Snapshotting Mechanisms
for
Persistent Memory-Mapped Files

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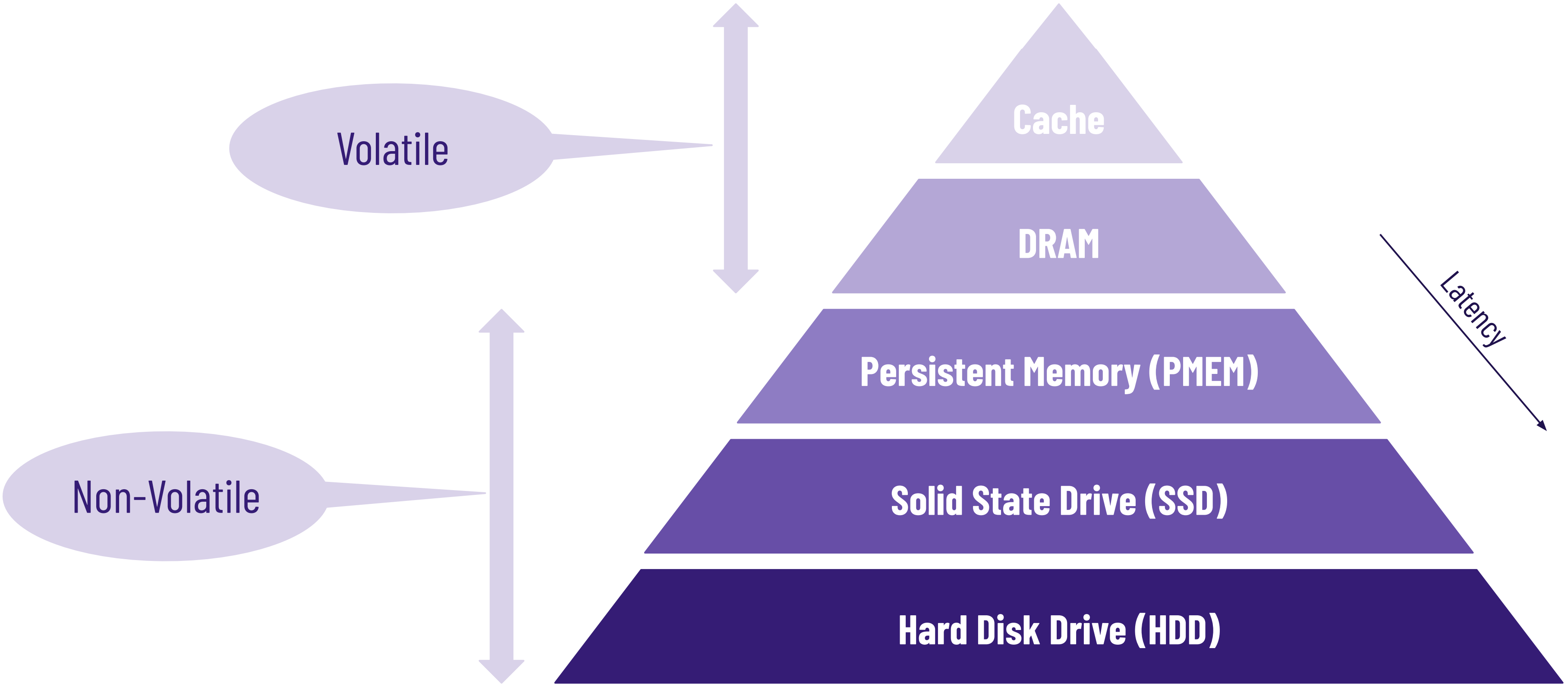
Persistent Memory in Memory Hierarchy



Background

- **Persistent memory** keeps data in memory after the power is lost.

Background

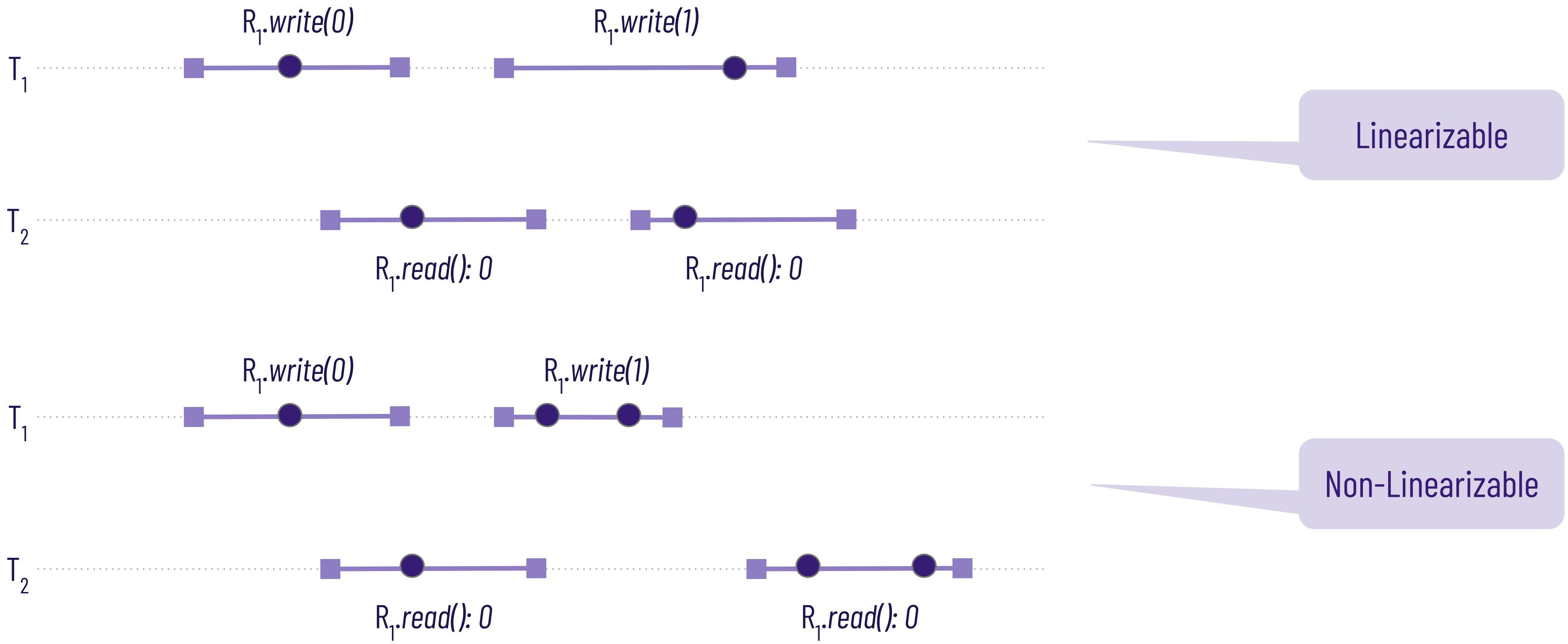
- Correctness Properties
  - **Linearizability**
  - **Durable Linearizability**
  - **Buffered Durable Linearizability**

Model

- **Threads**: The system consists of asynchronous entities, threads, that communicate using shared objects
- **Invocation** Event: It marks the initiation of an operation.
- **Response** Event: It signifies the conclusion of an operation.
- **Crash** Event: It signifies an unexpected system failure.
- **History**: A history models the system's execution as a **finite sequence** of *invocation*, *response*, and *crash* events.

Linearizability Example

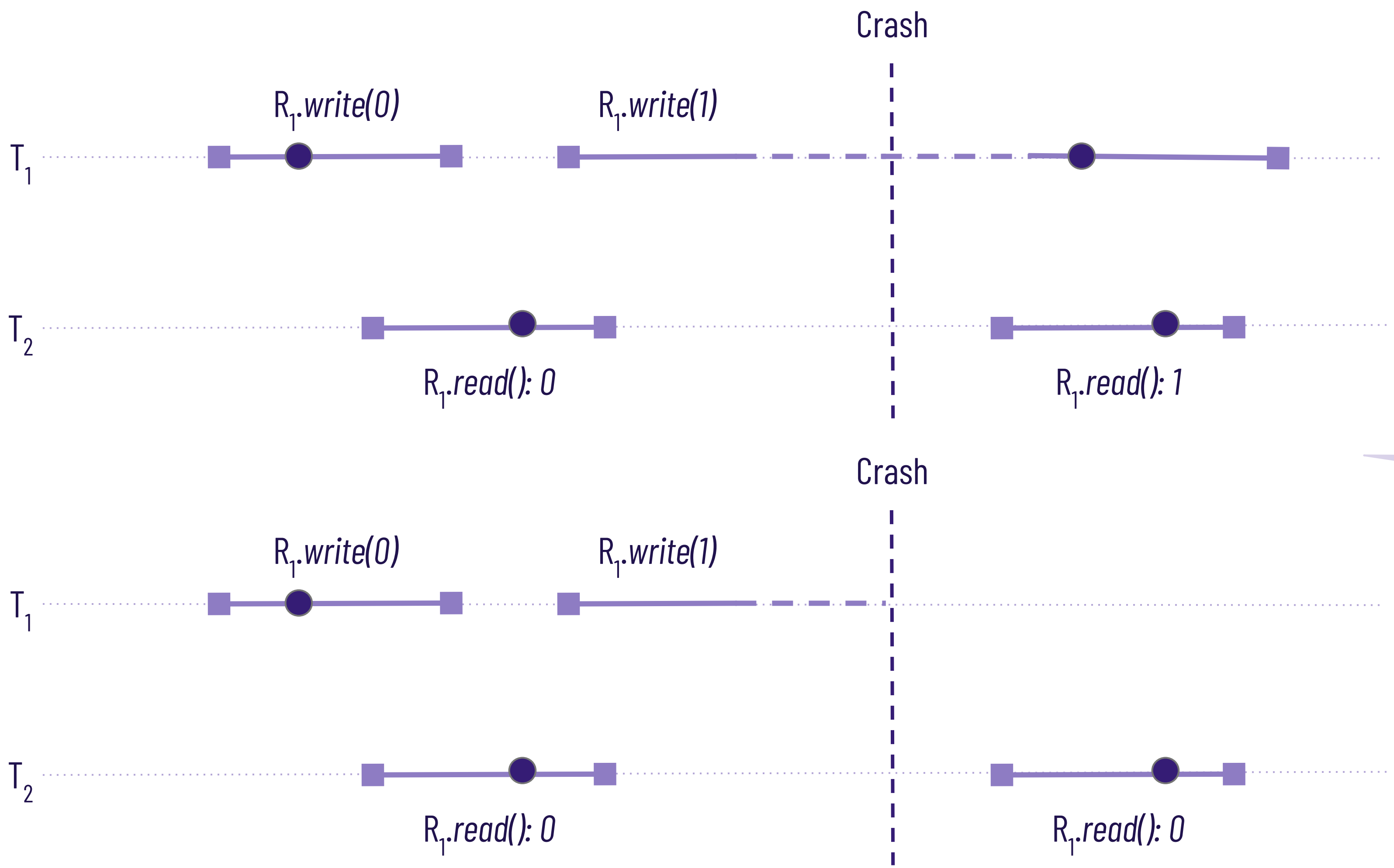
- Linearizability was originally defined by Herlihy and Wing [2]



Durable Linearizability (Definition)

- Durable Linearizability, as defined by Izraelevitz et al. [1]
  - **all threads** fail together
  - on recovery, **new threads** are created (no immediate reuse of thread IDs)
- A history is *durably linearizable* if it is *well-formed* (i.e., the projection onto each thread is sequential) and removing all crash events yields a *linearizable* history.

Durable Linearizability Example (Cont.)

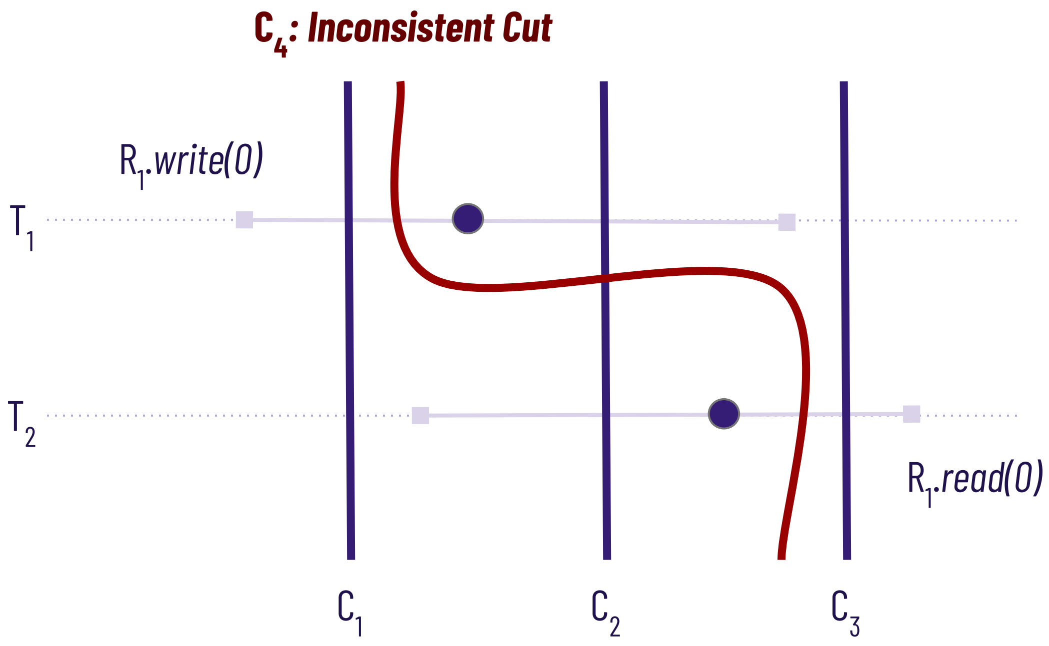


Both are Durably Linearizable

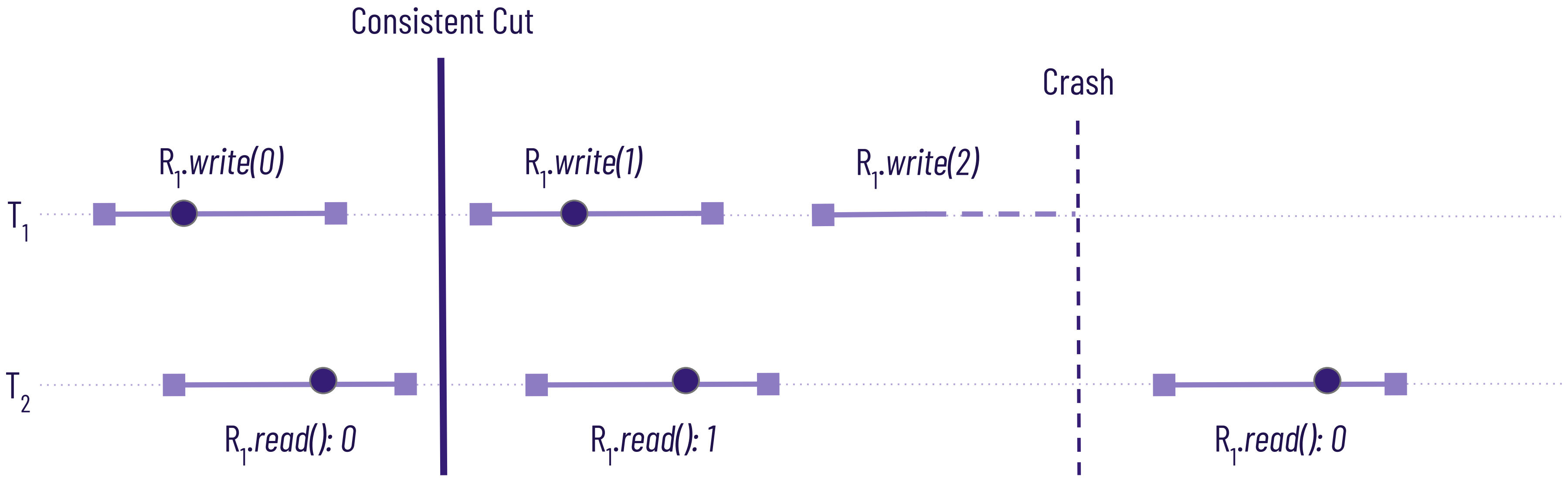
Buffered Durable Linearizability

- Buffered Durable Linearizability, as defined by Izraelevitz et al. [1]
- It is a more **relaxed** concept than durable linearizability.
- It allows for the **removal** of operations that have already been **completed**.
- The modified history should be a "**consistent cut**" of the original history.

Consistent Cut Example



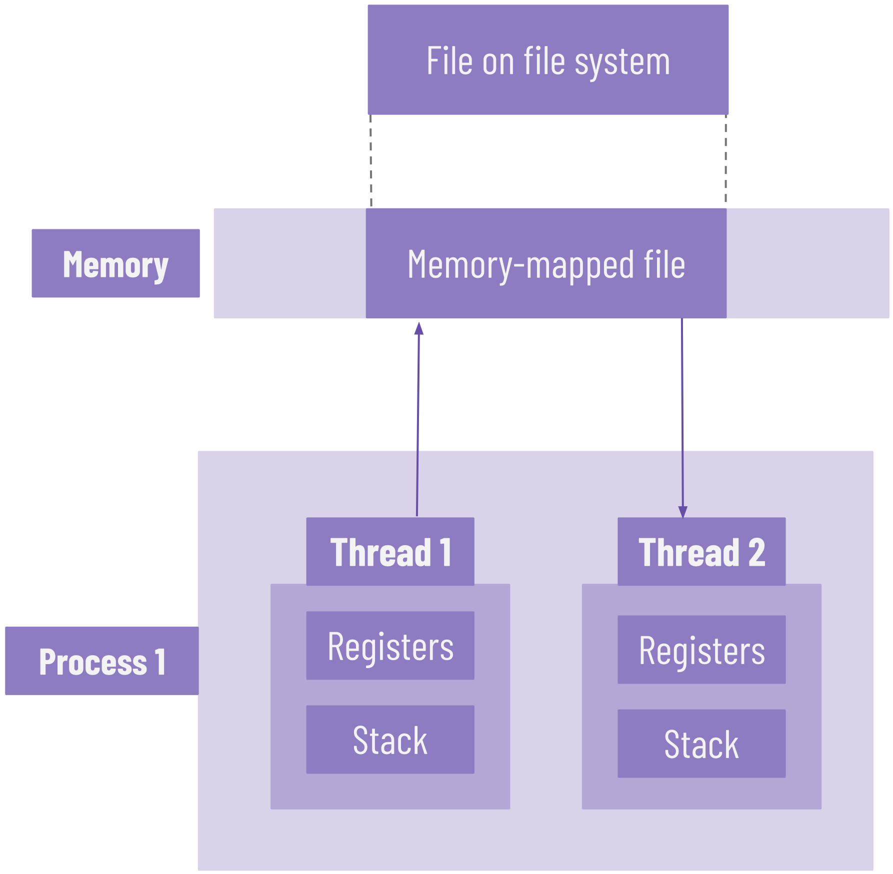
Buffered Durable Linearizability Example



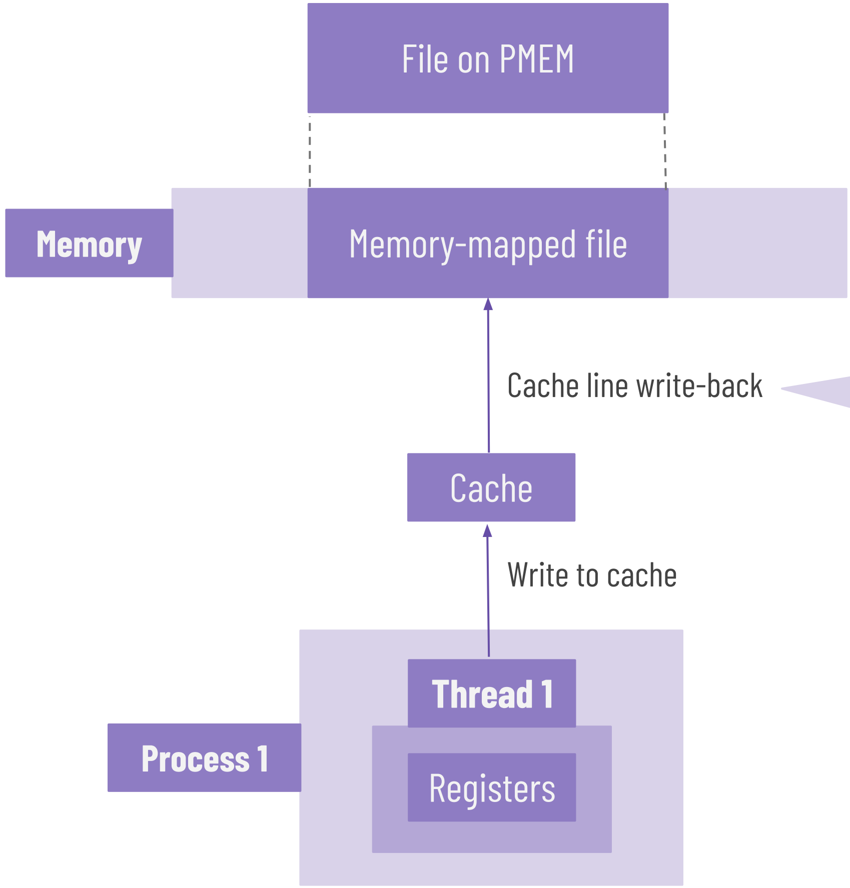
Background

- **Memory-Mapped Files**
- **Montage** is a buffered durable platform.

Memory-Mapped Files



Cache Line Write-Back (CLWB)

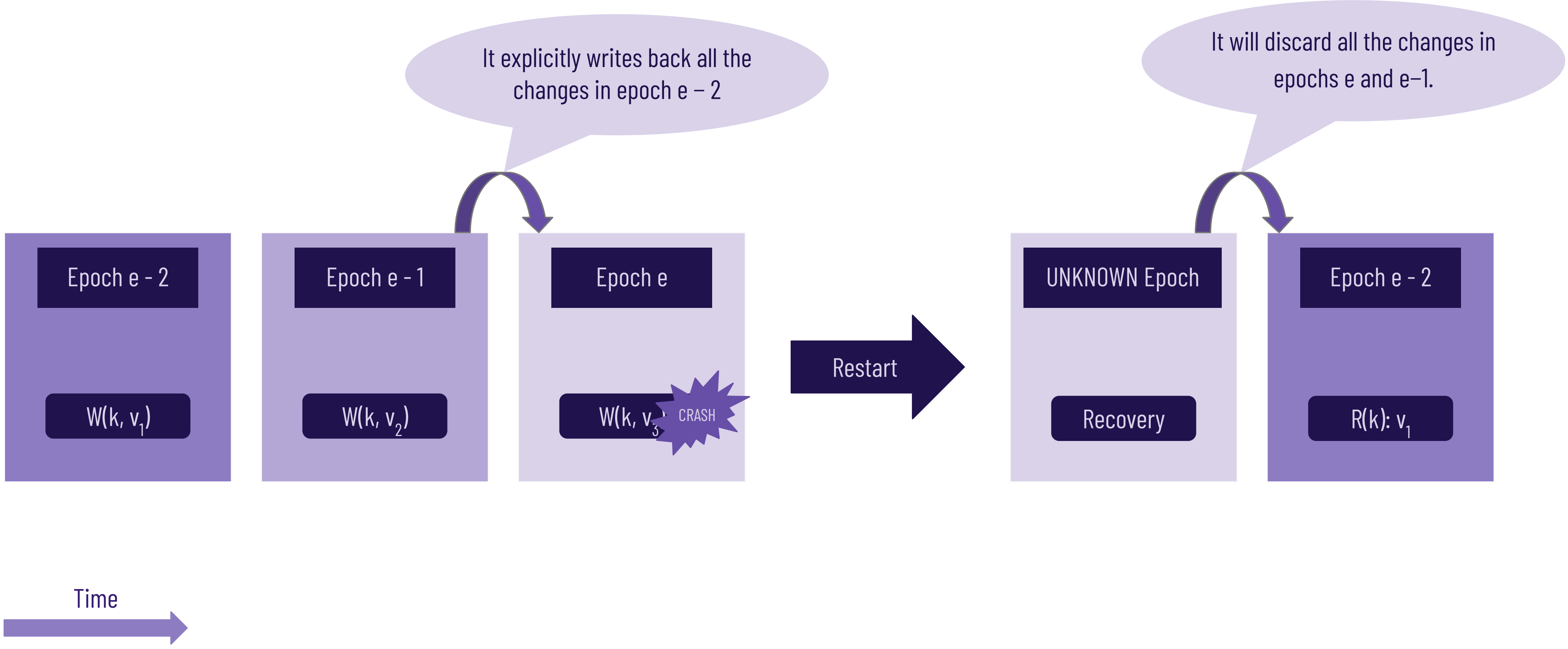


- **Implicit**
  - Automated by the processor's cache controller
- **Explicit**
  - Specific software components issue cache write-backs

Montage

- Montage is a **general-purpose** system for building *buffered durably linearizable* persistent data structures.
- Montage only persists changes to semantically essential *payloads*.
- Montage divides time into “**epochs**” to keep track of operations.
- **Periodic persistence:** changes applied in one epoch persist all together at the end of an epoch.
- On a crash, Montage’s recovery routine reverts state to an epoch boundary.

Periodic Persistence in Montage



Snapshotting

- A **point-in-time copy** of the state of a system.
- Create **recoverable views** of the memory-mapped files in the presence of persistent memory failures.

Snapshotting

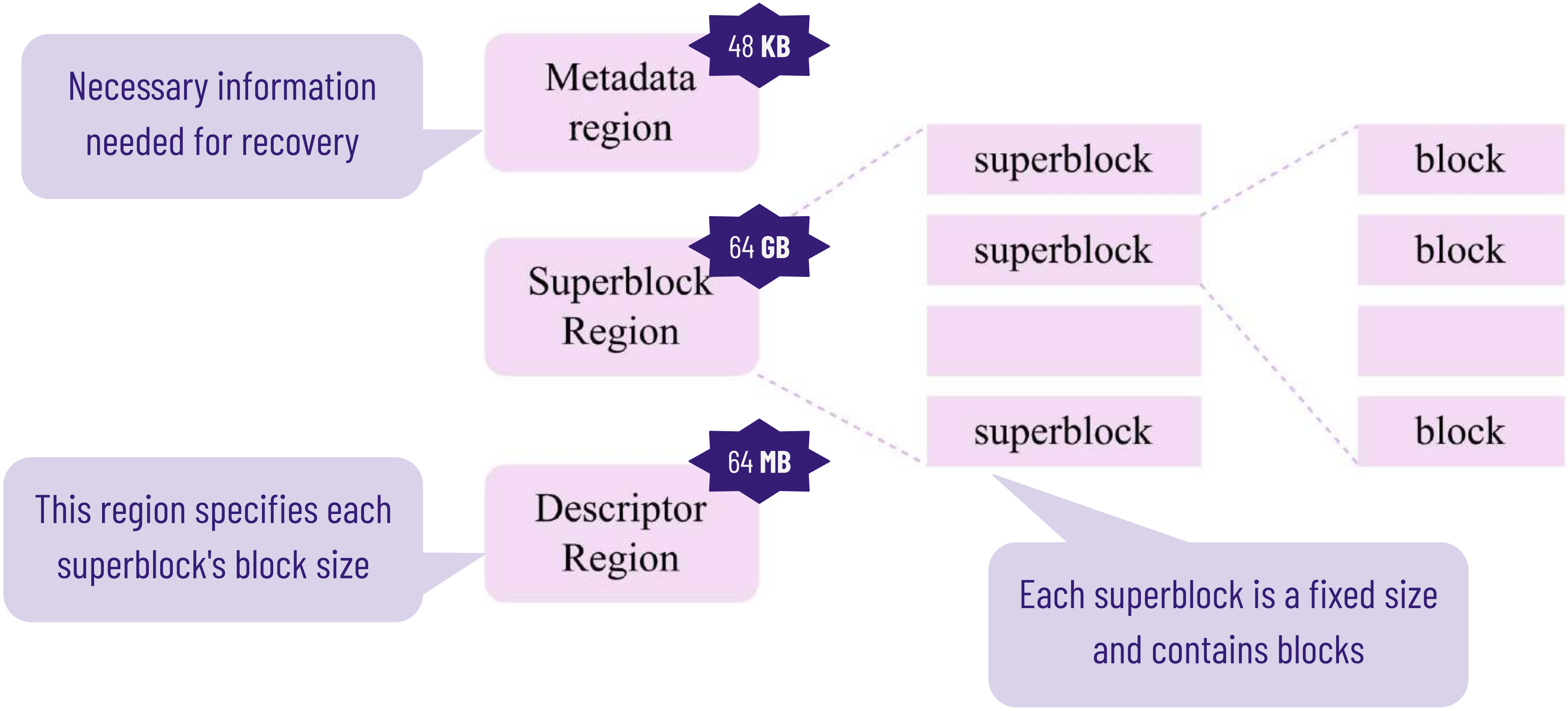
- Montage is vulnerable to the persistent memory failure due to hardware failures.
- Persistent memory challenges are not exclusive to Montage.
- Snapshotting provides a recoverable system state at specific moments.
- The process captures and stores the system's current state as a snapshot.
- After a failure, system can use these snapshots to recover from a persistent memory failure.

Stop-the-World Snapshotting

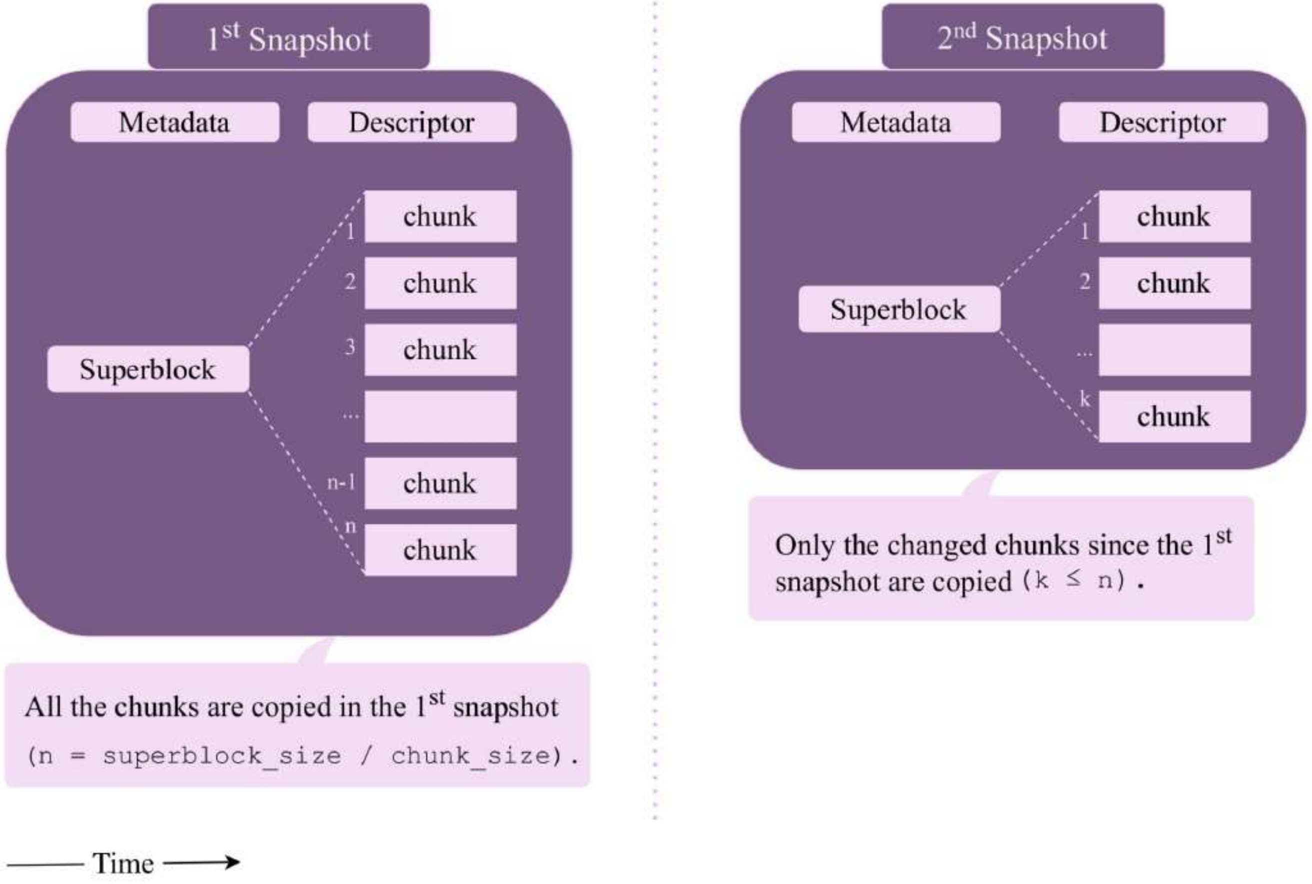
- This method requires pausing all changes to the memory-mapped files while snapshotting is in progress.

Ralloc

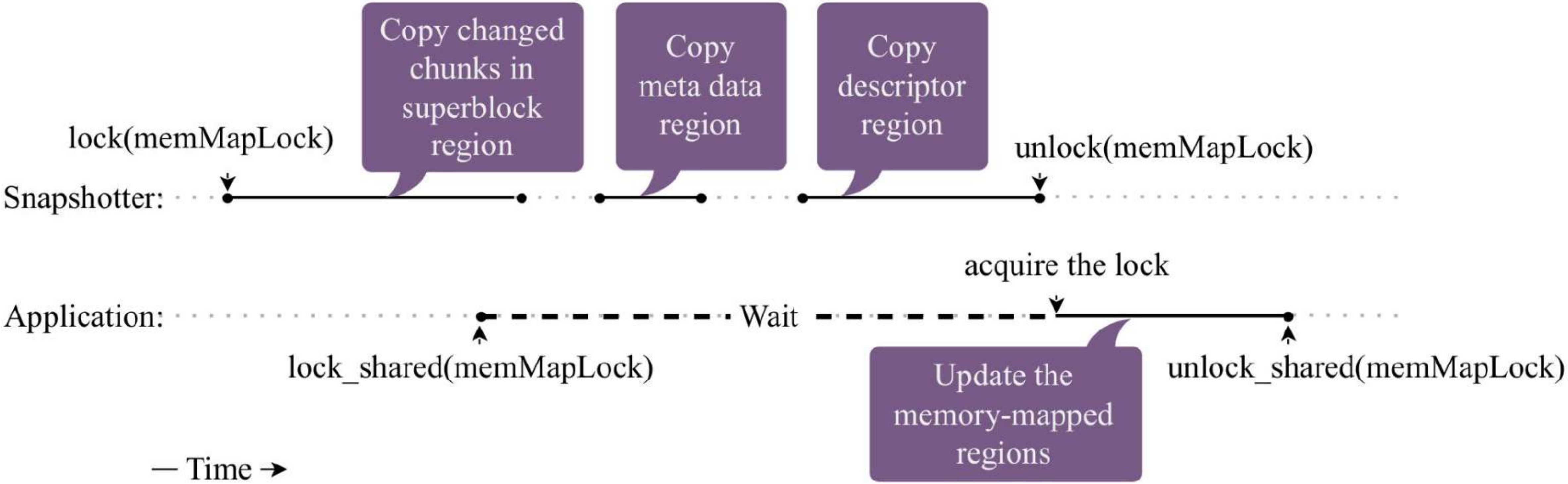
- A persistent memory **allocator** designed for applications that use large amounts of persistent memory like Montage [4].



First Two Snapshots



Stop-the-World Snapshotting



Online Snapshotting

- Online snapshotting is a technique used to create a **point-in-time copy** of data **while** it is still in use.

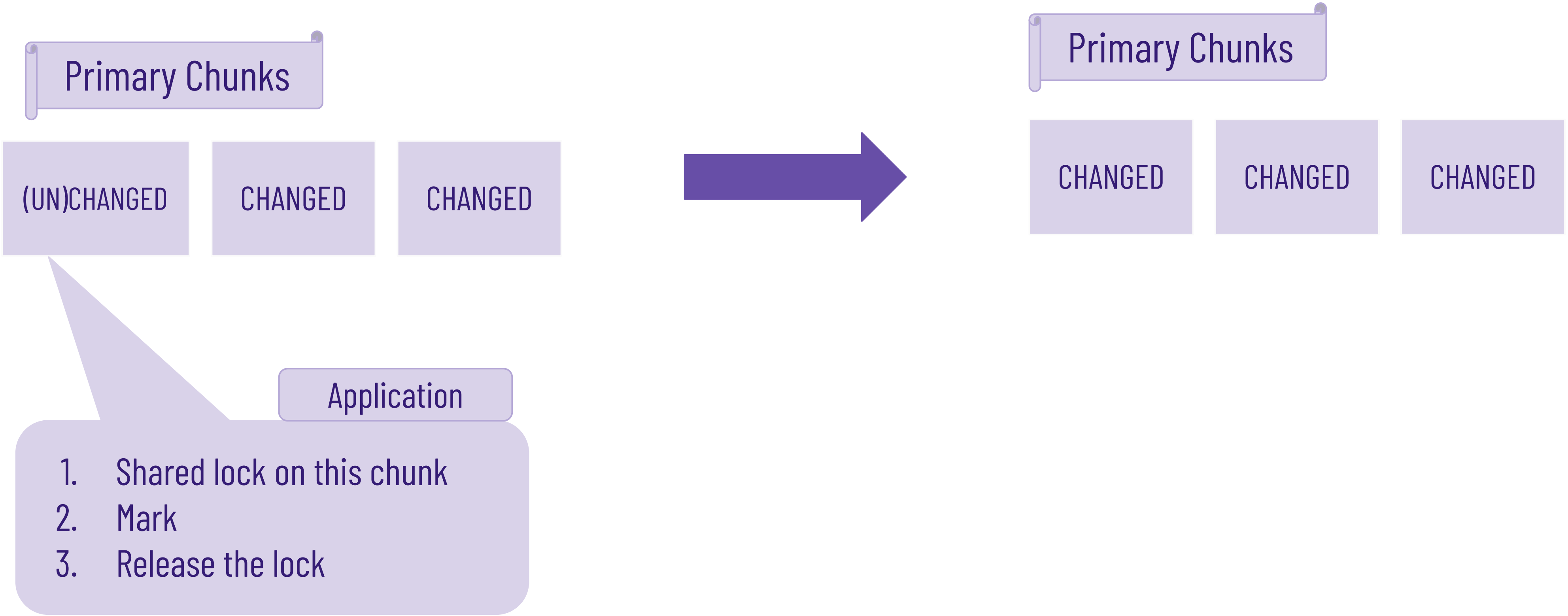
Online Snapshotting on Montage

There are four scenarios for an application thread trying to change a chunk:

1. There is **no snapshotting** is going on
2. There is an **ongoing snapshotting** process:
   - The chunk **has not been copied** yet.
   - The chunk **has already been copied**.
   - The chunk **is being** copied.

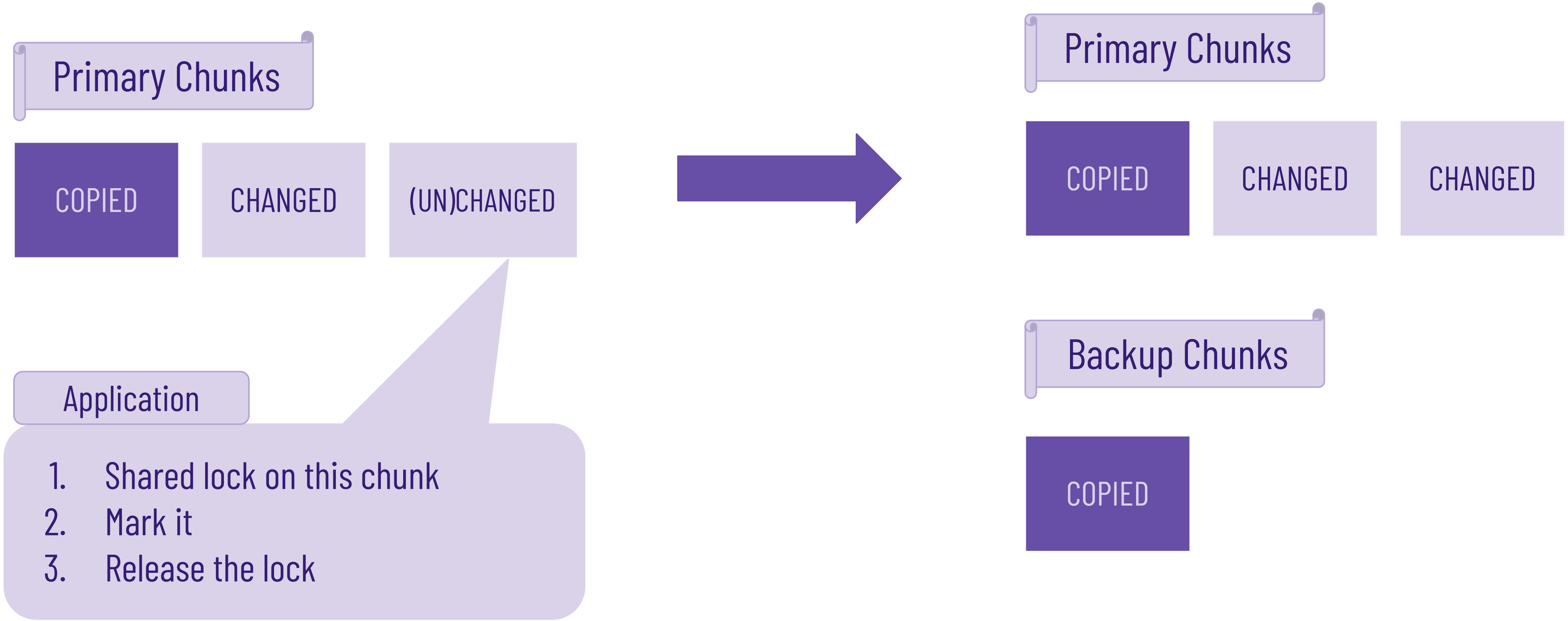
Online Snapshotting

1. **No snapshotting** is going on



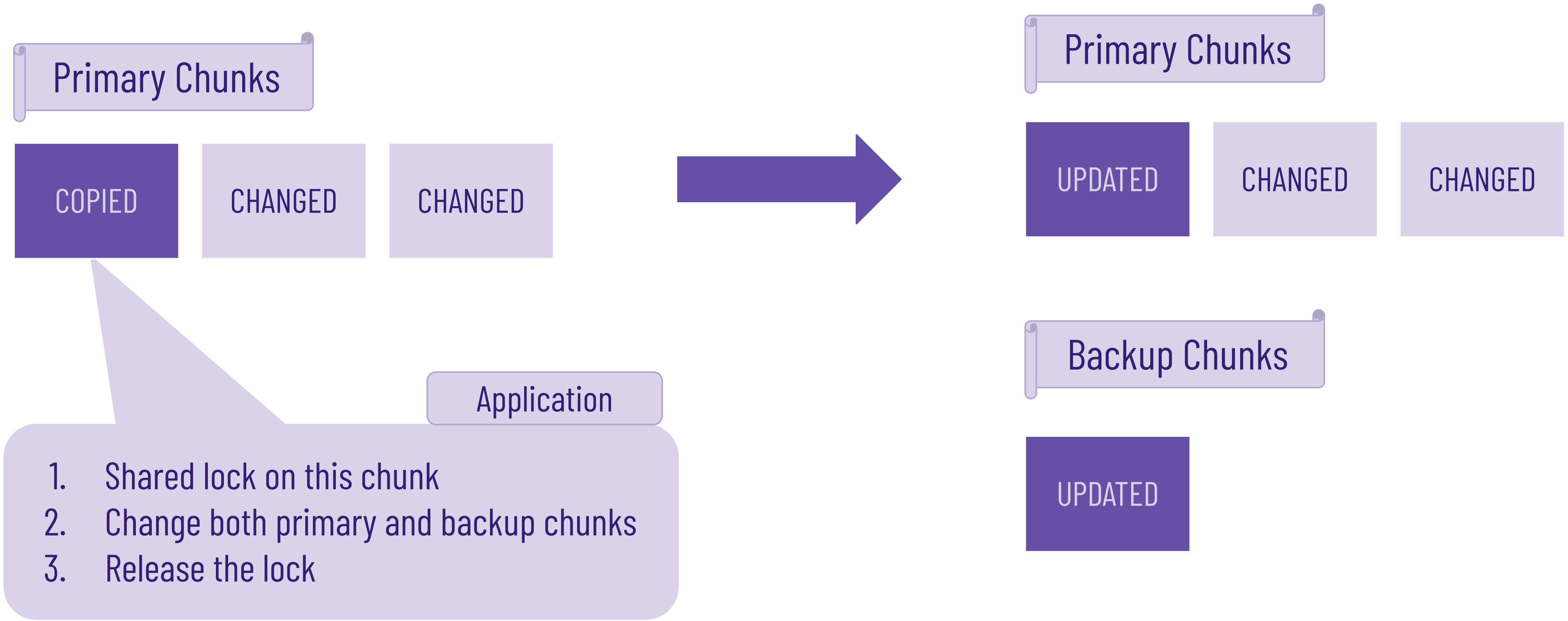
Online Snapshotting

2. The chunk **has not been copied** yet



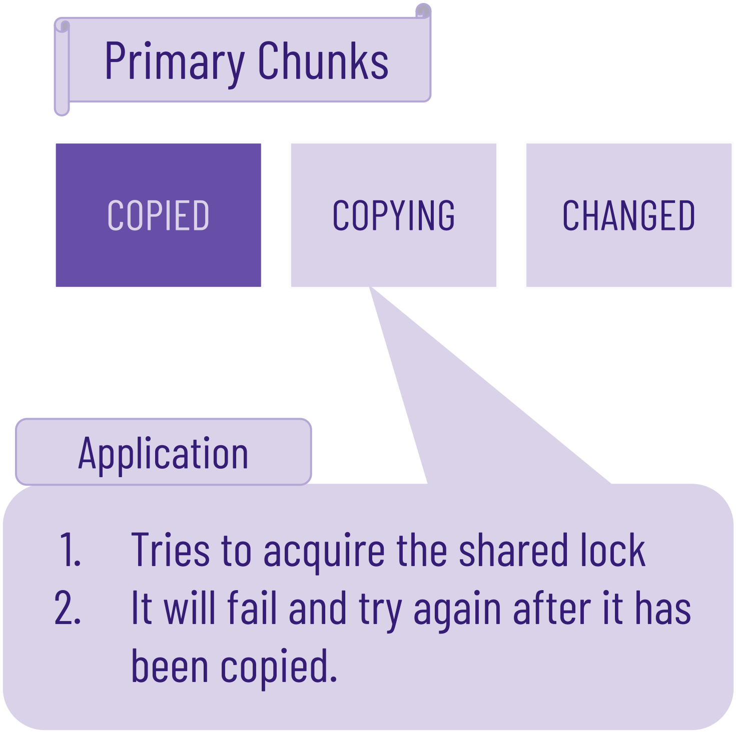
Online Snapshotting

3. The chunk **has already been copied**.



Online Snapshotting

4. The chunk **is being** copied.



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Double-Checked Locking (DCL)

- Minimize lock overhead by ensuring lock acquisition only when necessary.

Experimental Evaluation

- A detailed examination of snapshotting algorithms is conducted, in different experimental conditions.

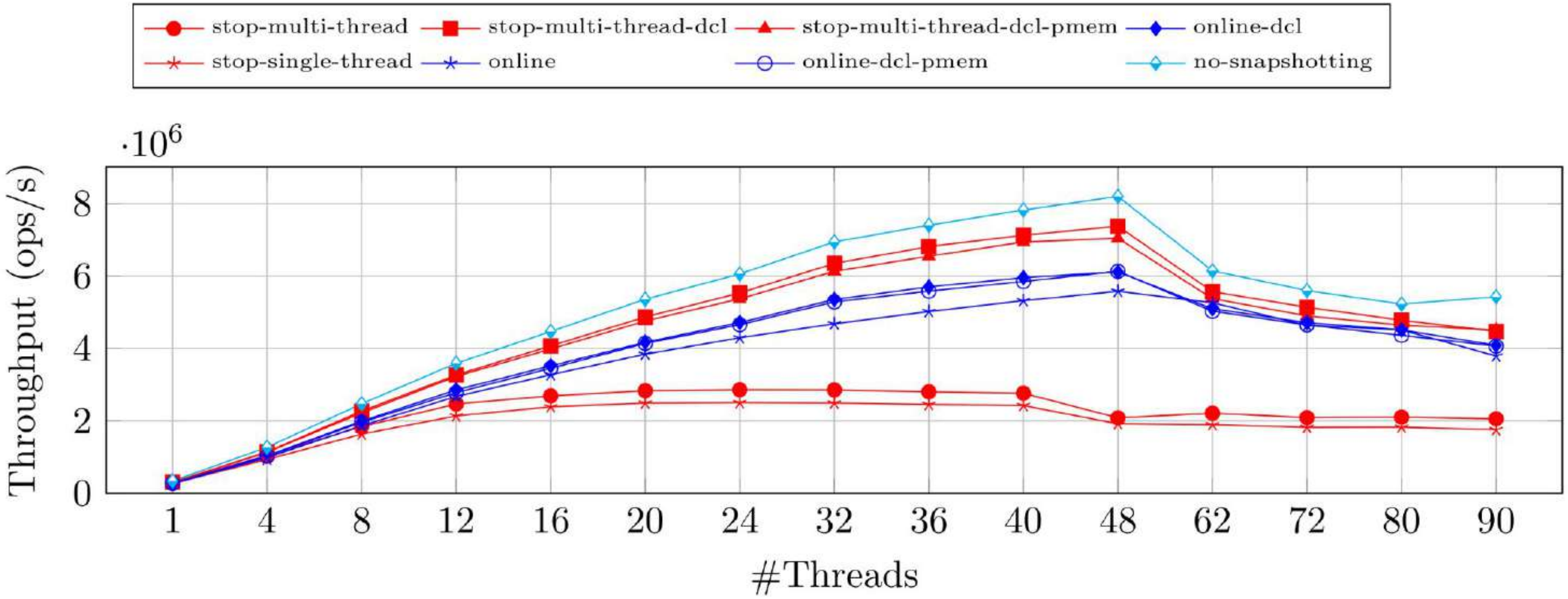
Working Environment

- Testing Environment:
  - Server Specs: Four Intel(R) Xeon(R) Gold 6230 processors with **Optane persistent memory** on Ubuntu 20.04.6 LTS.
- Thread Management:
  - Up to 20 threads: One socket, no hyperthreading.
  - 20-40 threads: Single socket with hyperthreading.
  - 40-80 threads: Two sockets.
  - 80-90 threads: Oversubscription on the first socket.

- Benchmarked Data Structure: Hashmap.
- Experimental Setup:
  - Hashmap: 0.5 million elements into 1 million hash buckets.
- Evaluation Details:
  - Averages over five trials
  - Standard deviation: Less than 2% of the mean

Throughput Analysis

Hashmap with 0% get, 50% insert, and 50% remove



Conclusion

- **Enhanced Fault Tolerance**: We've significantly improved Montage's fault tolerance through rigorous strategies.
- **Buffered-Durable Consistency**: Introduced a robust definition to ensure snapshot correctness.
- **Snapshotting Mechanisms**: Developed both **stop-the-world** and **online** methods.
- **Double-Checked Locking**: Minimized reader lock acquisitions, enhancing system performance.
- **Consistency and Recovery**: Our strategies ensure data consistency, durability, and efficient system recovery.

Future Work

- **Online Snapshotting for Large Allocations**: Address the current limitation in our online snapshotting mechanism for larger allocations.
- **PMEM vs. SSD**: Understand the performance differences between SSD-based and PMEM-based backup media.
- **NUMA-Aware Algorithms**: Optimize snapshotting algorithms to be aware of Non-Uniform Memory Access (NUMA) configurations for performance improvements.
- **Buffered Durably Linearizable Verifier**: Design and implement a verifier to efficiently test program correctness on buffered durably linearizable platforms.

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Related Work

- Pronto, Developed by Memaripour et al. [6]
  - Pronto uses a volatile memory allocator for snapshot creation and keeps them on PMEM.
  - However, it lacks backup protection against persistent memory hardware failures.
- In-Memory Databases
  - **Copy-on-Update** [7]: This method uses an extra data structure to create a duplicate of the primary dataset and a bit array to log the row update statuses.
  - **Ping-Pong** [8]: This technique involves two versions of the data; one is used for updates and the other for noting the progressive snapshot.

Double-Checked Locking

- **Purpose**: Minimize lock overhead by ensuring lock acquisition only when necessary.
- Application in Snapshotting:
    - Snapshotting is infrequent compared to the duration of an epoch.
    - Improves efficiency by avoiding redundant reader locks during non-snapshotting periods.

Double-Checked Locking

Function takeSnapshotDCL():

$isSnapshotting \leftarrow true$

takeSnapshot()

$isSnapshotting \leftarrow false$

Function doPersistProtected($addr$):

Input: $addr$: The memory address of the chunk to persist