Efficiently Detecting Concurrency Bugs in Persistent Memory Programs

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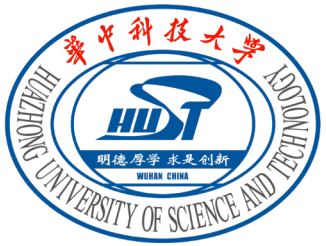
Huazhong University of Science and Technology

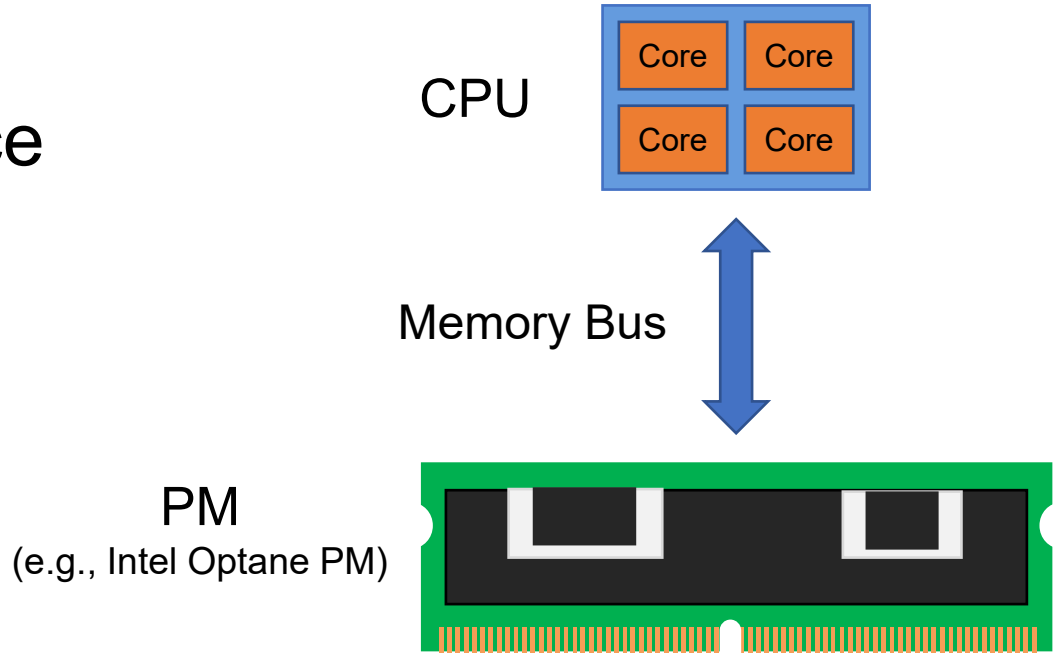
**Purdue University*

ASPLOS 2022



Persistent Memory (PM)

- PM characteristics
  - DRAM-comparable performance
  - TB-scale capacity
  - Non-volatility
  - Byte-addressability

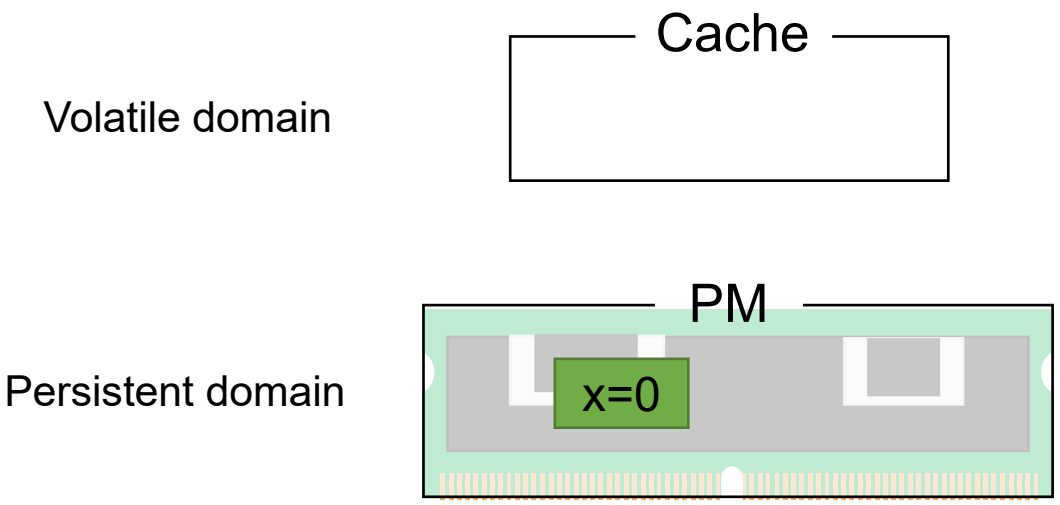


- New opportunities for memory systems
  - Lower cost/GB than DRAM
  - Instant recovery from PM

PM Programming

- PM programming is non-trivial
  - Volatile CPU caches

```
x = A;
```



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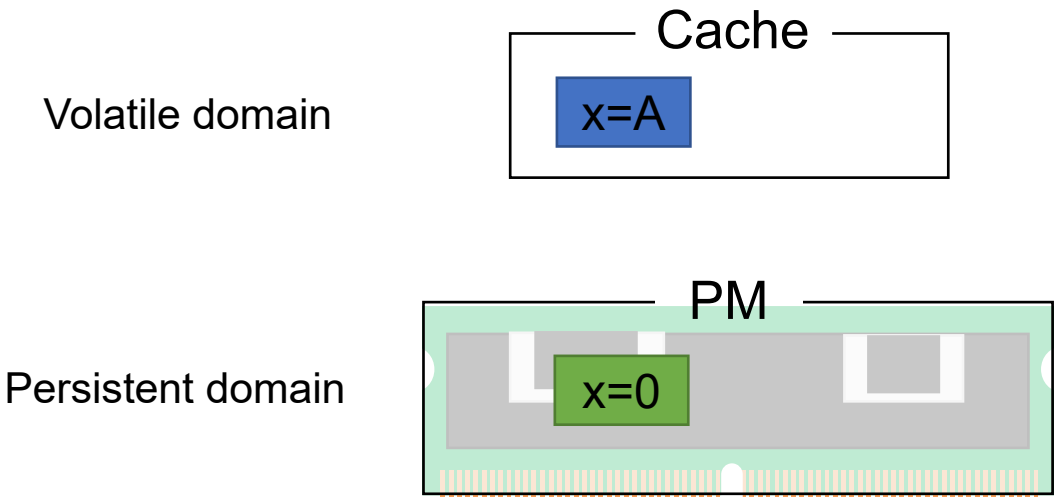

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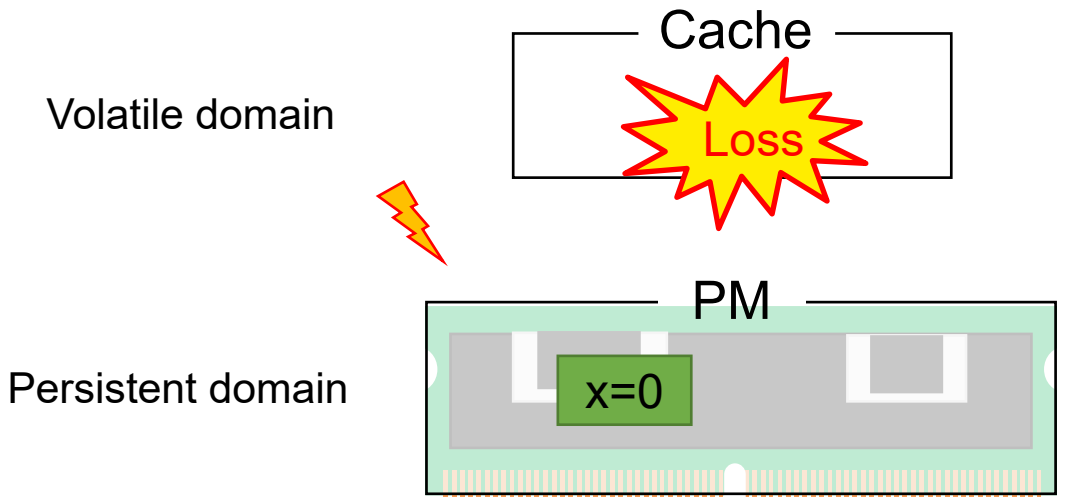

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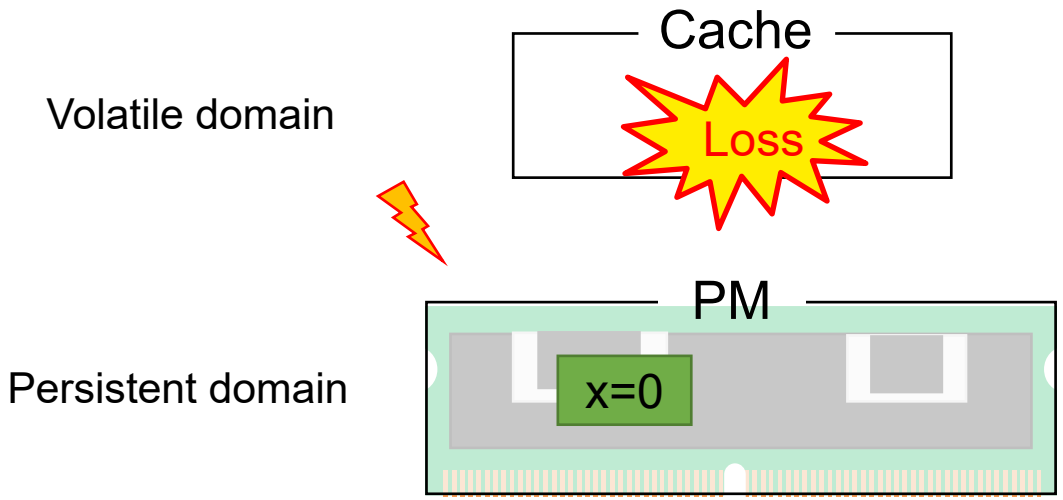

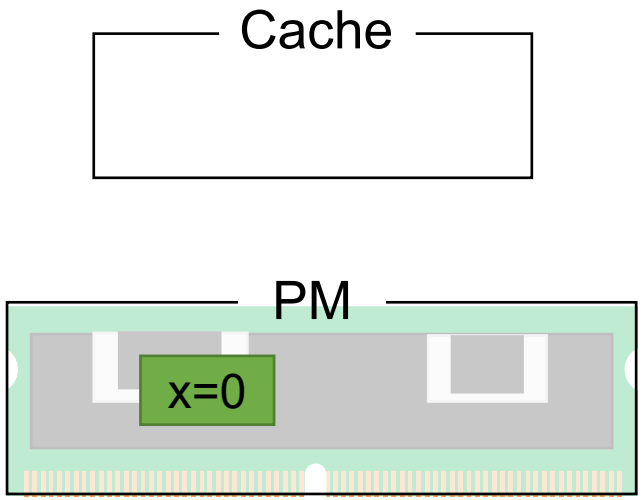

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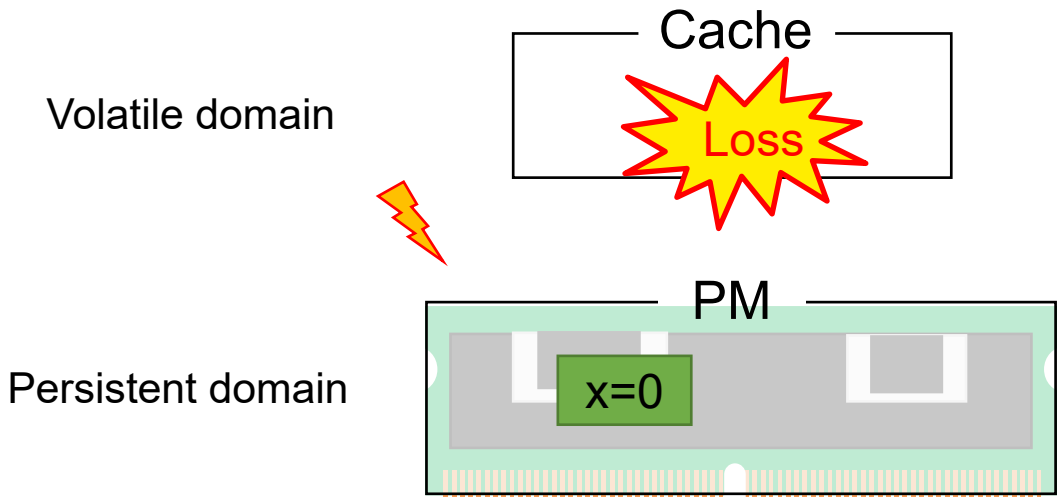

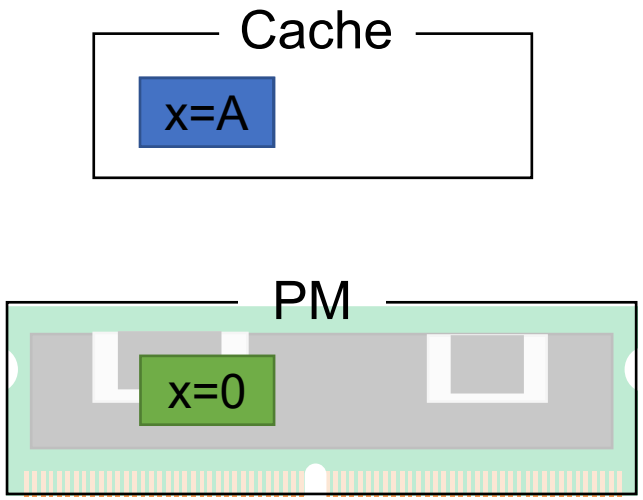

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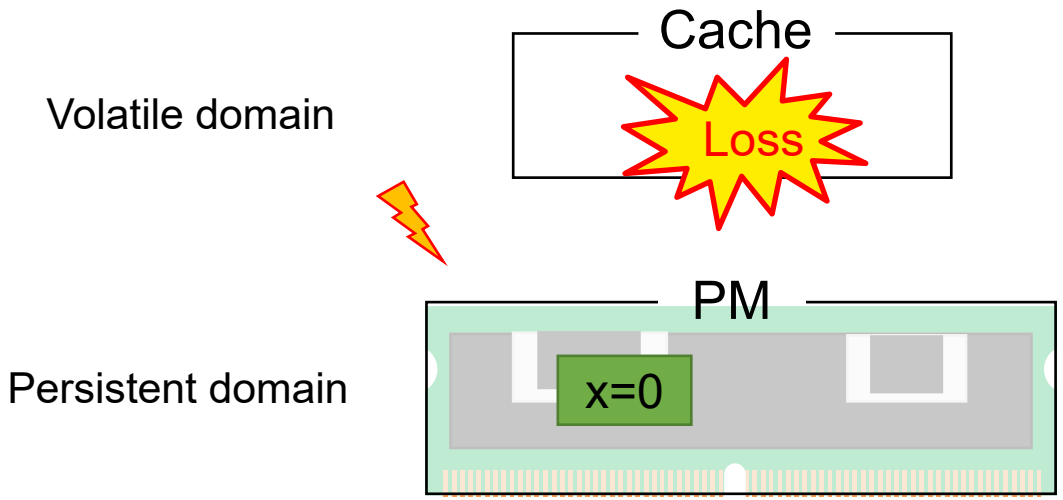

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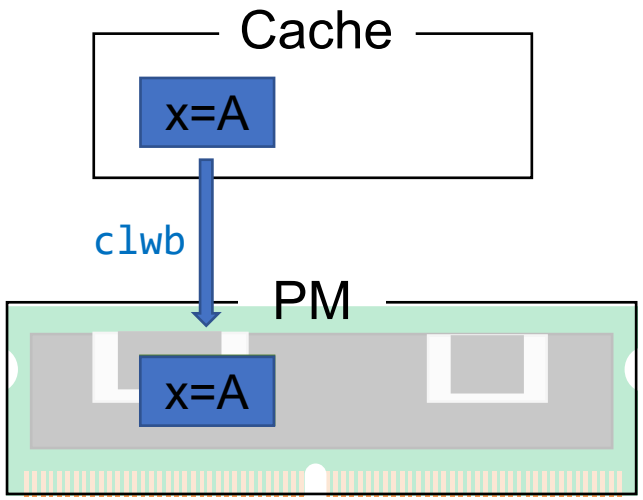

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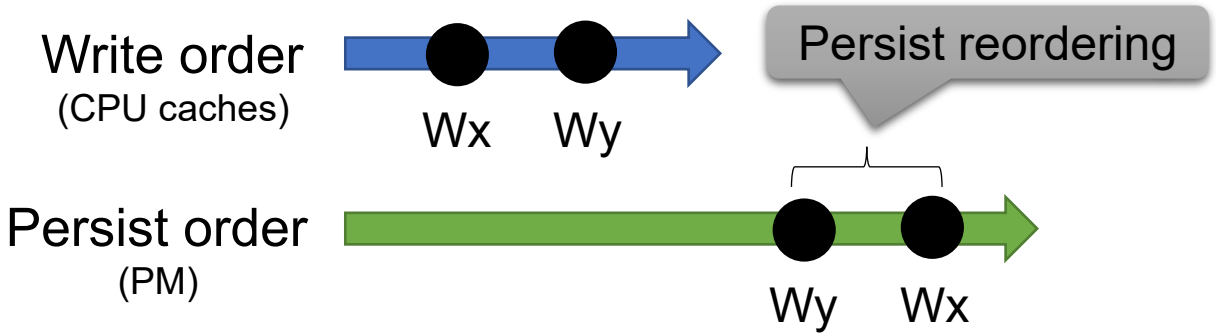

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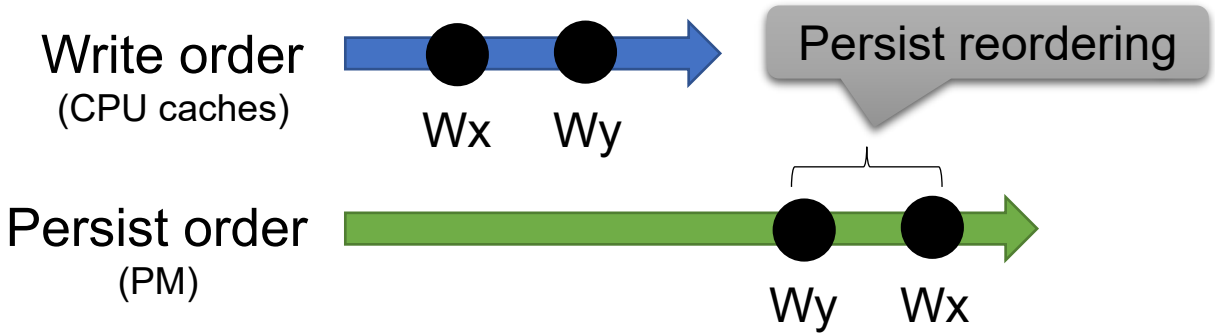

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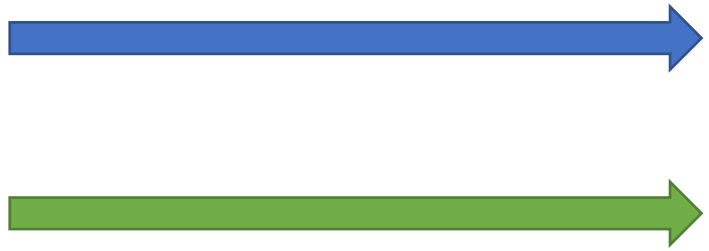

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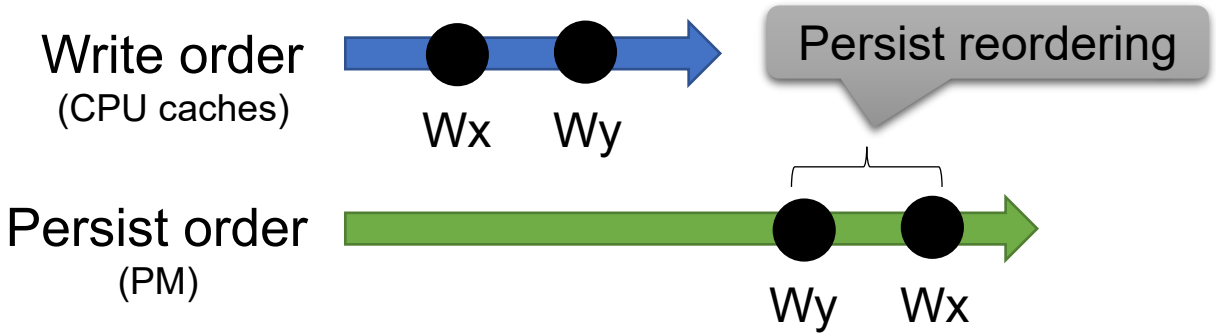

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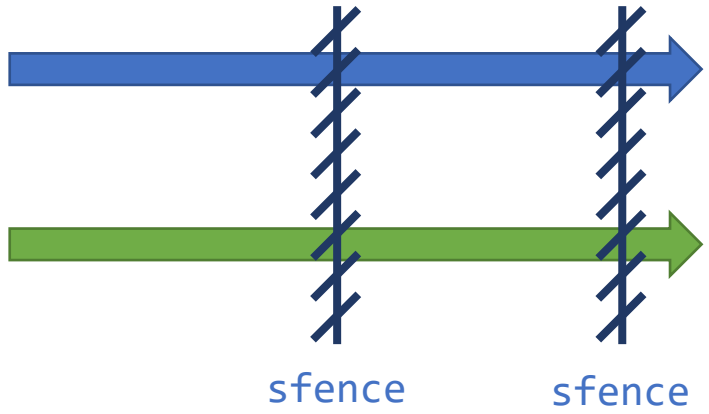

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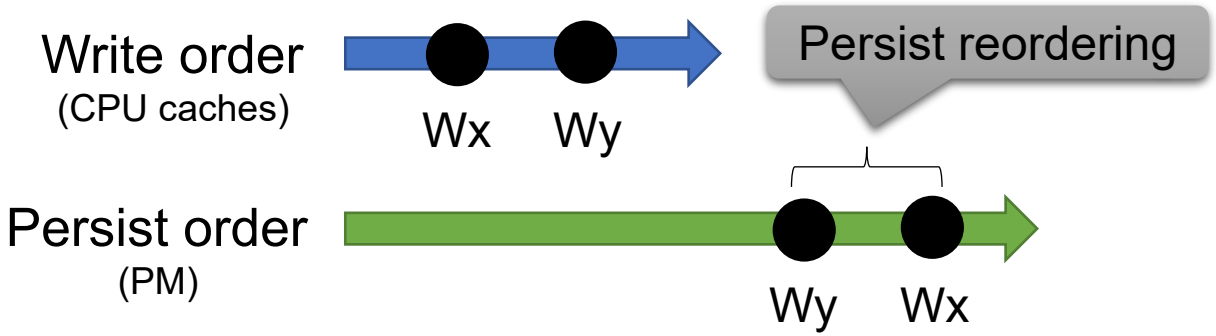

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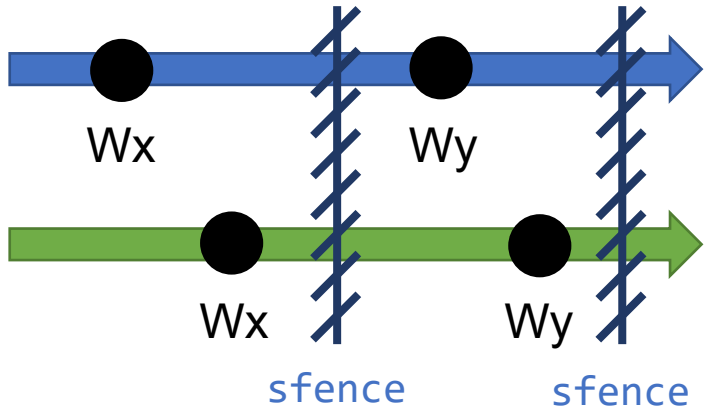

PM Crash-Consistency Bugs

- Correctness bugs
  - Causing correctness violation
  - Patterns:
    - Missing flush/fence
    - …

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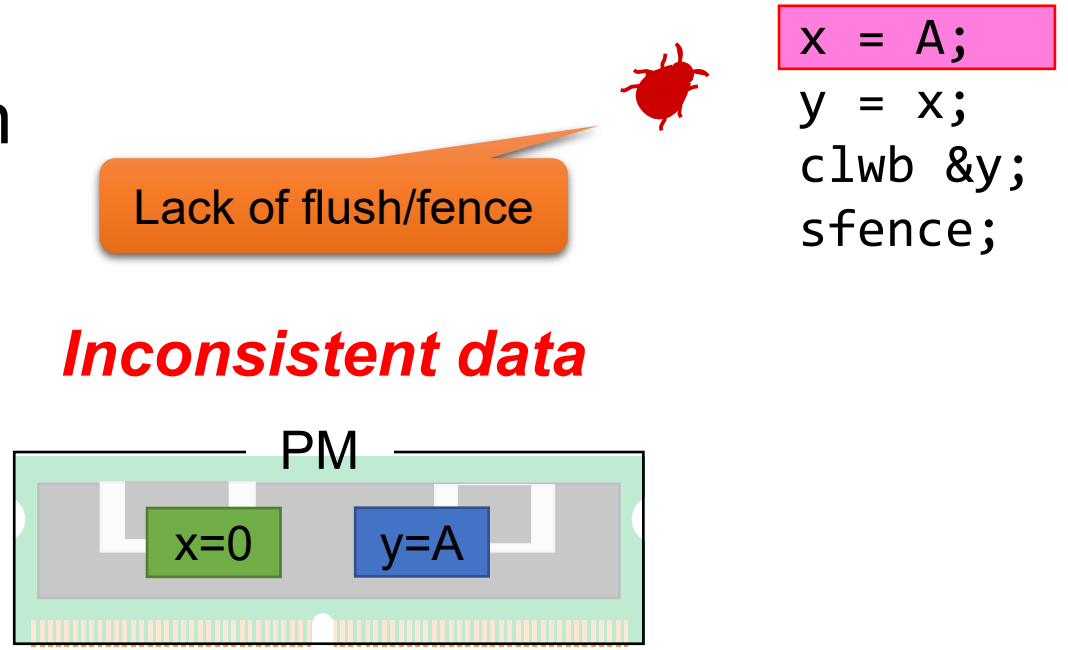

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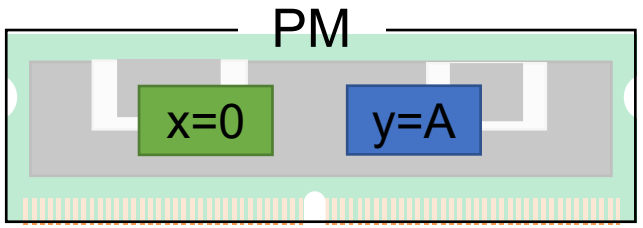
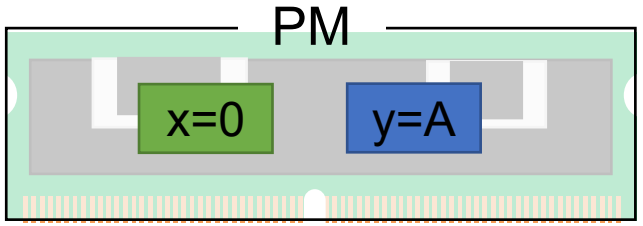
Lack of flush/fence

Inconsistent data



Restart



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Bugs still exist after restarts!

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Lack of flush/fence

Inconsistent data

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- Performance bugs
  - Causing performance degradation
  - Patterns:
    - Extra flush/fence
    - …

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Inconsistent data

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Extra flush

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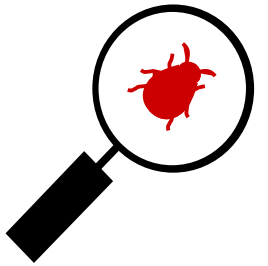
```

Unnecessary stall

Existing Automatic PM Debugging Tools

- Correctness bugs
  - Missing flush/fence
    - AGAMOTTO [OSDI '20]
    - PMDebugger [ASPLOS '21]
    - …



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Are PM writes followed by flush/fence?

- Performance bugs
  - Extra flush/fence
    - AGAMOTTO, PMDebugger, …

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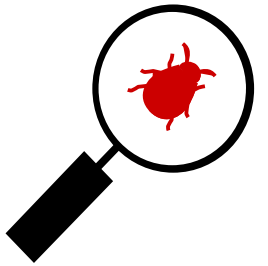
Are flushes/fences necessary?

Existing Automatic PM Debugging Tools

- Correctness bugs
  - Missing flush/fence
    - AGAMOTTO [OSDI '20]
    - PMDebugger [ASPLOS '21]
    - …
  - Other patterns
    - Cross-failure race: XFDetector [ASPLOS '20]
    - Application-specific bugs: WITCHER [SOSP '21]
    - ...
- Performance bugs
  - Extra flush/fence
    - AGAMOTTO, PMDebugger, …



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Are PM writes followed by flush/fence?

Lack of considerations for concurrent executions!

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Are flushes/fences necessary?

Crash-Inconsistency in Concurrent Executions

- Concurrency is important to PM system performance

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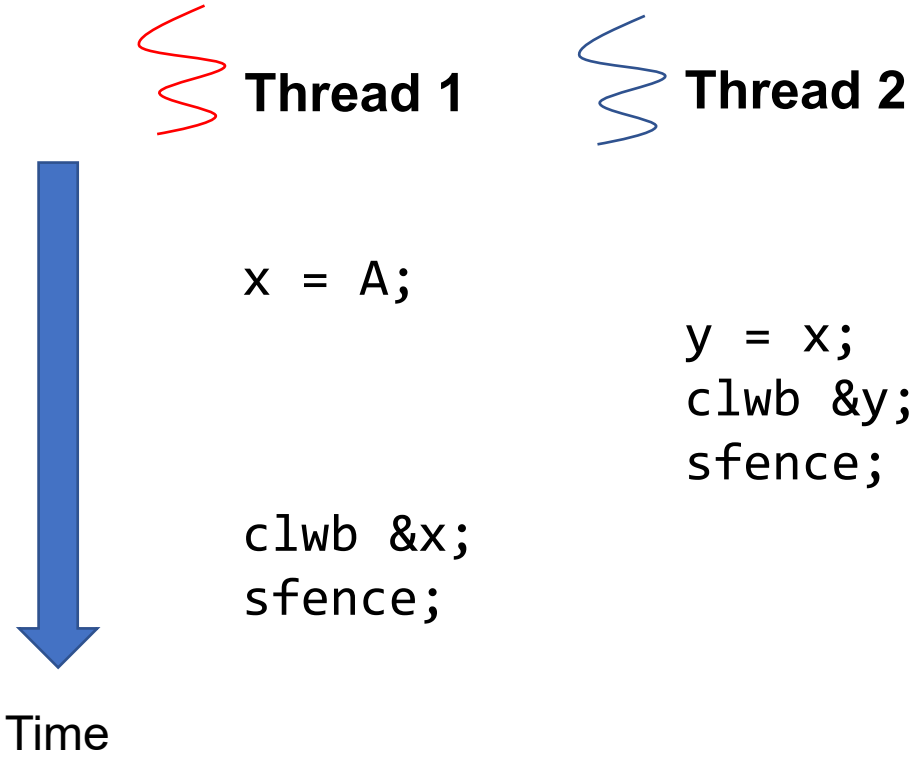

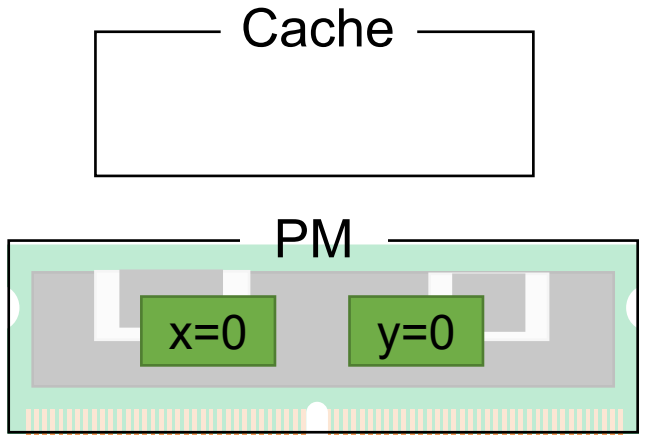

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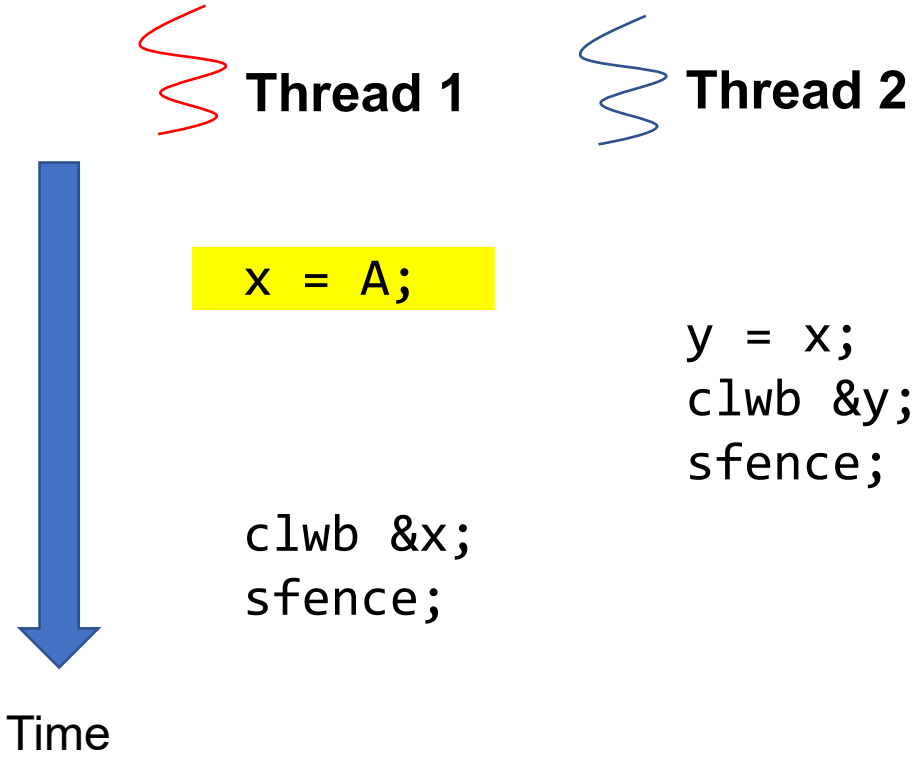

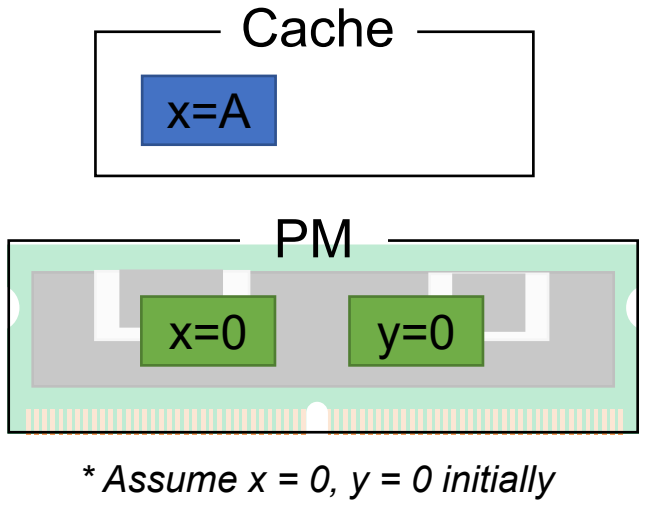

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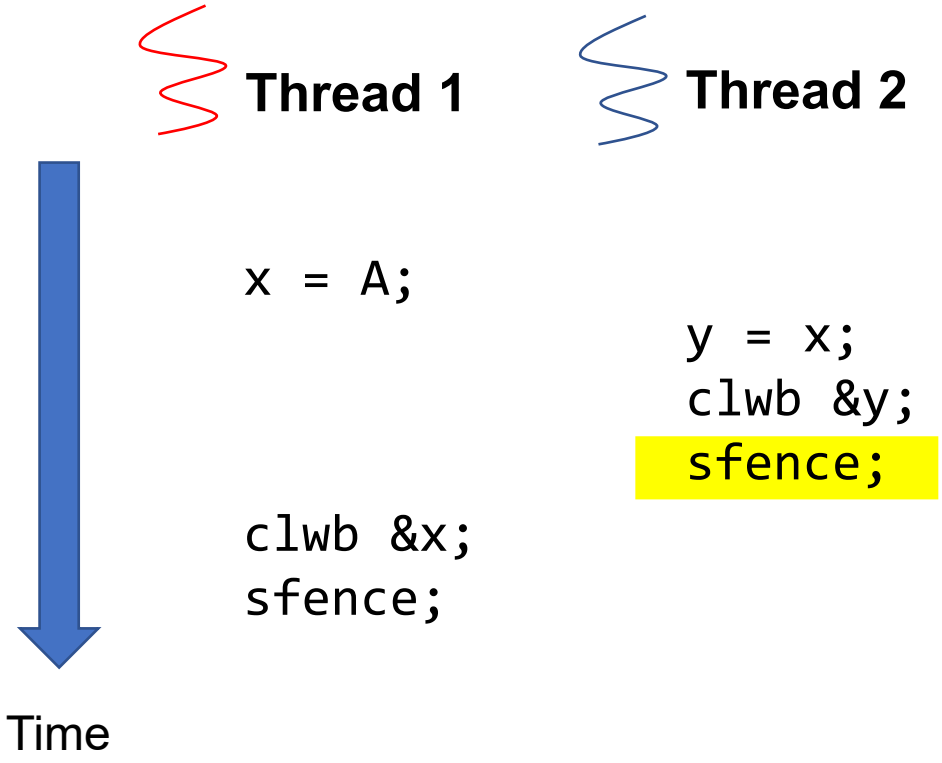

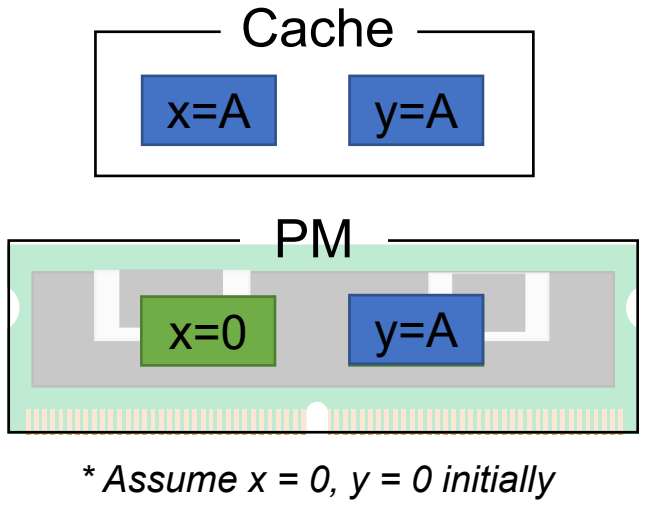

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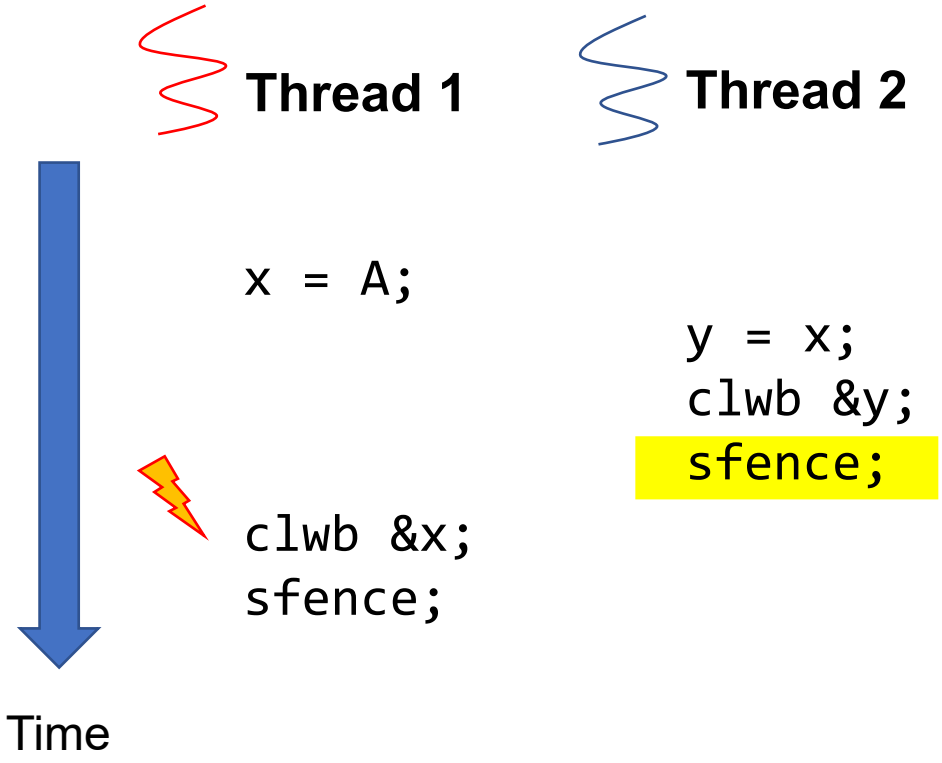

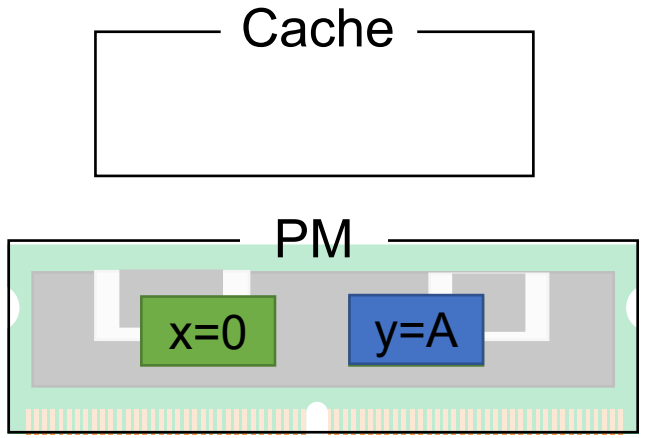

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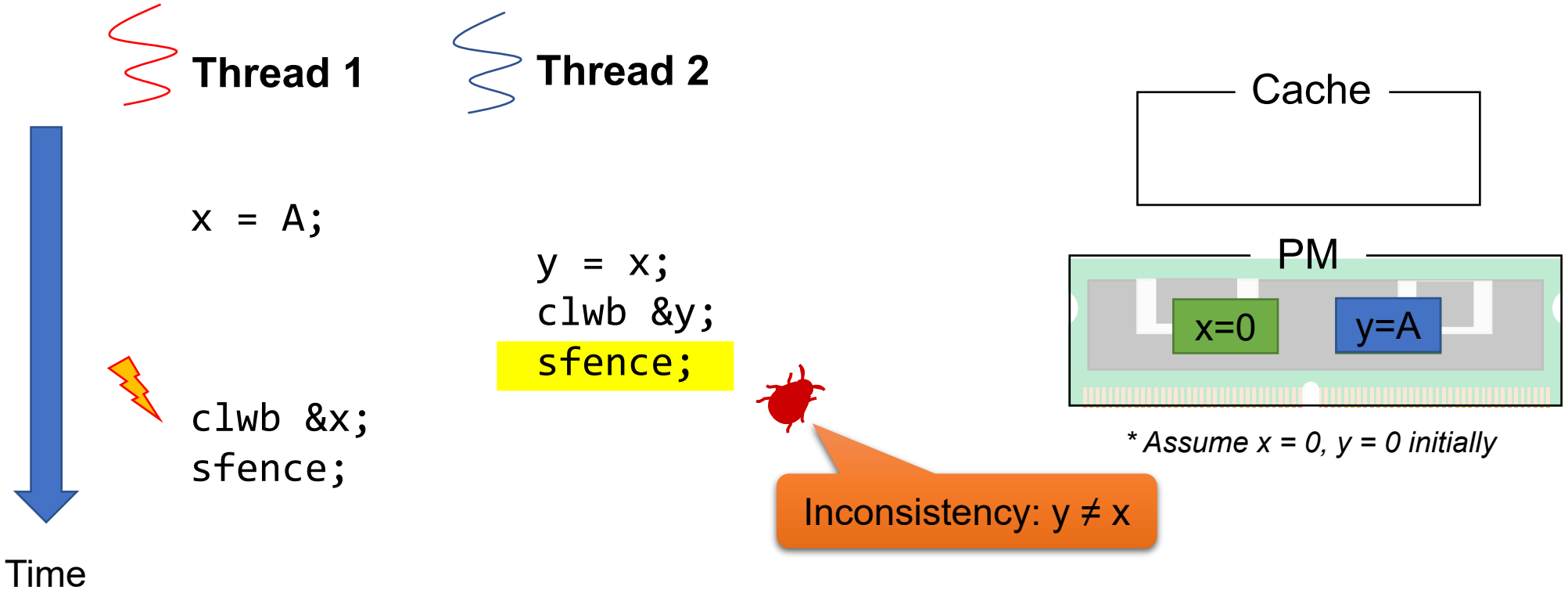

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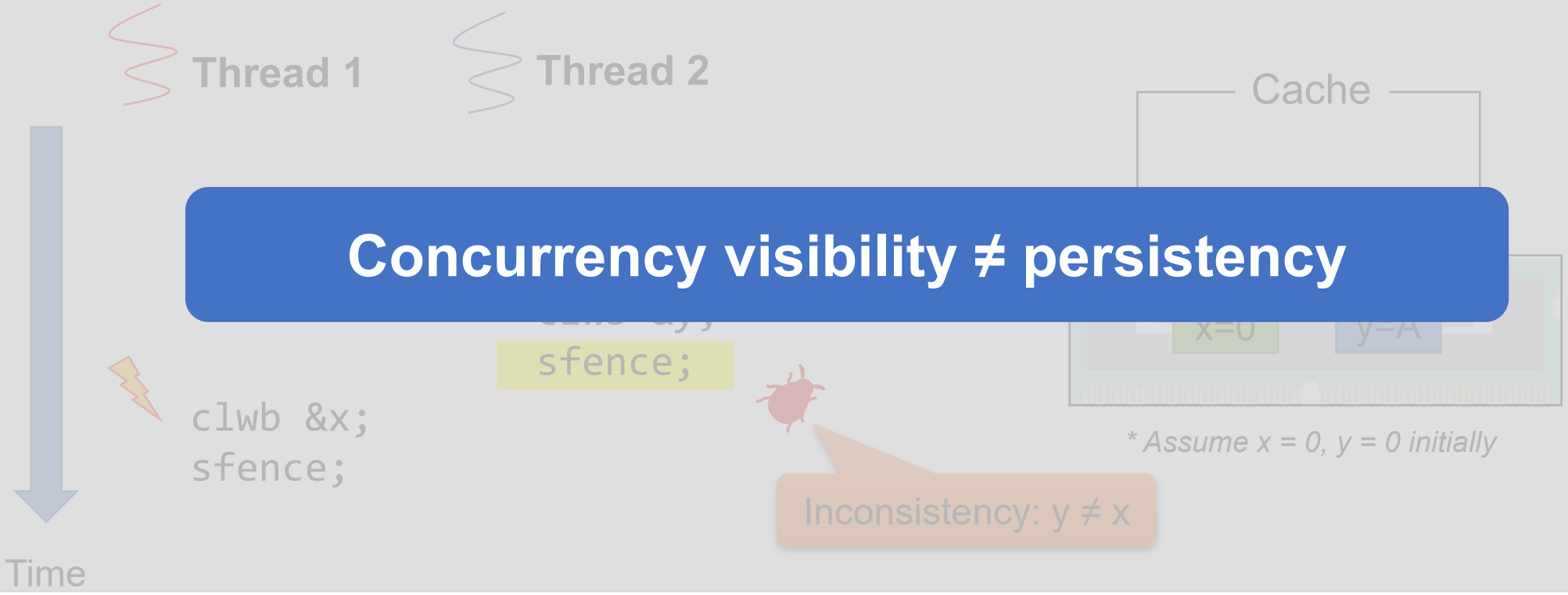

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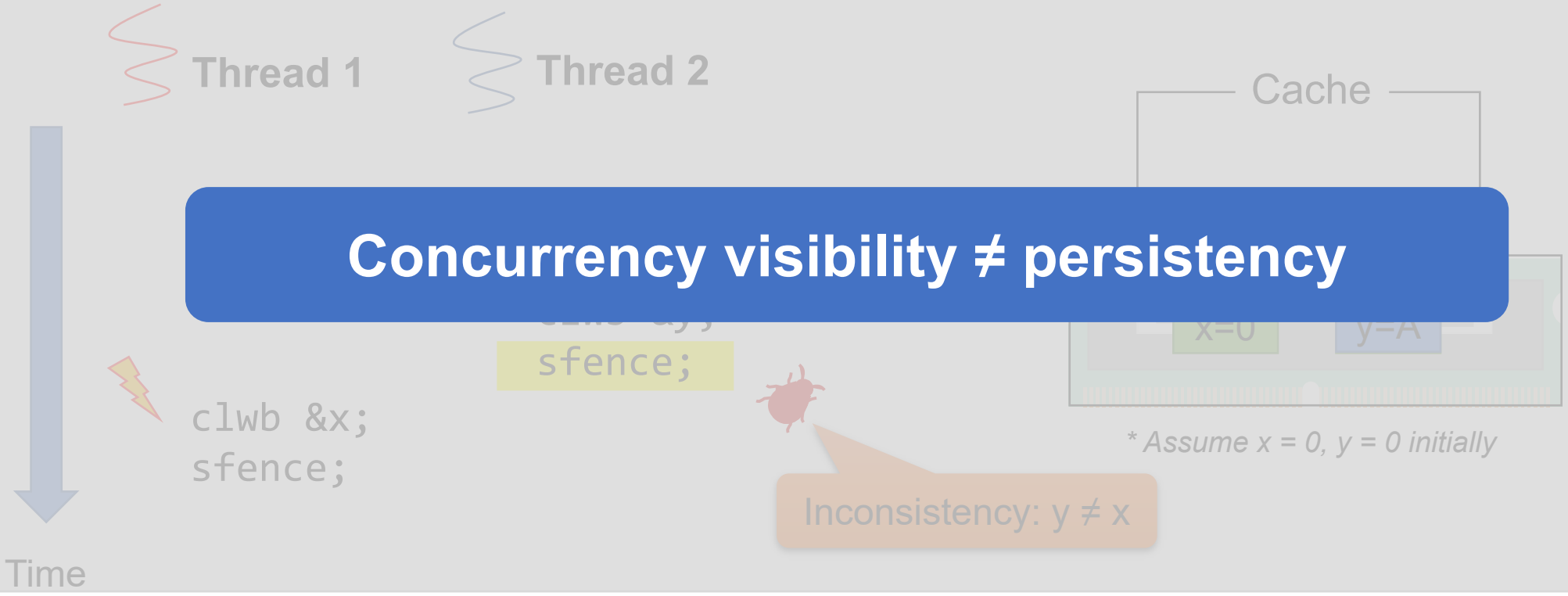

No PM debugging tools detect buggy thread interleavings!

Summary of Debugging Tools

➢ Targets and platforms

	Sequential Bugs	Concurrency Bugs
DRAM	• KLEE [OSDI '08] • LLVM sanitizers: AddressSanitizer [ATC '12], MemorySanitizer [CGO '15], … • …	• AVIO [ASPLOS '06] • TSVD [SOSP '19] • Krace [S&P '20] • Kard [ASPLOS '21] • …
PM	• XFDetector [ASPLOS '20] • AGAMOTTO [OSDI '20] • PMDebugger [ASPLOS '21] • WITCHER [SOSP '21] • …	Our approach: PMRace

Challenges for PM Concurrency Bug Detection

- Exponential interleaving search space
  - Exponential growth rate with respect to instructions

Thread 1

```
x = A;
clwb &x;
sfence;
```

Thread 2

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y = x;
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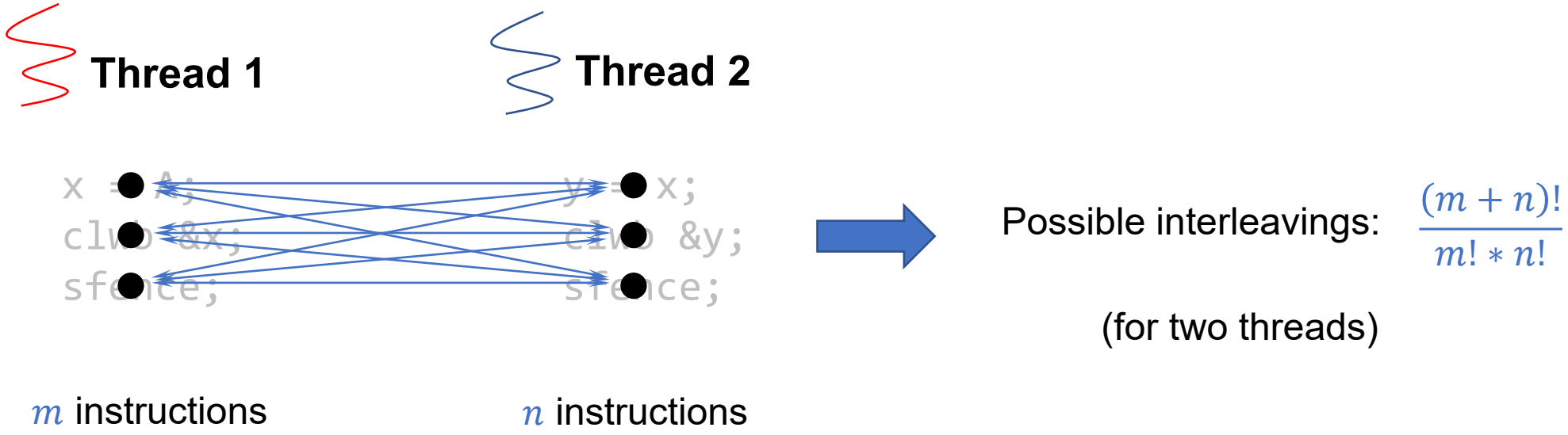

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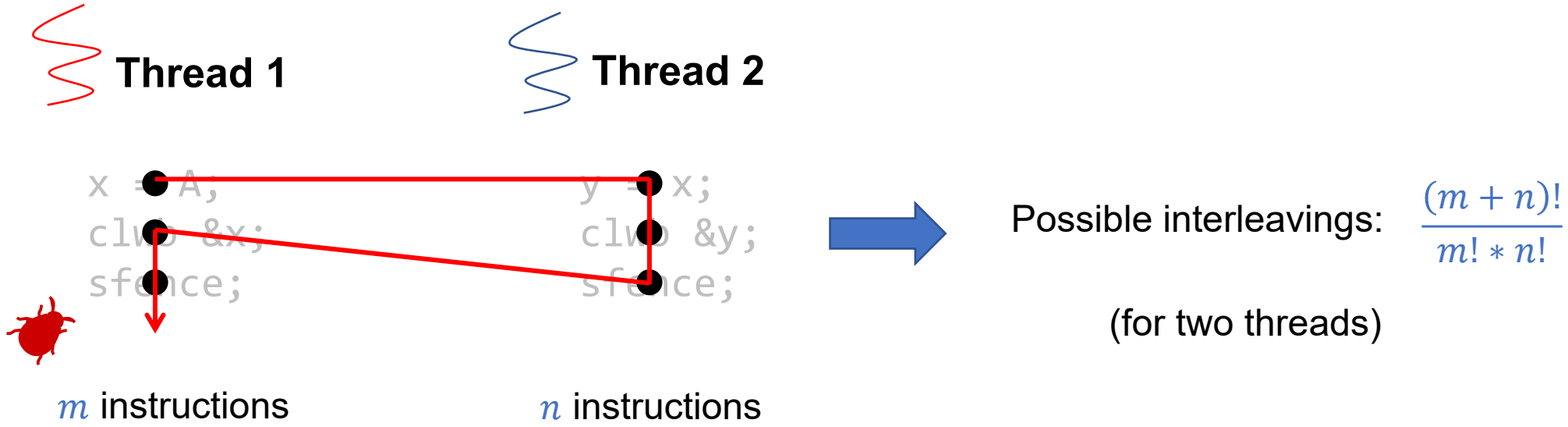
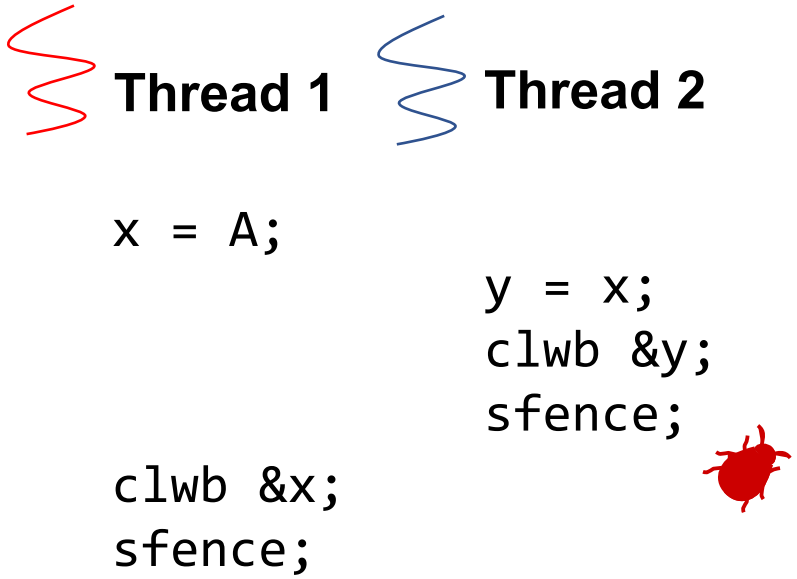


Challenges for PM Concurrency Bug Detection

- Exponential interleaving search space

- False positive
  - Definition: a detected bug is not a true bug
  - Reasons: inaccurate checkers, application-specific recovery…




```
Recover() {
  // Assume x = 0, y = 0 initially
  if (y != 0 && y != x) {
    // Handle inconsistent x and y
  }
}
```

An example of custom recovery code

Our Approach: PMRace

- Two new PM concurrency bug patterns
  - *PM Inter-thread Inconsistency* and *PM Synchronization Inconsistency*
- A fuzzer for PM concurrency bugs
  - Exponential interleaving: PM-aware coverage-guided fuzzing
  - False positive: Post-failure validation
- Found 14 bugs in 5 concurrent PM programs

The Two Bug Patterns

- PM Inter-thread Inconsistency
  - Durable side effects (e.g., PM writes) based on non-persisted data written by other threads

Thread 1

Thread 2

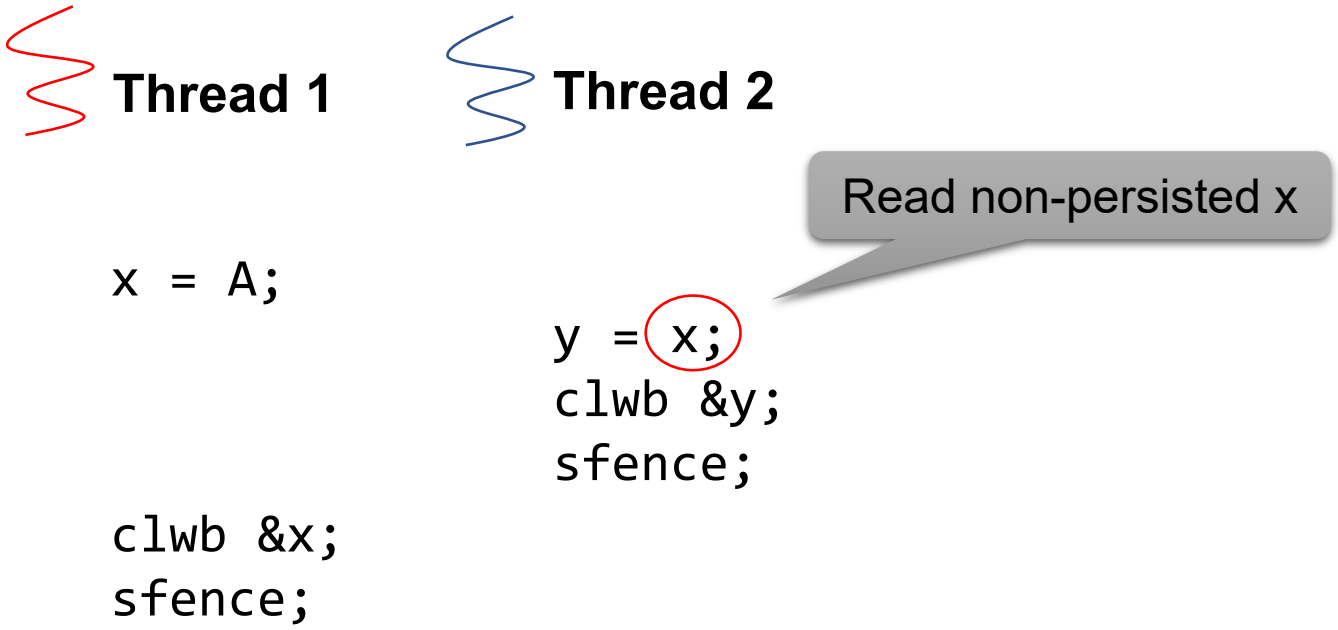
```
x = A;
```

```
clwb &x;
sfence;
```

```
y = x;
clwb &y;
sfence;
```

The Two Bug Patterns

- PM Inter-thread Inconsistency
  - Durable side effects (e.g., PM writes) based on non-persisted data written by other threads



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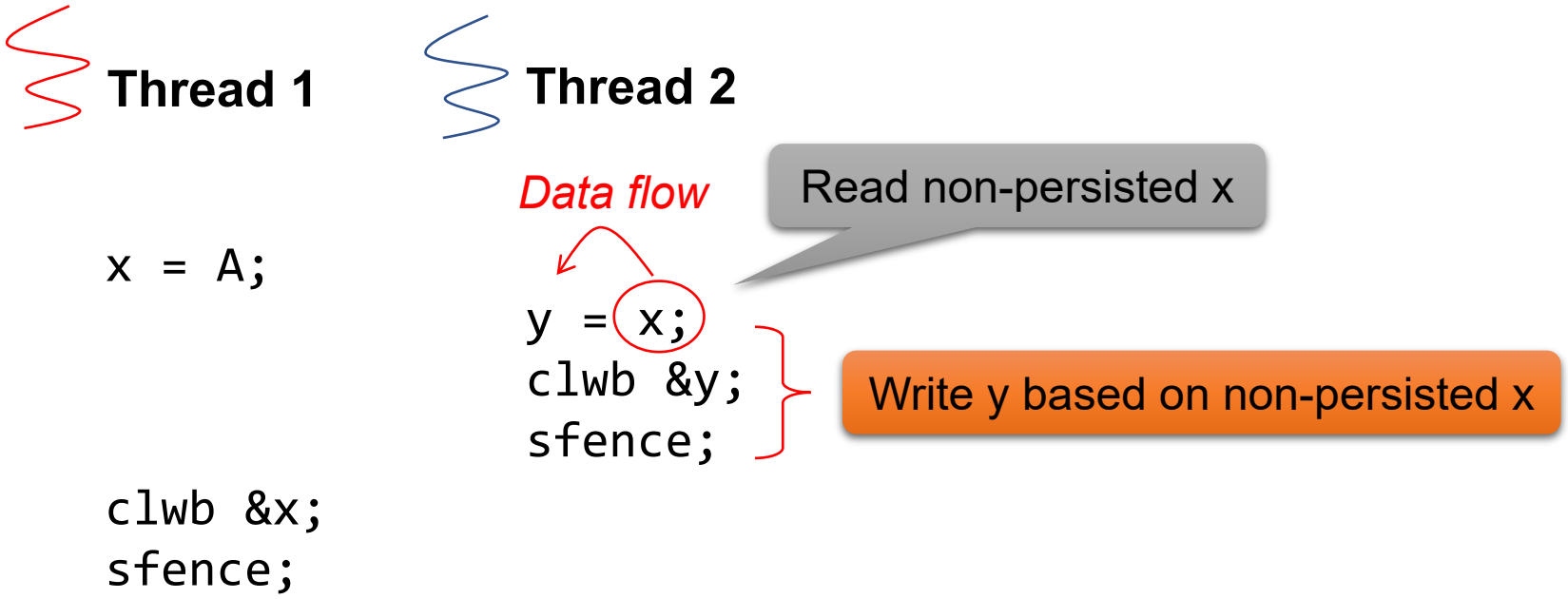

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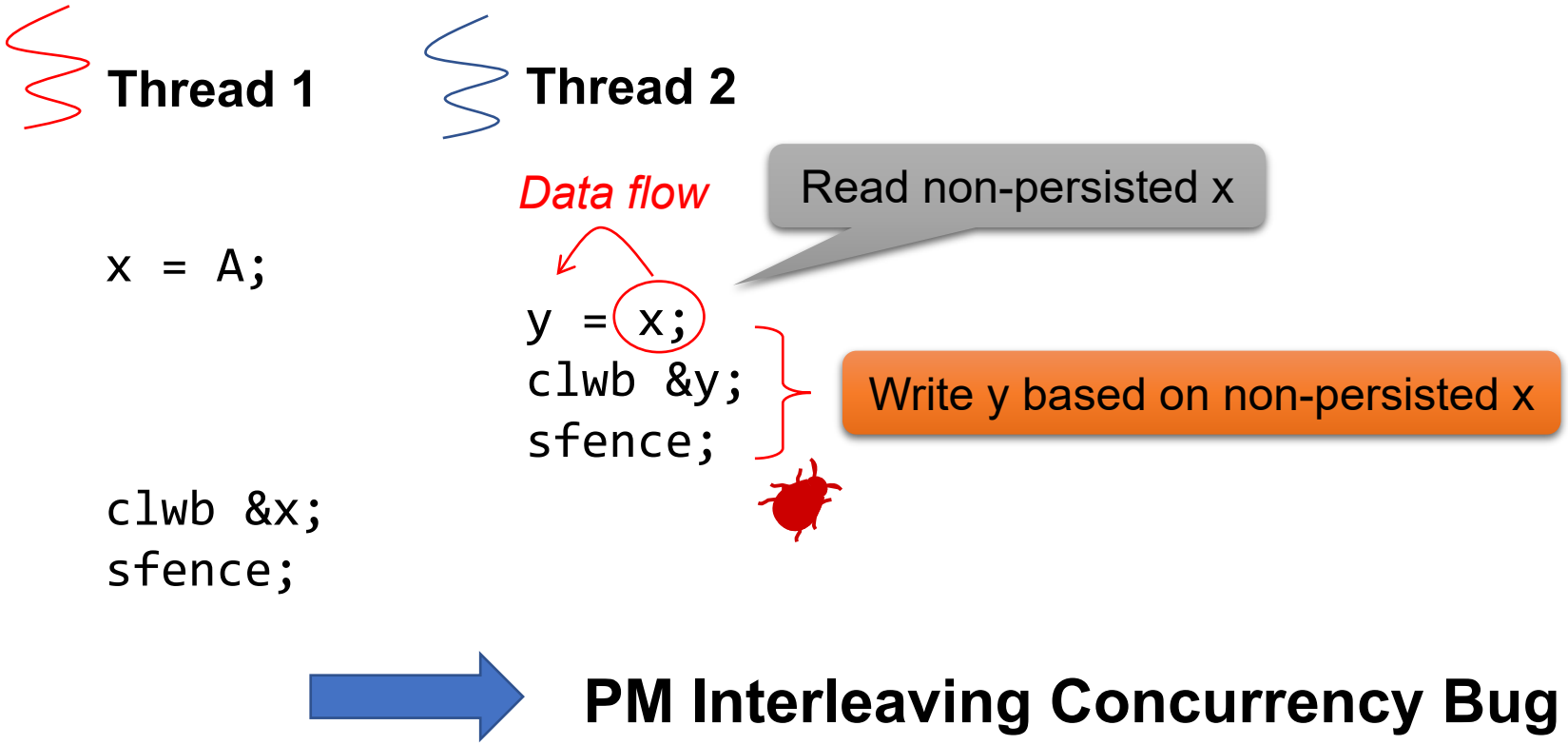
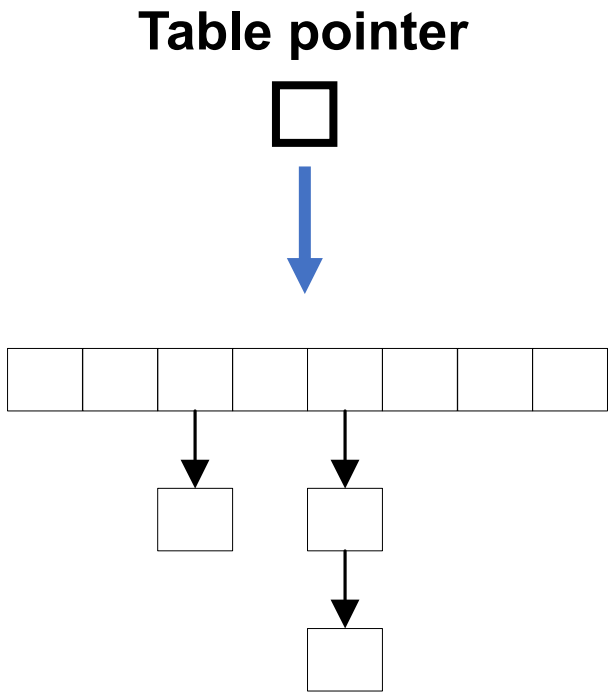


PM Interleaving Concurrency Bug

A PM Inter-thread Inconsistency in P-CLHT

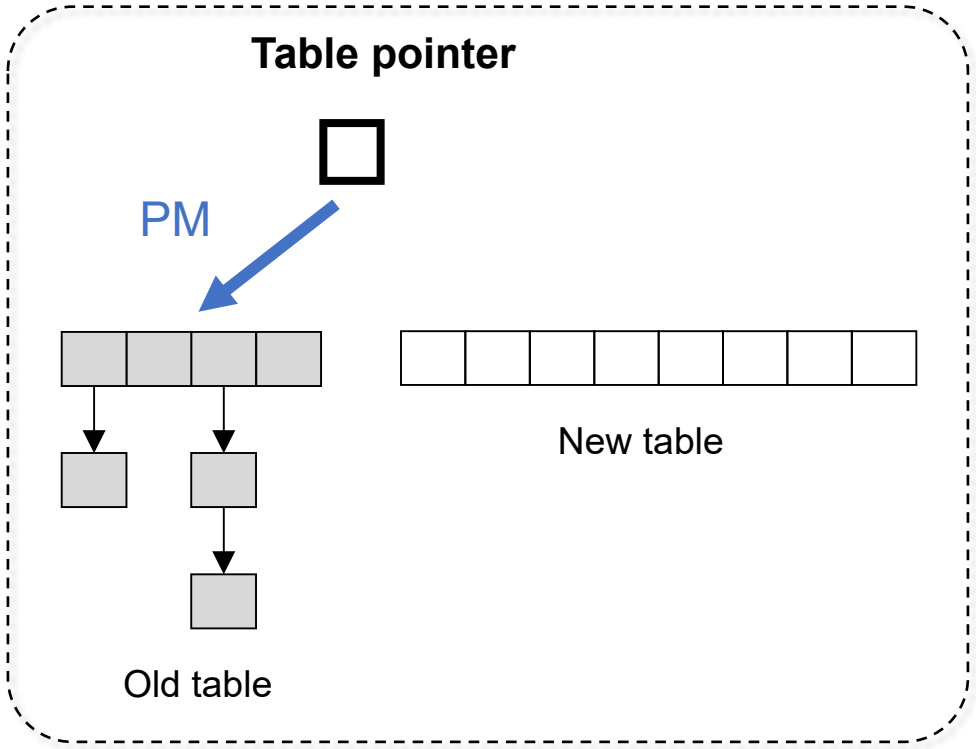
- P-CLHT from RECIPE [SOSP '19]
  - A chained hash table for PM
  - Lock-free read and bucket-grained locks for write



A PM Inter-thread Inconsistency in P-CLHT

Thread 1: ht_resize_pes

```
// Swap the hash table pointer for resizing
SWAP_U64(h->ht_off, pmemobj_oid(ht_new).off);
```




```
clwb(&h->ht_off); sfence();
```

Thread 2: ht_put

```
// Insert a key-value item
hashtable = clht_ptr_from_off(h->ht_off);
bin = clht_hash(hashtable, key)
bucket = clht_ptr_from_off(hashtable->table_off) + bin;

// Acquire the bucket lock
lock = &bucket->lock;
while (!LOCK_ACQ(lock, hashtable))
{
  ...
}

// Find an empty slot in the bucket
bucket->val[j] = val;
...
clwb(&bucket->val[j]); sfence();
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** The code is simplified for presentation*

A PM Inter-thread Inconsistency in P-CLHT

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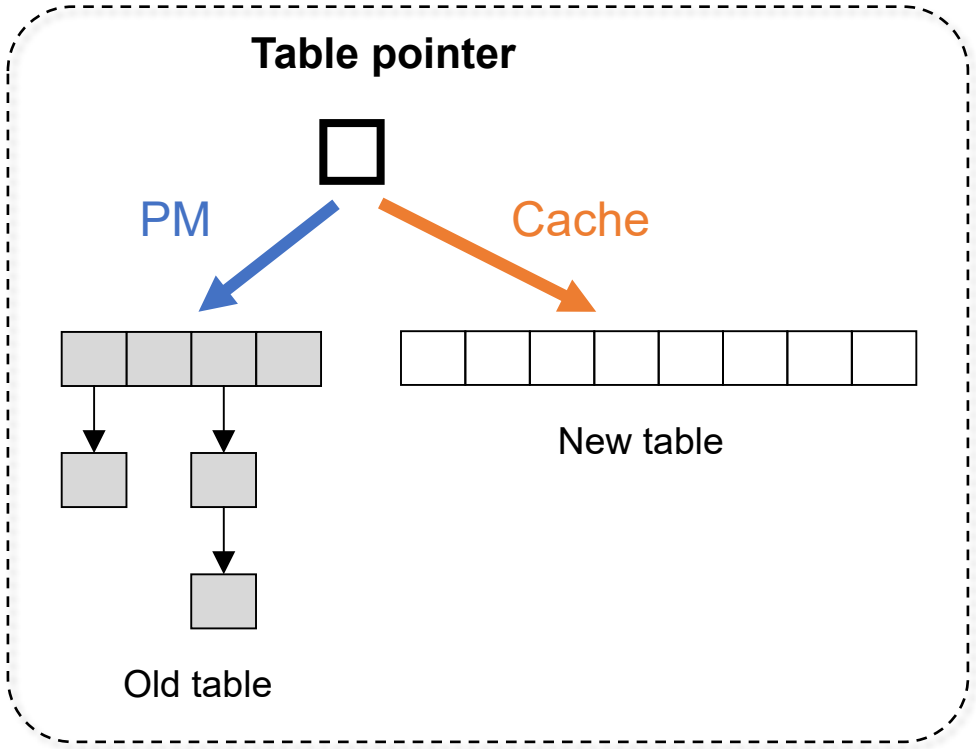


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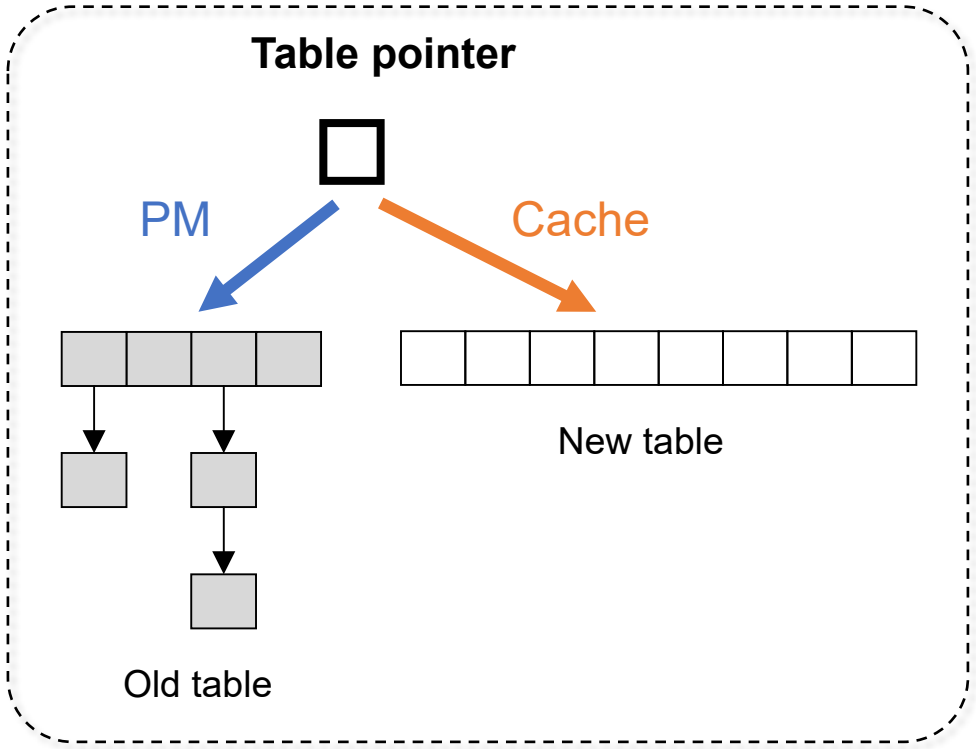


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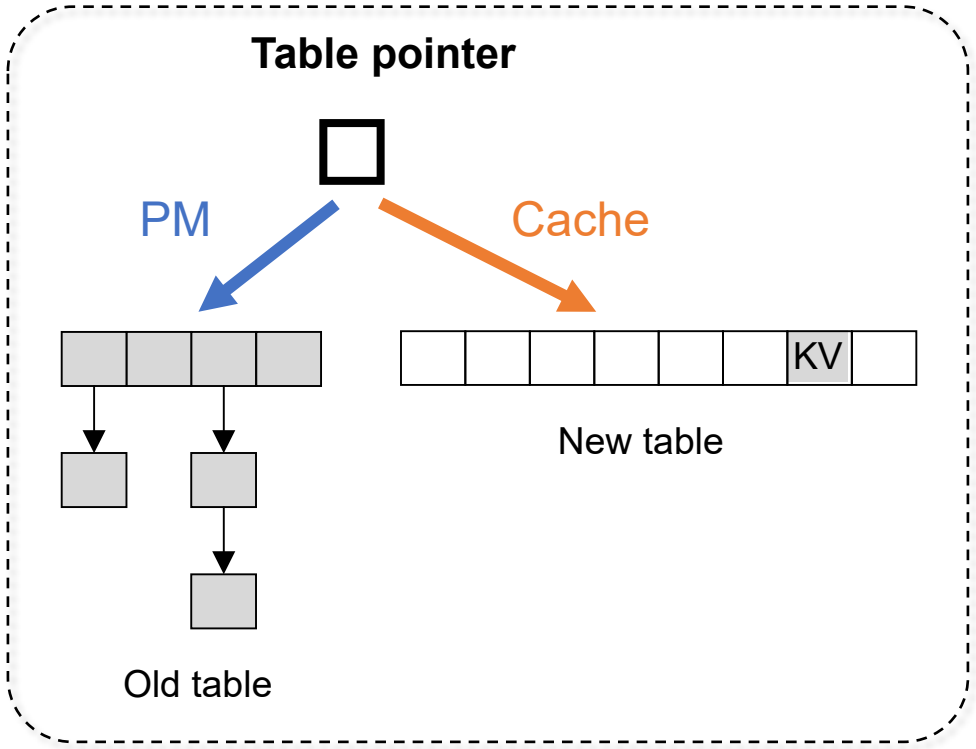


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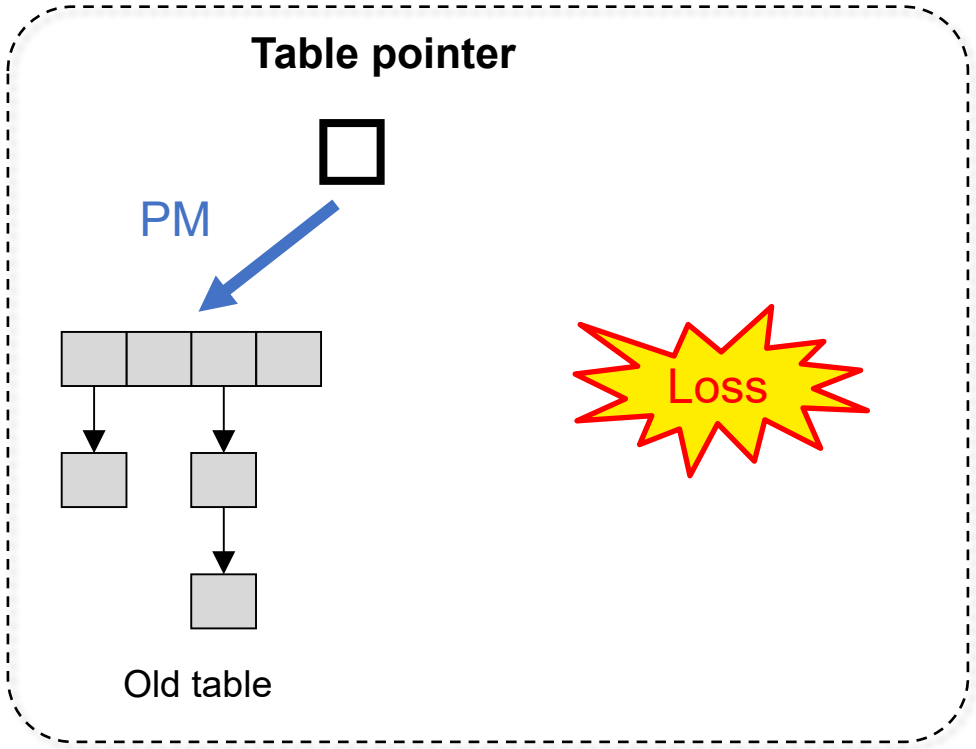


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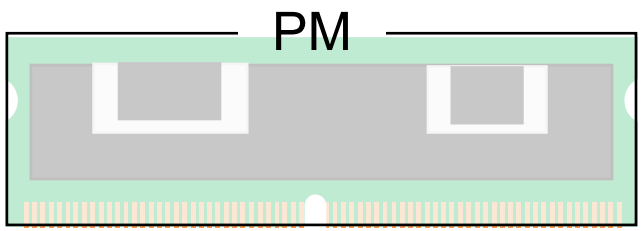
The Two Bug Patterns

- PM Inter-thread Inconsistency
  - Durable side effects (e.g., PM writes) based on non-persisted data written by other threads

- PM Synchronization Inconsistency
  - Unreleased synchronization data after restarts

```
lock(&g);
x = A;
…
unlock(&g);
```



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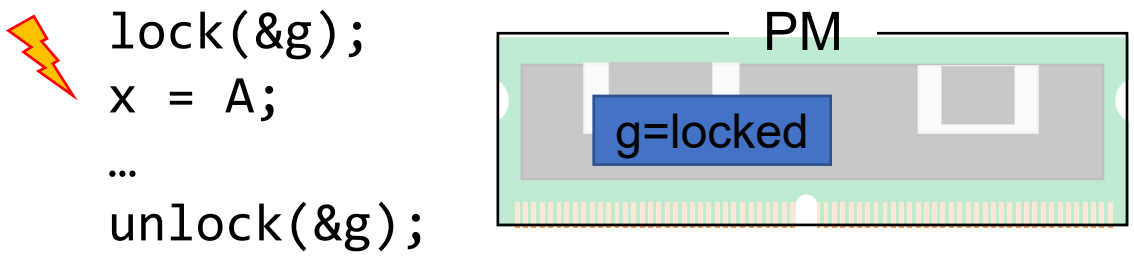

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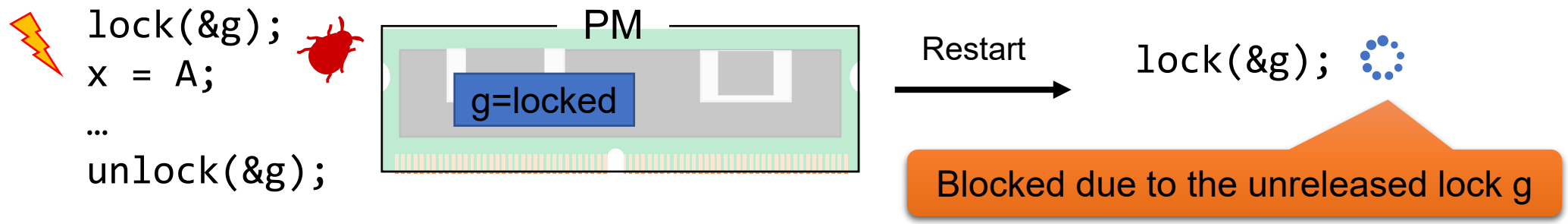
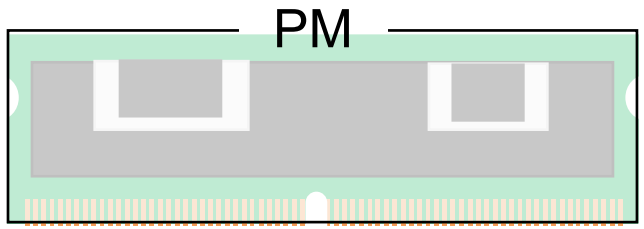
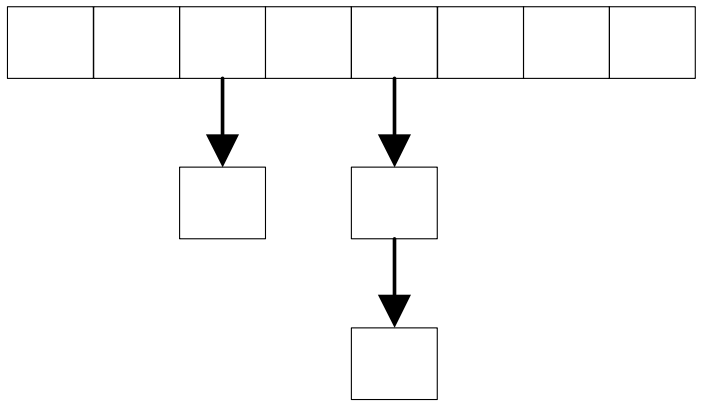


PM Execution Context Bug

A PM Synchronization Inconsistency in P-CLHT





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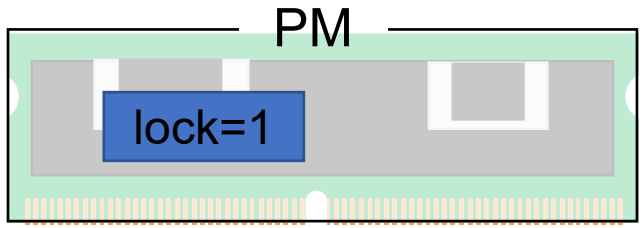
// Acquire the bucket lock
lock = &bucket->lock;
while (!LOCK_ACQ(lock, hashtable))
{
  ...
}

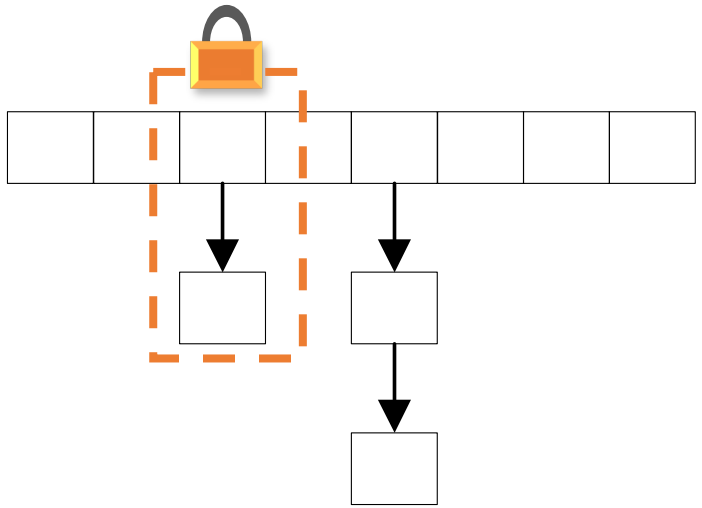
// Find an empty slot in the bucket
bucket->val[j] = val;
...
clwb(&bucket->val[j]); sfence();
movnt64(&bucket->key[j], key); sfence();

LOCK_RLS(lock);
```

** The code is simplified for presentation*

A PM Synchronization Inconsistency in P-CLHT





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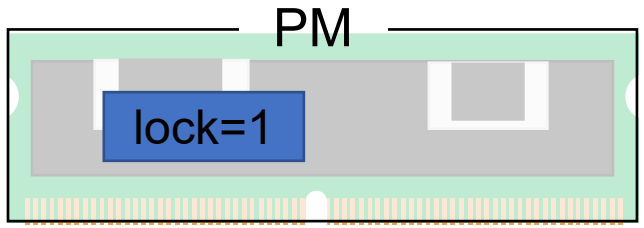

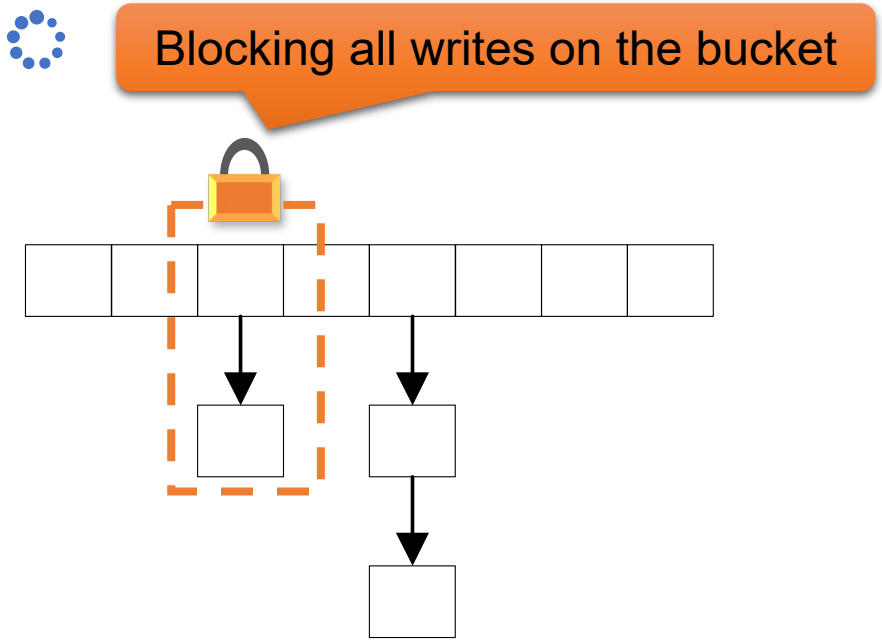

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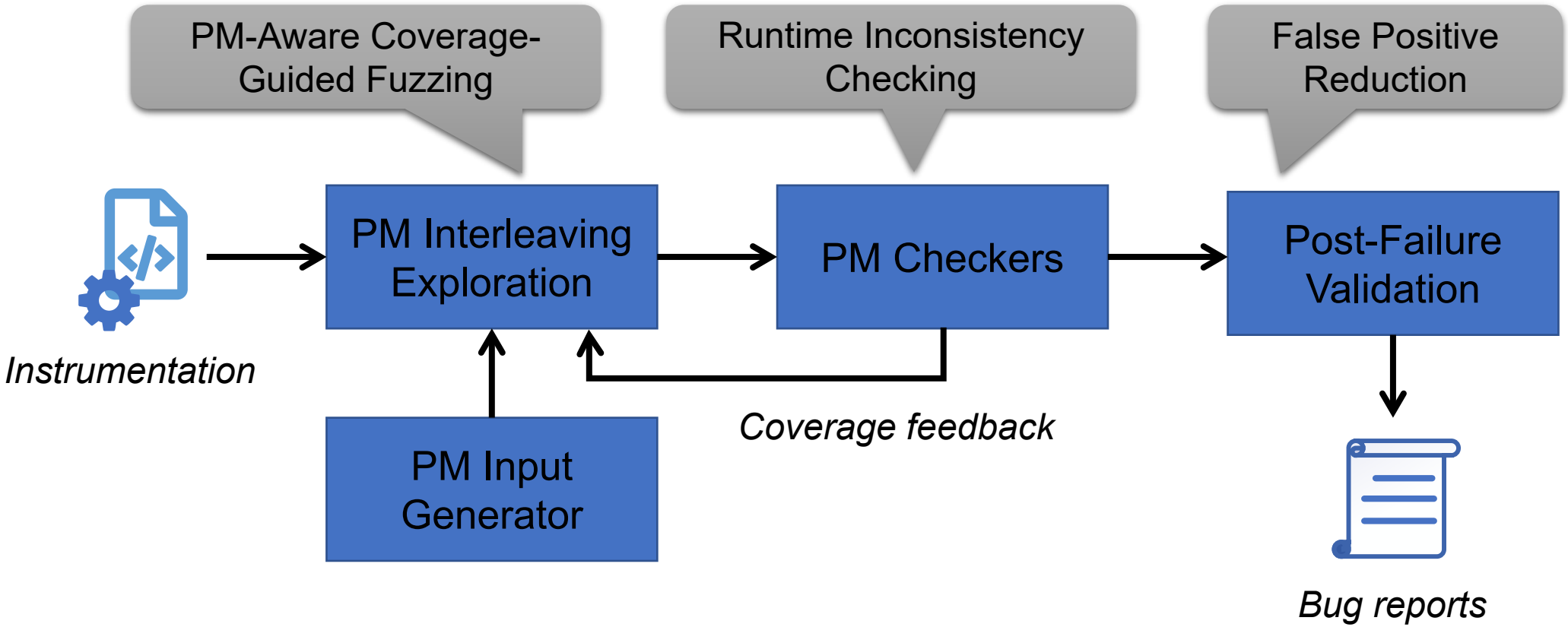
PMRace Overview



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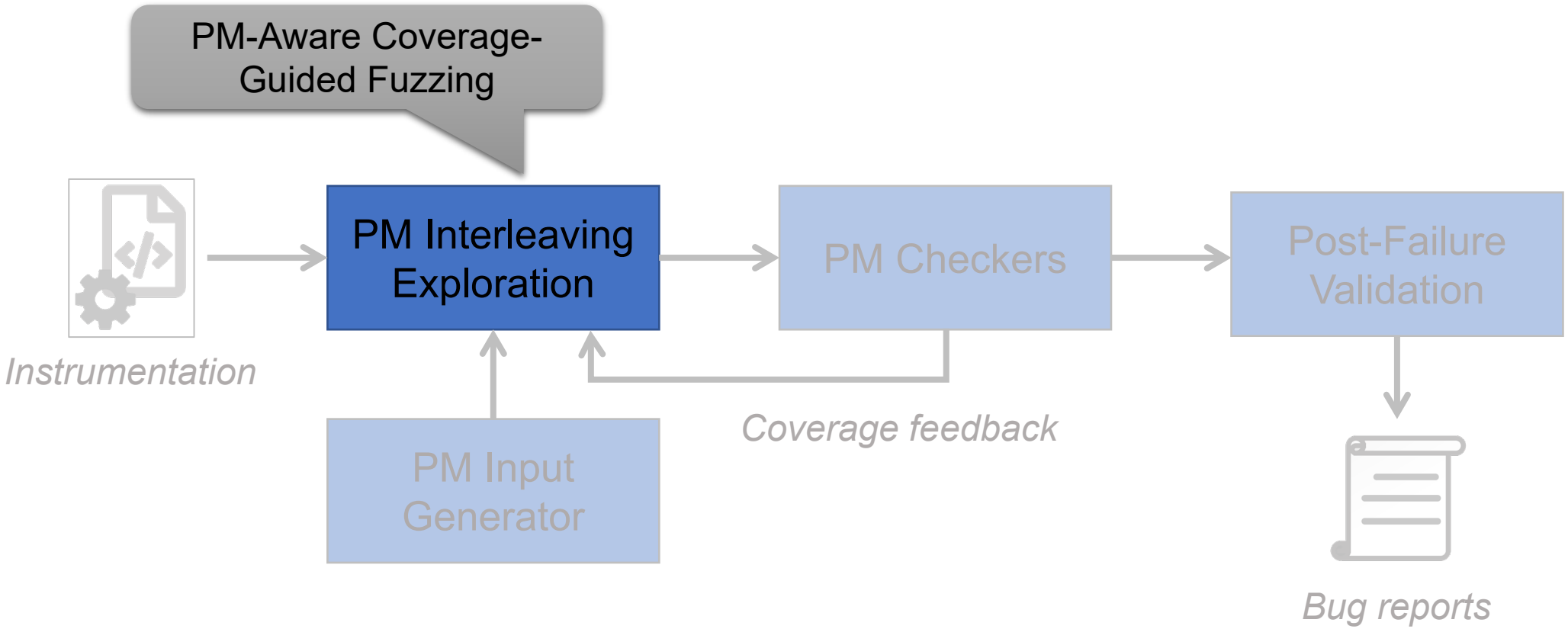
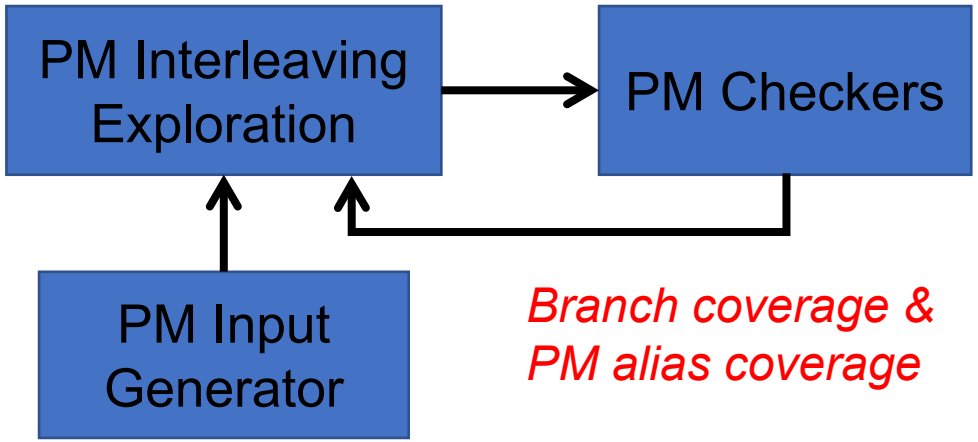


PM Alias (Pair) Coverage

- Recording concurrent PM accesses to the same address
- Guiding fuzzing to test “new” interleavings



PM-Aware Interleaving Exploration

- Exploration scheme
  - Driving the execution towards reading non-persisted data

Thread 1

```
x = A;
clwb &x;
sfence;
```

Thread 2

```
y = x;
clwb &y;
sfence;
```

PM-Aware Interleaving Exploration

- Exploration scheme
  - Driving the execution towards reading non-persisted data
  - Step 1: preemption point selection
    - PM accesses to shared data
    - A priority queue of PM access

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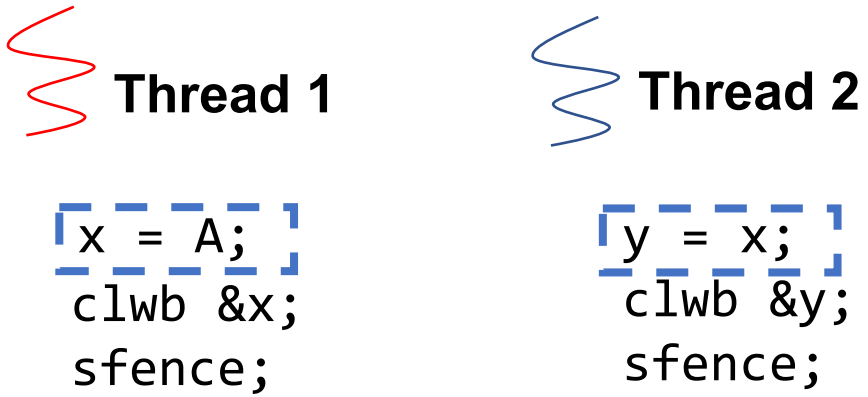

PM-Aware Interleaving Exploration

- Exploration scheme
  - Driving the execution towards reading non-persisted data
  - Step 1: preemption point selection
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    - `cond_wait` before PM reads
    - `cond_signal` after corresponding PM writes and before flushes
    - Pitfalls and solutions… (refer to the paper)

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```
cond_wait(&m);
y = x;
clwb &y;
sfence;
```

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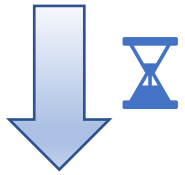

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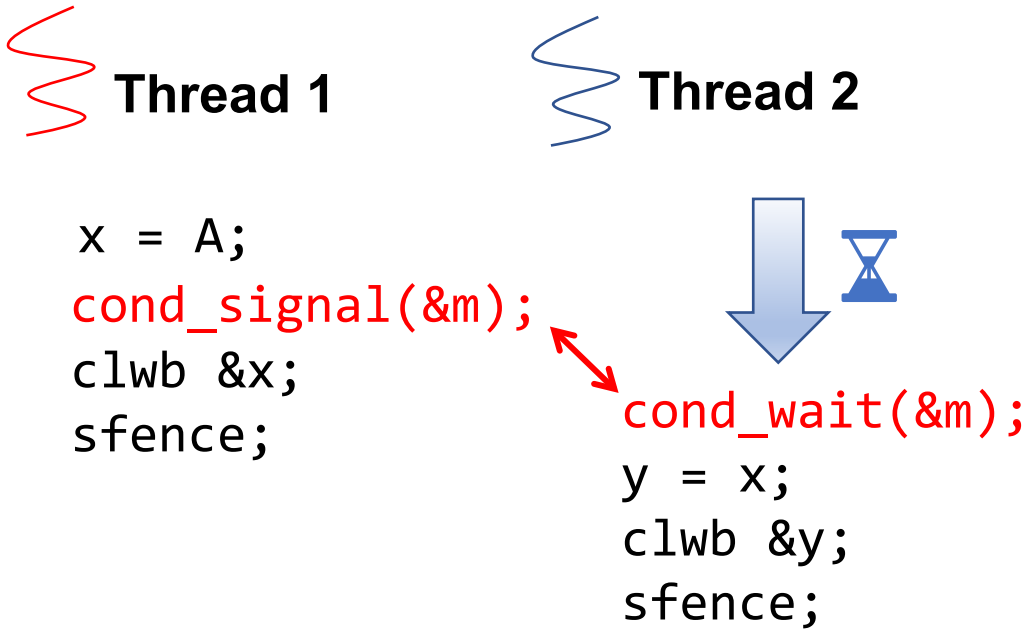

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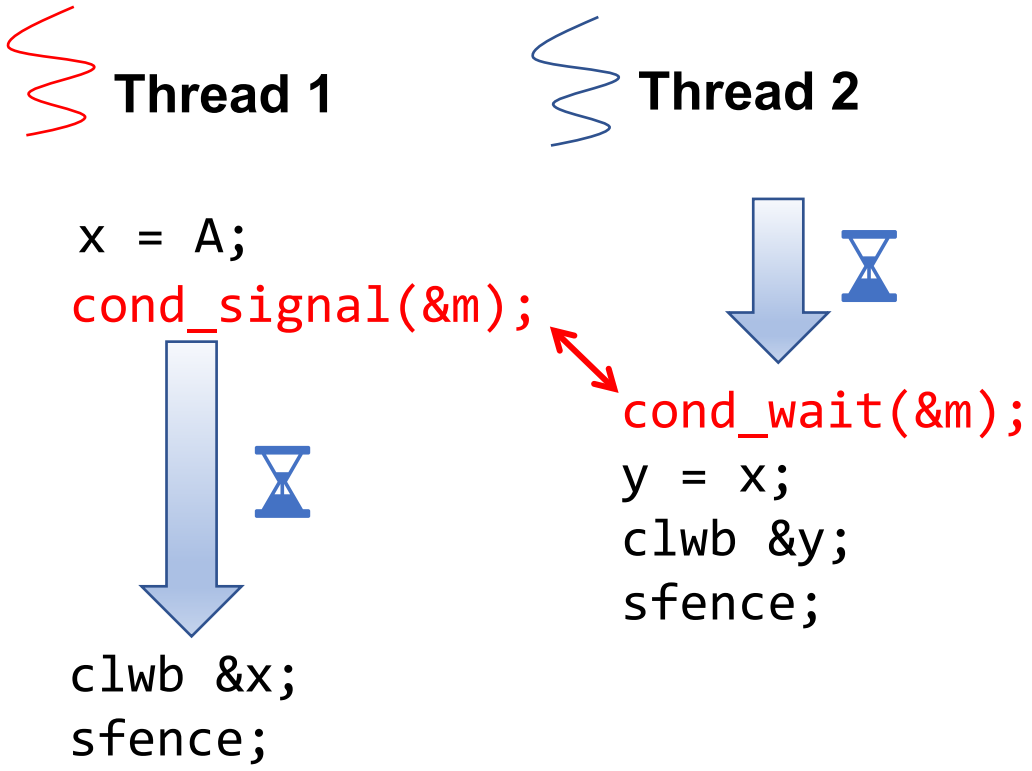

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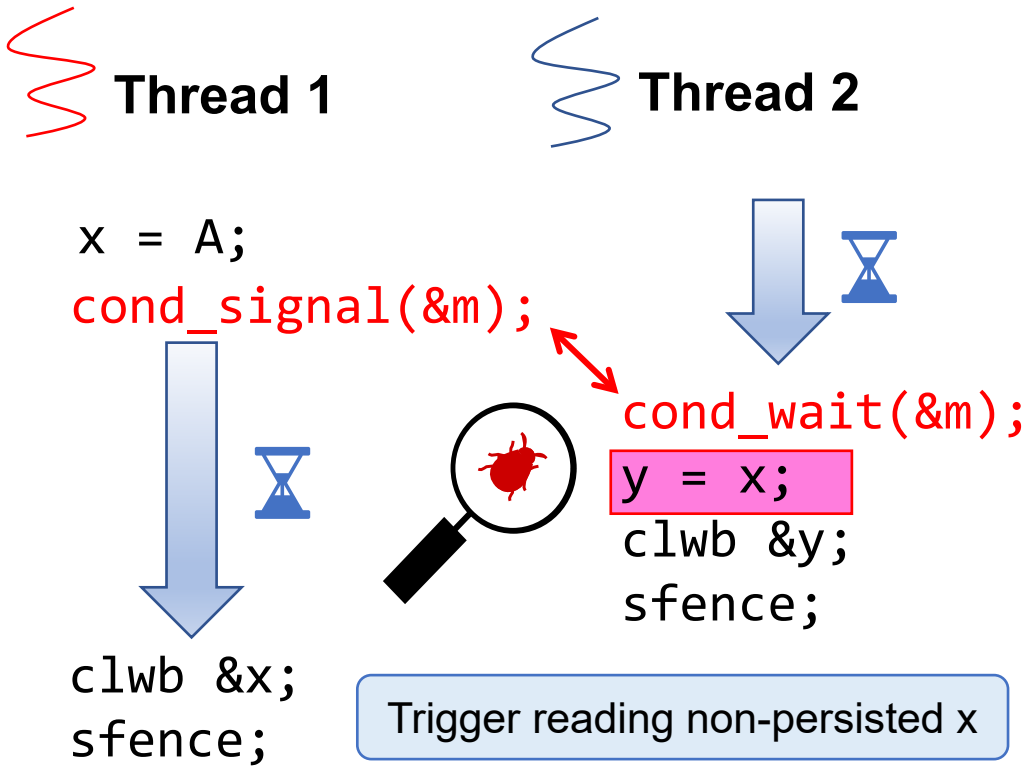

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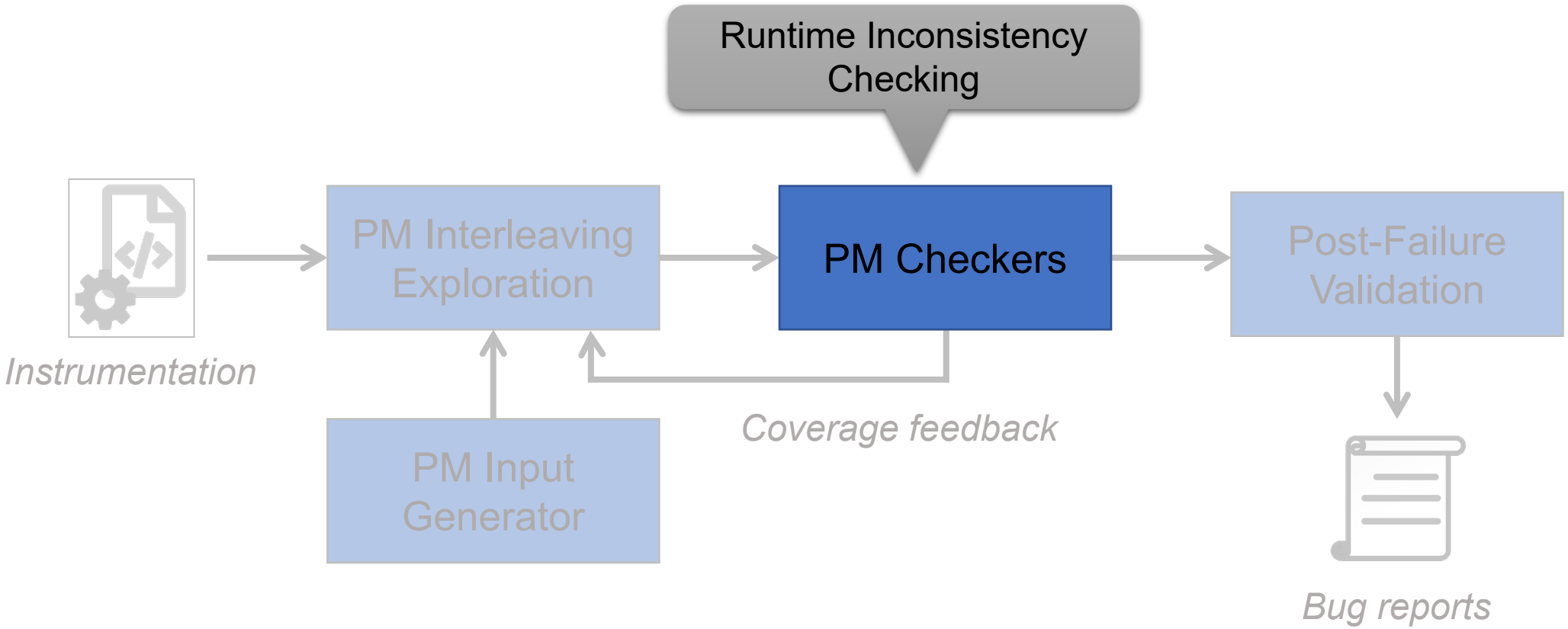
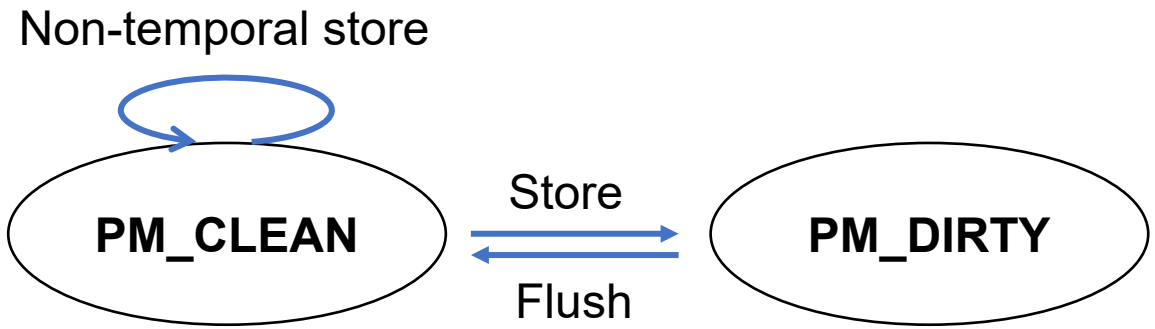


PM Inconsistency Checkers

- Persistency state tracking



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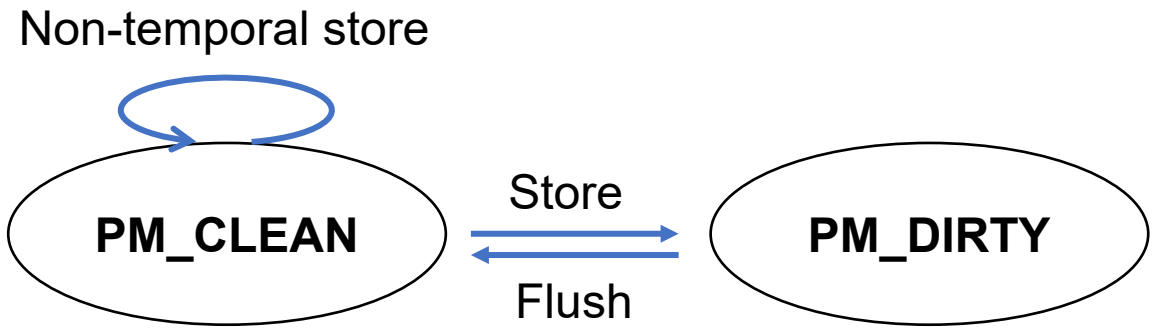

- Runtime PM checkers
  - *PM Inter-thread Inconsistency* when
    1. Reading non-persisted data (PM_DIRTY) and
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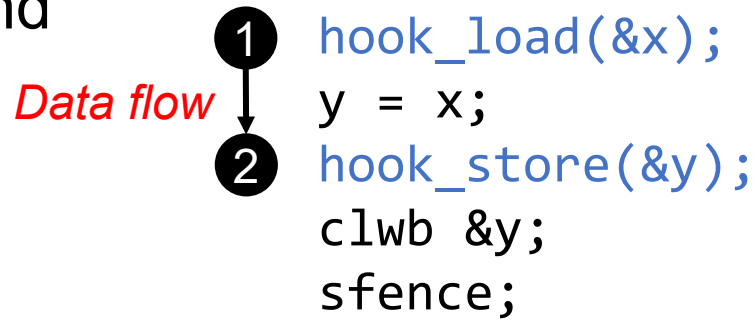

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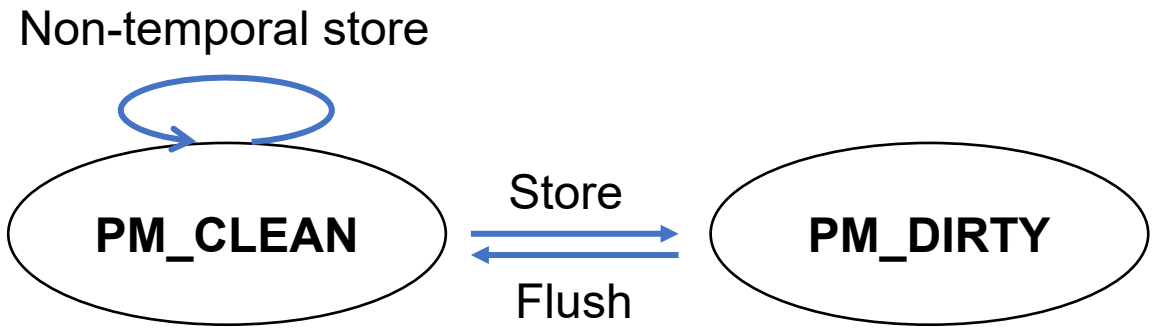
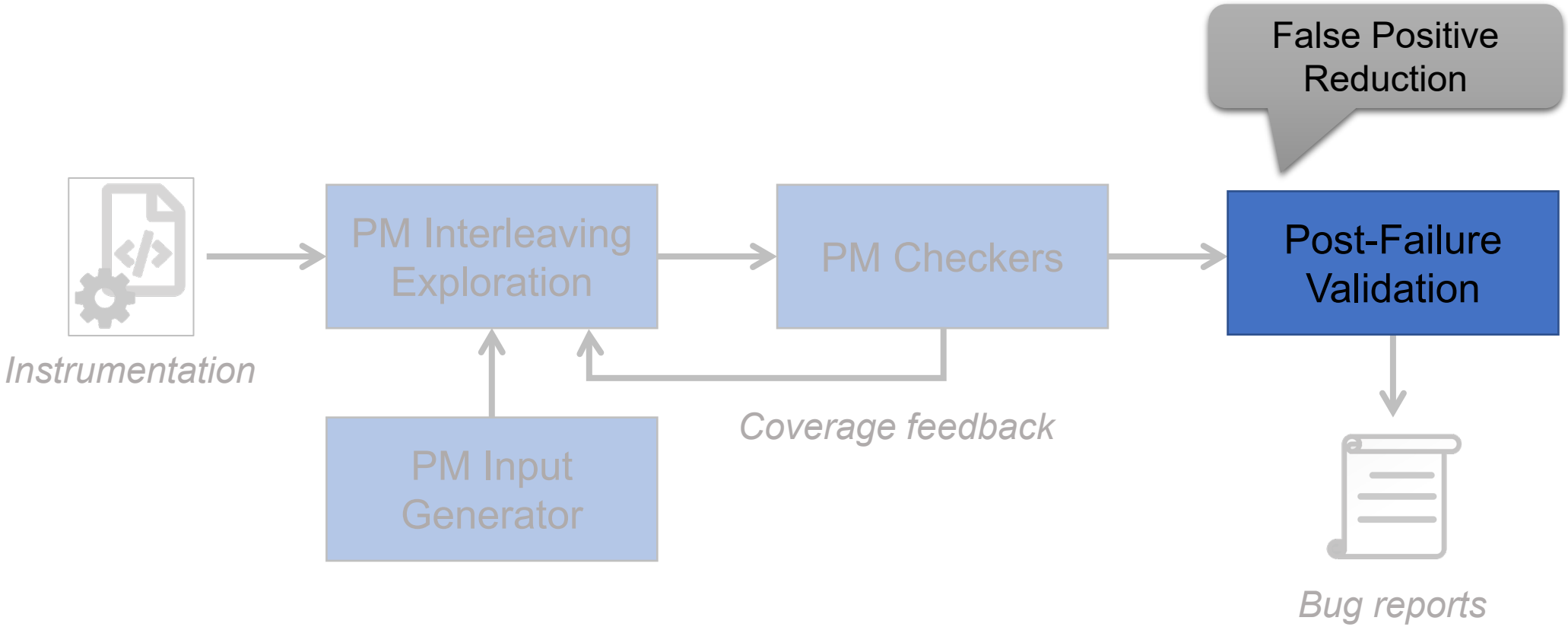


- Runtime PM checkers
  - *PM Inter-thread Inconsistency* when
    1. Reading non-persisted data (PM_DIRTY) and
    2. causing durable side effects (PM writes)
  - *PM Synchronization Inconsistency* when
    1. Updating annotated synchronization data

Data flow

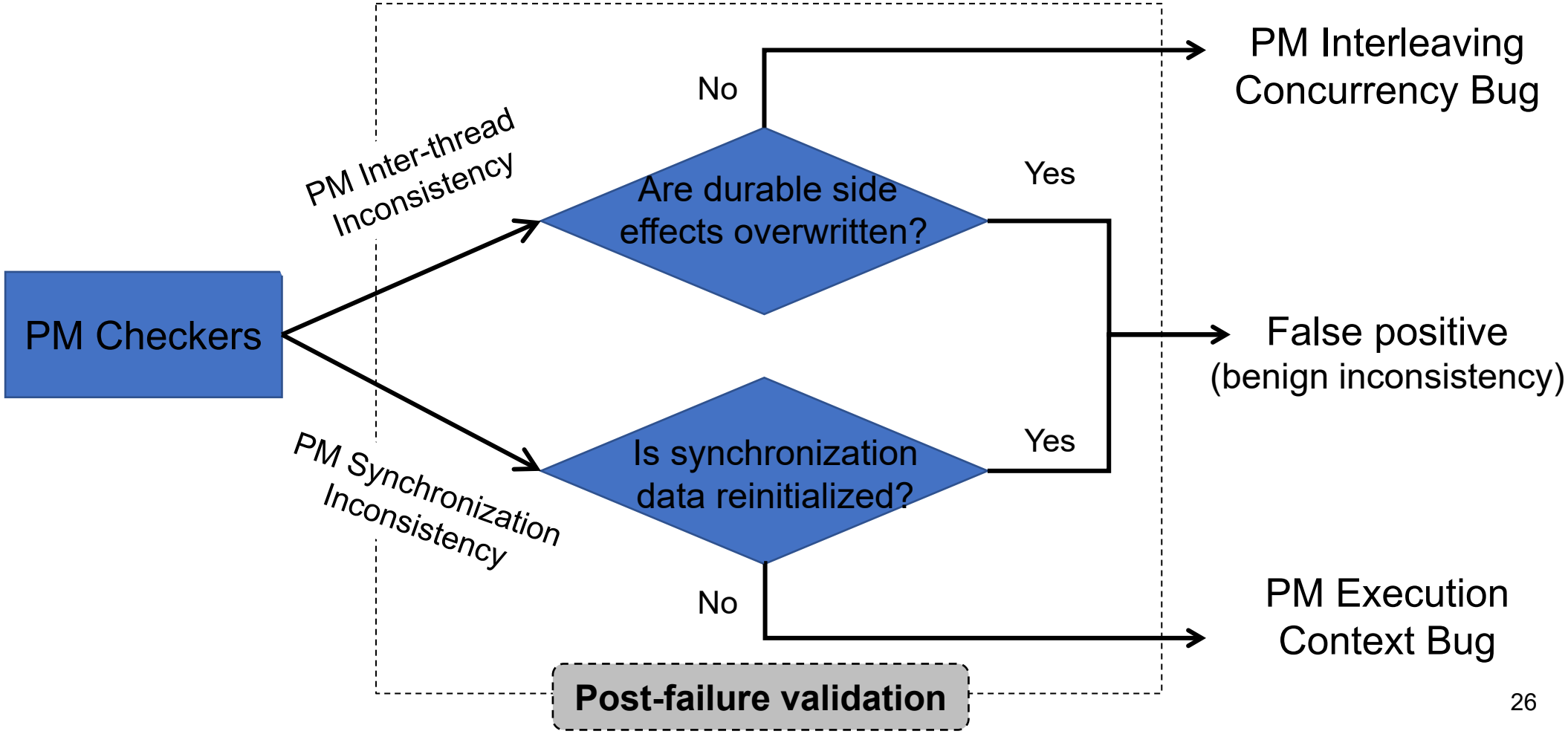
```
1  hook_load(&x);
   y = x;
2  hook_store(&y); 1
   clwb &y;
   sfence;
```

PMRace Overview



Post-Failure Validation

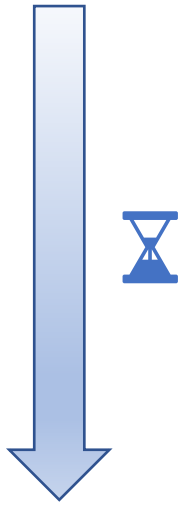
- To identify false positive (benign inconsistency)



An Example of Benign Inconsistency

Thread 1

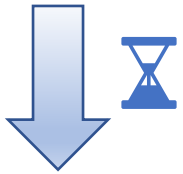
```
x = A;
hook_store(&x);
cond_signal(&m);
```



```
clwb &x;
sfence;
```

Thread 2

```
cond_wait(&m);
```



```
hook_load(&x);
y = x;
hook_store(&y);
clwb &y;
sfence;
```

```
Recover() {
  // Assume x = 0, y = 0 initially
  if (y != 0 && y != x) {
    // Handle inconsistent x and y
    x = 0;
    y = 0;
  }
}
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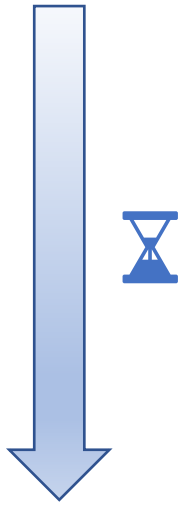

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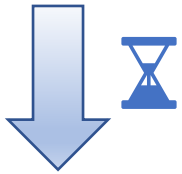

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PM checker: PM Inter-thread Inconsistency

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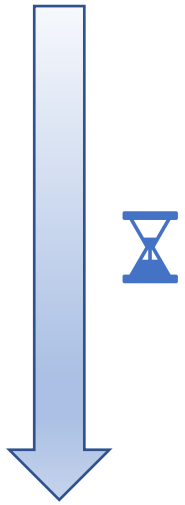

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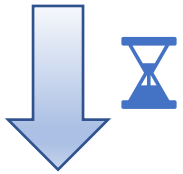

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Post-failure validation: benign inconsistency

PM checker: PM Inter-thread Inconsistency

Evaluation

- System configurations
  - Two 26-core Intel Xeon Gold 6230R CPUs
  - 1.5 TB Intel Optane PM 100 Series, 192 GB DRAM
- Tested 5 open-source concurrent PM programs based on PMDK

Systems	Scope	Concurrency
P-CLHT [SOSP '19]	Static hashing	Lock-based
Clevel Hashing [ATC '20]	PM-optimized hashing	Lock-free
CCEH [FAST '19]	Extendible hashing	Lock-based
FAST-FAIR [FAST '18]	B+-Tree	Lock-based
memcached-pmem	Key-value store	Lock-based

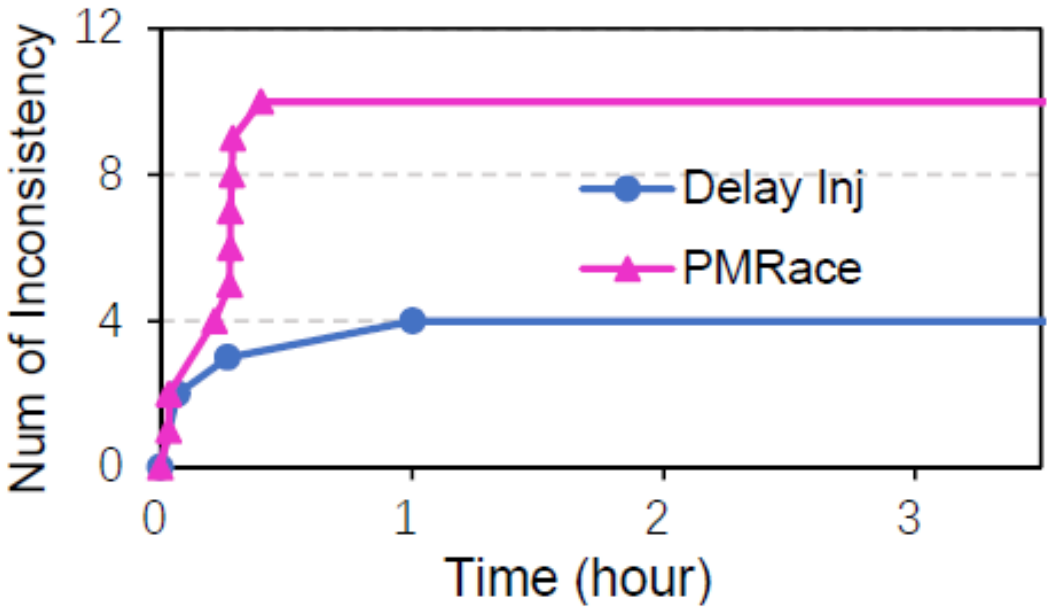
- Comparison
  - **PMRace**: our scheme
  - **Delay Inj**: PMRace with random delay injection for interleaving exploration

14 Bugs

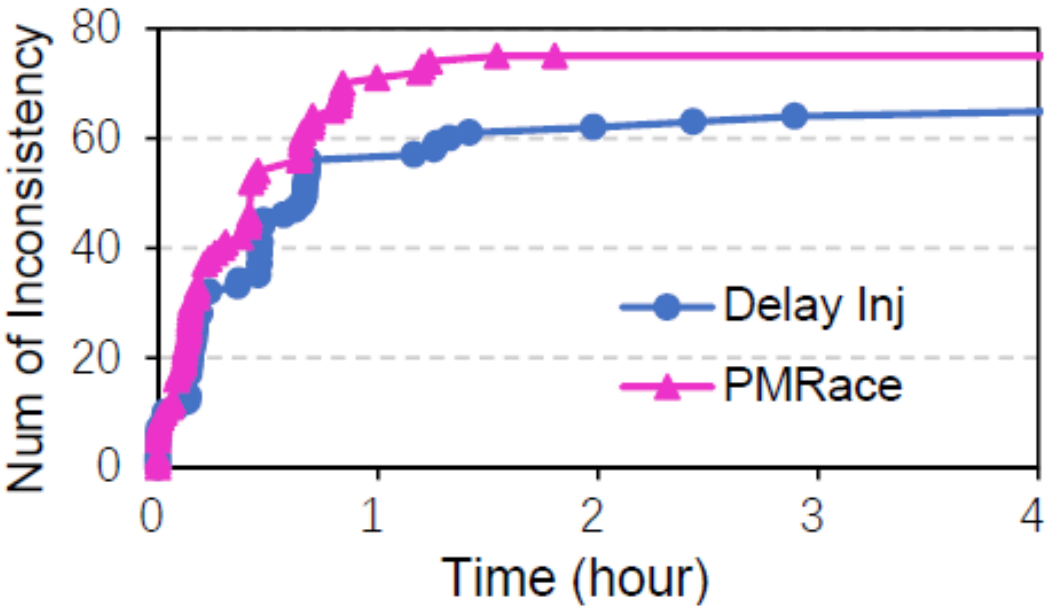
	#	Type	New	Description	Impact
P-CLHT	1	Inter	Y	read unflushed table pointer and insert items	data loss
	2	Sync	Y	do not initialize bucket locks after restarts	hang
	3	Intra	Y	read unflushed table pointer and perform GC	PM leakage
	4	Other	Y	read unflushed keys	redundant PM writes
	5	Other	Y	do not release bucket locks in update	hang
CCEH	6	Sync	Y	do not release segment locks after restarts	hang
	7	Intra	Y	read unflushed capacity and allocate segments	PM leakage
FAST-FAIR	8	Inter	Y	read unflushed pointer and insert data	data loss
memcached-pmem	9	Inter	Y	read unflushed value and write value	inconsistent data
	10	Inter	Y	read unflushed value and write value	inconsistent data
	11	Inter	N	read unflushed "prev" and write "slabs_clsid"	inconsistent data
	12	Inter	N	read unflushed "prev" and write "it_flags" or value	inconsistent index
	13	Inter	N	read unflushed "it_flags" and write value	inconsistent data
	14	Inter	N	read unflushed "slabs_clsid" and write "slabs_clsid" of others	inconsistent index

Inter: PM Inter-thread Inconsistency Intra: PM Intra-thread Inconsistency Sync: PM Synchronization Inconsistency

The Time to Identify PM Inter-thread Inconsistency



(1) P-CLHT



(2) FAST-FAIR

- PMRace efficiently triggers reading non-persisted data

Inconsistencies and False Positives

	PM Interleaving Concurrency Bug				PM Execution Context Bug		
	Inter-Cand	Inter	Filtered FP	Unique Bugs	Sync	Filtered FP	Unique Bugs
P-CLHT	35	10	0	1	4	3	1
clevel hashing	6	2	0	0	0	0	0
CCEH	15	0	0	0	1	0	1
FAST-FAIR	179	69	3	1	0	0	0
memcached-pmem	266	79	62	6	0	0	0
Total	501	160	65	8	5	3	2

Inter-Cand: PM Inter-thread Inconsistency Candidate
Filtered FP: Filtered false positives

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- Durable side effects refine inconsistencies
- Post-failure validation reduces false positives
- Limitation: false positives still exist due to lazy recovery mechanisms…

Conclusion

- PM-specific concurrency bugs are unexplored
- We identify two new PM concurrency bug patterns
- **PMRace**: the first tool to detect PM concurrency bugs
  - PM-aware coverage-guided fuzzing to accelerate interleaving exploration
  - Post-failure validation to reduce false positives
- Found 14 bugs in 5 concurrent PM programs
- Open-source at https://github.com/yhuacode/pmrace

Thanks!

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Homepage: https://chenzhangyu.github.io