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Performance Optimizations of Integrity Checking based on Merkle Trees

Salaheddine OUAARAB
<ouaarab@enst.fr>
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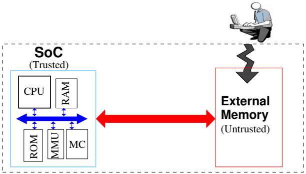

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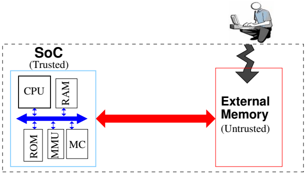

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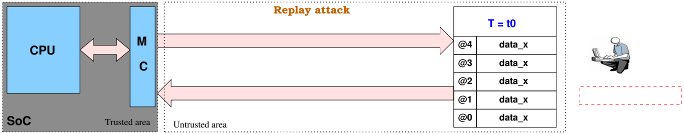

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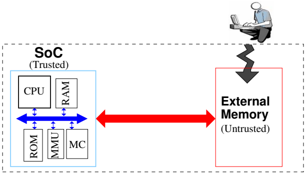

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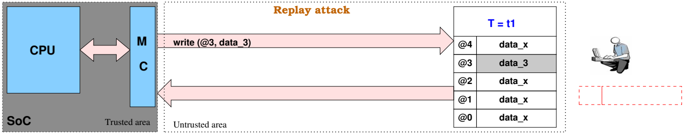

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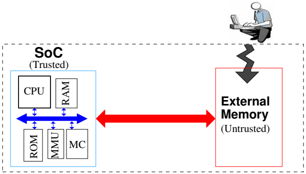

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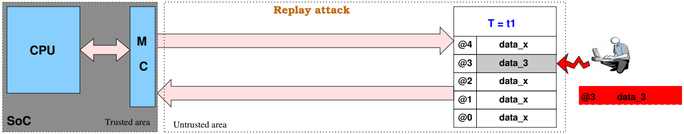

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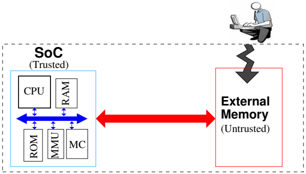

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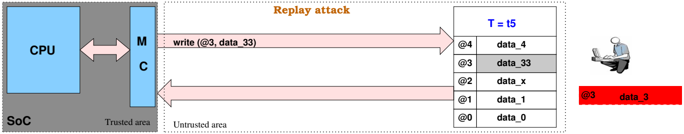

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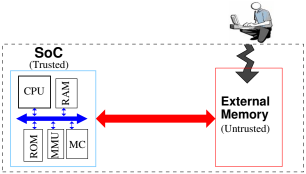

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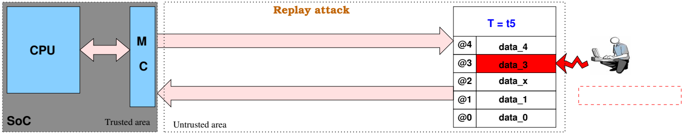

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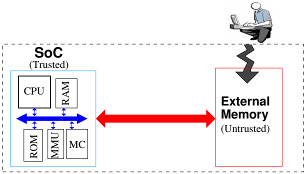

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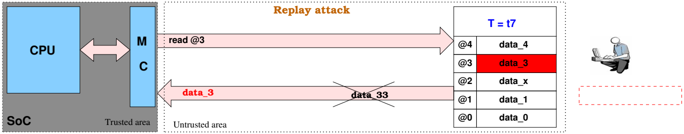

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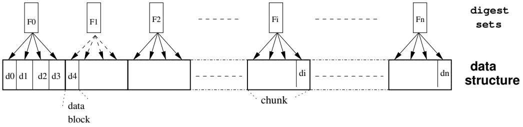

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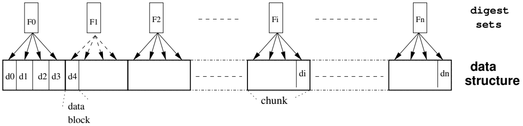

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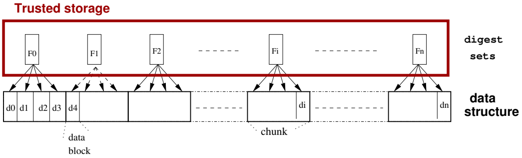

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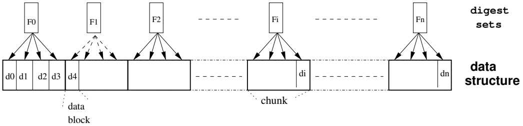

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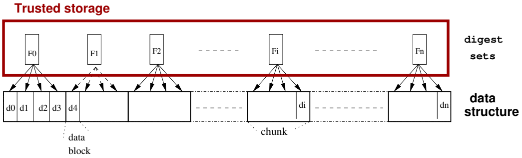
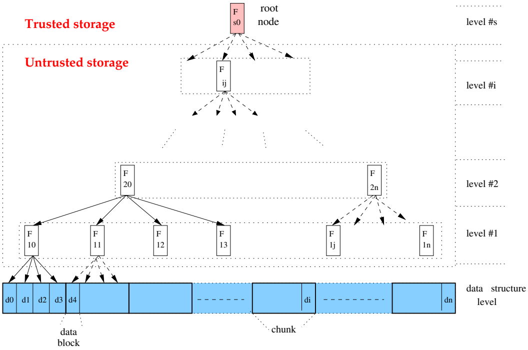


- **But** the secure storage is usually **small** and **expensive**

Merkle Tree
Definition

- Merkle Tree hierarchically organises the reference digests and stores the root in the secure storage



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Problematic

Issue

Merkle tree leads to significant storage and performance overheads:

- `initialization`: based on iterative function
- `Integrity Checking / Update`: increase the number of untrusted storage access and digest computations

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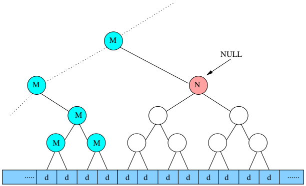
Optimization

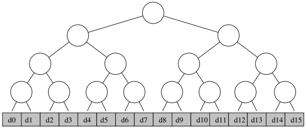
- `Initialization`: introduce **Hollow Merkle tree**
- `Integrity Checking / Update`: use of a customized **cache** located inside a secure area.



Merkle Trees

Initialization

- Regular Merkle Trees (**RMT**)



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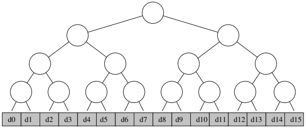

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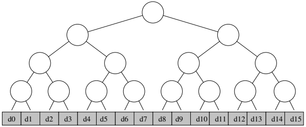

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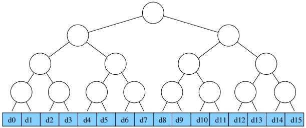

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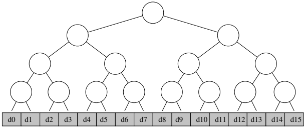

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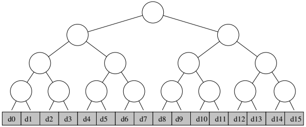

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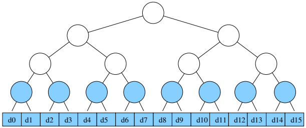

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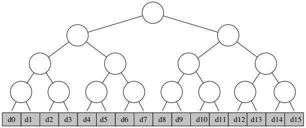

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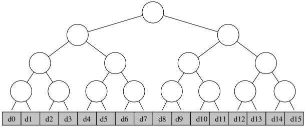

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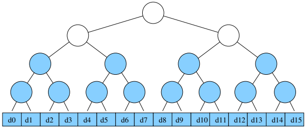

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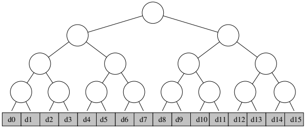

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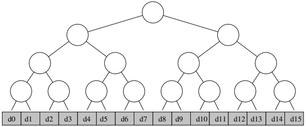

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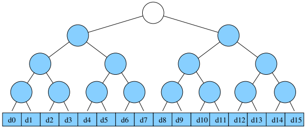

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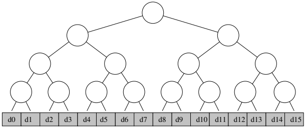

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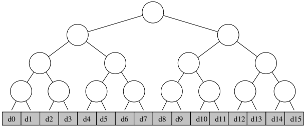

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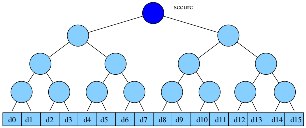

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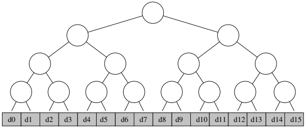

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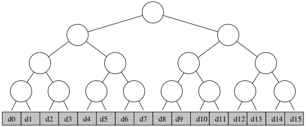

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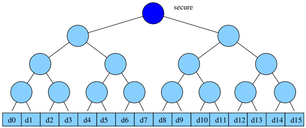

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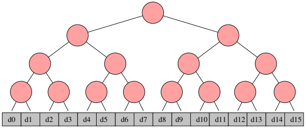

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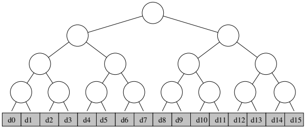

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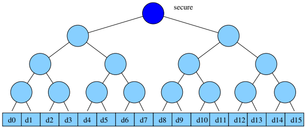

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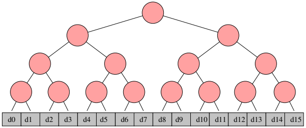

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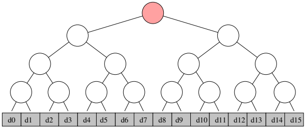

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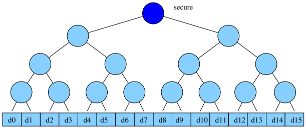

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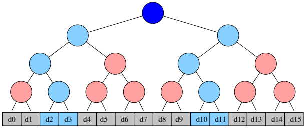

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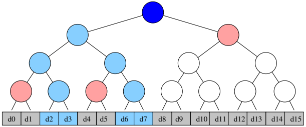

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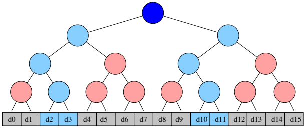

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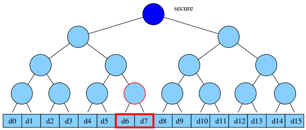

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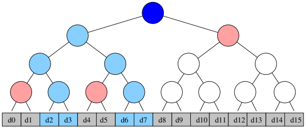

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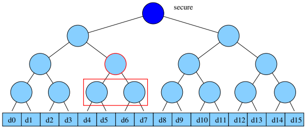

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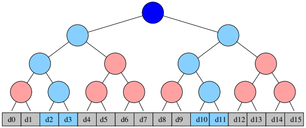

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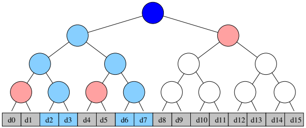

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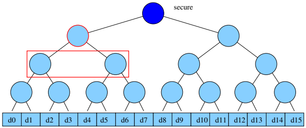

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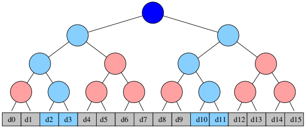

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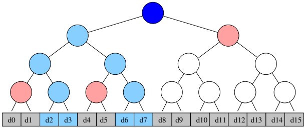

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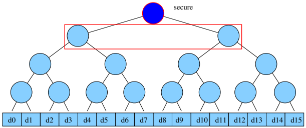

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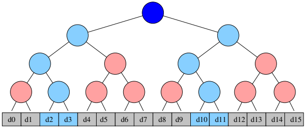

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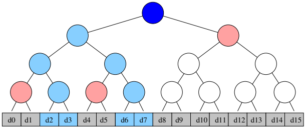

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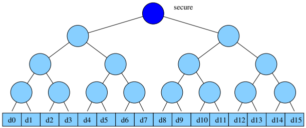

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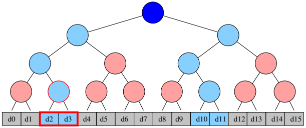

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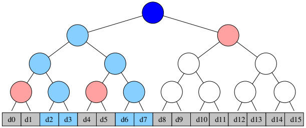

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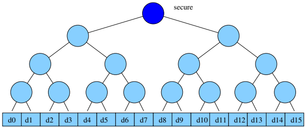
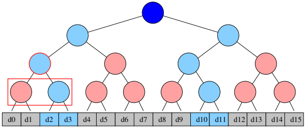
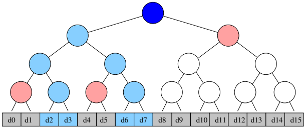
- Regular Merkle Trees (**RMT**)



- Initialized Hollow Merkle Trees (**I-HMT**)



- Non-Initialized Hollow Merkle Trees (**NI-HMT**)



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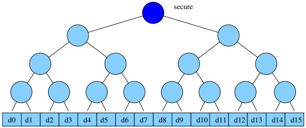

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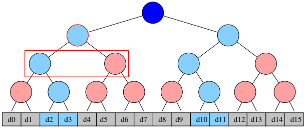

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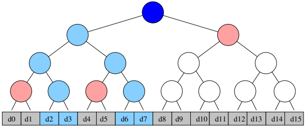

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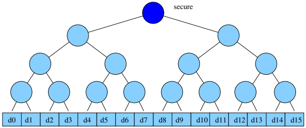

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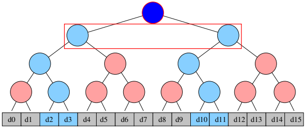

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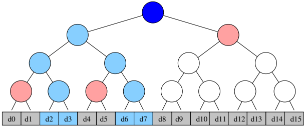

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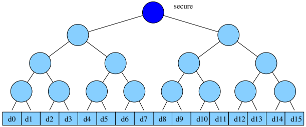

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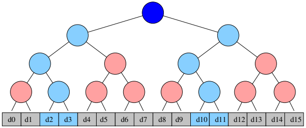

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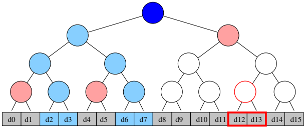

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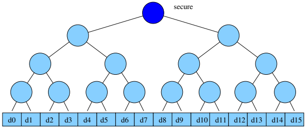

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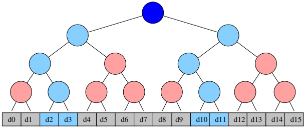

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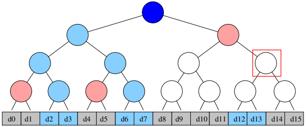

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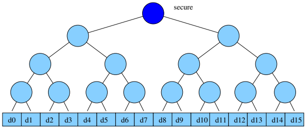

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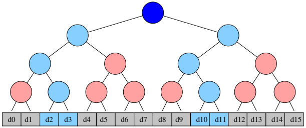

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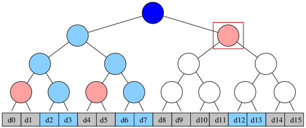

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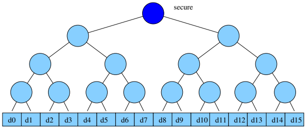

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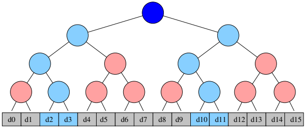

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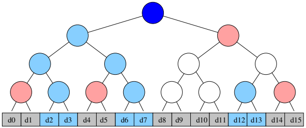

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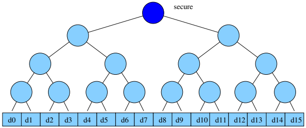

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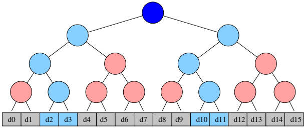

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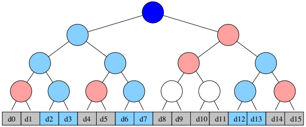

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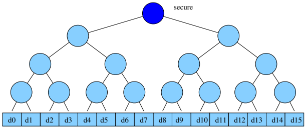

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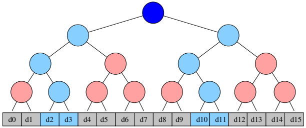

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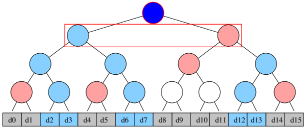

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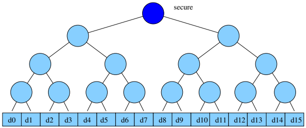

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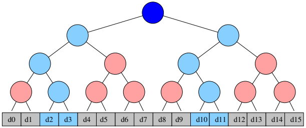

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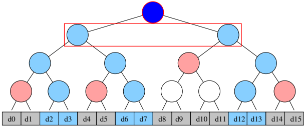

Plan

Use of Cache

- The use of cache decreases the bandwidth with the mass storage and, also reduces the number of digest computations
- Two particular algorithms are introduced:
  - **ASAP**: the integrity checking ends as soon as we match an intermediate node into the cache
  - **ALAP**: the update of node into the untrusted storage is delayed as late as possible storage

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Cache customisation

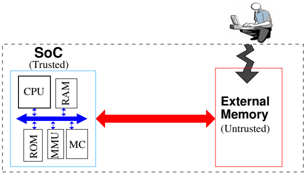
Modify the behavior of **Write-back** policy (i.e. modify `READ` and `WRITE` functions of cache controller and append new functions)

Plan

Case Study: SecBus Project

Purpose

Provide a strong confidentiality and integrity protection against on-board attacks (including replay attacks)



Initialization

- Memory interconnect latency: 100 CPU clock cycles
- DES algorithm latency: 4 CPU clock cycles
- Size of MT and memory page: 4 KB
- Number of random writes: 12.000
- Merkle Tree (MT) cache: Set associative, 64 sets, 8 blocks, 8-byte blocks, LRU, write-back

Use of HMT

- I-HMT: 22.5 times faster vs RMT
- NI-HMT: 186.5 times faster vs RMT

Schemes	cycle	access	MAC
RMT	4,219,439	29,142	10,885
NI-HMT	101,559	637	372
I-HMT	250,988	21,033	378

Table 1: Initialization step without cache

Schemes	cycle	access	MAC
RMT	4,097,234	28,480	10,331
NI-HMT	21,975	186	72
I-HMT	181,646	20,638	47

Table 2: Initialization step with cache

Random Writes

- Memory interconnect latency: 100 CPU clock cycles
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- Size of MT and memory page: 4 KB
- Number of random writes: 12.000
- Merkle Tree (MT) cache: Set associative, 64 sets, 8 blocks, 8-byte blocks, LRU, write-back

Use of Cache

with cache is 6.5 times faster vs without cache

Schemes	cycle	access	MAC
RMT	102,515,933	684,103	432,000
NI-HMT	102,929,333	688,063	432,264
I-HMT	102,515,933	684,103	432,000

Table 3: Random writes without cache

Schemes	cycle	access	MAC
RMT	15,808,417	130,917	36,91
NI-HMT	16,116,007	135,472	38,183
I-HMT	15,921,940	130,988	37,099

Table 4: Random writes with cache

Plan

Conclusion

- Two optimizations of Merkle trees have been introduced to speed up initialization, integrity checking and tree updates
- The results shows an improvement of the trees initialization by using Hollow Merkle trees
- The cache improves the performance after the initialization
- The choice between the two types of Hollow Merkle trees depends on the use case

Thank you for your attention