

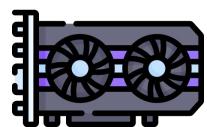
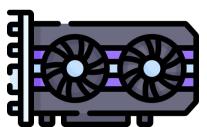
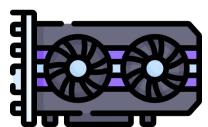
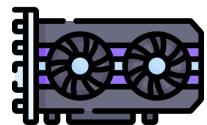
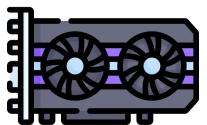
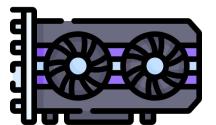
GPHash: An Efficient Hash Index for GPU with Byte-Granularity Persistent Memory

Menglei Chen, Yu Hua, Zhangyu Chen, Ming Zhang, Gen Dong
Huazhong University of Science and Technology, China

Various Applications Are Powered by GPUs

Various Applications Are Powered by GPUs

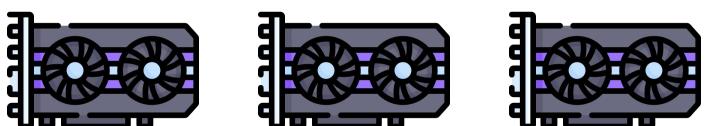
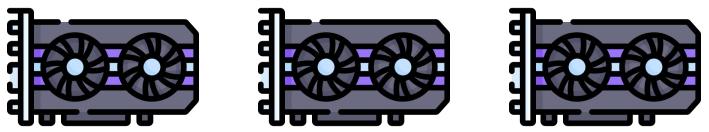
GPUs



...

Various Applications Are Powered by GPUs

GPUs



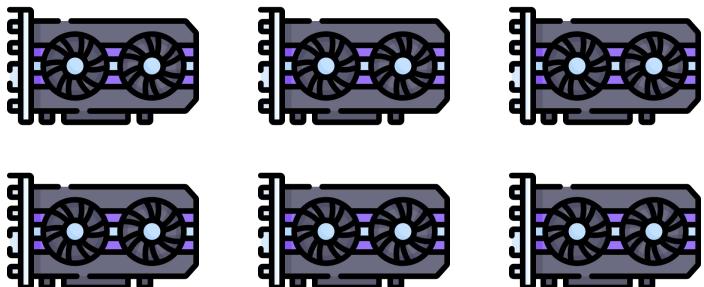
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Enhance



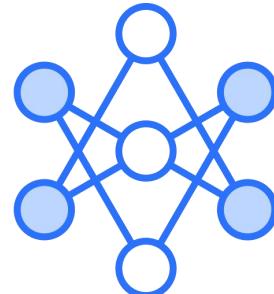
Various Applications Are Powered by GPUs

GPUs

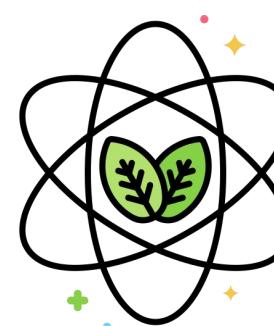


...

Enhance
A large red arrow pointing from left to right, indicating the enhancement process.



Deep Neural Network



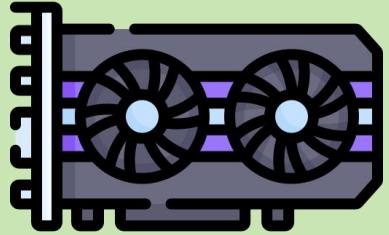
Scientific Computing



Autonomous driving

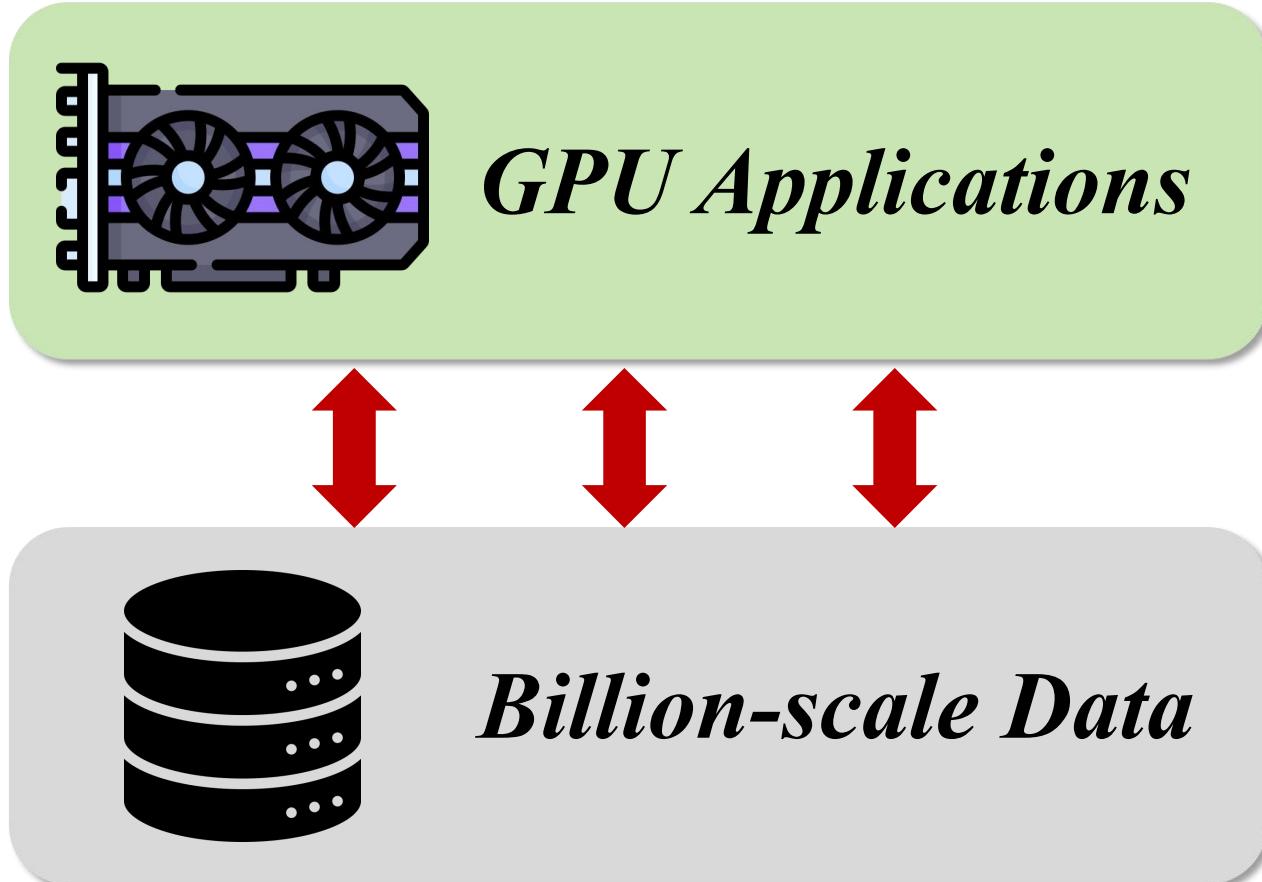
Unprecedented Data Scale of GPU App.

Unprecedented Data Scale of GPU App.

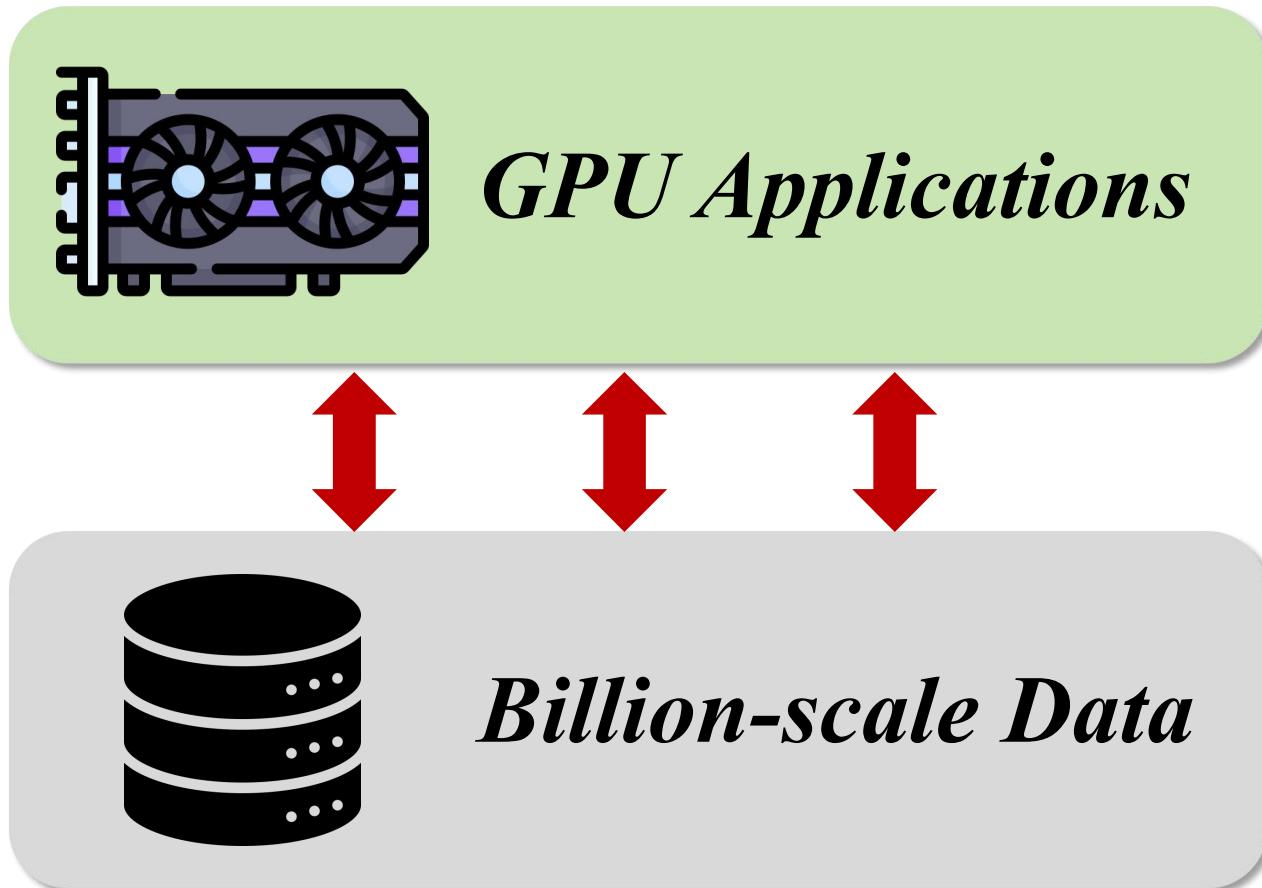


GPU Applications

Unprecedented Data Scale of GPU App.

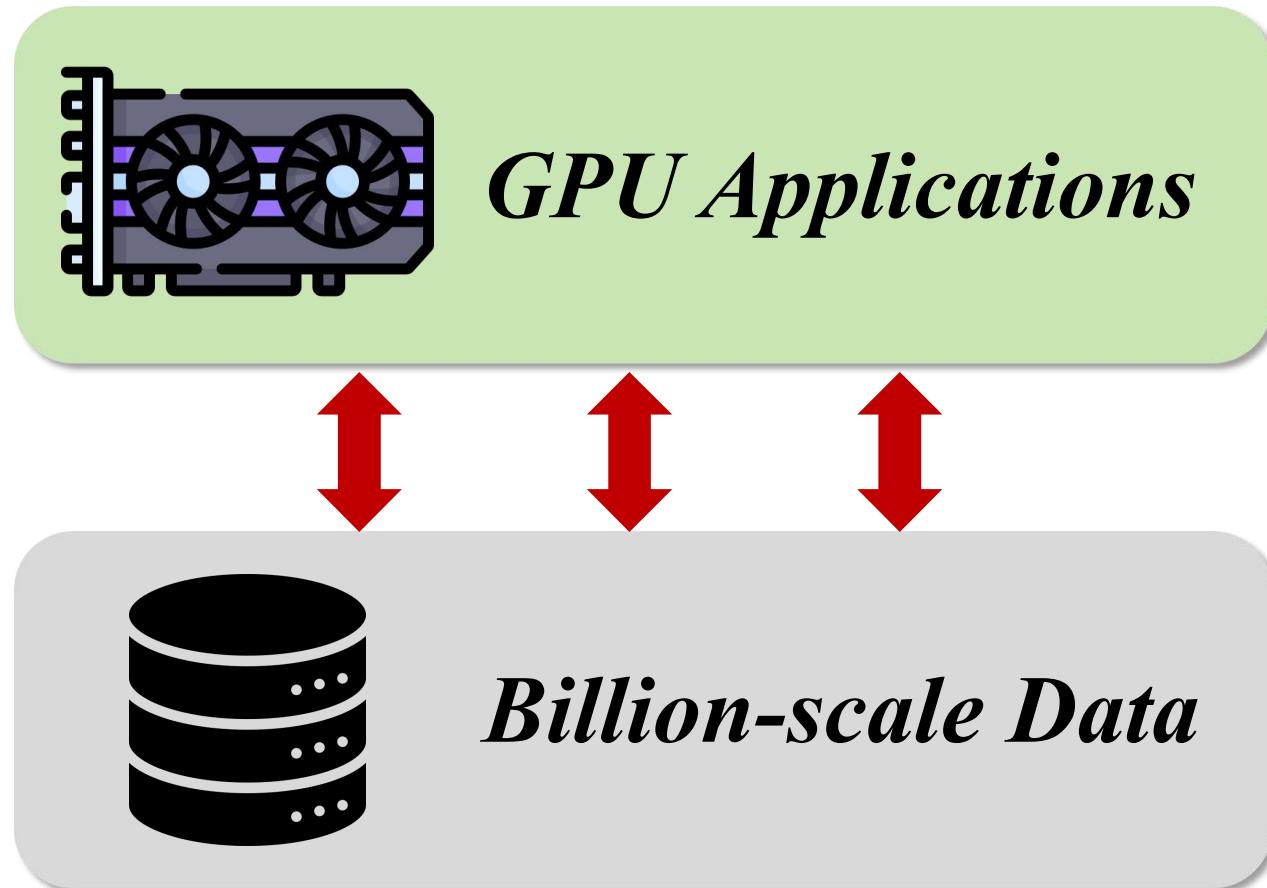


Unprecedented Data Scale of GPU App.



e.g., *Deep Recommendation Model*

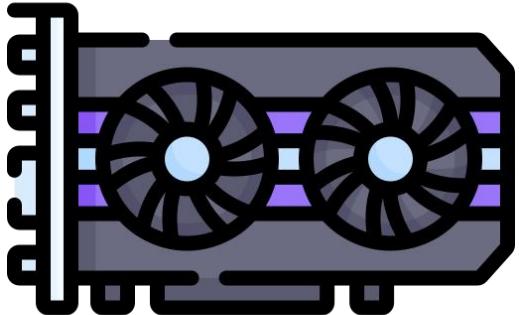
Unprecedented Data Scale of GPU App.



Existing Data Management of GPU App.

Existing Data Management of GPU App.

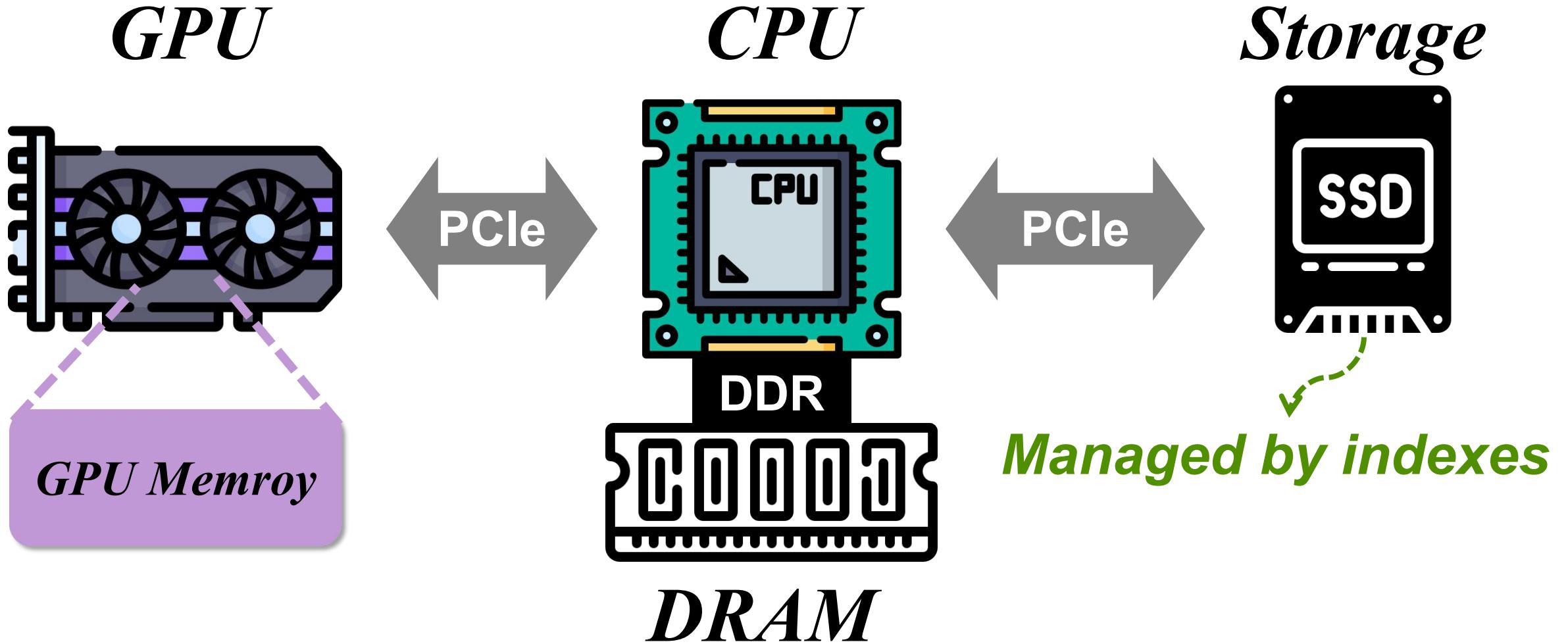
GPU



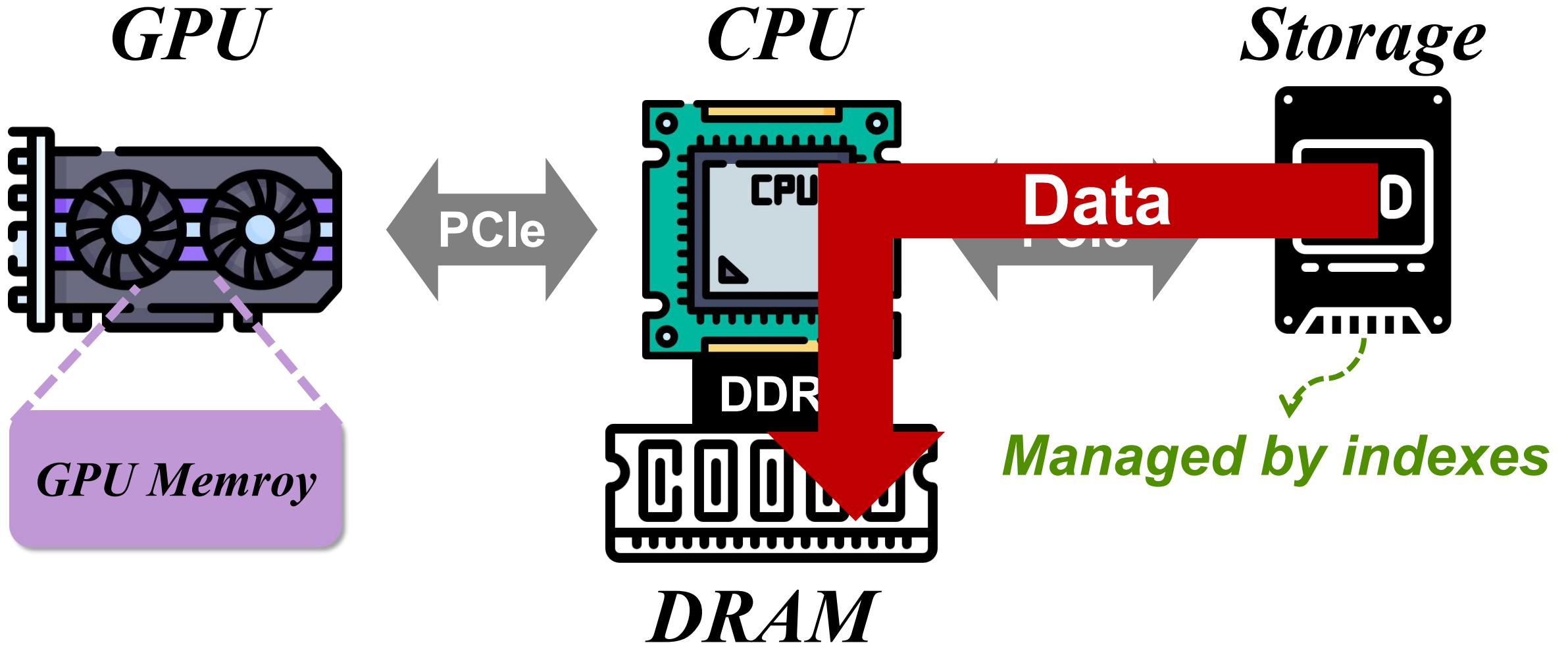
Storage



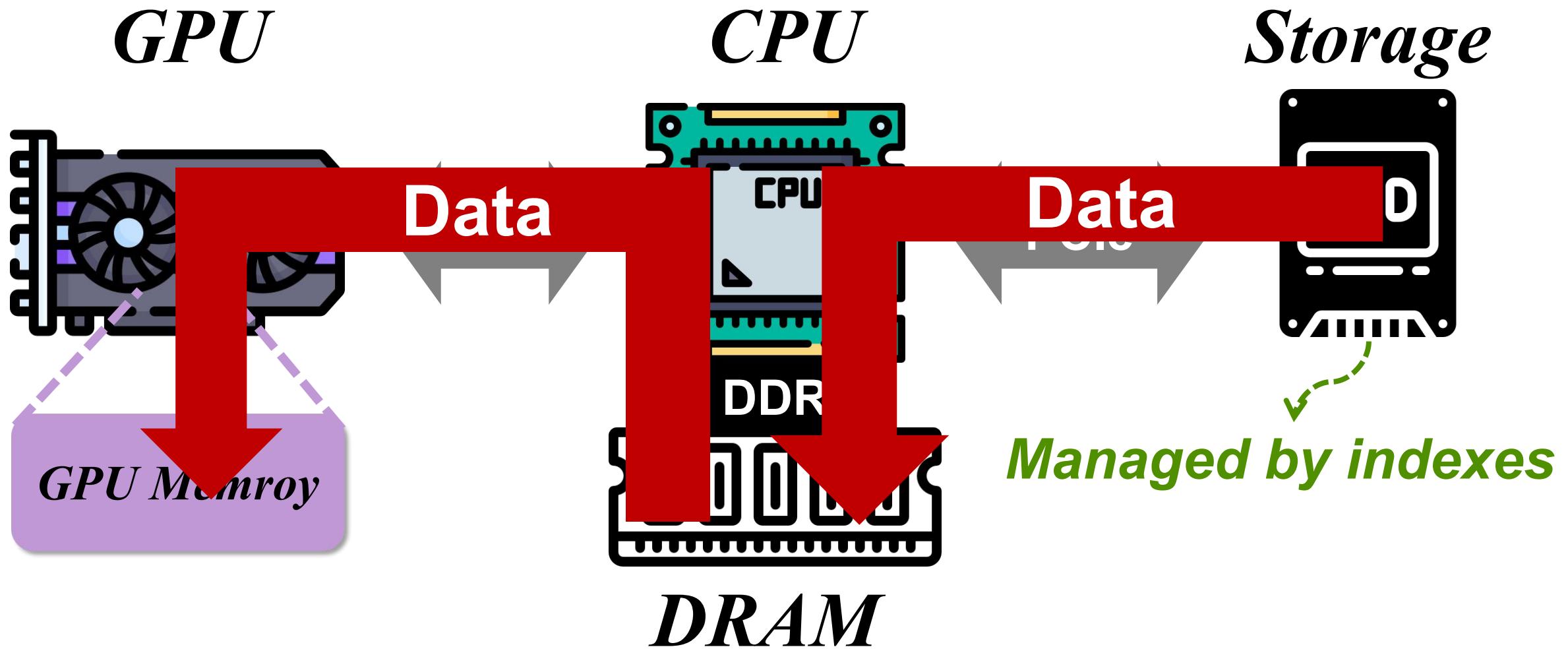
Existing Data Management of GPU App.



Existing Data Management of GPU App.



Existing Data Management of GPU App.



Existing Data Management of GPU App.



Existing Data Management of GPU App.



Existing Data Management of GPU App.



Large capacity and persistence



High overhead for data transfer

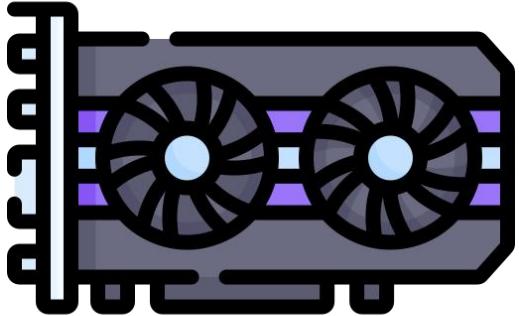


Extra CPU consumption

Direct Data Access from GPU

Direct Data Access from GPU

GPU



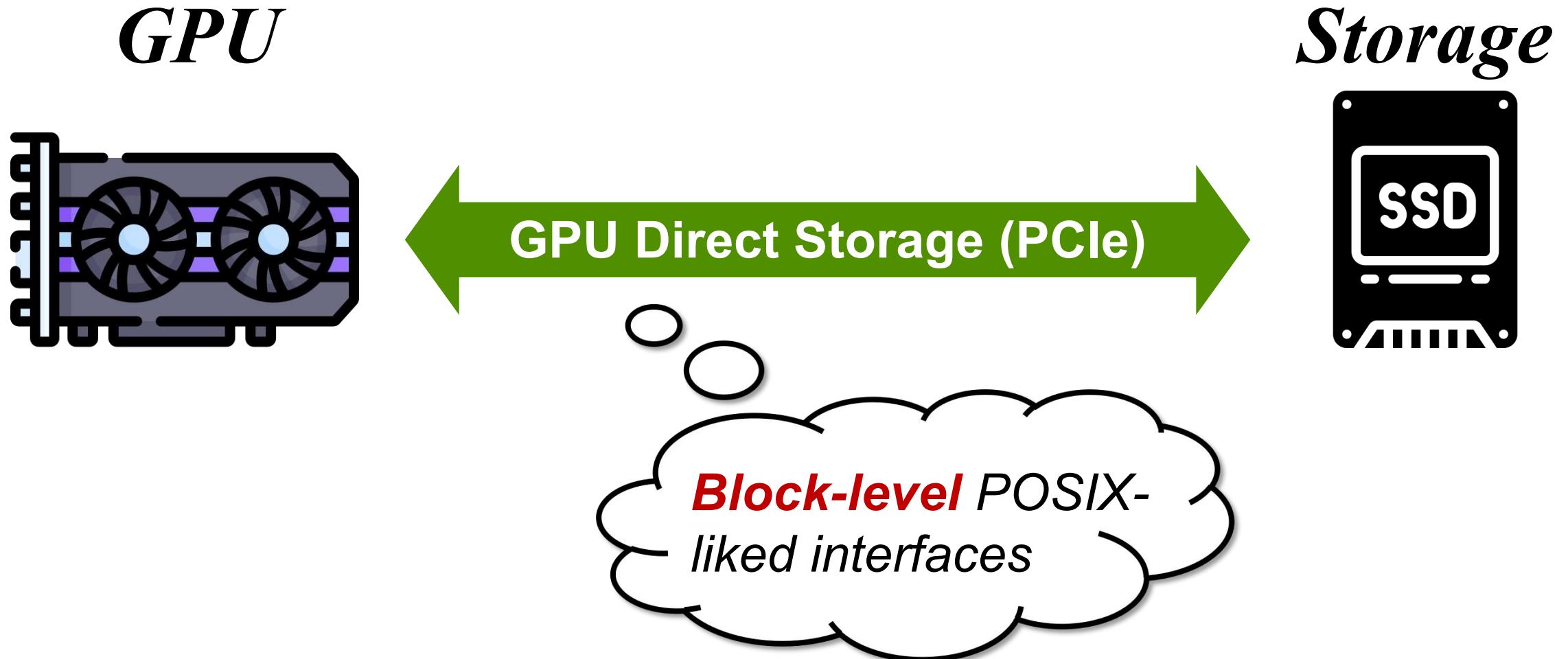
Storage



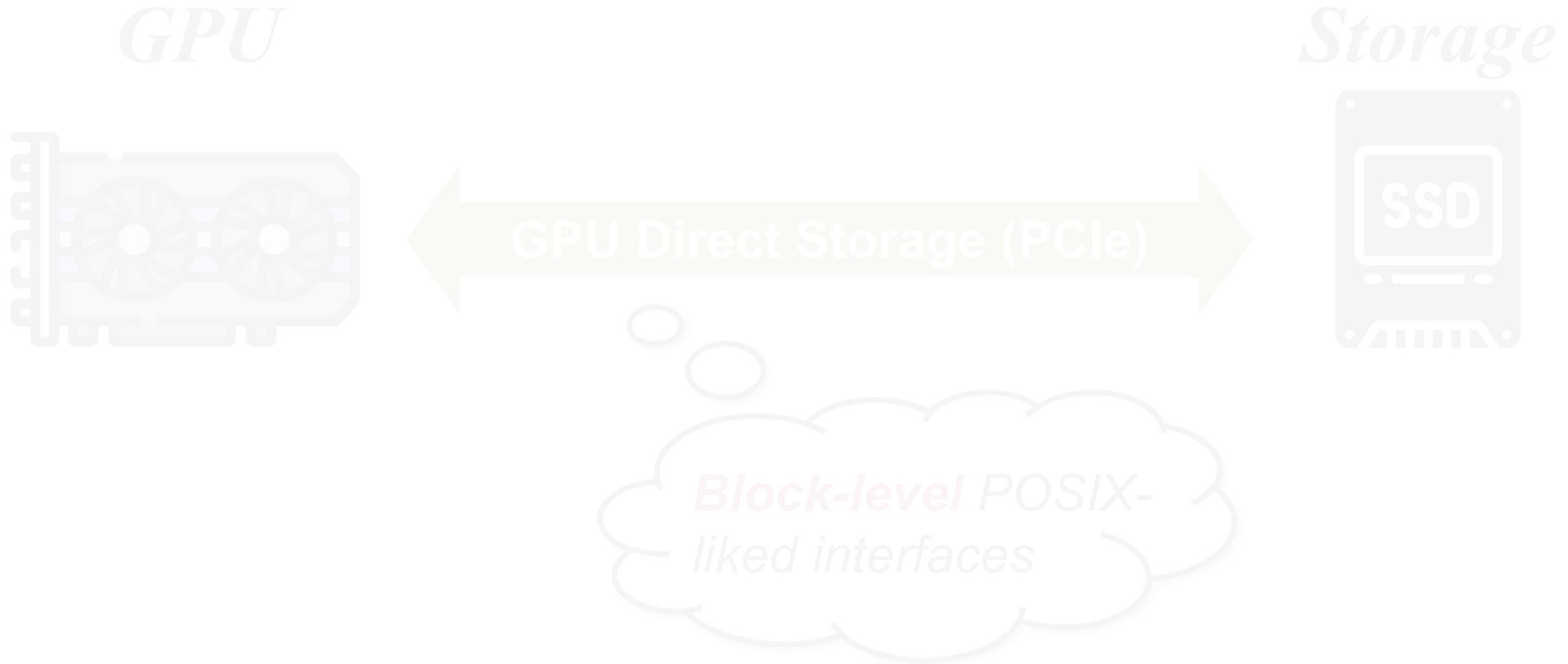
Direct Data Access from GPU



Direct Data Access from GPU



Direct Data Access from GPU



Direct Data Access from GPU



Large capacity and persistence



Cost-efficient data transfer



Direct Data Access from GPU



Large capacity and persistence



Cost-efficient data transfer



Hard to program data structure



Transfer extraneous data

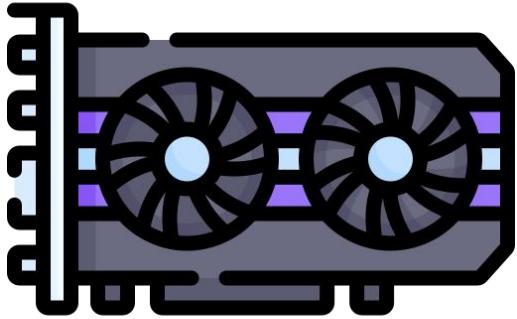
GPU with Persistent Memory (GPM)

¹ GPM: Leveraging Persistent Memory from a GPU [ASPLOS' 22]

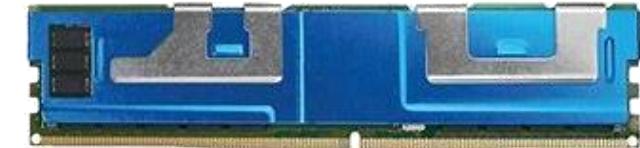
² Scoped Buffered Persistence Model for GPUs [ASPLOS' 23]

GPU with Persistent Memory (GPM)

GPU



*Persistent
Memory*

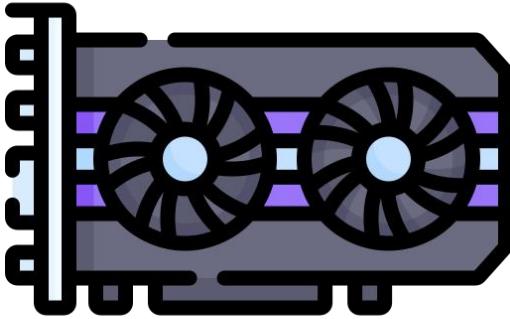


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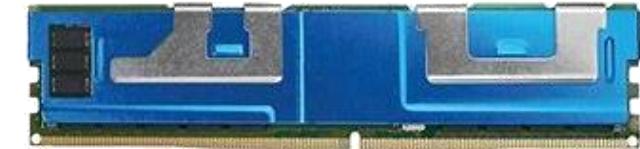
GPU



- ✓ Large capacity
- ✓ Byte granularity
- ✓ Persistence
- ✓ High performance

...

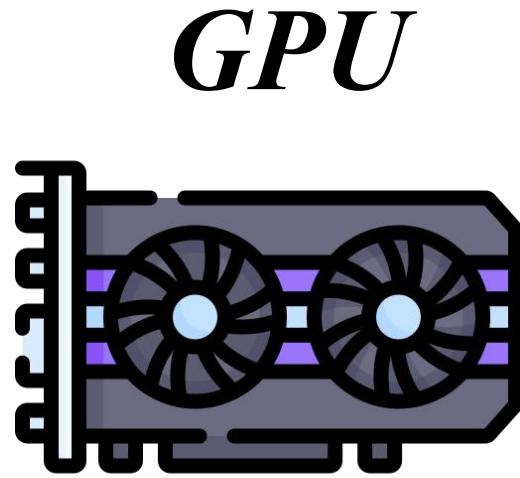
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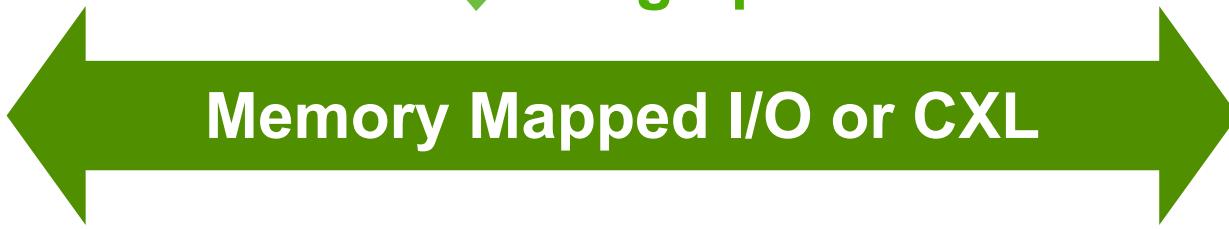
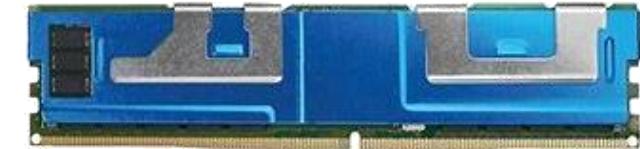
GPU with Persistent Memory (GPM)



GPU

- ✓ Large capacity
 - ✓ Byte granularity
 - ✓ Persistence
 - ✓ High performance
- ...

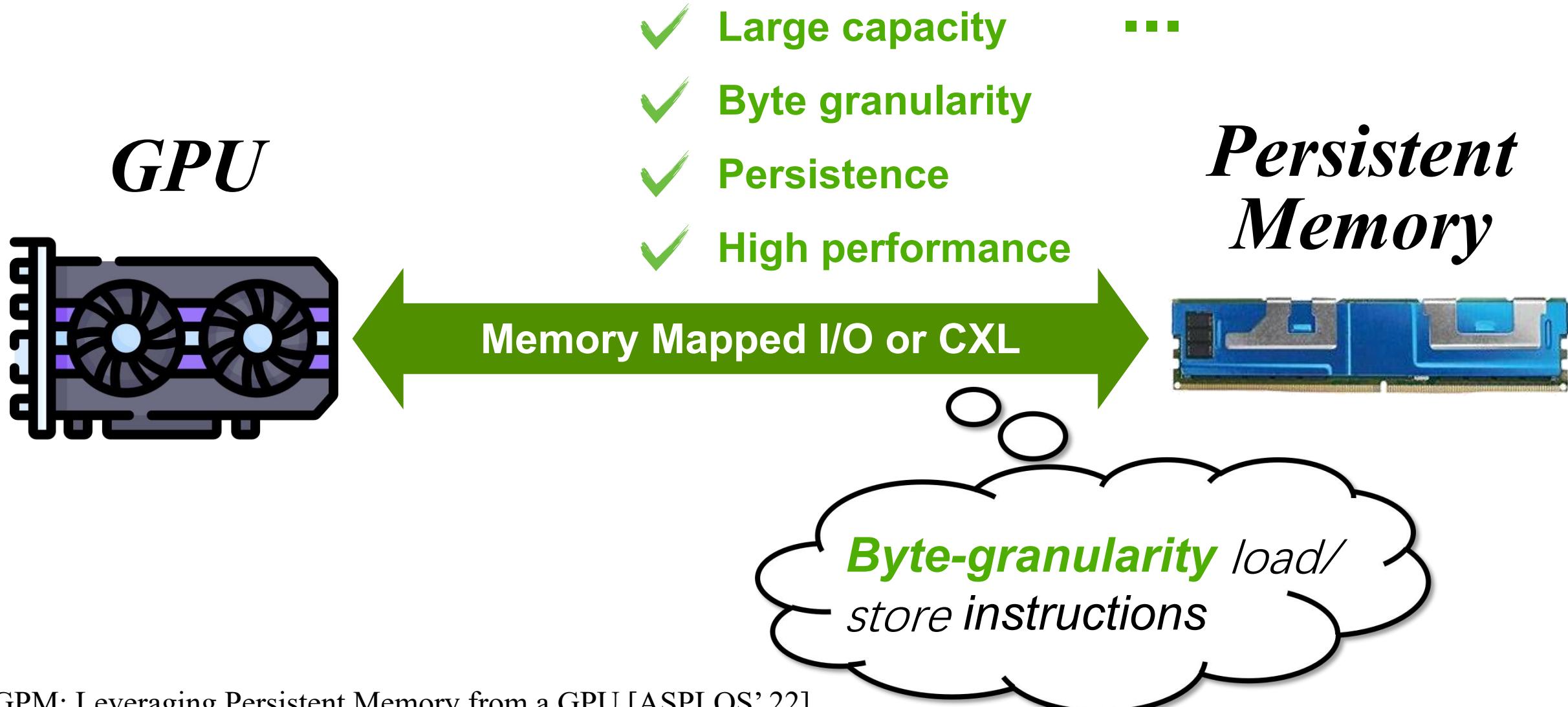
*Persistent
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GPU with Persistent Memory (GPM)



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GPU with Persistent Memory (GPM)



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² Scoped Buffered Persistency Model for GPUs [ASPLOS' 23]

GPU with Persistent Memory (GPM)



Large capacity and persistence



Cost-efficient and fine-grained data transfer



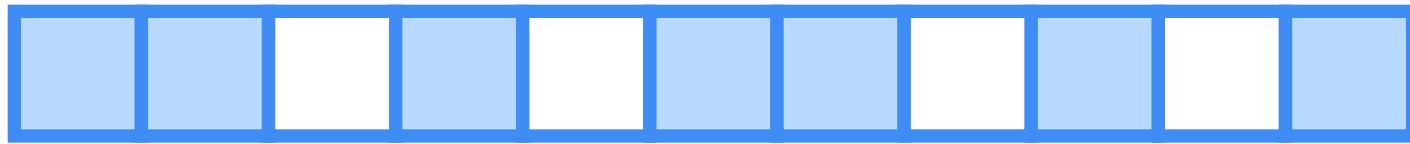
Easy to program data structure

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Hash Index

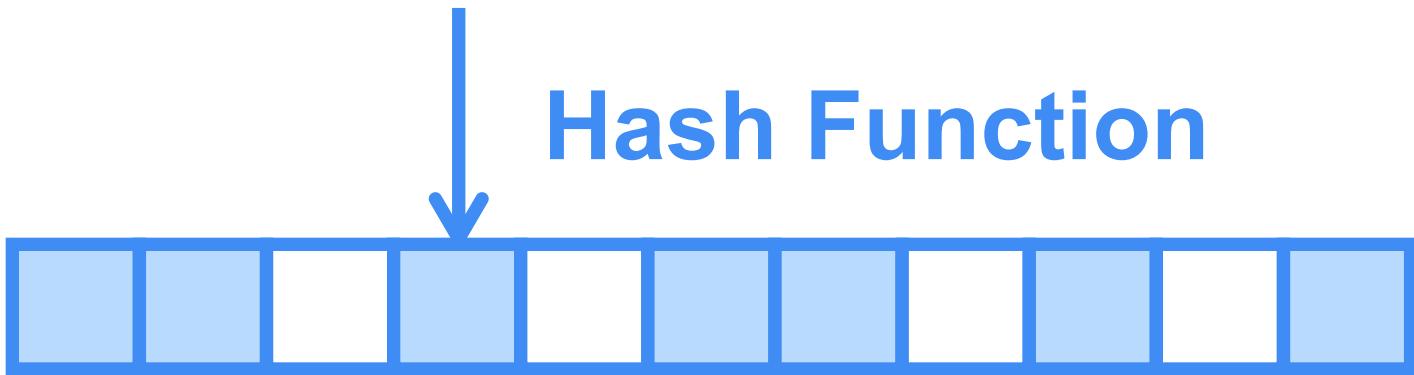
Hash Index



Hash Index



Hash Index



Constant-scale point query



Good for parallel access

Hash Index

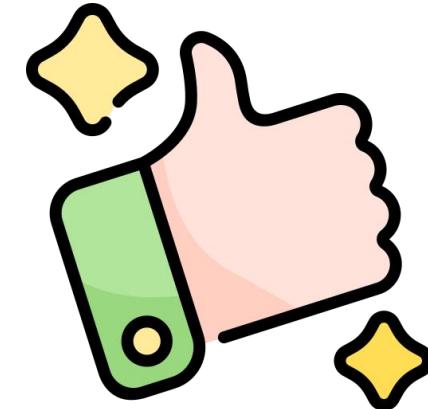


Constant-scale point query



Good for parallel access

GPM Hash Index



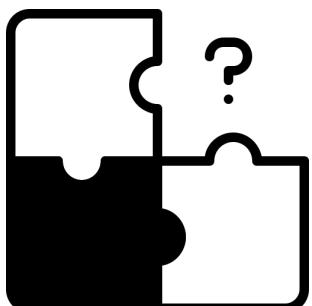
Hash Index



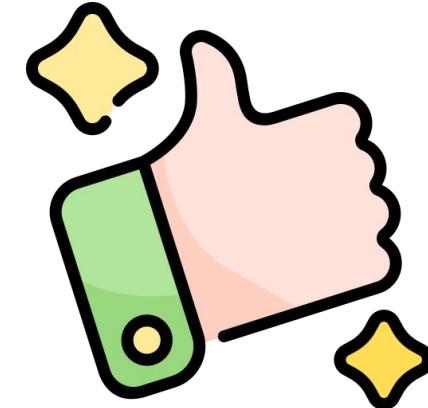
Constant-scale point query



Good for parallel access



GPM Hash Index



*However, it is non-trivial to implement
an efficient GPM hash index*

Challenge 1: Agnostic to GPU Execution Manner

Challenge 1: Agnostic to GPU Execution Manner

Warp Divergence

Challenge 1: Agnostic to GPU Execution Manner

Warp Divergence

```
if (thread_id < 4) {  
    A;  
    B;  
} else {  
    X;  
    Y;  
}  
Z;
```

Challenge 1: Agnostic to GPU Execution Manner

Warp Divergence

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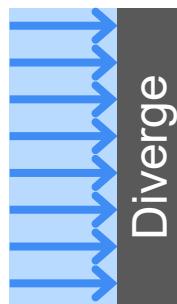


→ Time

Challenge 1: Agnostic to GPU Execution Manner

Warp Divergence

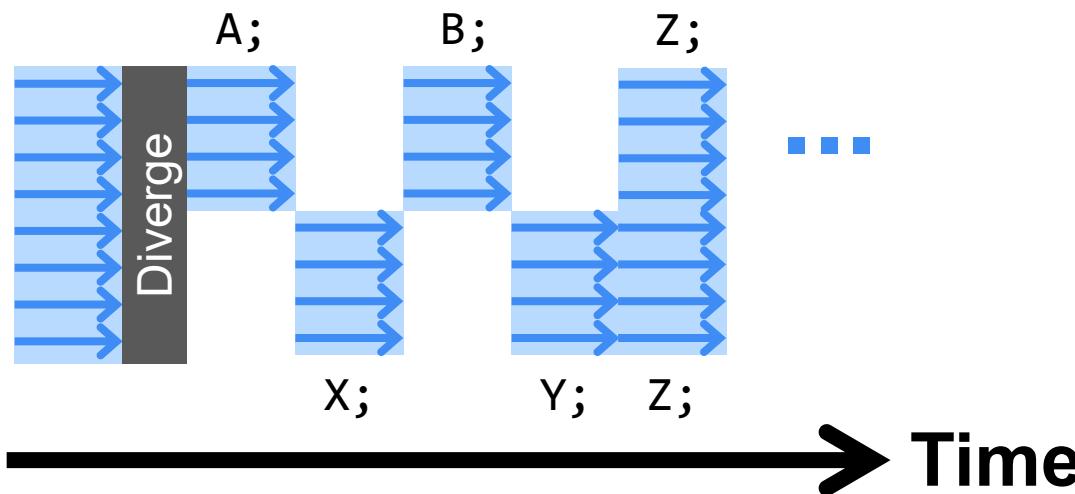
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Challenge 1: Agnostic to GPU Execution Manner

Warp Divergence

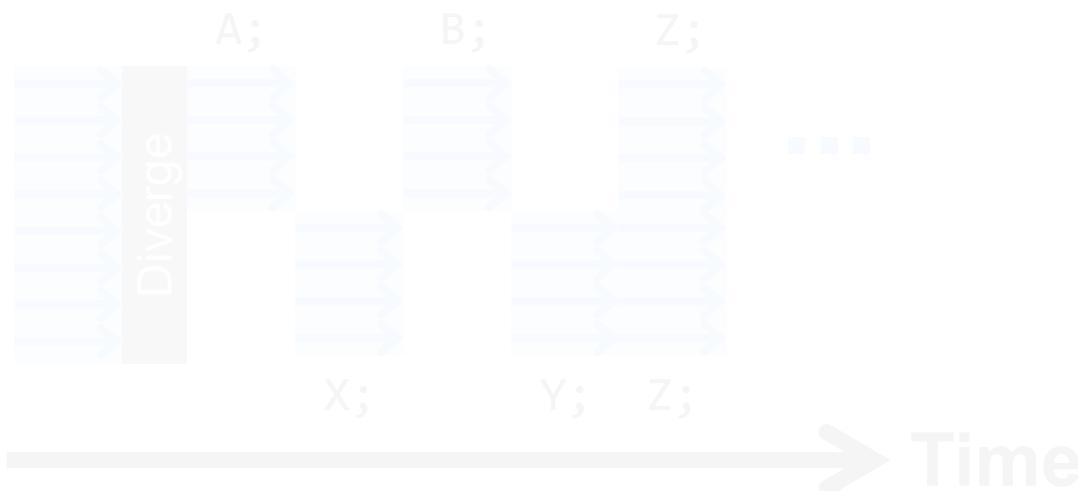
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Warp Divergence

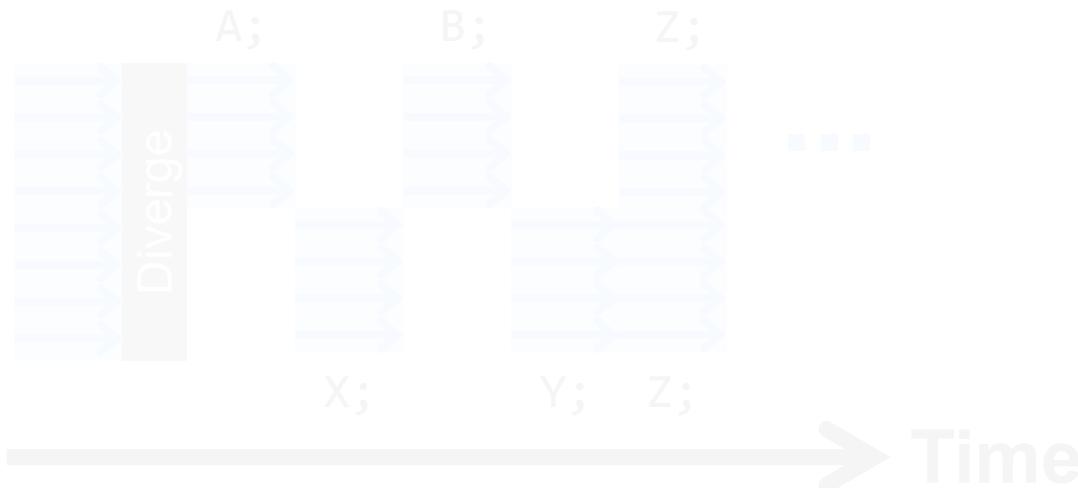
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Challenge 1: Agnostic to GPU Execution Manner

Warp Divergence

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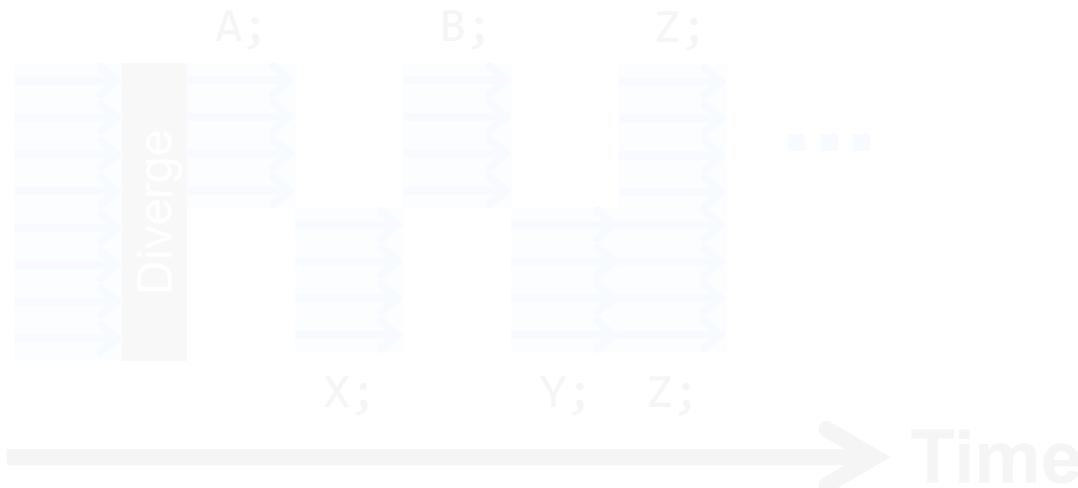


Coalesced memory accesses

Challenge 1: Agnostic to GPU Execution Manner

Warp Divergence

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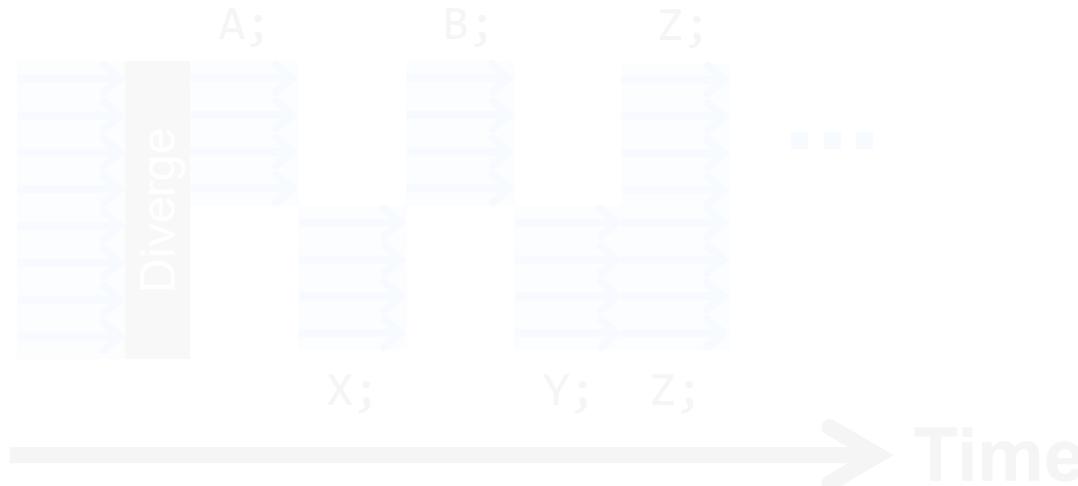
Coalesced memory accesses



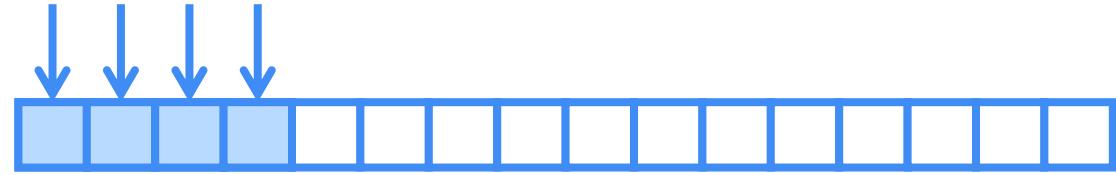
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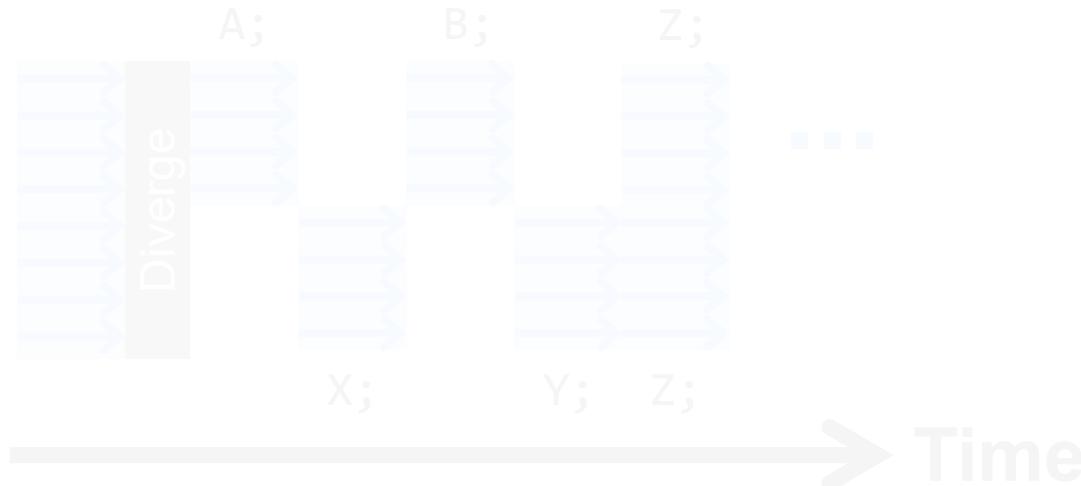
Coalesced memory accesses



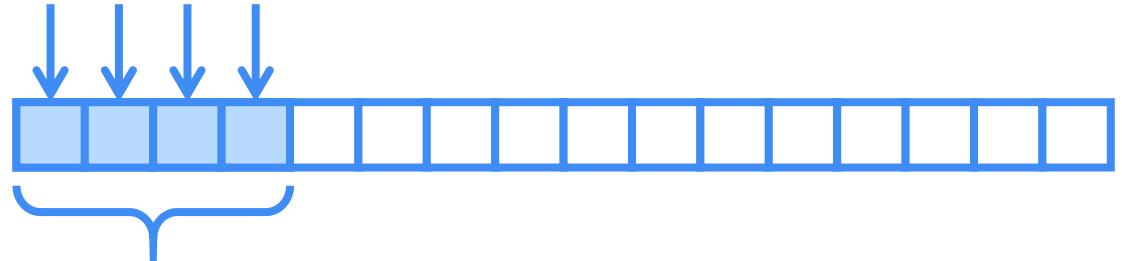
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Warp Divergence

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Coalesced memory accesses

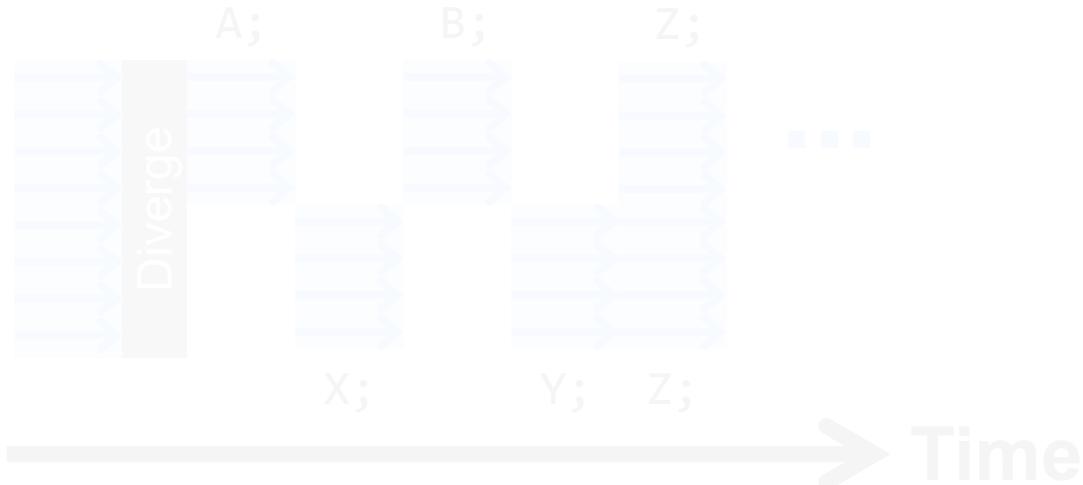


Memory Block

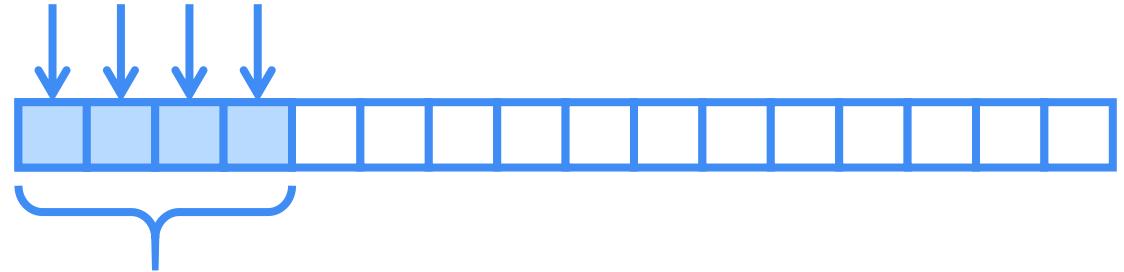
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Warp Divergence

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Coalesced memory accesses



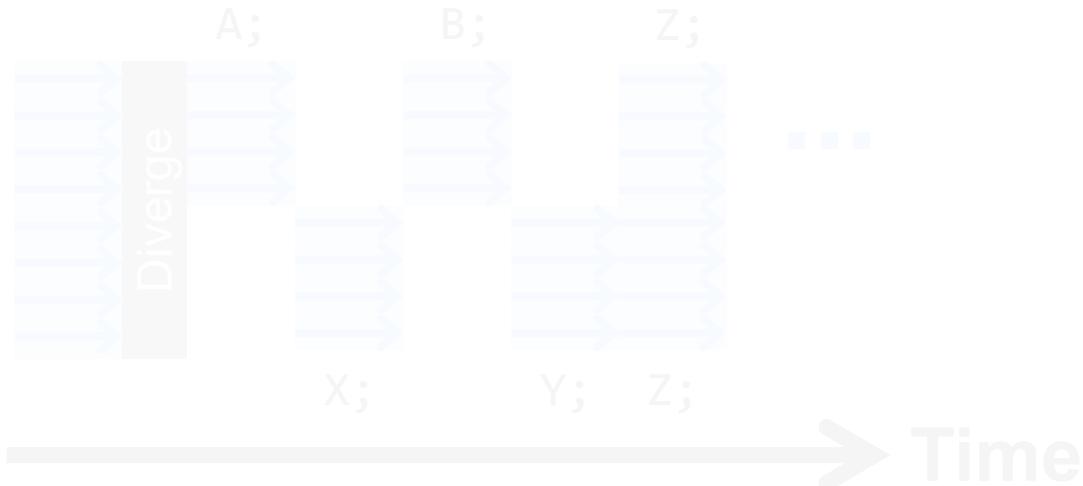
Memory Block

Uncoalesced memory accesses

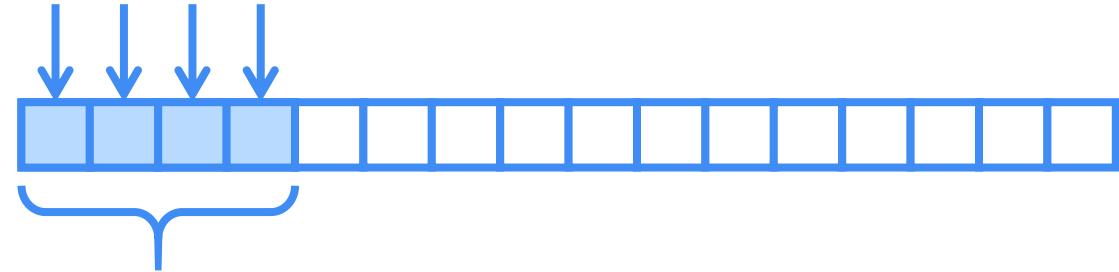
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Warp Divergence

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Coalesced memory accesses



Memory Block

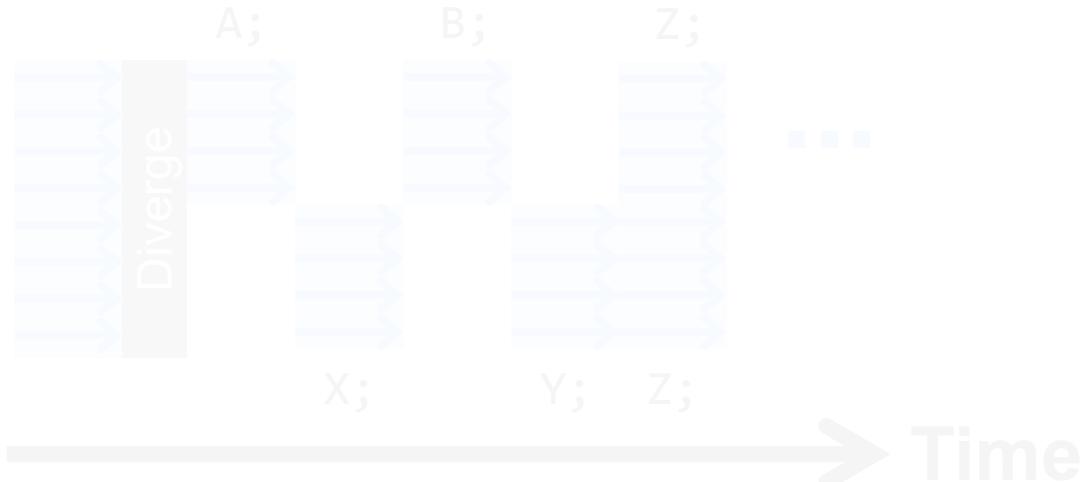
Uncoalesced memory accesses



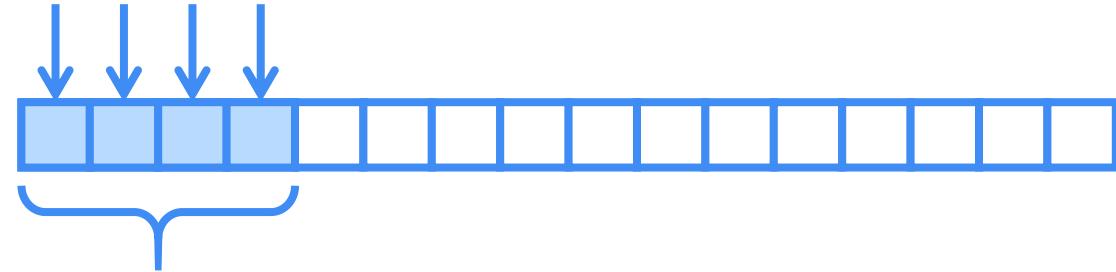
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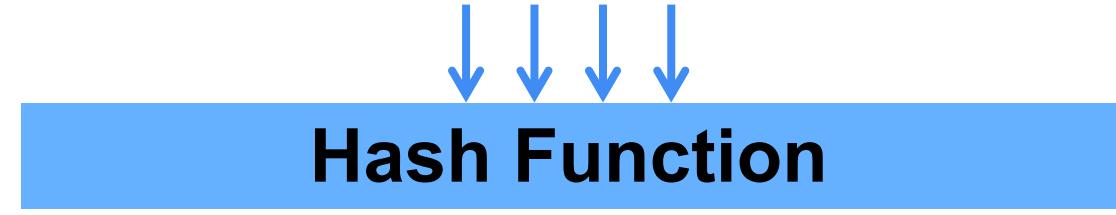


Coalesced memory accesses



Memory Block

Uncoalesced memory accesses

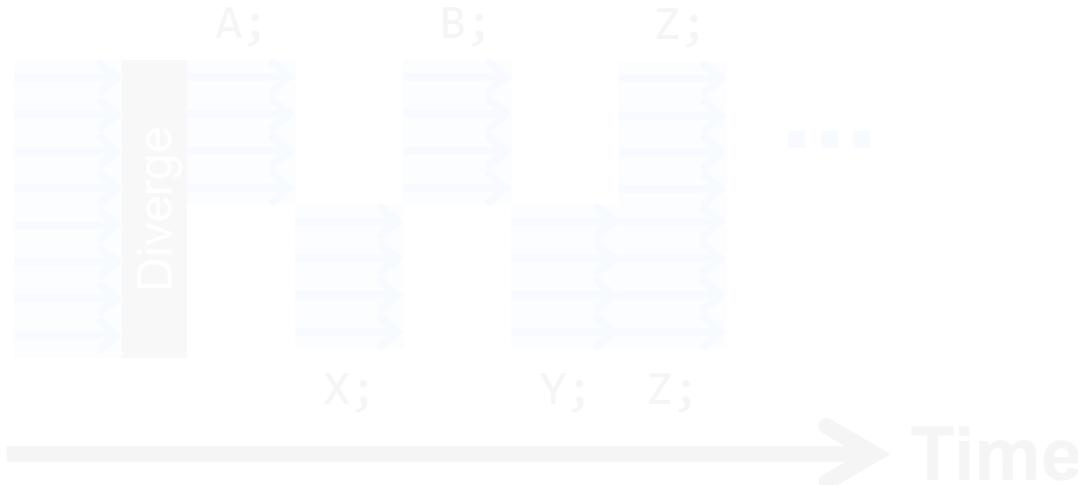


Hash Function

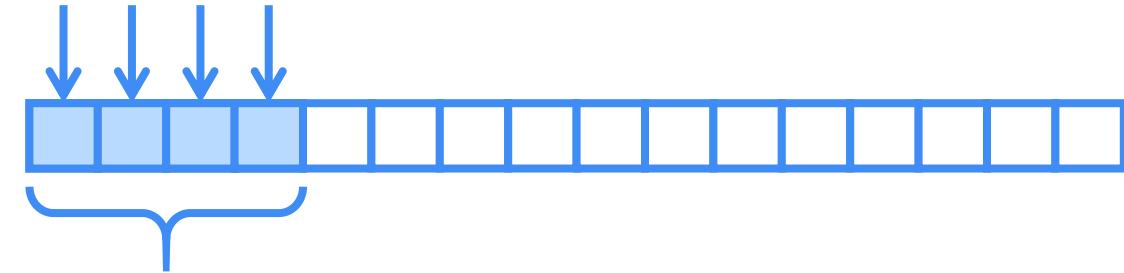
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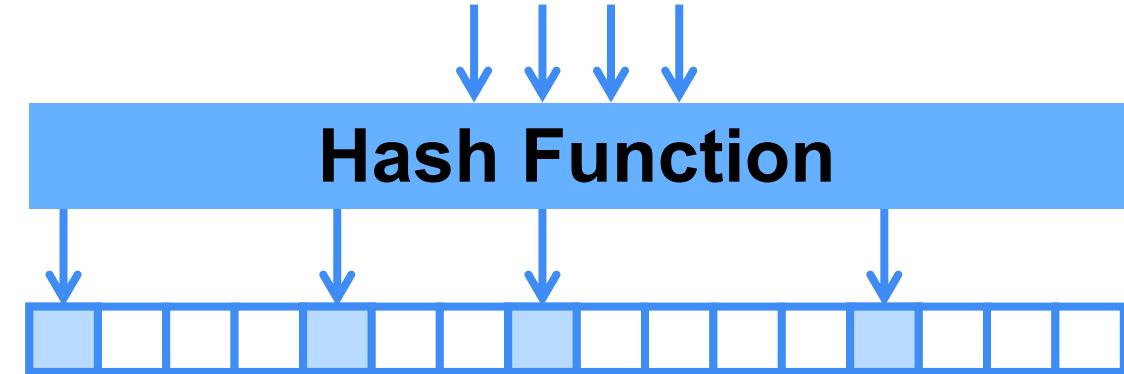


Coalesced memory accesses



Memory Block

Uncoalesced memory accesses



Challenge 1: Agnostic to GPU Execution Manner

Severe *warp divergence* and *uncoalesced memory accesses*
lead to **Performance Degradation**

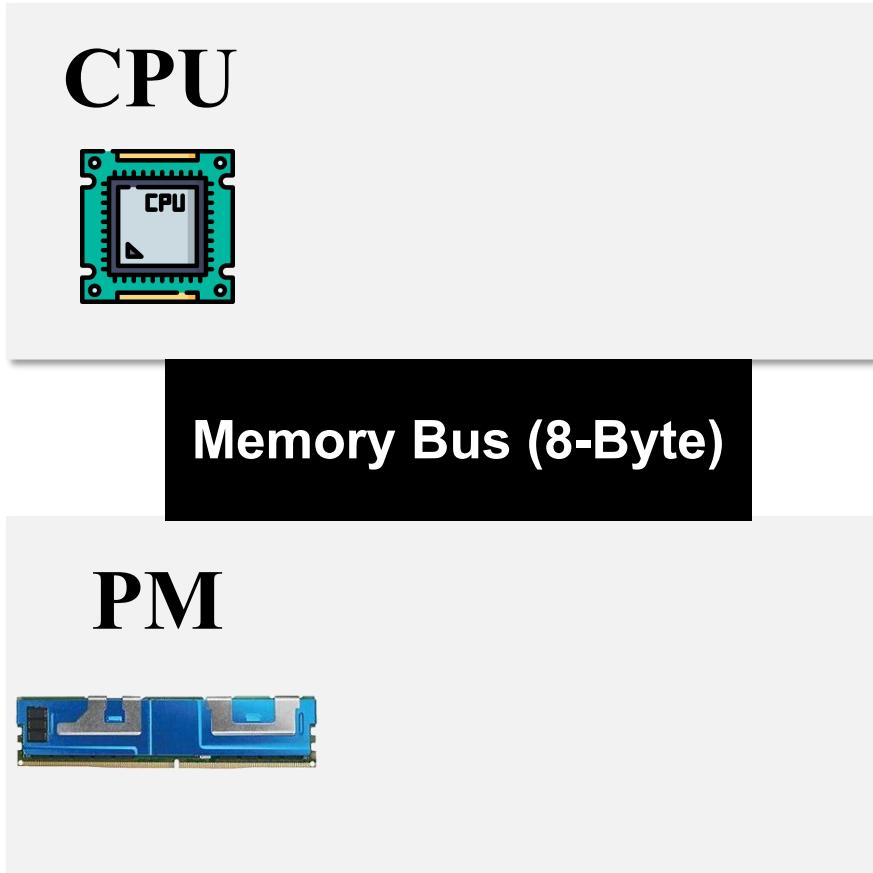
Challenge 2: Ensure Crash Consistency

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Without Consistency Guarantee

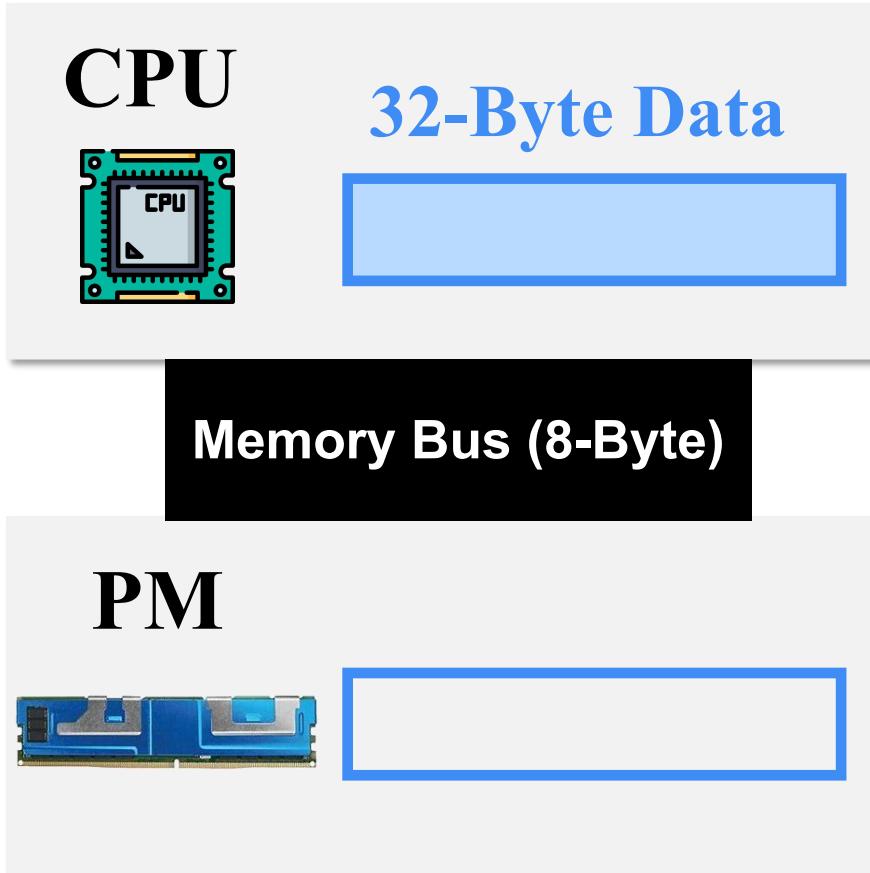
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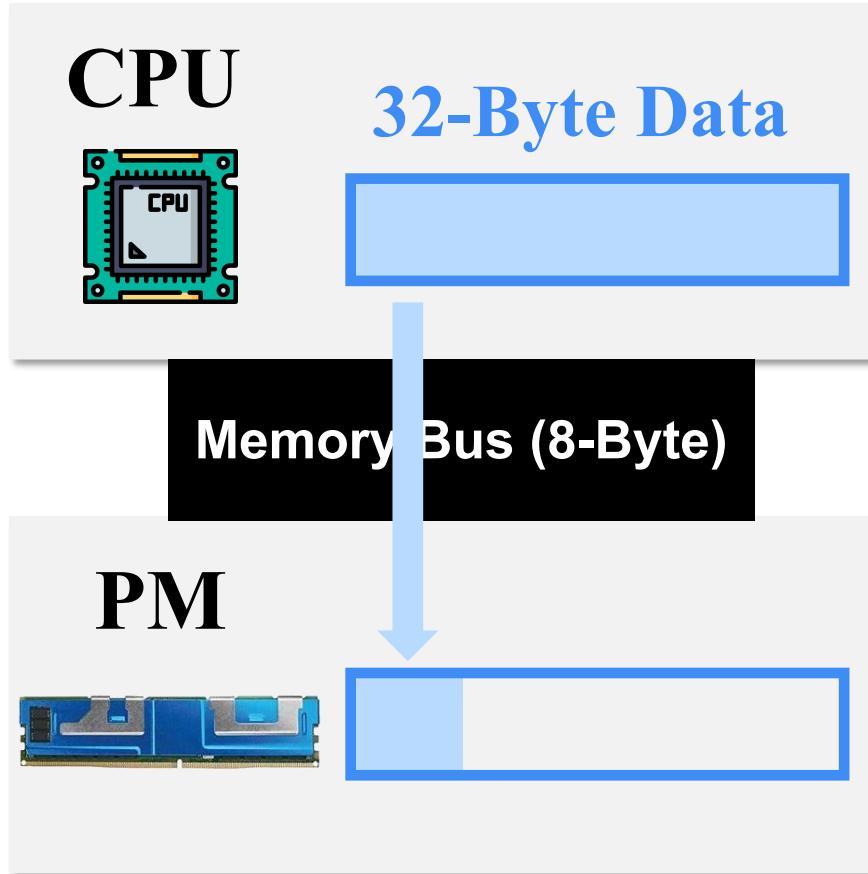
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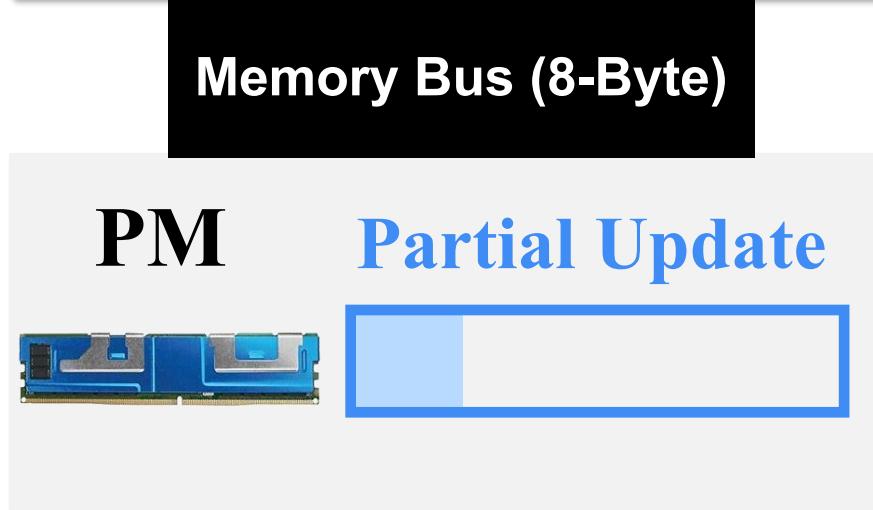
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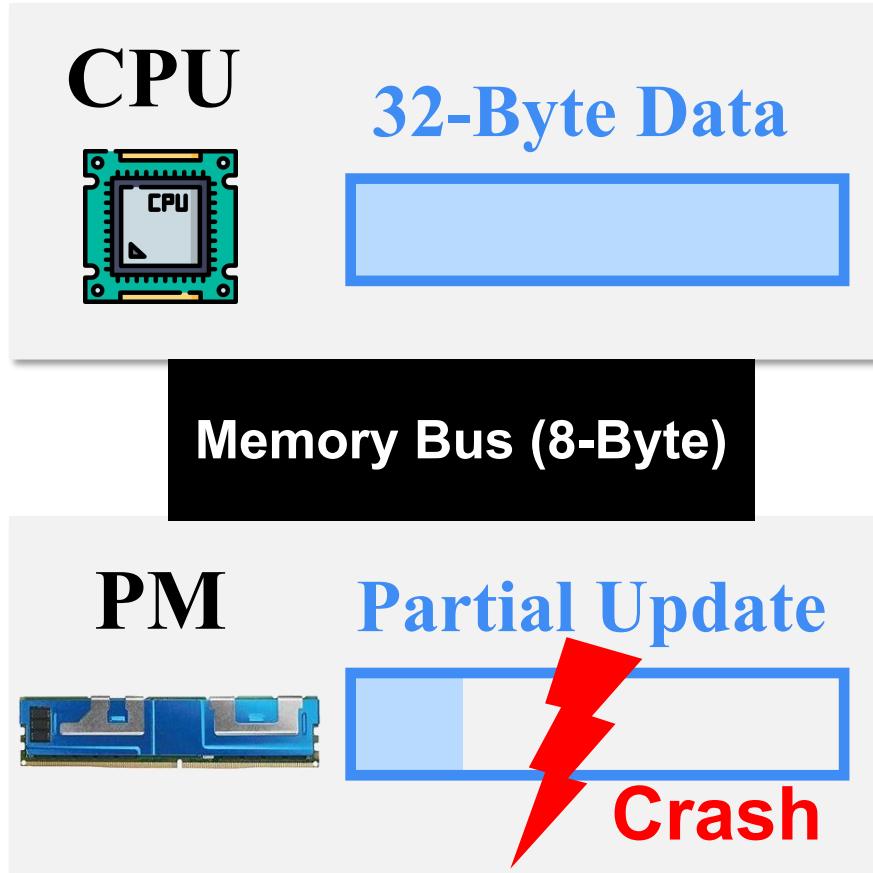
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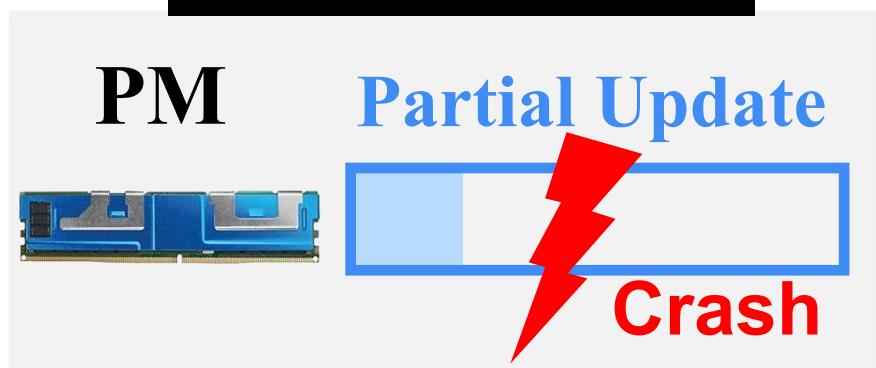
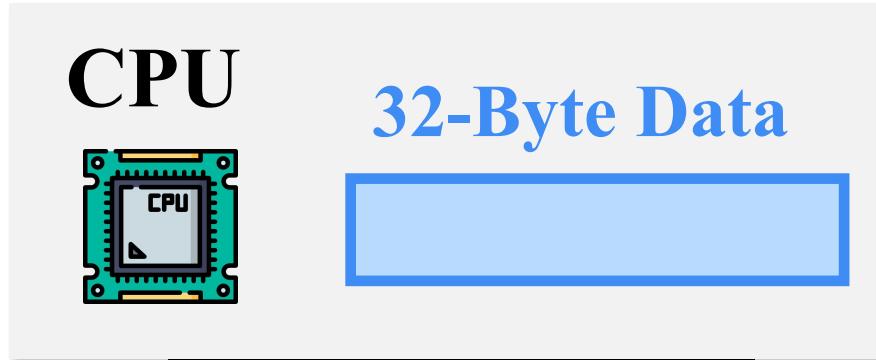
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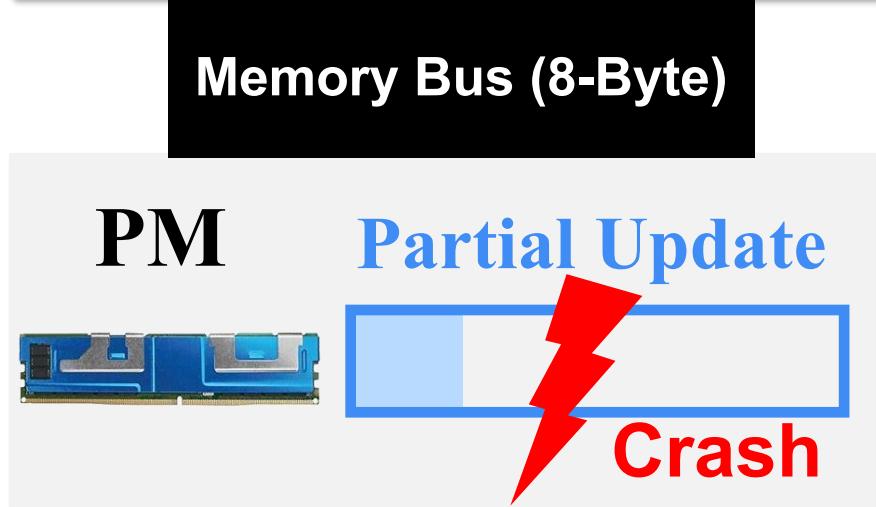
Data Inconsistency!

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee



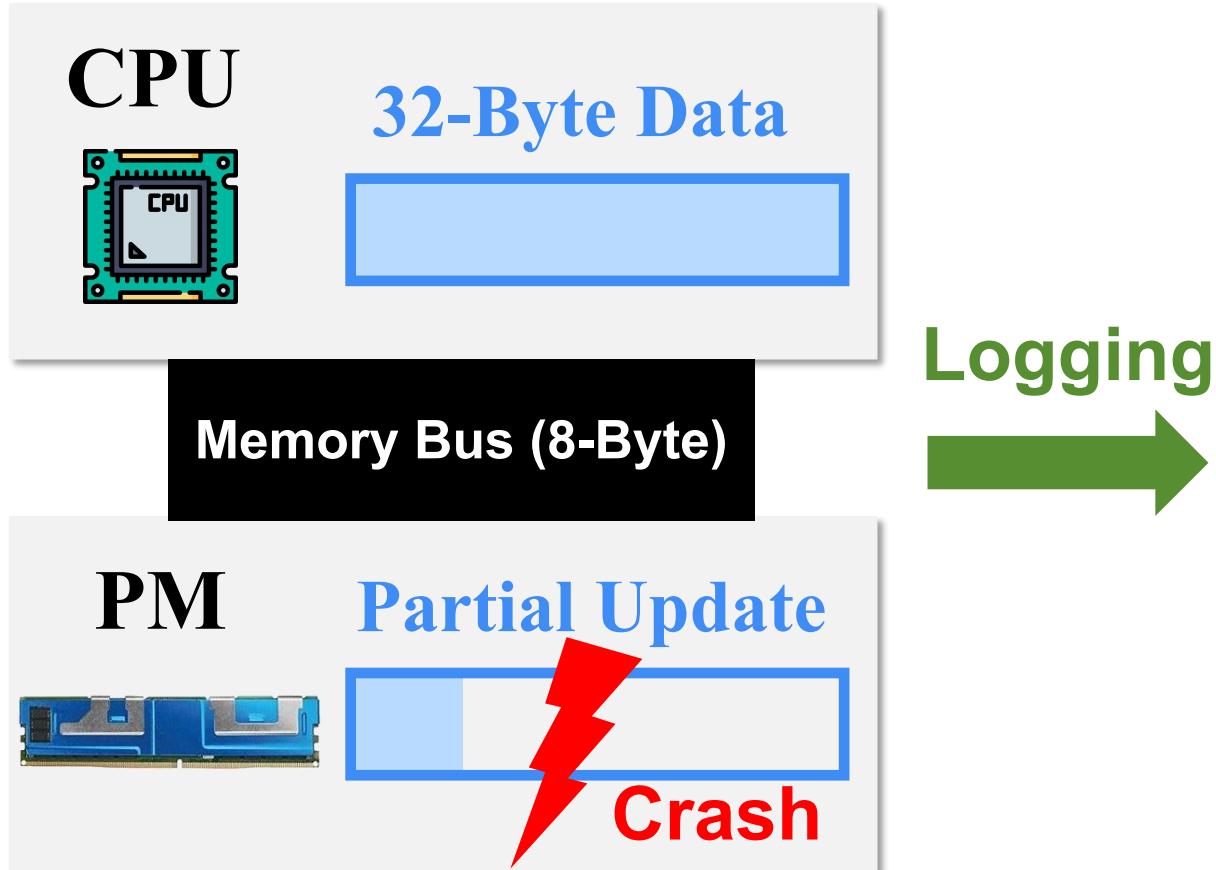
With Consistency Guarantee



Data Inconsistency!

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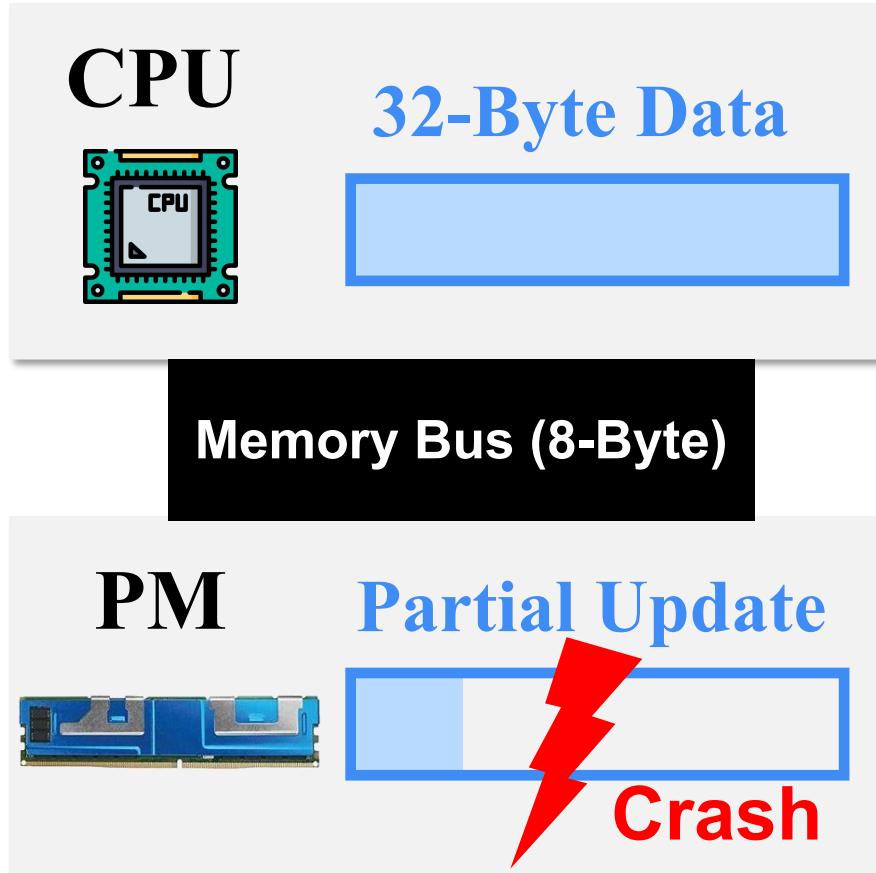


With Consistency Guarantee

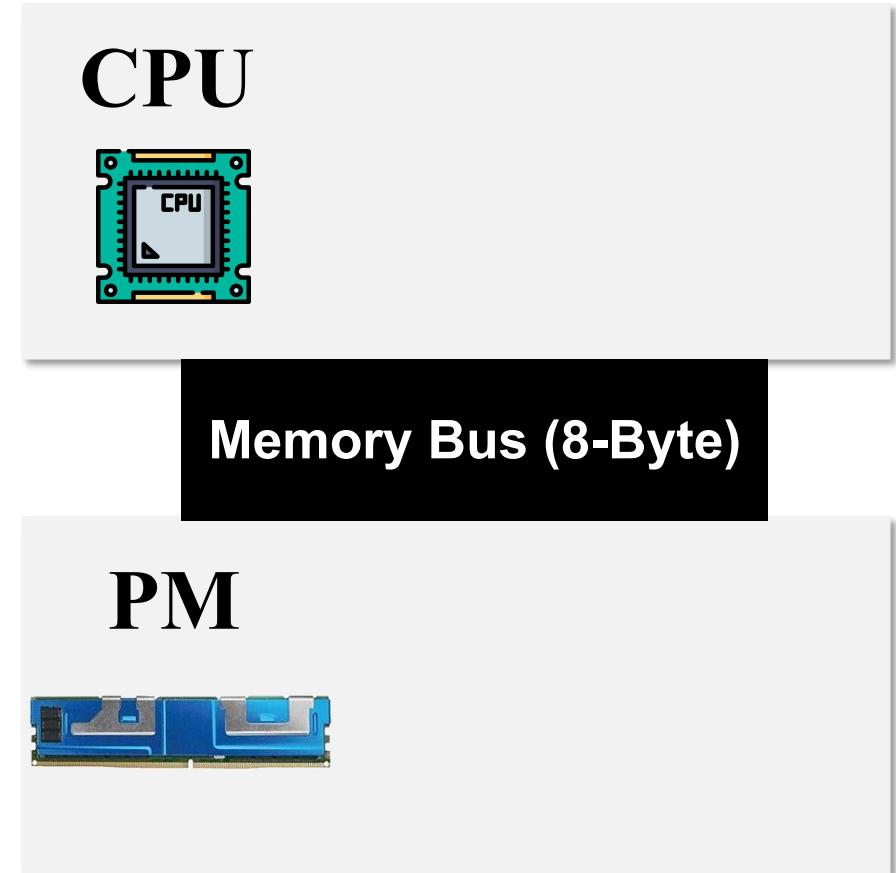
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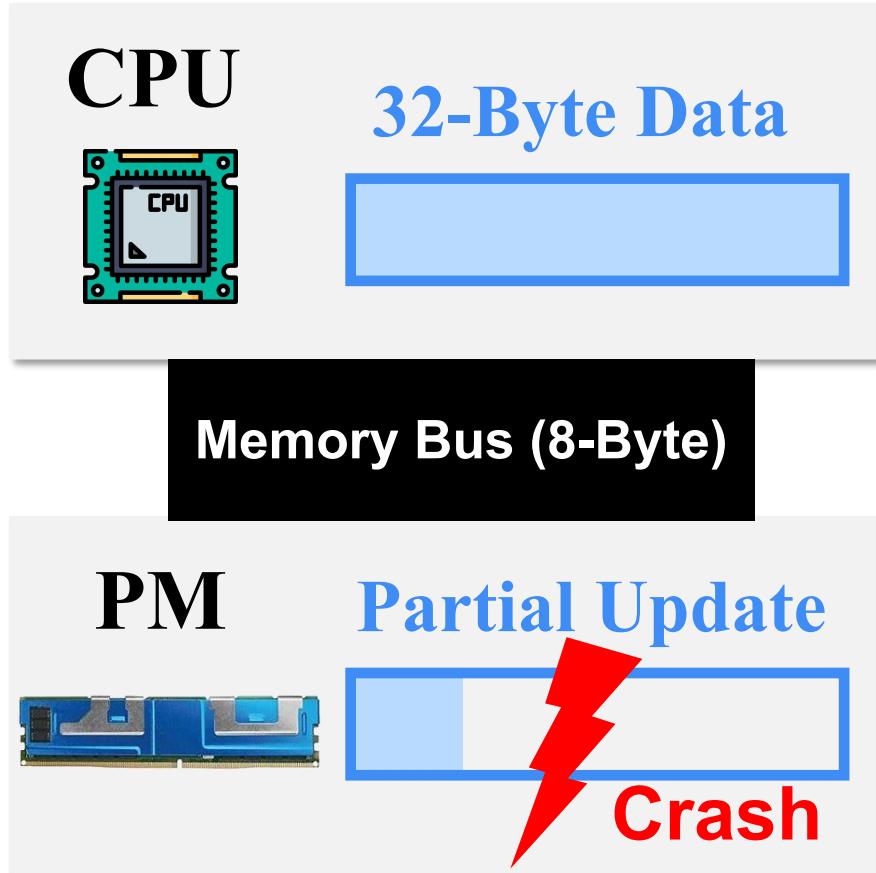
With Consistency Guarantee



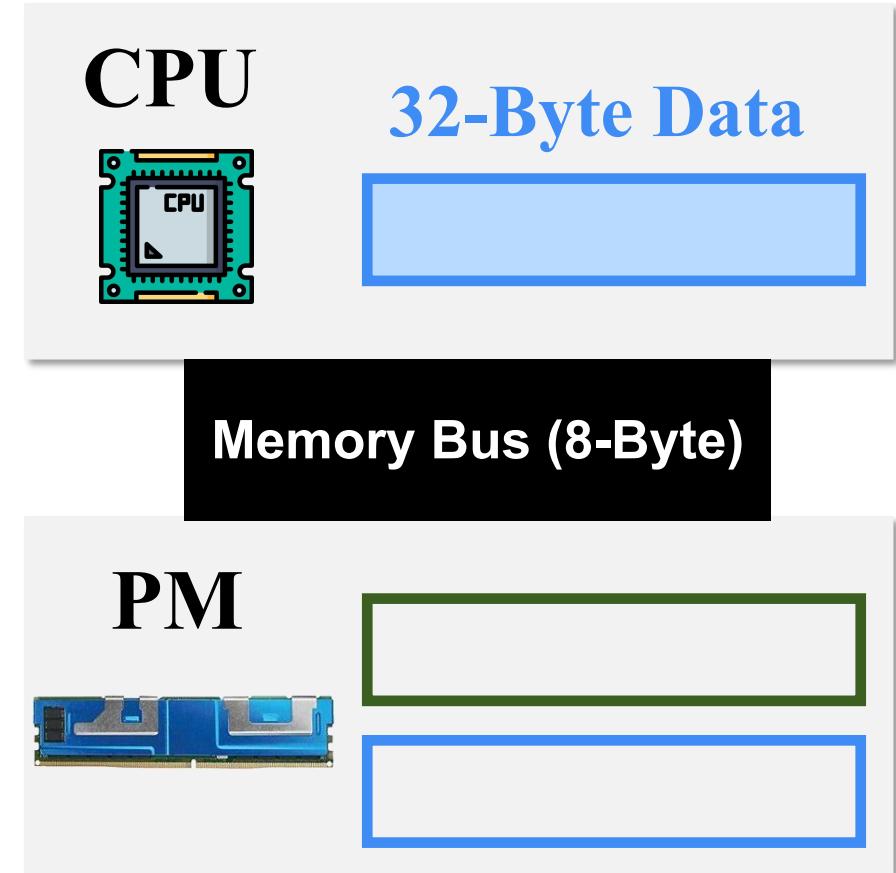
Data Inconsistency!

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee



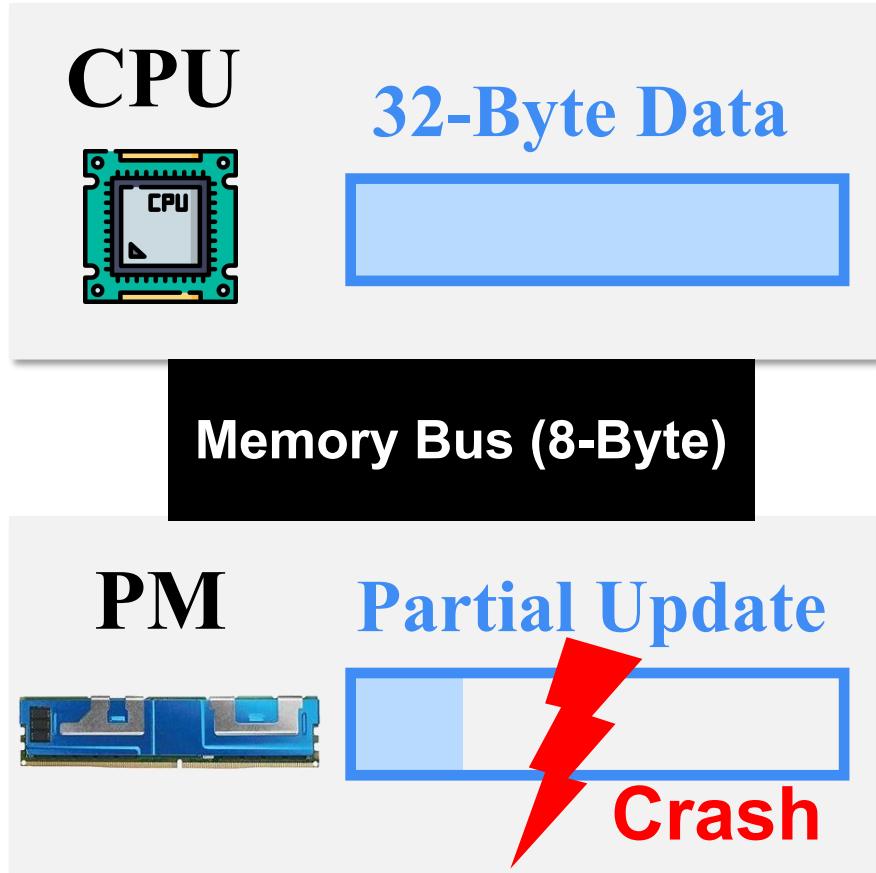
With Consistency Guarantee



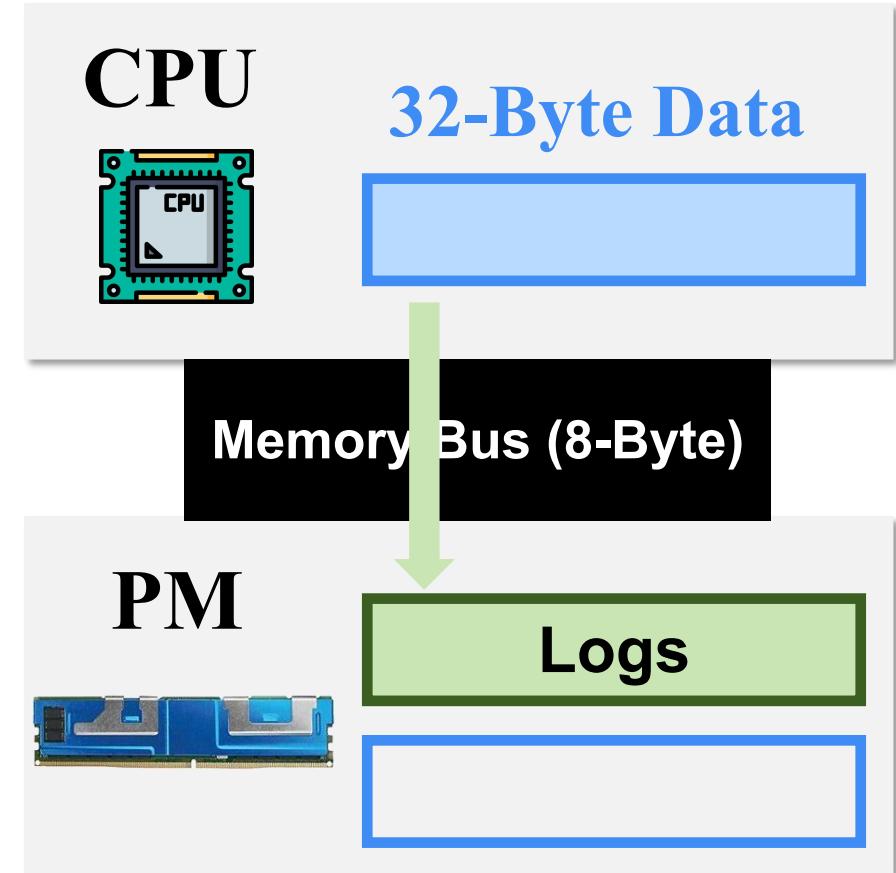
Data Inconsistency!

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee



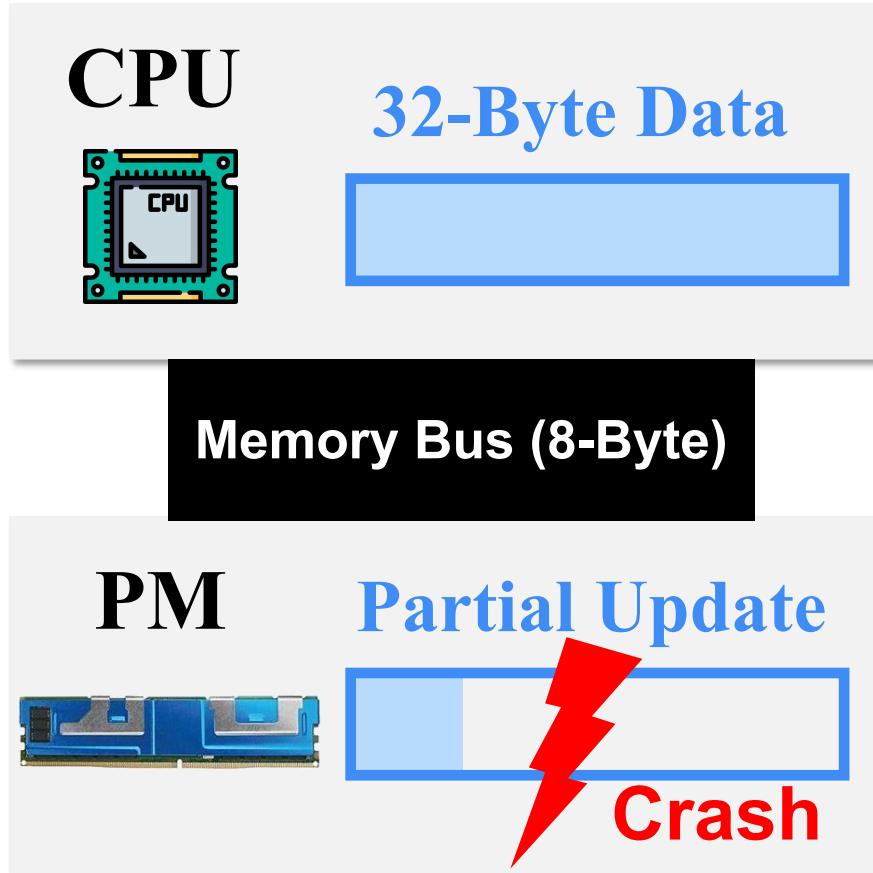
With Consistency Guarantee



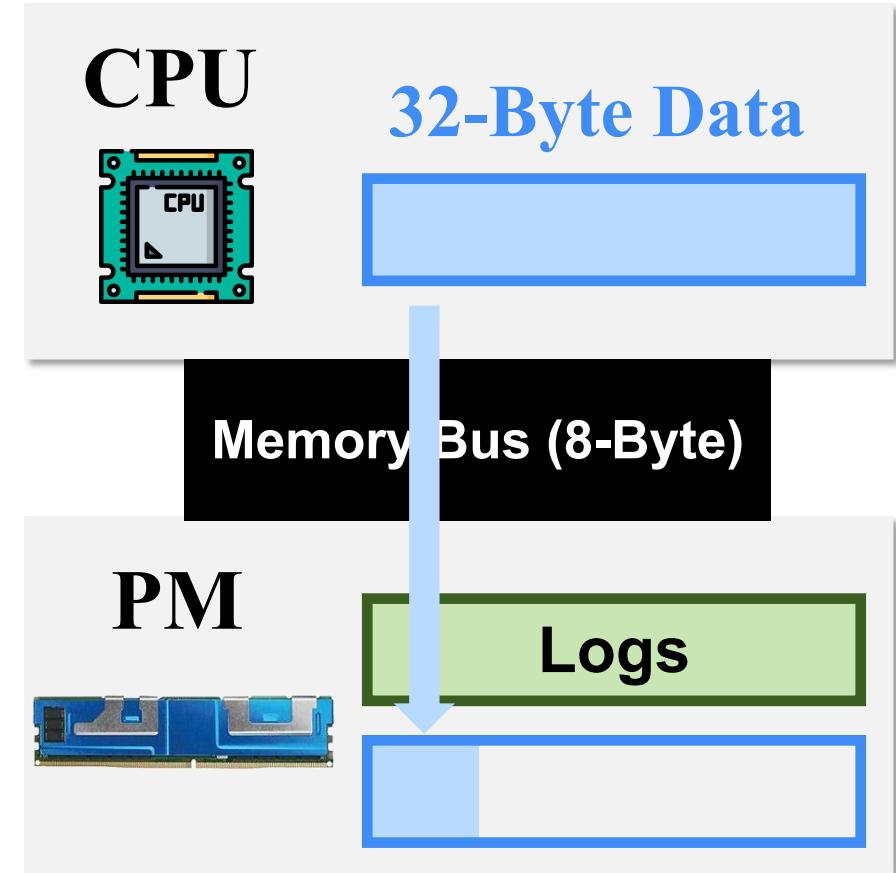
Data Inconsistency!

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee



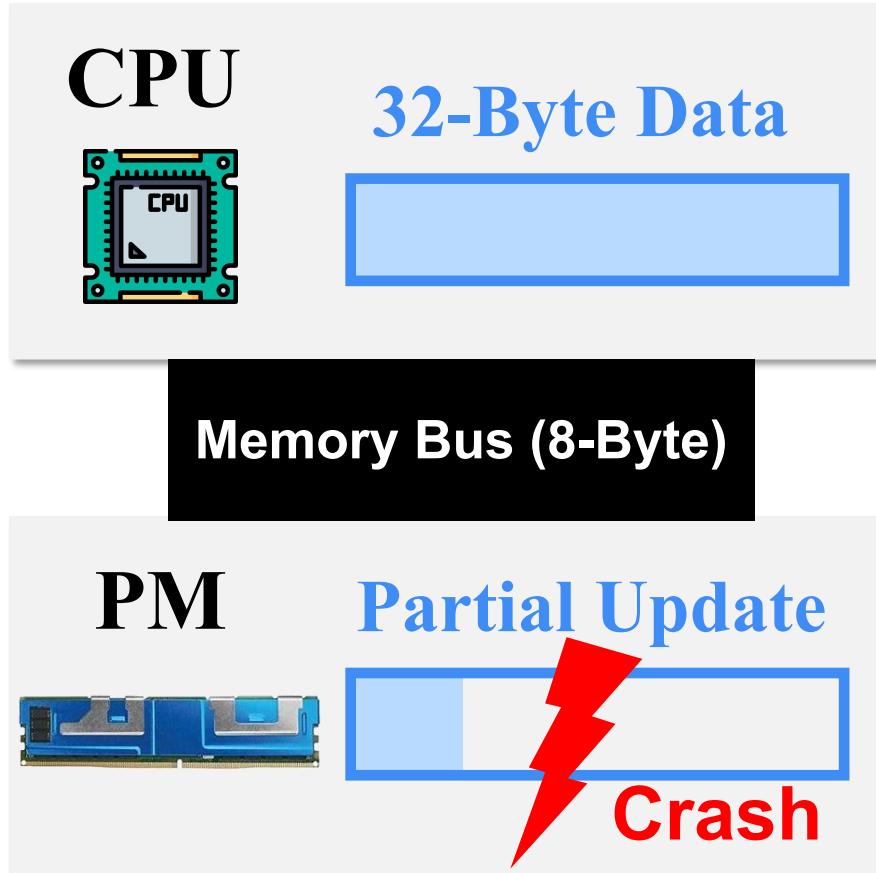
With Consistency Guarantee



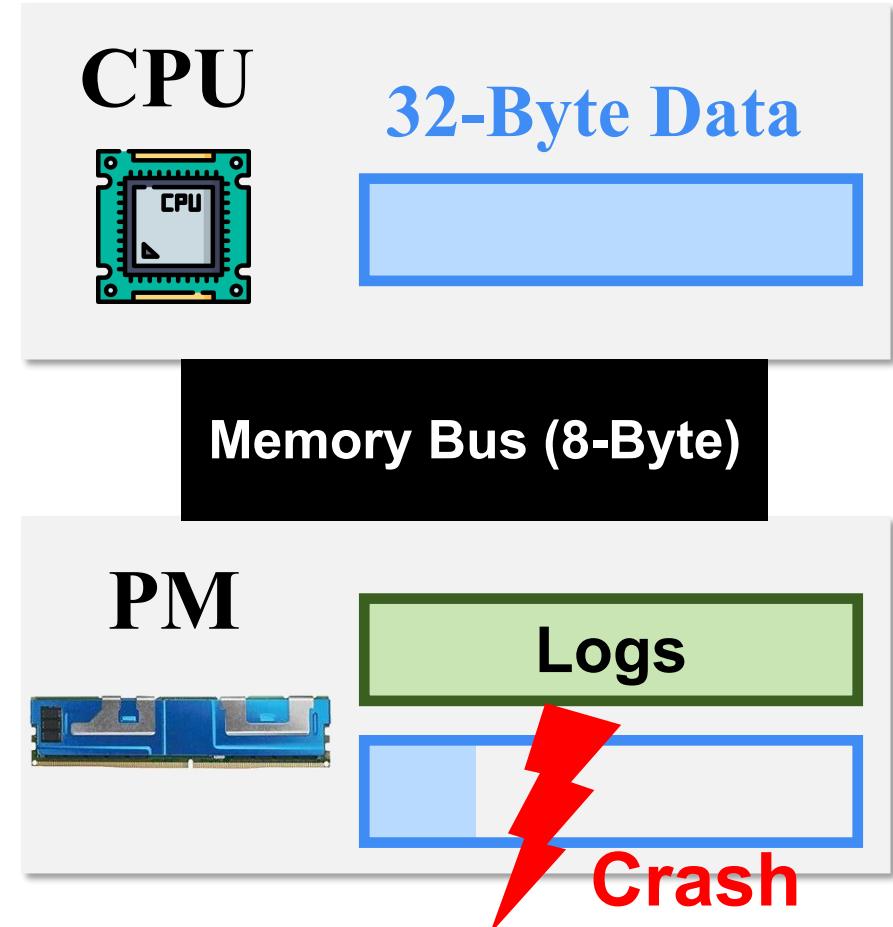
Data Inconsistency!

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee



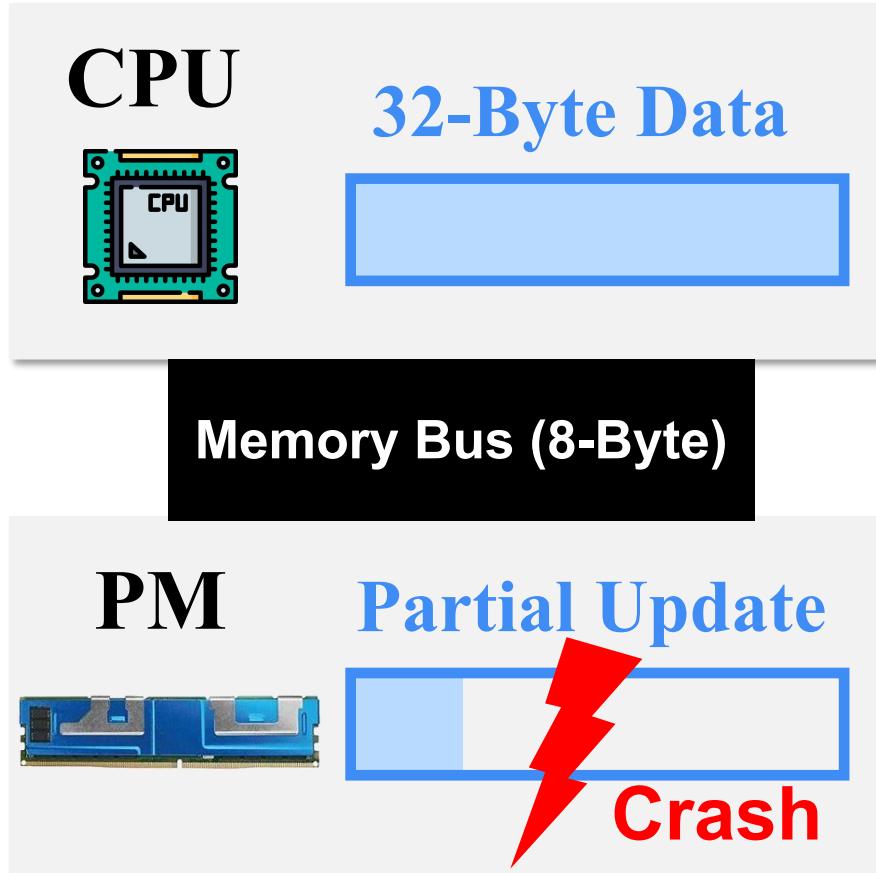
With Consistency Guarantee



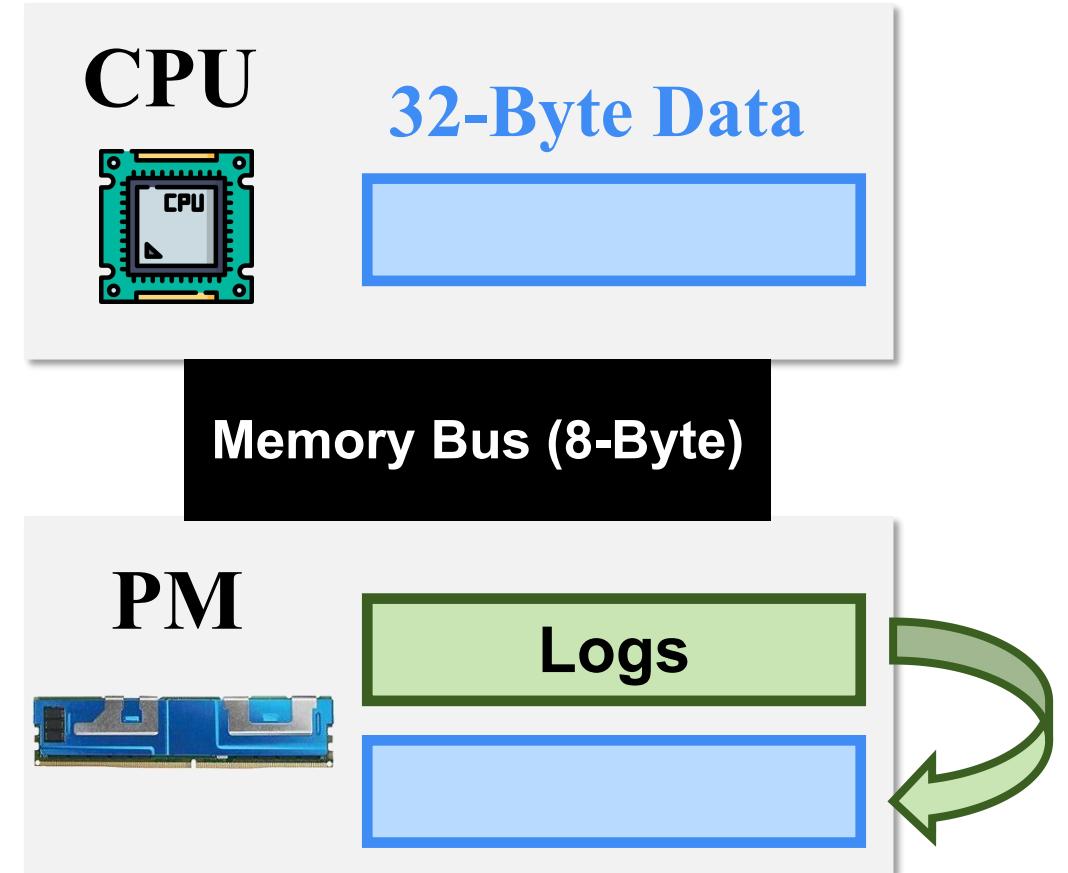
Data Inconsistency!

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee



With Consistency Guarantee

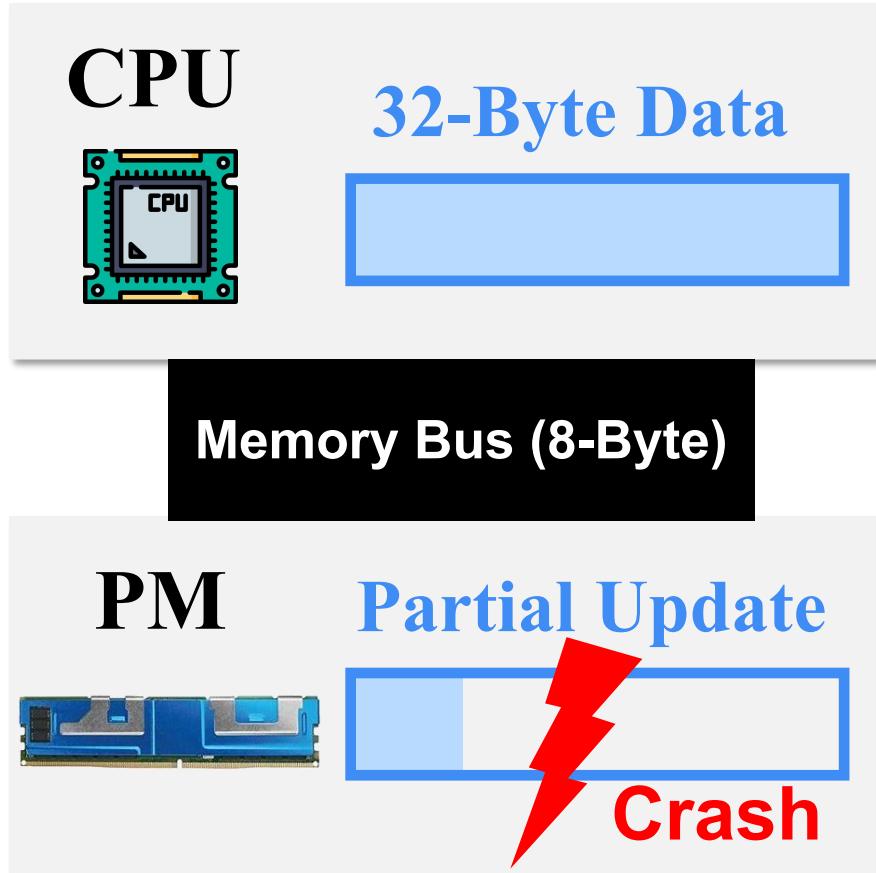


Data Inconsistency!

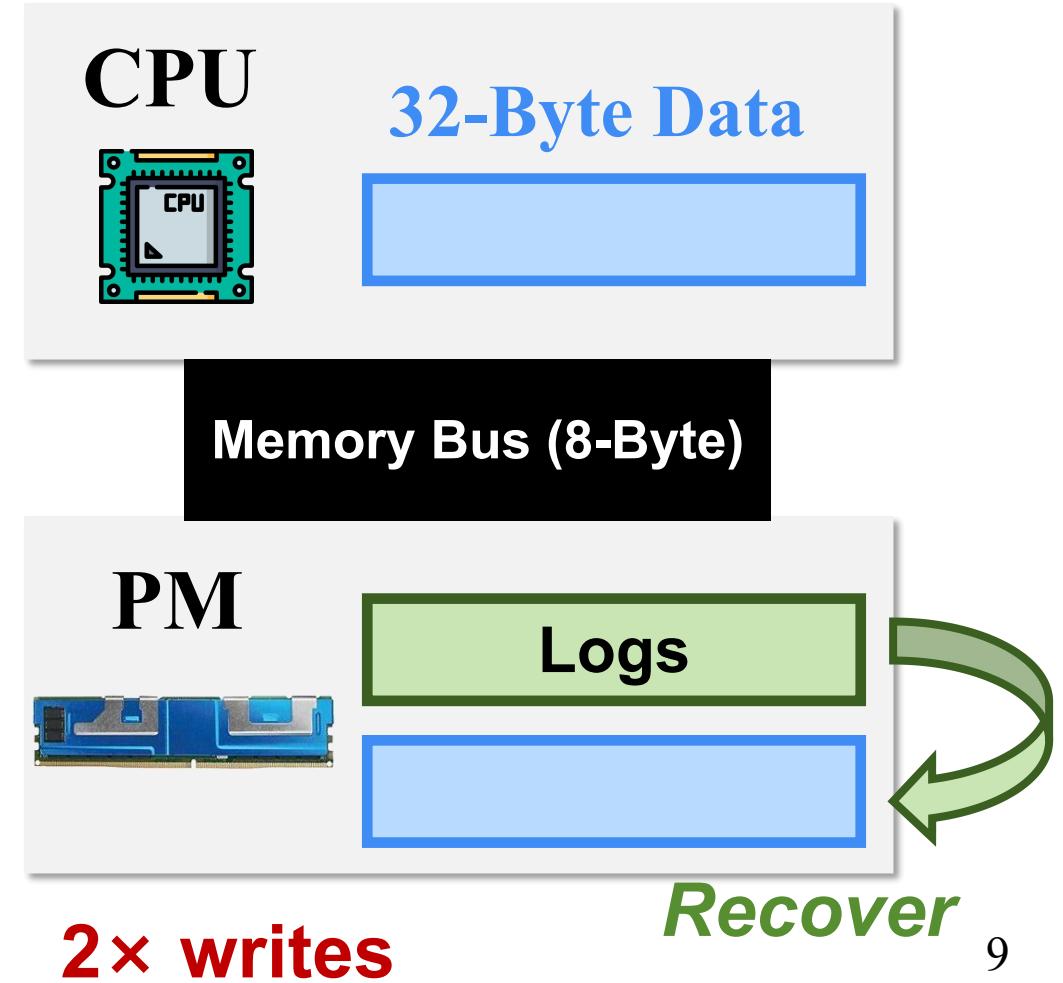
Recover 9

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee



With Consistency Guarantee



Data Inconsistency!

2x writes

Recover 9

Challenge 2: Ensure Crash Consistency

Without Consistency Guarantee

With Consistency Guarantee

CPU

32-Byte Data



CPU

32-Byte Data



Crash consistency guarantee introduces **High Overhead**

Memory Bus (8-Byte)

Memory Bus (8-Byte)

PM

Partial Update



Data Inconsistency!

PM

Logs



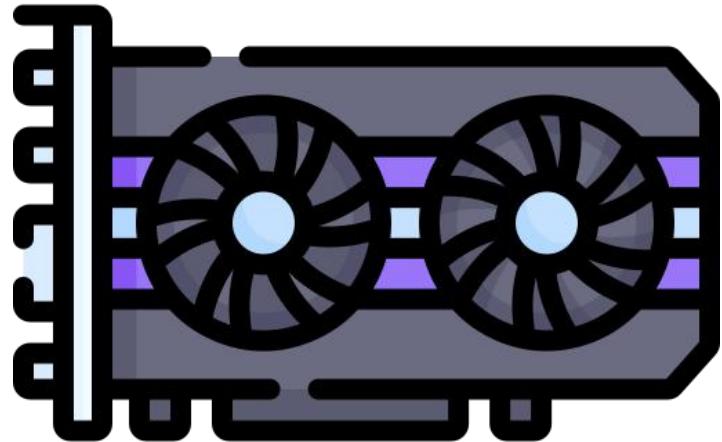
2× writes

Recover

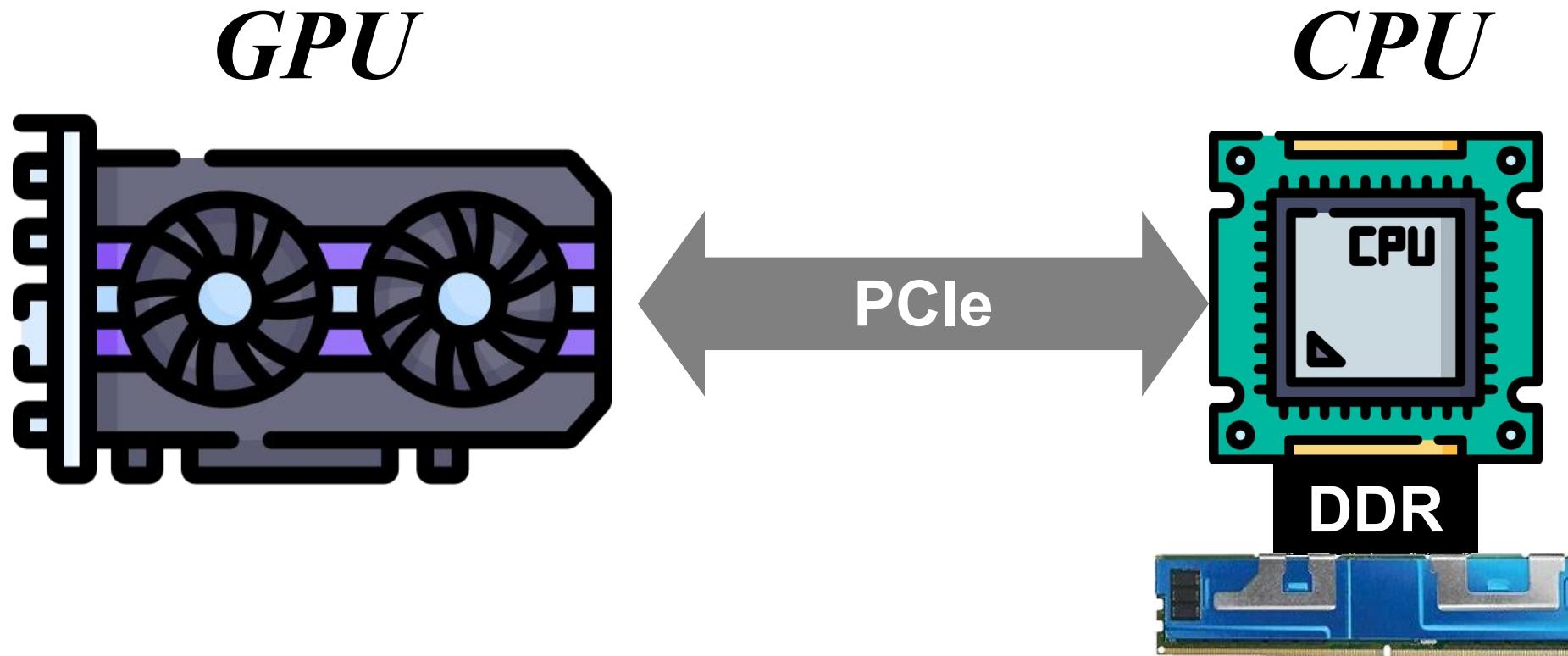
Challenge 3: Huge Bandwidth Gap

Challenge 3: Huge Bandwidth Gap

GPU

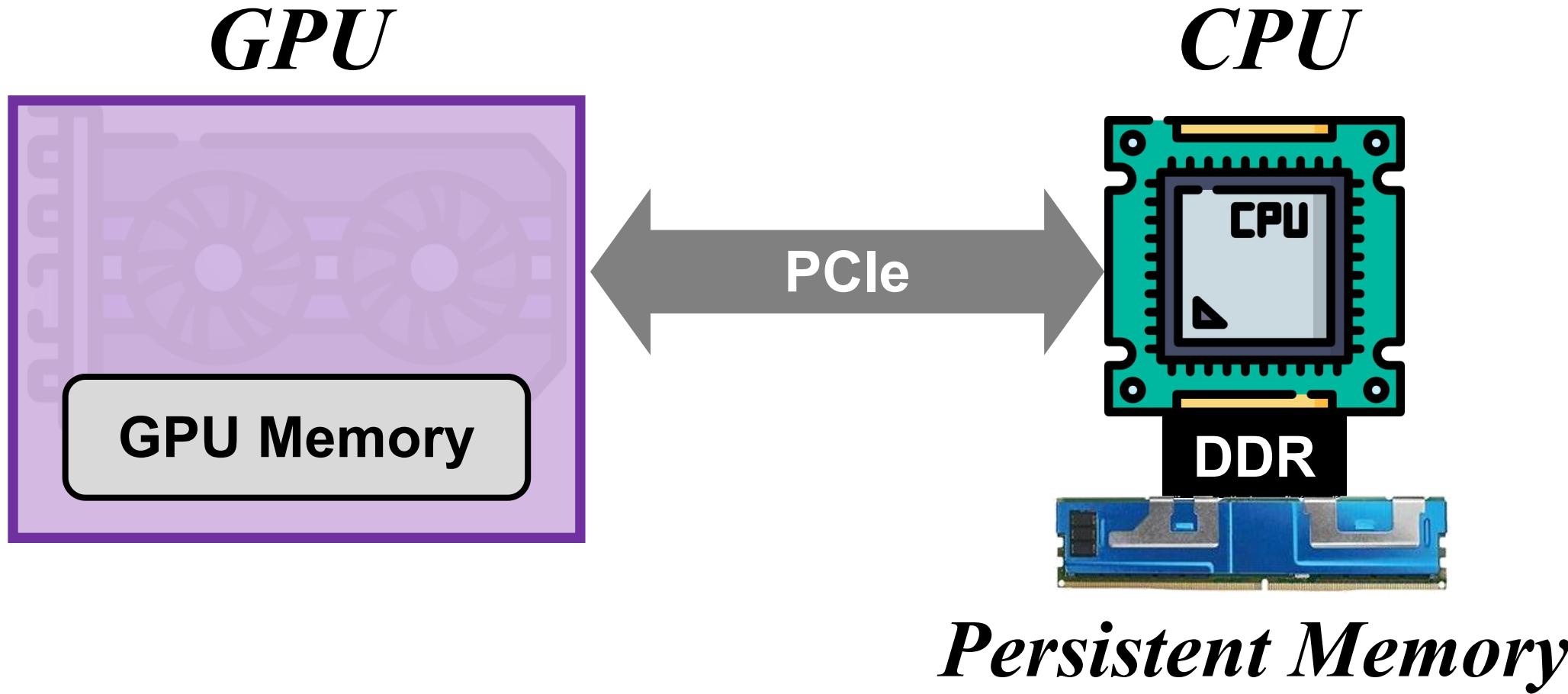


Challenge 3: Huge Bandwidth Gap

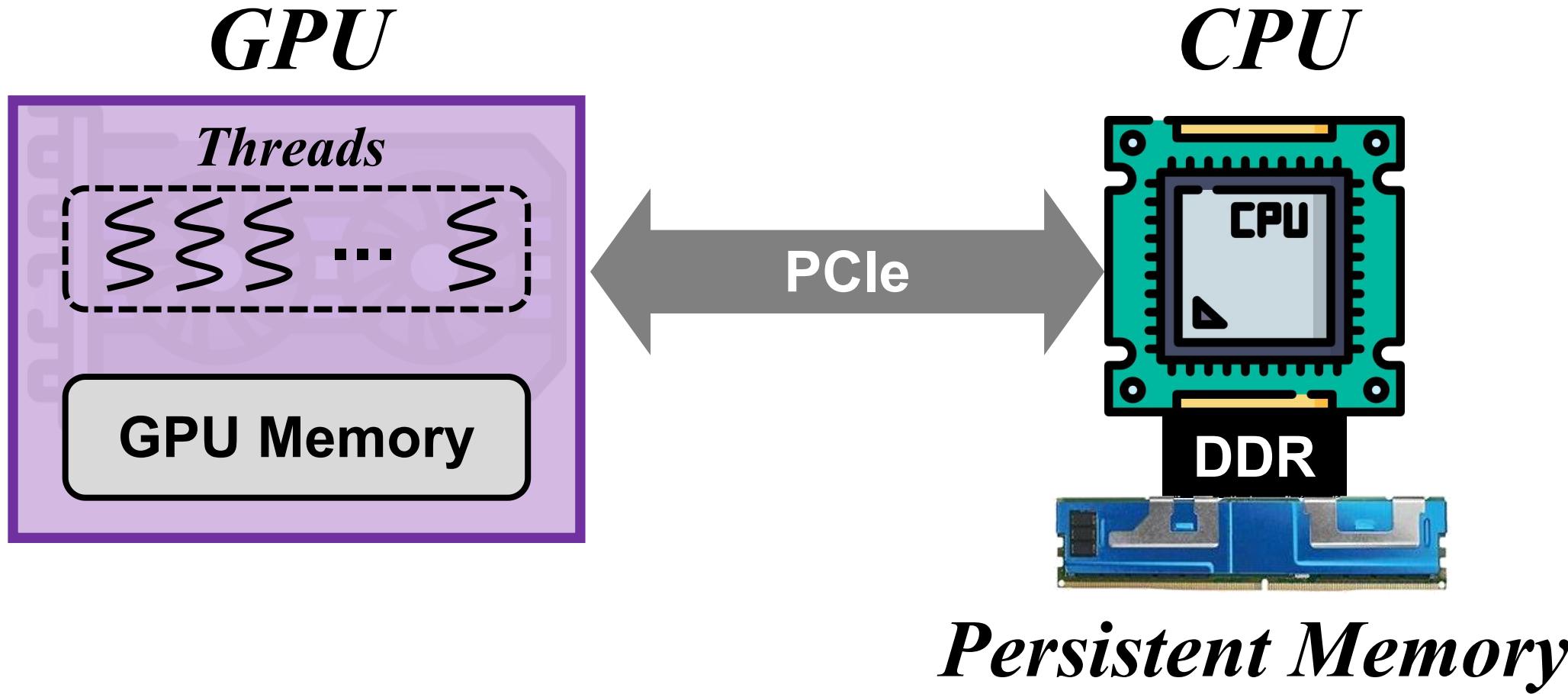


Persistent Memory

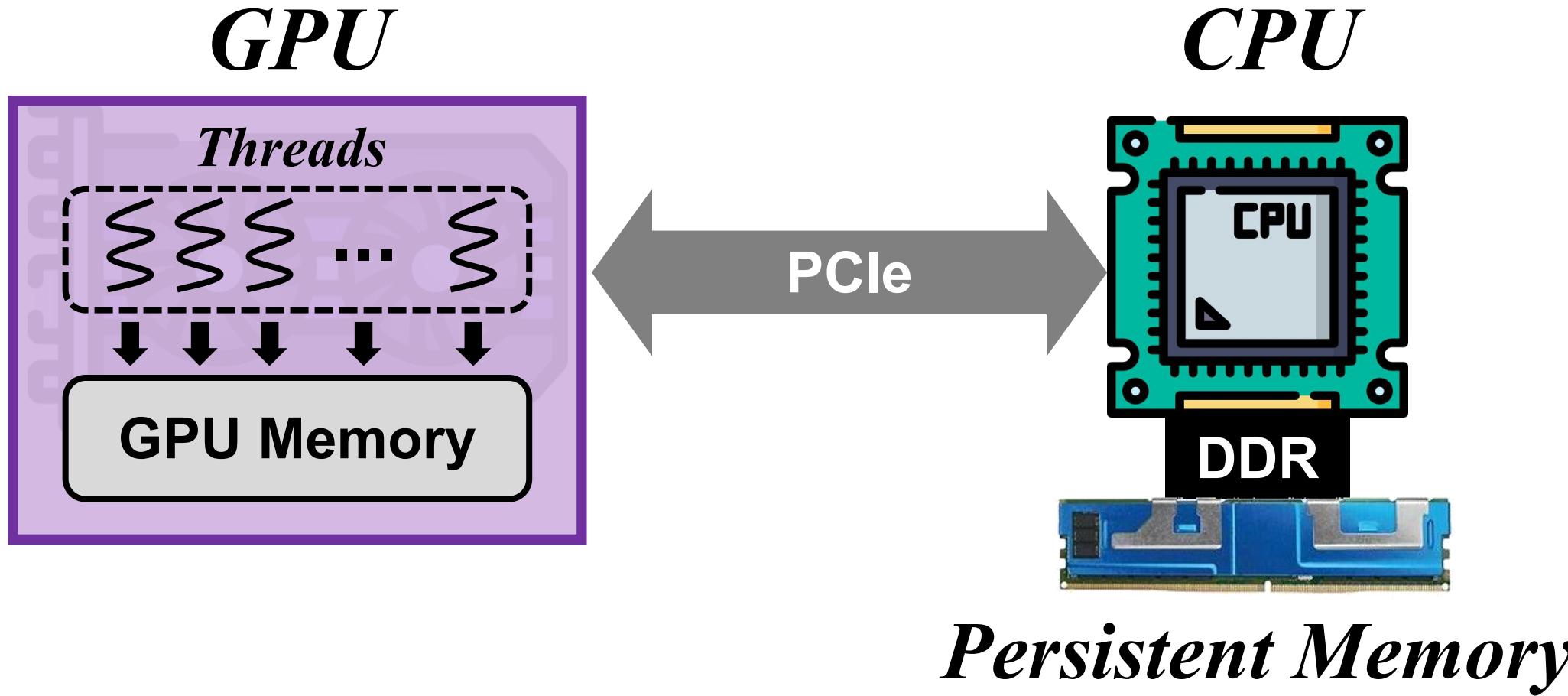
Challenge 3: Huge Bandwidth Gap



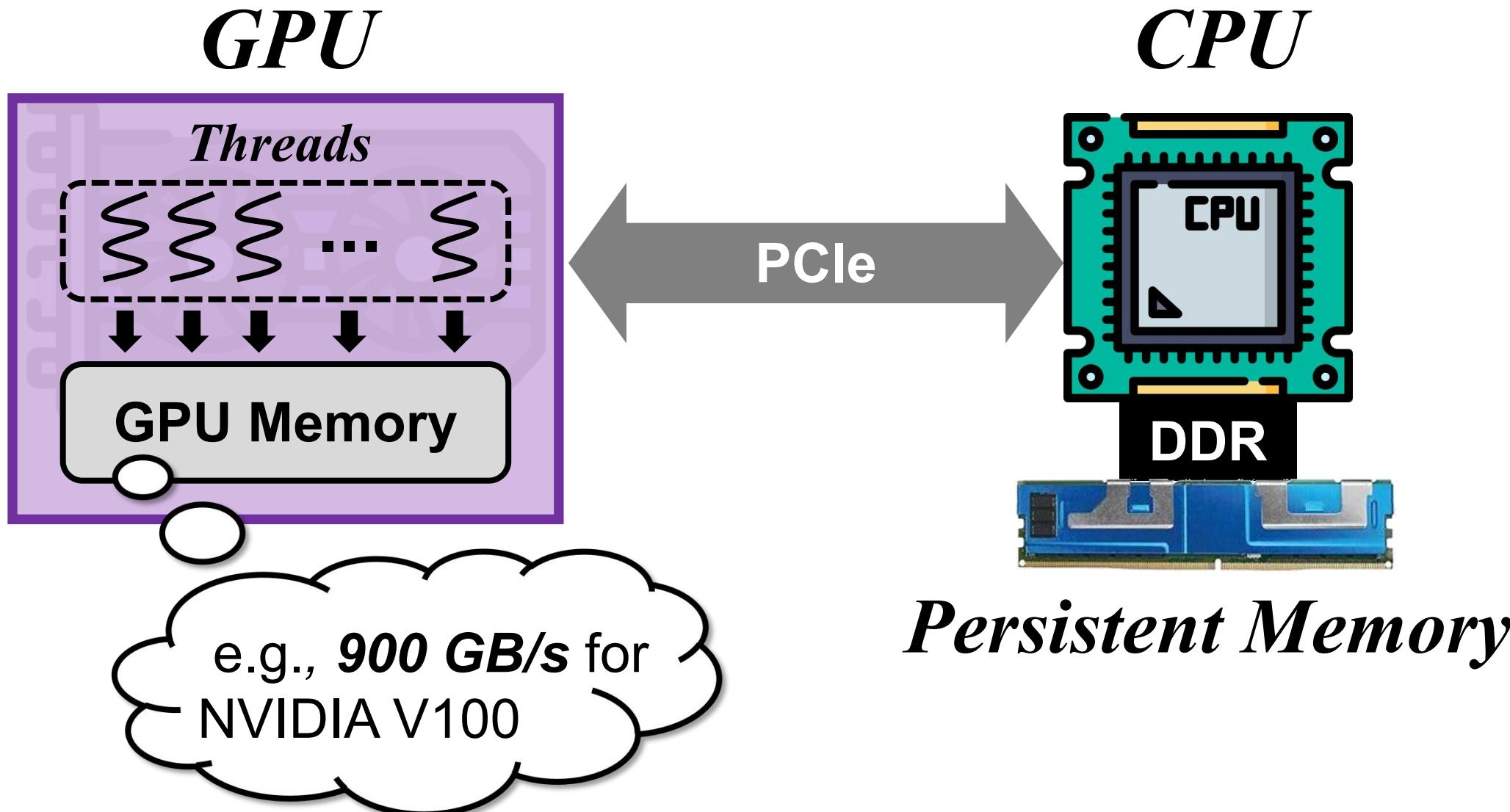
Challenge 3: Huge Bandwidth Gap



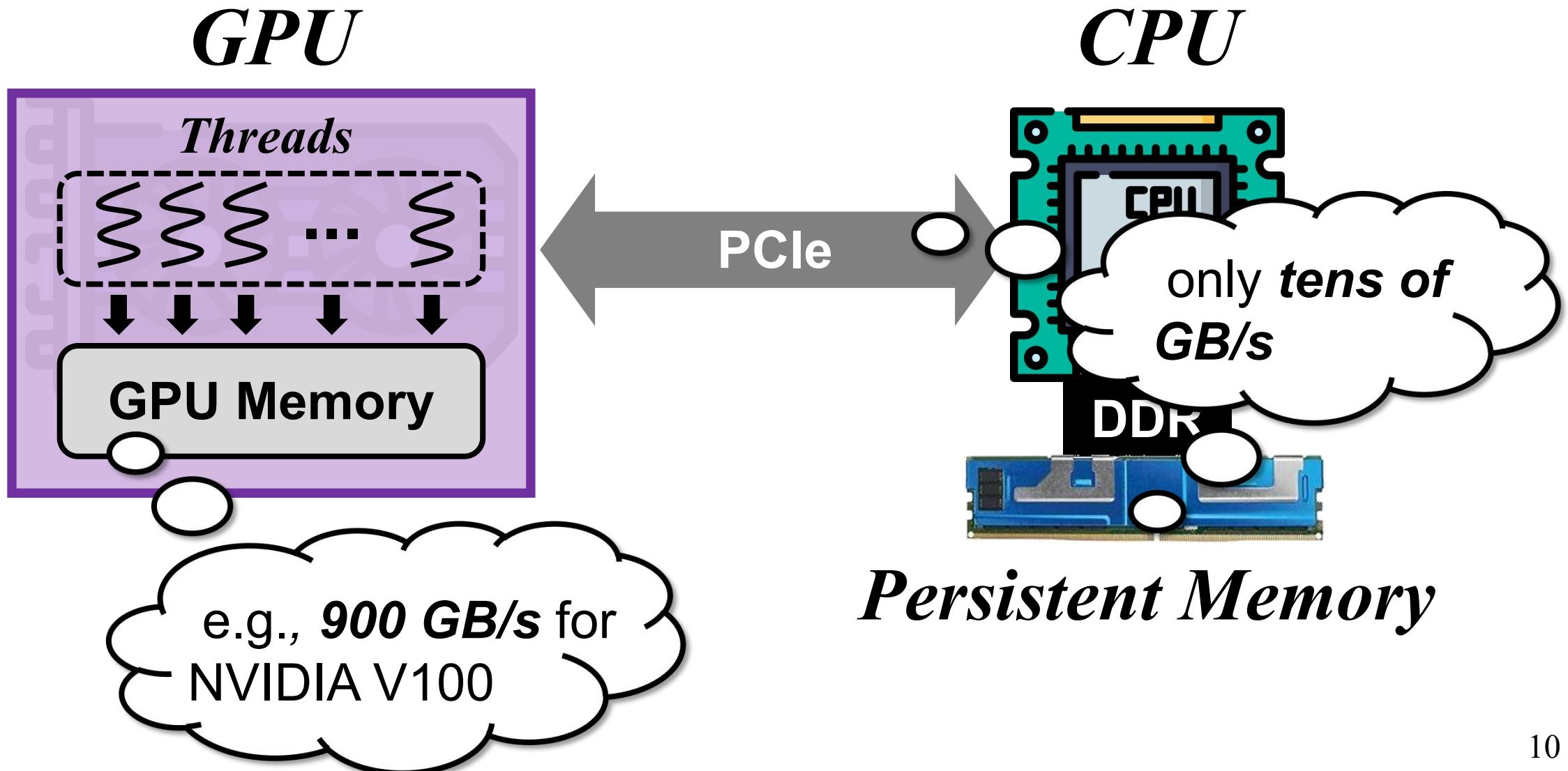
Challenge 3: Huge Bandwidth Gap



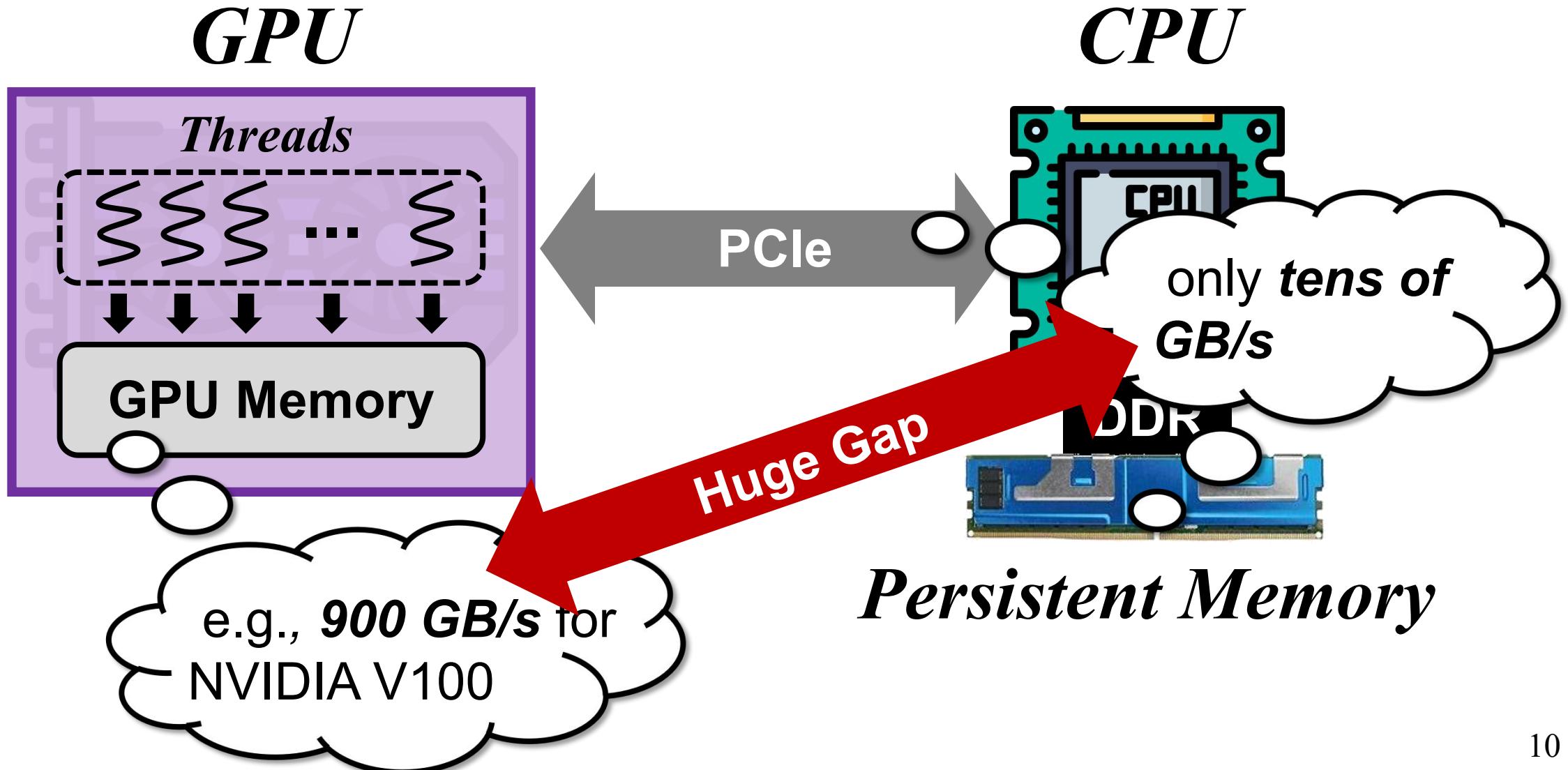
Challenge 3: Huge Bandwidth Gap



Challenge 3: Huge Bandwidth Gap



Challenge 3: Huge Bandwidth Gap



Challenge 3: Huge Bandwidth Gap

GPU

Threads

CPU

Huge bandwidth gap between PM and GPU **Limits the Utilization** of GPU's high parallelism



Huge Gap



Persistent Memory

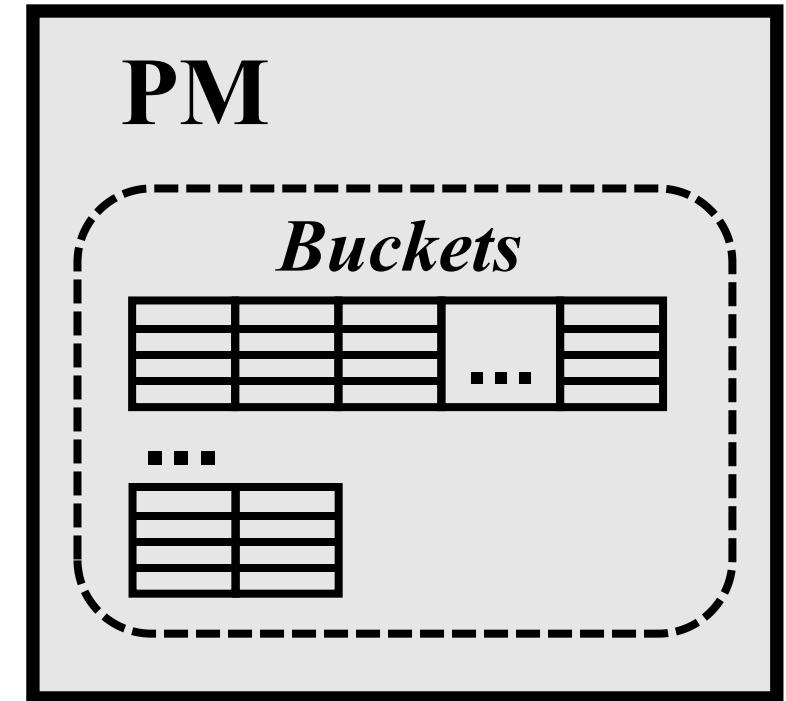
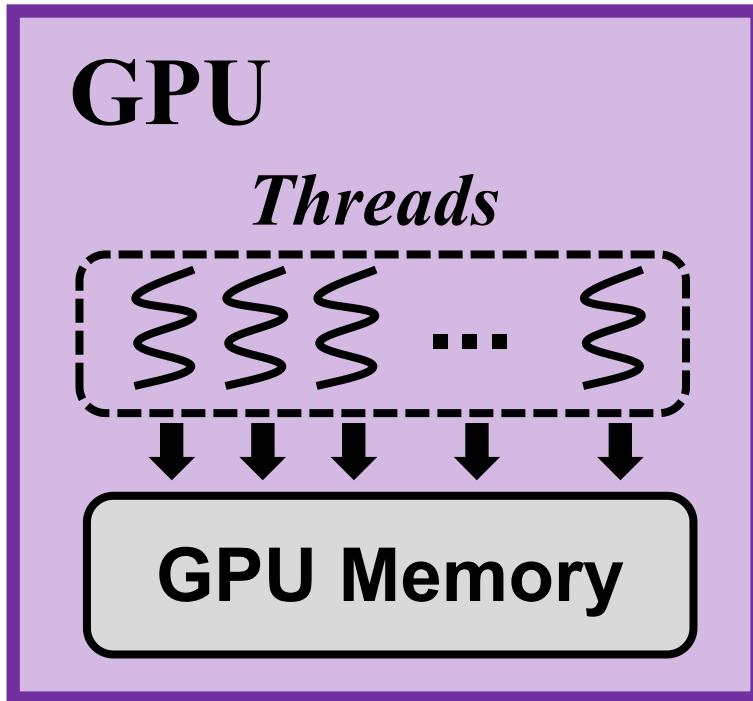
Our Solution: GPHash

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- **GPHash: An Efficient Hash Index for GPM Systems**

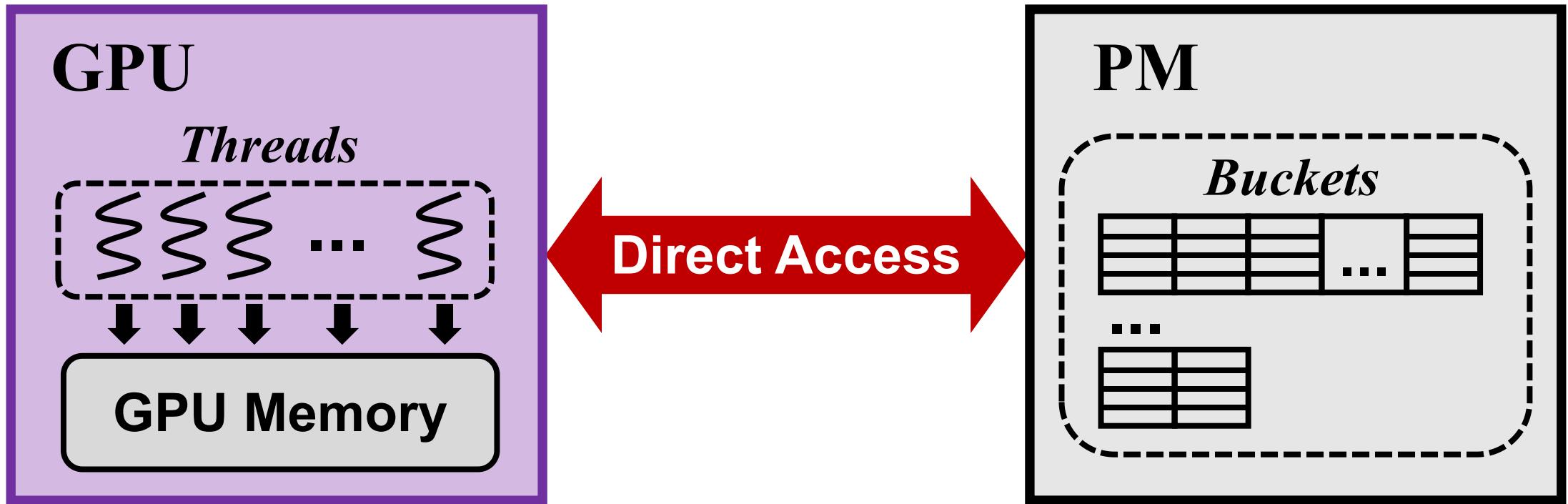
Our Solution: GPHash

- **GPHash: An Efficient Hash Index for GPM Systems**



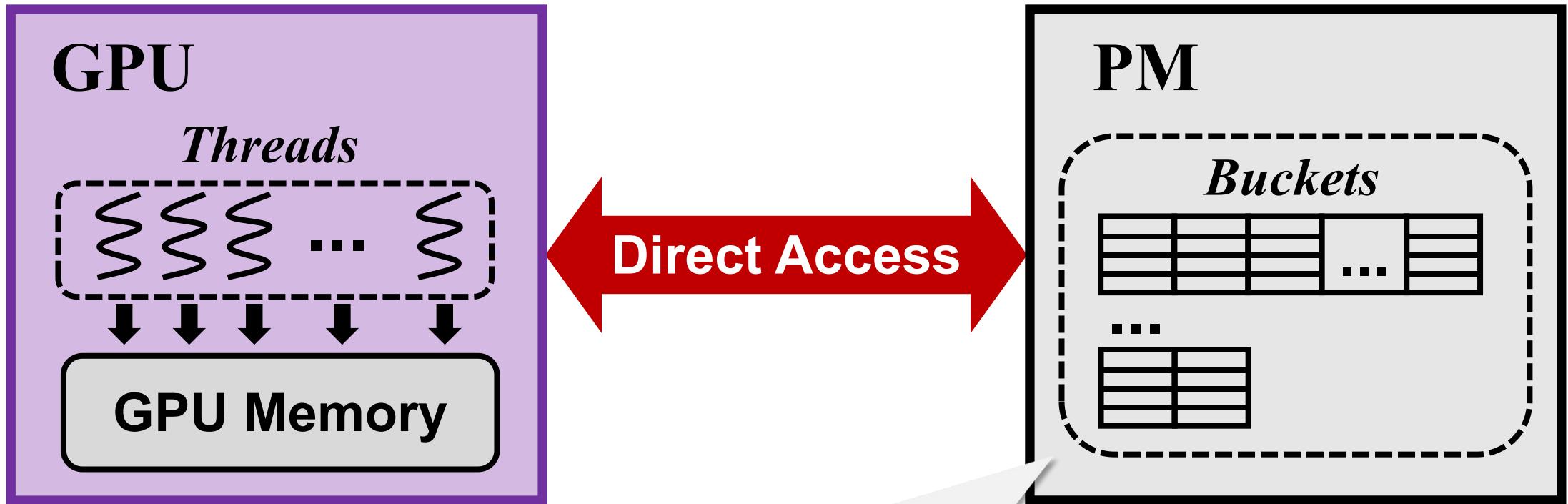
Our Solution: GPHash

- **GPHash: An Efficient Hash Index for GPM Systems**



Our Solution: GPHash

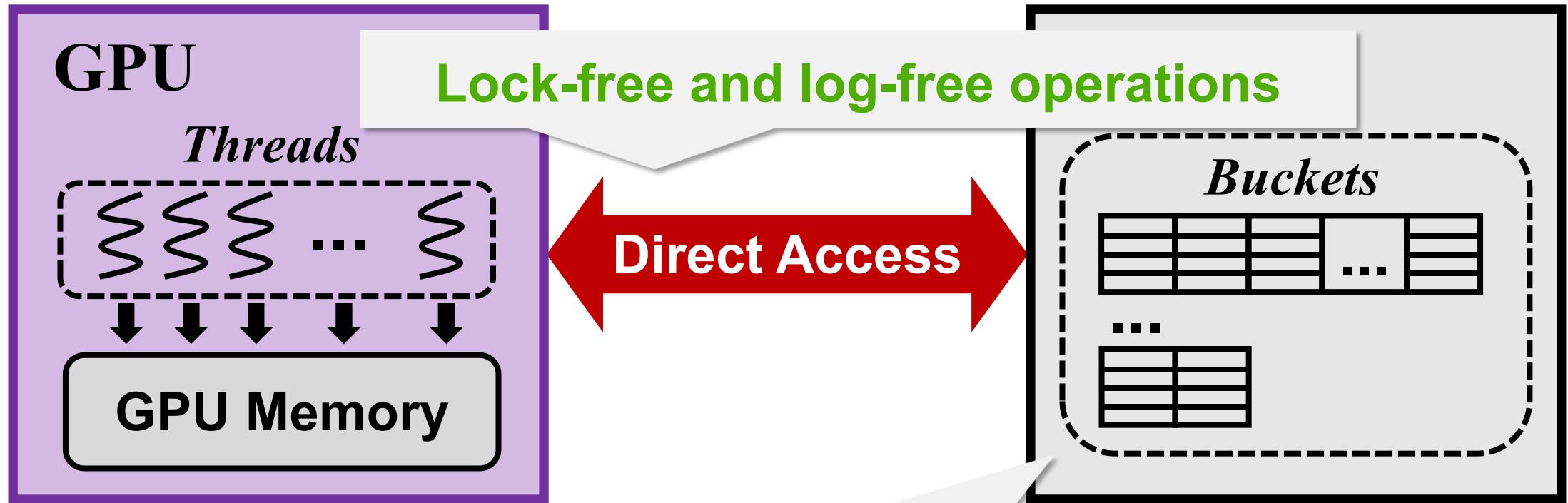
- **GPHash: An Efficient Hash Index for GPM Systems**



GPU-conscious and PM-friendly hash table

Our Solution: GPHash

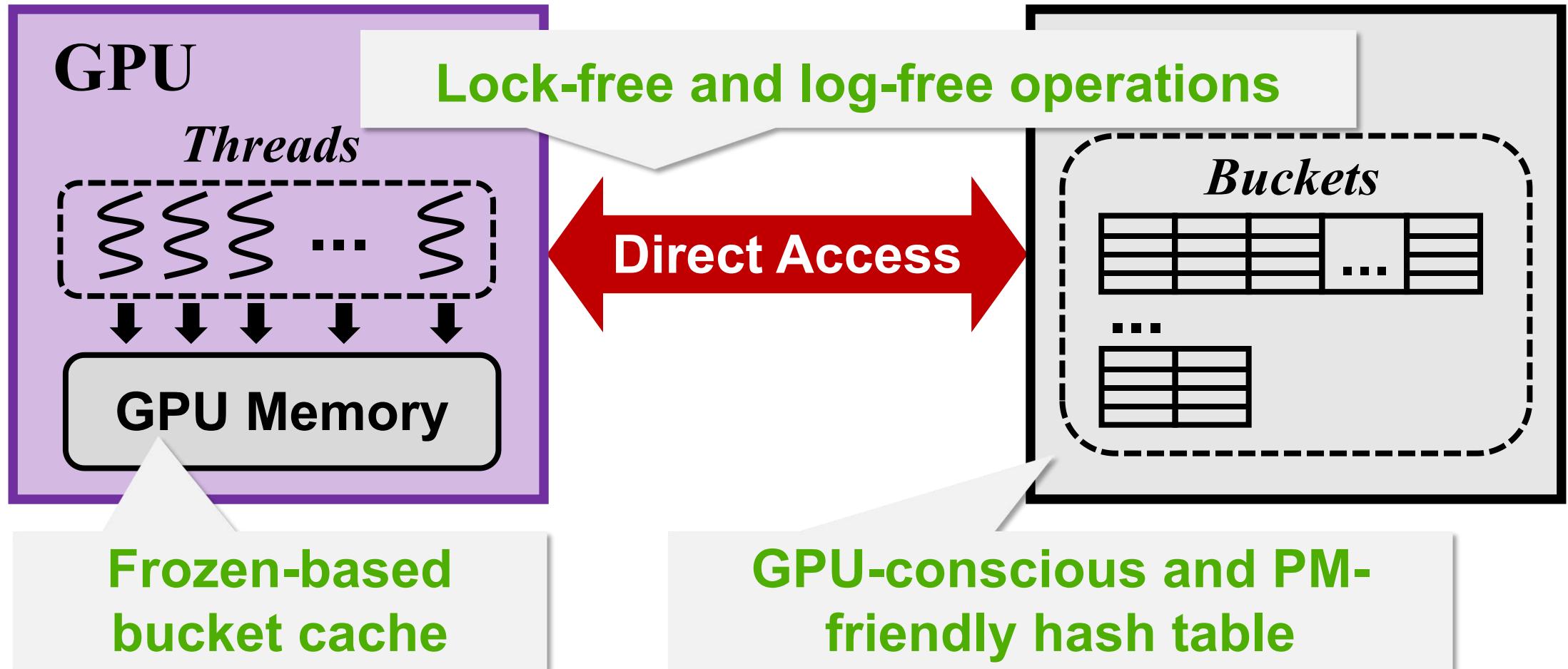
- **GPHash: An Efficient Hash Index for GPM Systems**



GPU-conscious and PM-friendly hash table

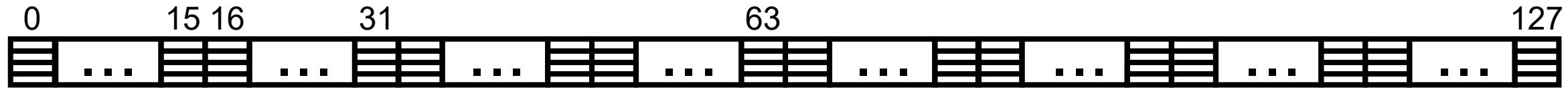
Our Solution: GPHash

- **GPHash: An Efficient Hash Index for GPM Systems**

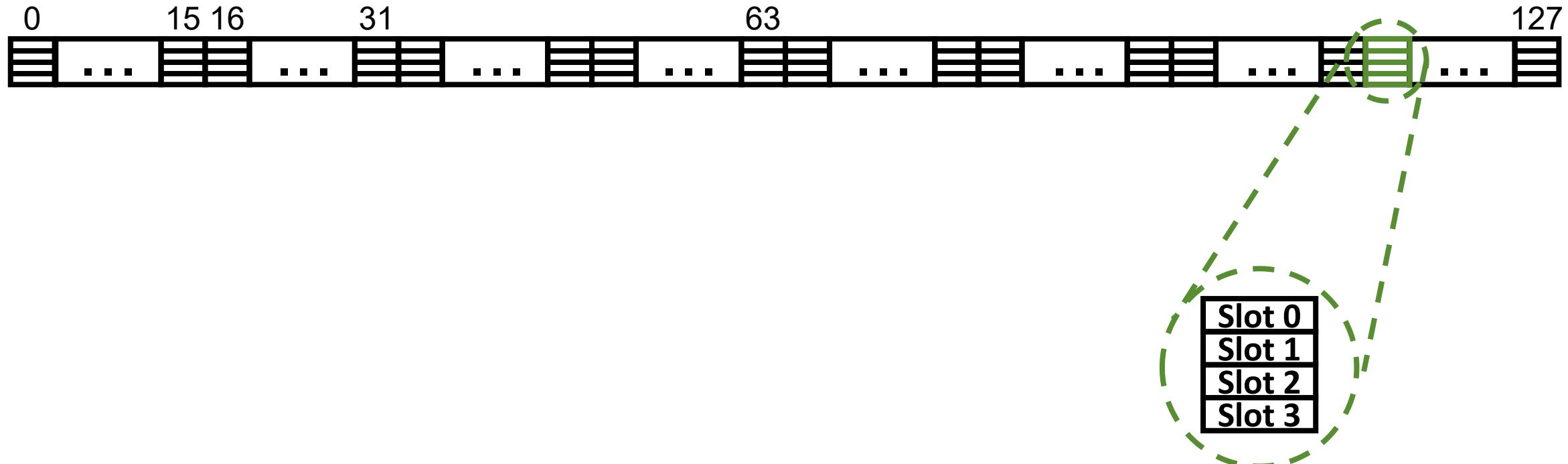


GPU-Conscious and PM-Friendly Hash Table

GPU-Conscious and PM-Friendly Hash Table

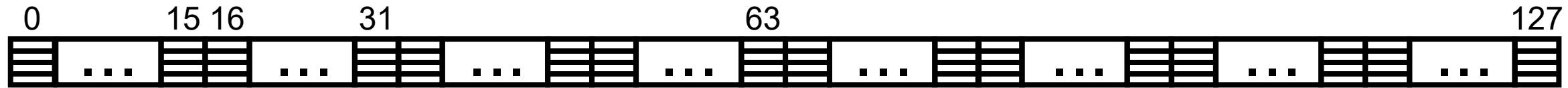


GPU-Conscious and PM-Friendly Hash Table

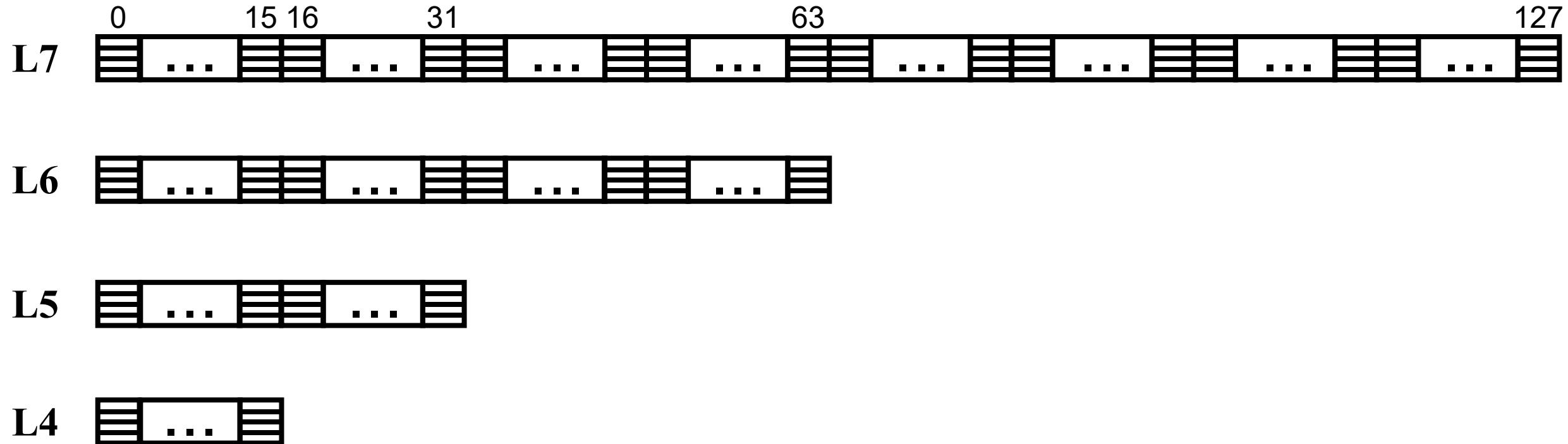


- *Slot Associativity* ₁₂

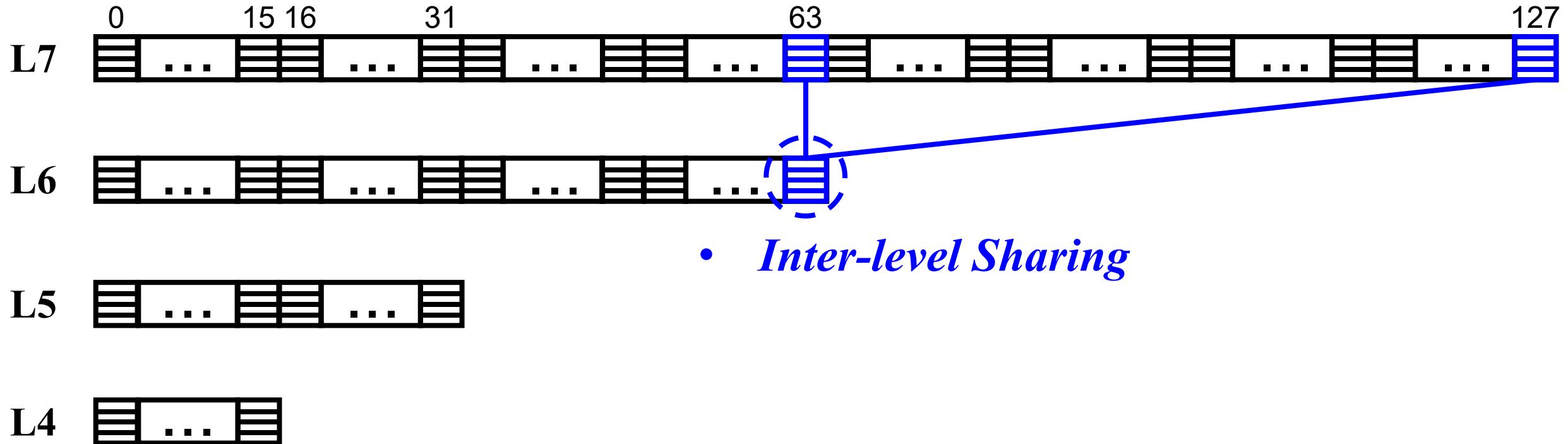
GPU-Conscious and PM-Friendly Hash Table



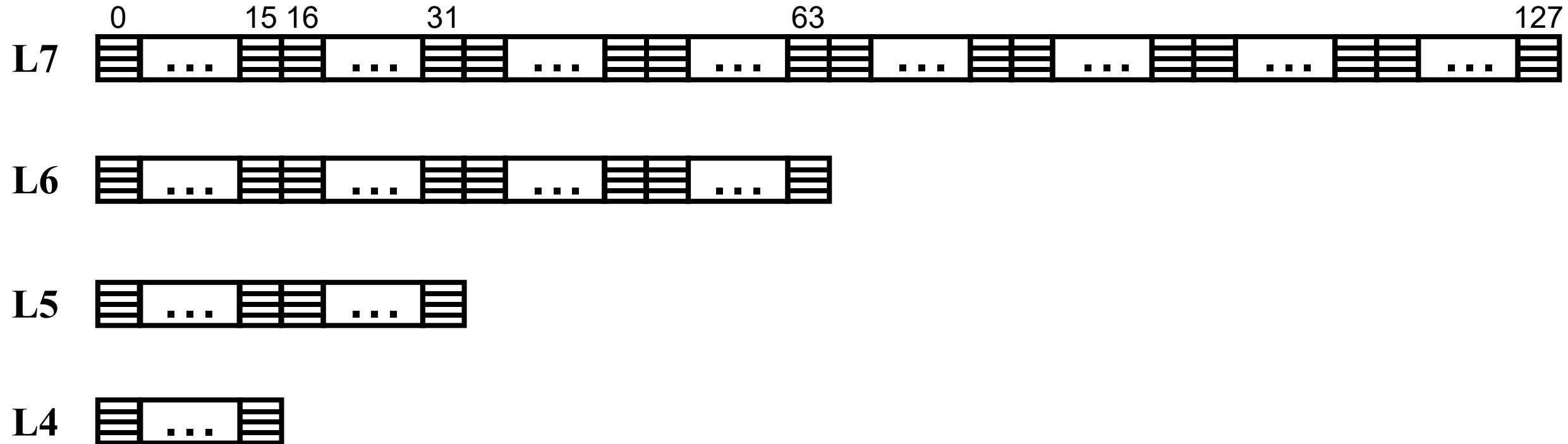
GPU-Conscious and PM-Friendly Hash Table



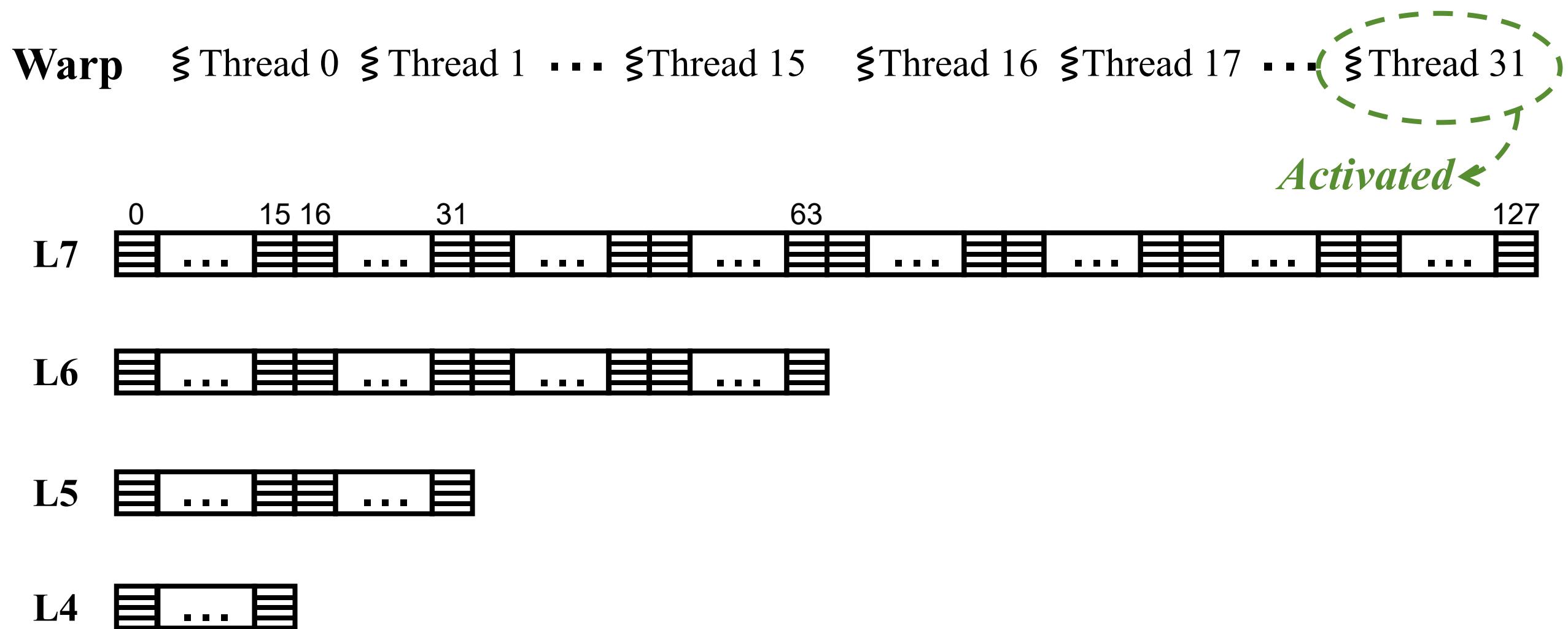
GPU-Conscious and PM-Friendly Hash Table



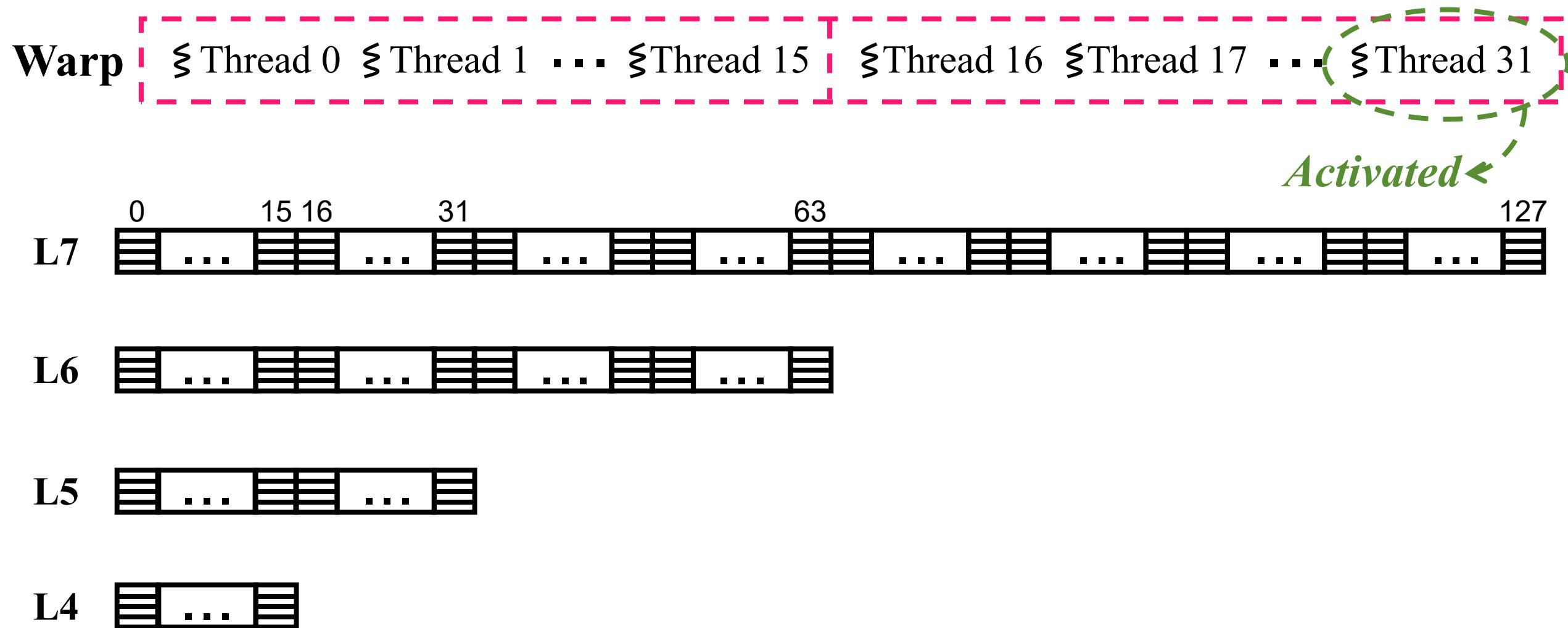
GPU-Conscious and PM-Friendly Hash Table



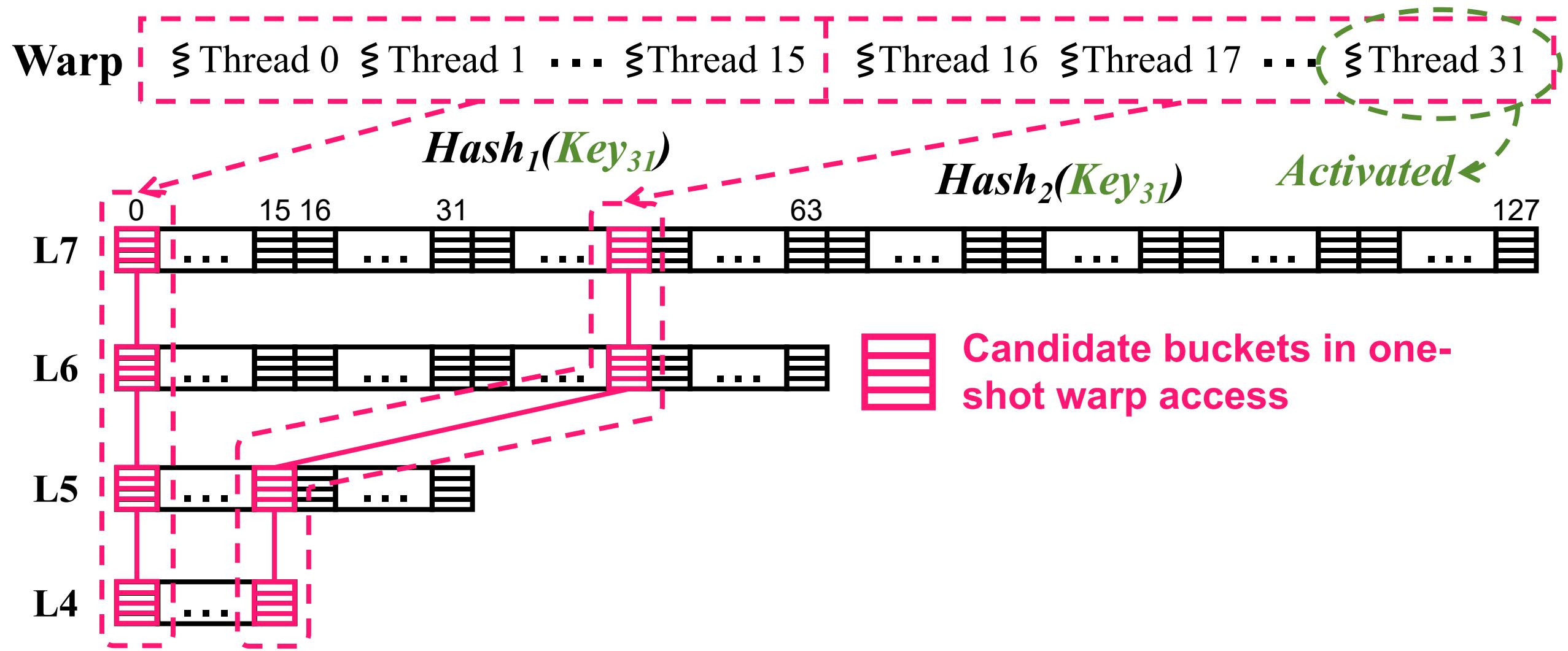
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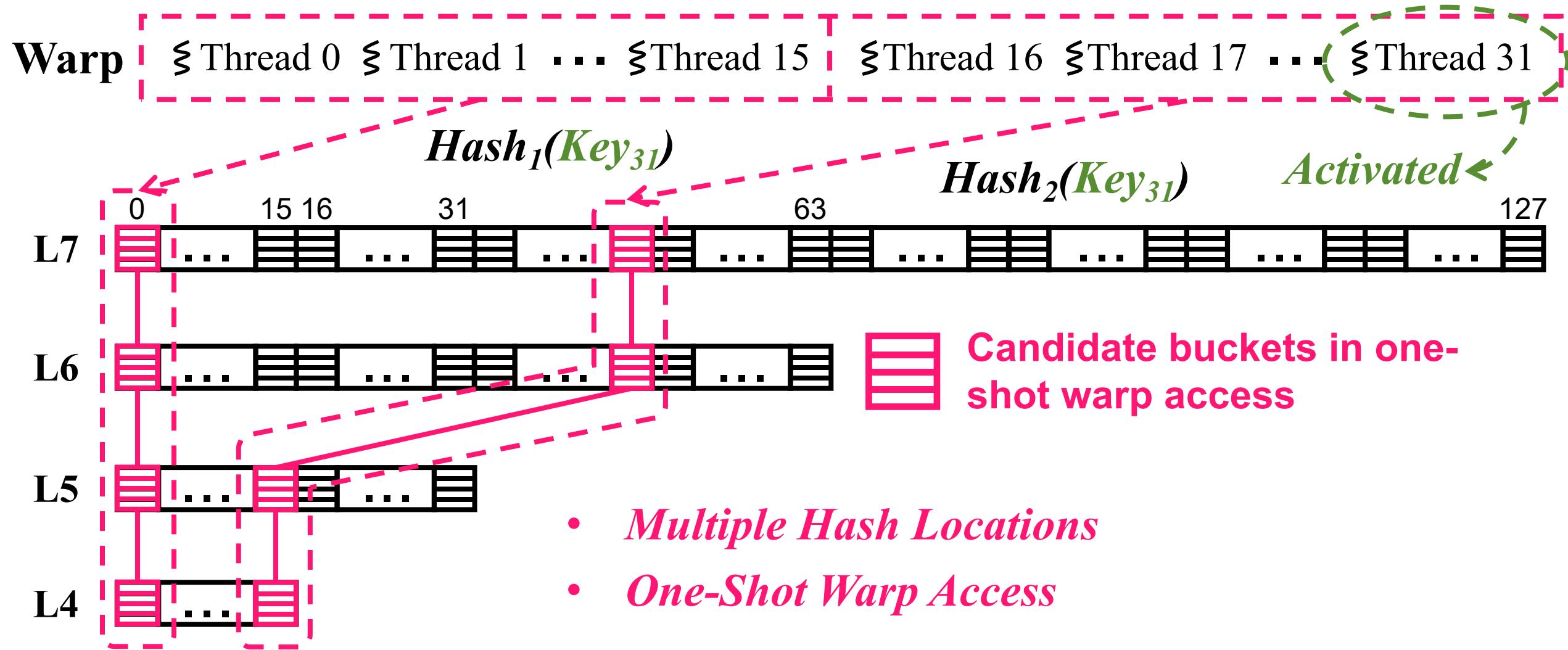
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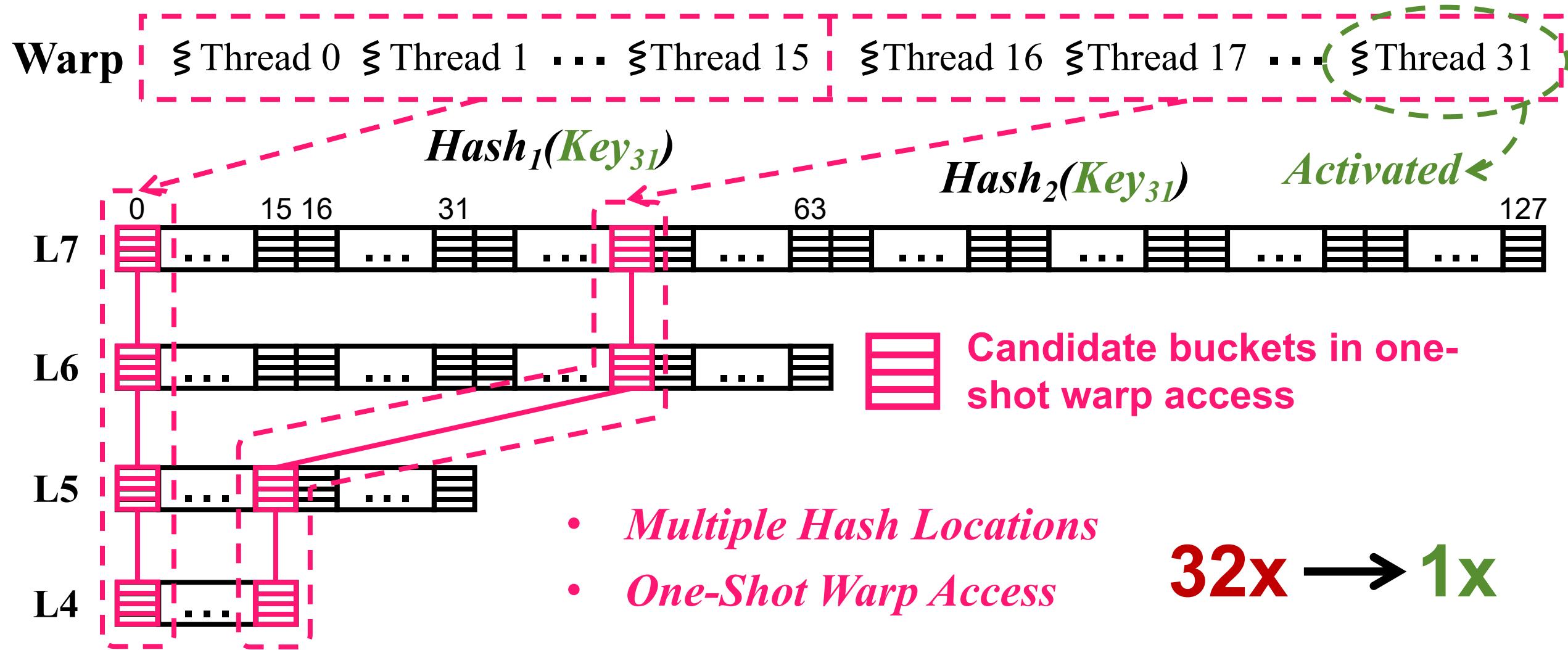
GPU-Conscious and PM-Friendly Hash Table



GPU-Conscious and PM-Friendly Hash Table

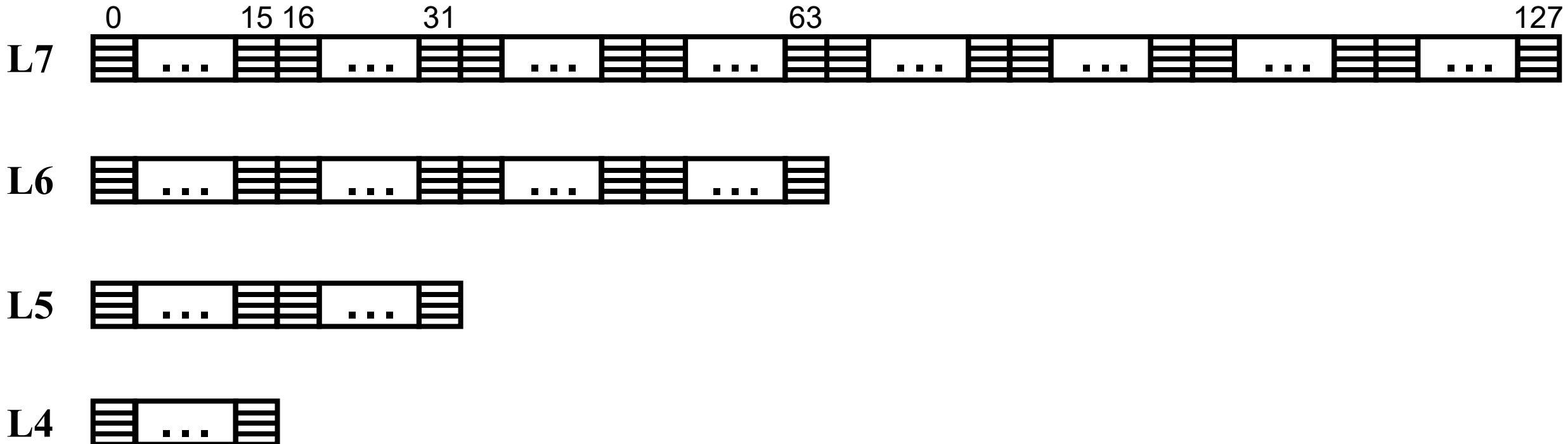


GPU-Conscious and PM-Friendly Hash Table

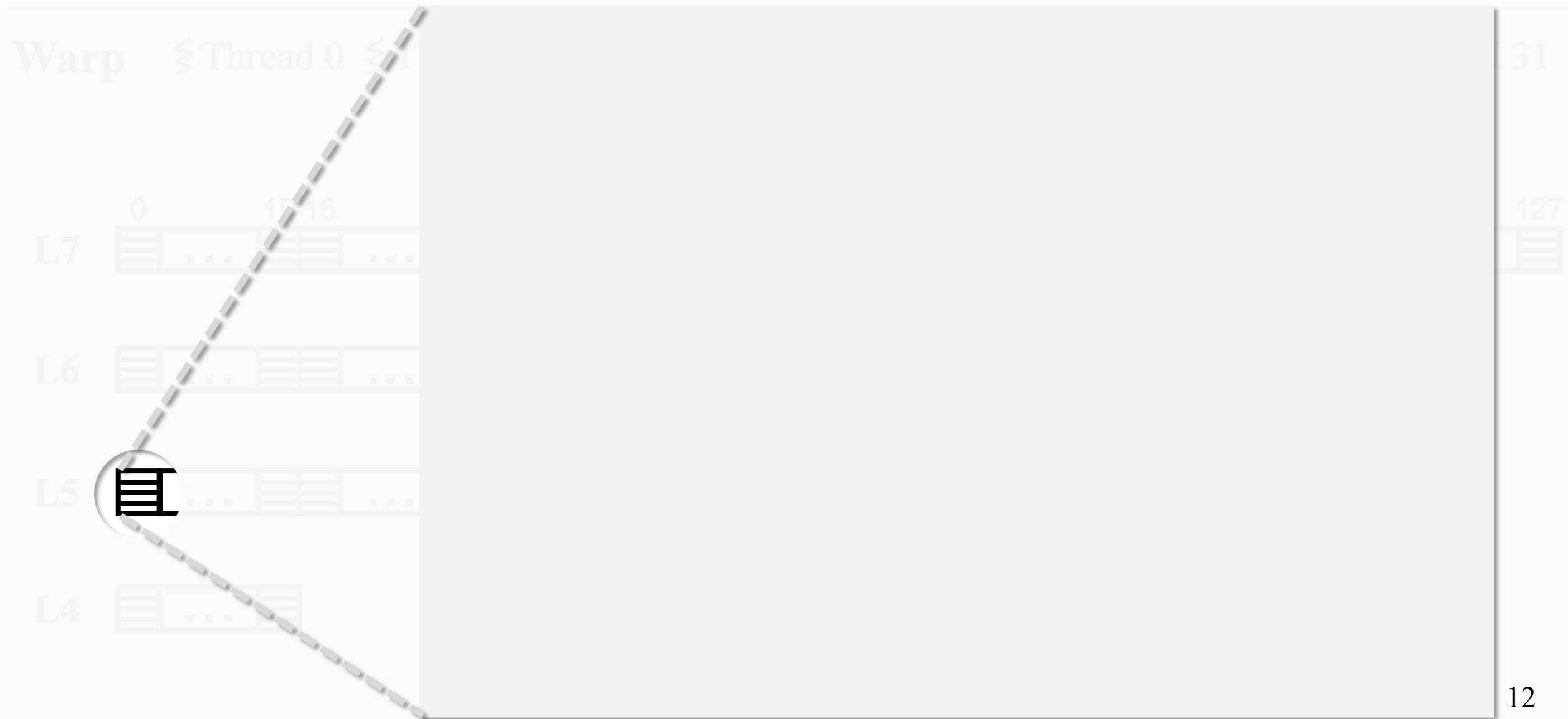


GPU-Conscious and PM-Friendly Hash Table

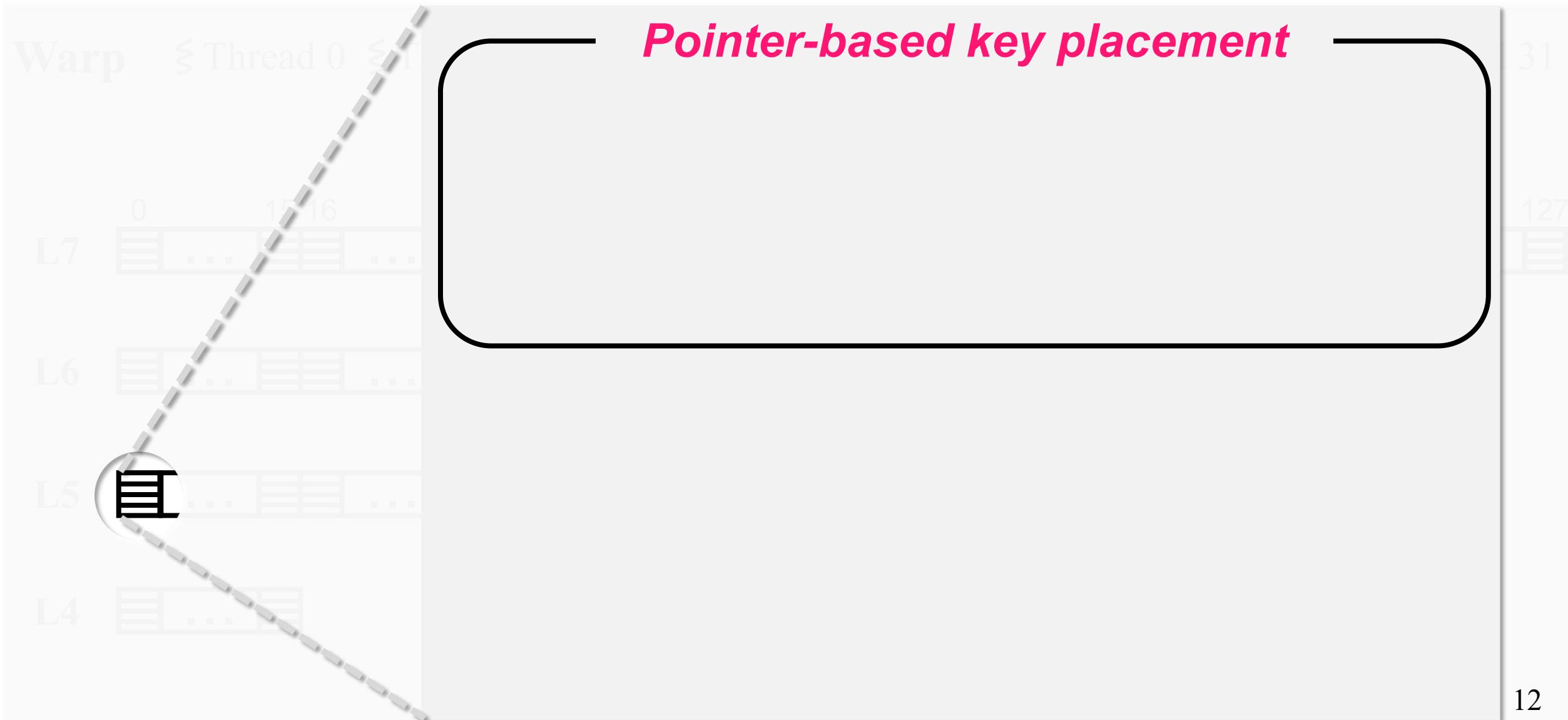
Warp § Thread 0 § Thread 1 ... § Thread 15 § Thread 16 § Thread 17 ... § Thread 31



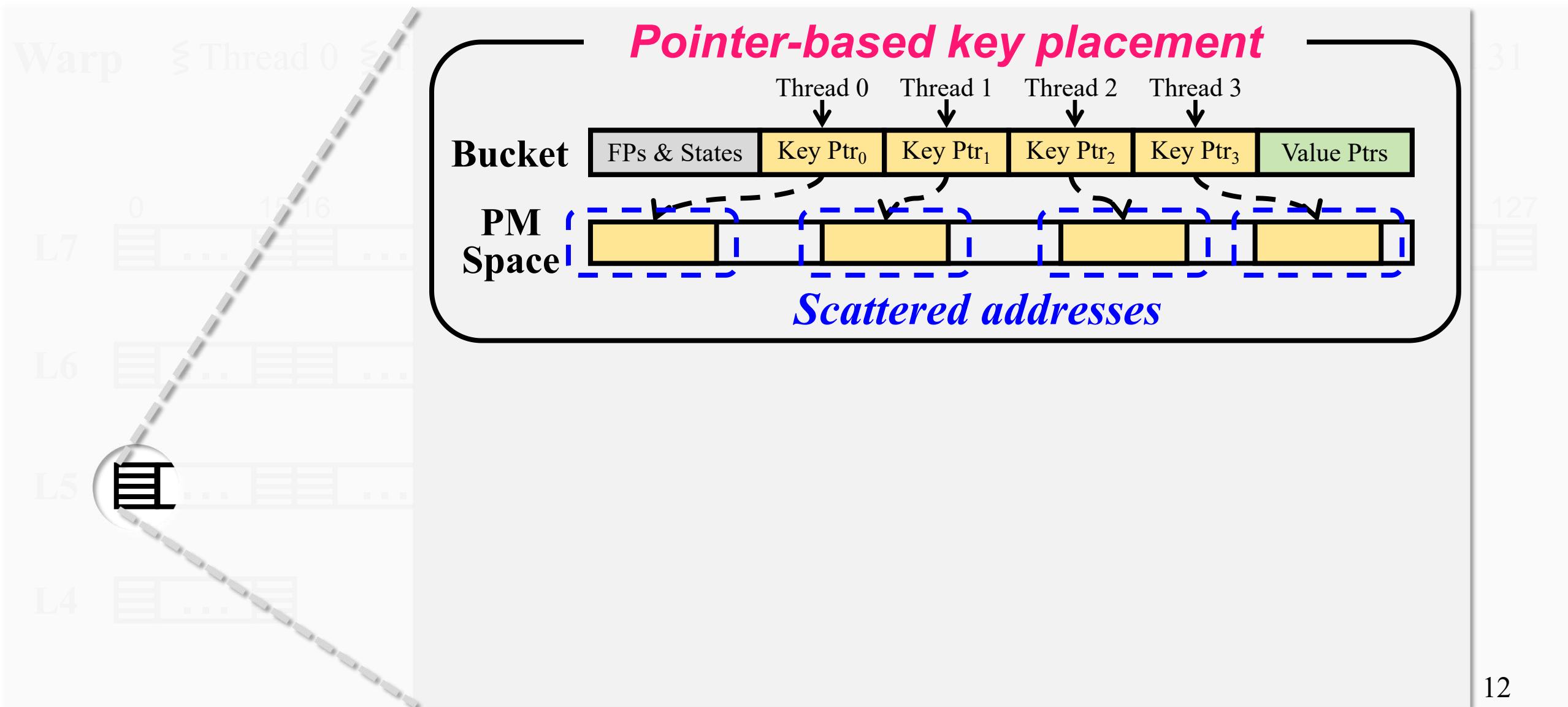
GPU-Conscious and PM-Friendly Hash Table



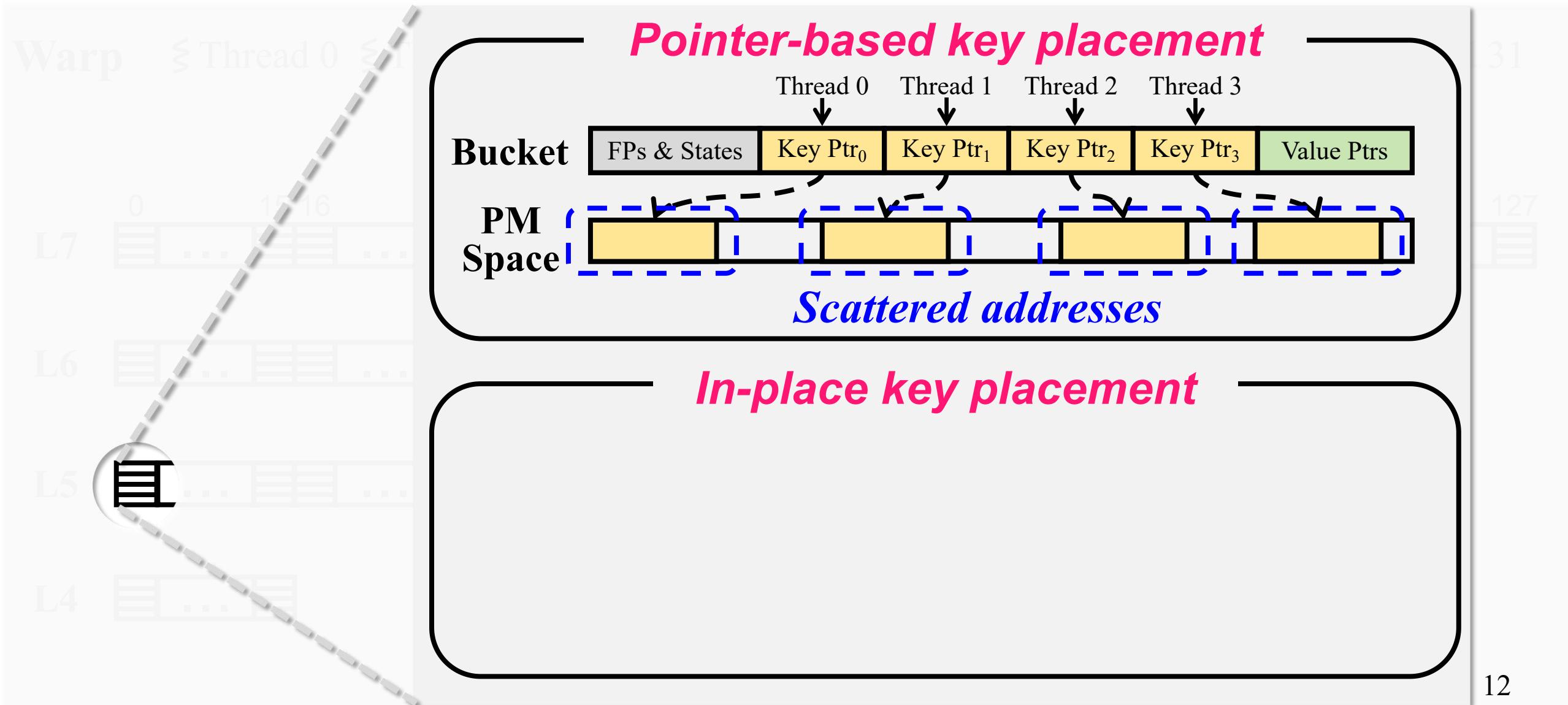
GPU-Conscious and PM-Friendly Hash Table



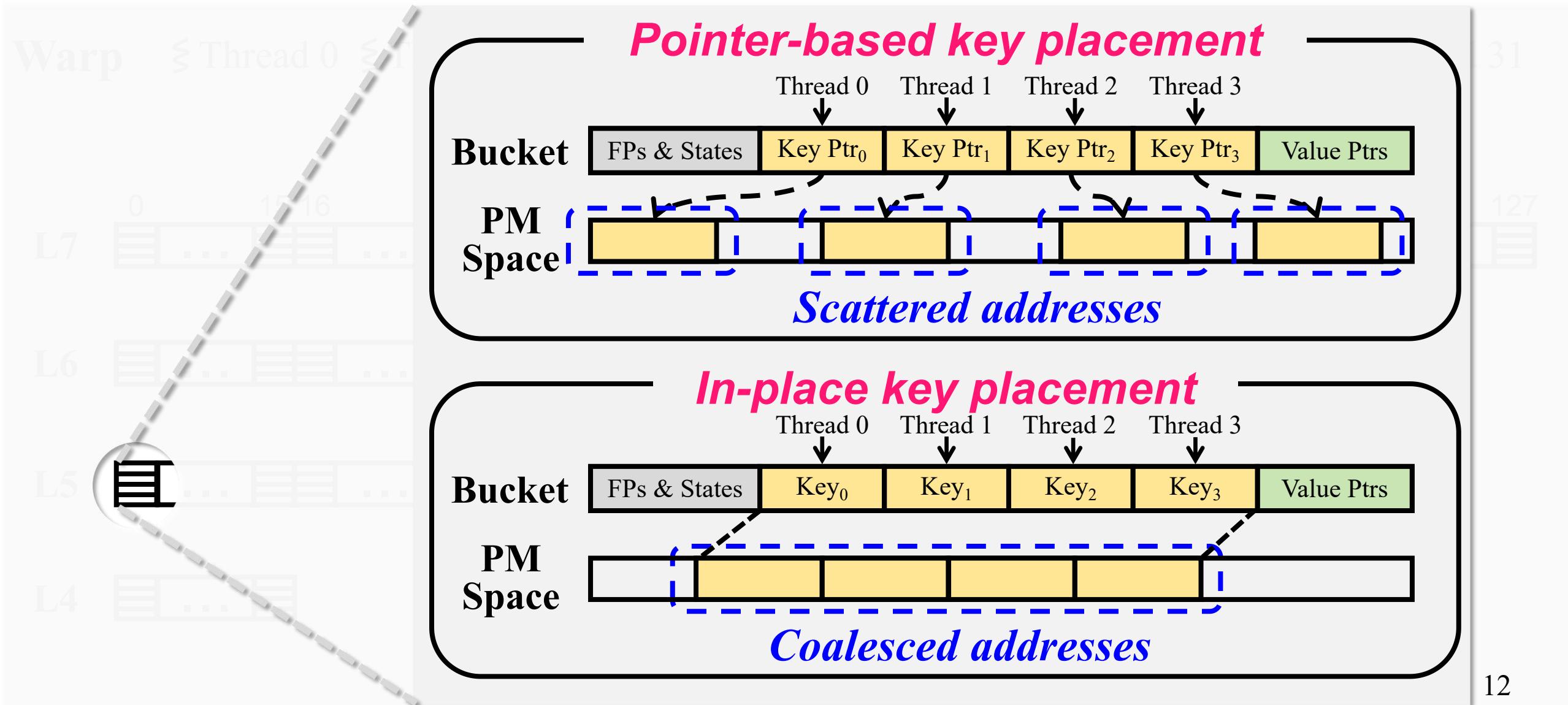
GPU-Conscious and PM-Friendly Hash Table



GPU-Conscious and PM-Friendly Hash Table



GPU-Conscious and PM-Friendly Hash Table



GPU-Conscious and PM-Friendly Hash Table



GPU-Conscious and PM-Friendly Hash Table



GPU-friendly: *minimize warp divergence and uncoalesced memory accesses*



Write-optimized: *each insertion only involves a constant number of buckets without any data movement*



Memory-efficient: *achieve a high load factor that is up to 92%*

Lock-Free and Log-Free Insertion

Lock-Free and Log-Free Insertion

Warp



Lock-Free and Log-Free Insertion

Warp



Buckets



Lock-Free and Log-Free Insertion

Warp

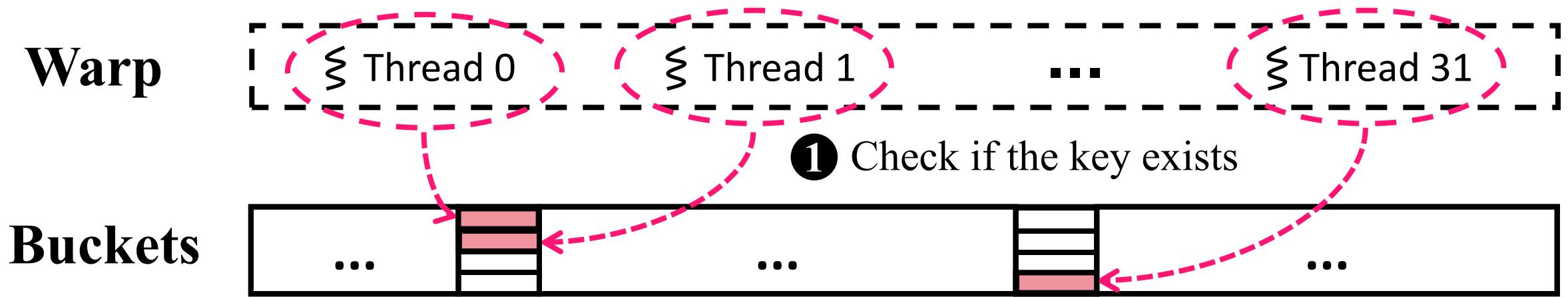


① Check if the key exists

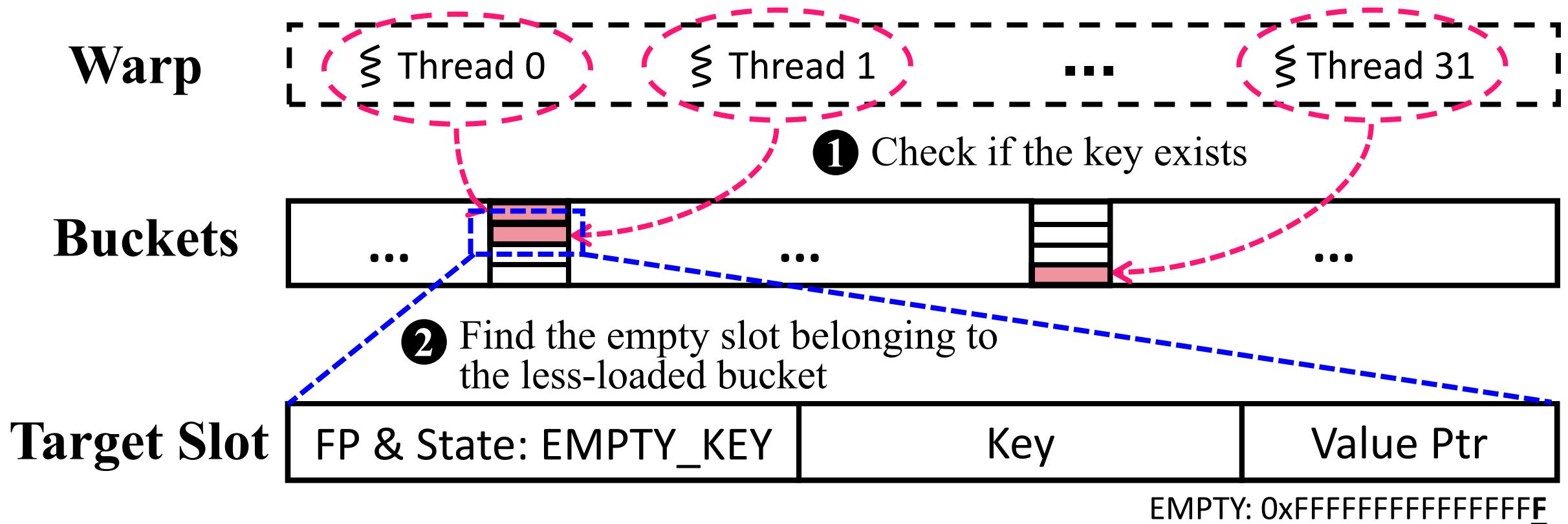
Buckets



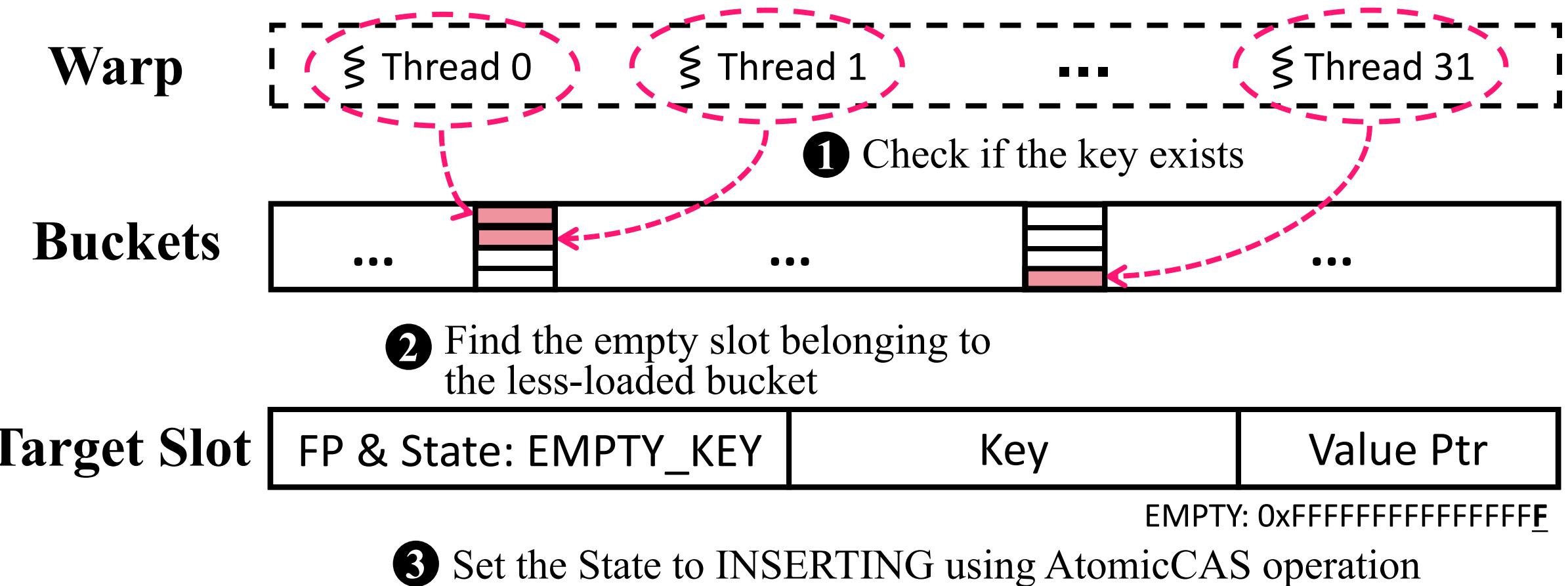
Lock-Free and Log-Free Insertion



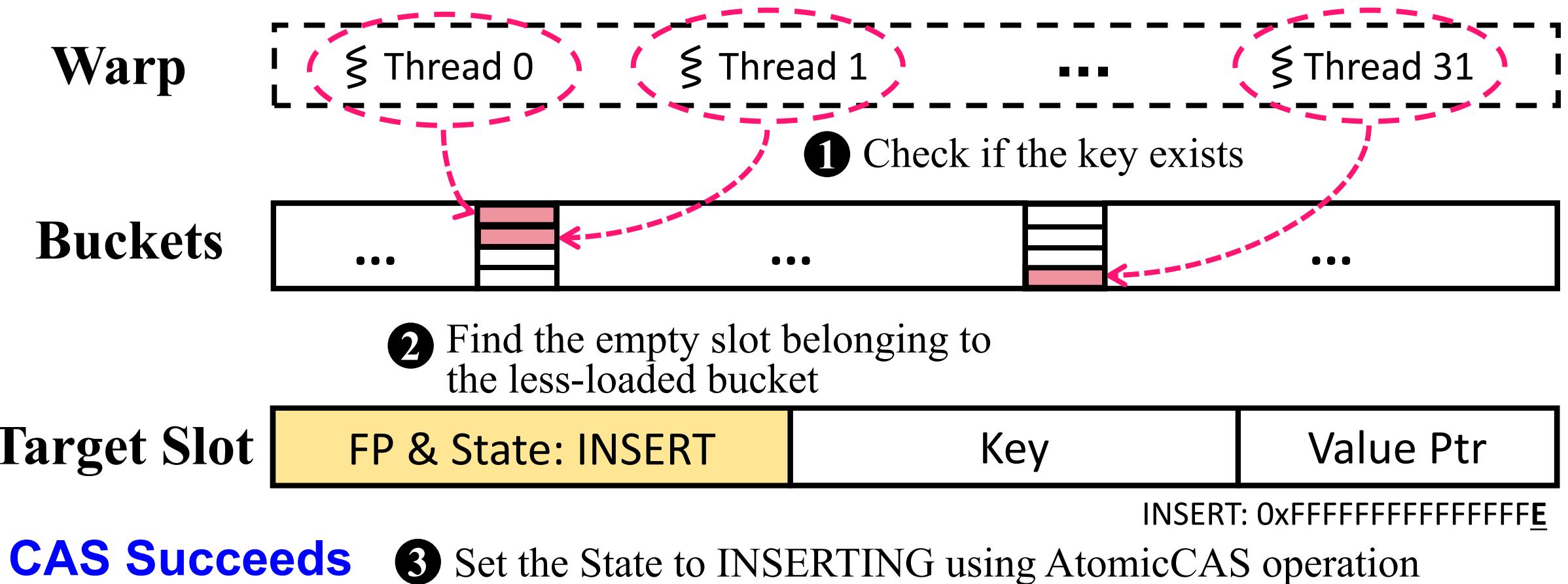
Lock-Free and Log-Free Insertion



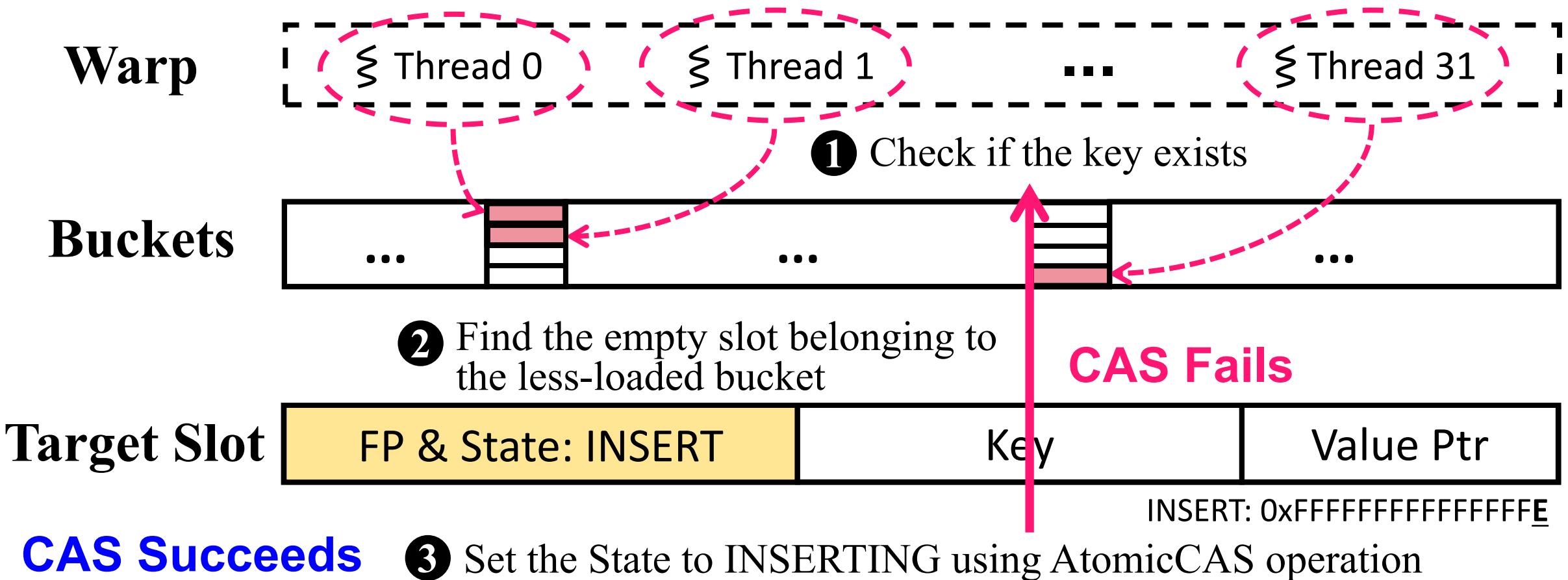
Lock-Free and Log-Free Insertion



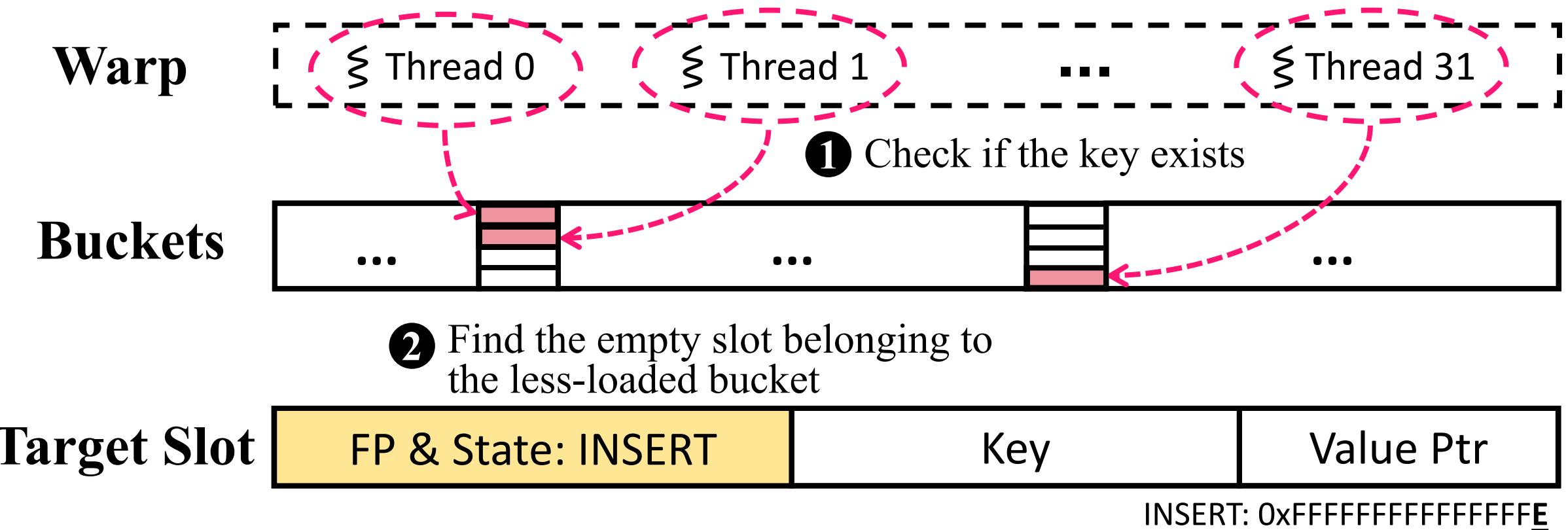
Lock-Free and Log-Free Insertion



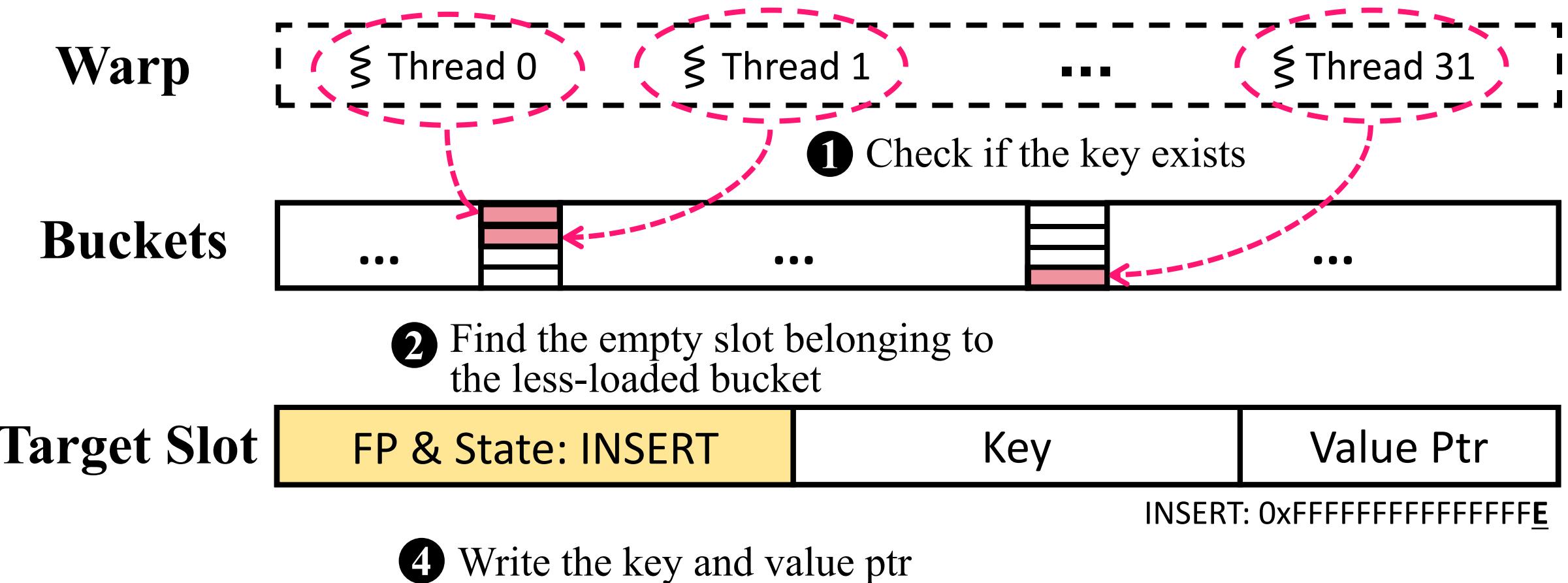
Lock-Free and Log-Free Insertion



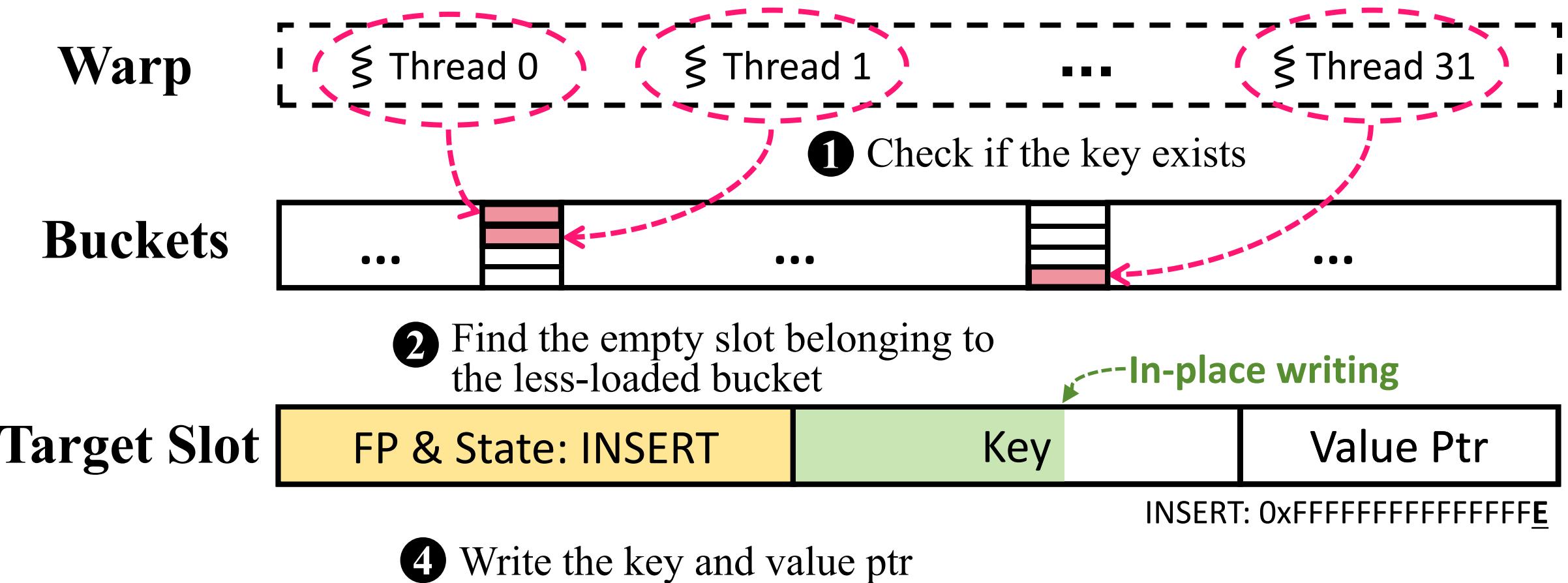
Lock-Free and Log-Free Insertion



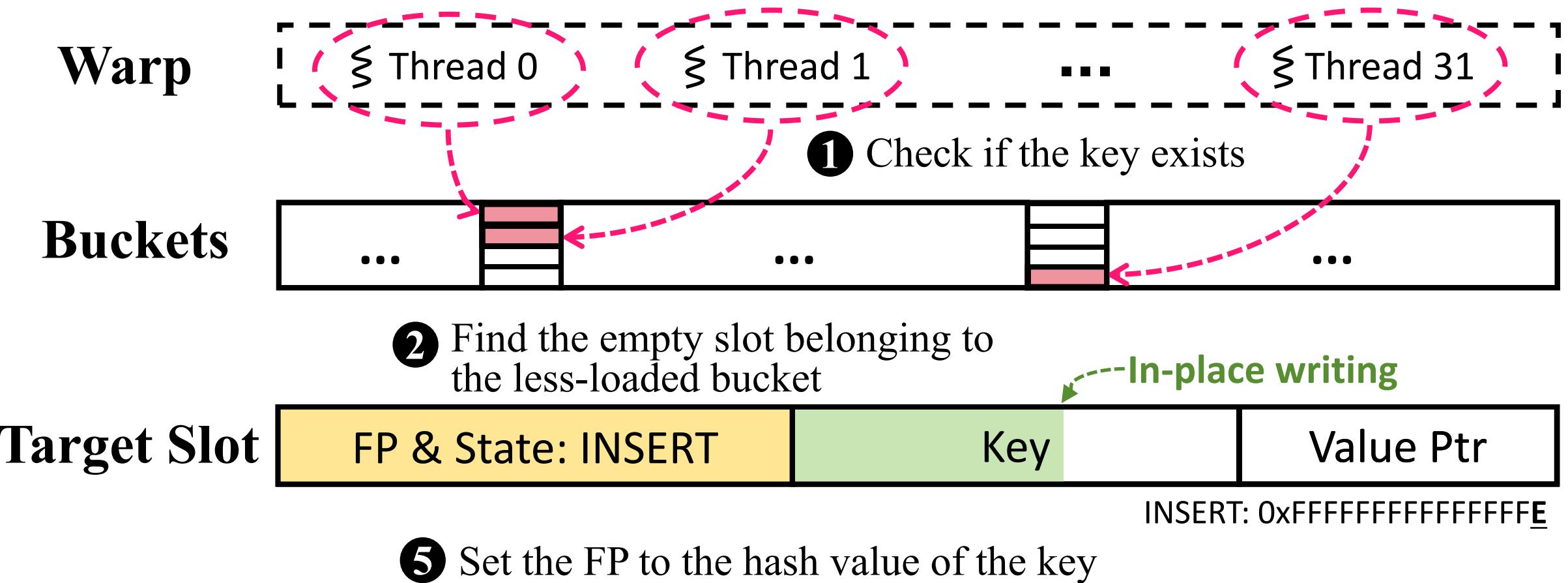
Lock-Free and Log-Free Insertion



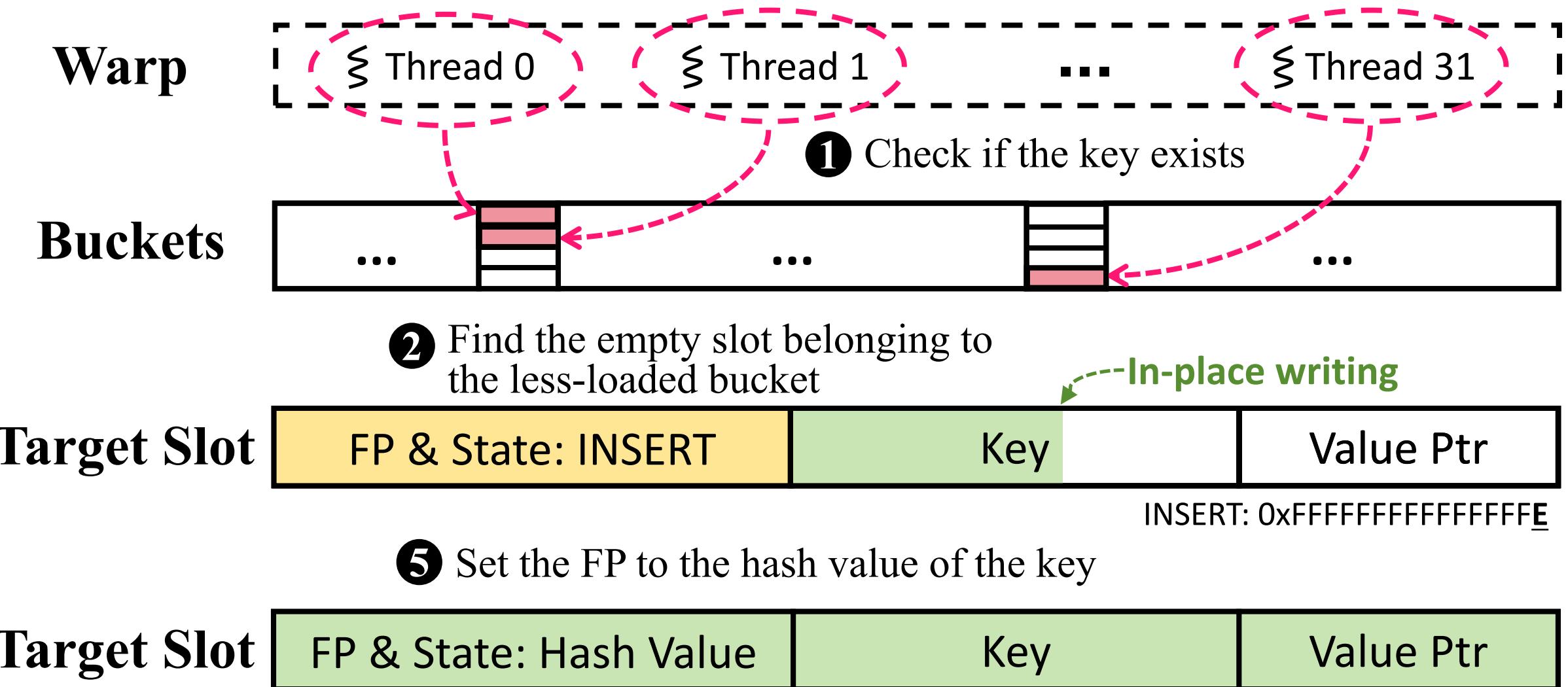
Lock-Free and Log-Free Insertion



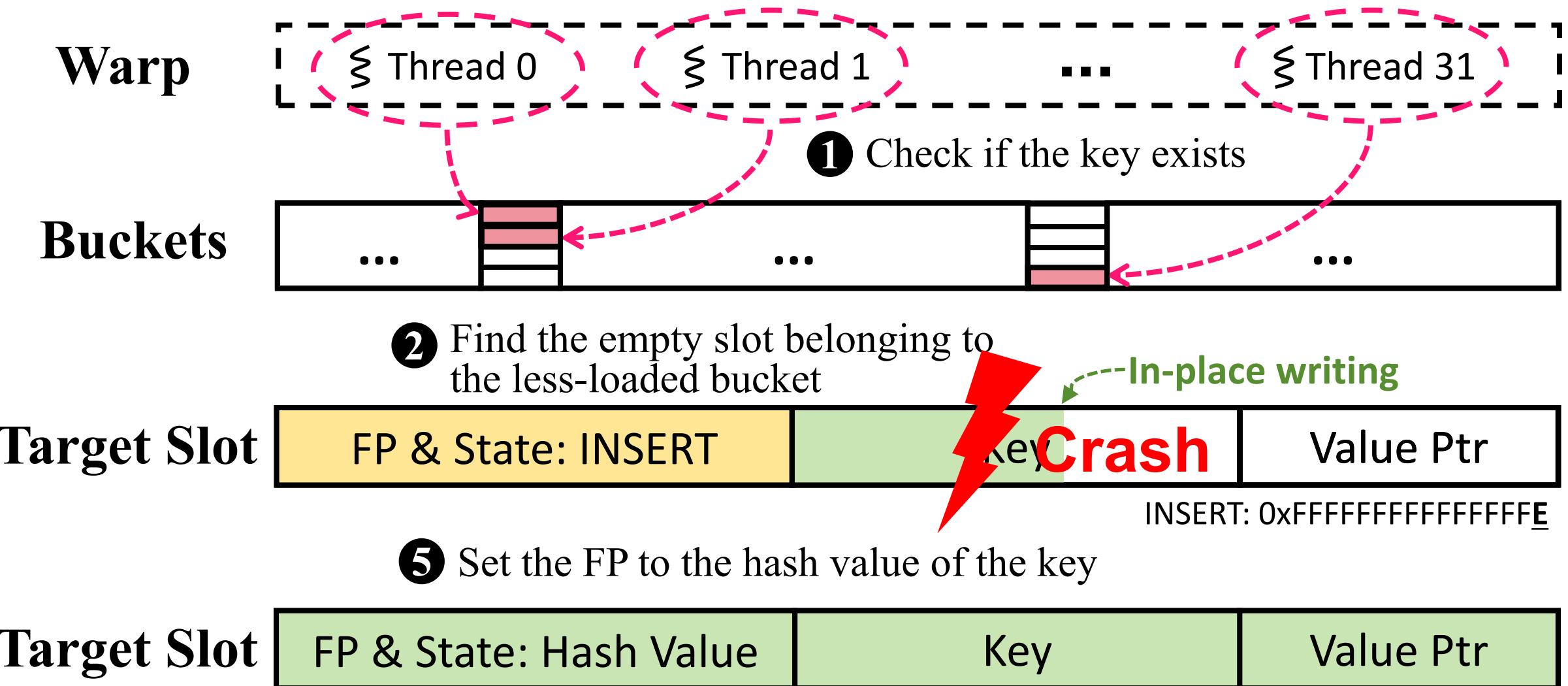
Lock-Free and Log-Free Insertion



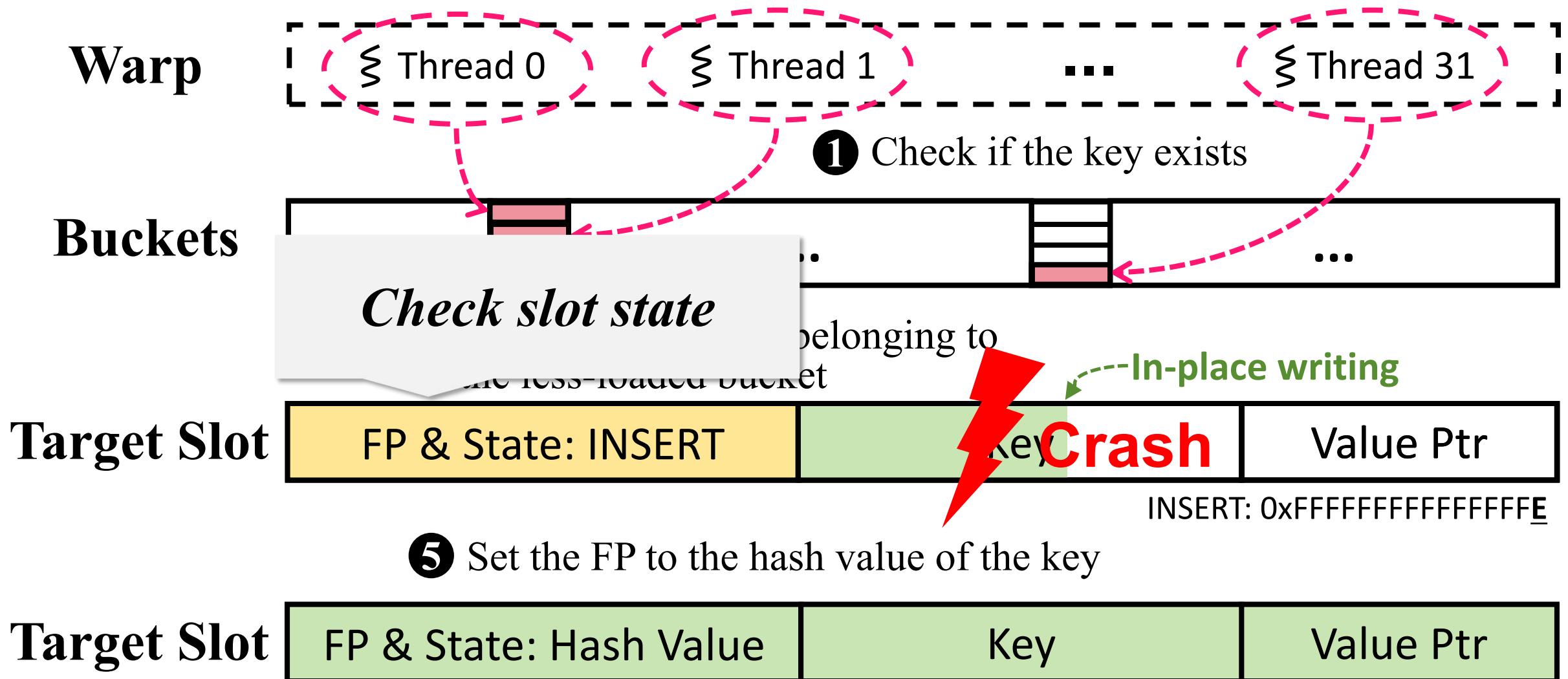
Lock-Free and Log-Free Insertion



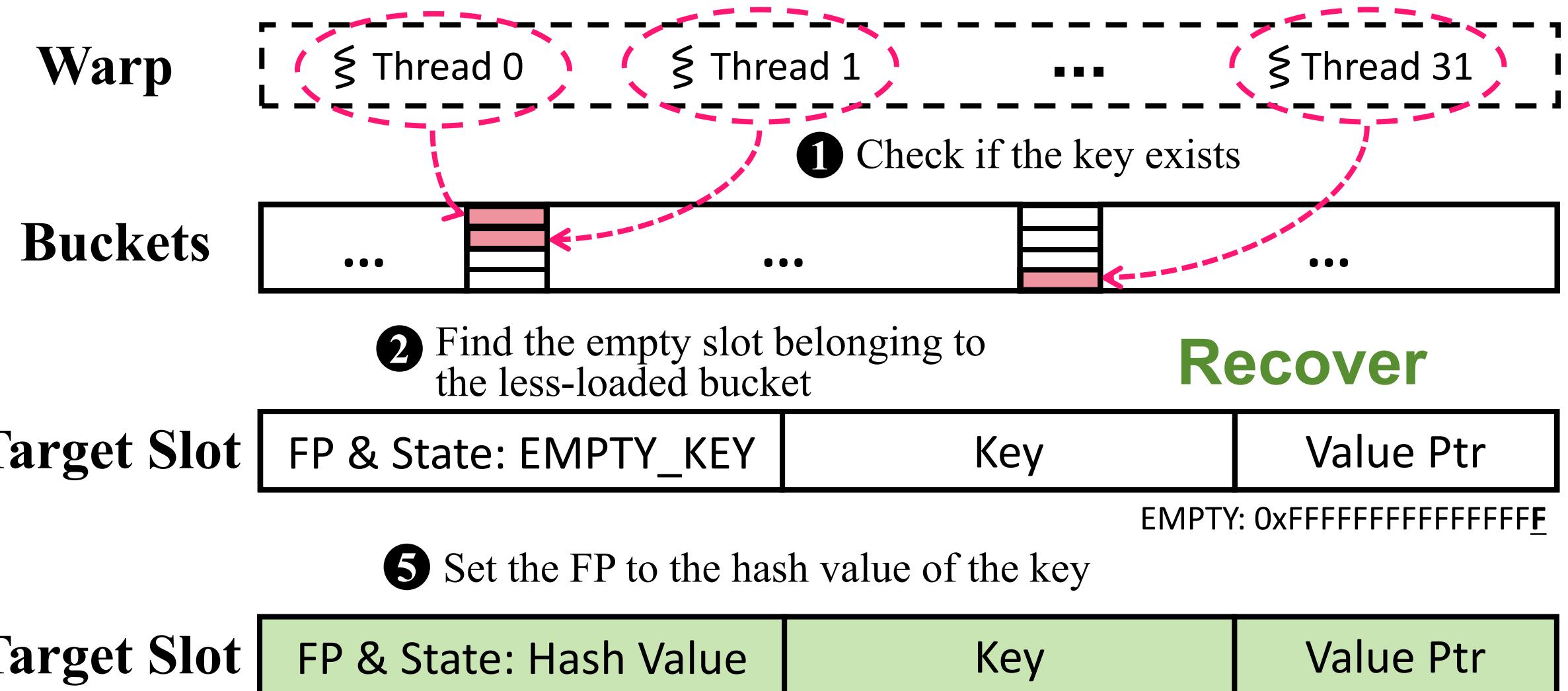
Lock-Free and Log-Free Insertion



Lock-Free and Log-Free Insertion

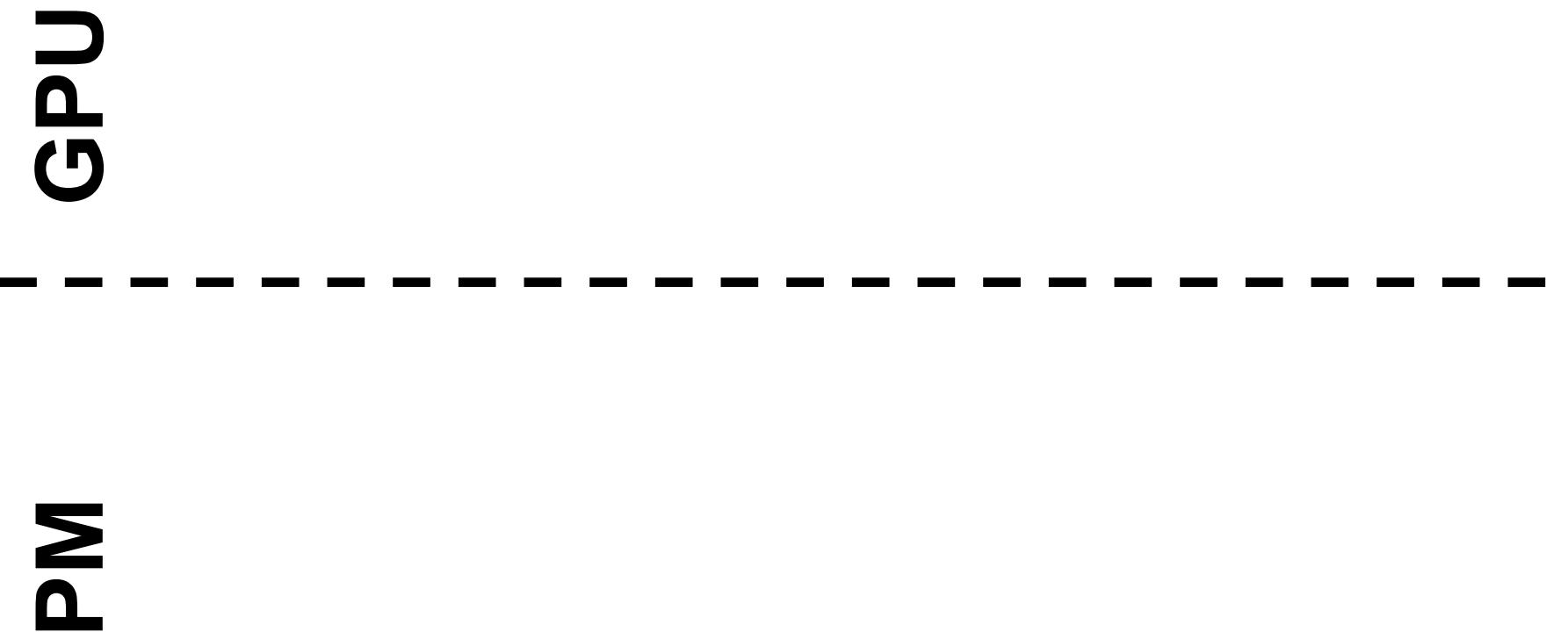


Lock-Free and Log-Free Insertion



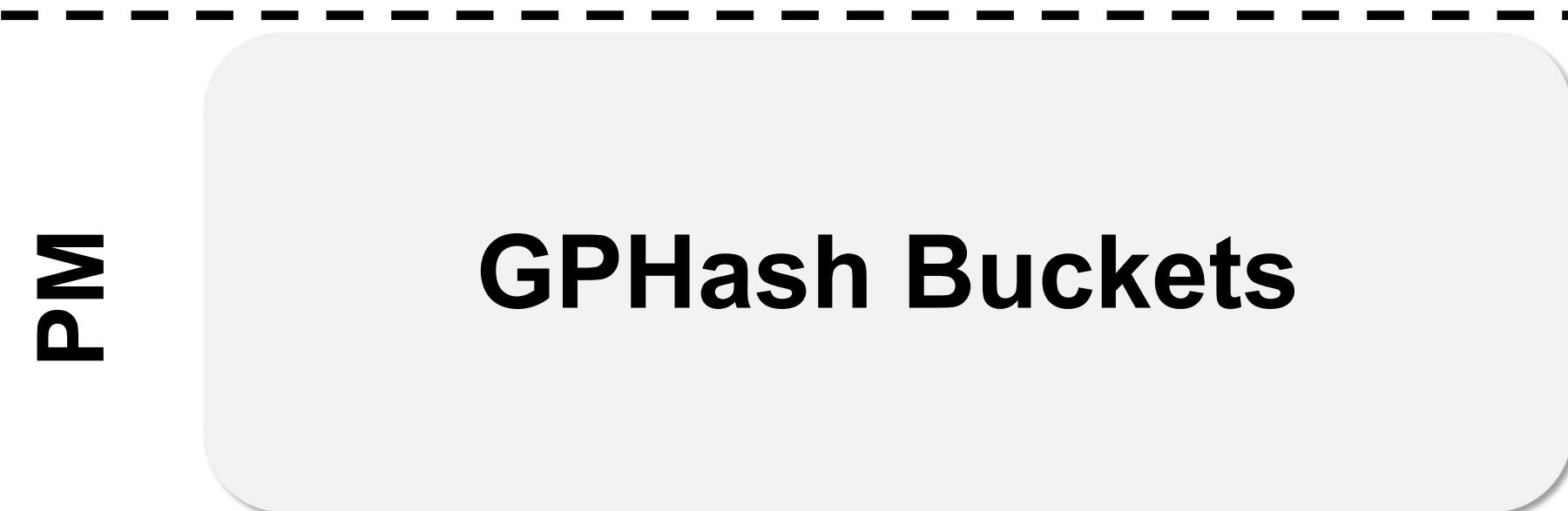
Frozen-Based Bucket Cache

Frozen-Based Bucket Cache

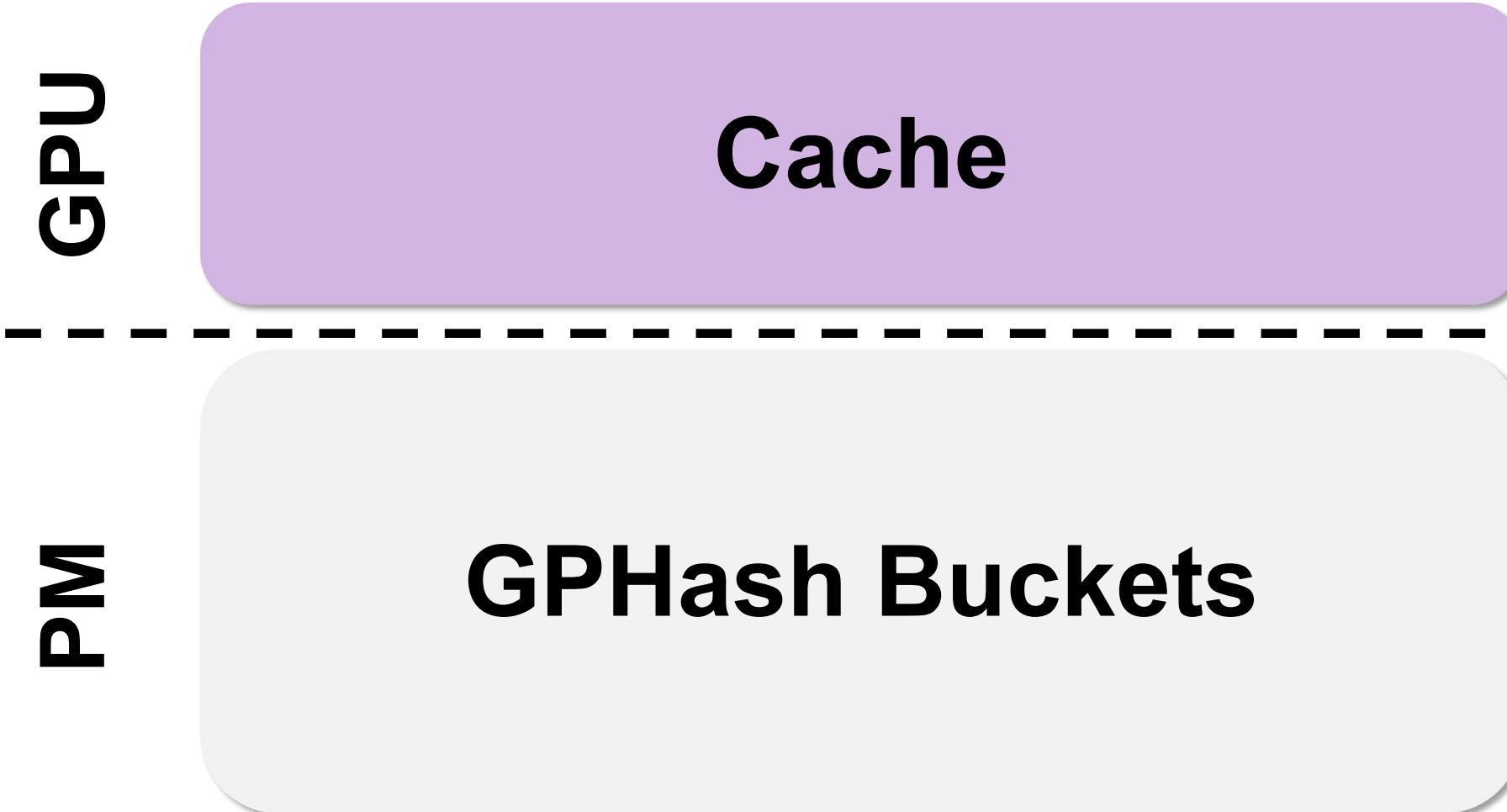


Frozen-Based Bucket Cache

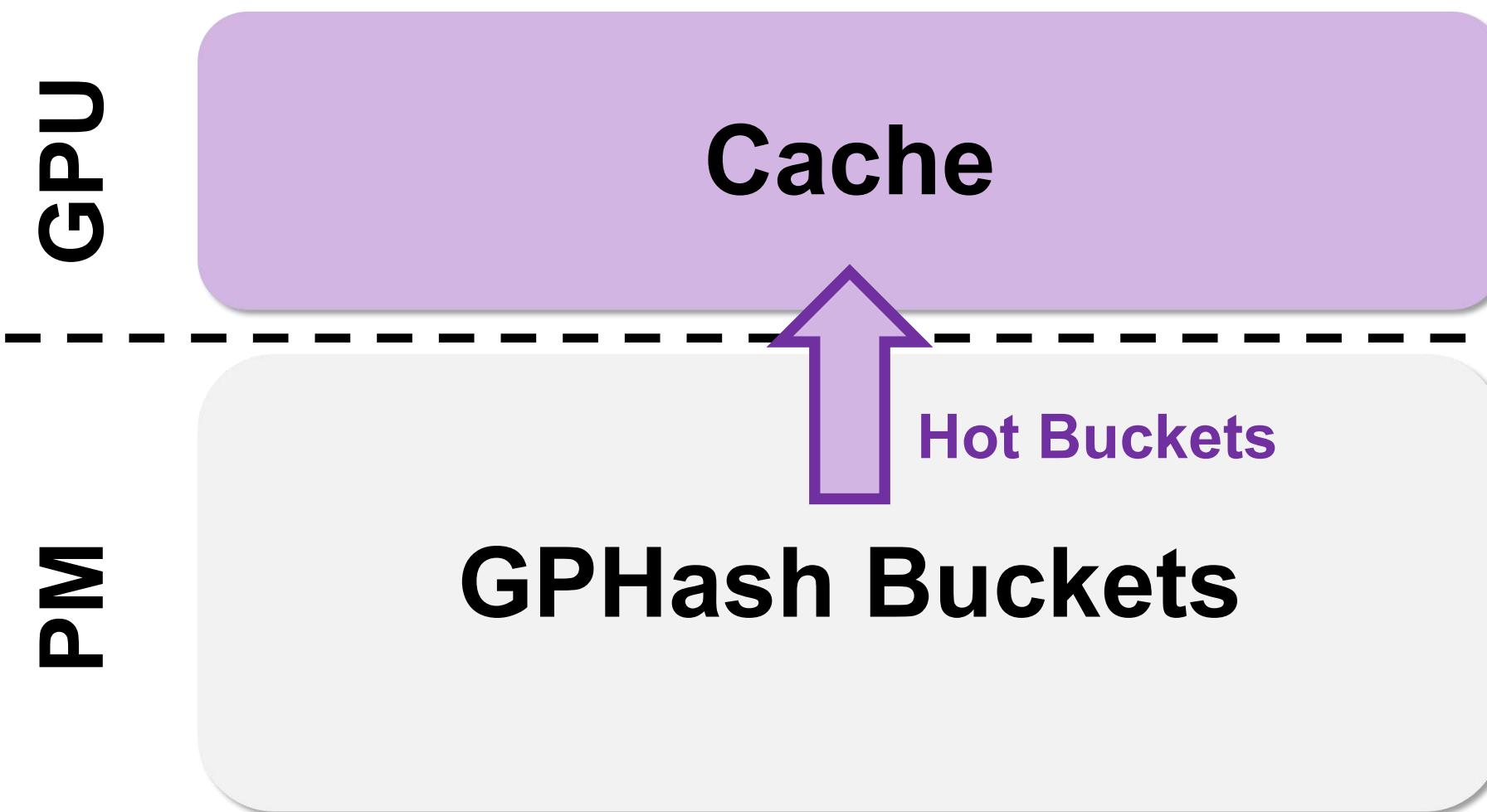
GPU



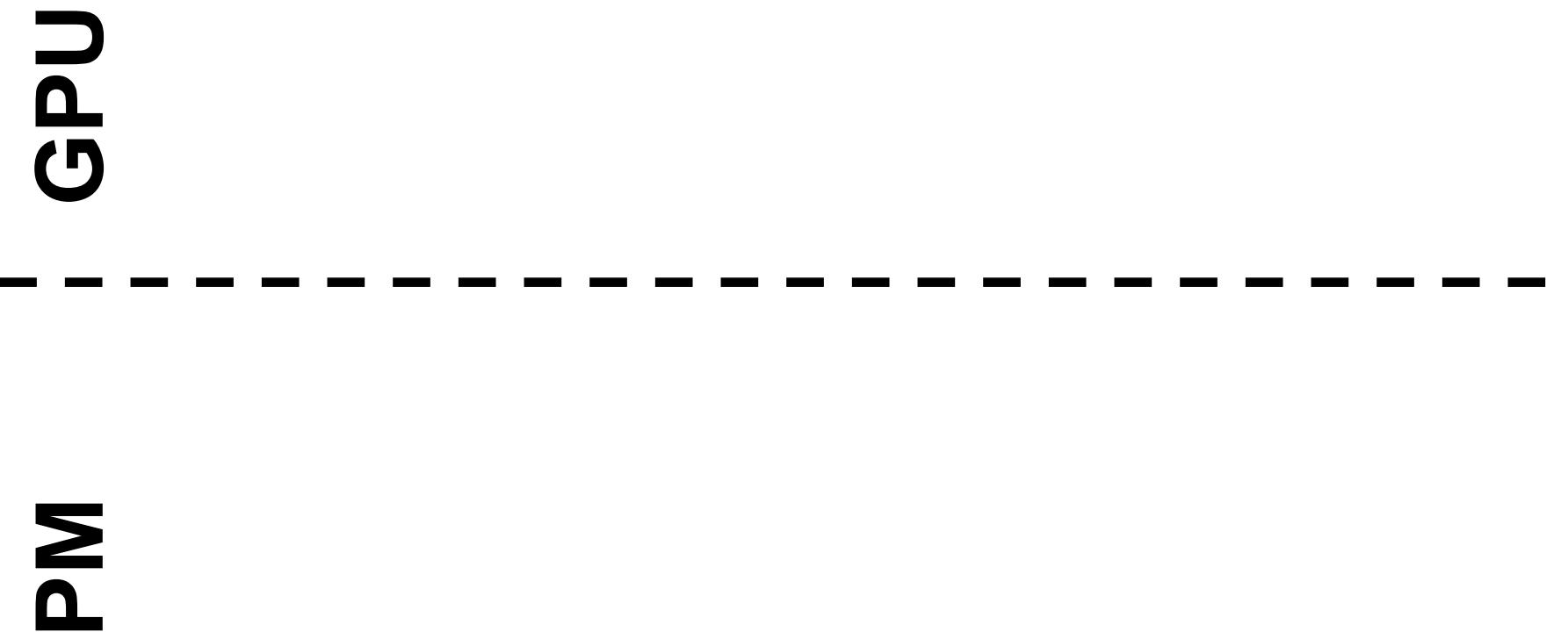
Frozen-Based Bucket Cache



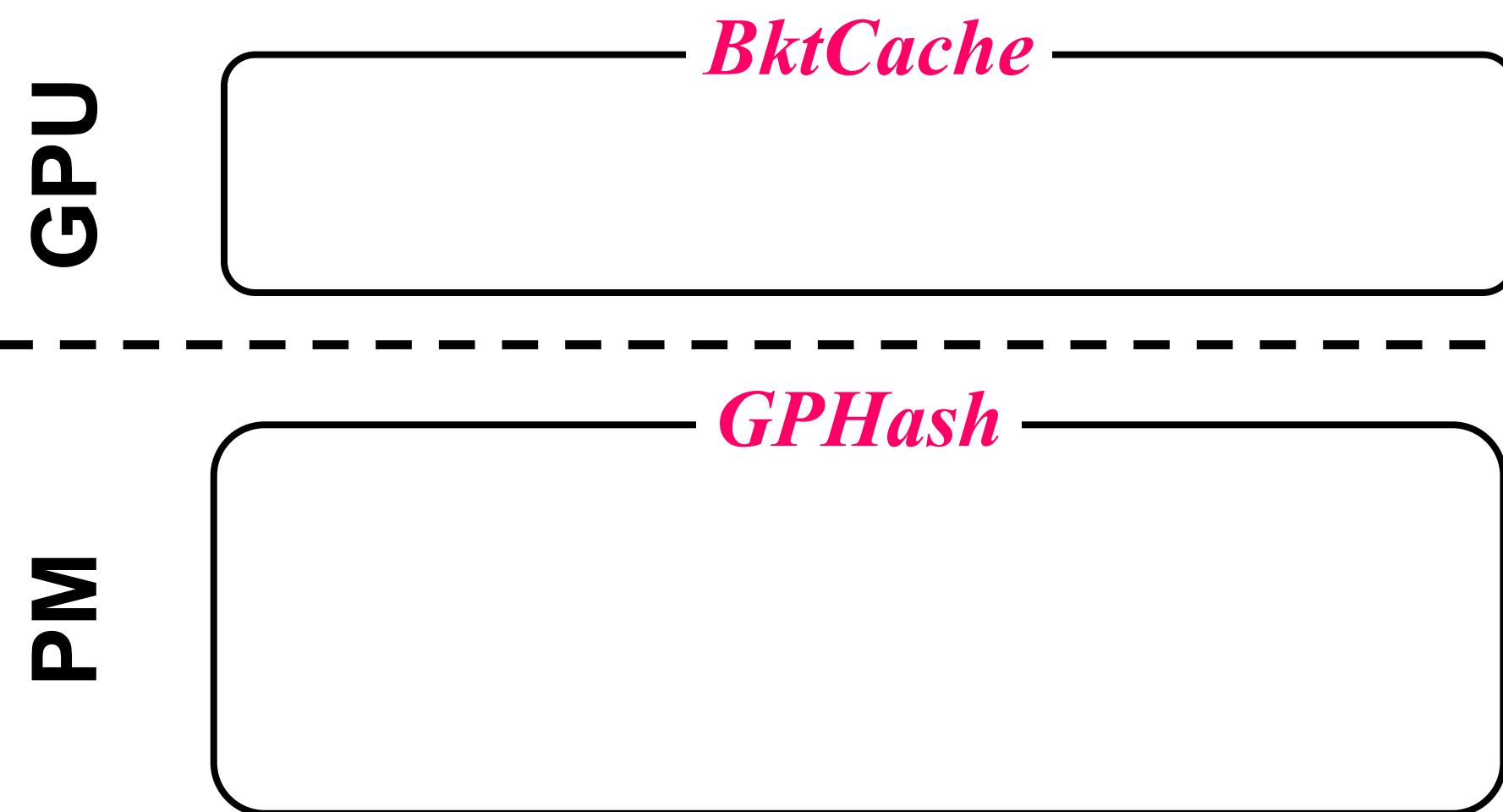
Frozen-Based Bucket Cache



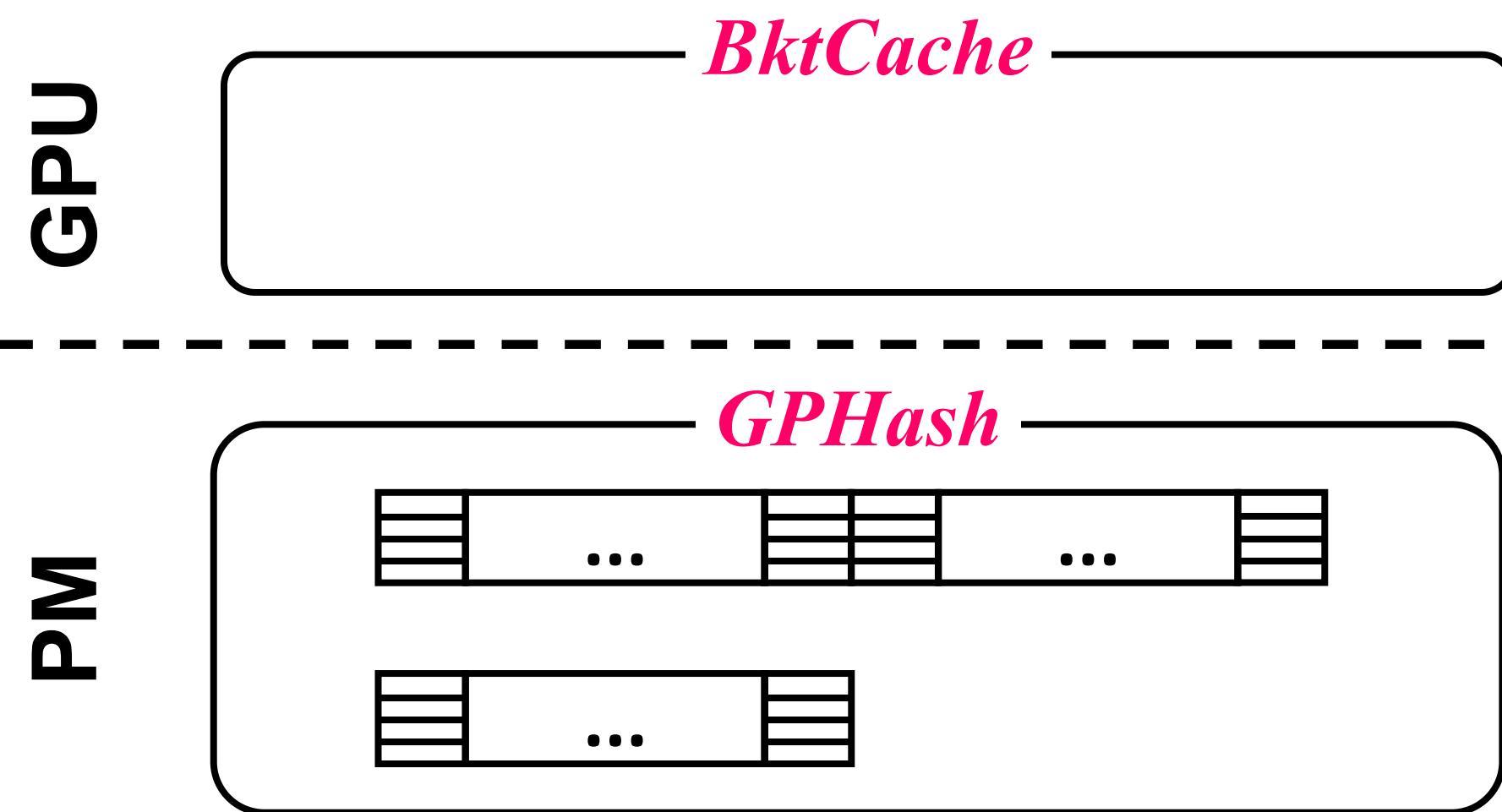
Frozen-Based Bucket Cache



Frozen-Based Bucket Cache



Frozen-Based Bucket Cache

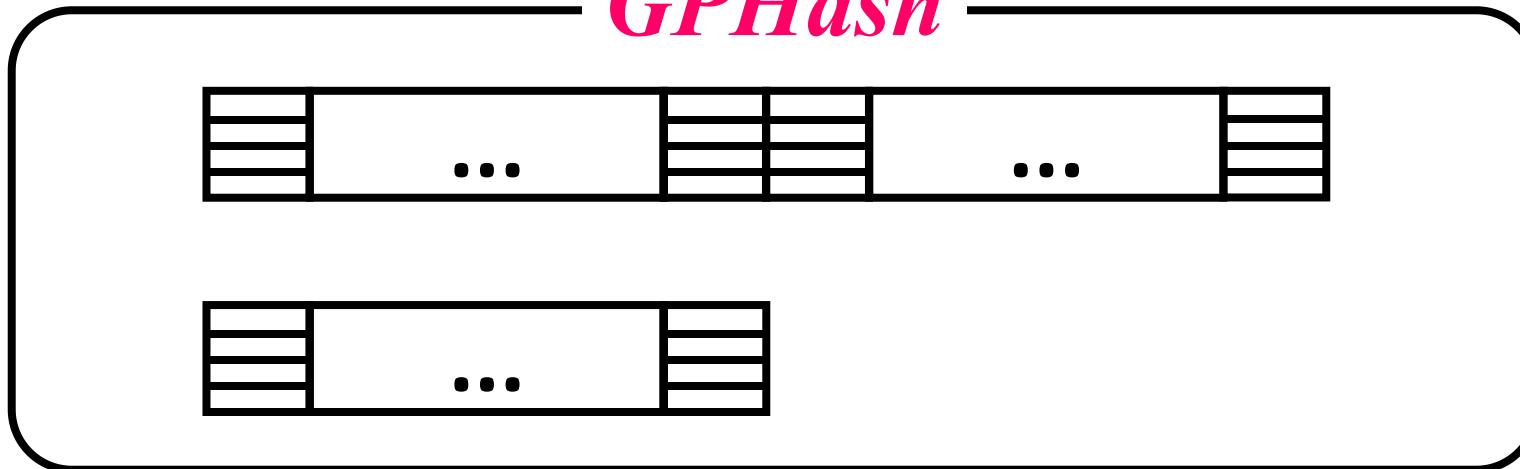


Frozen-Based Bucket Cache

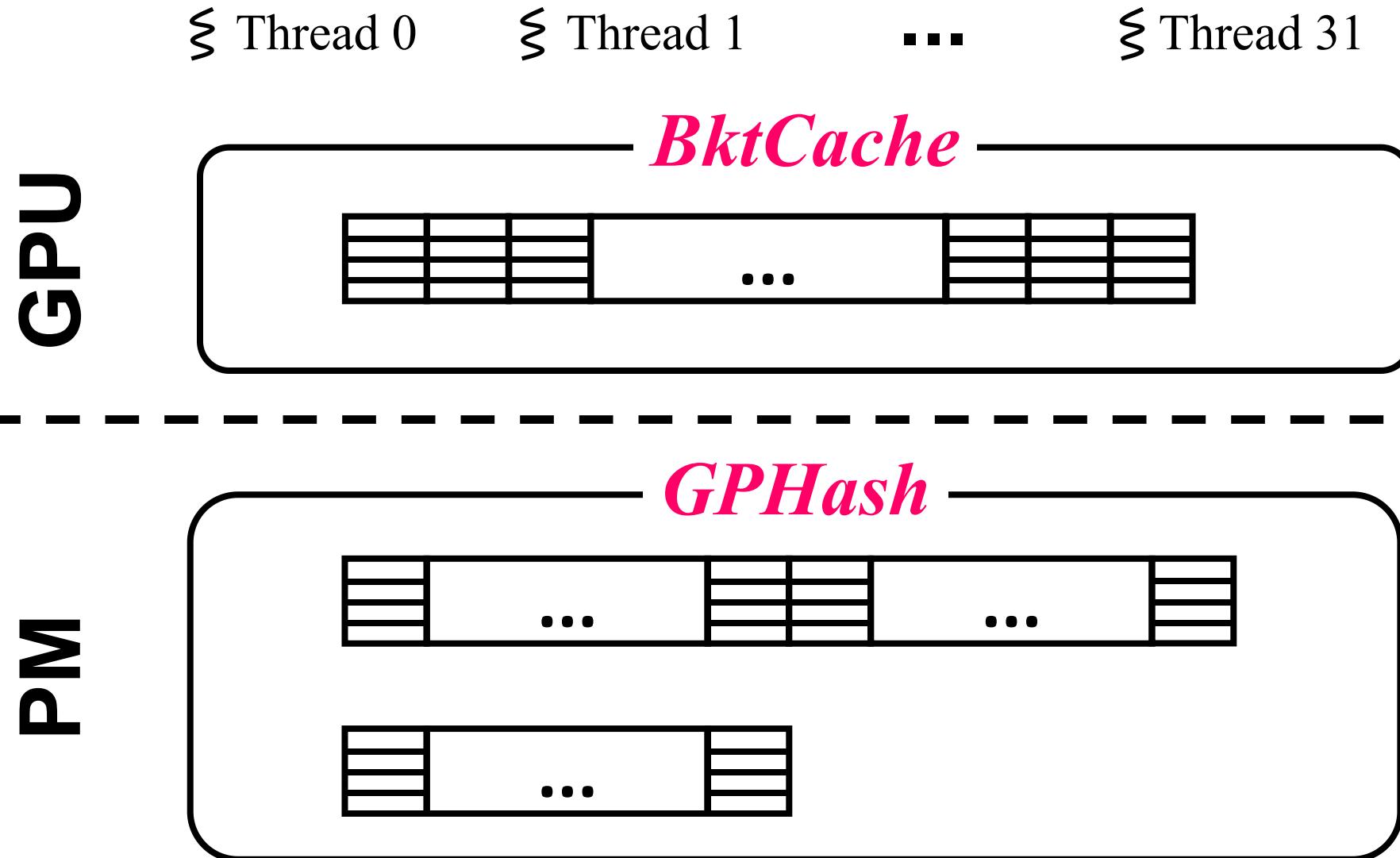
GPU



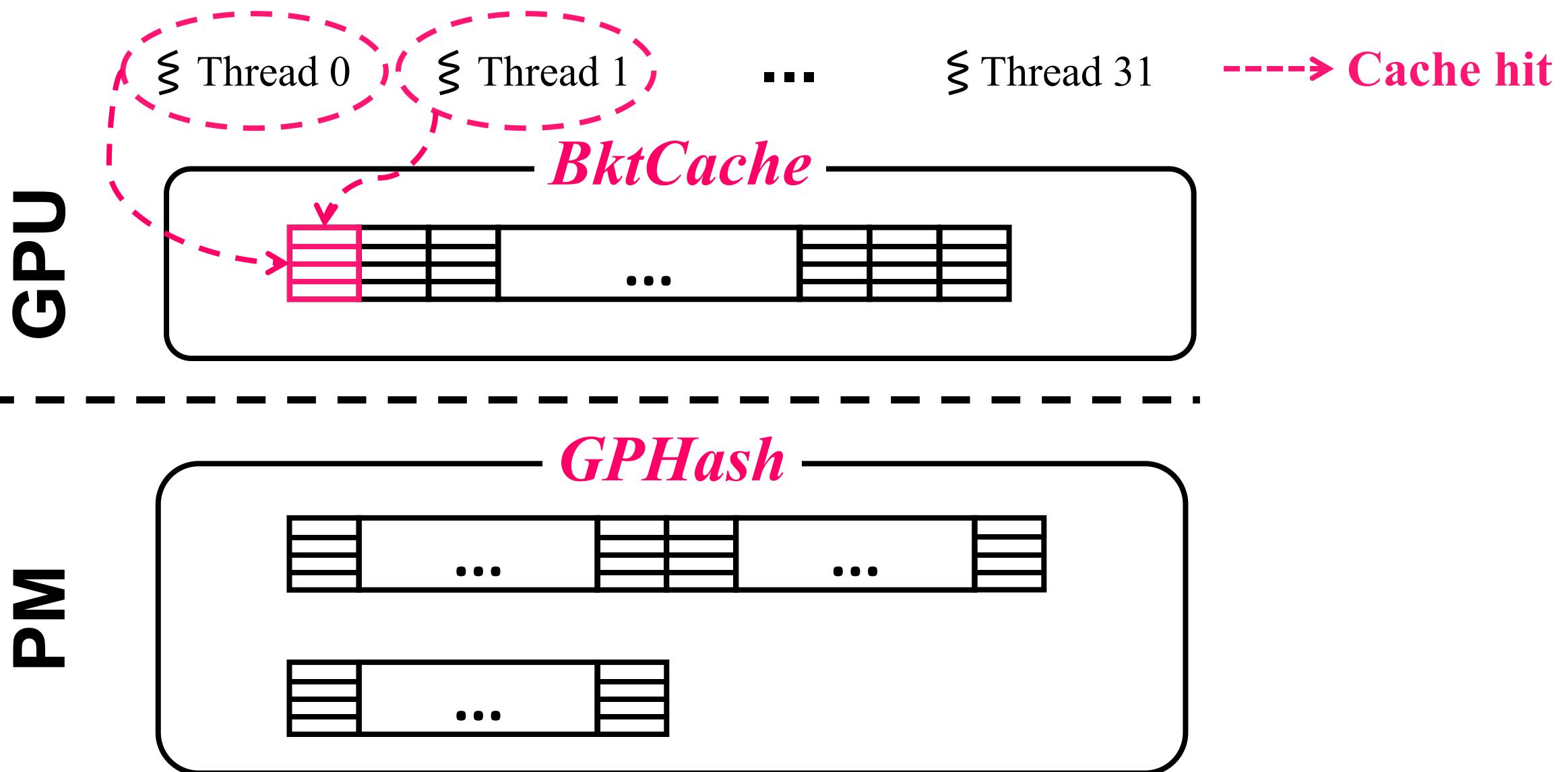
PM



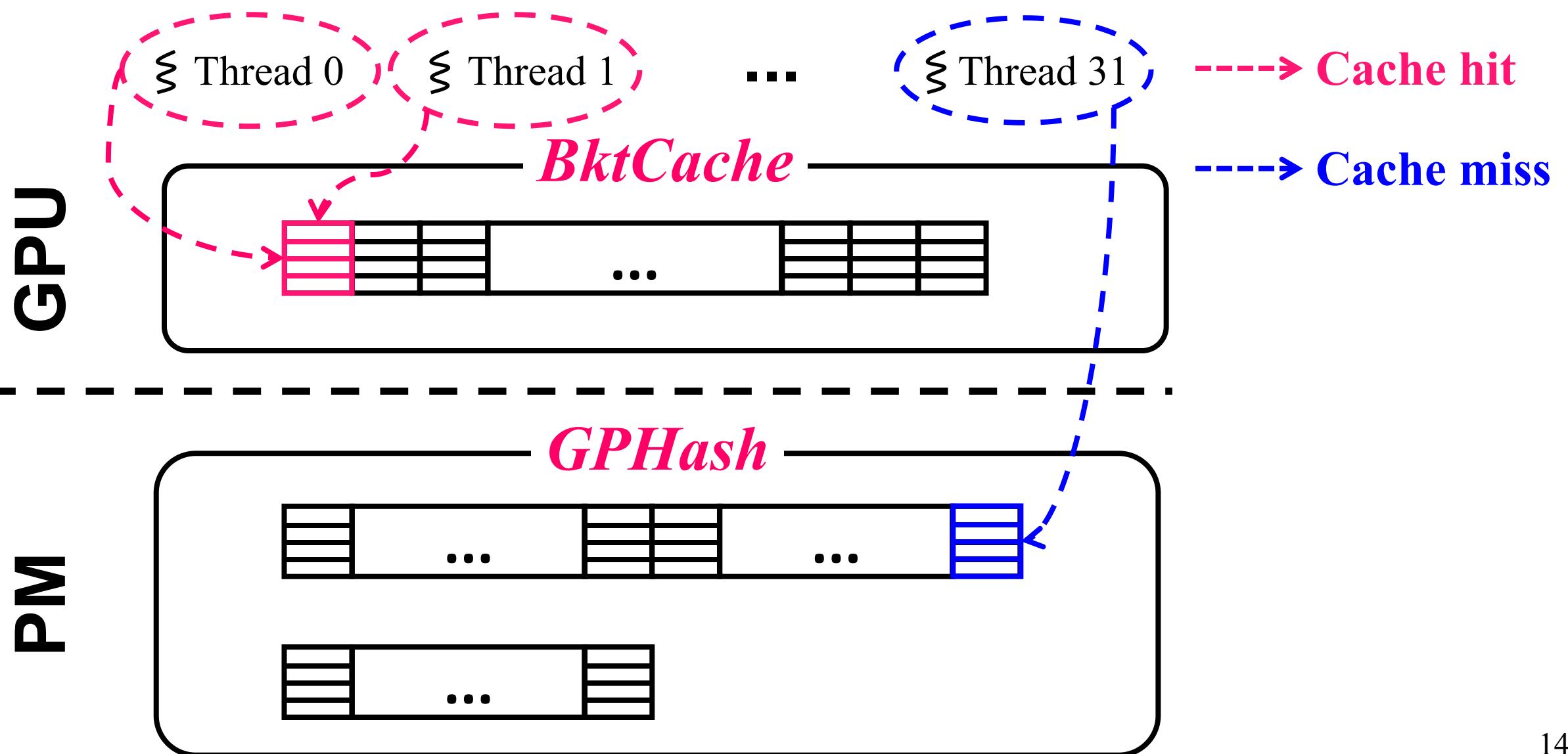
Frozen-Based Bucket Cache



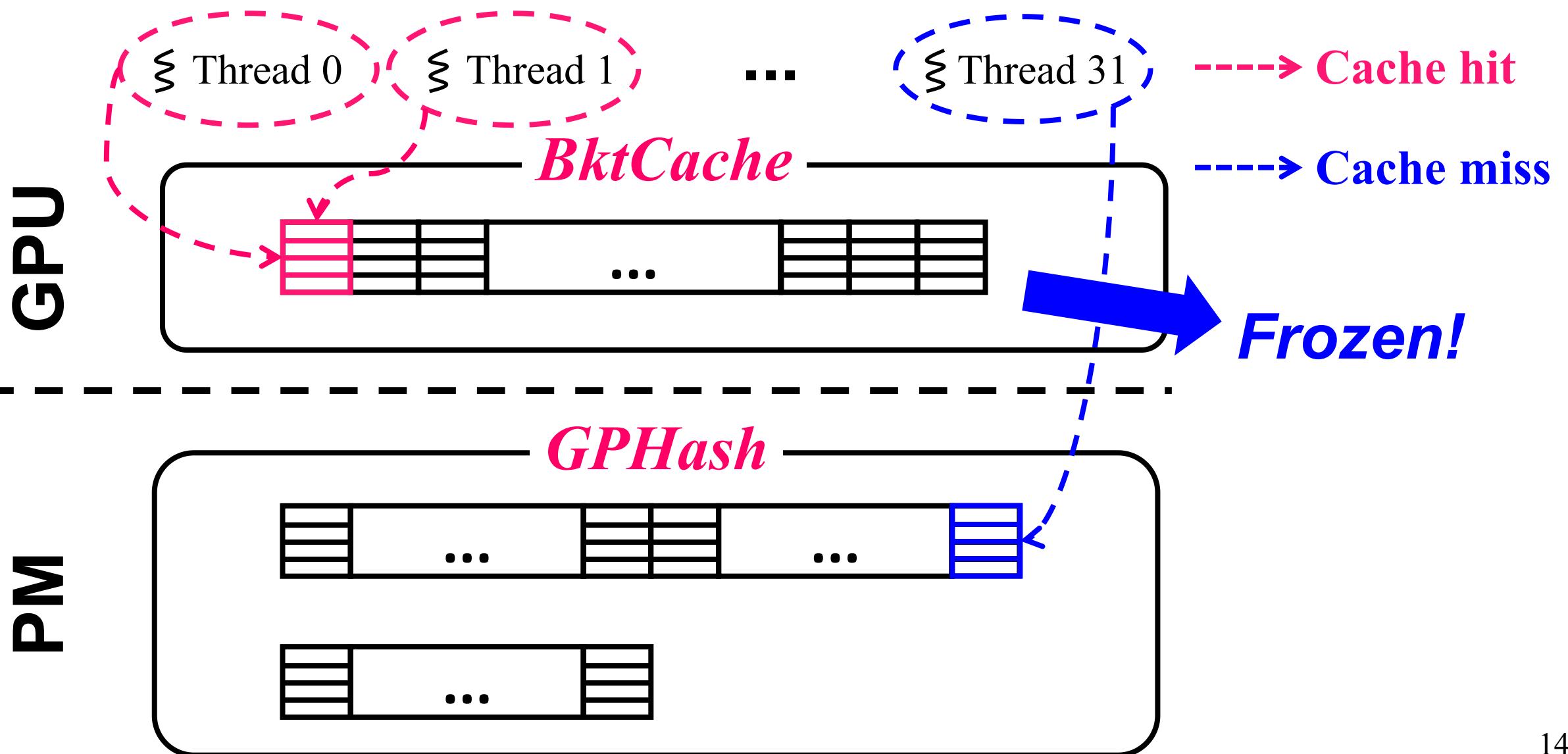
Frozen-Based Bucket Cache



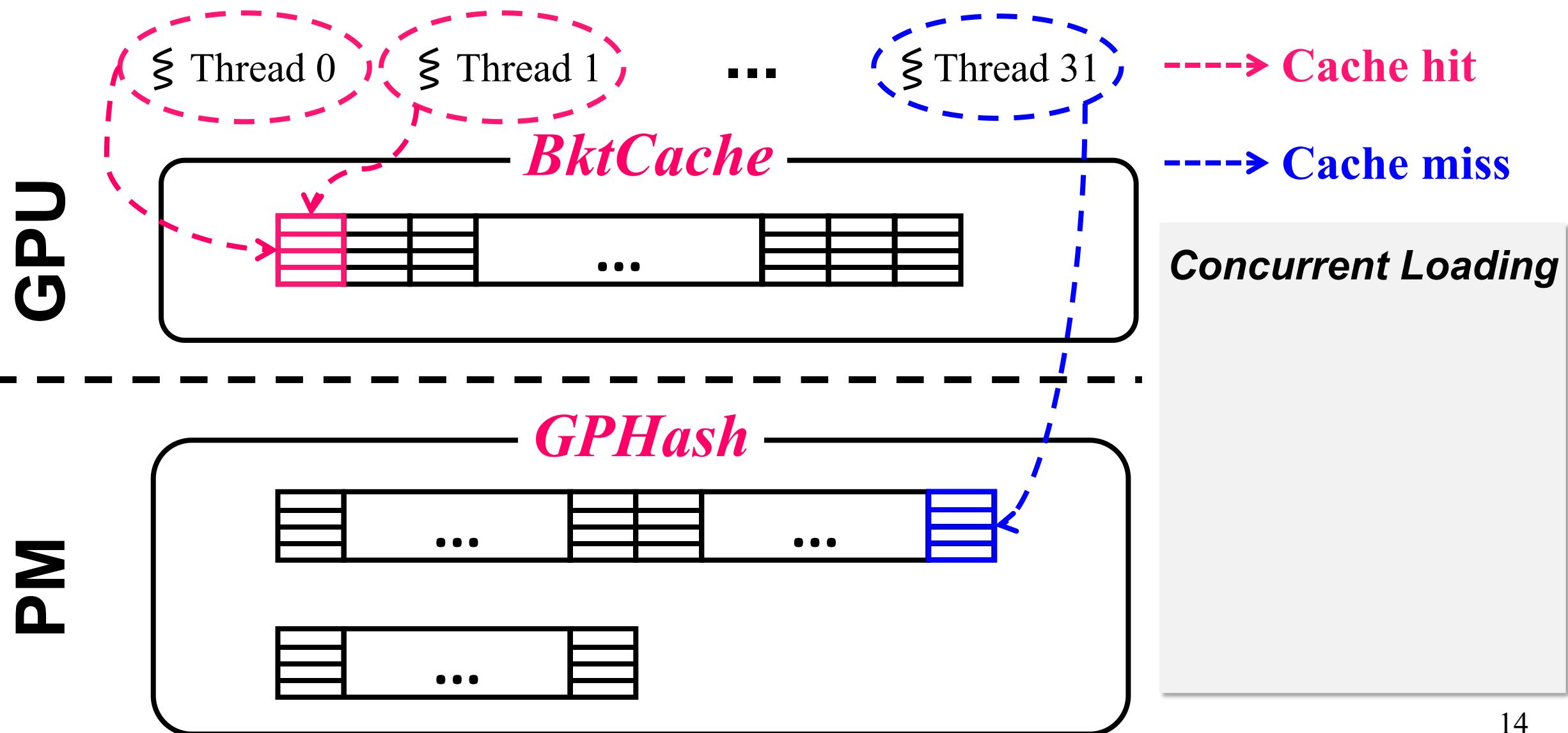
Frozen-Based Bucket Cache



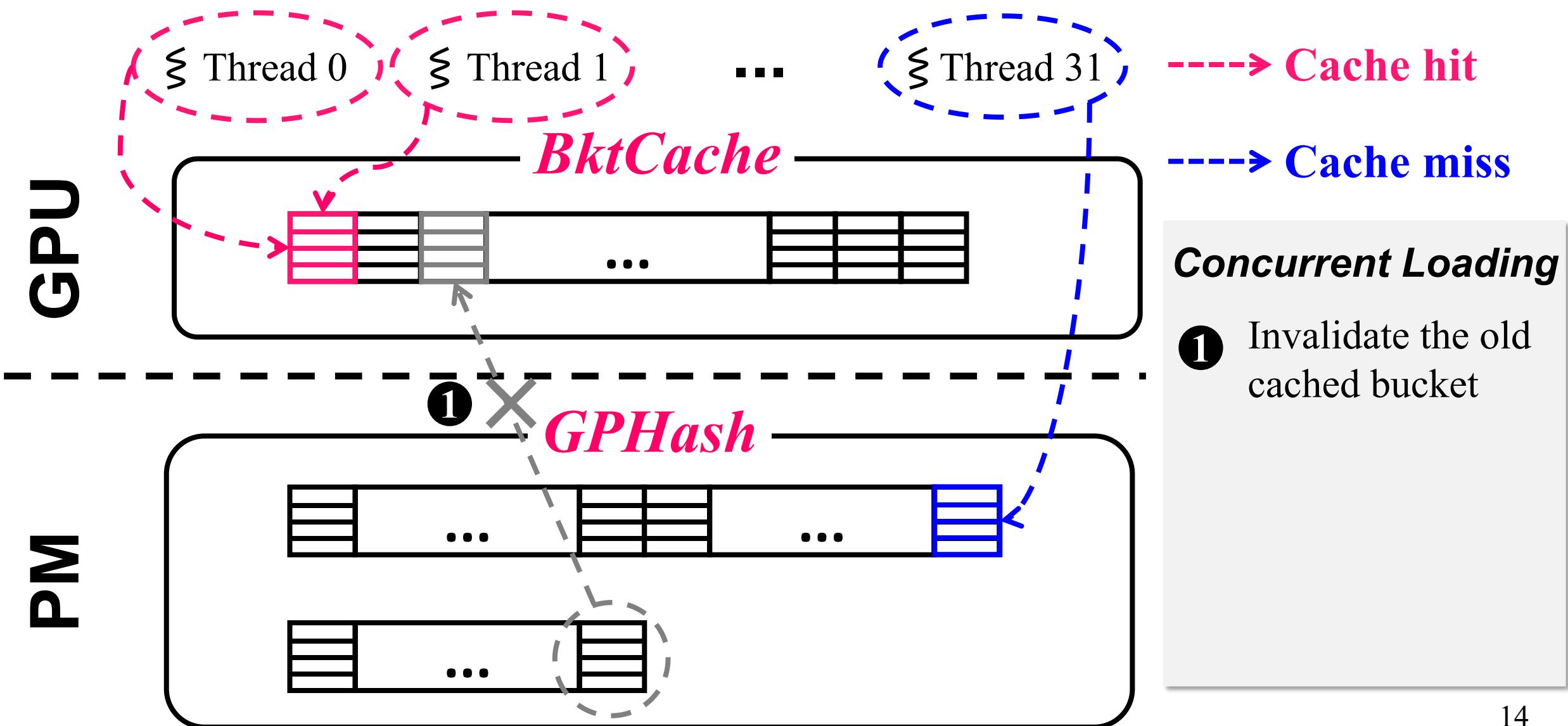
Frozen-Based Bucket Cache



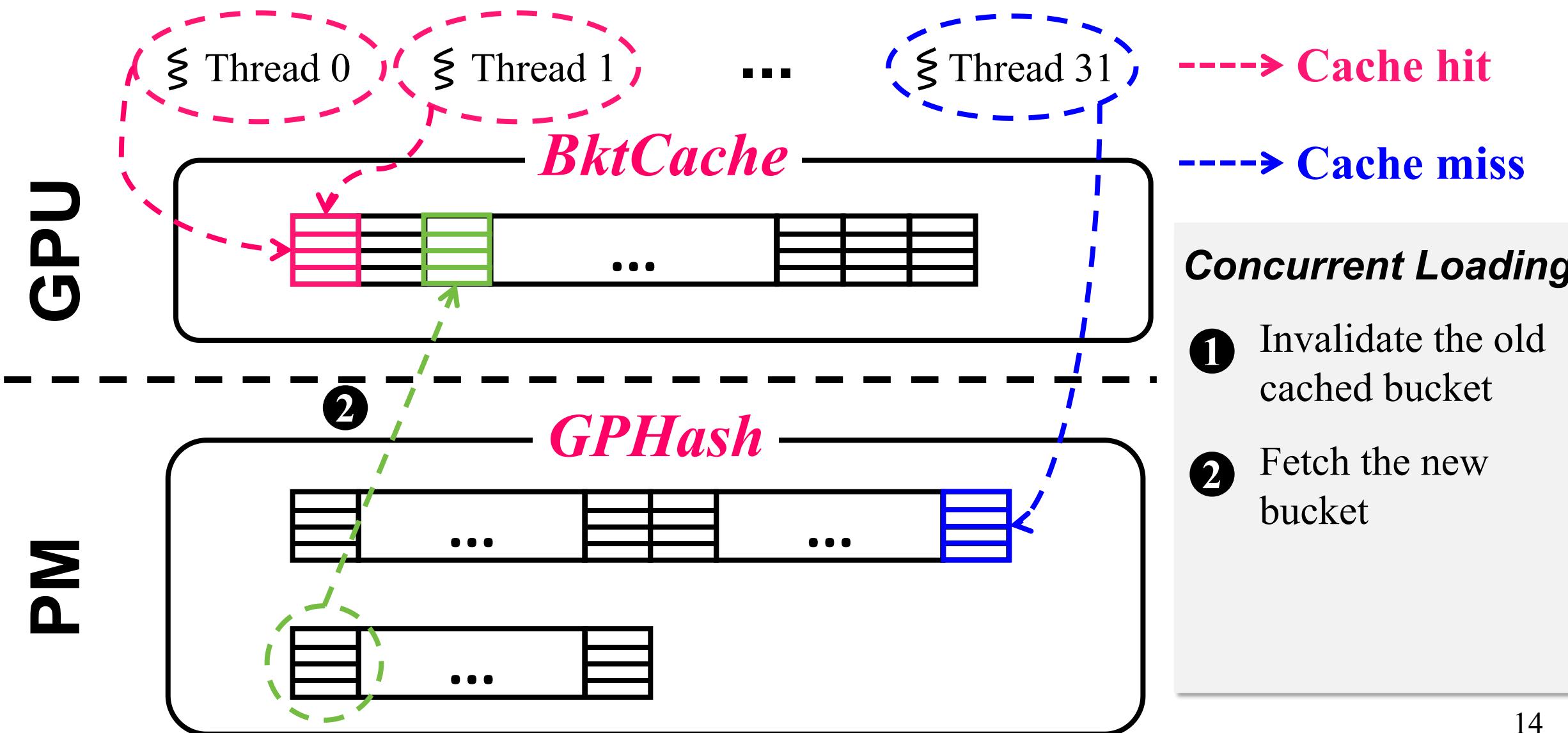
Frozen-Based Bucket Cache



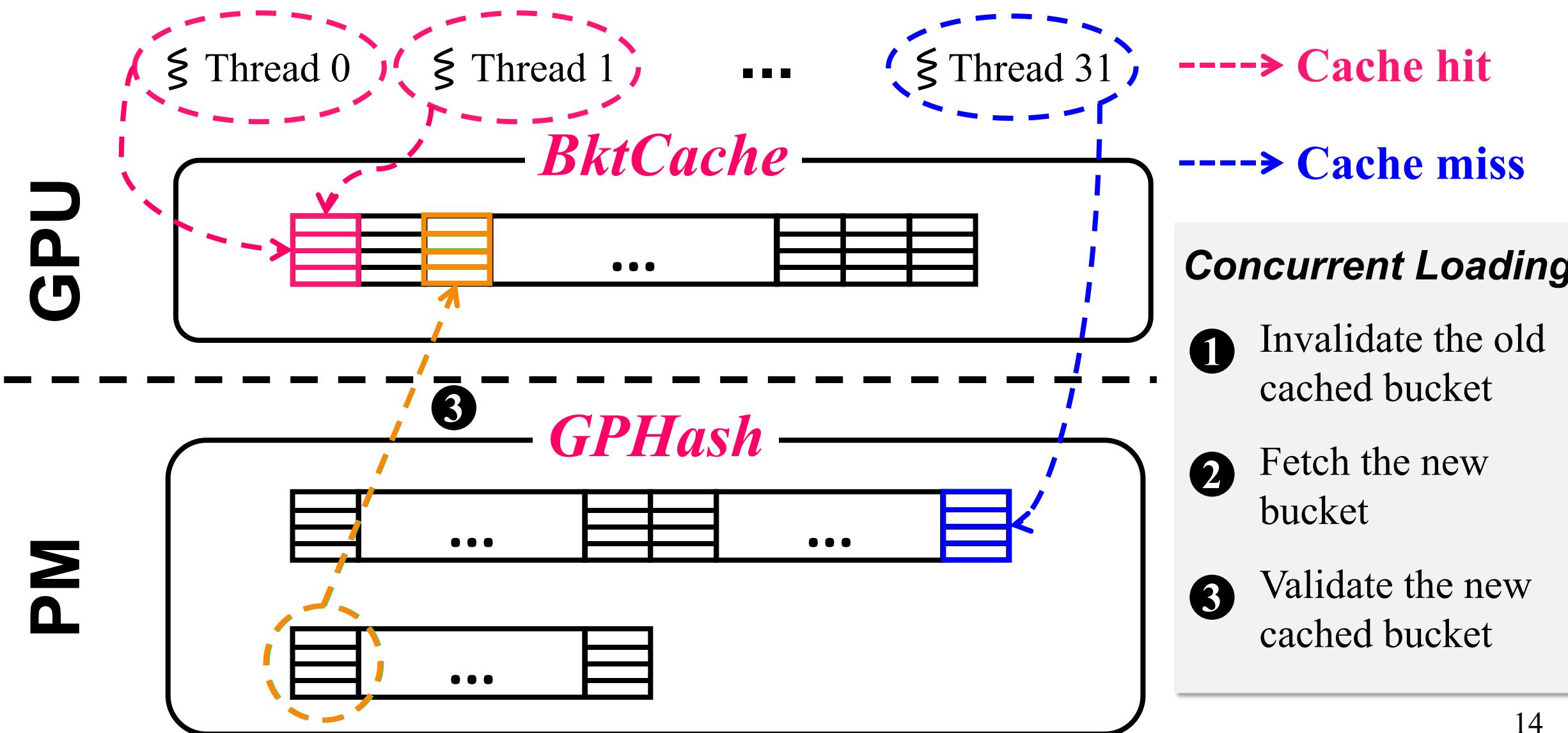
Frozen-Based Bucket Cache



Frozen-Based Bucket Cache



Frozen-Based Bucket Cache



More Details

More Details

- Warp-cooperative Execution Manner
- More Index Operations
- Bucket Caching Granularity
- ...

More Details

- Warp-cooperative Execution Manner
- More Index Operations
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- ...



More Details

- Warp-cooperative Execution Manner
- More Index Operations
- Bucket Caching Granularity
- ...



work [78], GPHash determines the *valid* item of a key. Given multiple items of the same key, the valid item is the one having the maximal level number, the minimal bucket number, and the minimal slot number. When finding duplicates, GPHash keeps the valid item and deletes other duplicates.

Congruency correctness. When threads concurrently perform the search and the IDU (i.e., insertion/deletion/update) operations with the same key, the readers may return the partial-updated value, which violates the congruency correctness. To ensure congruency correctness while providing high performance, GPHash follows the “*no lost key*” concurrent correctness condition akin to prior schemes [38, 78]. Specifically, when threads concurrently perform the search and the update operations, the search operations return either the old or the new values instead of partial-updated values. When a search and a deletion run in parallel, the search operation returns either the value or no-key statement.

Crash consistency guarantee. When directly managing data in persistent memory, a crash would interrupt the ongoing index operations, which can lead to persistent partial updates for keys and values. Such data inconsistency causes data loss and unpredictable errors. To guarantee data consistency in the presence of crashes, GPHash uses CAS primitive and the slot state to achieve log-free operations with negligible overhead.

3.2.3 Lock-Free and Log-Free Operations

We introduce the details of lock-free and log-free operations. Here, we focus on operations of the fixed-length large keys whose sizes are larger than 8 bytes, while the operations of fixed-length small keys (i.e., ≤ 8 bytes) and variable-length keys can be implemented in a similar way using the CAS primitive. We use system-scoped thread fence [46] to order the persists for the correct consistency guarantee.

Insertion. Figure 3 illustrates the lock-free and log-free insertion. First, GPHash obtains the fingerprints and the keys of all candidate slots of the activated key with one-shot warp access. GPHash then checks if the key exists by comparing these keys with the activated key, while leveraging the fingerprints for fast comparison. If the activated key does not exist, GPHash finds the empty slots, i.e., the slots whose states are `EMPTY`². If there are several empty slots, GPHash inserts the activated key into the slot belonging to the less-loaded bucket. After deciding the target slot for insertion, the activated thread uses CAS primitive to atomically change the slot state (i.e., fingerprint region) from `EMPTY` to `INSERT`. If the CAS fails, meaning that the slot is changed by another thread, GPHash re-executes the insertion from the beginning. If CAS succeeds, the activated thread writes the item into the target slot. Finally, the activated thread sets the fingerprint region of the target slot to the hash value of the activated key.

The insertion can easily recover from crashes. There are two cases of a slot after crashes. (1) The slot state is `INSERT`,

²We reserve two 8-byte values in the fingerprint value range, i.e., `EMPTY` and `INSERT`, to indicate the slot is empty or under insertion.

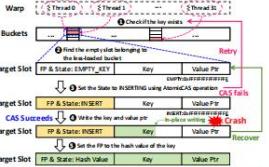


Figure 3: The illustration of lock-free and log-free insertion (using the logical structure of a slot for easy understanding).

indicating that the slot is under insertion (i.e., writing a new item) before crashes. In this case, the slot may be broken, and thus we need to clear the slot and set the slot state to `EMPTY`. (2) The slot state is `NOT INSERT`, meaning that the slot is empty or contains an unbroken item. In this case, we do not need to do anything since the slot is already in a valid state.

Deletion. For deletion operation, GPHash first locates the target items whose keys are equal to the activated key, including duplicate items. Similar to insertion, the activated thread is responsible for atomically deleting all these items by using the CAS primitive to set the slot state to `EMPTY`. Thanks to the atomicity of the CAS primitive, the deletion does not introduce any invalid slot state in the presence of crashes.

Update. For the update operation in GPHash, after locating the target slot and deleting the other duplicates, the activated thread atomically changes the value pointer to point to the new value via the CAS primitive. GPHash writes the new value to the pre-allocated space before updating the value pointer. After crashes, the value pointer either points to the old value or the new one, both of which are unbroken.

Search. Since GPHash takes advantage of the atomicity of the CAS primitive to perform the IDU operations, the lock-free search operation can be easily implemented. After locating all slots whose keys are equal to the activated key, the activated thread reads the value that is pointed by the value pointer of the valid slot. If the activated key does not exist, the thread returns a no-key statement. Based on the above introduction to other operations, the search operation can be proved to meet the “*no lost key*” concurrent correctness condition.

Resizing. As the load factor increases, more hash collisions will occur in hash indexes, which results in performance degradation and insertion failure. Thanks to the one-shot warp access, GPHash does not suffer from performance degradation caused by more hash collisions. However, GPHash still needs to handle insertion failure to avoid item loss. If failing to find an empty slot to insert a new item, GPHash has to resize. Specifically, GPHash first allocates a new level as the new top one. GPHash then leverages thousands of GPU threads to scan the bottom level in parallel and rehashes the items. Each rehashing operation consists of reading the item in the

Evaluation

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➤ Platform

- 1 V100 GPU + 768 GB Intel Optane DC PM (6×128 GB)

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➤ Comparisons

- CPU-assisted approaches^[1]: *Clevel*^[ATC'20], *Dash*^[VLDB'20], and *SEPH*^[OSDI'23]
- GPM-enabled approaches: *Clevel-GPM* and *SlabHash*^[IPDPS'18]-*GPM*

¹ For fair evaluation, we use PM to store the data and leverage PM hash indexes to manage the data in PM

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➤ Workloads

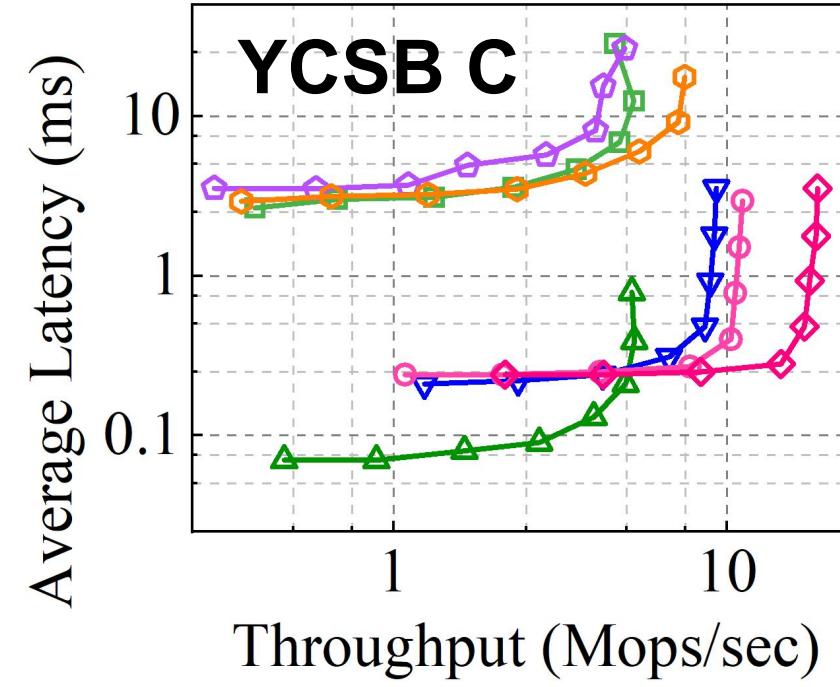
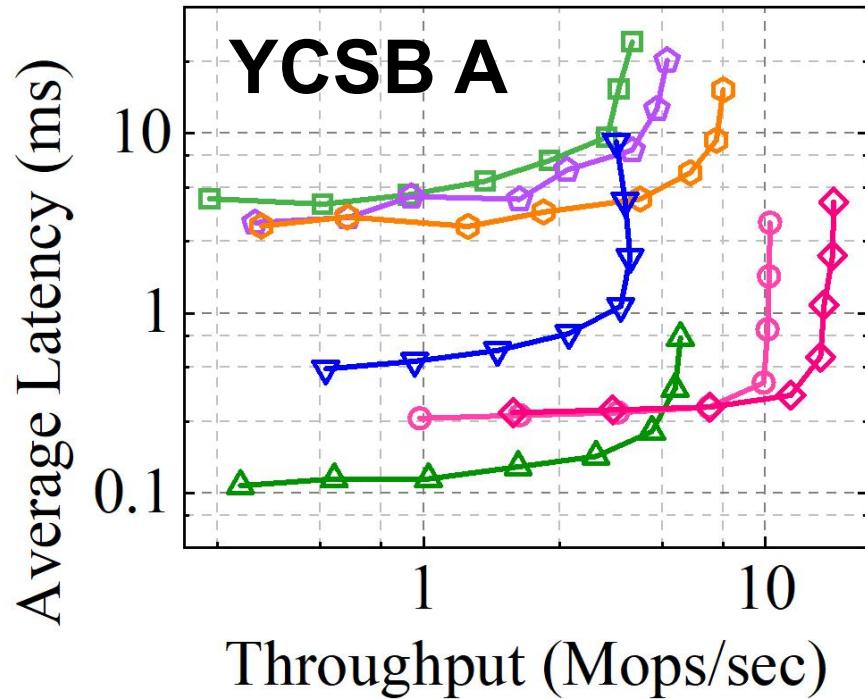
- YCSB workloads: *8-byte and 32-byte keys, 128-byte values*
- Real-world workloads: *DLRM* and *PageRank*

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End-to-End Performance

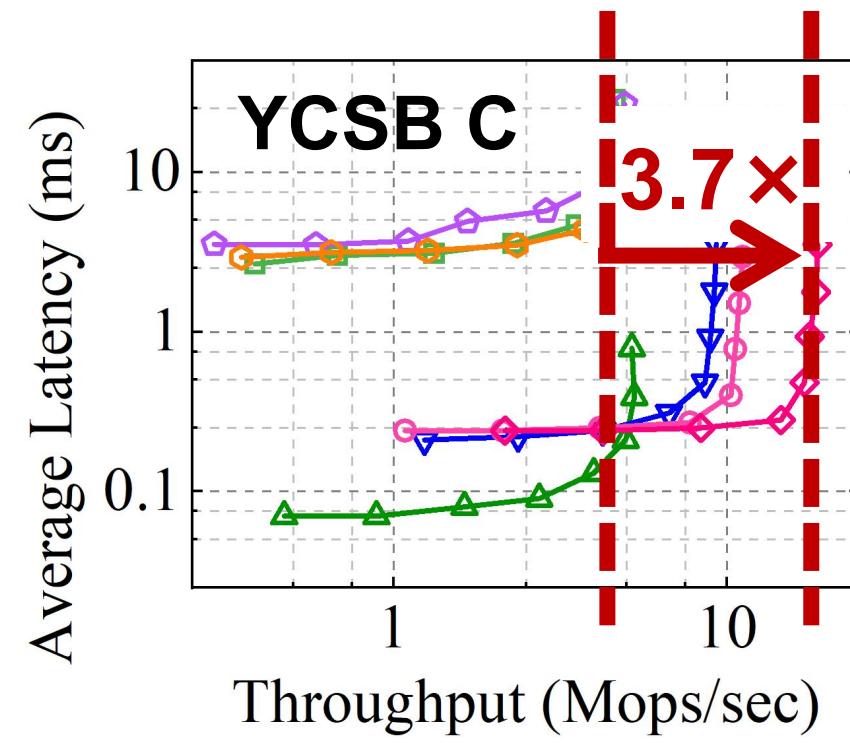
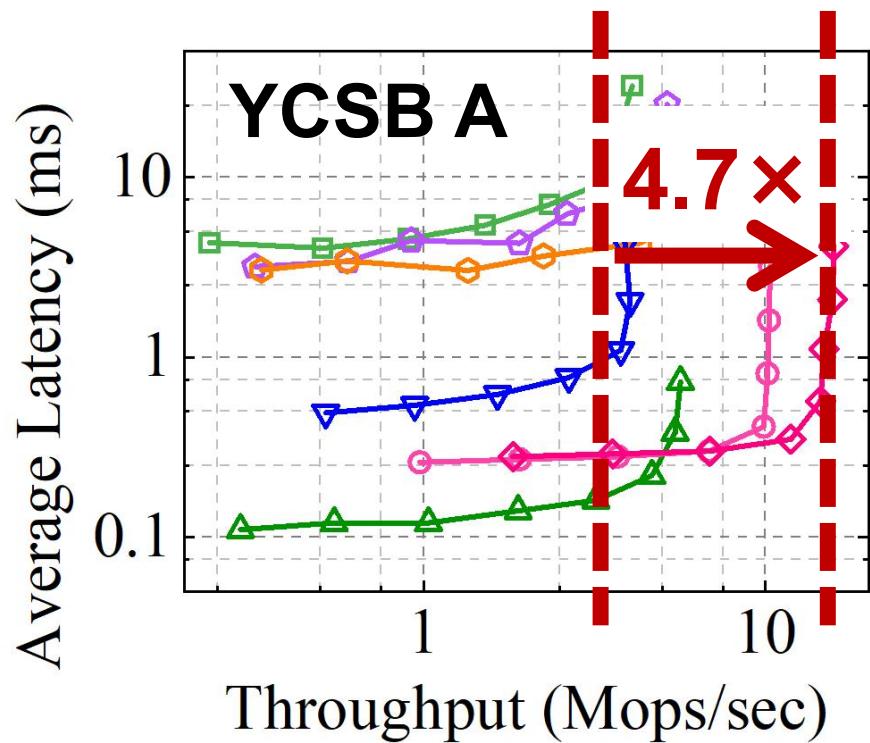
End-to-End Performance

Legend: Clevel (green square), Dash (purple diamond), SEPH (orange hexagon), Clevel-GPM (green triangle), SlabHash-GPM (blue inverted triangle), GPHash w/o cache (pink circle), GPHash (pink diamond)



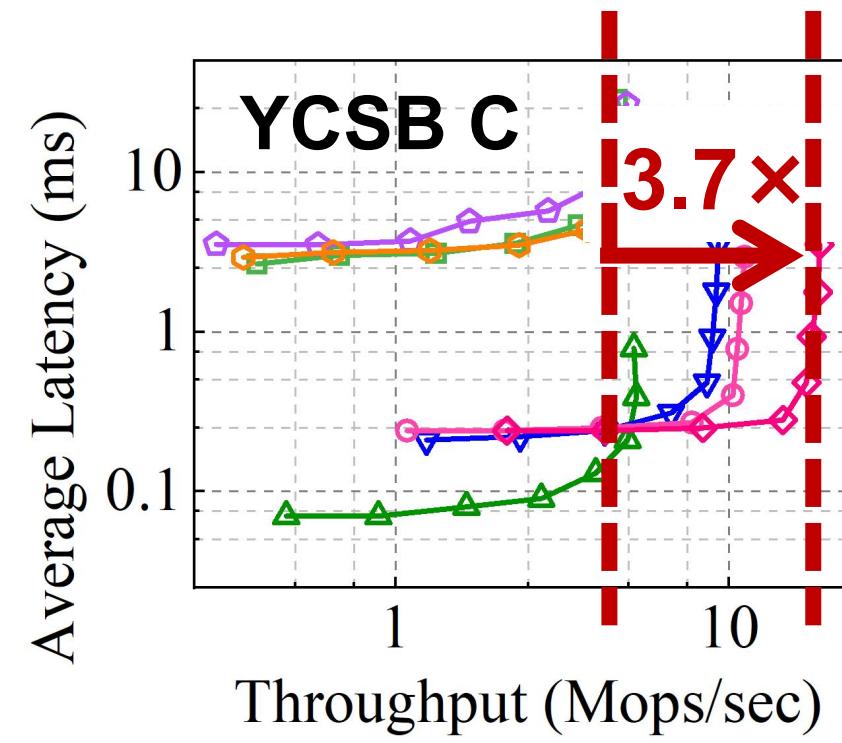
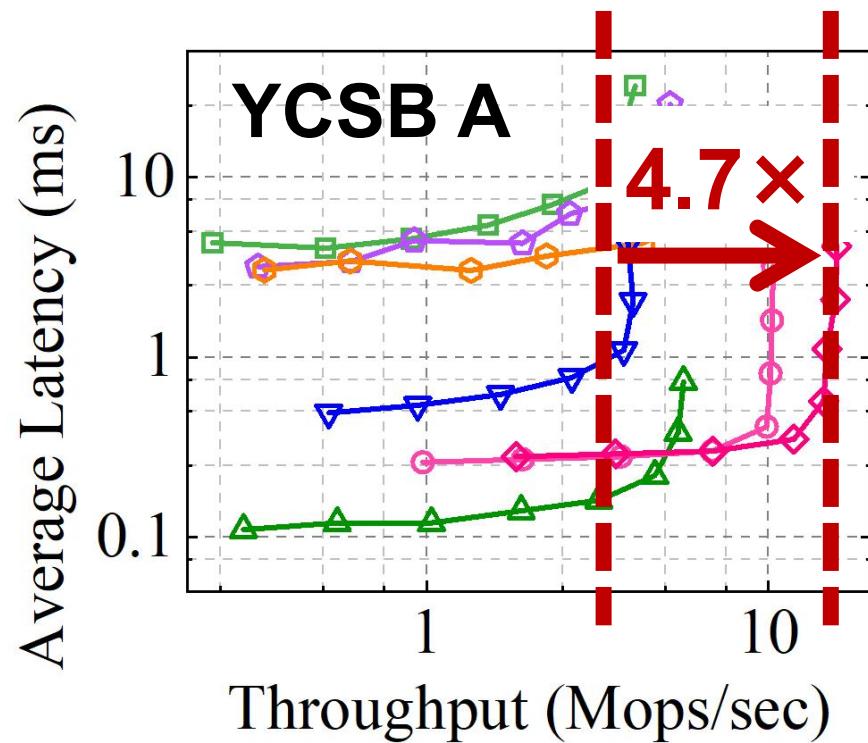
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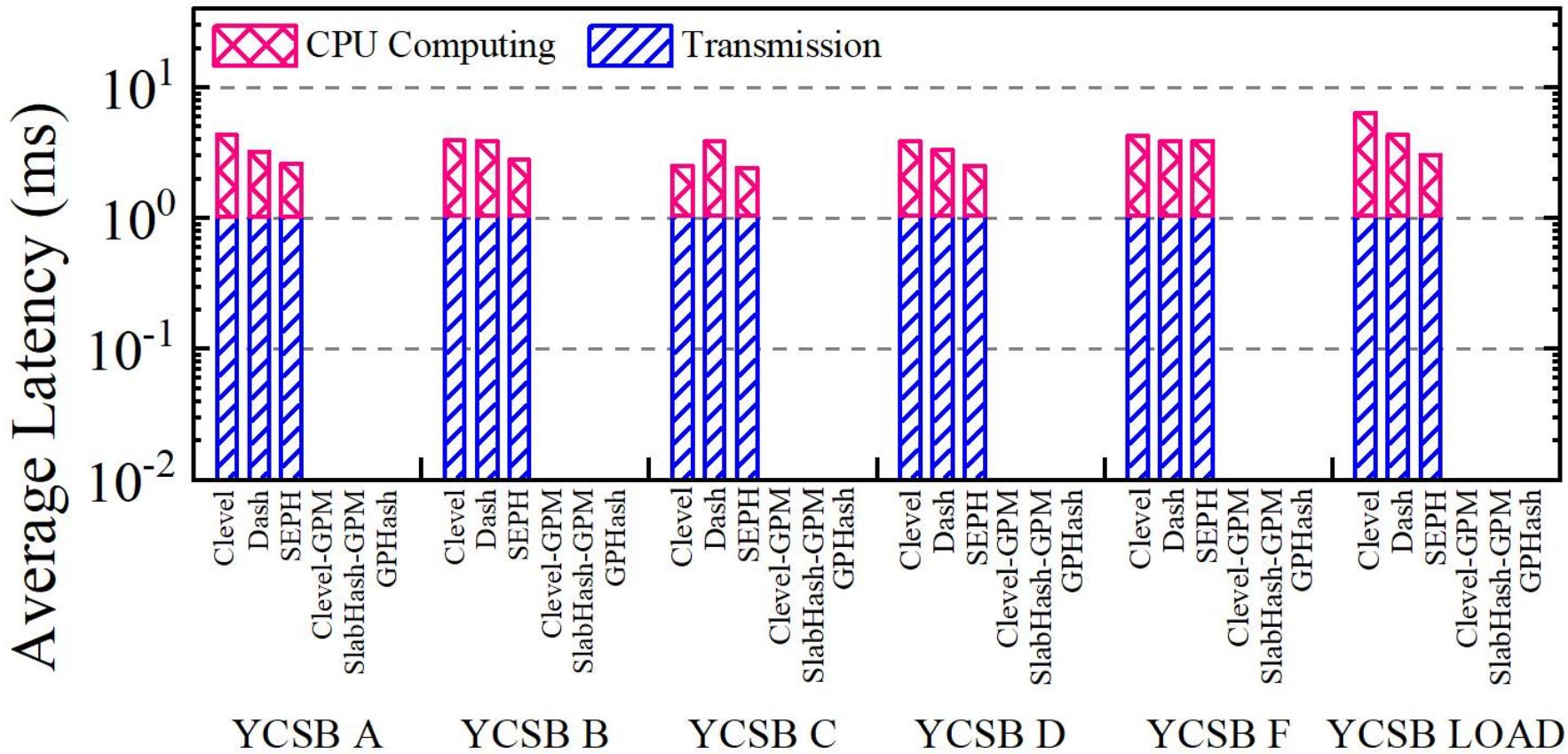
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GPHash improves the throughput by **1.9~6.3×**

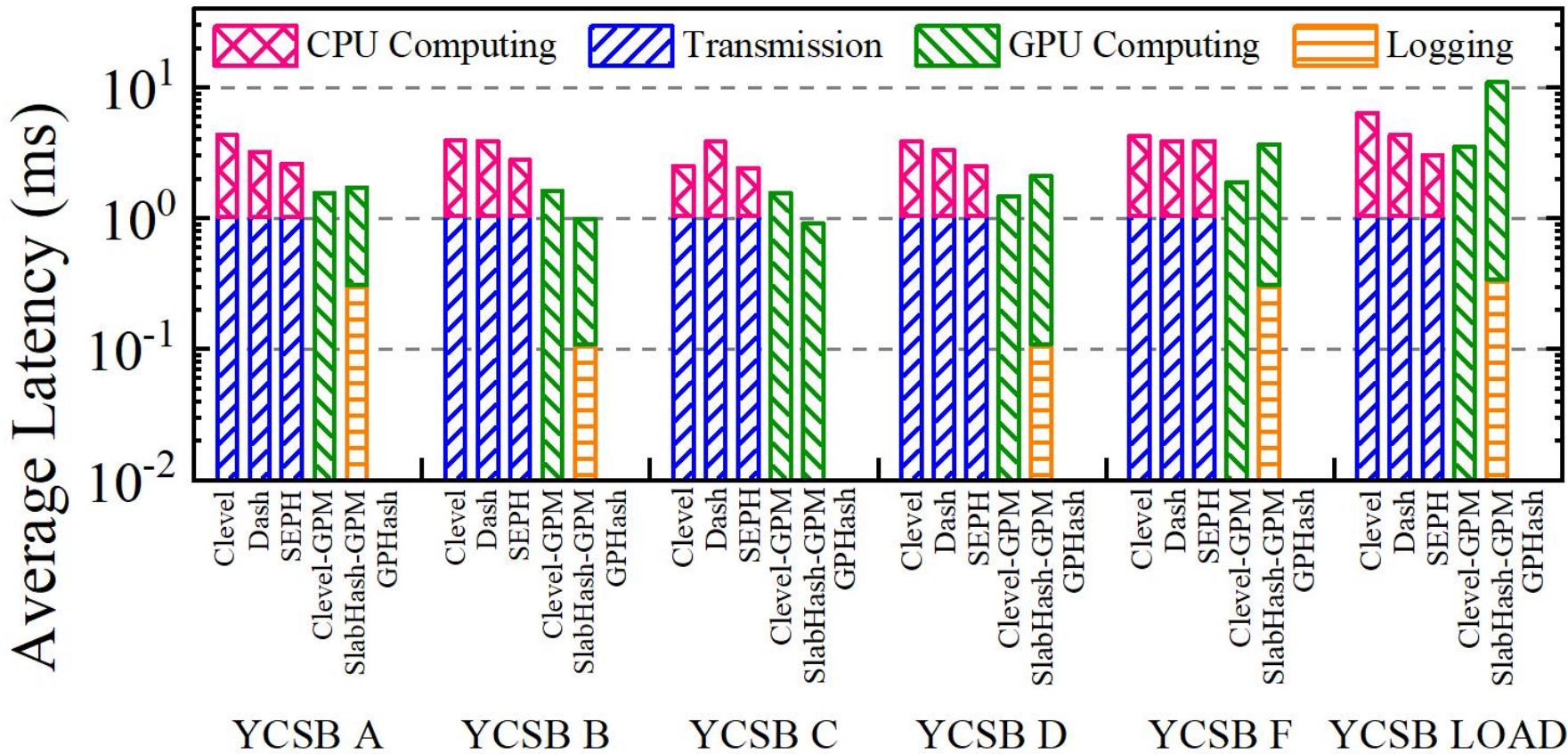
Latency Breakdown

Latency Breakdown



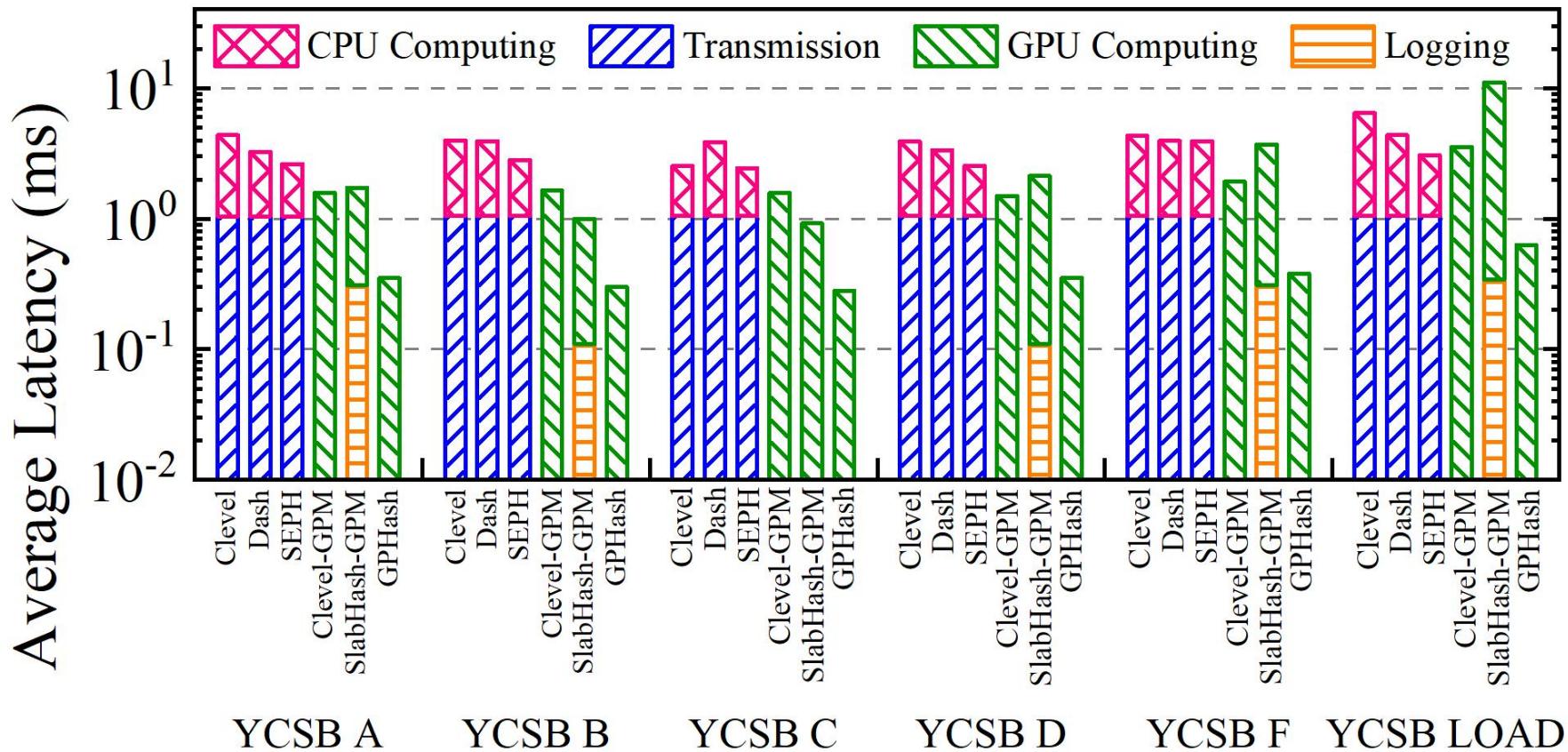
CPU-assisted approaches suffer from *high transmission cost*

Latency Breakdown



Naive GPM-enabled approaches suffer from *severe warp divergence* and *high-overhead consistency guarantee*

Latency Breakdown



GPHash fully leverages the *high parallelism of GPU* and provides a *low-overhead consistency guarantee*

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 - *GPU-conscious and PM-friendly hash table*
 - *Lock-free and log-free operations*
 - *Frozen-based bucket cache*

Conclusion



<https://github.com/LighT-chenml/GPHash>



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Thank you! Q&A