privileged code attacks

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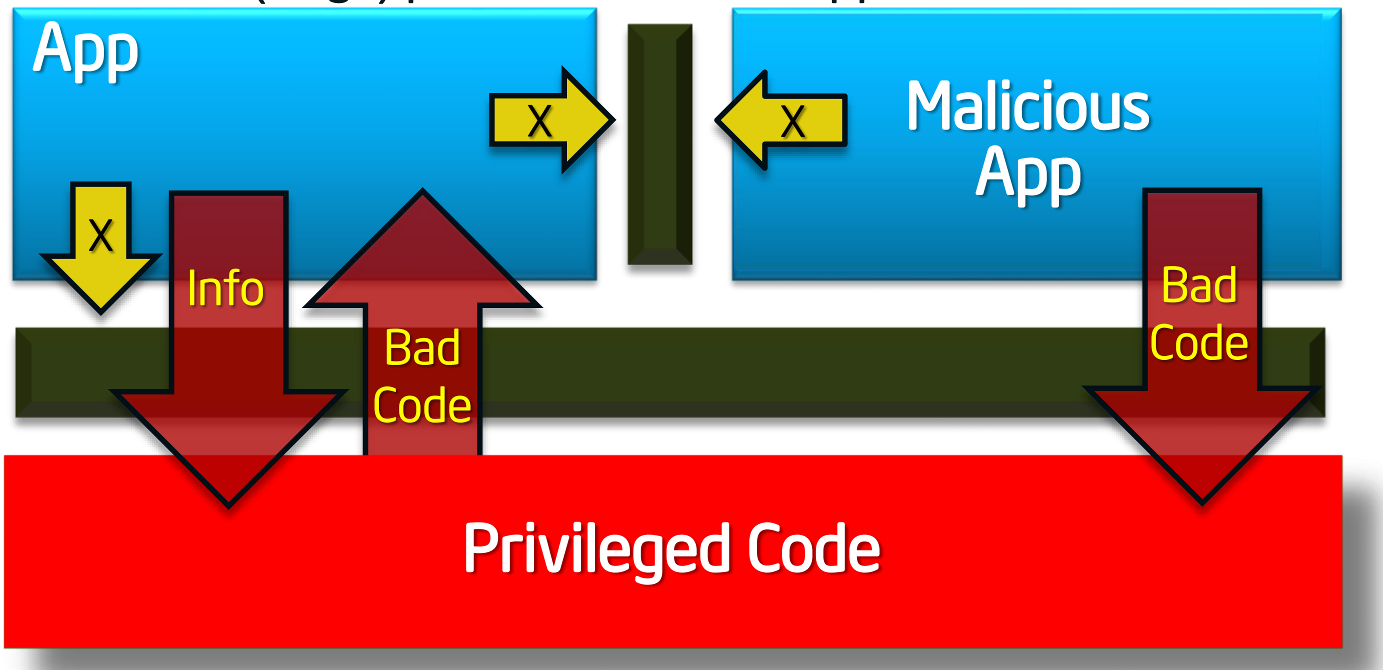

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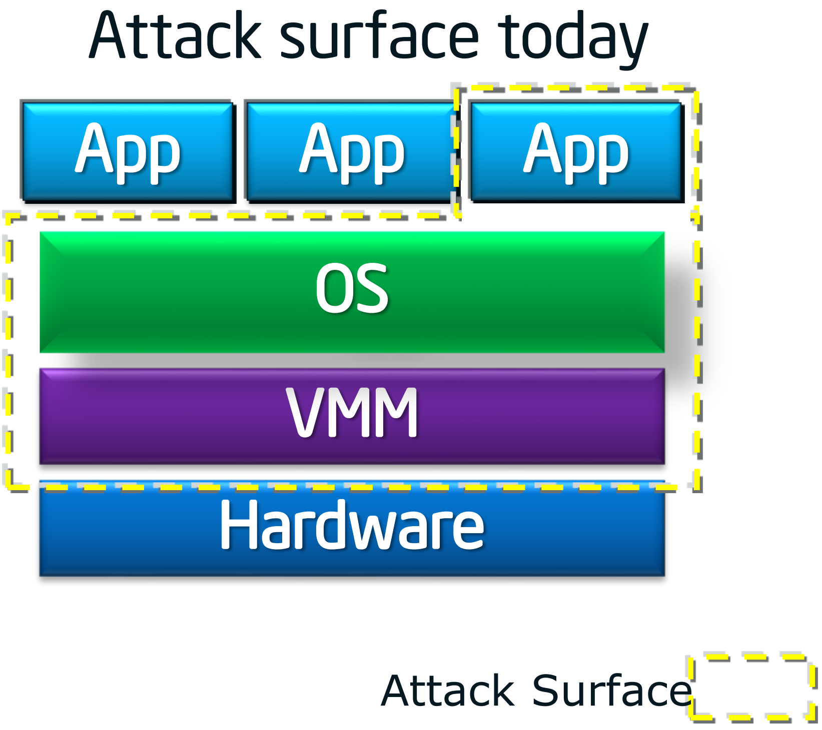
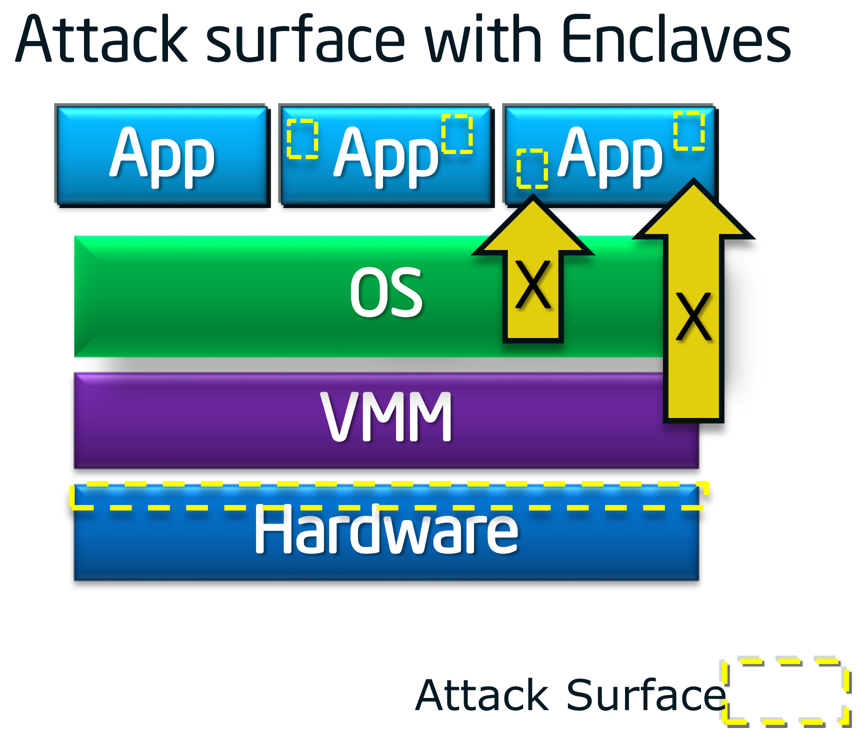
Reduced attack surface with SGX



Reduced attack surface with SGX

Application gains ability to defend its own secrets

- Smallest attack surface (App + processor)
- Malware that subverts OS/VMM, BIOS, Drivers etc. cannot steal app secrets



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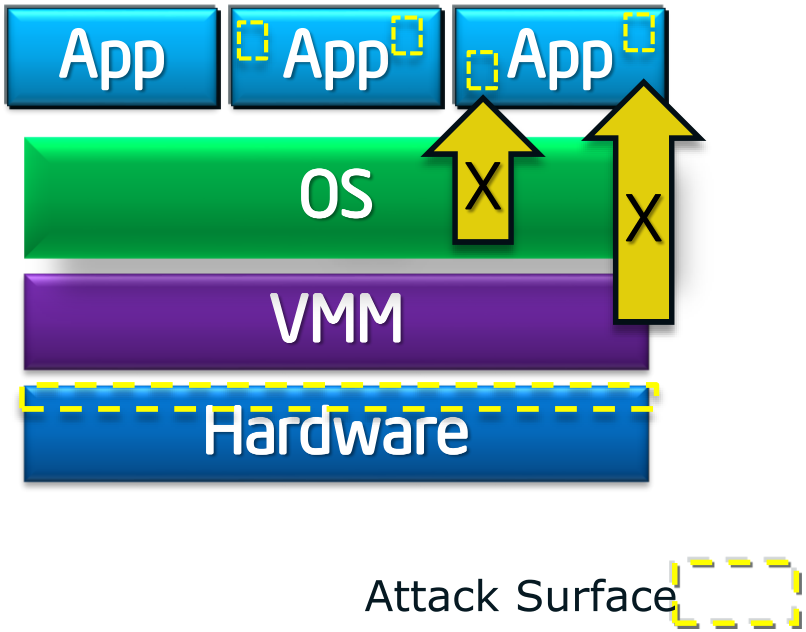
Familiar development/debug

- Single application environment
- Build on existing ecosystem expertise

Attack surface with Enclaves



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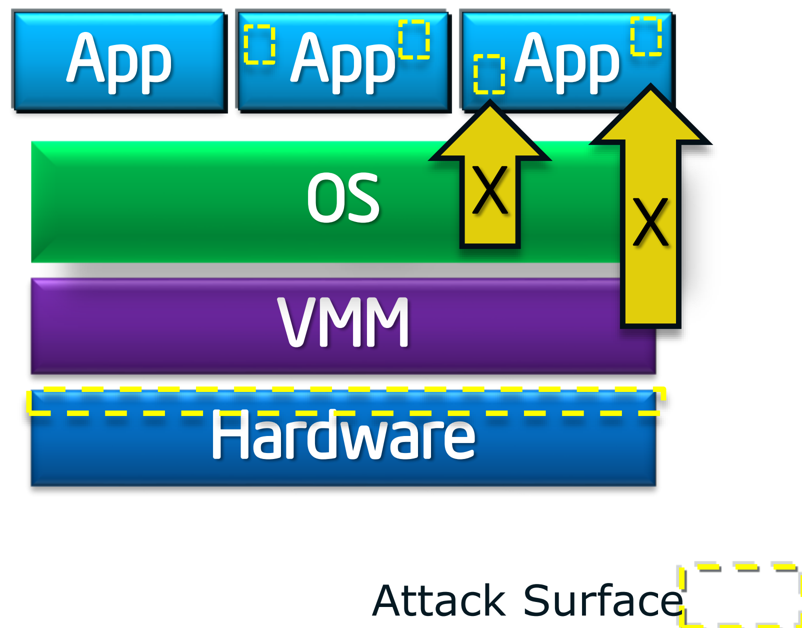
Familiar deployment model

- Platform integration not a bottleneck to deployment of trusted apps

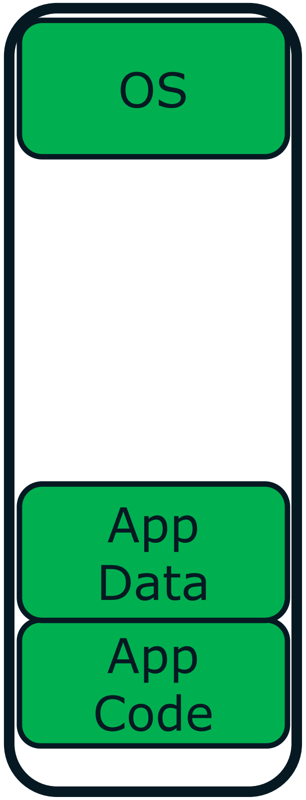
Attack surface with Enclaves



Scalable security within mainstream environment

SGX Programming Environment

Trusted execution environment embedded in a process



User Process

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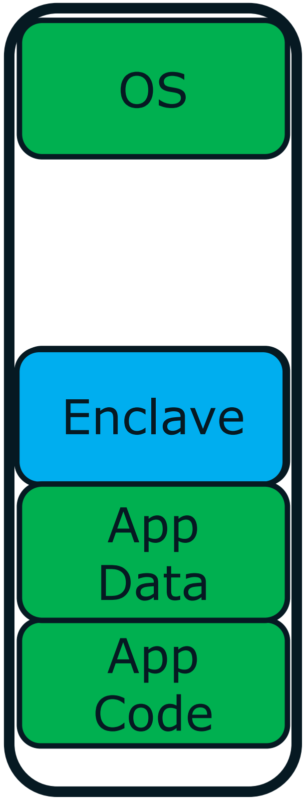

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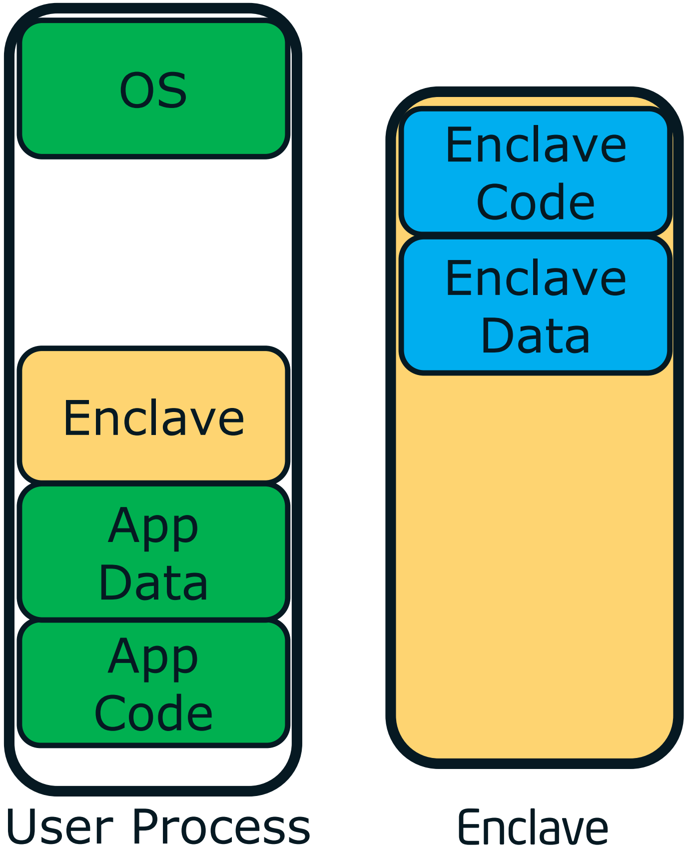

- With its own code and data
- Provide Confidentiality
- Provide integrity
- With controlled entry points

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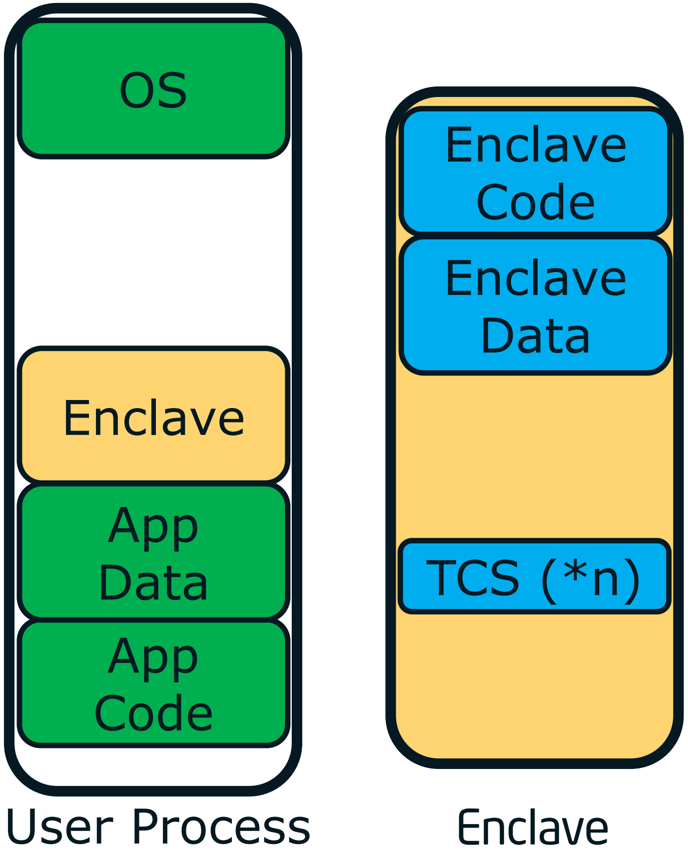

With its own code and data

Provide Confidentiality

Provide integrity

With controlled entry points

Supporting multiple threads

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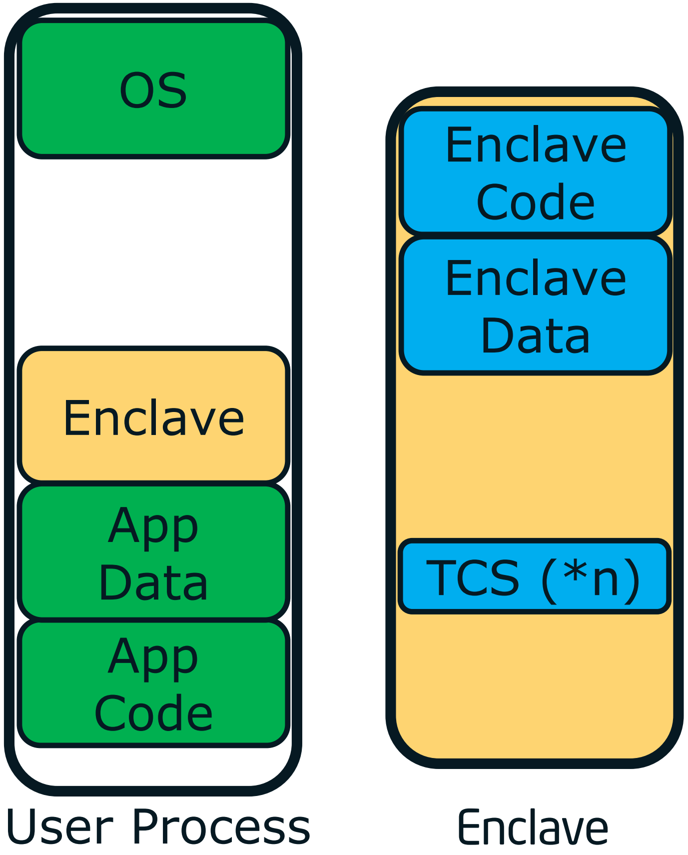


With its own code and data

Provide Confidentiality

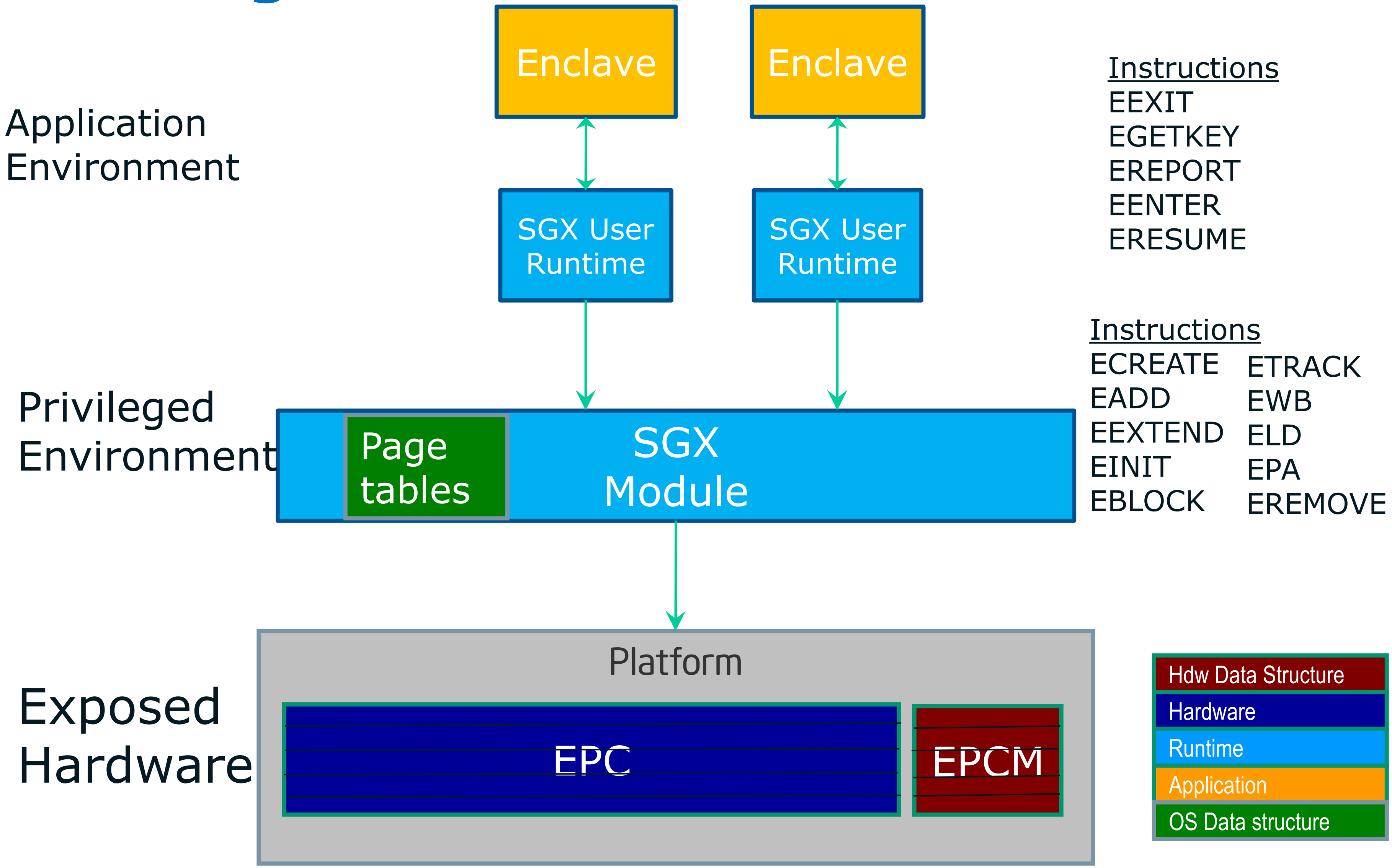
Provide integrity

With controlled entry points

Supporting multiple threads

With full access to app memory

SGX High-level HW/SW Picture



Life Cycle of An Enclave

Build

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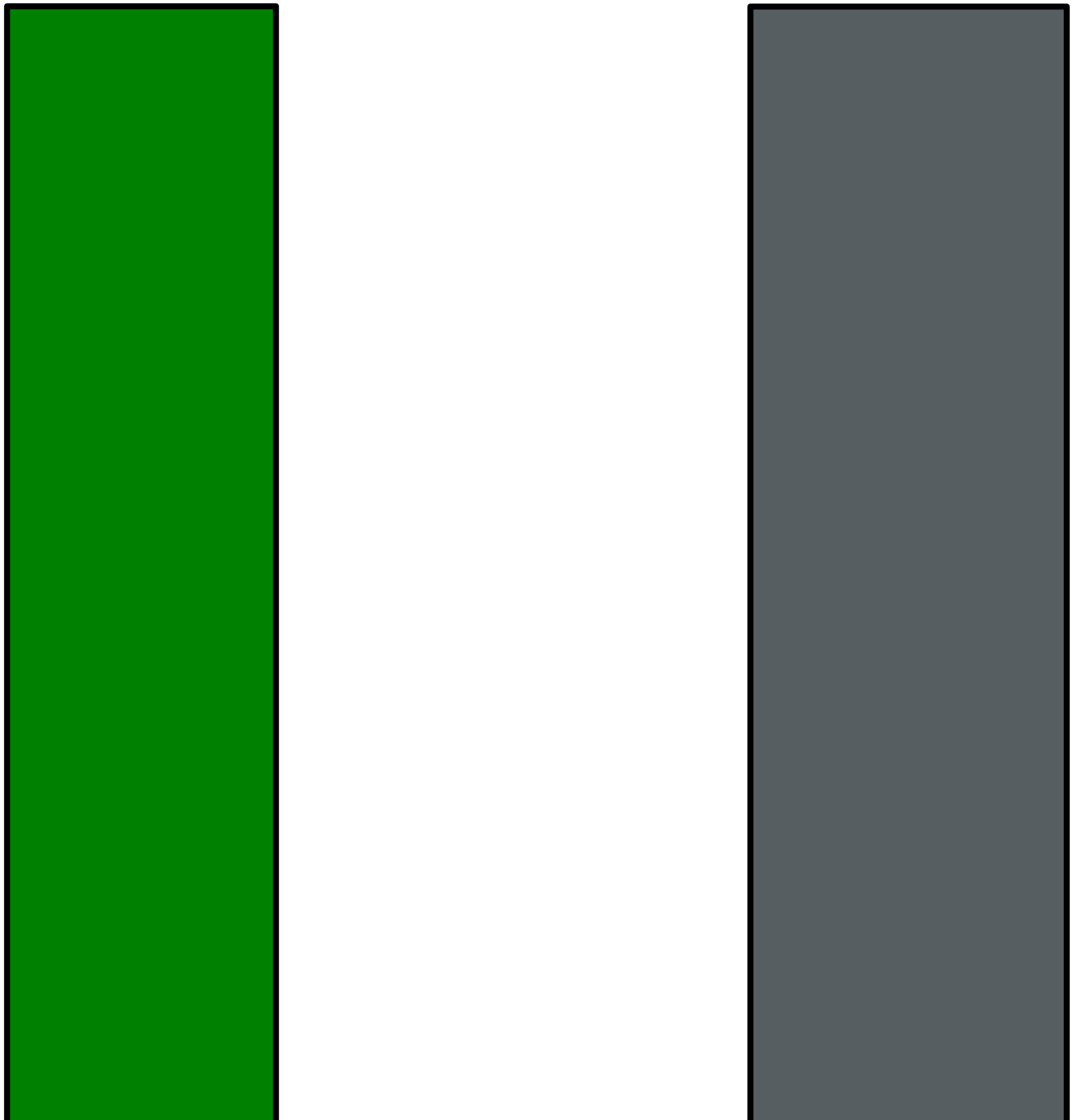
Virtual Addr Space

Physical Addr Space



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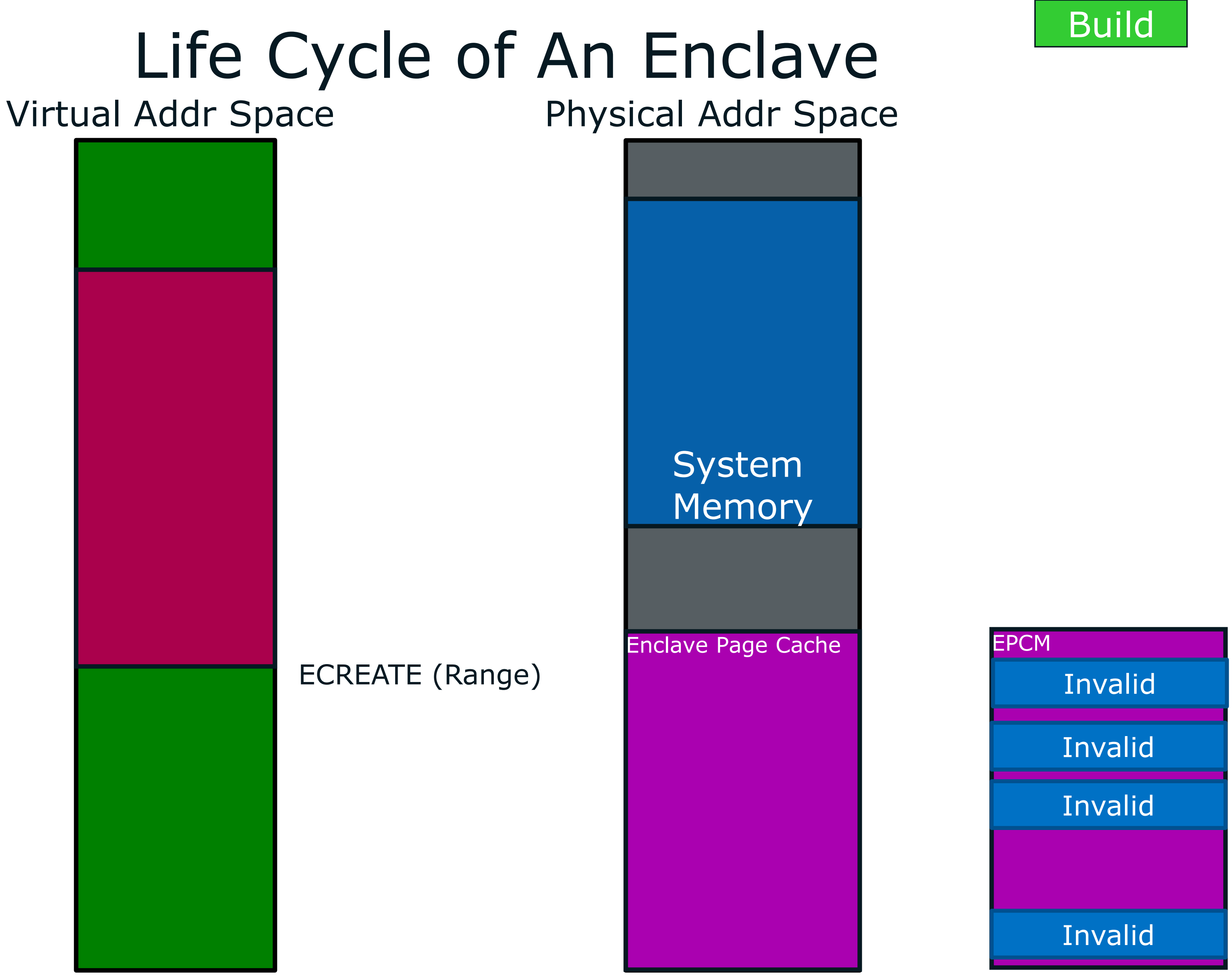

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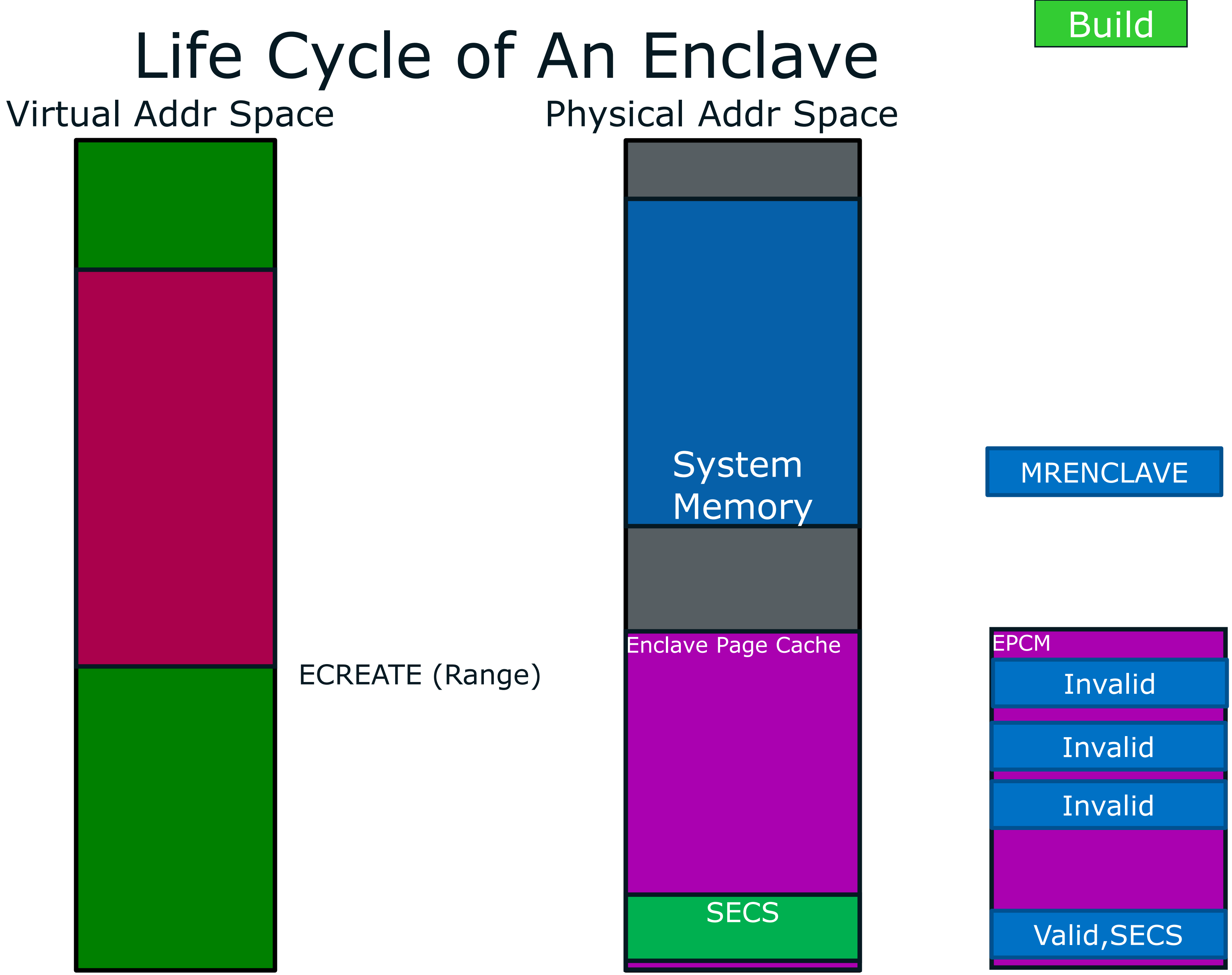

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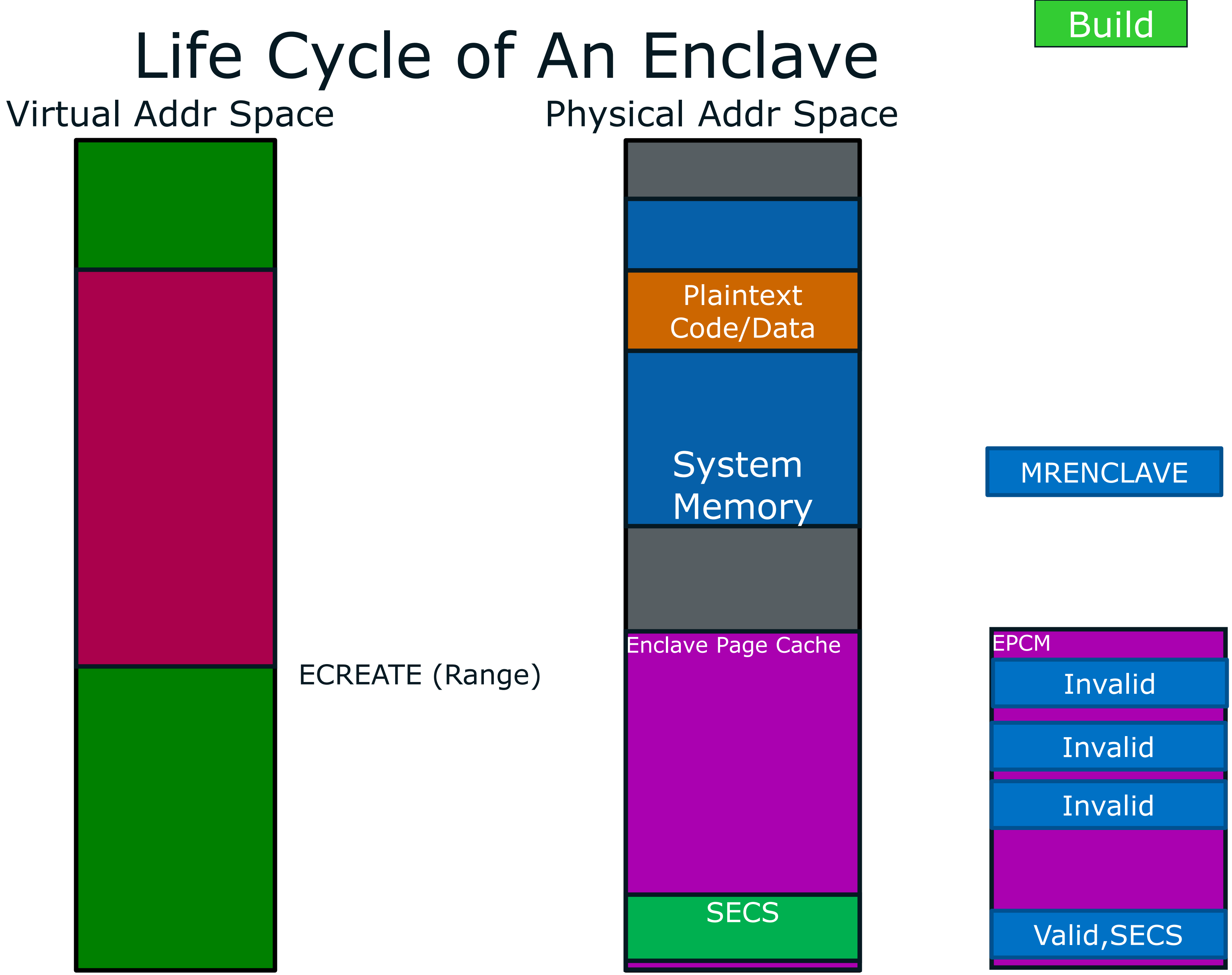

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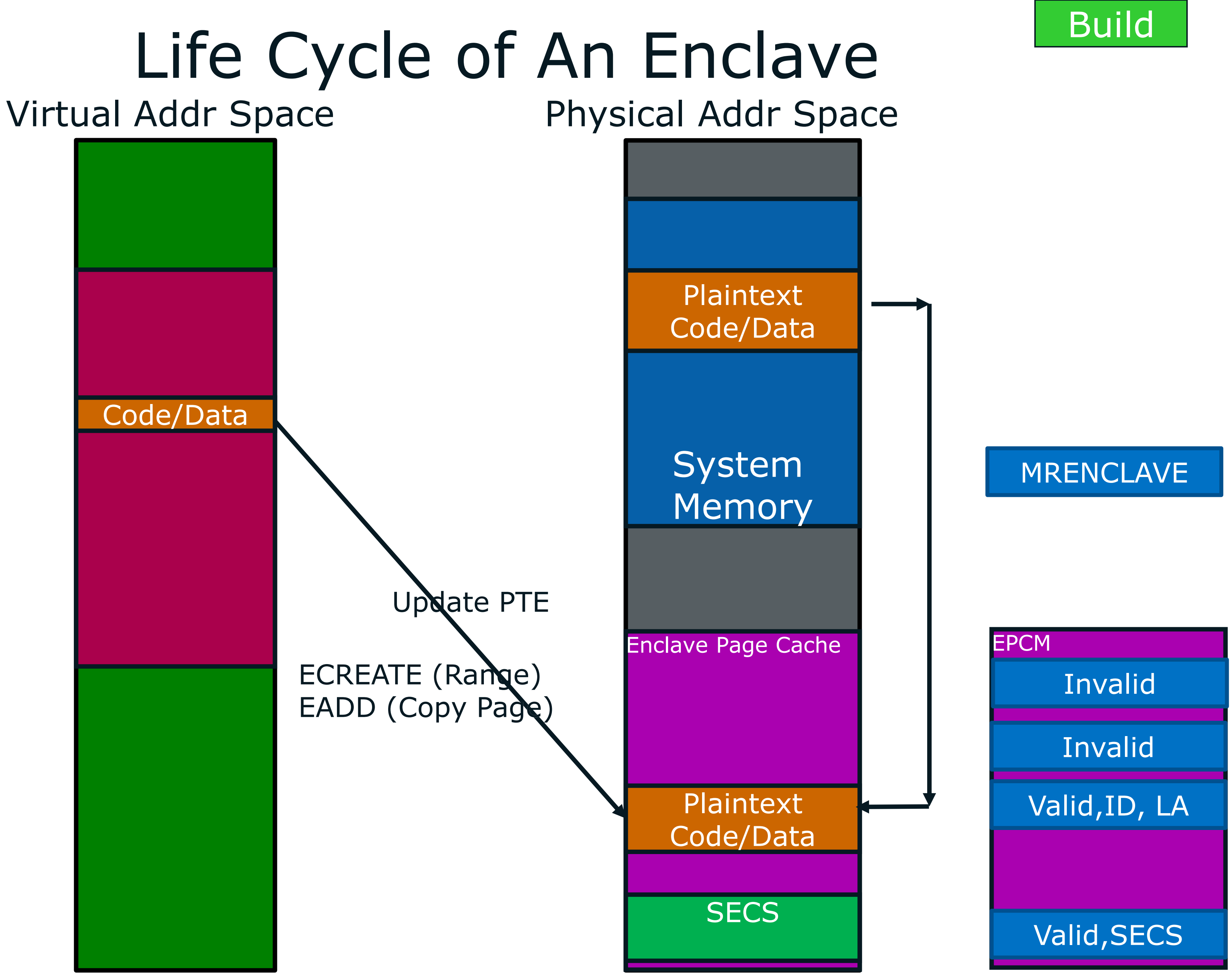

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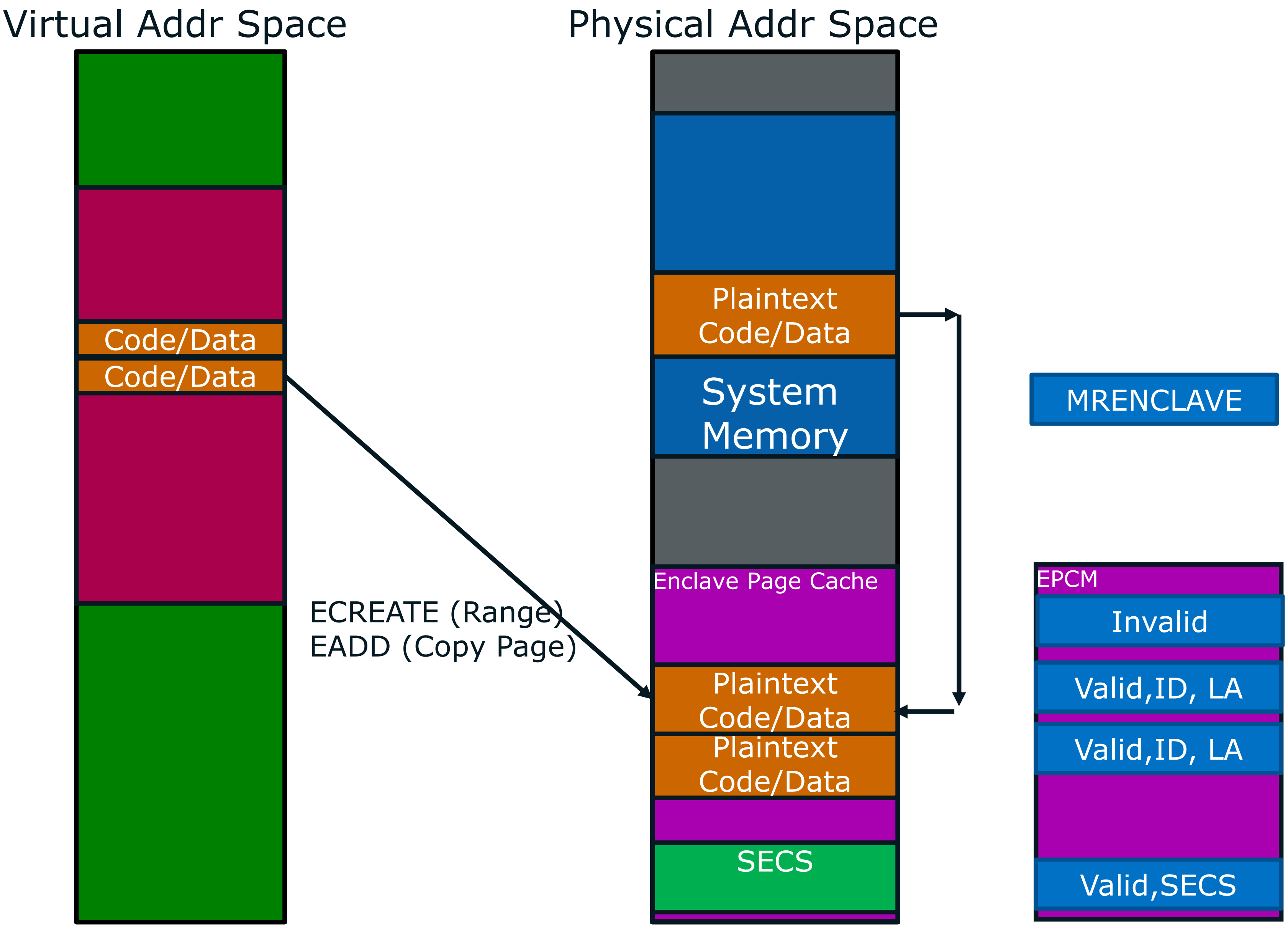

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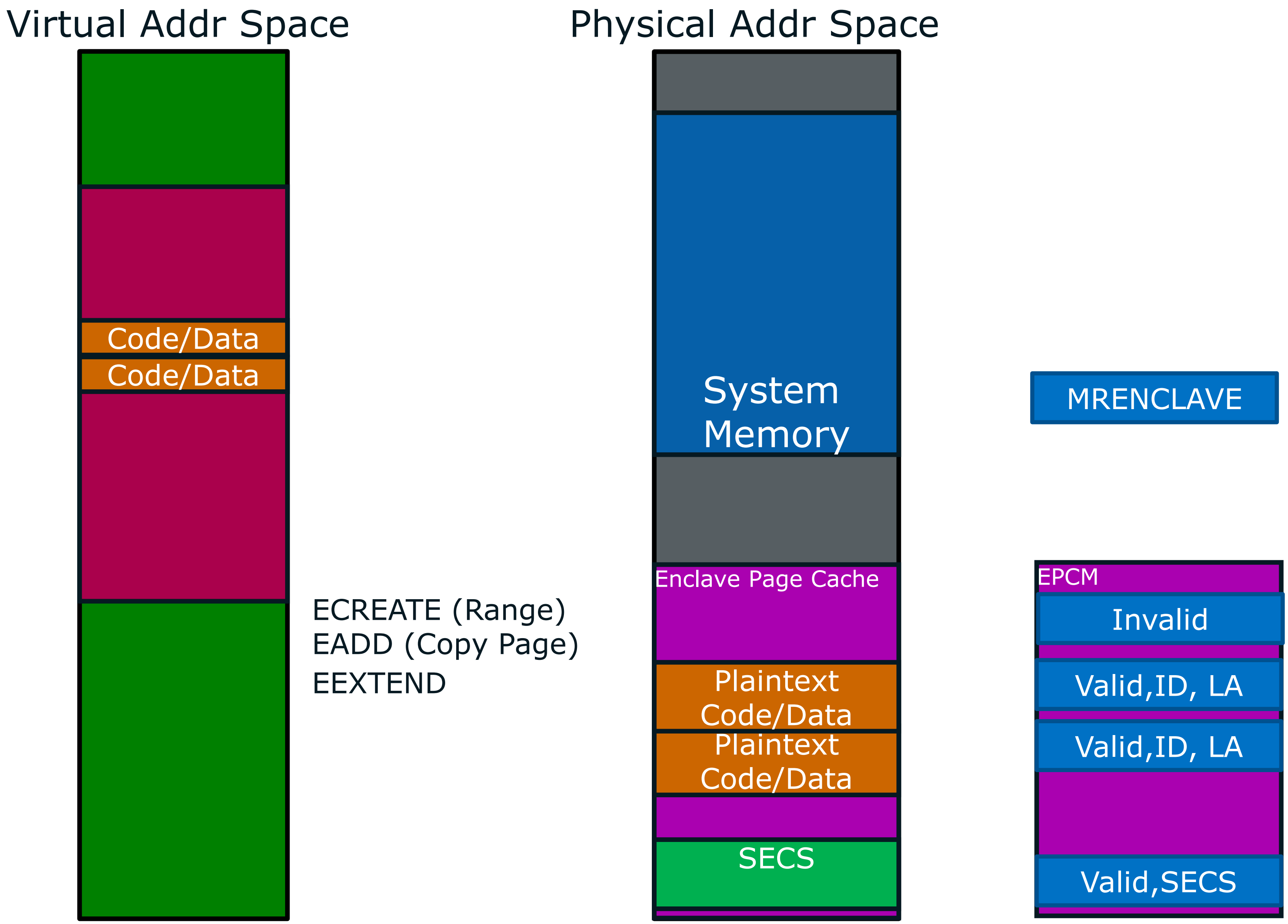

ECREATE (Range)
EADD (Copy Page)
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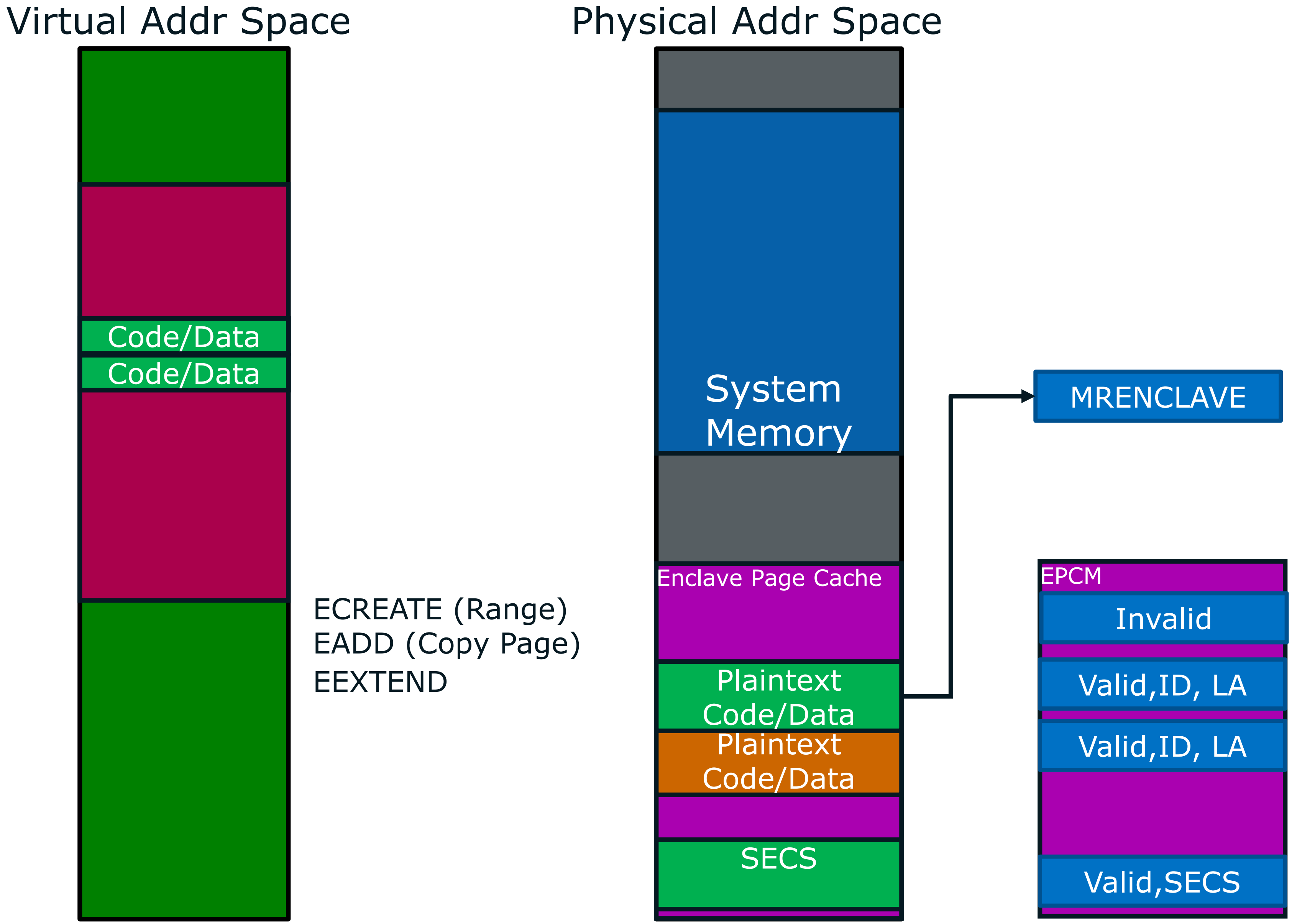

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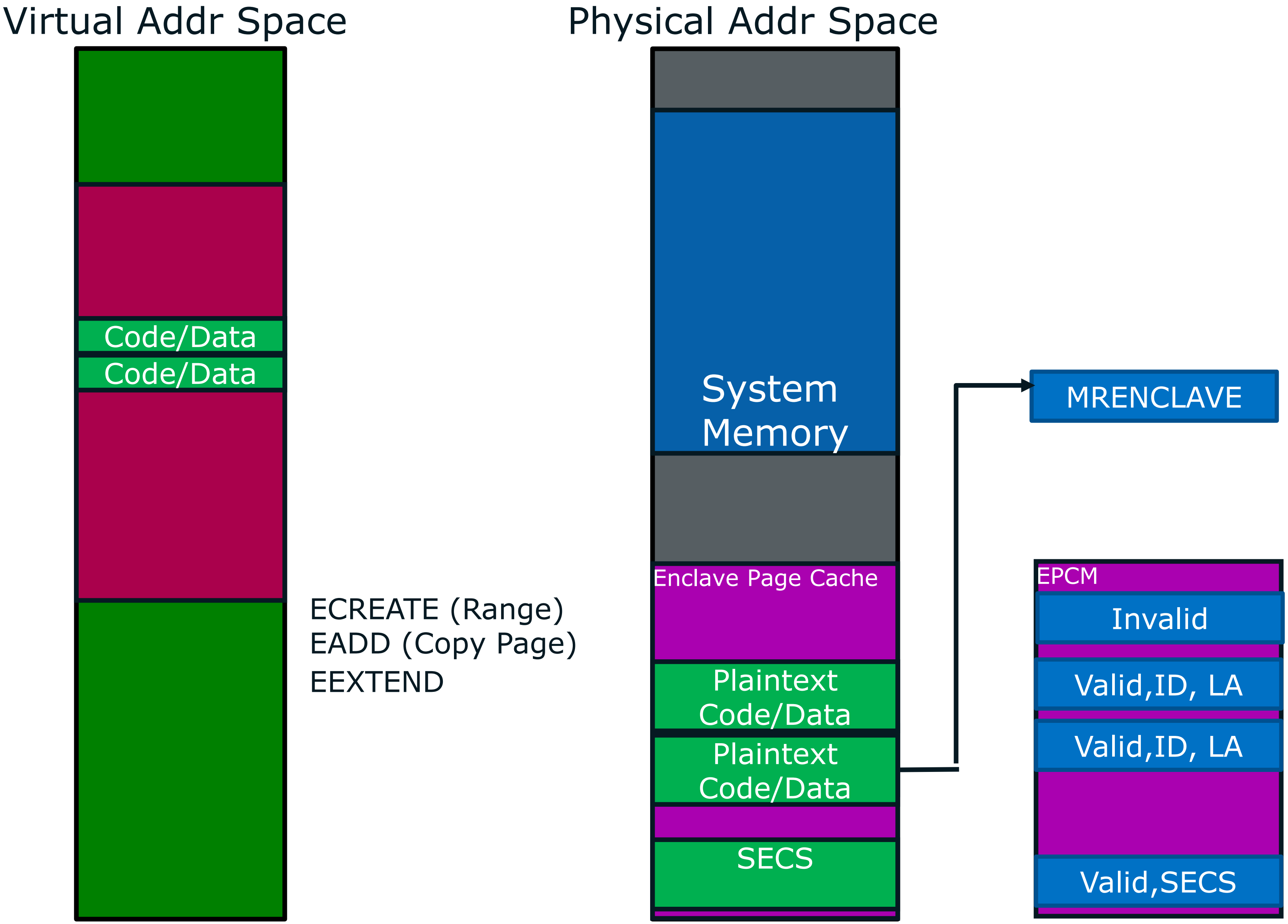

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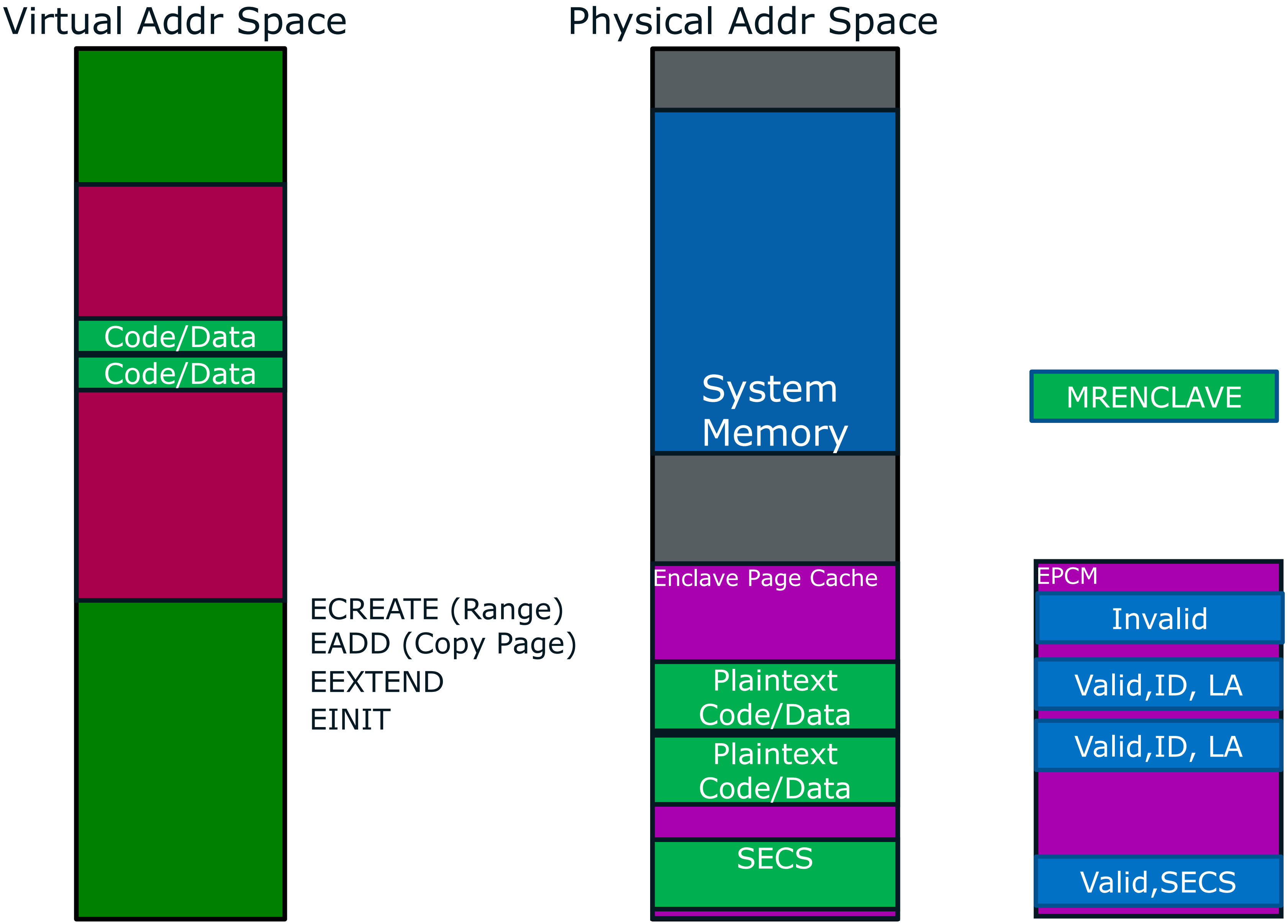

ECREATE (Range)
EADD (Copy Page)
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EINIT

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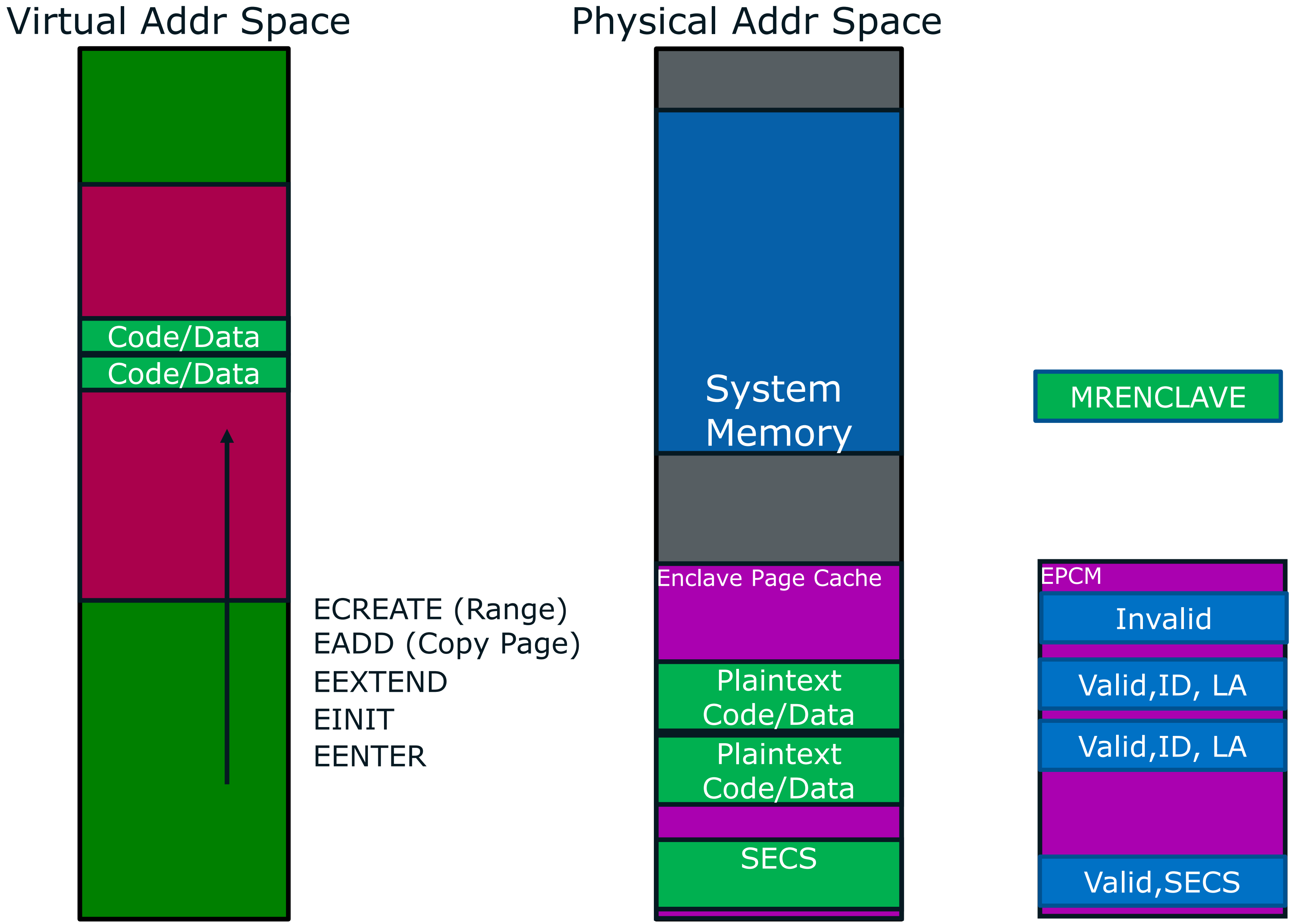

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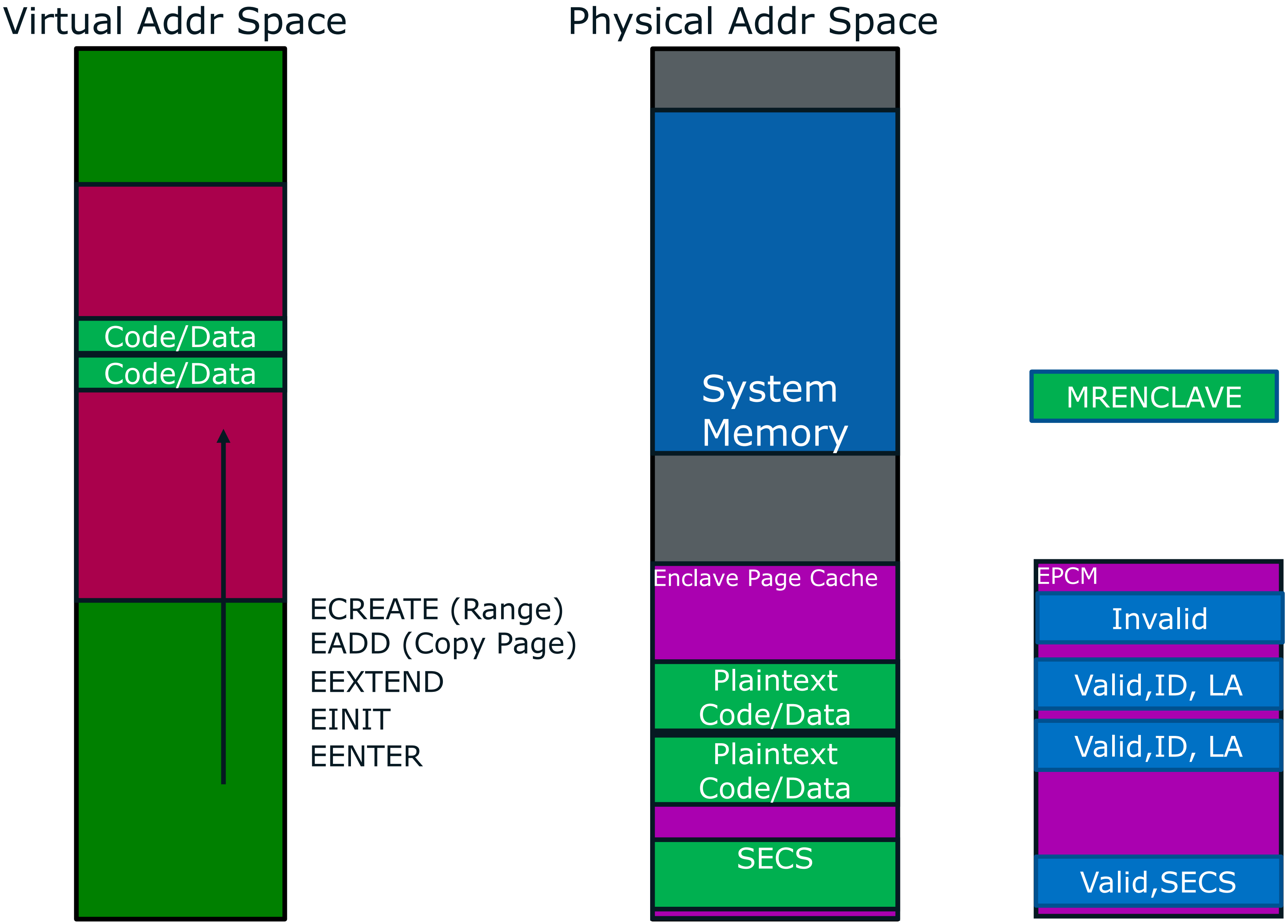

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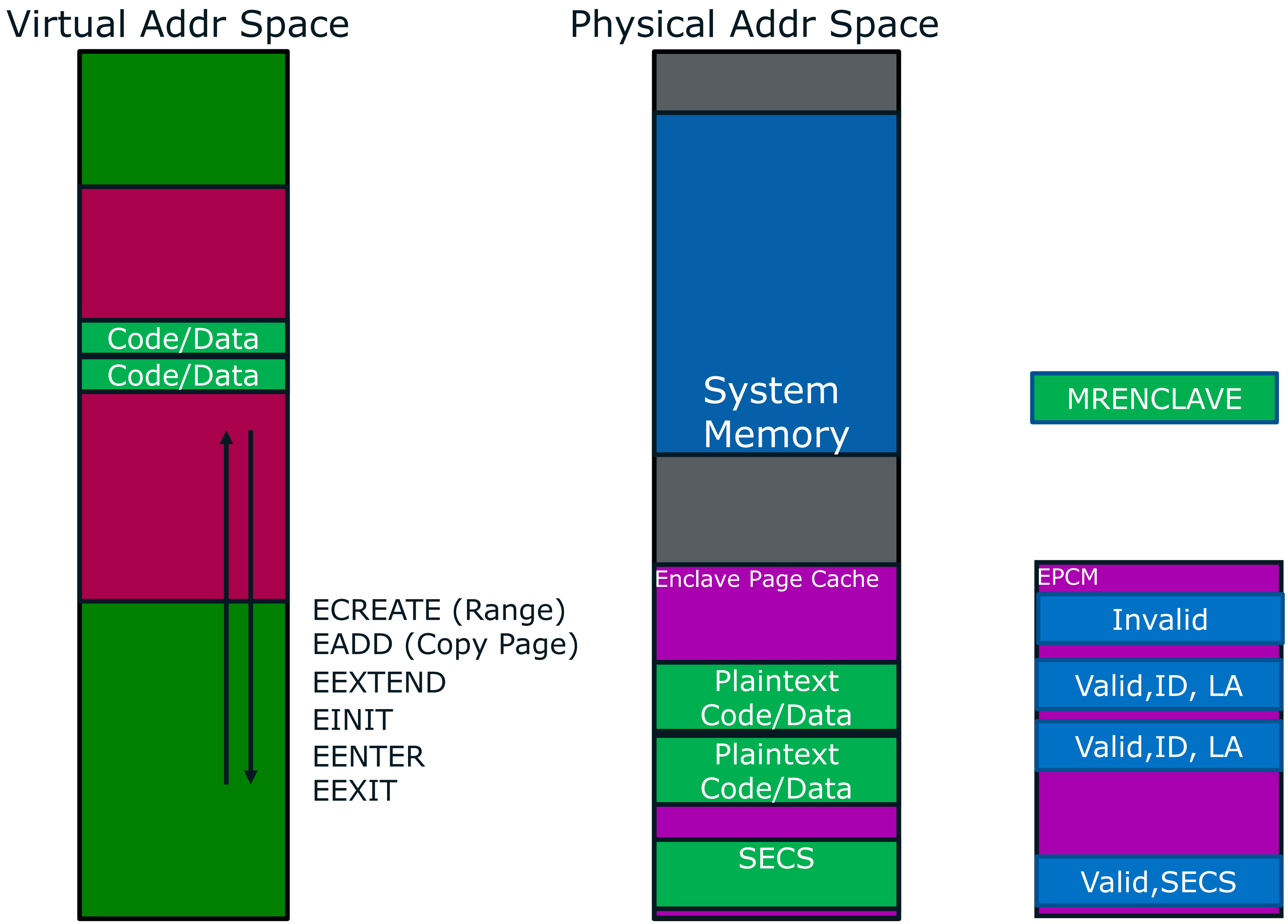

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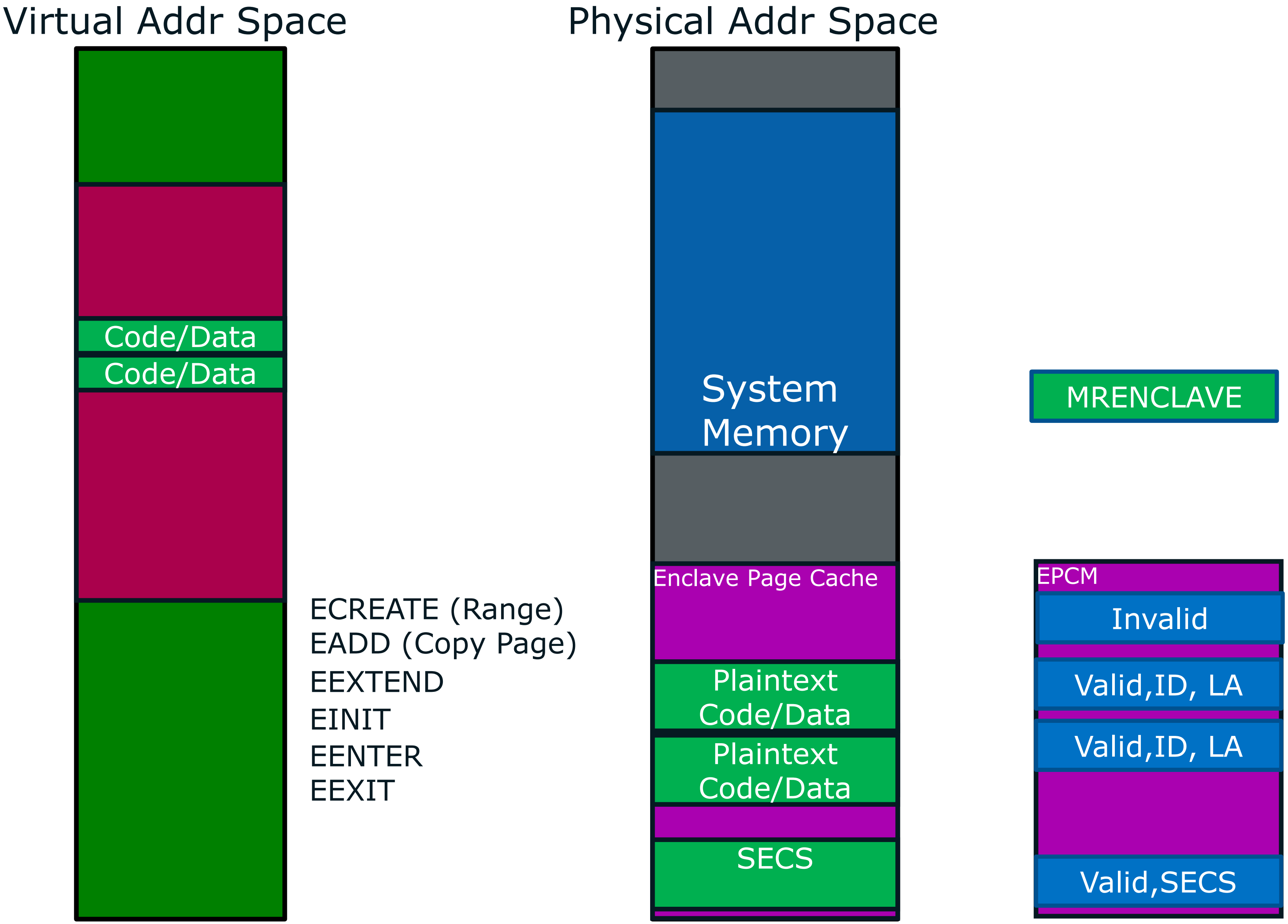

ECREATE (Range)
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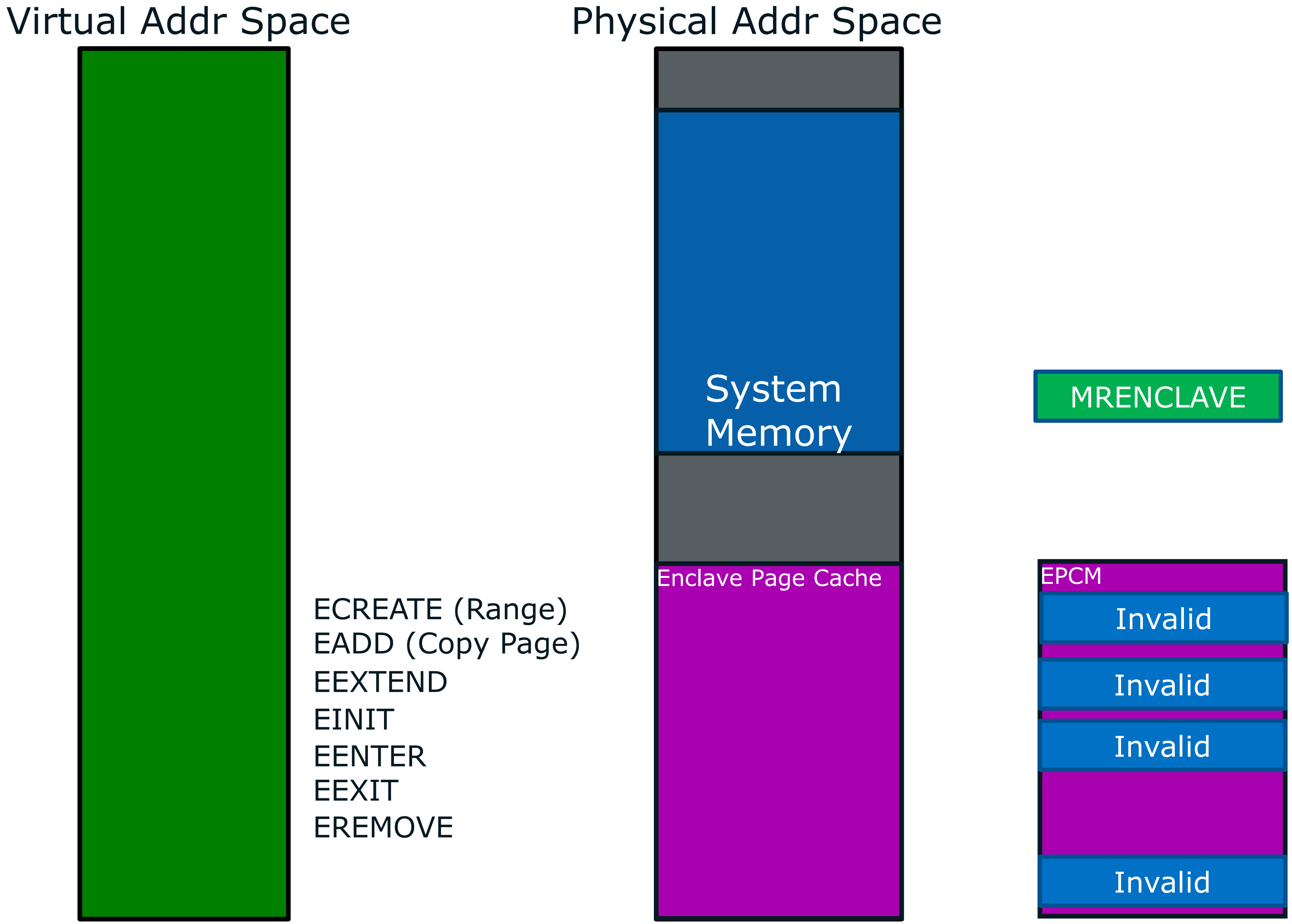
EEXTEND
EINIT
EENTER
EEXIT

Build

Life Cycle of An Enclave



SGX Access Control

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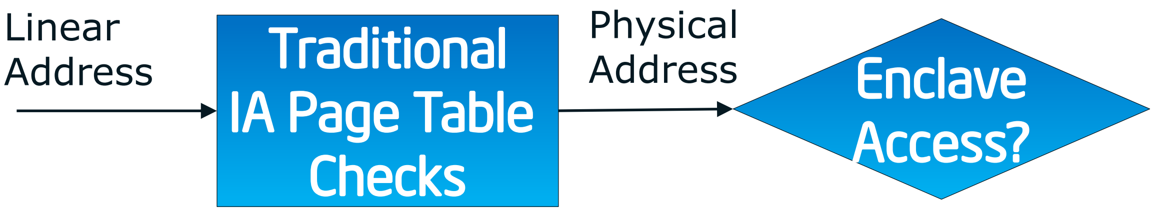

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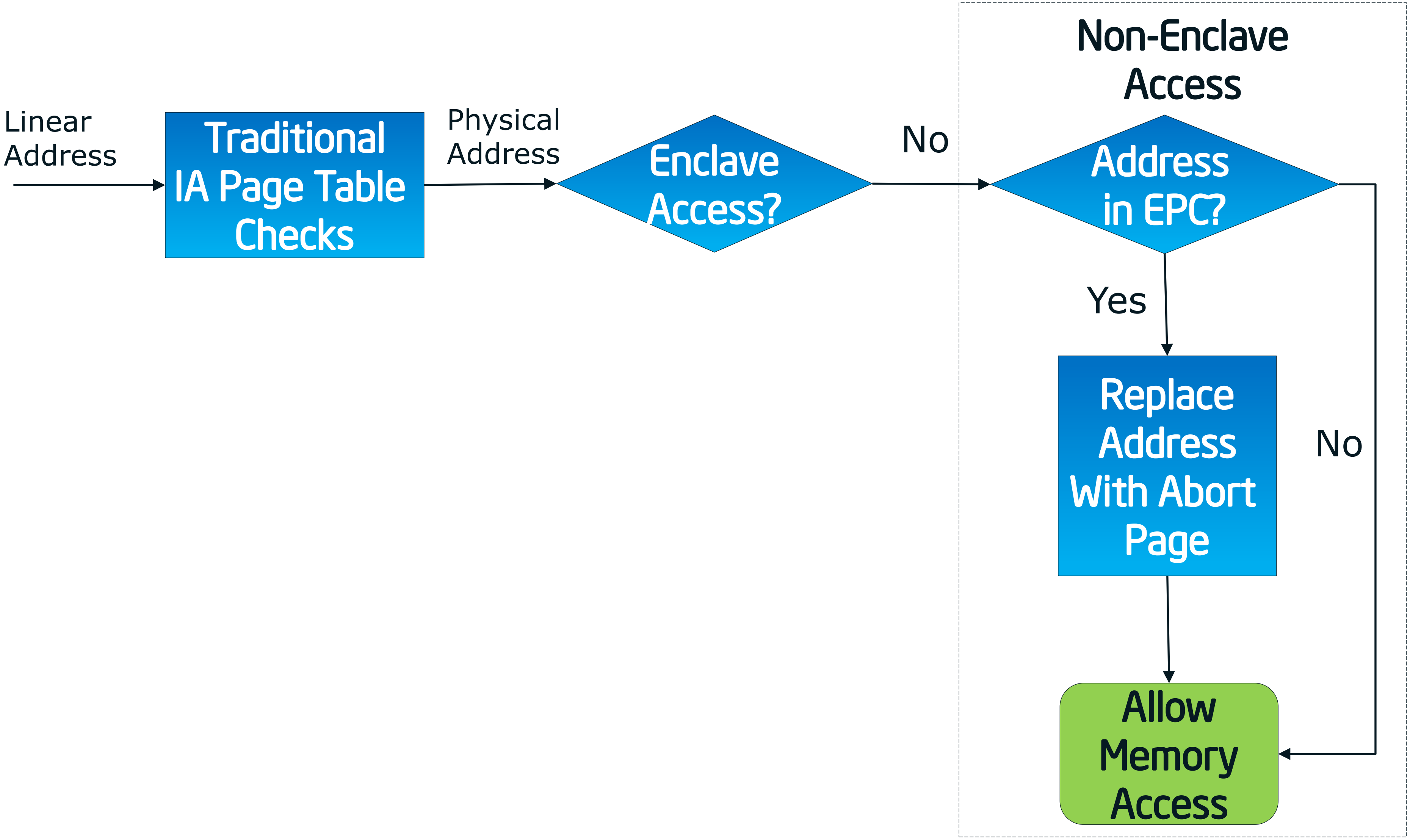

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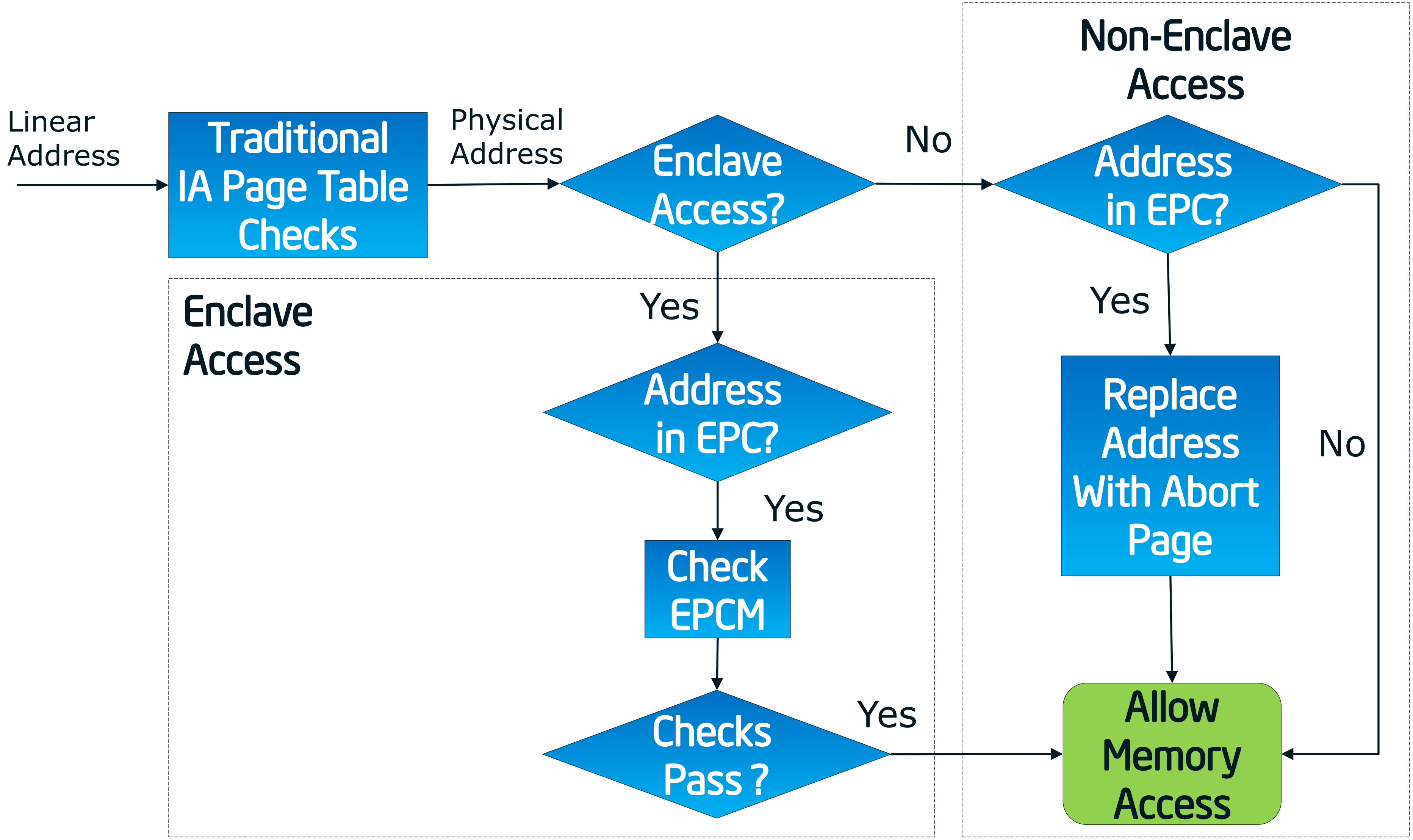

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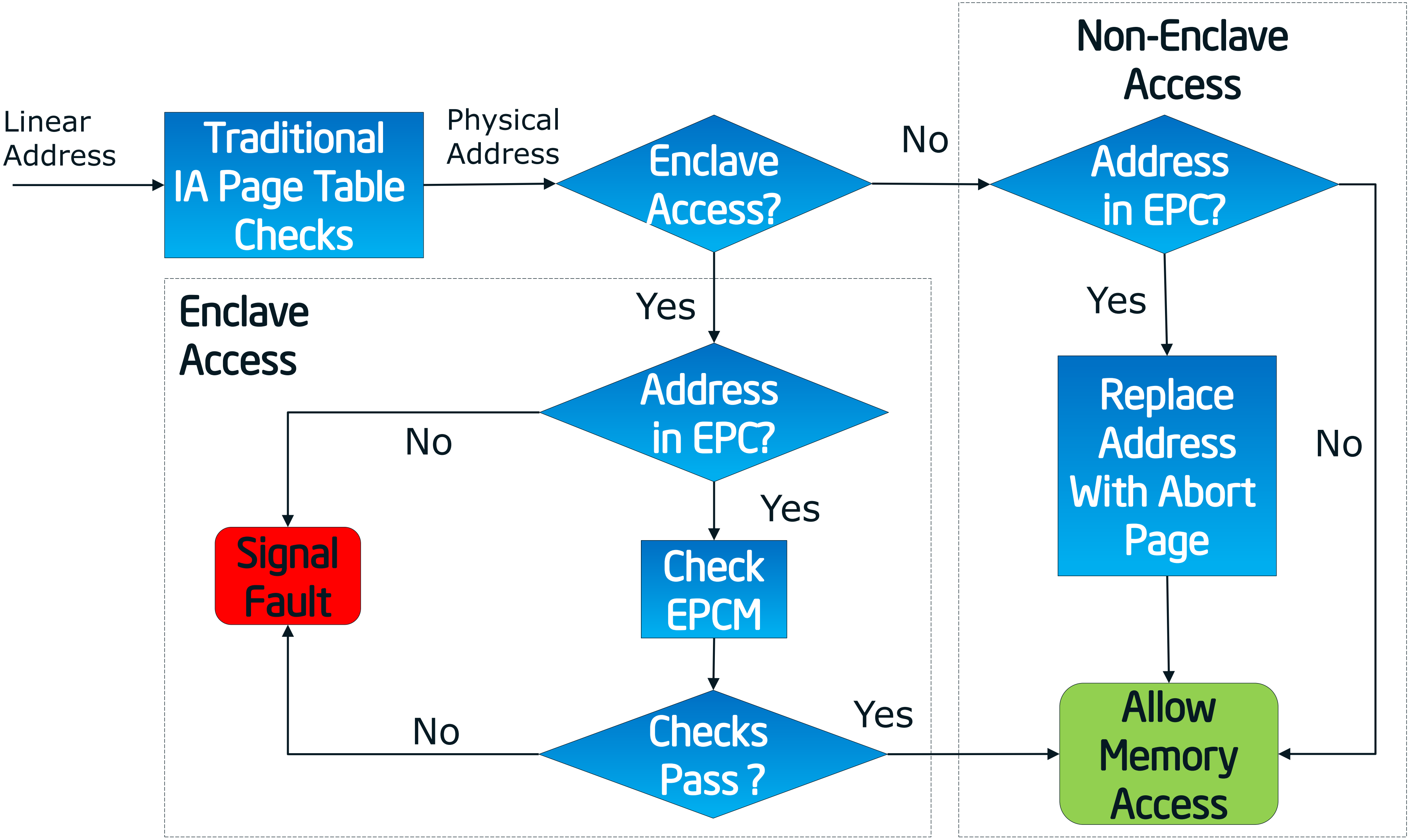
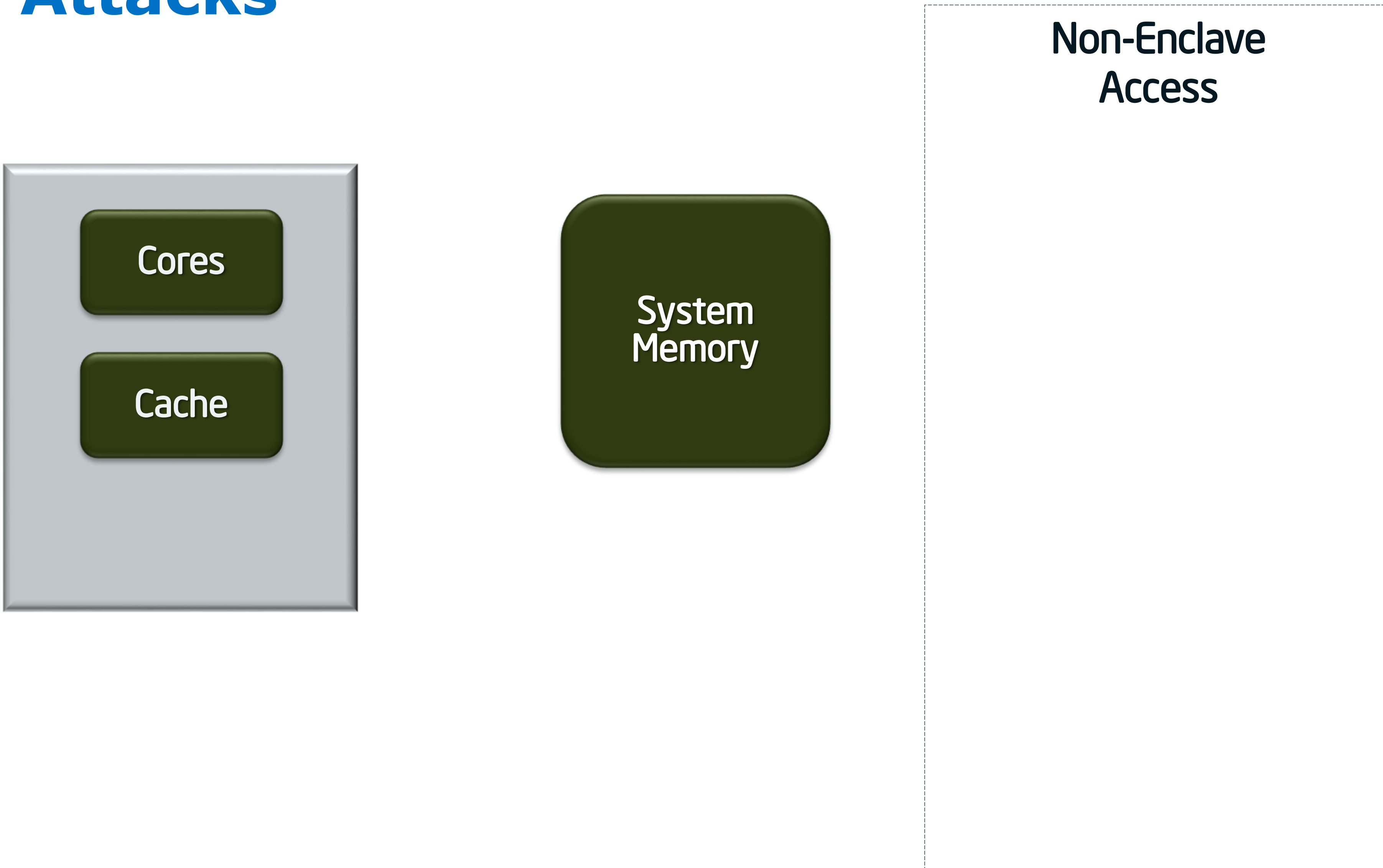


Protection vs. Memory Snooping Attacks



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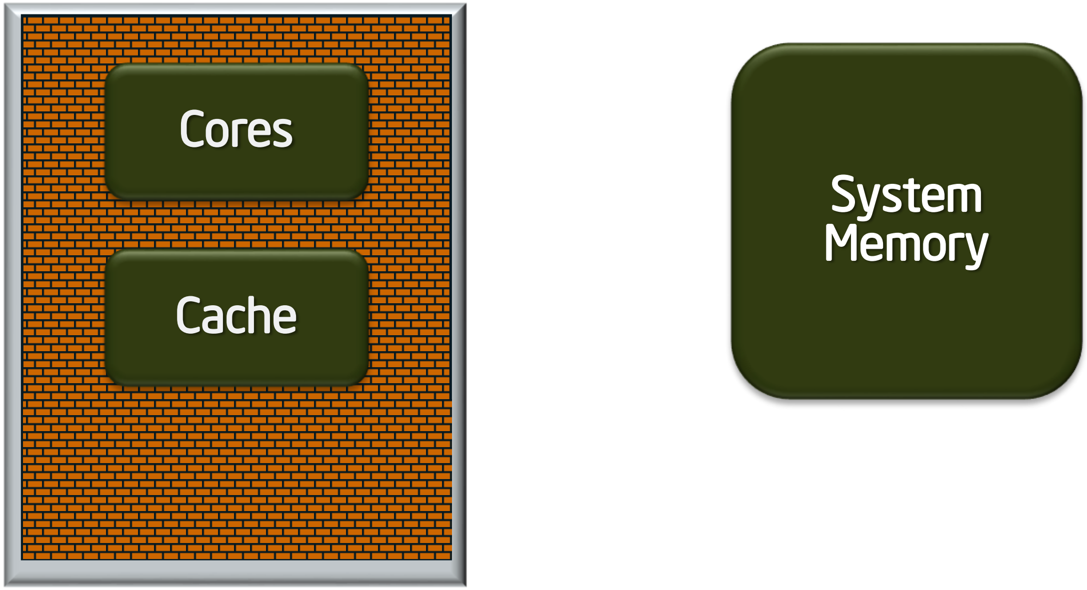

Non-Enclave Access

- Security perimeter is the CPU package boundary

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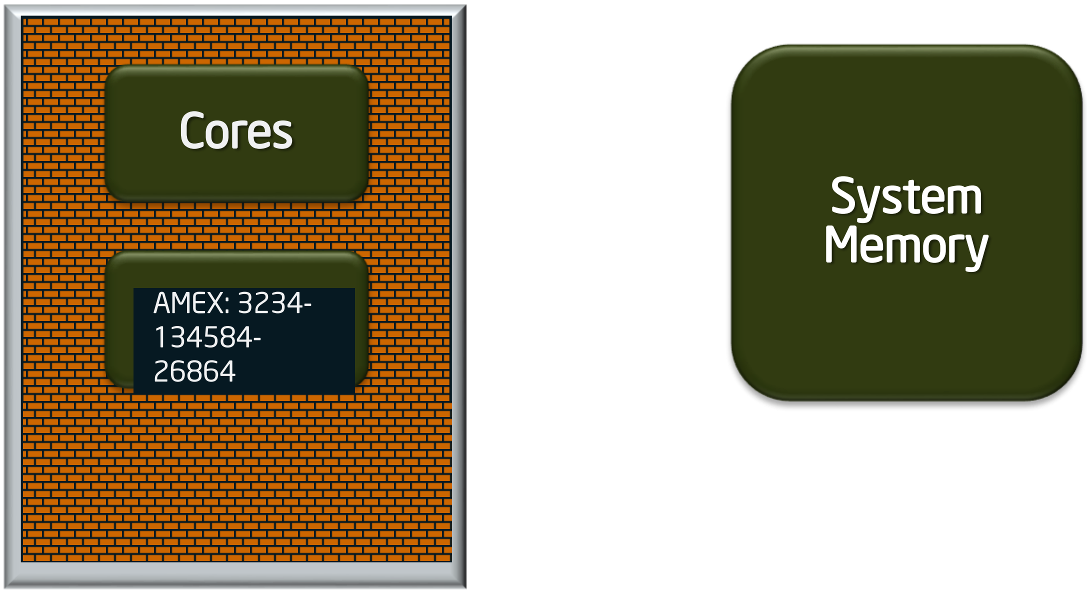

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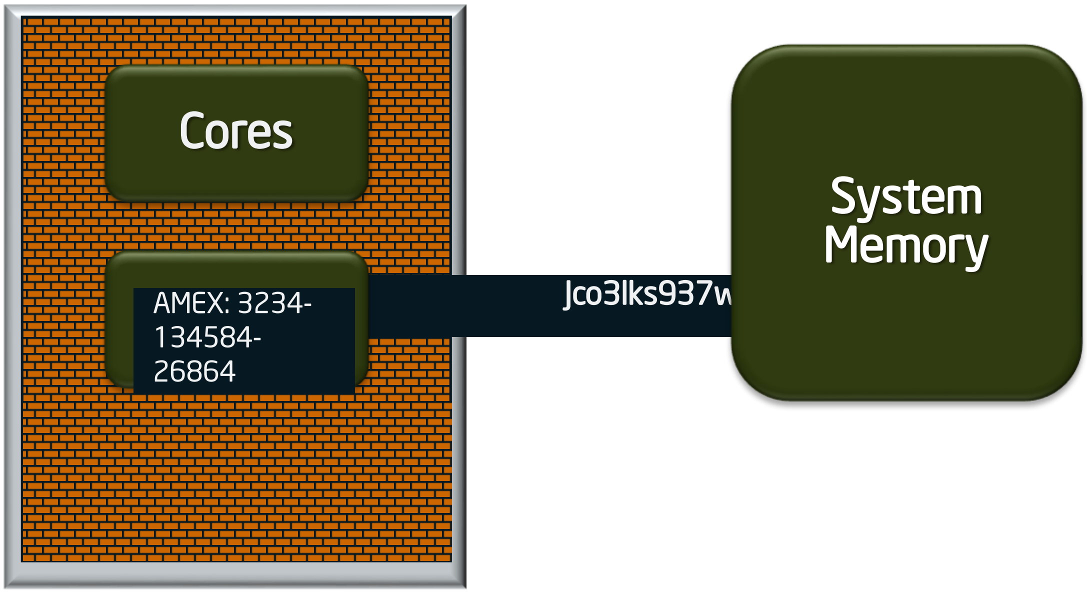

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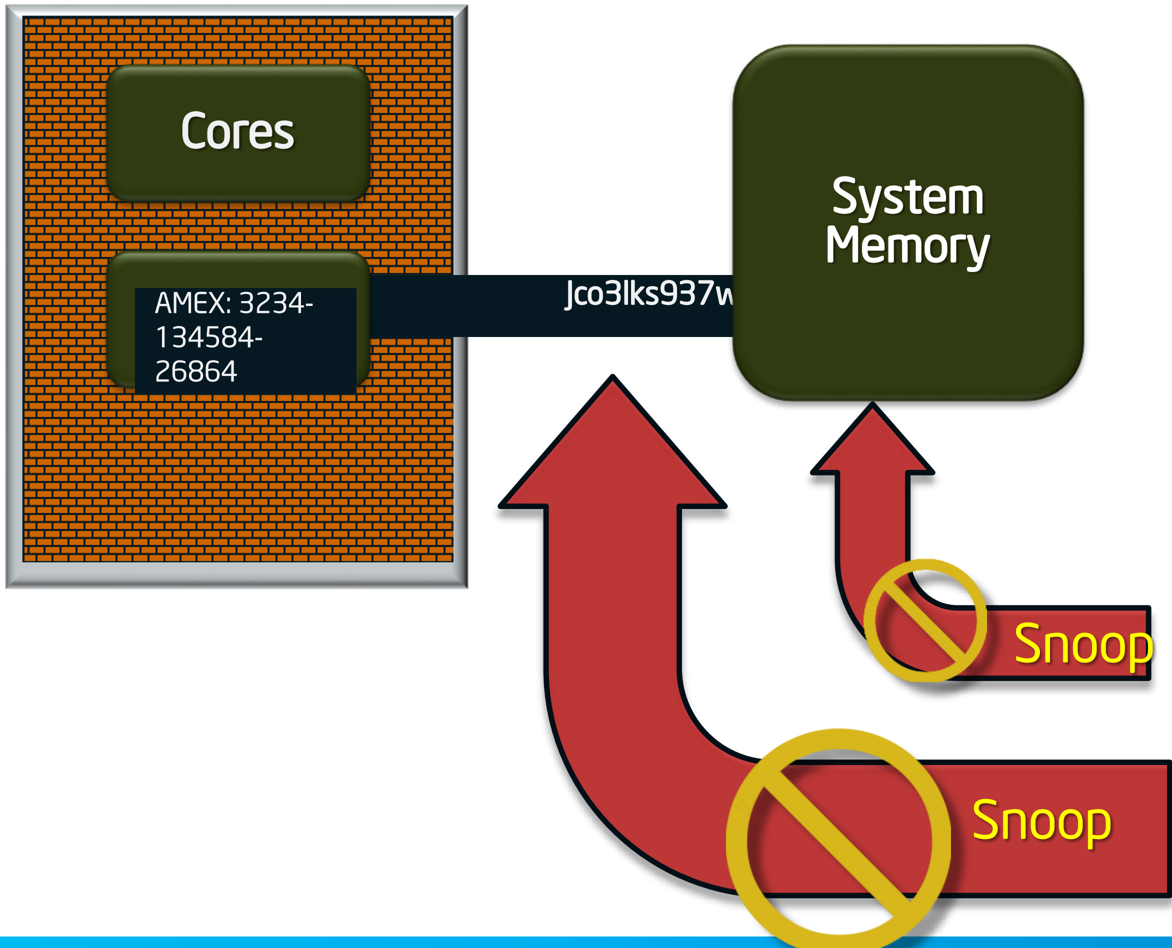

Non-Enclave Access

- Security perimeter is the CPU package boundary
- Data and code unencrypted inside CPU package
- Data and code outside CPU package is encrypted and/or integrity checked
- External memory reads and bus snoops see only encrypted data

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- **Attestation and Sealing**
- **Developing with SGX**
- **Summary**

The Challenge – Provisioning Secrets to the Enclave

- An enclave is in the clear before instantiation
  - Sections of code and data could be encrypted, but their decryption key can't be pre-installed
- Secrets come from outside the enclave
  - Keys
  - Passwords
  - Sensitive data
- The enclave must be able to convince a 3rd party that it's trustworthy and can be provisioned with the secrets
- Subsequent runs should be able to use the secrets that have already been provisioned

Trustworthiness

- A service provider should vet the enclave's Trusted Computing Base (TCB) before it should trust it and provide secrets to it
  - The enclave's software
  - The CPU's hardware & firmware

- Intel® SGX provides the means for an enclave to securely prove to a 3rd party:
  - What software is running inside the enclave
  - Which execution environment the enclave is running at
  - Which Sealing Identity will be used by the enclave
  - What's the CPU's security level

Attestation – Software TCB

- When building an enclave, Intel® SGX generates a cryptographic log of all the build activities
  - Content: Code, Data, Stack, Heap
  - Location of each page within the enclave
  - Security flags being used
- MRENCLAVE (“Enclave Identity”) is a 256-bit digest of the log
  - Represents the enclave’s software TCB
- A software TCB verifier should:
  - Securely obtain the enclave’s software TCB
  - Securely obtain the expected enclave’s software TCB
  - Compare the two values

Local Attestation

- "Local attestation": The process by which one enclave attests its TCB to another enclave on the same platform
- Using Intel® SGX's *EREPORT* and *EGETKEY* instructions
  - EREPORT generates a cryptographic REPORT that binds MRENCLAVE to the target enclave's REPORT KEY
  - EGETKEY provides the REPORT KEY to verify the REPORT

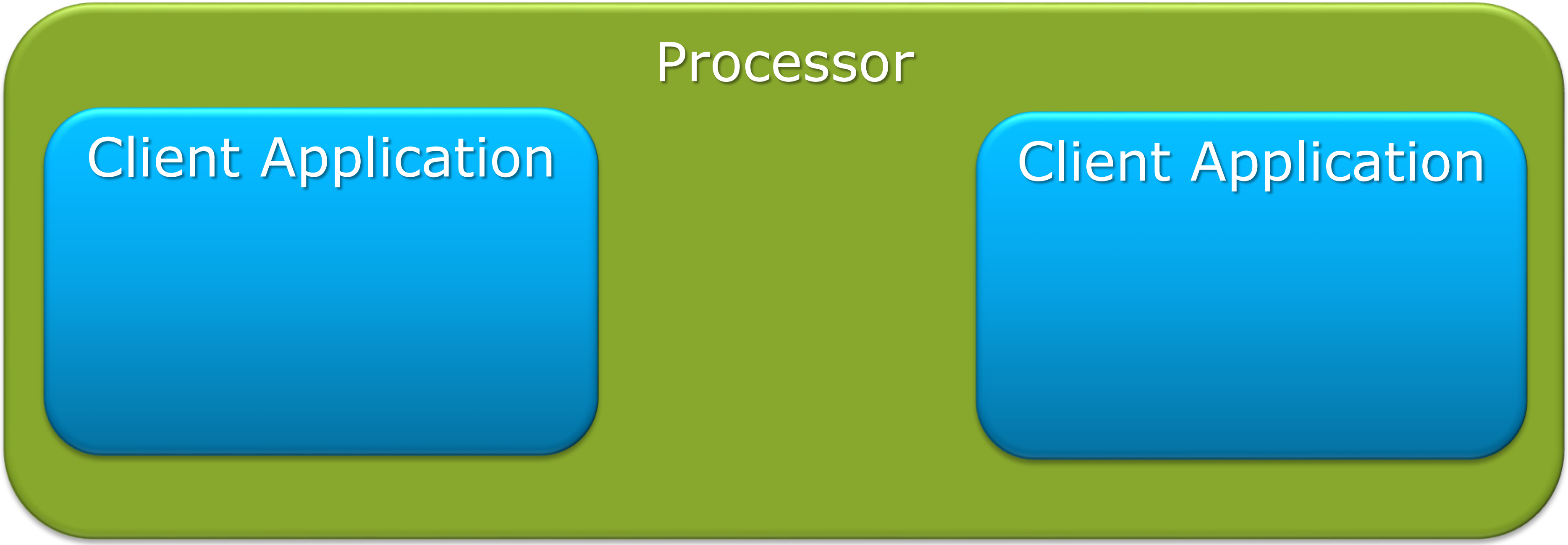
TCB component	Attestation
CPU Firmware & hardware	Symmetric - CPU REPORT KEY
Software	MRENCLAVE

Remote Attestation

- "Remote attestation": The process by which one enclave attests its TCB to another entity outside of the platform
- Intel® SGX Extends Local attestation by allowing a Quoting Enclave (QE) to use Intel® EPID to create a QUOTE out of a REPORT
  - Intel® EPID is a group signature scheme

TCB component	Attestation
CPU Firmware & hardware	Asymmetric - Intel® EPID
Software	MRENCLAVE

Local Attestation - Flow



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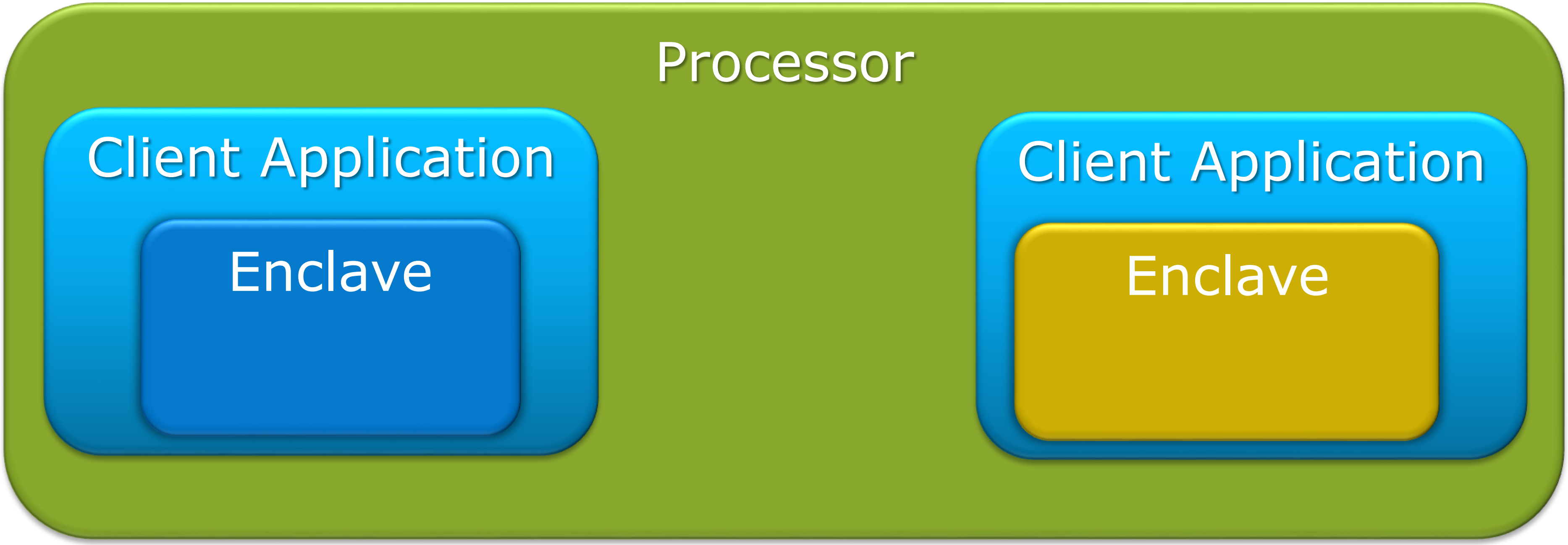

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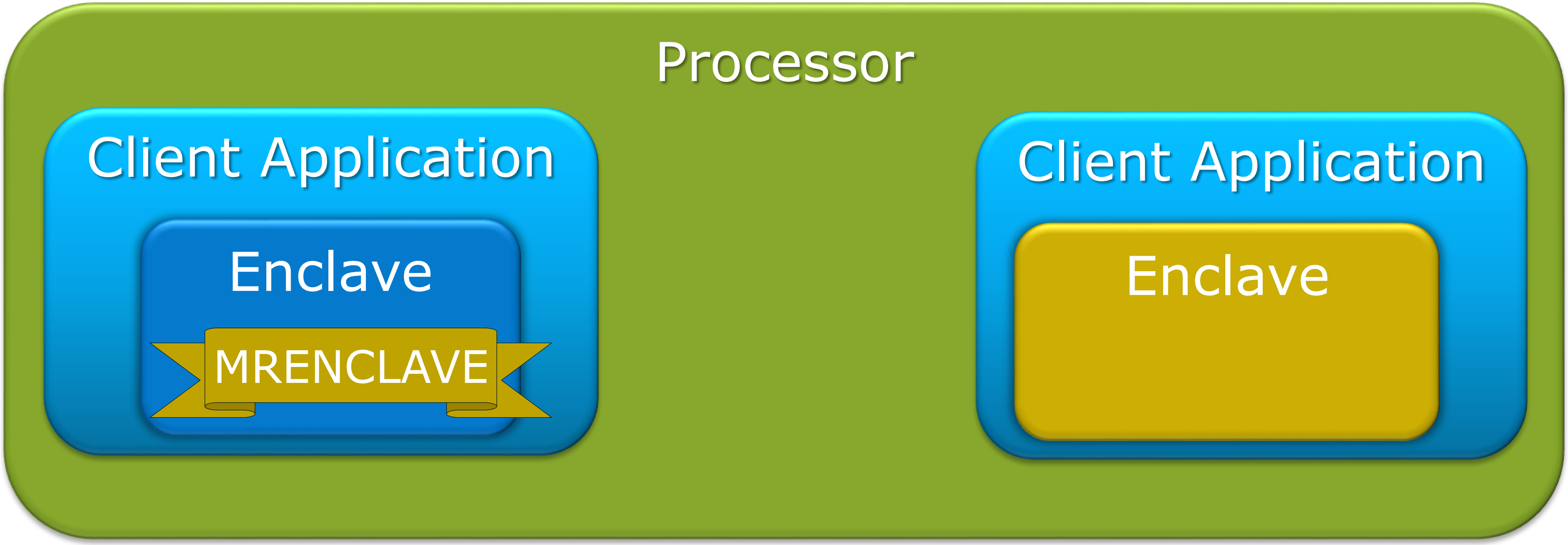

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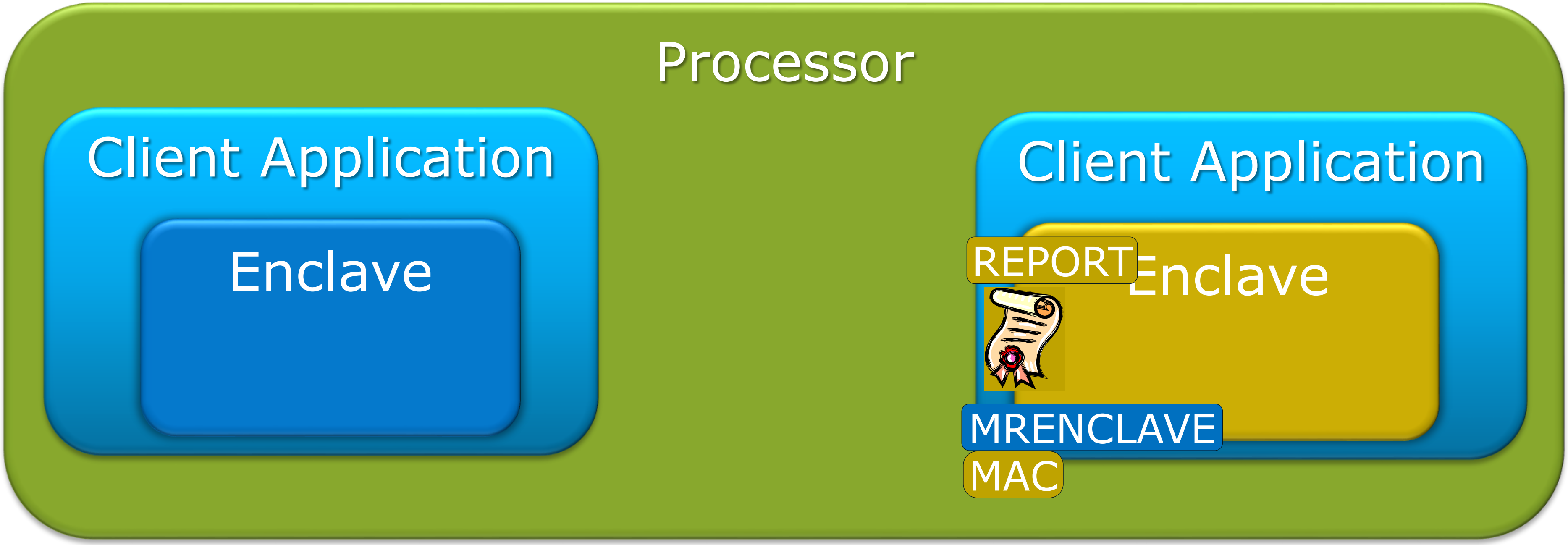

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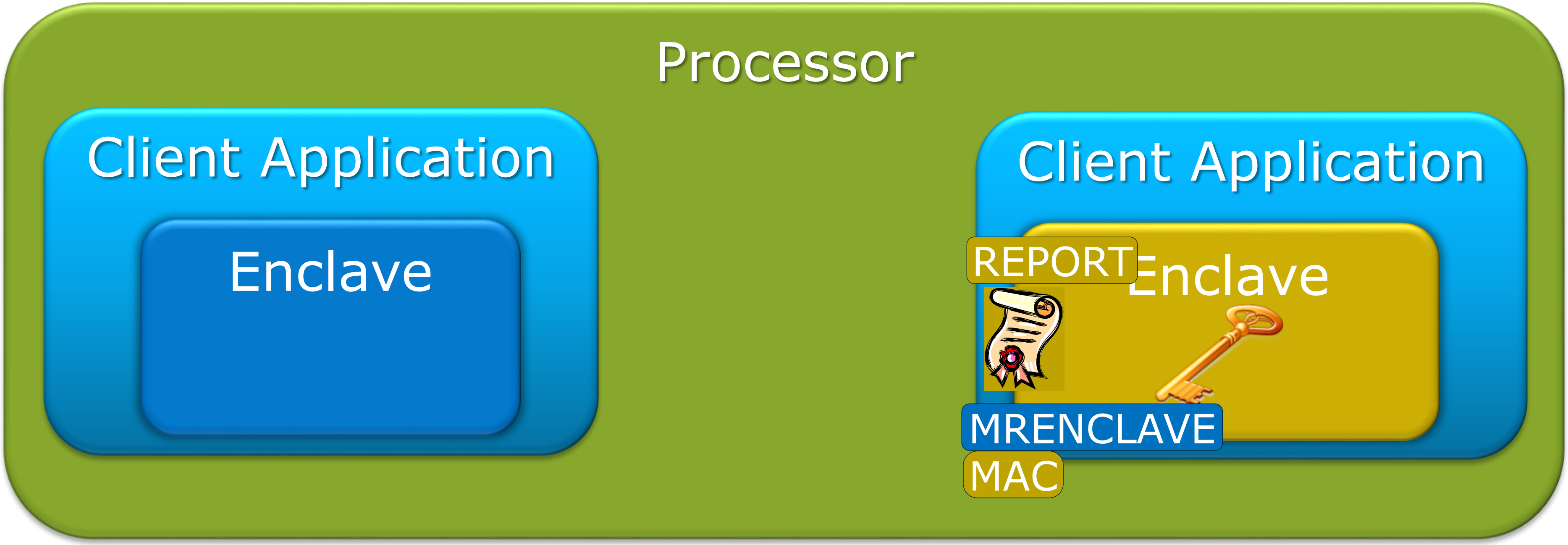

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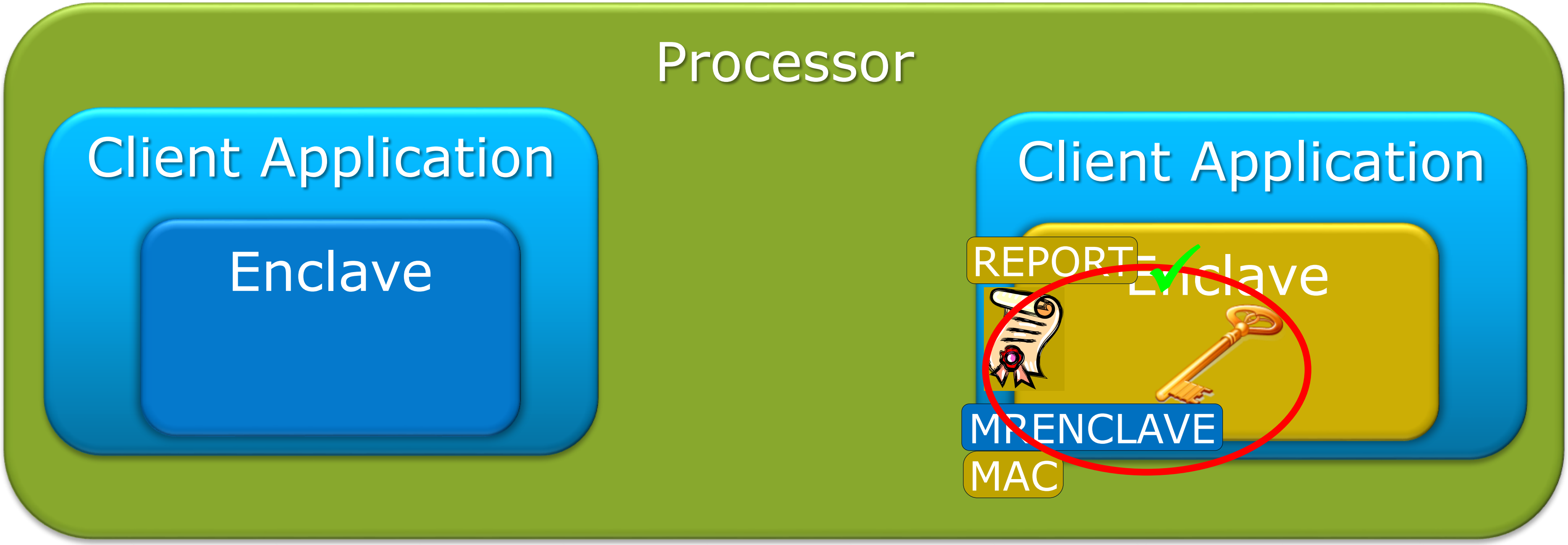

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Remote Attestation - Flow

1. Verifying enclave becomes the Quoting Enclave.
2. After verifying the REPORT the, QE signs the REPORT with the EPID private key and converts it into a QUOTE
3. Remote platform verifies the QUOTE with the EPID public key and verifies MRENCLAVE against the expected value

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Sealing Authority

- Every enclave has an Enclave Certificate (SIGSTRUCT) which is signed by a Sealing Authority
  - Typically the enclave writer
  - SIGSTRUCT includes:
    - Enclave's Identity (represented by MRENCLAVE)
    - Sealing Authority's public key (represented by MRSIGNER)
- *EINIT* verifies the signature over SIGSTRUCT prior to enclave initialization

Sealing

- "Sealing": Cryptographically protecting data when it leaves the enclave.

- Enclaves use EGETKEY to retrieve an enclave, platform persistent key and encrypts the data

- EGETKEY uses a combination of enclave attributes and platform unique key to generate keys
  - Enclave Sealing Authority
  - Enclave Product ID
  - Enclave Product Security Version Number (SVN)

Example: Secure Transaction

Remote Platform

1. Enclave built & measured against ISV's signed certificate
2. Enclave calls *EREPORT* to obtain a REPORT that includes enclave specific data (ephemeral key)
3. REPORT & user data sent to Quoting Enclave who signs the REPORT with an EPID private key
4. QUOTE sent to server & verified
5. Ephemeral key used to create a trusted channel between enclave and remote server
6. Secret provisioned to enclave
7. Enclave calls *EGETKEY* to obtain the SEAL KEY
8. Secret is encrypted using SEAL KEY & stored for future use

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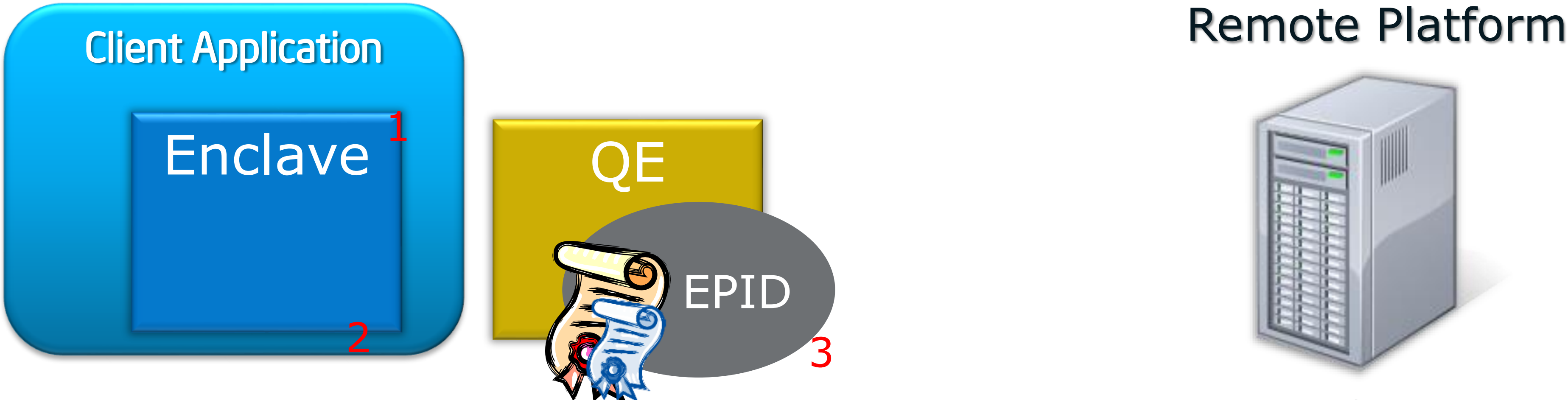

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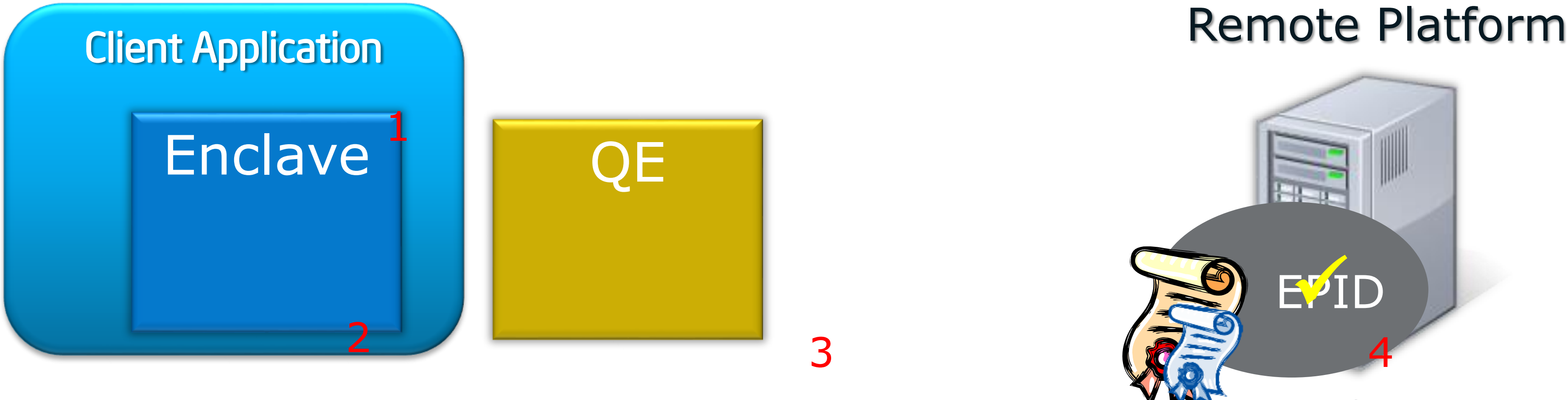

1. Enclave built & measured against ISV's signed certificate
2. Enclave calls *EREPORT* to obtain a REPORT that includes enclave specific data (ephemeral key)
3. REPORT & user data sent to Quoting Enclave who signs the REPORT with an EPID private key
4. QUOTE sent to server & verified
5. Ephemeral key used to create a trusted channel between enclave and remote server
6. Secret provisioned to enclave
7. Enclave calls *EGETKEY* to obtain the SEAL KEY
8. Secret is encrypted using SEAL KEY & stored for future use

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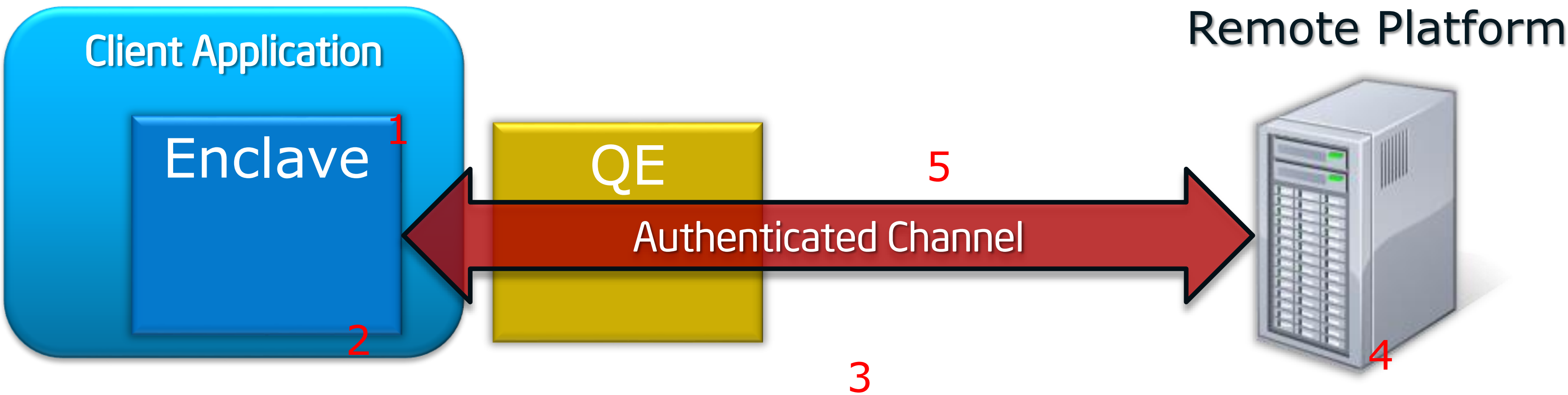

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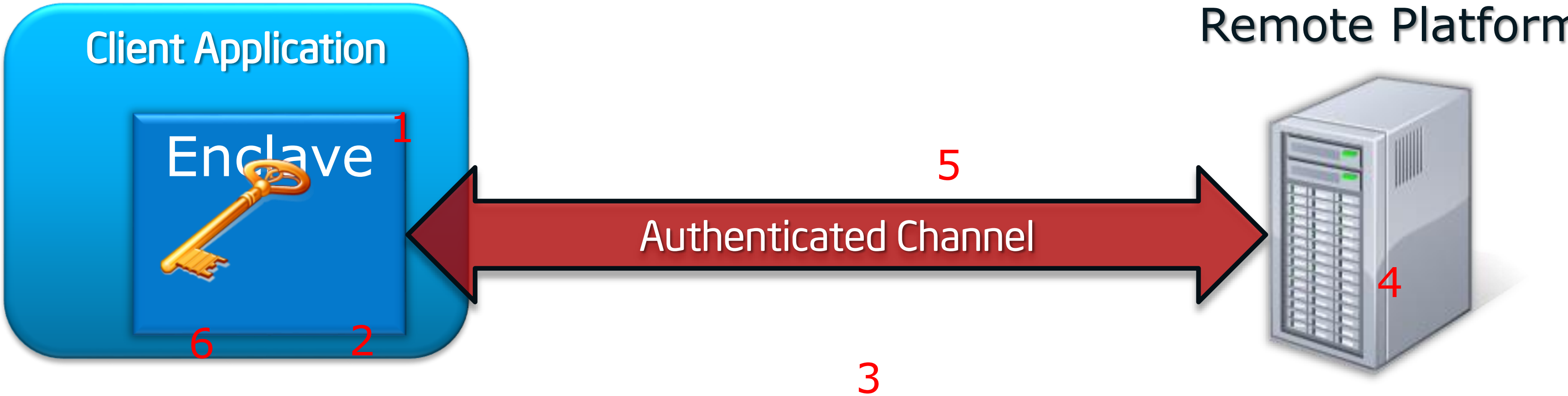

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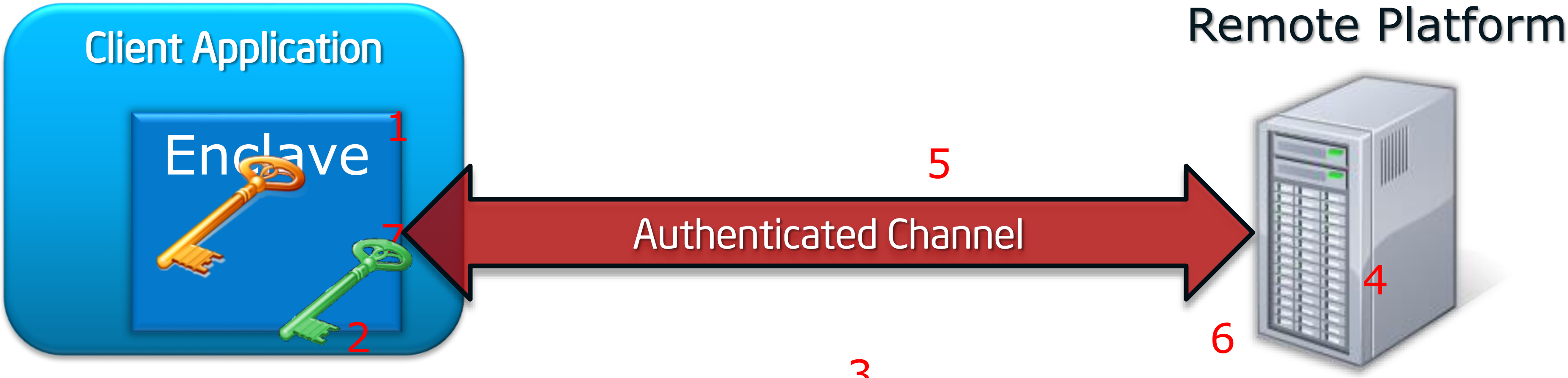

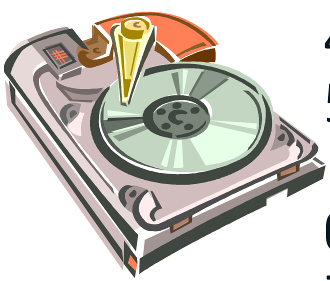

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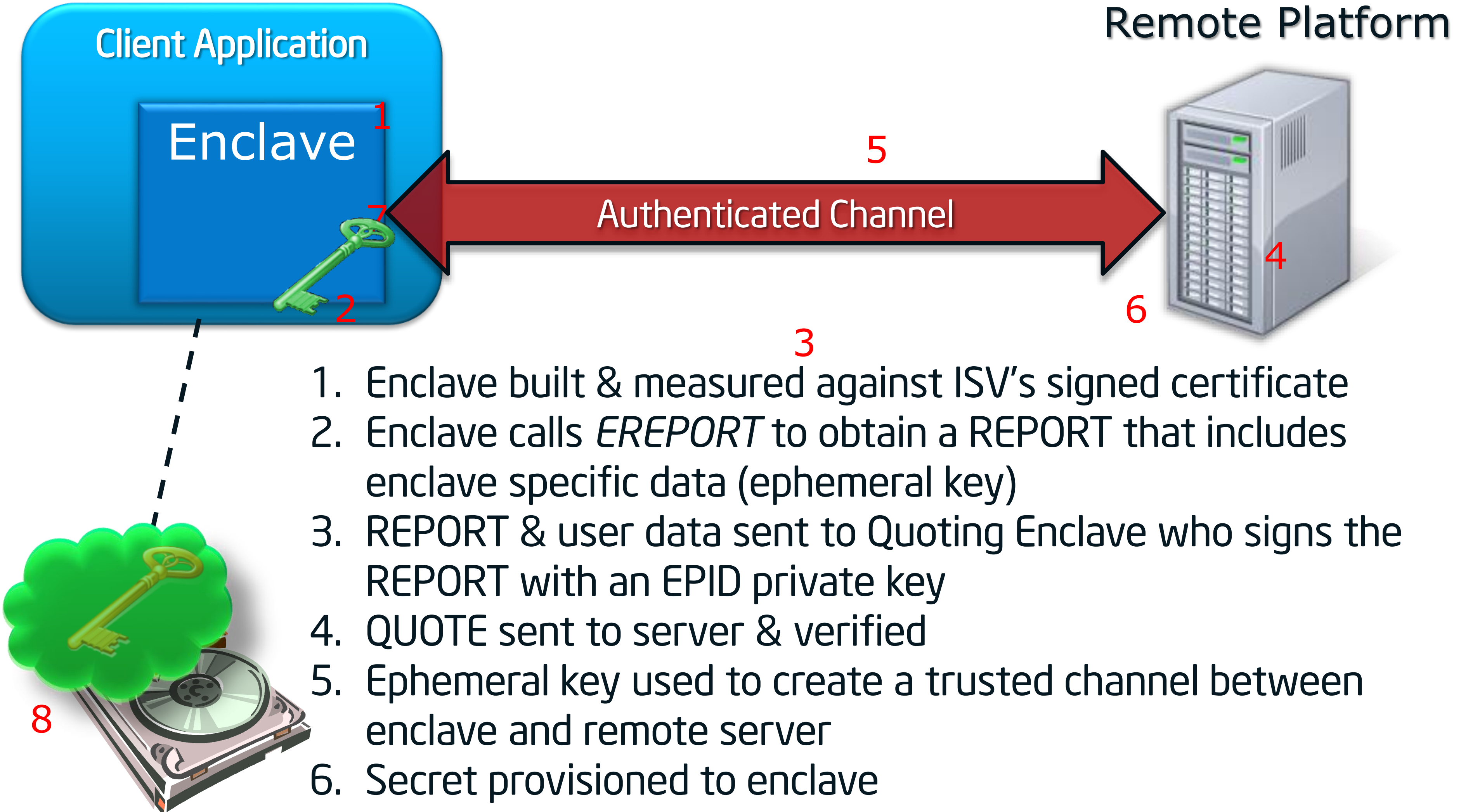

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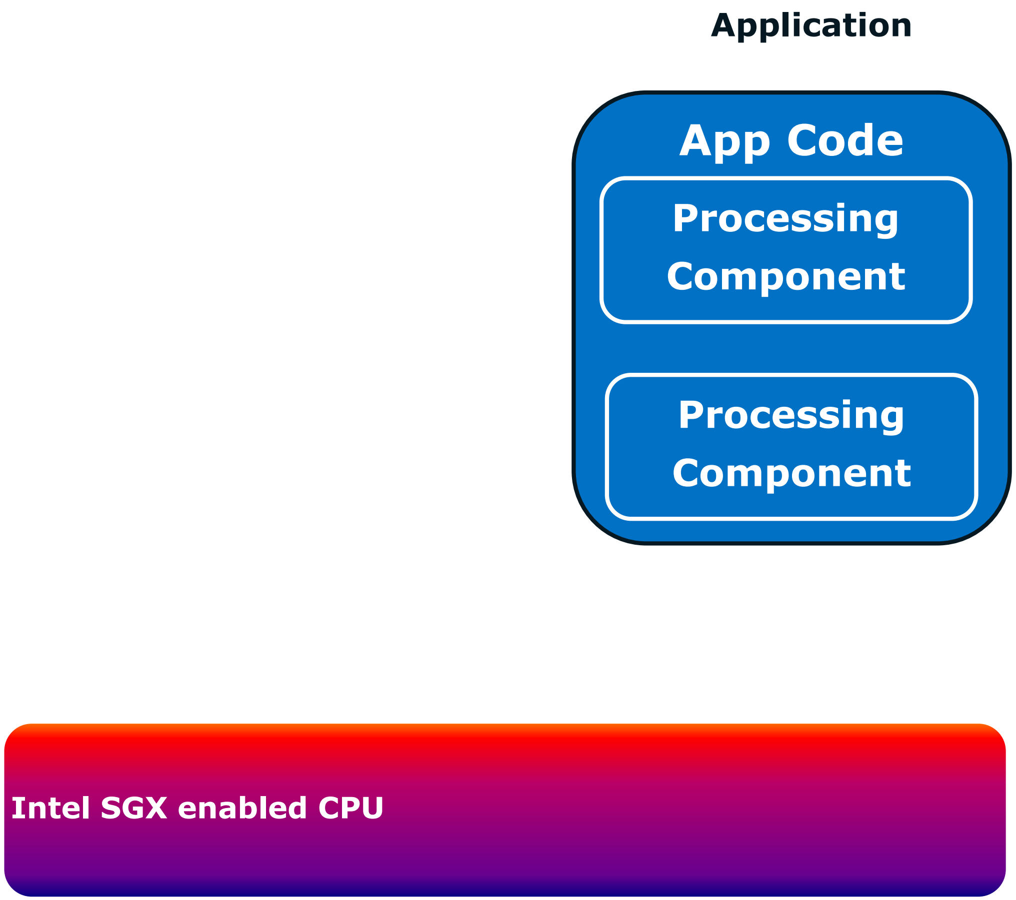
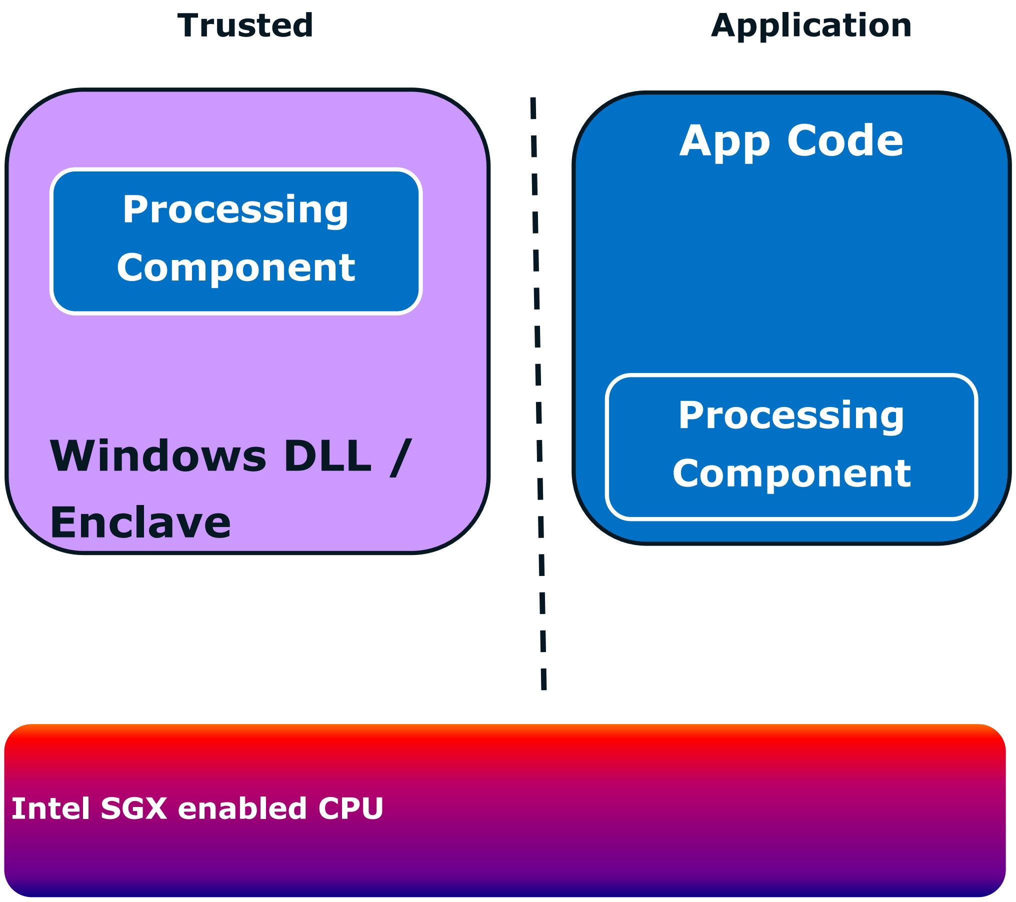
Intel® SGX Software Development

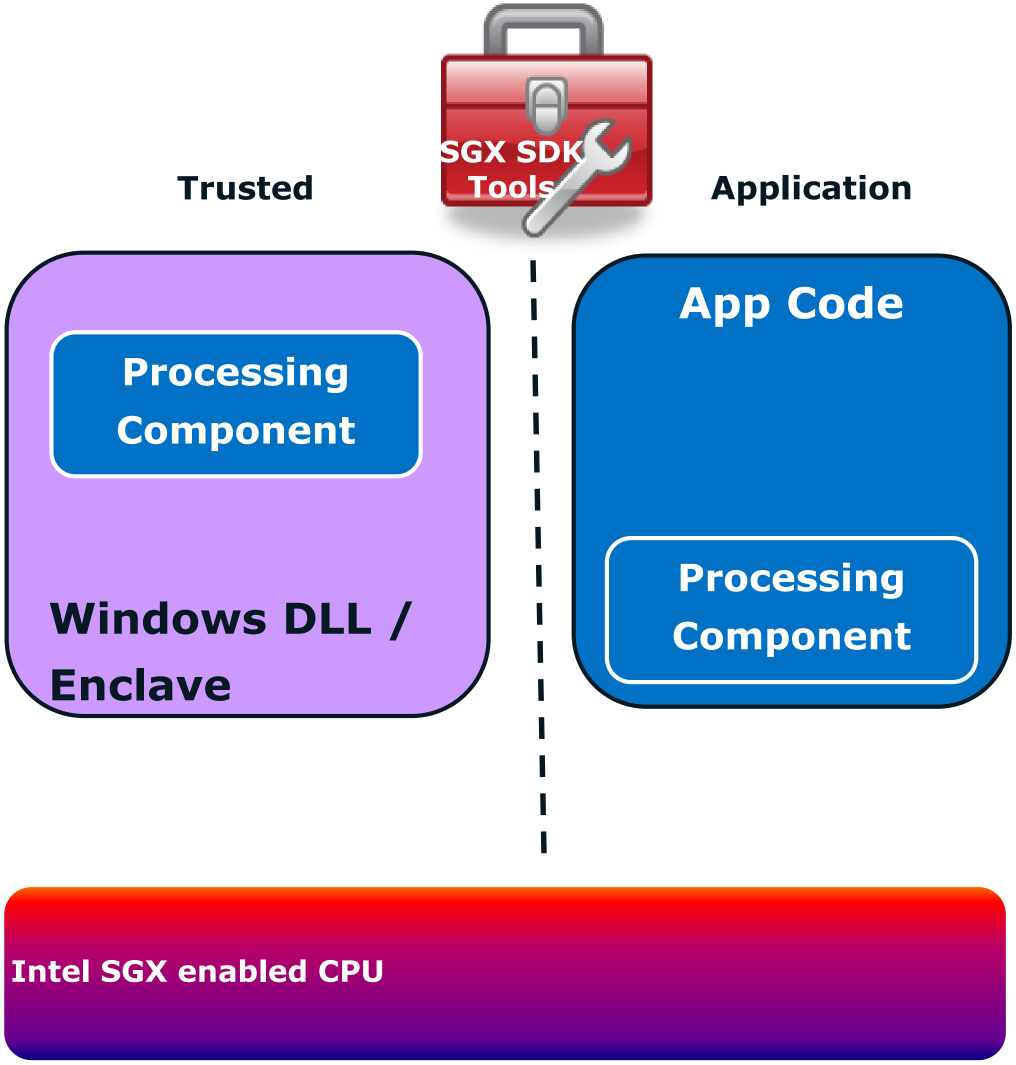


Intel® SGX Software Development



- Software Developer decides which components should execute within an enclave

Intel® SGX Software Development



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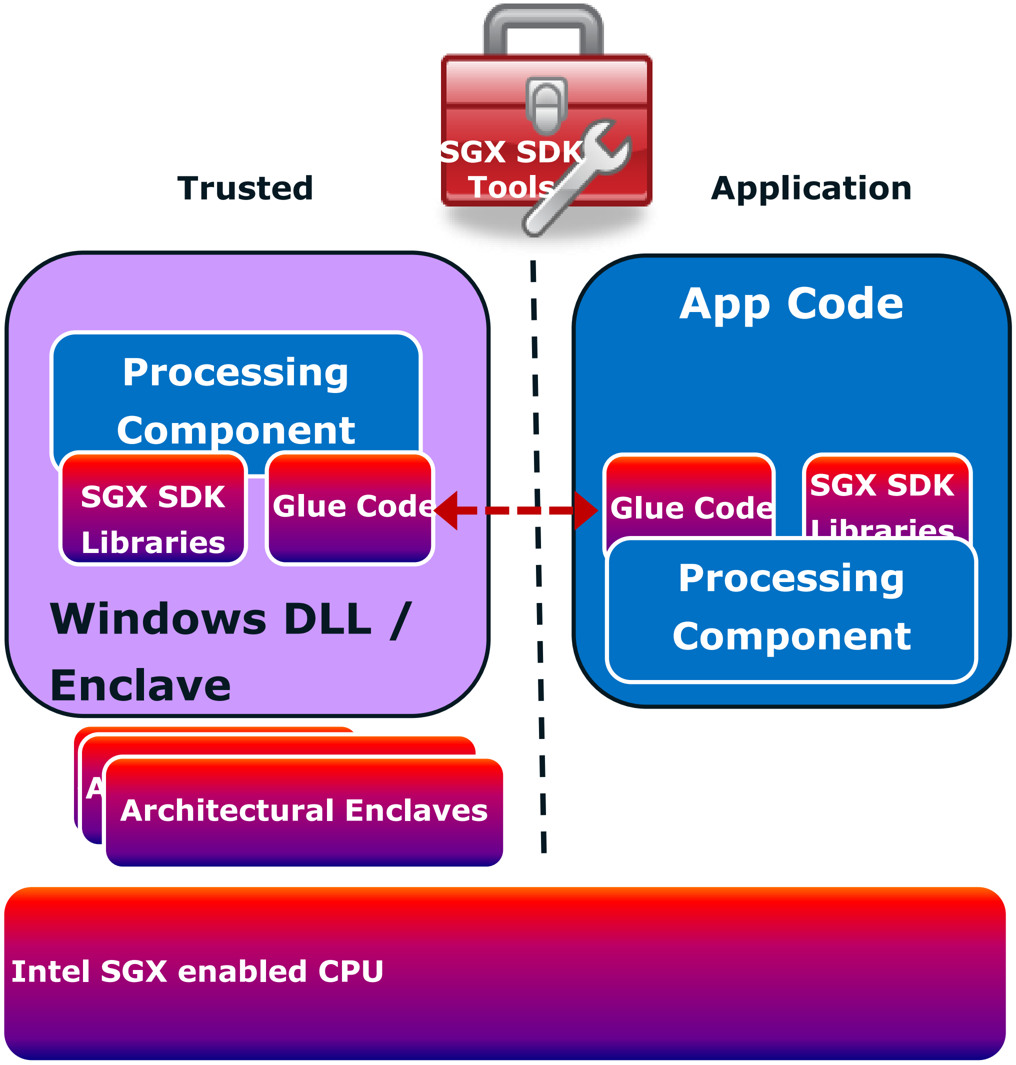
Intel® SGX Software Development



- Software Developer decides which components should execute within an enclave
- Development Environment allows the Developer to quickly develop enclave enabled binaries
- Including support for common software libraries, exporting interfaces, and support for provisioning

SGX Technical Summary

- Provides any application the ability to keep a secret
  - Provide capability using new processor instructions
  - Application can support multiple enclaves
- Provides integrity and confidentiality
  - Resists hardware attacks
  - Prevent software access, including privileged software and SMM
- Applications run within OS environment
  - Low learning curve for application developers
  - Open to all developers
- Resources managed by system software

Links

Joint research poster session:
http://sigops.org/sosp/sosp13/

Public Cloud Paper using SGX2:

https://www.usenix.org/sites/default/files/osdi14_full_proceedings.pdf

Programming Reference for SGX1 & SGX2:
http://www.intel.com/software/isa

HASP Workshop:
https://sites.google.com/site/haspworkshop2013/workshop-program

Thank You

Backup

SGX Paging Introduction

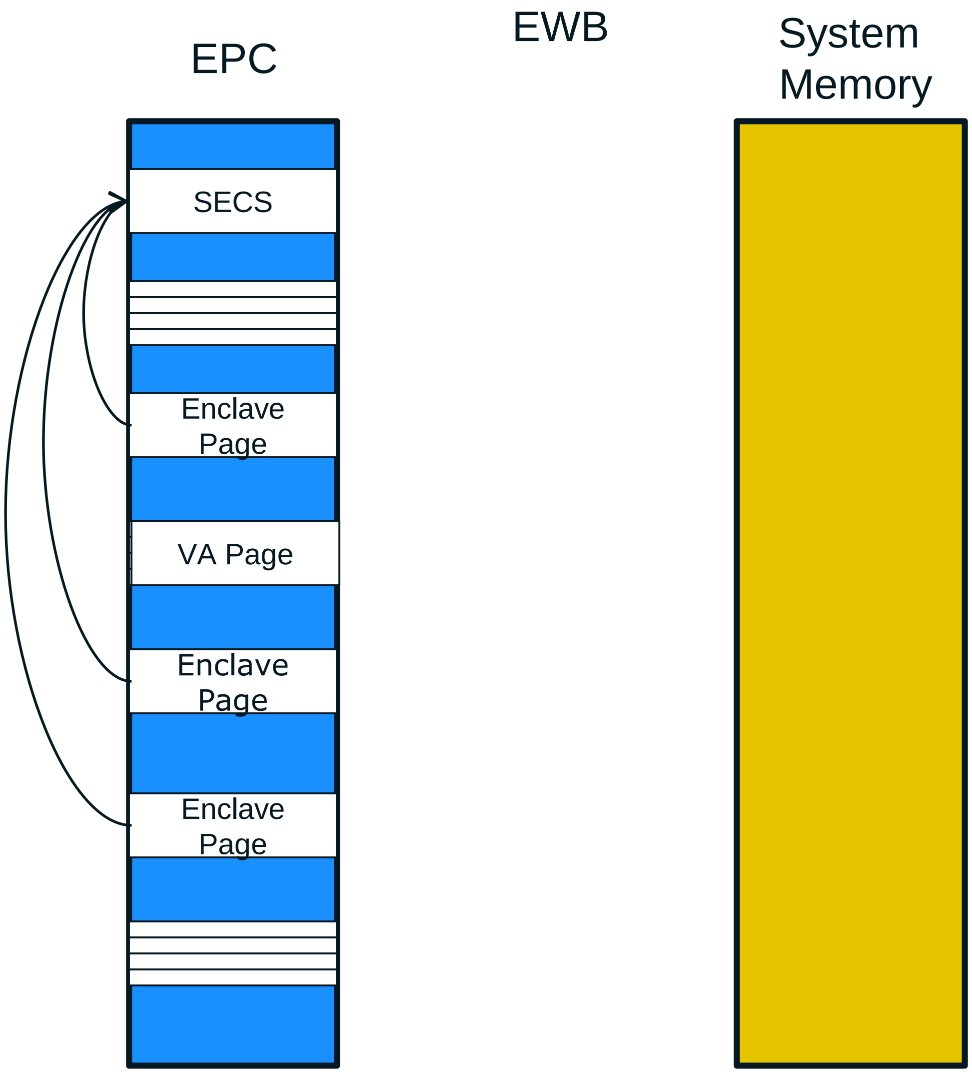
Requirement:

- Remove an EPC page and place into unprotected memory. Later restore it.
- Page must maintain same security properties (confidentiality, anti-replay, and integrity) when restored

Instructions:

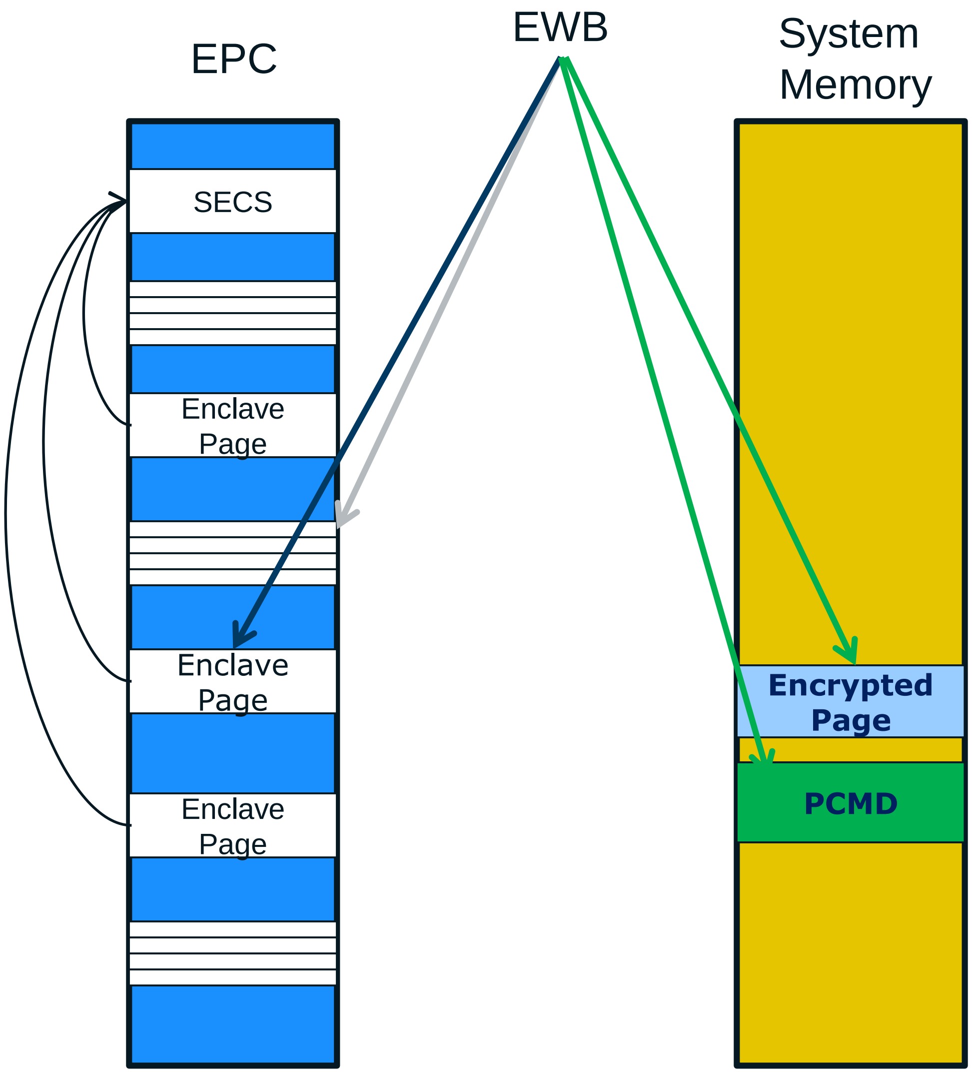
- EWB: Evict EPC page to main memory with cryptographic protections
- ELDB/ELDU: Load page from main memory to EPC with cryptographic protections
- EPA: Allocate an EPC page for holding versions
- EBLOCK: Declare an EPC page ready for eviction
- ETRACK: Ensure address translations have been cleared

Page-out Example



BUILD

Page-out Example

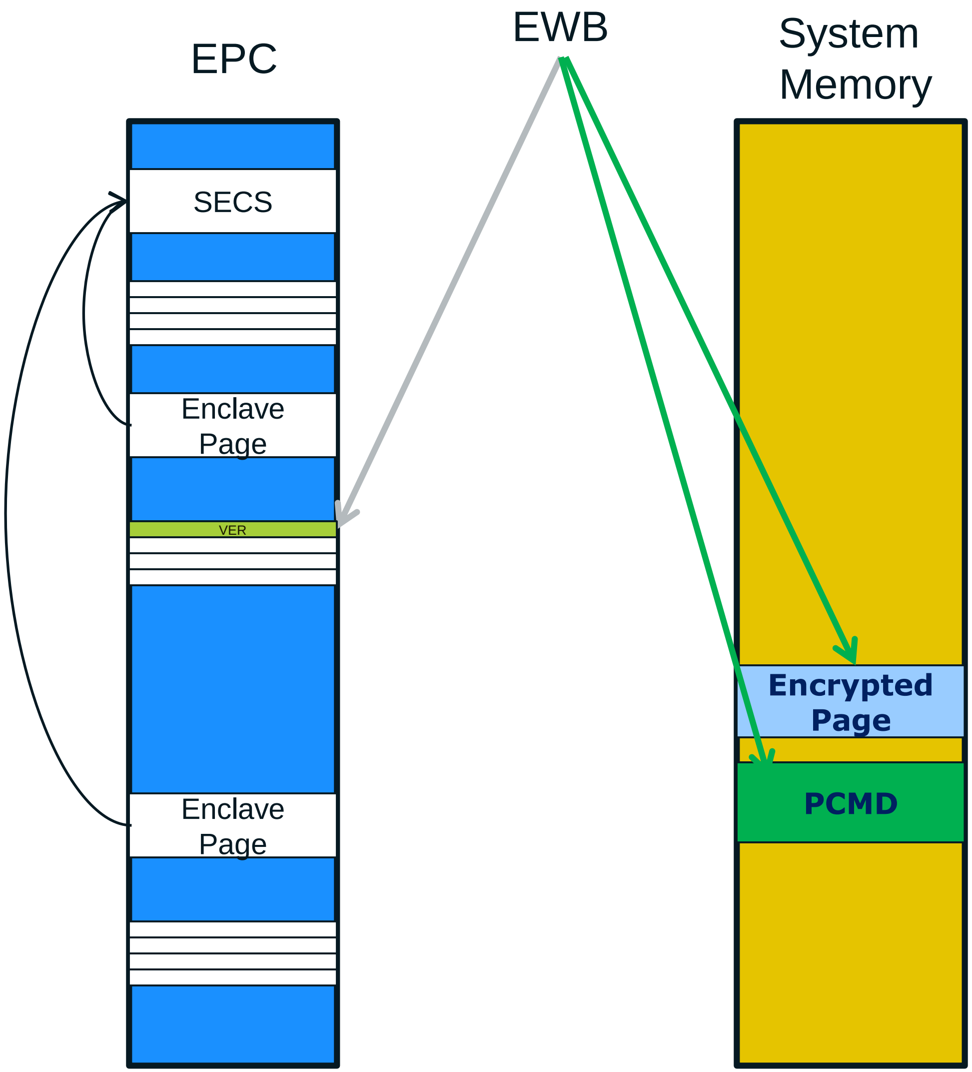


EWB Parameters:

- Pointer to EPC page that needs to be paged out
- Pointer to empty version slot
- Pointers outside EPC location

BUILD

Page-out Example



EWB Parameters:

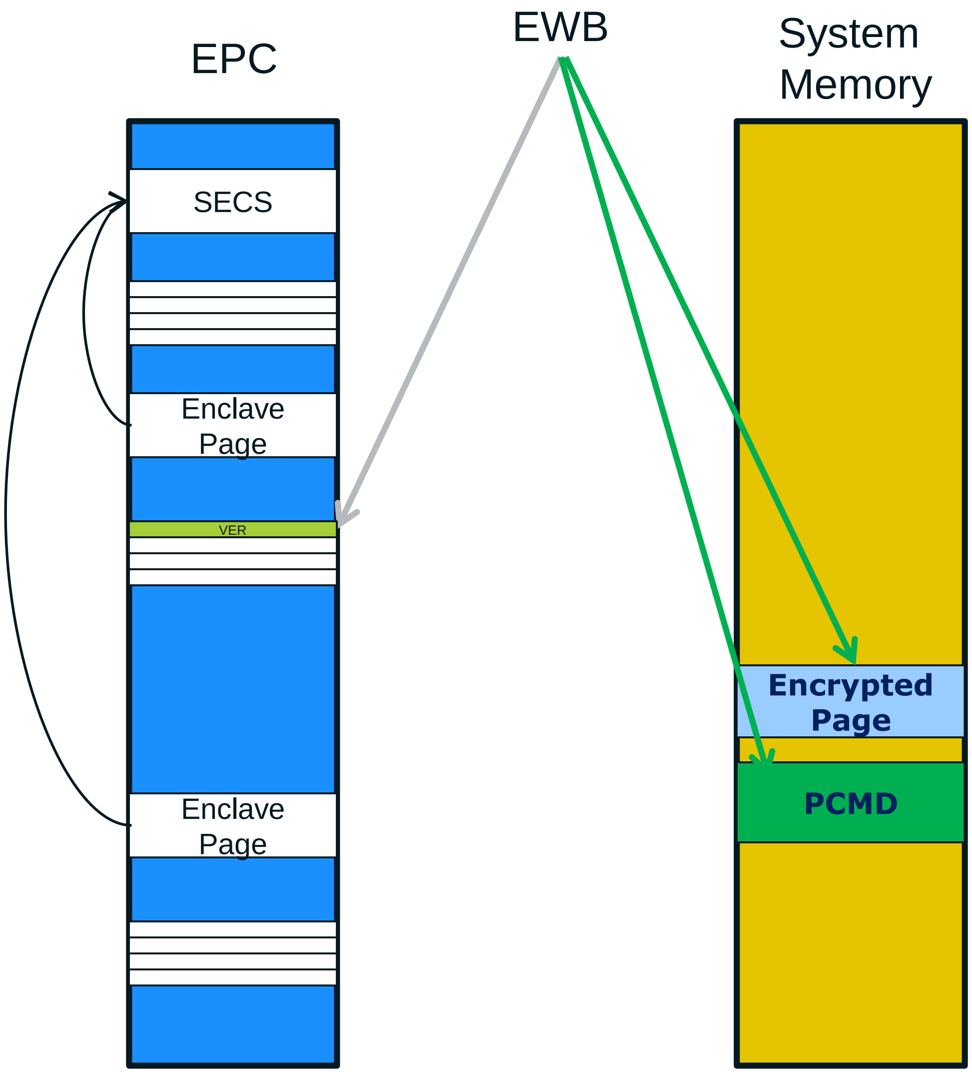
- Pointer to EPC page that needs to be paged out
- Pointer to empty version slot
- Pointers outside EPC location

EWB Operation

- Remove page from the EPC
- Populate version slot
- Write encrypted version to outside
- Write meta-data, PCMD

BUILD

Page-out Example



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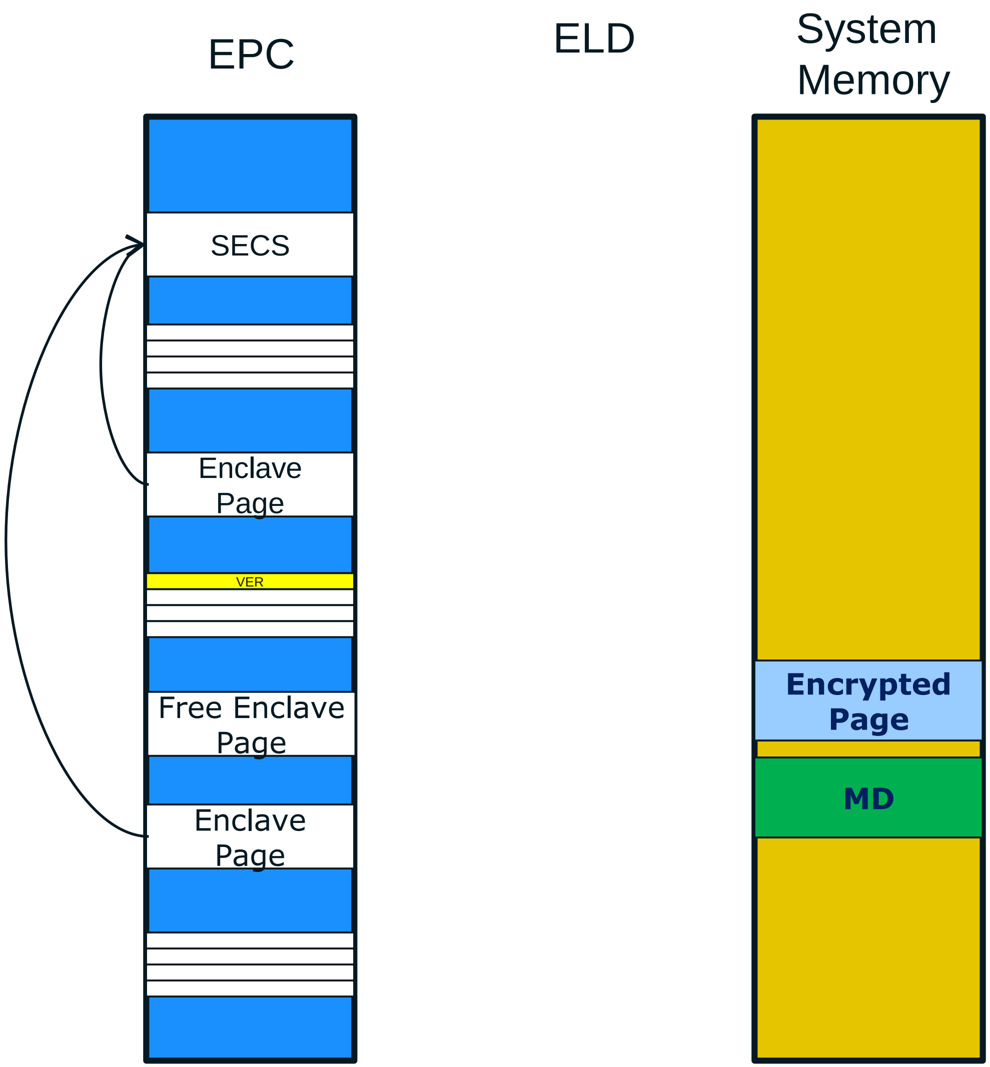
All pages, including SECS and Version Array can be paged out

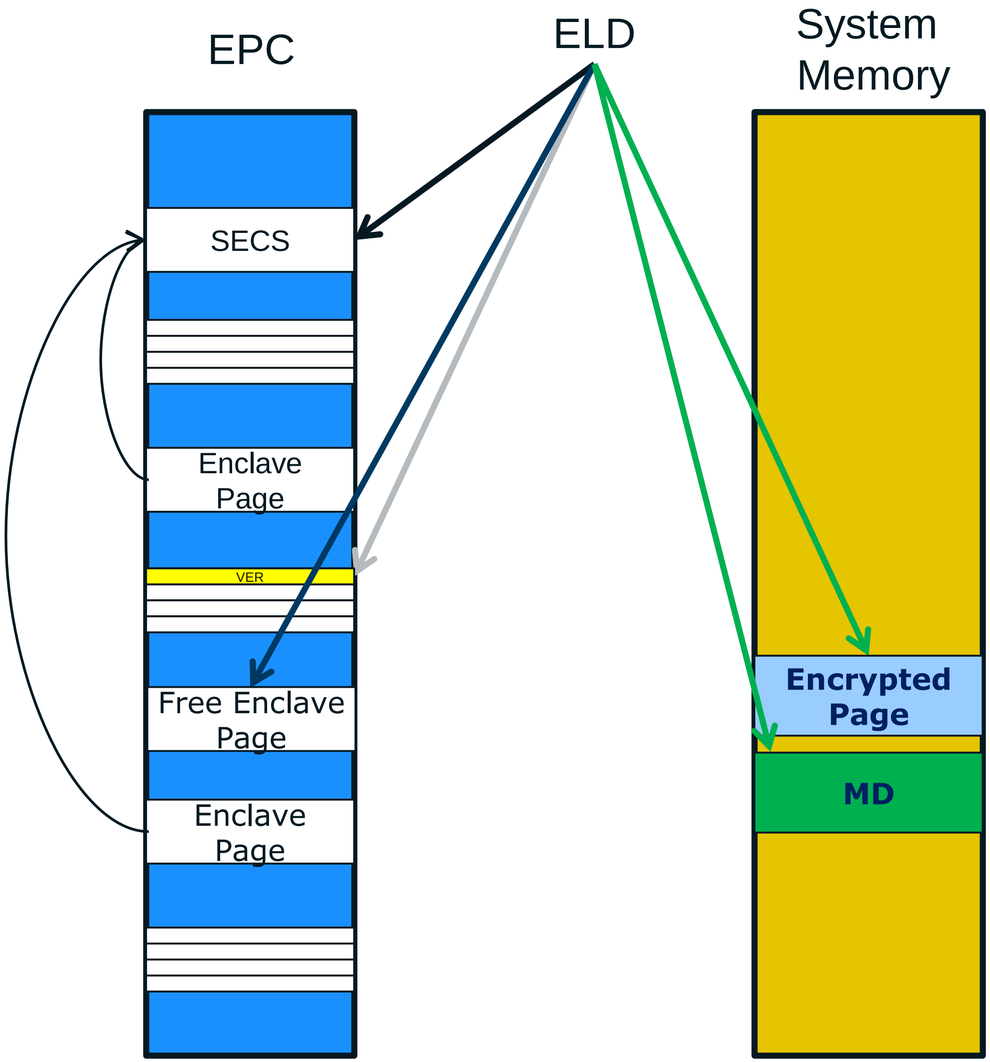
BUILD

Page-in Example



Page-in Example

BUILD

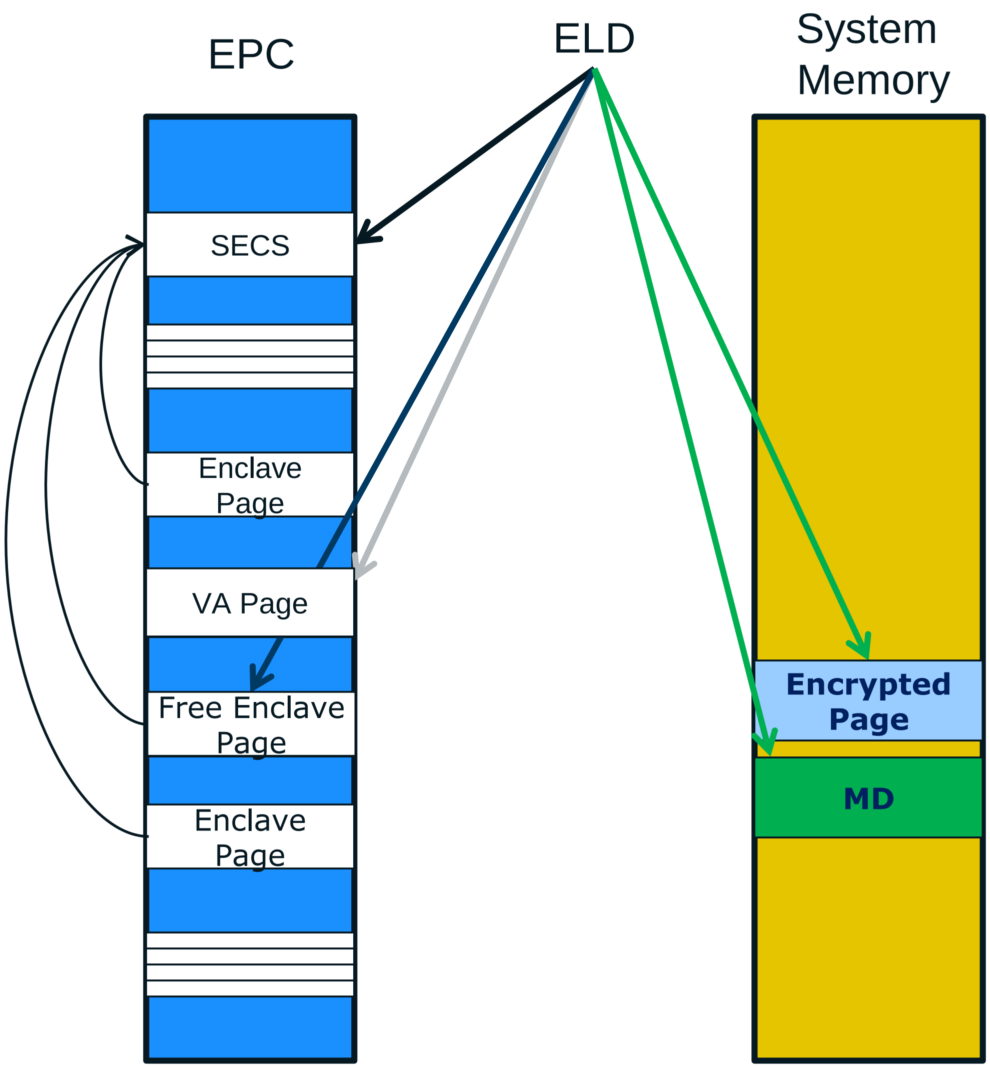


ELD Parameters:

- Encrypted page
- Free EPC page
- SECS (for an enclave page)
- Populated version slot

Page-in Example

BUILD



ELD Parameters:

- Encrypted page
- Free EPC page
- SECS (for an enclave page)
- Populated version slot

ELD Operation

- Verify and decrypt the page using version
- Populate the EPC slot
- Make back-pointer connection (if applicable)
- Free-up version slot