IvLeague: *Side Channel-resistant Secure Architectures* Using Isolated Domains of Dynamic Integrity Trees

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Orlando, USA

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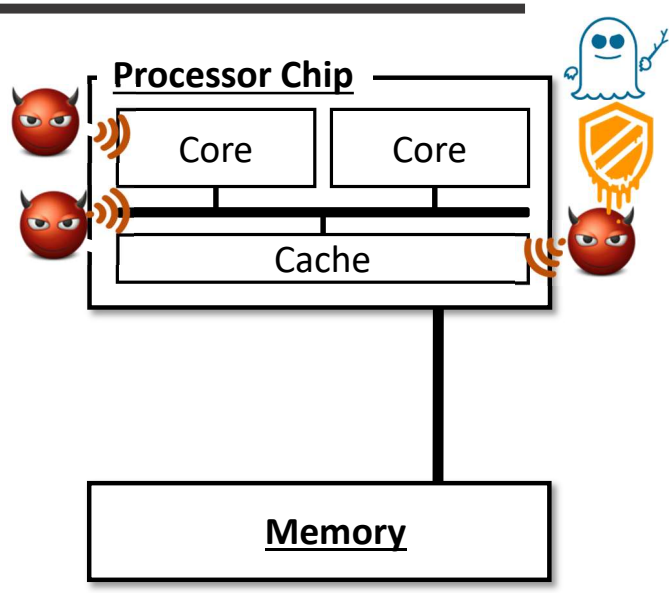
µArch Security Problems in Secure Processors

- Two different attack domains are possible:
  - **On-chip:** uArch side channel attacks (e.g., cache attacks, BPU attacks).



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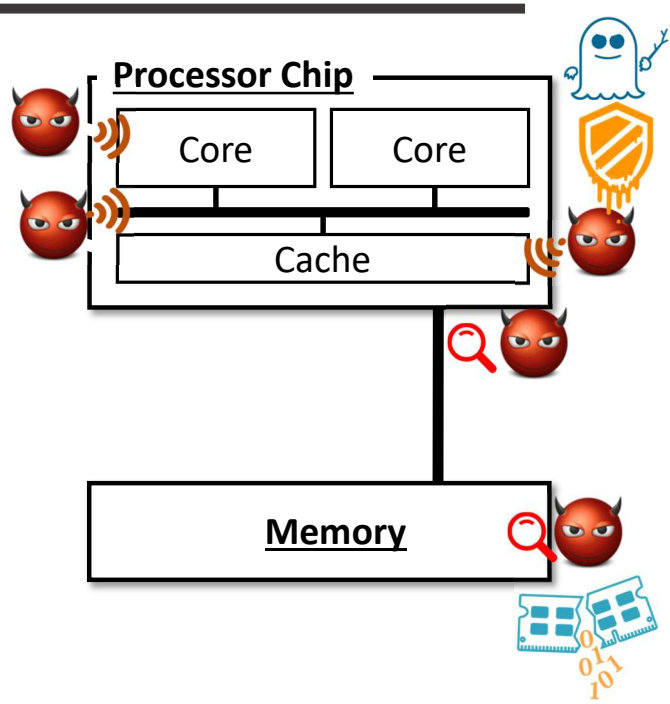

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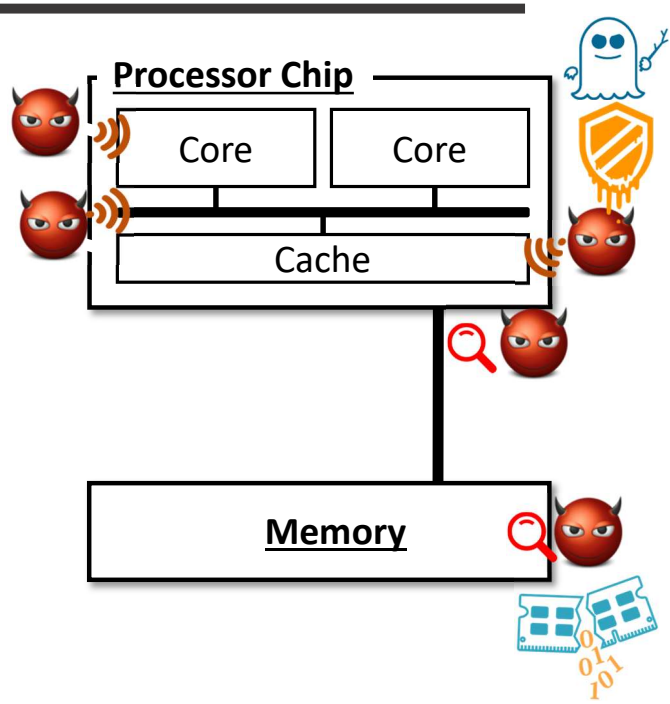

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  - ***Encryption*** when data leave processor chip.
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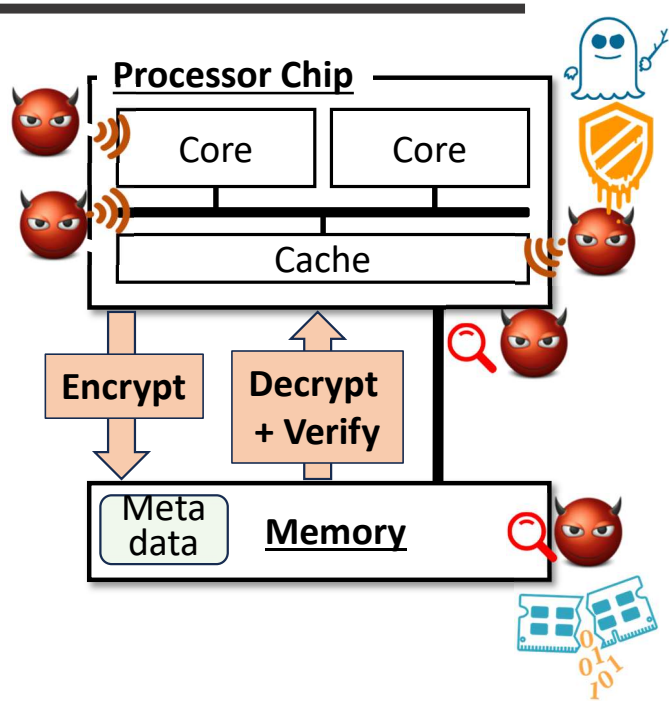

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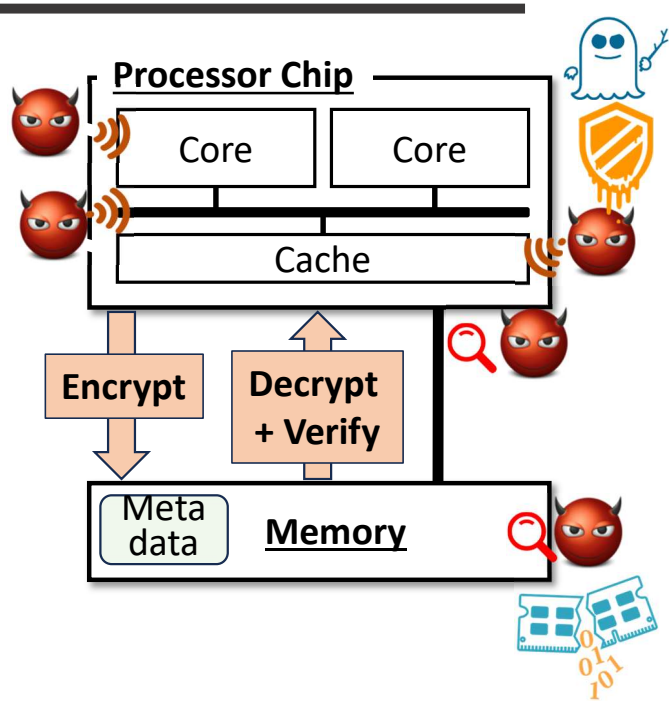

Traditional **secure processor designs** only consider security of **off-chip data**.

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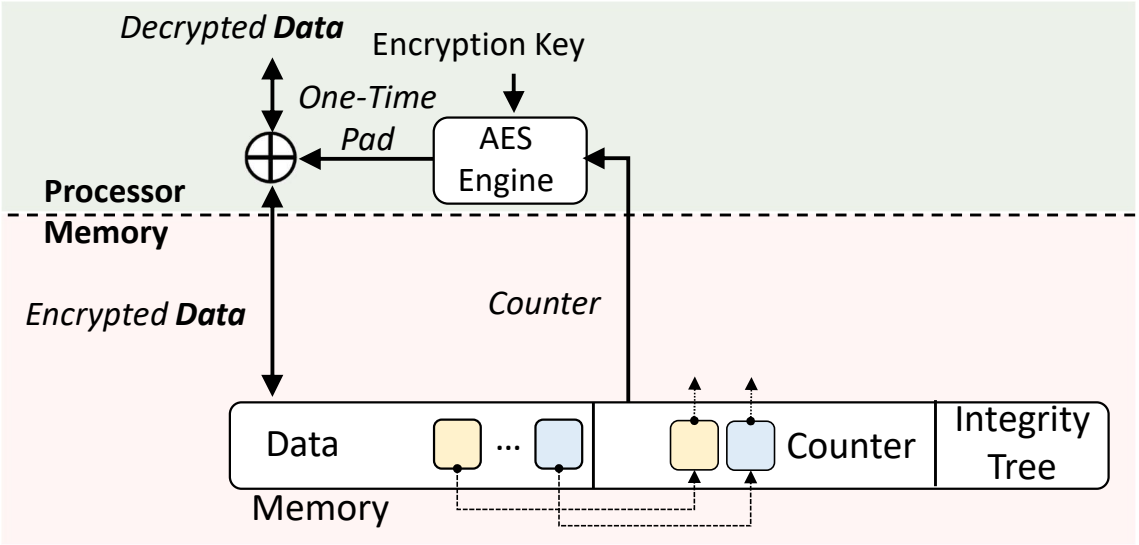
Side Channel Security of Secure Processor Metadata



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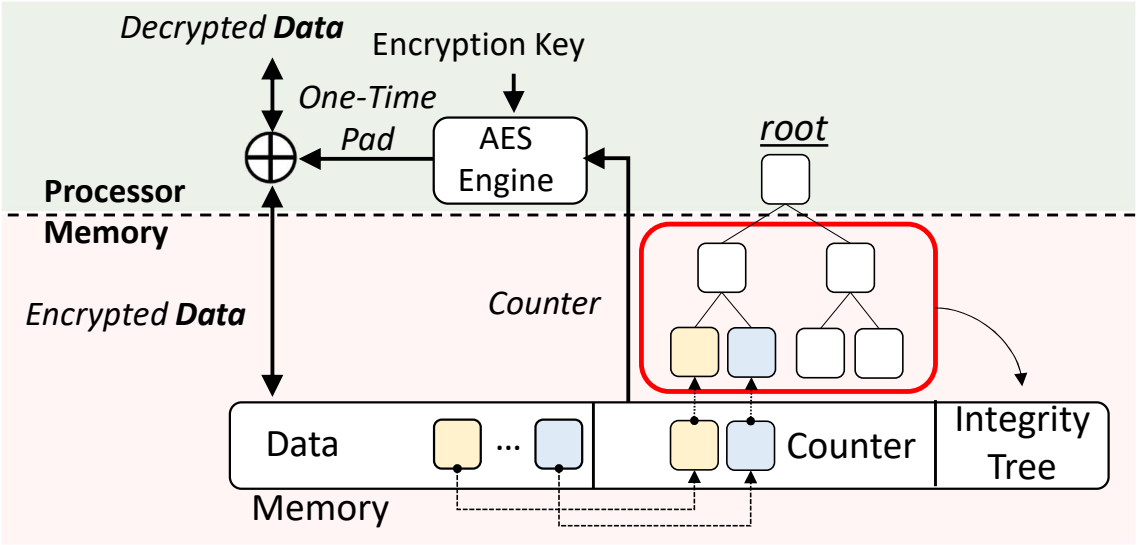

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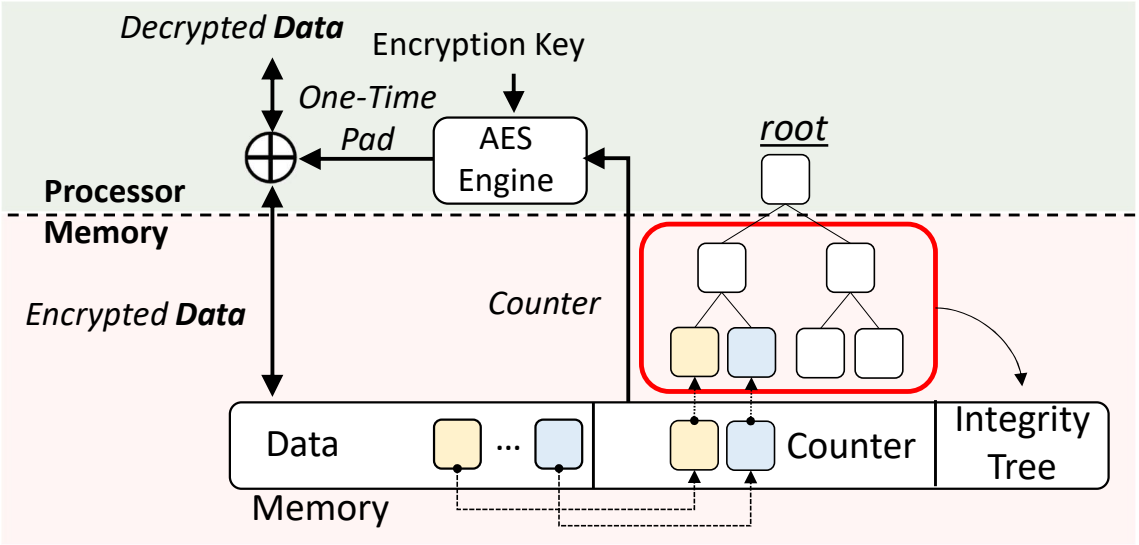

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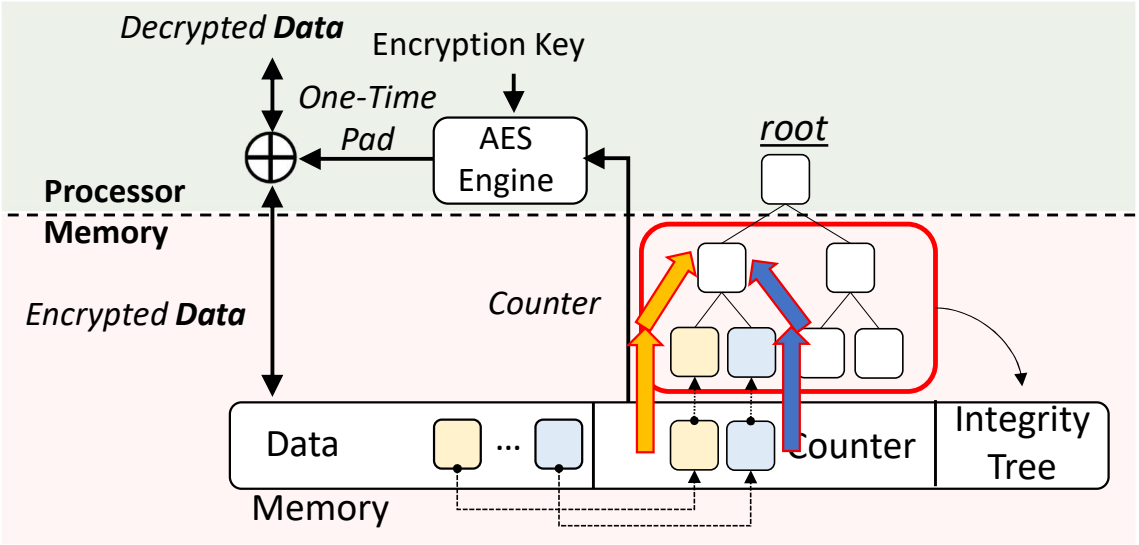

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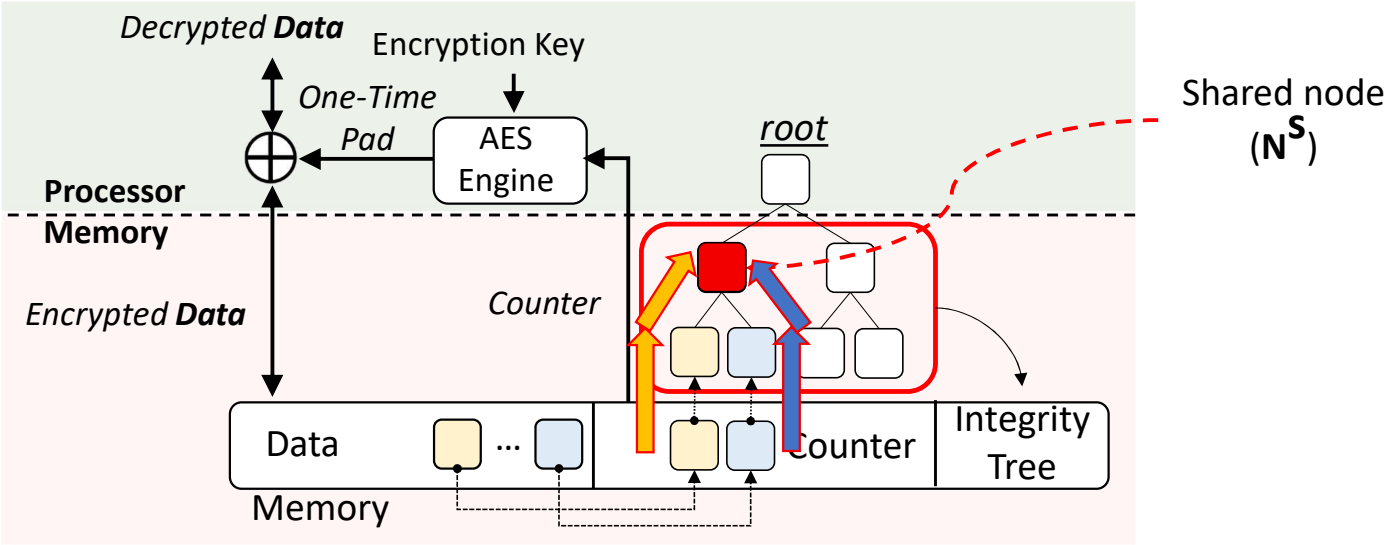

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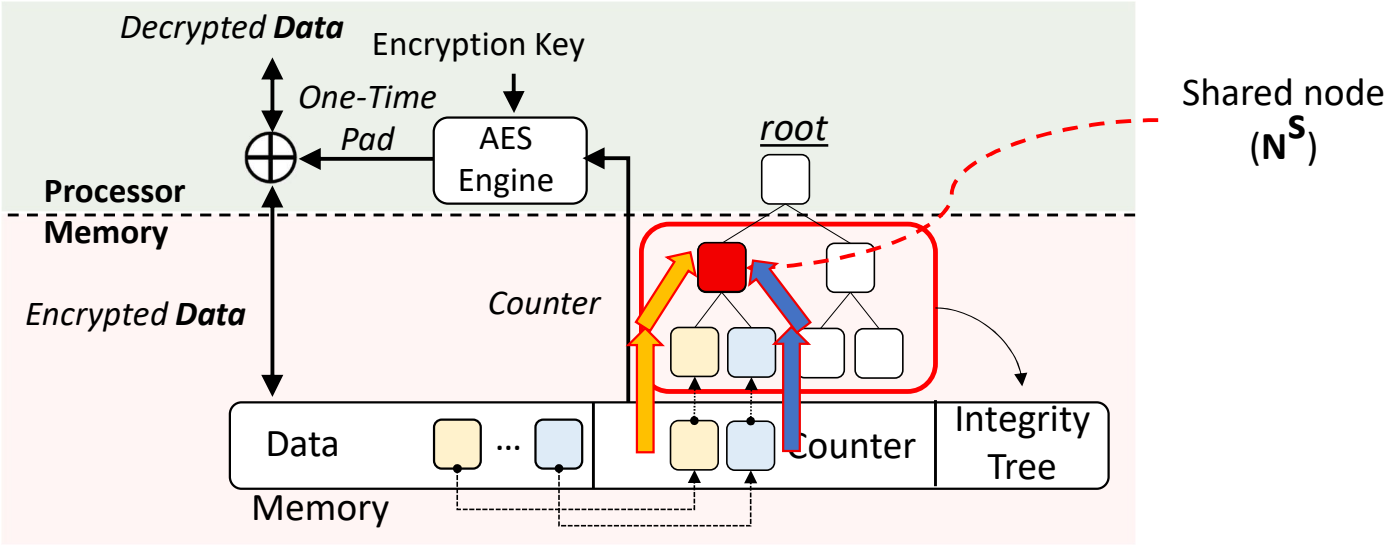

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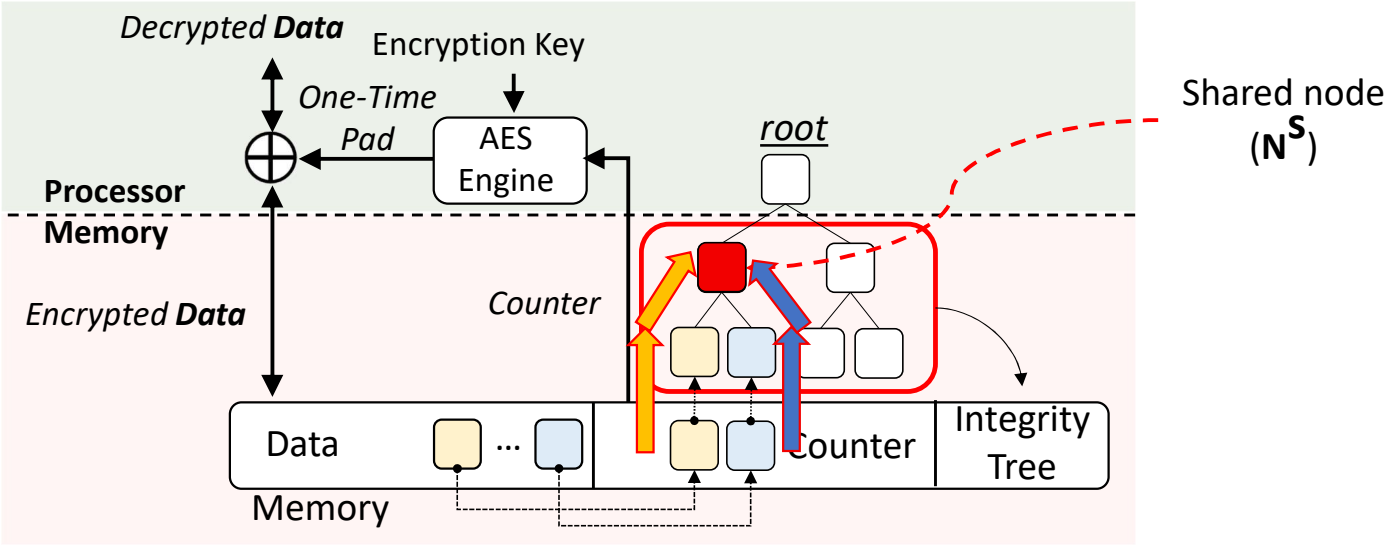

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Secure processors introduce **new source of side channel leakage** (MetaLeak [ISCA'24]).

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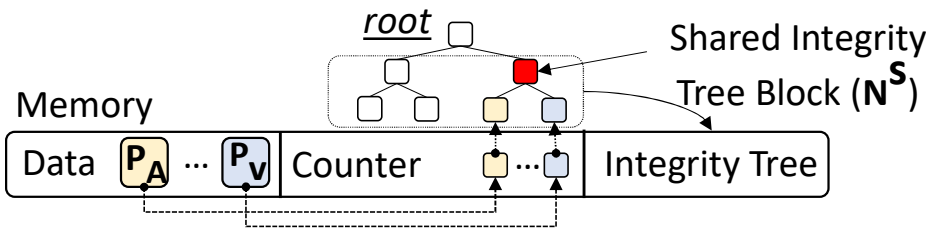
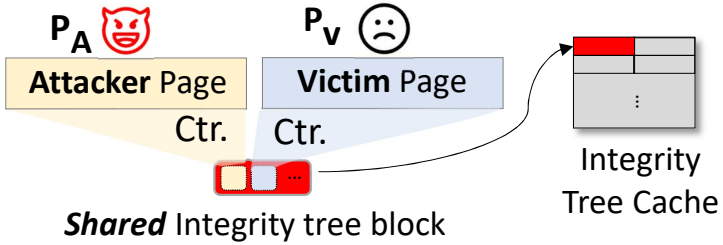
Side Channel Exploiting Tree Metadata Sharing



Implicit sharing of integrity tree metadata



Shared Integrity tree block

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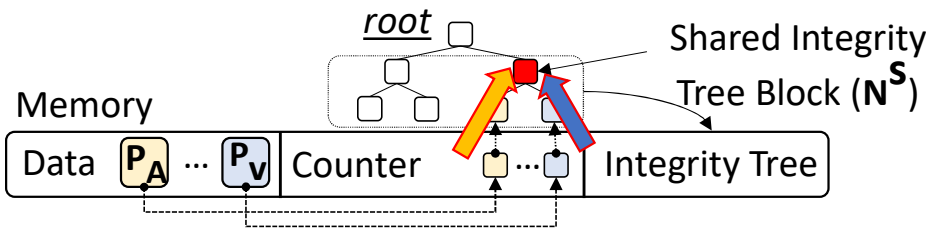

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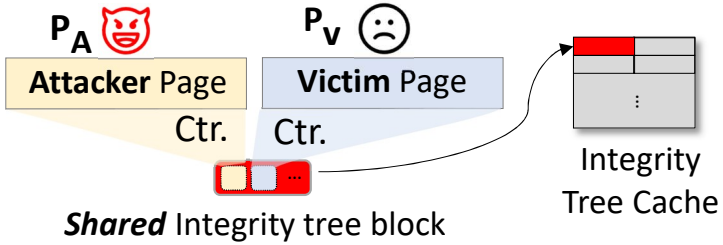

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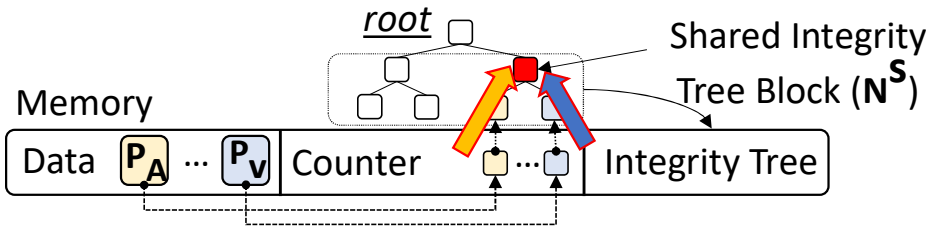

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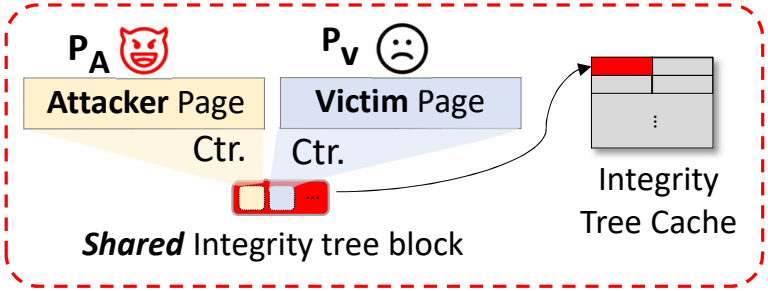

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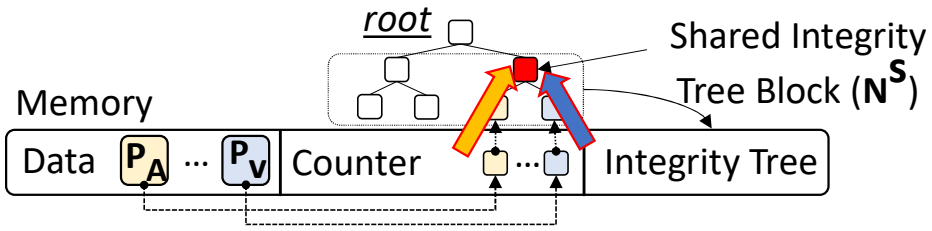

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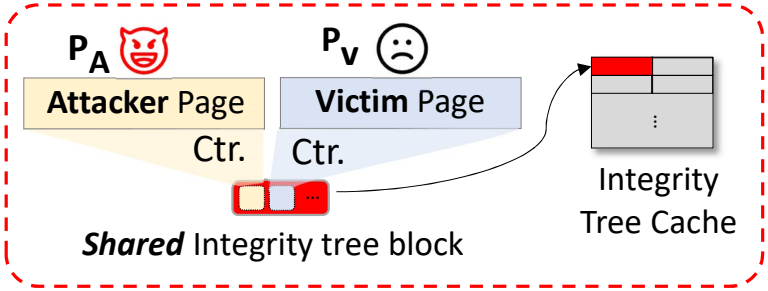

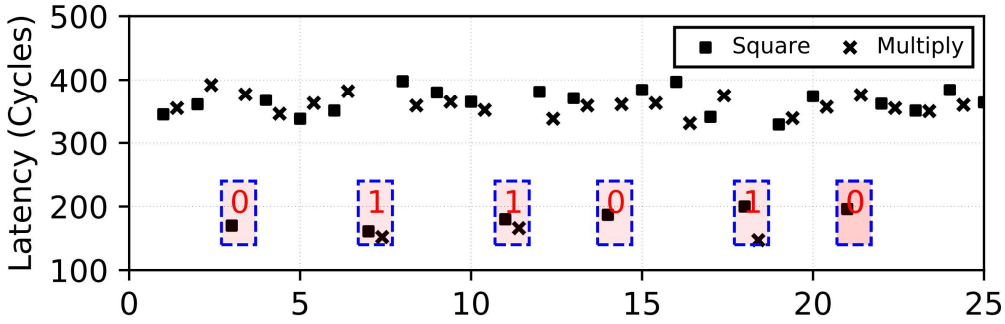

Figure: RSA private exponent recovery in **Intel SGX** (Core i7-9700K)*

* Reproduction of attack demonstrated in MetaLeak [ISCA'24]

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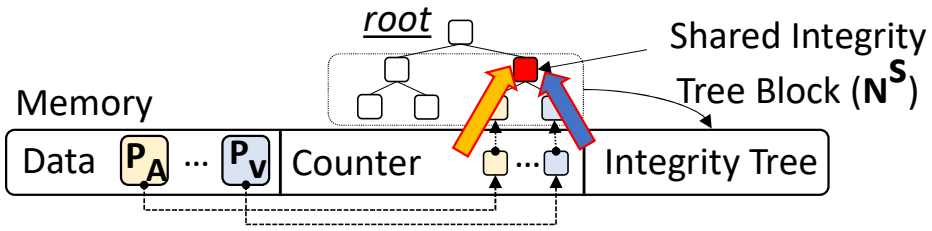

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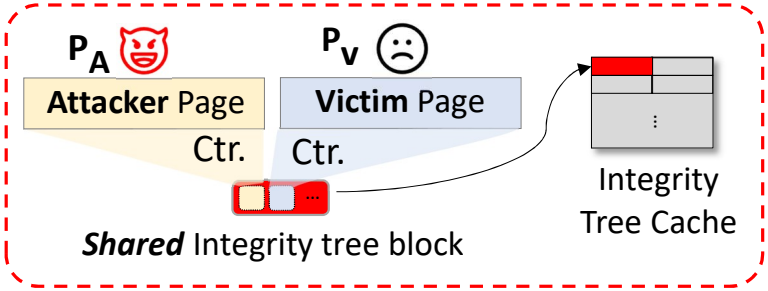

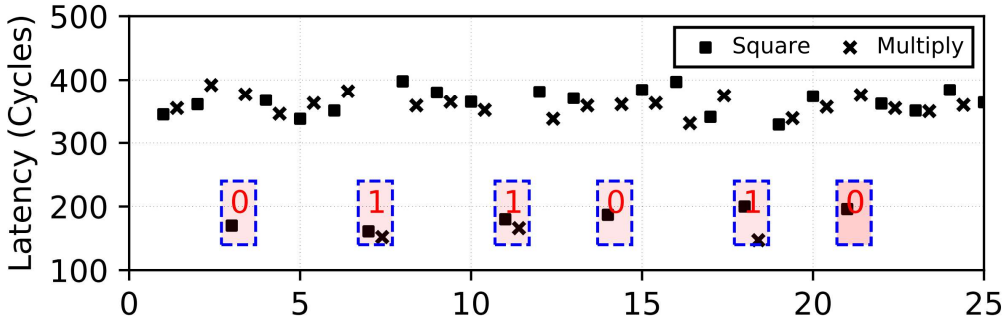

Figure: RSA private exponent recovery in **Intel SGX** (Core i7-9700K)*

Key vulnerability: **Integrity verification metadata is shared** across domains, leading to **shared-memory side channels** even when regular data sharing is prohibited.

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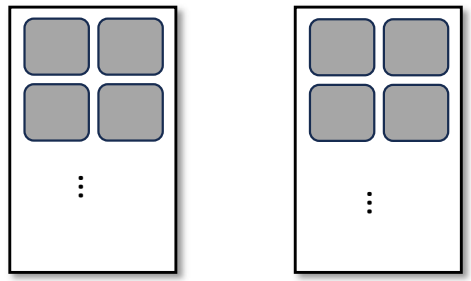
Uniqueness of Metadata-based Exploits

- MetaLeak breaks assumptions the fundamental assumptions of uArch defenses (**sharing**).
- Existing µArch defenses are typically based on ***randomization*** or ***partitioning***.
  - Mainstream protection schemes against ***shared-memory attack requires read-only sharing***.
  - Secure processor metadata is ***shared and updated during runtime***.

Cache partitioning



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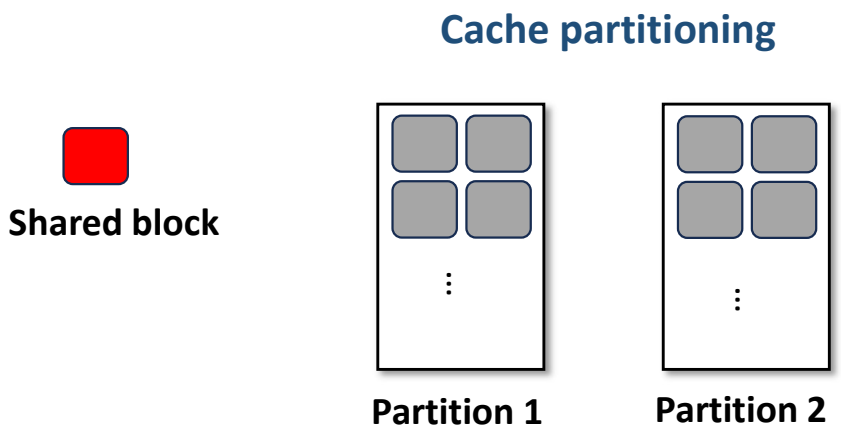

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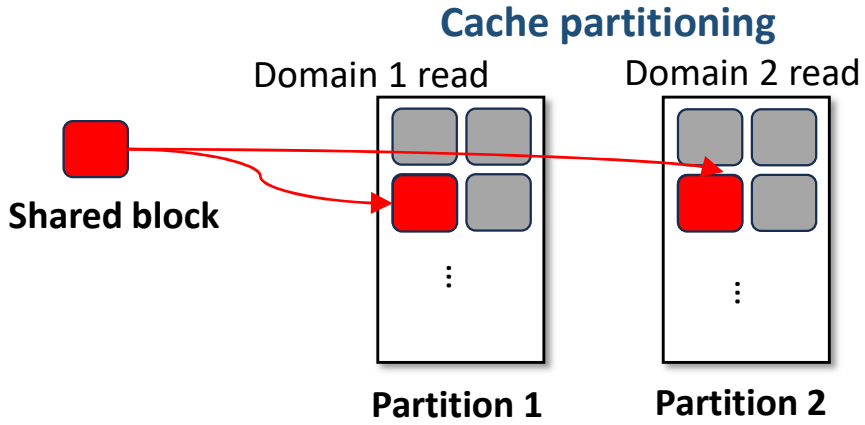

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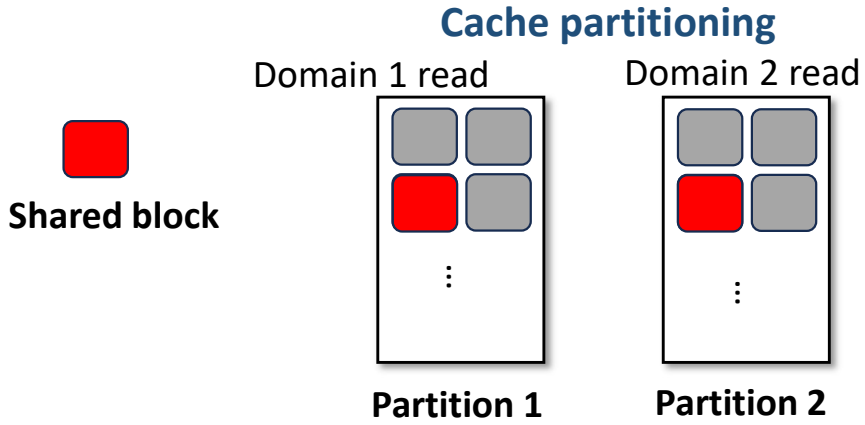

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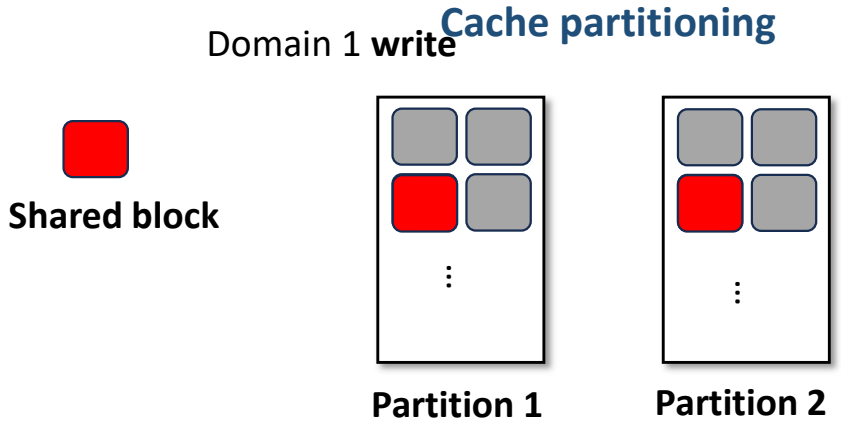

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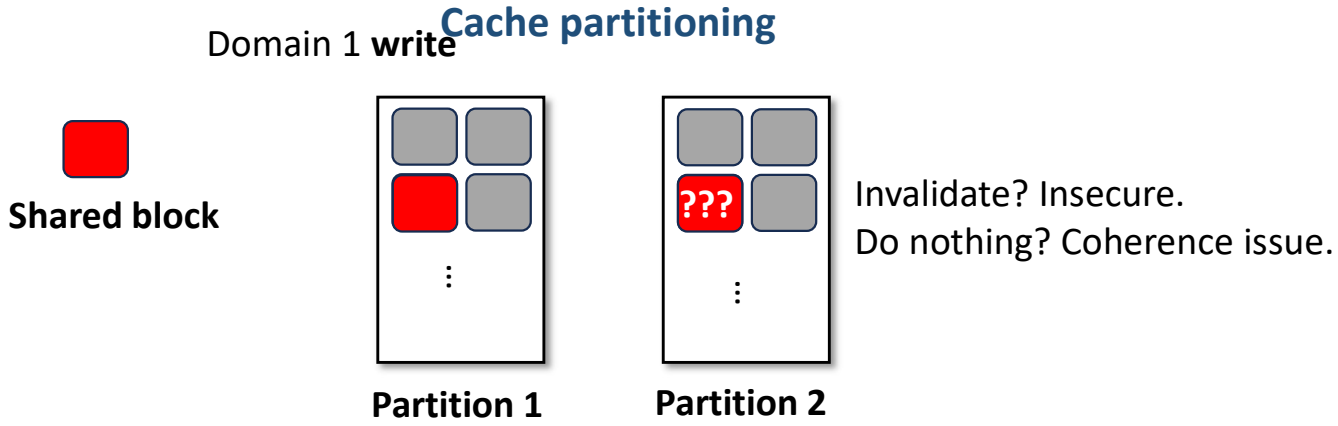

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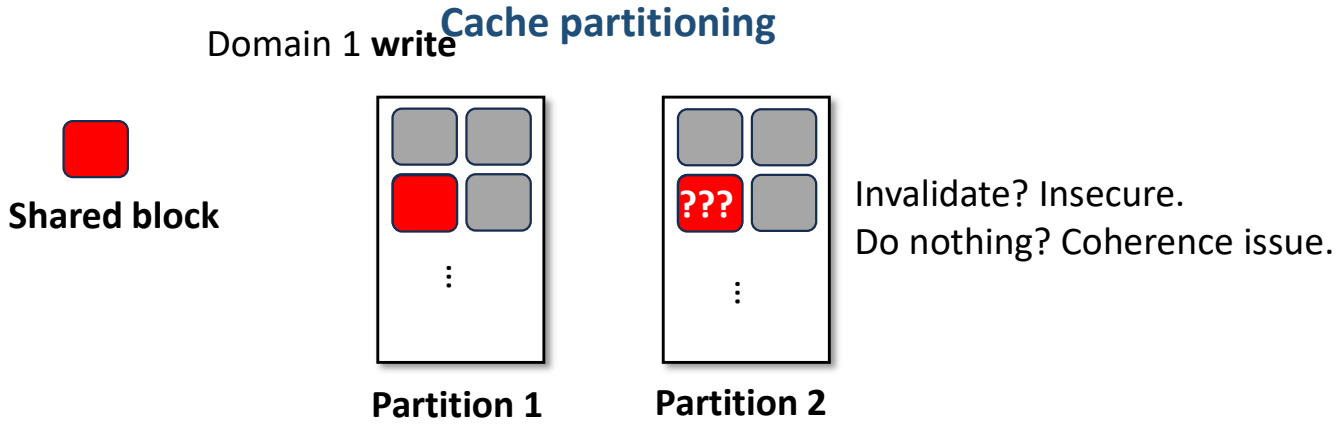

Integrity tree metadata is ***shared and writable*** → cannot be protected using classical defenses.

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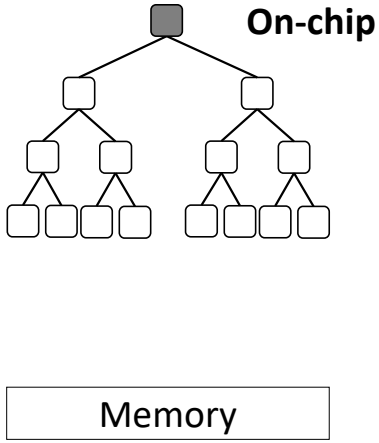
This work

Architecture support for **side channel-resistant** secure processor metadata to prevent metadata-sharing side channel.

Design Objectives of Isolated Integrity Tree

- **Main idea:** Metadata-level isolation for integrity verification.
  - Ensure no tree node sharing in memory between domains.



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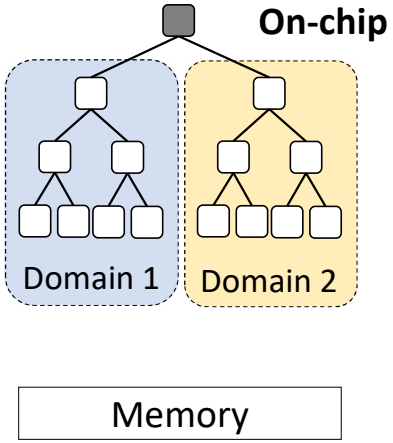

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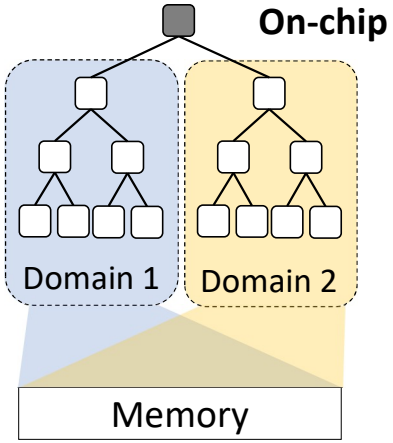

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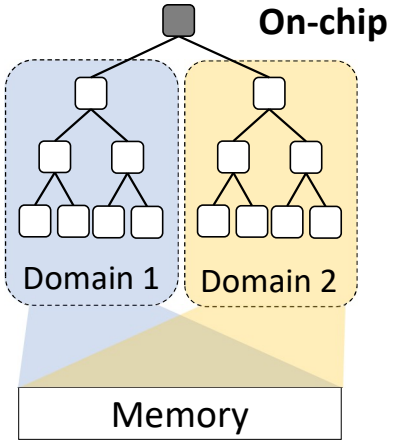

Obj. (#) : Support for a *sufficient number of isolated integrity domains*.

Obj. (⤡) : Ability to *resize integrity coverage of each domain* on-demand.

Obj. ($) : *Low-overhead maintenance* of tree nodes during runtime.

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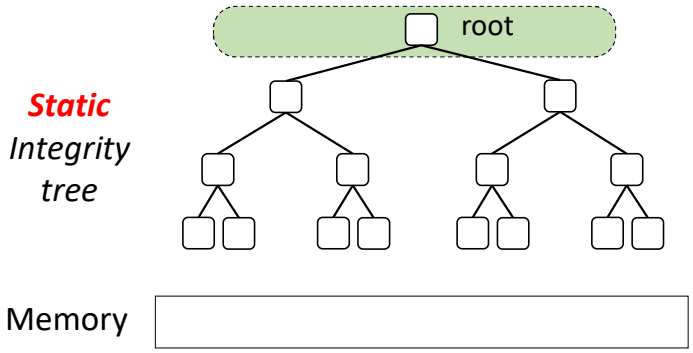
Design Space Exploration: Fully Static Partitioning



- Statically partition the global tree.

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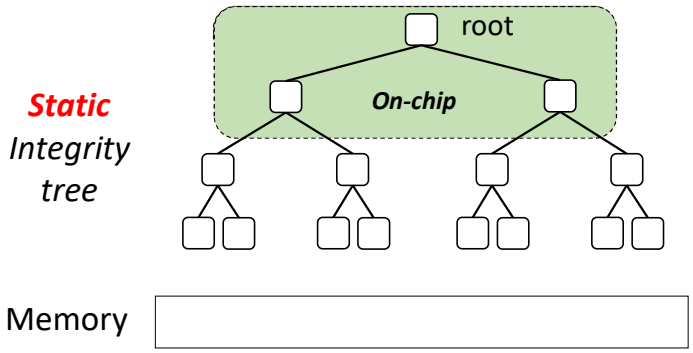

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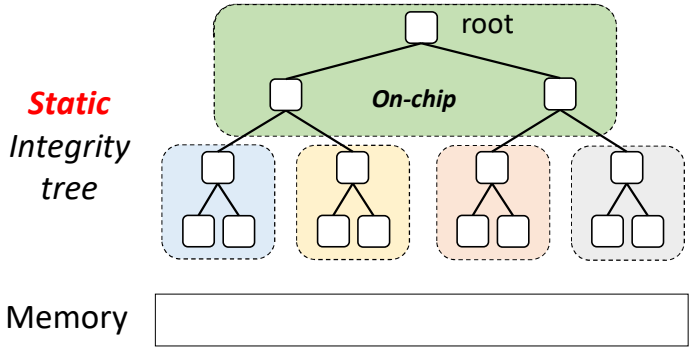

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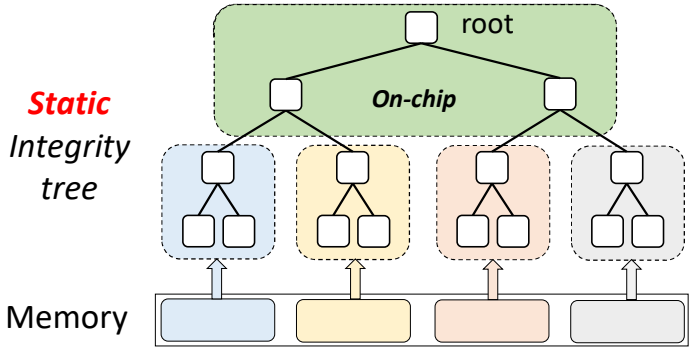

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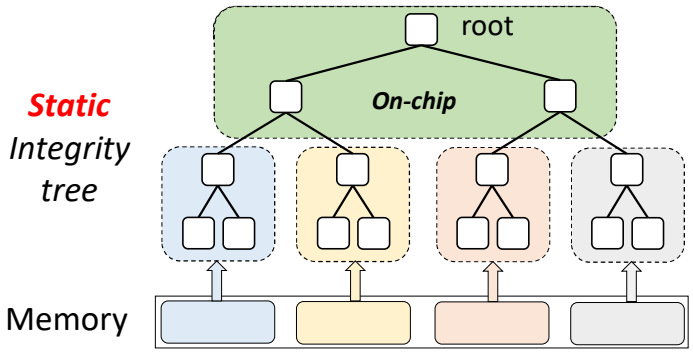

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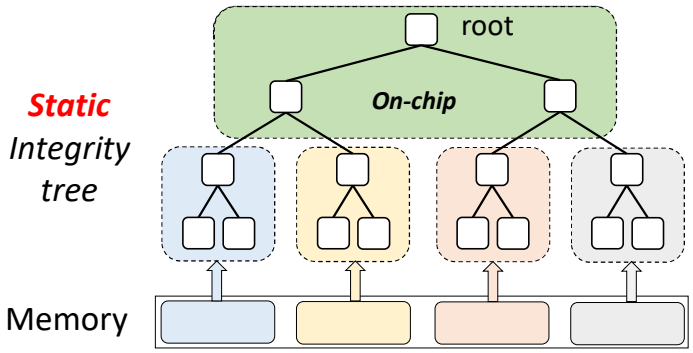

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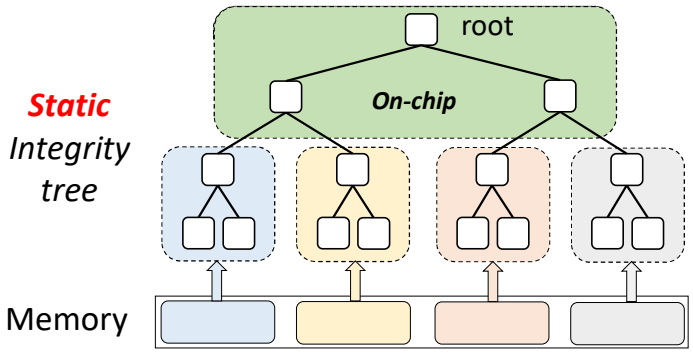

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Fixed memory coverage of each partition → cannot resize memory footprint on-demand (**Obj. ⤡ Not-satisfied**).

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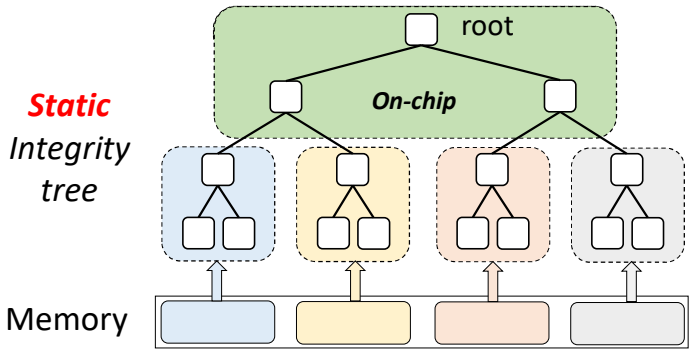
Design Space Exploration: Fully Static Partitioning



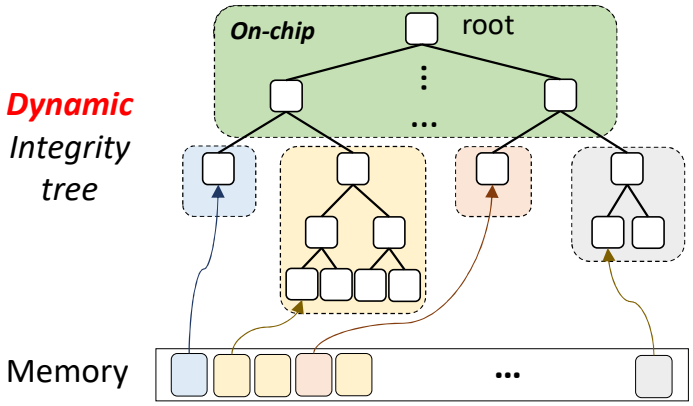
- Statically partition the global tree.
- Each sub-tree covers a fixed chunk of memory.
- Static one-to-one mapping between data to sub-tree node:
  - Low-overhead maintenance of tree nodes (**Obj. $ Satisfied**).
- Relies on the OS to strictly *allocate continuous physical pages* to domains.

Number of security domains does not scale → limited number of domains (**Obj. # Not-satisfied**).

Fixed memory coverage of each partition → cannot resize memory footprint on-demand (**Obj. ⤡ Not-satisfied**).

UCF

Design Space Exploration: Fully Dynamic Partitioning



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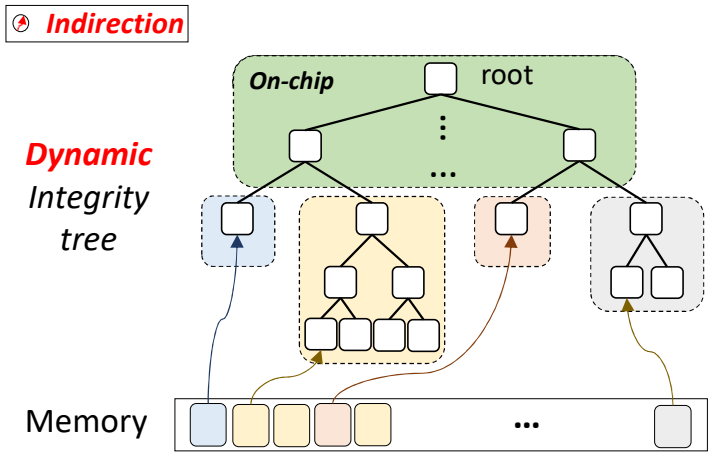

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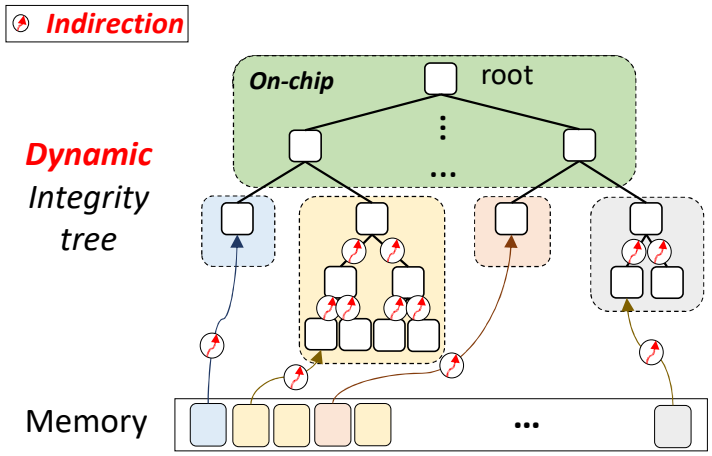

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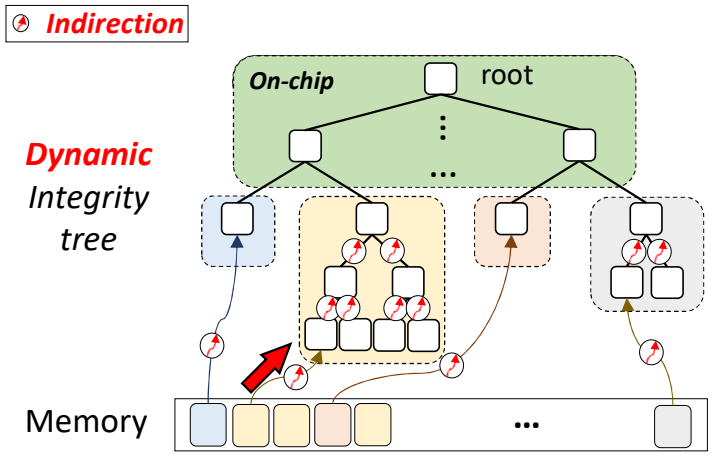

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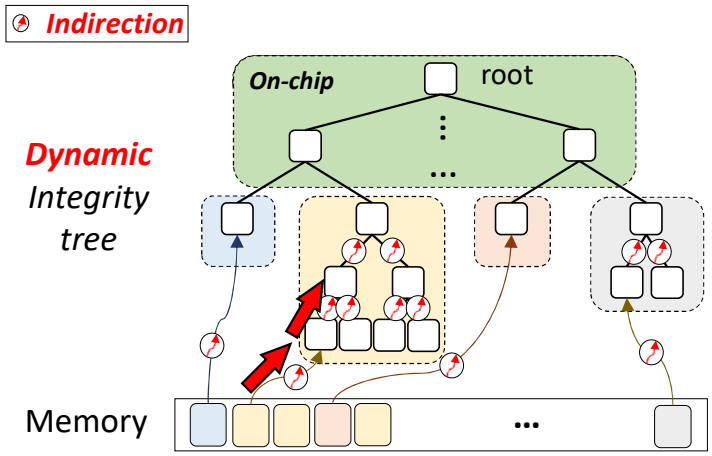

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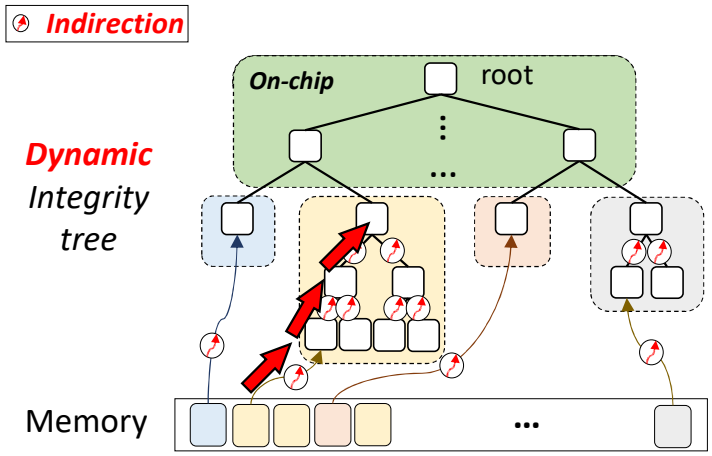

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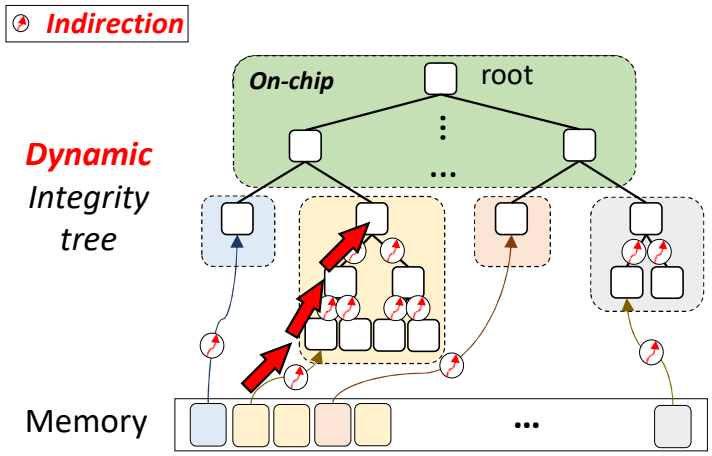

- Each domain hosts individual integrity sub-tree which can dynamically grow or shrink (**Obj. # Satisfied**).

UCF

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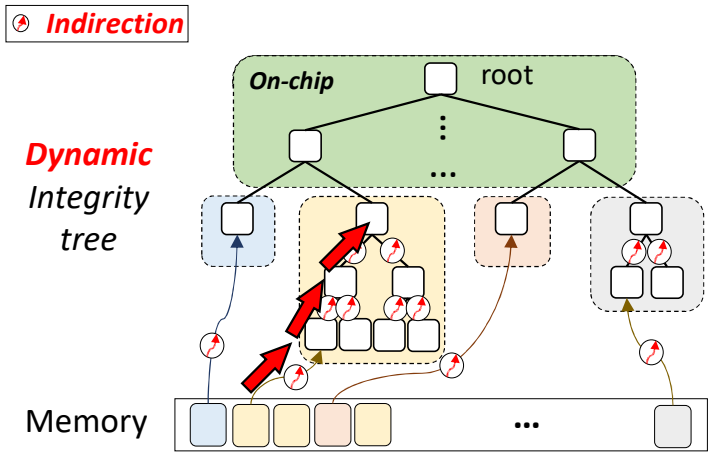

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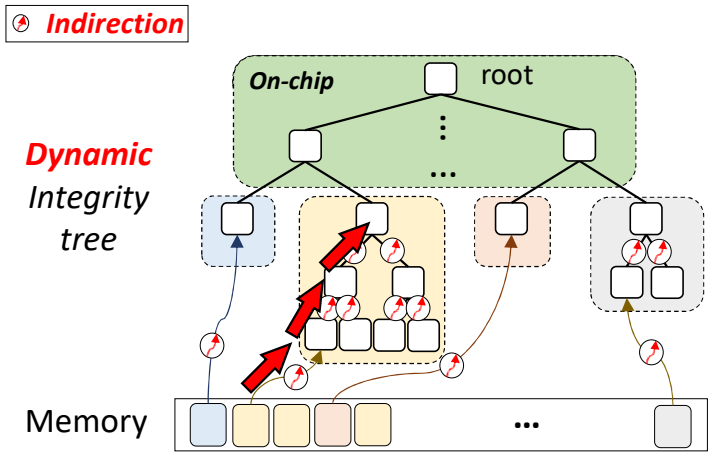

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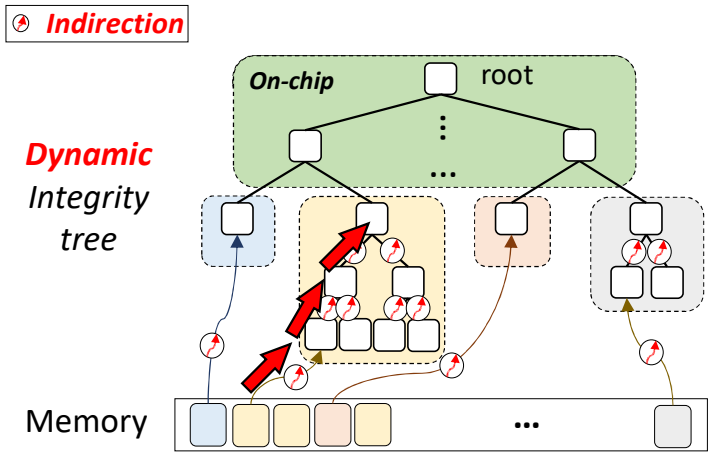

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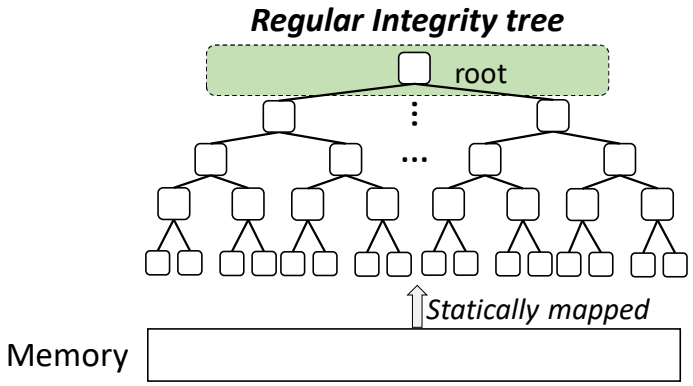
- **Multiple indirections for single integrity verification** (1x data-to-leaf mapping, n-x leaf-to-root mapping).

Prohibitive overheads of runtime integrity verification→ high-overhead of tree maintenance (**Obj. $ not-satisfied**).

UCF

IvLeague Conceptual Overview

Split the integrity tree into many ***small but fixed-sized*** sub-trees (**TreeLing**).
Roots of the TreeLings are always ***kept on-chip***.



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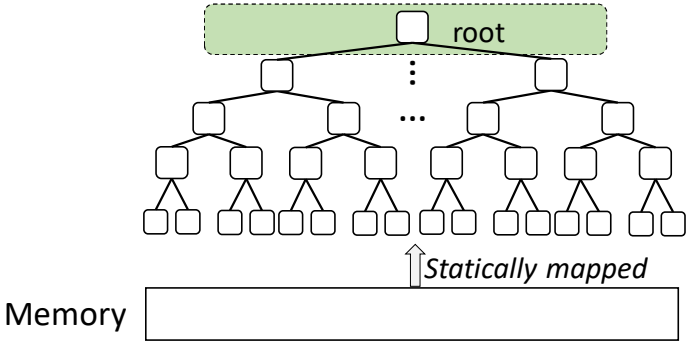
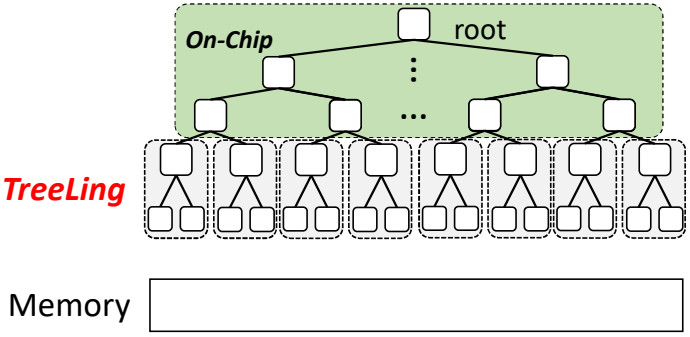
Regular Integrity tree



IvLeague Integrity tree



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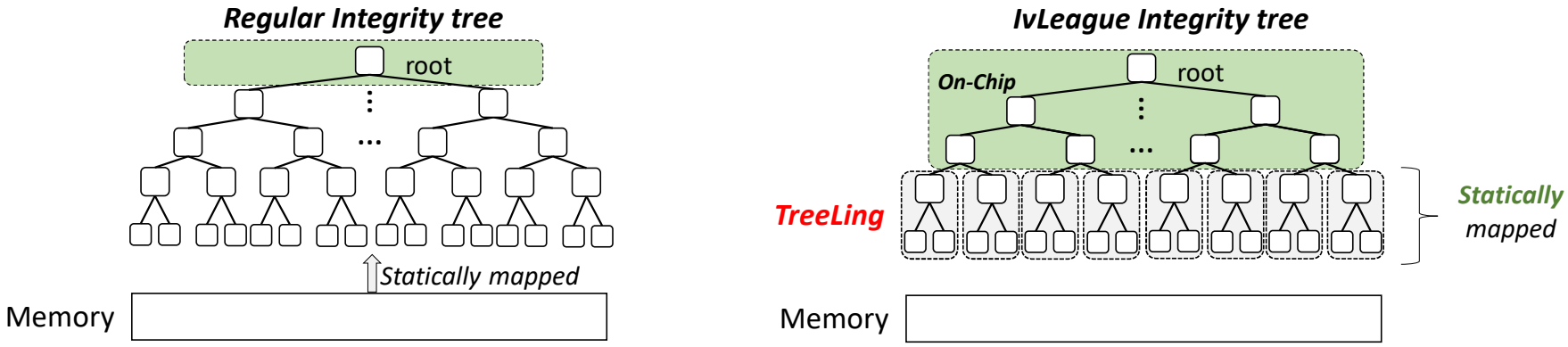

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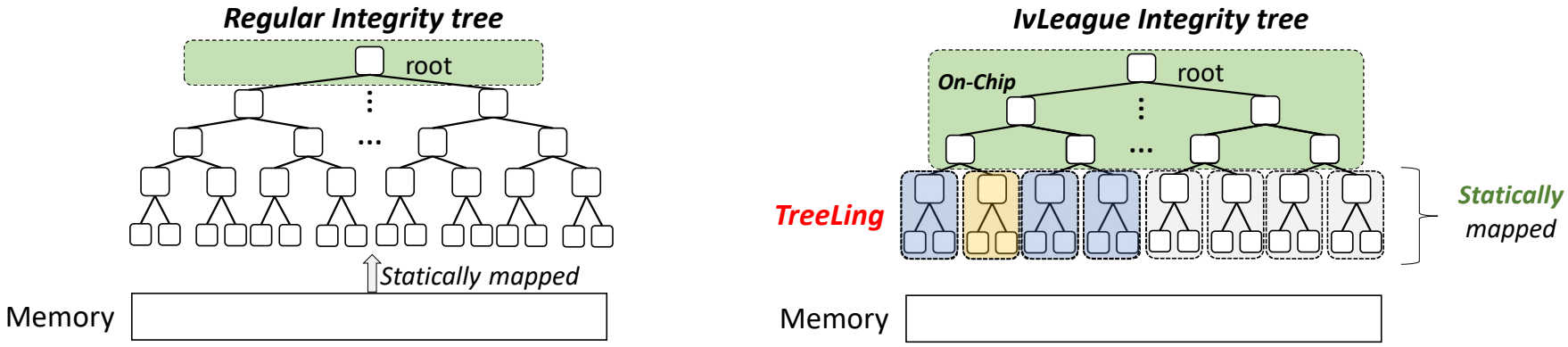

- Each sub-tree (TreeLing) is statically mapped, ***no indirection needed for leaf-to-root traversal***.
- TreeLings are allocated to domain on-demand, ***resize integrity coverage during runtime***.

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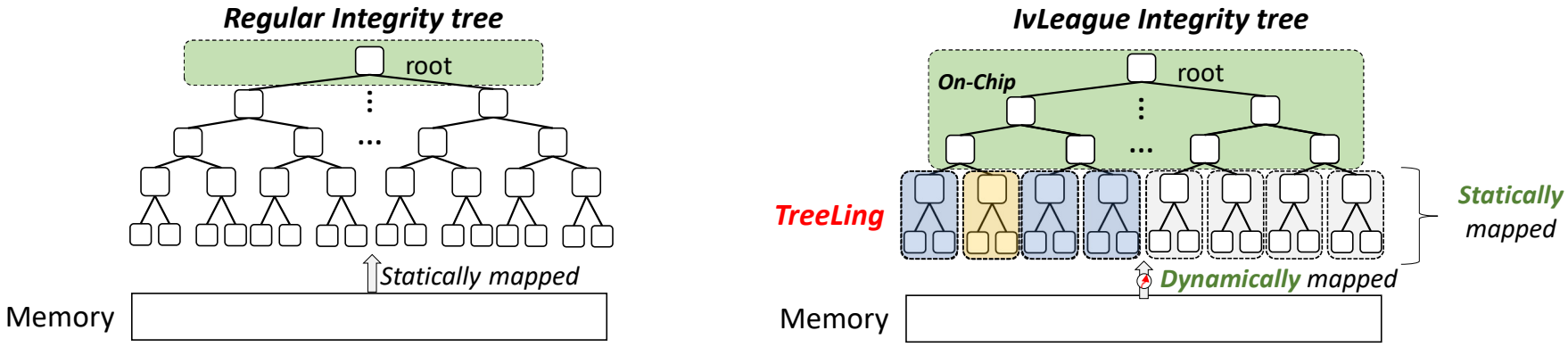

- Each sub-tree (TreeLing) is statically mapped, ***no indirection needed for leaf-to-root traversal***.
- TreeLings are allocated to domain on-demand, ***resize integrity coverage during runtime***.
- Supports as many domains as fully dynamic partitioning, ***scalable for larger domain support***.

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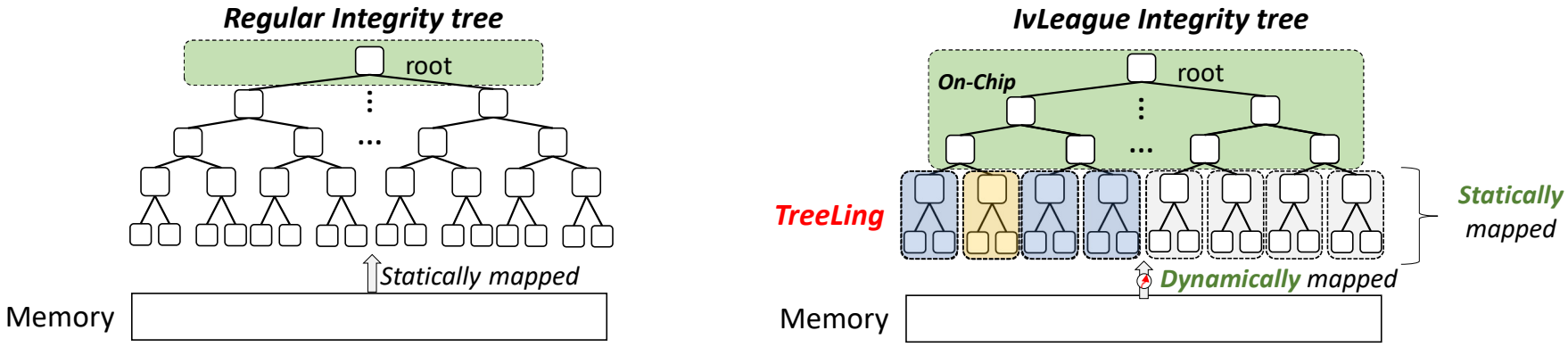
Roots of the TreeLings are always ***kept on-chip***.



Challenges:

- ***Intra-TreeLing management:*** Efficient hardware-controlled allocation policy for TreeLing nodes.
- ***Inter-TreeLing management:*** TreeLing configuration (# and size of TreeLing) considering diverse memory footprints.

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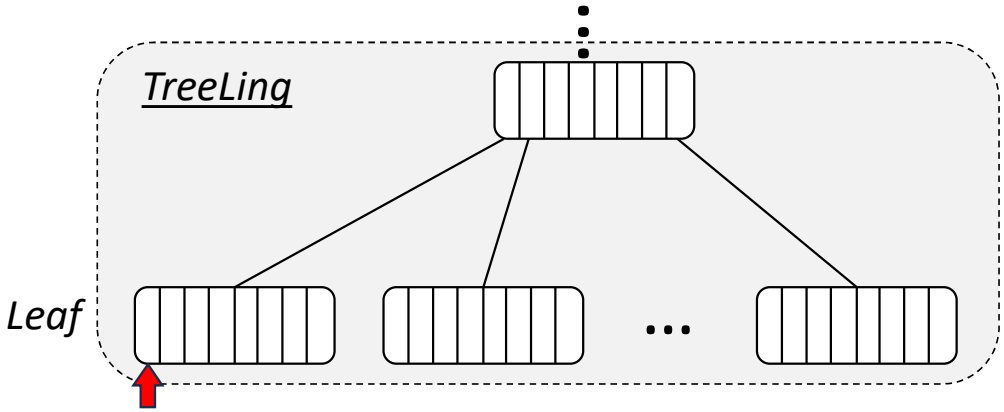
Need for Efficient Page to Tree Node Mapping Mechanism

Problems with simple page to tree node mapping mechanism:



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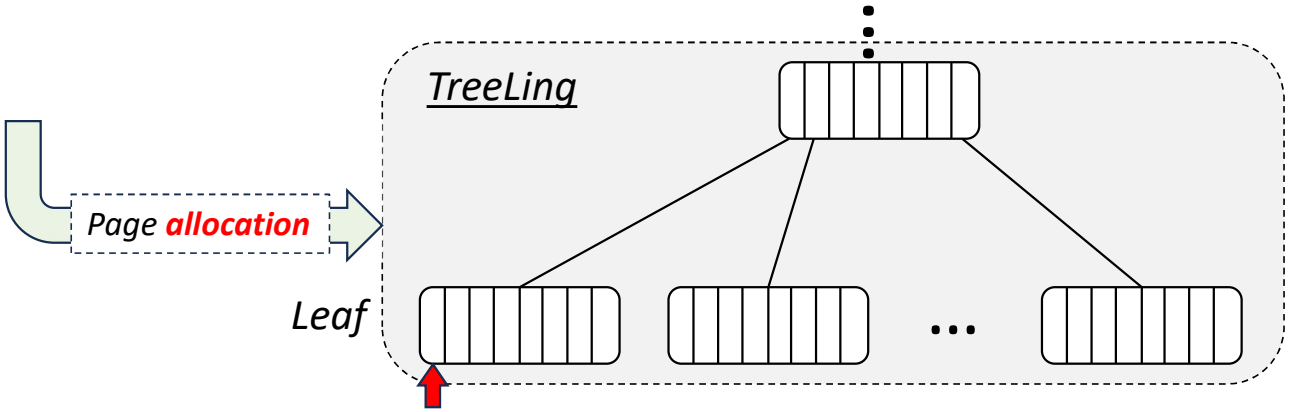

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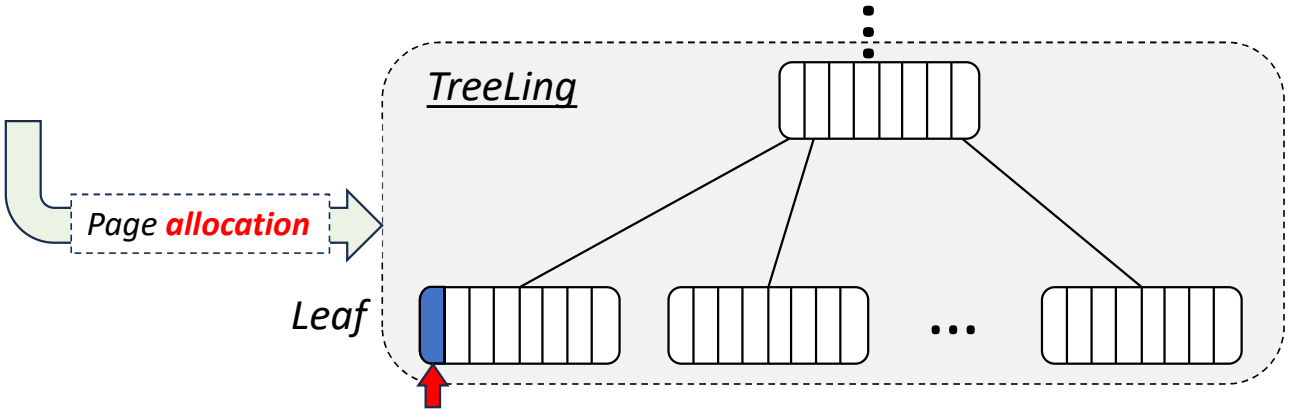

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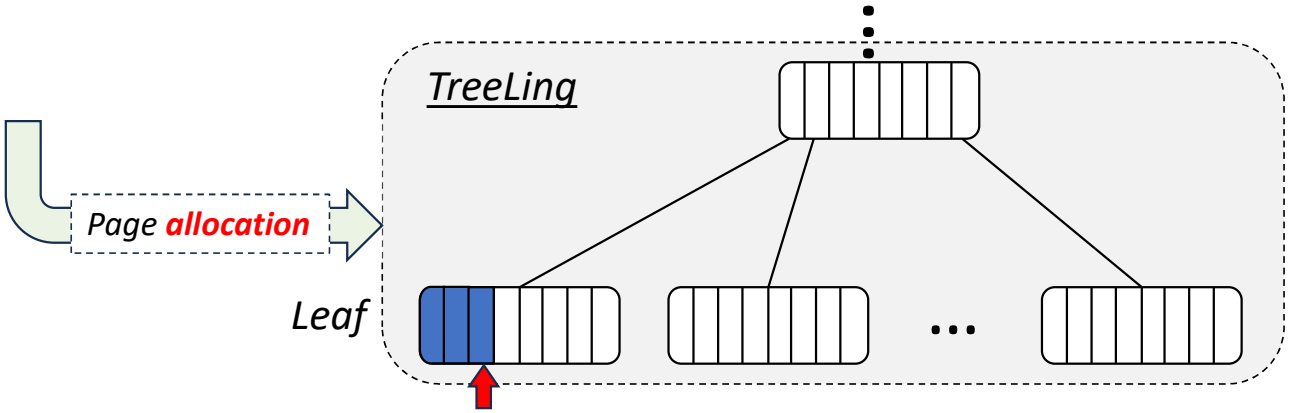

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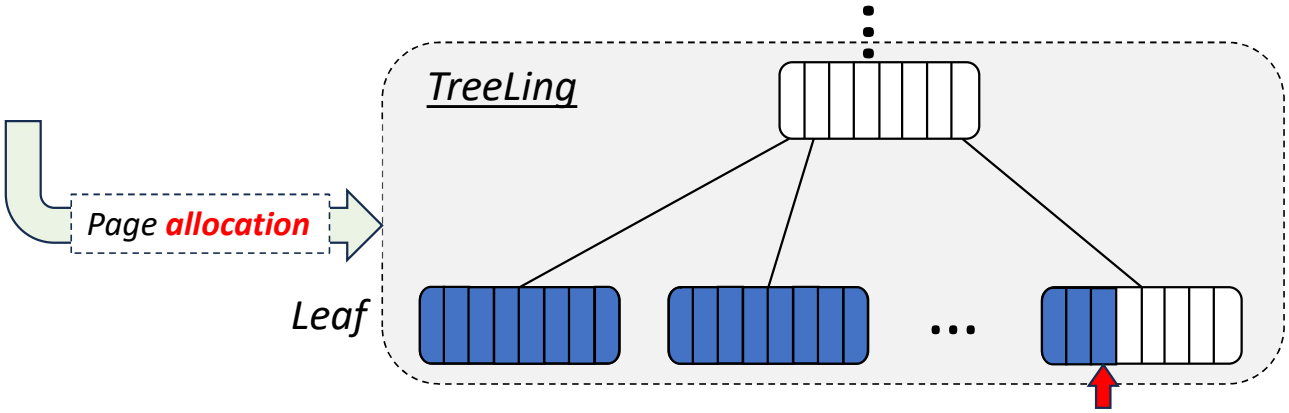

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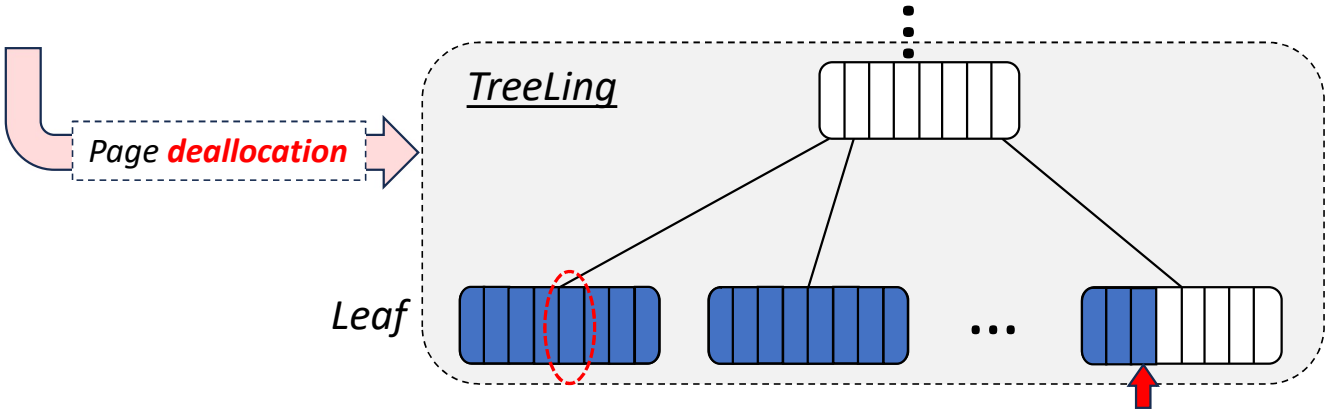

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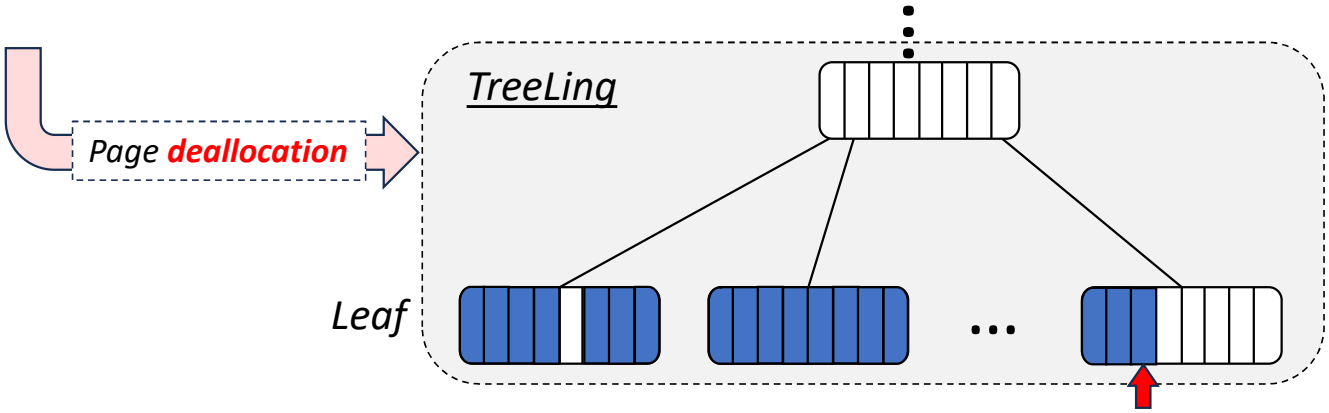

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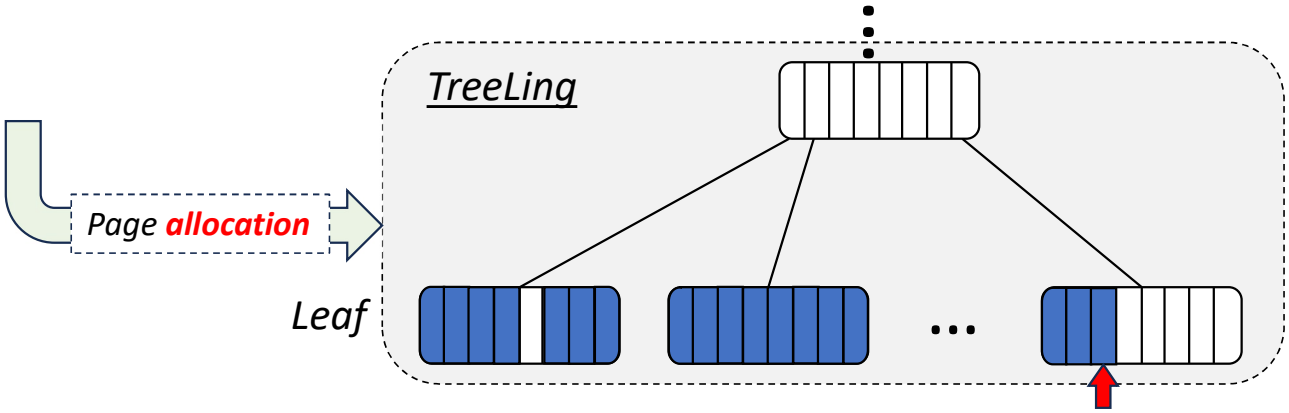

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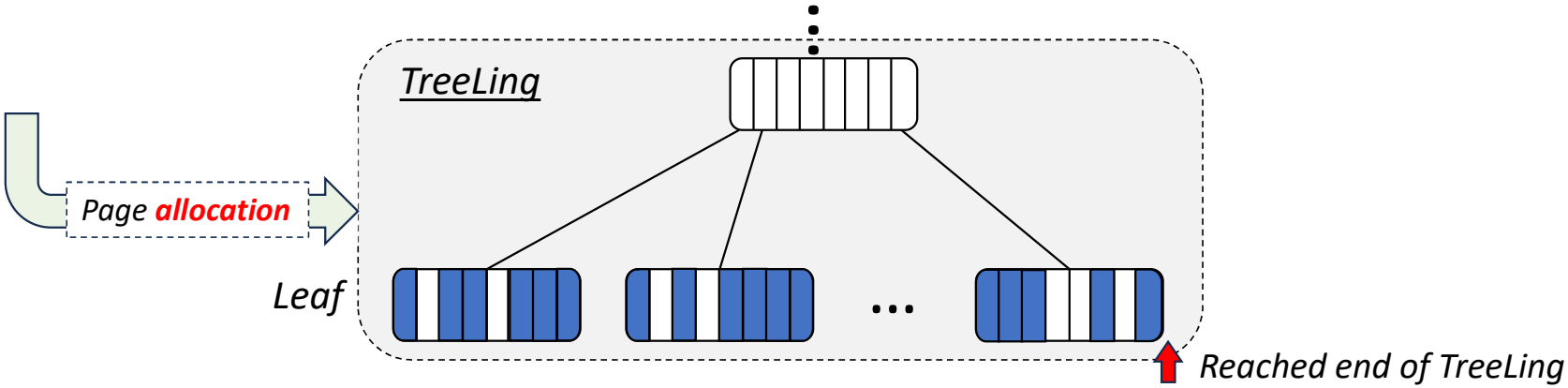

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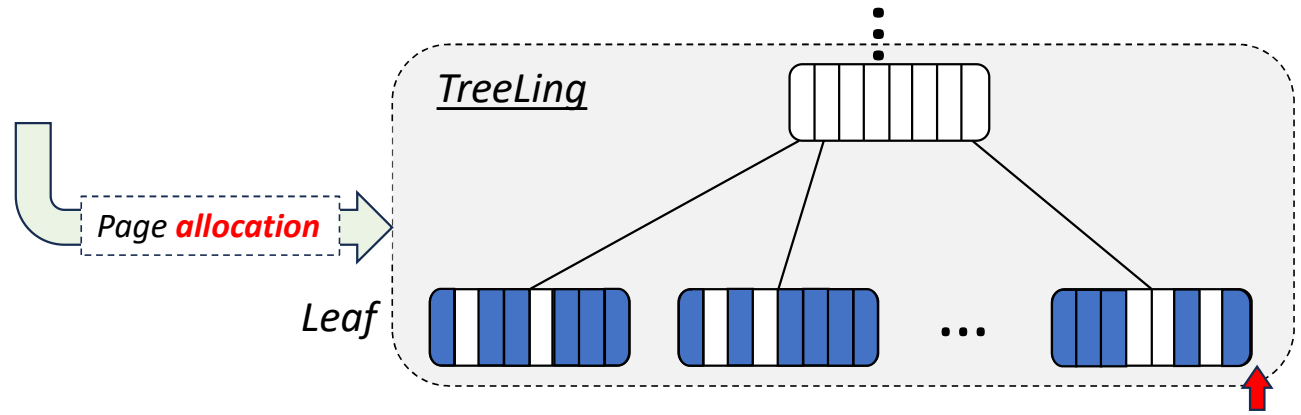

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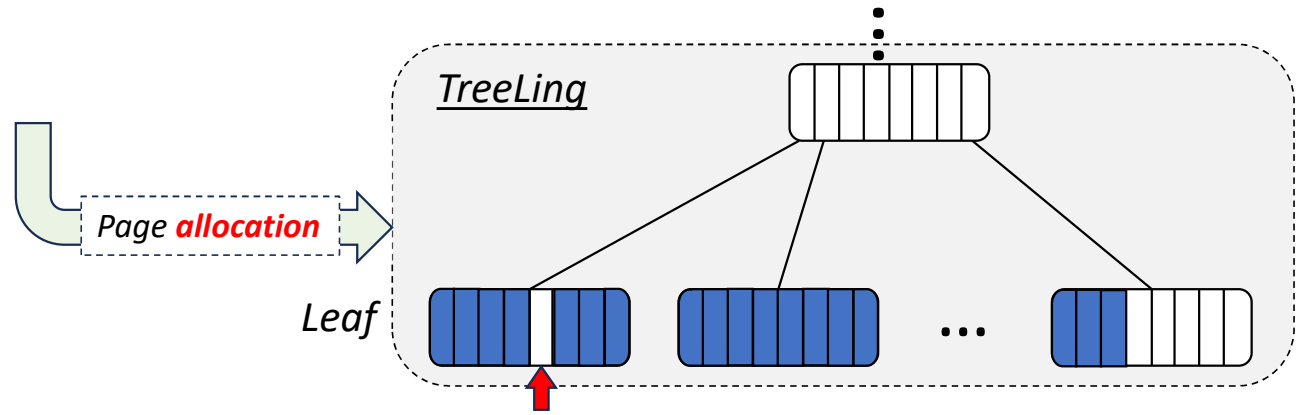

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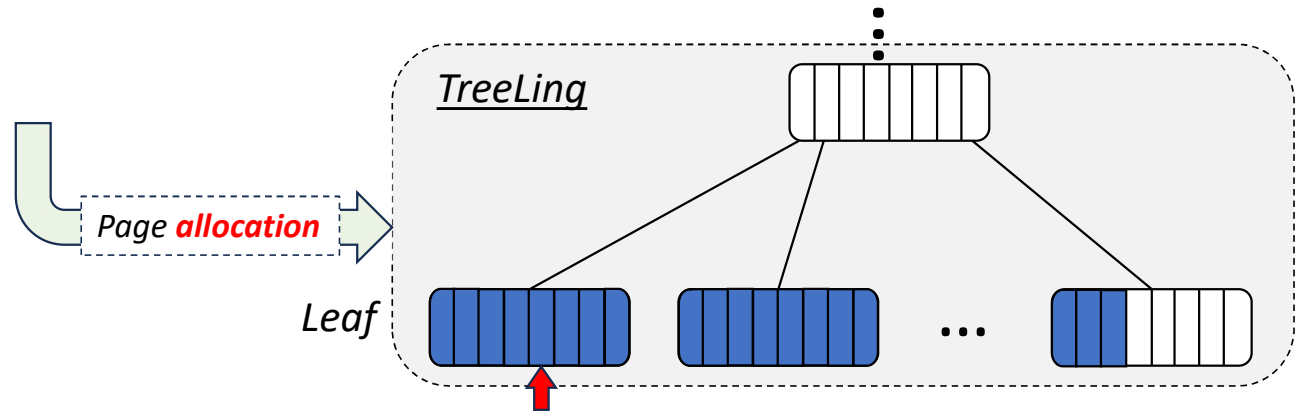

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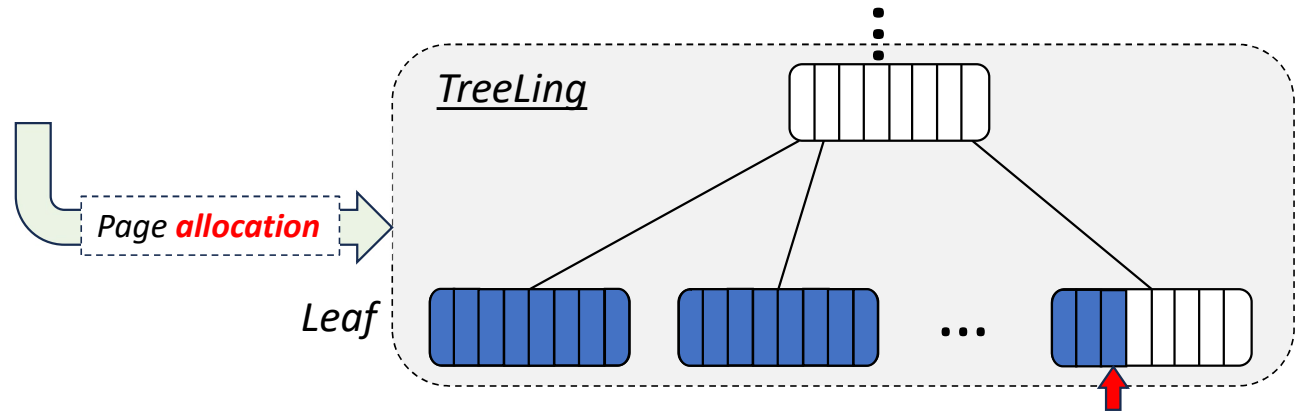

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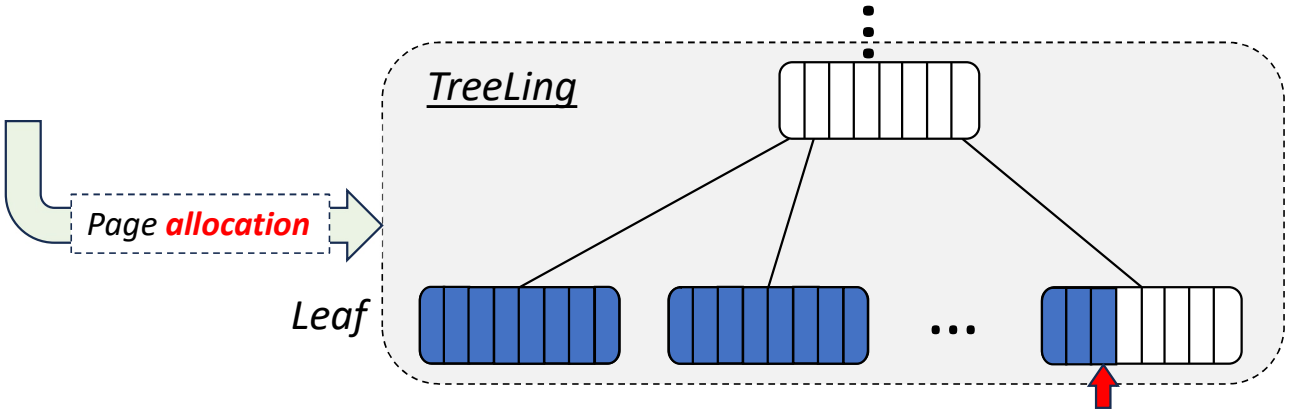

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Alternative: *Scan through all leaf nodes* to find an available node **(up to $O(N = \#\ of\ nodes)$** overhead**).**

In critical path of program execution

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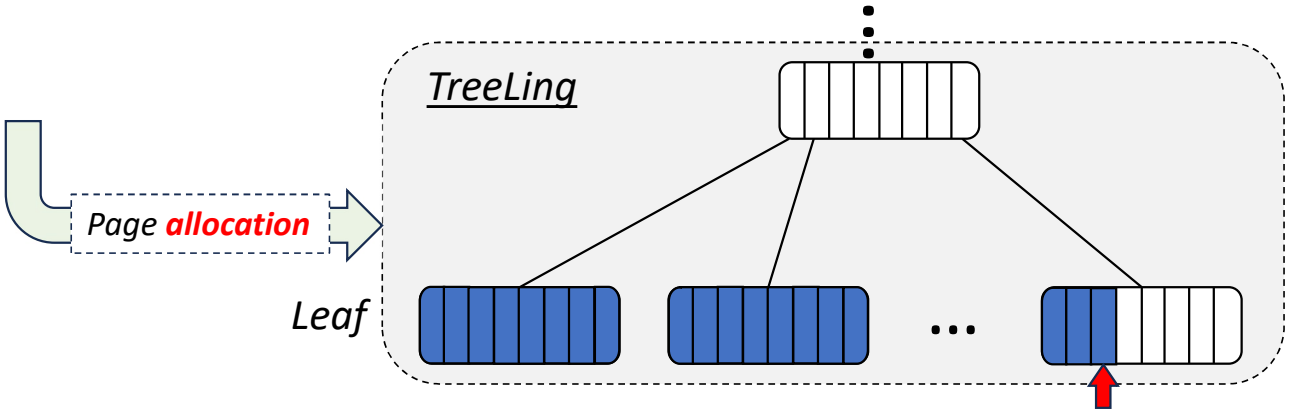

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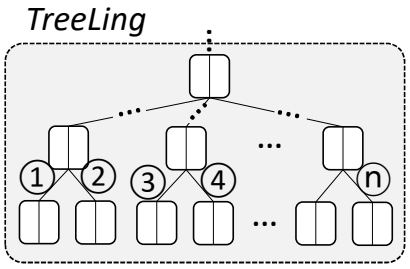
Need ***hardware-only*** design to provide ***efficient and scalable*** TreeLing node mapping to pages.

UCF

Node Free-List: Efficient Mapping of Leaf

- Track *available leaf nodes* in a Node Free-List (NFL).



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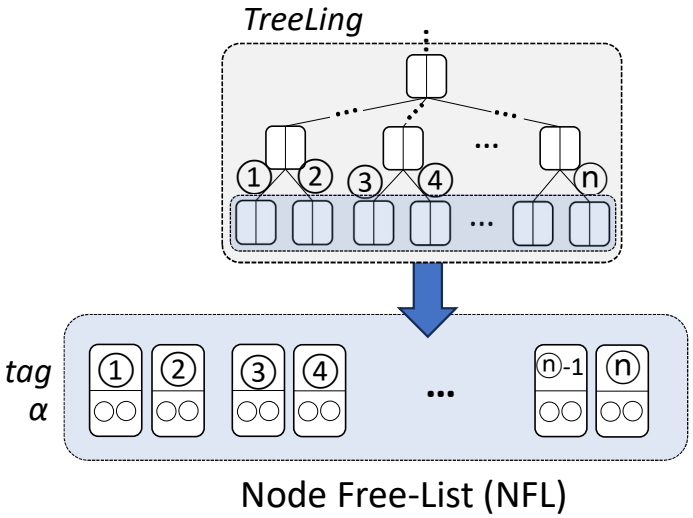

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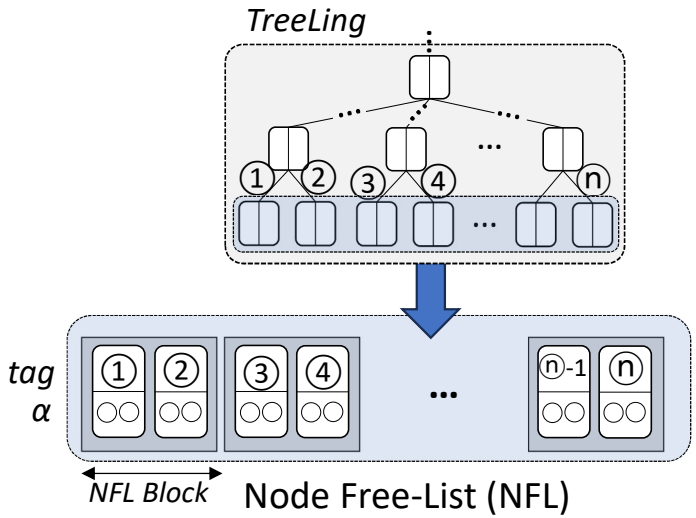

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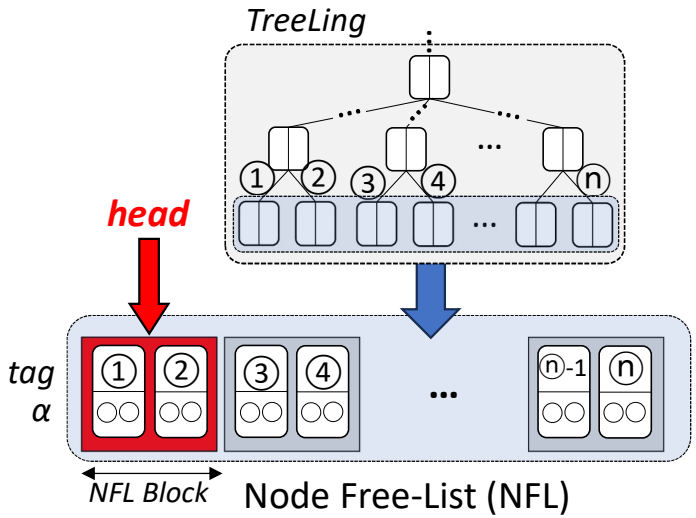
- ***head*** register denotes currently active NFL block.



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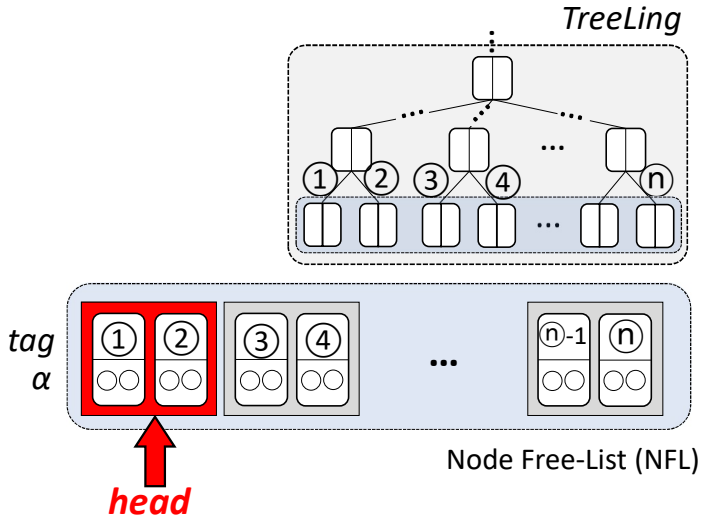
Efficient Mapping of Tree Nodes via NFL



- During program page allocation, NFL tracks *available tree nodes*.

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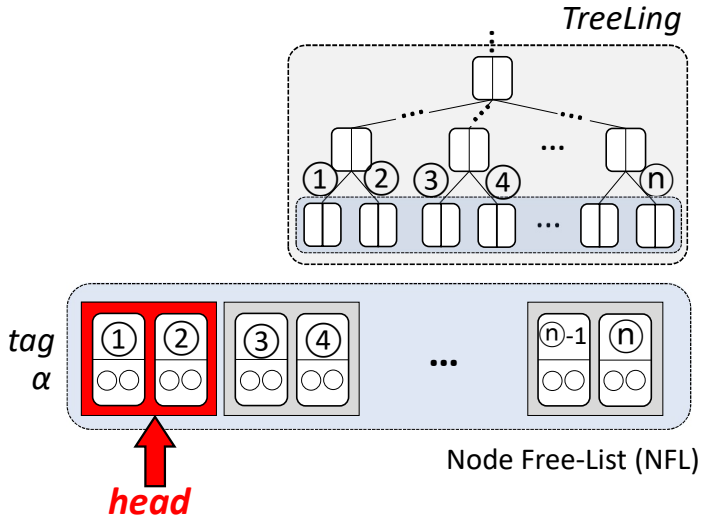

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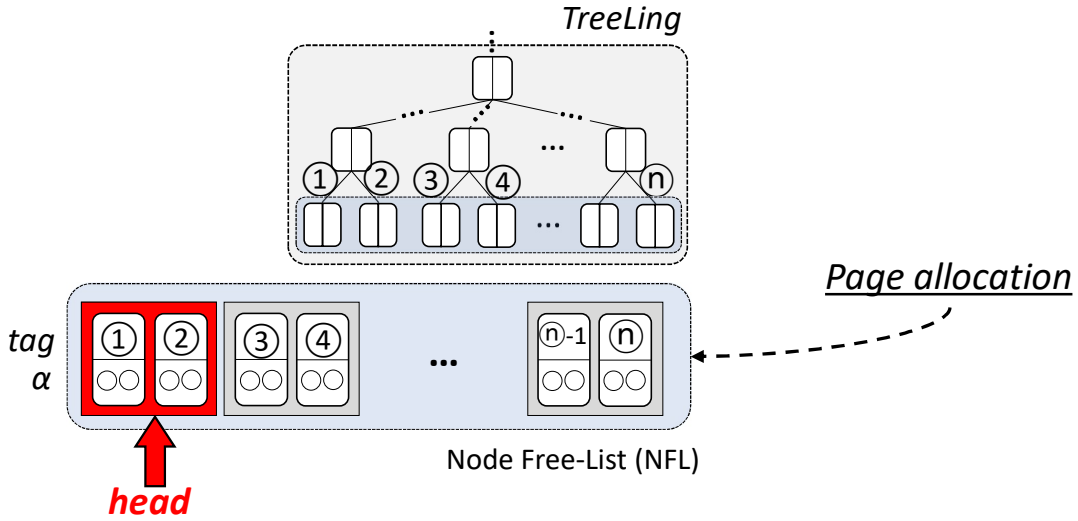

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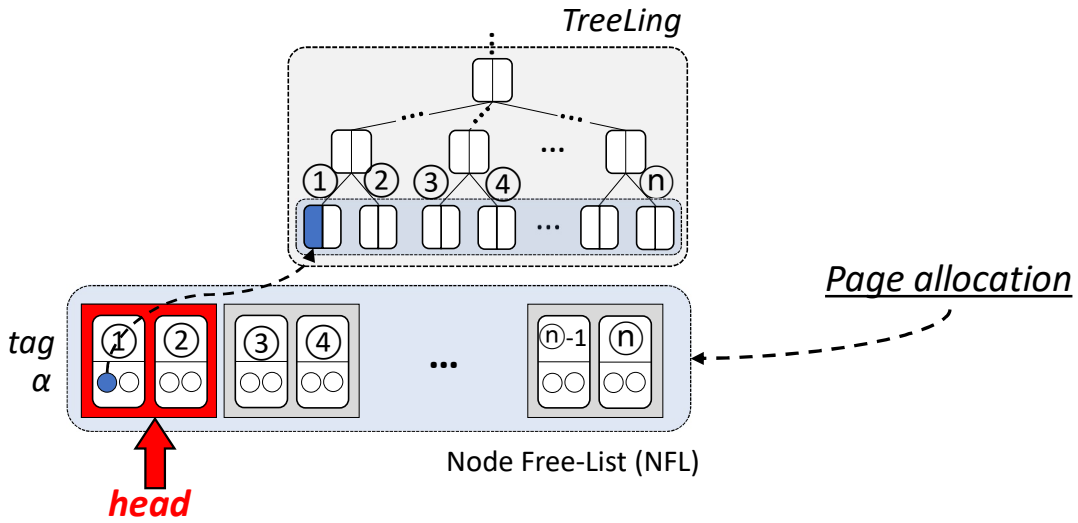

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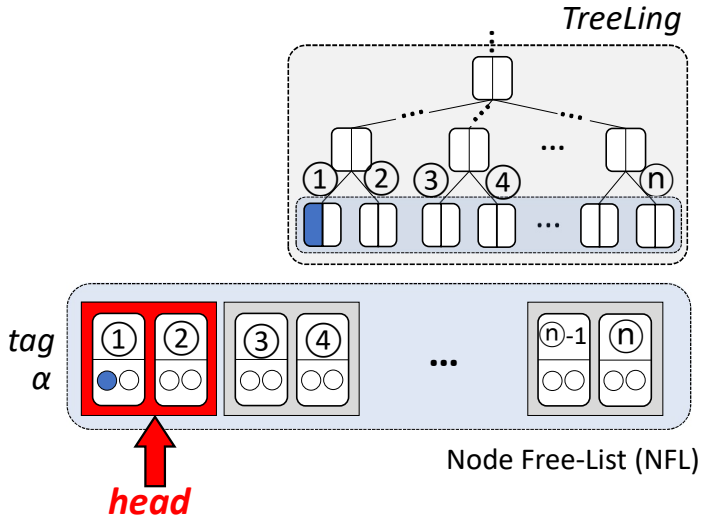

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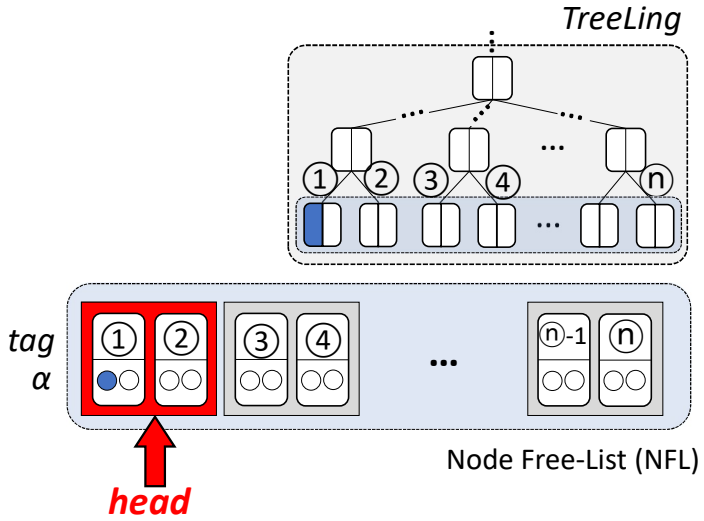

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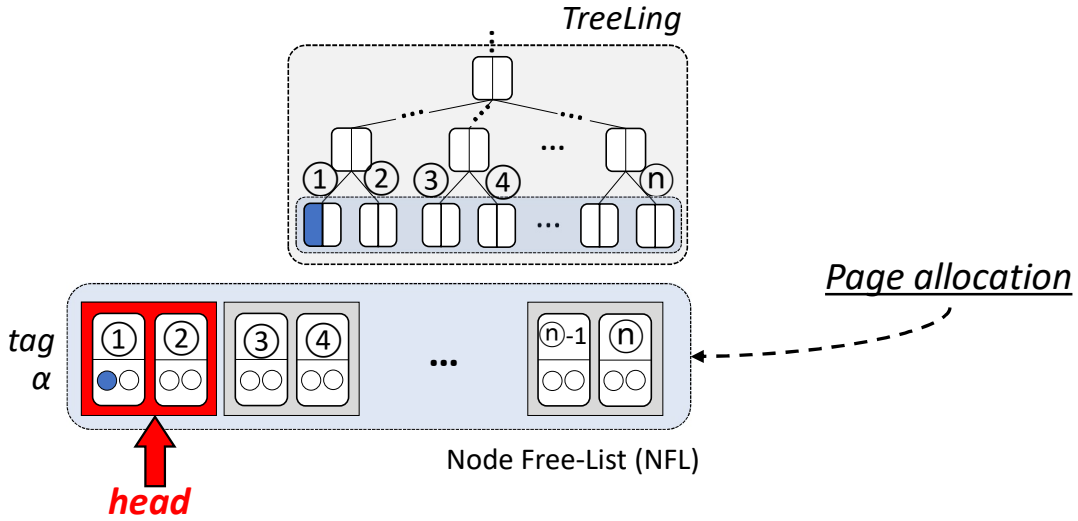

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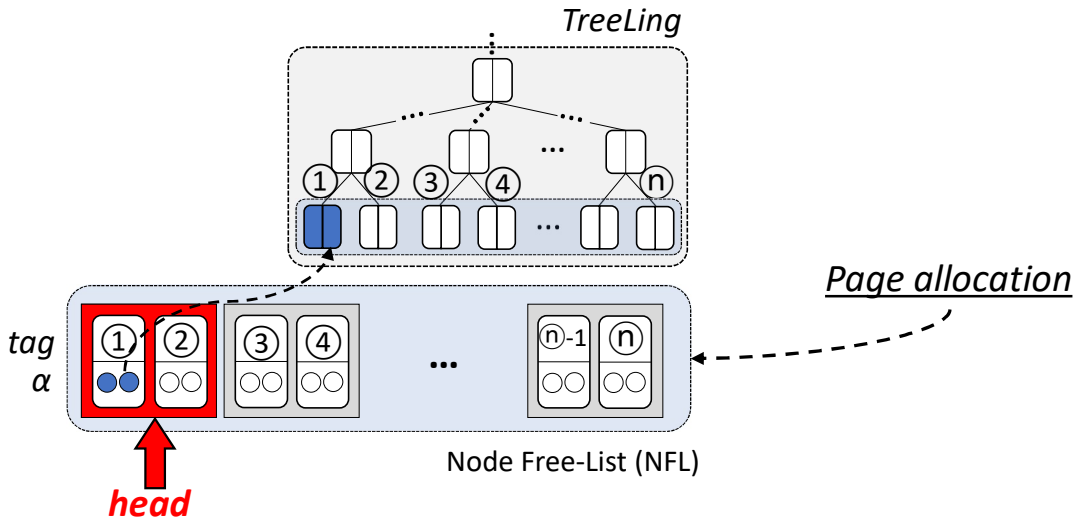
UCF

Efficient Mapping of Tree Nodes via NFL



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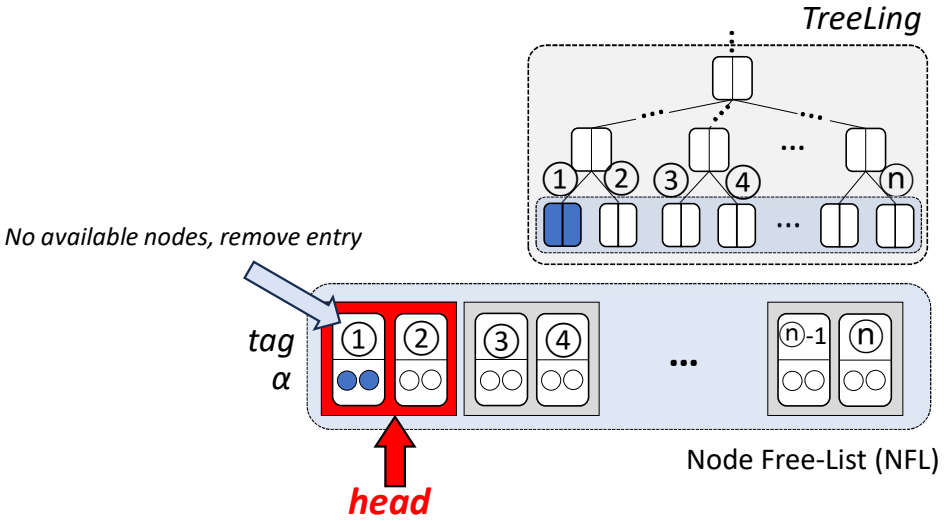

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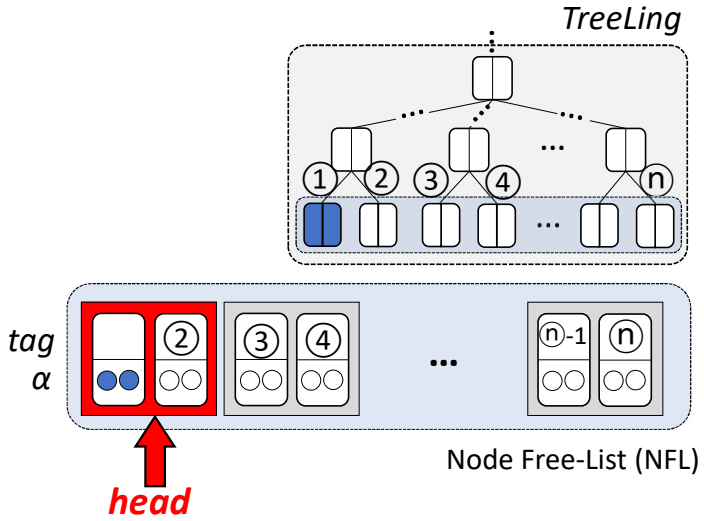

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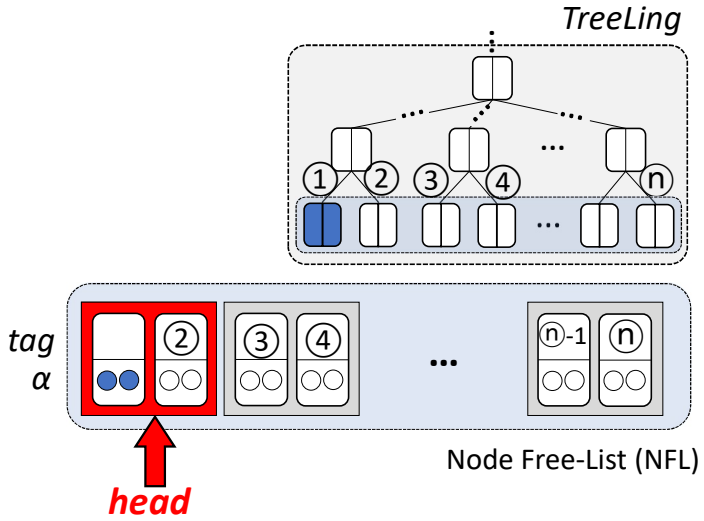

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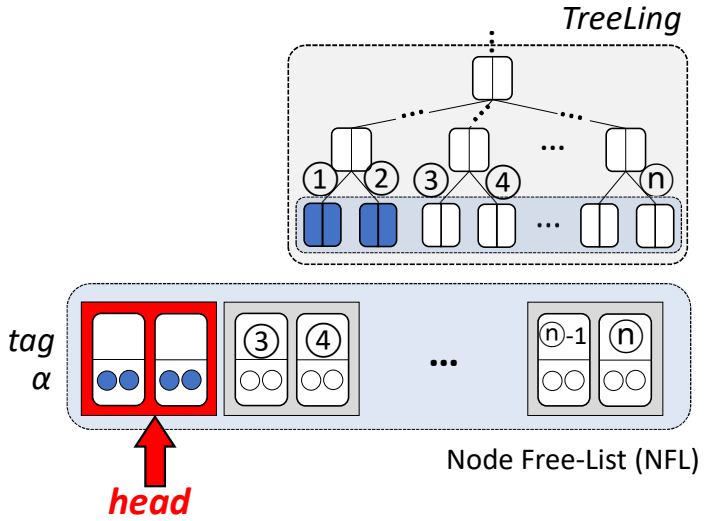

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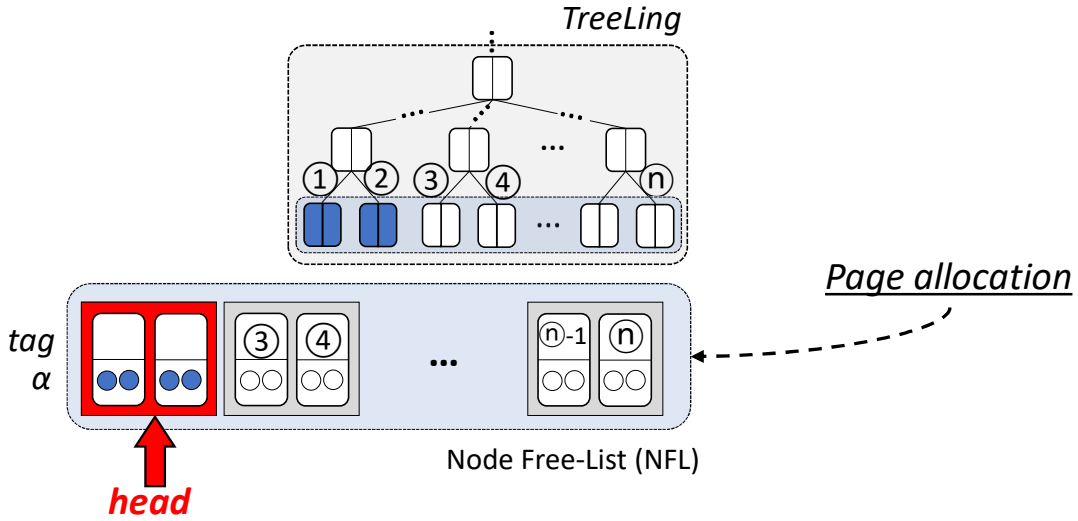

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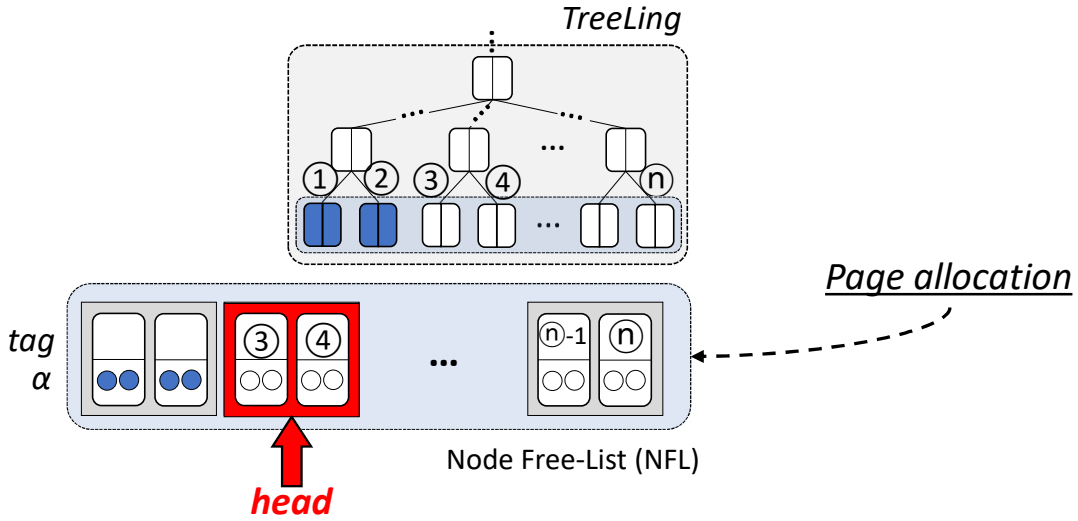

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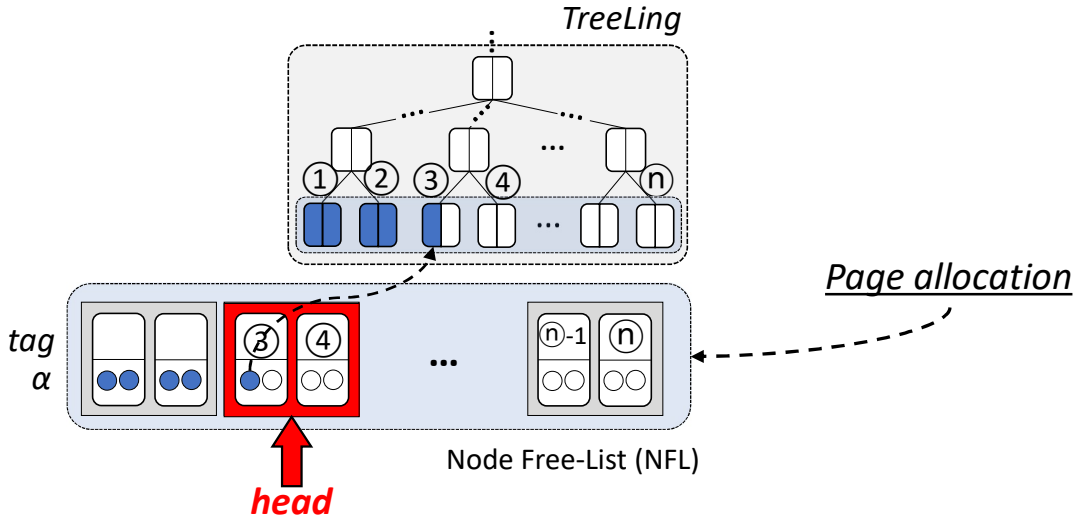

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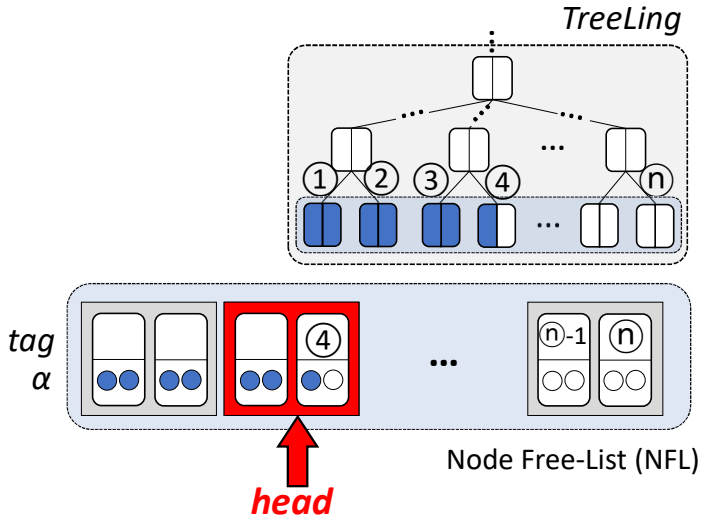
Tracking of Deallocated Tree Nodes via NFL



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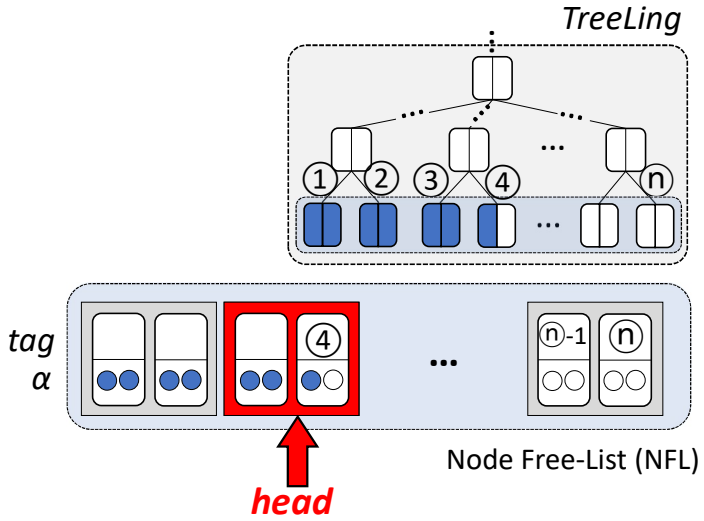

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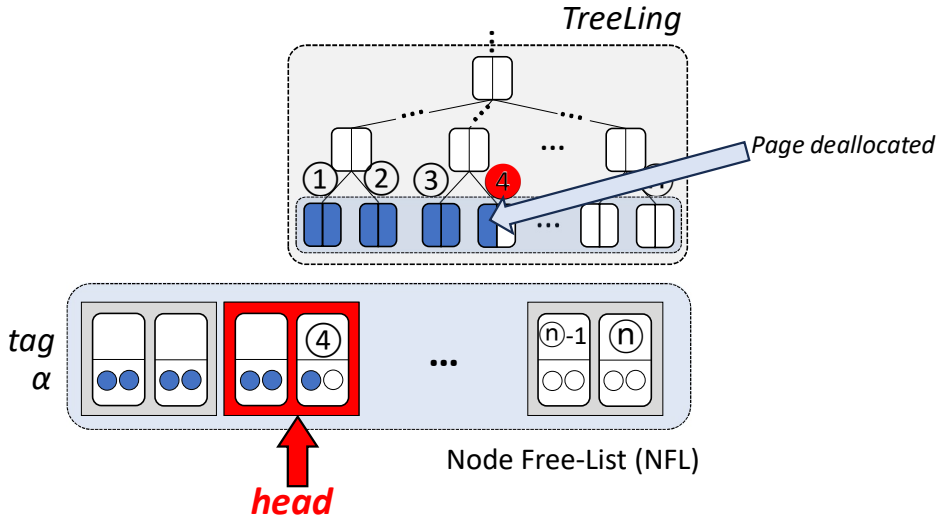

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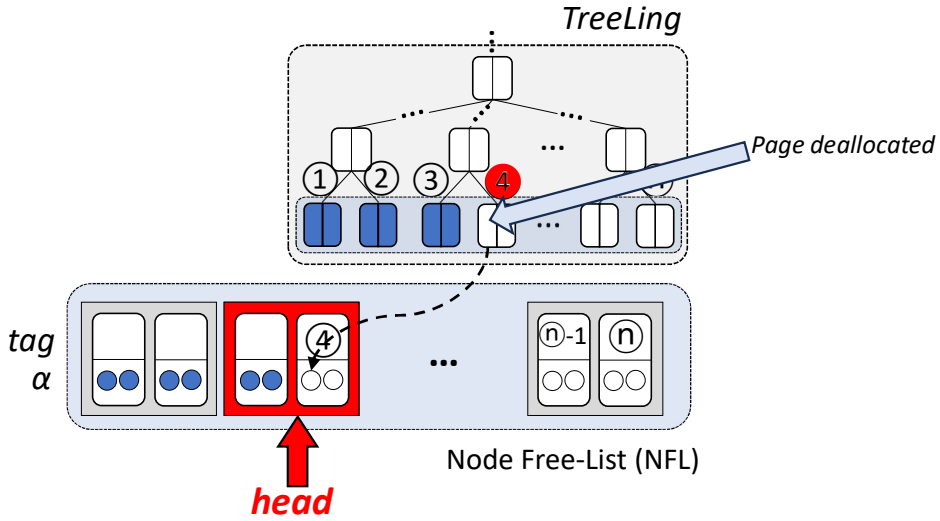

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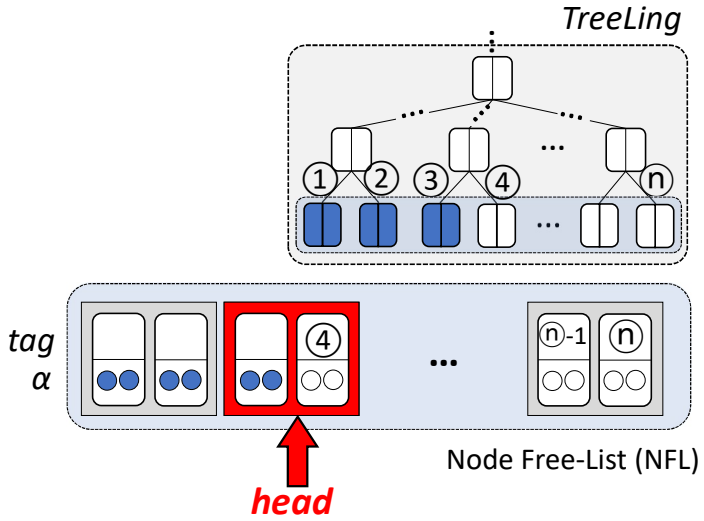

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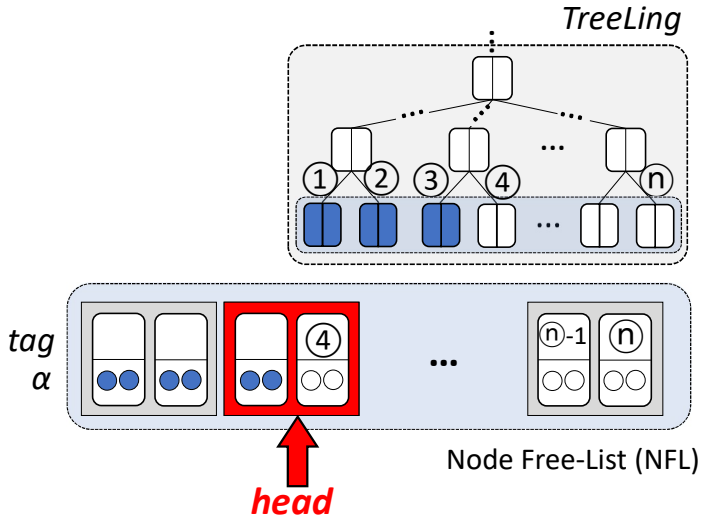

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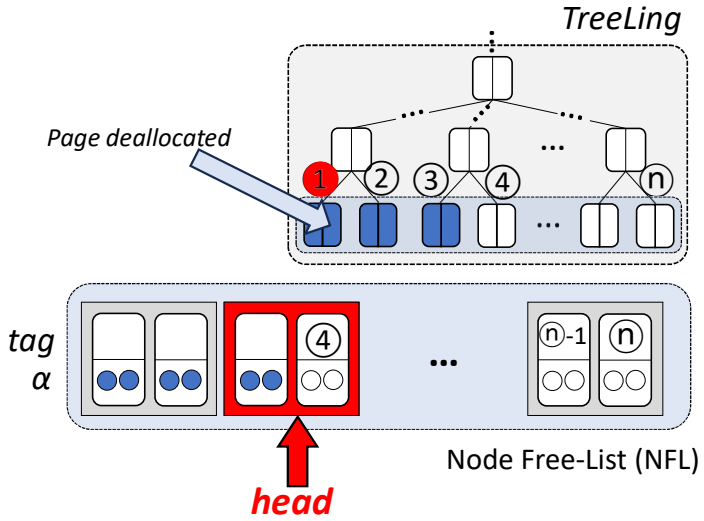

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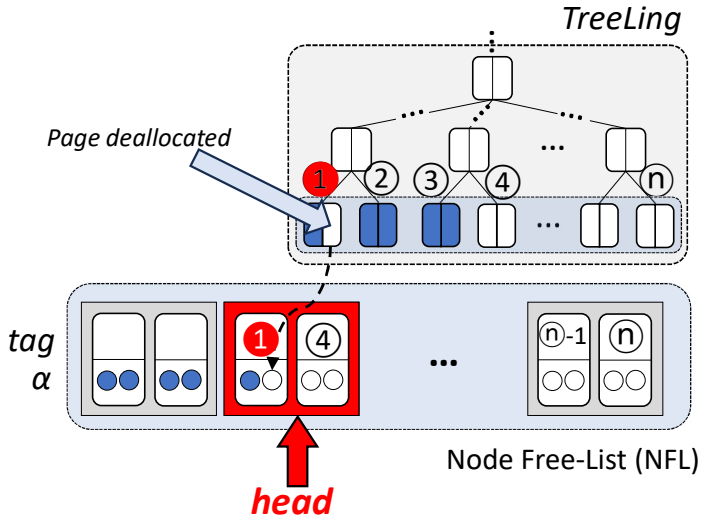

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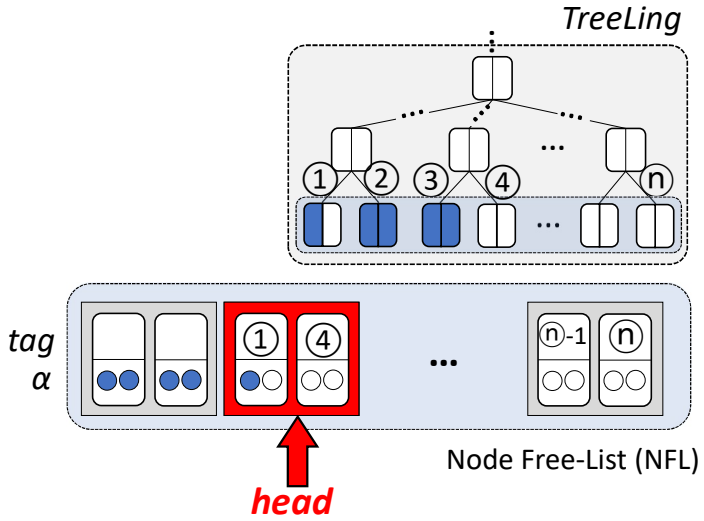

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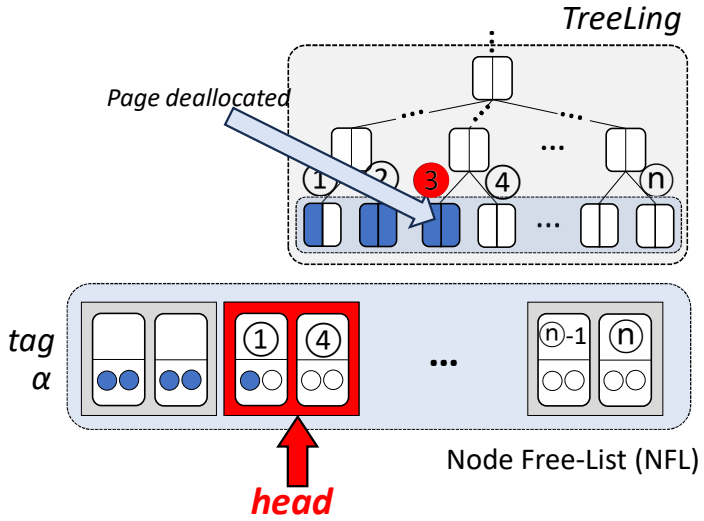

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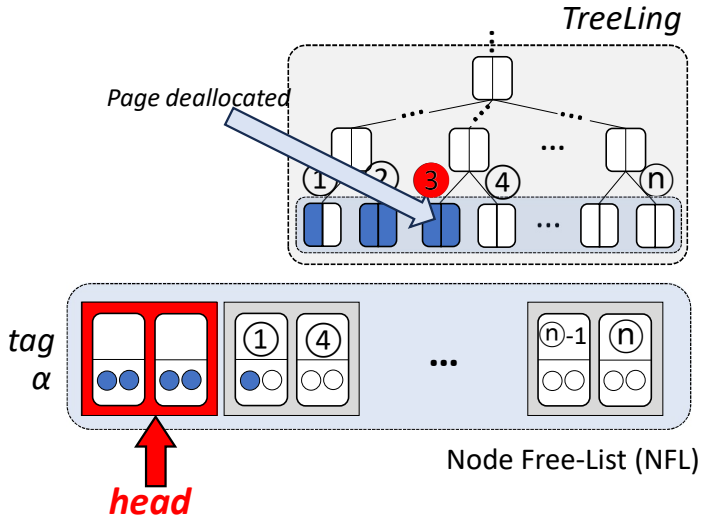

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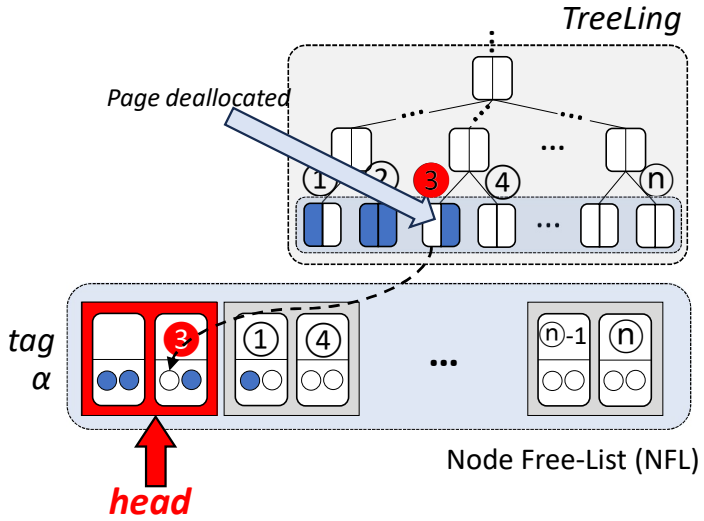

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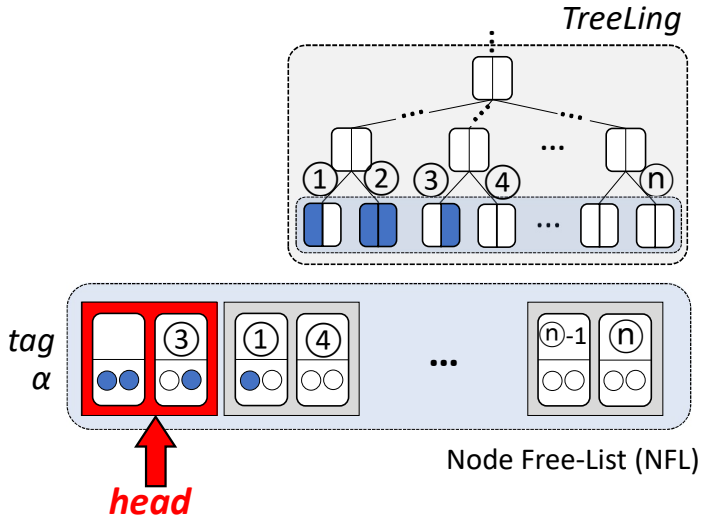

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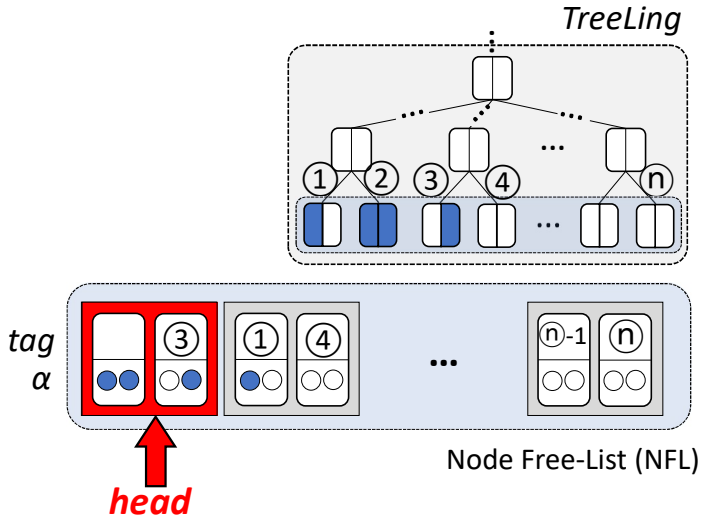

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Maximum of ***O(1) overhead*** for locating an available/empty slot for allocation/deallocation.

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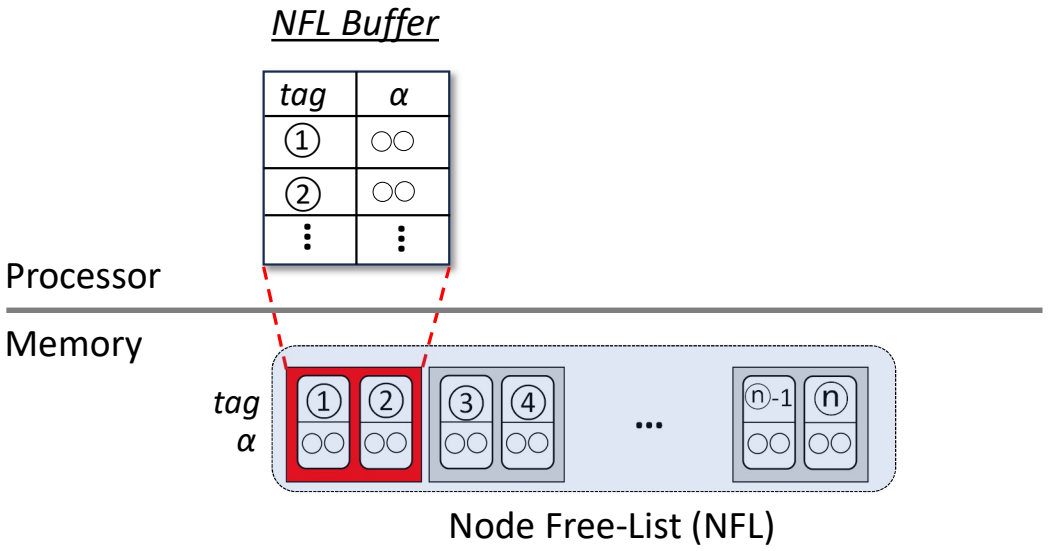
Runtime Maintenance of NFL Blocks

- During runtime, NFL Buffer caches most recently used NFL blocks (i.e., *active NFL block).*
- *NFL buffer* is a CAM structure.



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Determining Optimal TreeLing Configuration

- Real-world workloads has skewed memory distributions.

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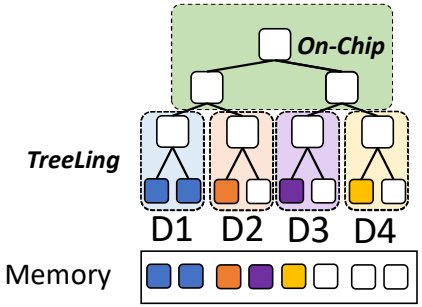

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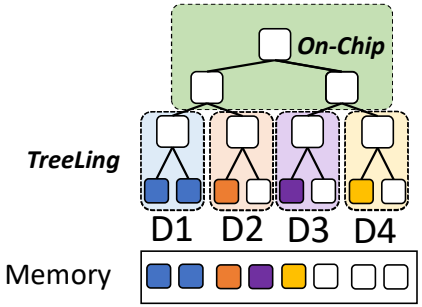

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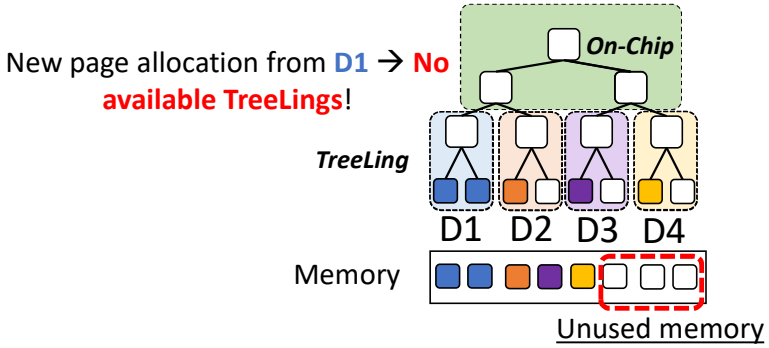

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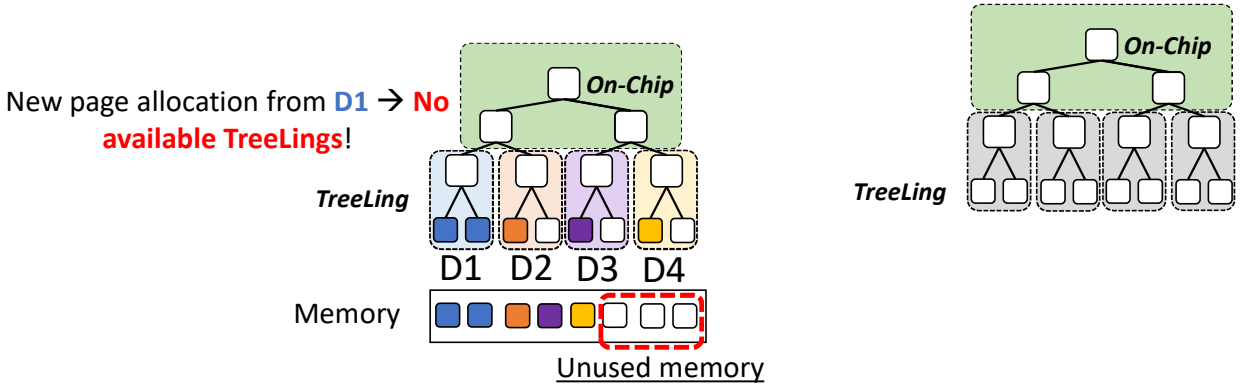

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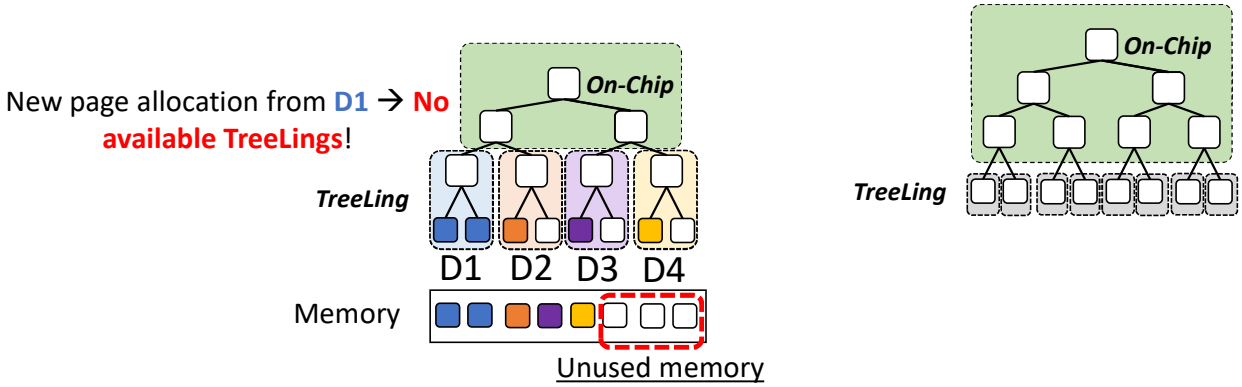

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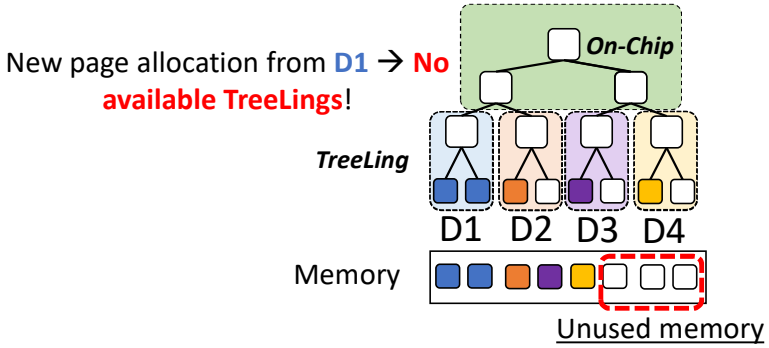

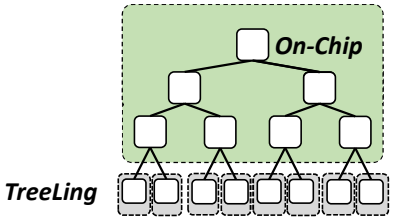

More TreeLings available.
Higher on-chip overheads.

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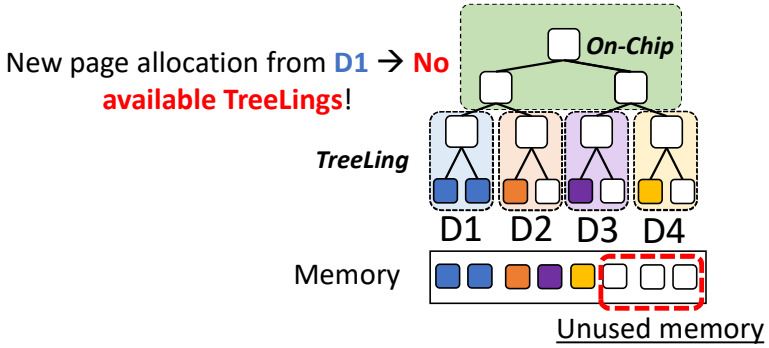

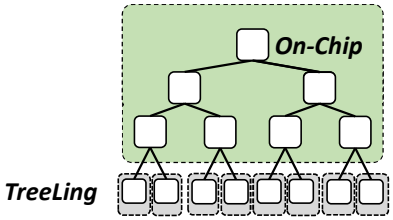

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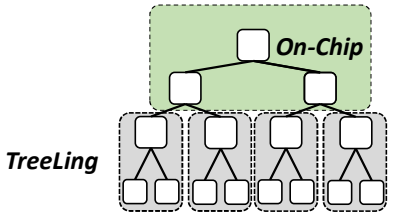

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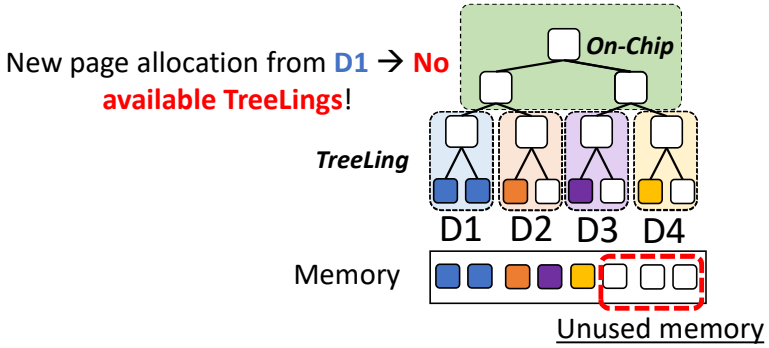

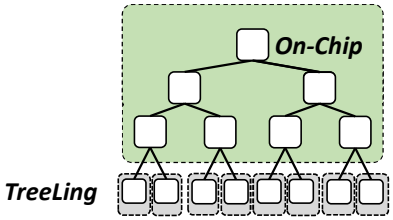

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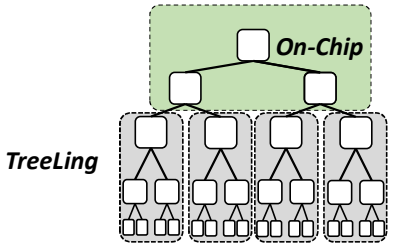

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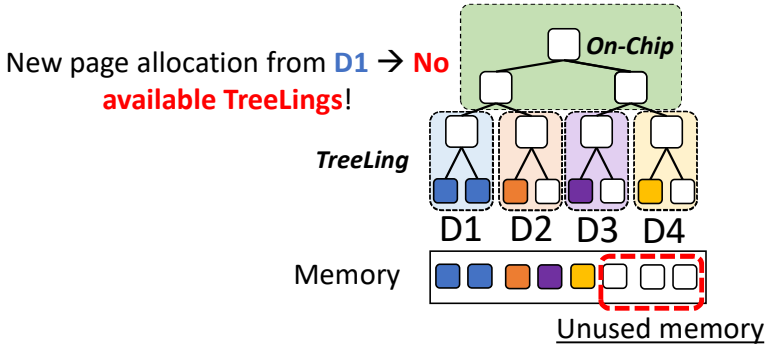

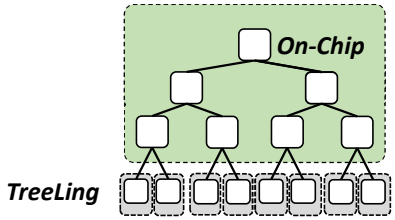

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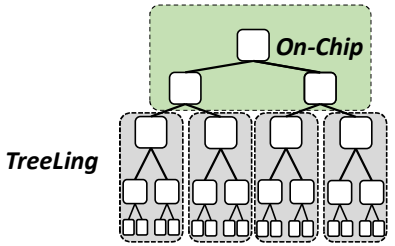

More per-TreeLing coverage.
Higher memory storage overhead.

UCF

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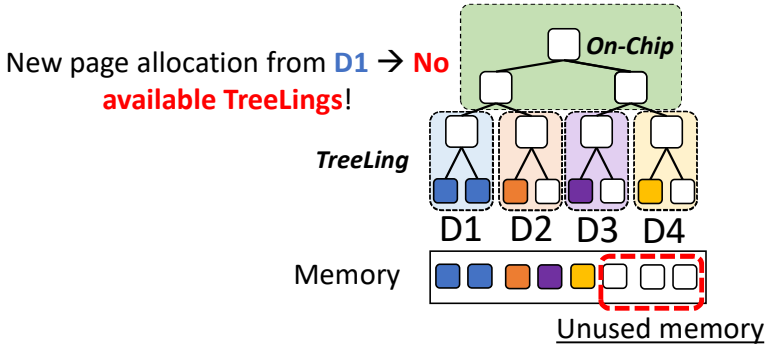

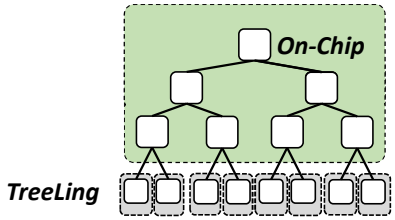

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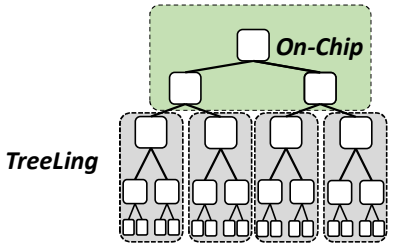

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Determining *optimal number of TreeLings* require *multi-dimensional optimization*.
(considering memory size, number of domains and available on-chip storage)

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IvLeague-Invert: Dynamic TreeLing Extension

- Classical integrity tree structure has sub-optimal allocation policy.
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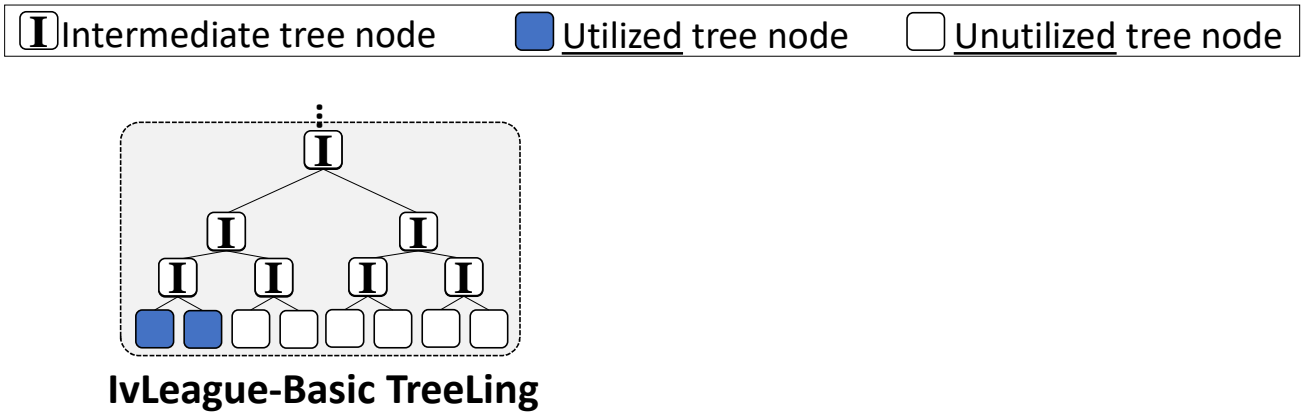

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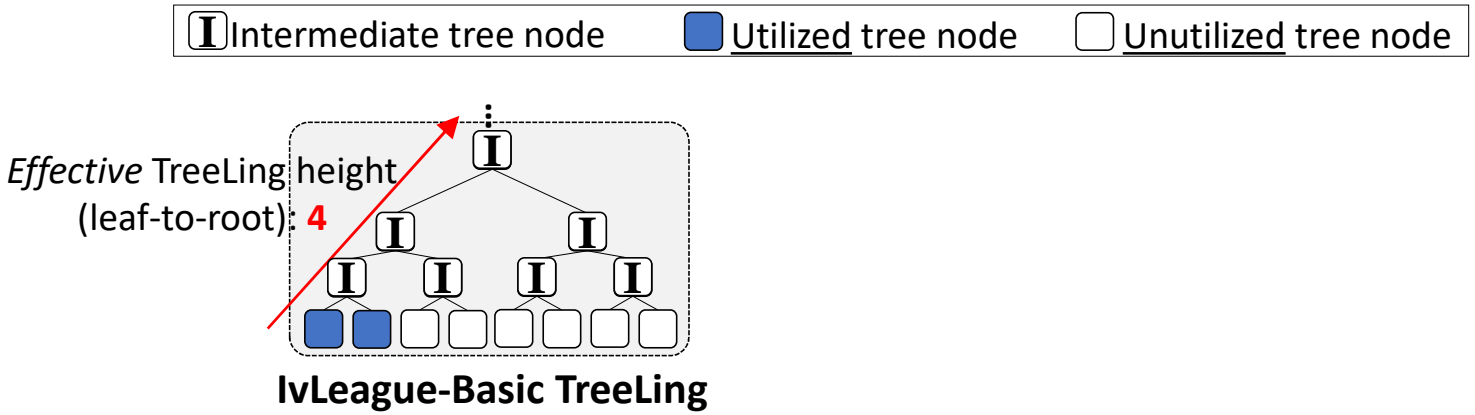

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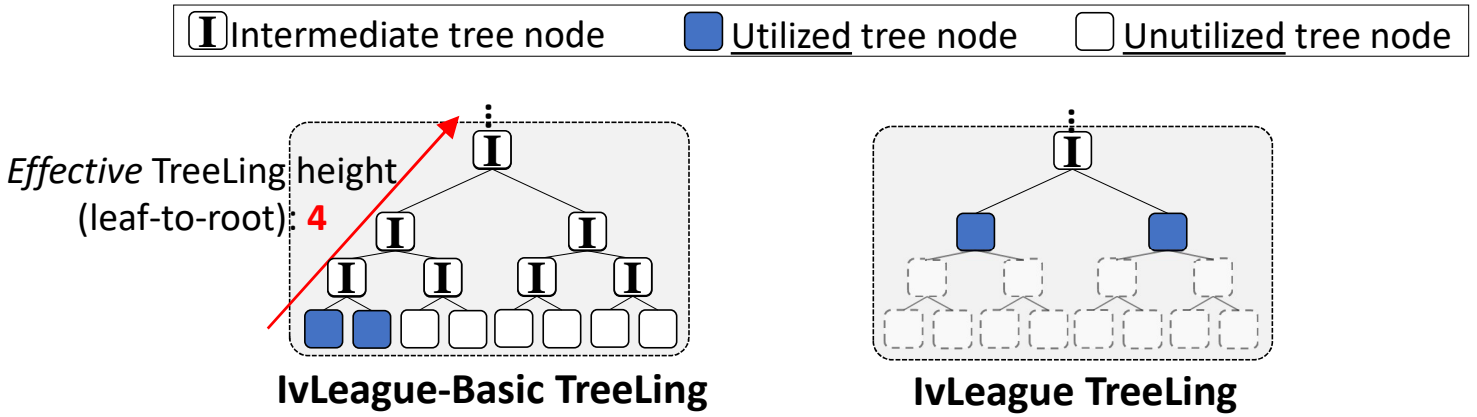

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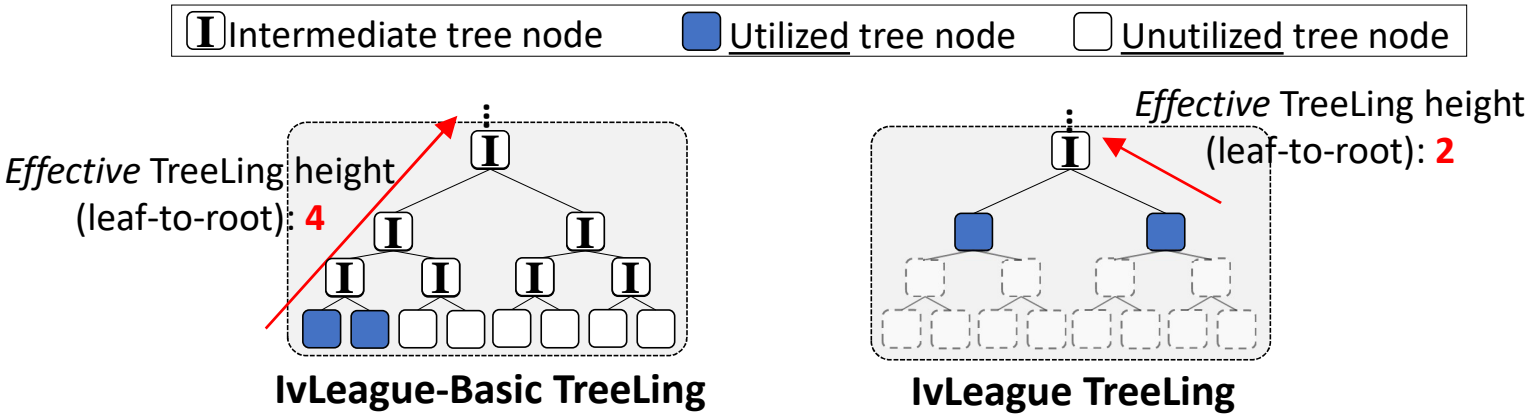

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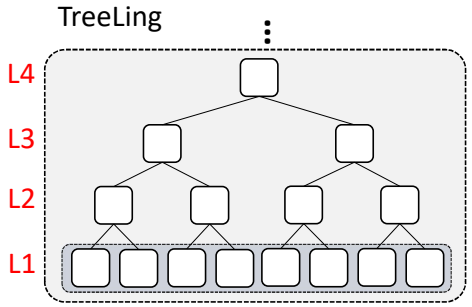
Dynamic TreeLing Extension of IvLeague-Invert



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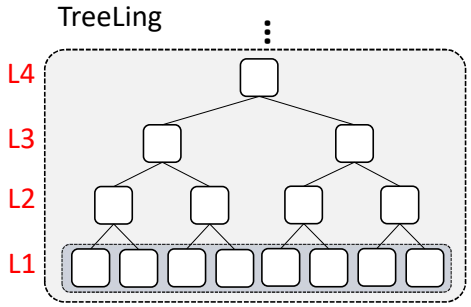

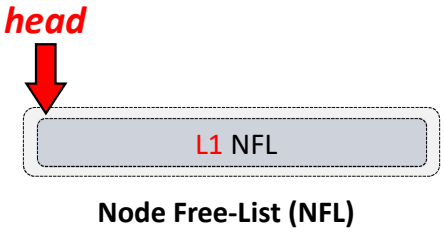

Node Free-List (NFL)

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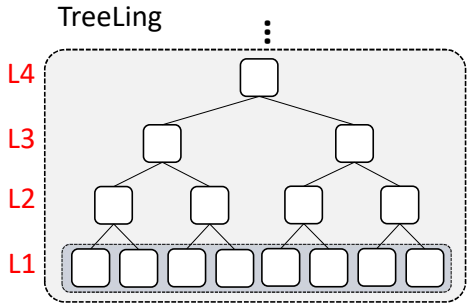

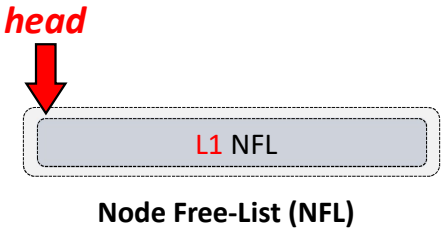

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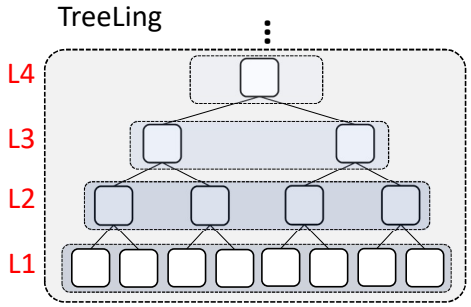

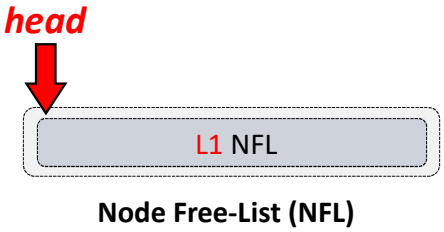

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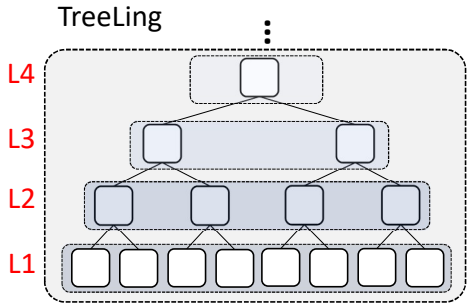

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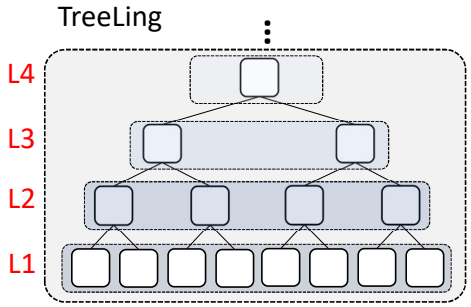

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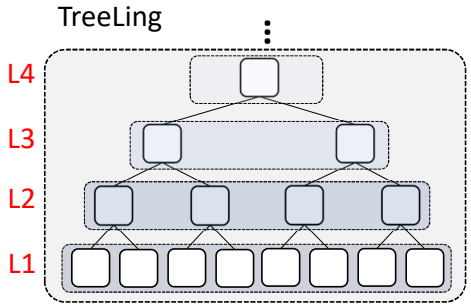

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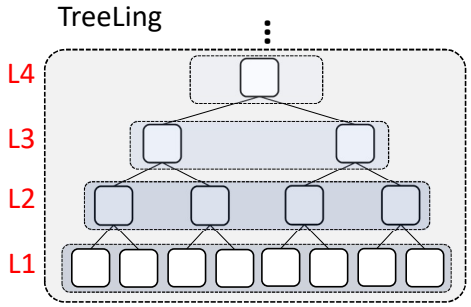

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Can significantly reduce integrity verification overhead by ***decreasing the number of levels to be traversed***.

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IvLeague-Pro: Optimize High-Frequency Pages

- In typical real-world workloads, a small portion of memory is accessed very frequently (i.e., ***hotpages***).
- Place *hotpages closer to root* → ***reduced integrity verification overhead*** for high frequency pages.

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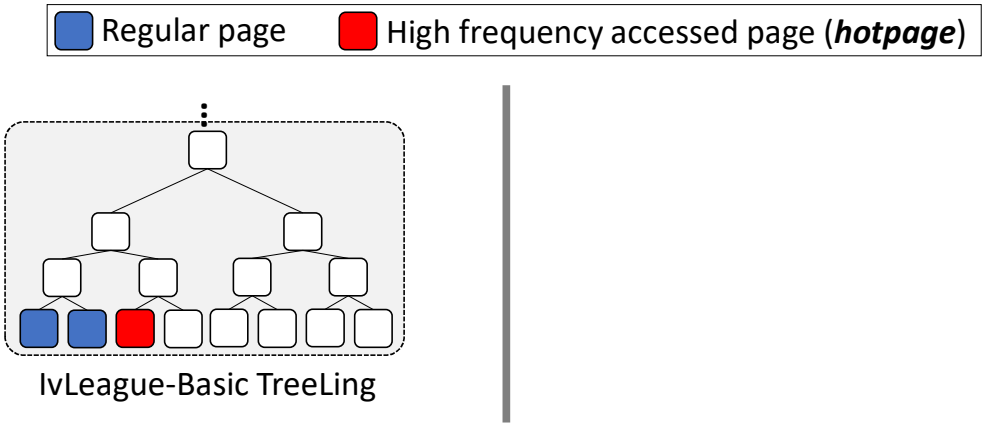

IvLeague-Basic TreeLing

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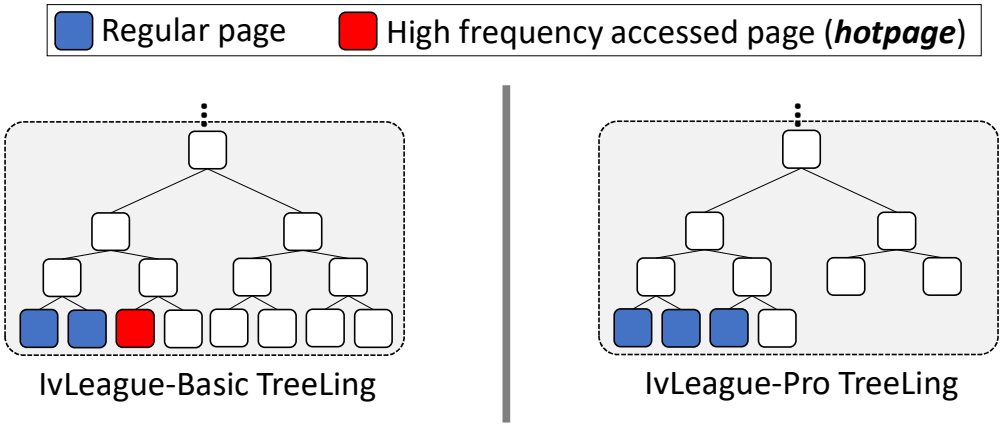

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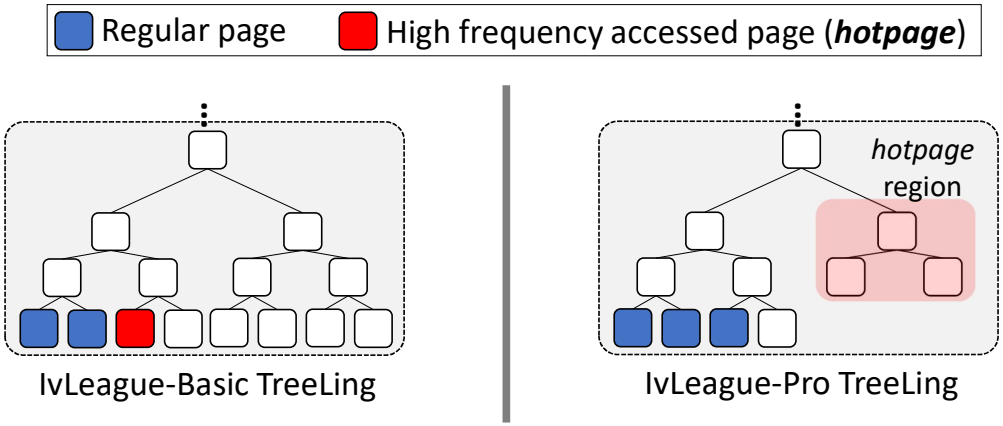

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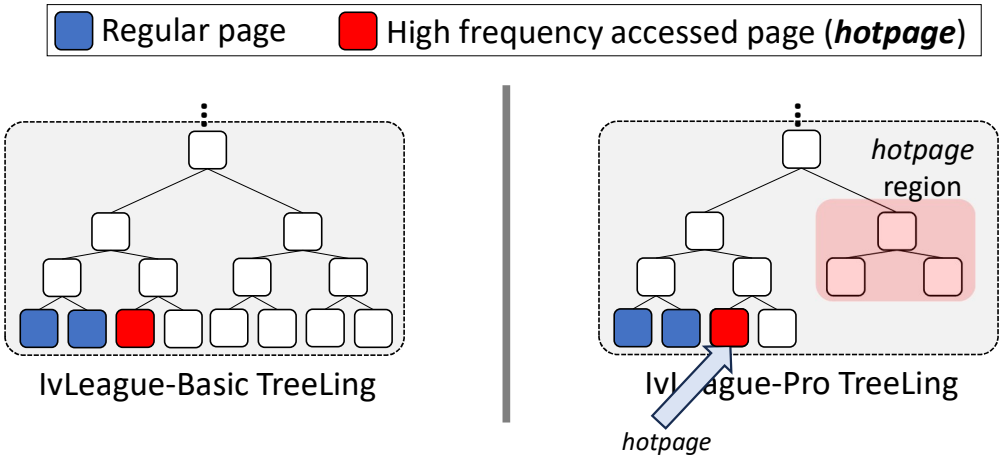

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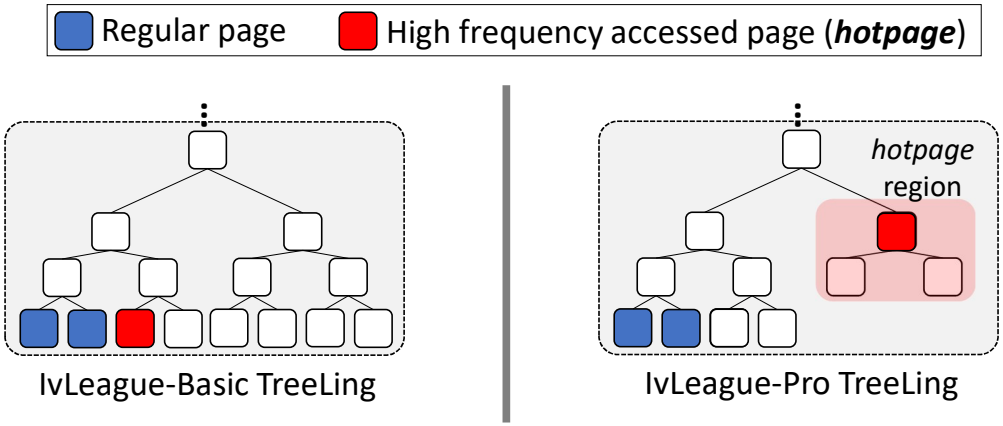

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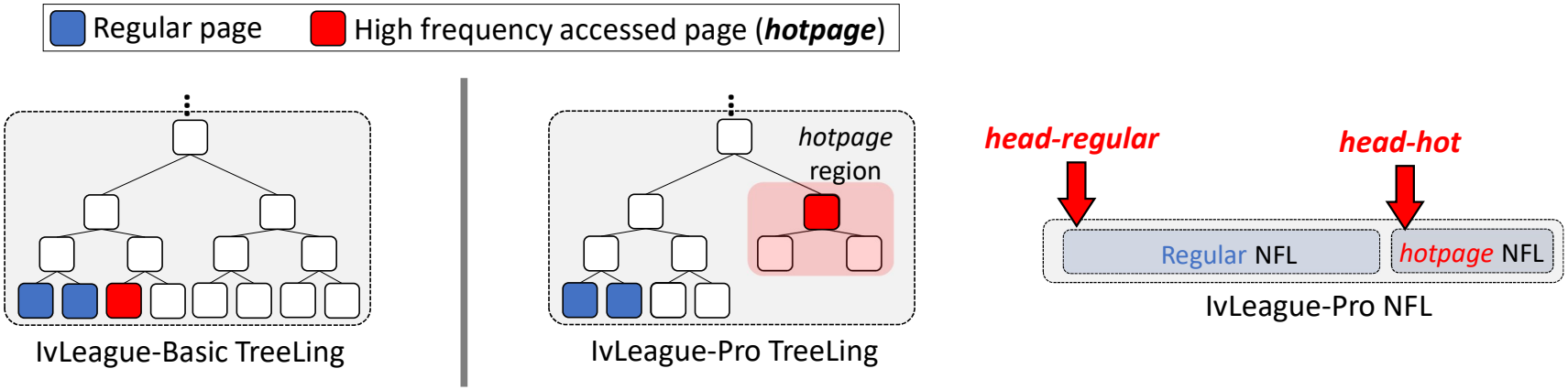
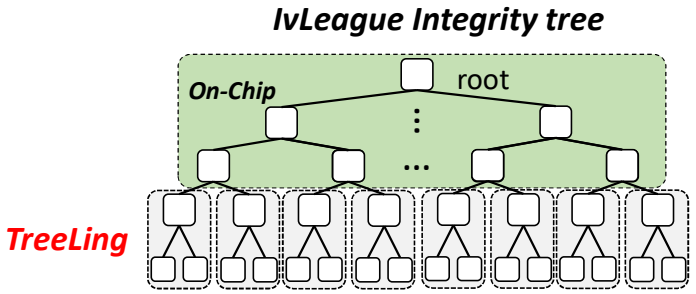


Security Analysis



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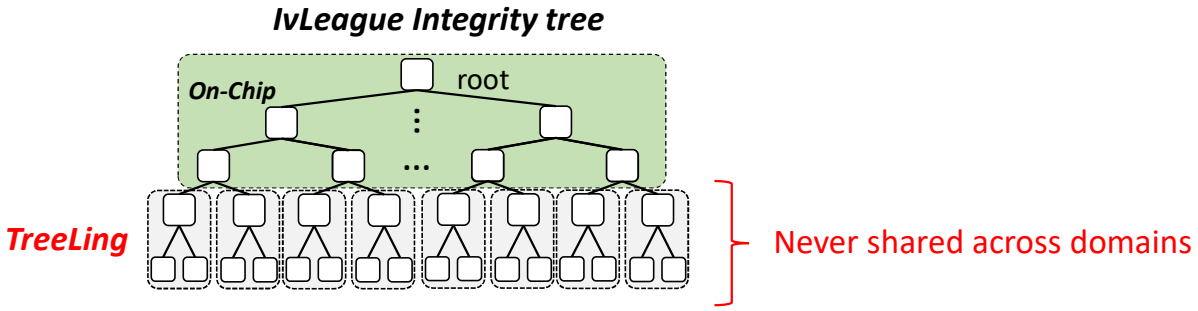

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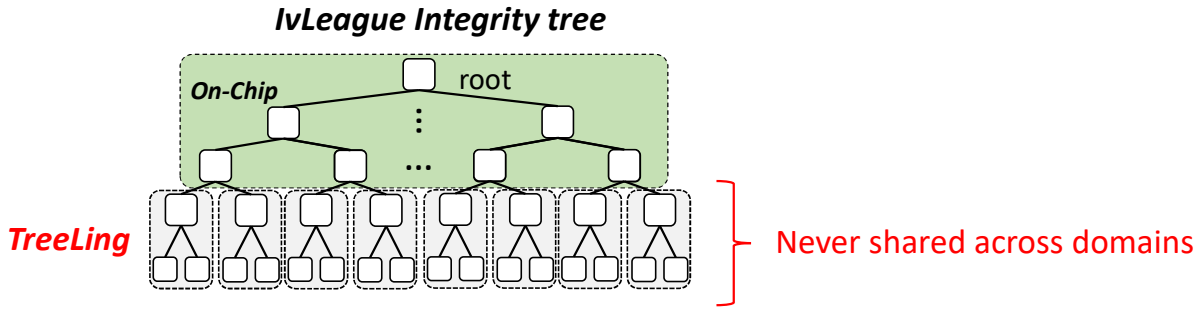

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- TreeLing roots are always kept on-chip → **no timing channel possible** for shared roots.

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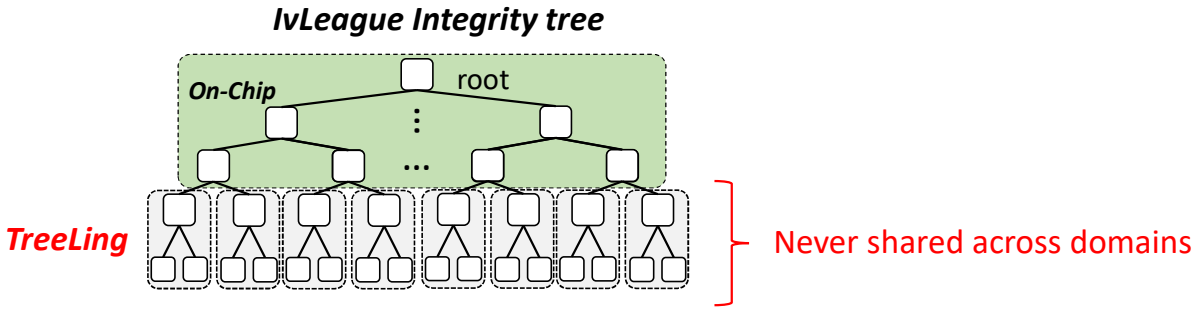

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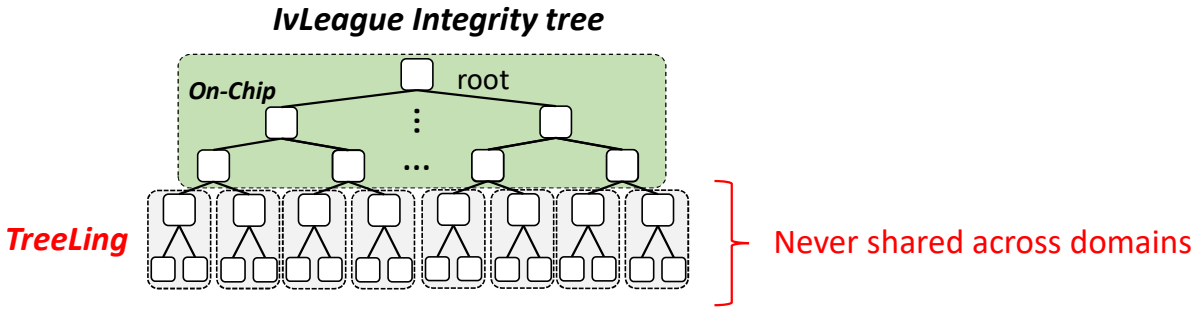

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- IvLeague is designed specifically to thwart shared metadata across security domains.
  - Contention-based attacks on non-shared part of integrity tree is prevented using classical side channel protection.

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Experimental Setup

- **Simulator:** Gem5 full system simulation.
- **Architecture configuration:** 8-core, Out-of-order, x86.
- **Memory:** 32GB, 2-rank.
- **Secure processor configuration:**
  - *Integrity tree:* 8-ary Bonsai Merkle Tree.
  - *Tree cache:* 8-way 256KB.
- **IvLeague configuration:**
  - 16-way 204KB *leaf-mapping metadata* cache.
  - 2-entry (per-domain) *NFL buffer*.
  - Size of TreeLing: 64MB; # of TreeLings: 4K.

- **Schemes:**
  - ***Baseline***: State-of-the-art secure processor design following Bonsai Merkle Tree.
  - ***IvLeague-Basic***.
  - ***IvLeague-Invert***.
  - ***IvLeague-Pro***.

Performance of IvLeague Schemes

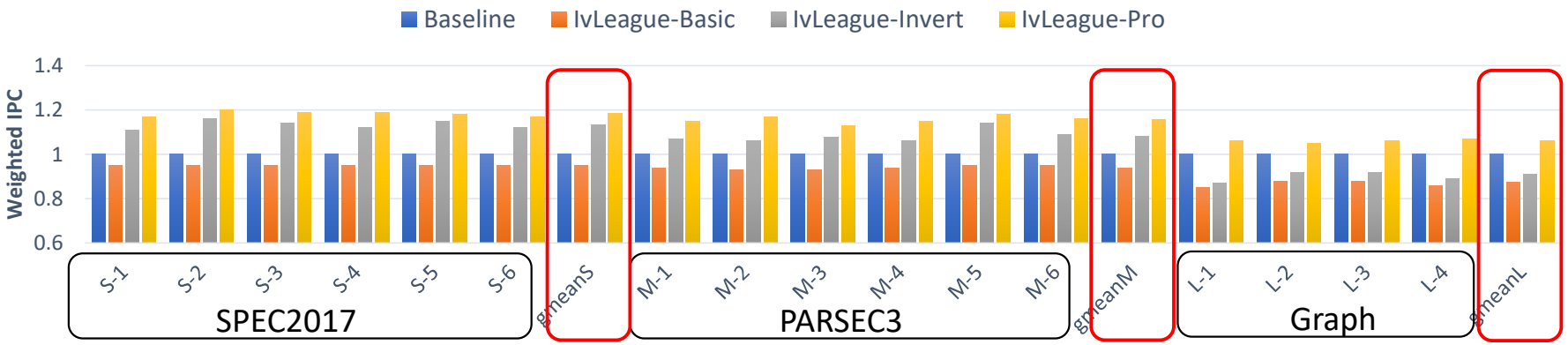

Figure: Comparison of performance (i.e., Weighted IPC normalized to Baseline) under different schemes.

Performance of IvLeague-Basic: Compared to *baseline*	↓2.7% Small	↓5.5% Medium	↓17.4% Large

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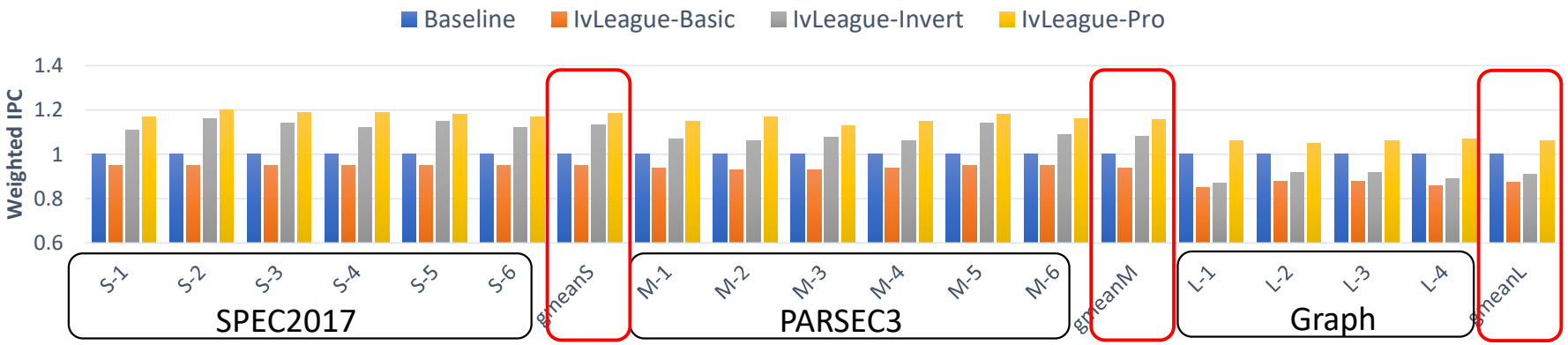

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Performance of IvLeague-Invert/IvLeague-Pro: Compared to *baseline*	↑8.2%/↑13.5% Small	↑3.4%/↑9.3% Medium	↓13.2%/↑3.4% Large

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Effectiveness of NFL Design

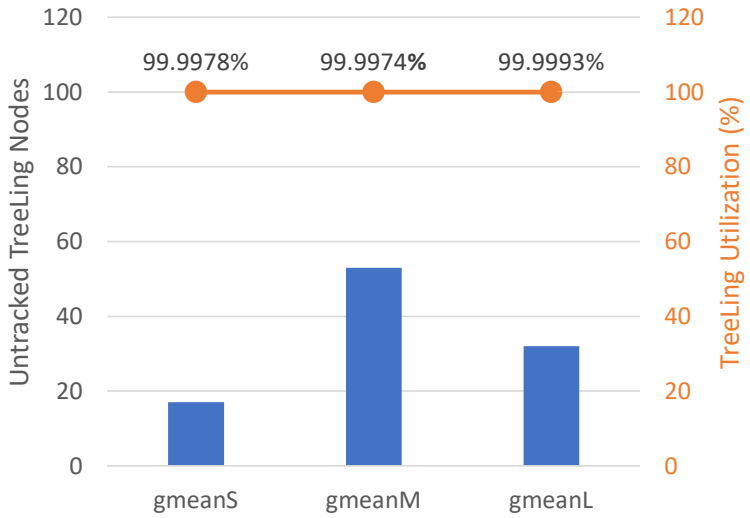

Figure: Utilization of TreeLing nodes using NFL.

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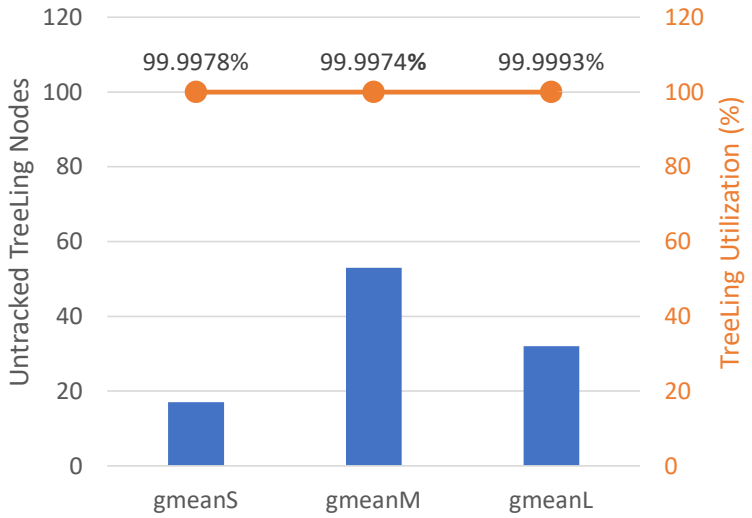

Figure: Utilization of TreeLing nodes using NFL.

IvLeague can achieve near-optimal tree node utilization (> 99.99%) with NFL.

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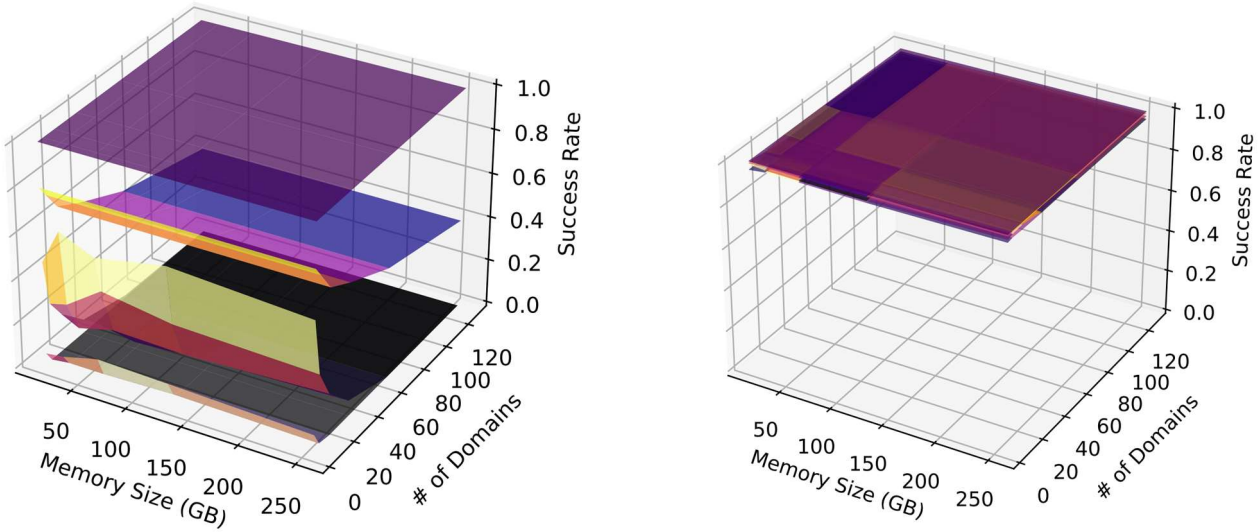
Scalability of IvLeague Scheme



Static partitioning scheme ***IvLeague scheme***

Figure: Comparison of different number of domain support.

- Static partitioning has significantly low success rate when system memory utilization is high.
- IvLeague shows consistently high success rate under any give system memory utilization.

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Sensitivity Analysis of IvLeauge

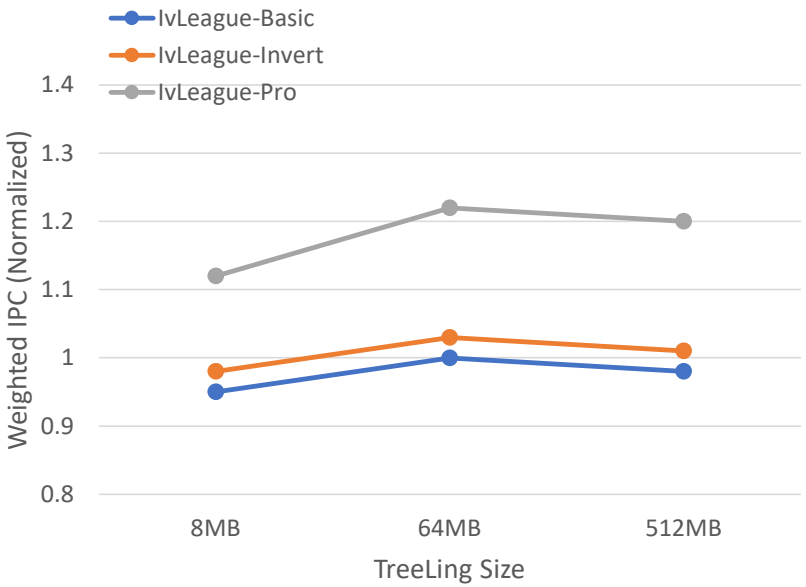

Figure: Sensitivity to TreeLing size (normalized to 64MB TreeLing size).

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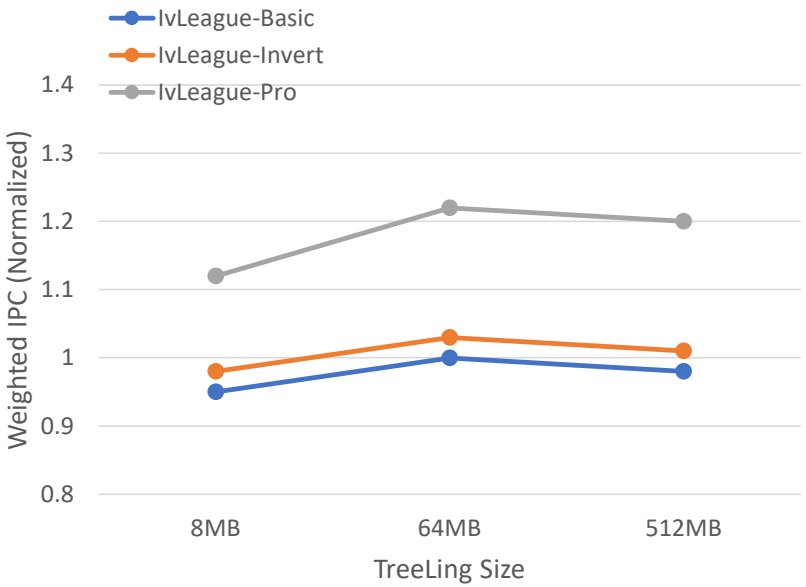

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64MB TreeLing configuration offers the best balance between levels inside TreeLing and on-chip locked blocks.

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More on Paper…

- Additional discussion on IvLeauge design.
- NFL buffer performance analysis.
- Analysis of additional memory accesses.
- Analytical investigation of TreeLing configurations.
- Hardware overhead analysis.
- And more…

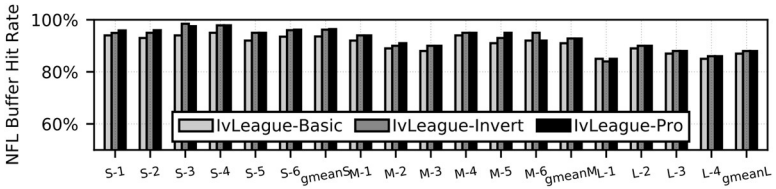
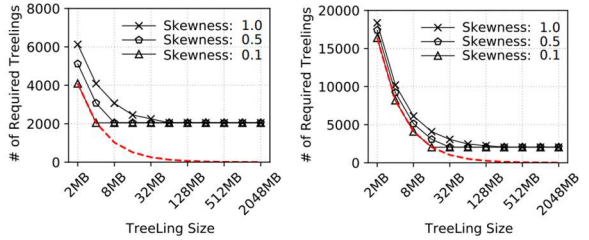


Figure: NFLB hit rate for all workloads.



(a) System memory: 8GB (b) System memory: 32GB

Figure: TreeLings required under different memory allocation distributions across programs (number of IV Domains: 2^{12}). Red dashed line represents *minimum* number of TreeLing that covers the entire available memory (i.e., assuming all TreeLings are fully utilized).

Component	Storage	Area
NFL Logic and Buffer	528-byte	$0.0071mm^2$
LMM Cache	204KB	$0.33mm^2$
Hotpage Predictor (IvLeague-Pro)	848-byte	$0.018mm^2$

TABLE III: On-chip hardware cost for IvLeague components.

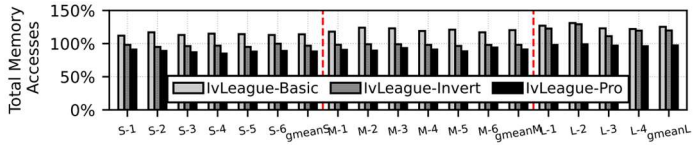


Figure: Additional memory accesses due to IvLeague operations (normalized to *baseline* scheme).

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Key Takeaways

- Existing integrity verification mechanisms use a global integrity tree shared across security domains.
  - Introduce side channel leakage through integrity tree metadata sharing.
- IvLeague provides side channel-resistant isolated integrity trees among dynamic domains.
  - Splits the global tree into multiple fixed-size subtrees.
  - Dynamically allocating these subtrees to domains during runtime.
- IvLeague optimizations shortens the integrity verification path significantly.
- IvLeague provides 3%-13% speedup over the insecure baseline.
  - With minimal hardware and logic overheads.

Thanks! Questions?

Md Hafizul Islam Chowdhuryy
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Email: hafizul.islam@ucf.edu