Lessons Learned During the Development of the CapoOne Deterministic Multiprocessor Replay System

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- Enabled by using Deterministic Replay of Execution

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  - Re-execute and use log to force software down the same execution path

SW-Based vs HW-Based Deterministic Replay

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- ➖ Very slow on multiprocessors

- ➖ Poor integration with SW
- ➕ Fast multiprocessor execution

HW-Assisted Deterministic Replay

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CapoOne

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- **CapoOne:** first implementation of Capo

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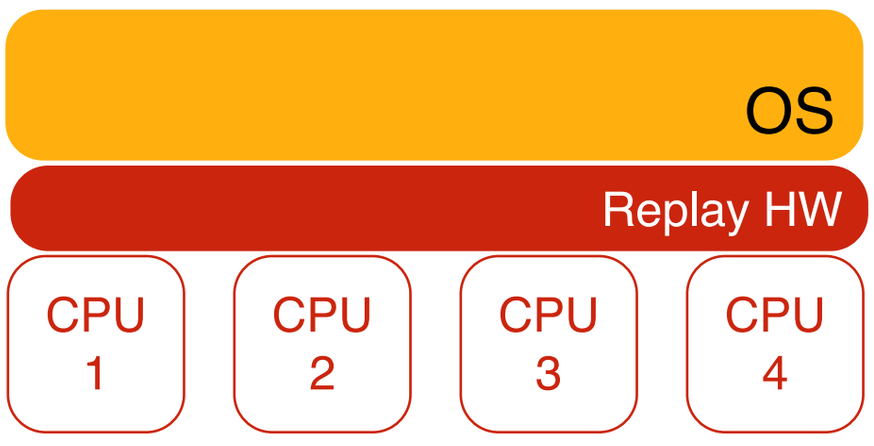

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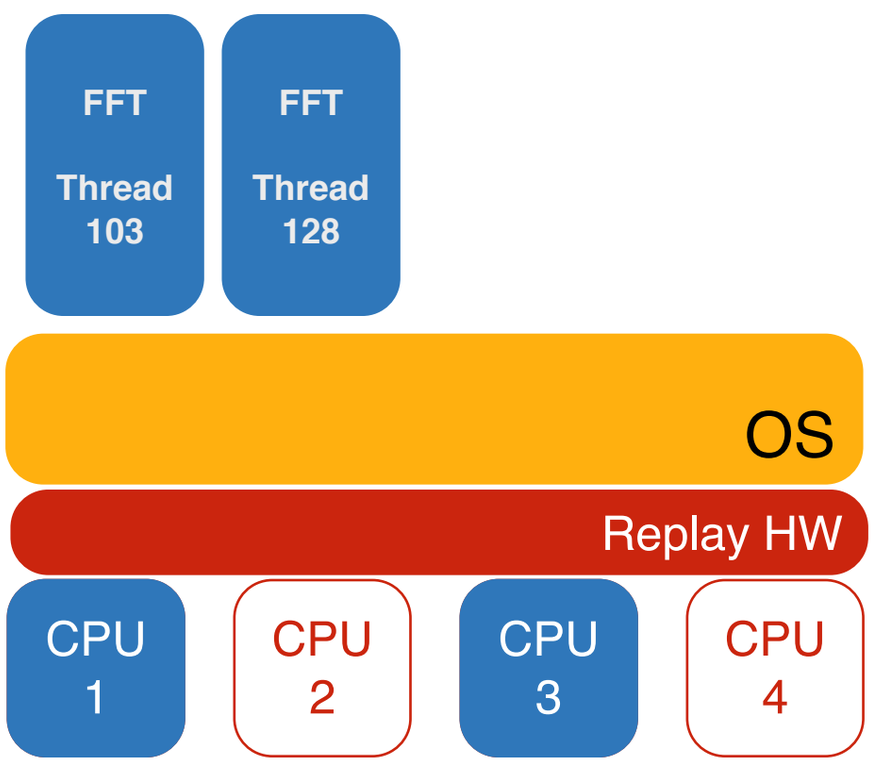

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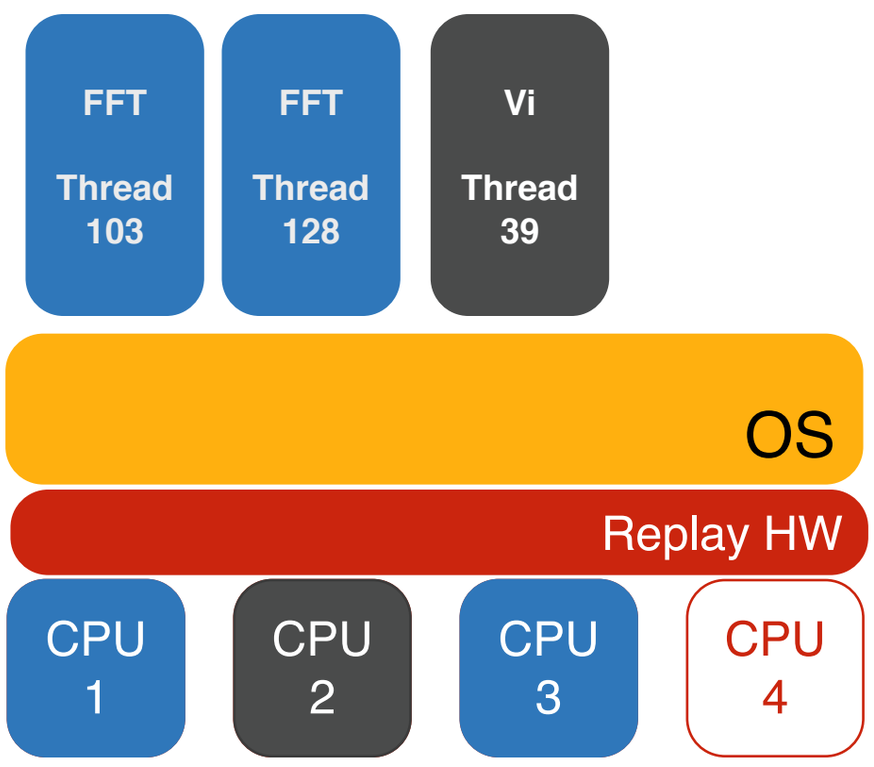

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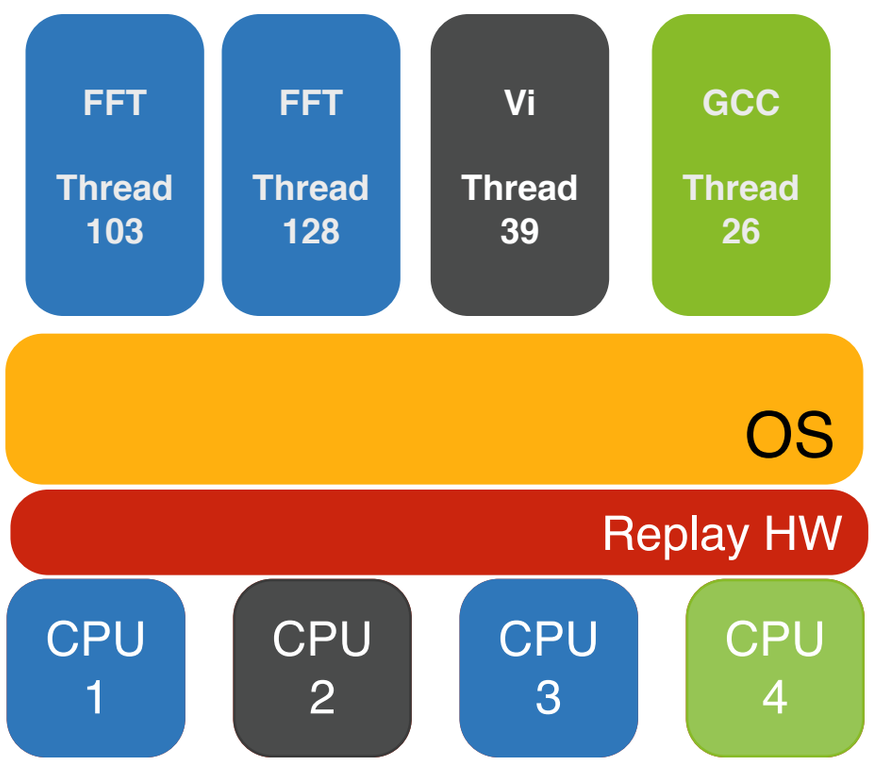

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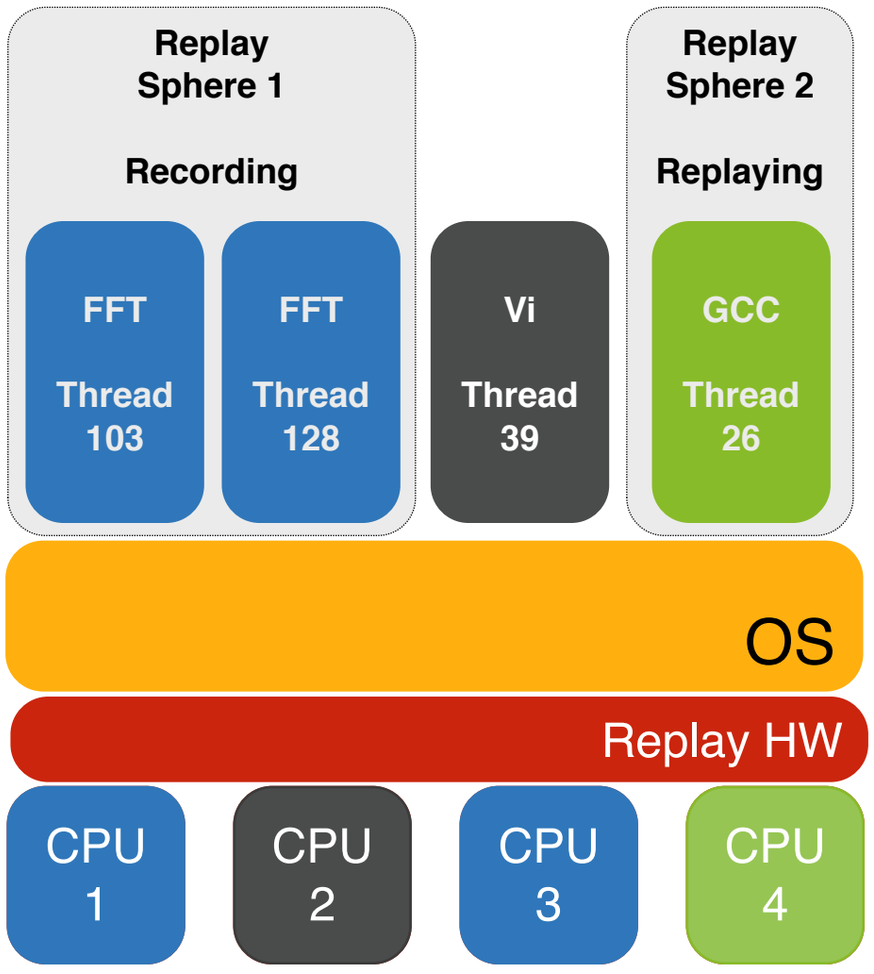

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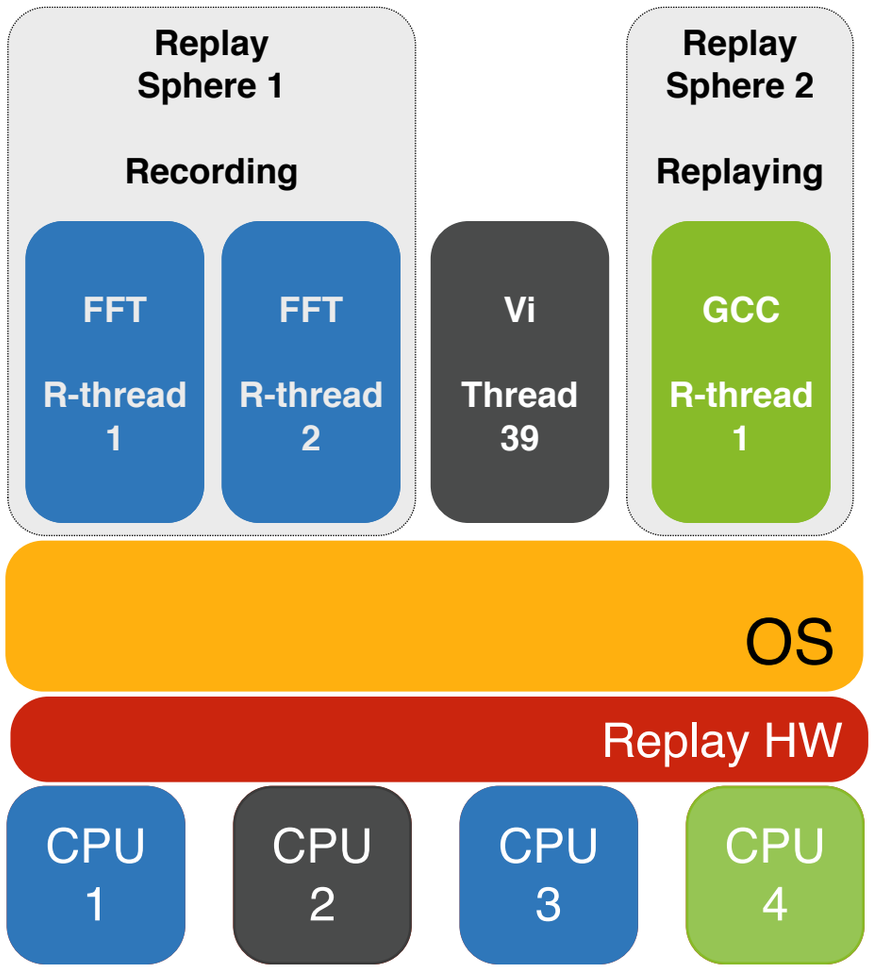

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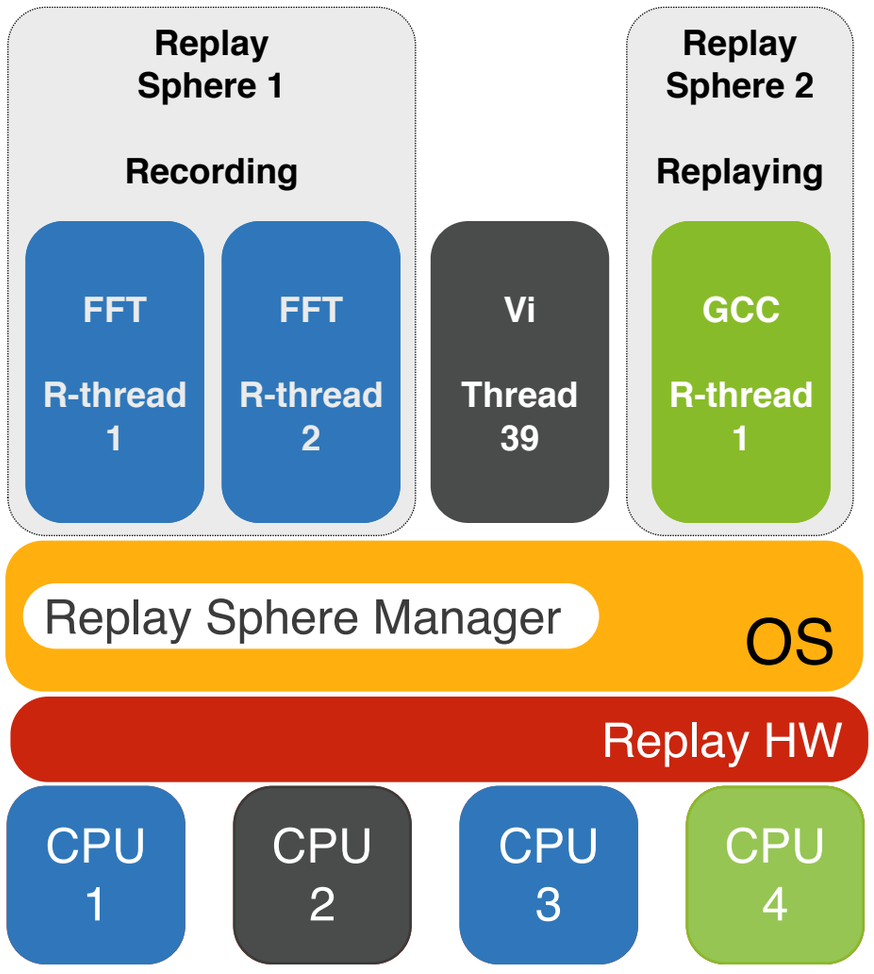

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- Replay Sphere Manager:
  - Logs the other sources of non-determinism that affect the sphere
  - Produces per-sphere **Input Log**
    - Includes system call return values, signals, data copied into the sphere...
  - Injects data from log into sphere during replay

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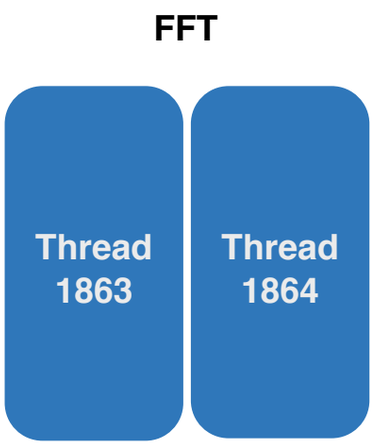

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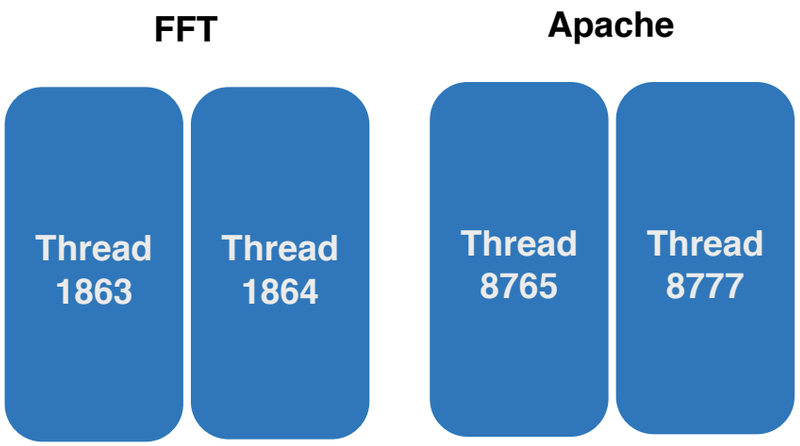

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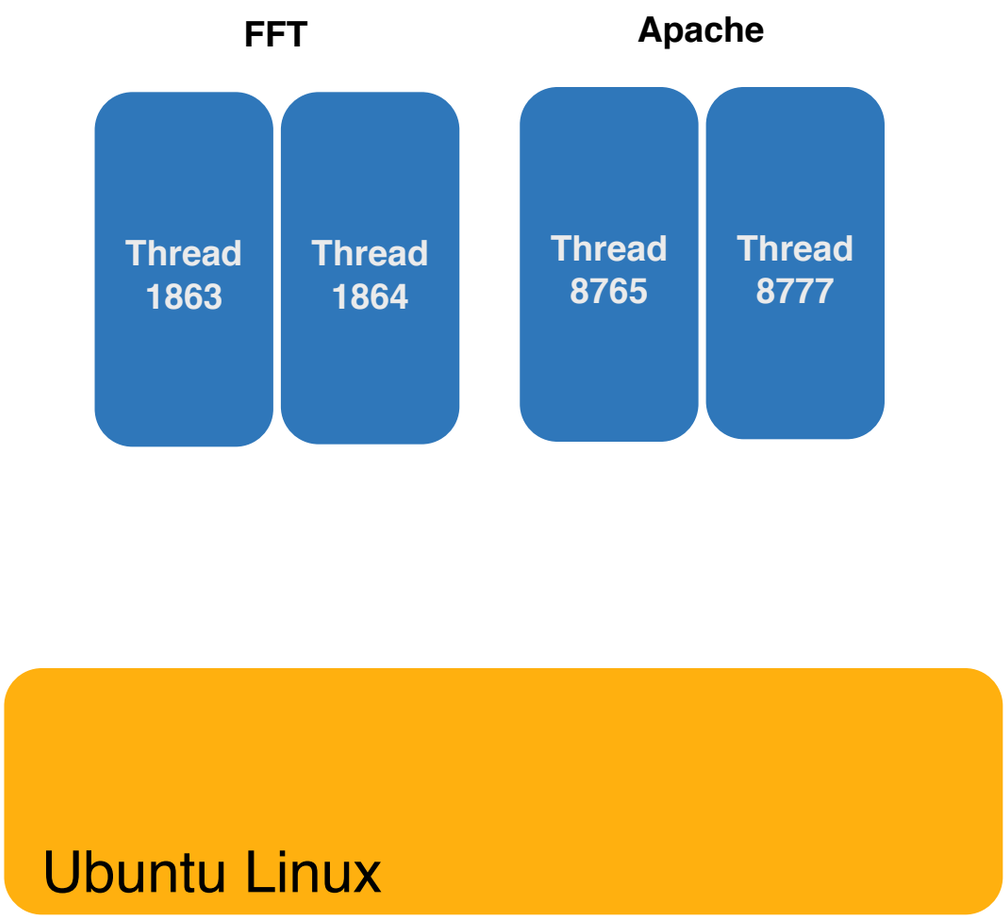

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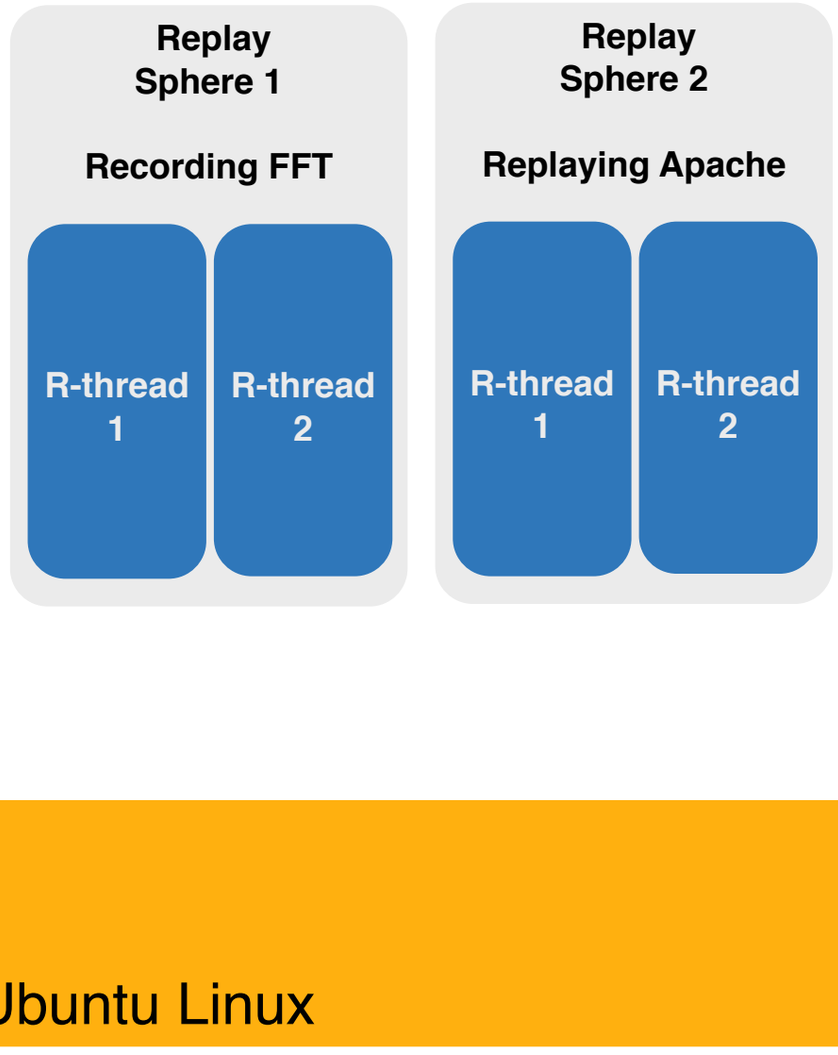

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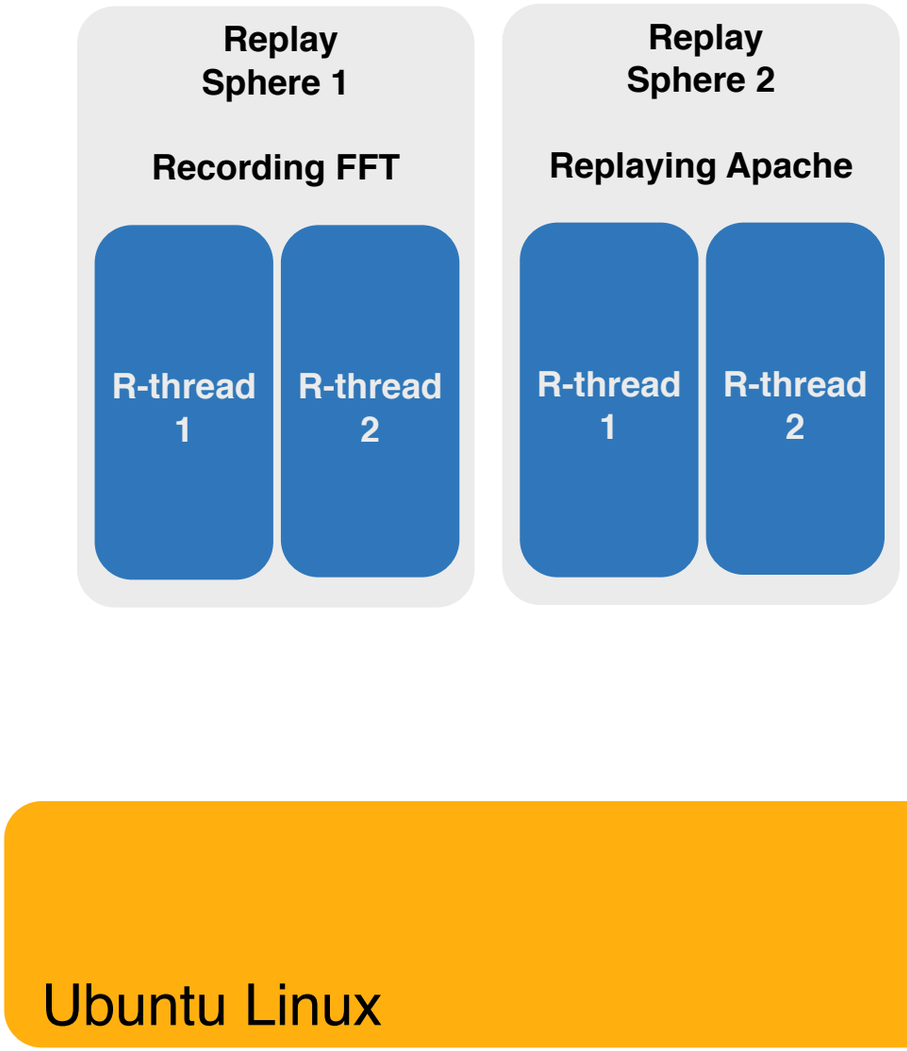

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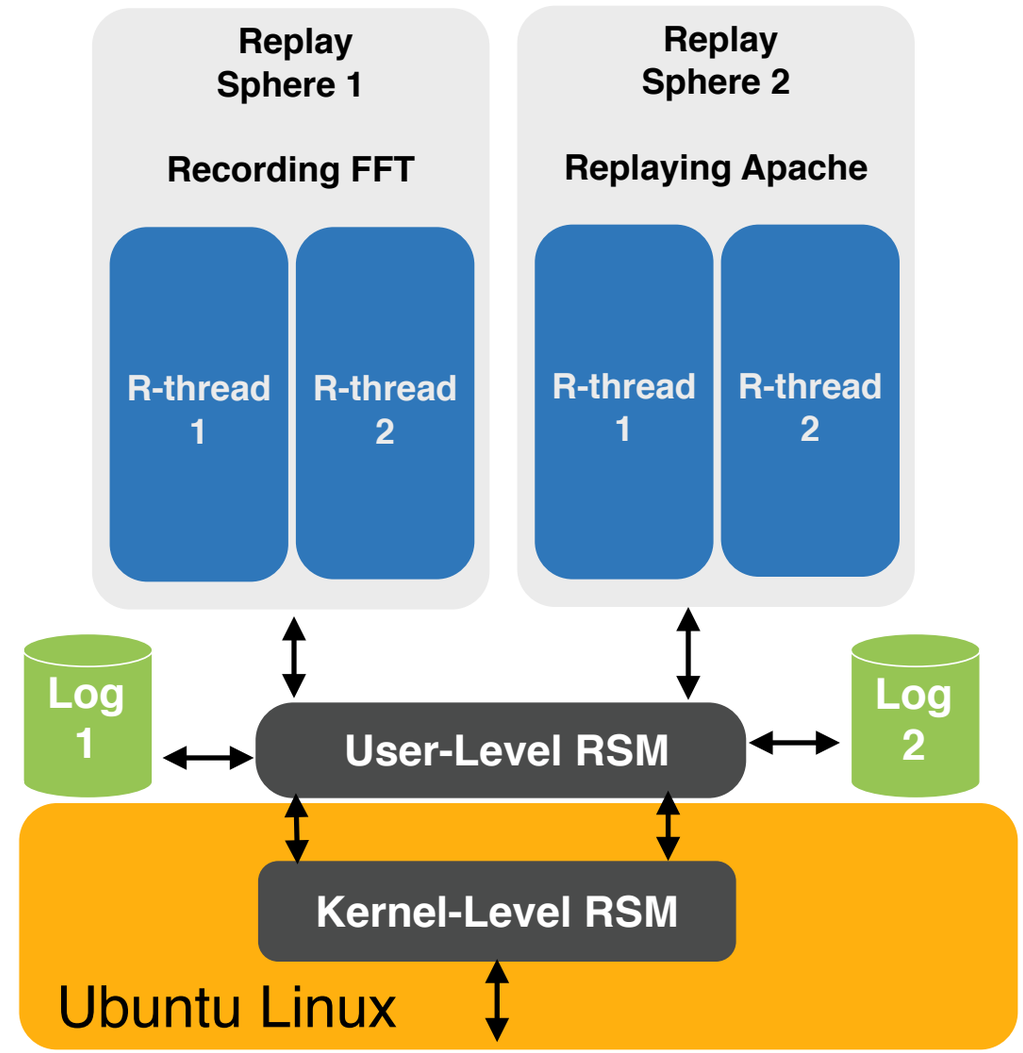

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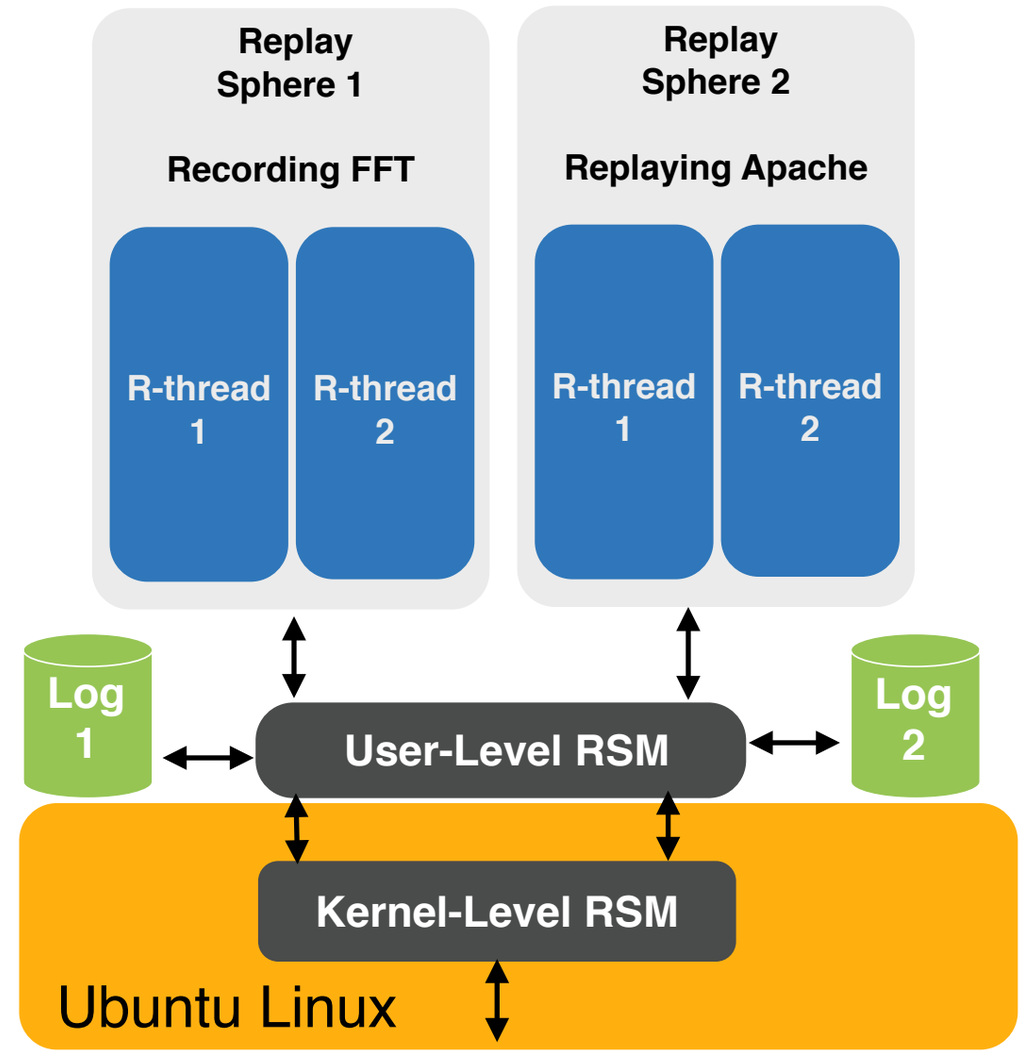

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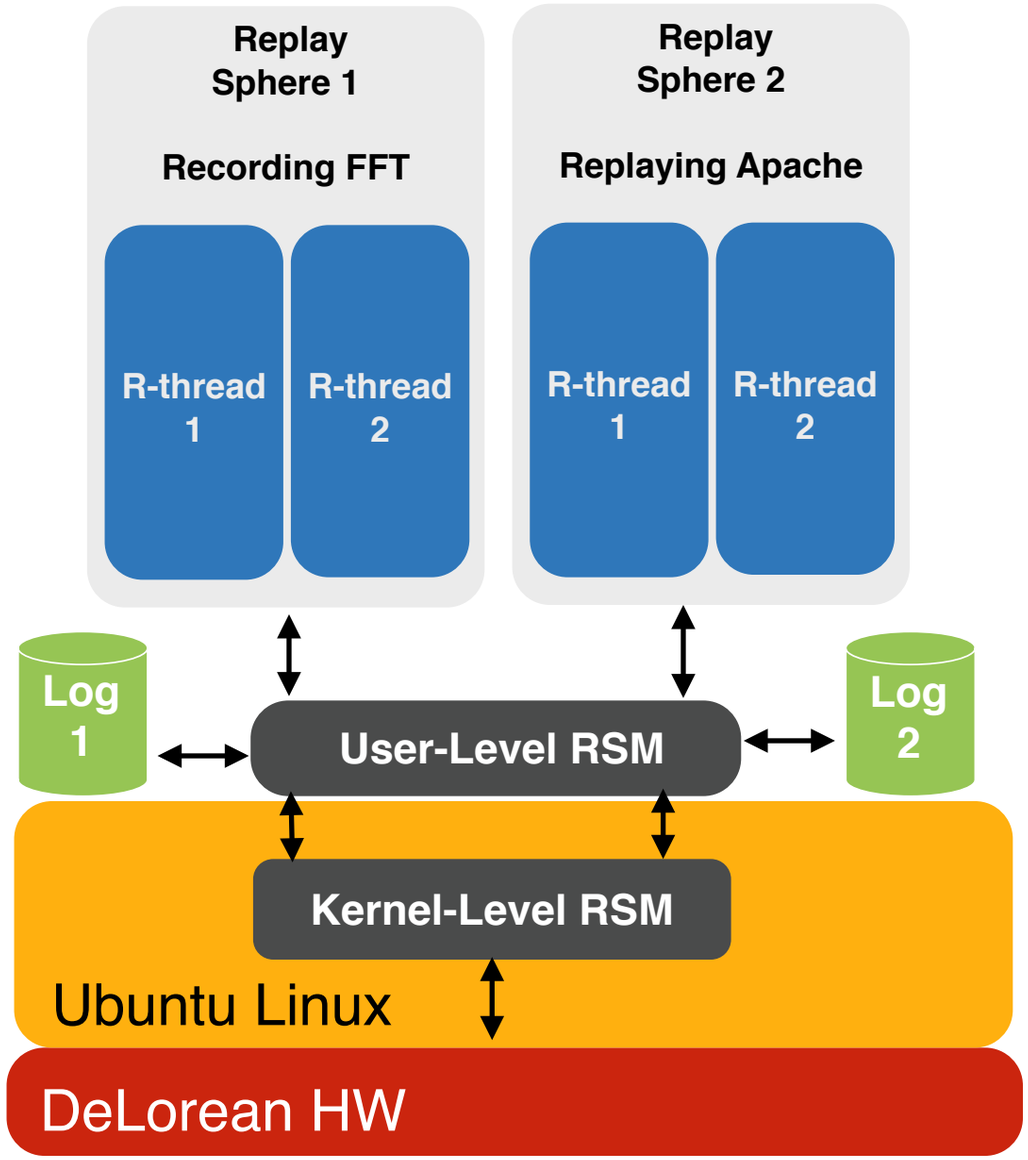

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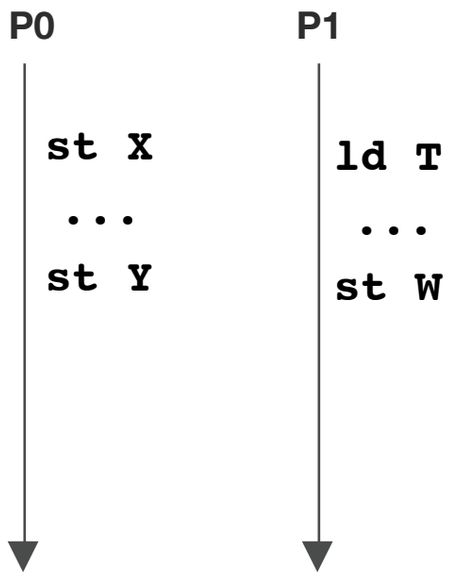

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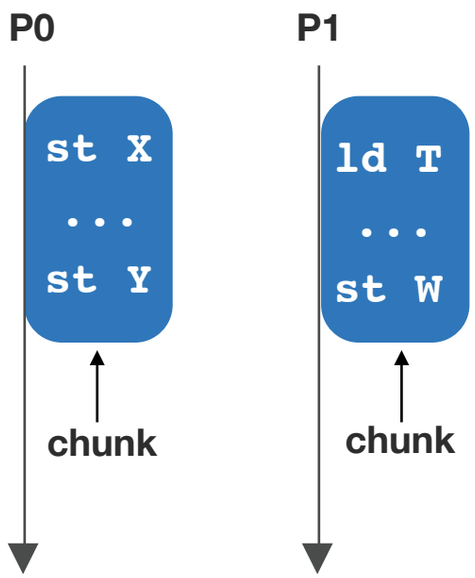

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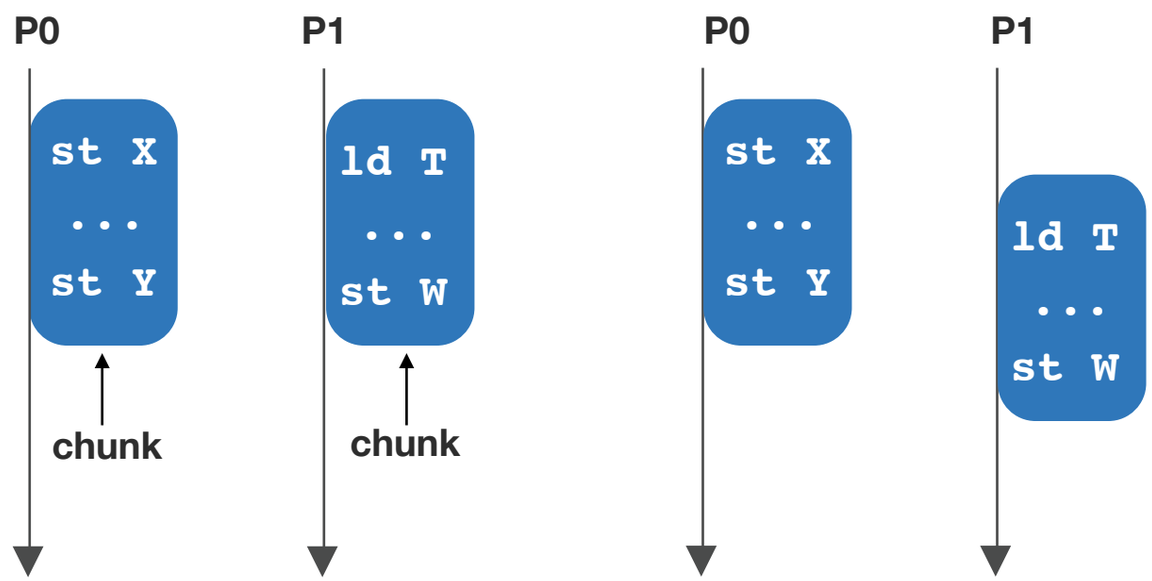

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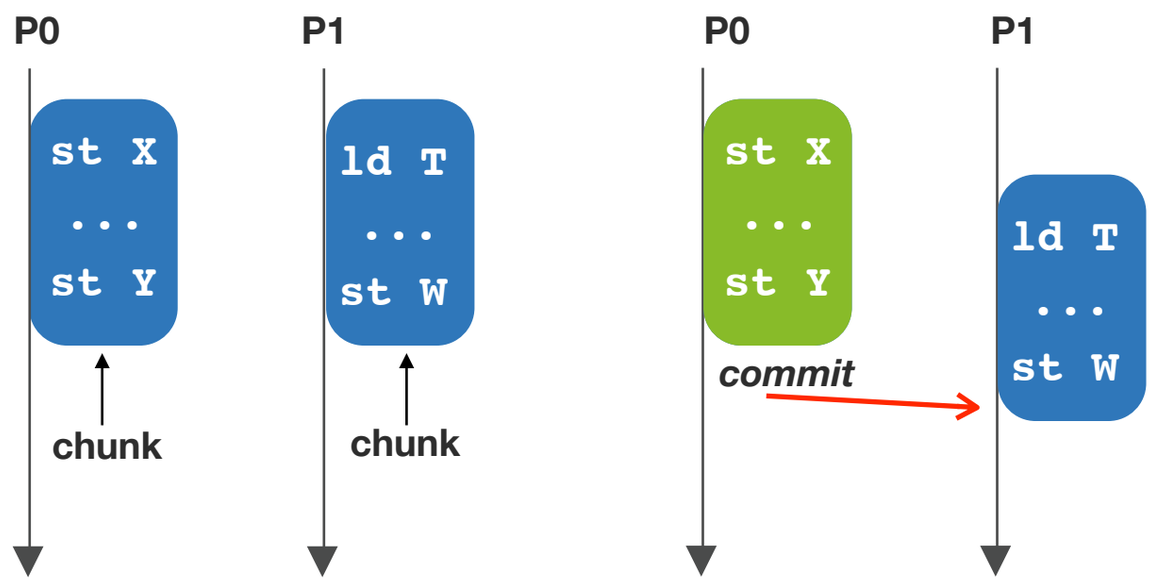

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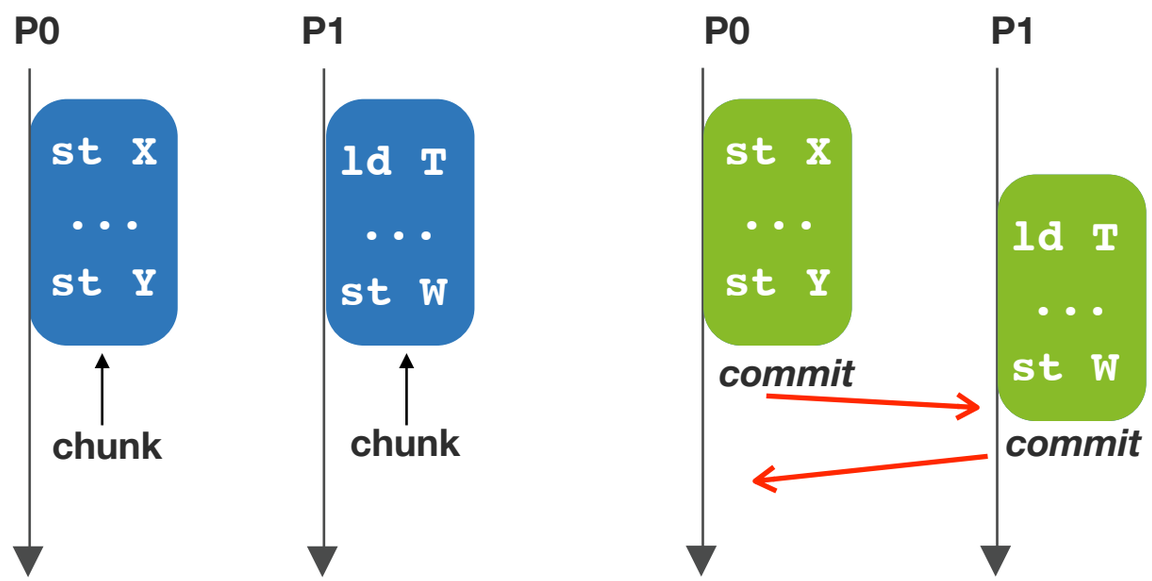

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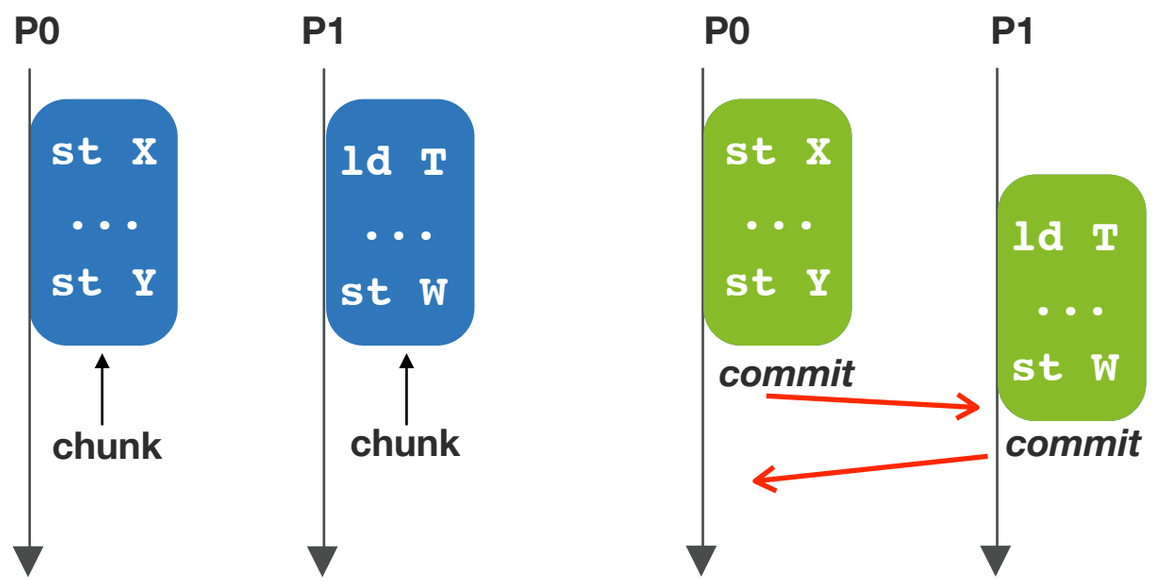

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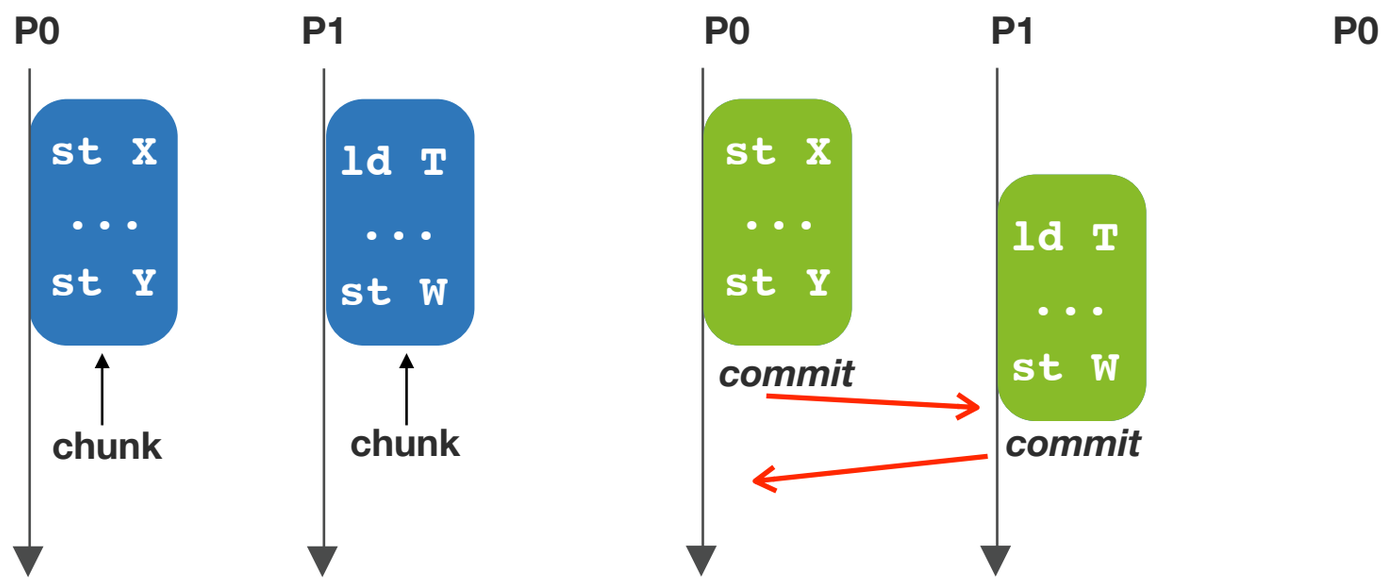

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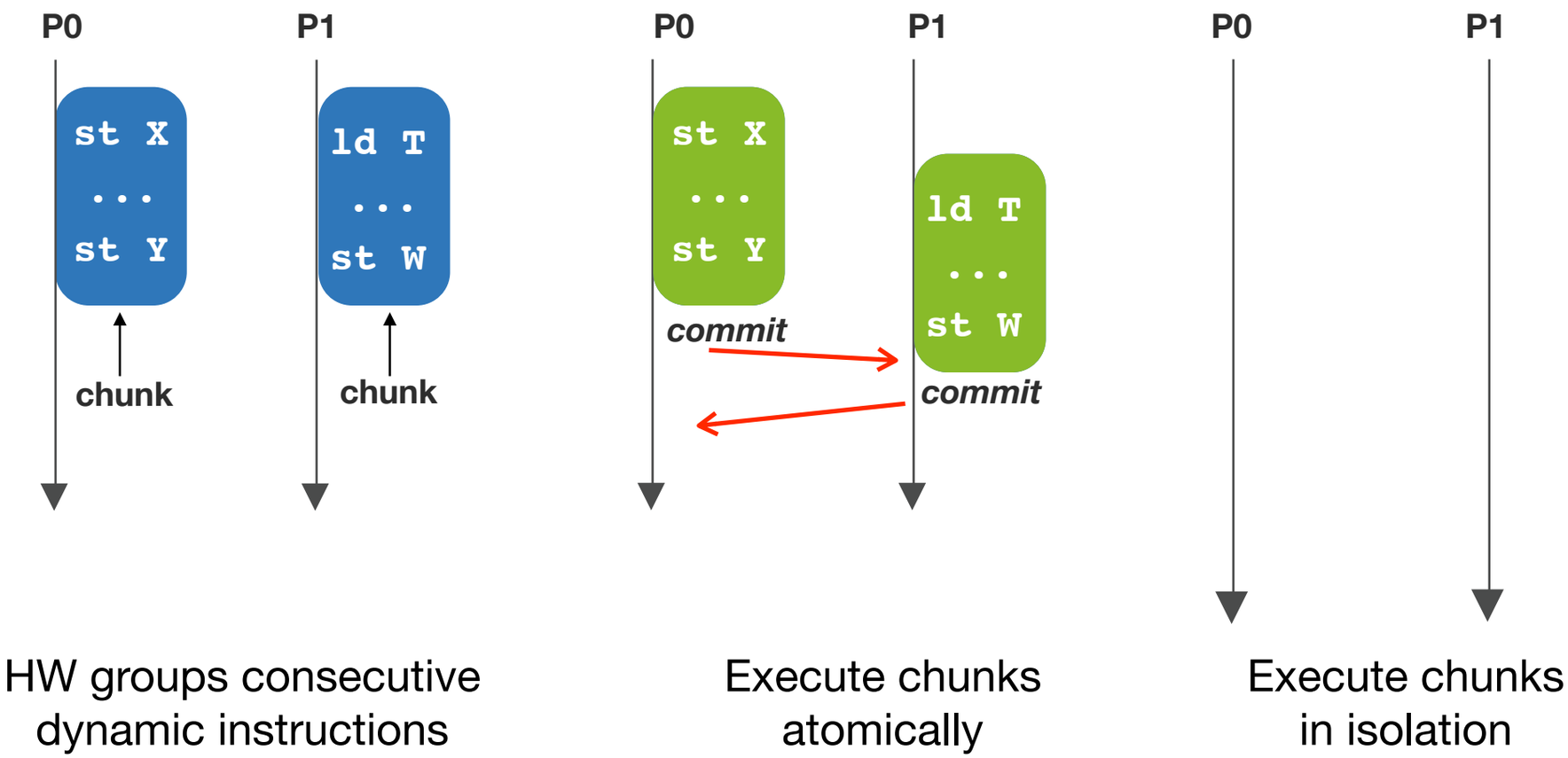

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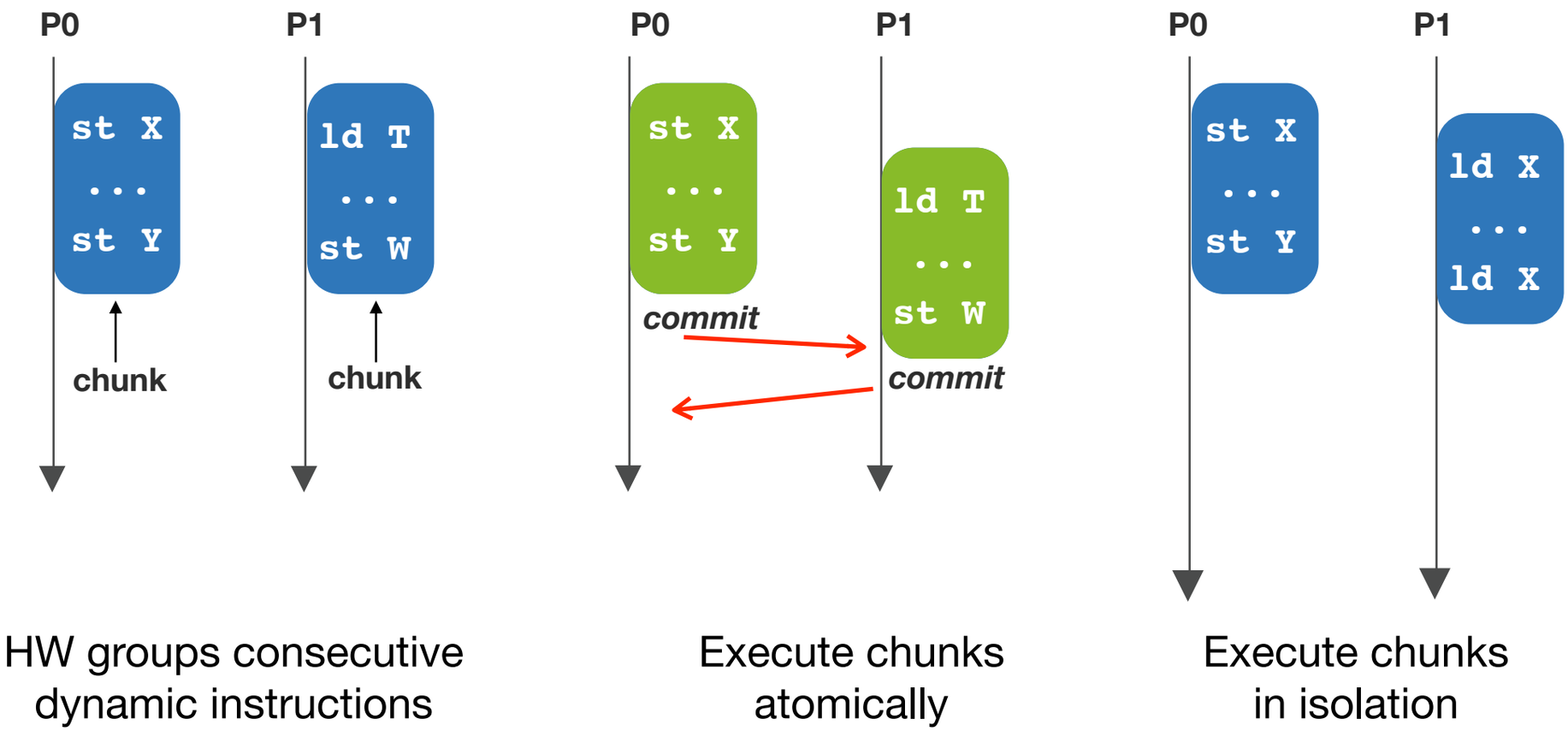

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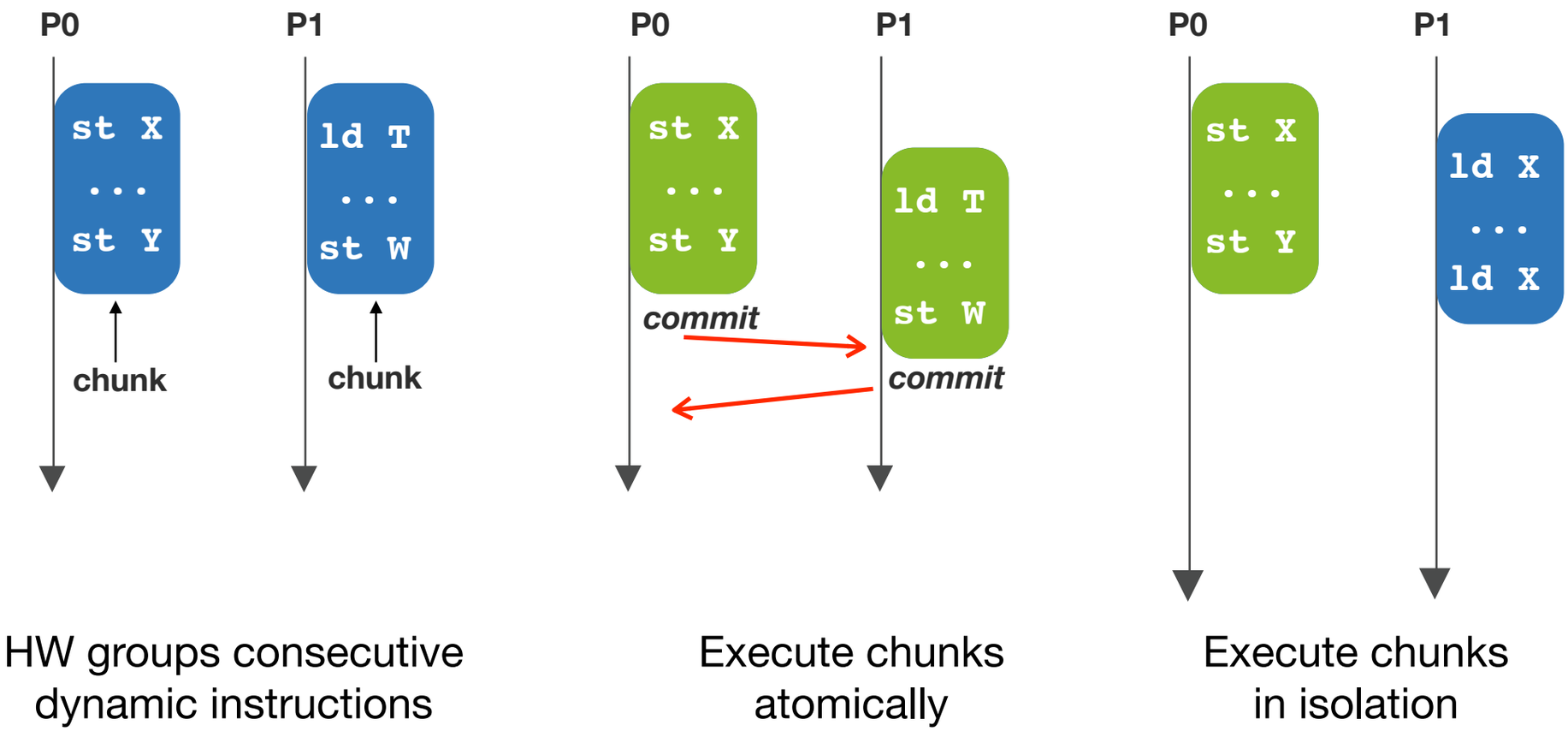

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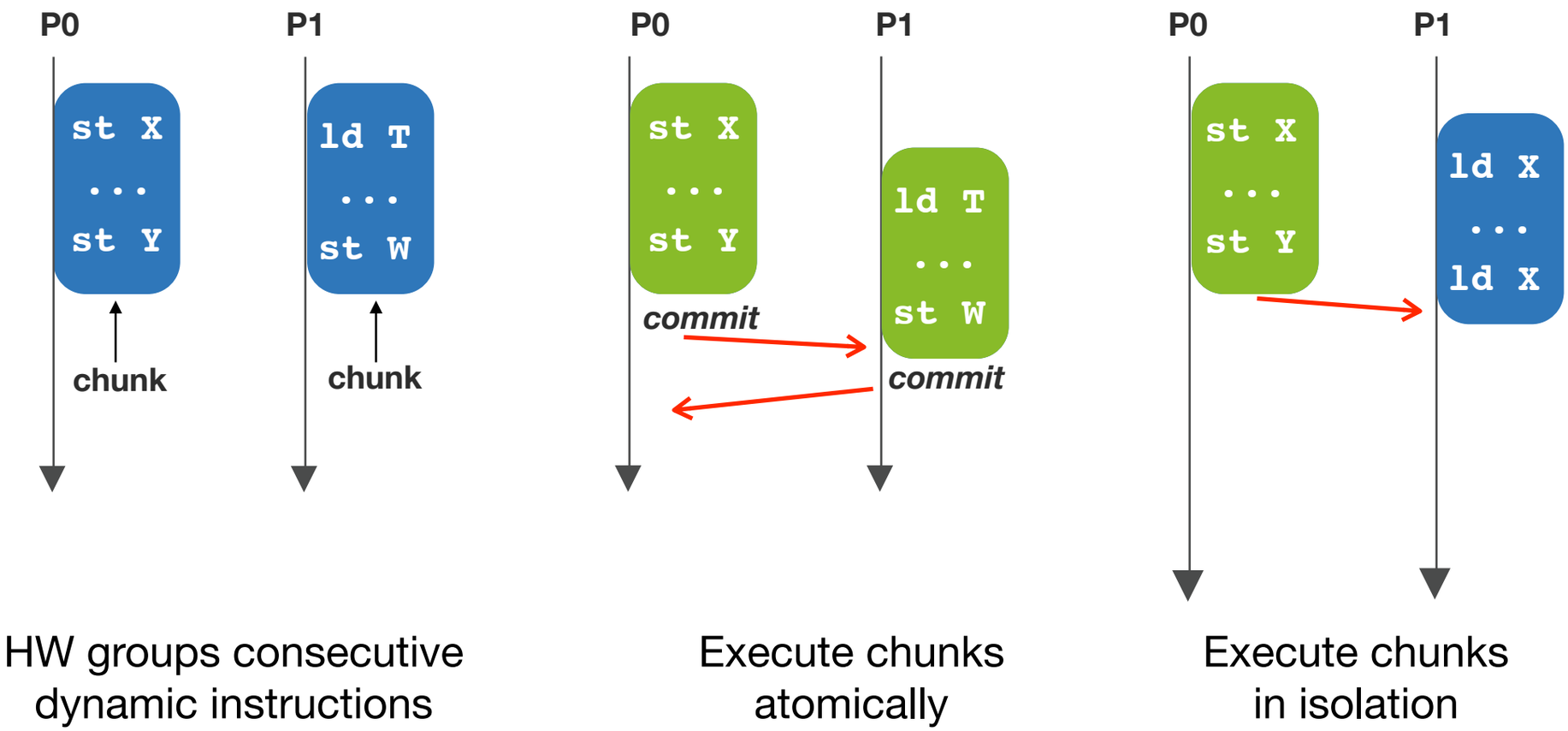

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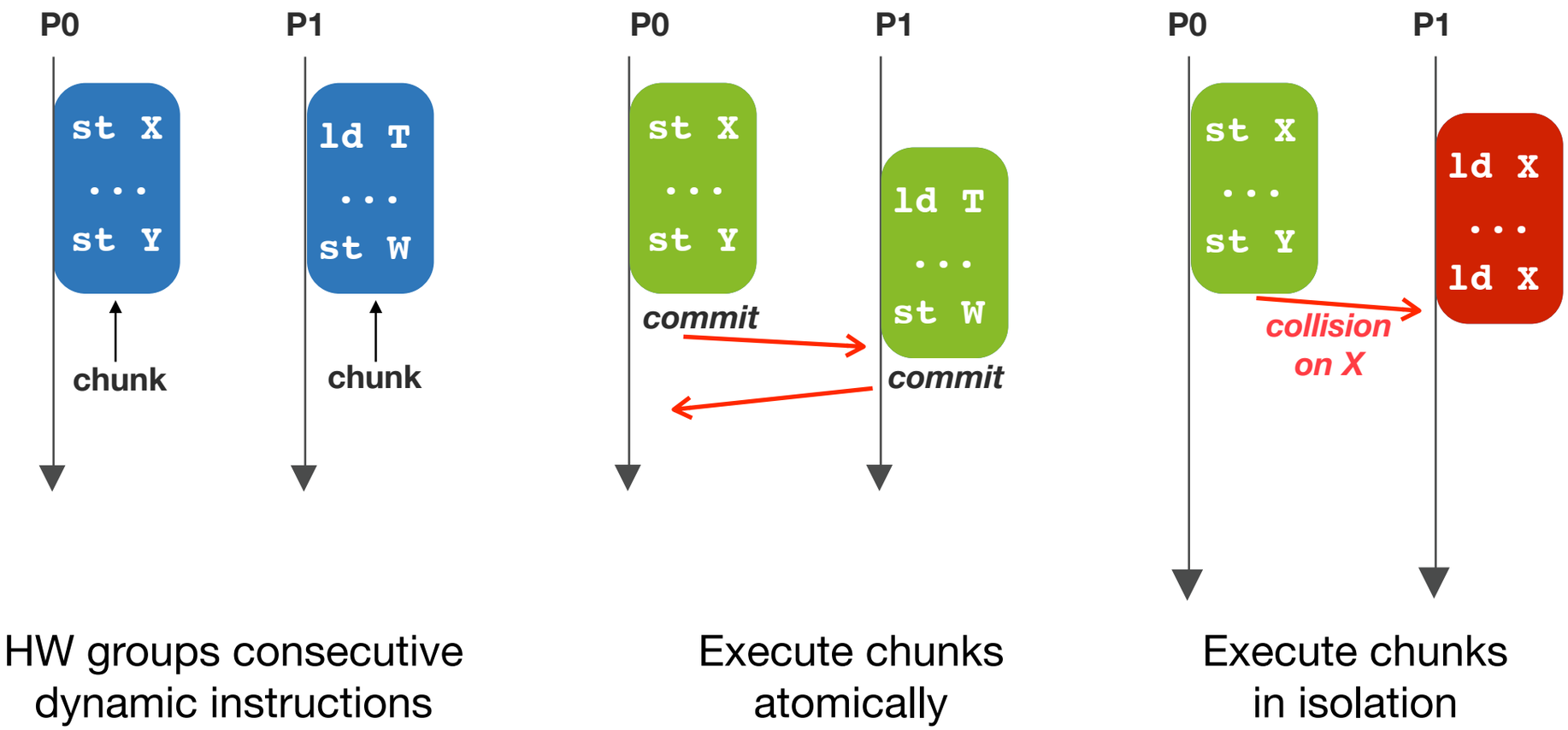

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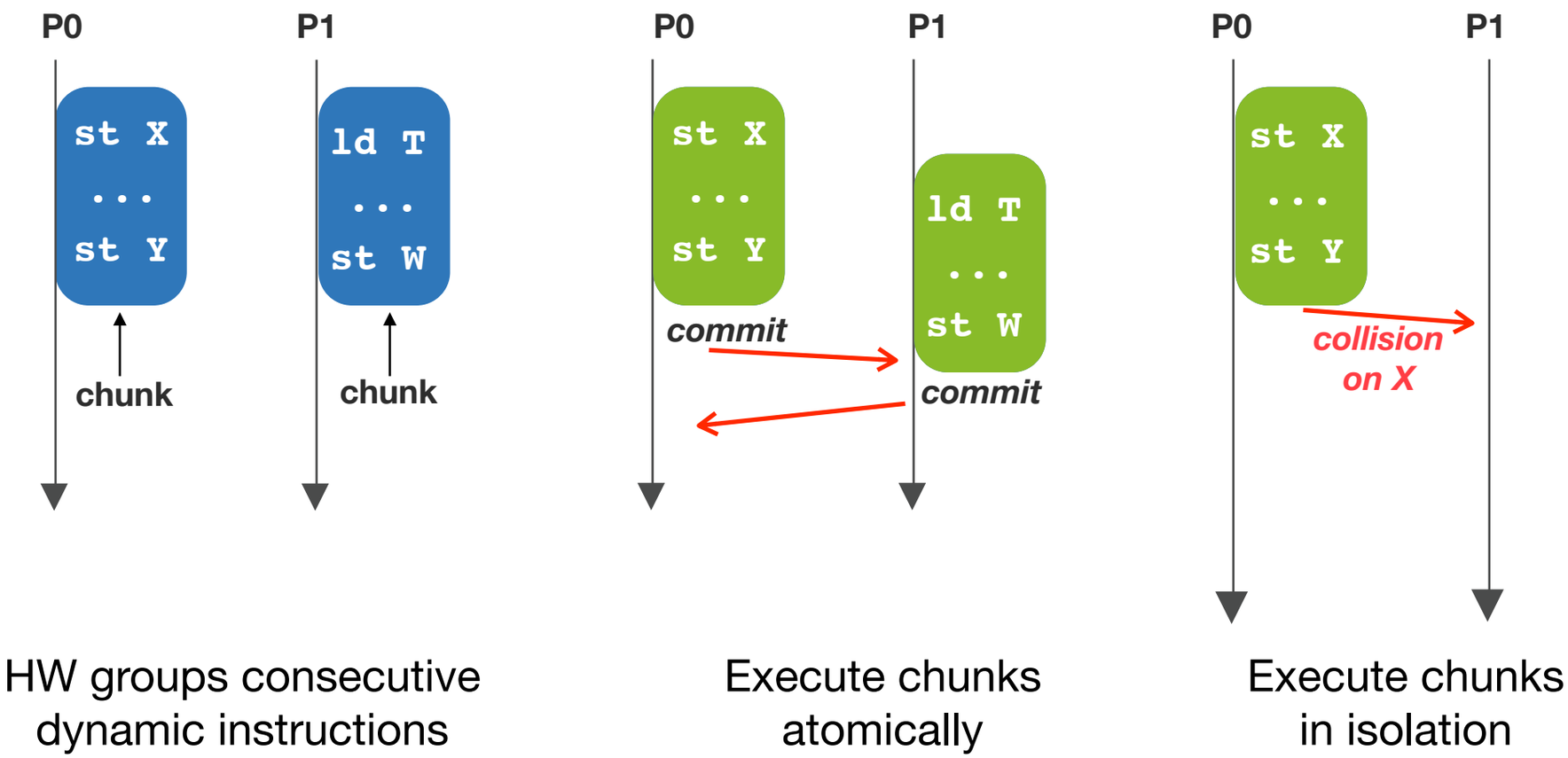

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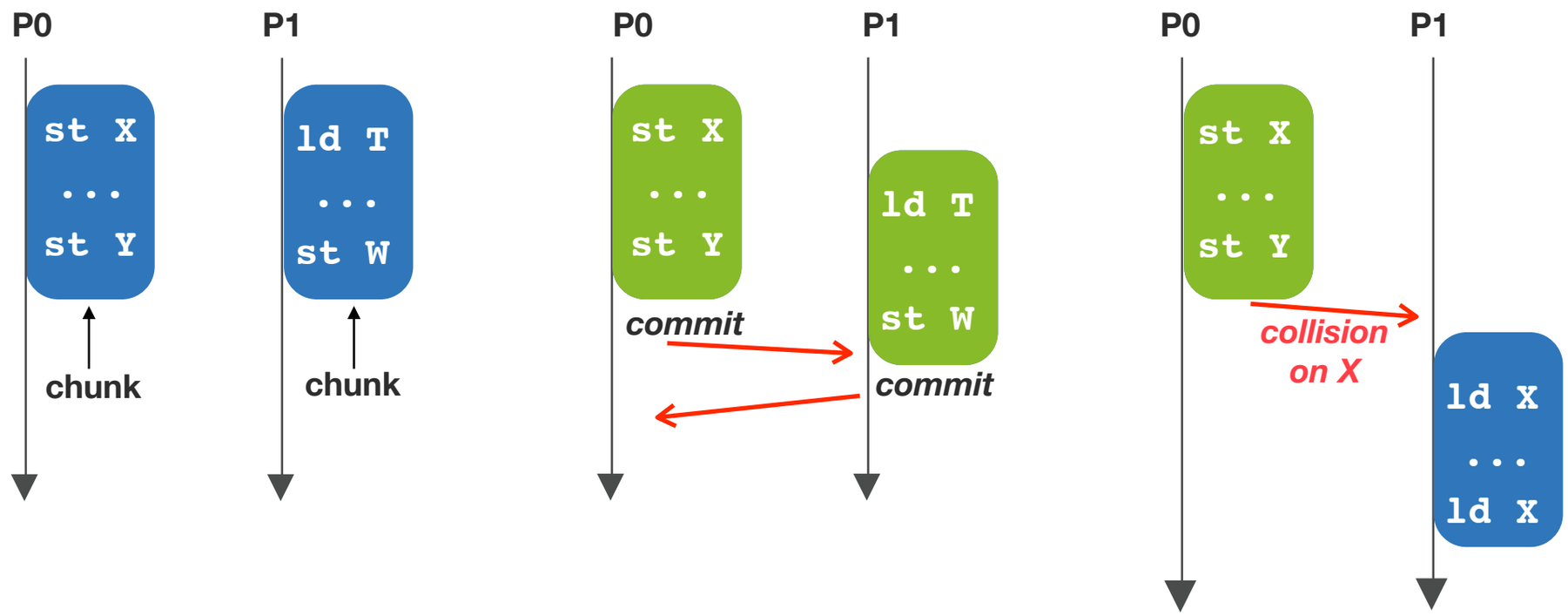

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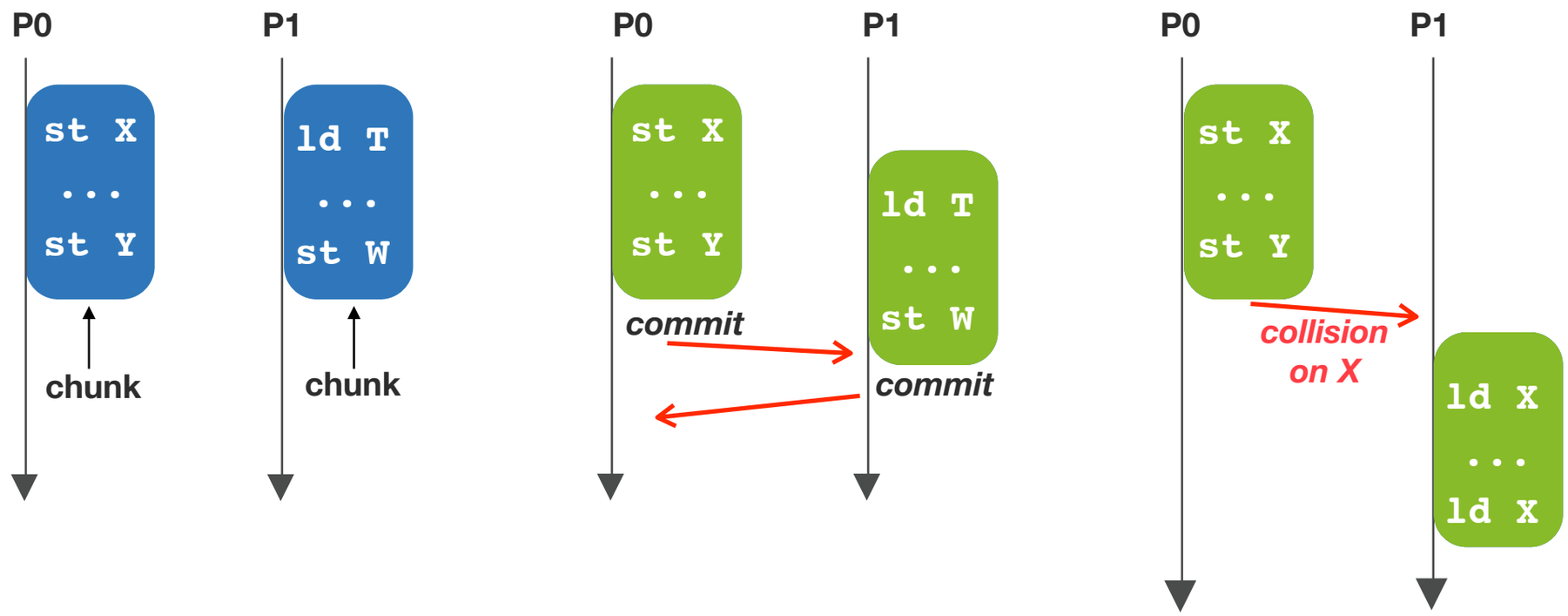

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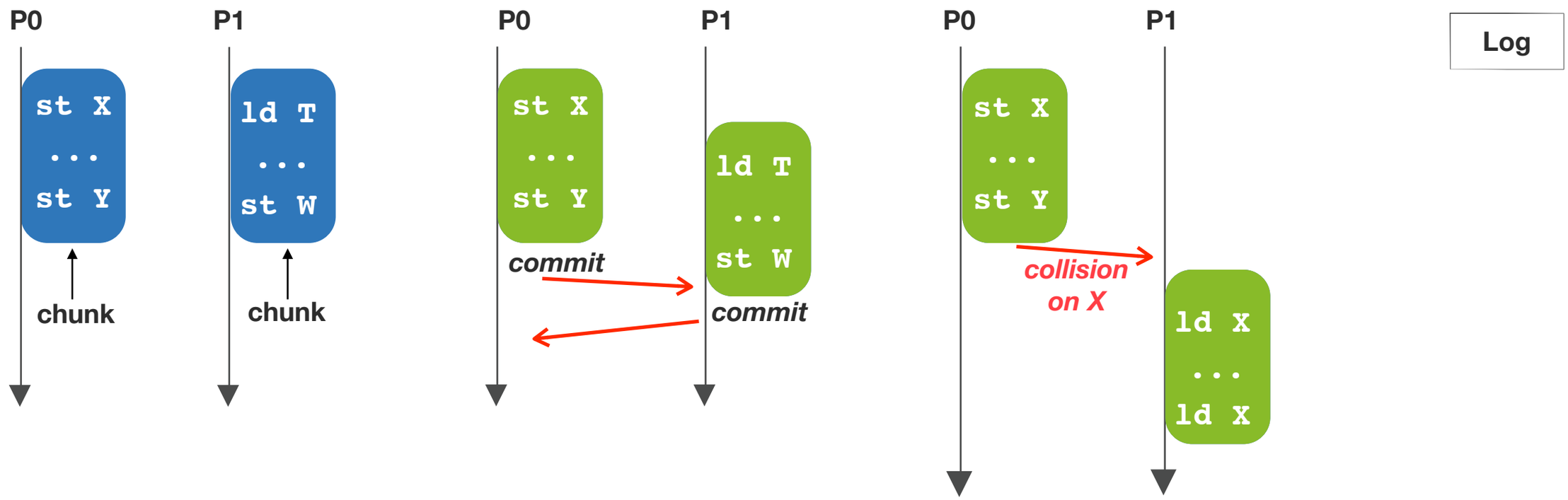

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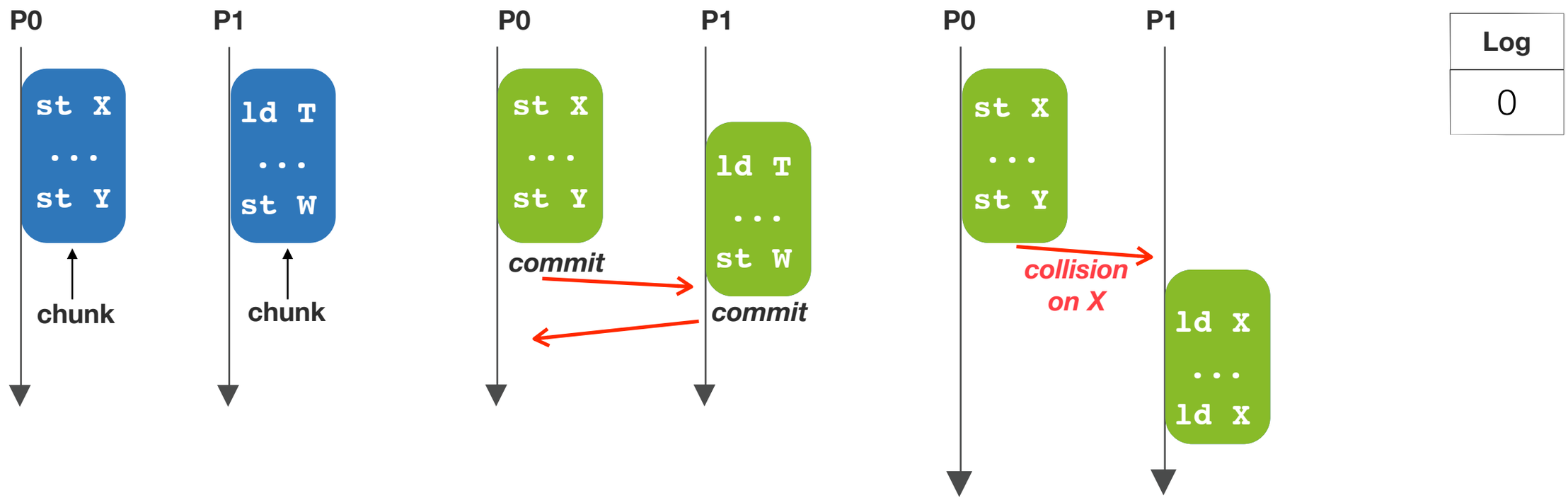

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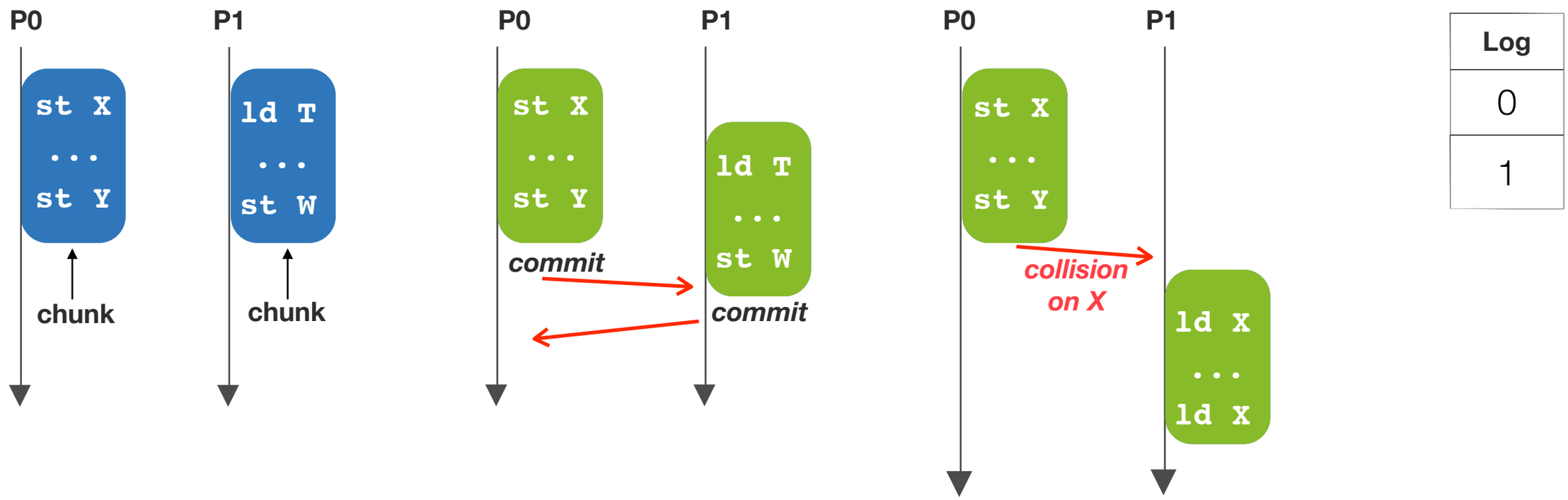

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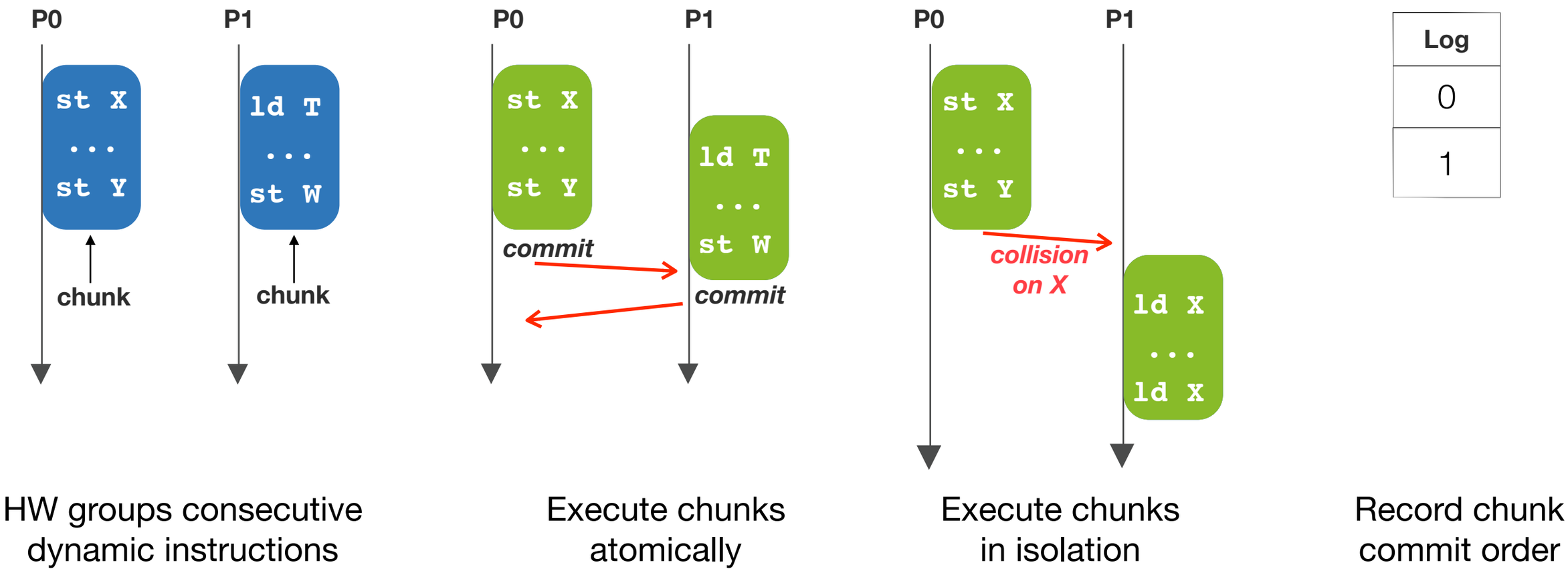

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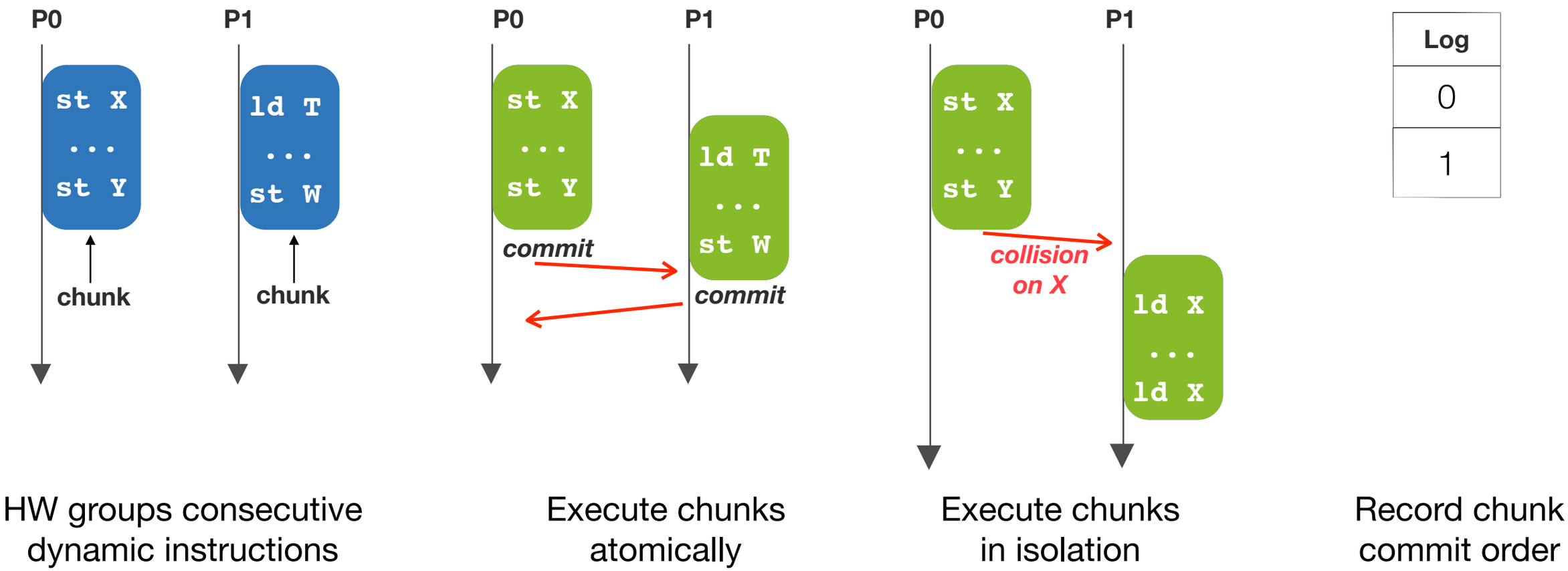

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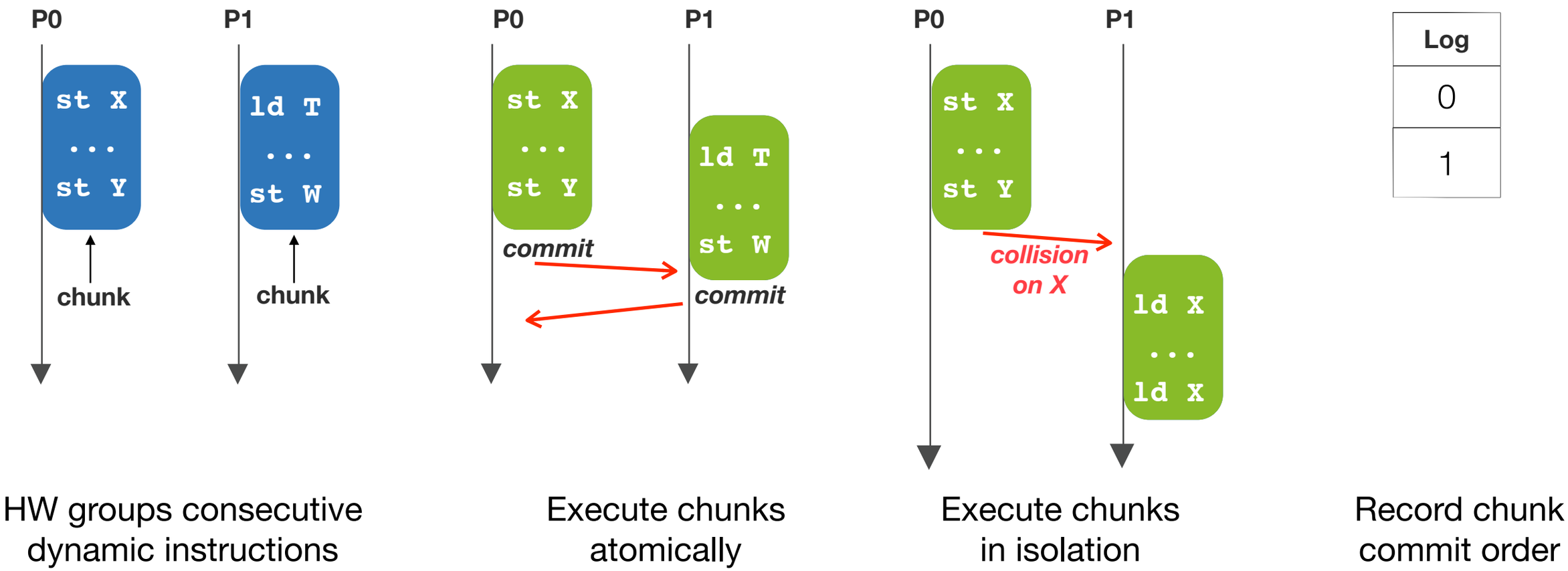

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- During replay: generate same chunks and commit them in same order

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- Memory Interleaving Log must only include interleaving of instructions from R-threads within same sphere
  - Changed DeLorean's chunk truncation rules to enforce isolation

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- Only log non-deterministic events that affect a sphere
  - Log entries record R-thread IDs, not processor IDs
  - Information about other non-deterministic events is discarded
- Memory Interleaving Log must only include interleaving of instructions from R-threads within same sphere
  - Changed DeLorean's chunk truncation rules to enforce isolation
  - Example: System calls cause chunk truncation in CapoOne, not in DeLorean

New Chunking Rules Provide R-Thread Isolation

New Chunking Rules Provide R-Thread Isolation

DeLorean

Processor P1

Processor
Interleaving
Log

New Chunking Rules Provide R-Thread Isolation

DeLorean

Processor P1

500
501

Processor
Interleaving
Log

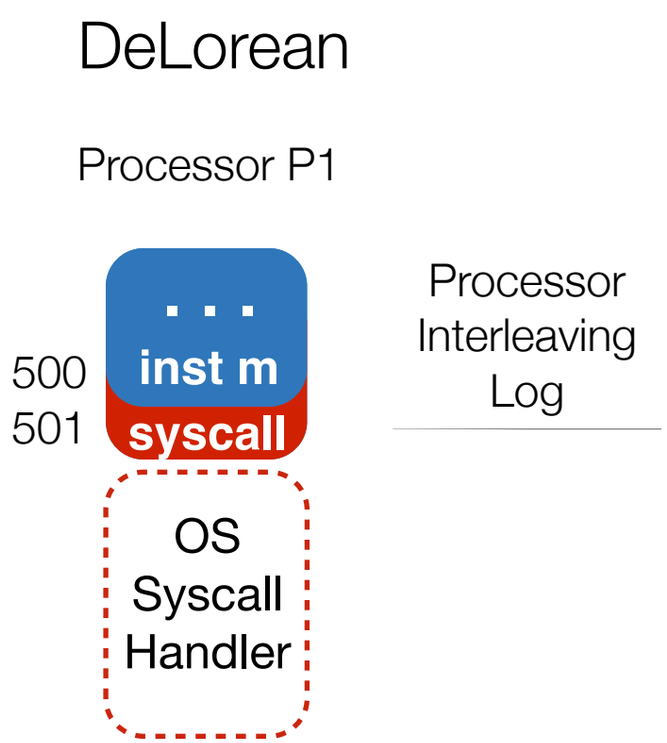
New Chunking Rules Provide R-Thread Isolation

DeLorean

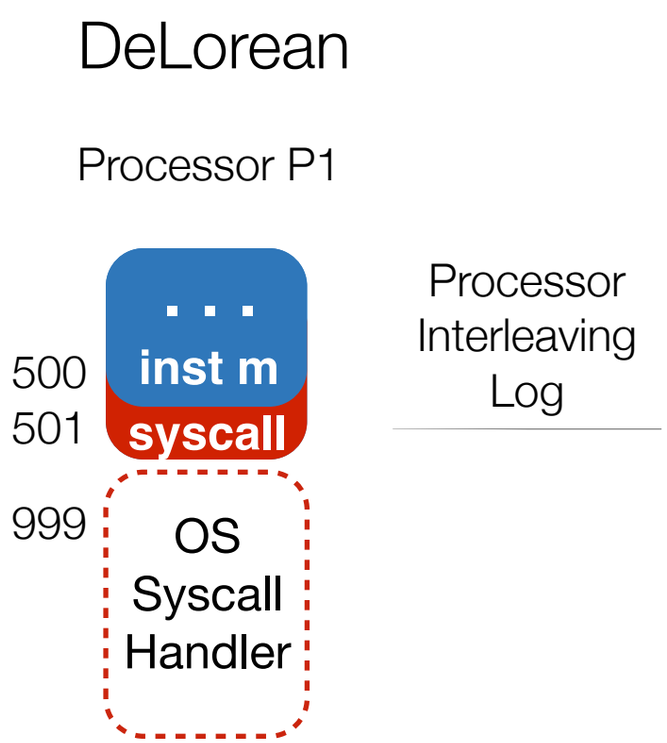
Processor P1

Processor Interleaving Log

New Chunking Rules Provide R-Thread Isolation



New Chunking Rules Provide R-Thread Isolation



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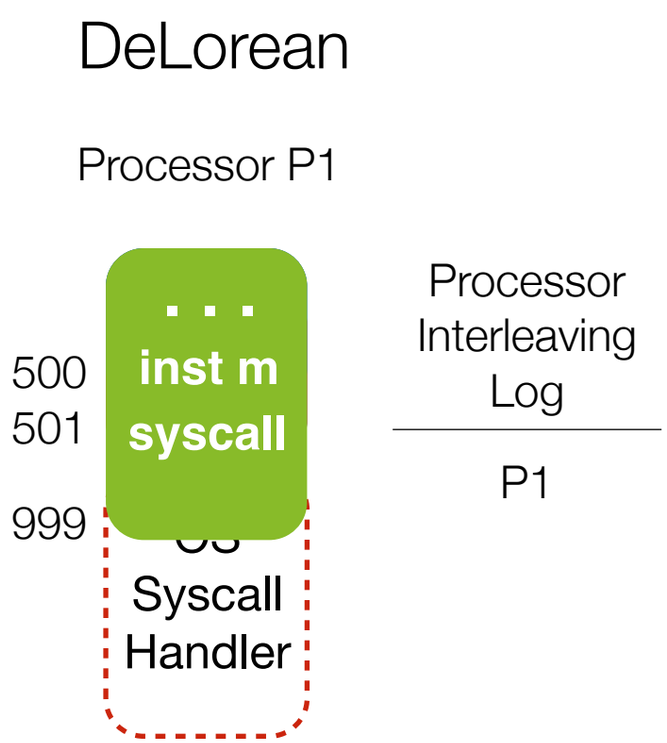
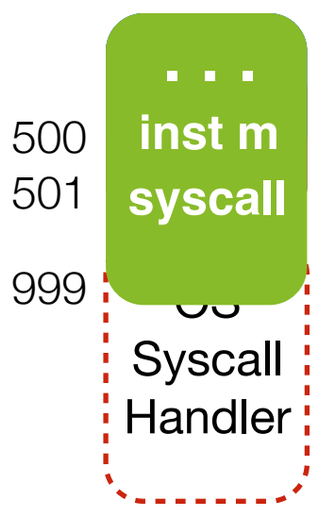


New Chunking Rules Provide R-Thread Isolation

DeLorean

Processor P1



Processor Interleaving Log

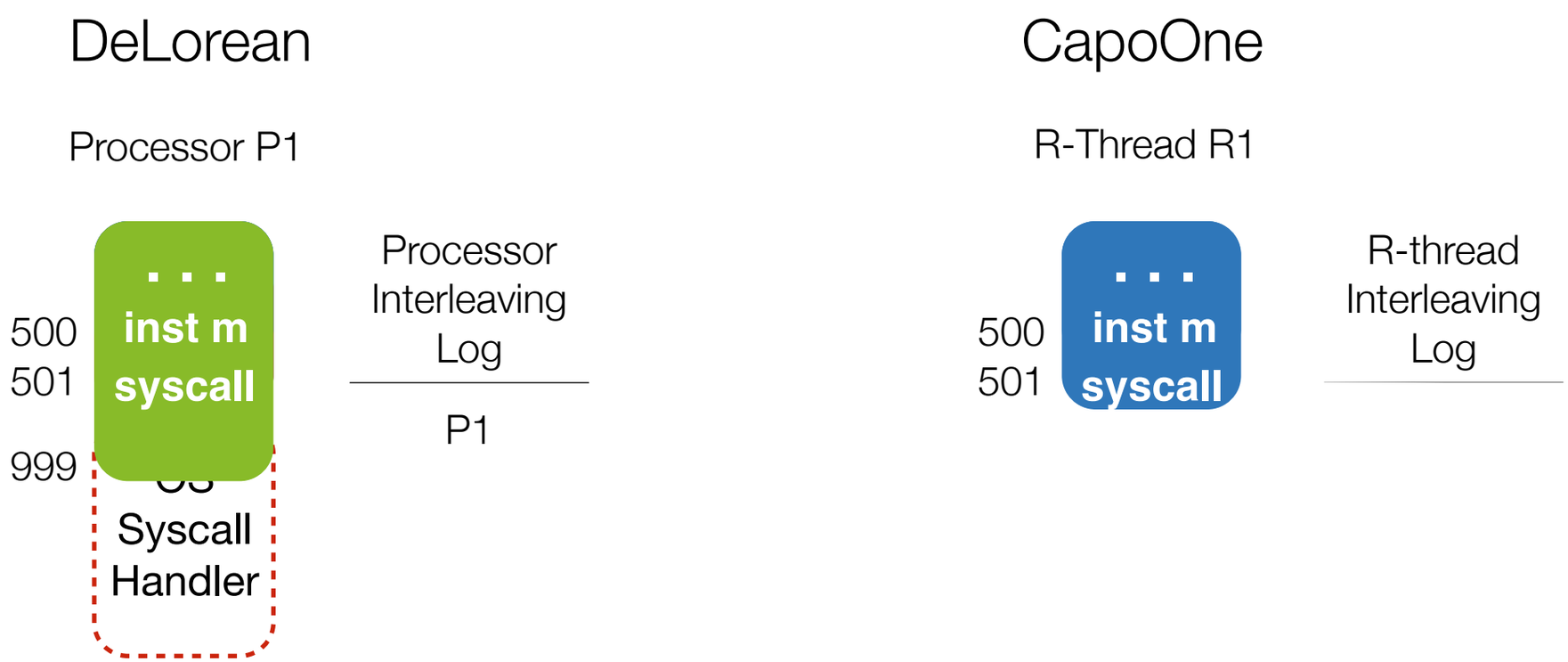
P1

CapoOne

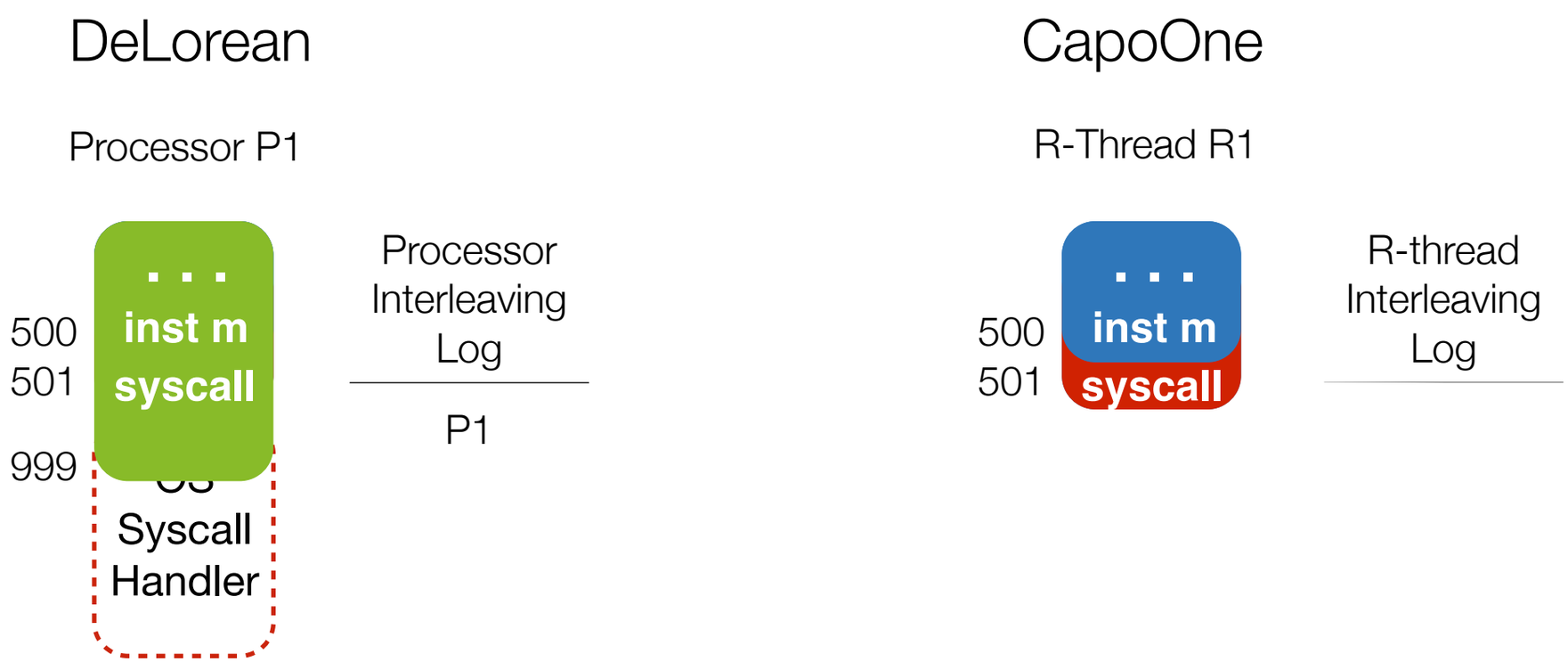
R-Thread R1

R-thread Interleaving Log

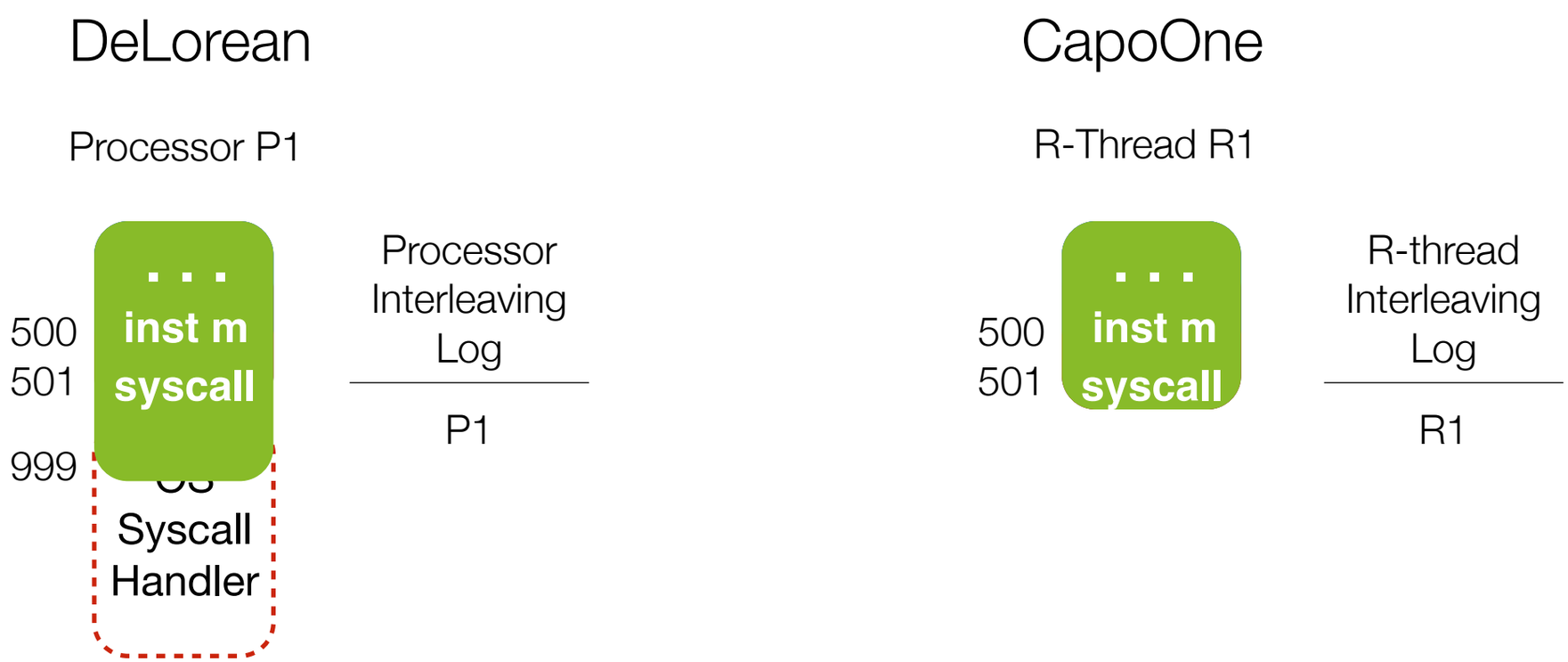
New Chunking Rules Provide R-Thread Isolation



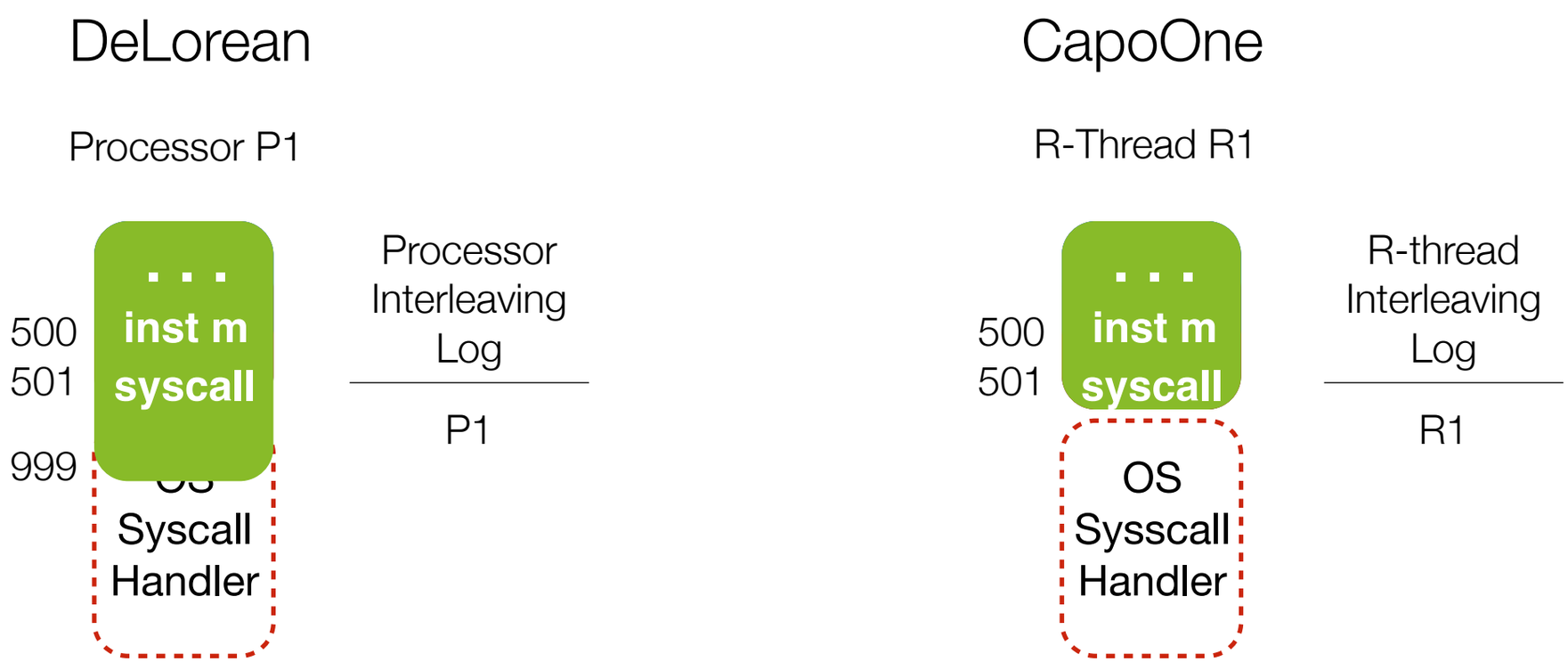
New Chunking Rules Provide R-Thread Isolation



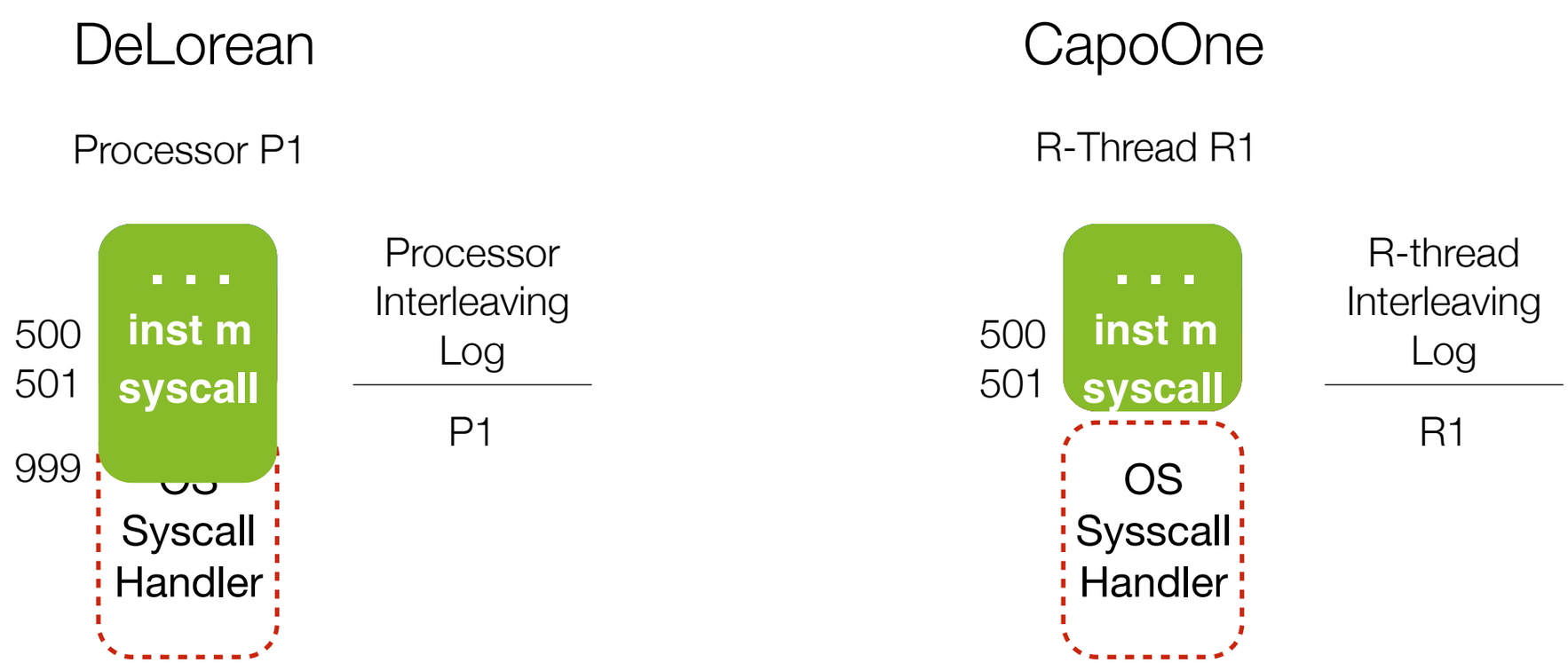
New Chunking Rules Provide R-Thread Isolation



New Chunking Rules Provide R-Thread Isolation

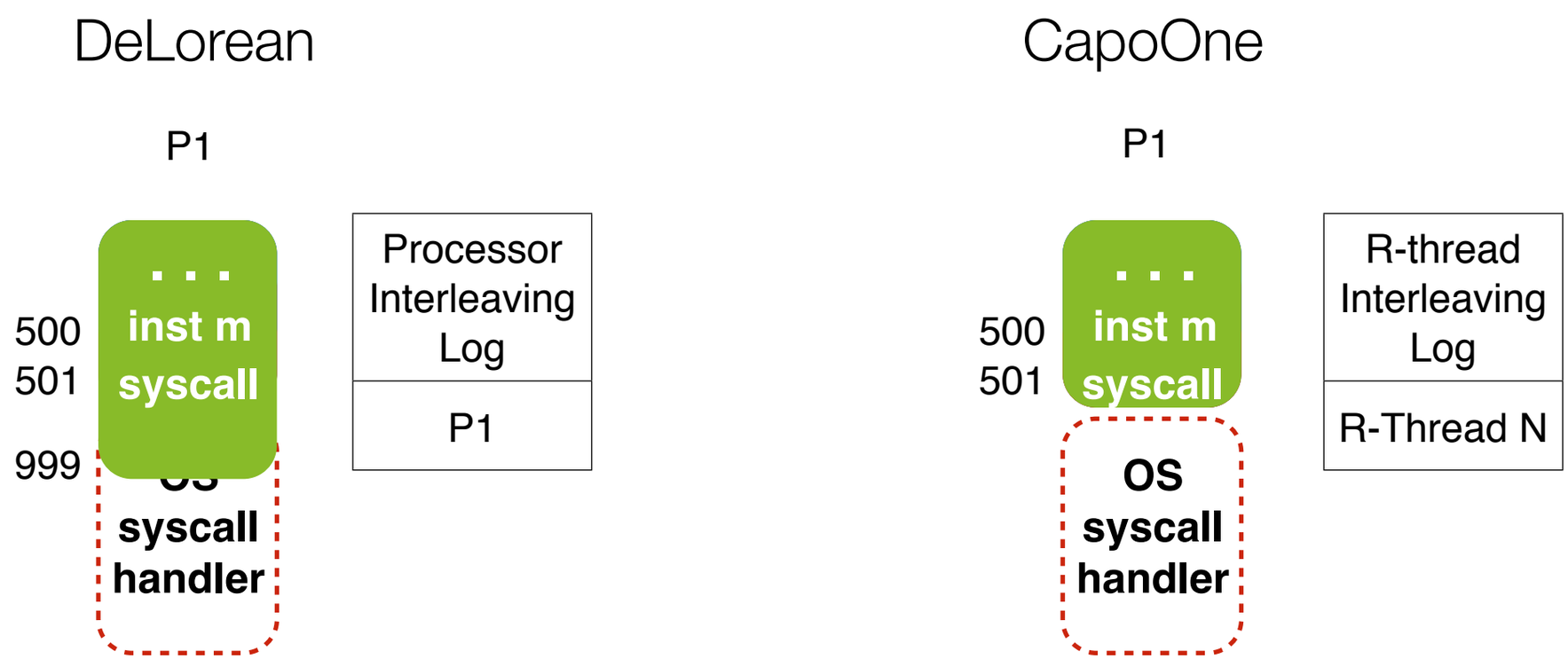


New Chunking Rules Provide R-Thread Isolation



- Inform HW to stop logging interleaving of instructions from current proc
  - Always do it when execution leaves replay sphere
  - Otherwise, OS instructions might become part of interleaving log

New Chunking Rules Provide R-Thread Isolation



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  - Otherwise, OS instructions might become part of interleaving log

New Chunking Rules Provide R-Thread Isolation

DeLorean

CapoOne

RSM and HW must work together to avoid any OS instruction to pollute the Memory Interleaving Log

- Inform HW to stop logging interleaving of instructions from current proc
  - Always do it when execution leaves replay sphere
  - Otherwise, OS instructions might become part of interleaving log

Handling Interrupts

Handling Interrupts

- Ensure interrupt handler code is not part of Memory Interleaving Log

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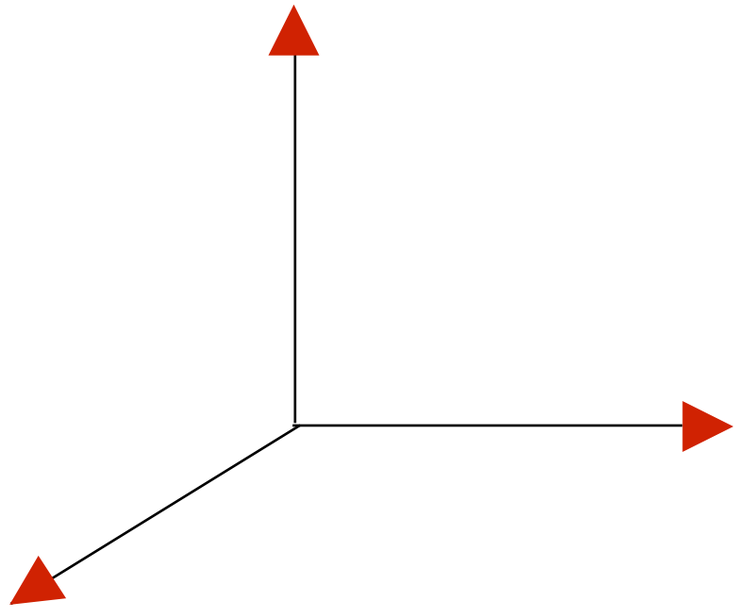

Handling Interrupts

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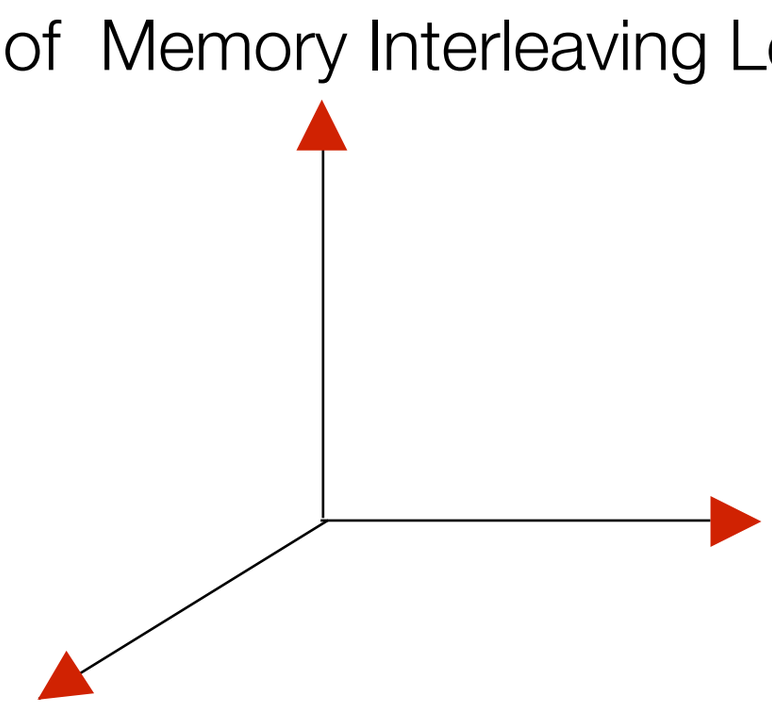

Handling Interrupts

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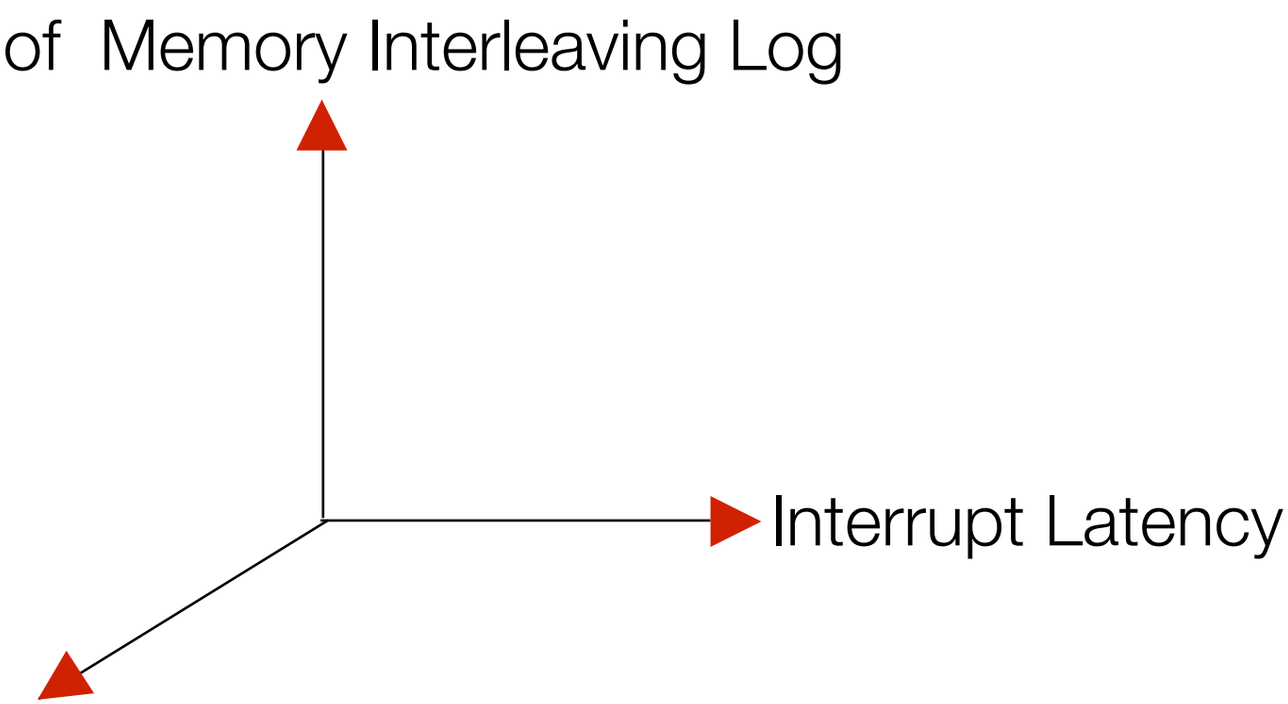

Handling Interrupts

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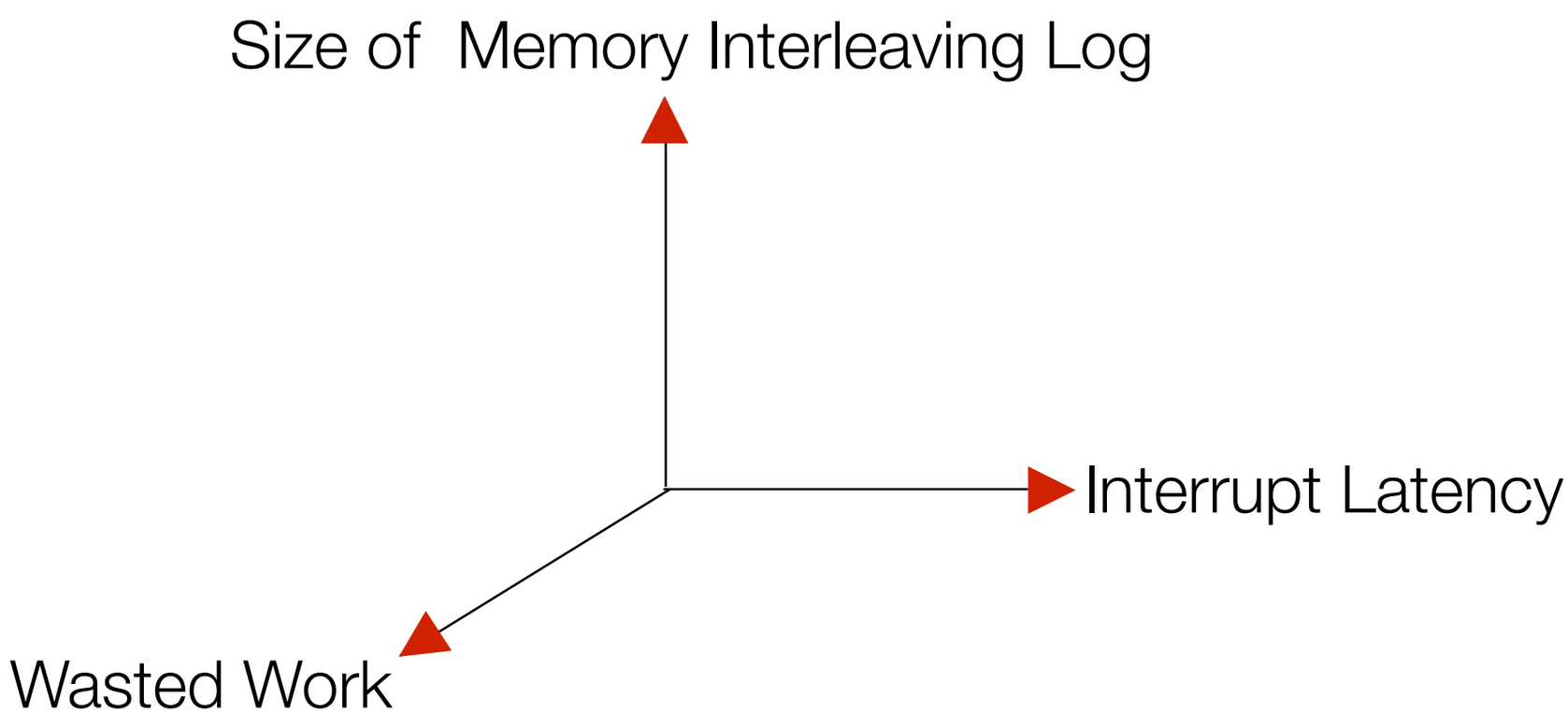

Handling Interrupts: Three Approaches

Handling Interrupts: Three Approaches

Finish First

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First			

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First			

Original Execution

R-thread R1

Chunk Size Log

Handling Interrupts: Three Approaches

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Finish First			

Original Execution

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Chunk Size Log

Handling Interrupts: Three Approaches

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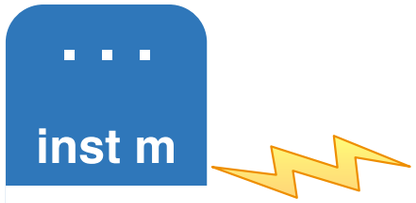
Original Execution

R-thread R1



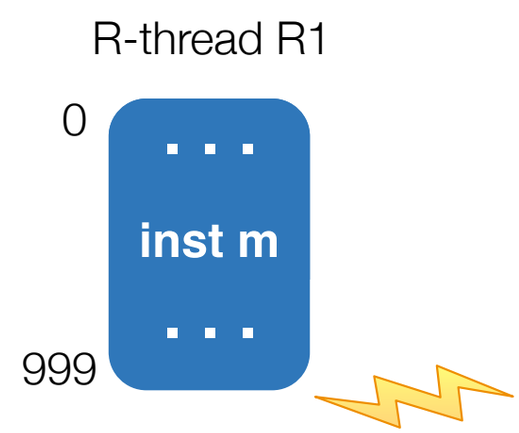
Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First			

Original Execution

Chunk Size Log

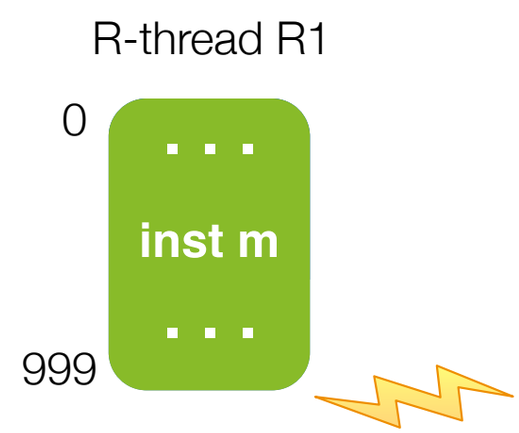


Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First			

Original Execution

Chunk Size Log



Handling Interrupts: Three Approaches

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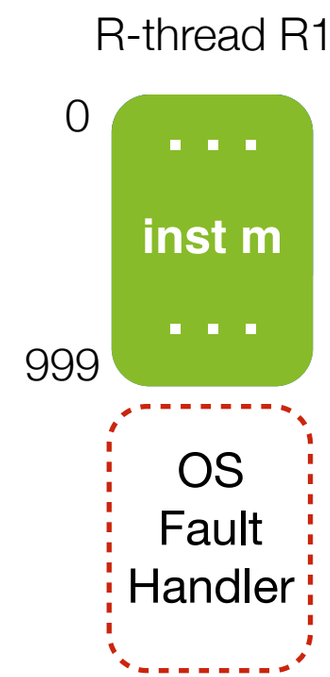
Finish First			

Original Execution



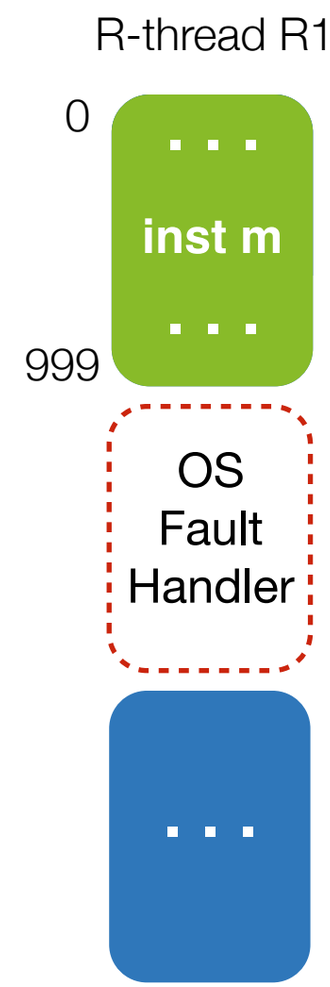
Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First			

Original Execution

Chunk Size Log

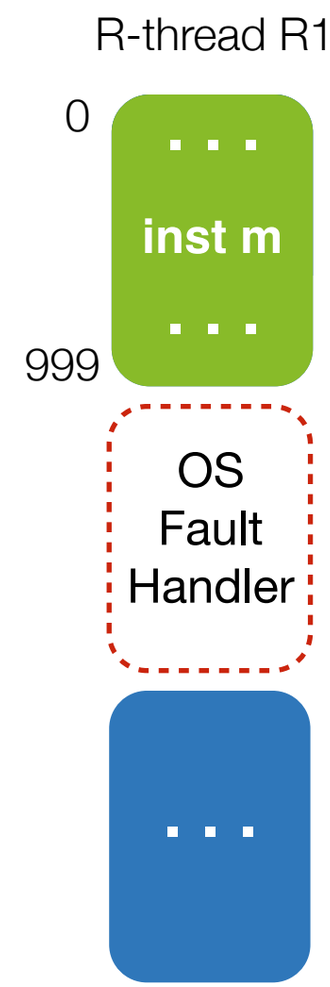


Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔		

Original Execution

Chunk Size Log

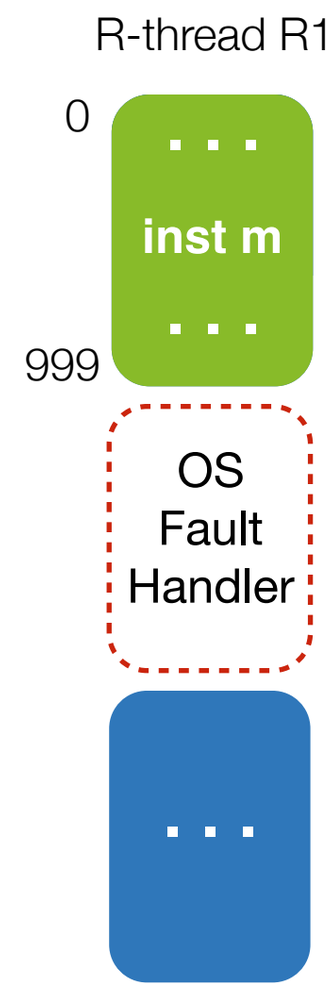


Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	

Original Execution

Chunk Size Log

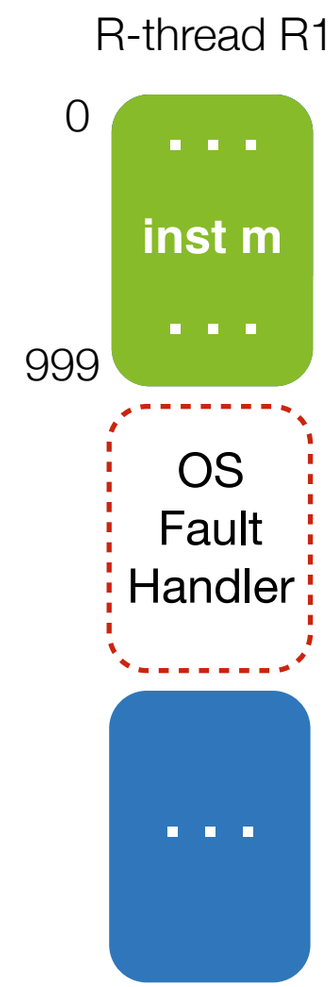


Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—

Original Execution

Chunk Size Log



Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now			

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—
Commit Now			

Original Execution

R-thread R1

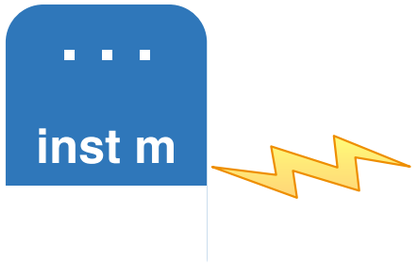
Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—
Commit Now			

Original Execution

R-thread R1

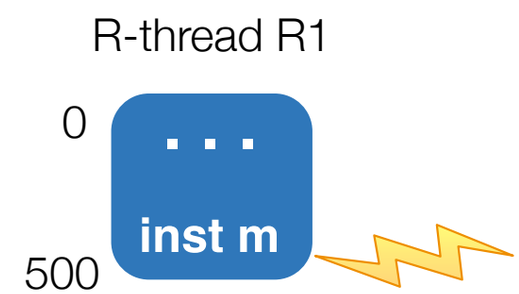


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—
Commit Now			

Original Execution

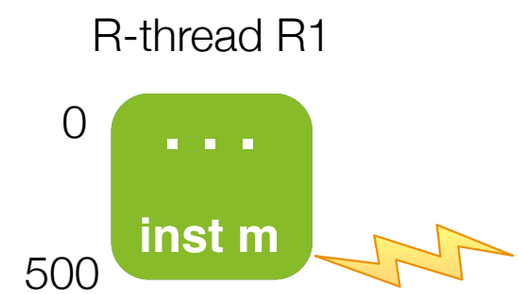


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—
Commit Now			

Original Execution

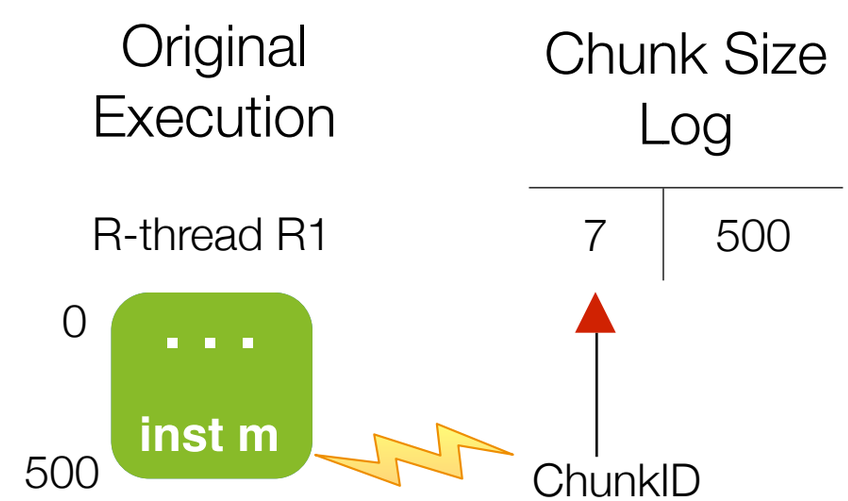


Chunk Size Log

7	500

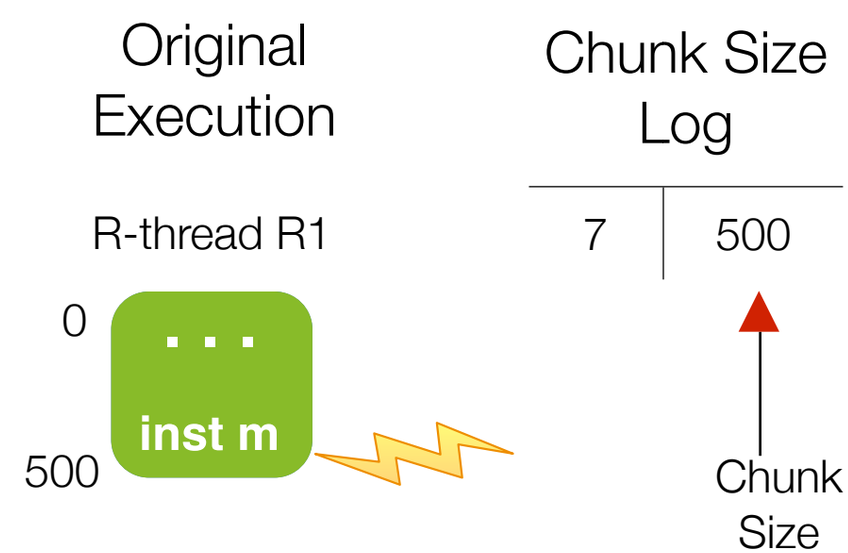
Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now			



Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now			



Handling Interrupts: Three Approaches

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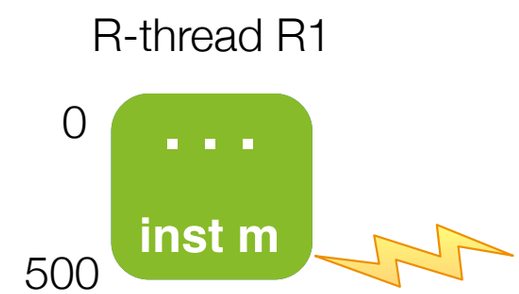
Finish First	✔	✔	—
Commit Now			

Original Execution



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Handling Interrupts: Three Approaches

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Finish First	✔	✔	—
Commit Now			

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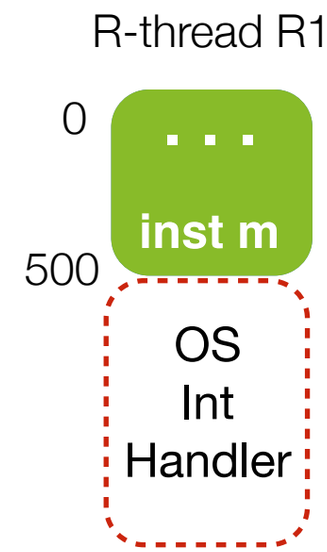

Chunk Size Log

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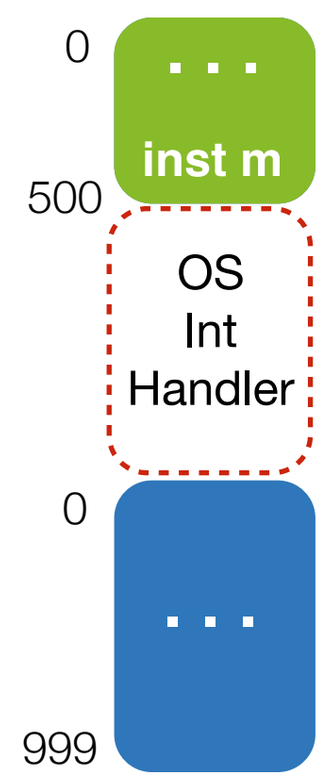
Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—
Commit Now			

Original Execution



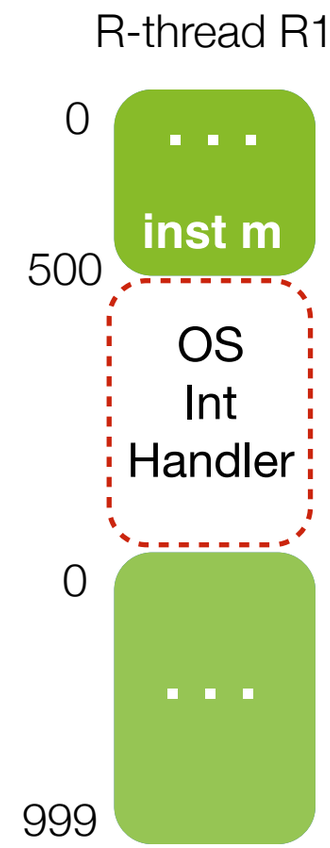
Chunk Size Log

7	500

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—
Commit Now			

Original Execution

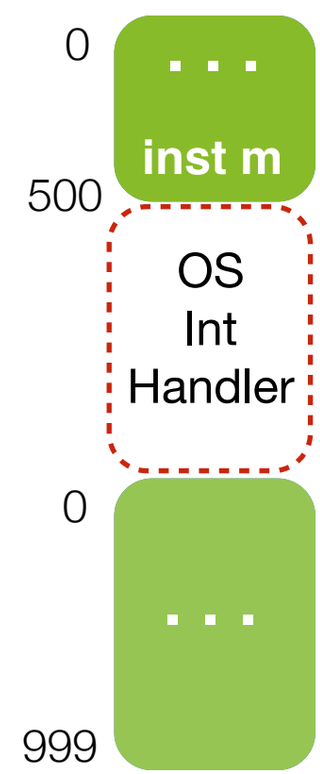


Chunk Size Log	
7	500

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✔	✔	—
Commit Now	—		

Original Execution

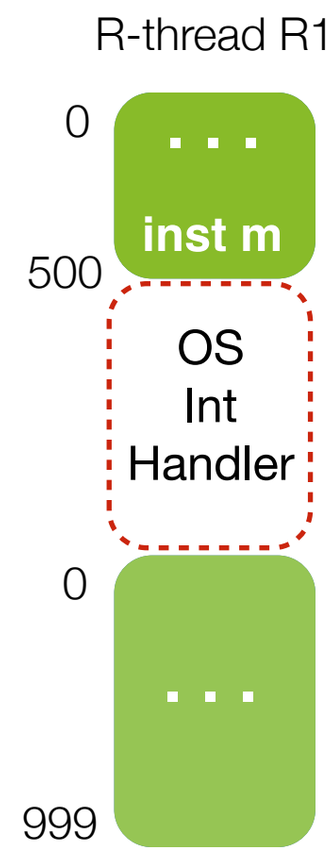


Chunk Size Log	
7	500

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	

Original Execution

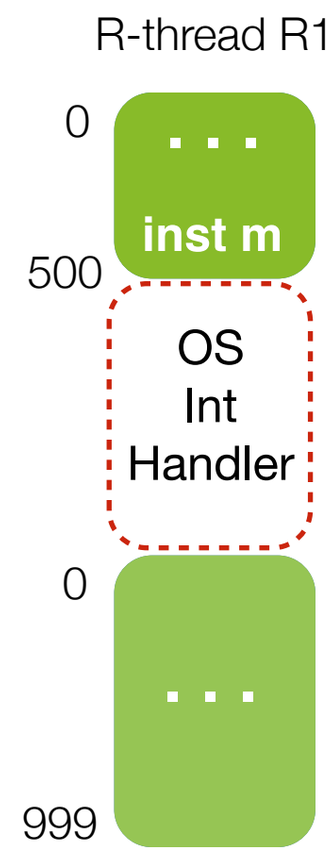


Chunk Size Log	
7	500

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓

Original Execution



Chunk Size Log

7	500

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now			

Handling Interrupts: Three Approaches

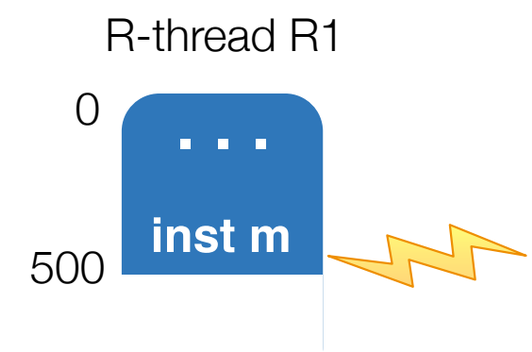
	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now			

Original Execution	Chunk Size Log
R-thread R1	

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now			

Original Execution

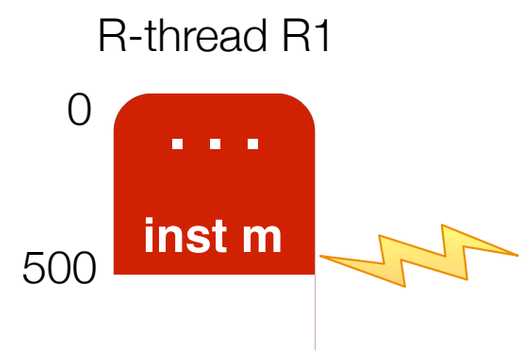


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	–
Commit Now	–	✓	✓
Squash Now			

Original Execution



Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now			

Original Execution

R-thread R1

Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now			

Original Execution

R-thread R1

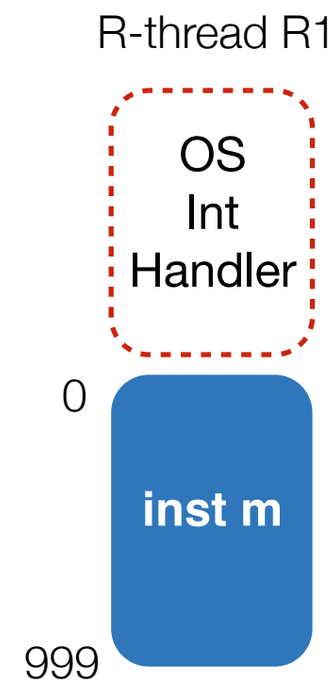
OS Int Handler

Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now			

Original Execution

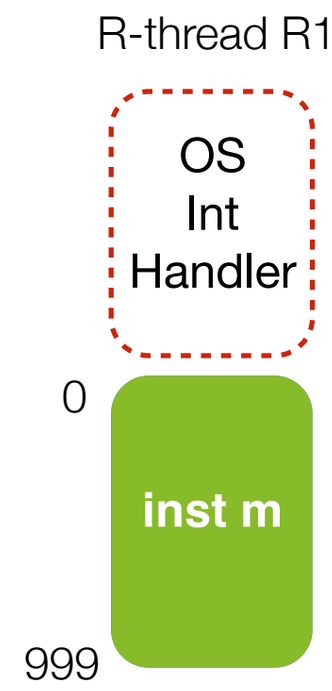


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	–
Commit Now	–	✓	✓
Squash Now			

Original Execution

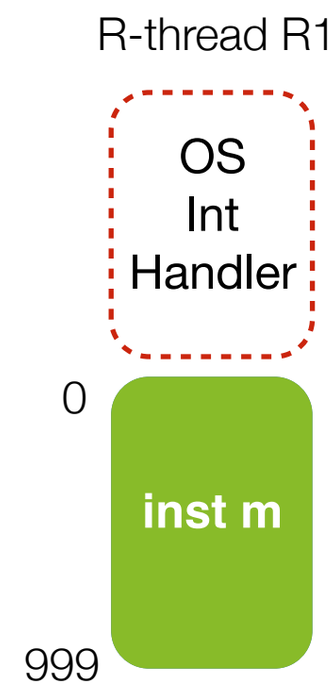


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now	✓		

Original Execution

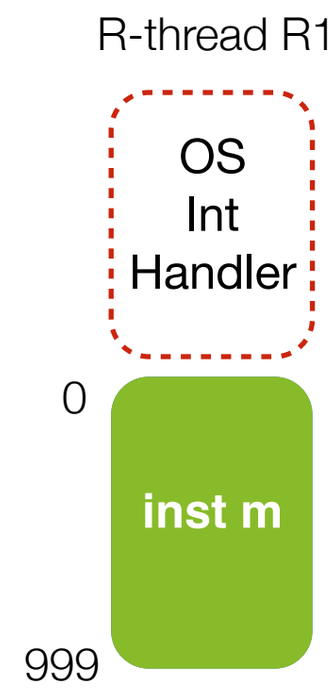


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	–
Commit Now	–	✓	✓
Squash Now	✓	–	

Original Execution

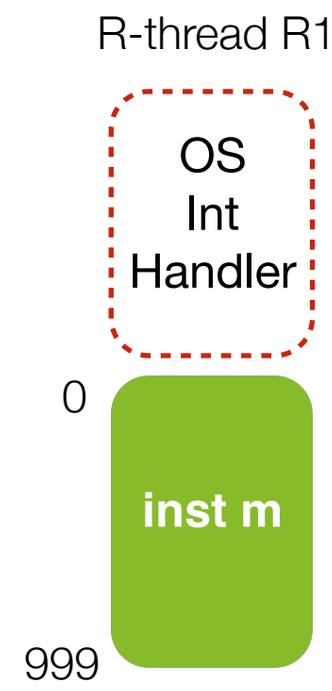


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now	✓	—	✓

Original Execution

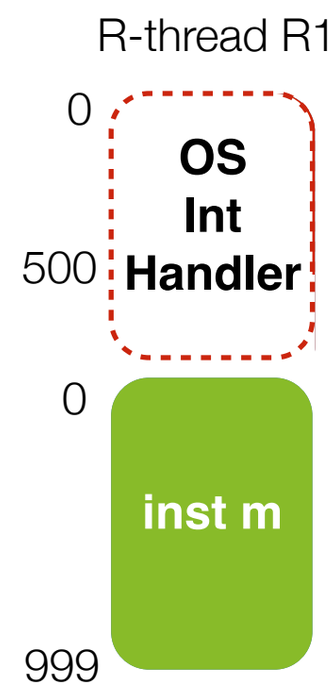


Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency
Finish First	✓	✓	—
Commit Now	—	✓	✓
Squash Now	✓	—	✓

Original Execution



Chunk Size Log

Handling Interrupts: Three Approaches

	Log Size	Wasted Work	Interrupt Latency	Original Execution	Chunk Size Log
Finis					
Com					
Squa					

Highly non-deterministic events, such as interrupts, can be treated as deterministic events

CapoOne uses SquashNow: easy to implement and little overhead

Handling Faults

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- Commit all instructions up to faulting one and log chunk size

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Original Execution	Chunk Size Log
R-thread R1	

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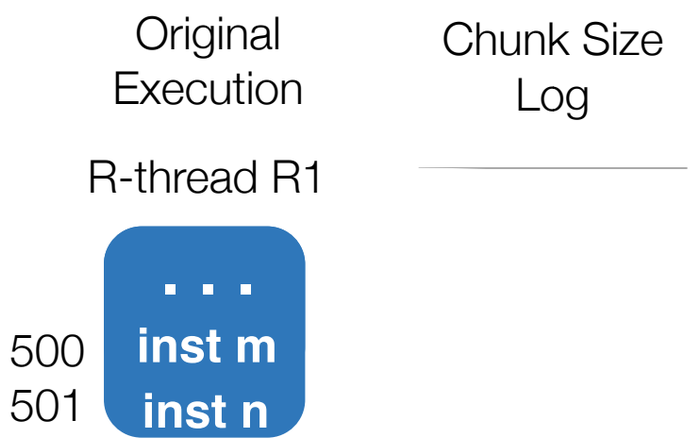

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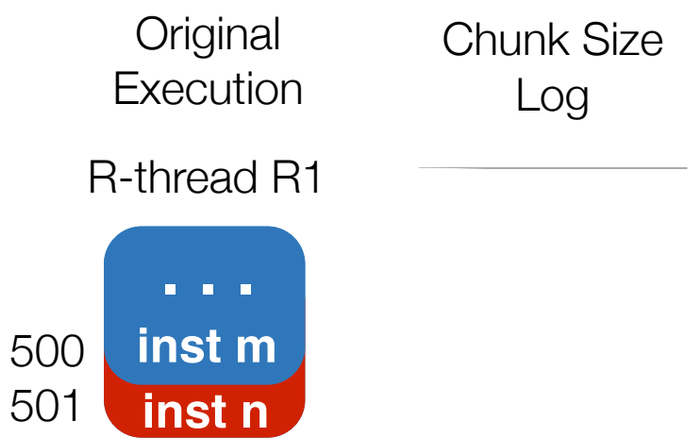

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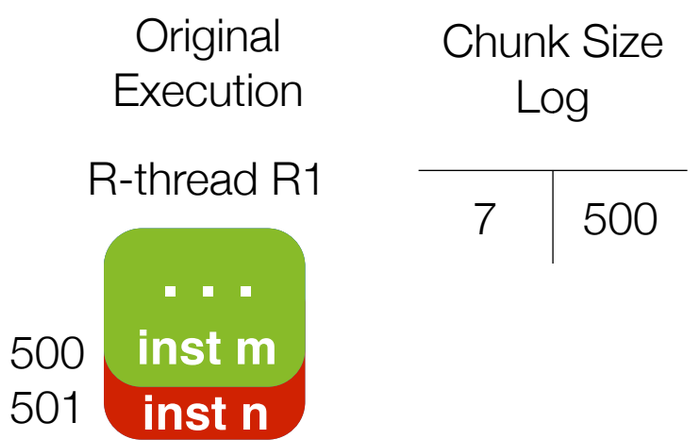

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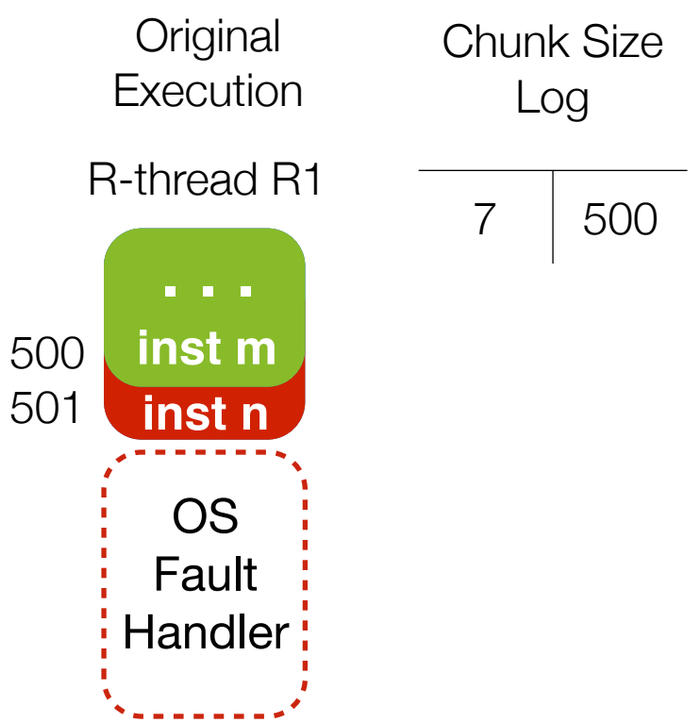

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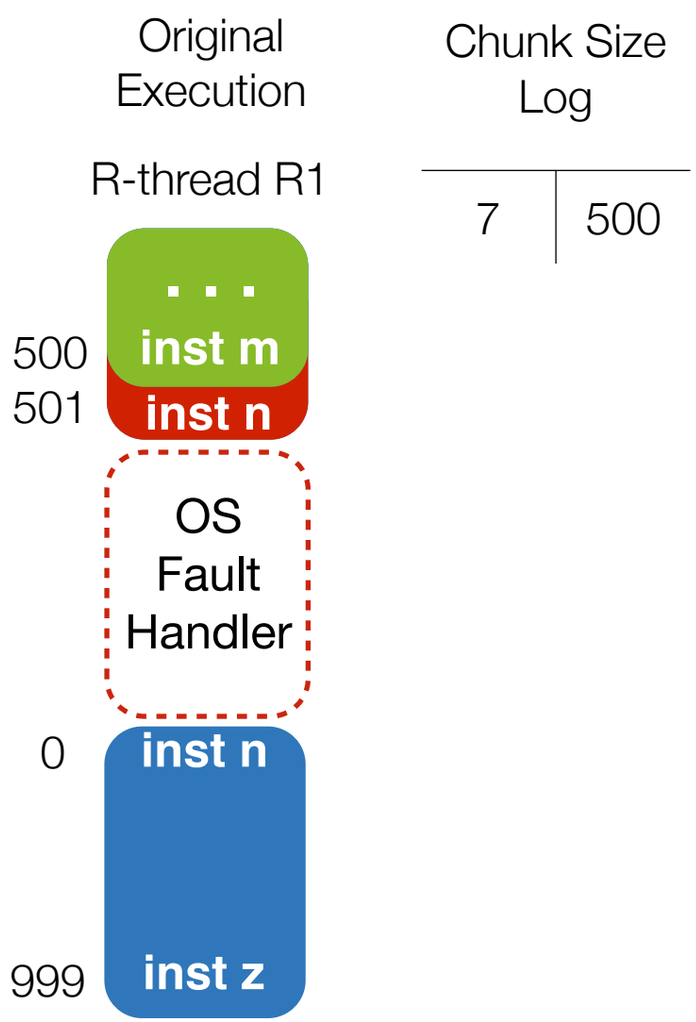

Chunk Size Log

7	500

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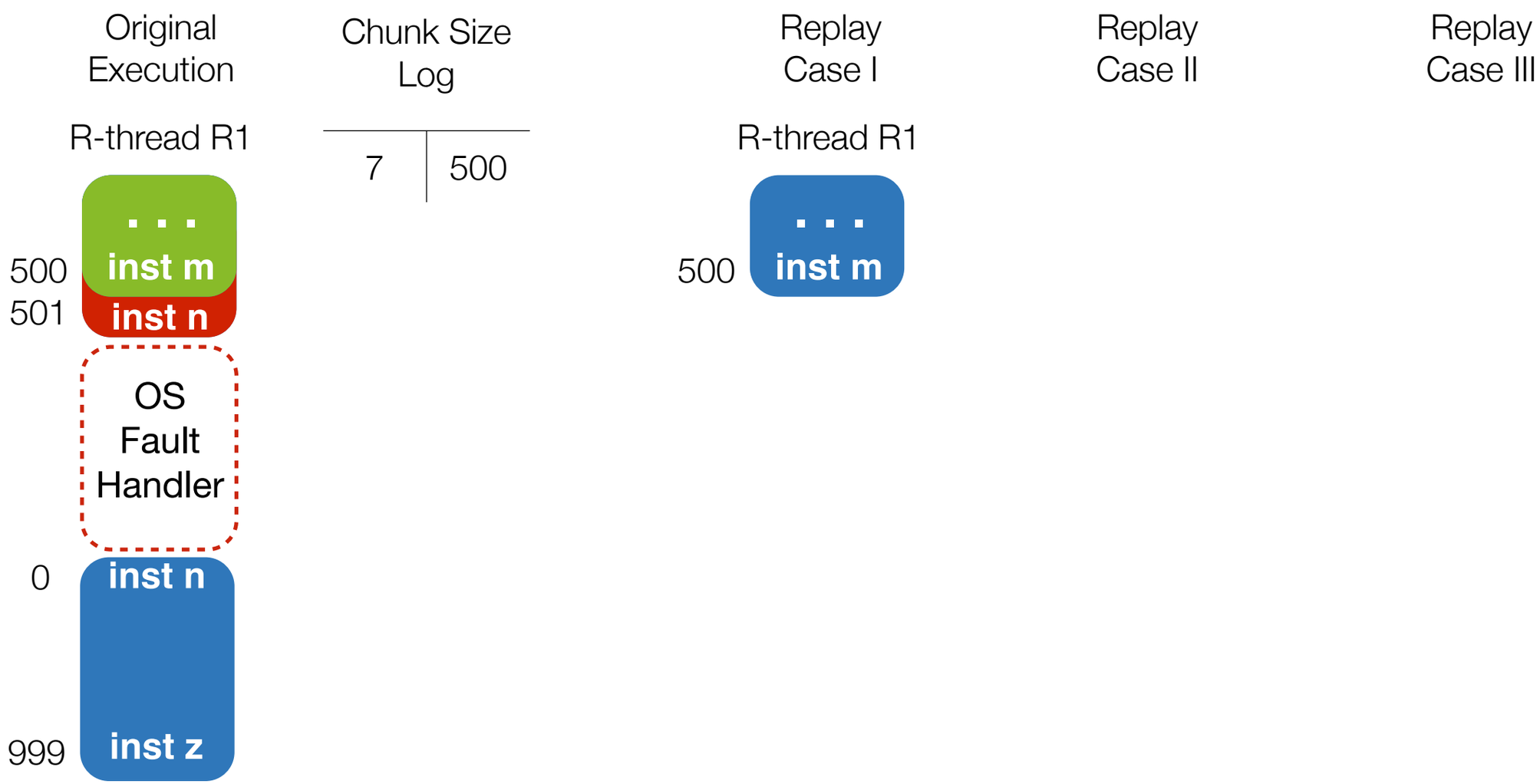

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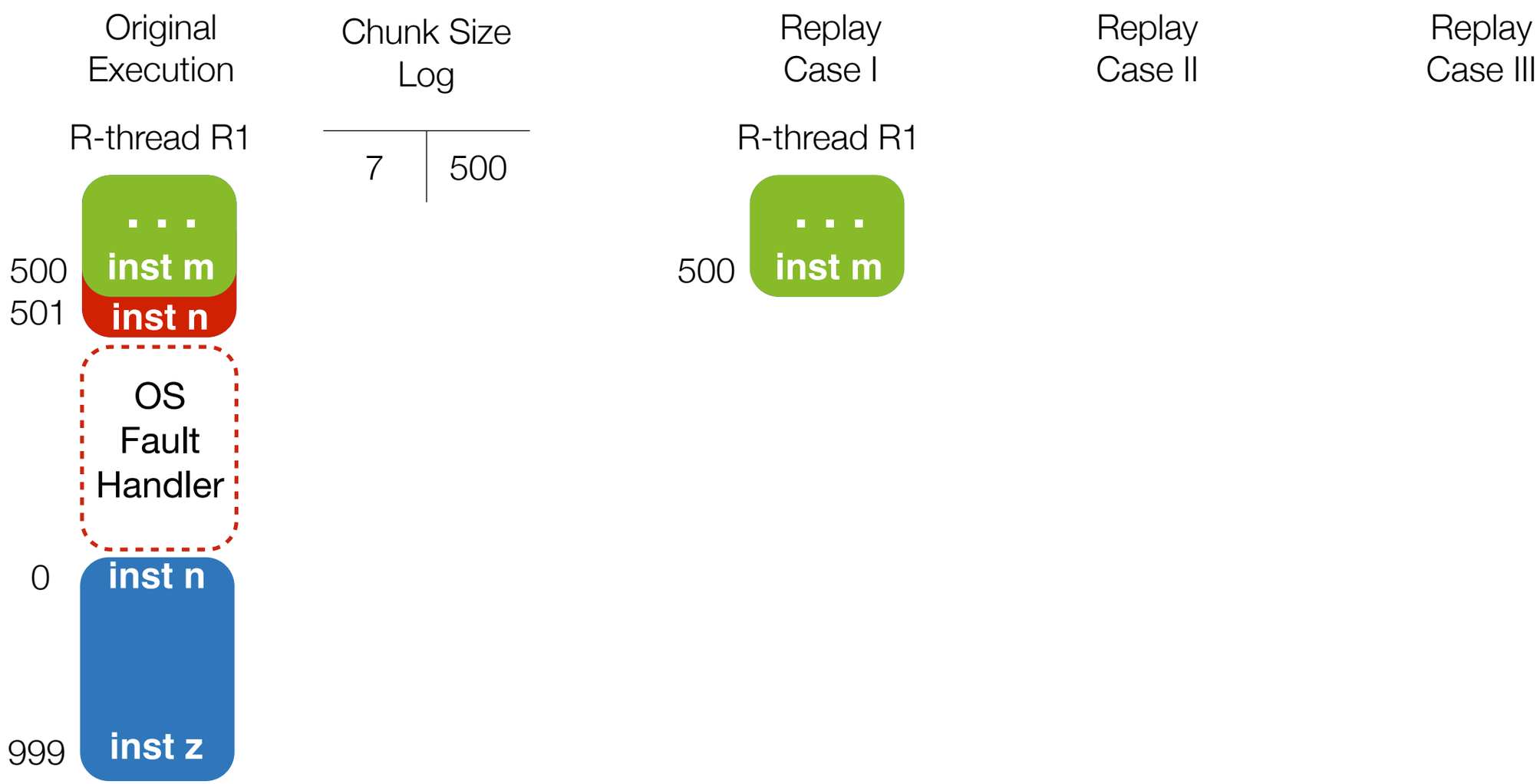

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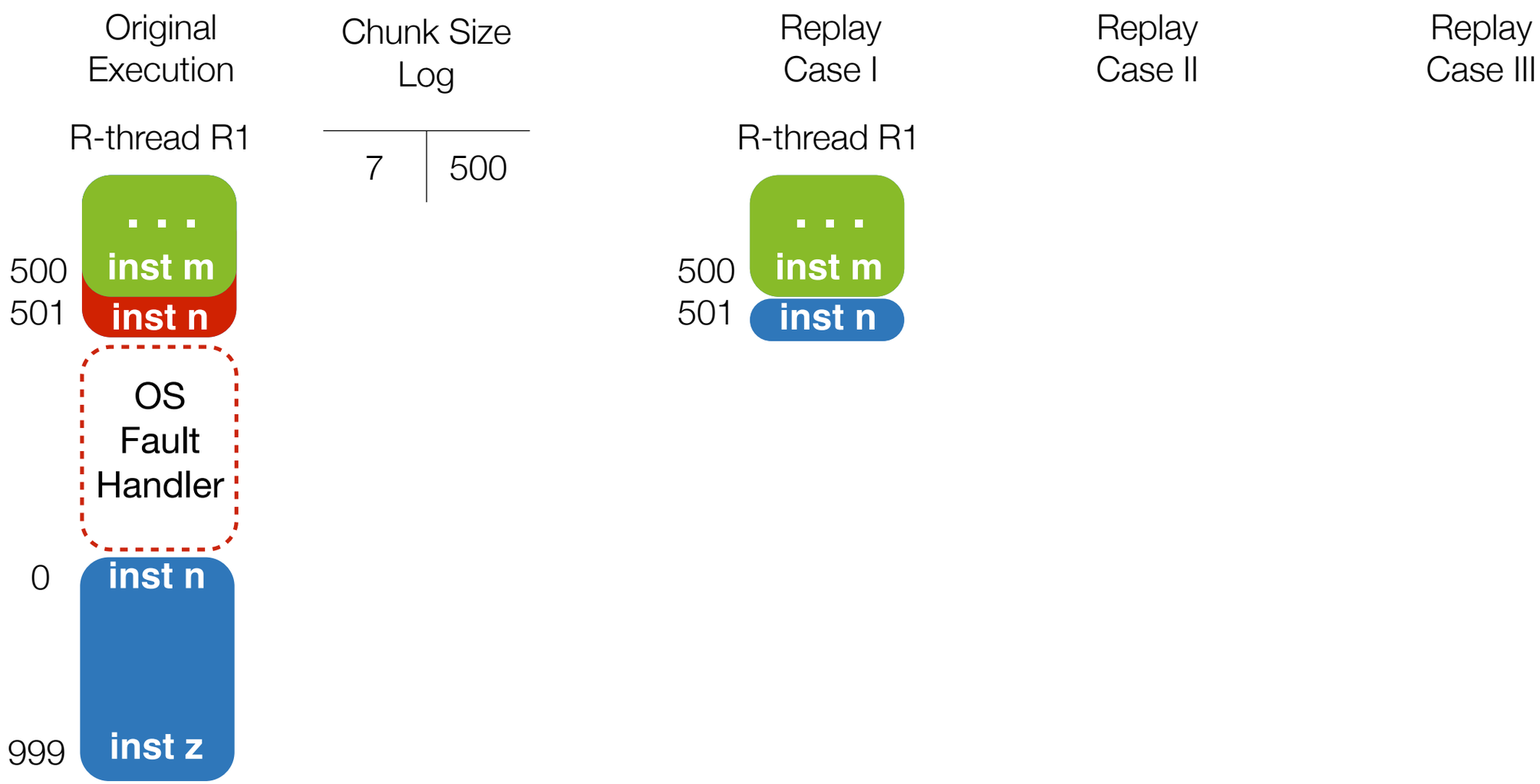

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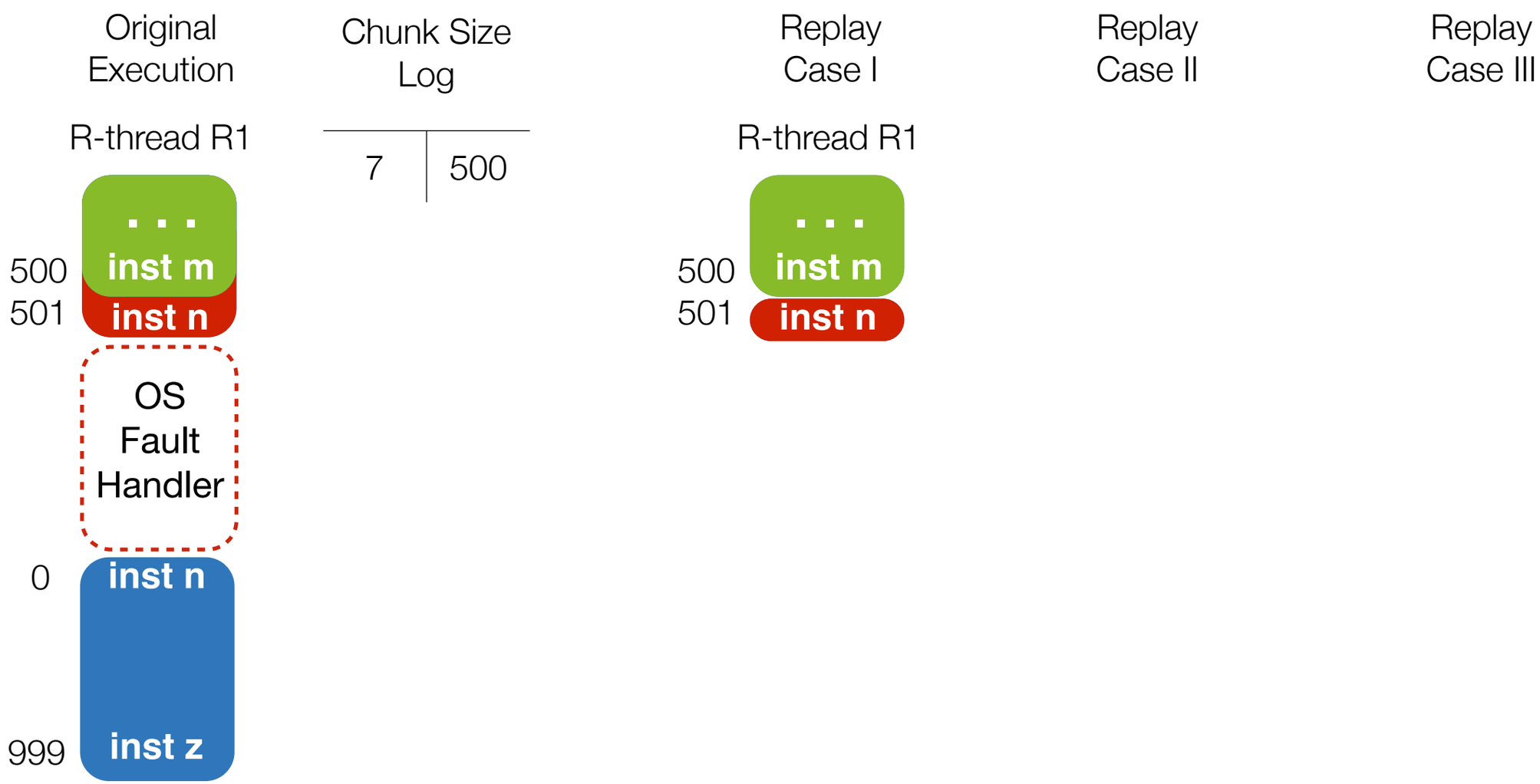

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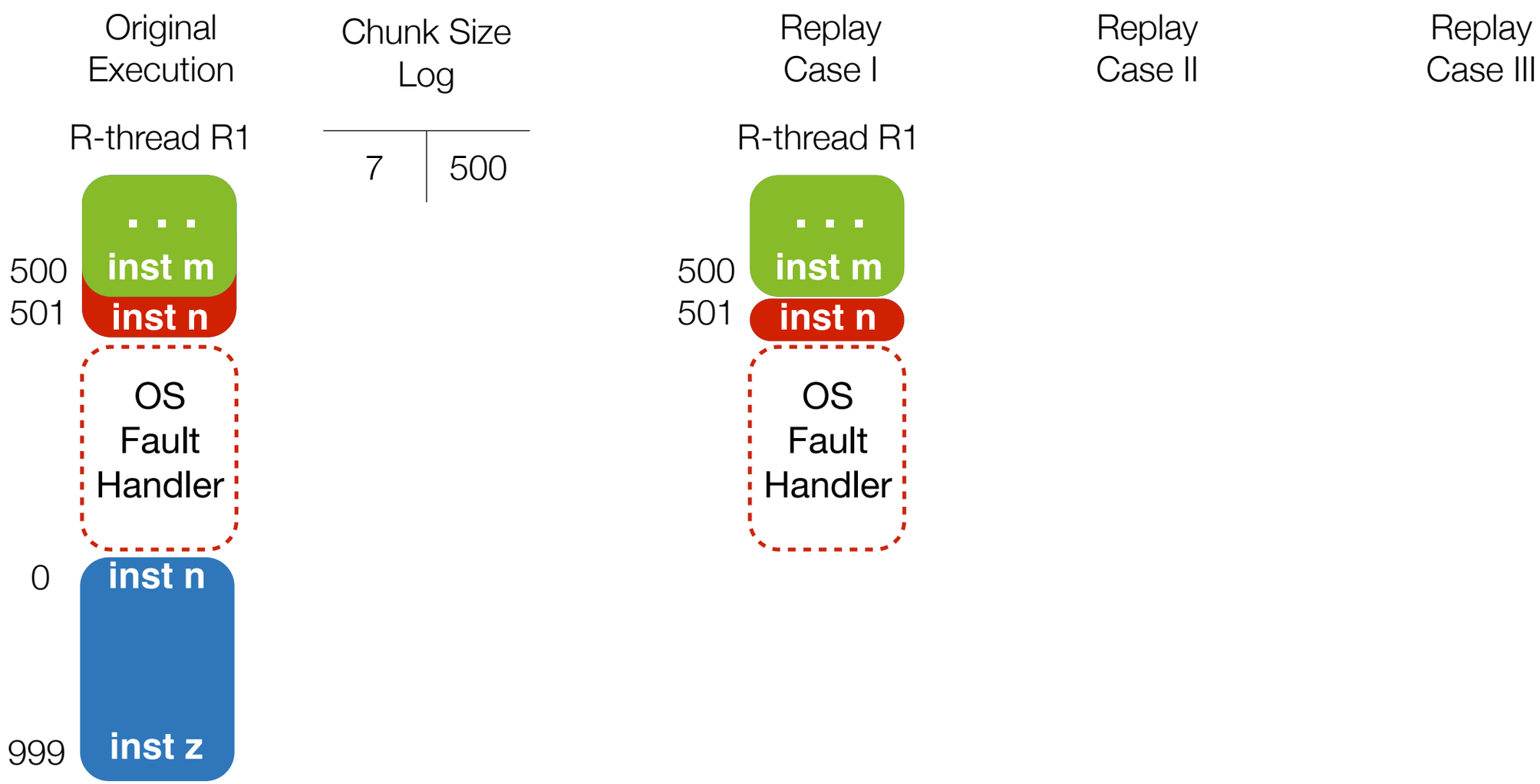

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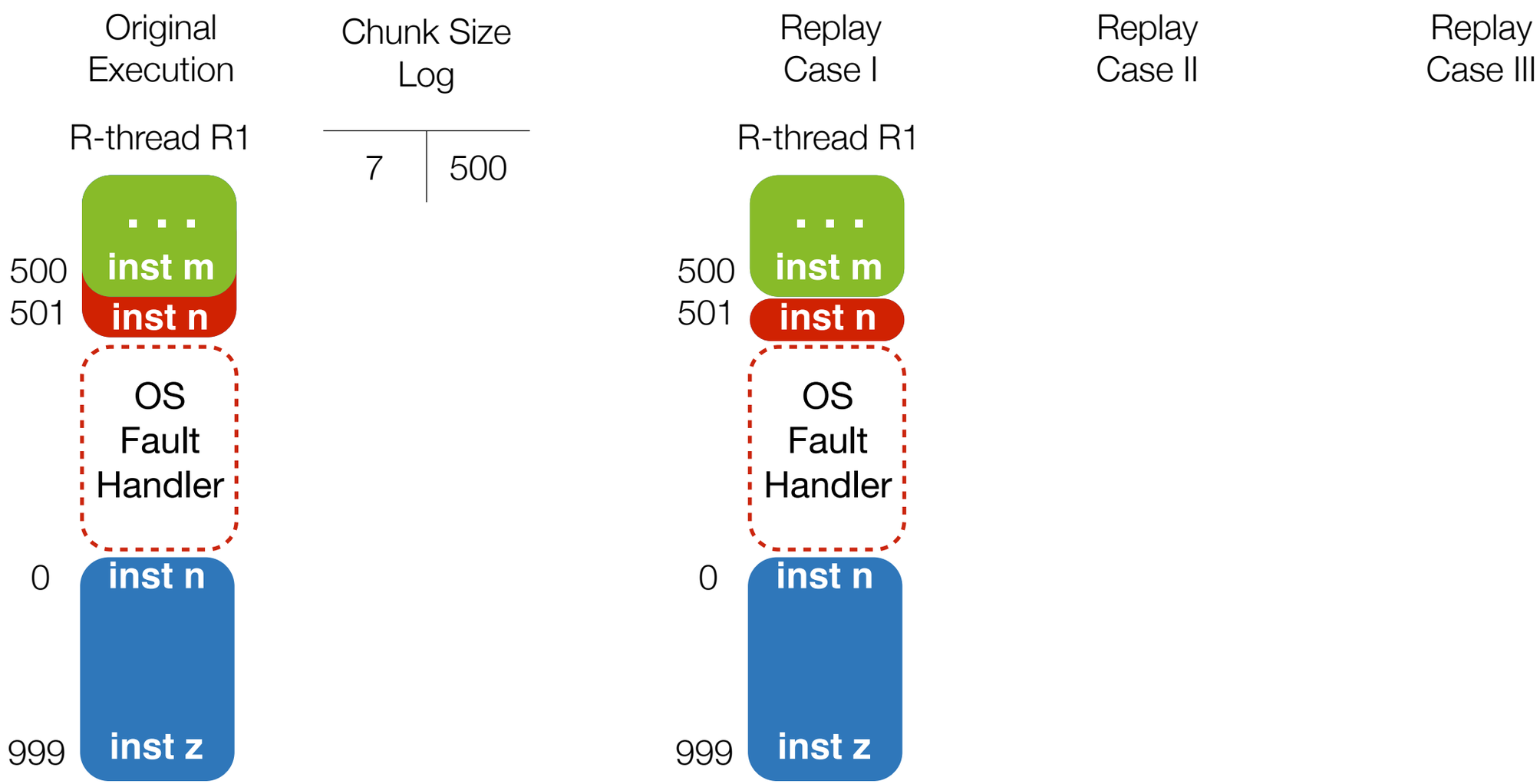

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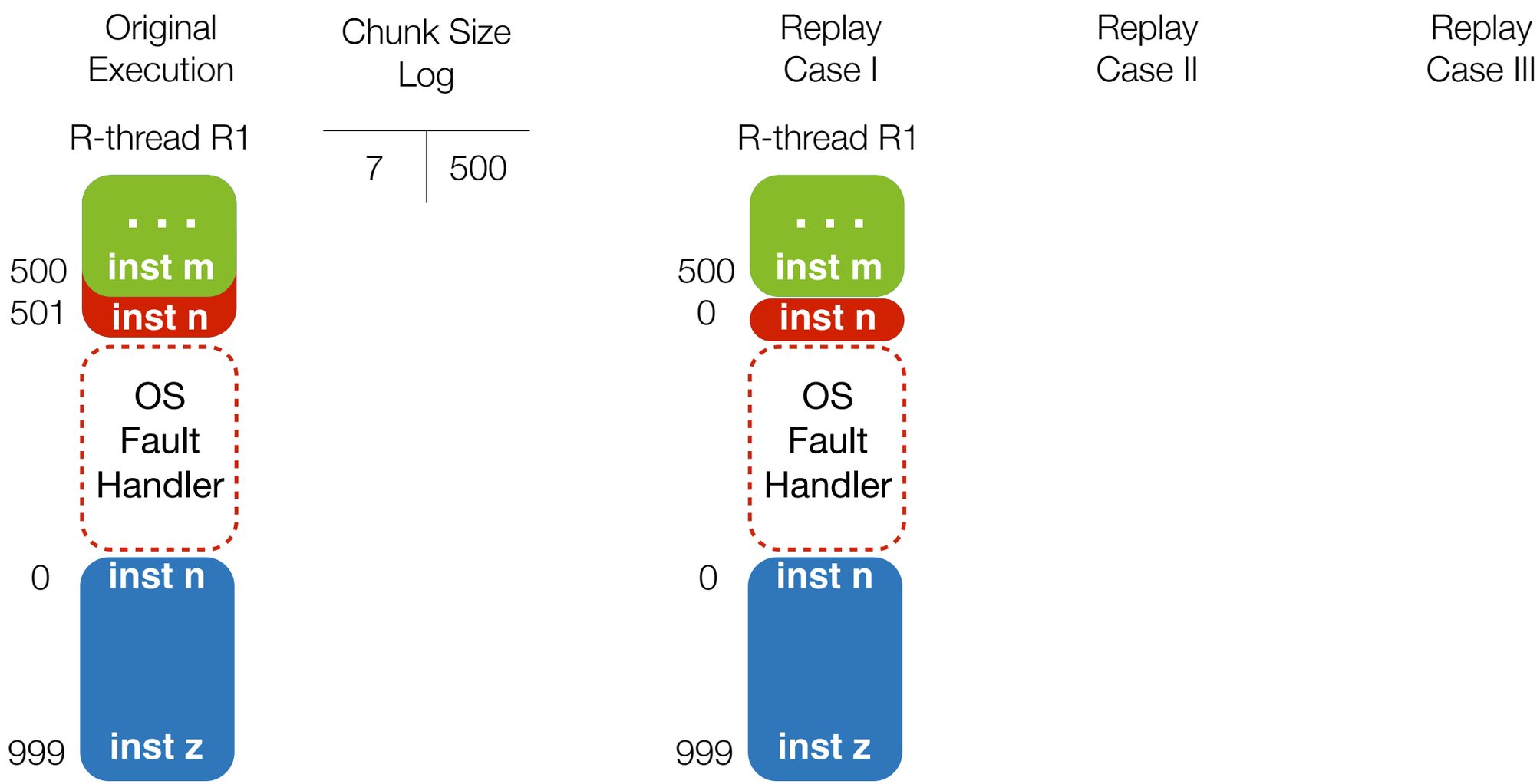

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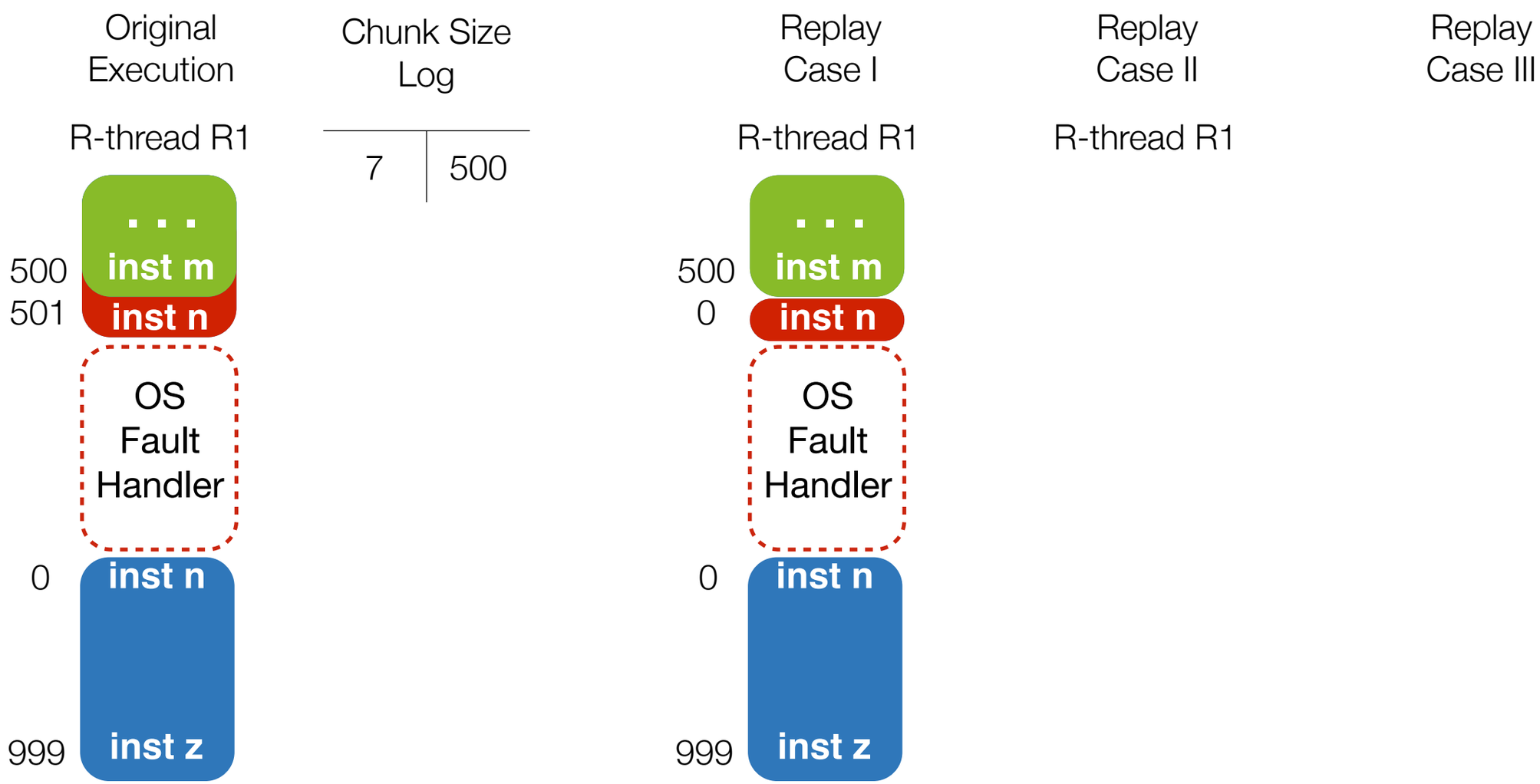

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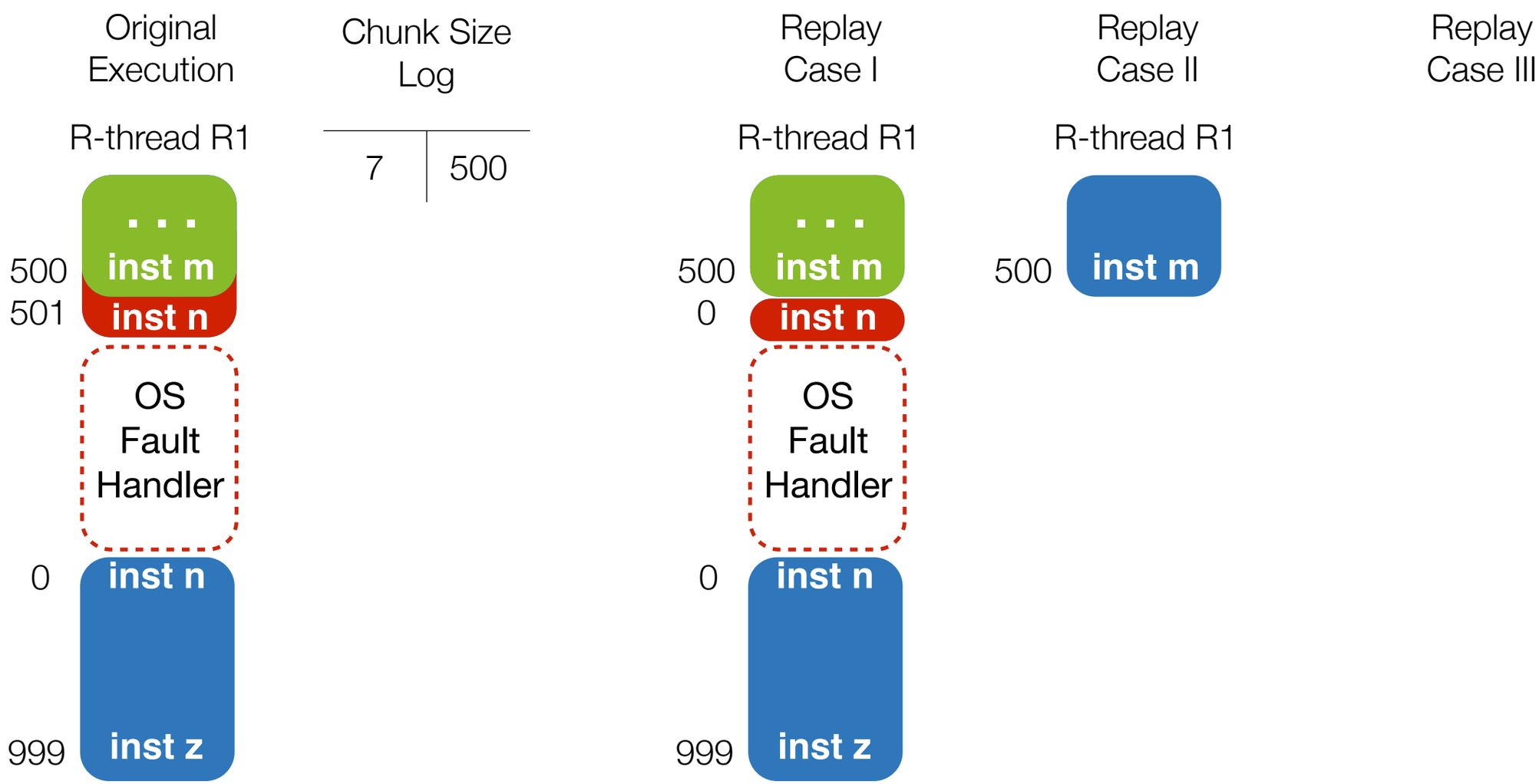

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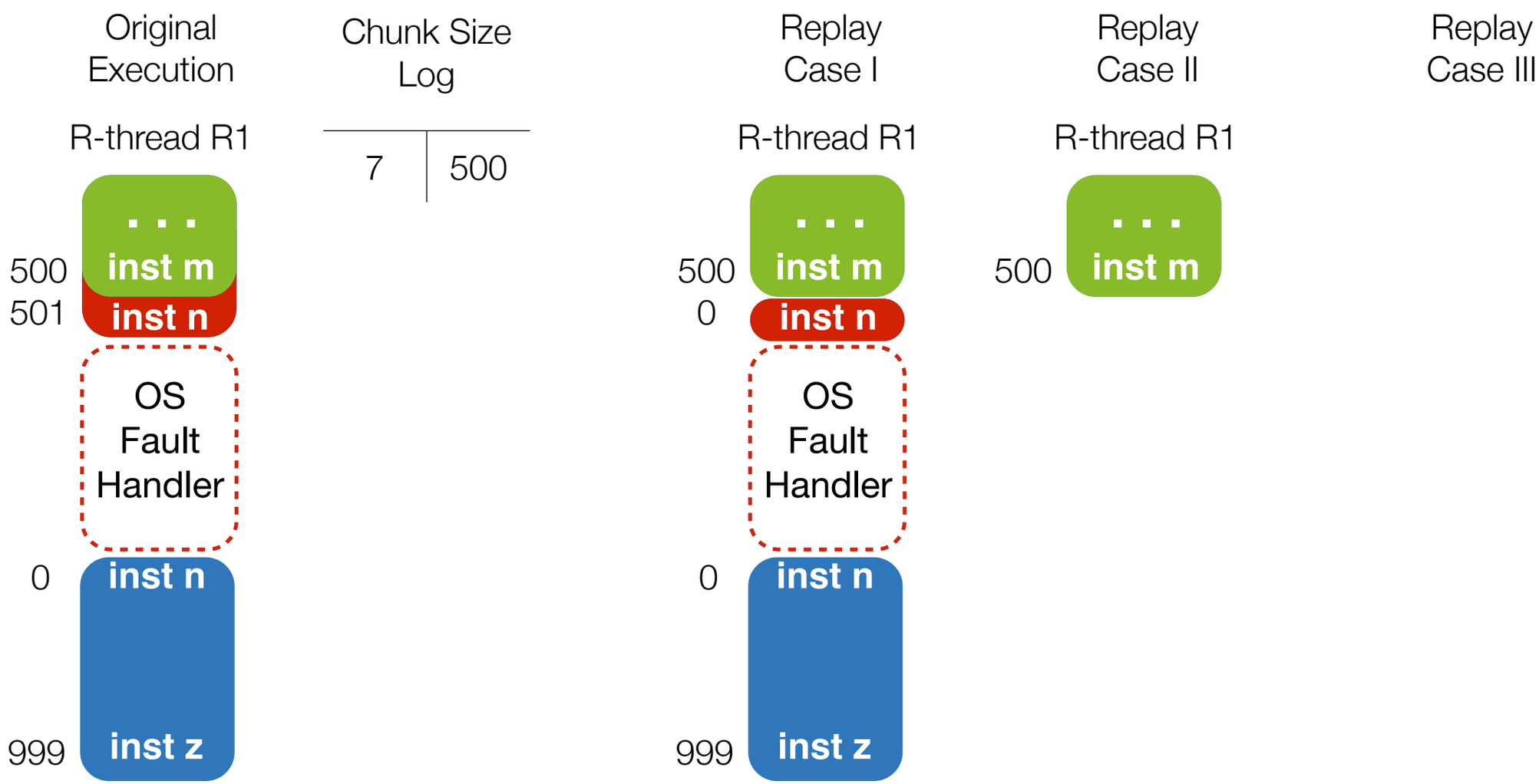

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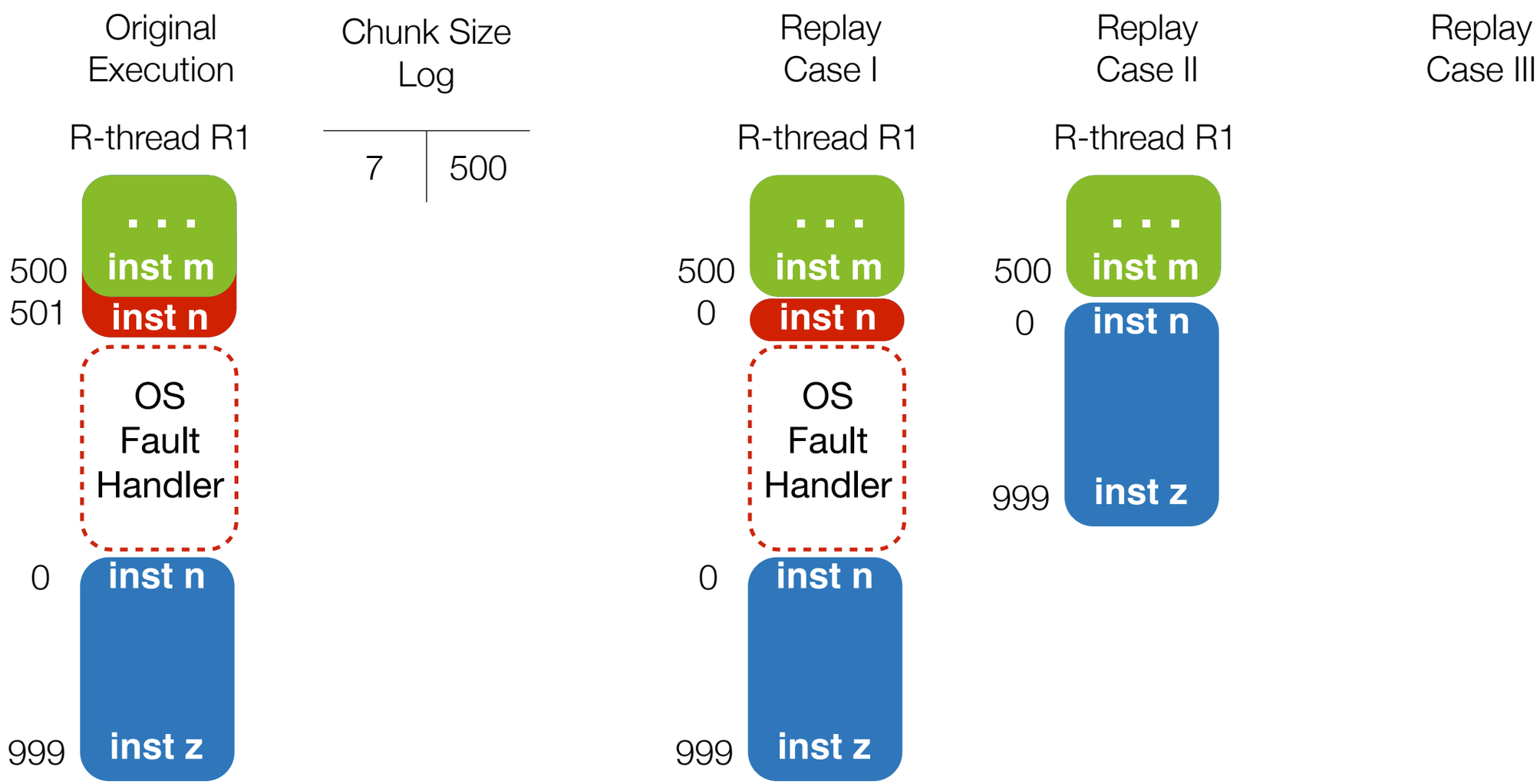

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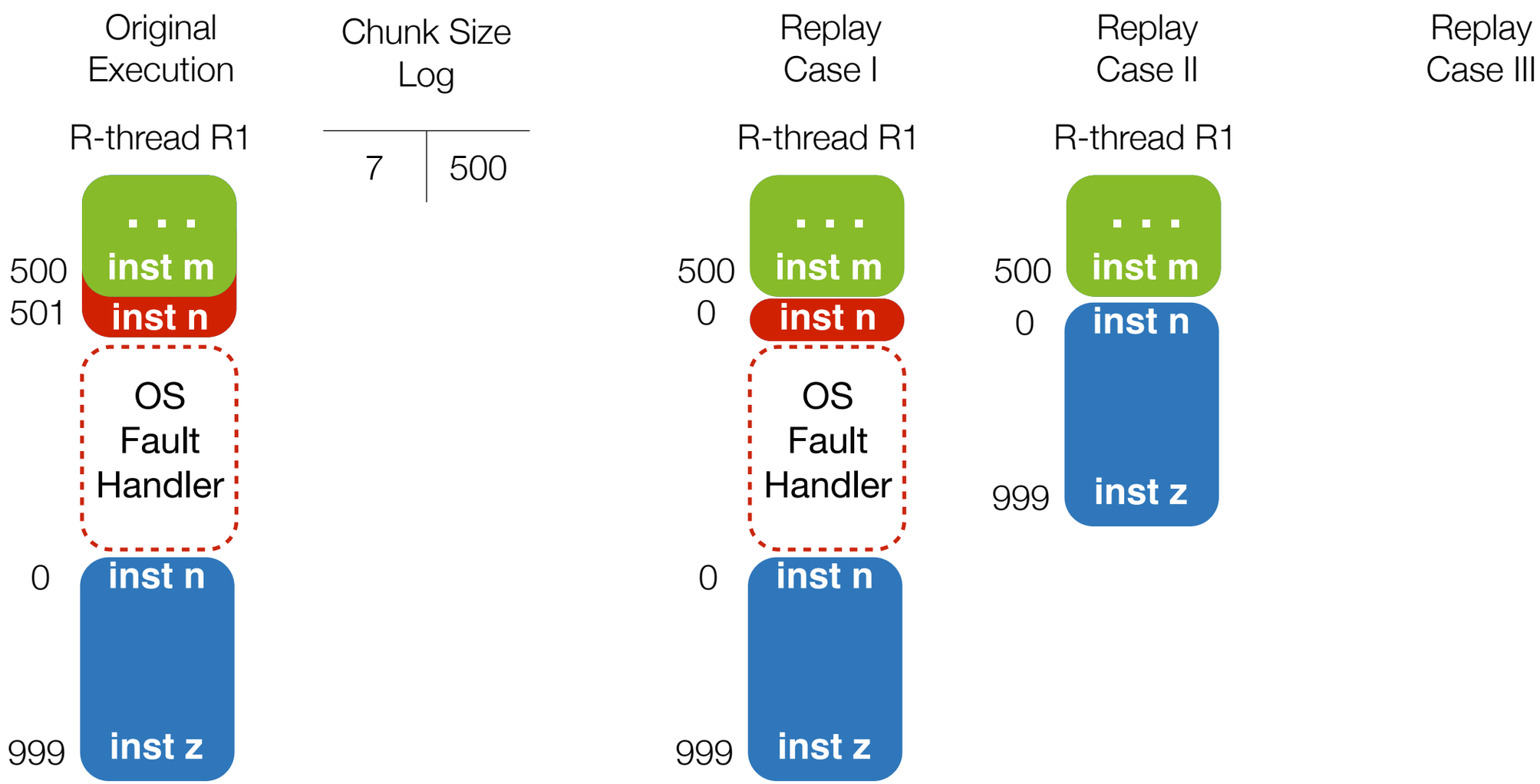

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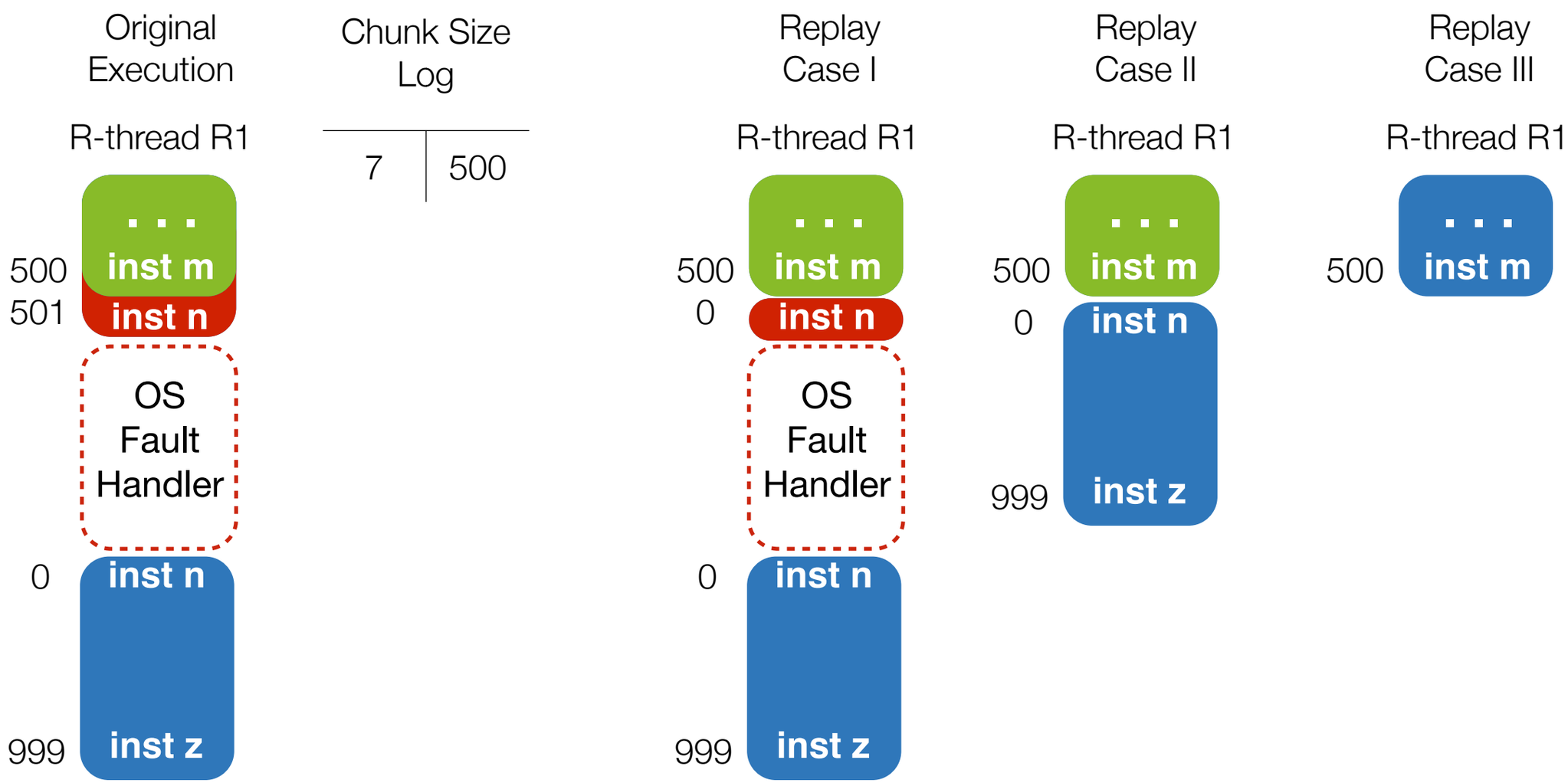

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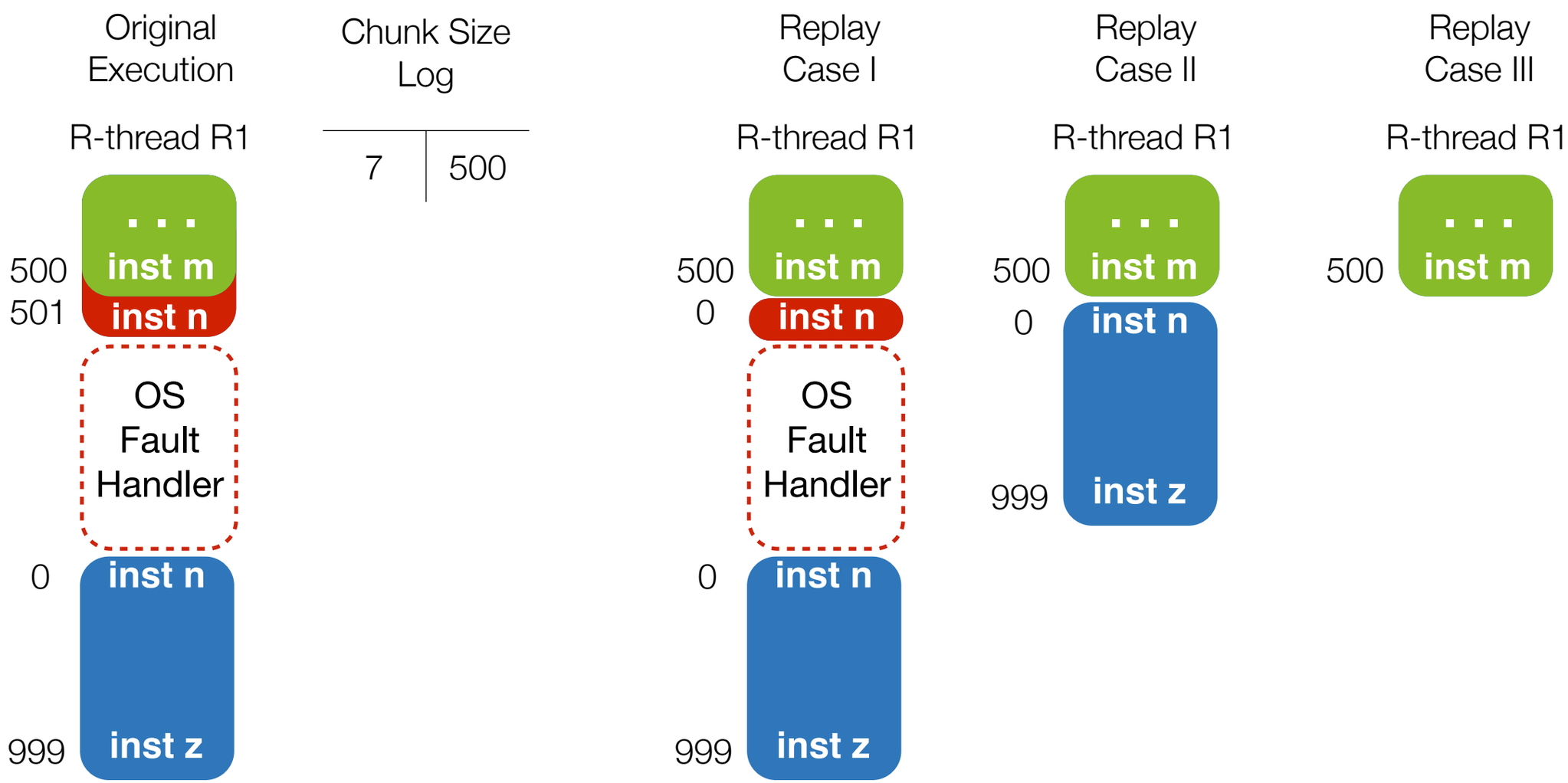

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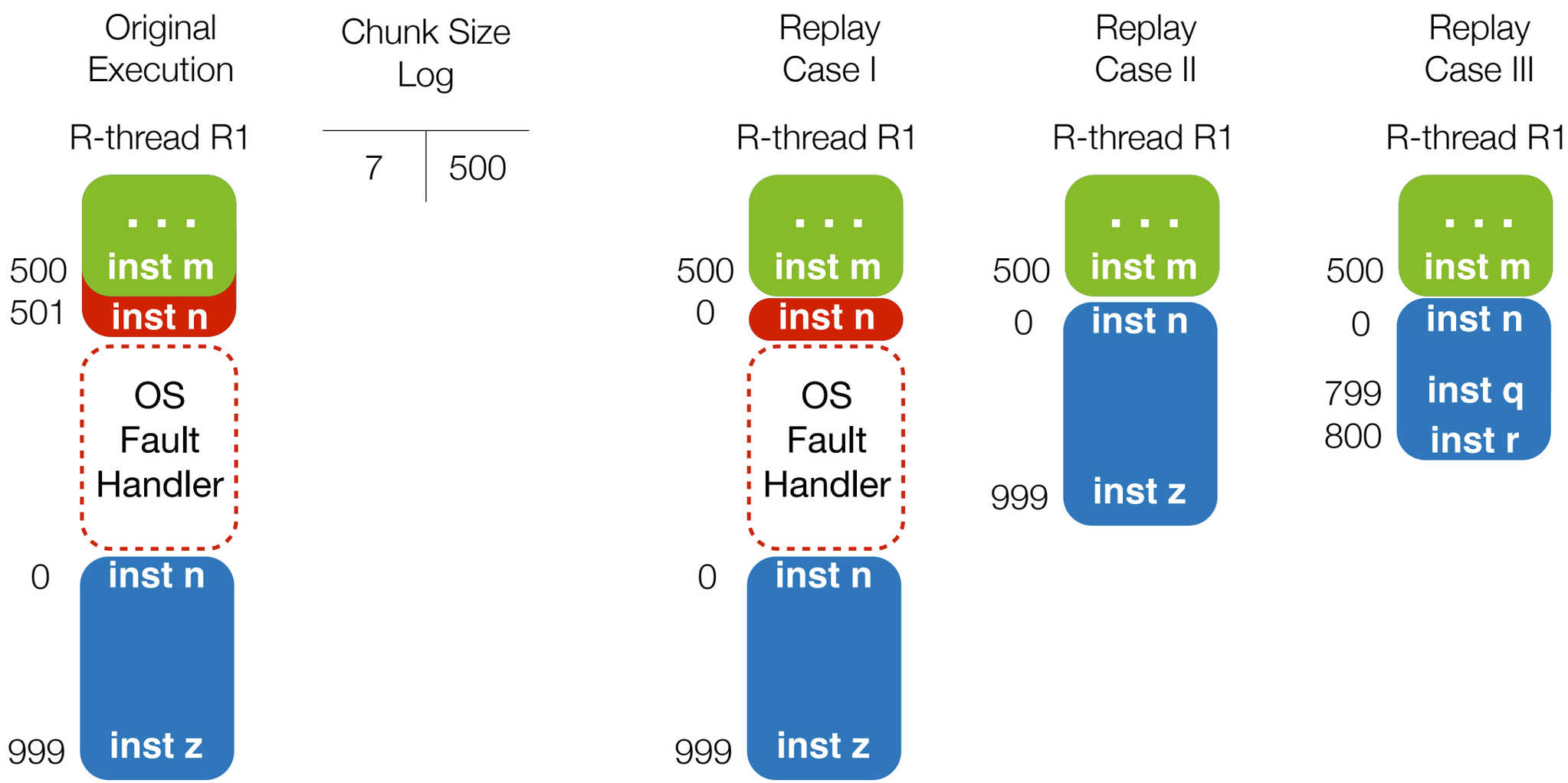

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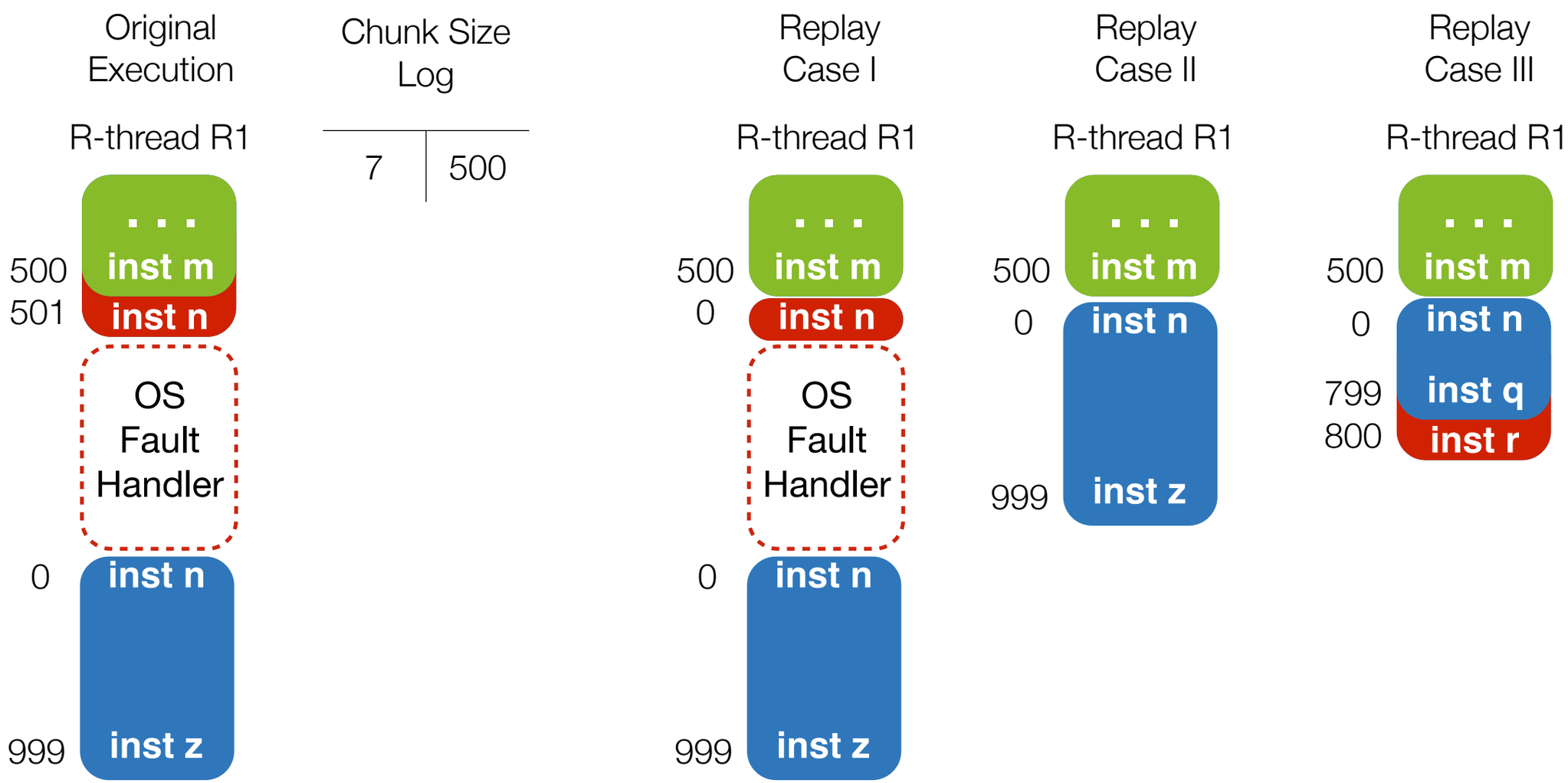

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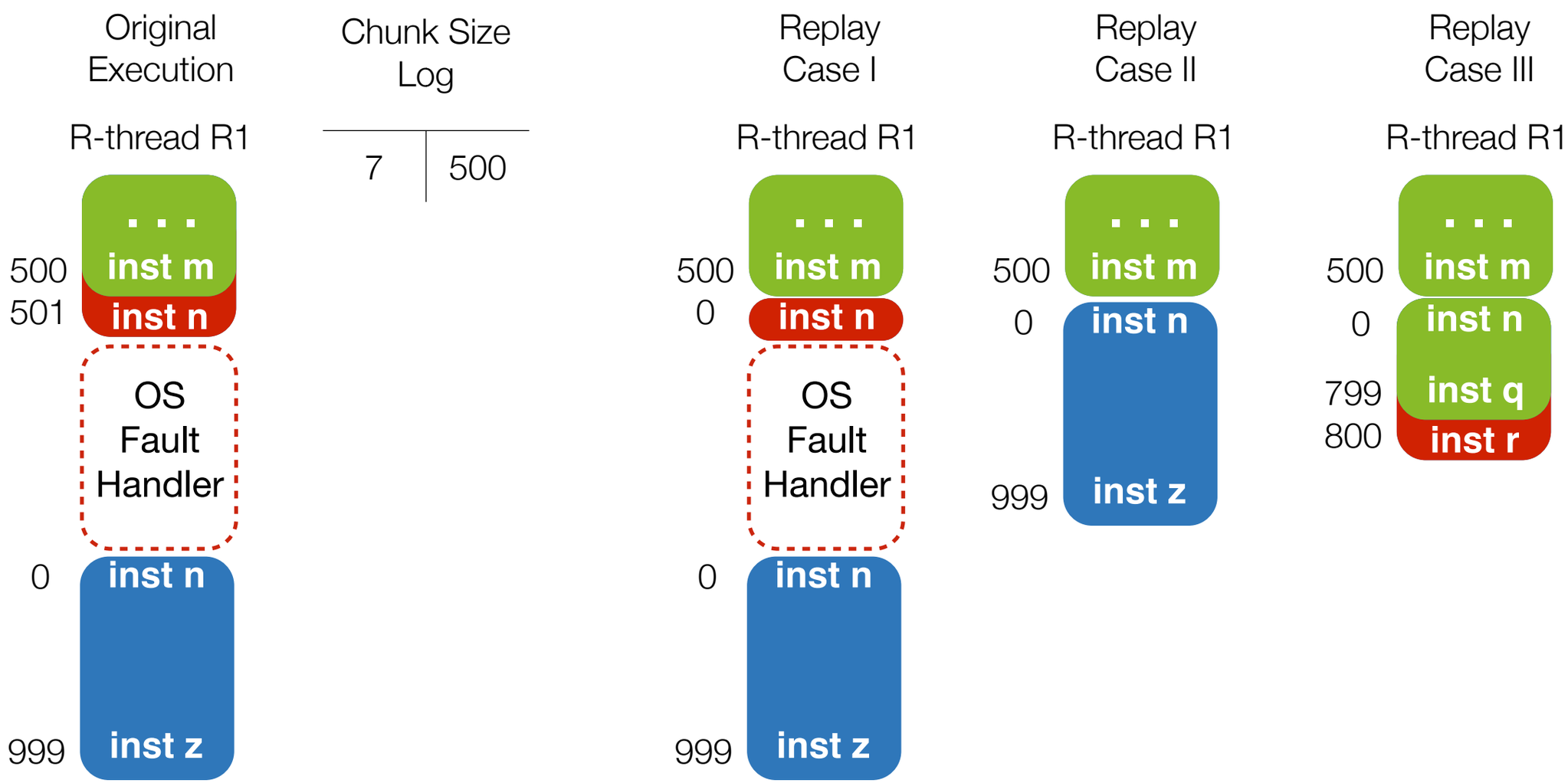

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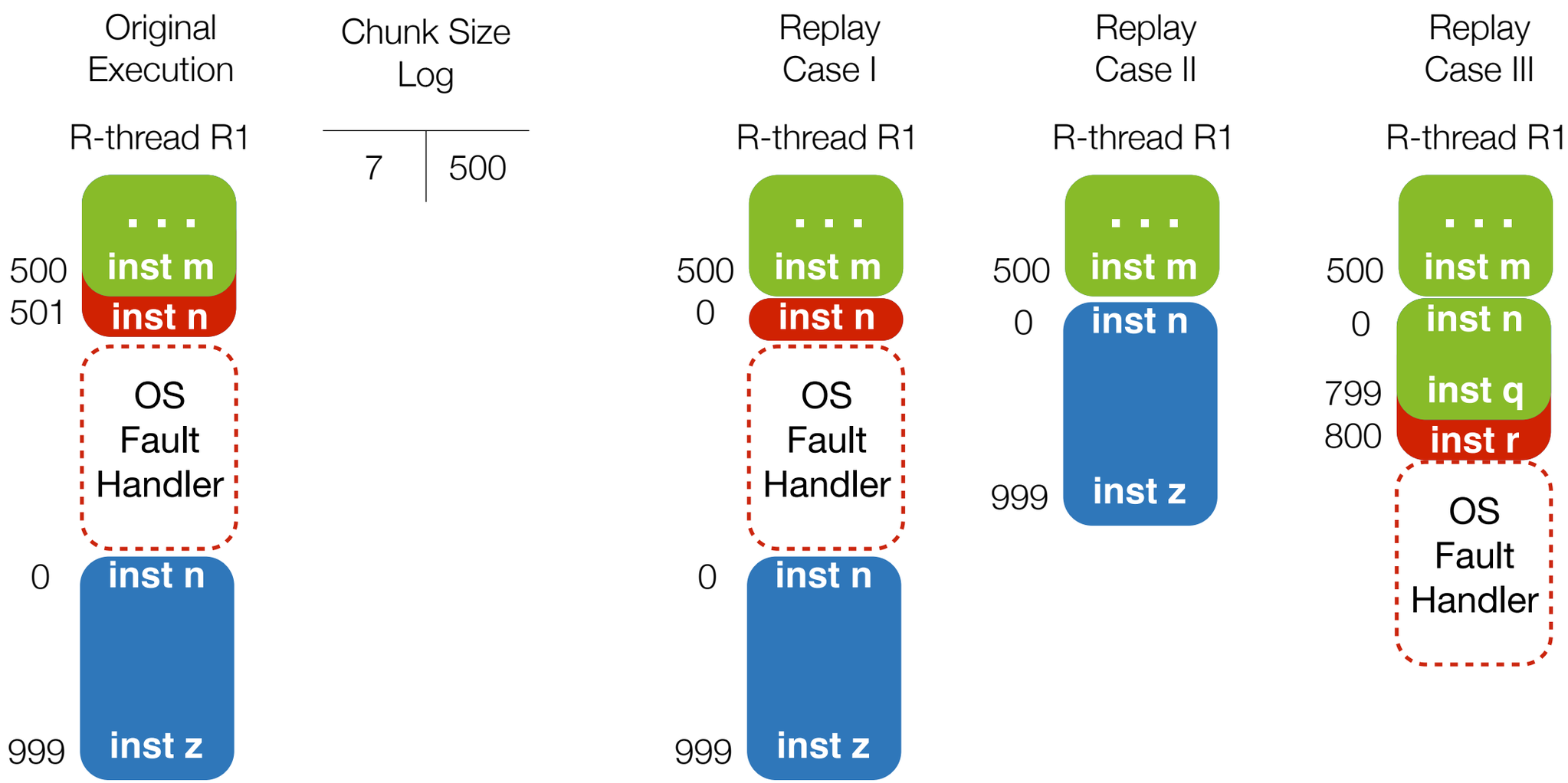

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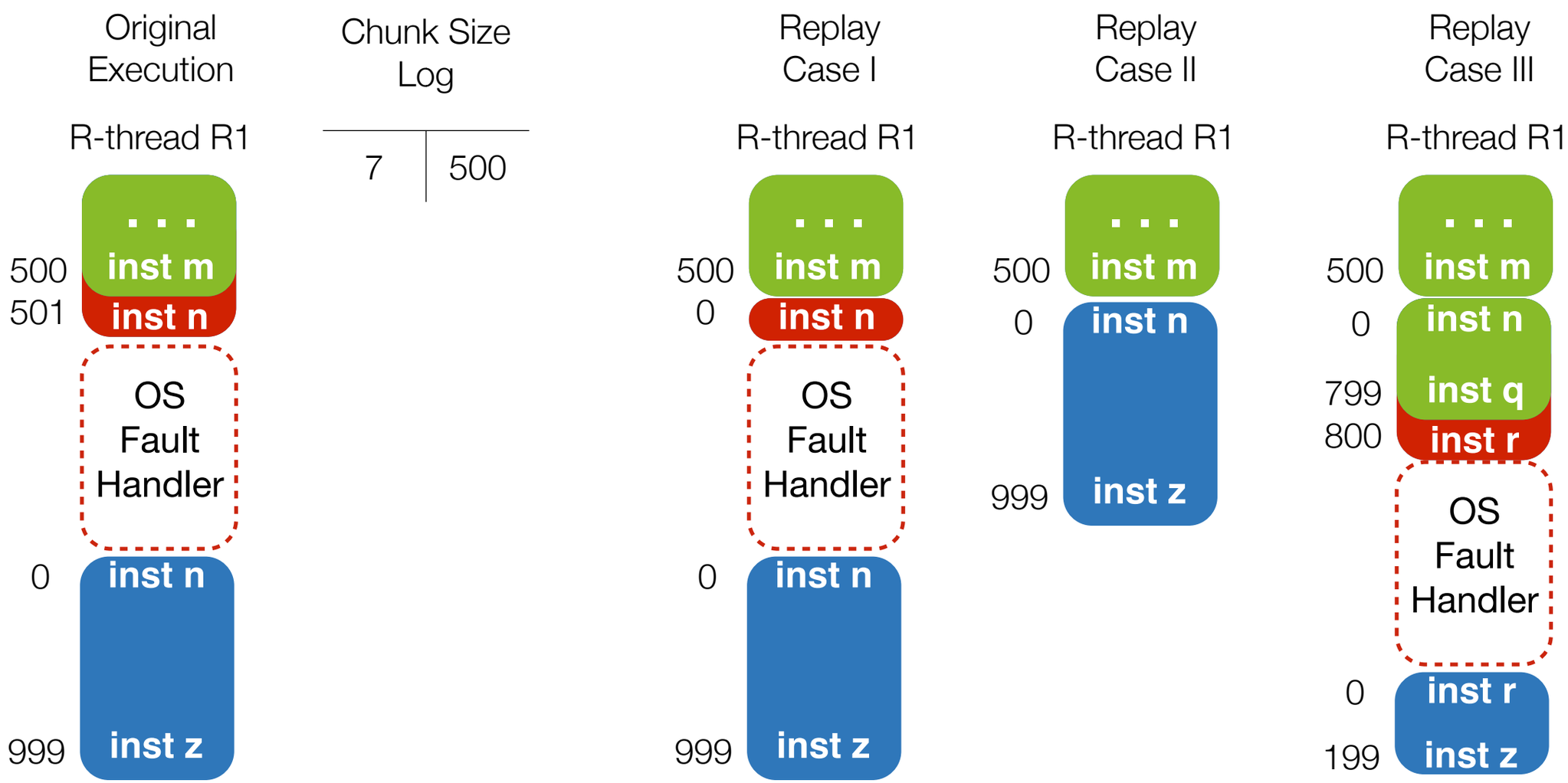

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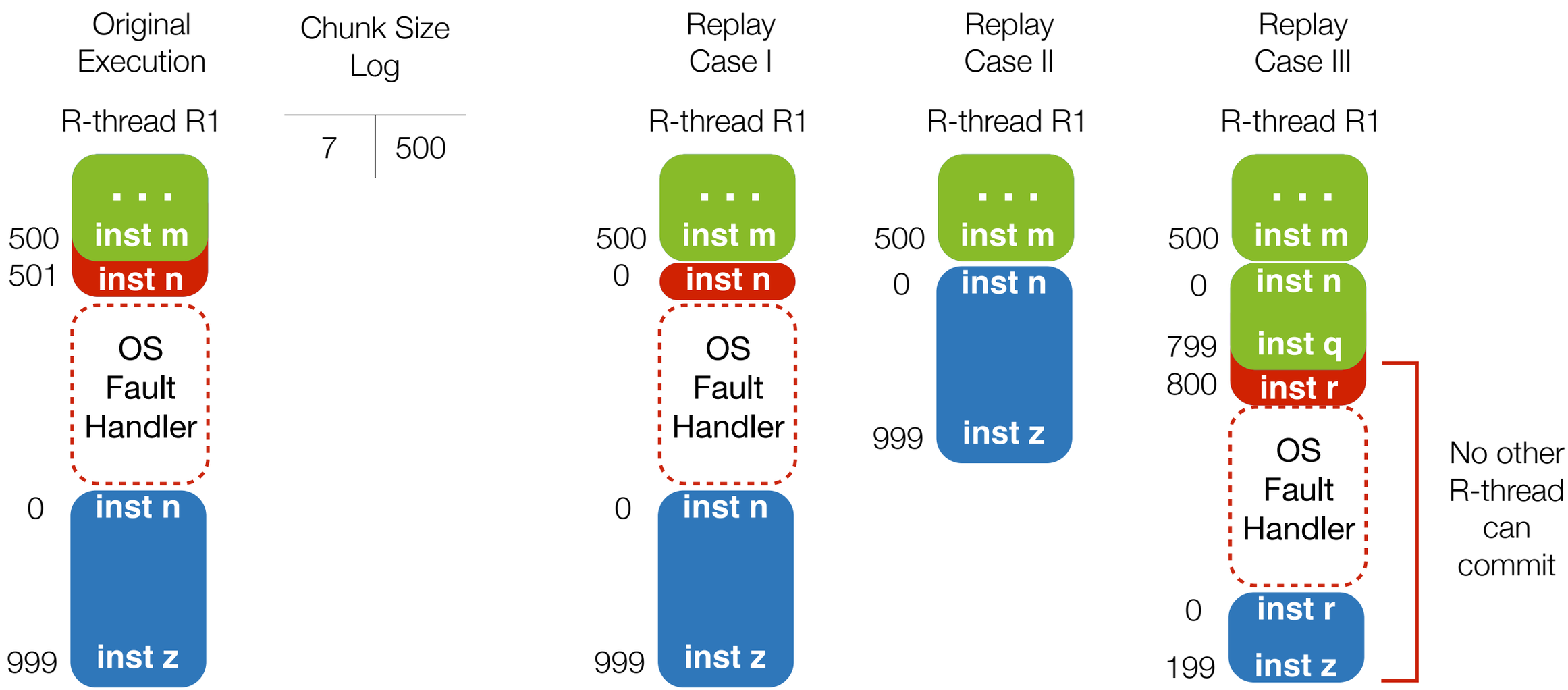

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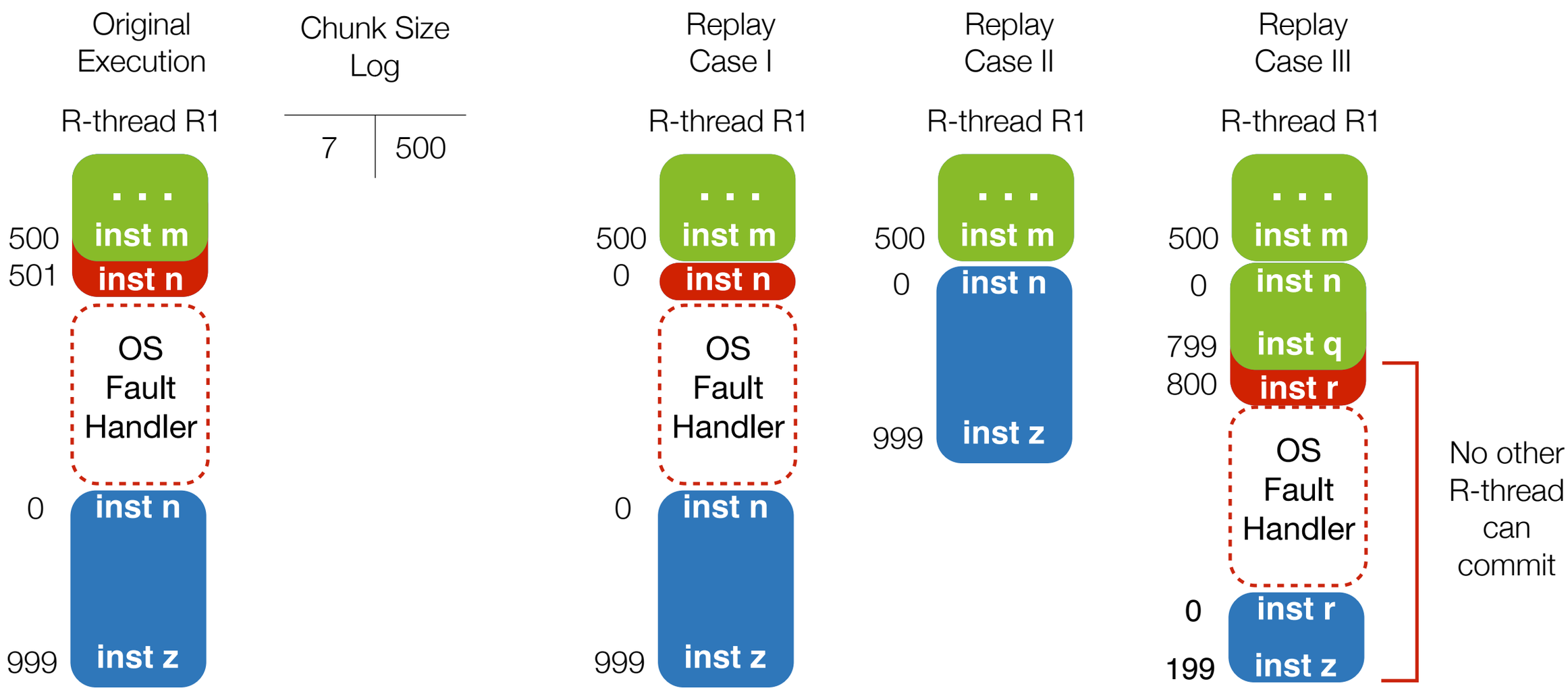

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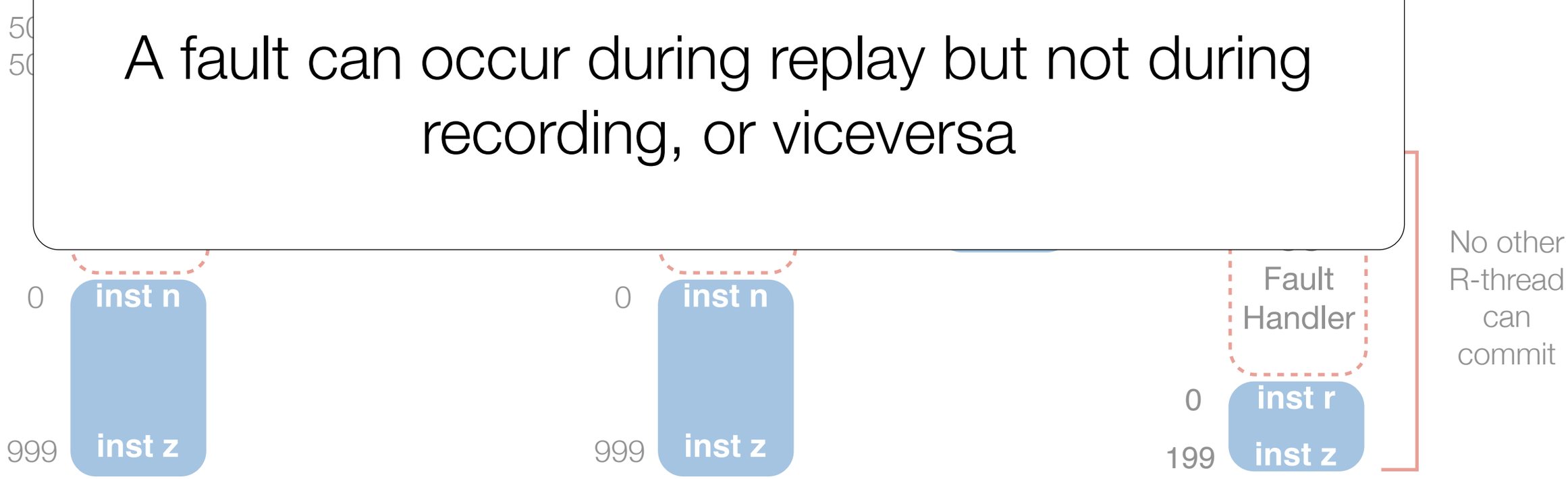
Faults are synchronous events, but they are not necessarily deterministic

A fault can occur during replay but not during recording, or viceversa



Handling Traps and Programmed Exceptions

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R-thread R1

Chunk Size
Log

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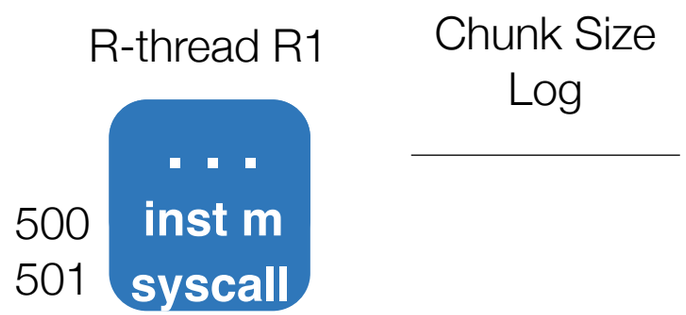

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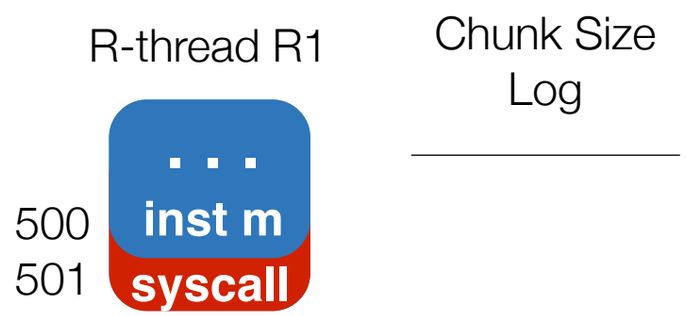

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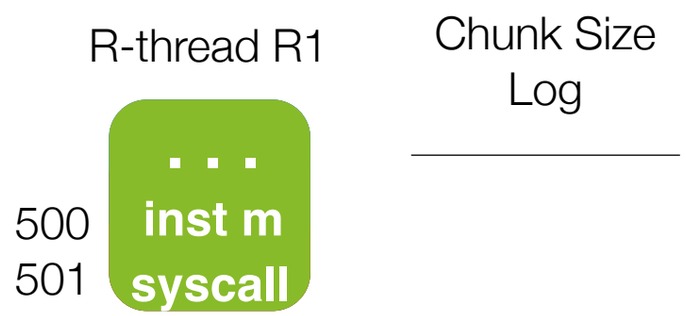

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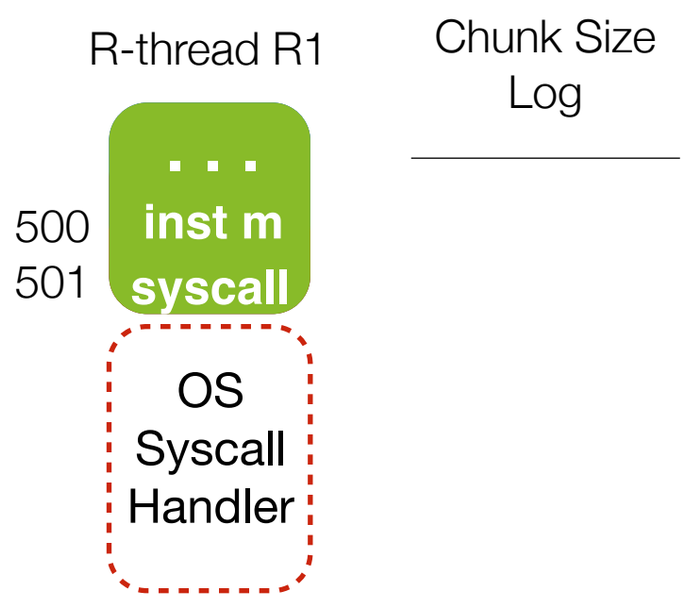

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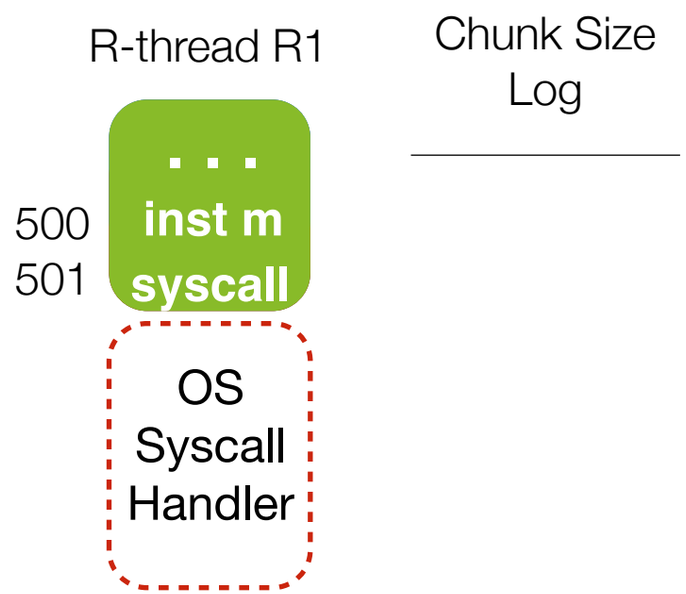
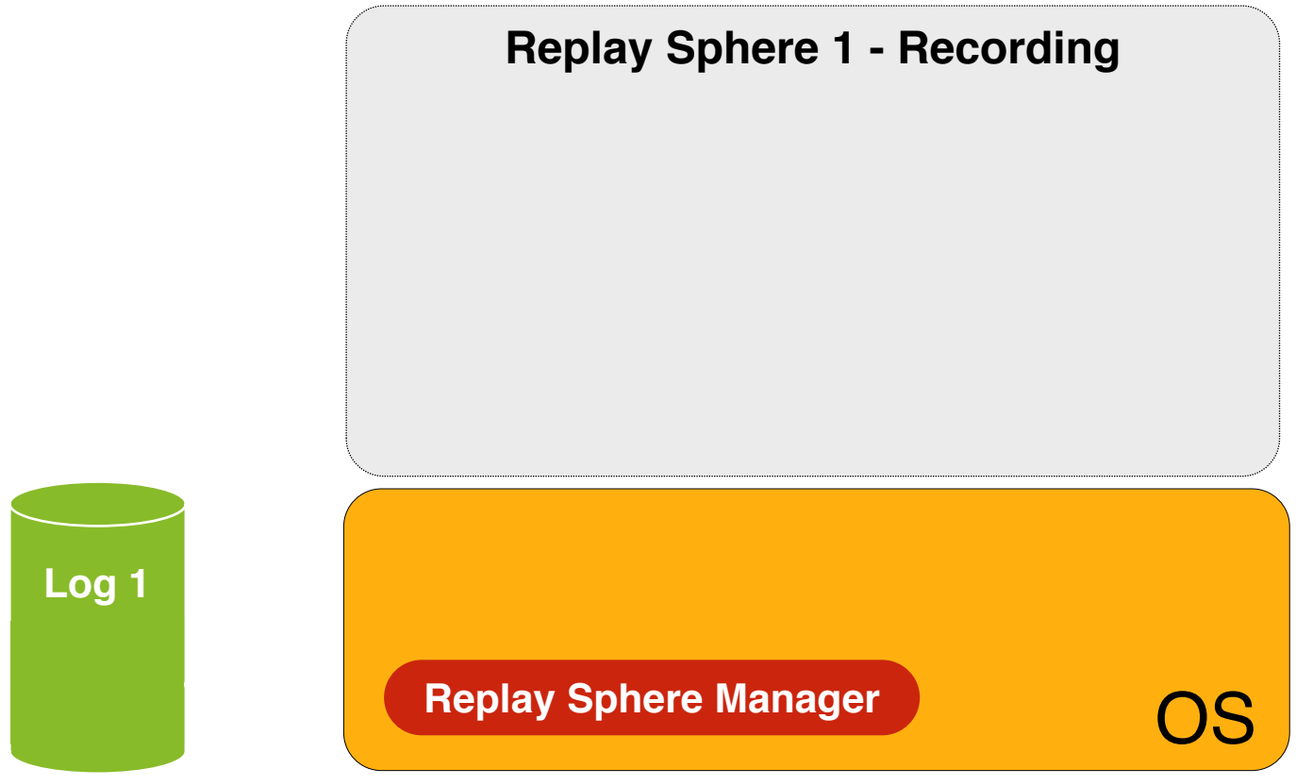


Handling Traps and Programmed Exceptions

- Commit all instructions including the one raising the trap
- Never attempt to recover the origin of irregular-sized chunks

Traps and programmed exceptions are deterministic events: no need to record irregular-sized chunks

Injecting Data into Spheres



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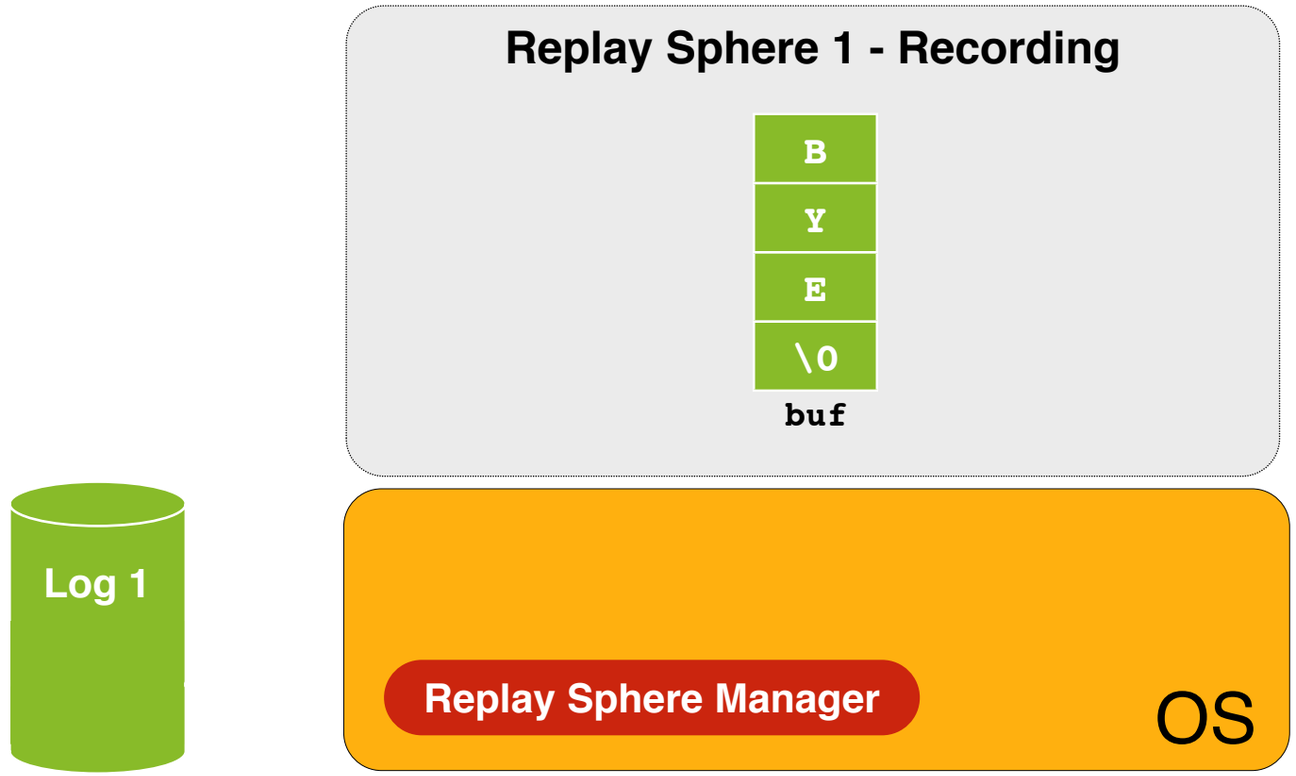

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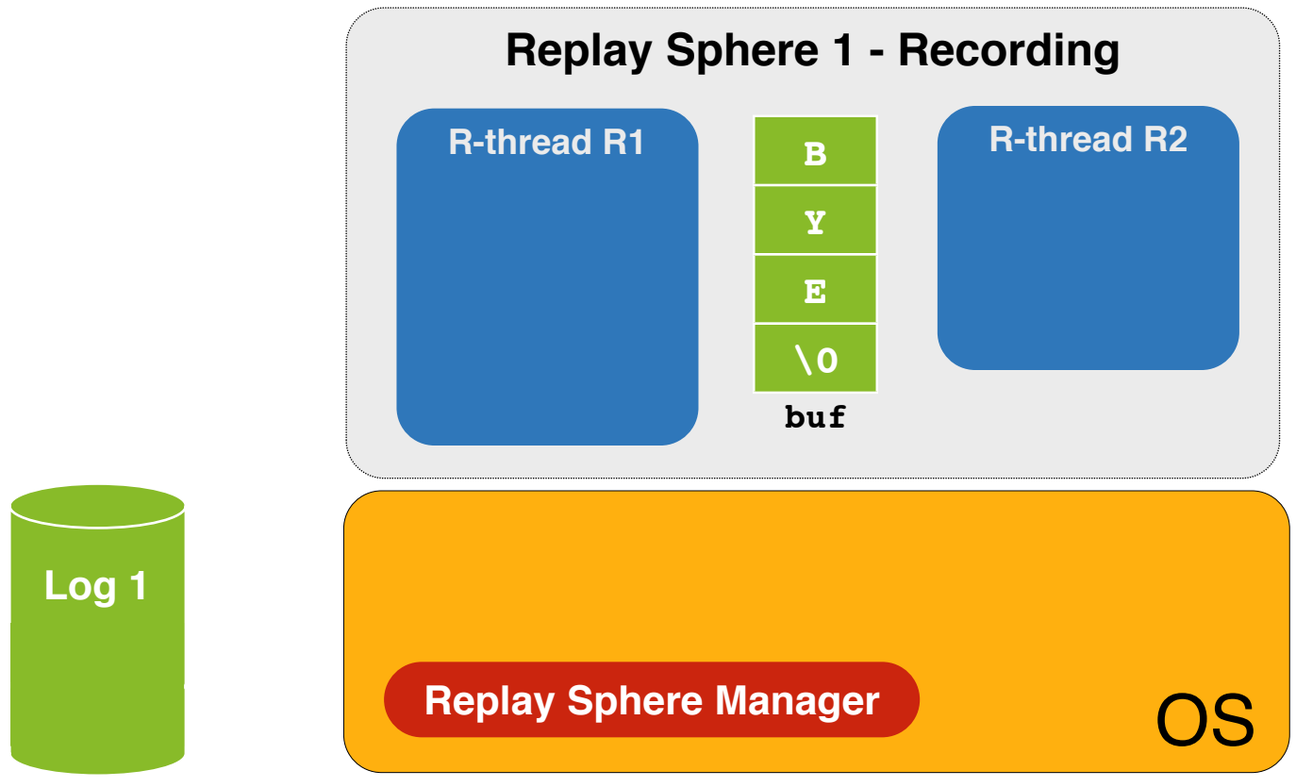

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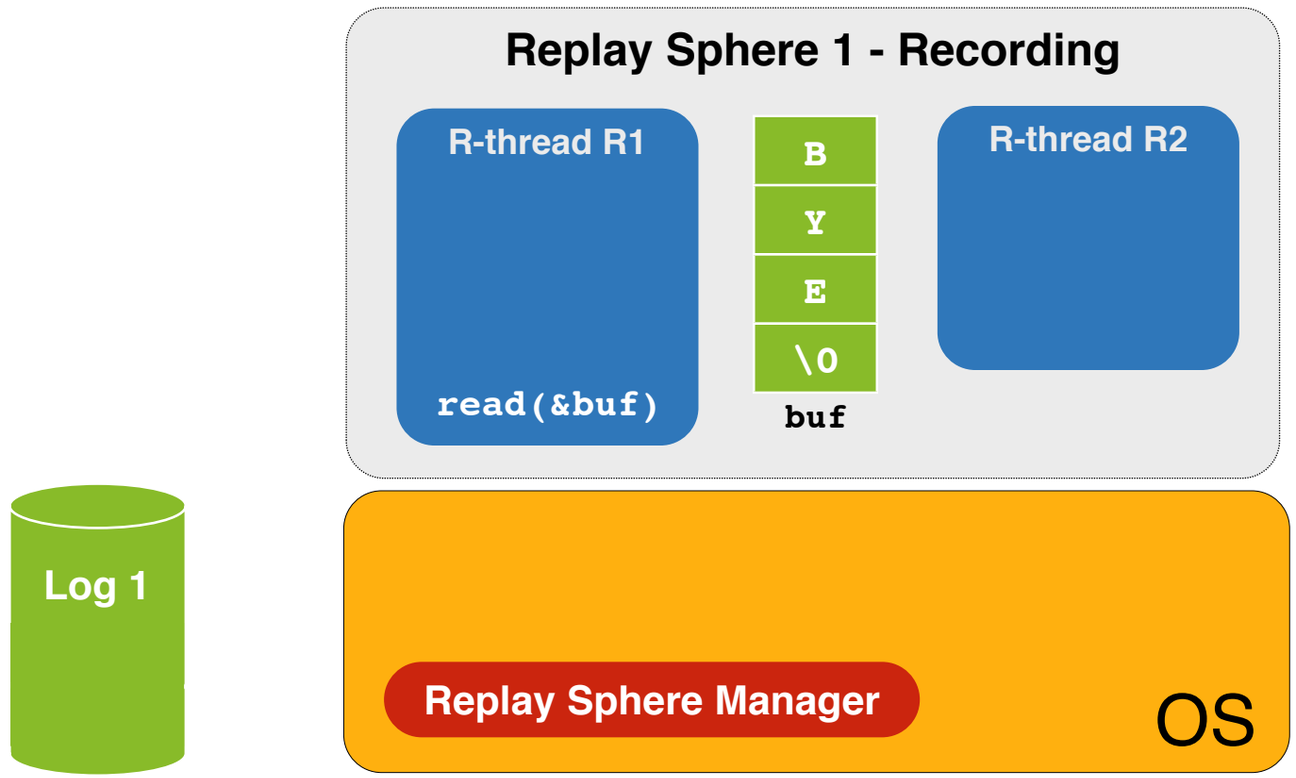

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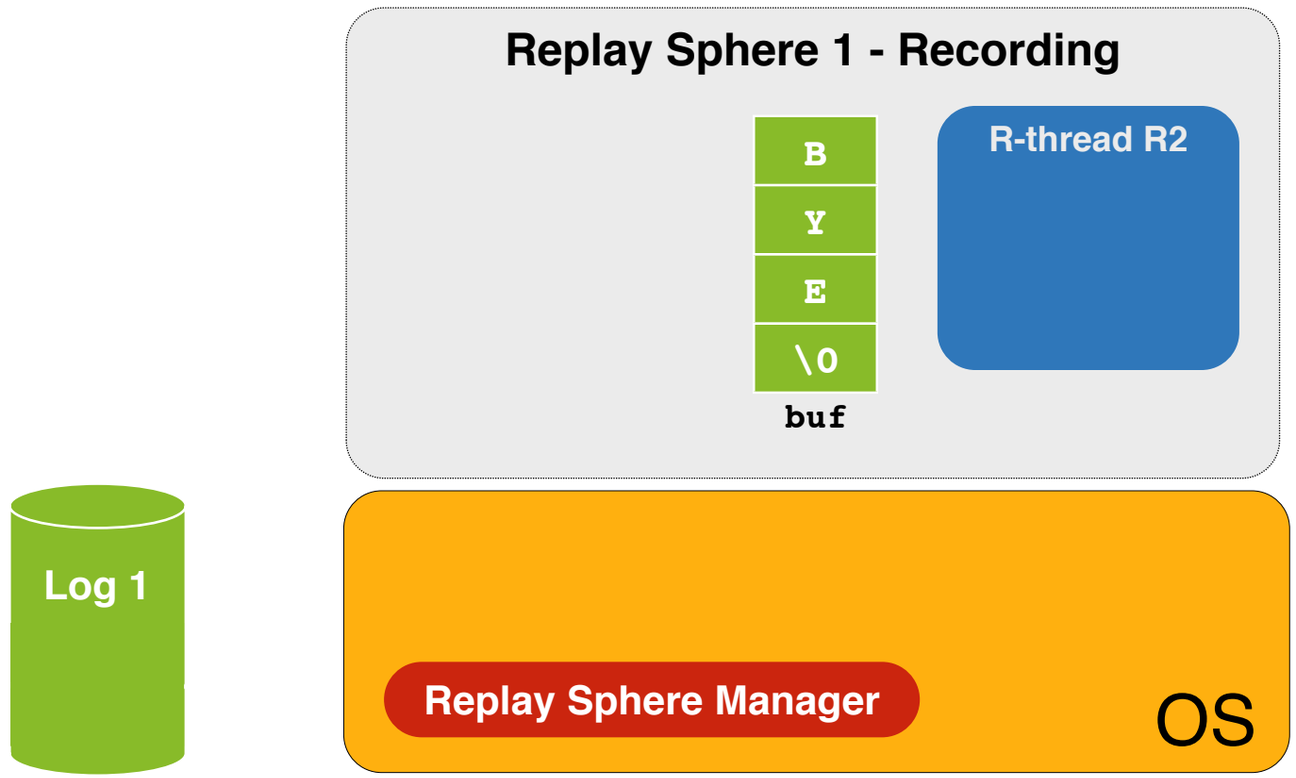

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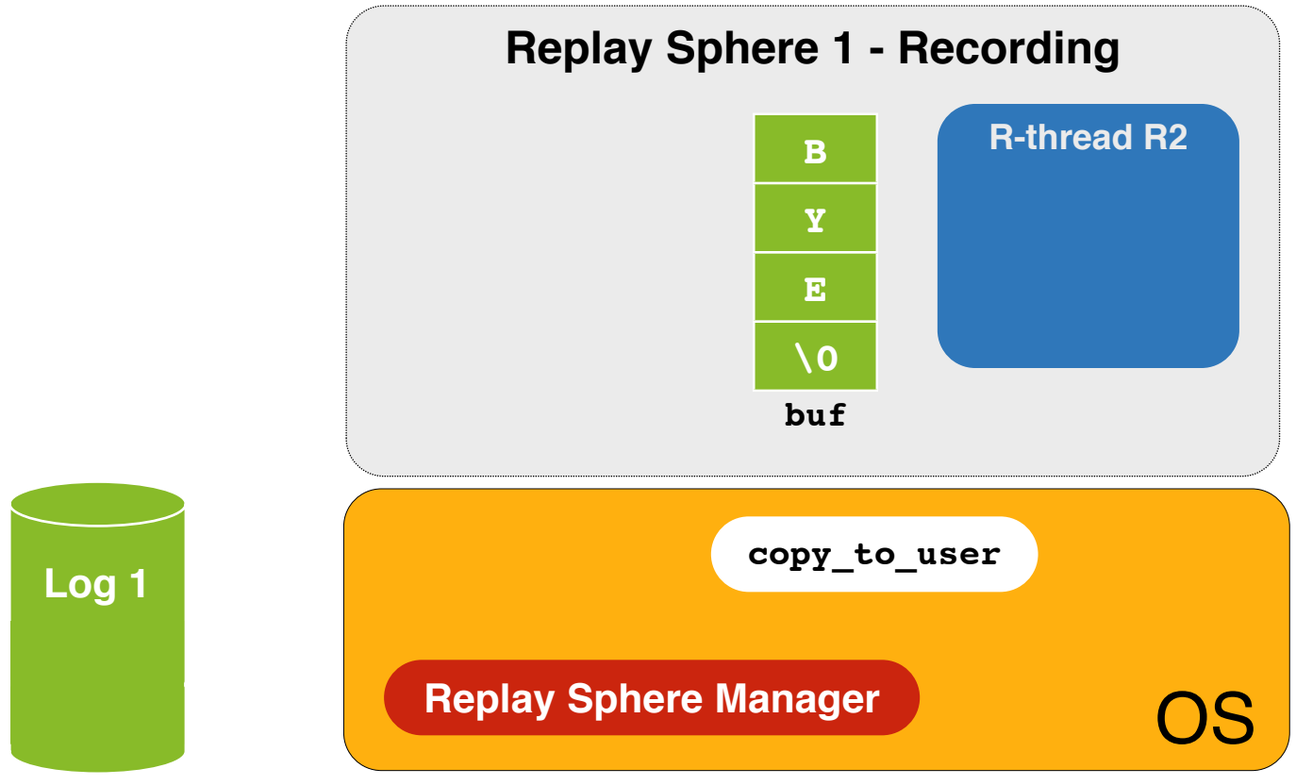

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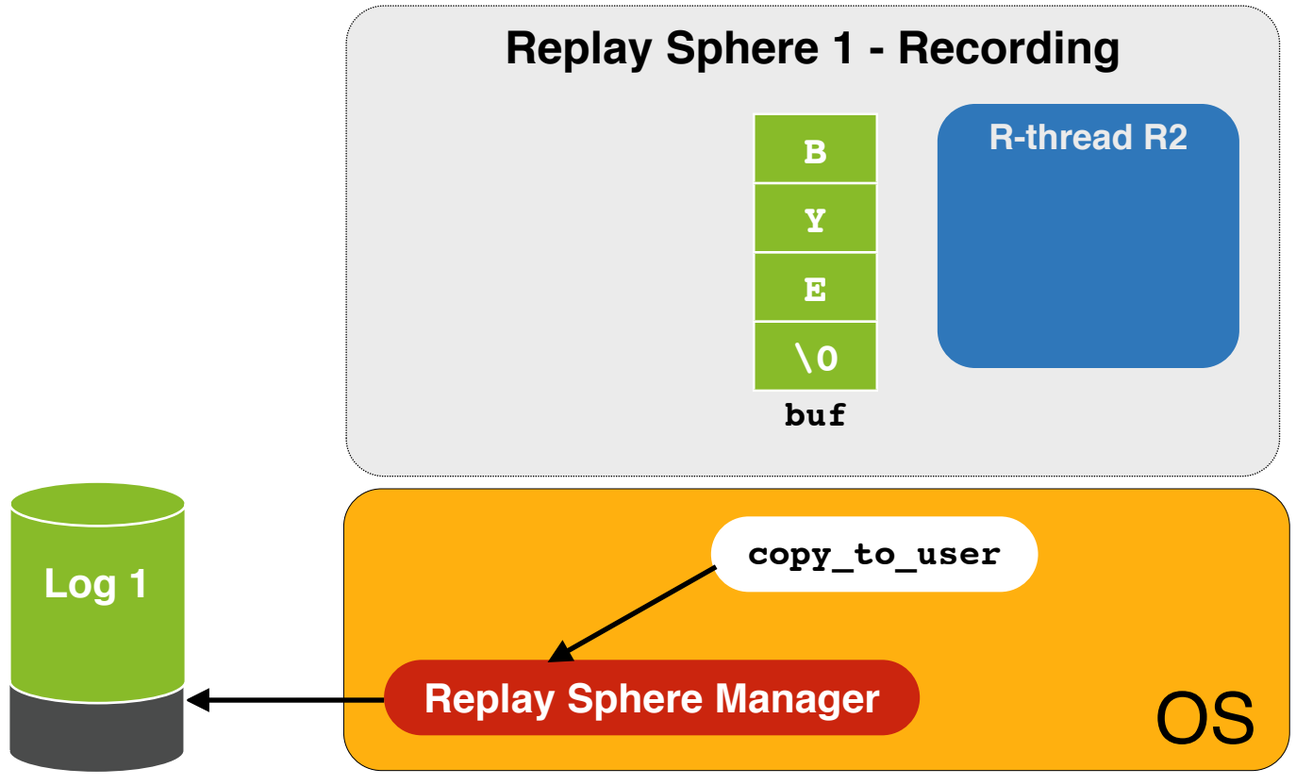

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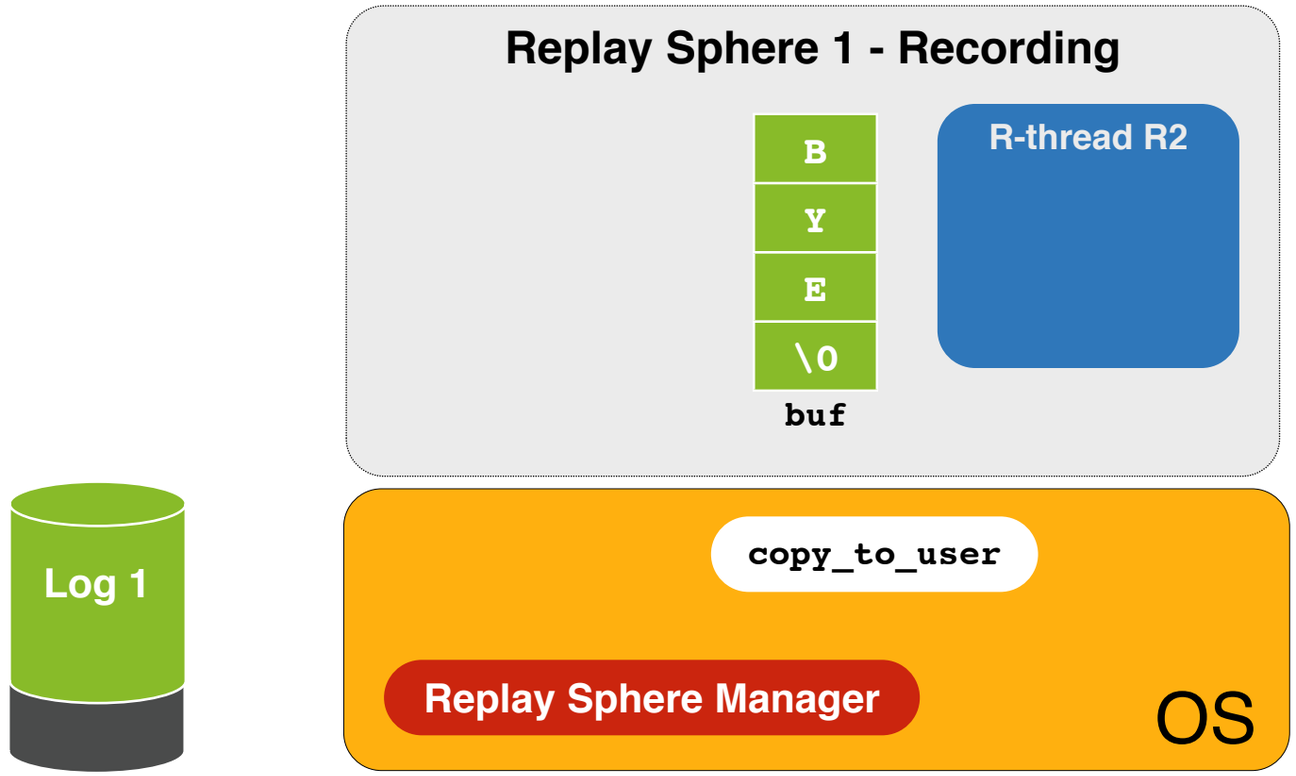

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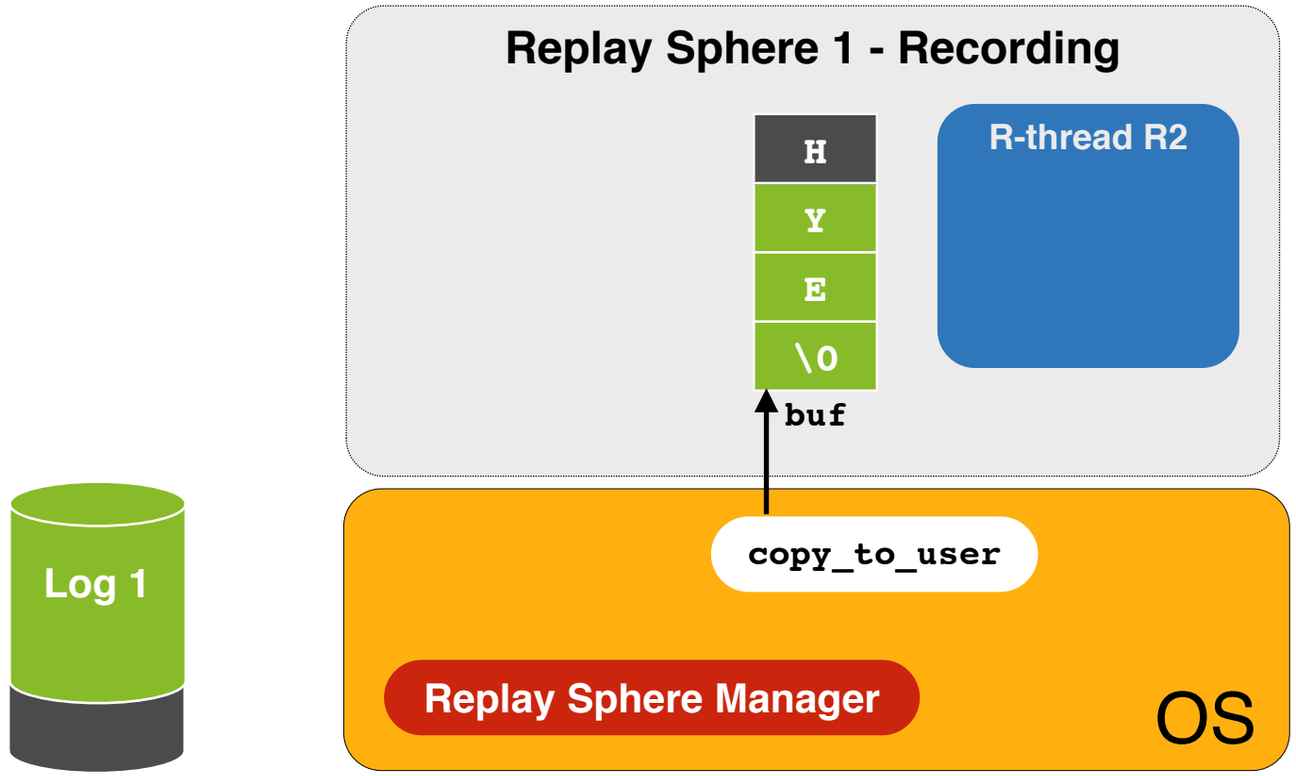

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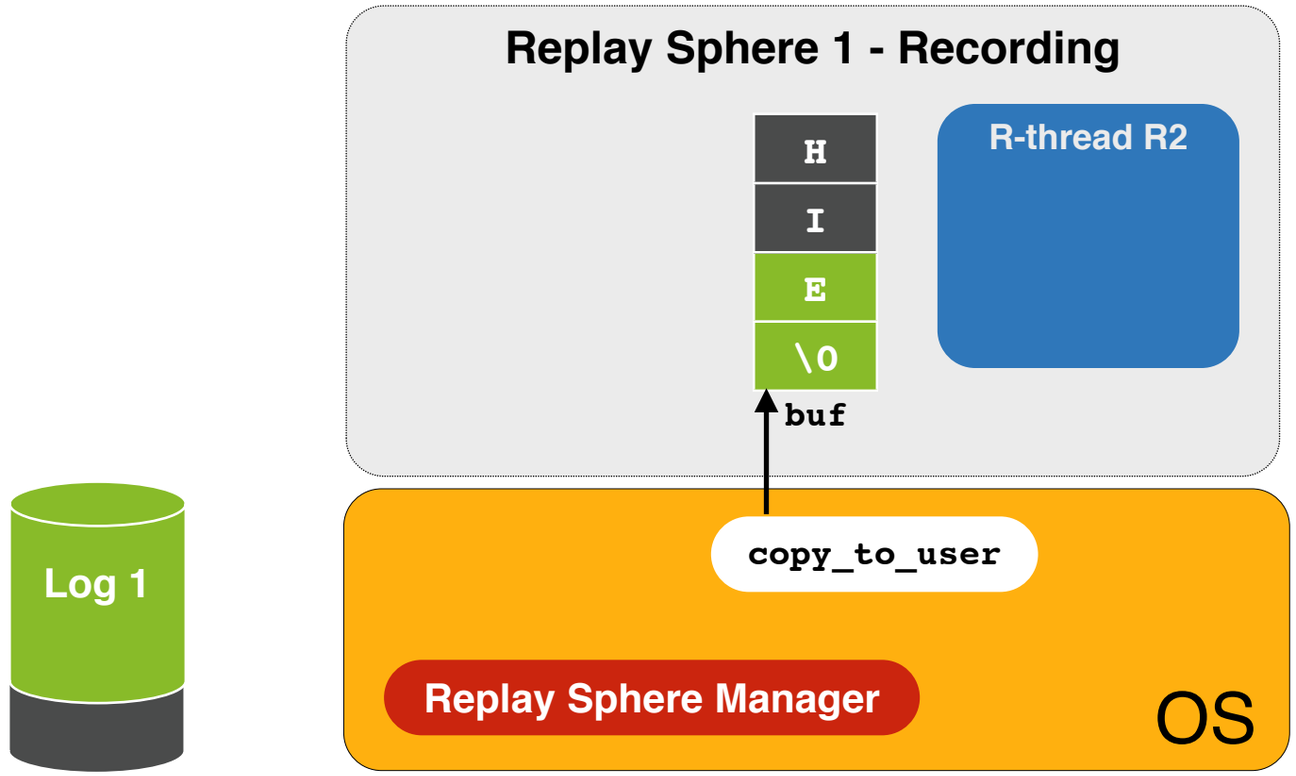

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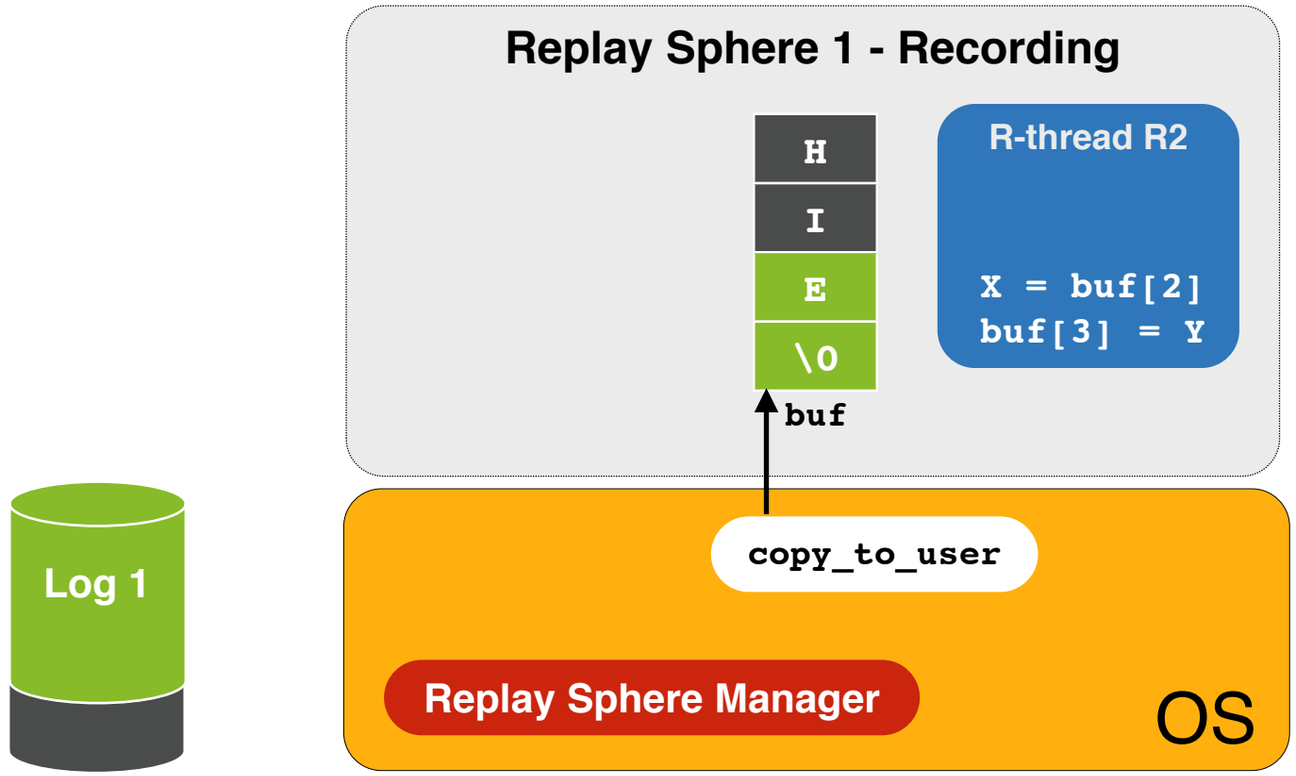

- Problem: interleaving between OS copies and R-threads not recorded

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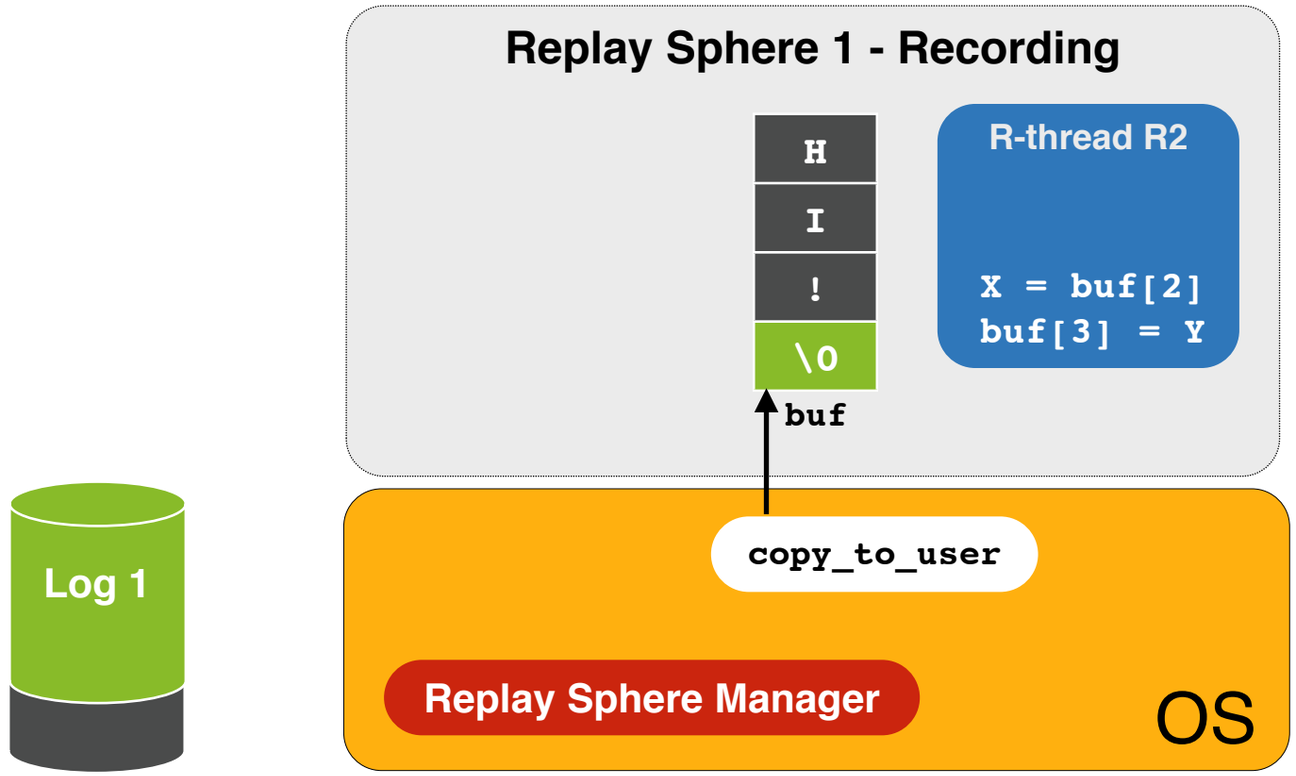

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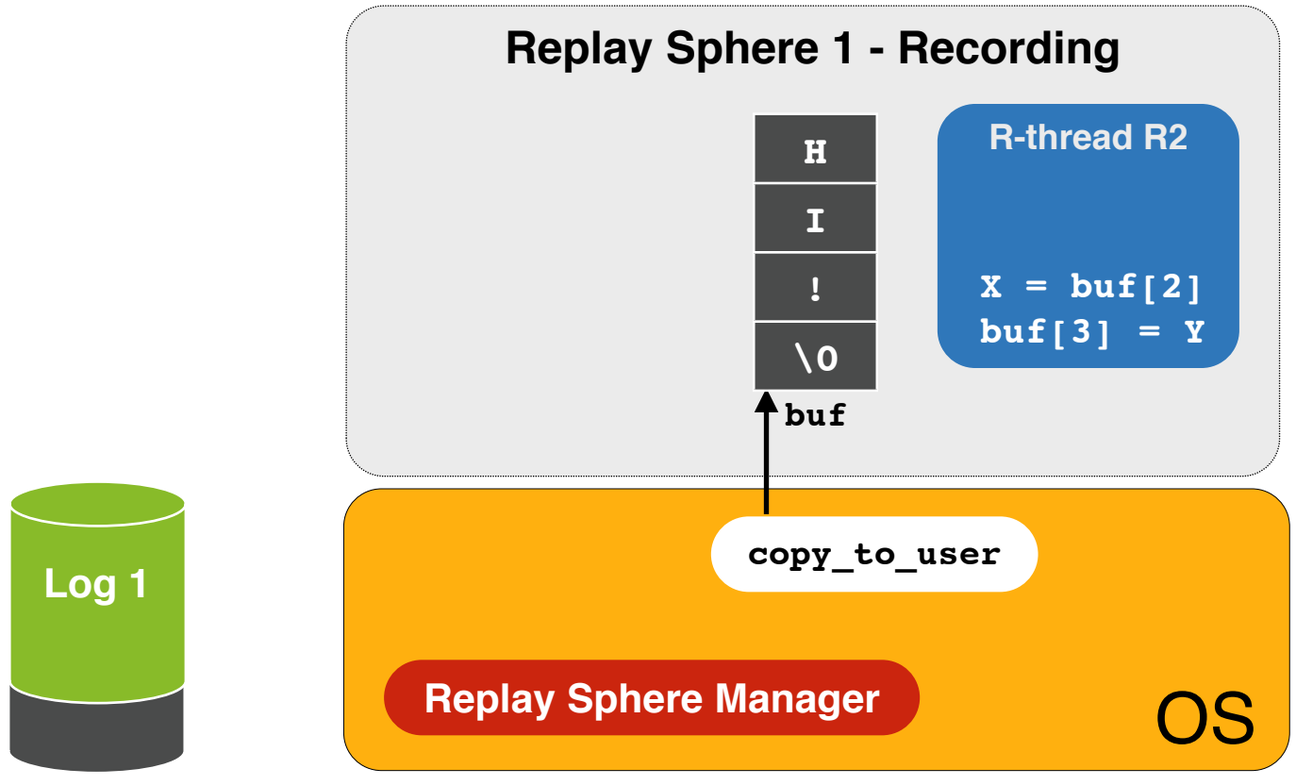

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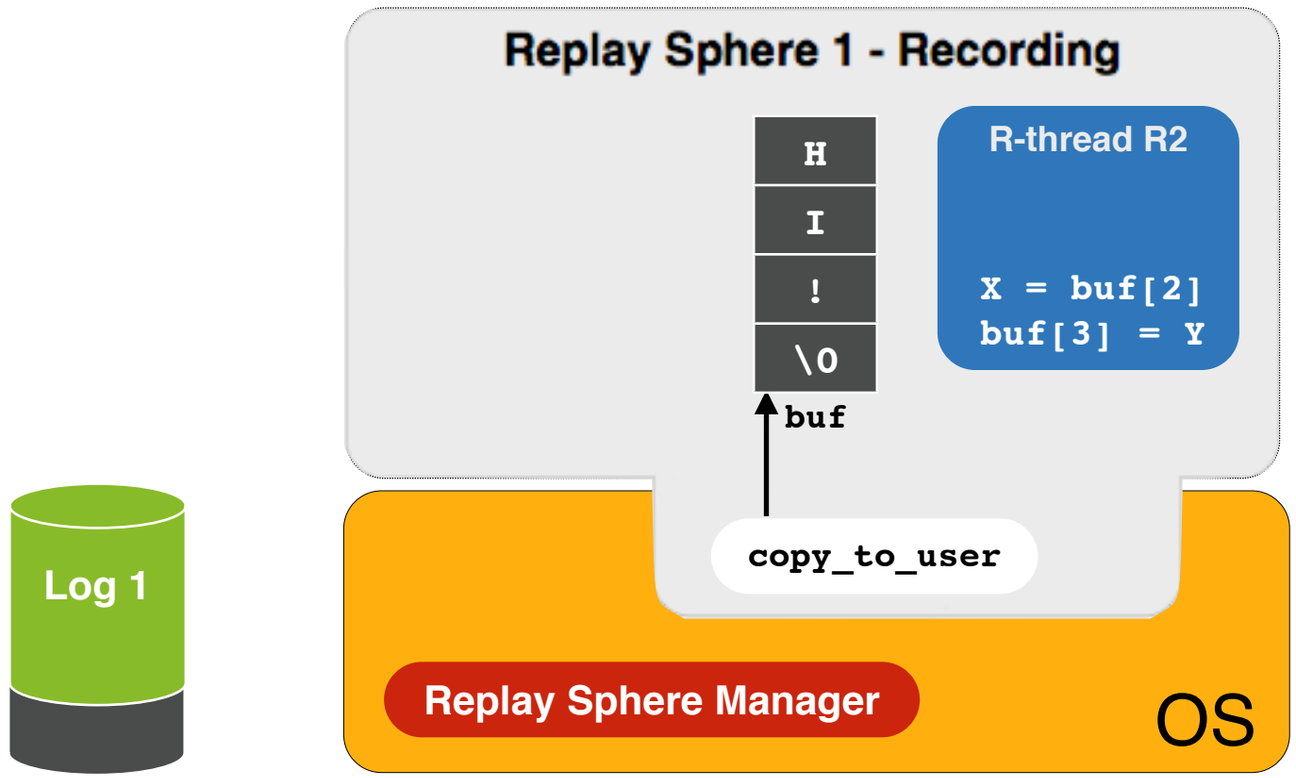

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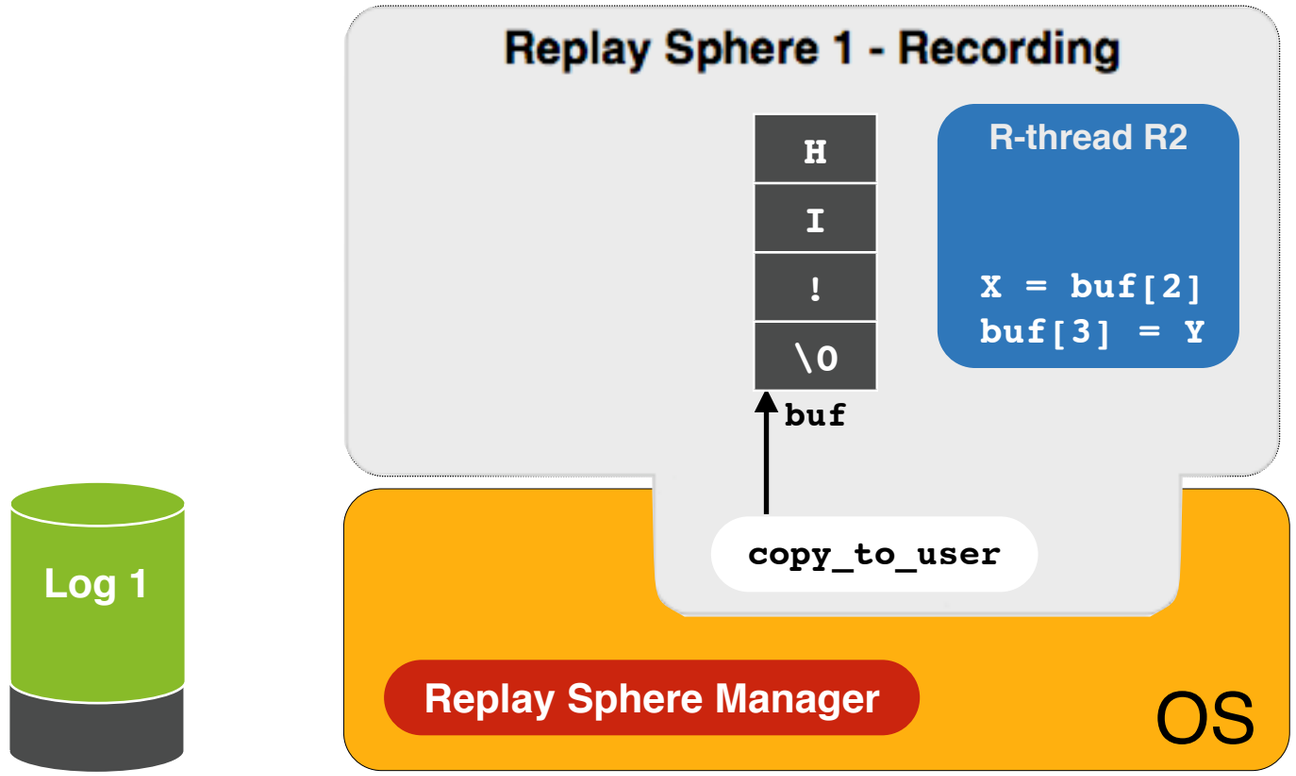

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  - HW can log memory access interleaving

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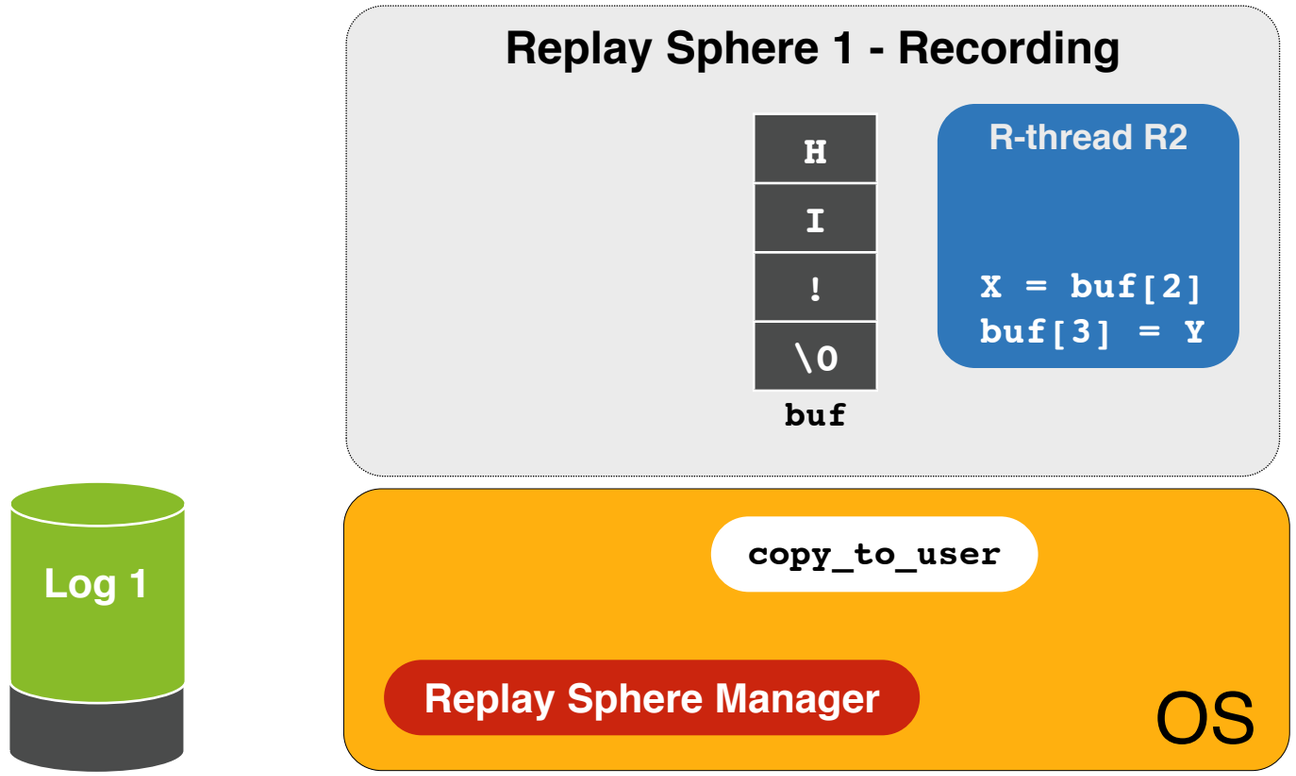

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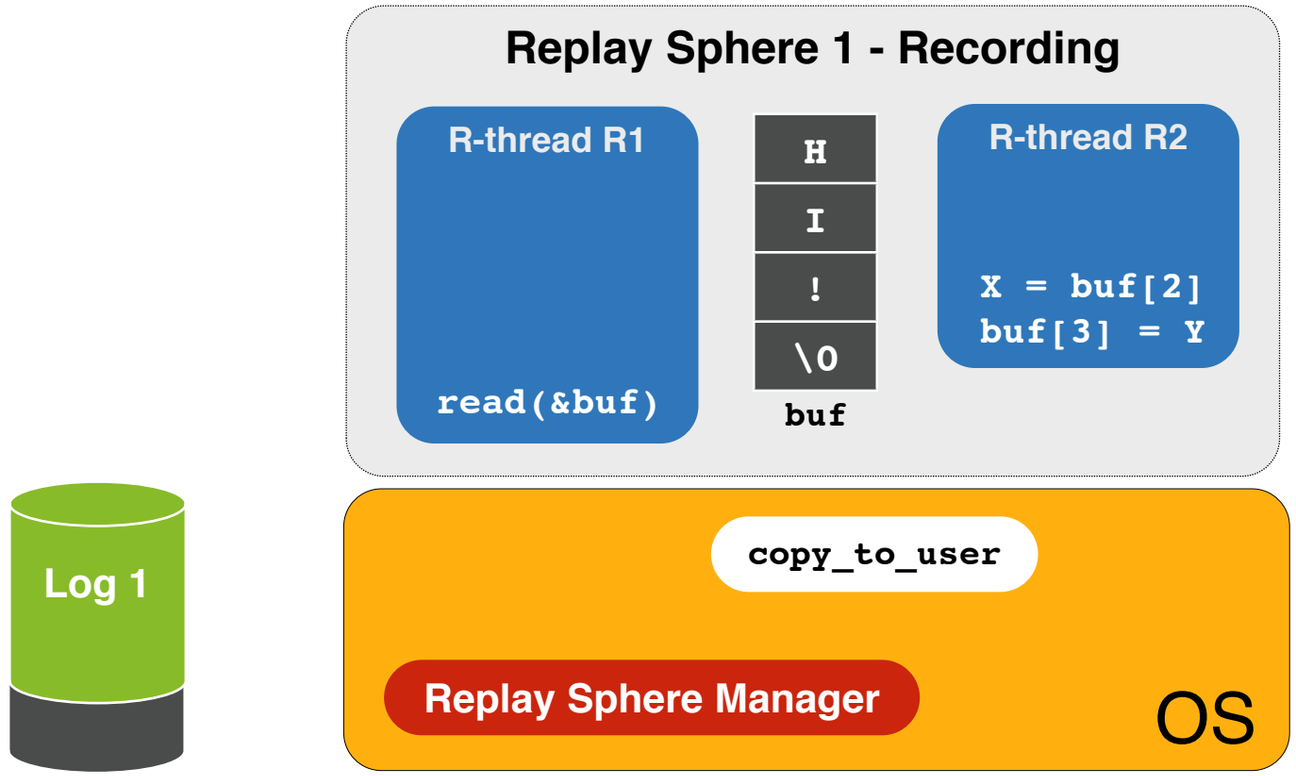

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  - `copy_to_user` exits sphere once copy is over

Injecting Data into Spheres (II)

- Look for interactions between R-thread Interleaving Log and Input Log

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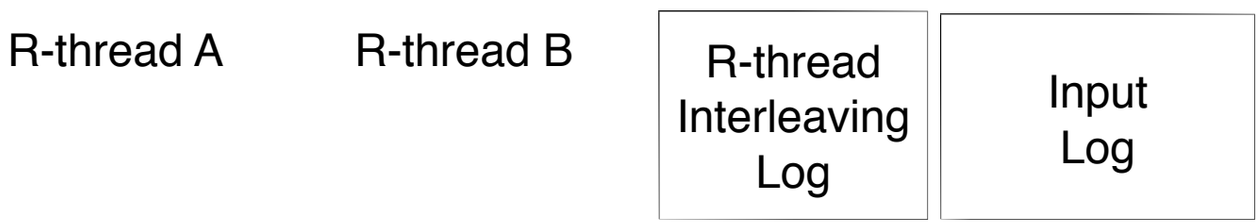

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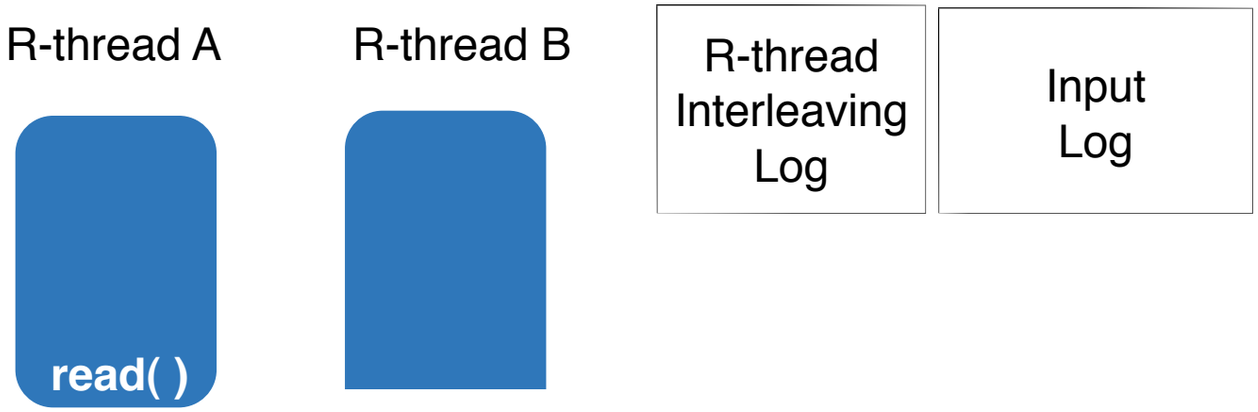

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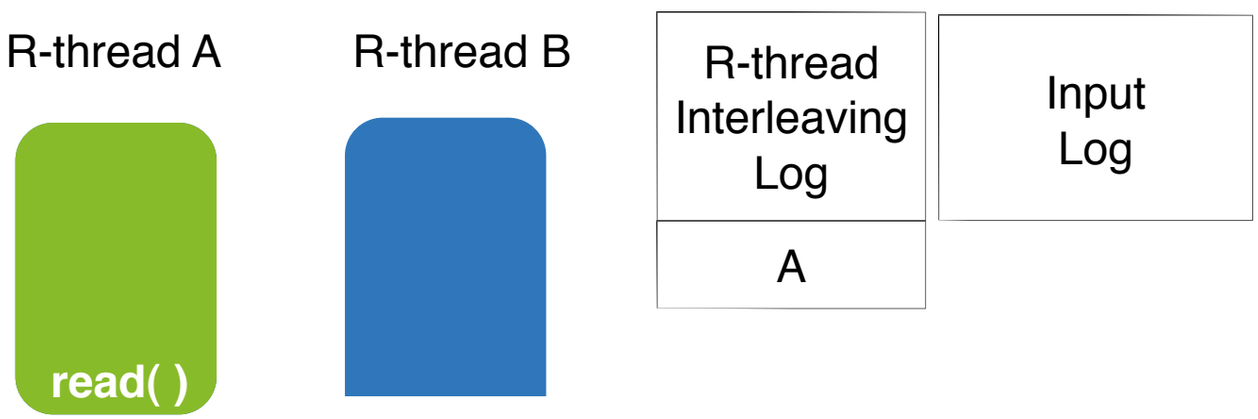

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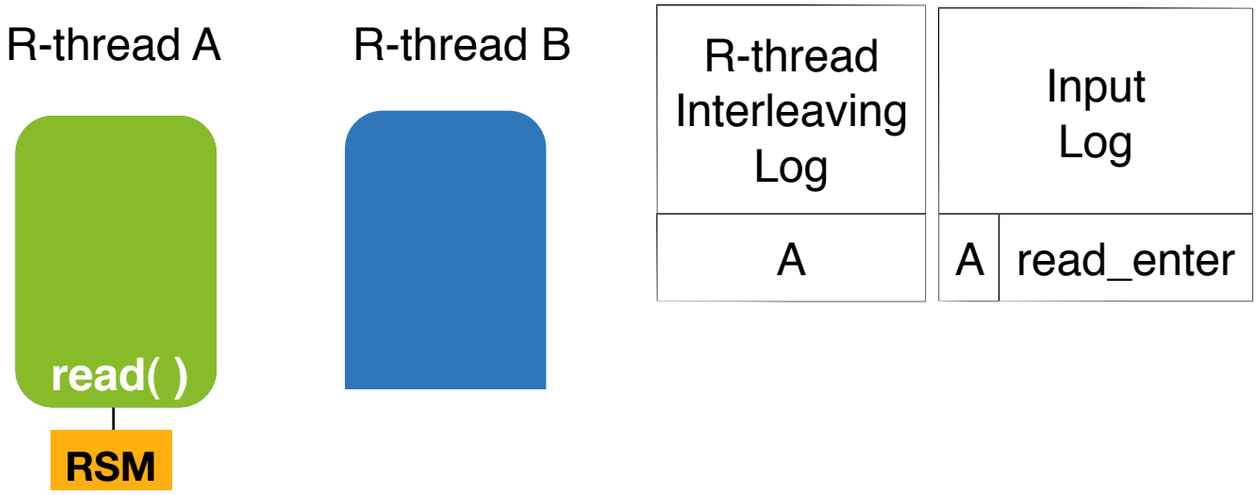

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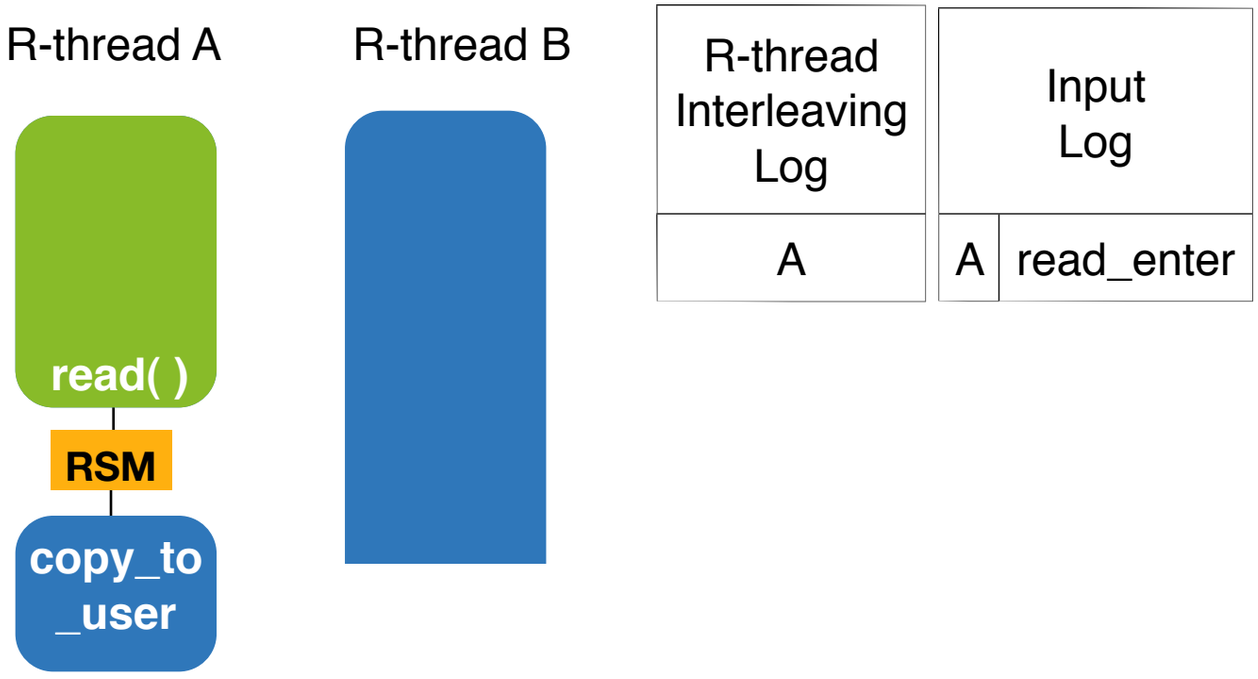

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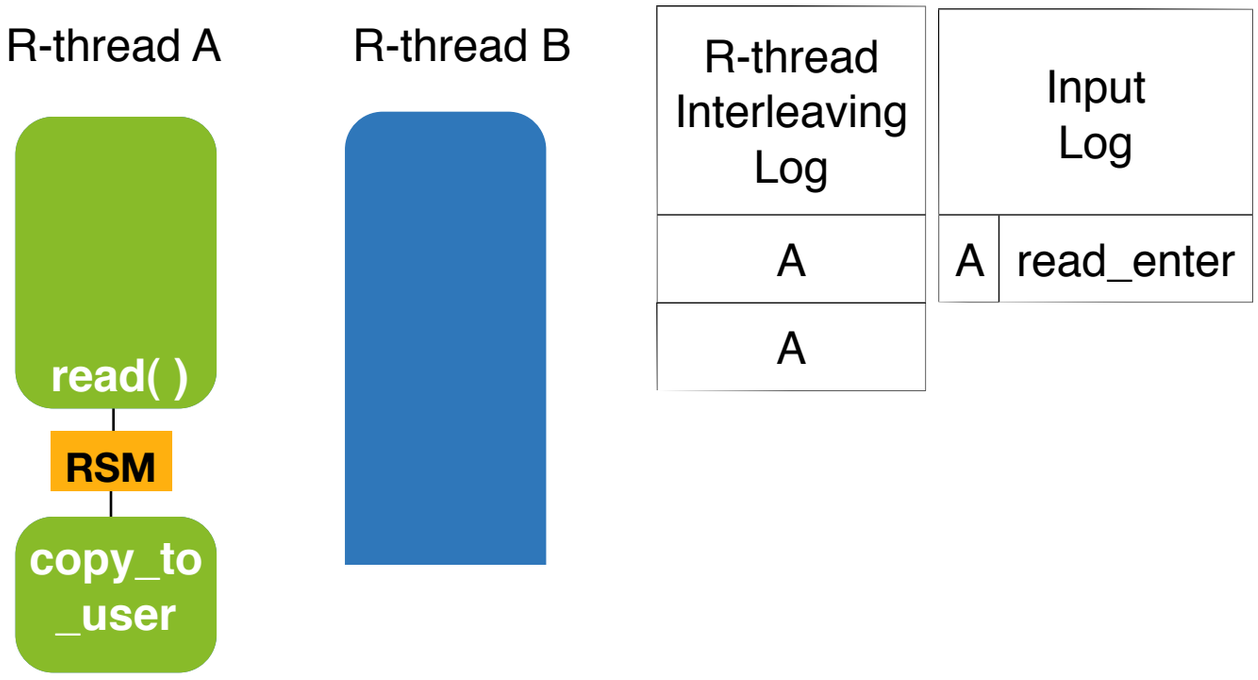

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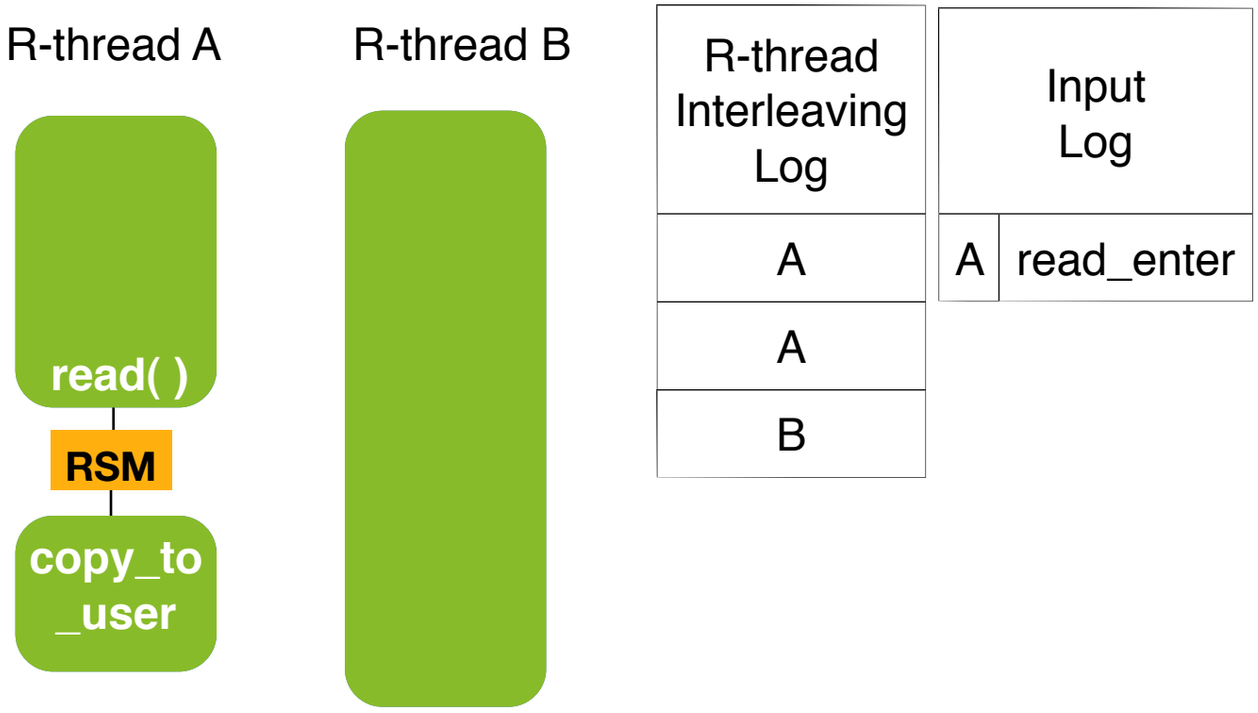

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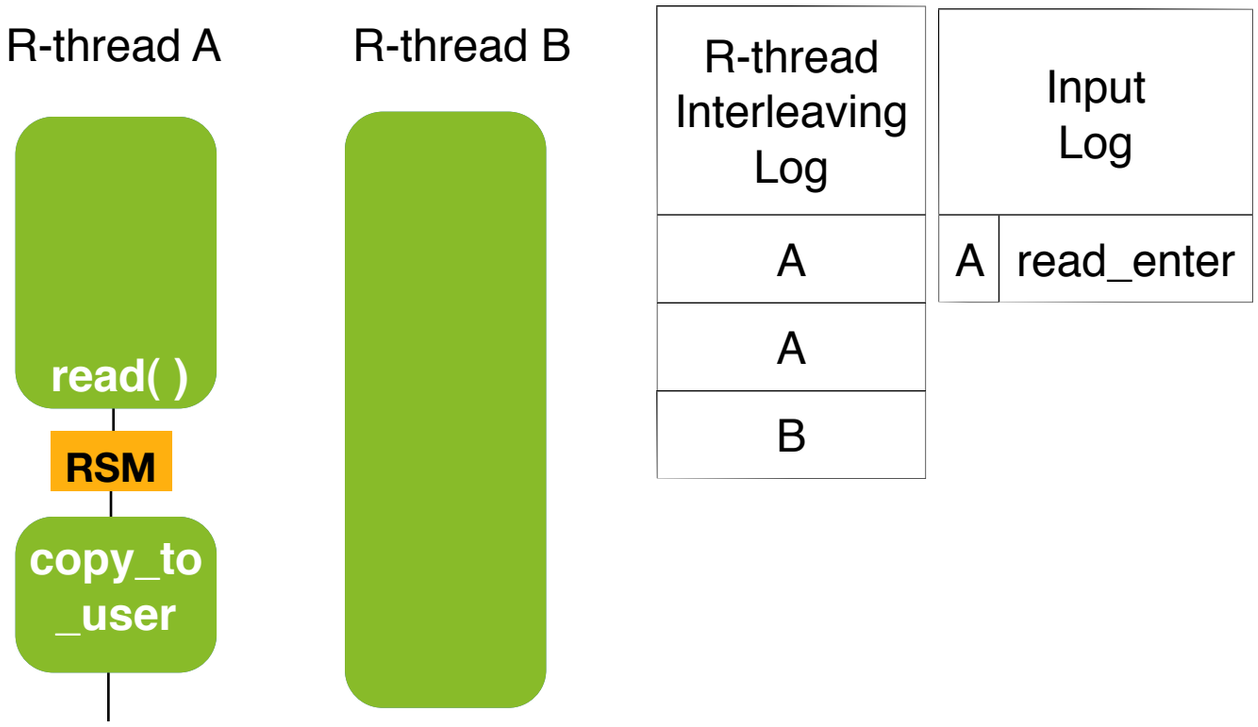

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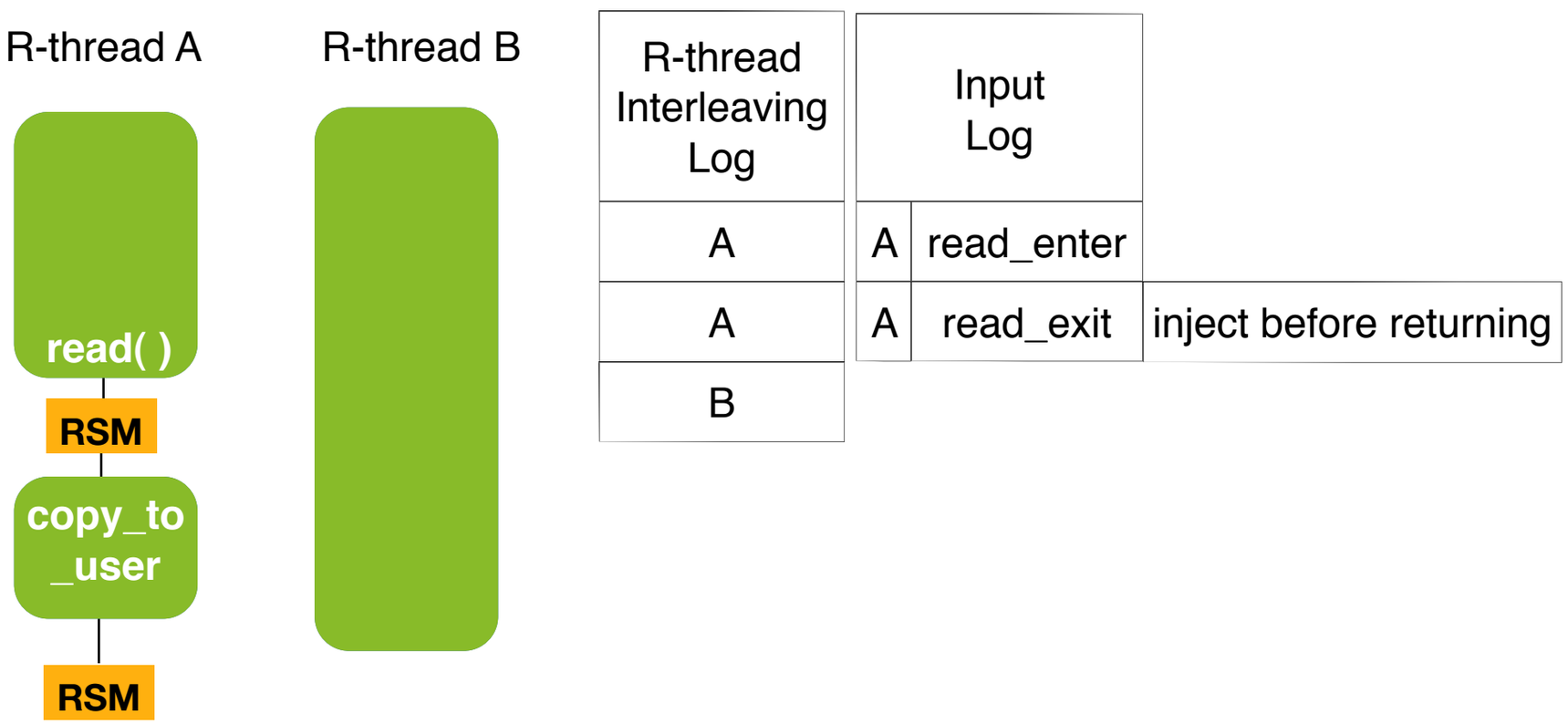

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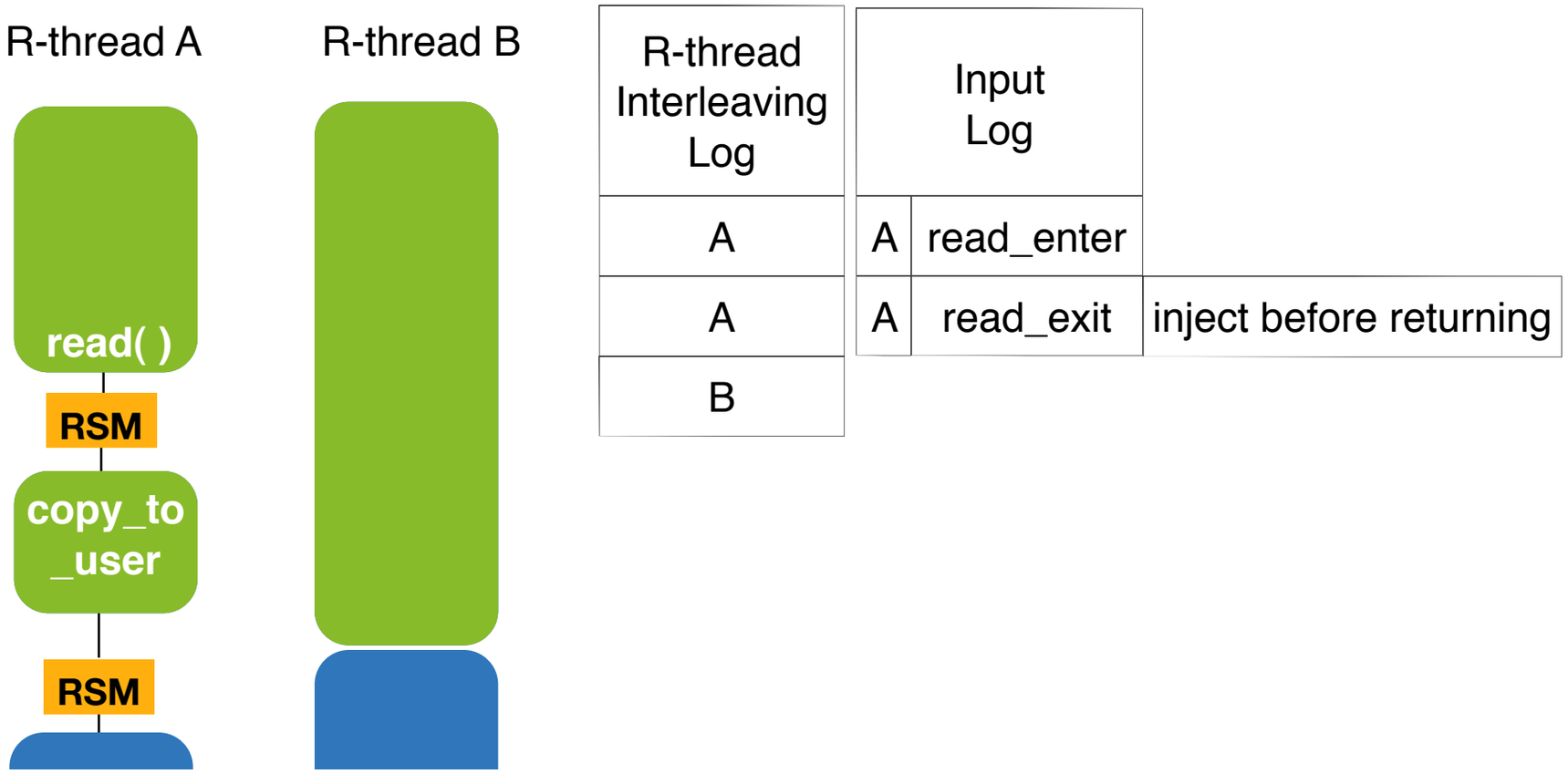

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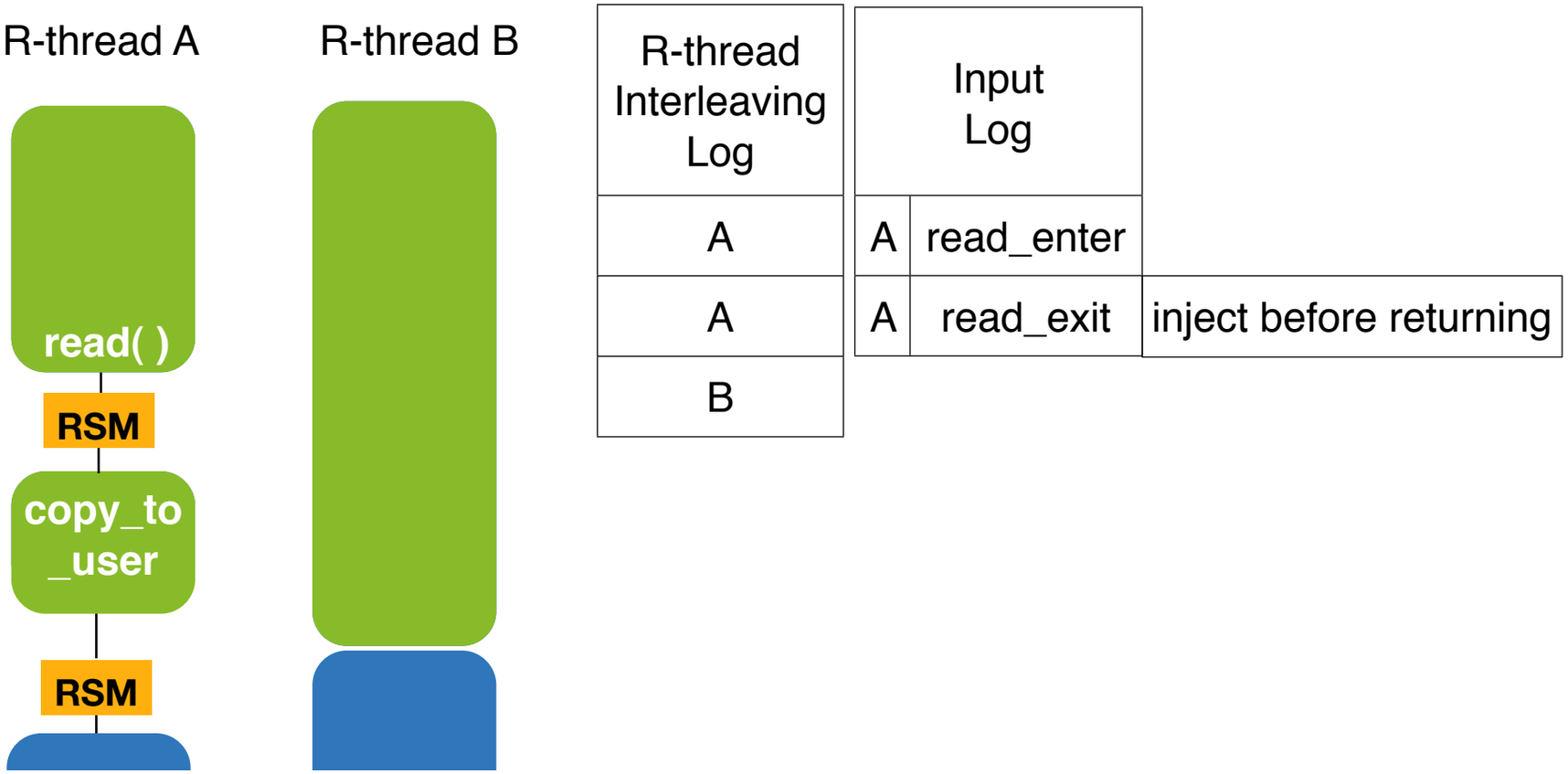

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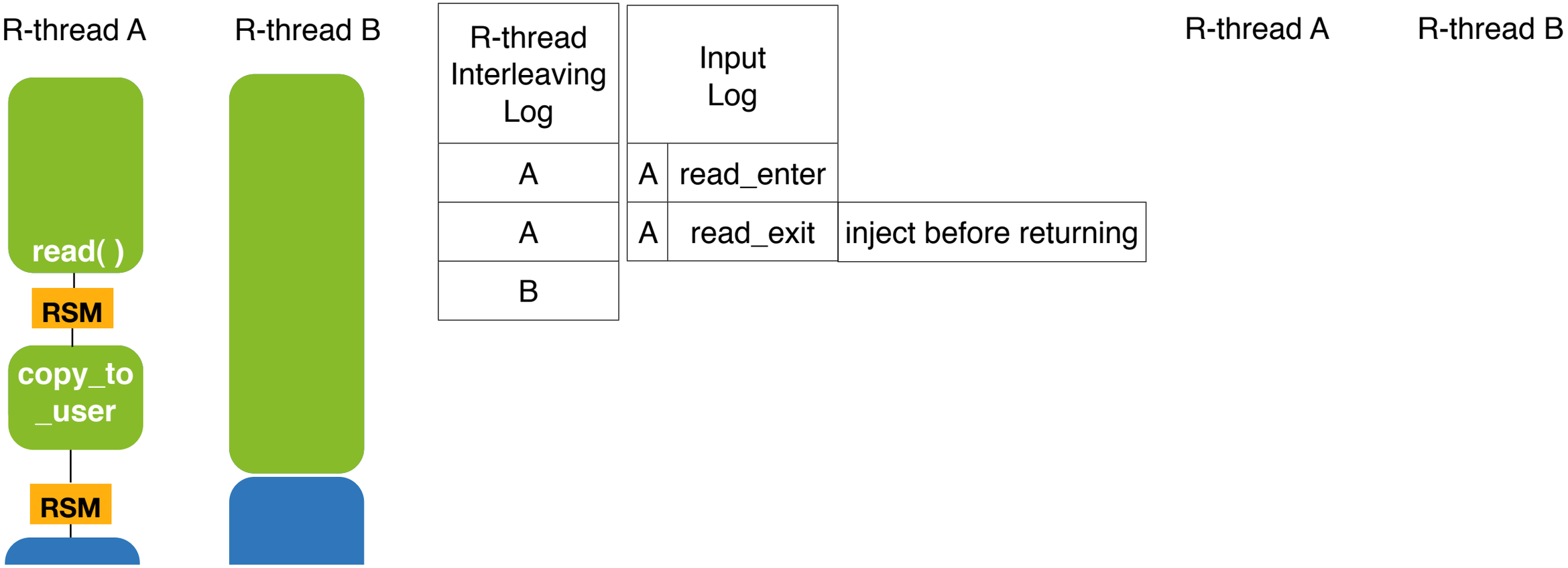

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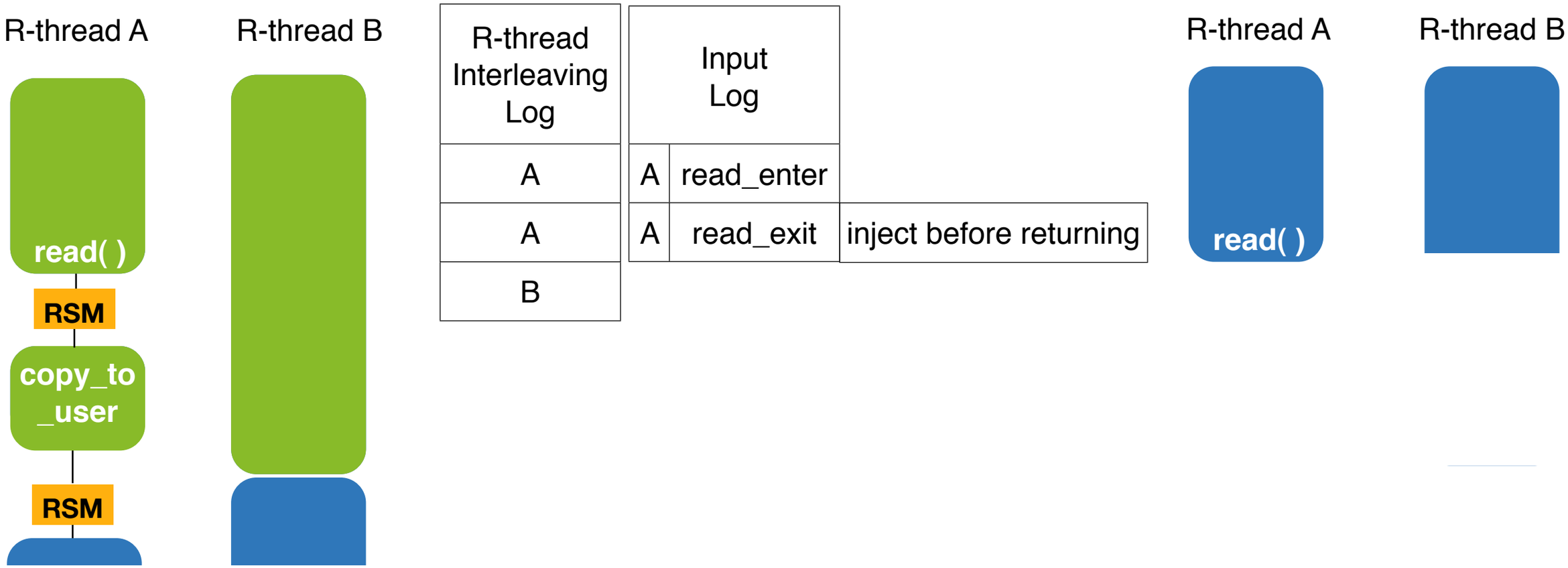

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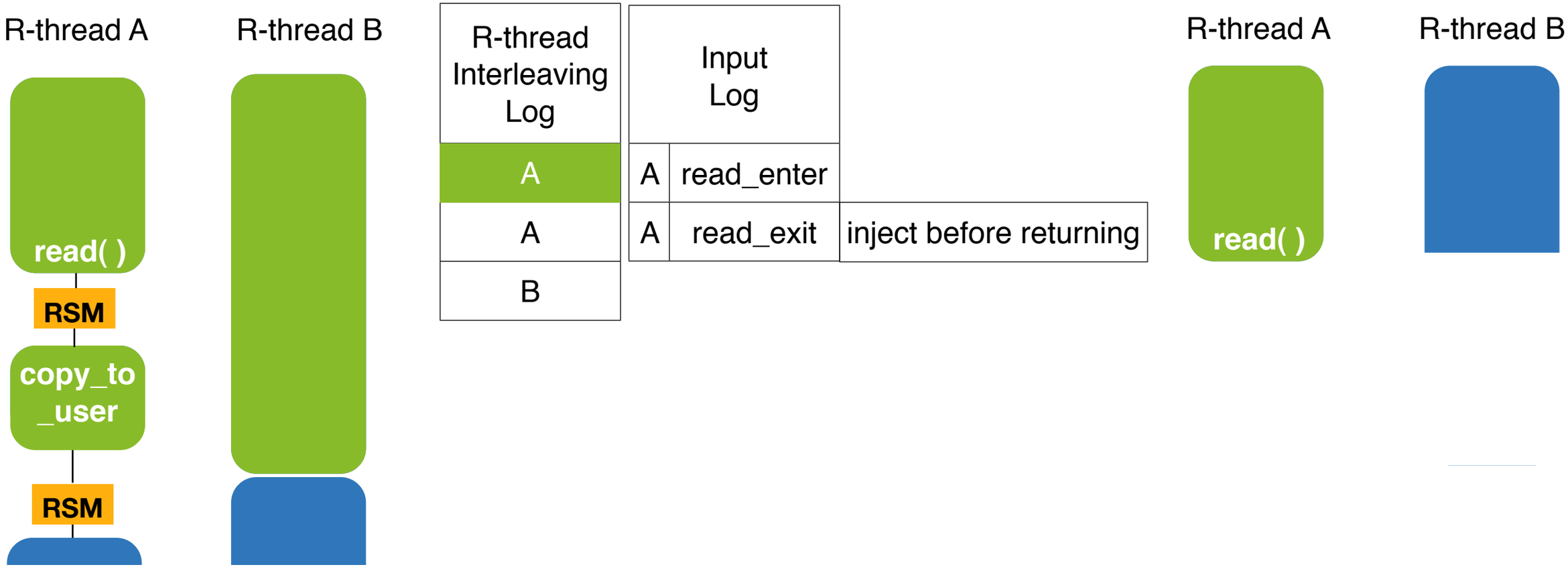

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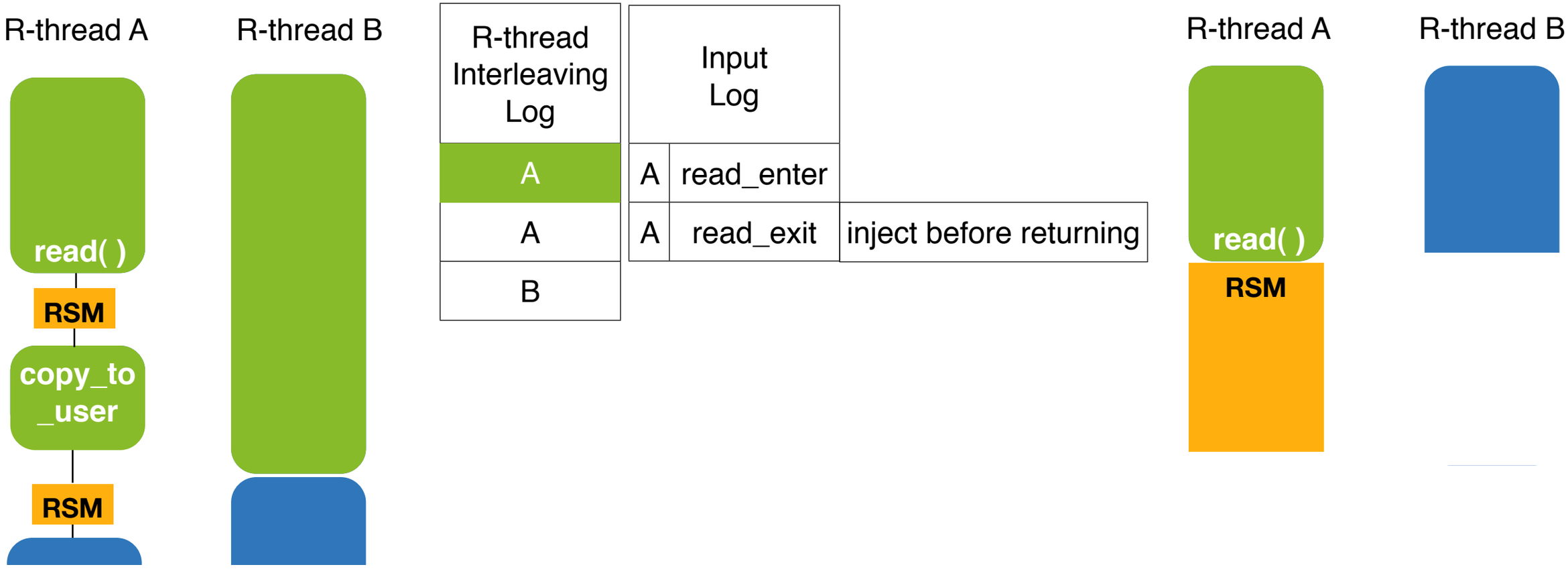

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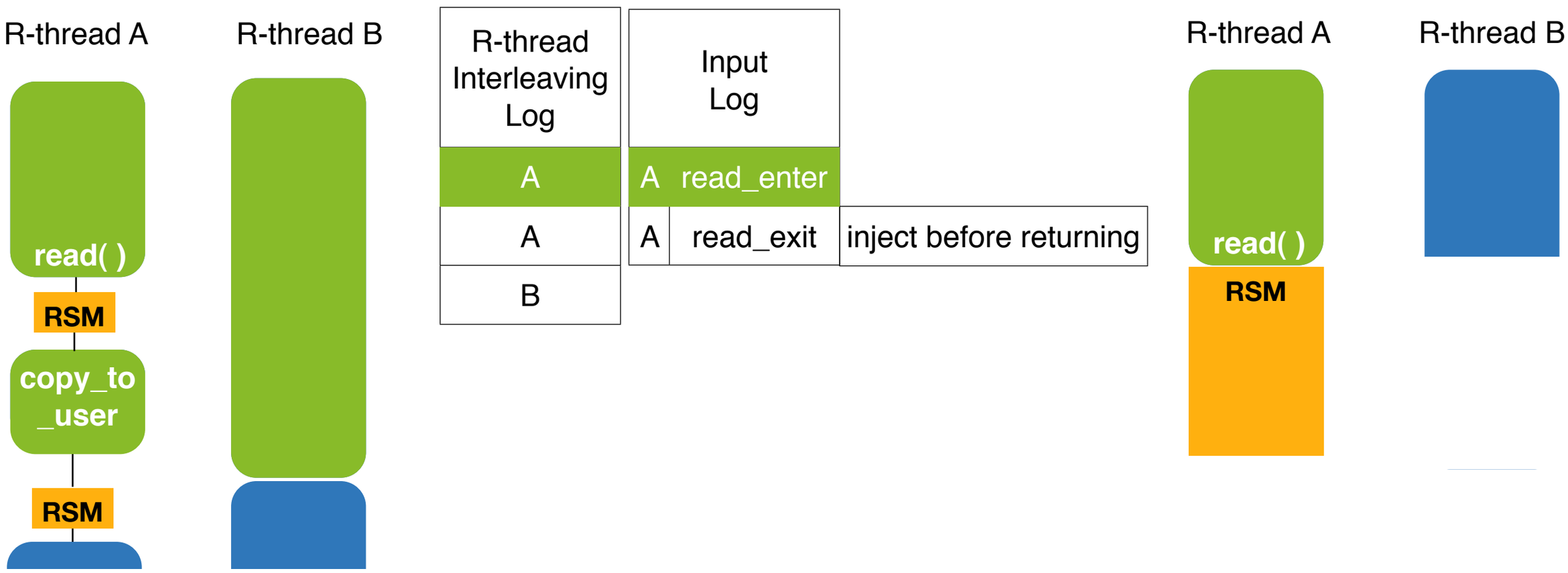

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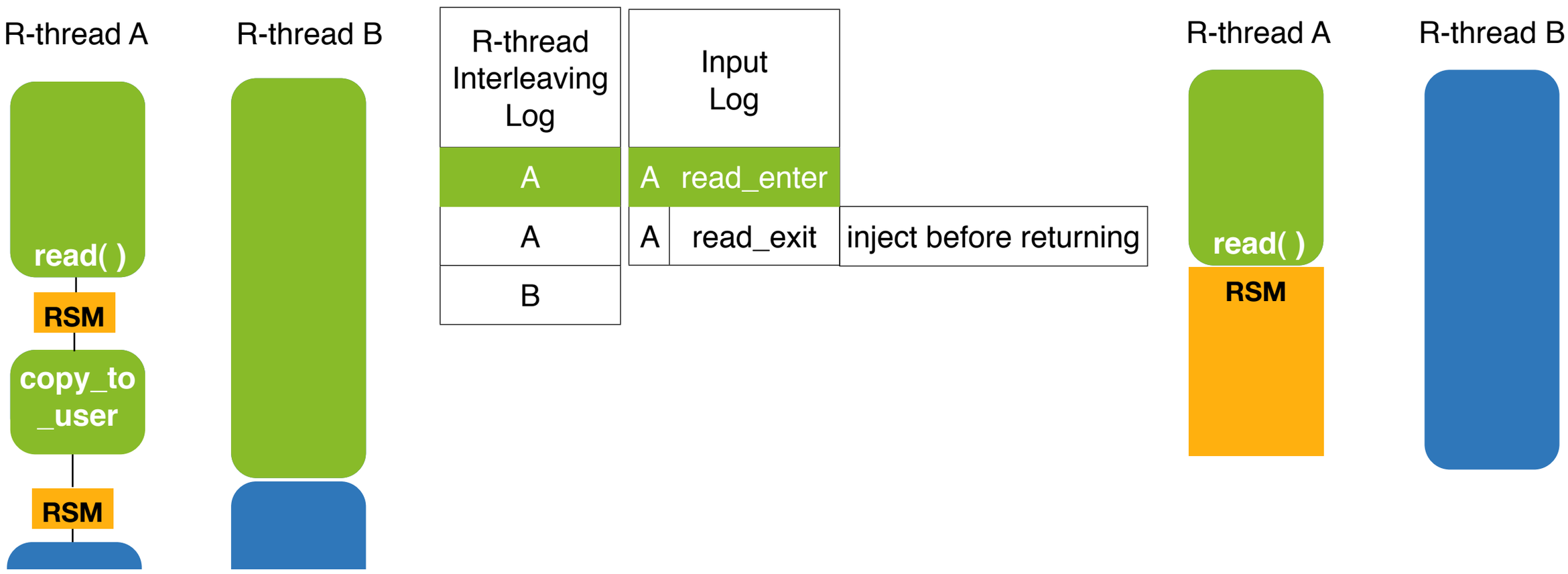

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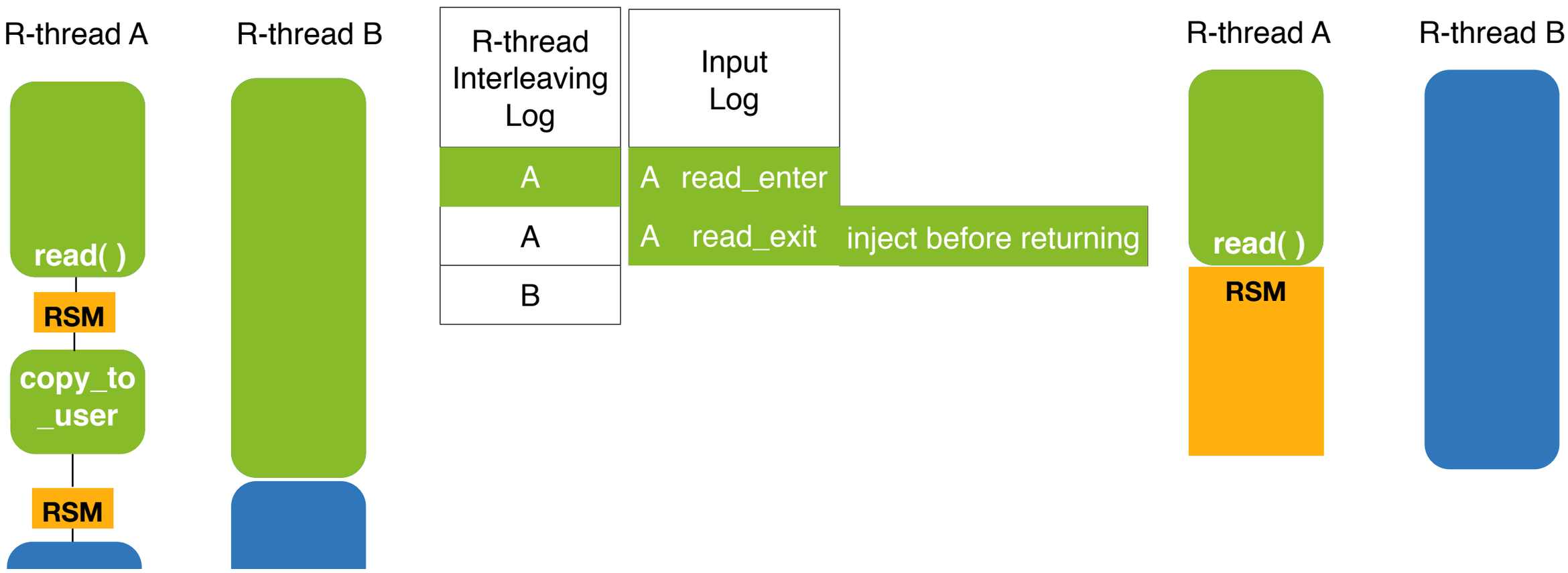

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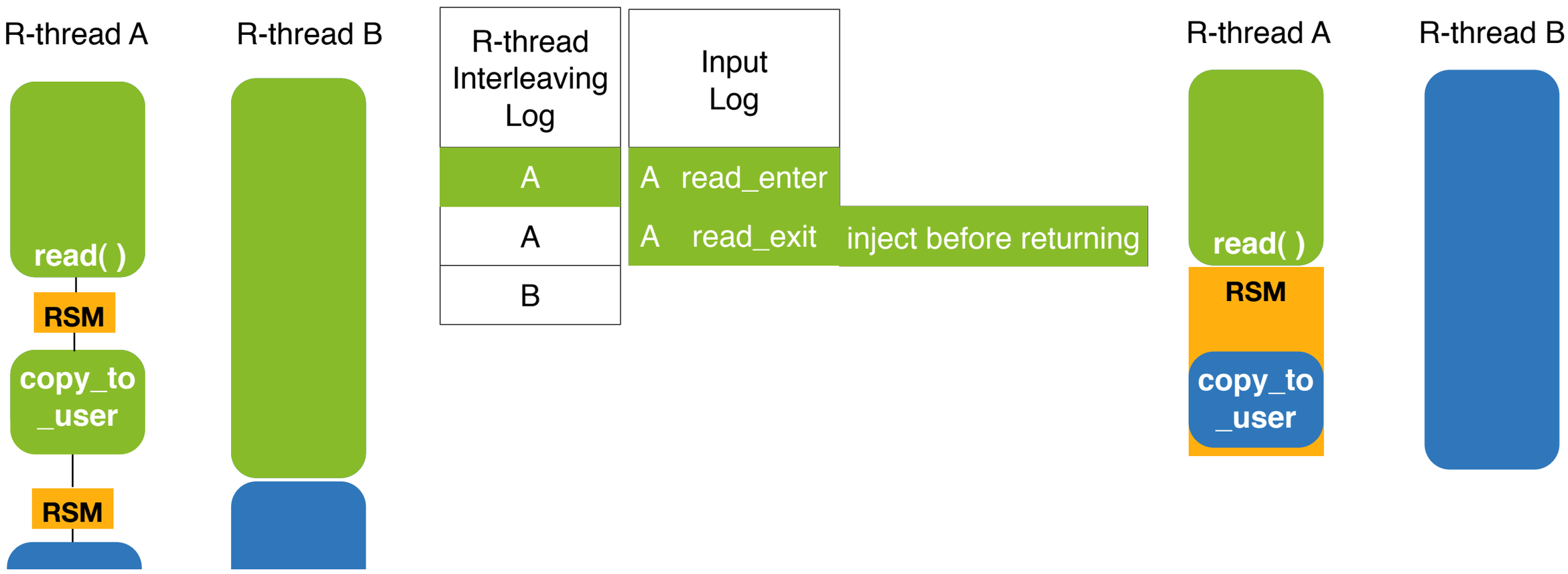

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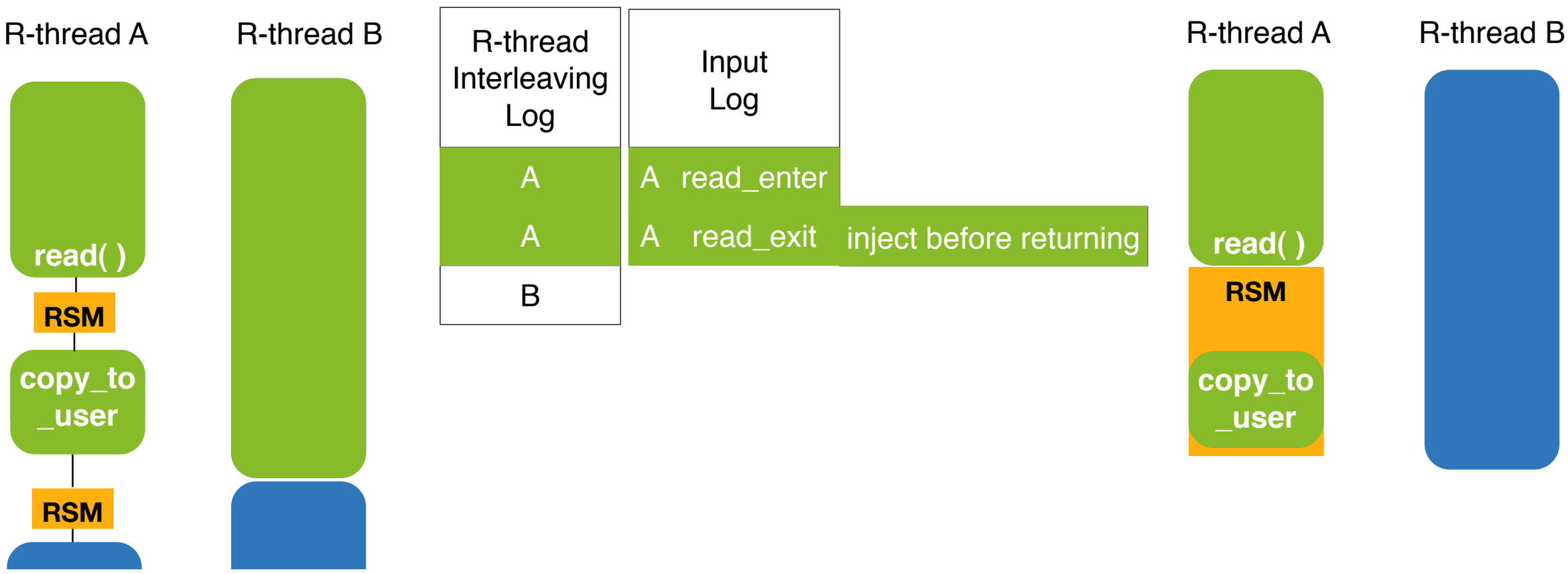

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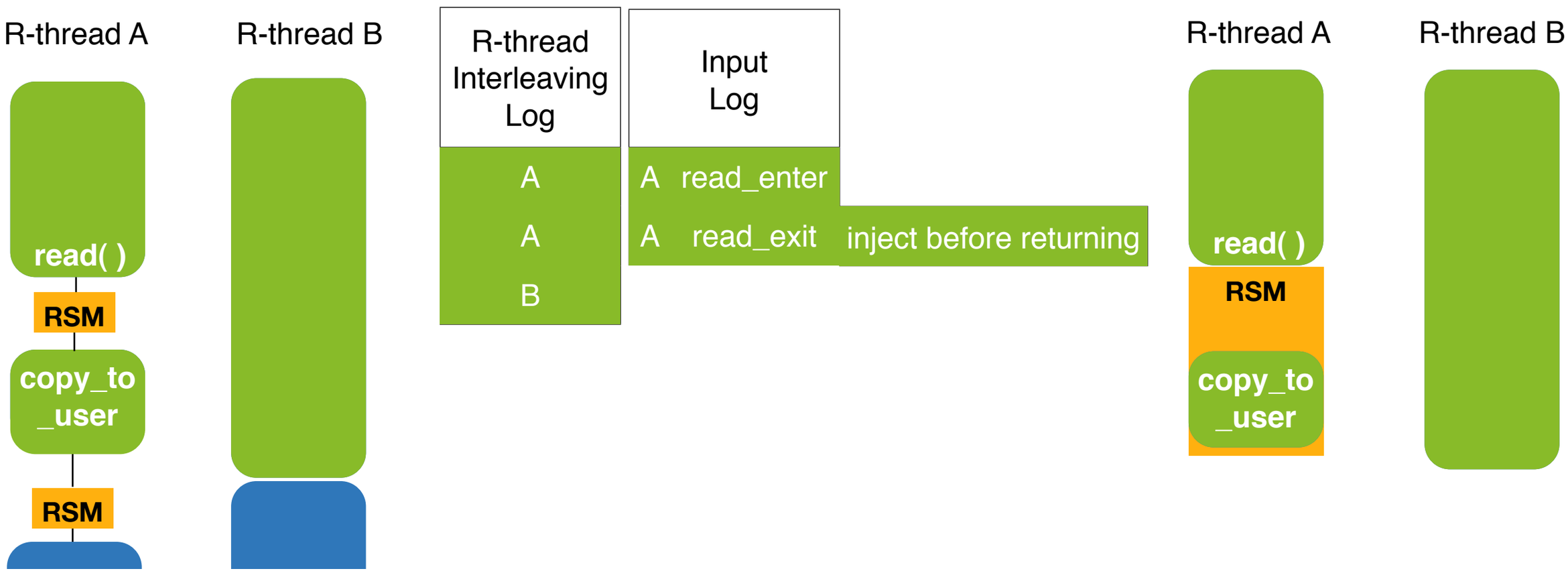

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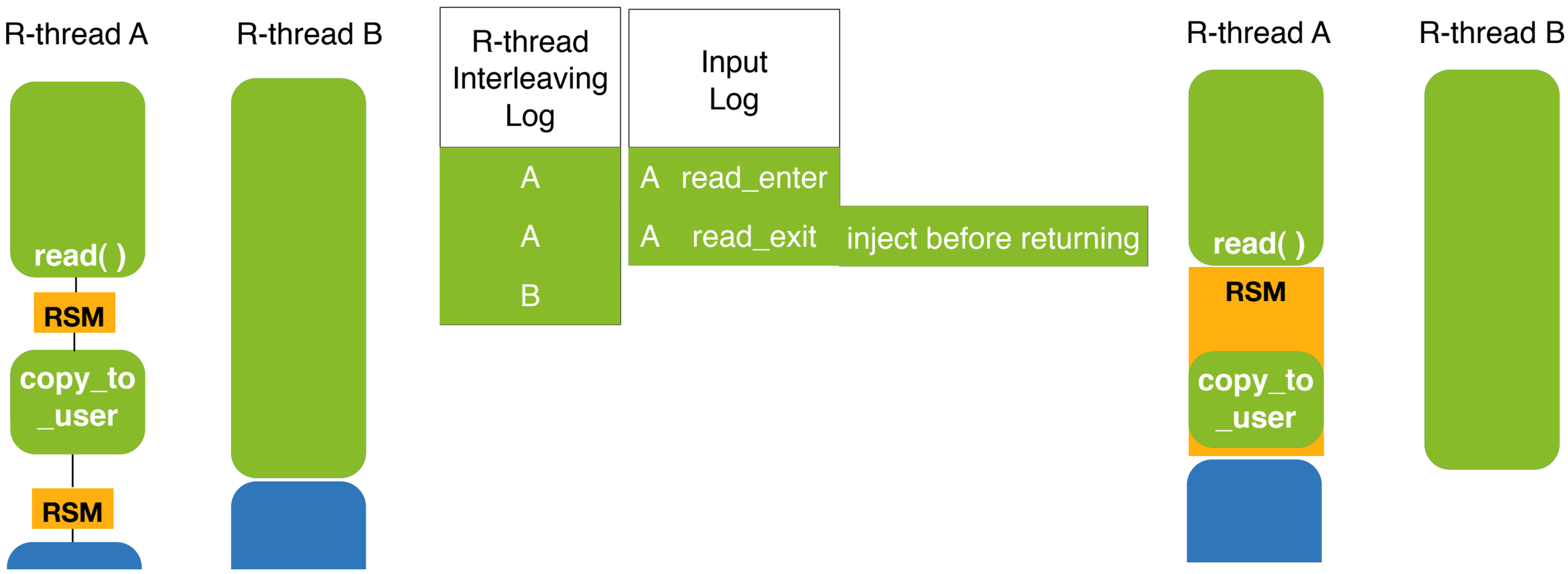

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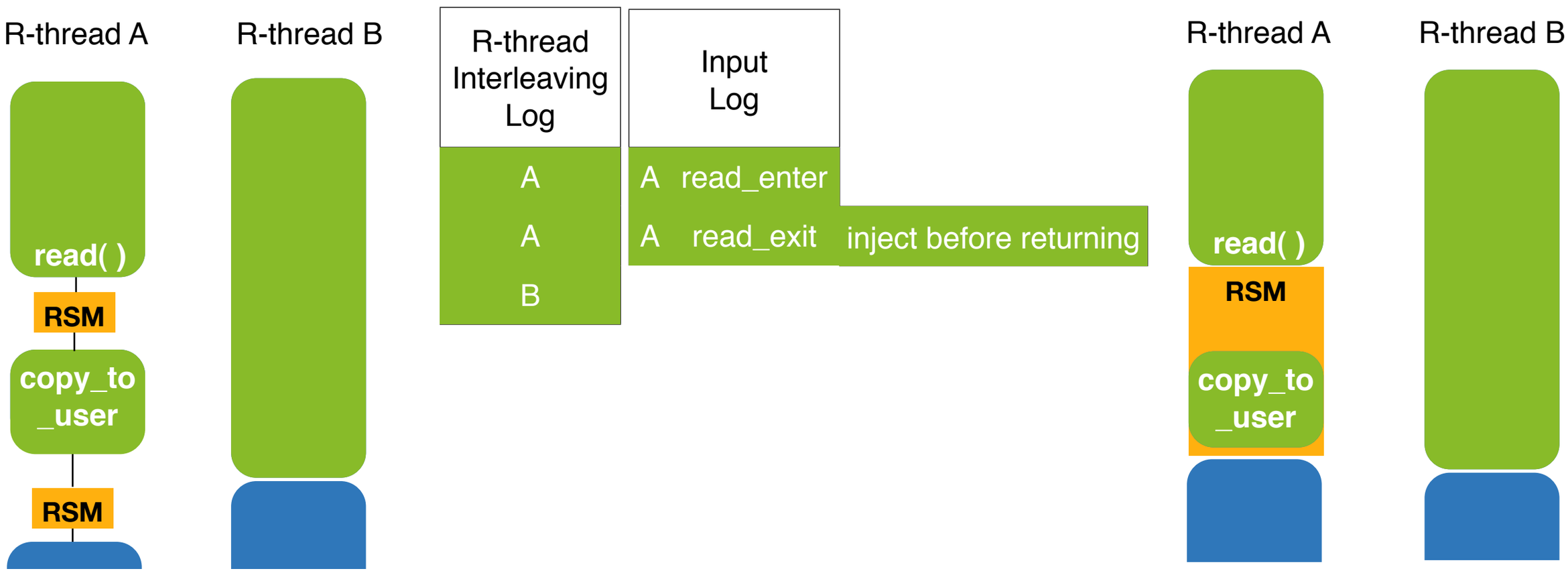

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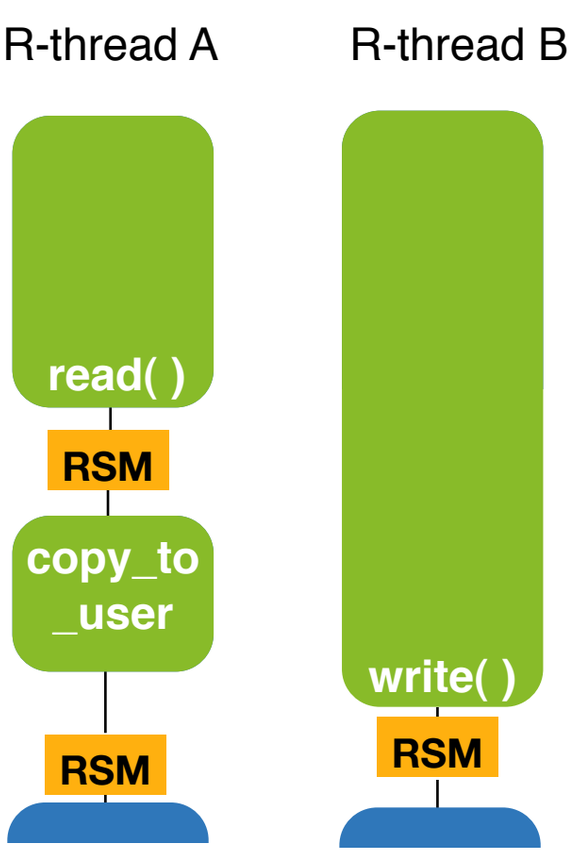

R-thread Interleaving Log	Input Log		
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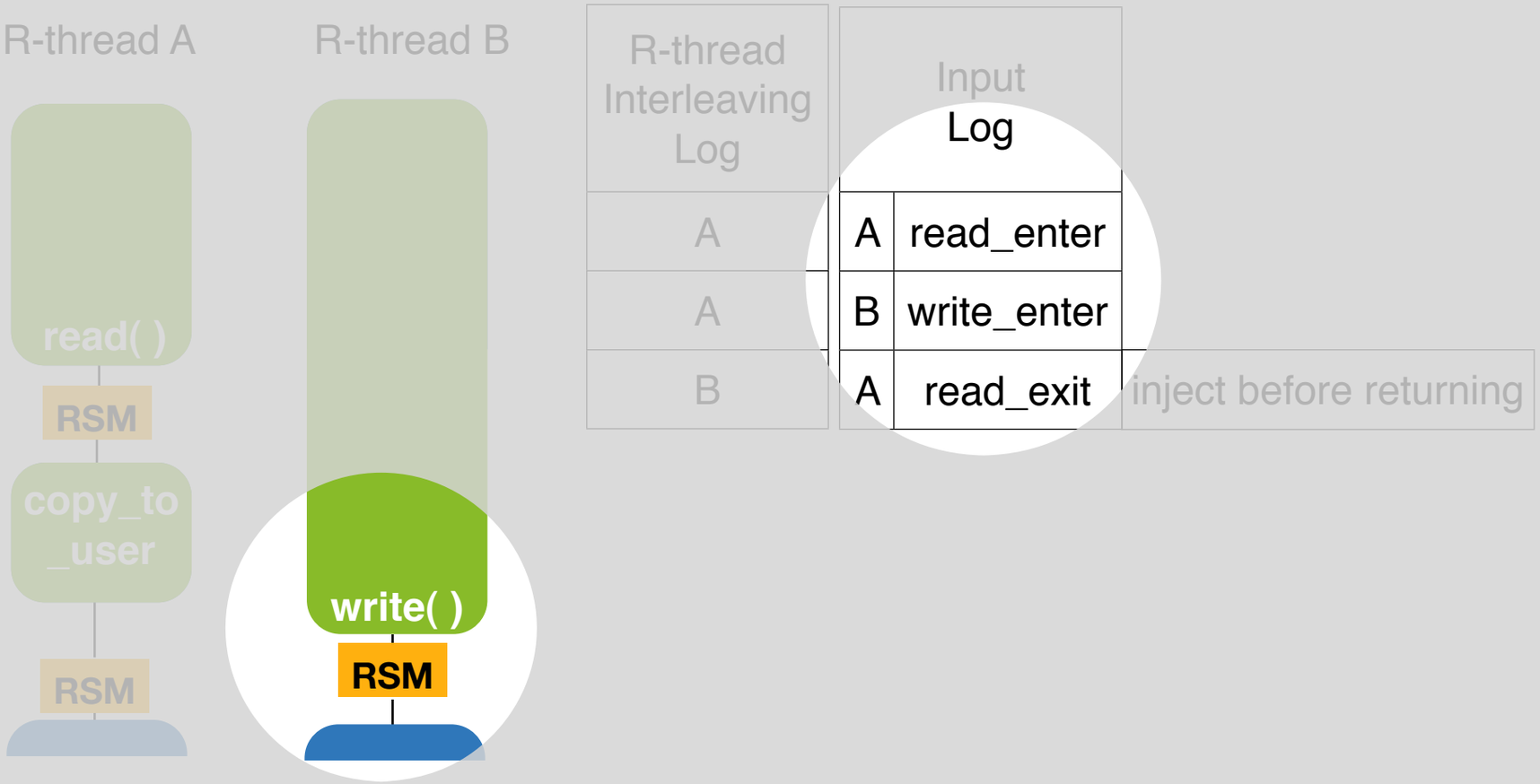

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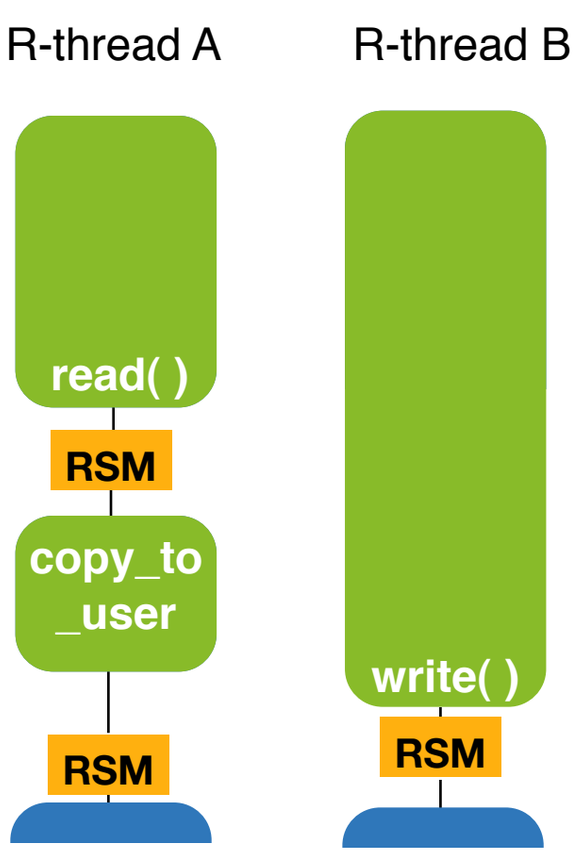

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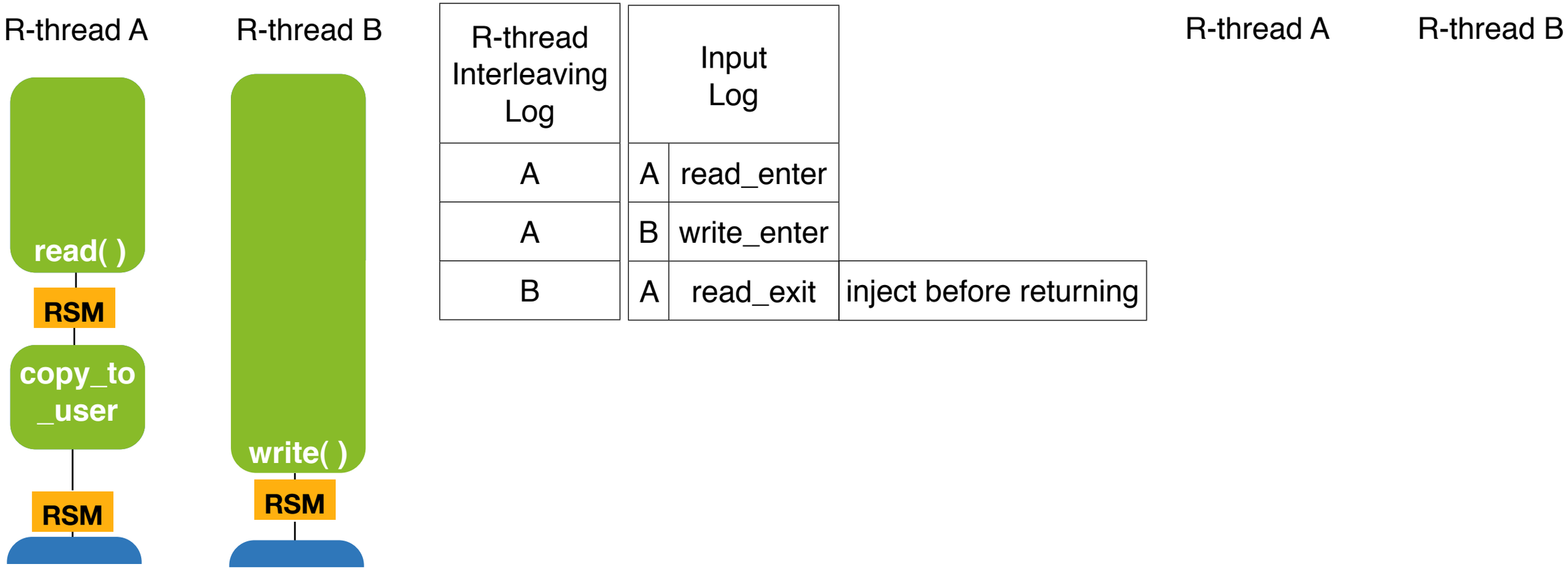

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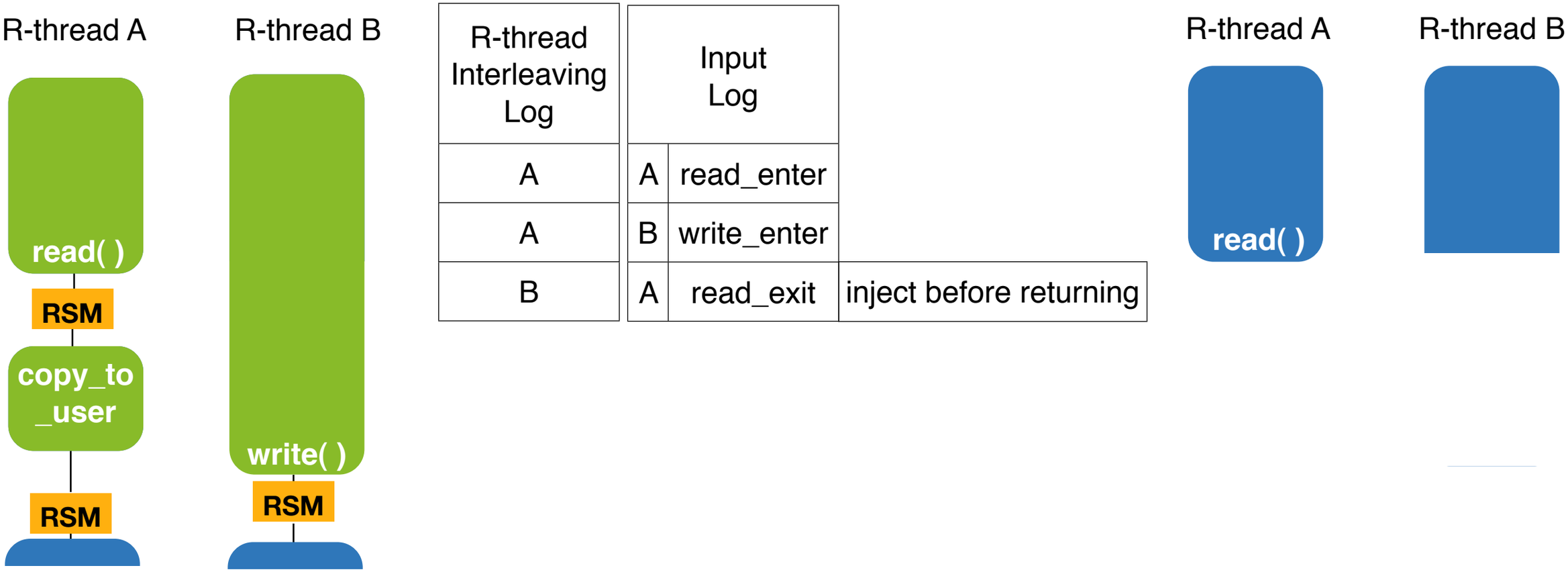

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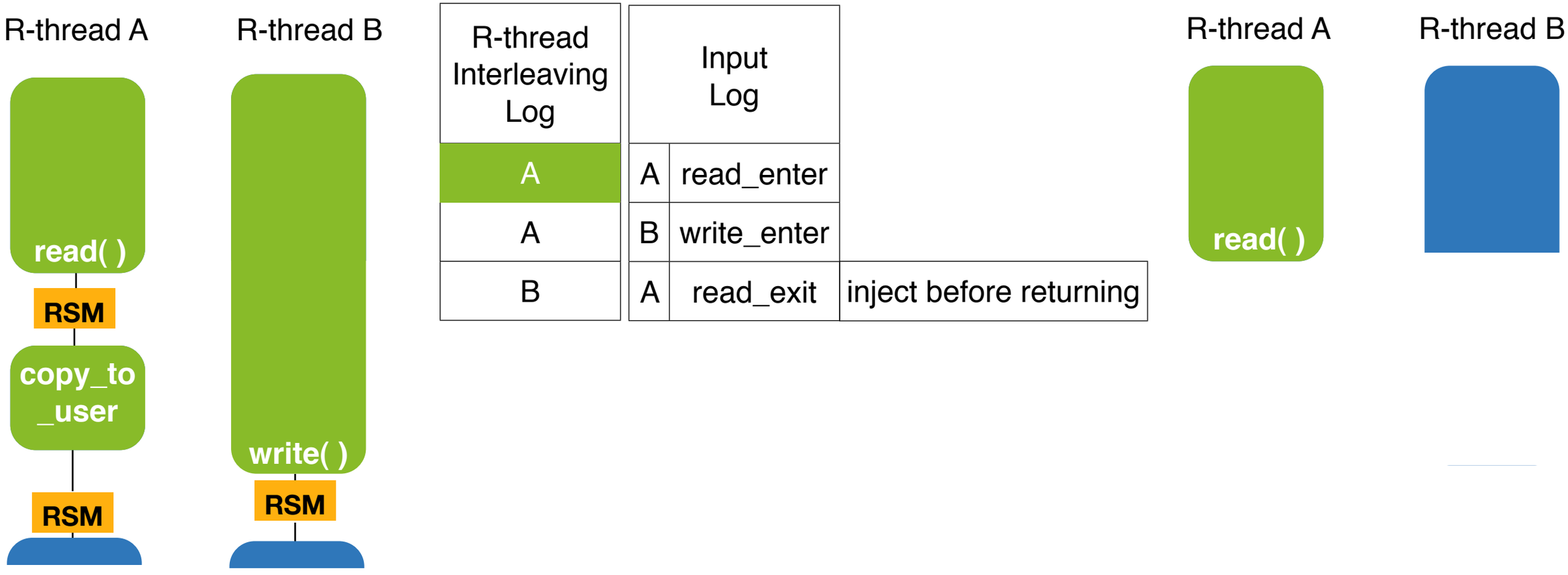

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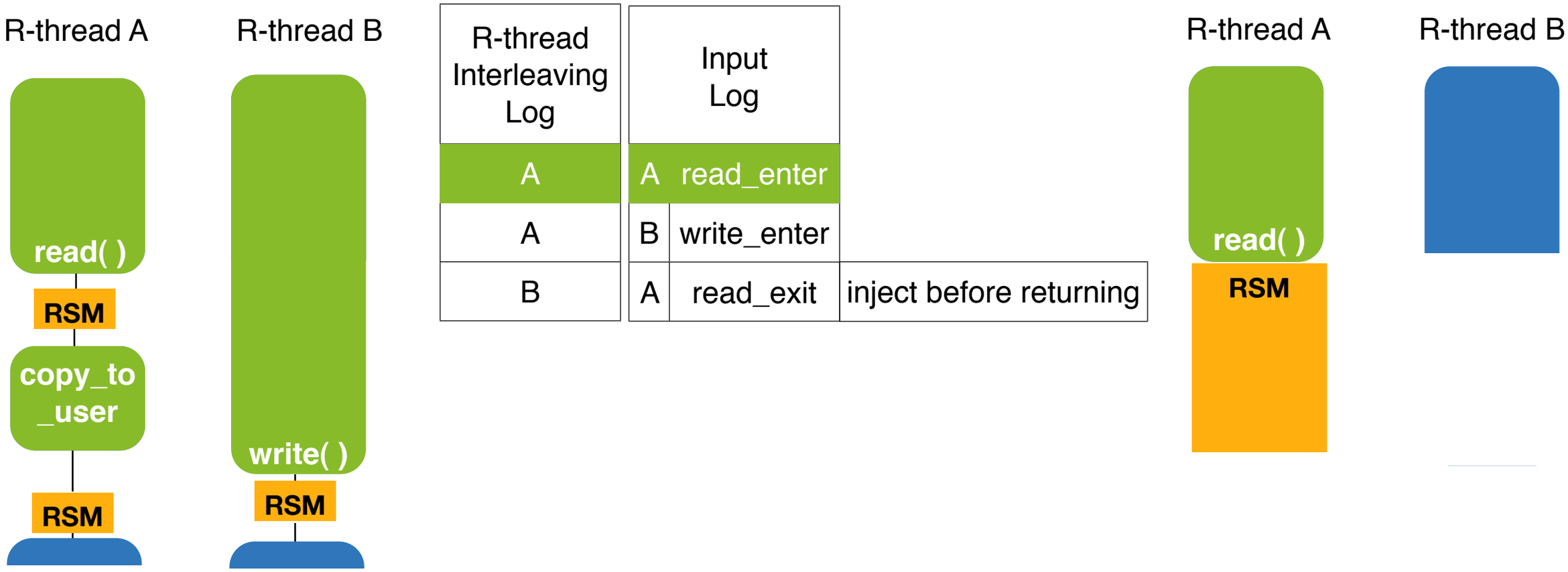

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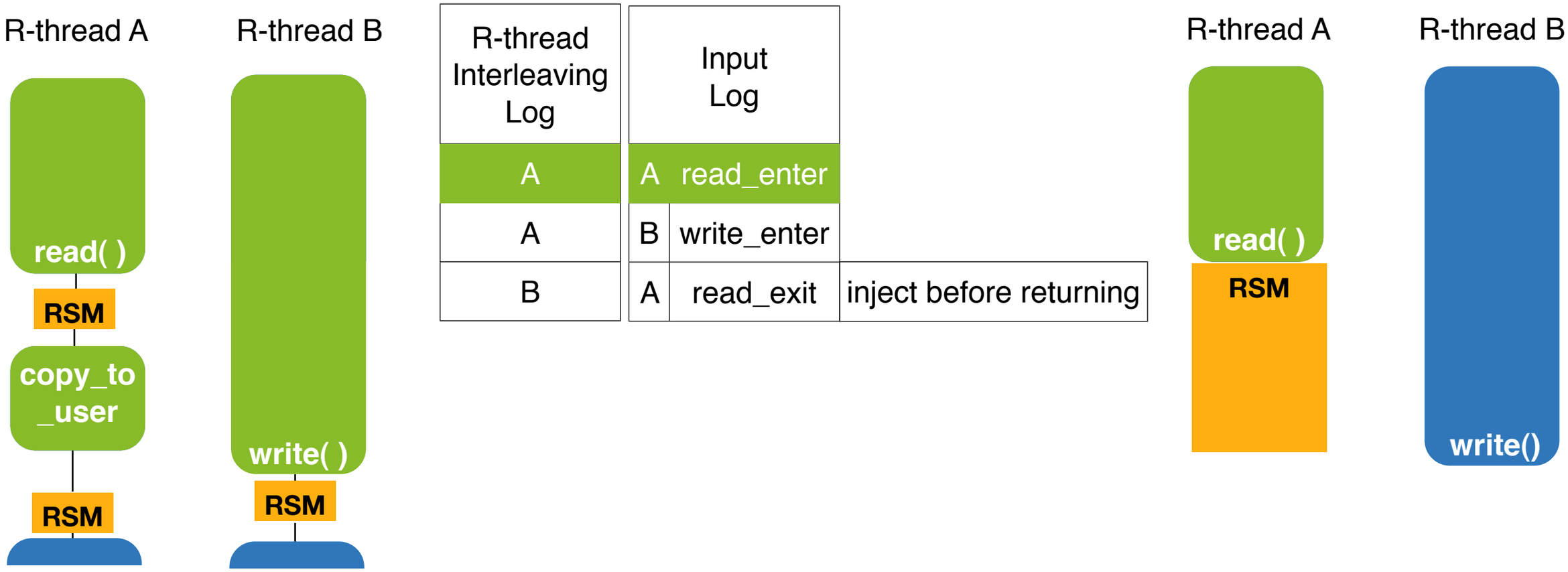

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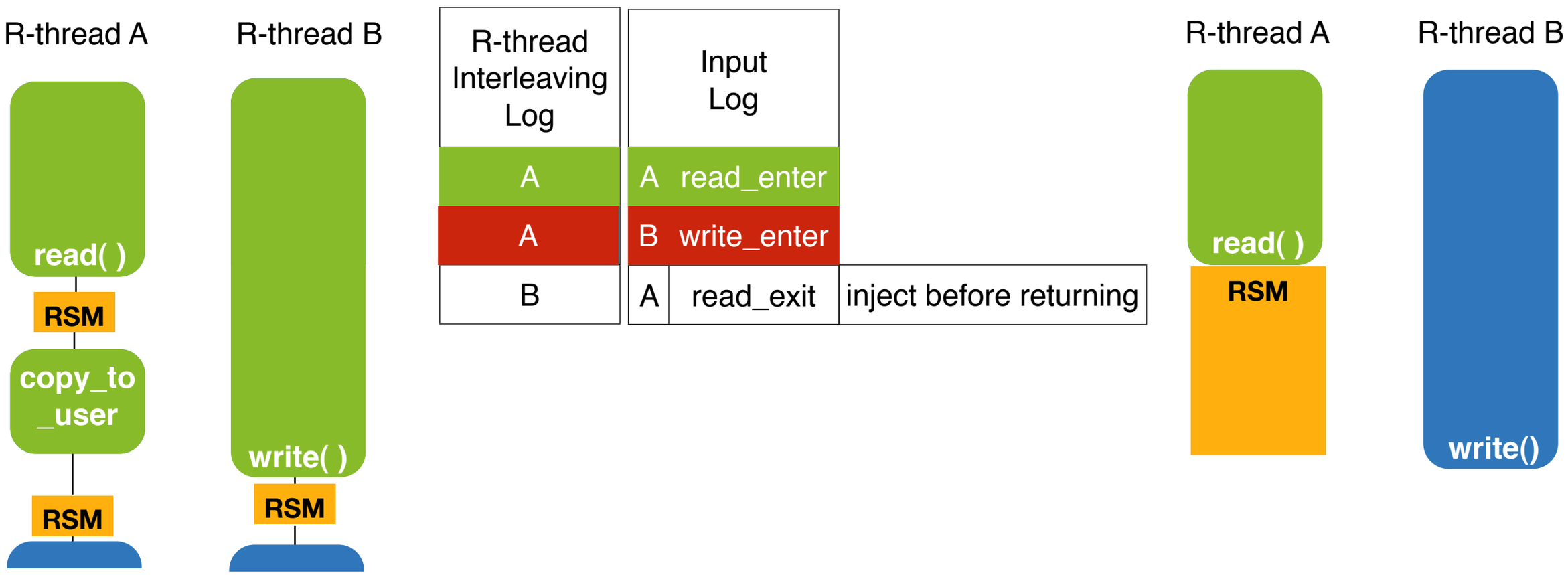

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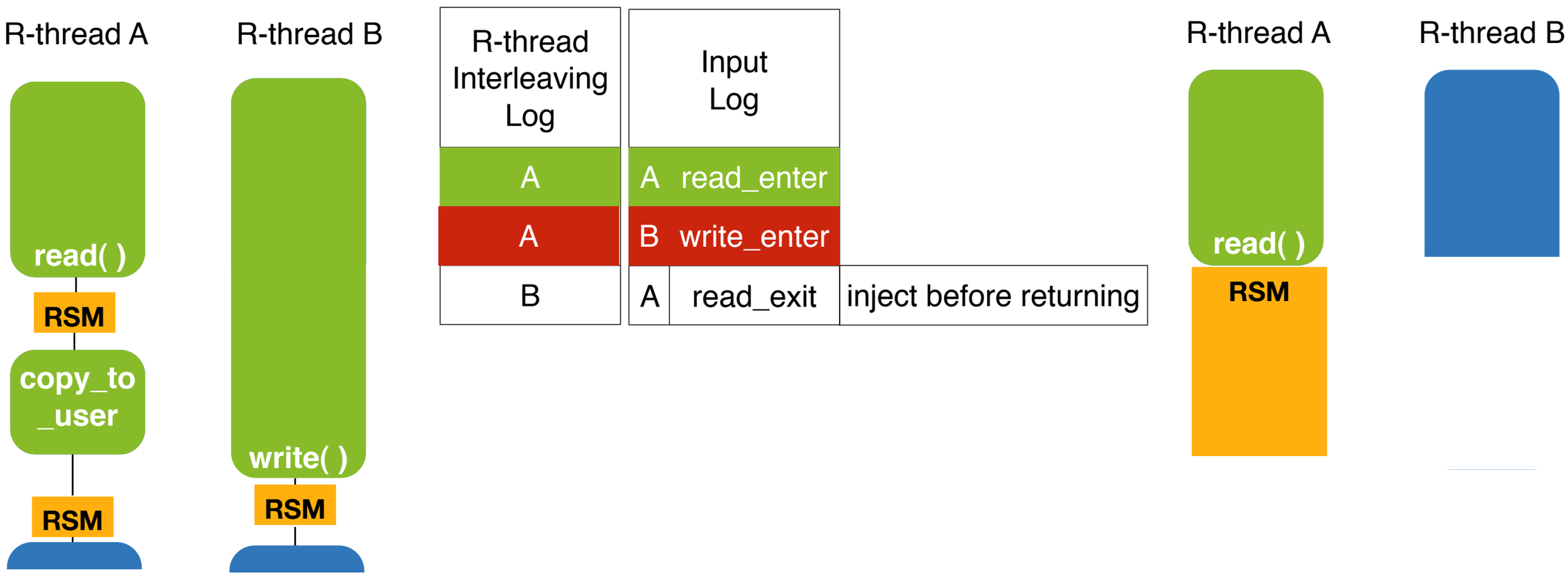

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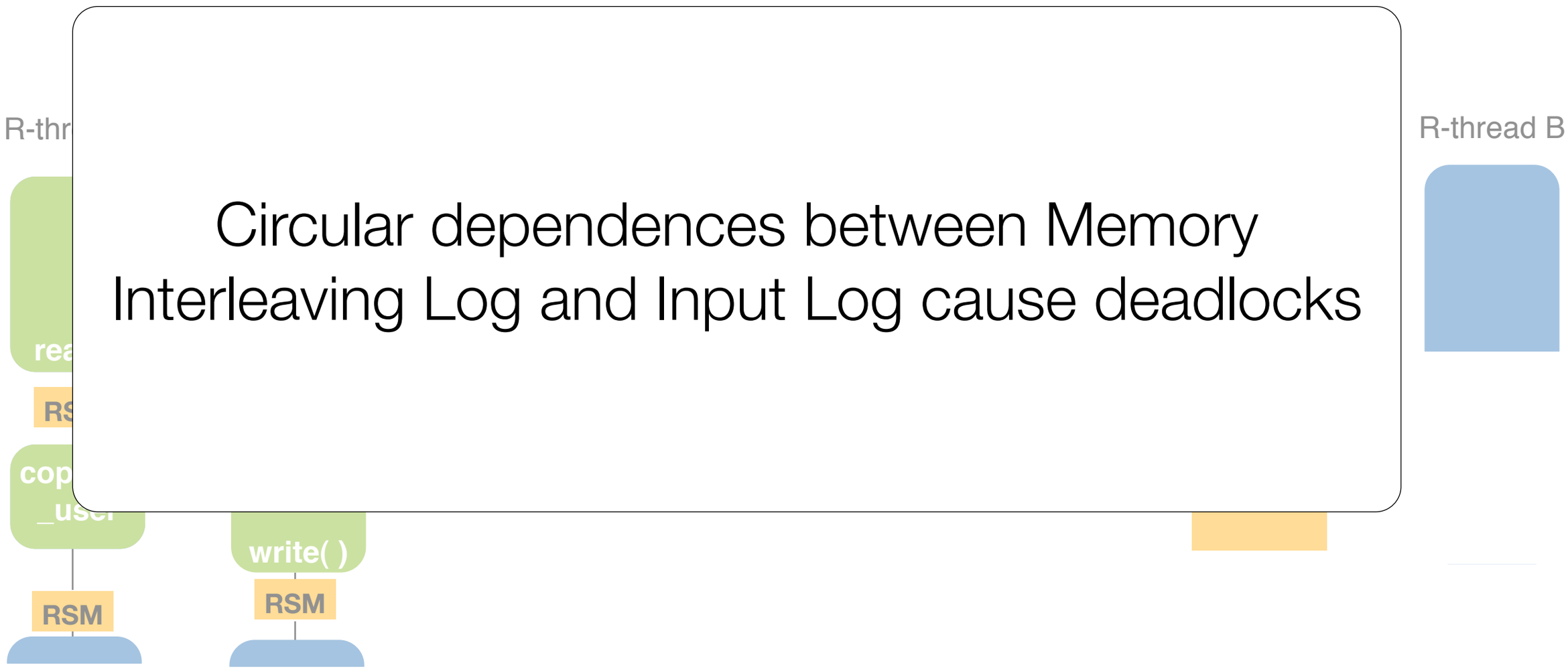


Circular dependences between Memory Interleaving Log and Input Log cause deadlocks

Cache Overflows

- CapoOne keeps speculative data in cache until commit
  - A chunk may access more lines mapping to a cache set than ways the set has
  - BulkSC-based system do not allow storing speculative state in memory
- When a cache would overflow, CapoOne must commit current chunk
  - Non-deterministic event: must log chunk size

Cache Overflows

Cache Overflows

Original Execution	Chunk Size Log
R-thread R1	

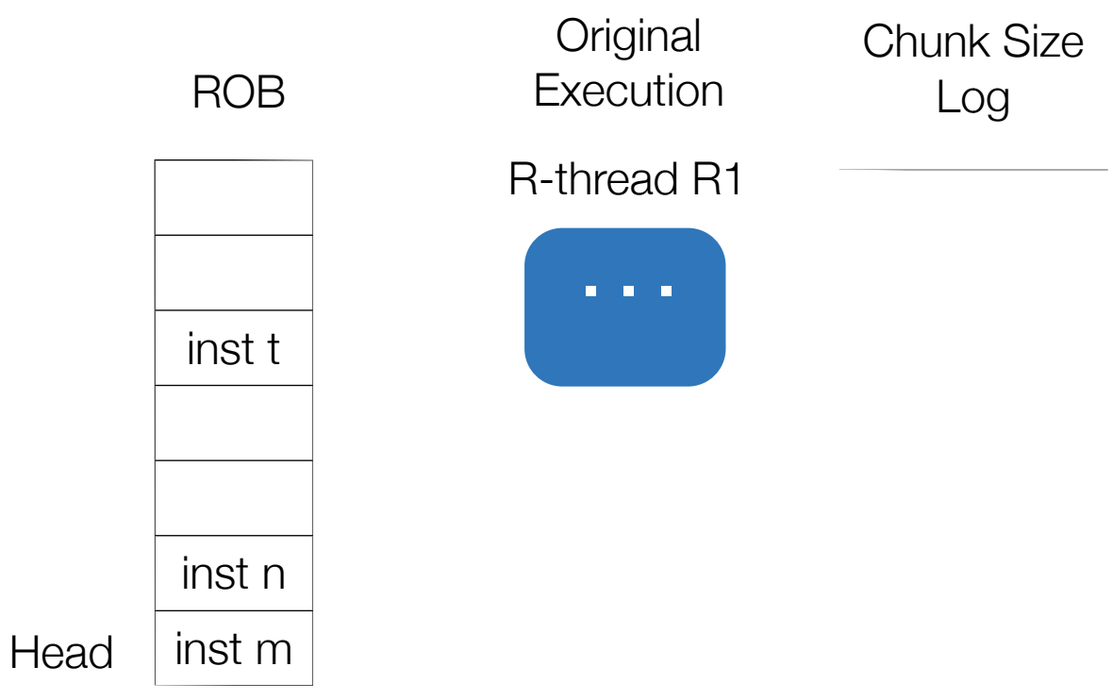
Cache Overflows

Original Execution

R-thread R1

Chunk Size Log

Cache Overflows



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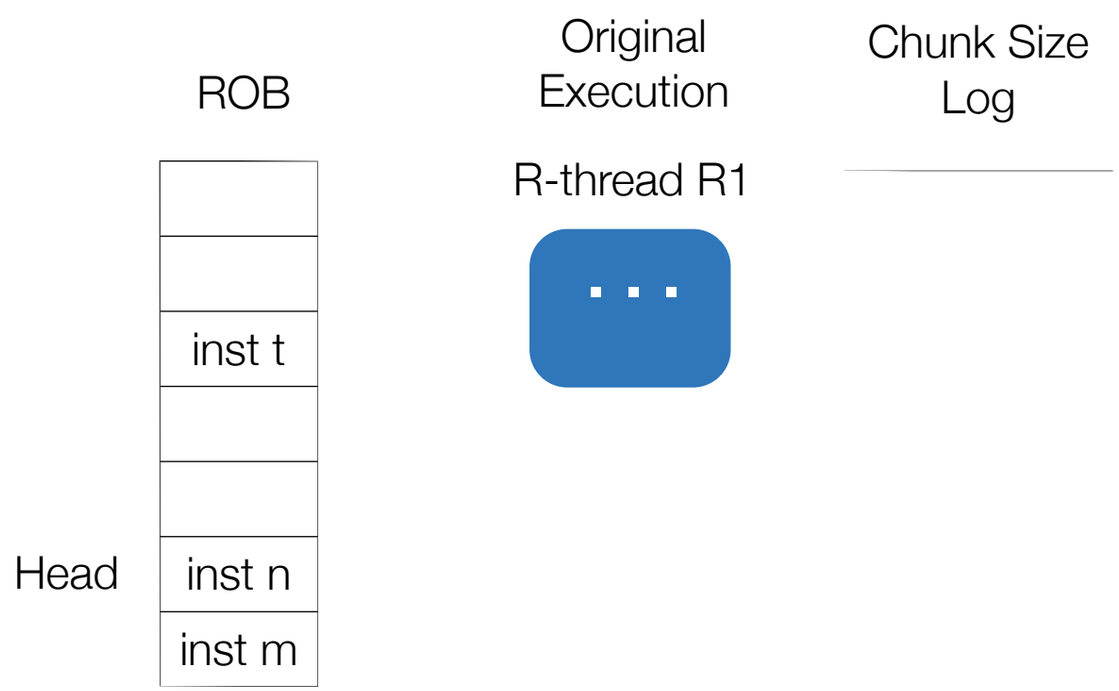

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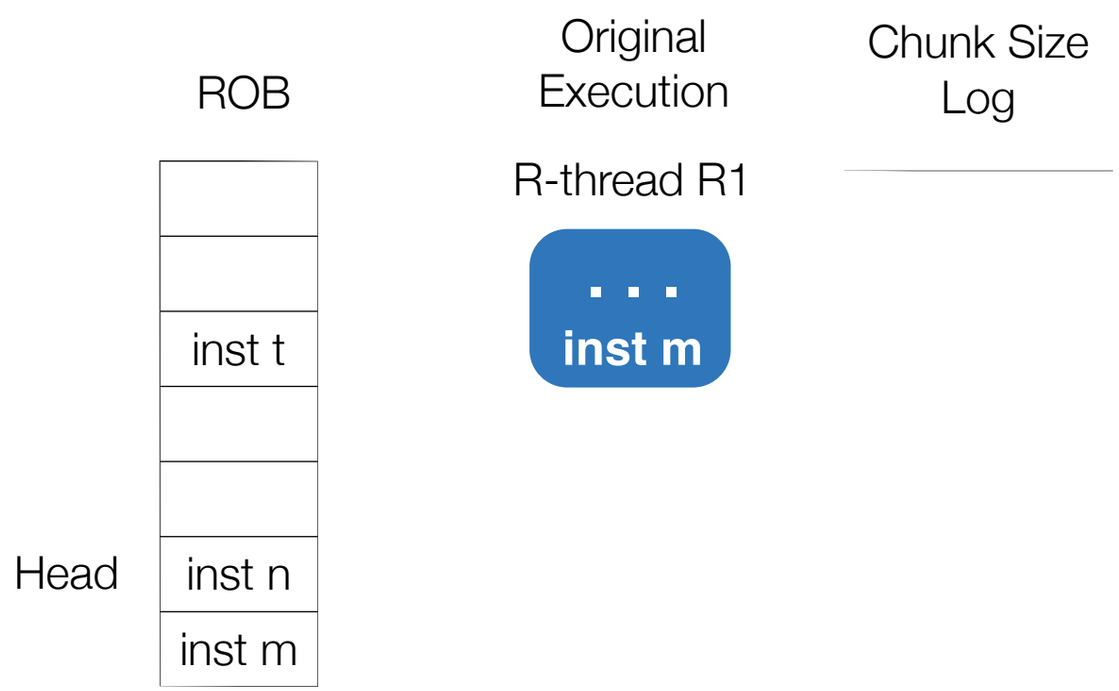

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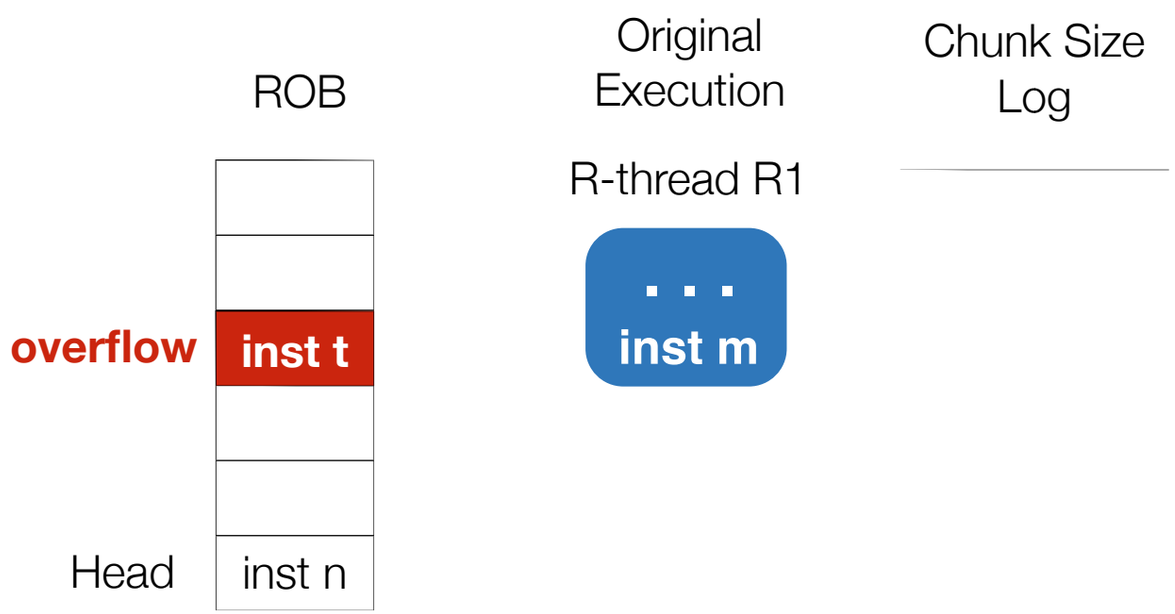
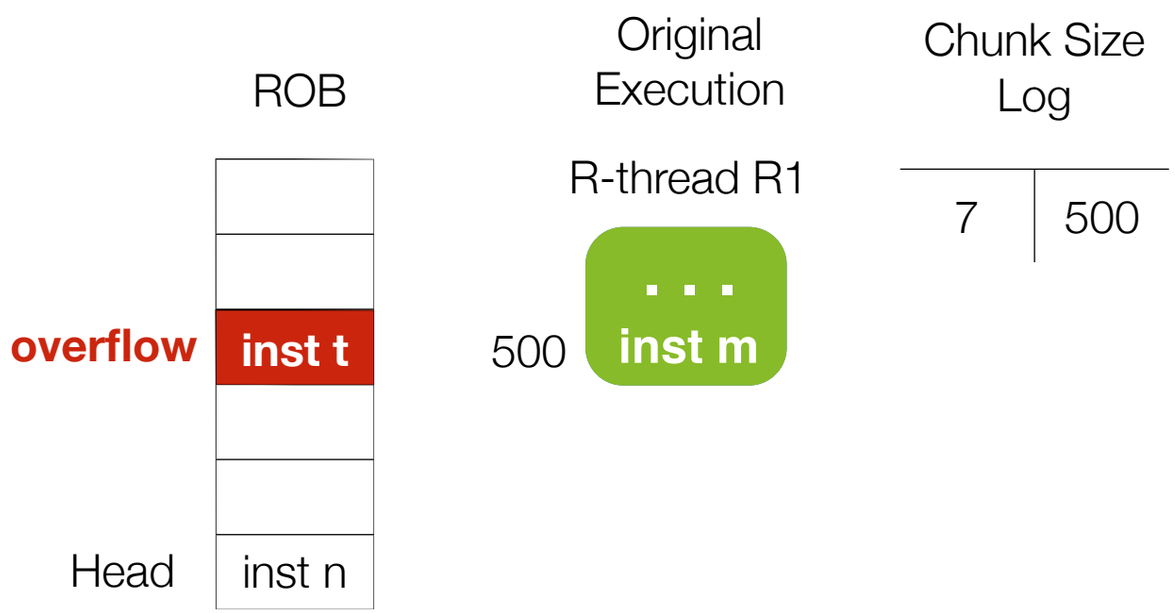


- The instruction causing the overflow might not be at the head of ROB

Cache Overflows



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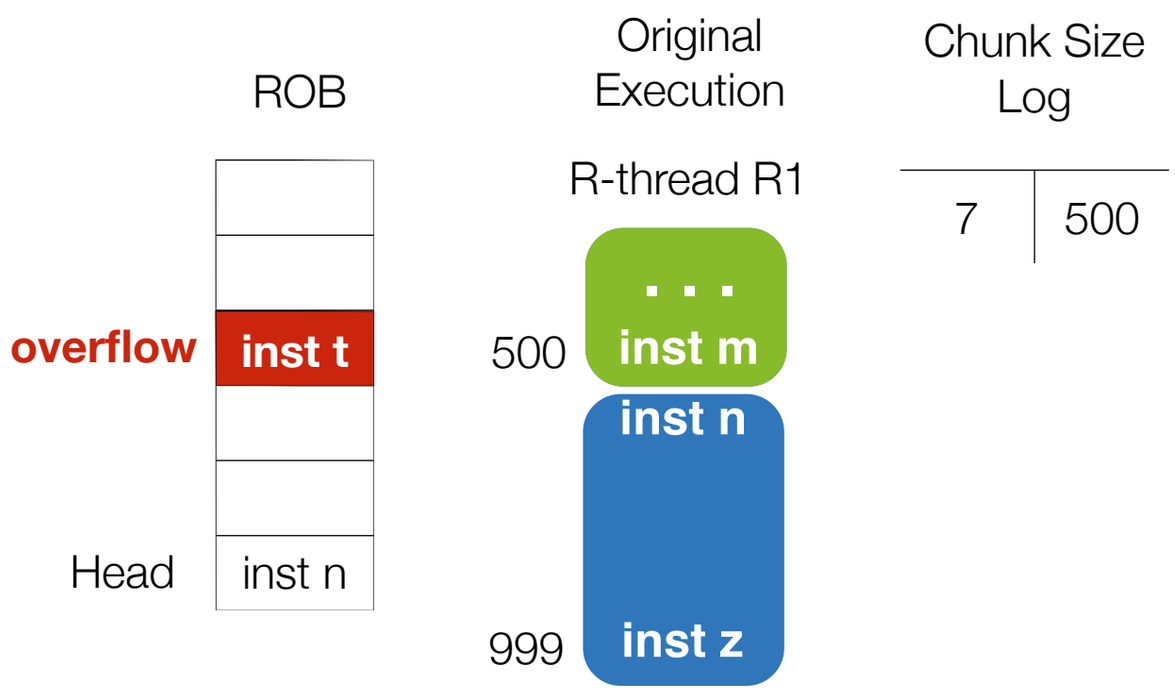

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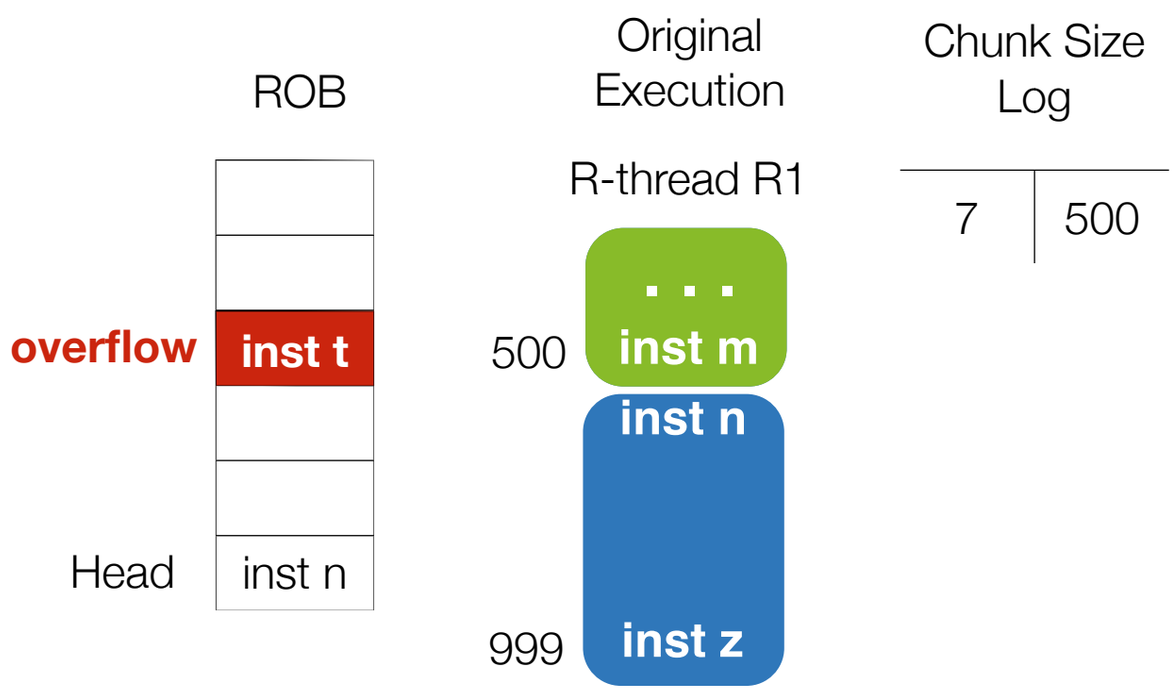

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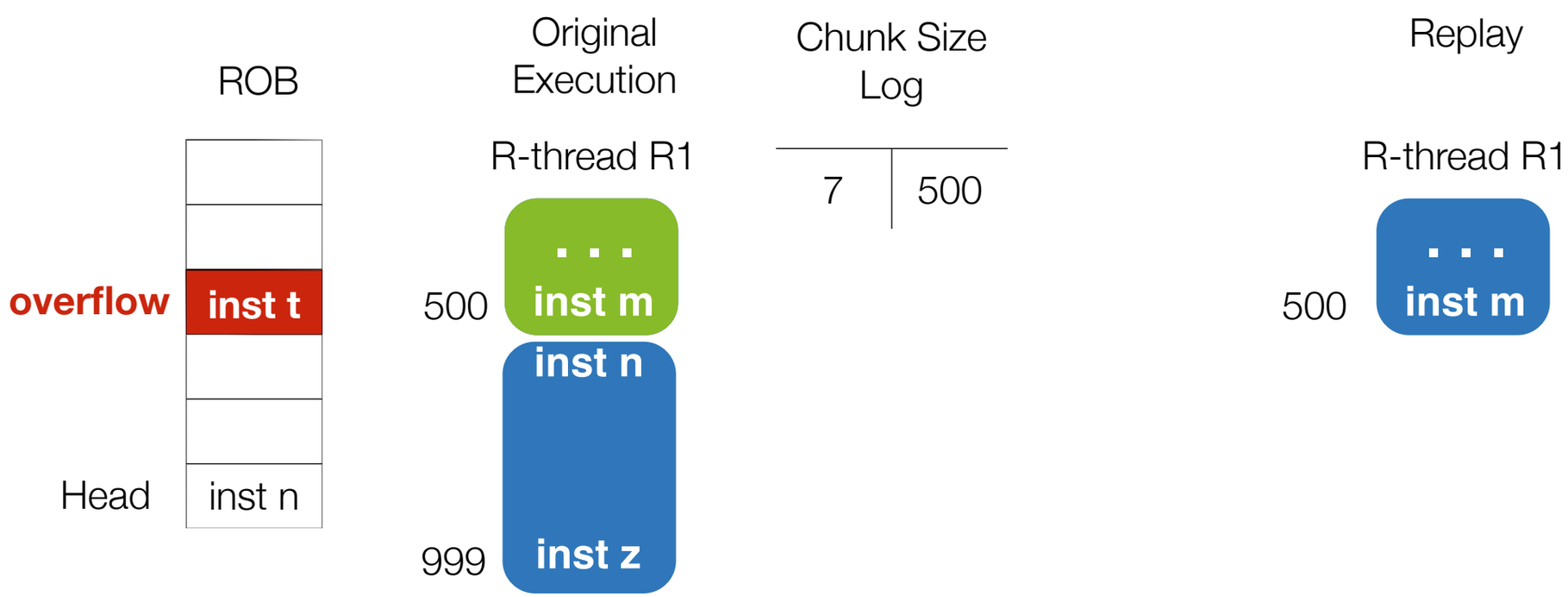

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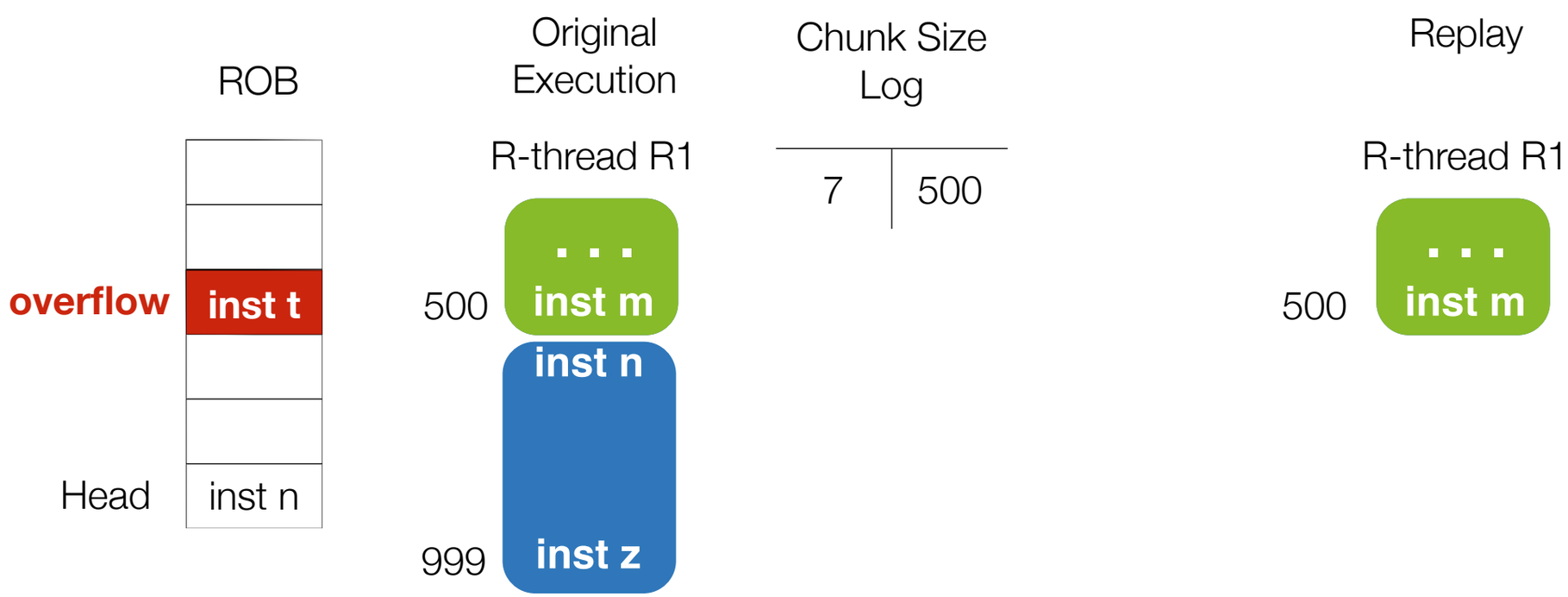

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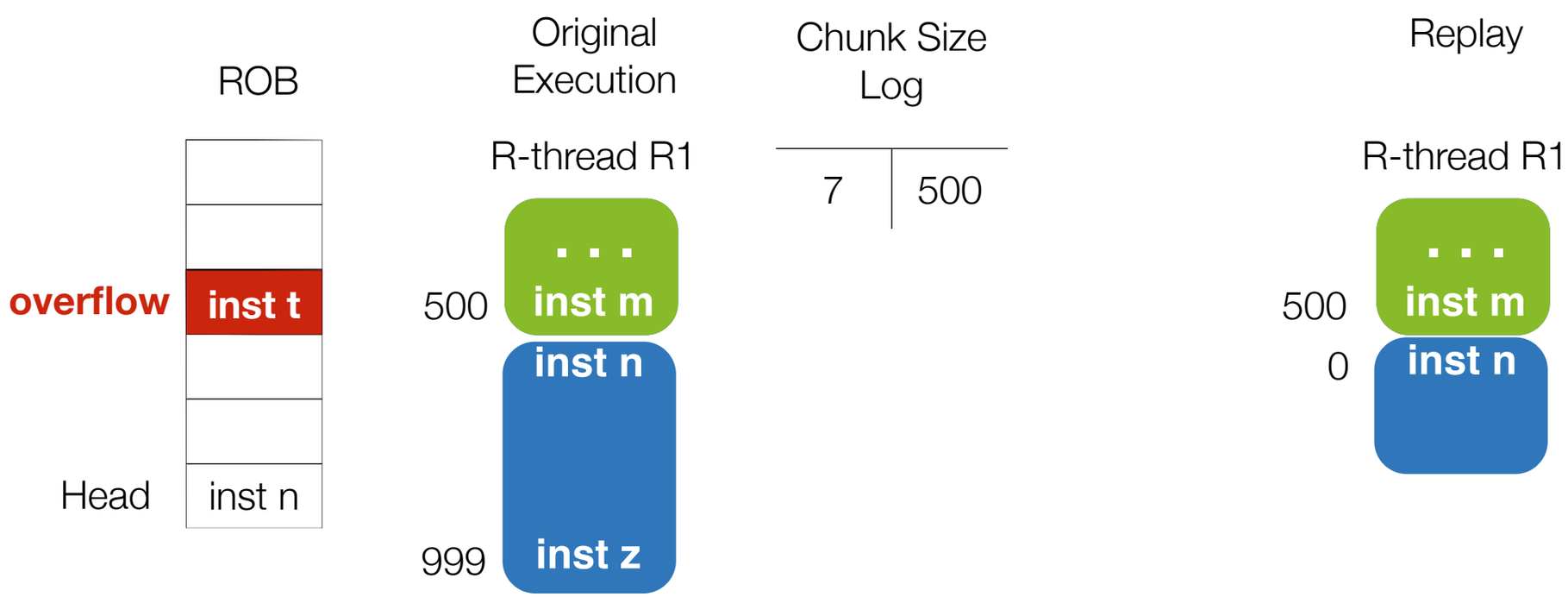

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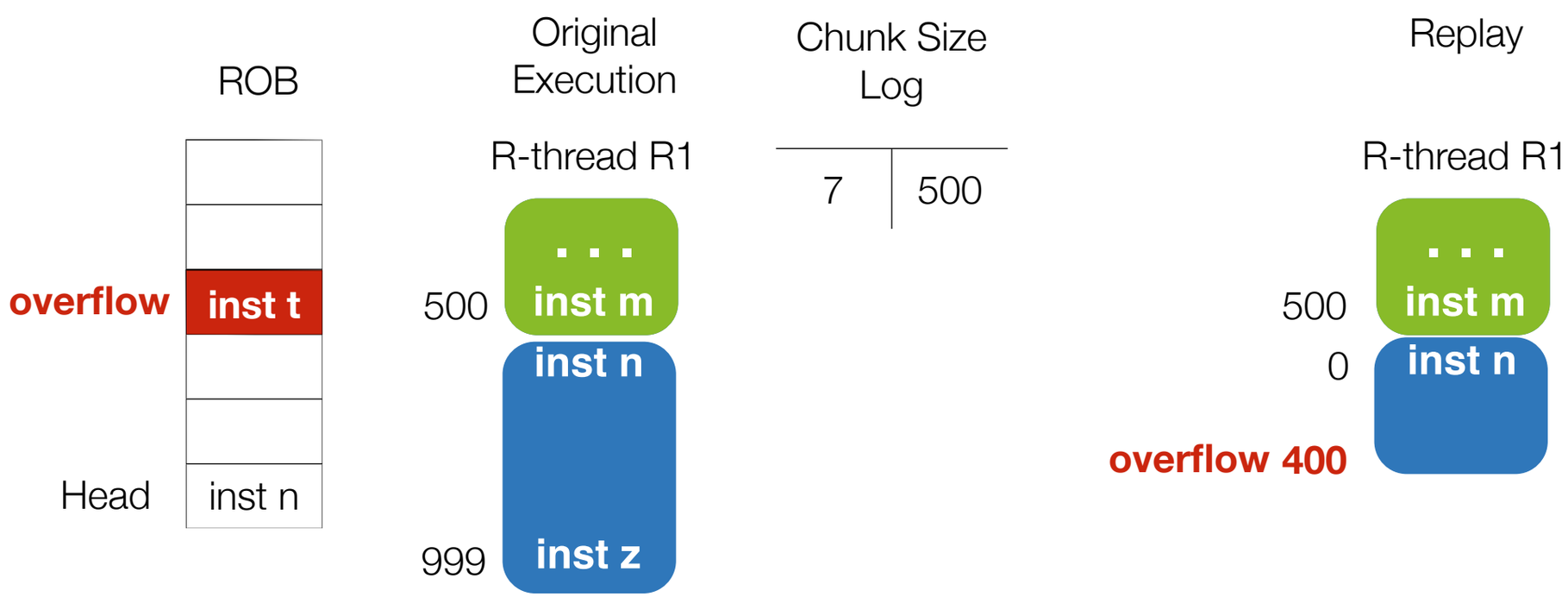

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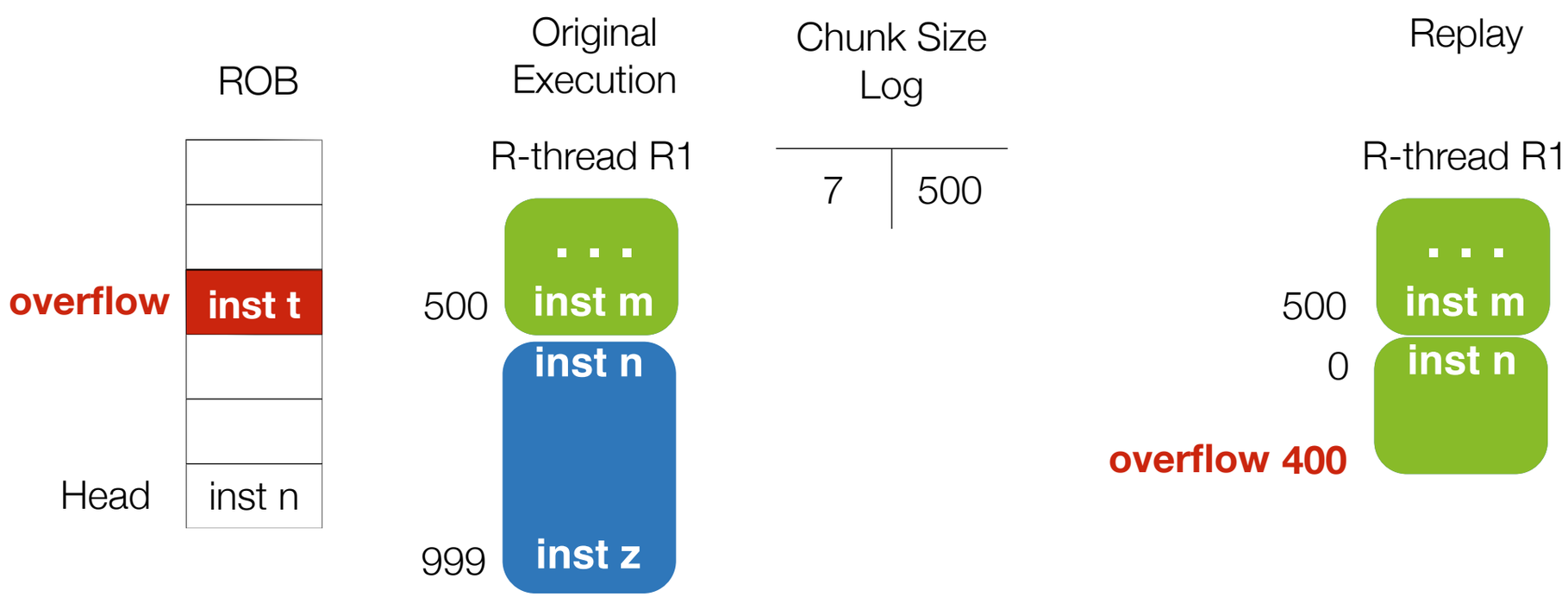

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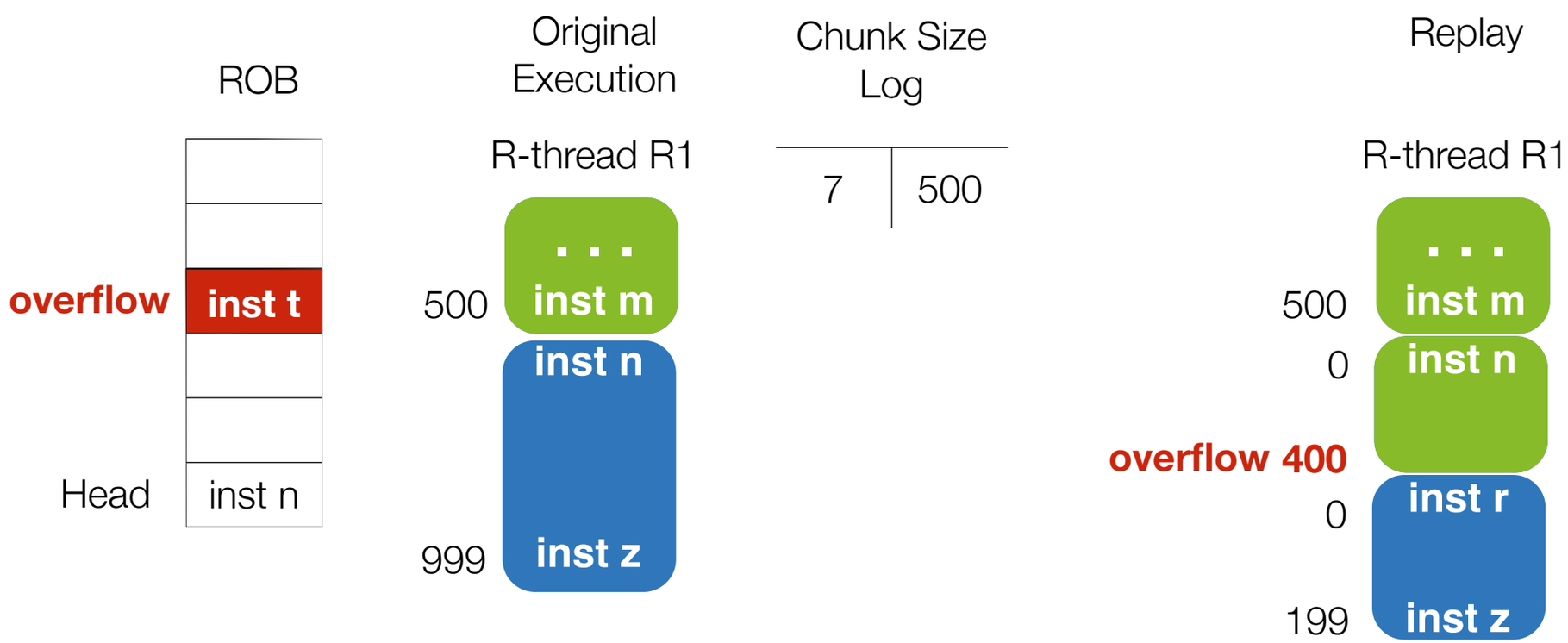

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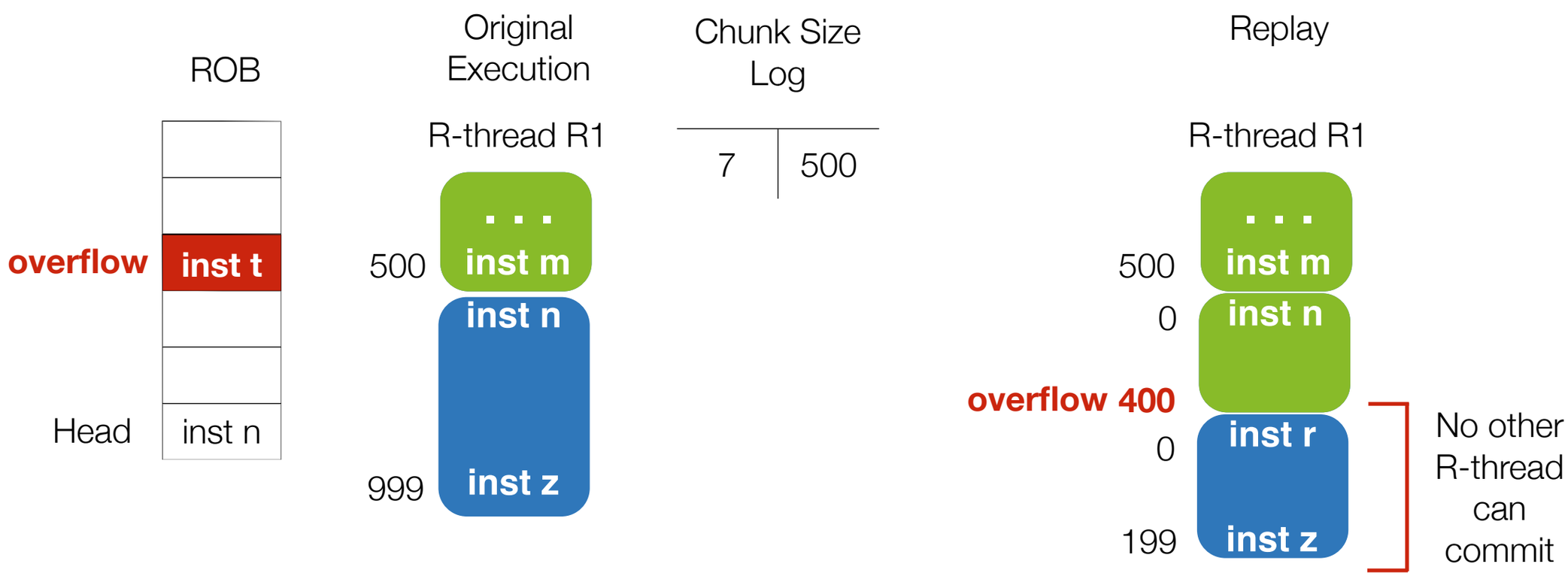

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Cache Overflows

ROB | Original Execution | Chunk Size Log | Replay

over

H

The instruction that caused cache overflow might not be the first instruction of next chunk

HW must ensure that chunk boundaries are consistent

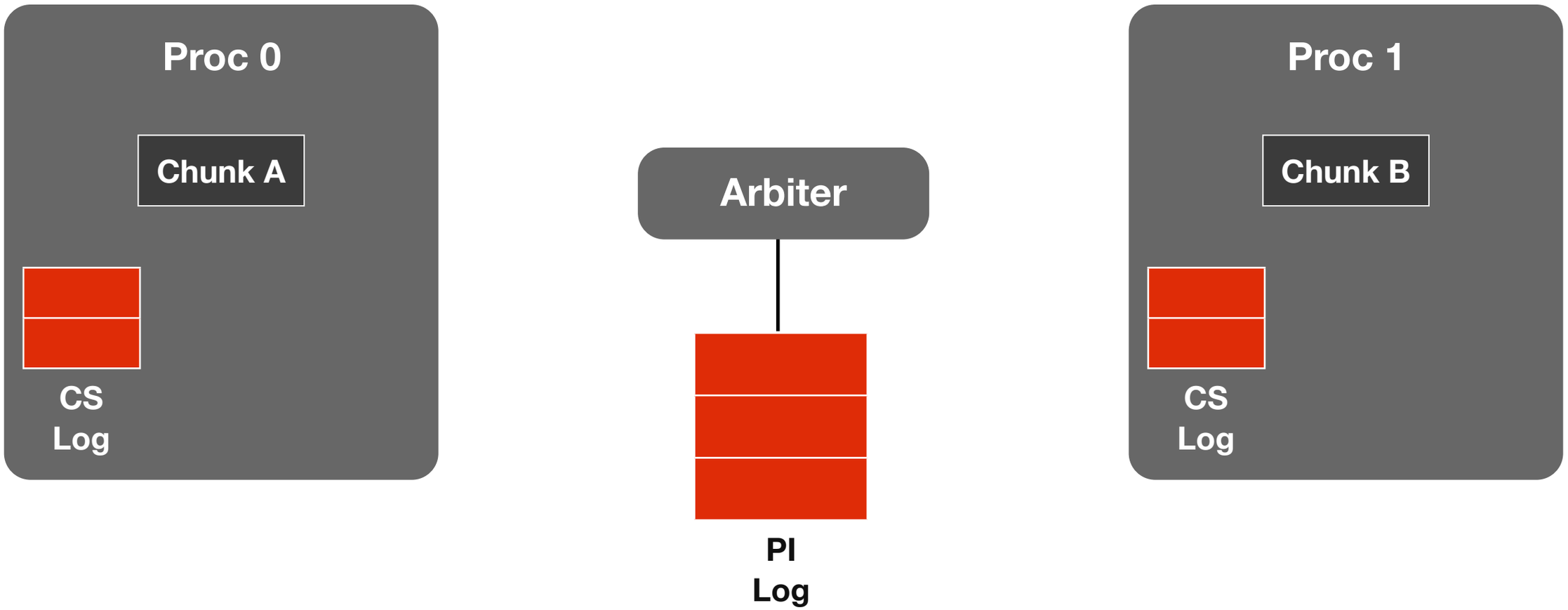
- The instruction causing the overflow might not be at the head of ROB
- Can happen during initial execution and/or during replay

Lessons Learned During the Development of the CapoOne Deterministic Multiprocessor Replay System

Pablo Montesinos, Matthew Hicks, Wonsun Ahn, Samuel T. King and Josep Torrellas

Department of Computer Science
University of Illinois at Urbana-Champaign

Overall DeLorean System



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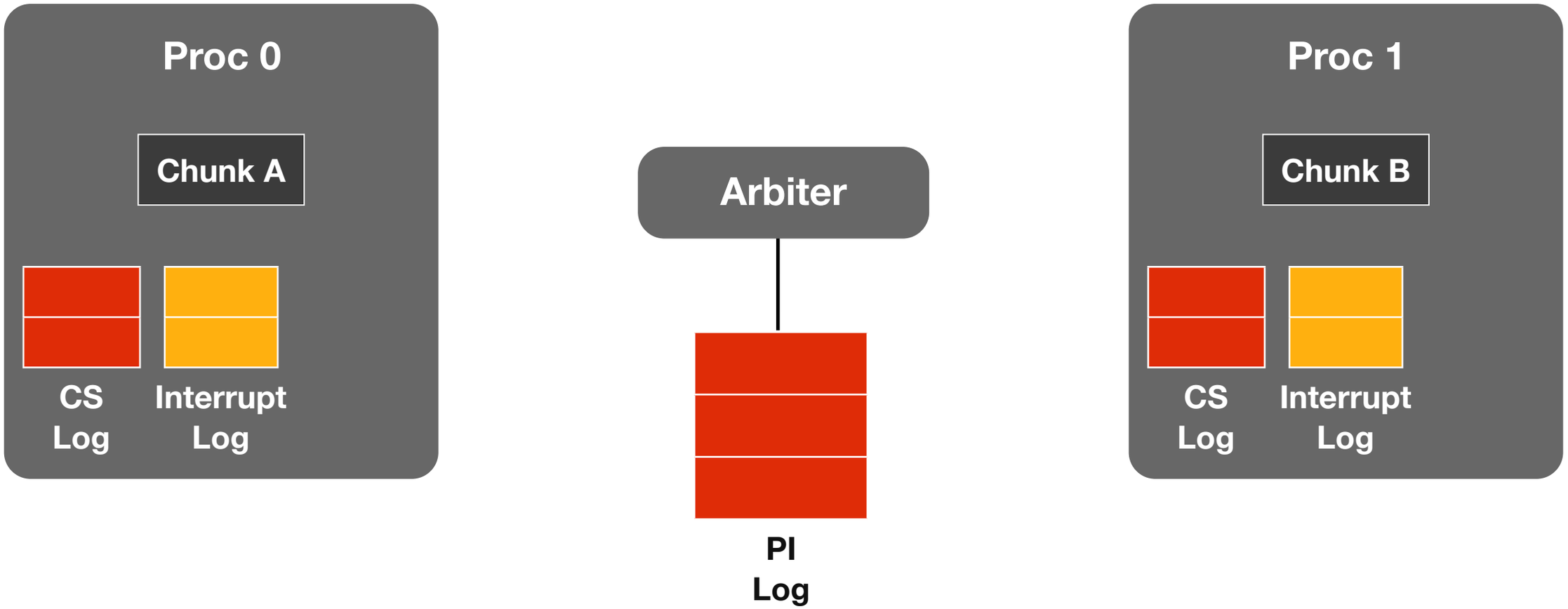

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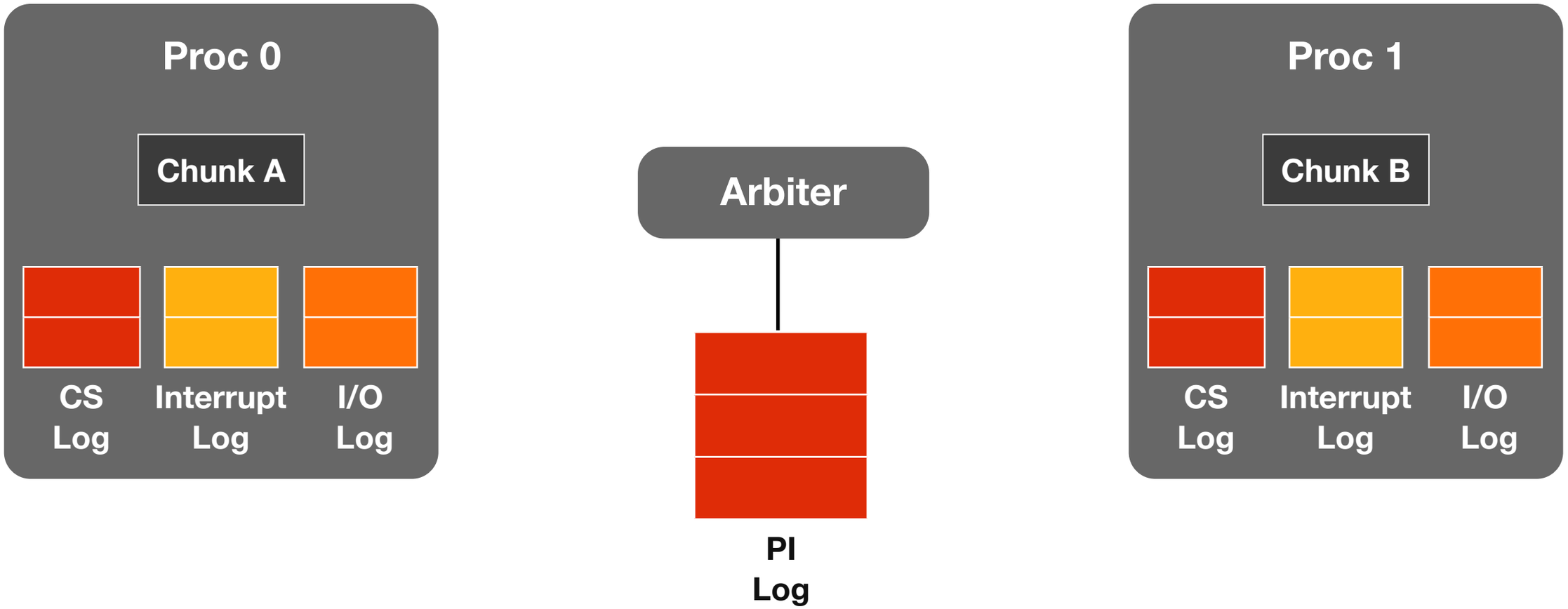

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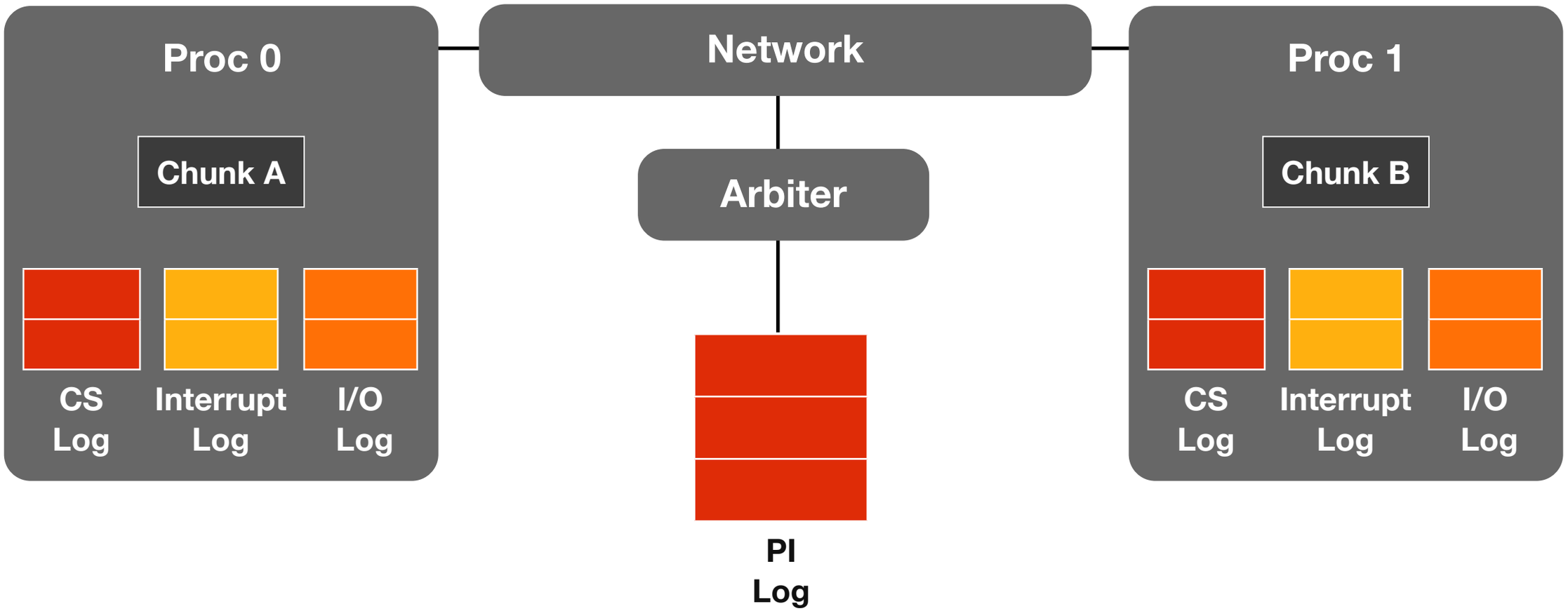

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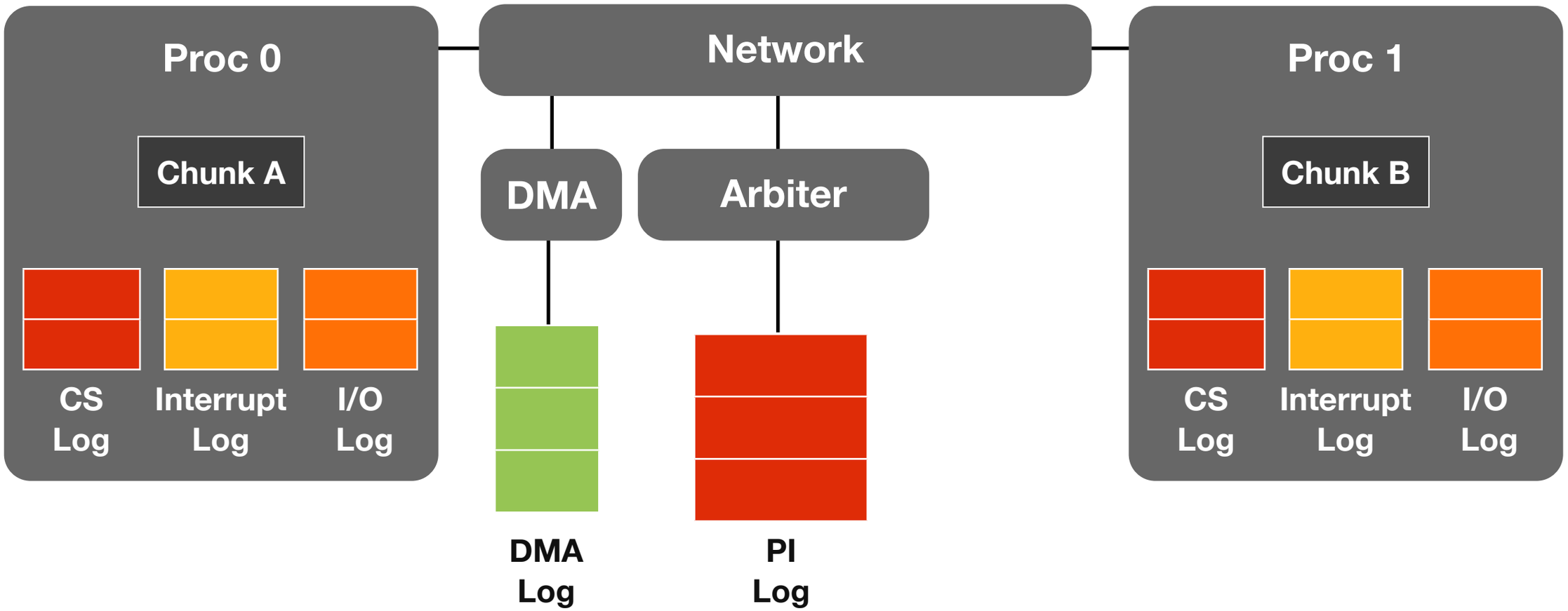

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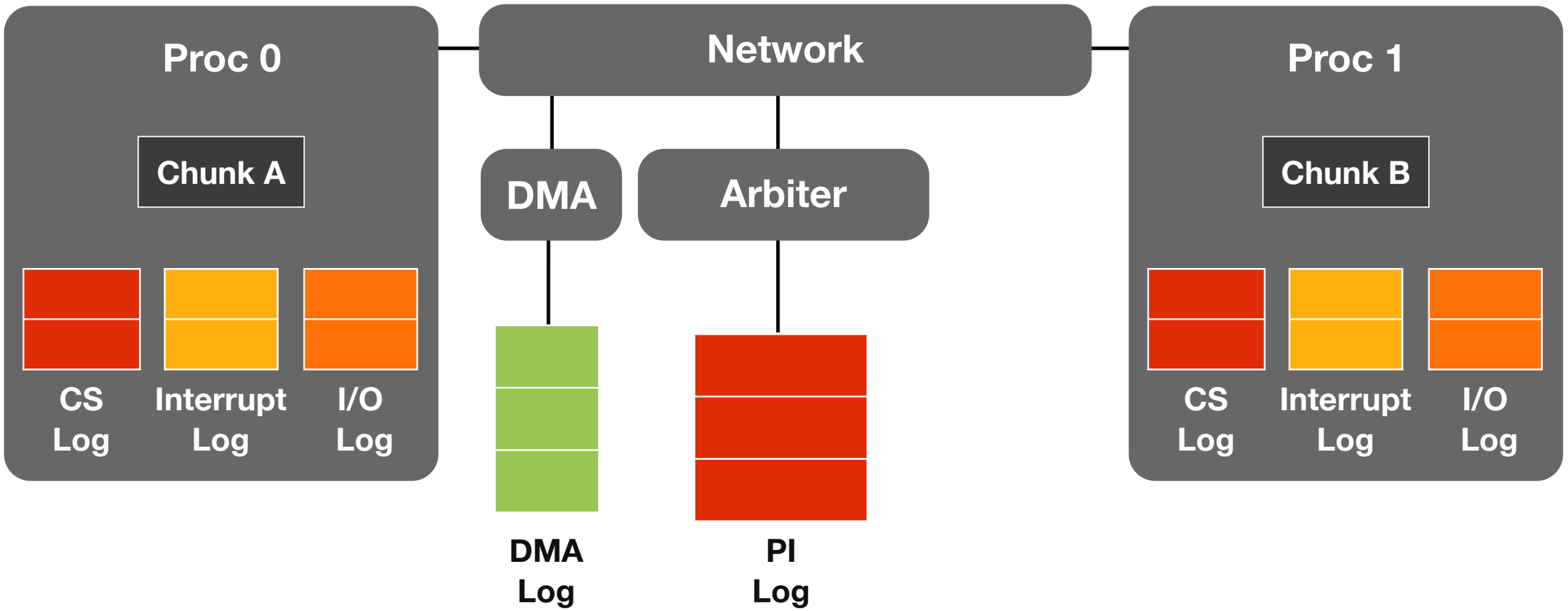

- Interrupt, I/O and DMA logs are common to other HW-based schemes

CapoOne: HW Implementation

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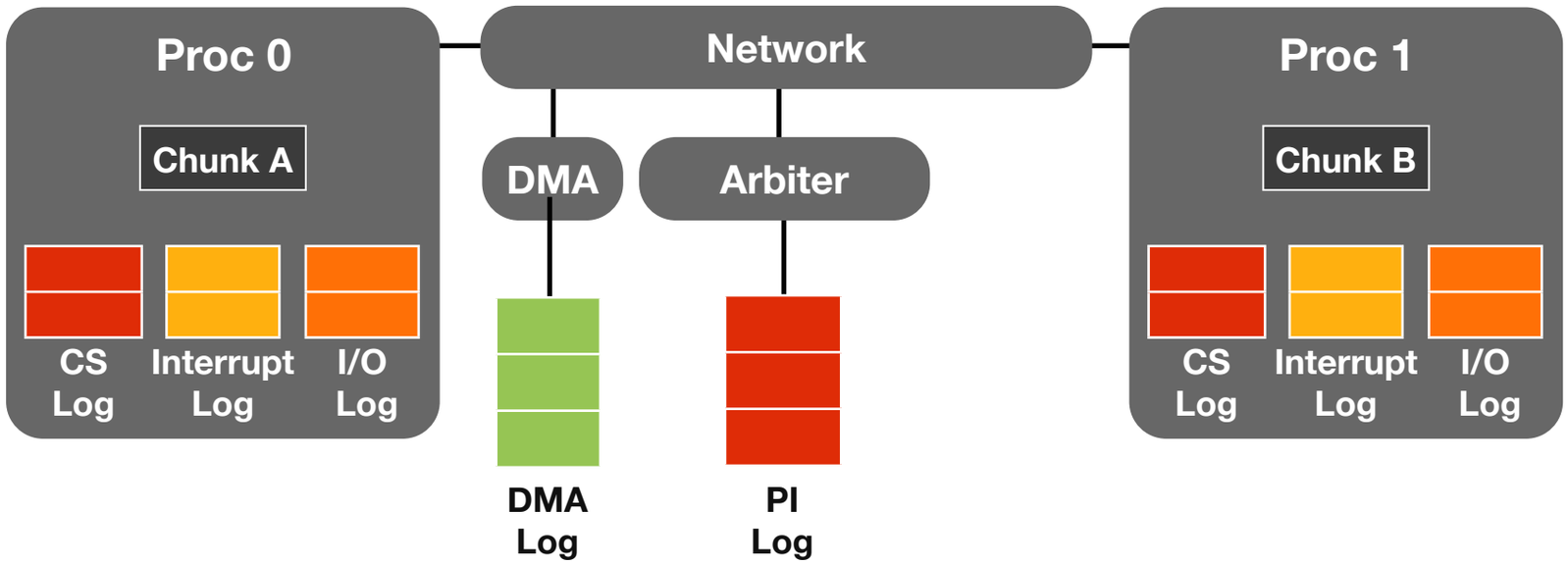

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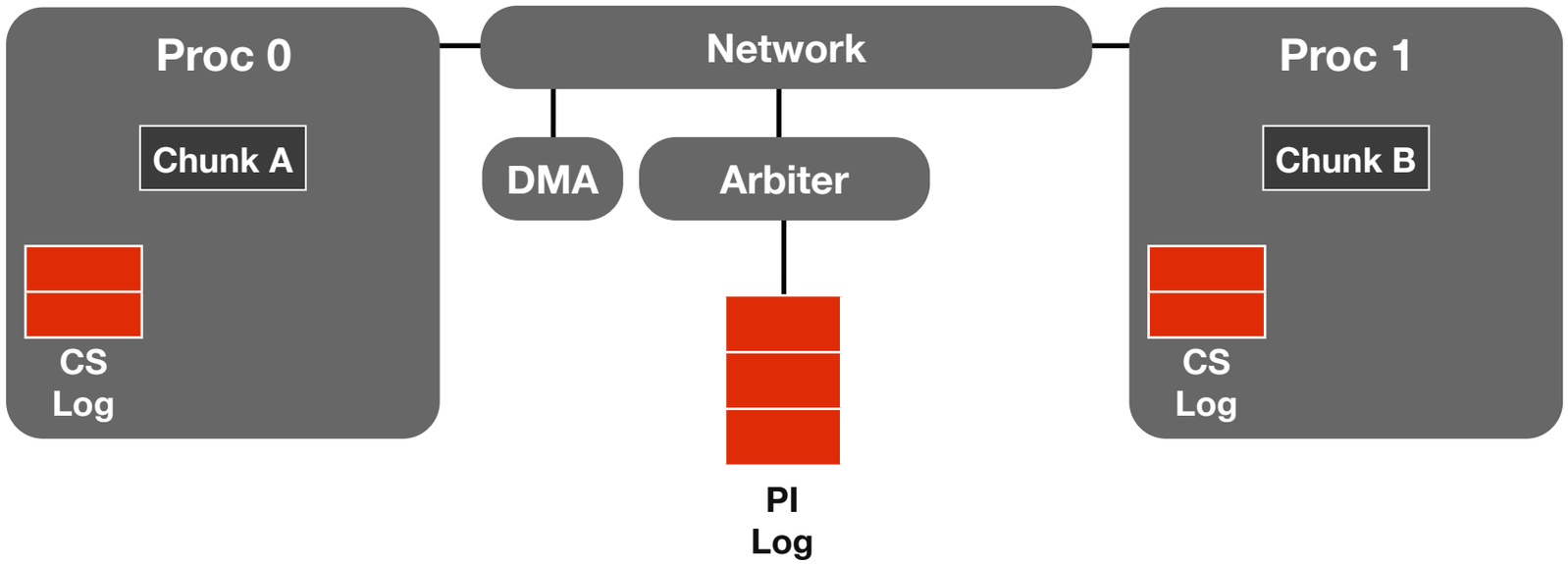

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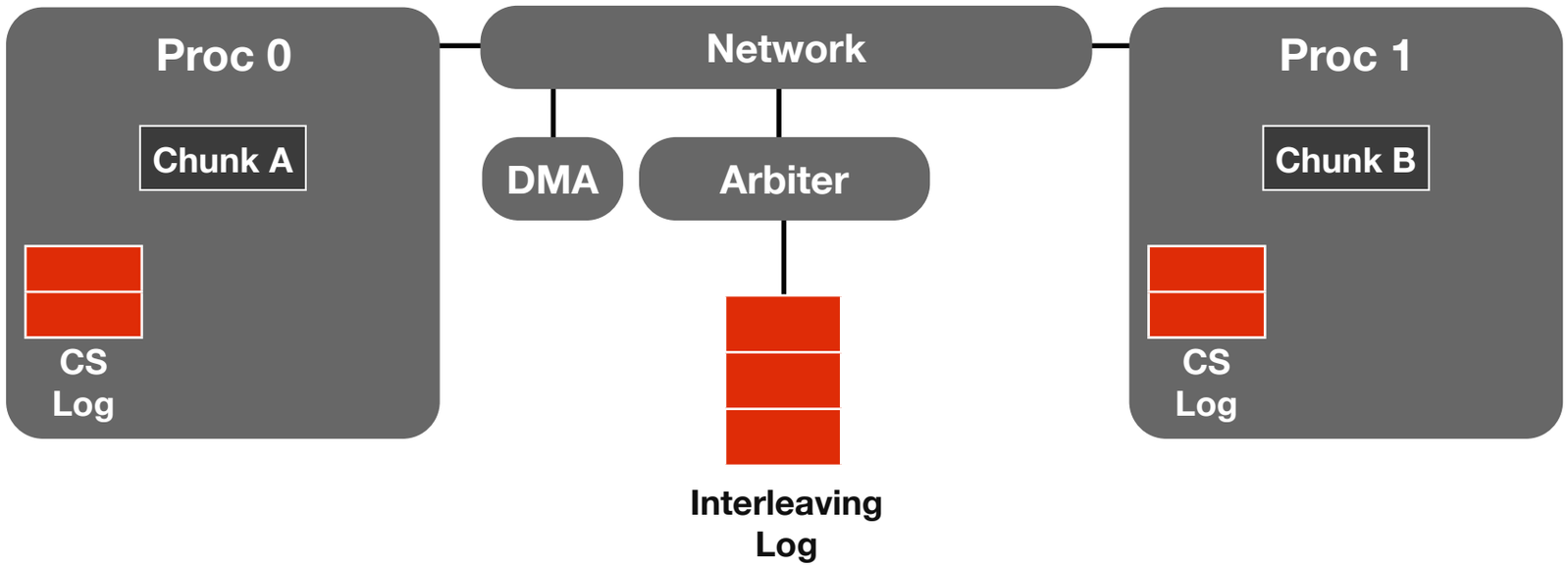

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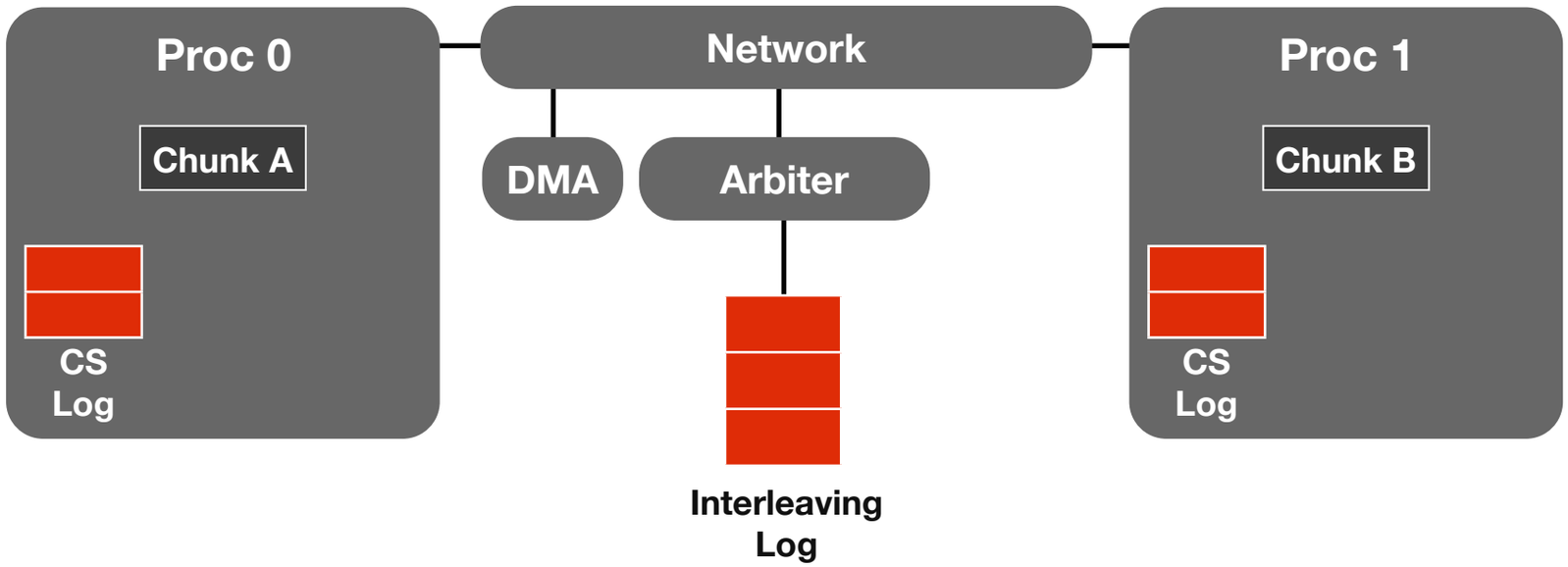

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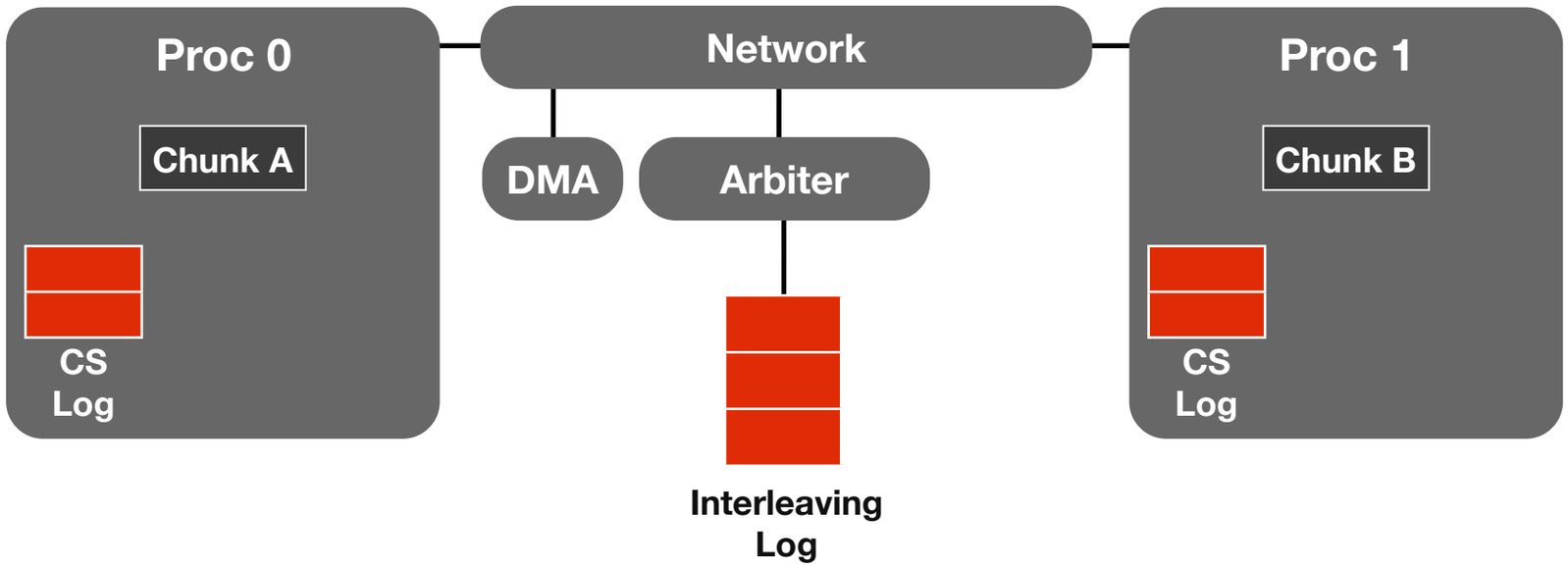

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- Chunks only have instructions from one application (or the kernel)

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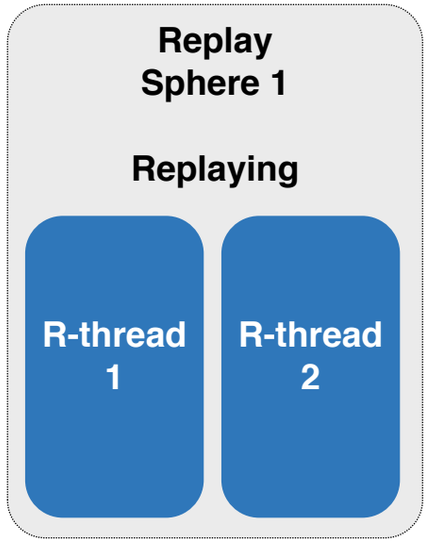

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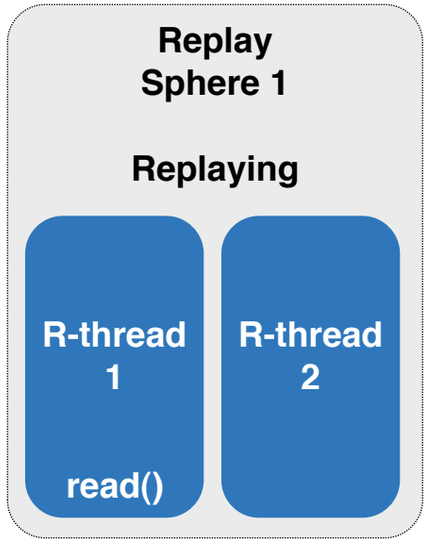

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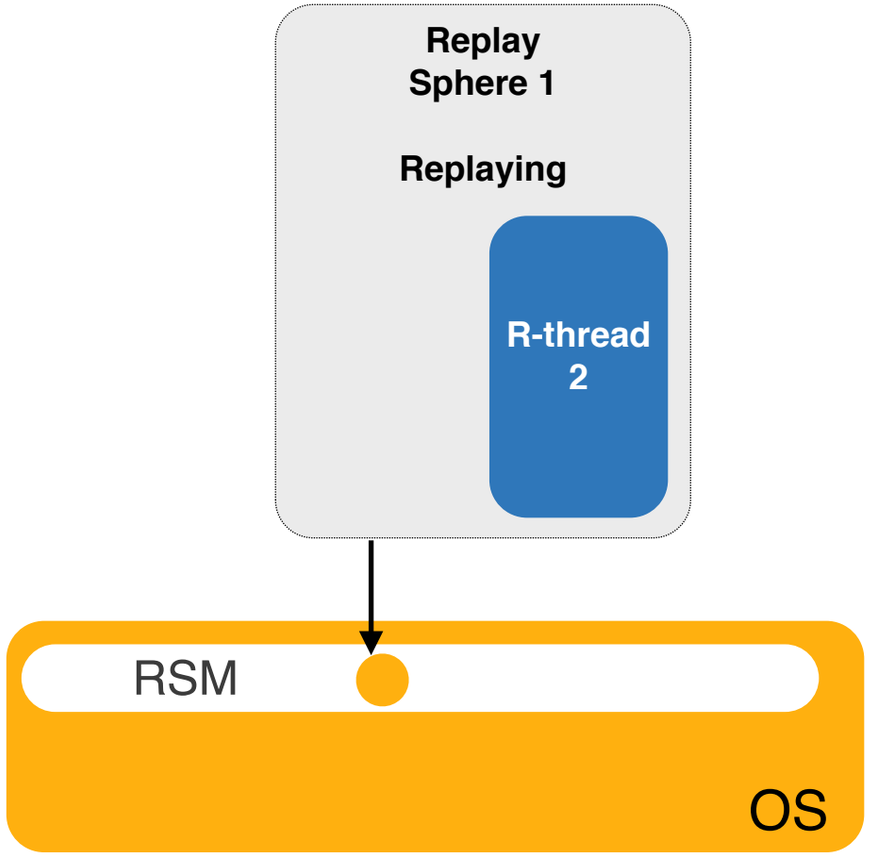

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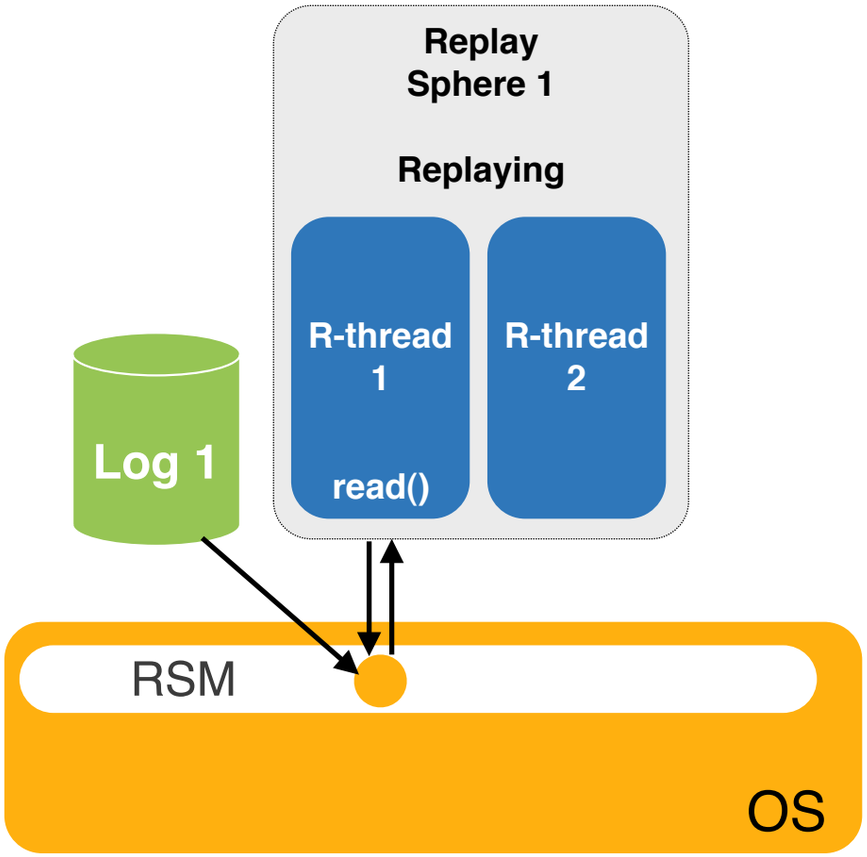

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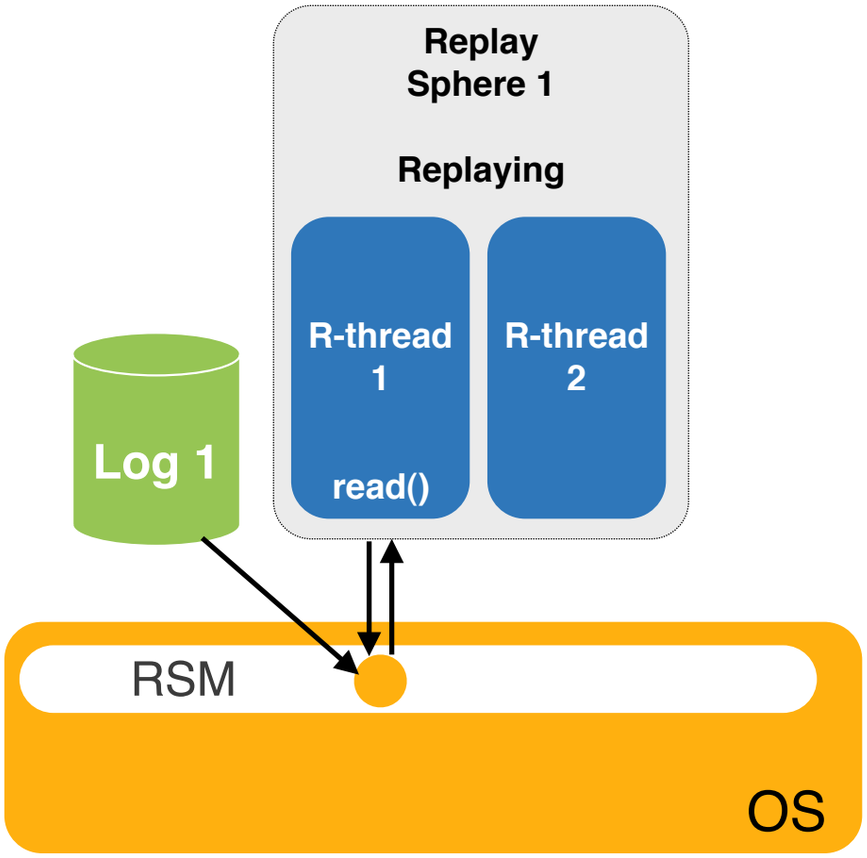

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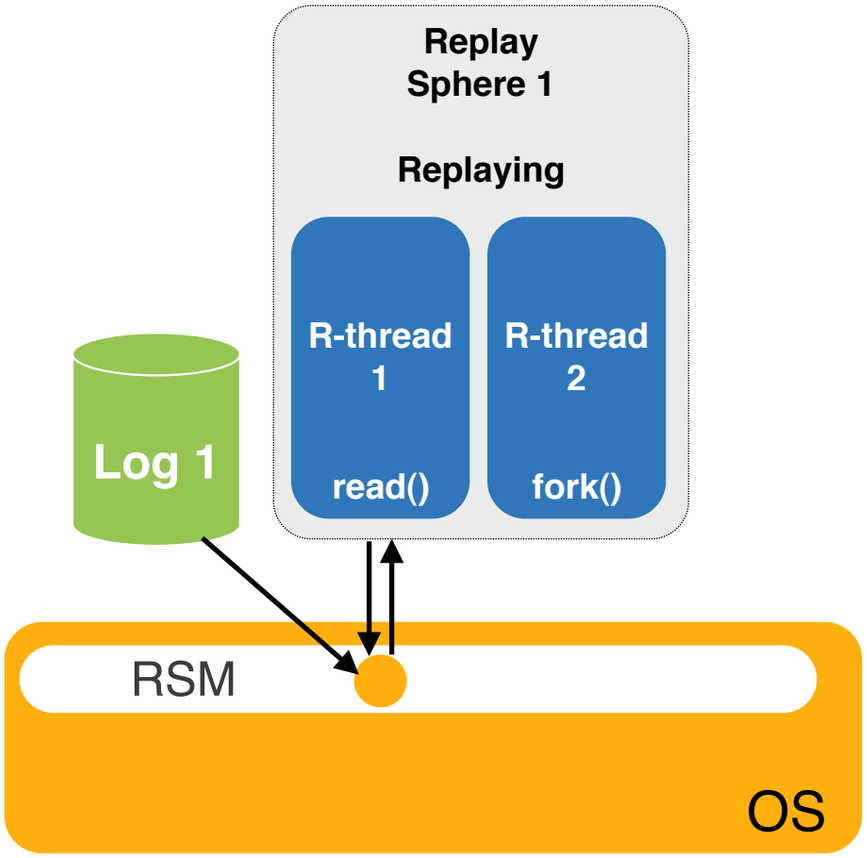

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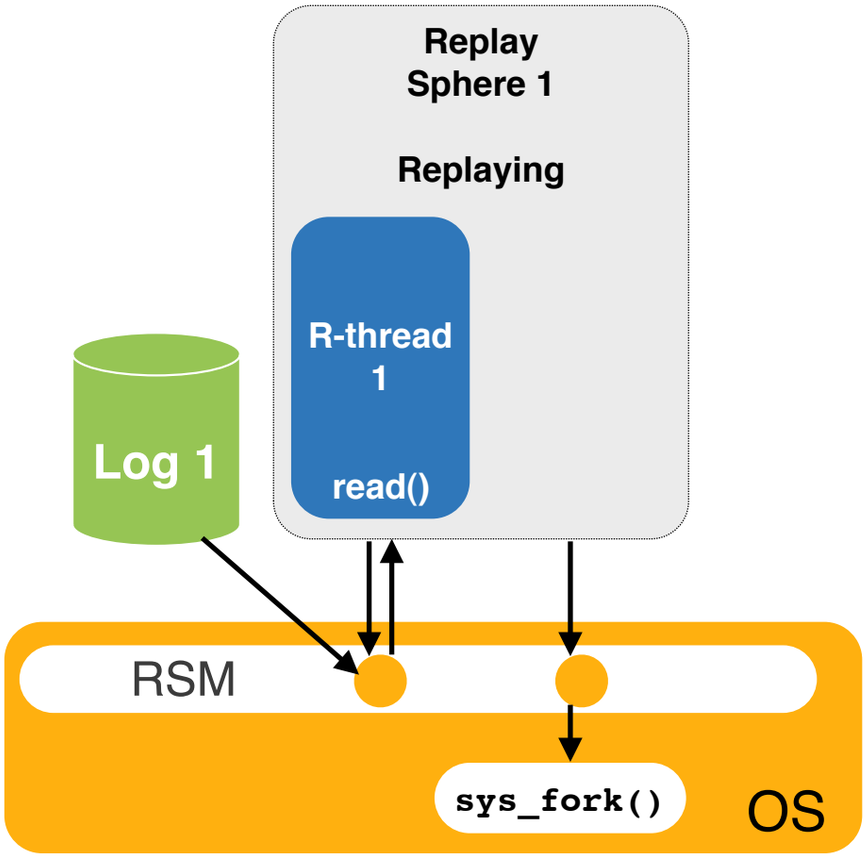

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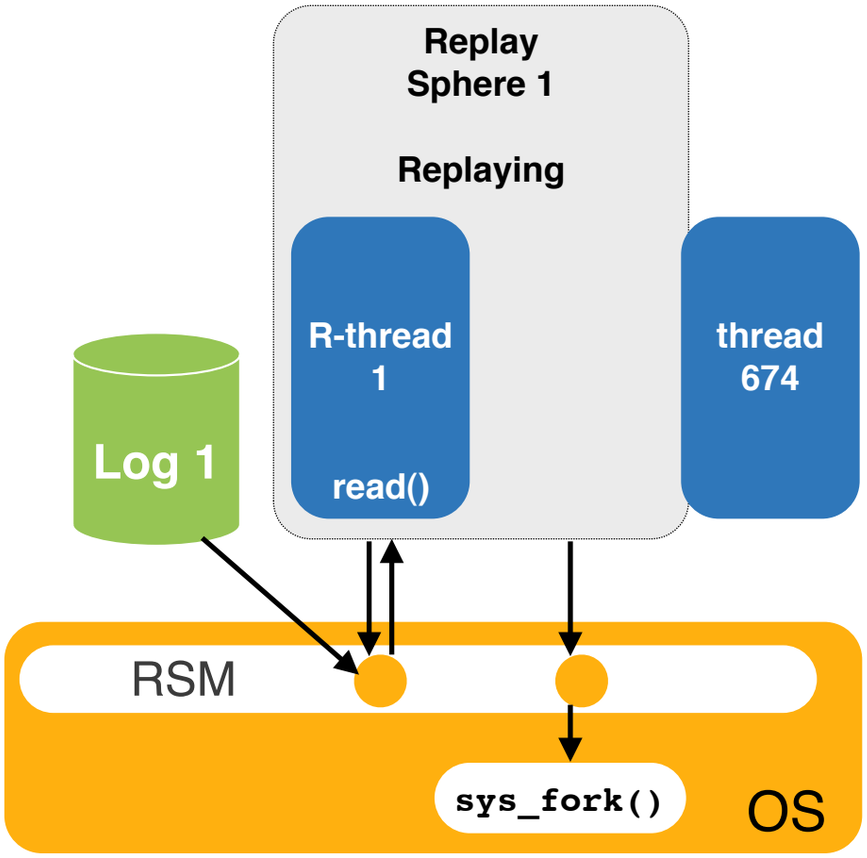

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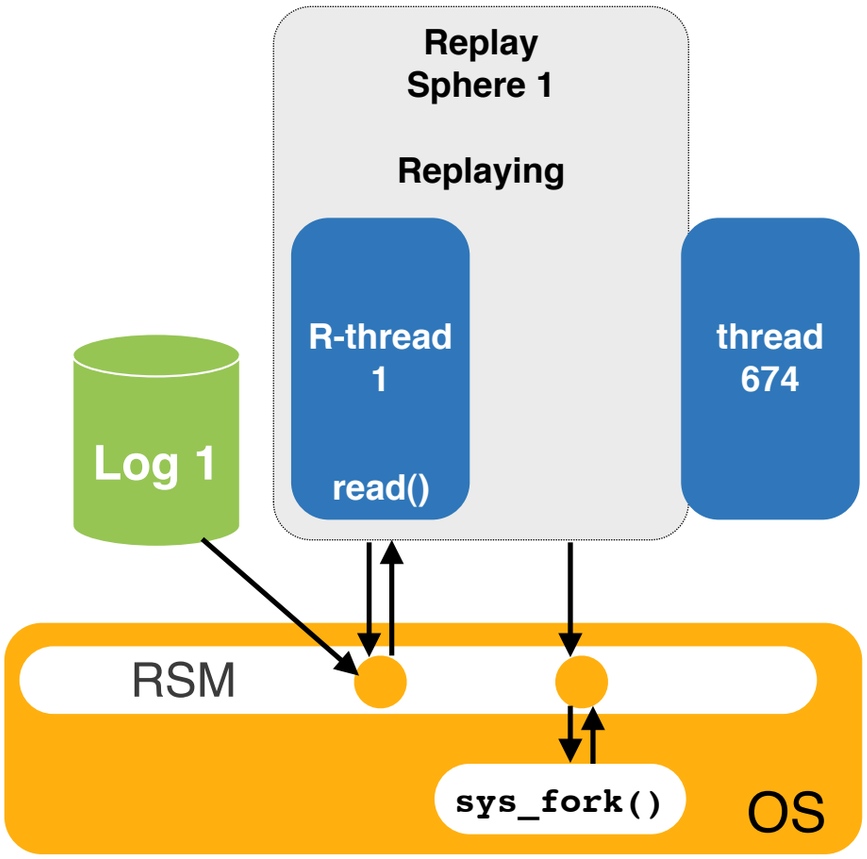

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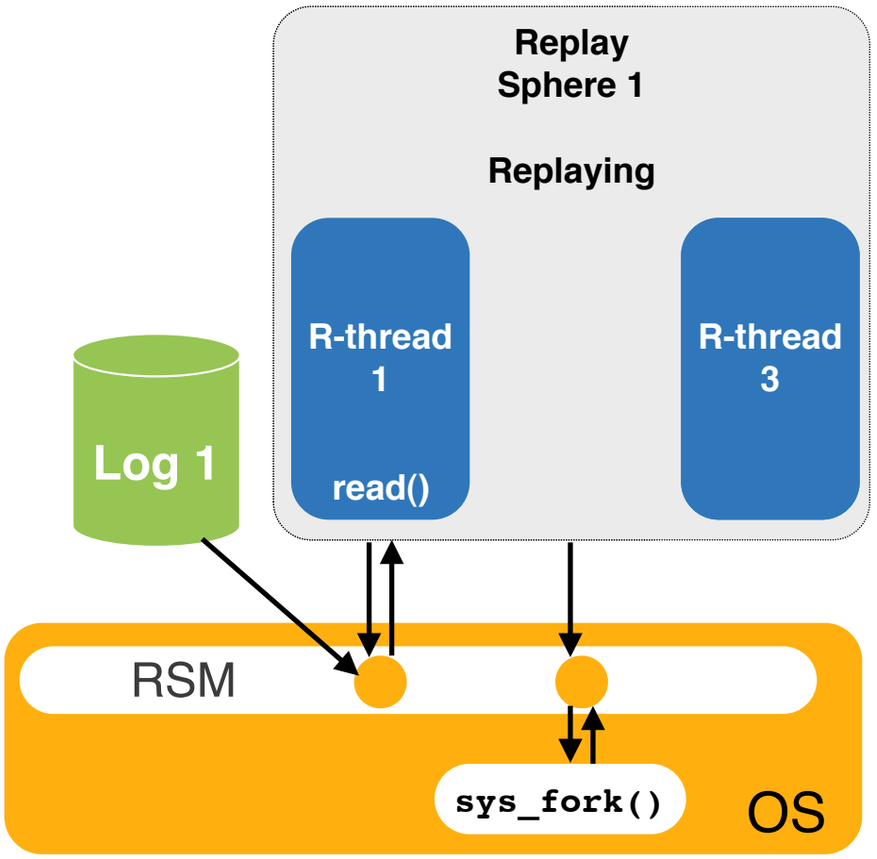

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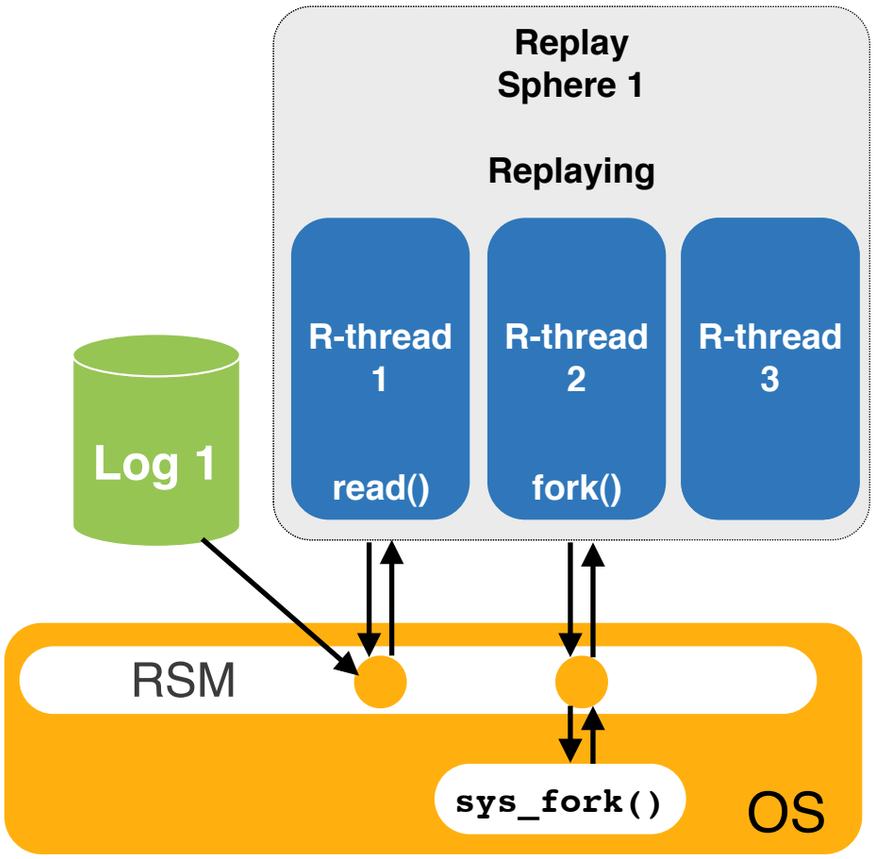

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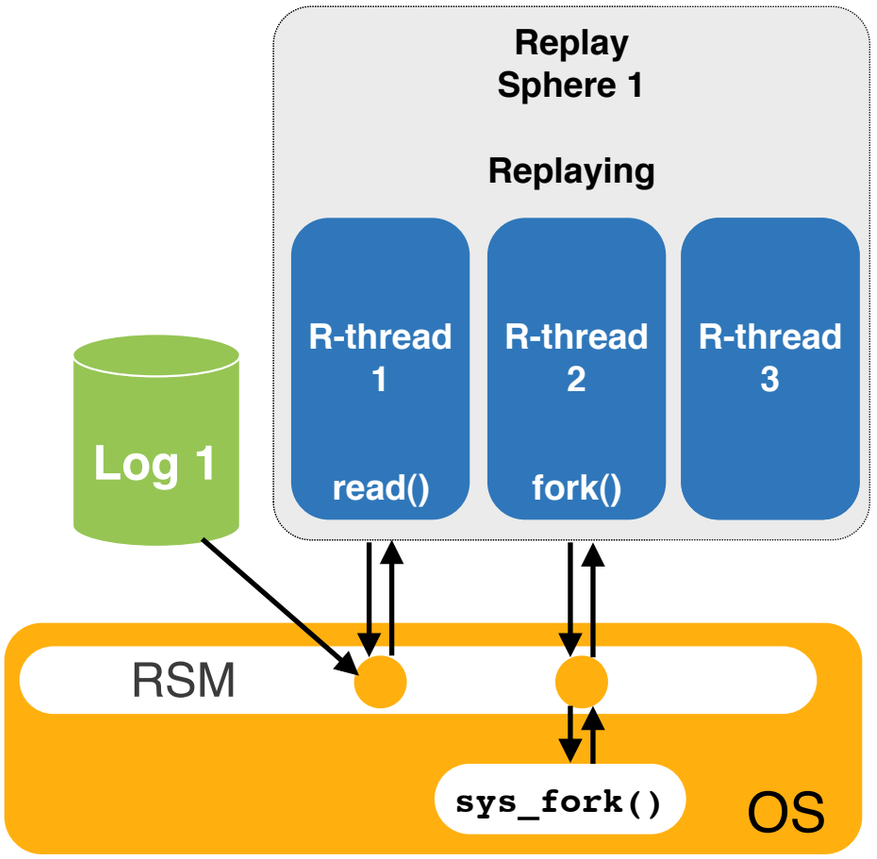

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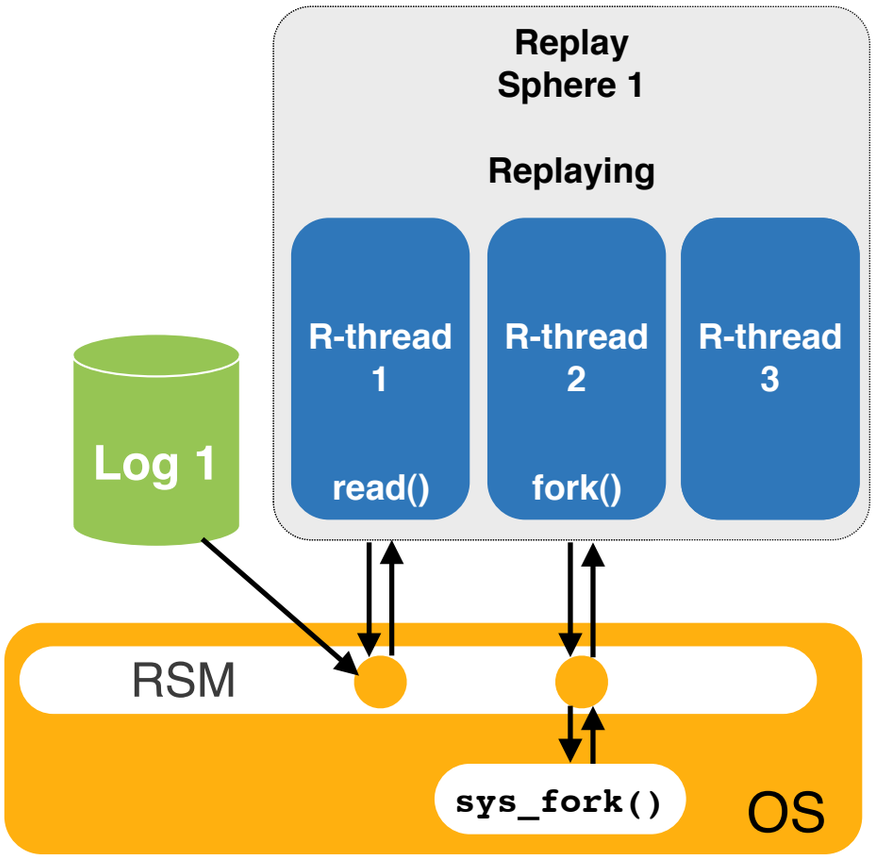

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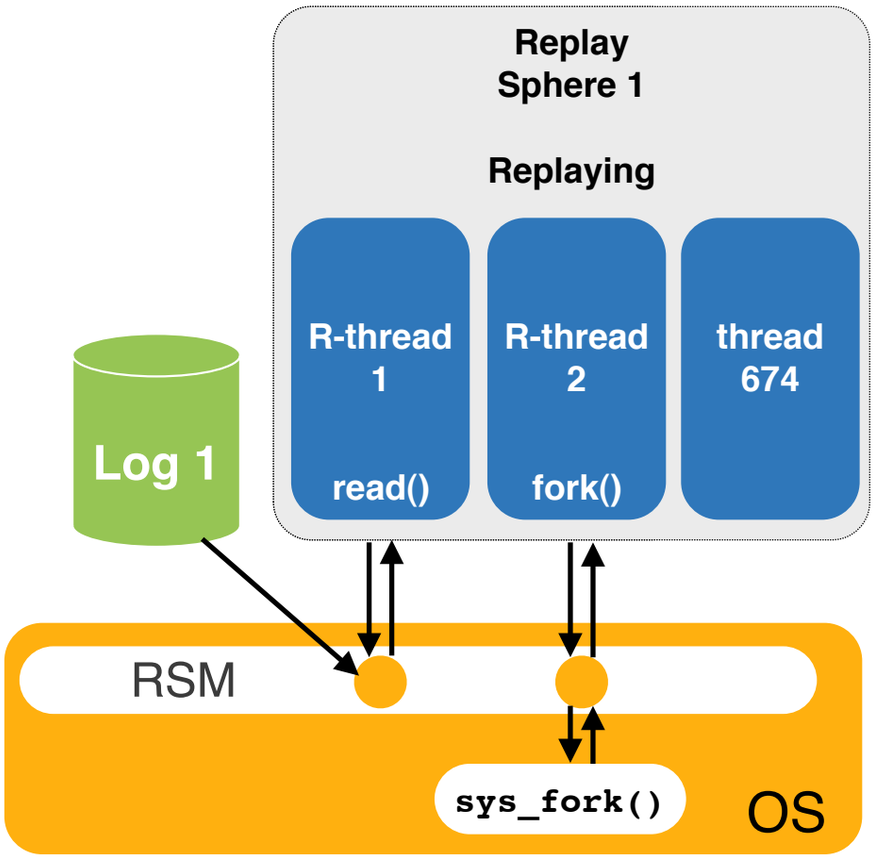

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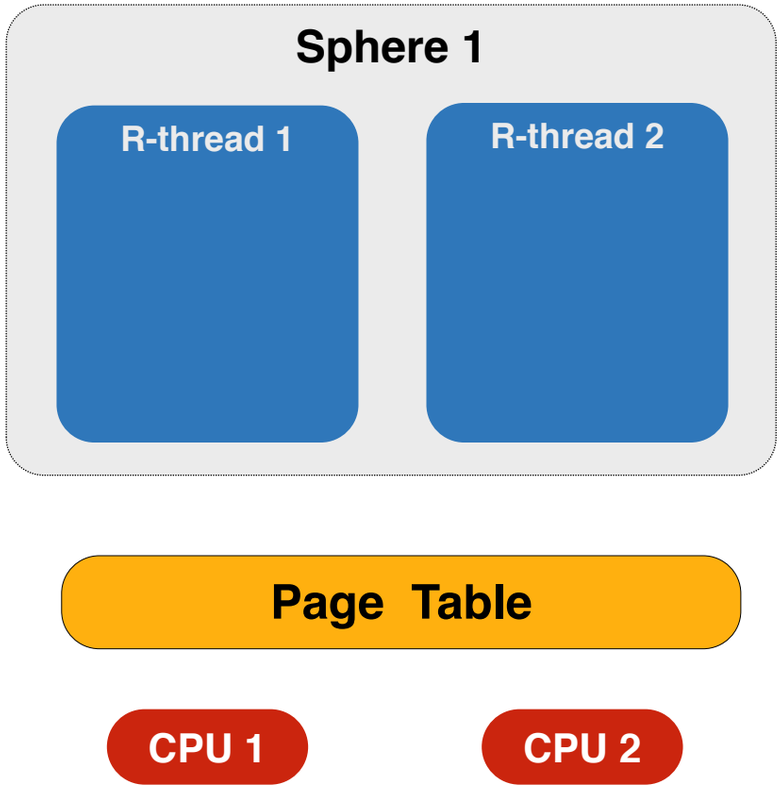

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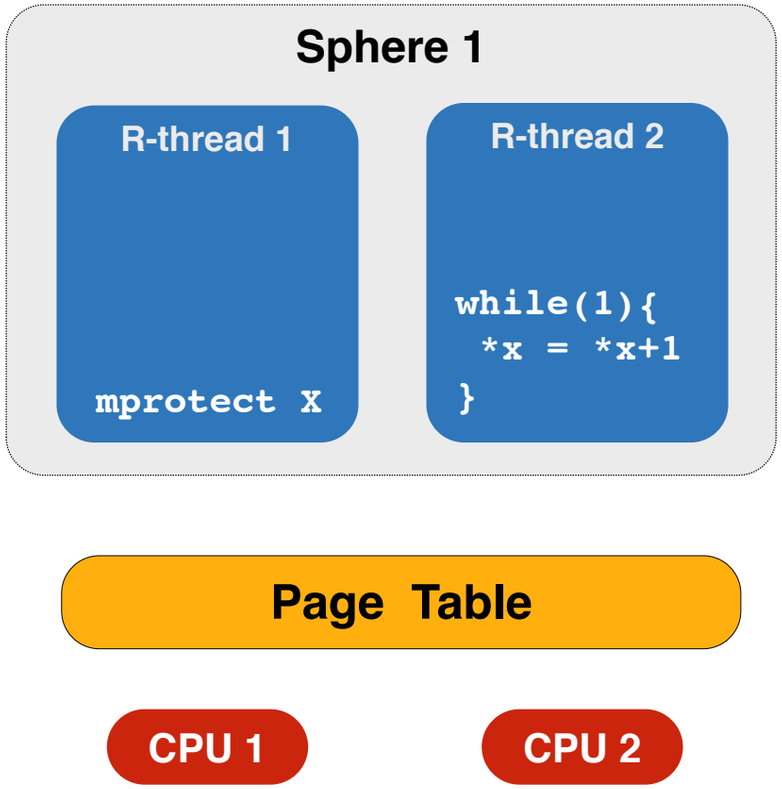

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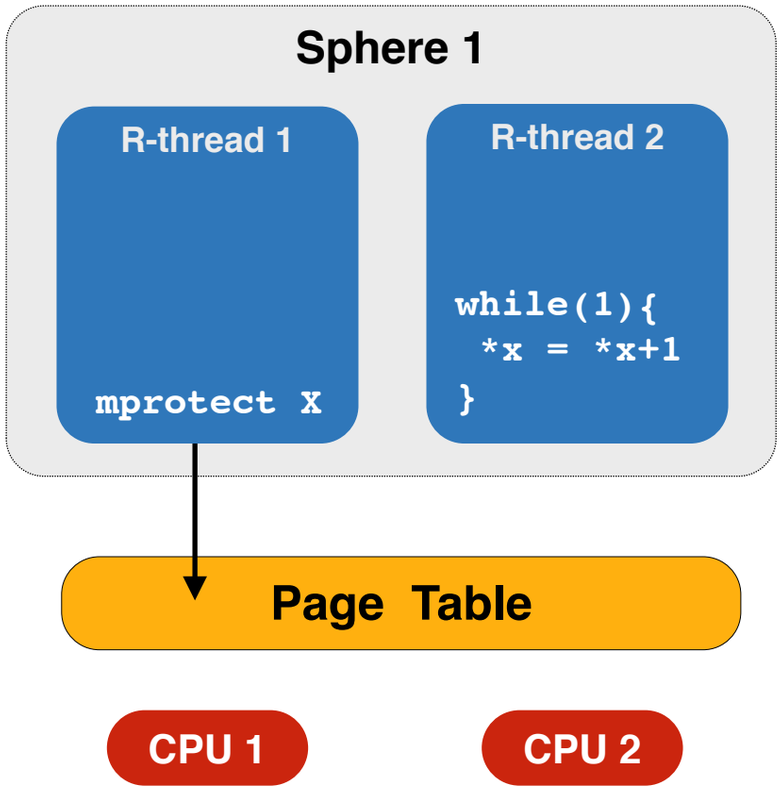

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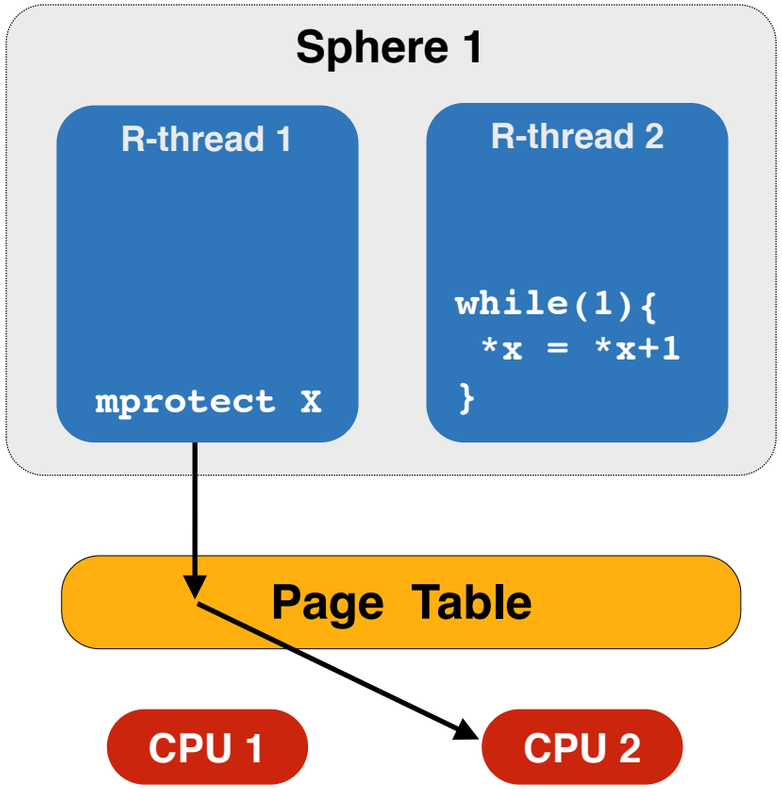

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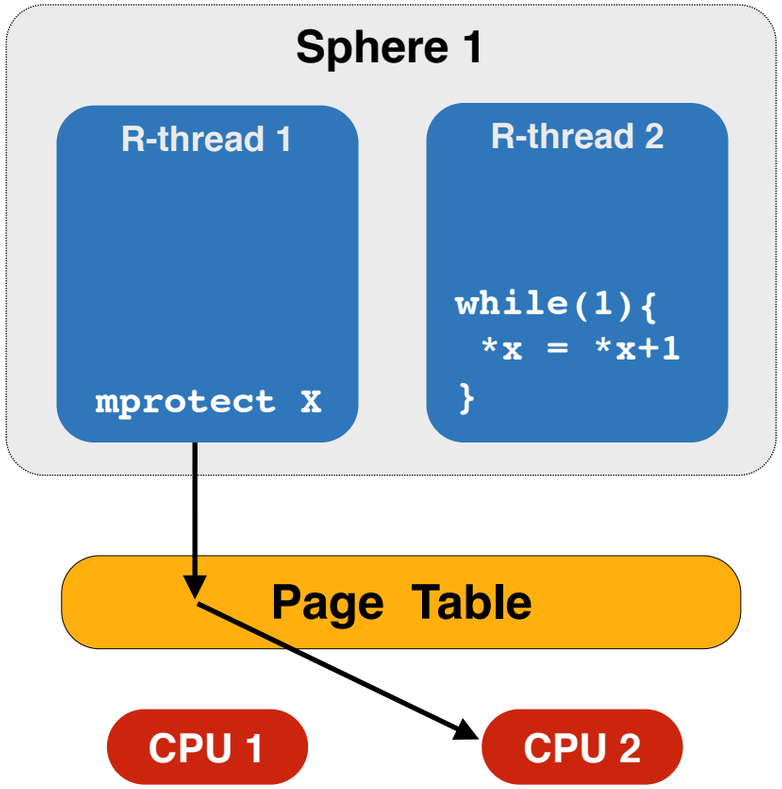

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- RSM can express these dependencies to hardware so these interactions can be recorded

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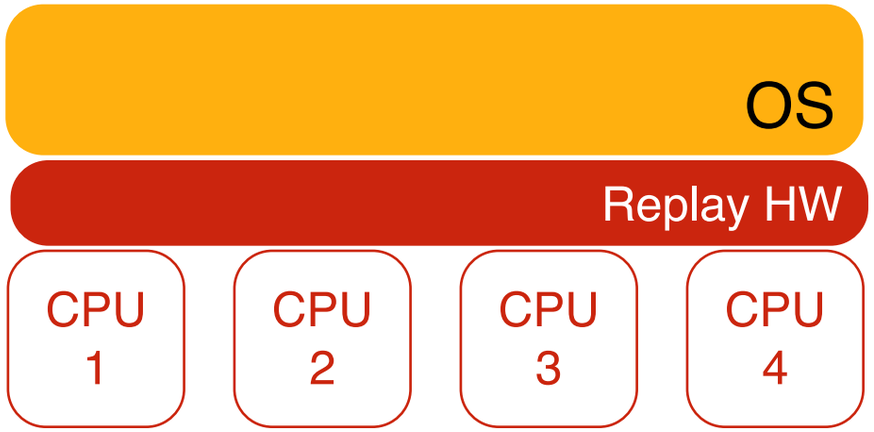

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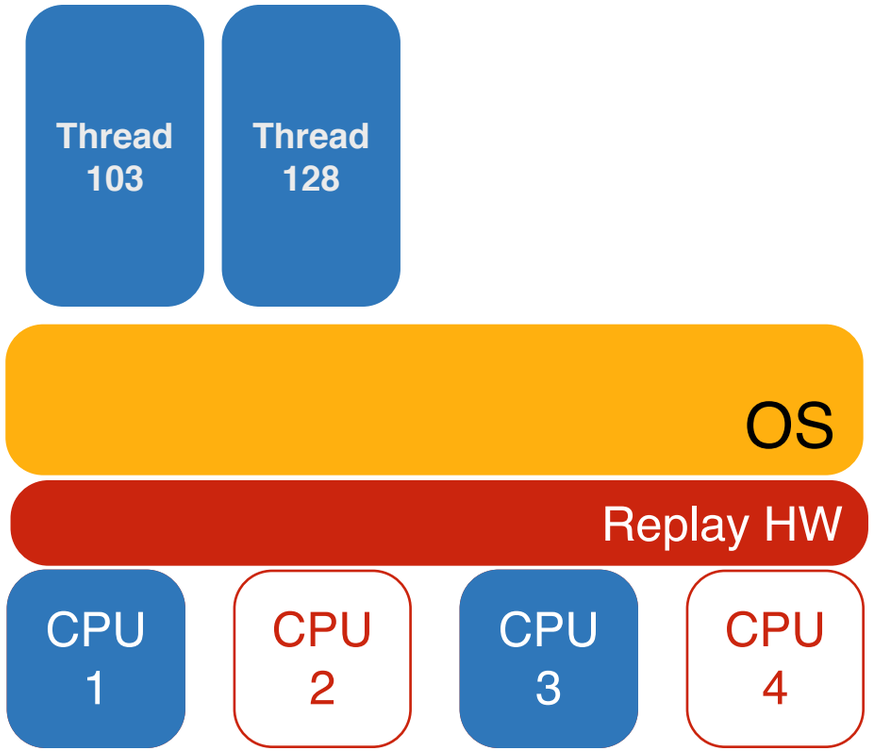

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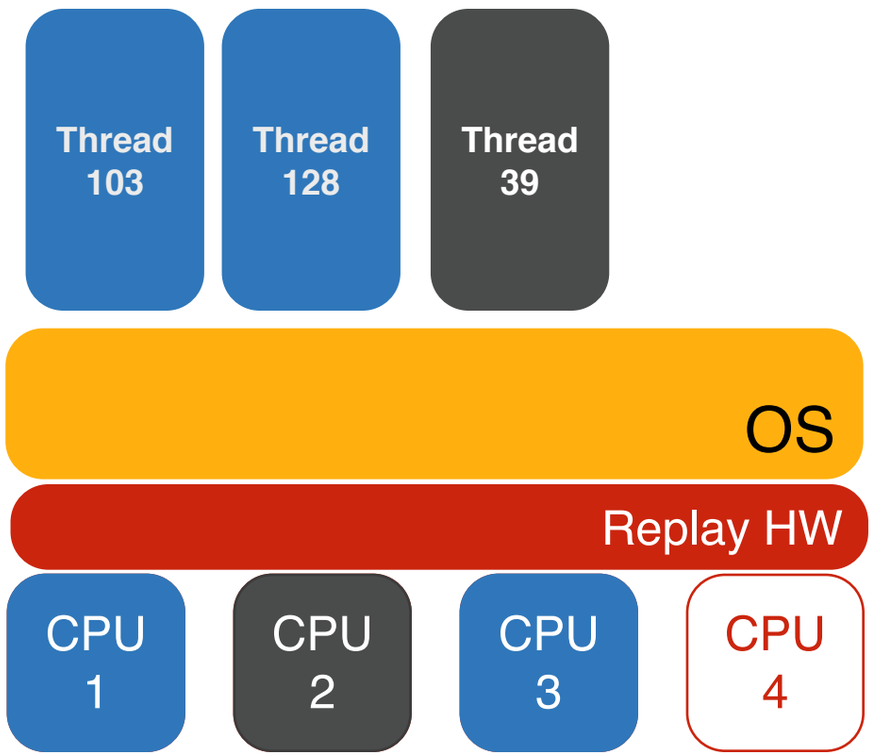

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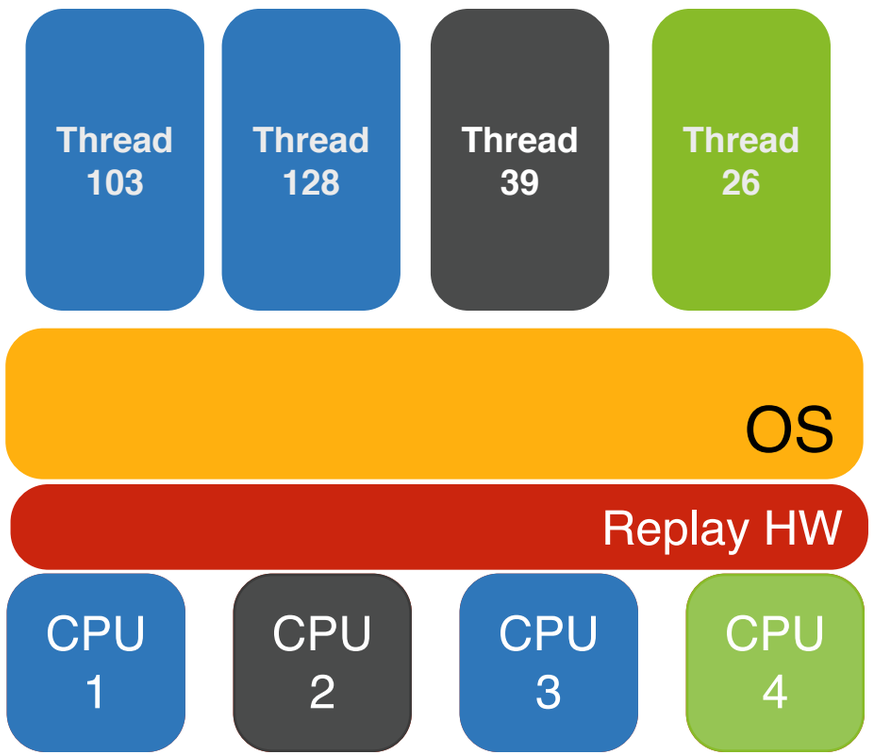

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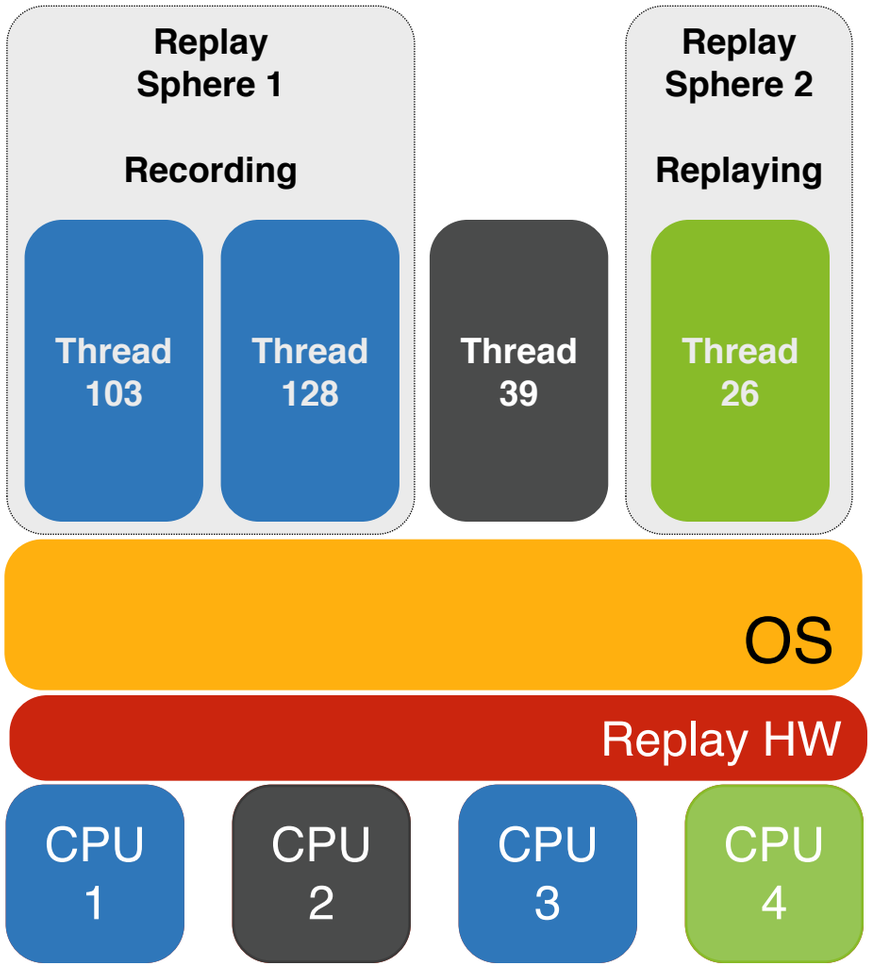

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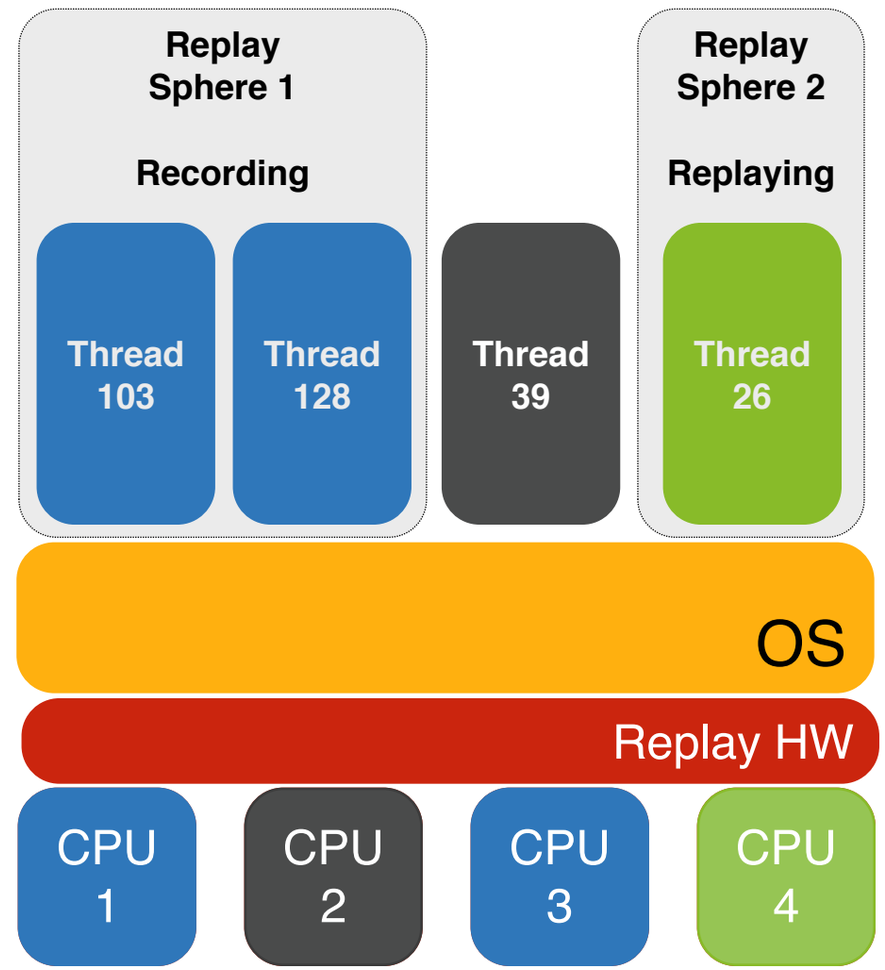

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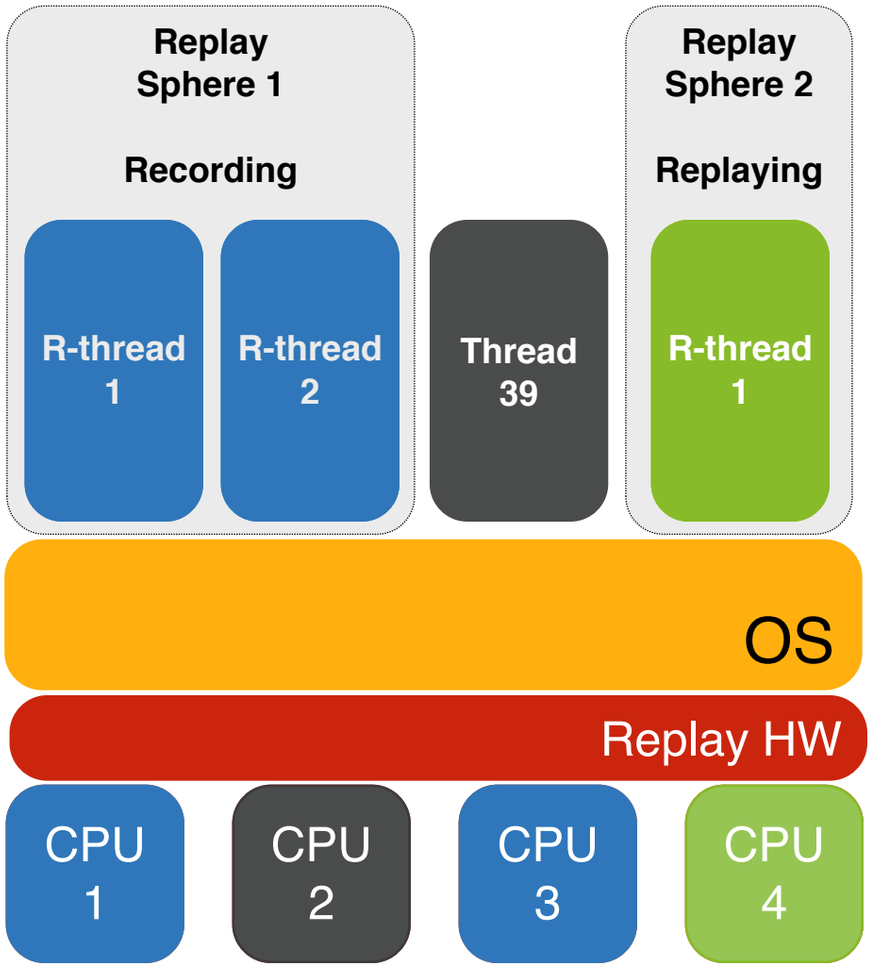

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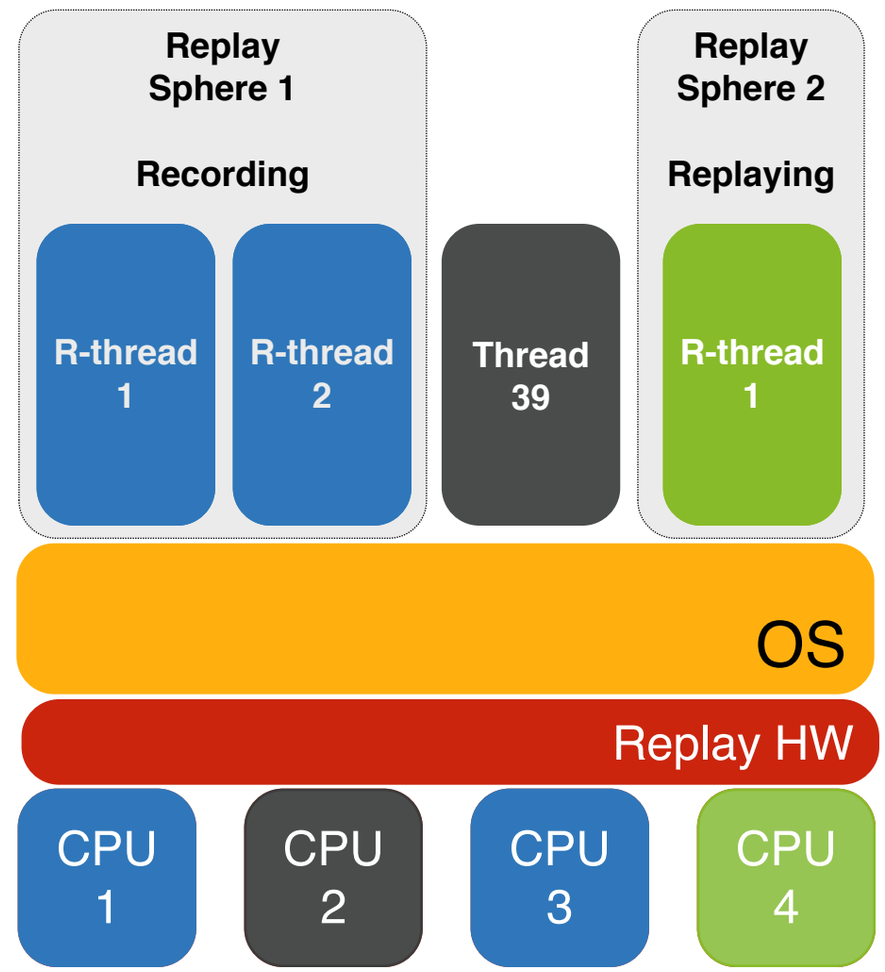

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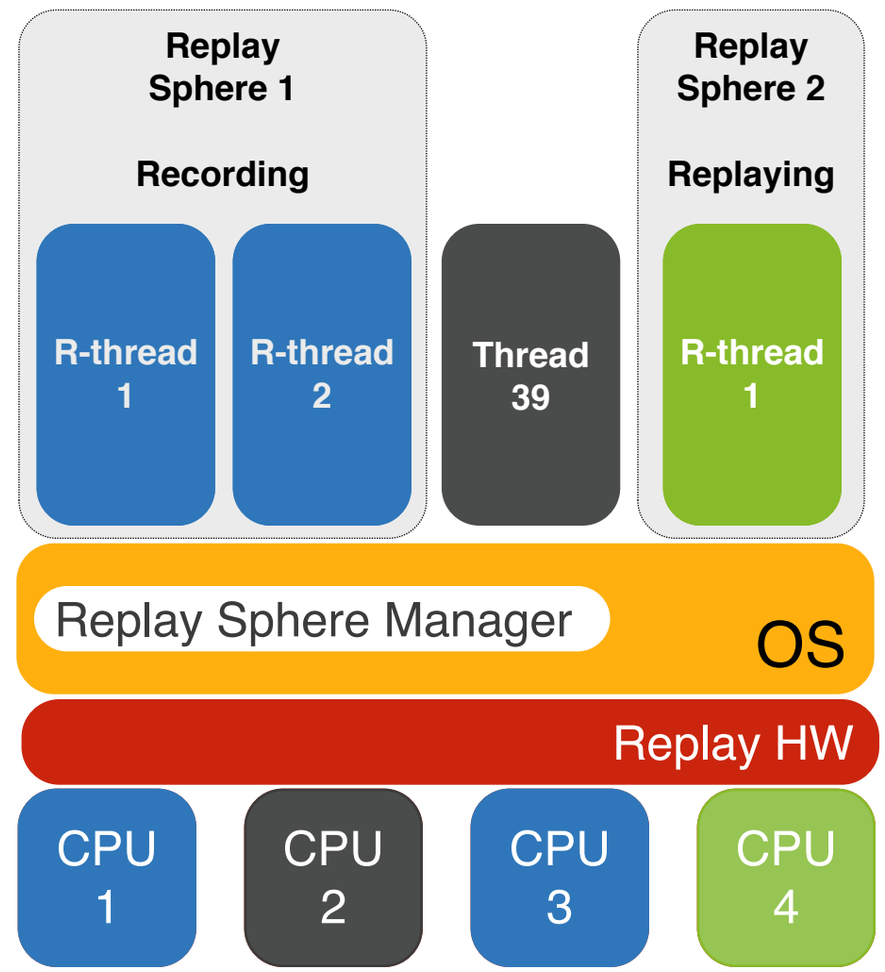

Self-Modifying Code

- Handling self-modifying code in chunk-based systems is laborious:
  - HW adds instruction fetches to read set
  - Instruction fetches are checked against local write set
- In CapoOne, when a processor detects it has modified code
- However,

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- Records and replays parallel Linux apps

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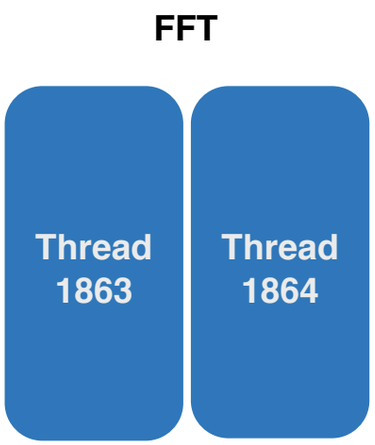

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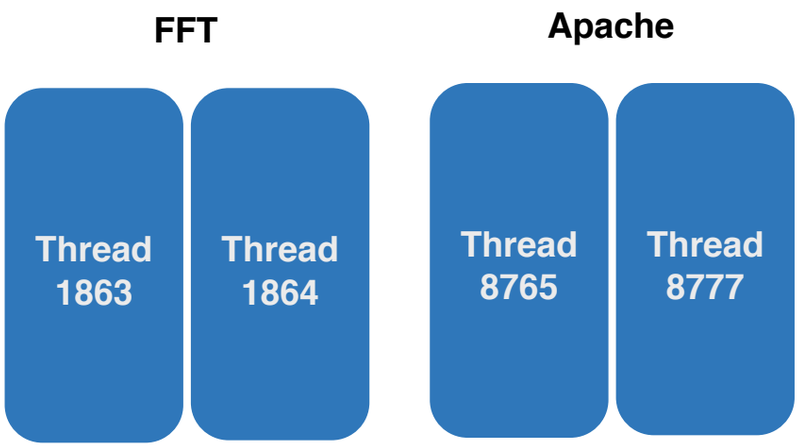

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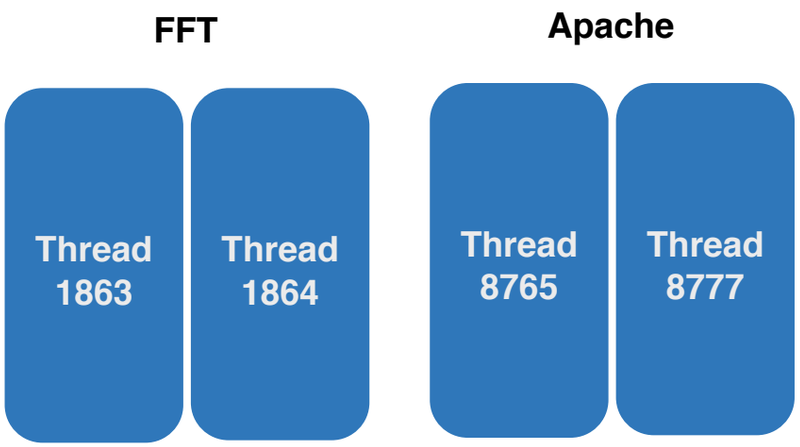

DeLorean HW

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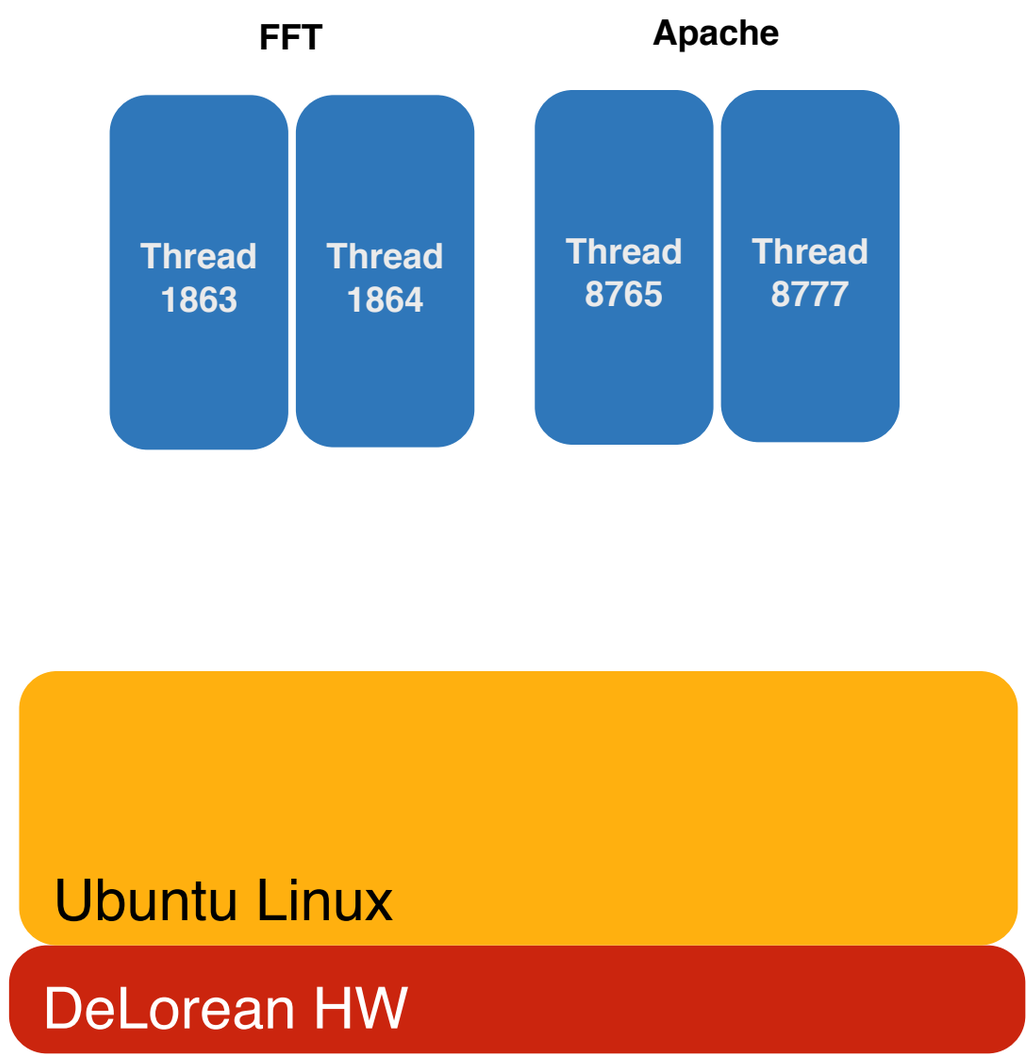

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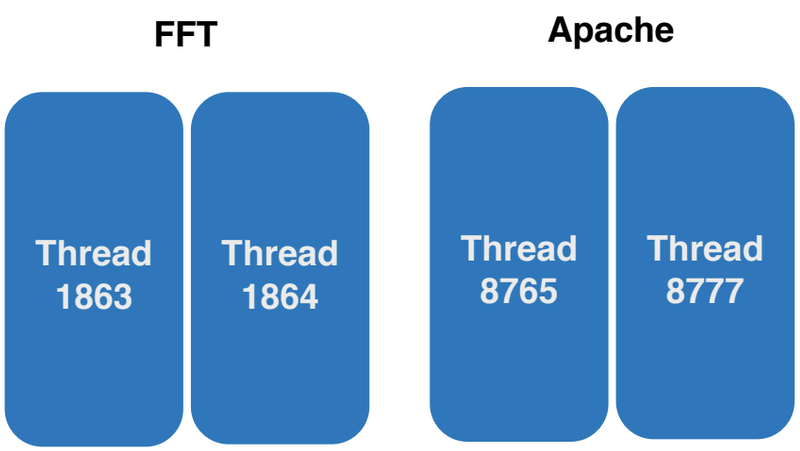

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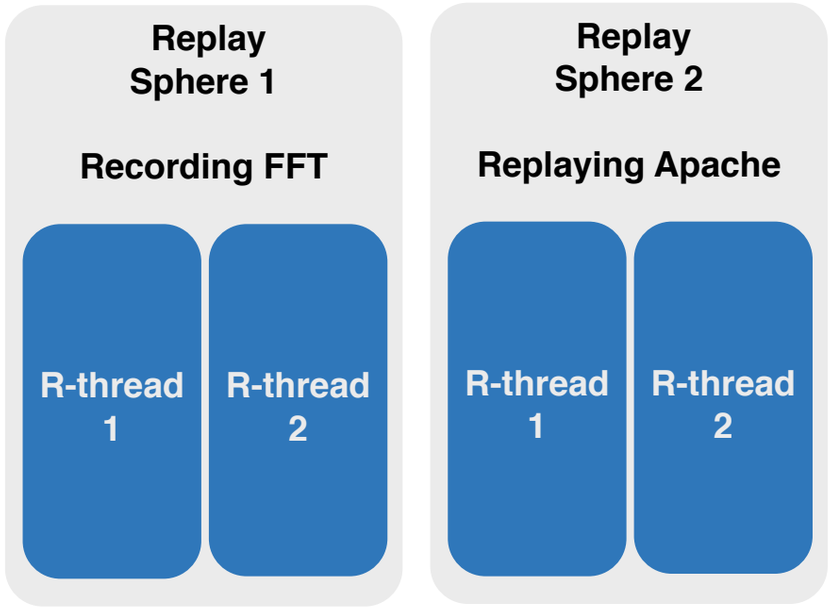

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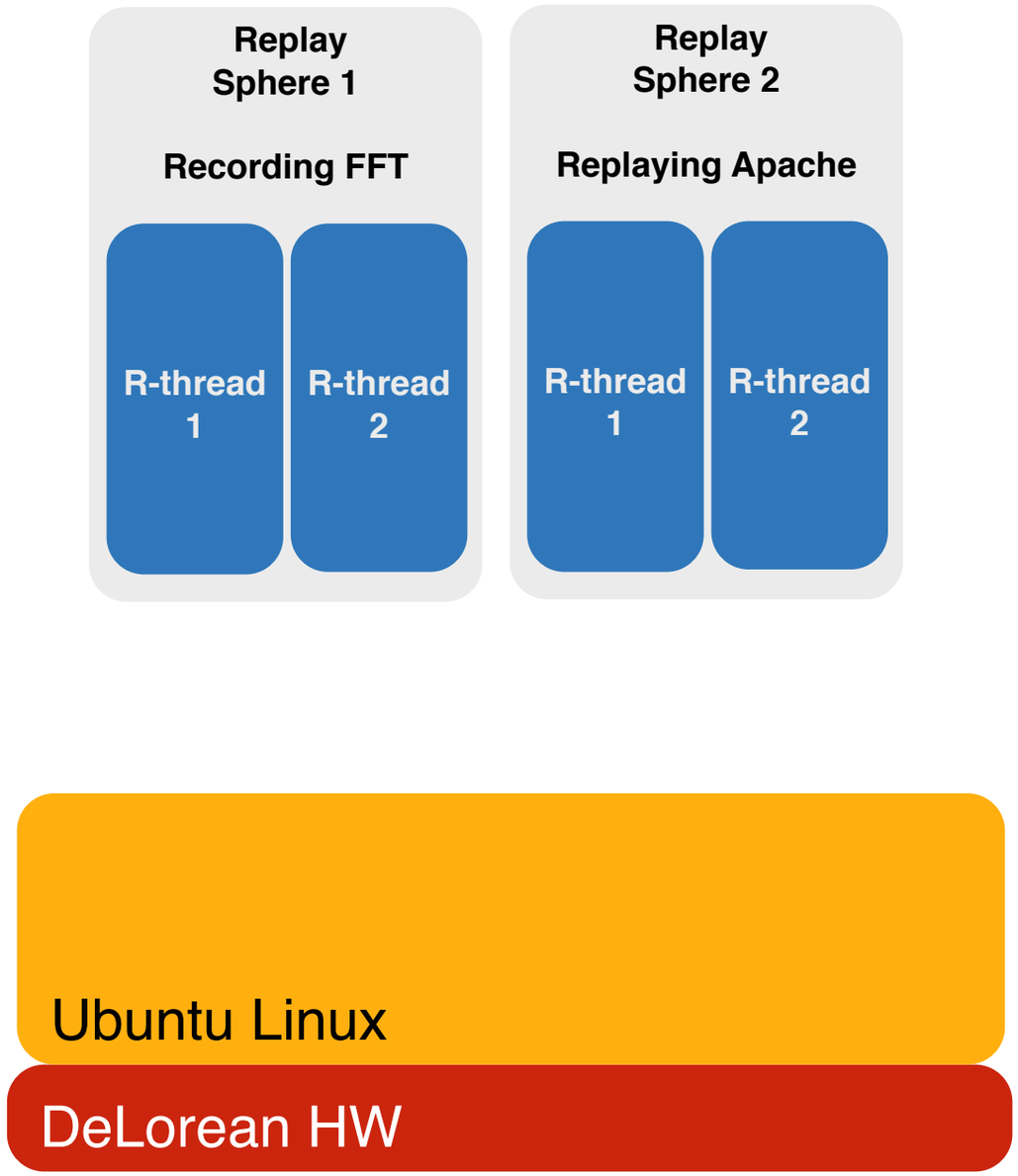

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