D-Shield: Enabling Processor-side Encryption and Integrity Verification for Secure NVMe Drives

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Hardware Security Threats to System

- Data is the main target of exploitation
- Multiple attack vectors are possible for off-chip data

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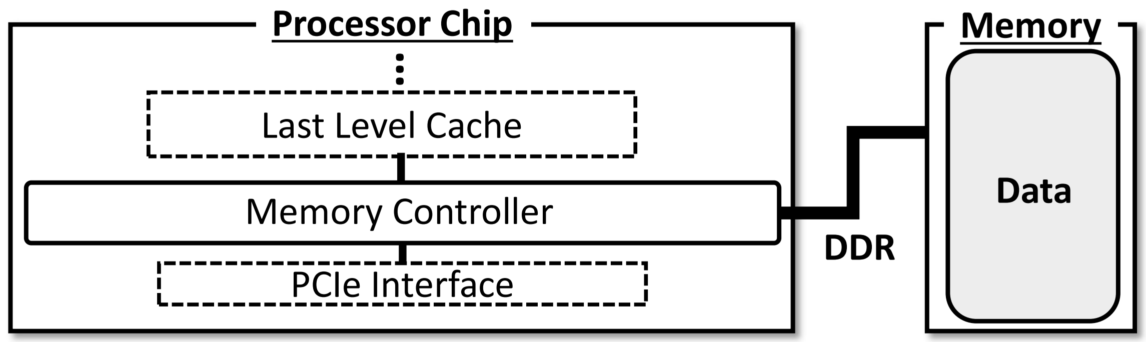

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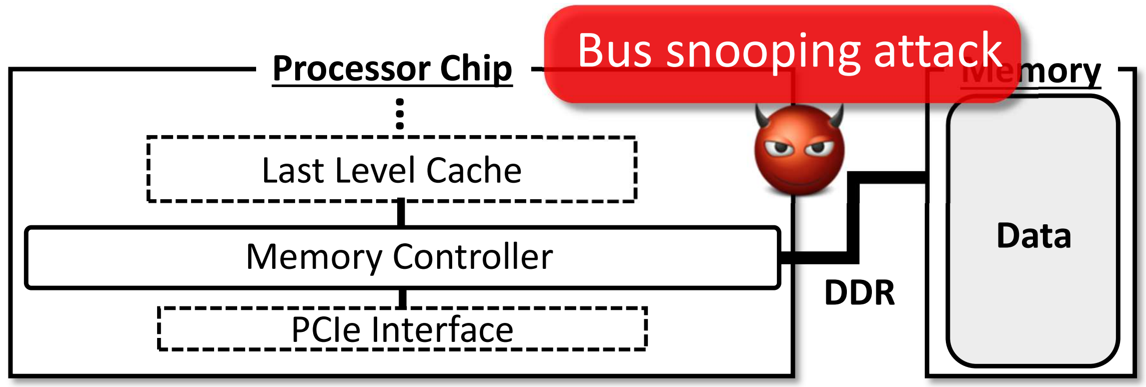

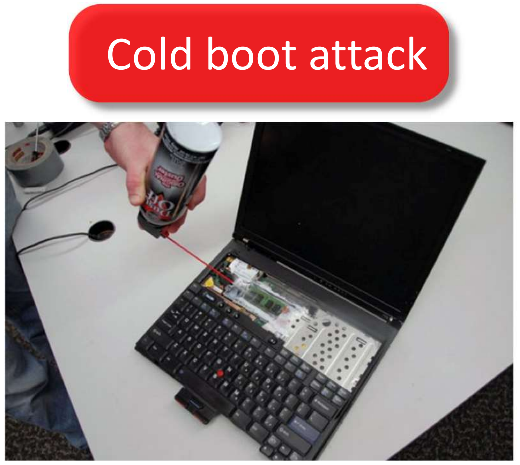

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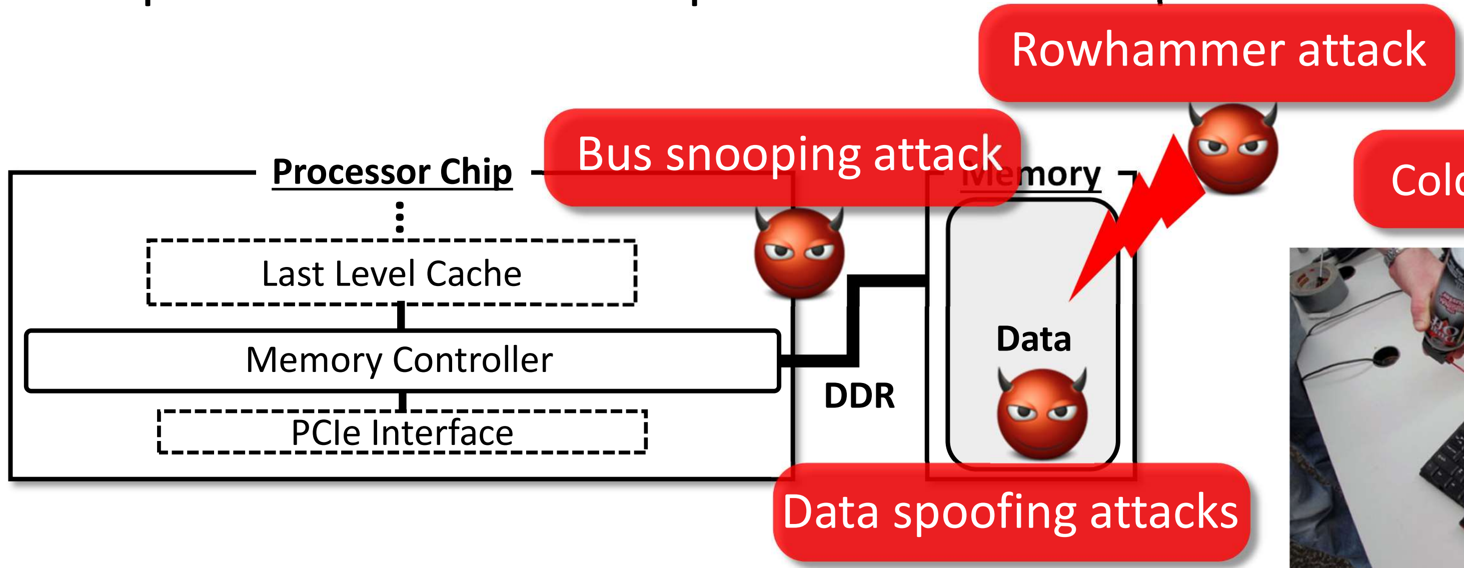

Cold boot attack

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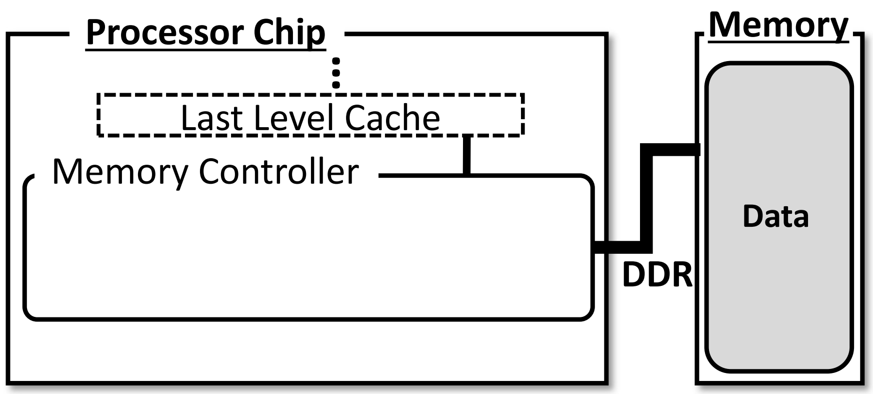
Secure Memory Architecture



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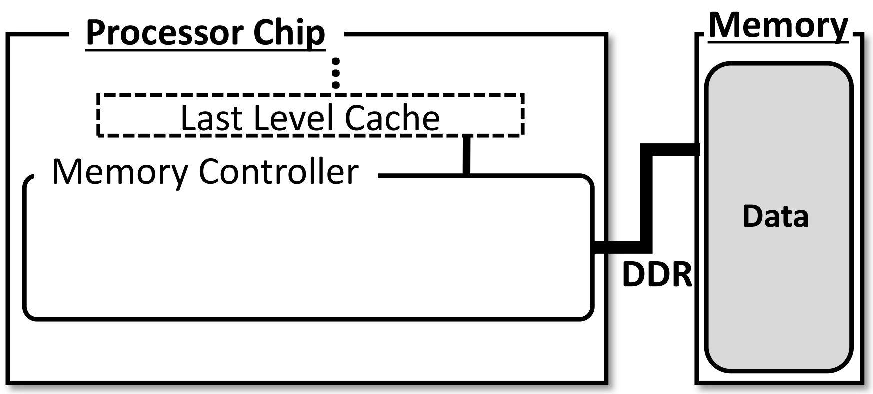

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Protect confidentiality and integrity of **off-chip data**

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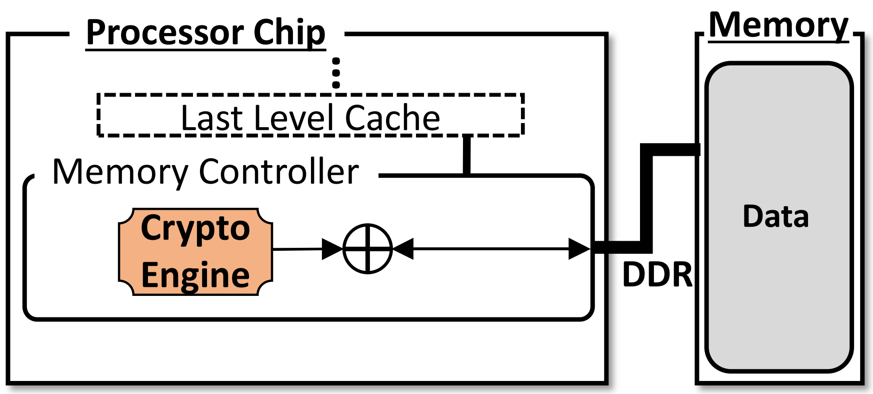

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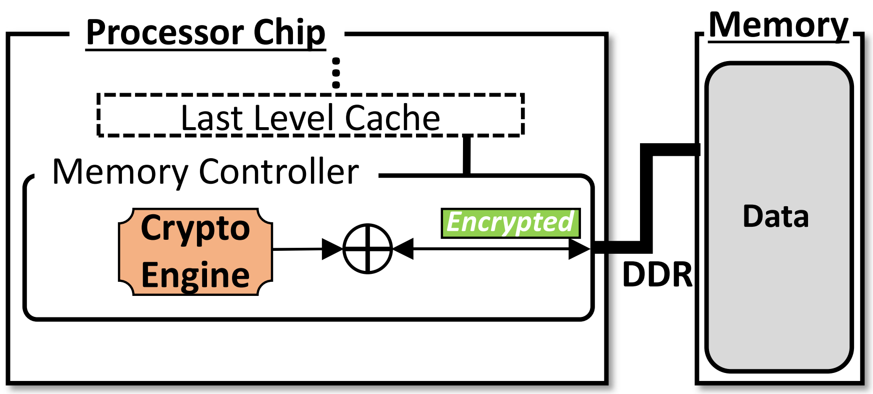

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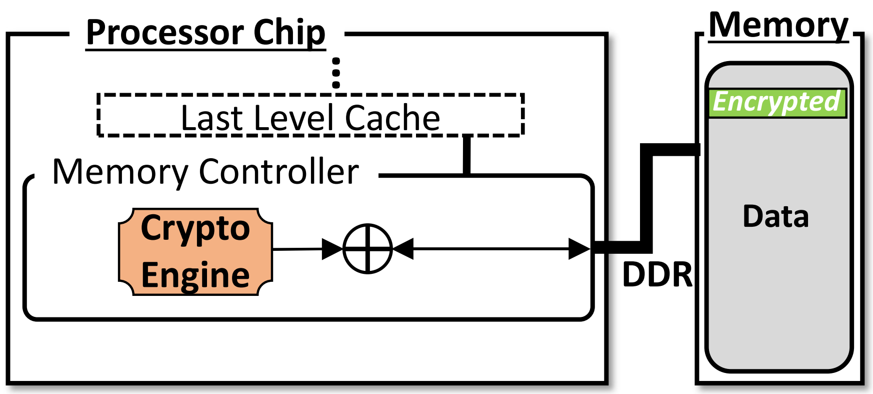

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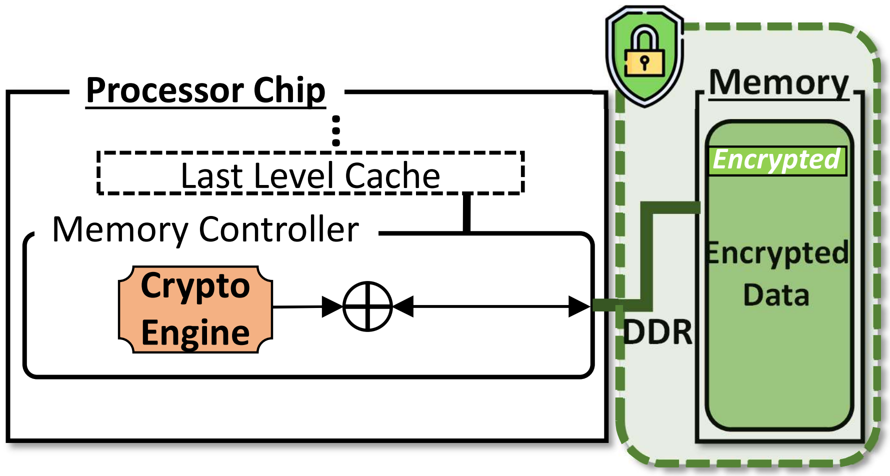

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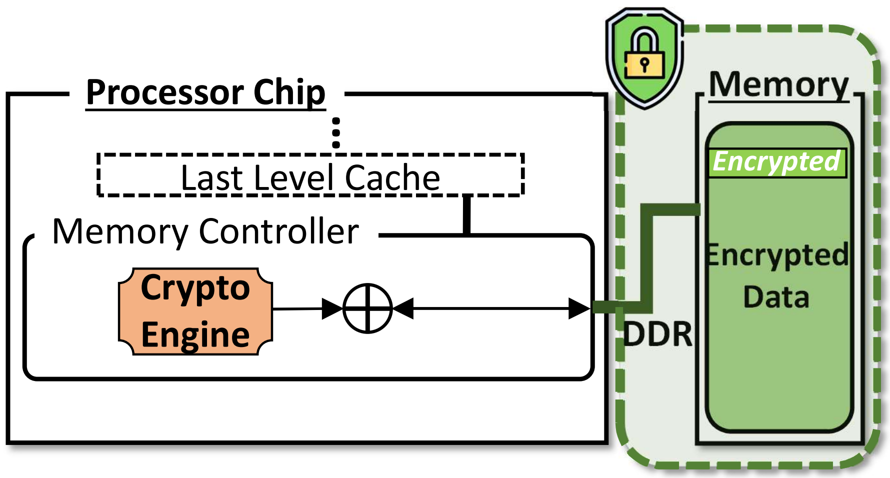

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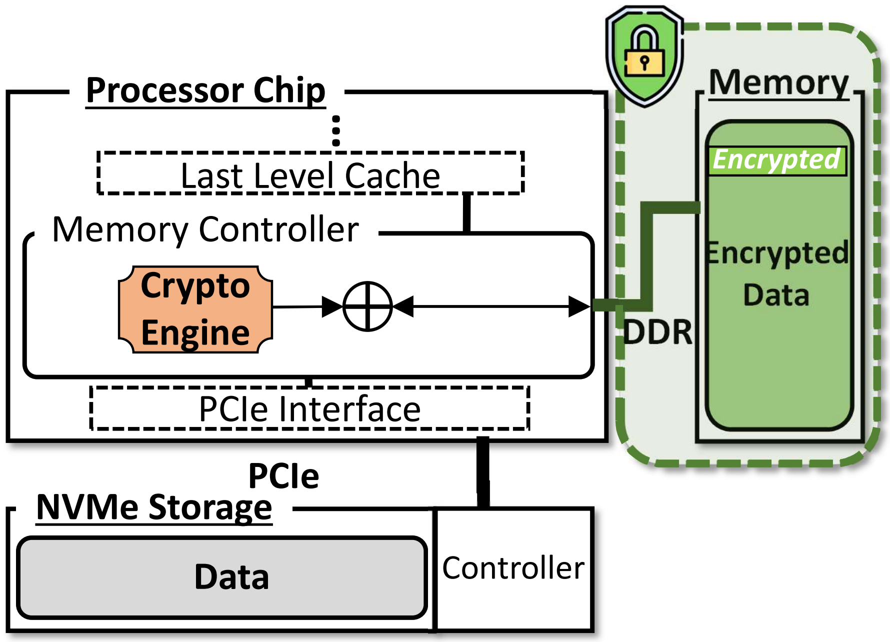

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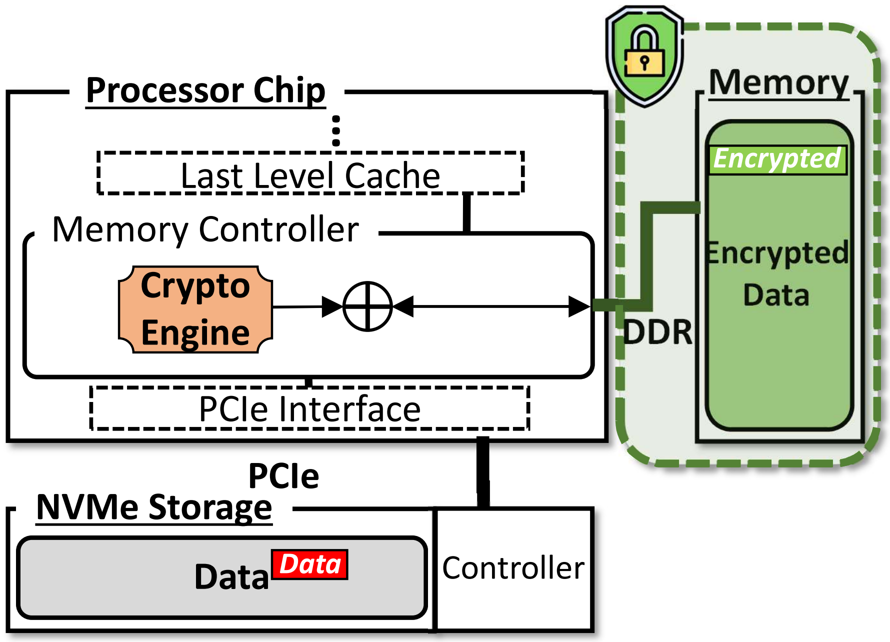

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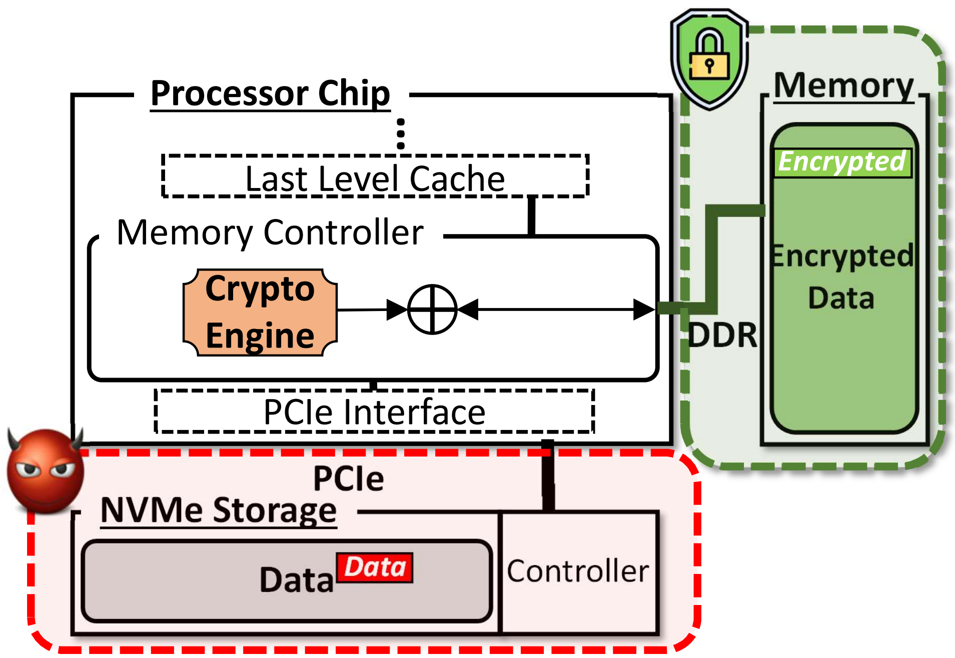

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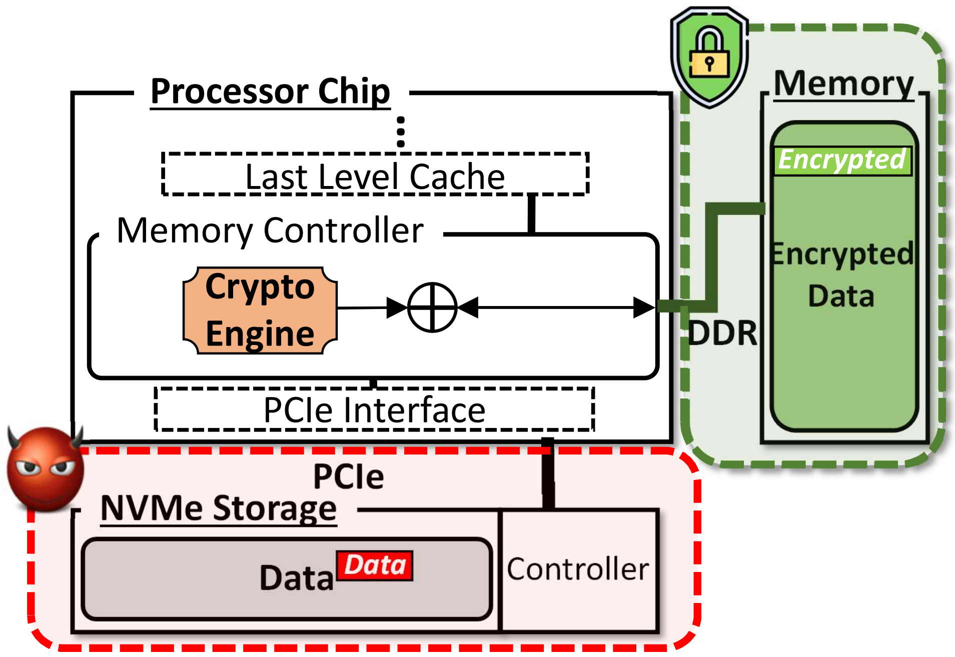

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Mainly focus on **memory security**

Storage security provided through **software** or **disk** itself
No processor-side support for fast storage security

UCF

Need for Architectural Support for Storage Security

- Pitfalls of existing solutions:
    - **Self-encryption disks:** encrypts data in the storage itself
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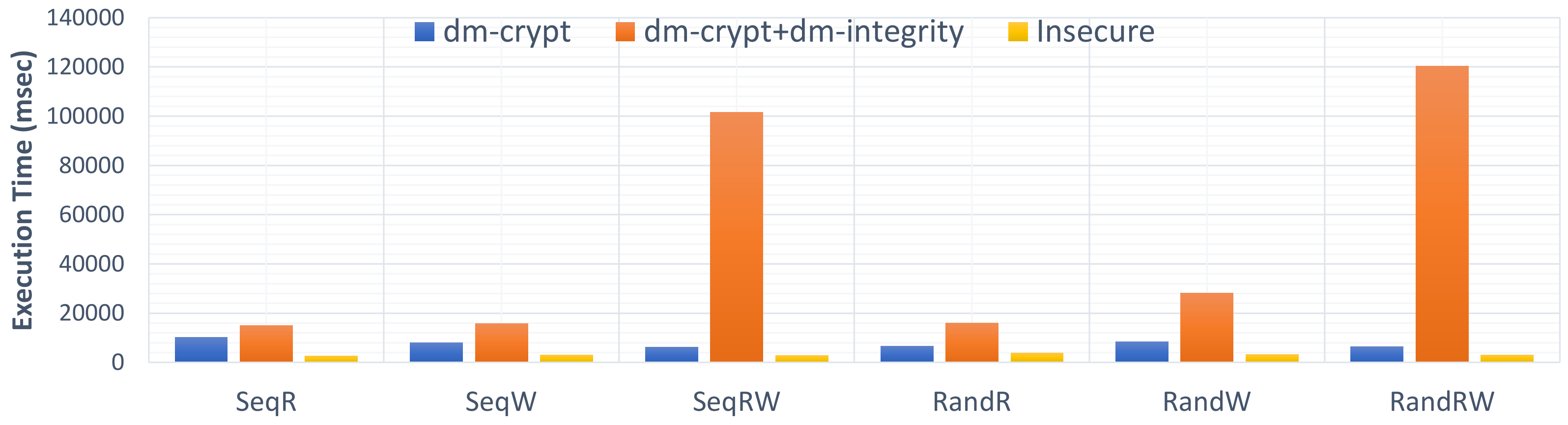

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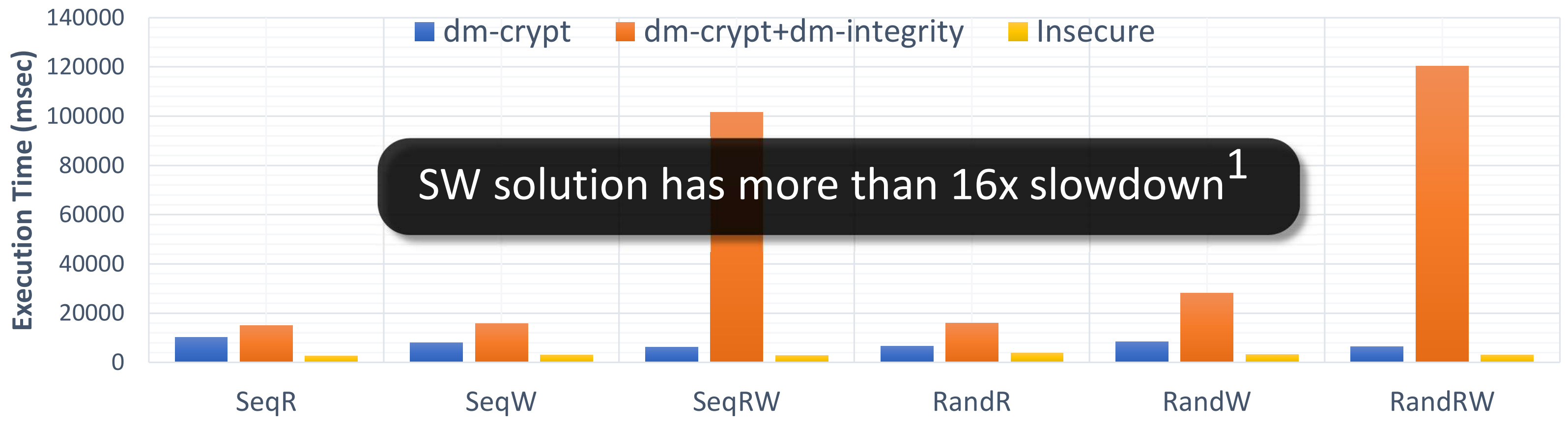

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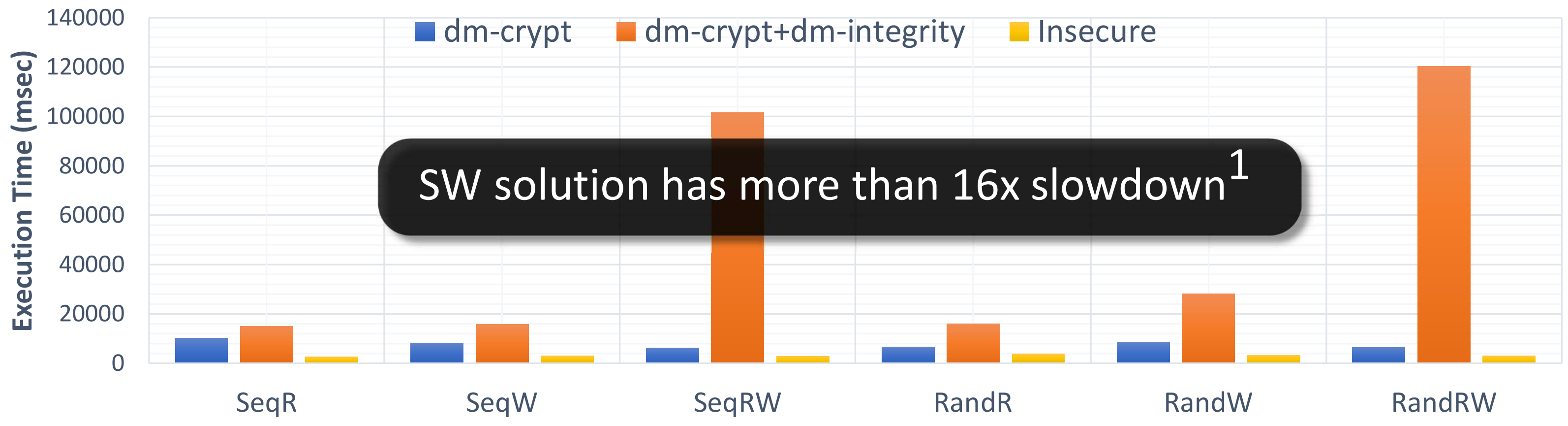

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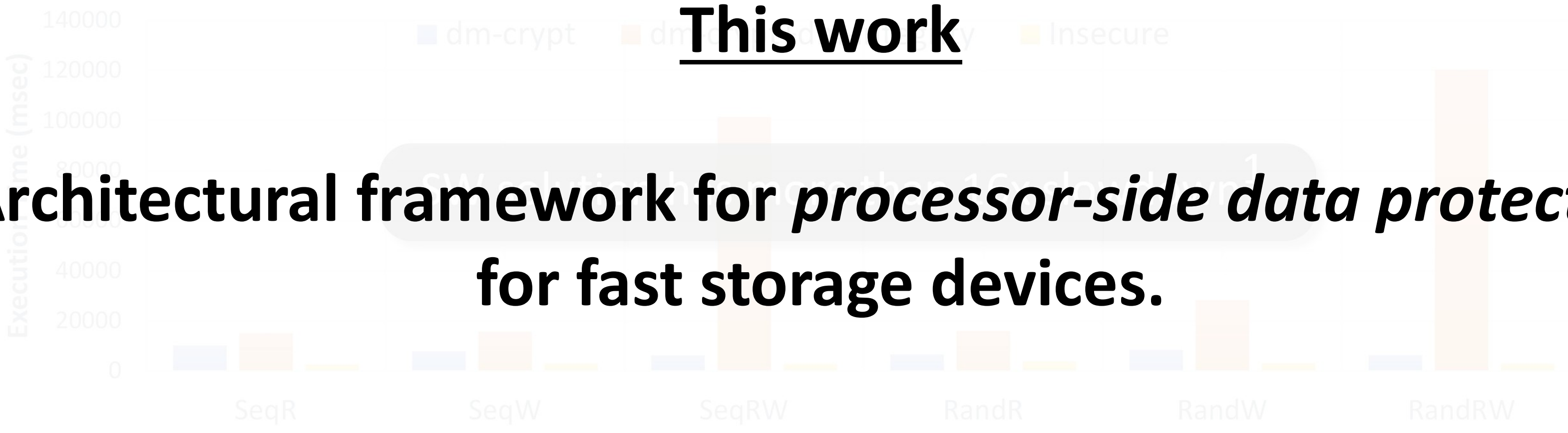

SW solution has more than 16x slowdown[1]

<u>This work</u>

Architectural framework for *processor-side data protection* for fast storage devices.

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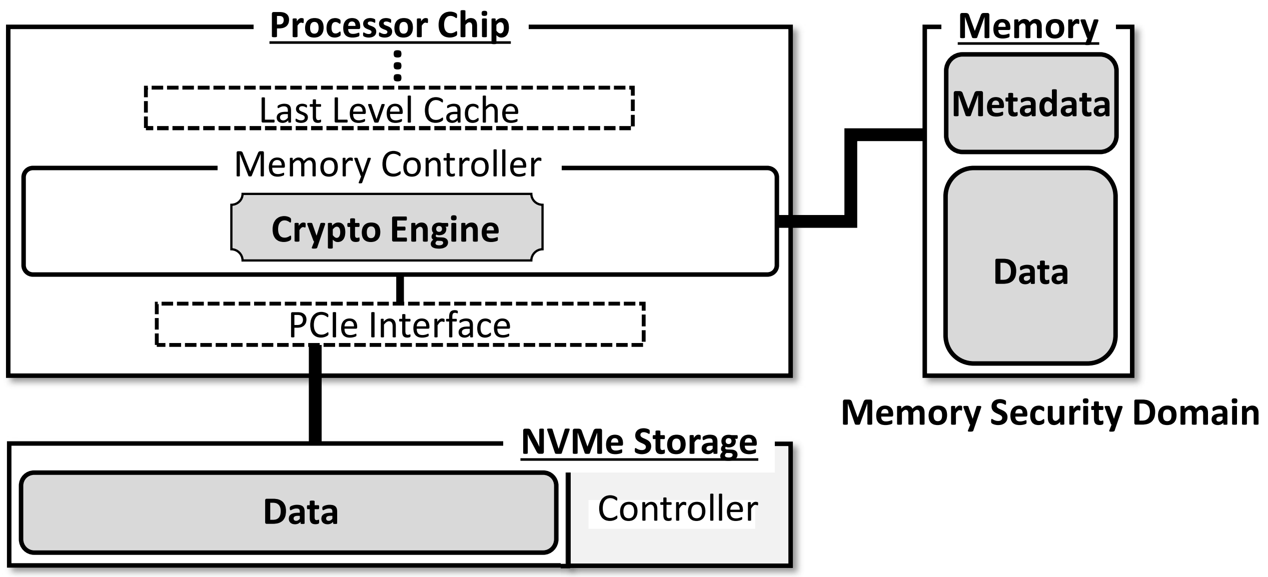

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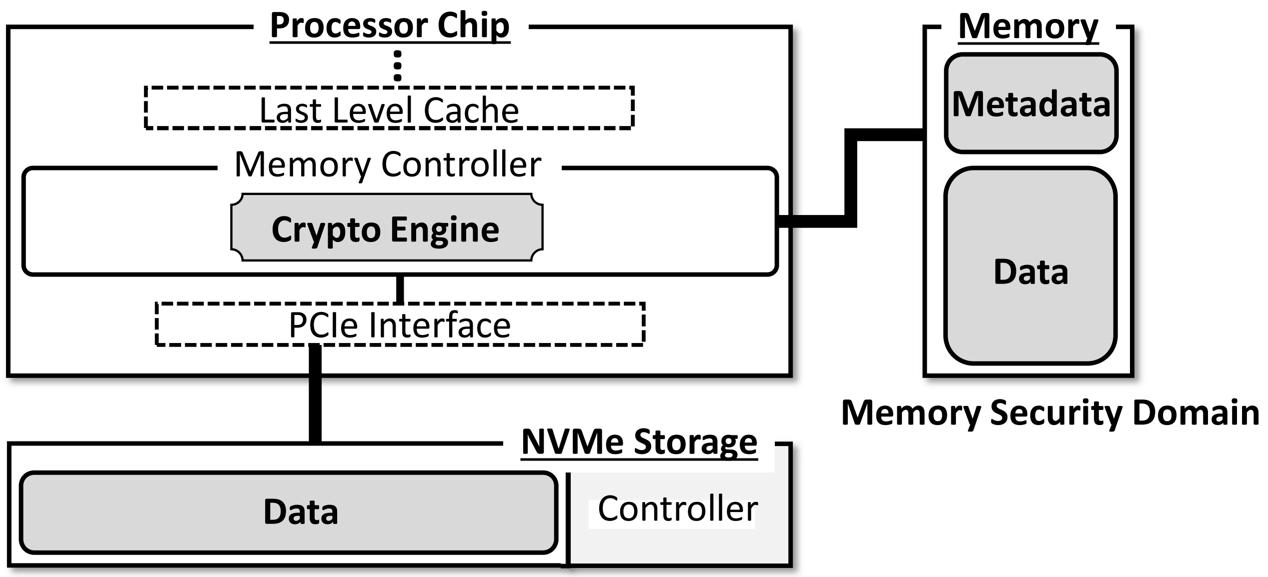

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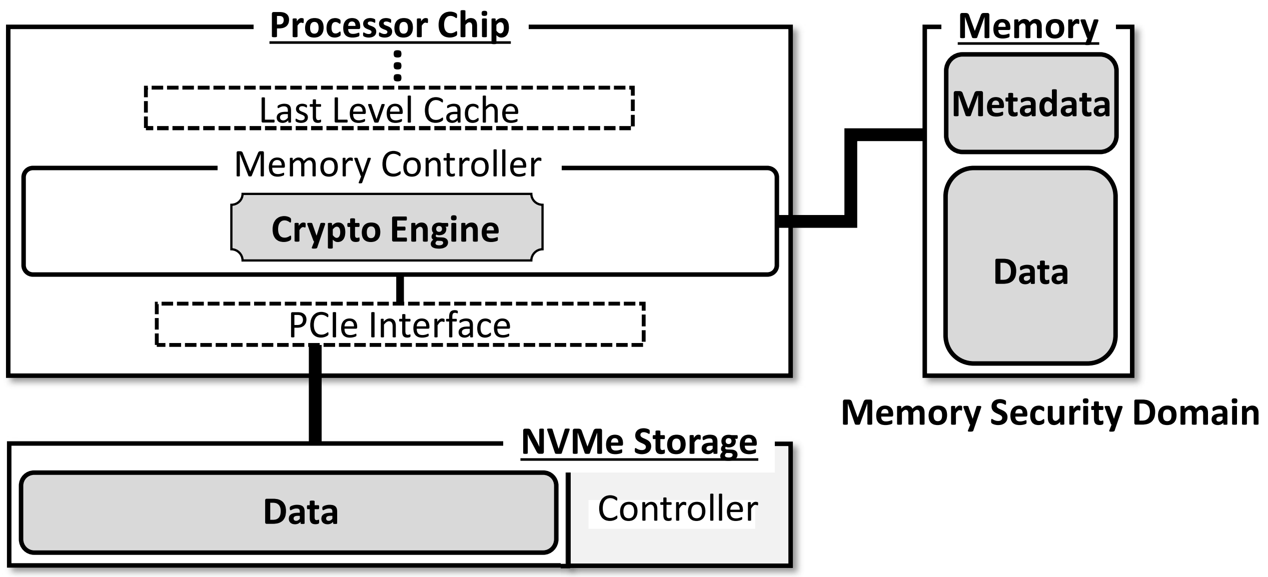

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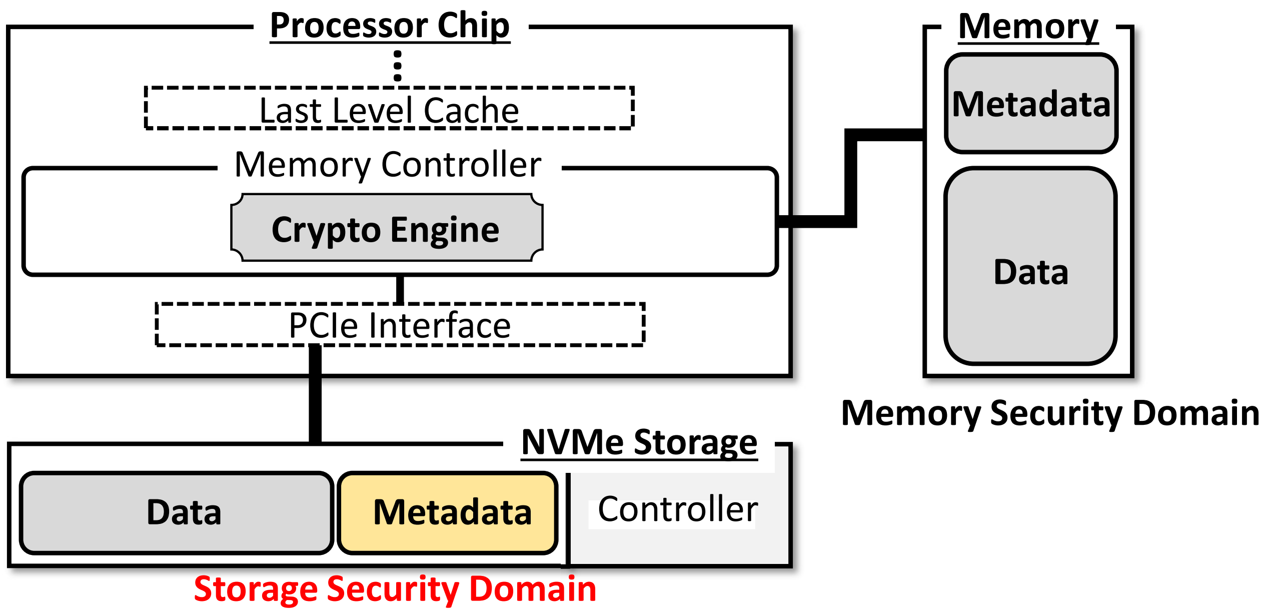

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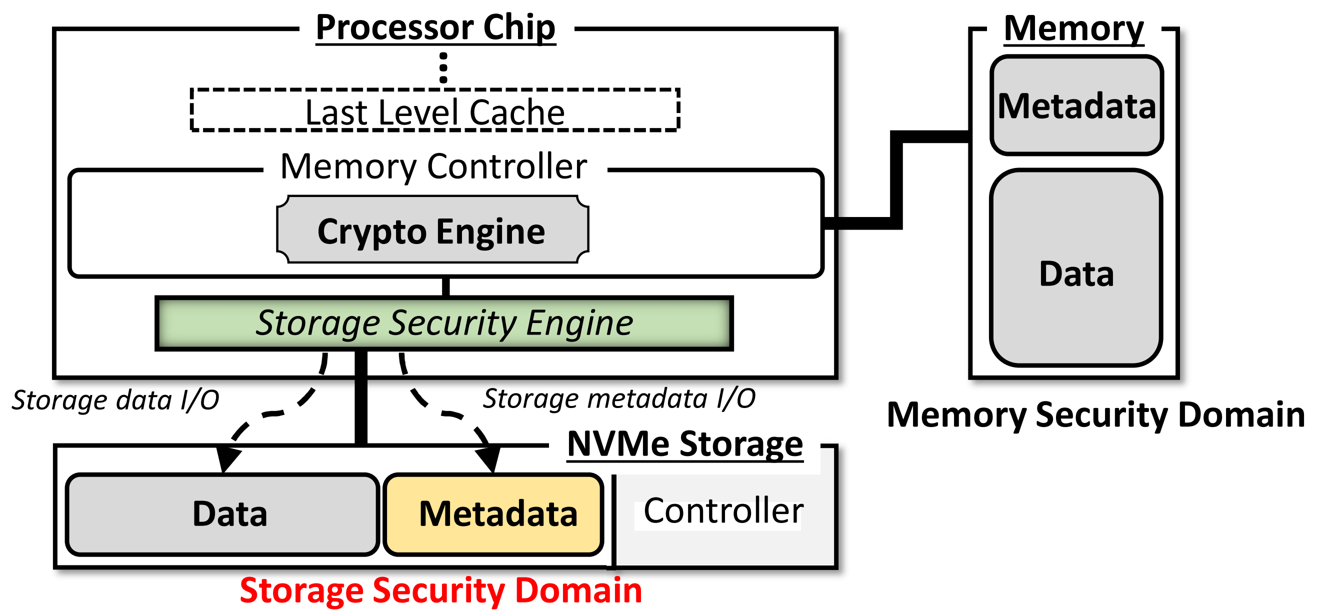

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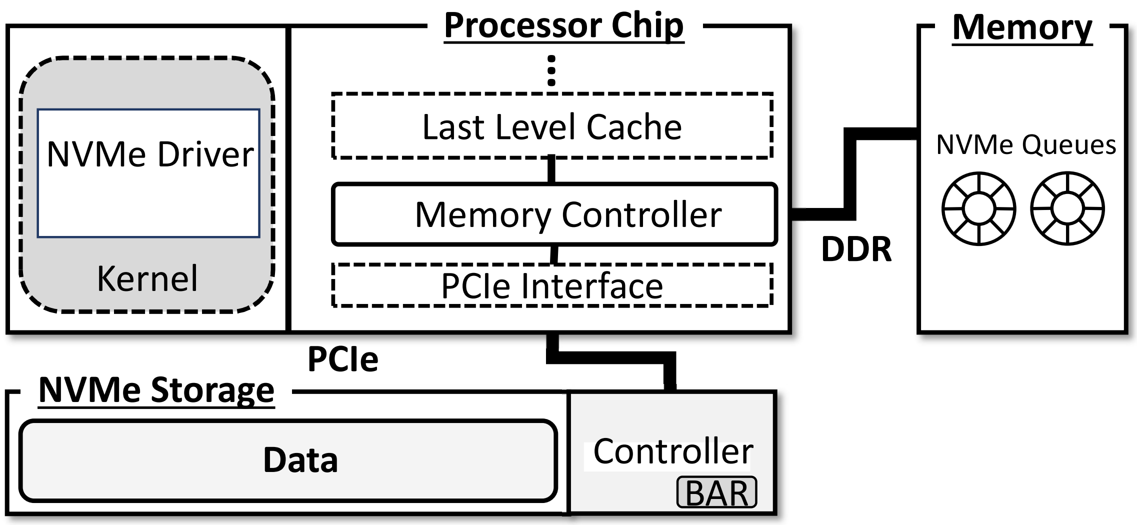

C1: Intricate SW/HW interactions → excessive software intervention can be expensive

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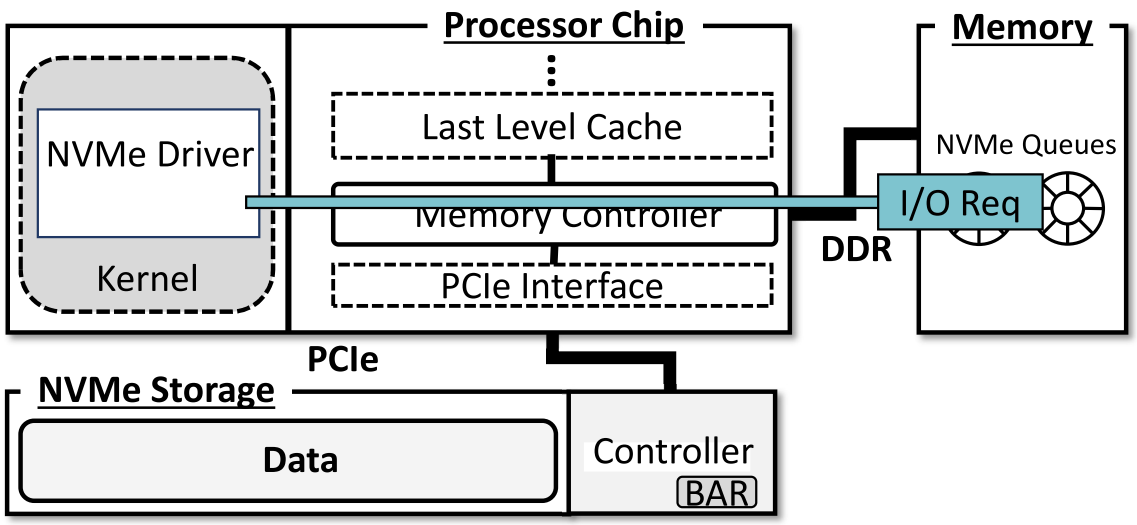

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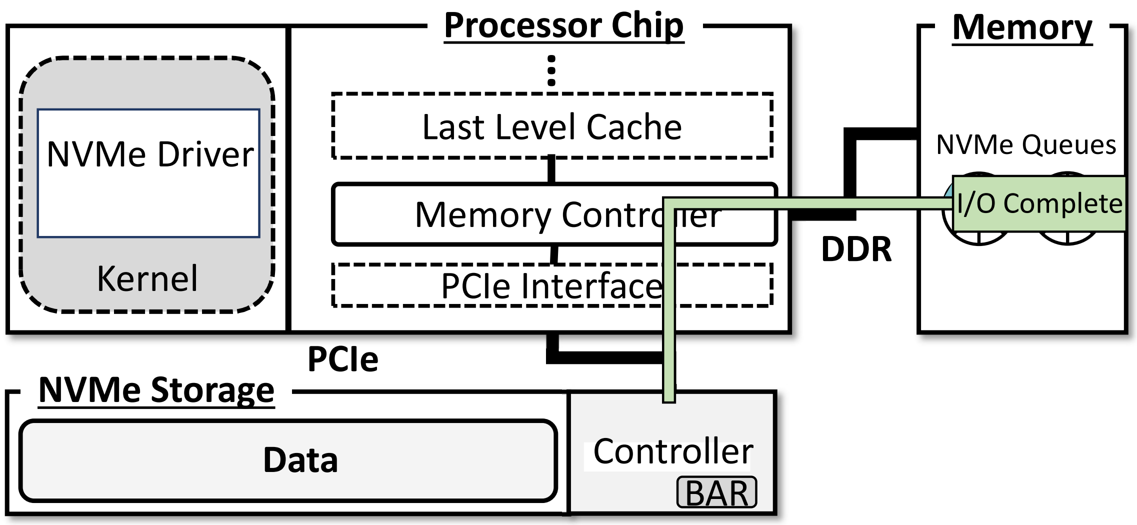

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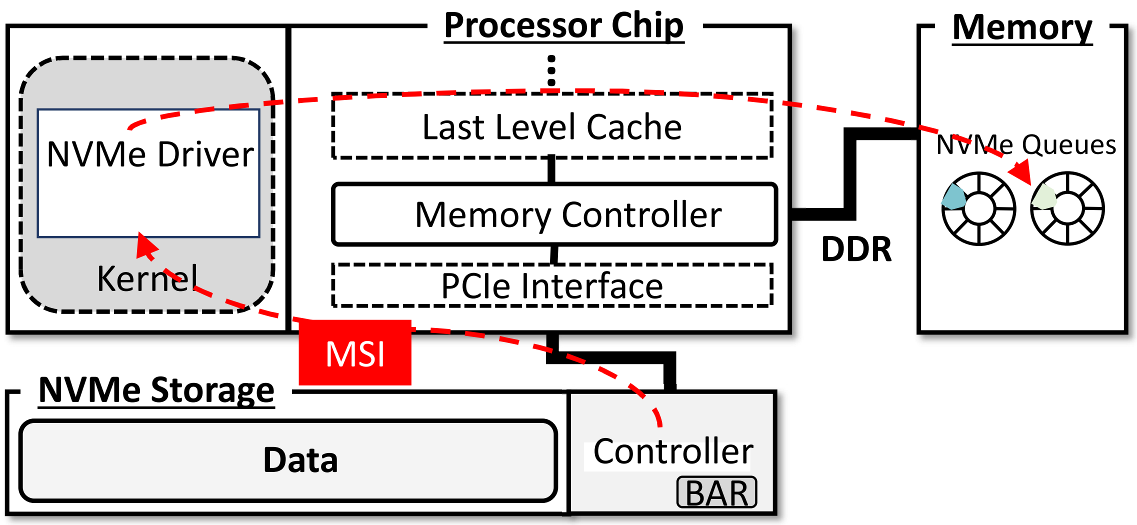

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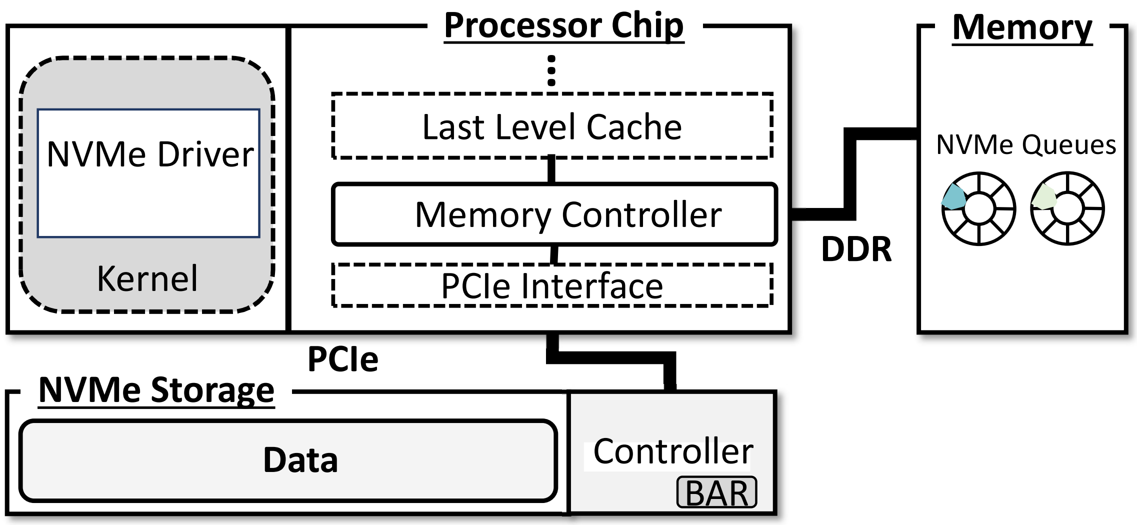

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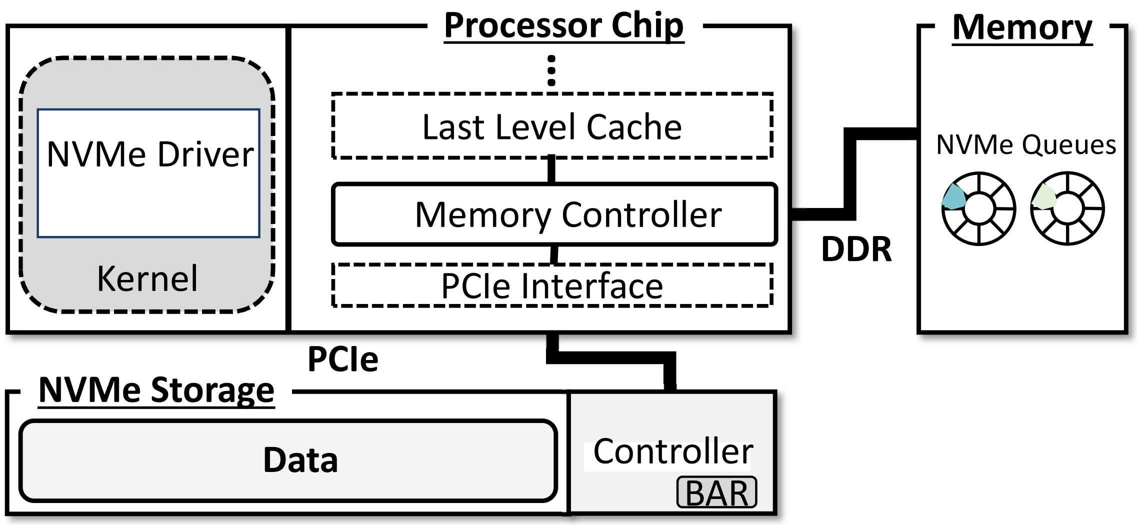

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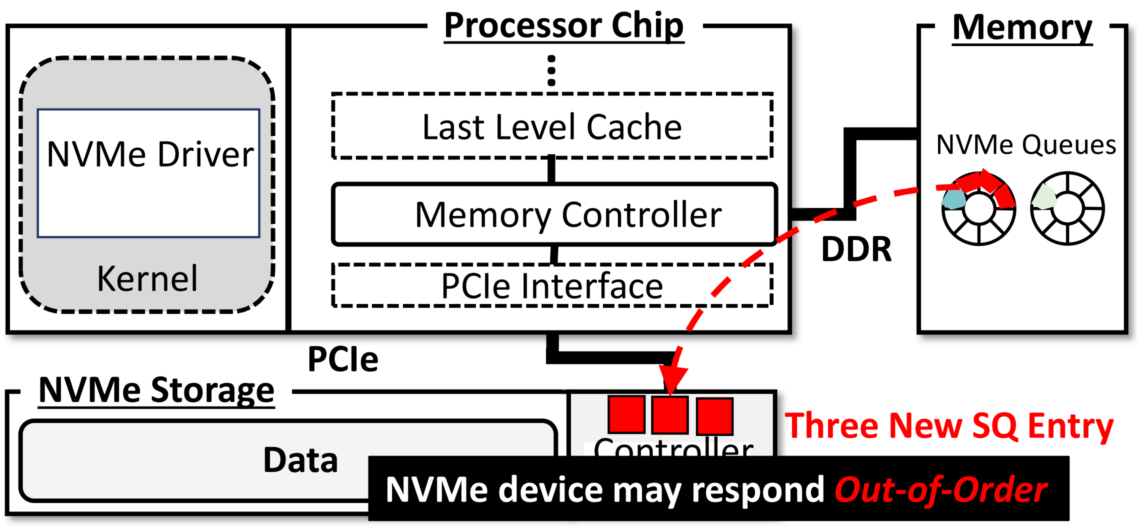

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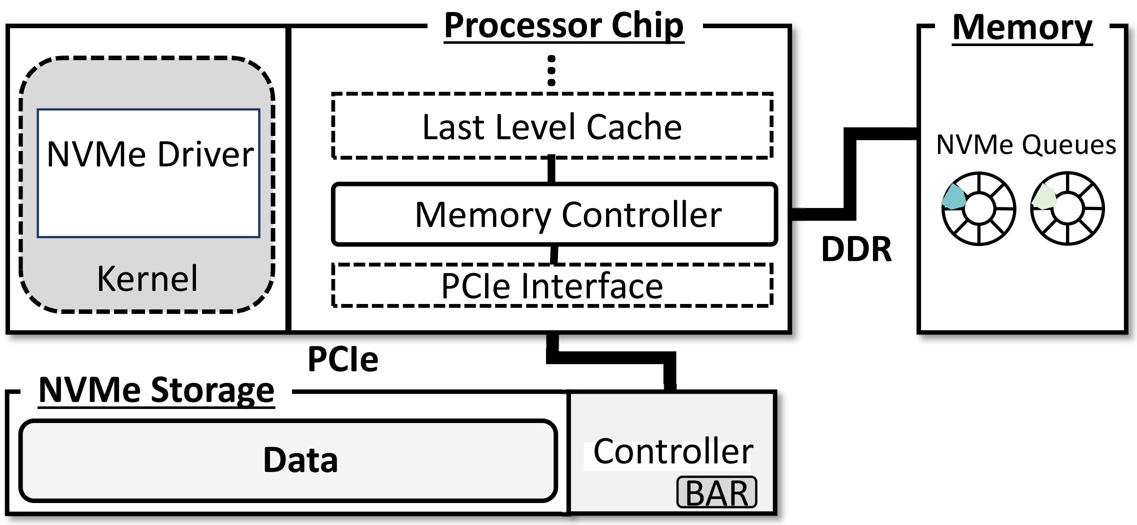

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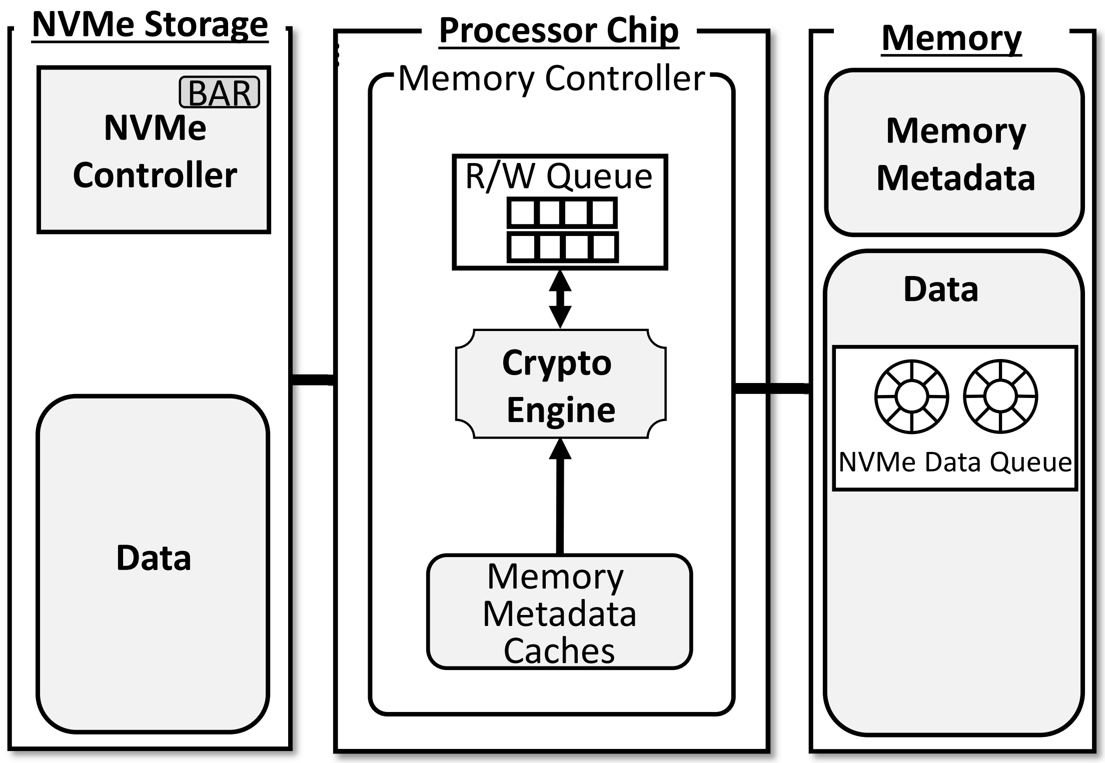
C3: Metadata I/O overheads → efficient metadata management tailored for storage I/O characteristics

Basic D-Shield Design



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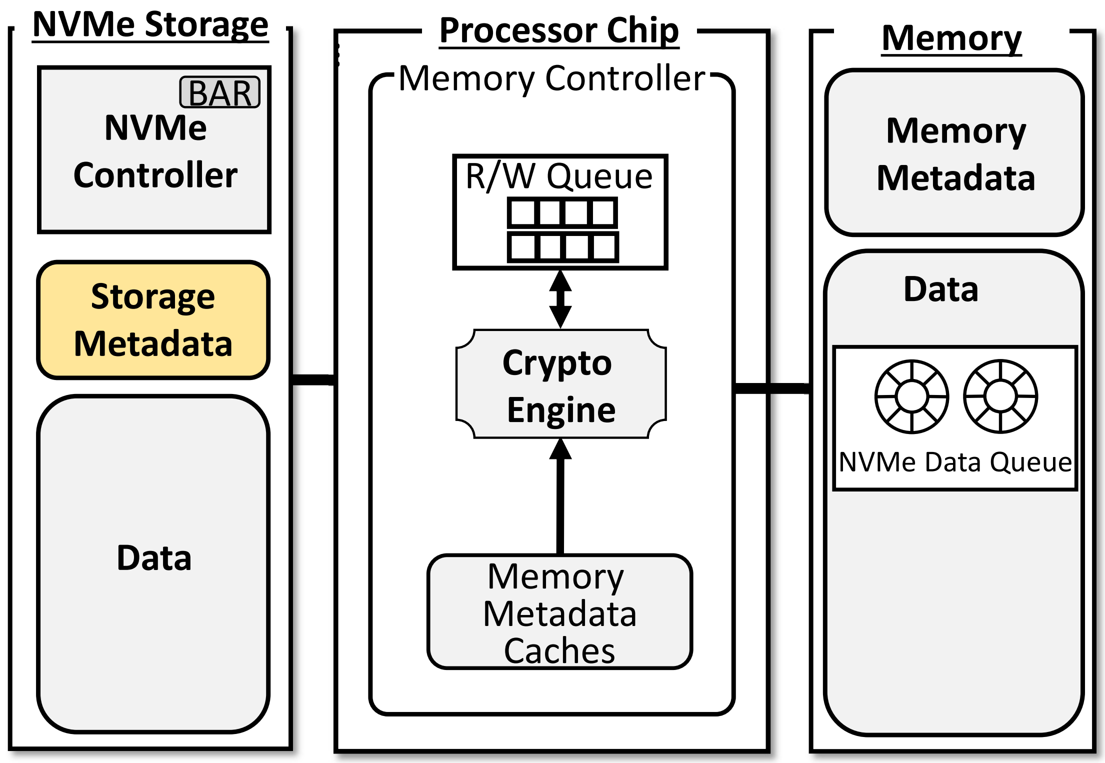

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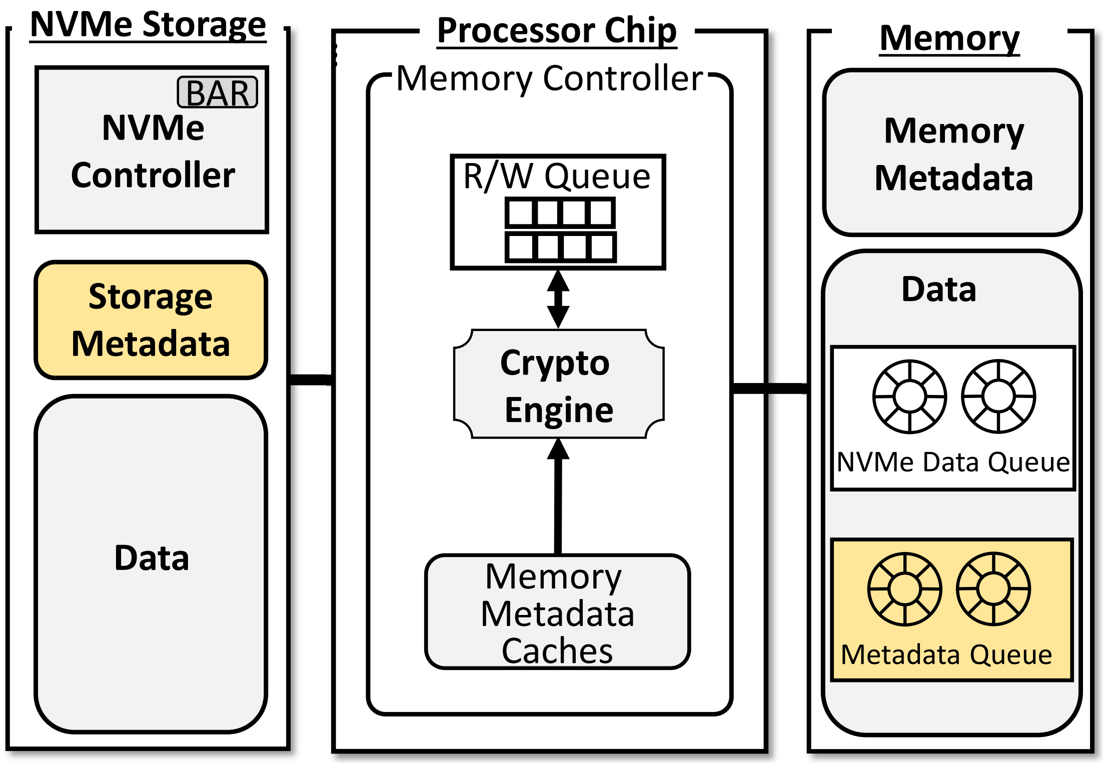

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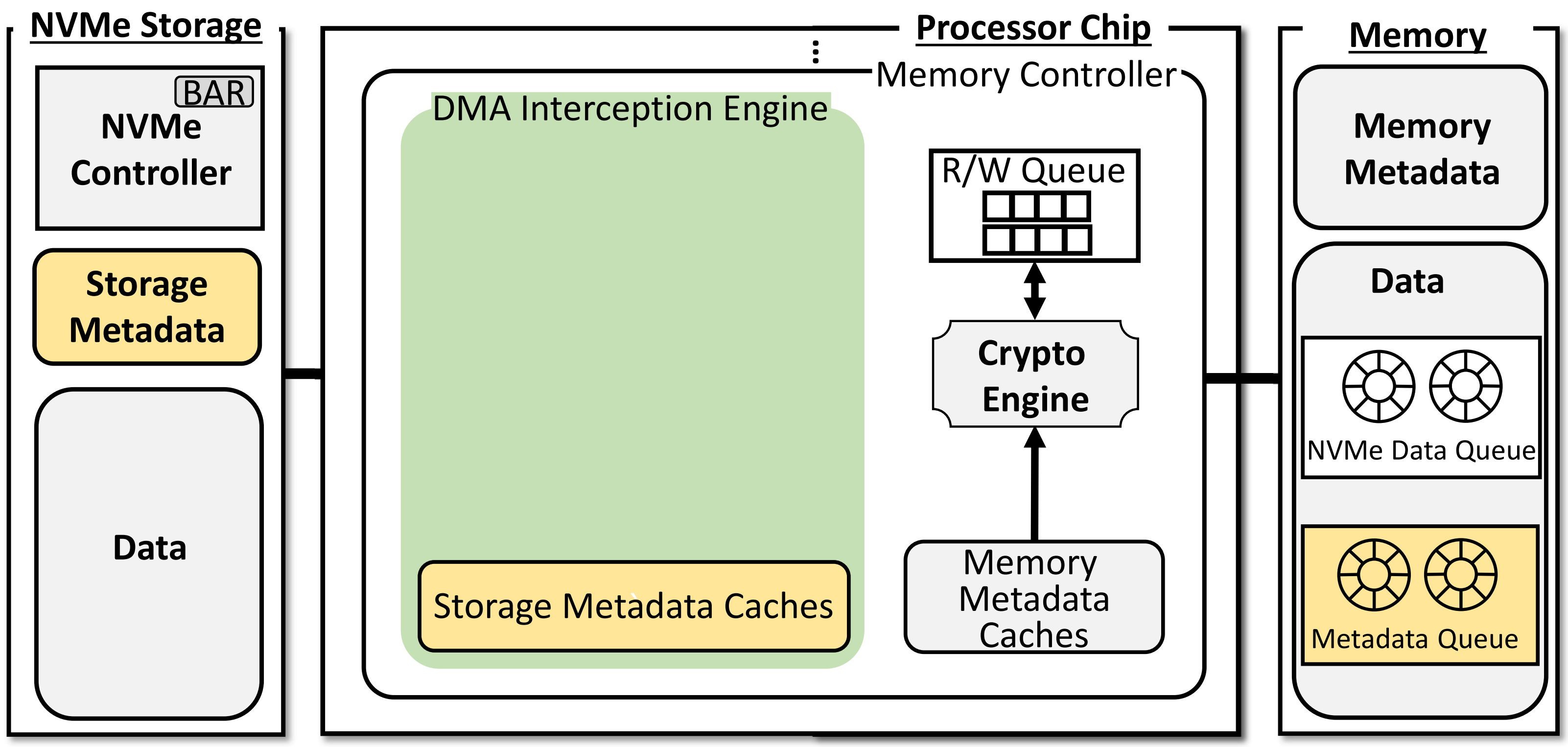

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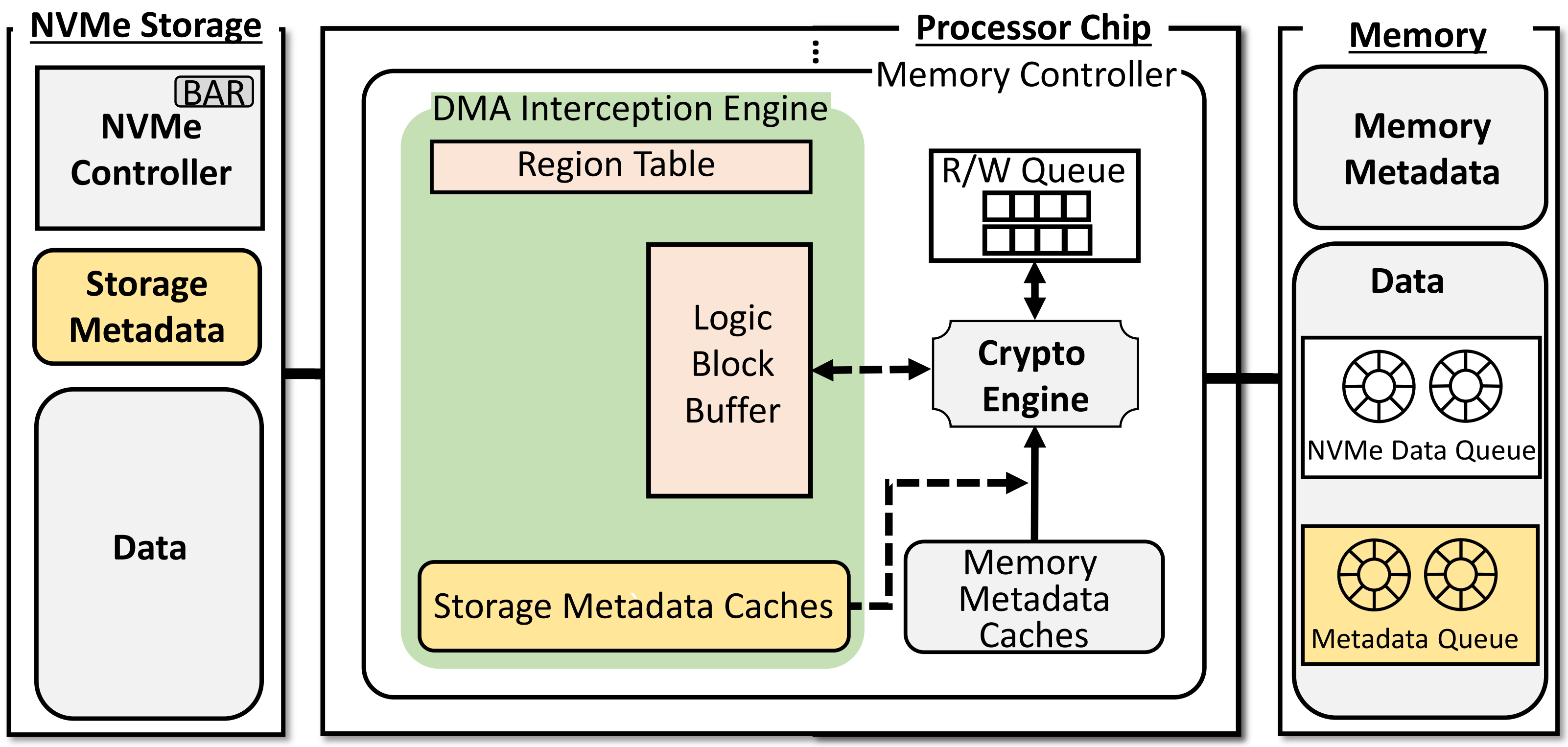

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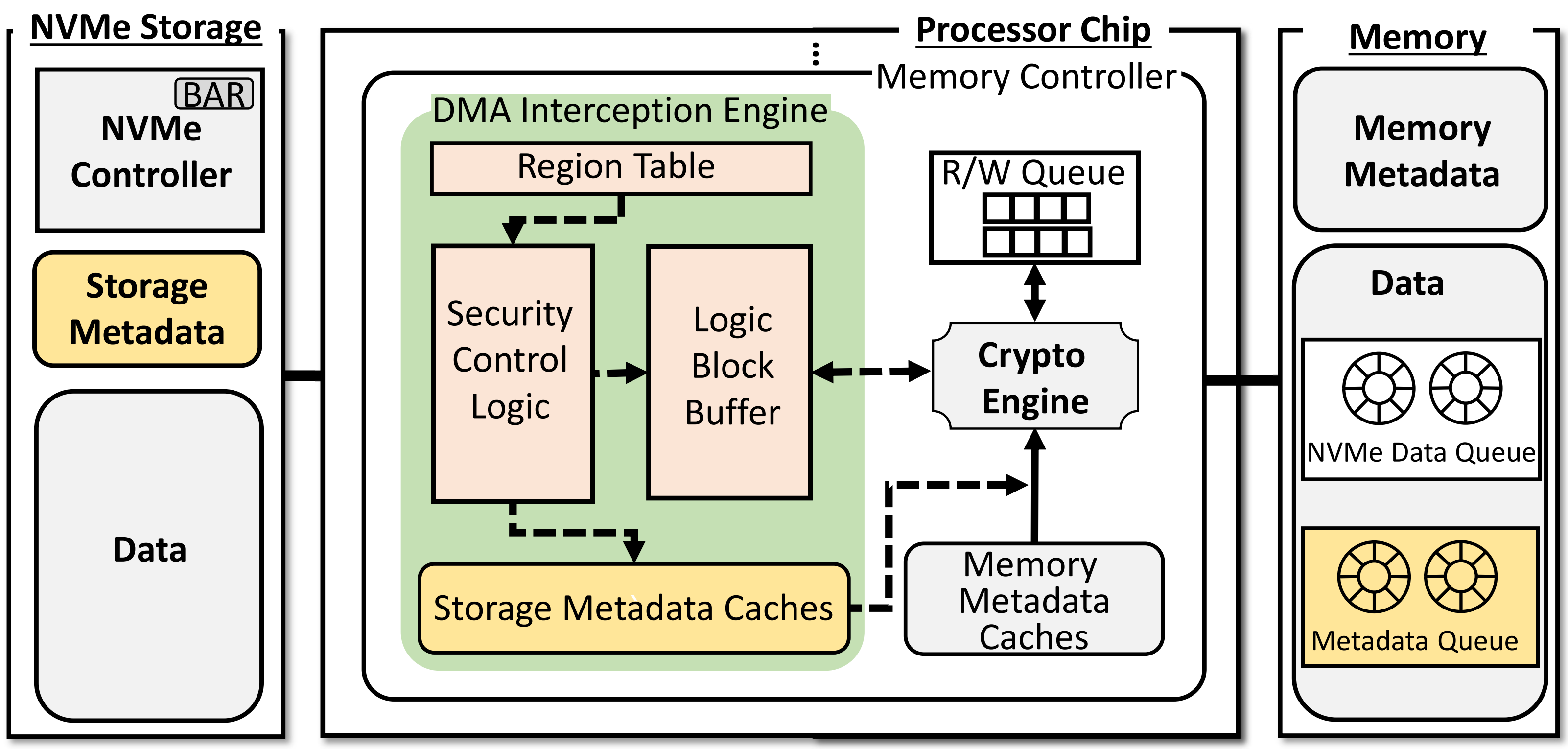

NVMe-optimized Security Metadata

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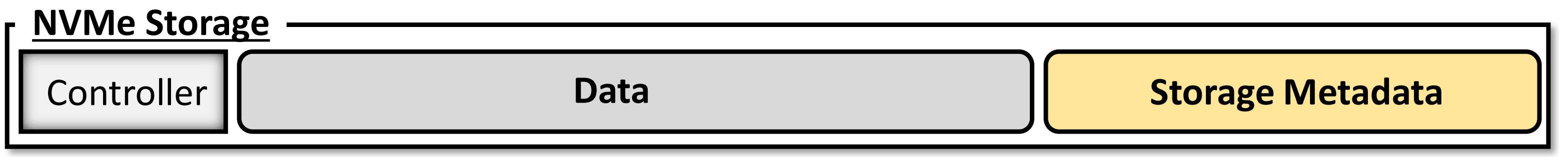

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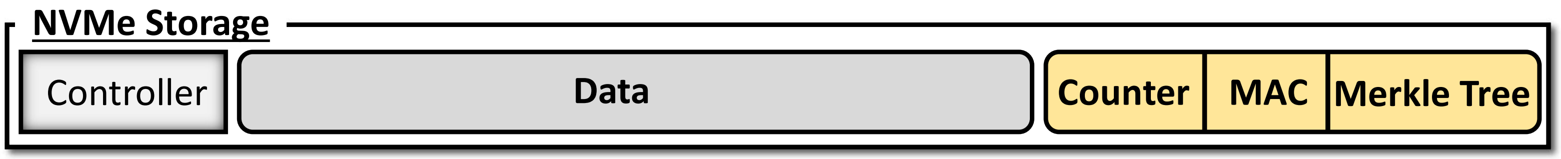

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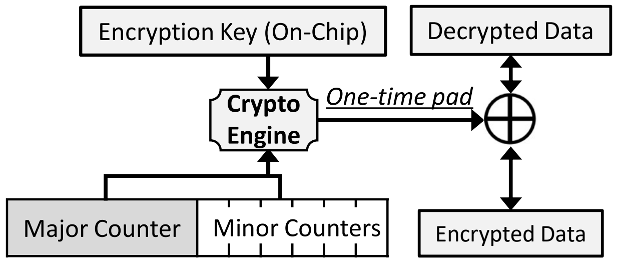
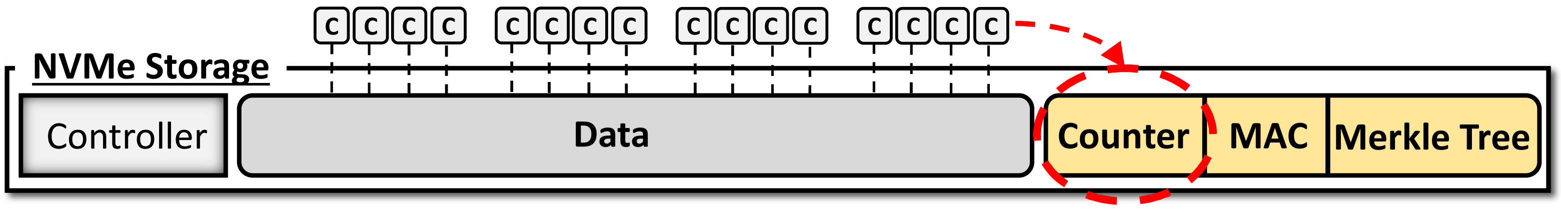


Counter-mode Encryption



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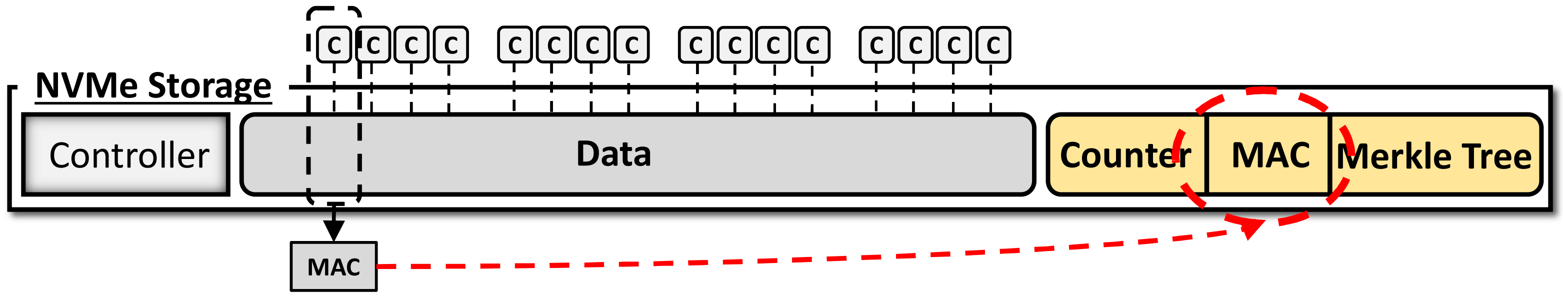

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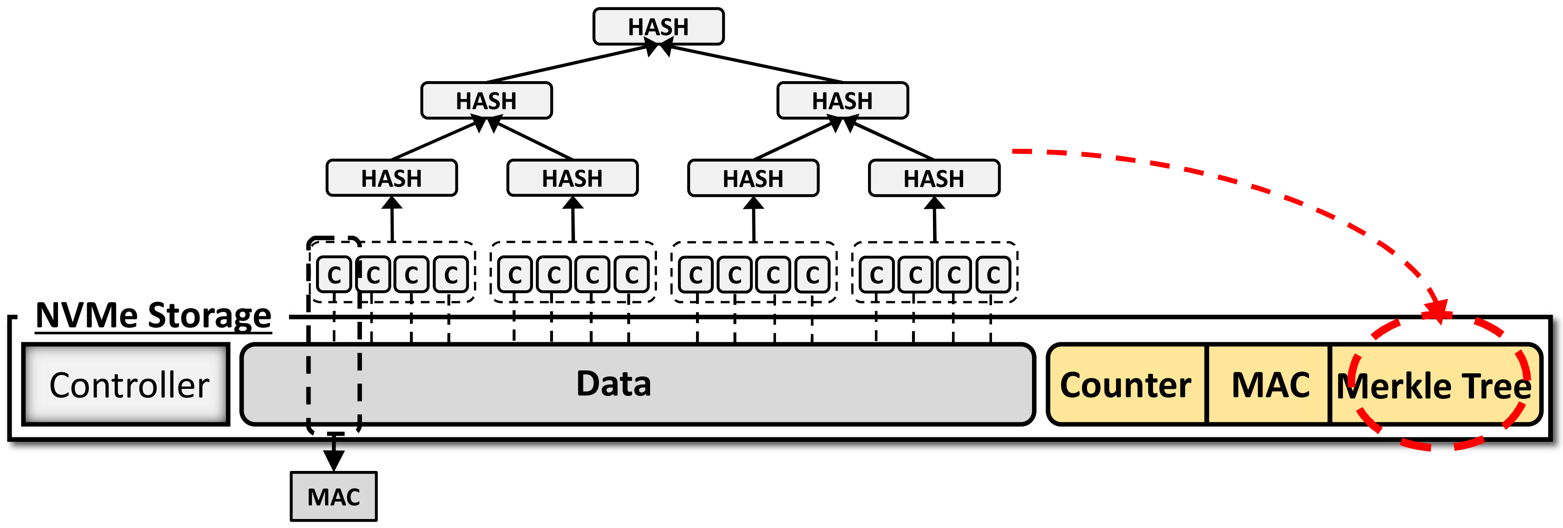

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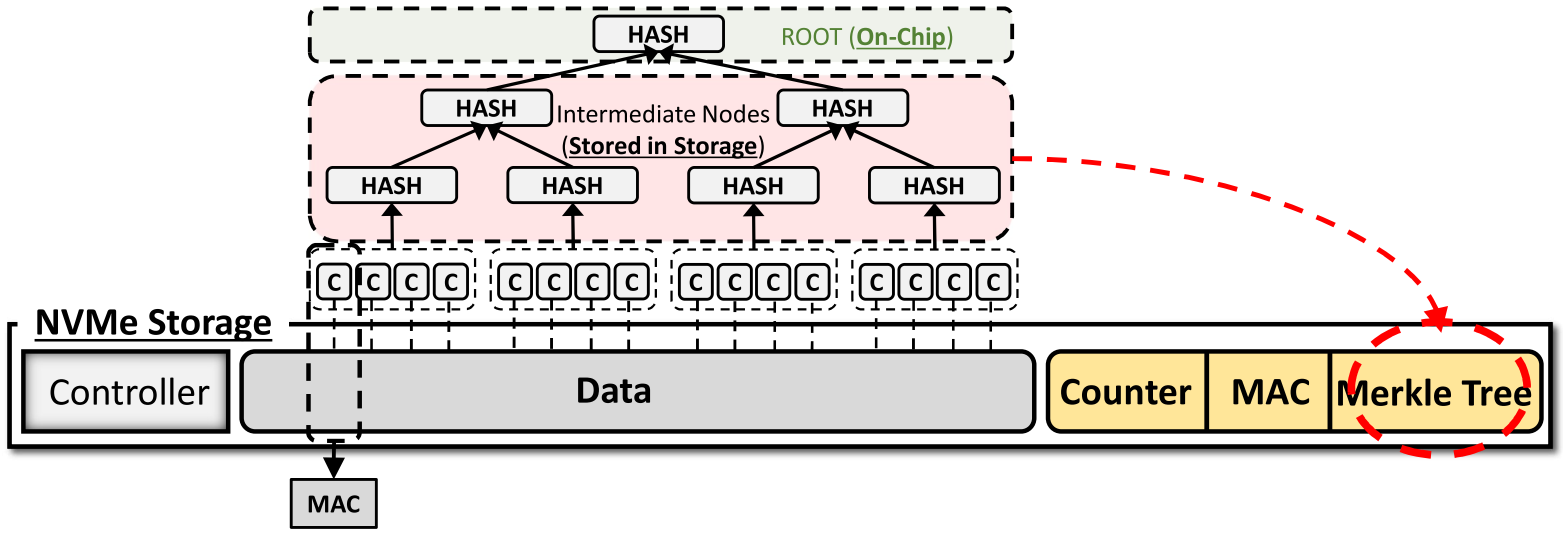

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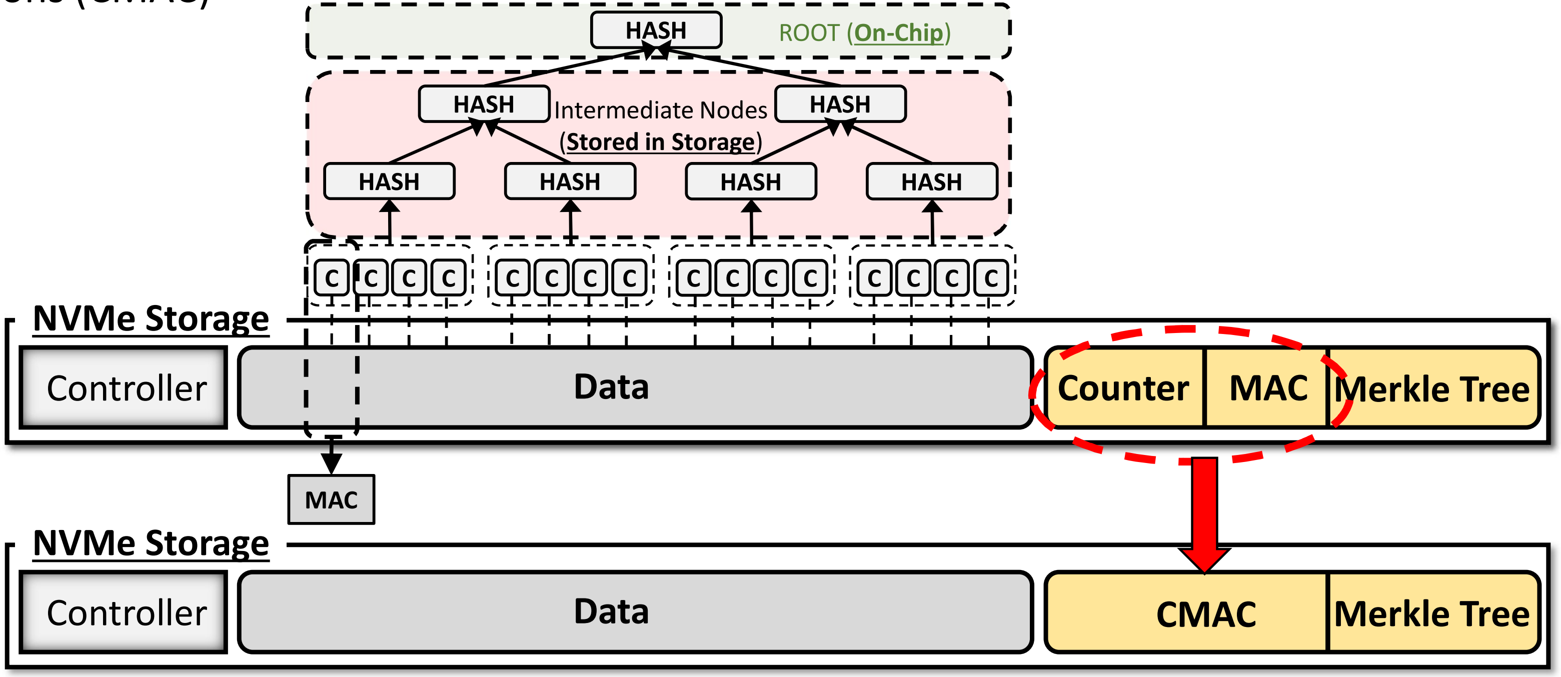
- Counter and MAC are required for each data access → store them together to reduce metadata I/O operations (CMAC)



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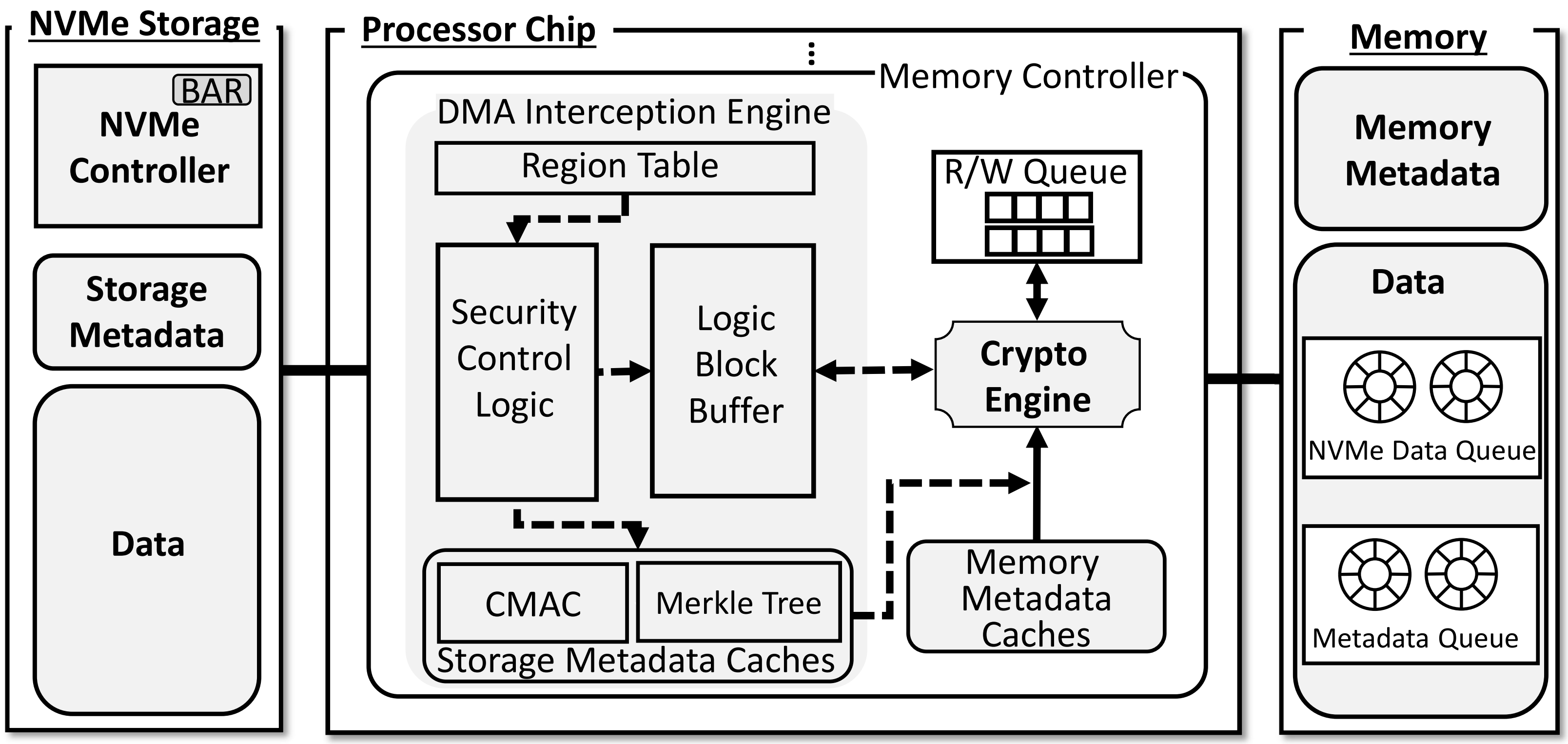
D-Shield Operation (Read)



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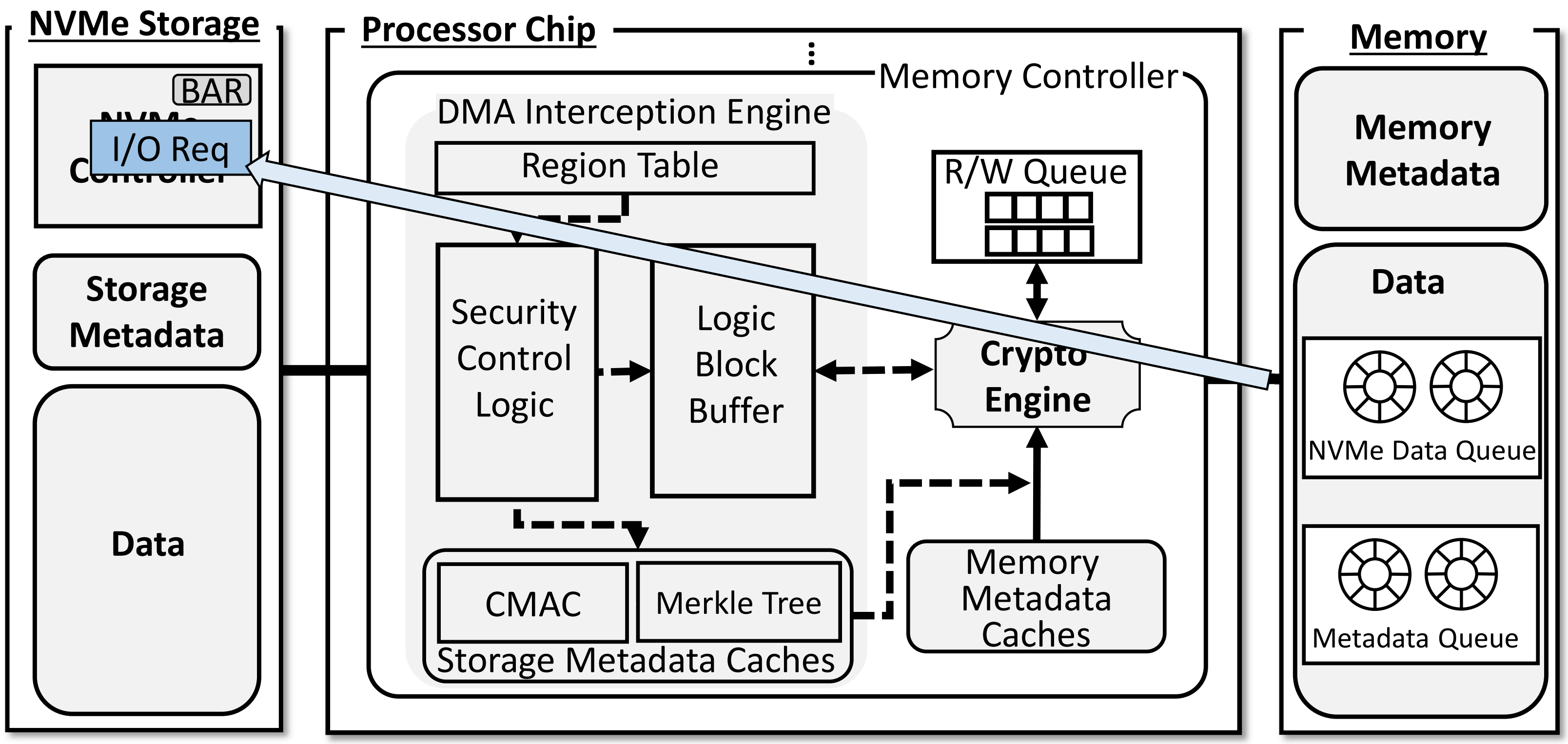

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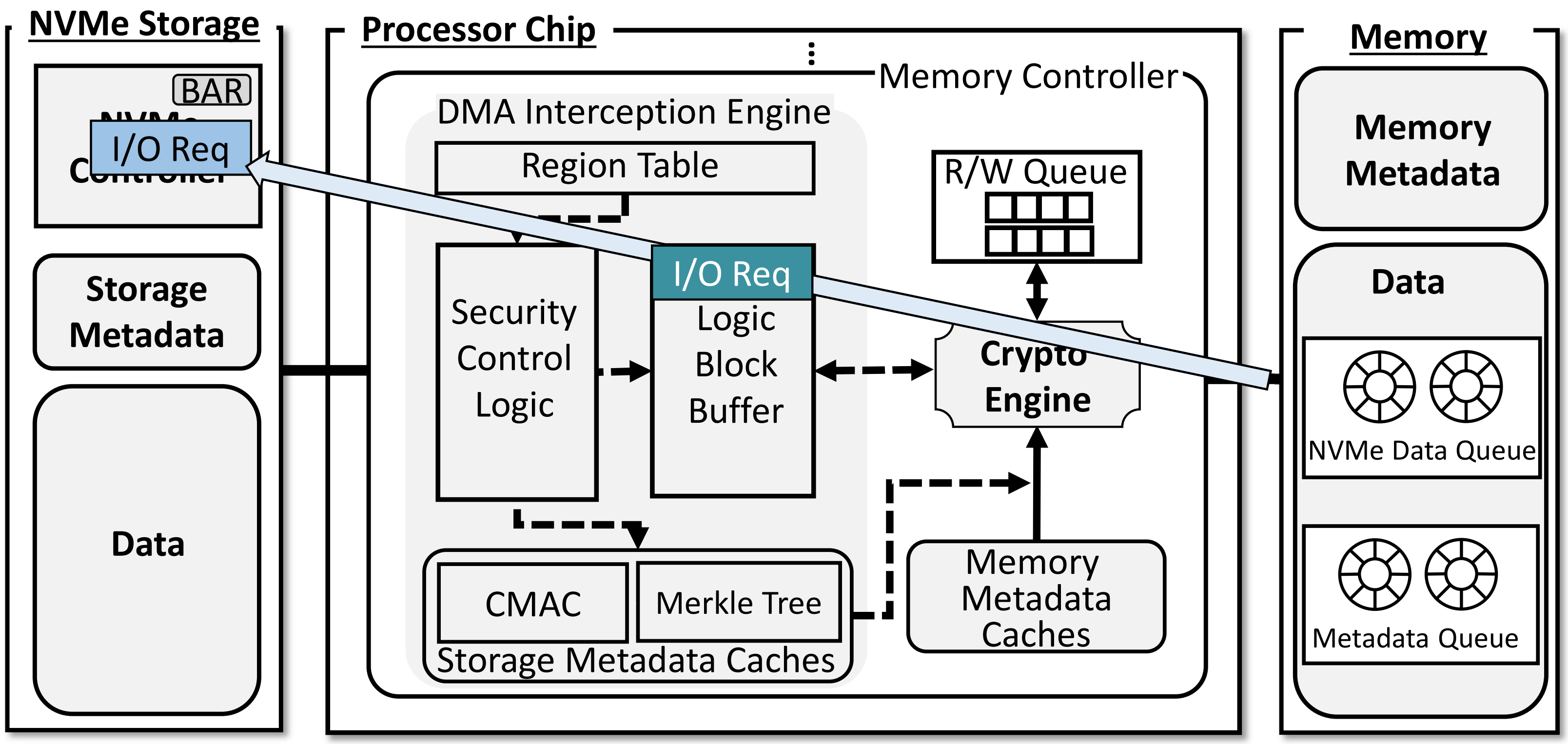

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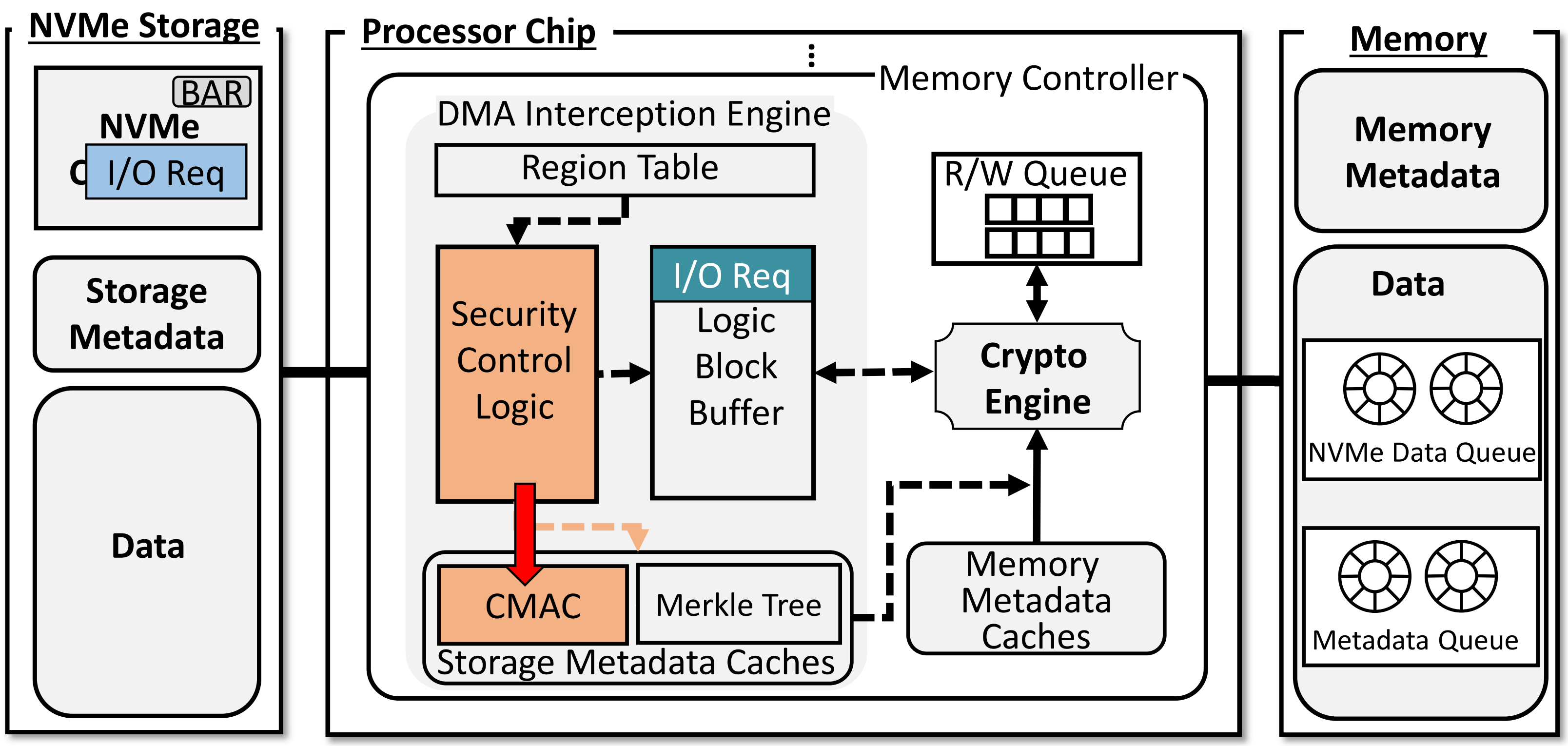

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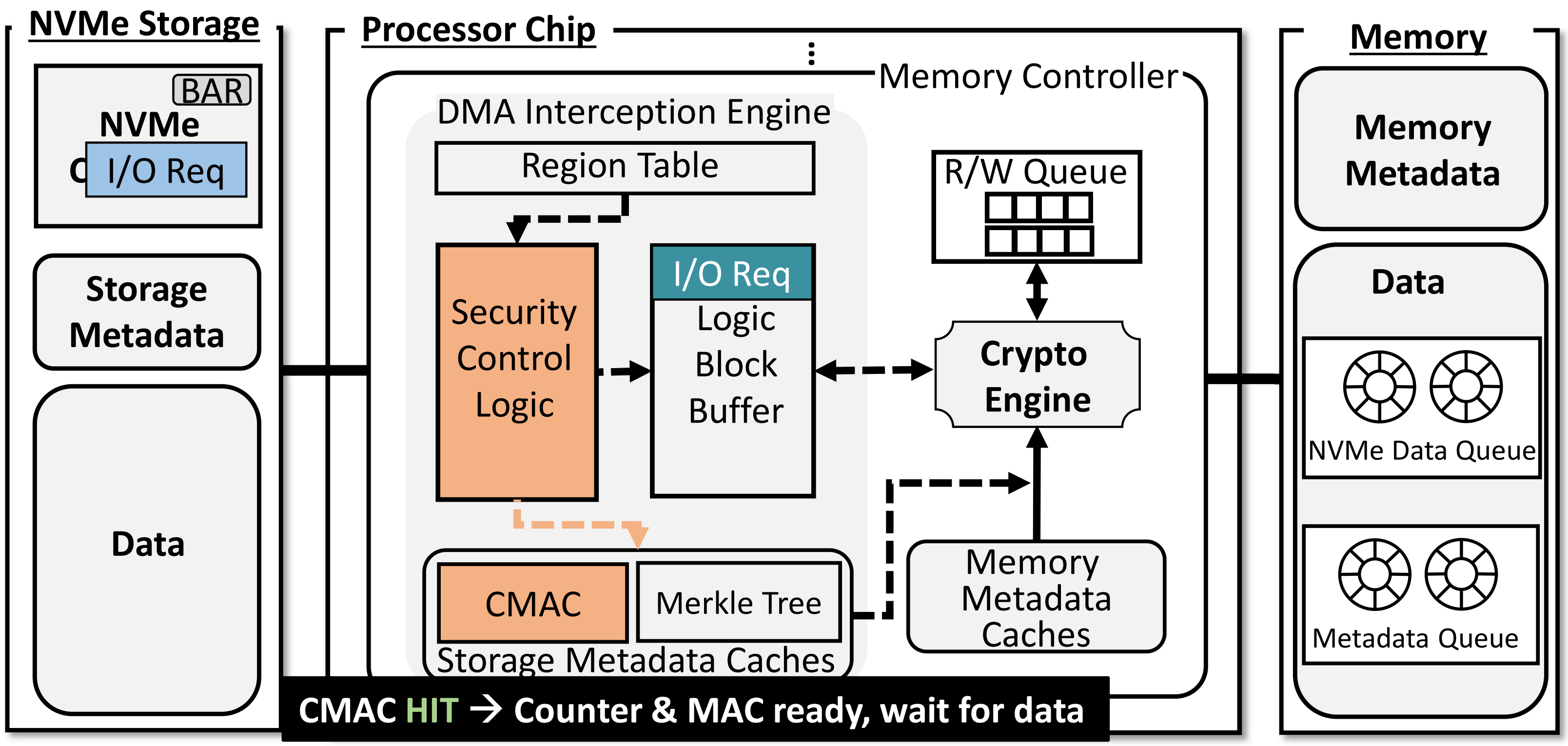

CMAC HIT → Counter & MAC ready, wait for data

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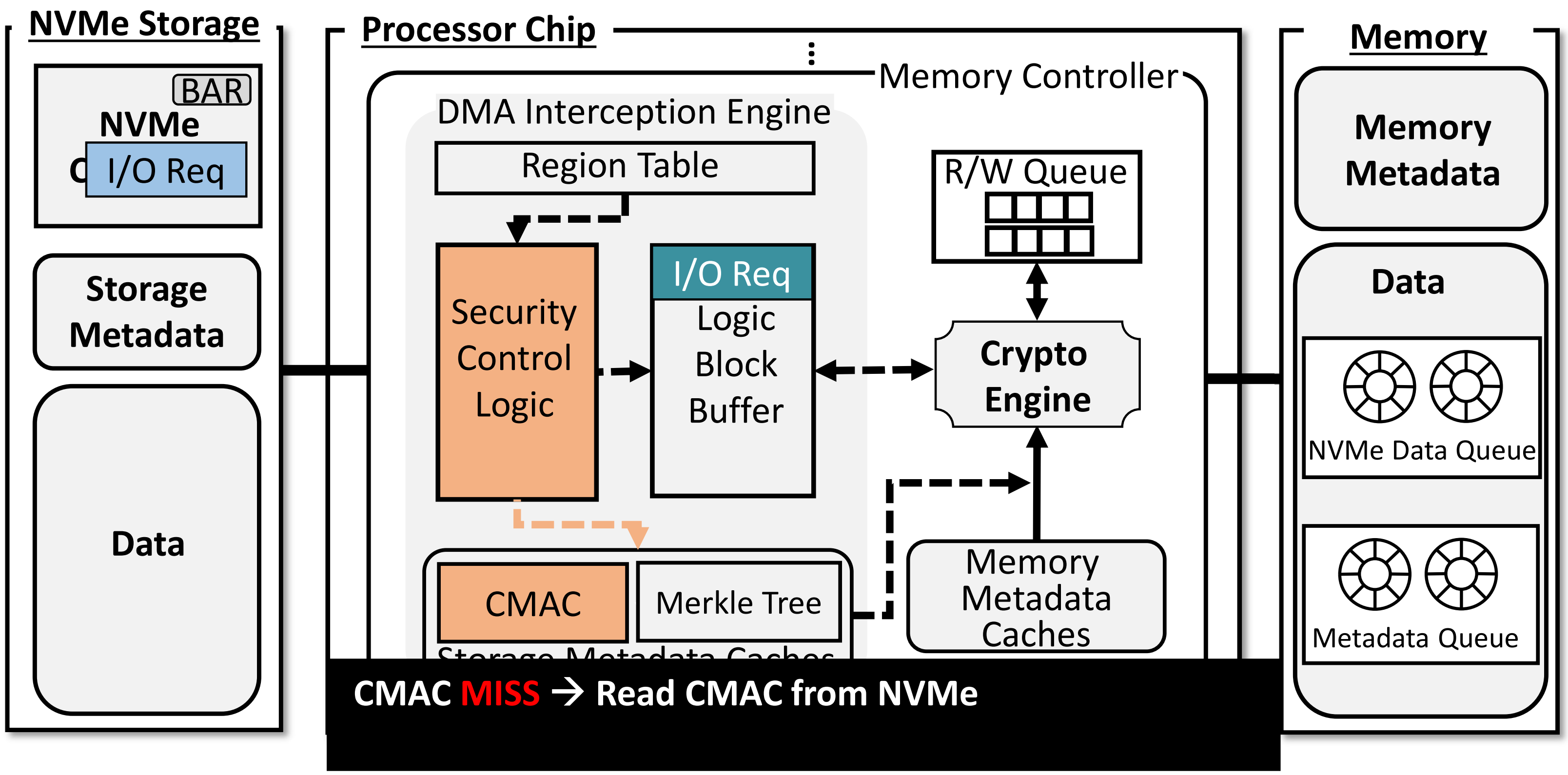

CMAC MISS → Read CMAC from NVMe

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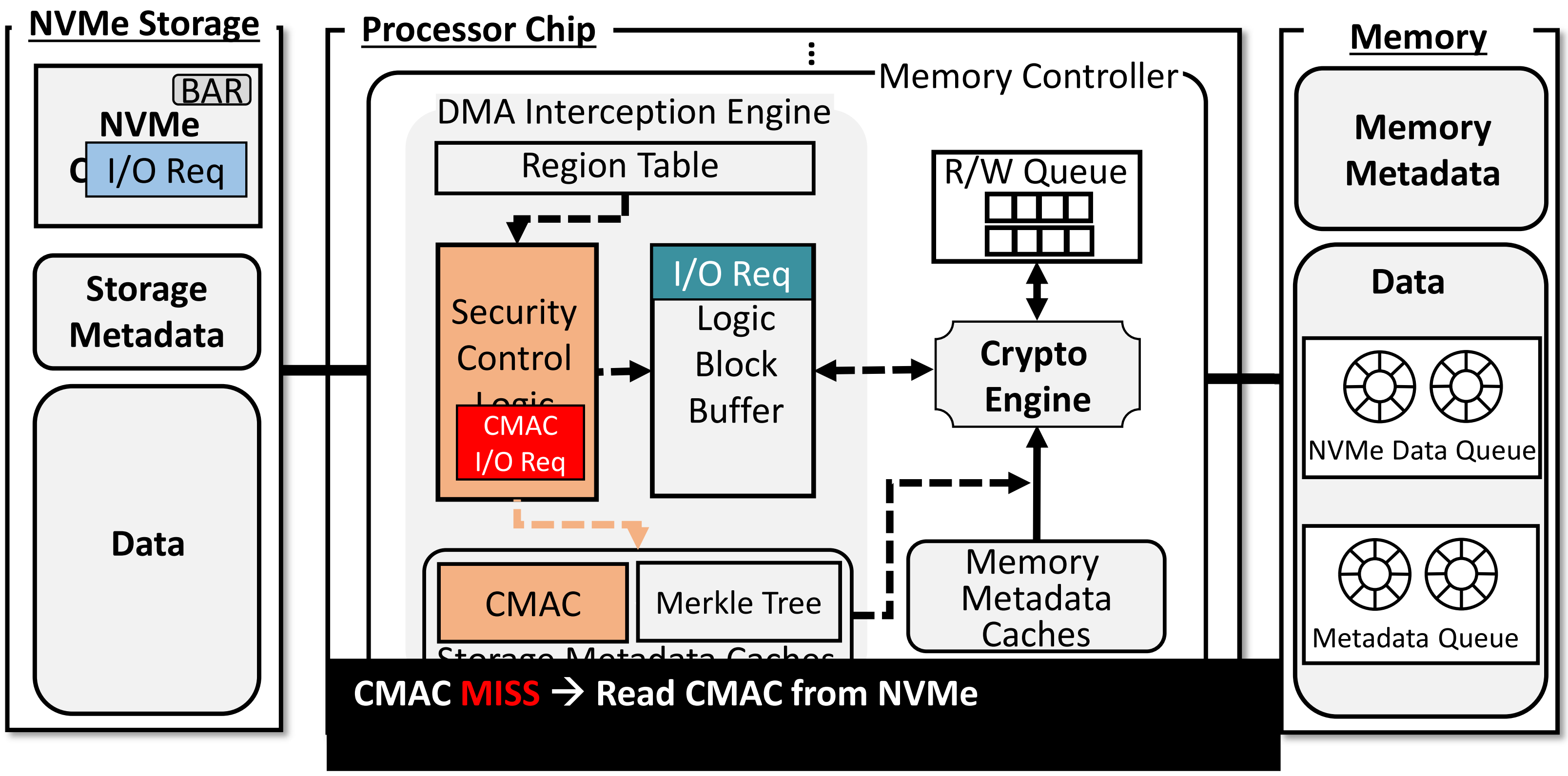

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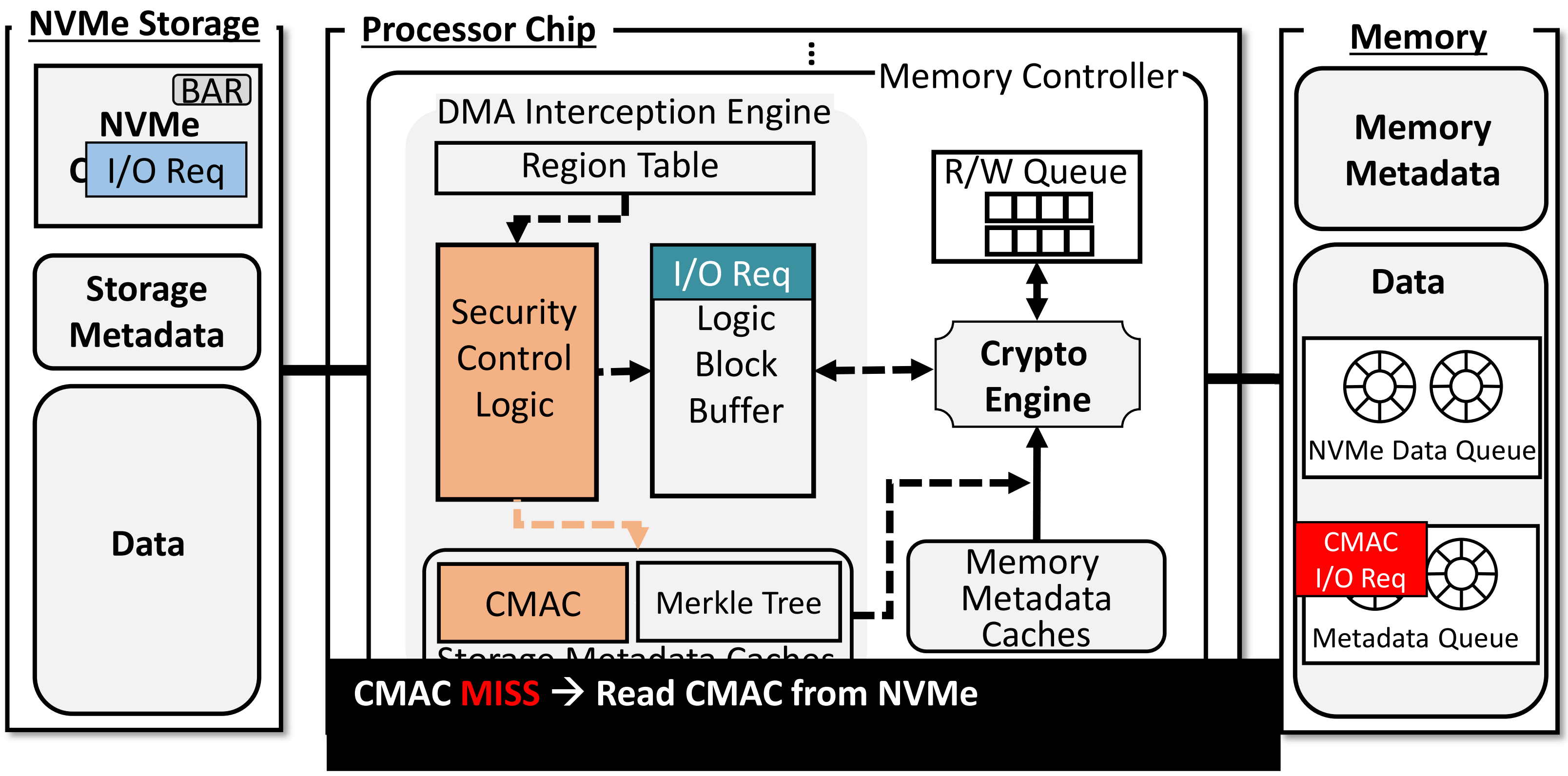

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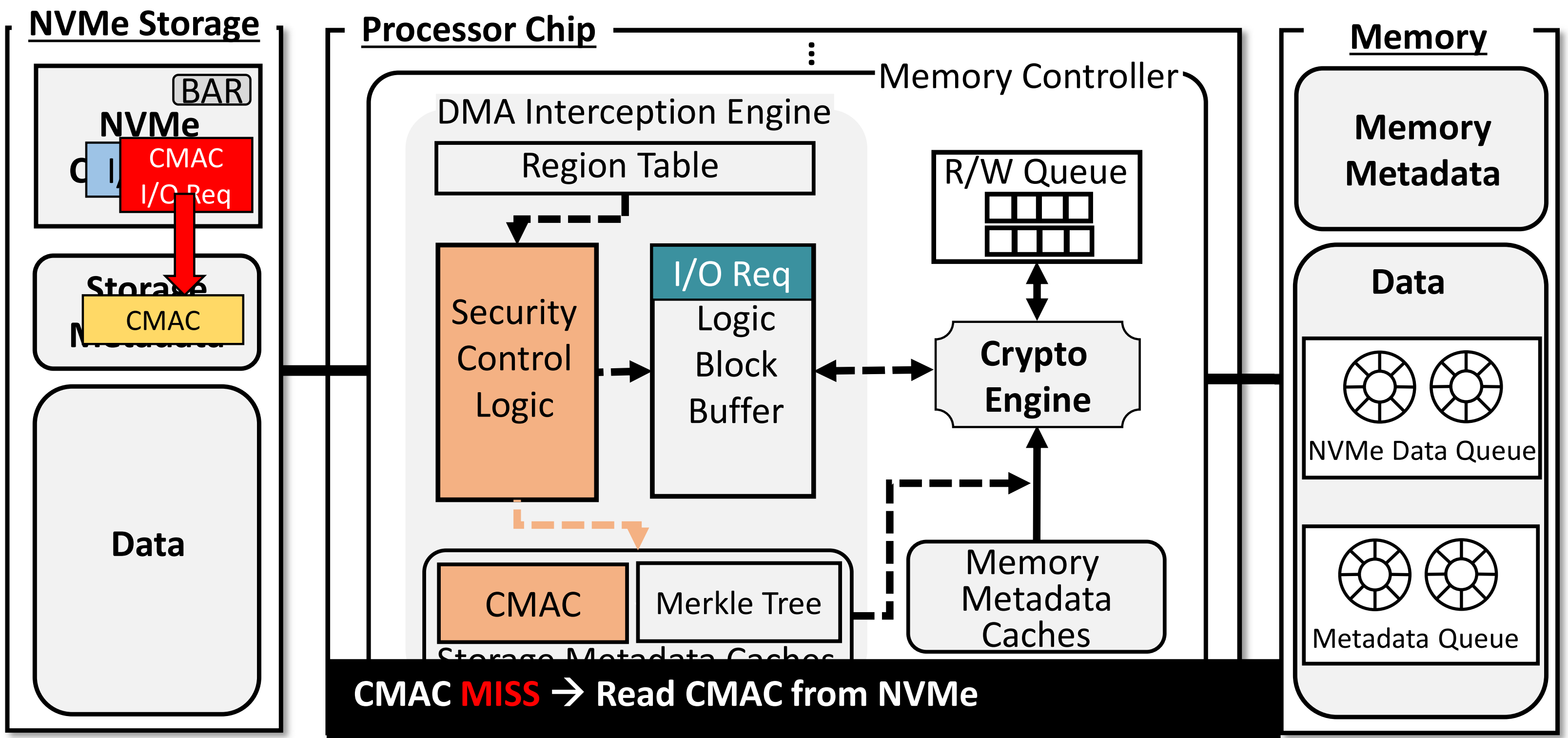

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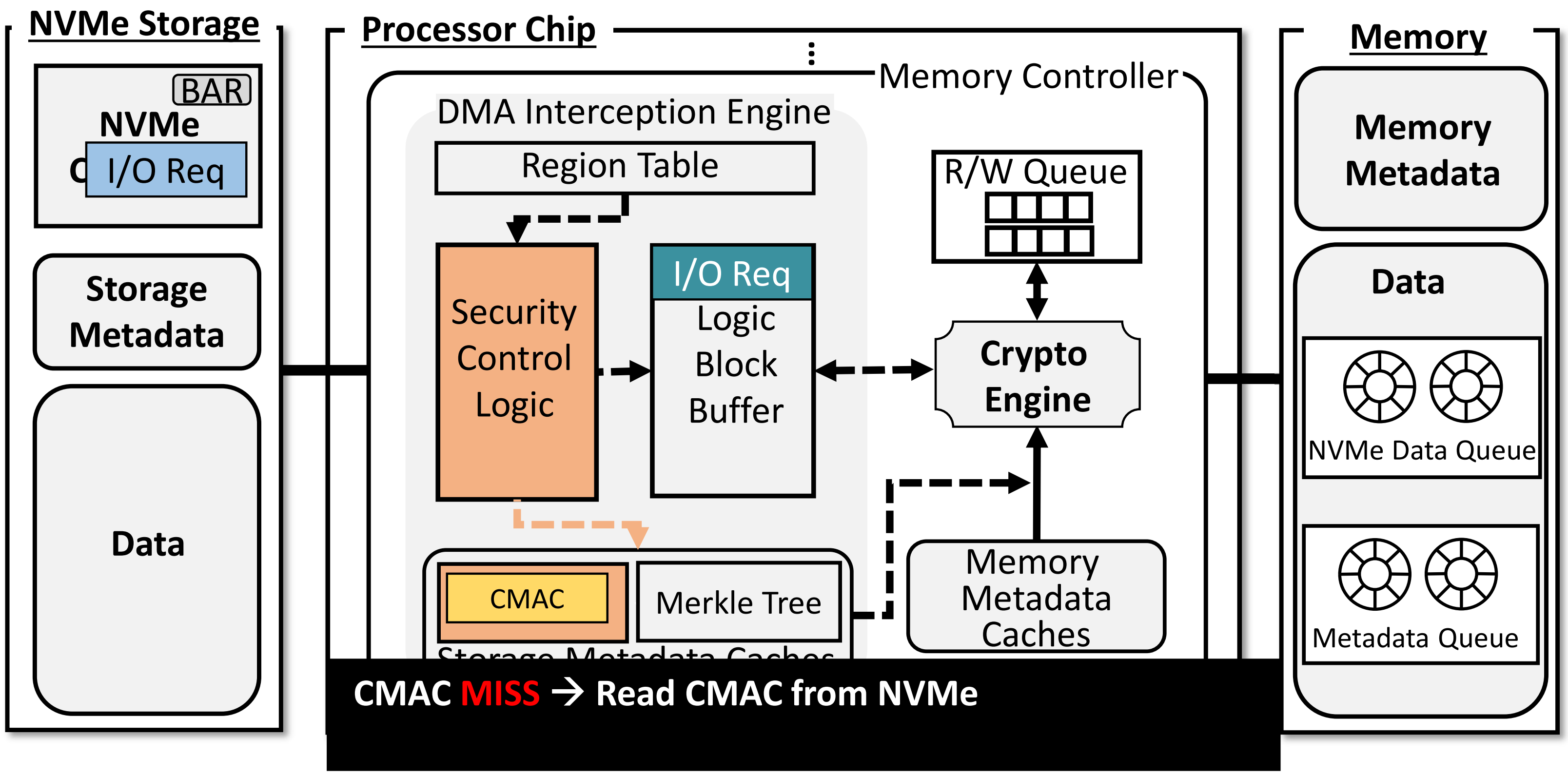

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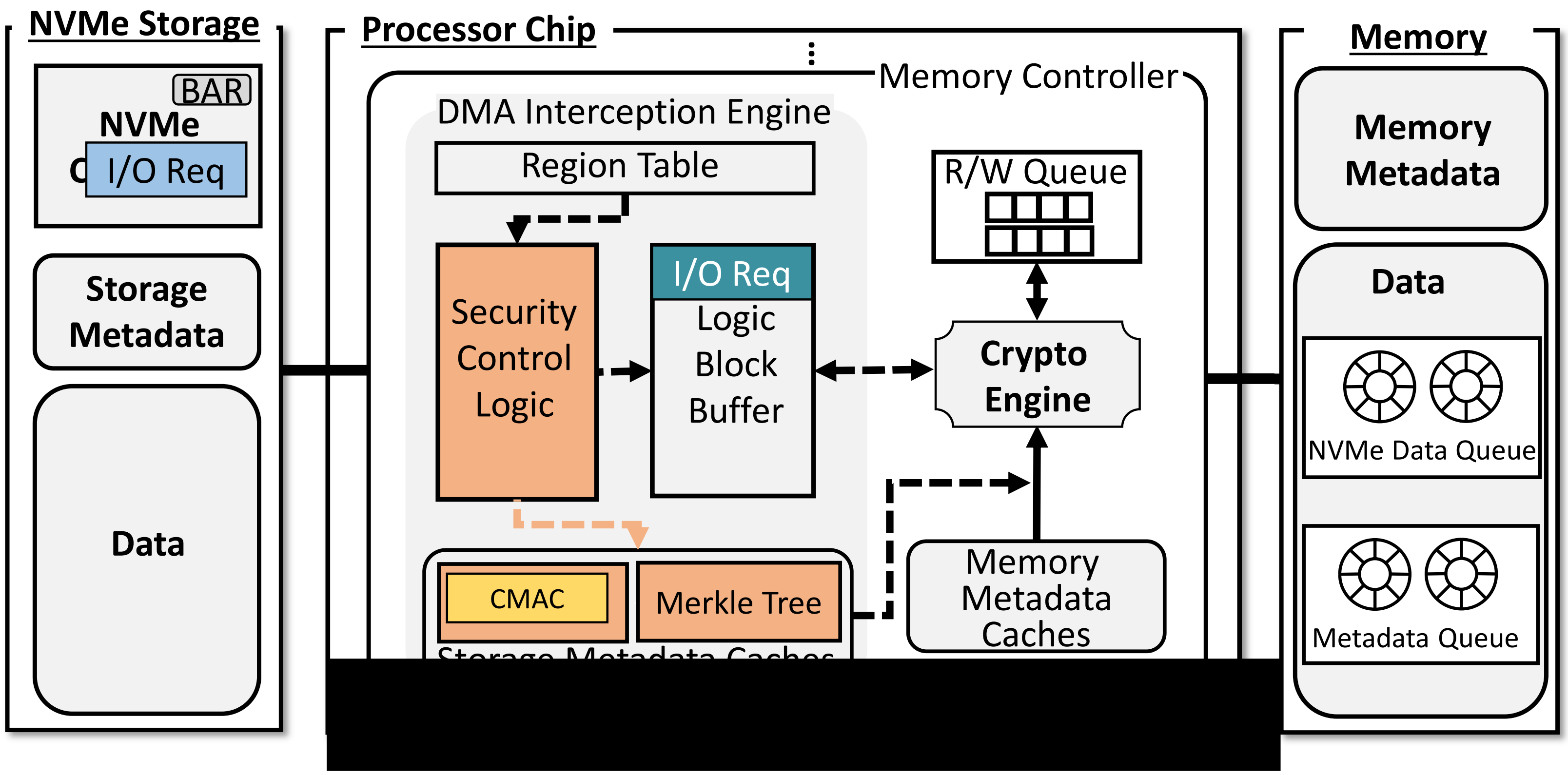

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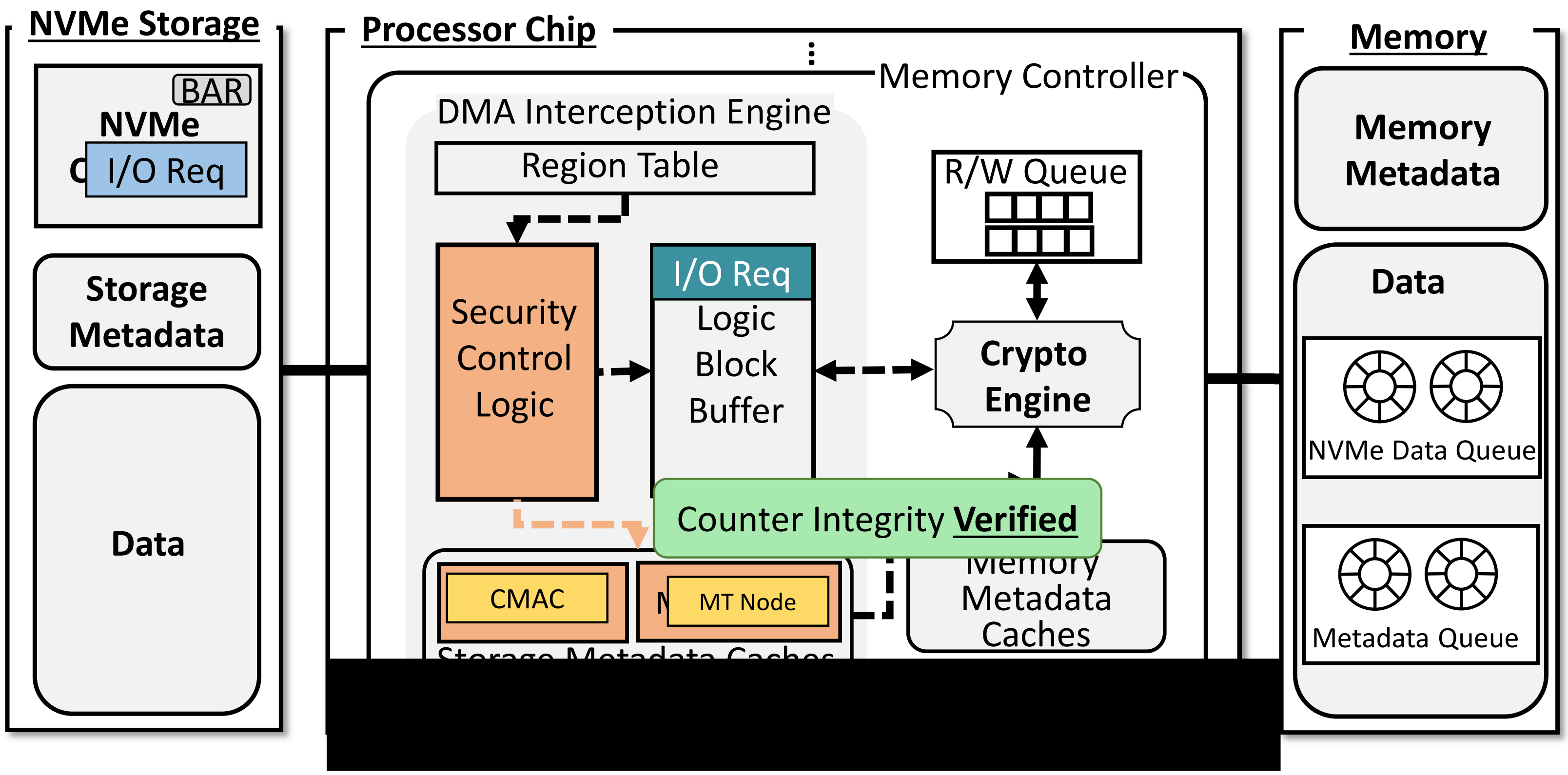

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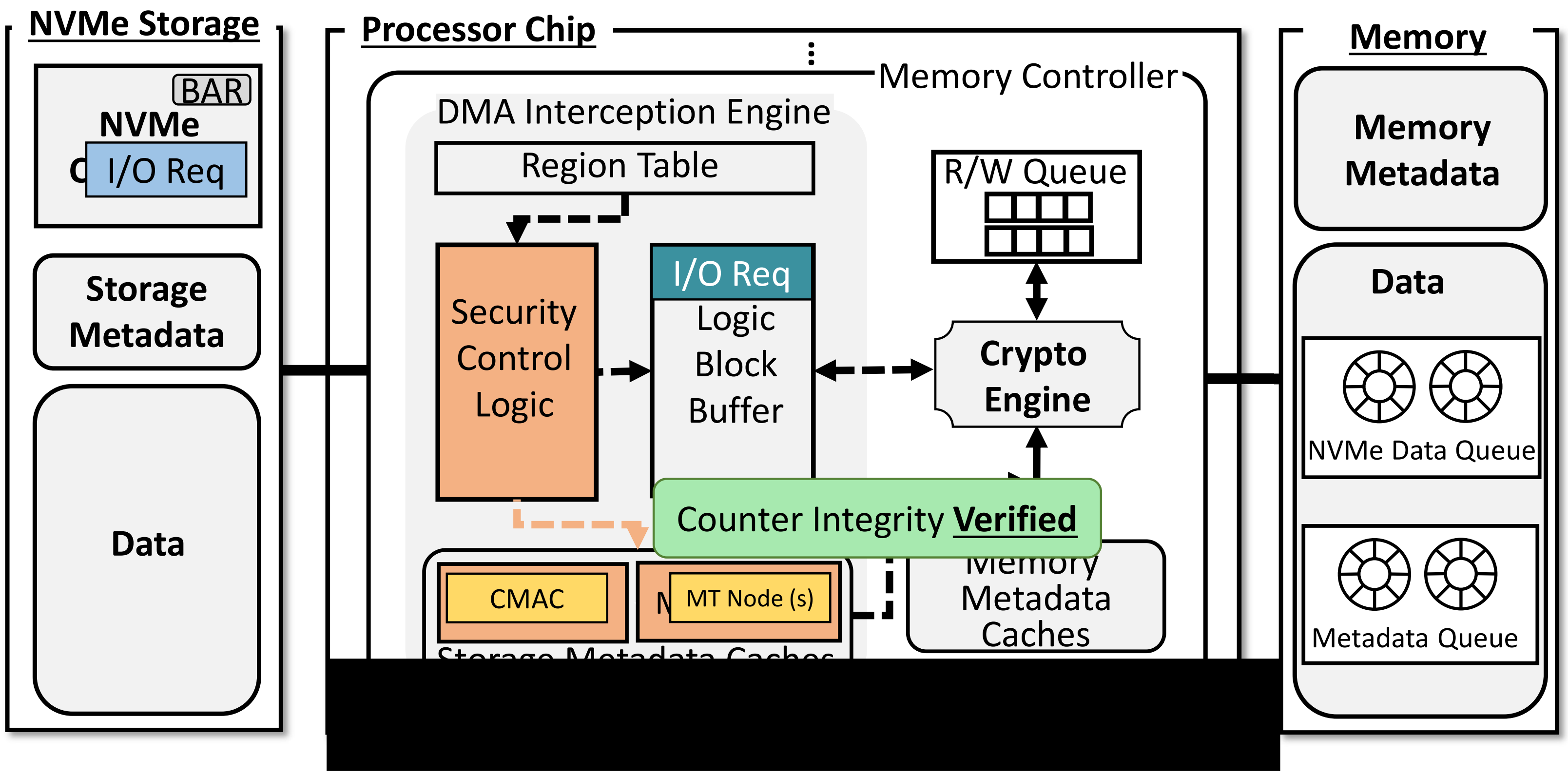

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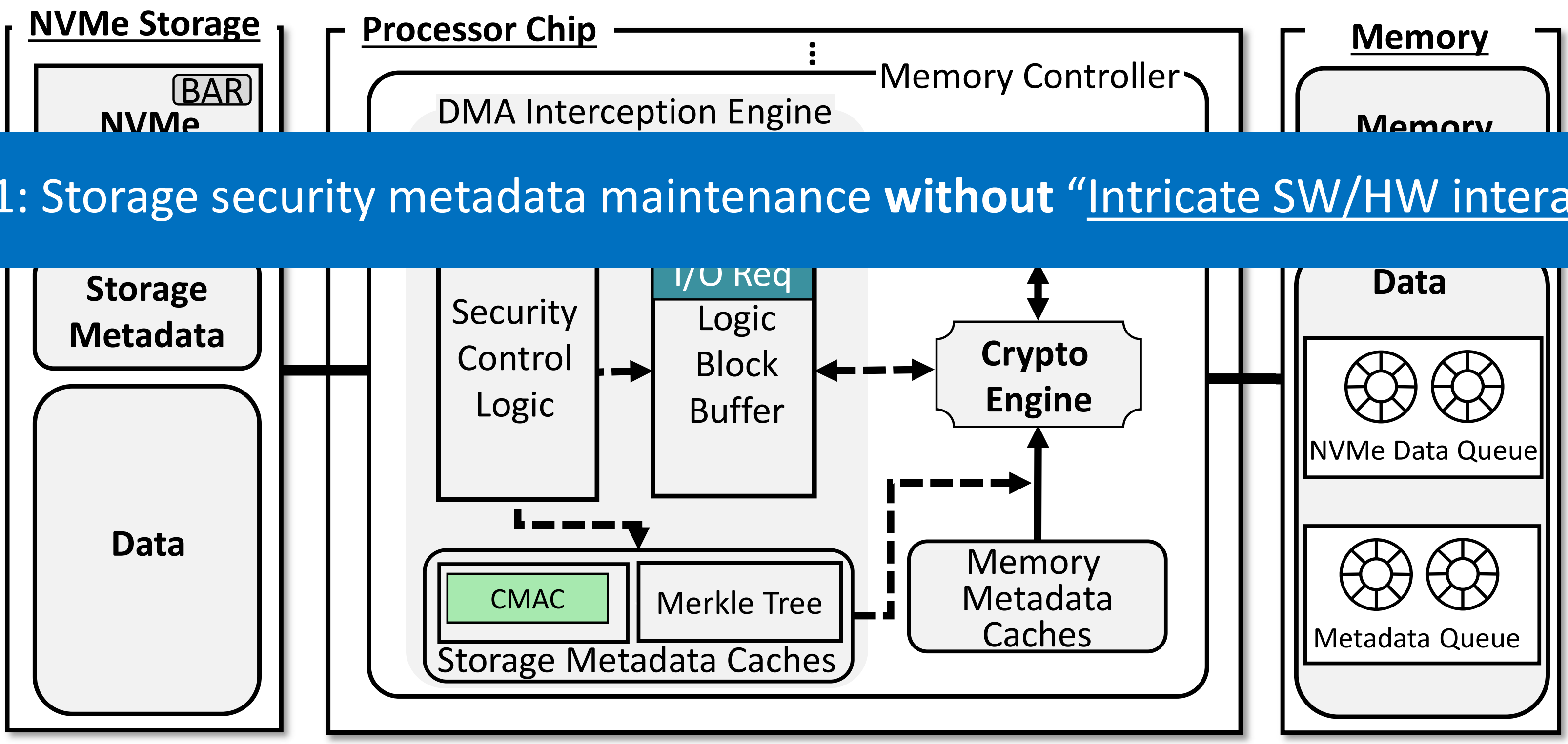
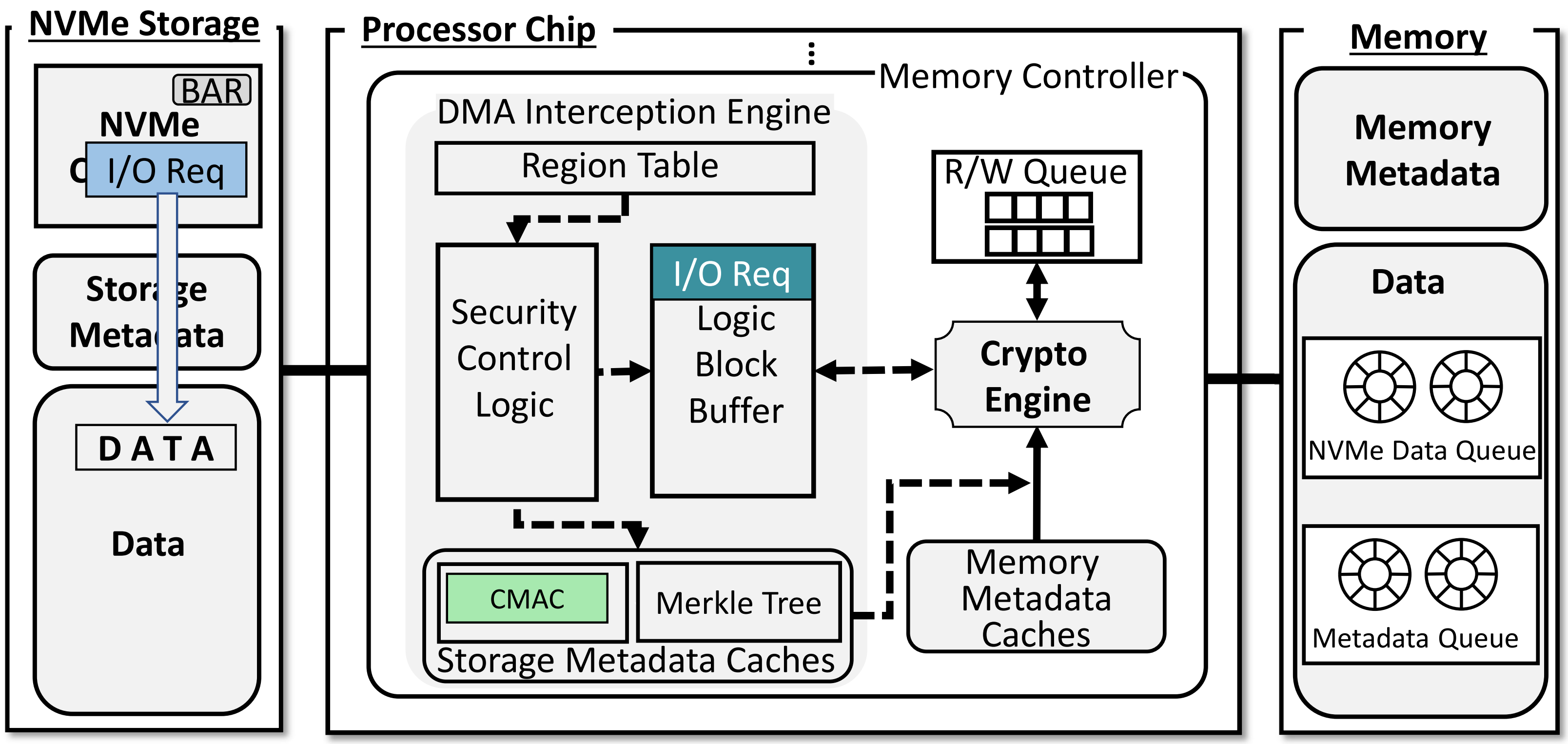


C1: Storage security metadata maintenance **without** "Intricate SW/HW interactions"

D-Shield Operation (Read)



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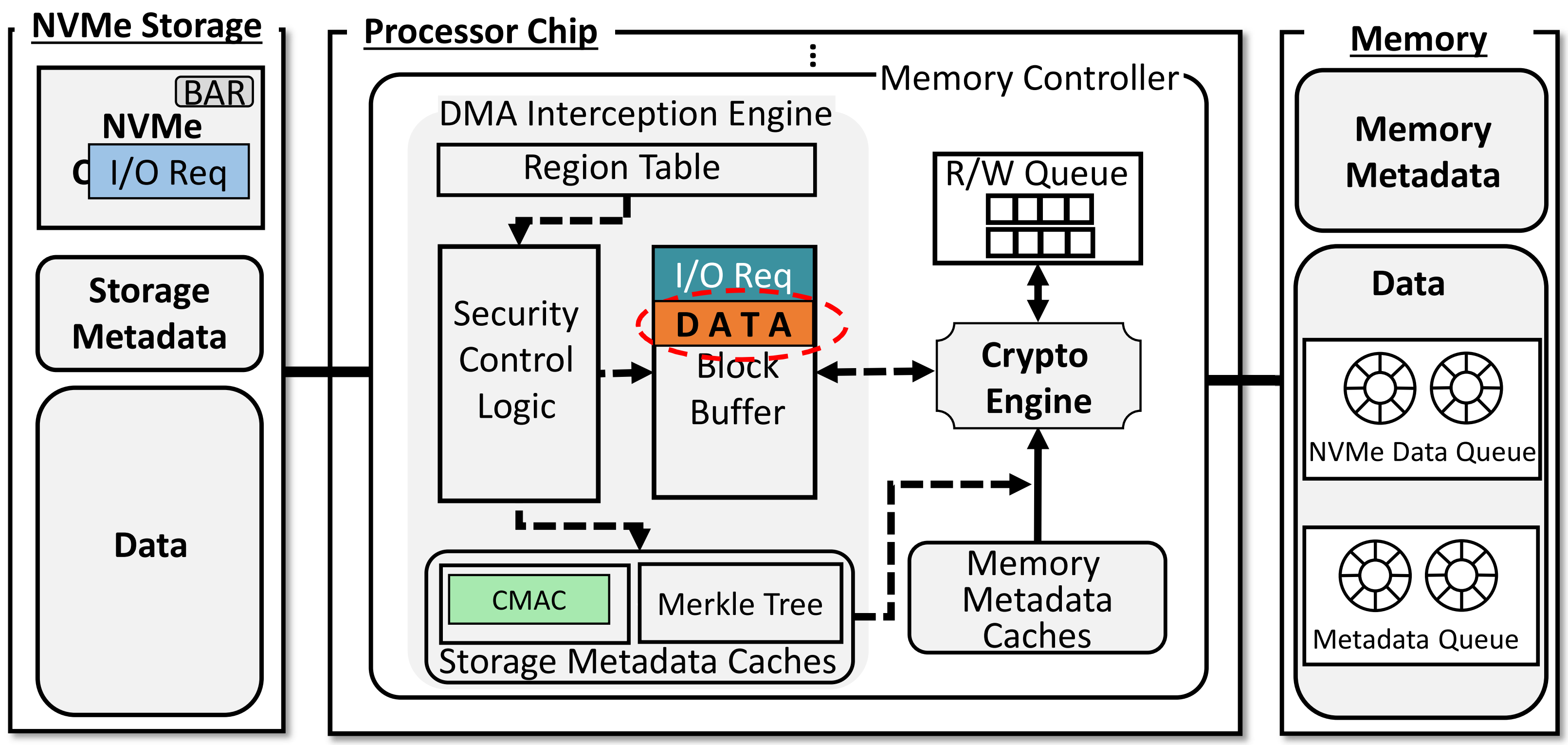
D-Shield Operation (Read)



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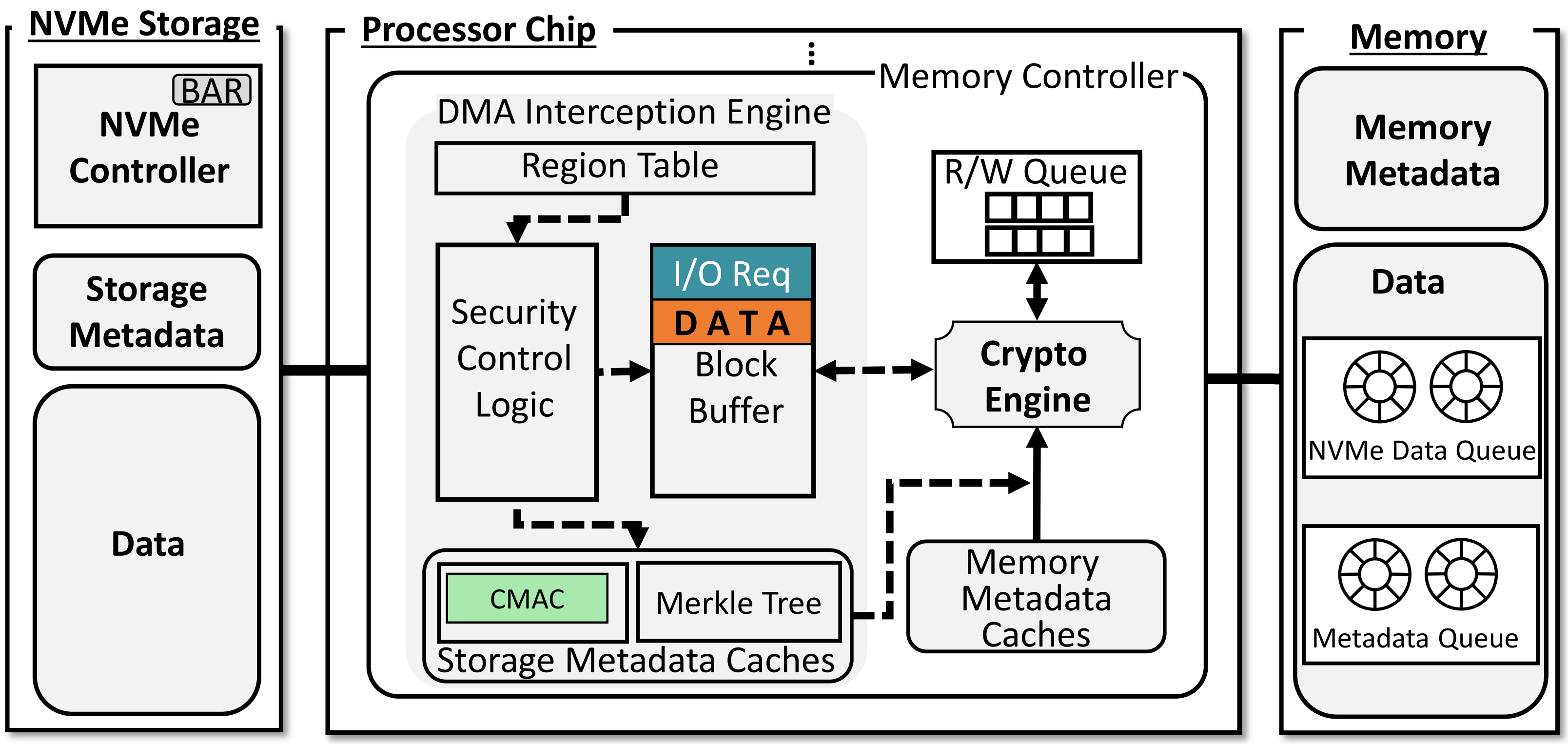

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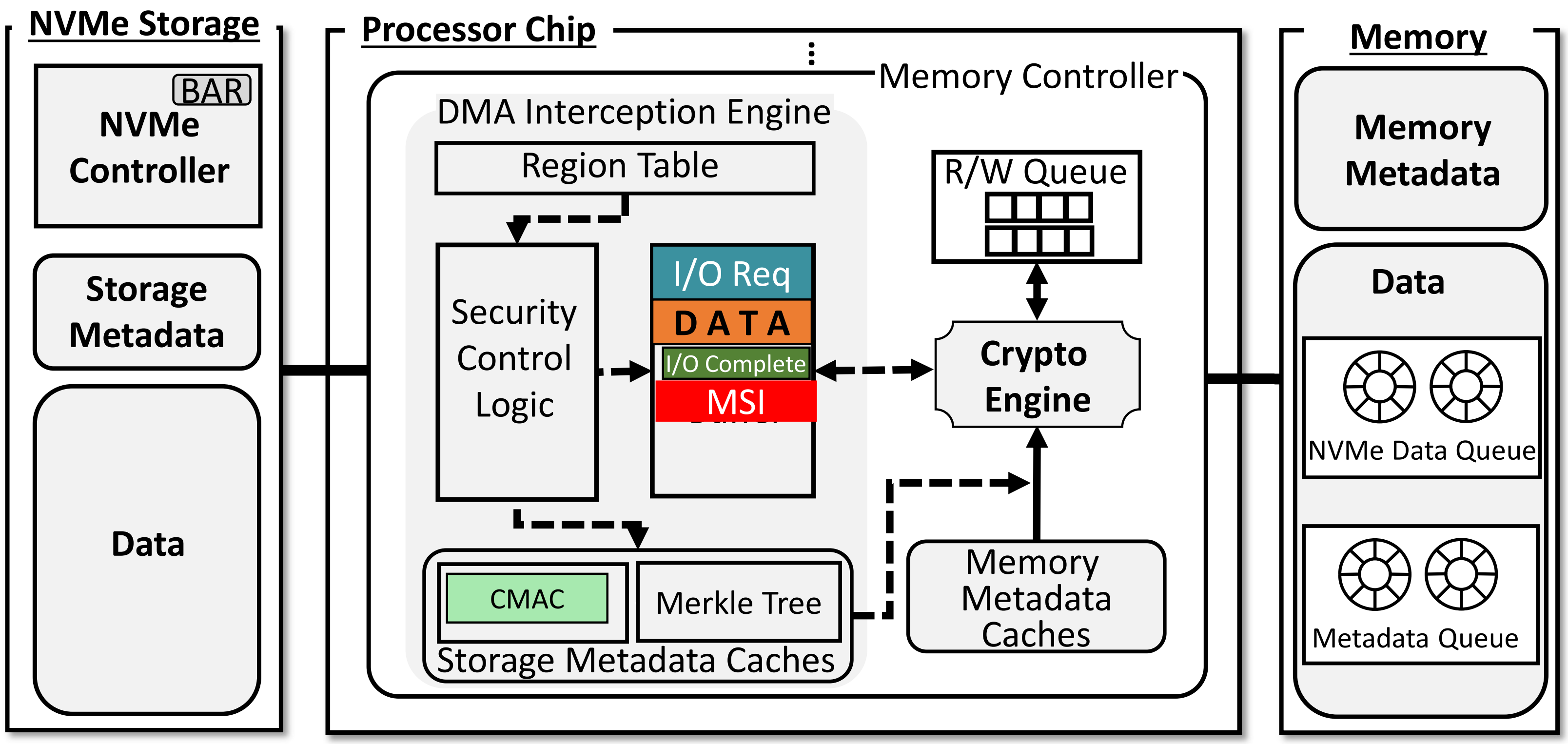

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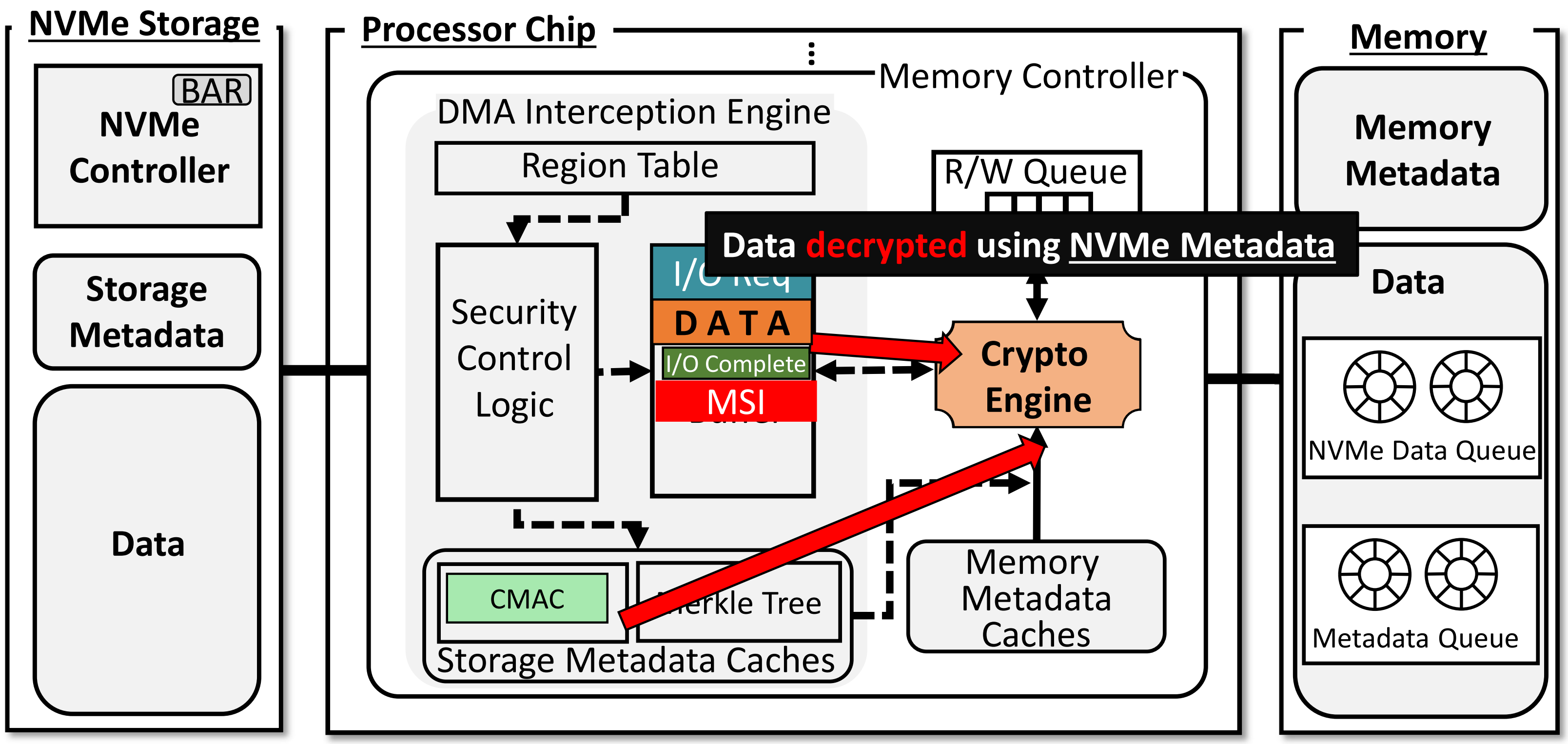

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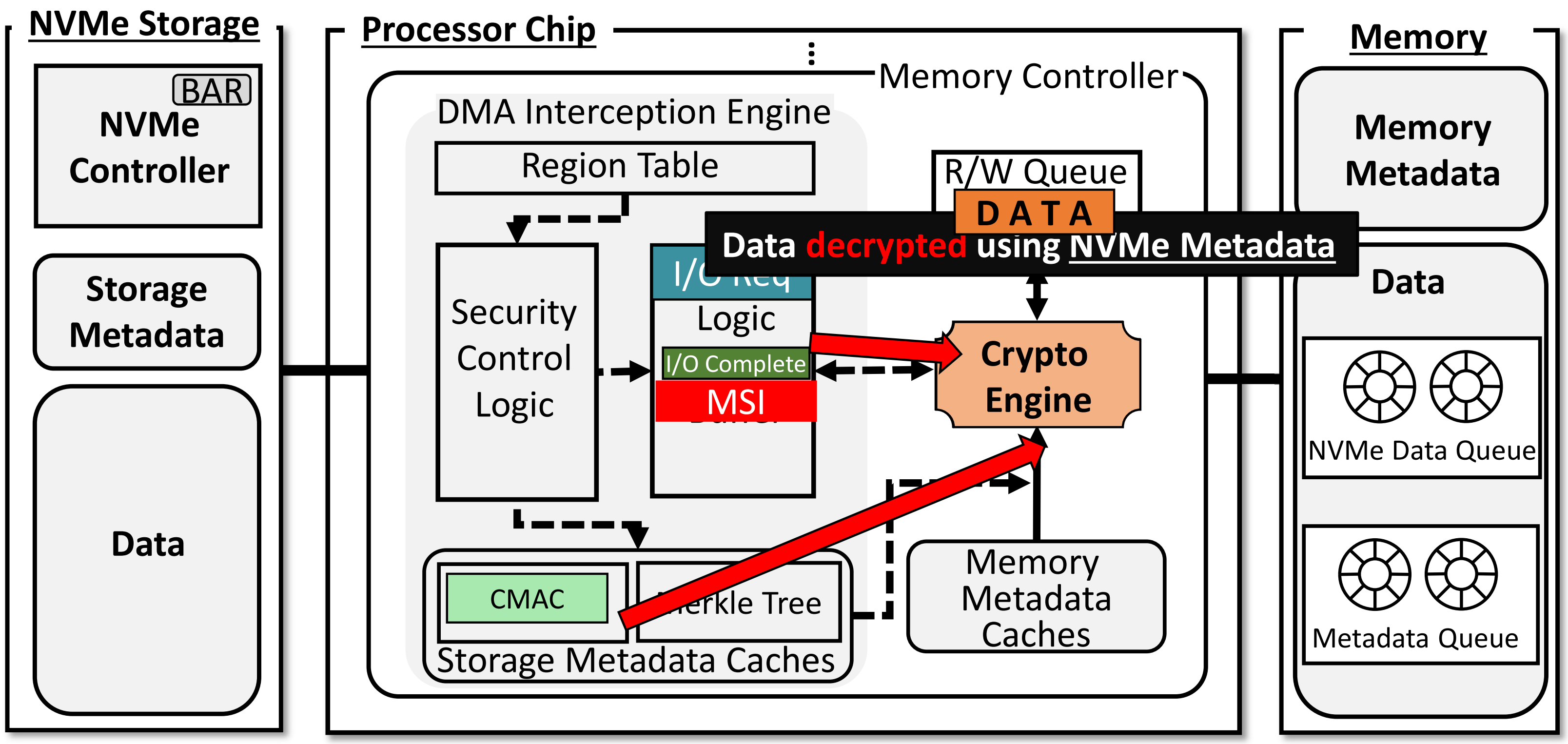

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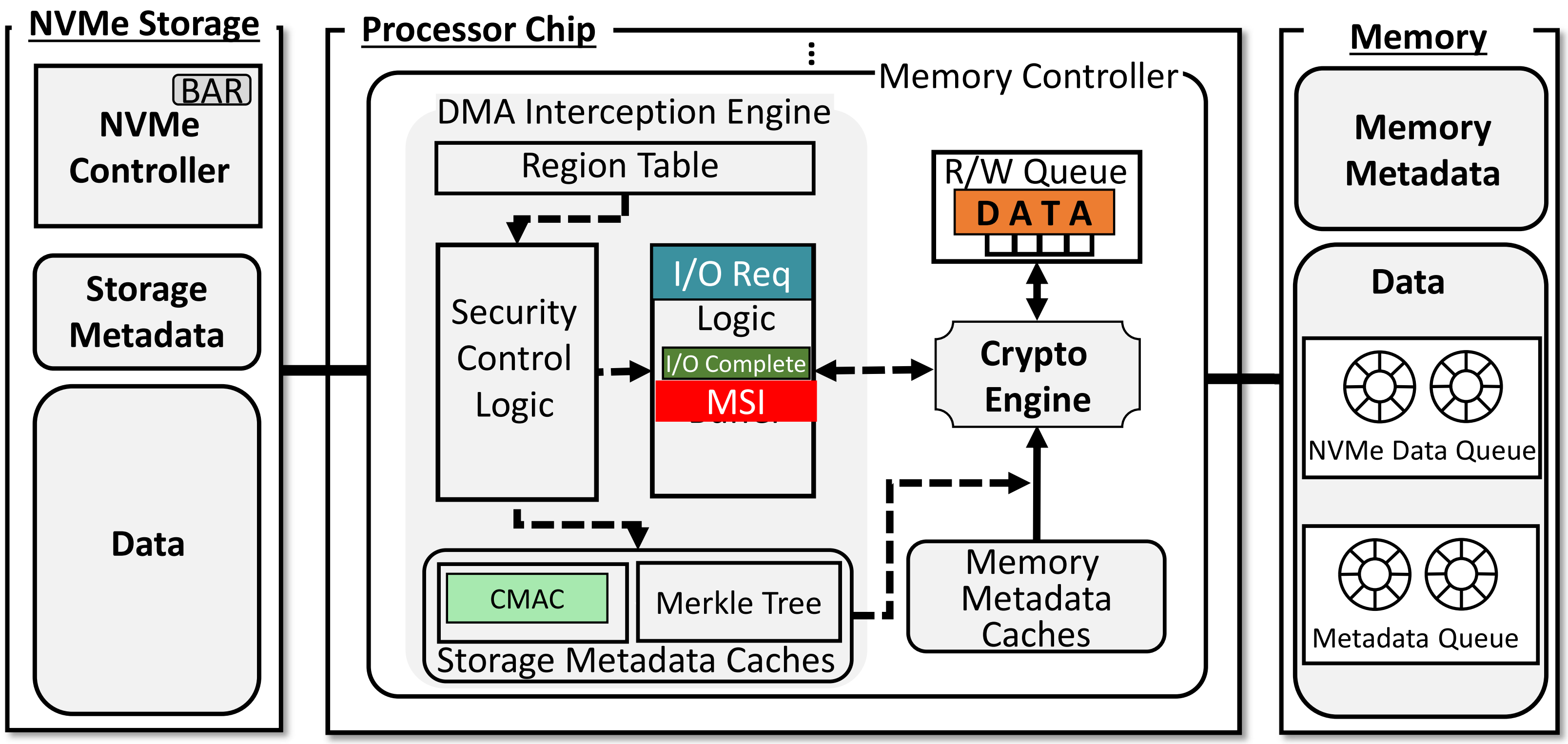

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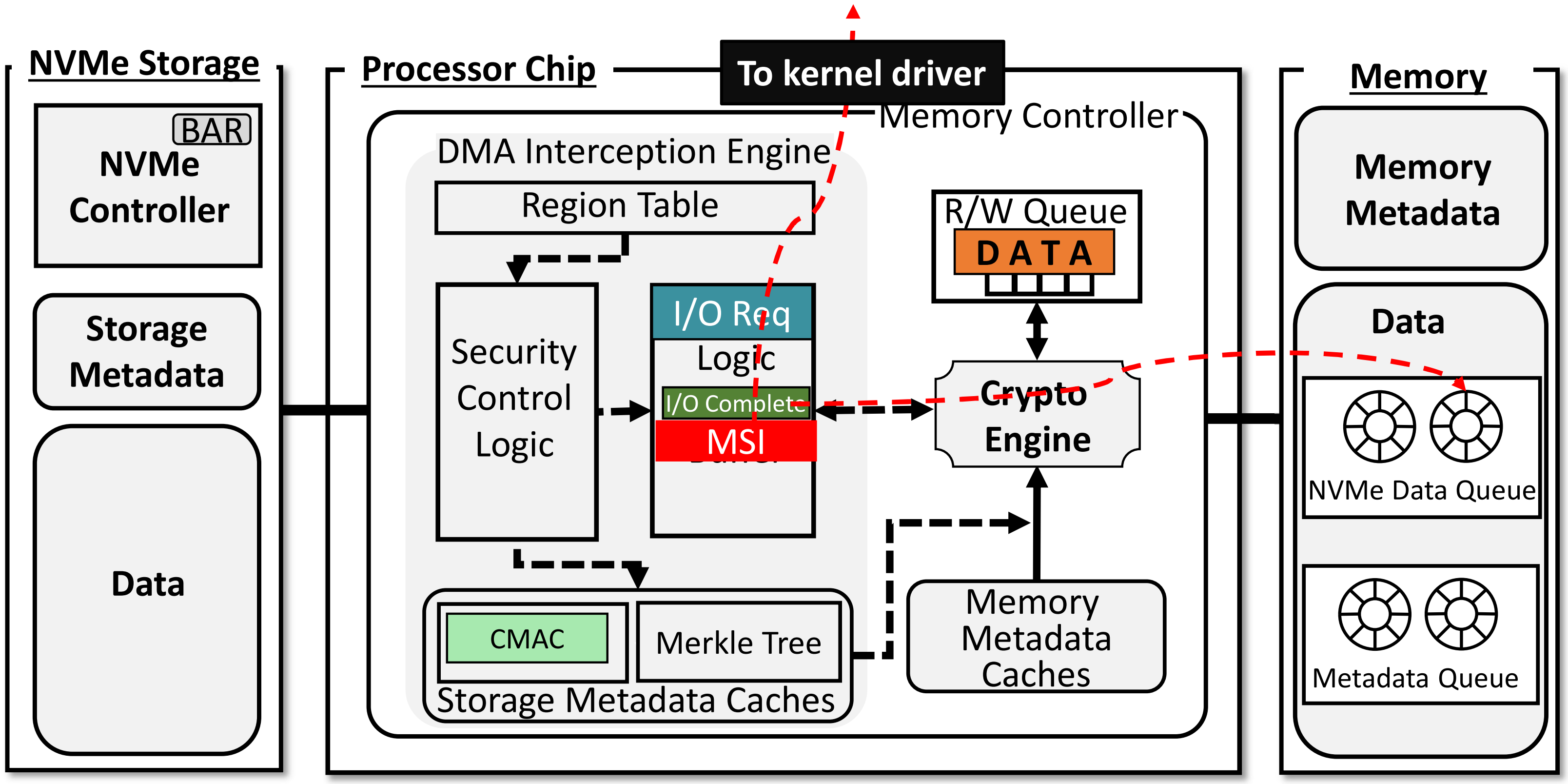

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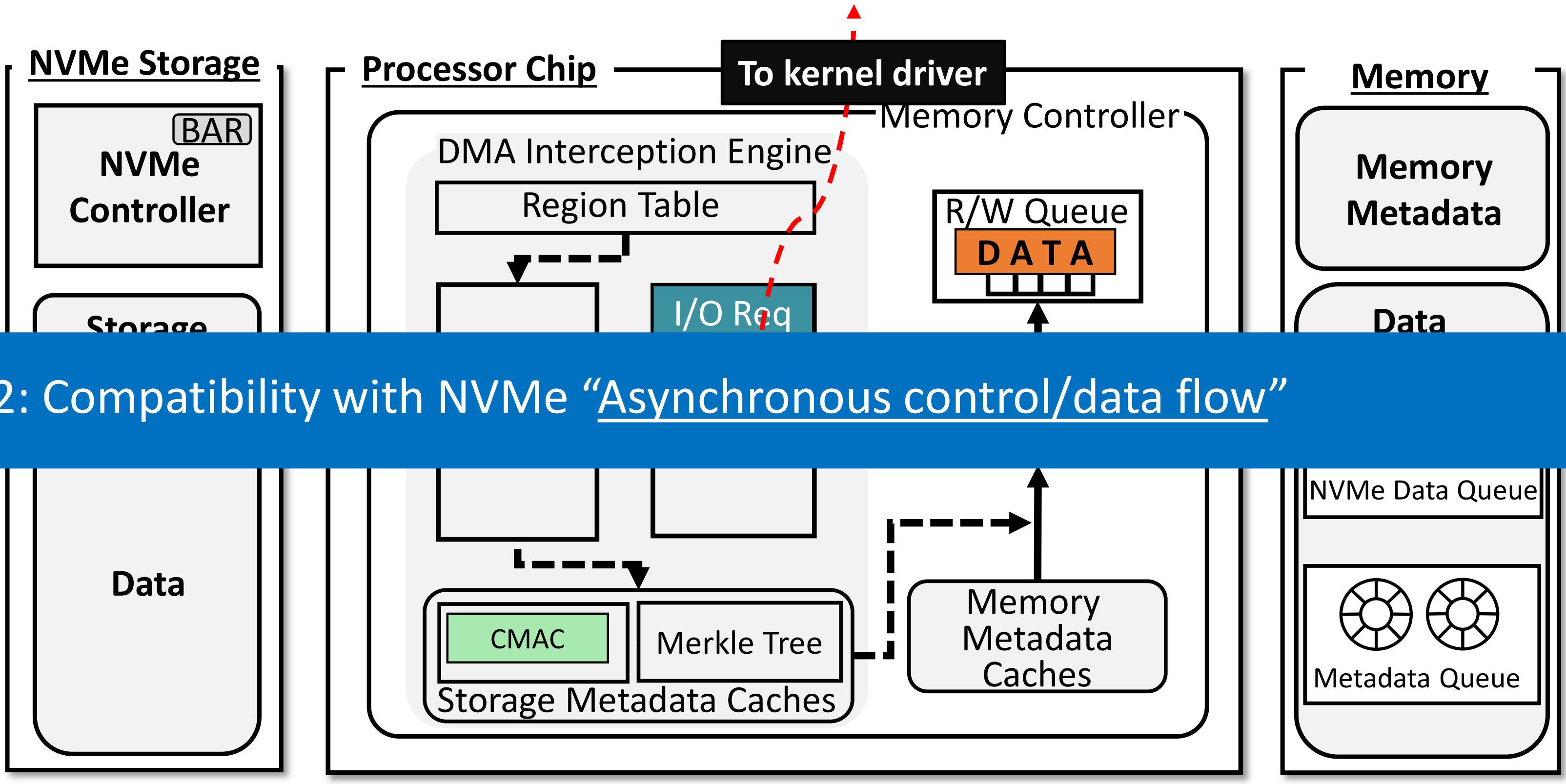
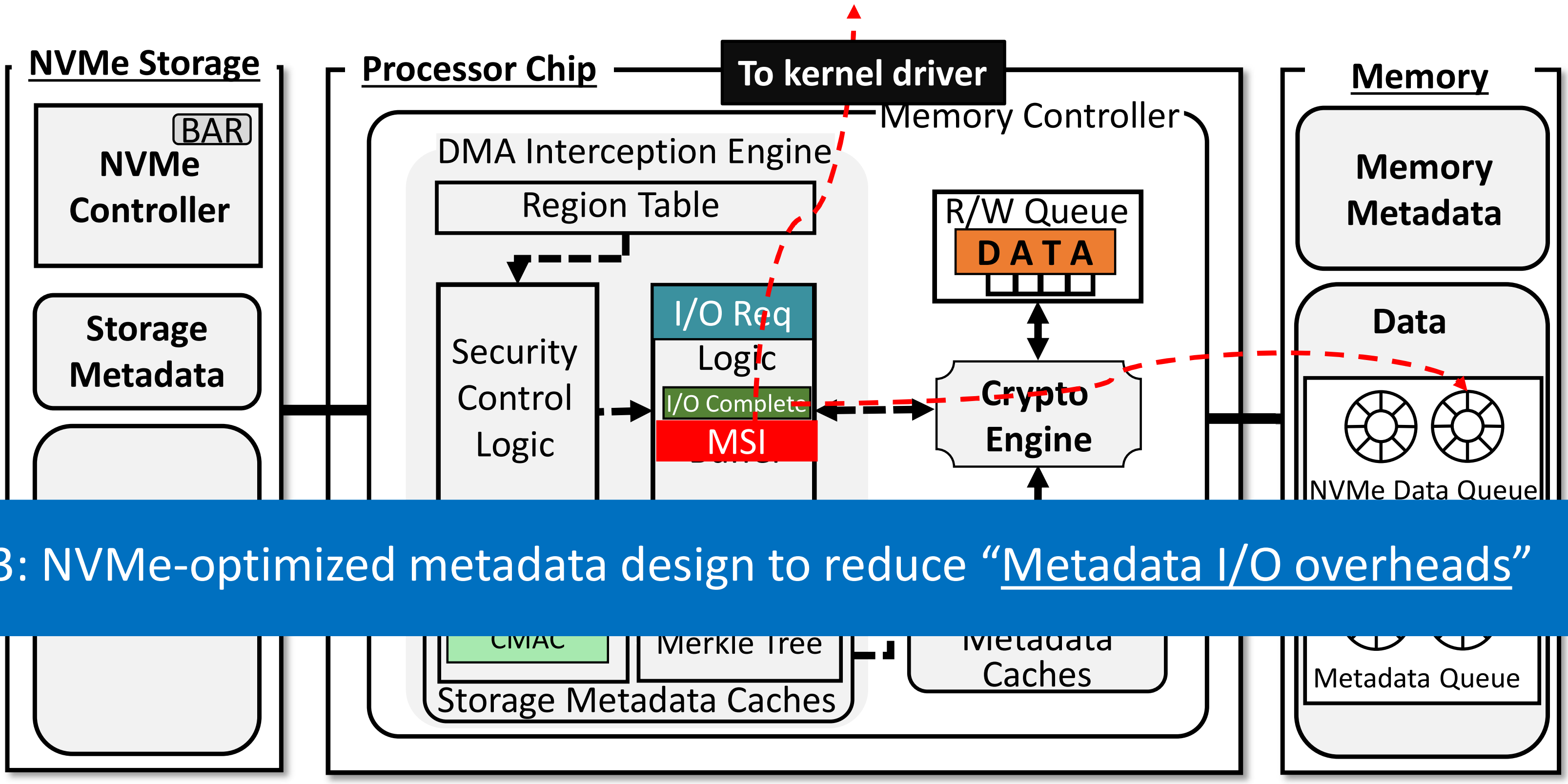


C2: Compatibility with NVMe "Asynchronous control/data flow"

D-Shield Operation (Read)



C3: NVMe-optimized metadata design to reduce "Metadata I/O overheads"

D-Shield-Hyb: Cross Domain Access Optimization

- Basic D-Shield provides proper off-chip data security with standalone protection for memory and storage

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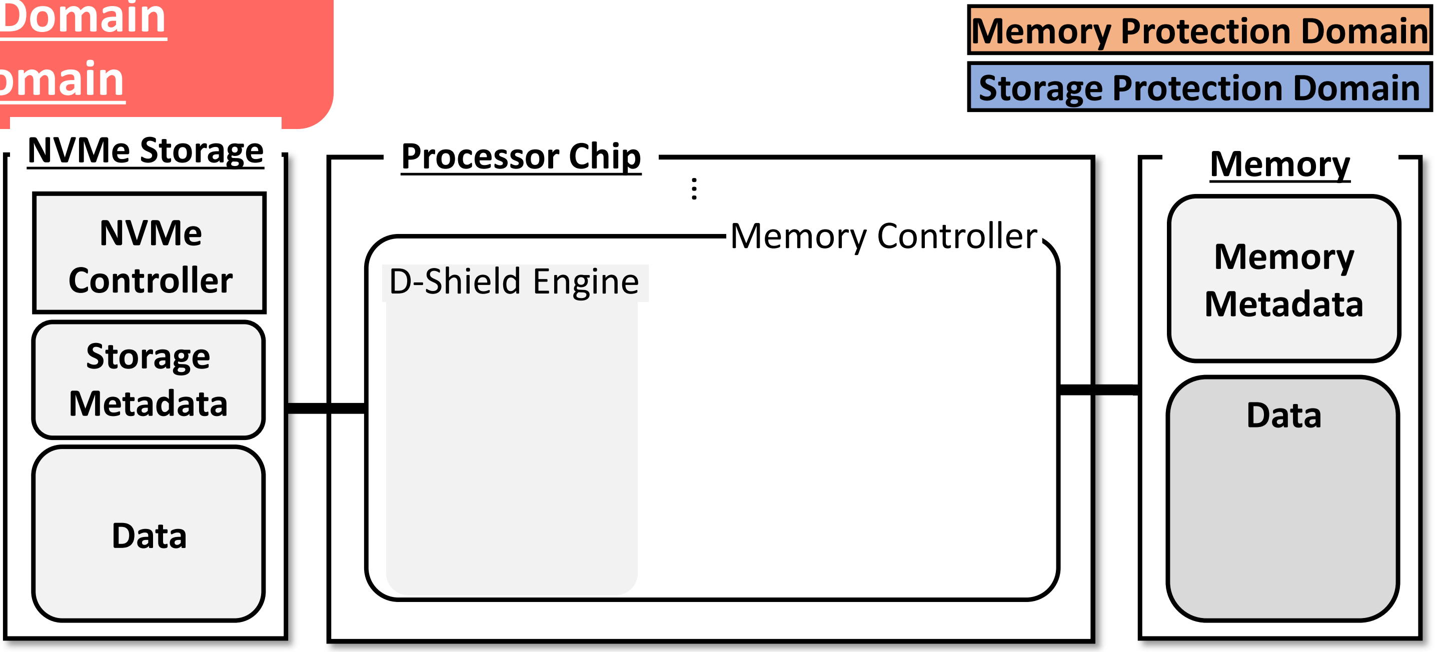
Cross-domain data transfer:
From Storage Domain
To Memory Domain



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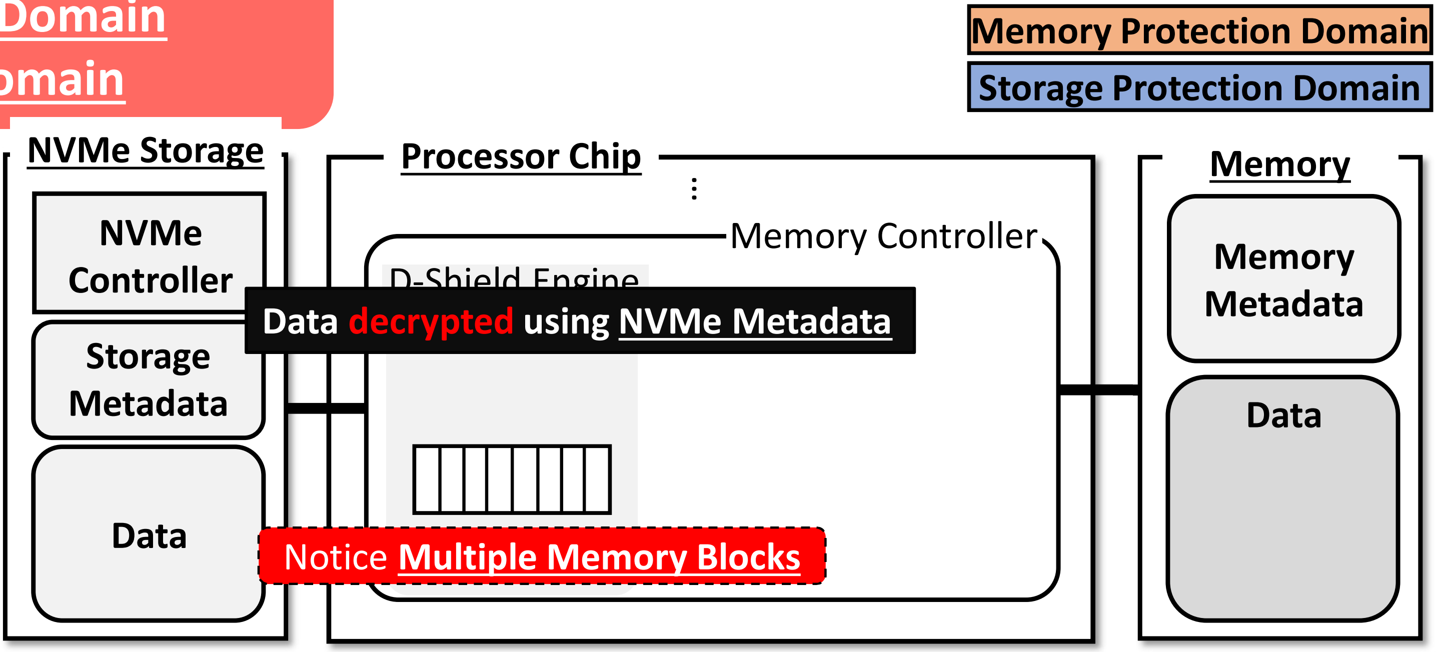

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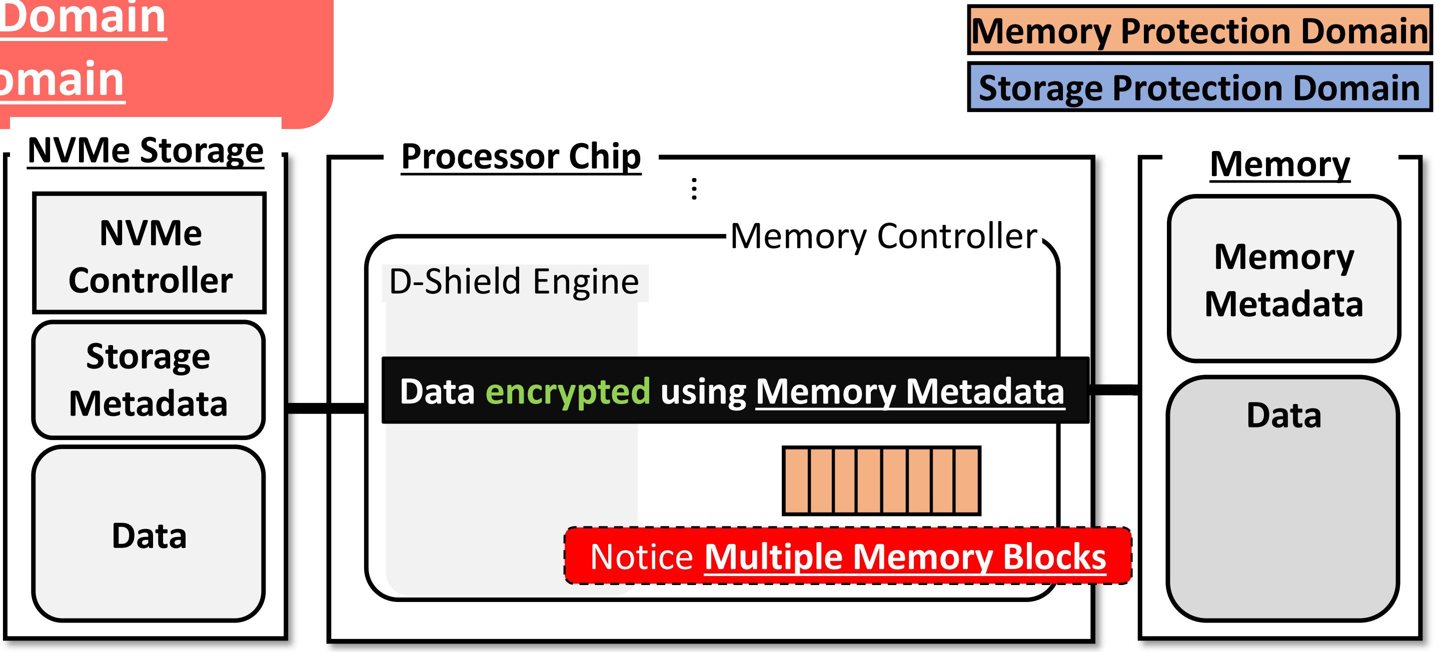

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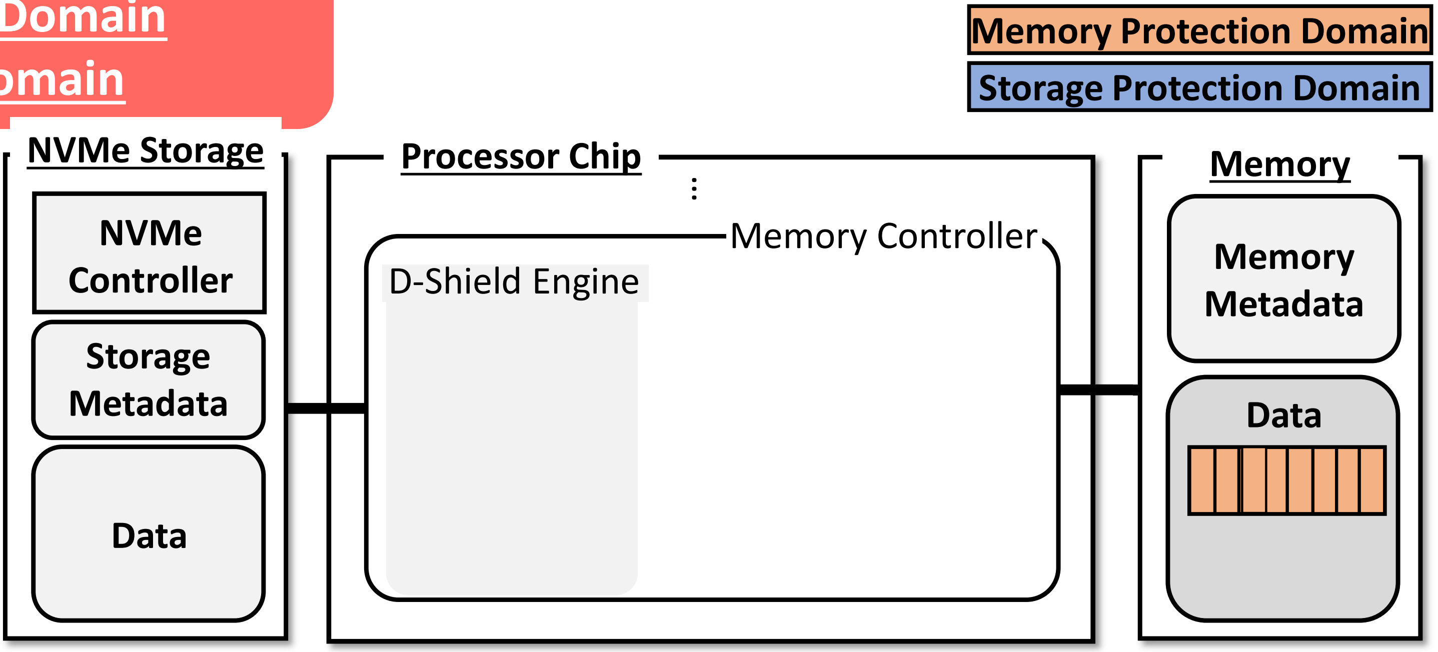

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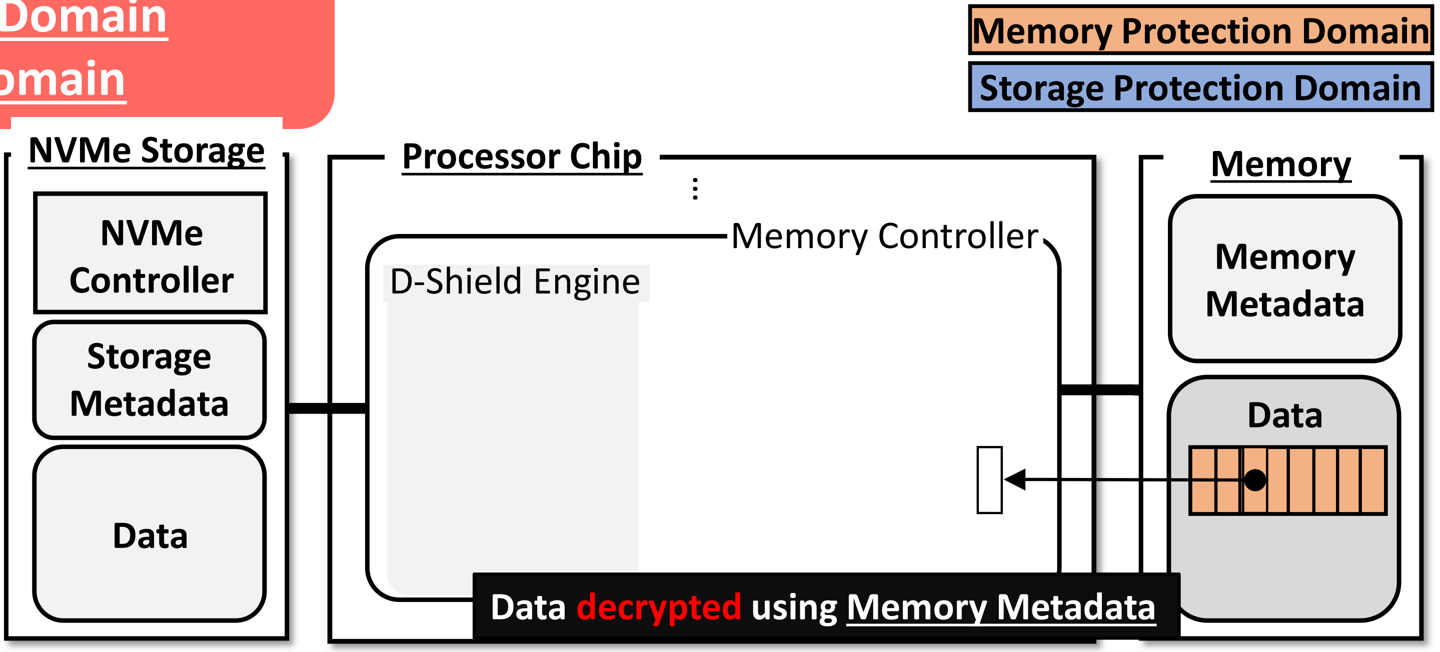

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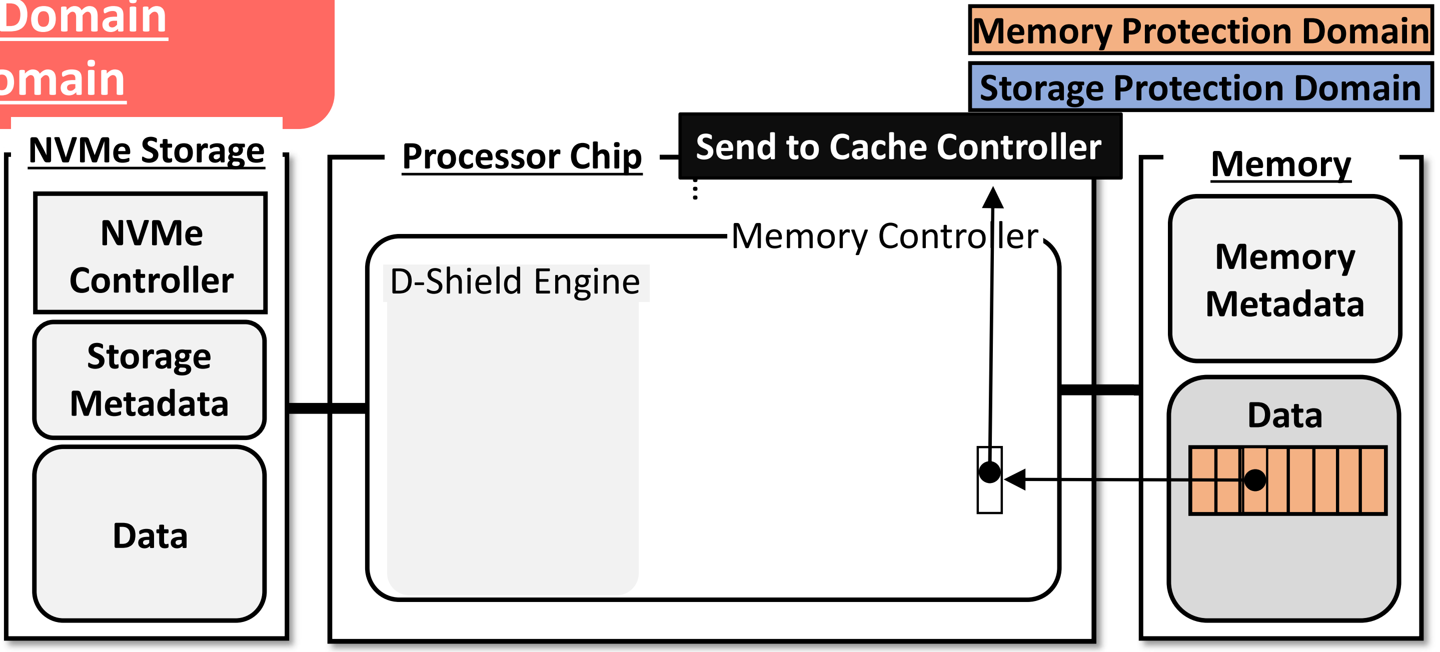
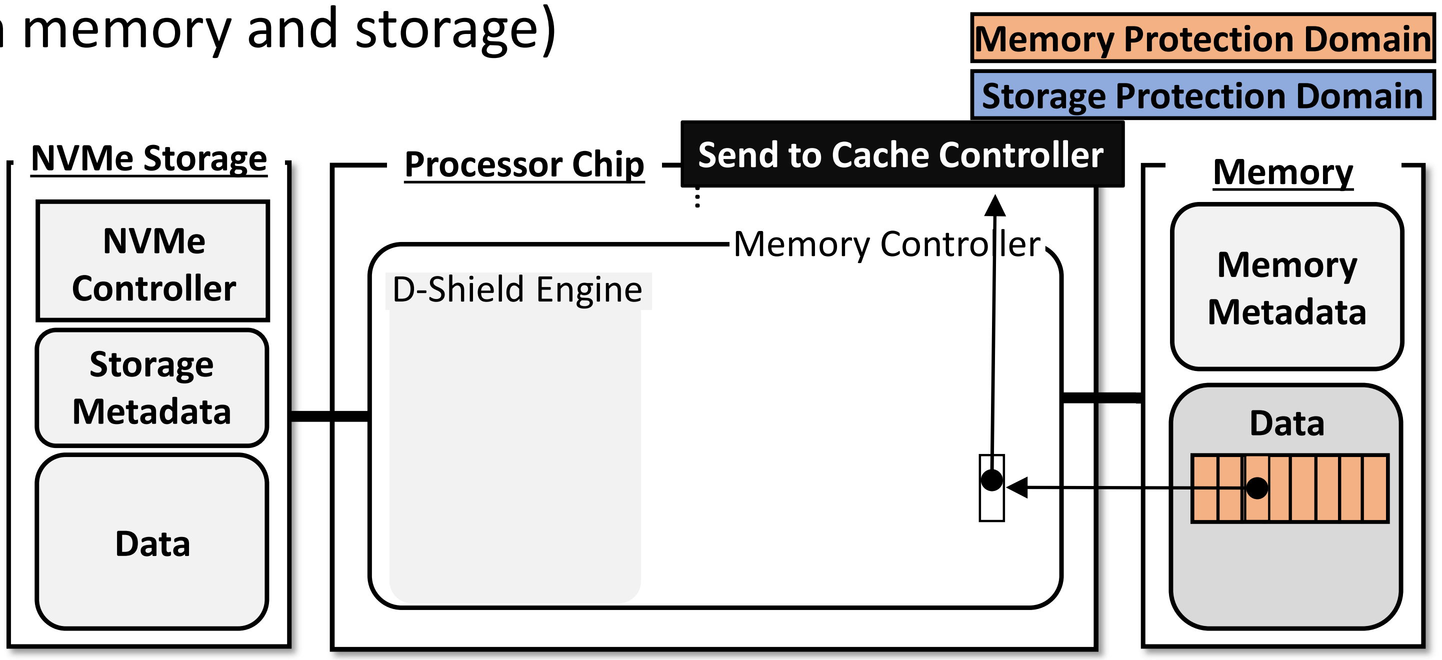


D-Shield-Hyb: Cross Domain Access Optimization

- Basic D-Shield provides proper off-chip data security with standalone protection for memory and storage
- Re-encryption of data is needed as it transfers between domains (i.e., between memory and storage)



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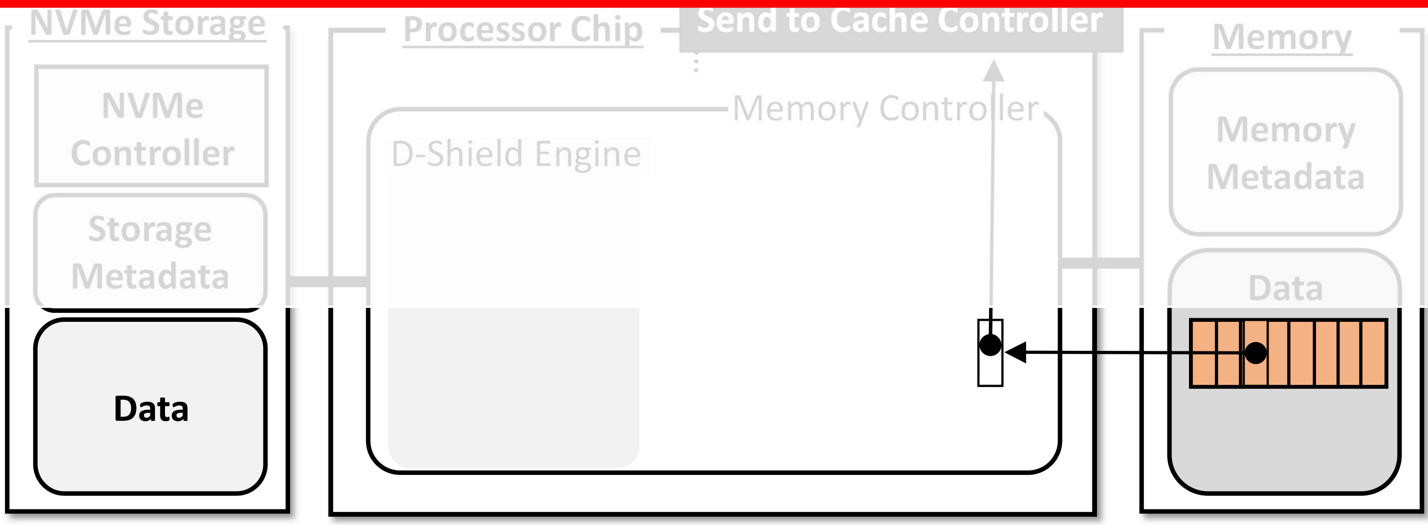
D-Shield-Hyb: Cross Domain Access Optimization

- Basic D-Shield provides proper off-chip data security with standalone protection for memory and storage

Moving data between protection domains (i.e., memory and storage) can be *expensive*

Additional utilization of the cryptographic engine

Prolonged NVMe data path



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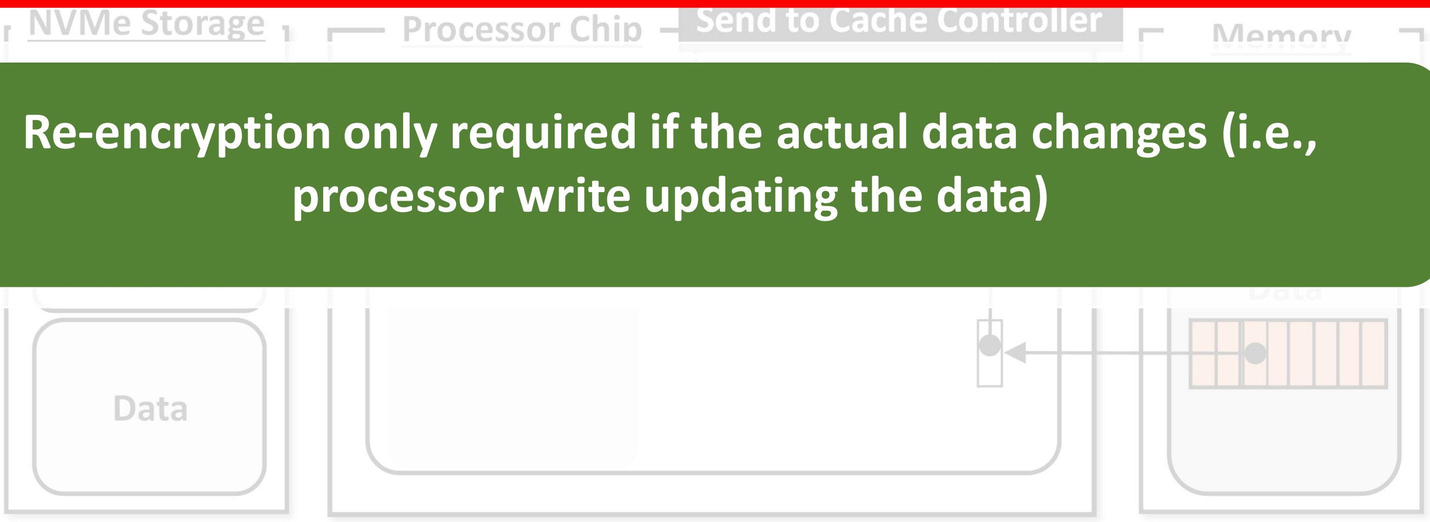

Re-encryption only required if the actual data changes (i.e., processor write updating the data)

D-Shield-Hyb: Cross Domain Access Optimization

- Bookkeep the ownership of logic blocks **in memory**

D-Shield-Hyb: Cross Domain Access Optimization

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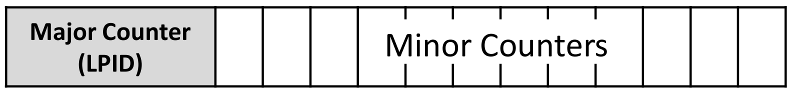

Memory counter block (Original)

D-Shield-Hyb: Cross Domain Access Optimization

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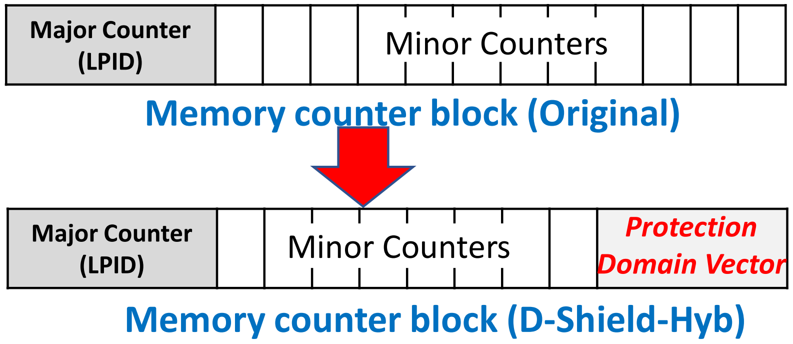

D-Shield-Hyb: Cross Domain Access Optimization

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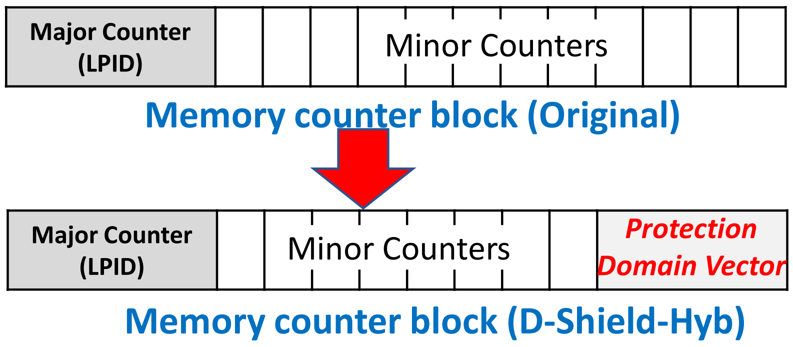
- Track the security domain for transferred data block



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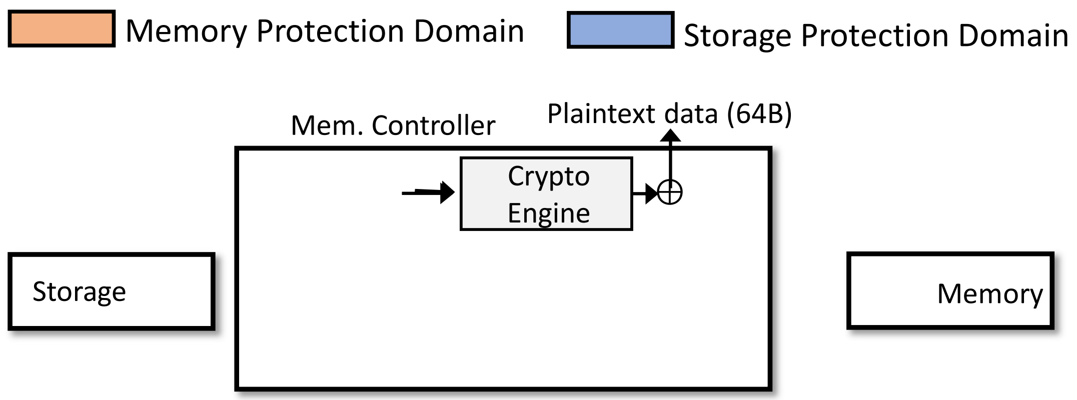

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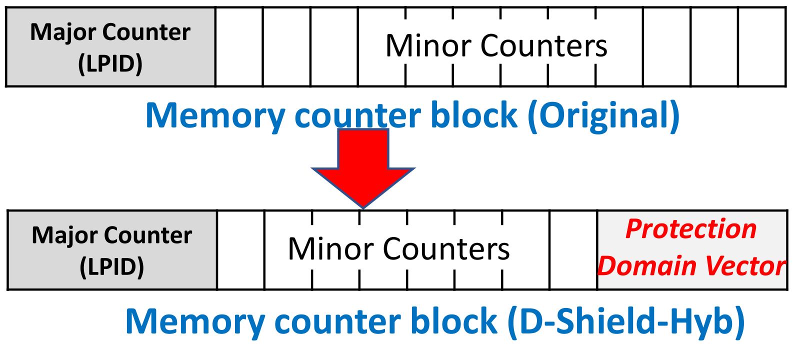

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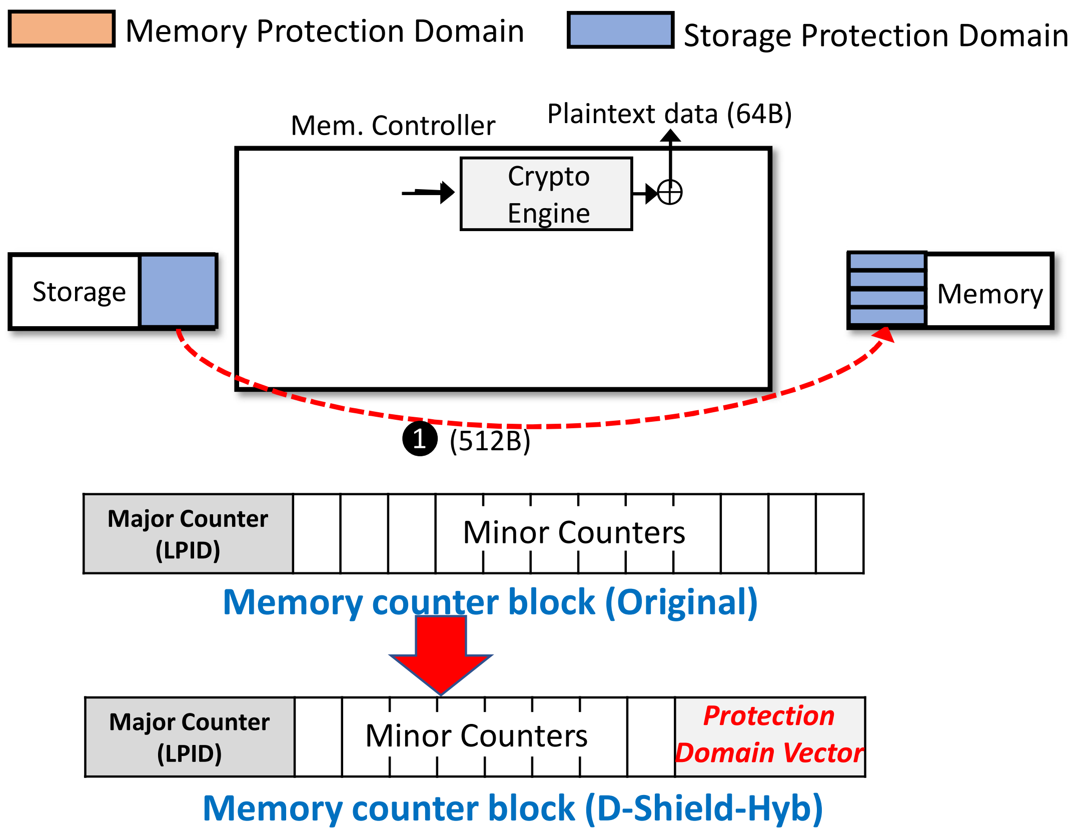

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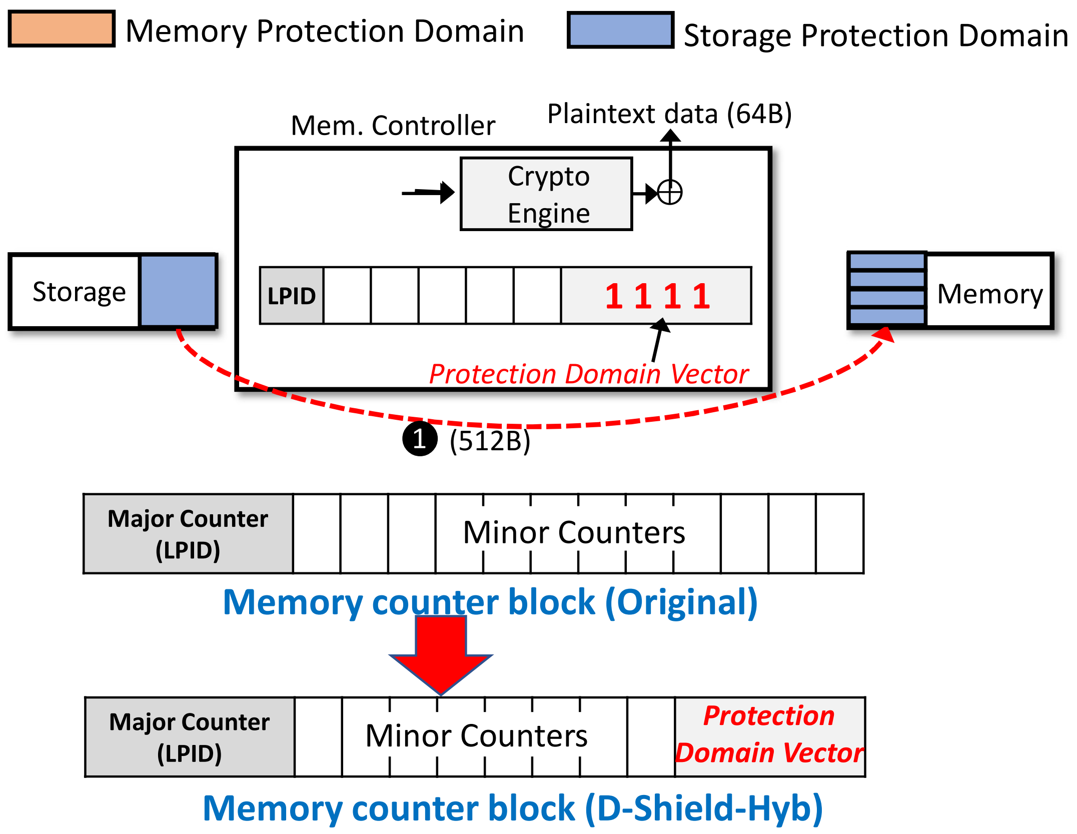

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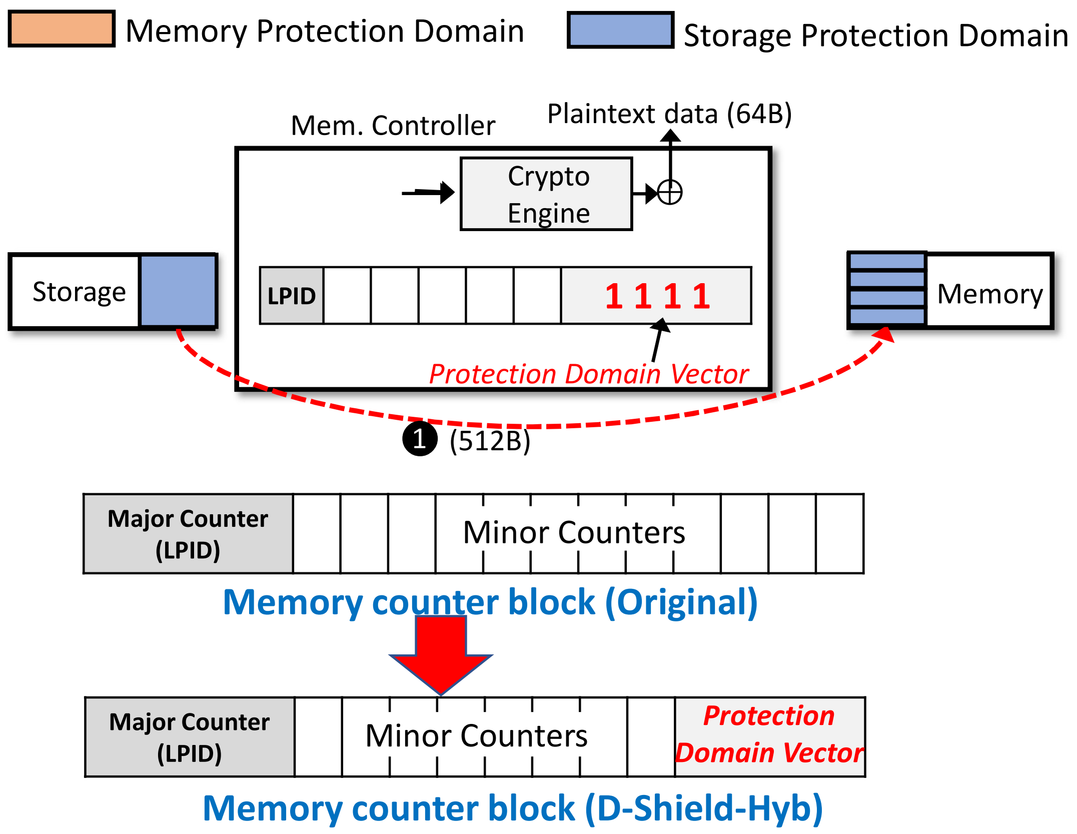

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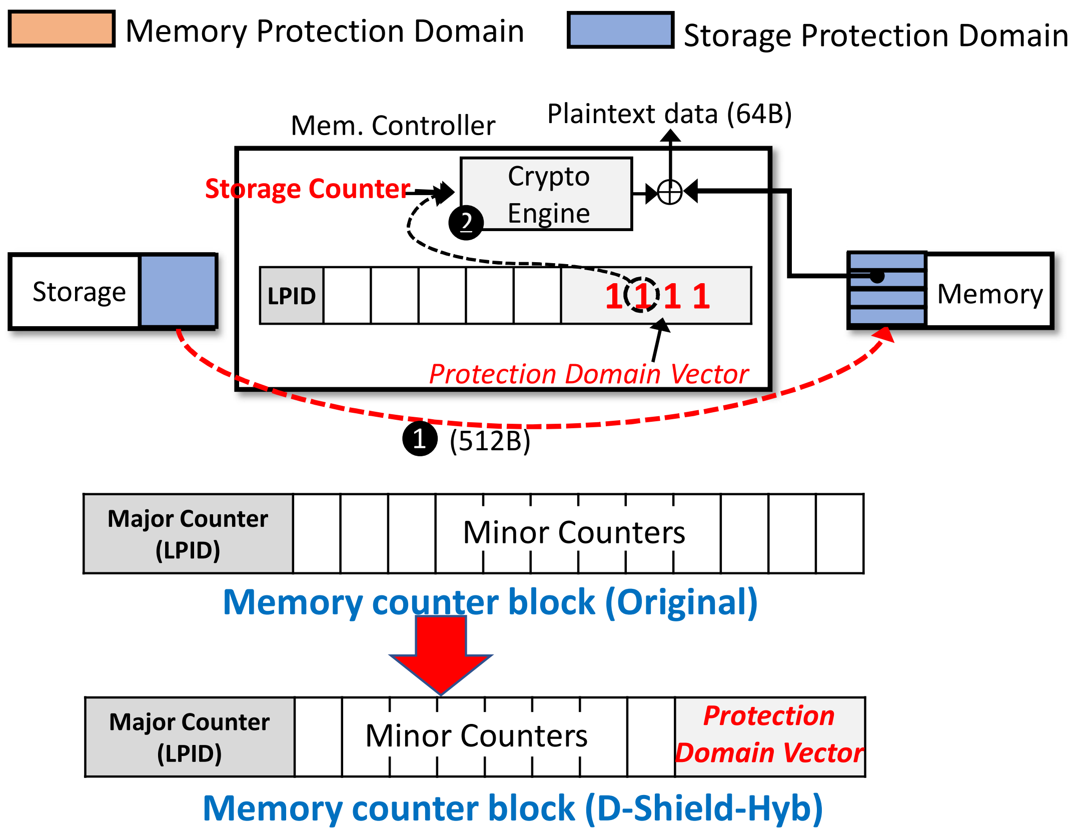

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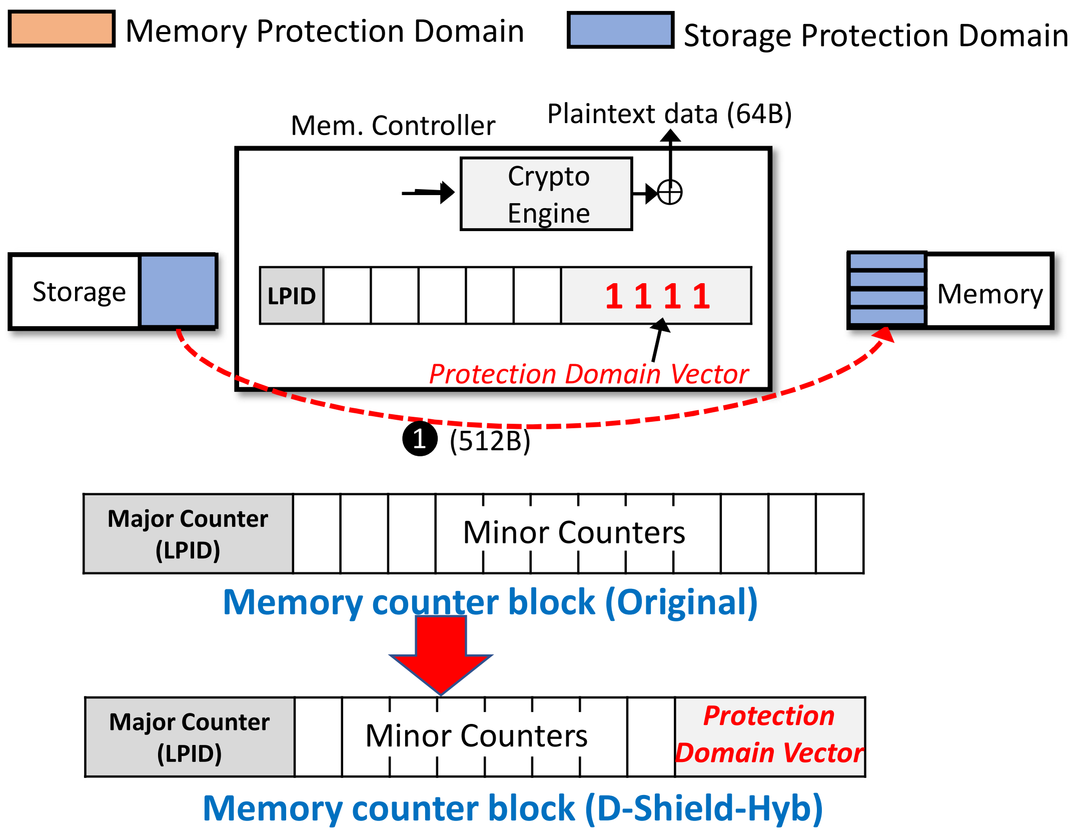

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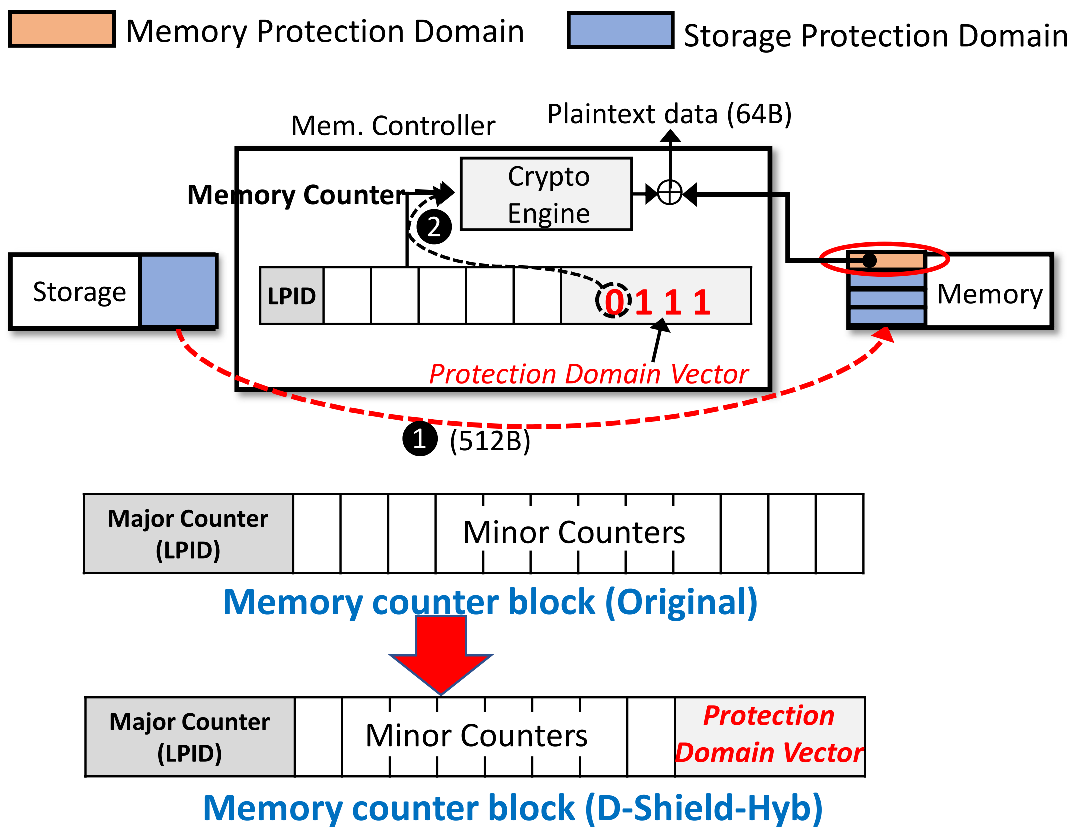

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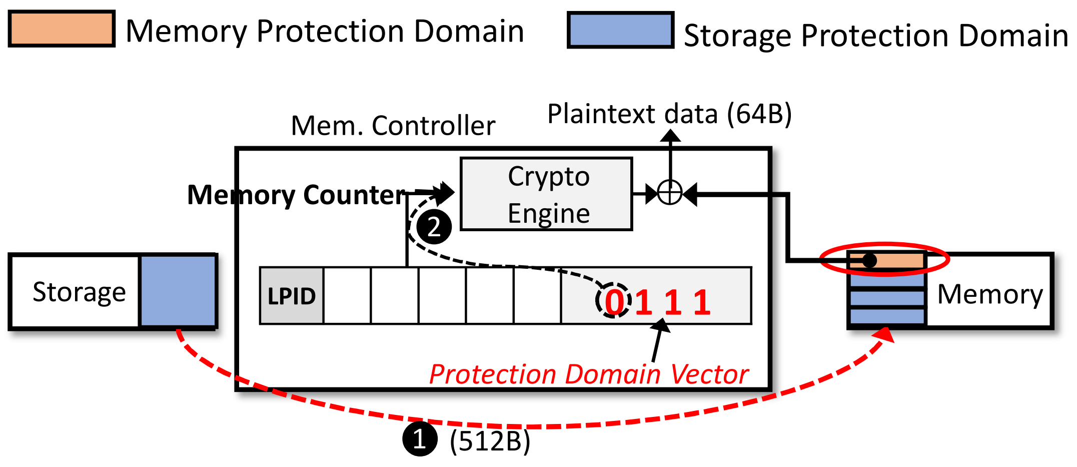

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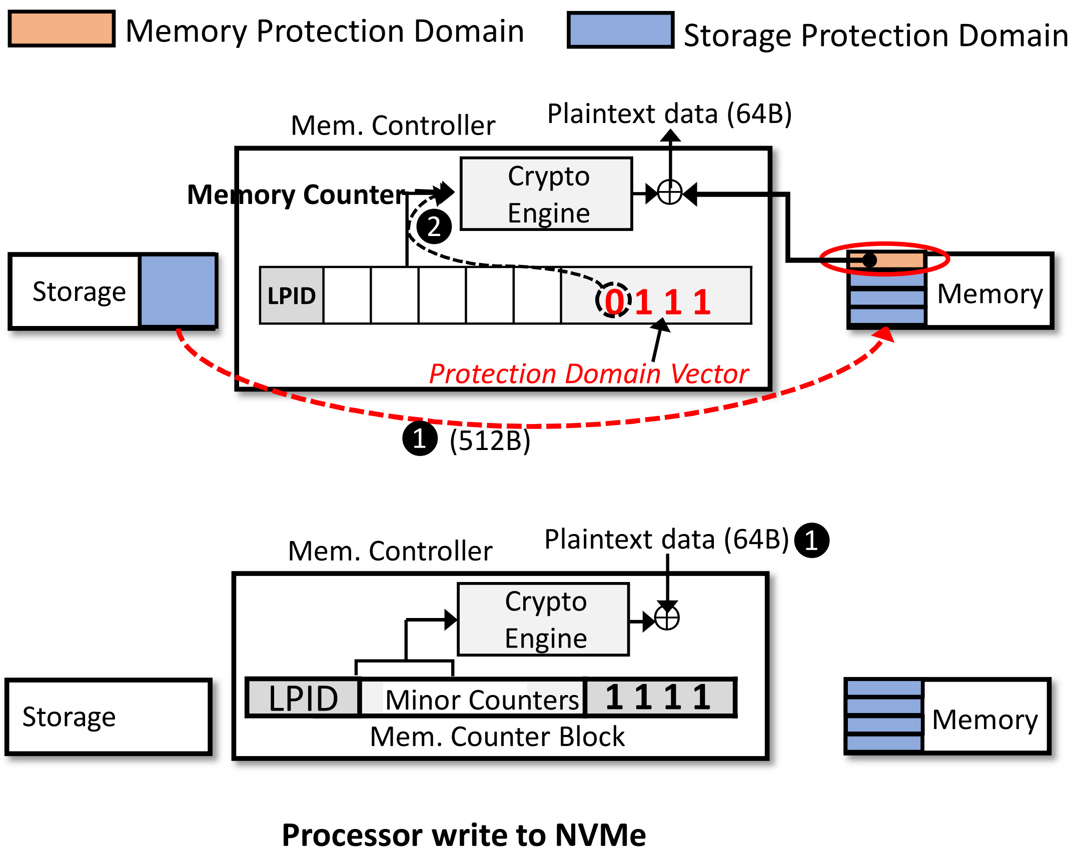

Processor write to NVMe

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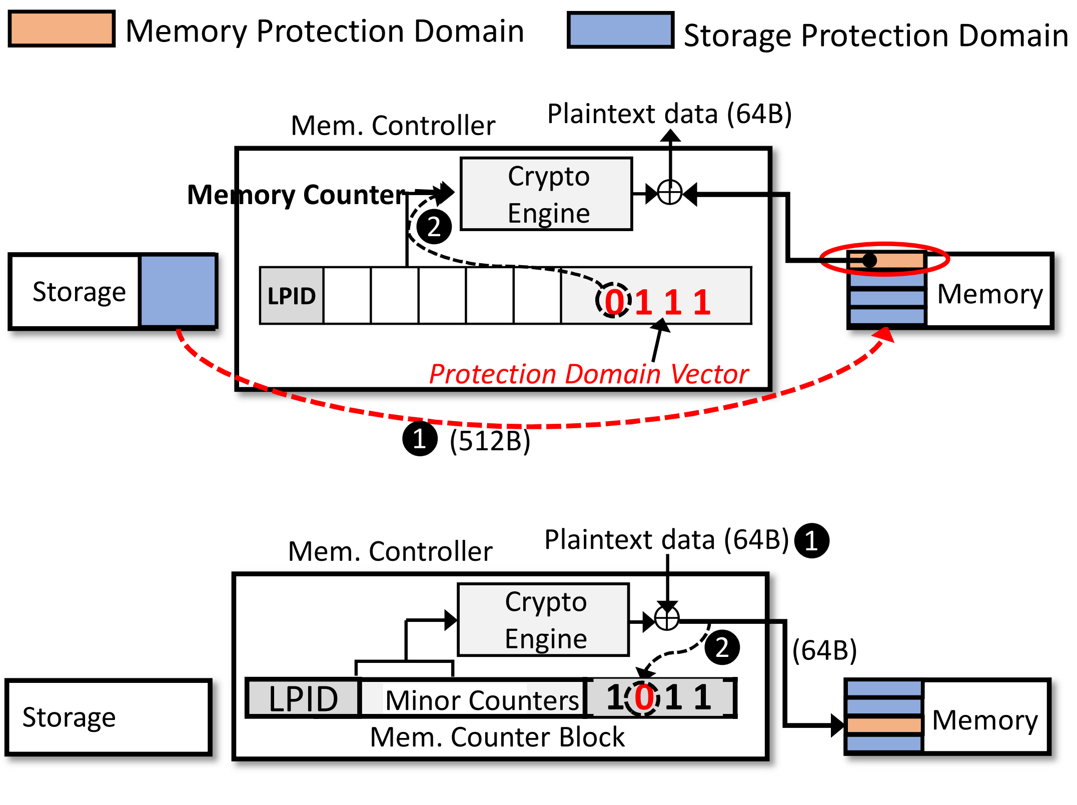

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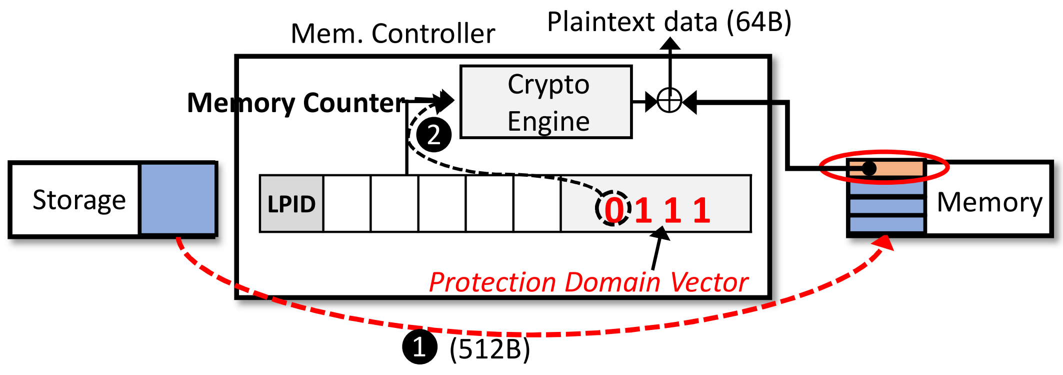
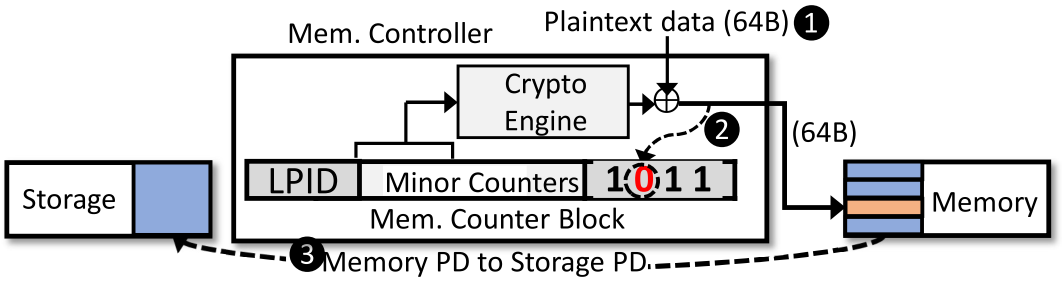
🟧 Memory Protection Domain 🟦 Storage Protection Domain





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D-Shield-Pro: In-Memory Caching

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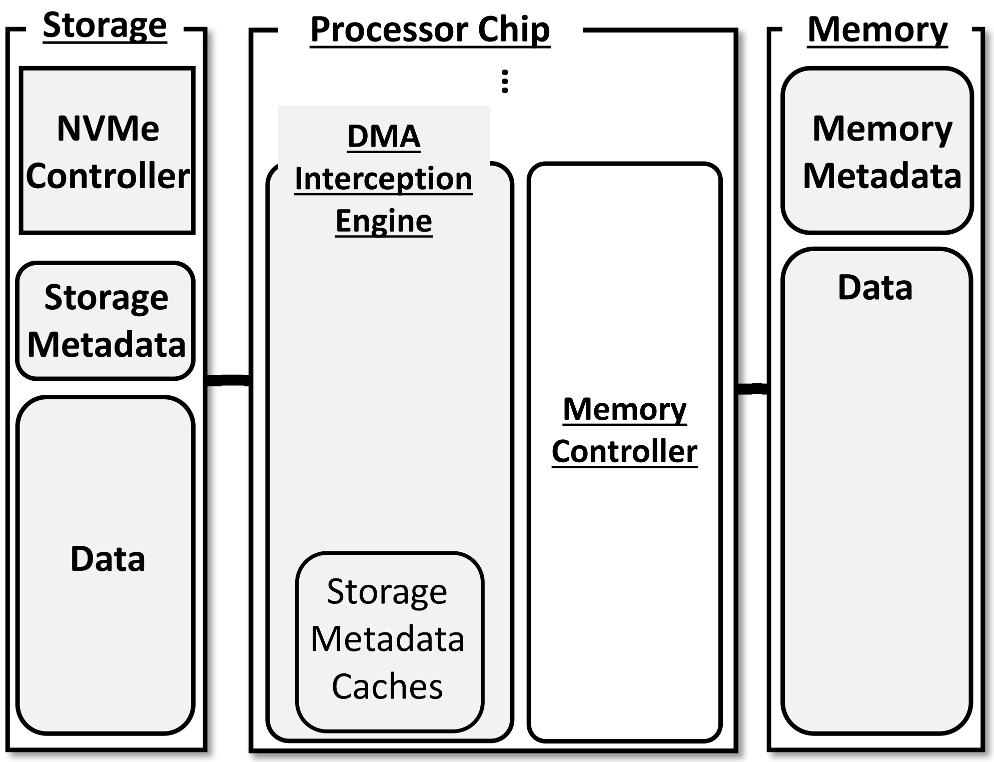

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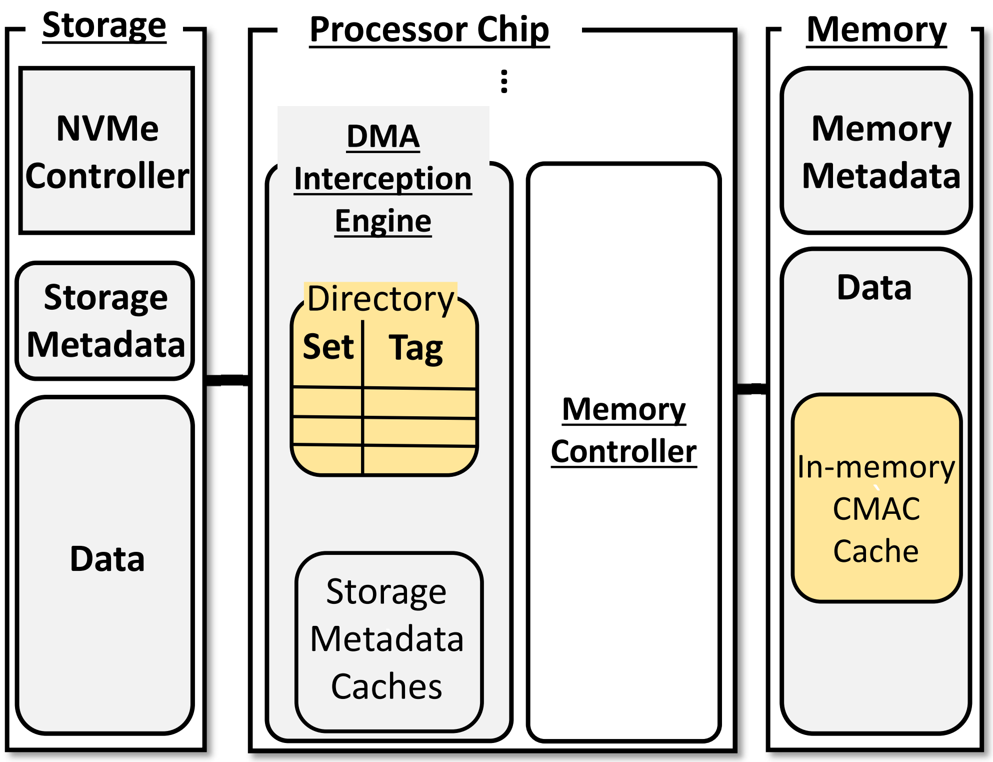

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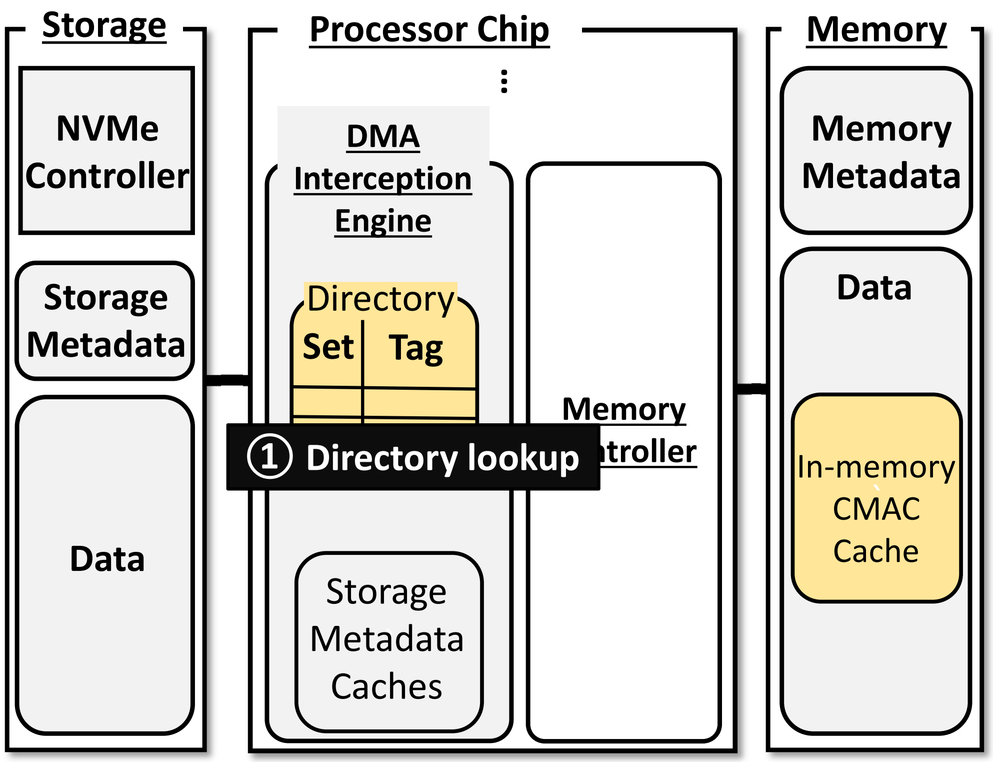

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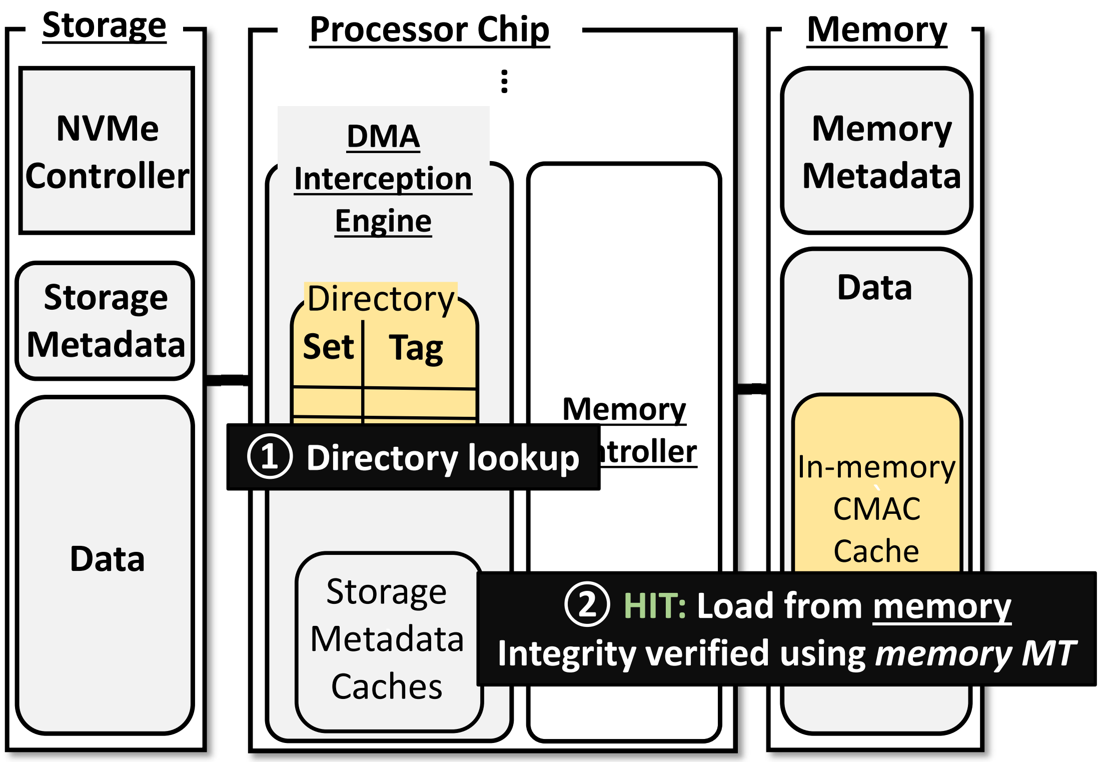

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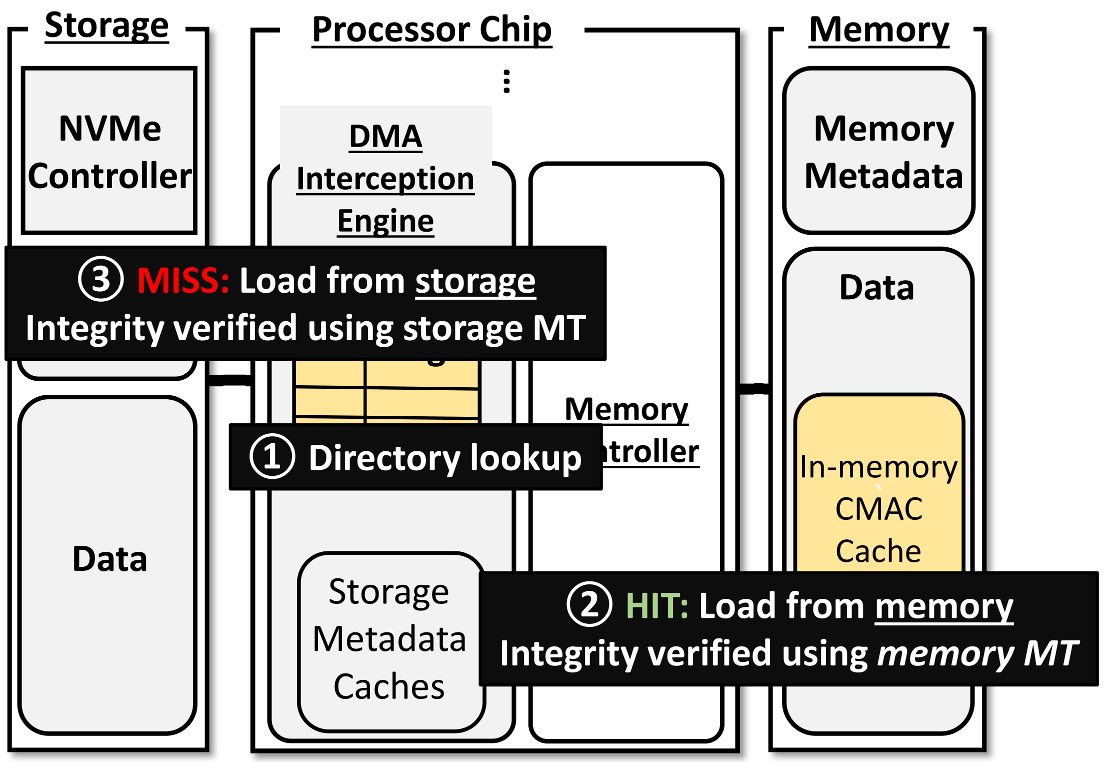

UCF

Experimental Setup

- **Simulator:** Gem5-based full-system simulation (SimpleSSD)
- **OS:** Ubuntu 18.04; **Kernel:** Linux 4.9

Hardware	***Configurations***
Processor	4-core, 3.0 GHz in-order, x86
L1 I/D-cache	Private, 64KB, 4-way
L2 cache	Shared, 16MB, 16-way
Main memory	DDR4 based 16GB
Cryptographic Engine	
Encryption/Hash operation (64B)	40 cycles
DMA Interception Engine	
Metadata cache	256KB 8-way each
Hash operation (512B)	320 cycles
NVMe Disk	
Capacity	512GB
Cell model	Z-NAND based MLC PCM
Avg. random access latency(µS)	READ: 10.5, WRITE: 9

Evaluation Methodology

❖ **Workloads:**

- **I/O intensive applications:** Flexible I/O
- **Server-class applications:** database, document storage system
- **Graph algorithms:** YCSB suite (twitter follow network)

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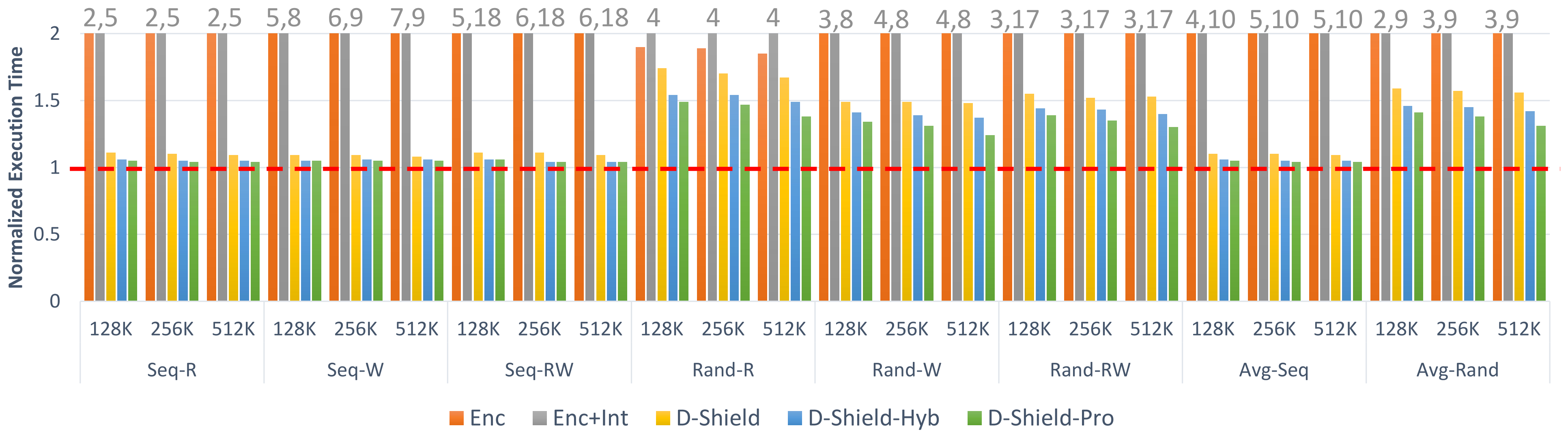
❖ **Baselines (All variants include *secure memory*):**

- **Insecure:** Default NVMe storage system without security mechanism
- **Enc:** dm-crypt-based encryption for NVMe storage system
- **Enc+Int:** dm-crypt with dm-integrity for NVMe disk encryption and integrity checking

Evaluations: D-Shield Performance



# of transactions (from left to right): **128K, 256K, 512K**

Runtime (normalized to Insecure) of FIO benchmark

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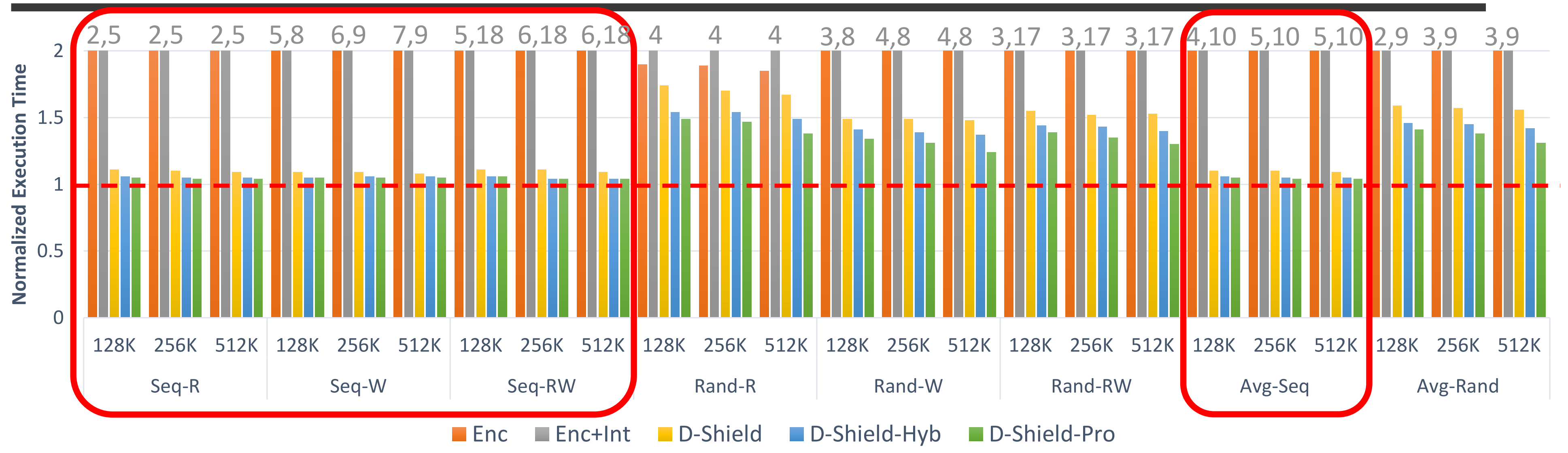

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Runtime (normalized to Insecure) of FIO benchmark

Sequential workloads: 4.4% overhead compared to *Insecure* (Avg)

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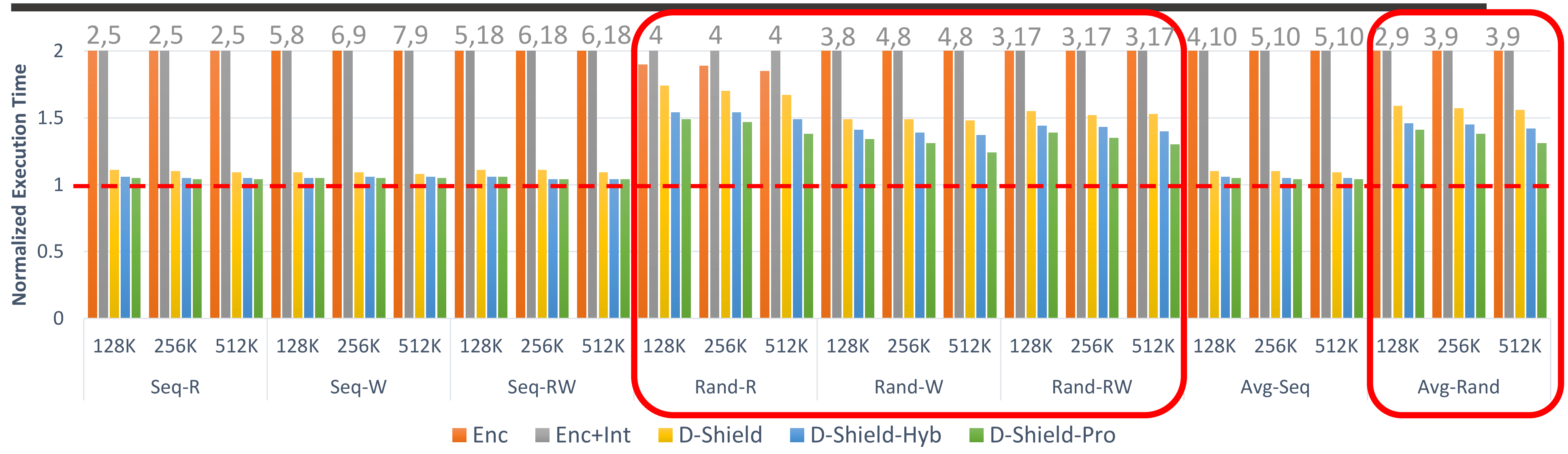

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Runtime (normalized to Insecure) of FIO benchmark

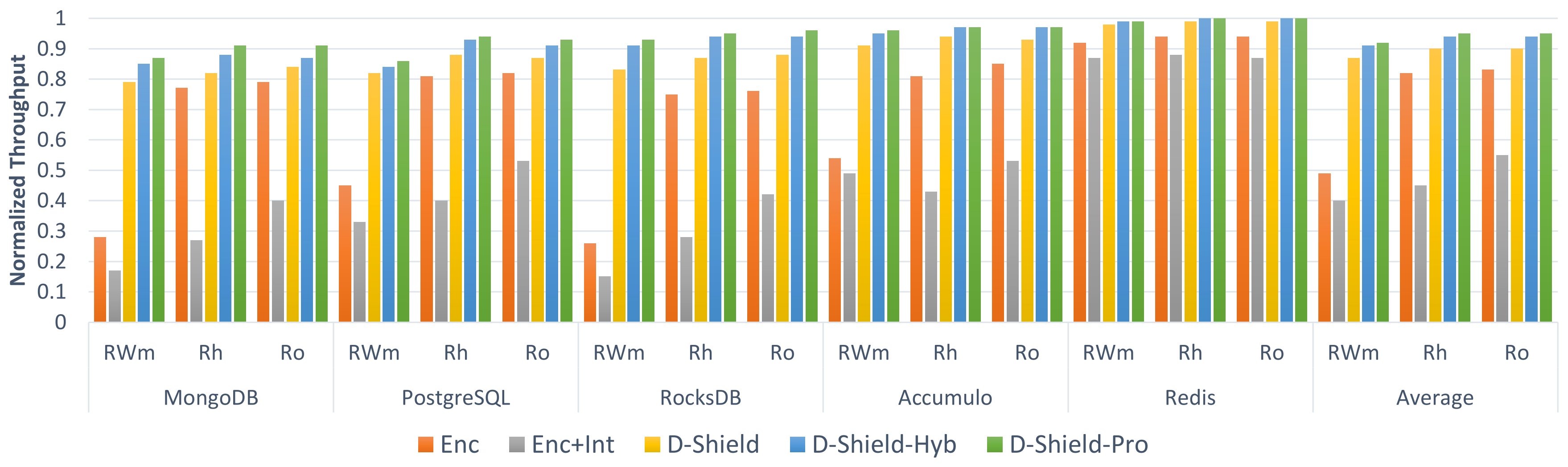
Sequential workloads: 4.4% overhead compared to *Insecure* (Avg)

4.1x less compared to **Enc**, **10x less** compared to **Enc+Int**

Random workloads: 39% overhead compared to *Insecure* (Avg)

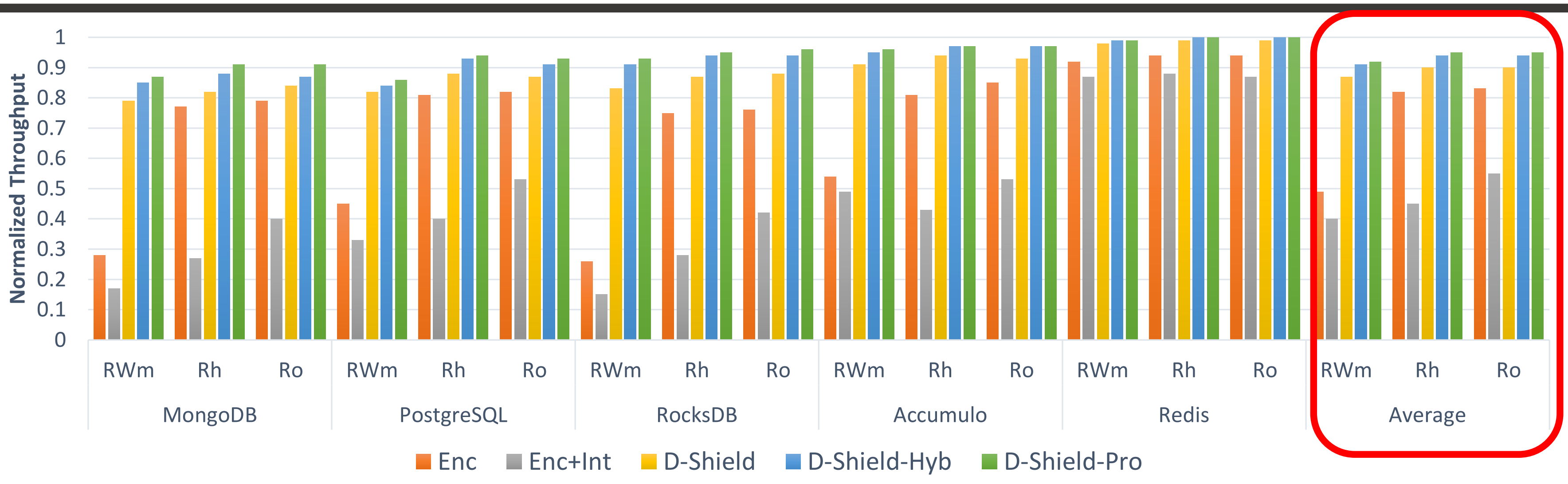
2.05x less compared to **Enc**, **7x less** compared to **Enc+Int**

Evaluations: D-Shield Performance



Throughput of D-Shield on real-world server applications

Evaluations: D-Shield Performance



Throughput of D-Shield on real-world server applications

D-Shield can maintain 94% (Avg) throughput compared to *Insecure*

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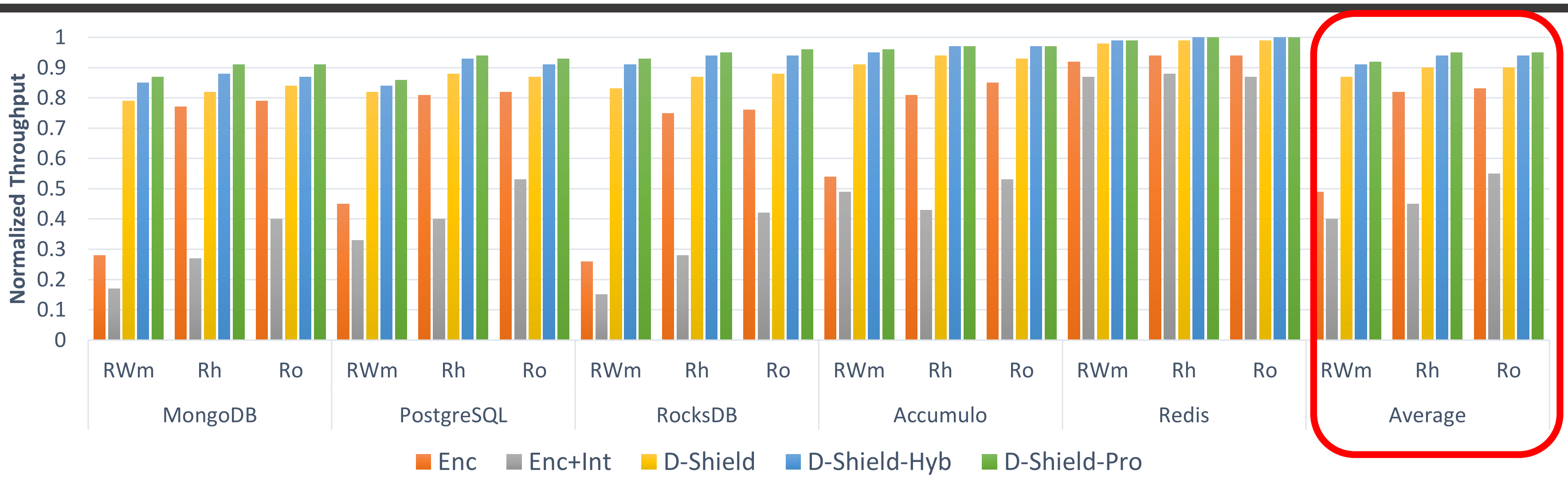

Throughput of D-Shield on real-world server applications

D-Shield can maintain 94% (Avg) throughput compared to *Insecure*

24% higher compared to <u>**Enc**</u> and **49%** higher compared to <u>**Enc+Int**</u>

Evaluations: Hardware Overhead

- NVMe storage overhead: **3.14%** for **Security Metadata**
- On-chip storage overhead: **2x256KB** for **Storage Metadata Caches**

  552 Bytes for **Region Table**
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Module	**Area (mm^2)**
Logic Block Buffer	0.23
Security Control Logic	0.08

UCF

Conclusion

- **Existing storage protection offers limited security and impose high overhead**
- **D-Shield offers architectural framework for processor-side storage security**
- **D-Shield-Hybrid optimizes cross-domain data transfer substantially**
- **D-Shield-Pro reduces metadata overheads through in-memory caching**
- **Modest performance overheads in real-world workloads**
  - While providing state-of-the-art data security

More on Paper

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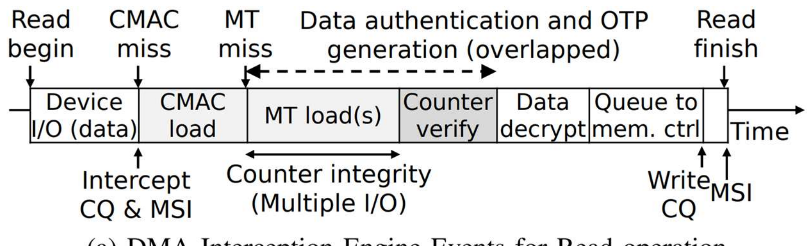
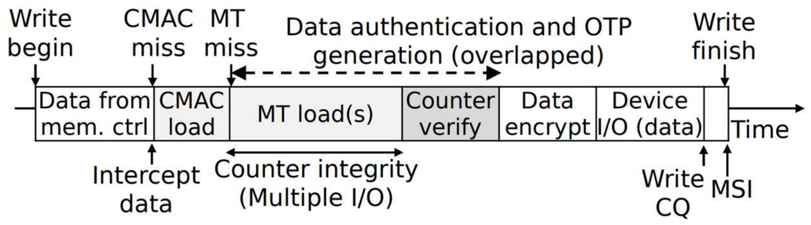
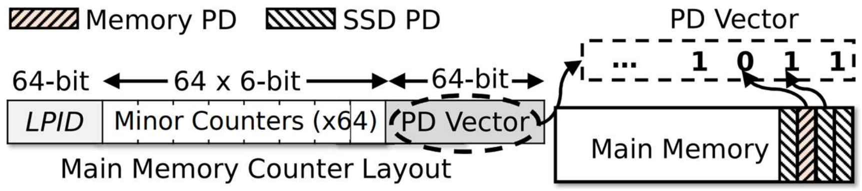
  - Metadata arrangements and maintenance



(a) DMA Interception Engine Events for Read operation



NVMe Read/Write path in D-Shield



D-Shield-Hybrid metadata storage

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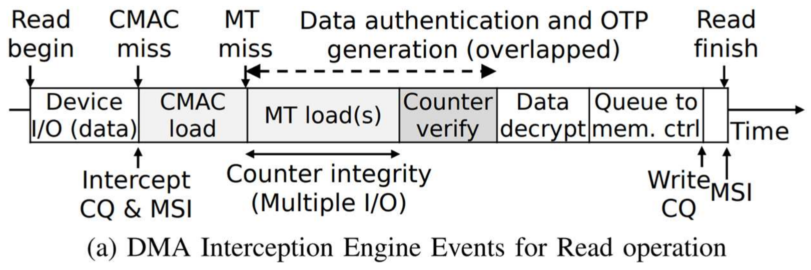

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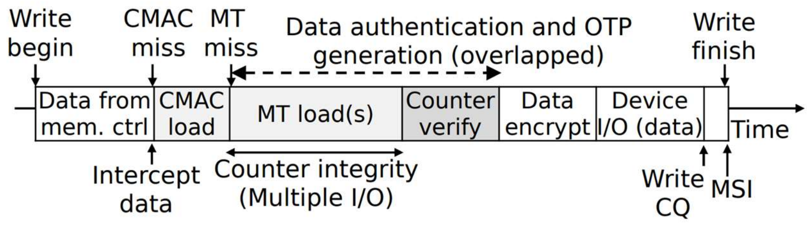

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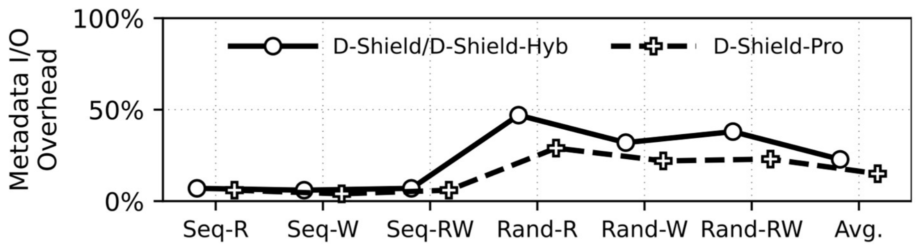
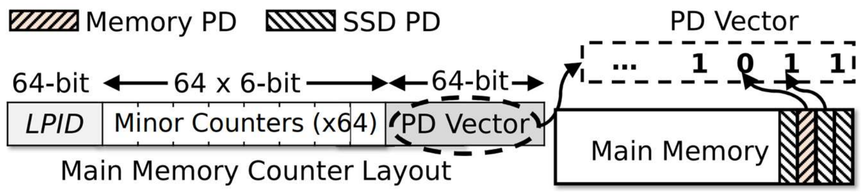


D-Shield I/O overheads



D-Shield-Hybrid metadata storage

More on Paper

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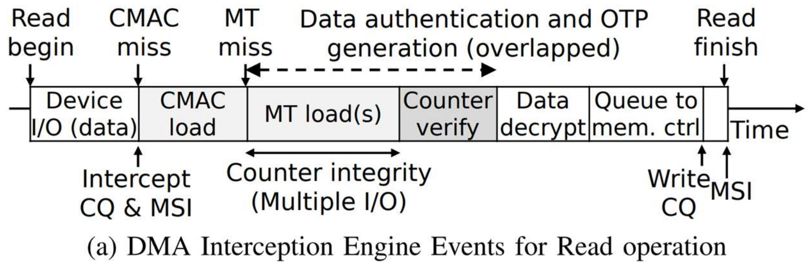
  - Logic and storage overheads
- **Sensitivity analysis of D-Shield schemes**
- **And more…**



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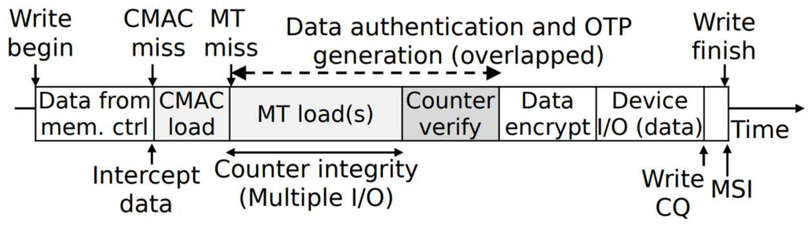

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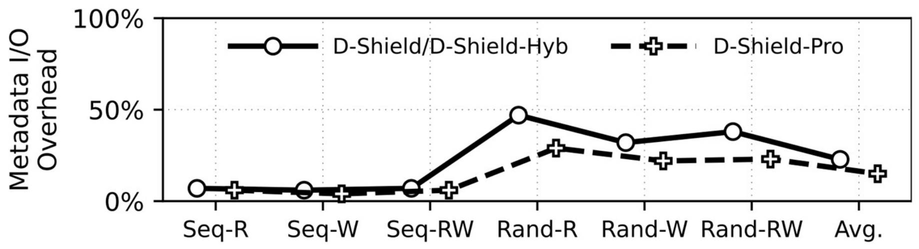

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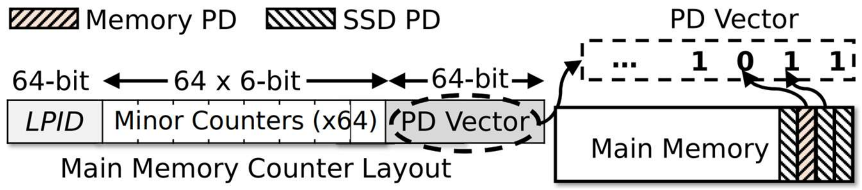

D-Shield-Hybrid metadata storage

Thanks! Questions?

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