RRC: Responsive Replicated Containers

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***Looking for a faculty job**

Server Applications Need Responsive Fault Tolerance

Server Applications:

- Low latency
- High throughput

- High reliability

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Fault Tolerance Mechanism Requirements

- Low latency overhead
- Maintain high throughput
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Fault Tolerance Mechanism Requirements

- Low latency overhead
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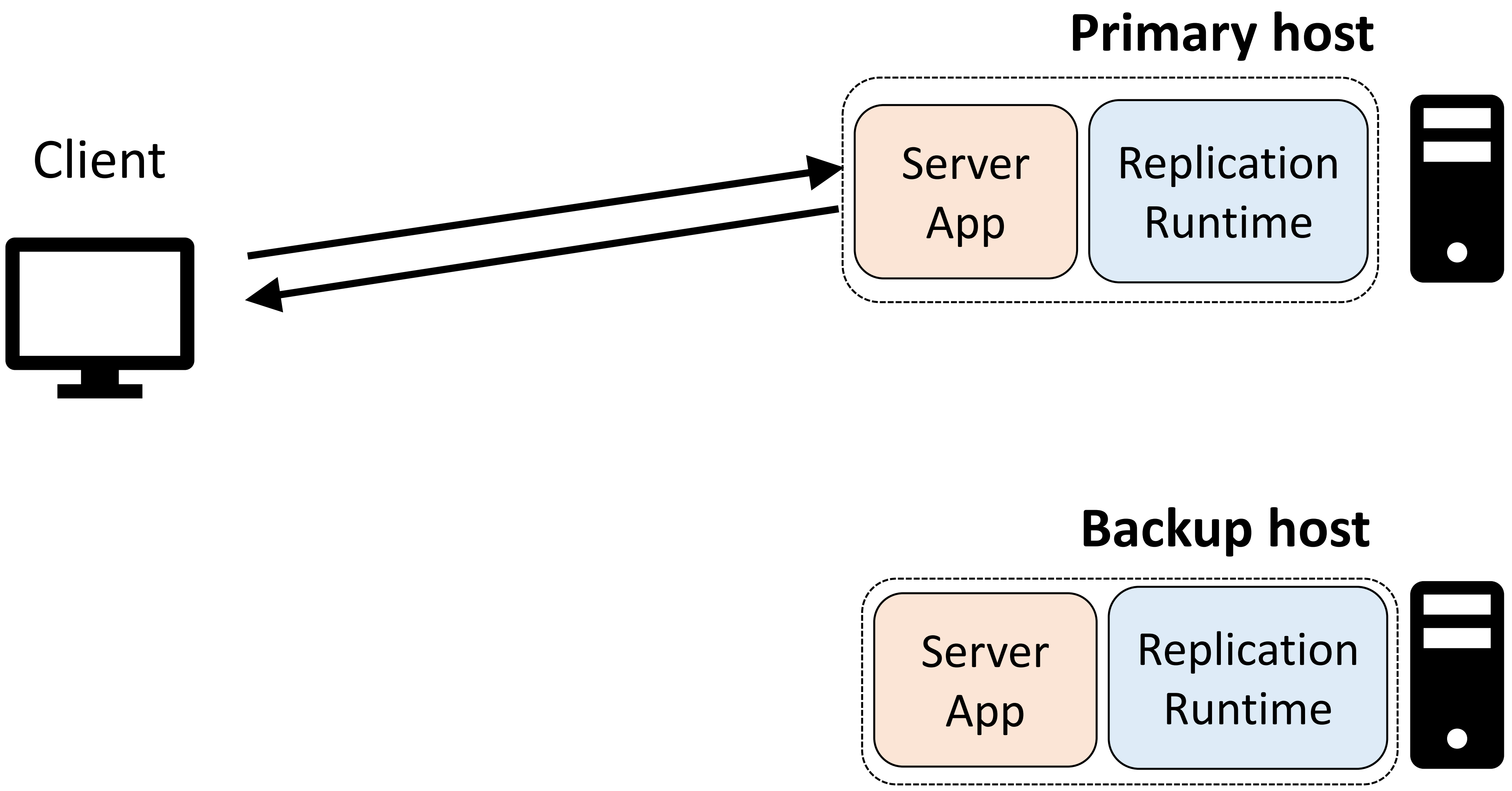
  - Support multithreading
- Minimize development cost
  - No code modification
  - Compatibility with existing clients

  → Application Transparency

Replication → Application-Transparent Fault Tolerance



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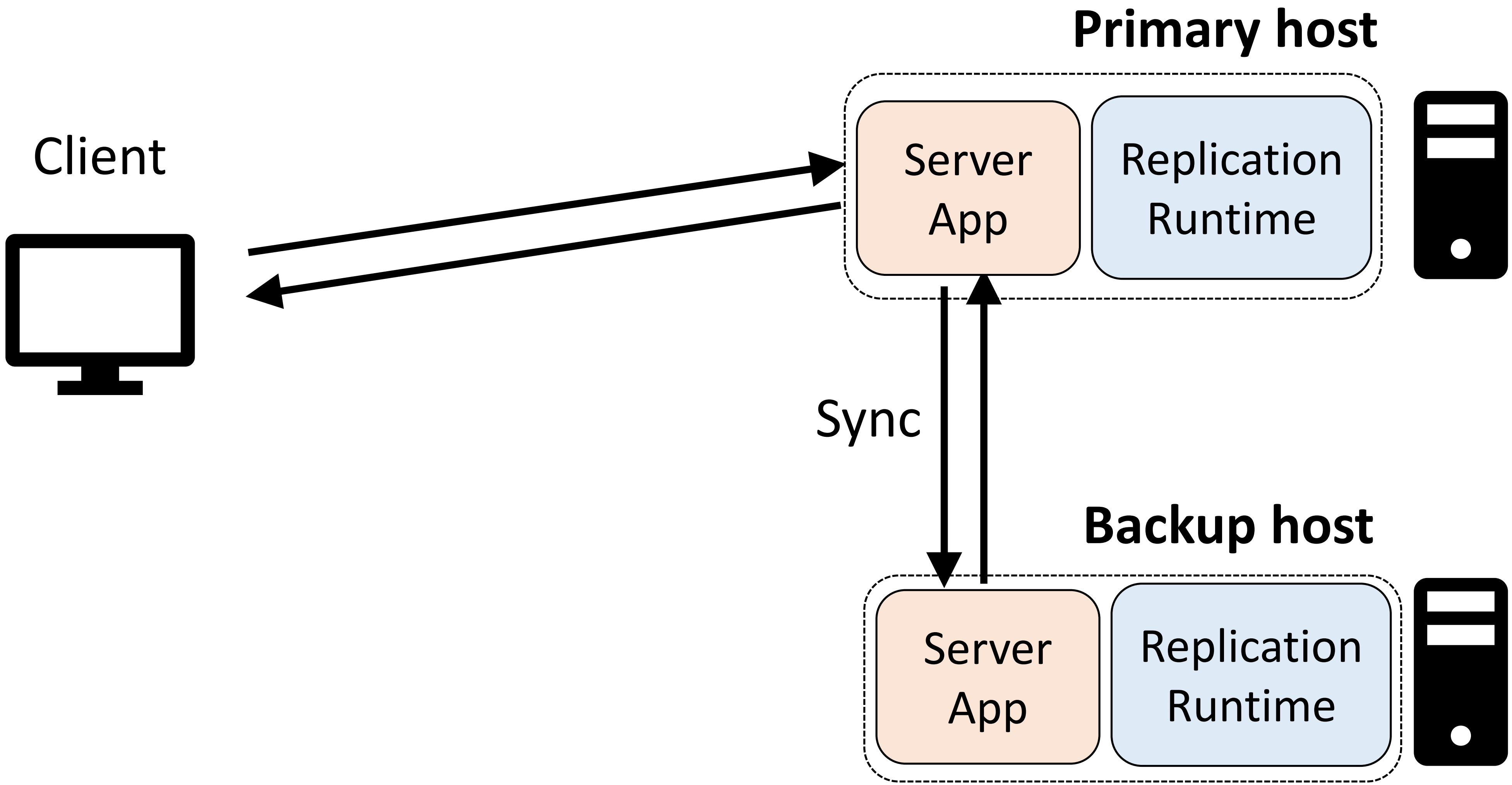

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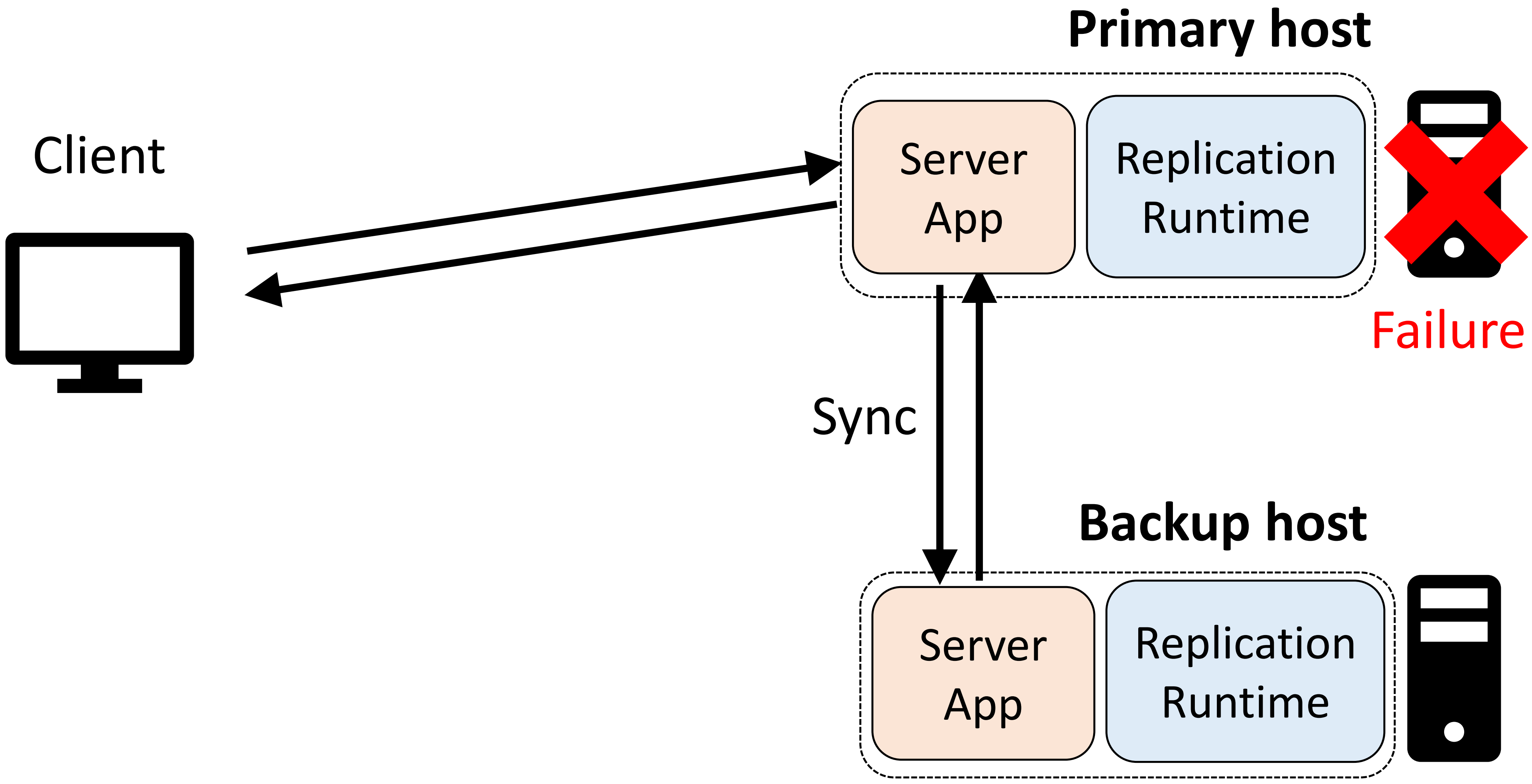

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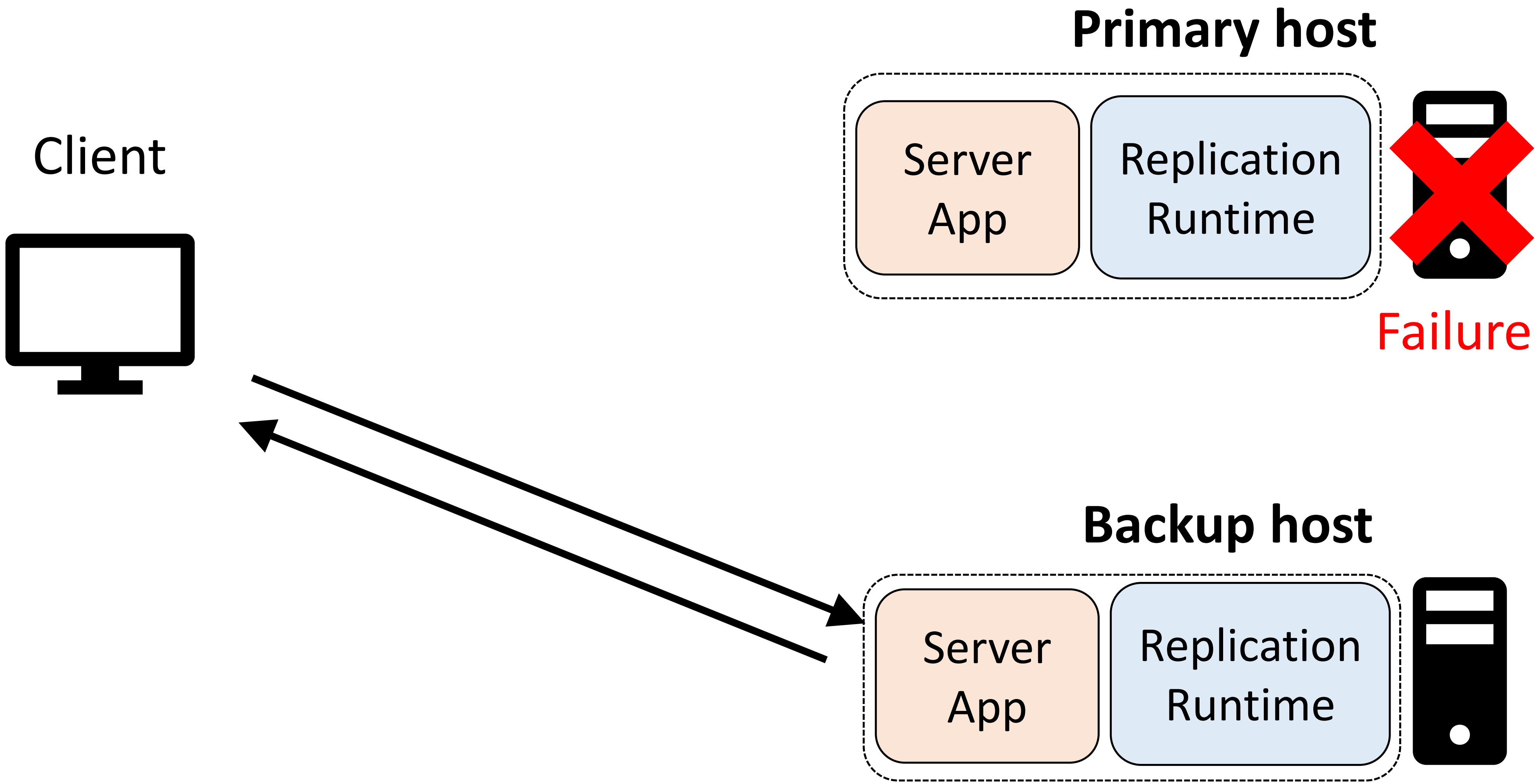
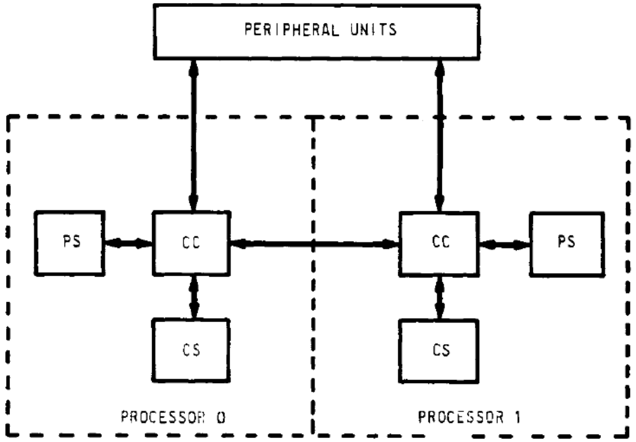
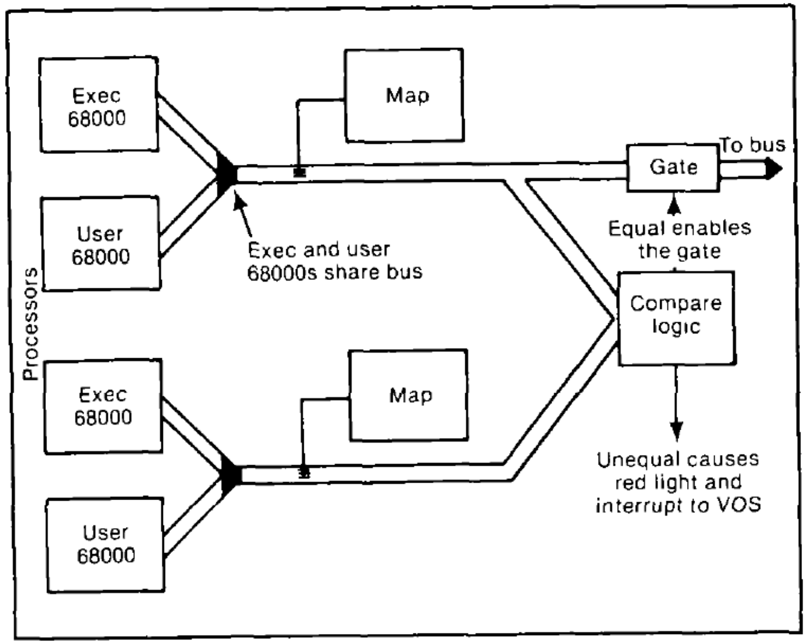


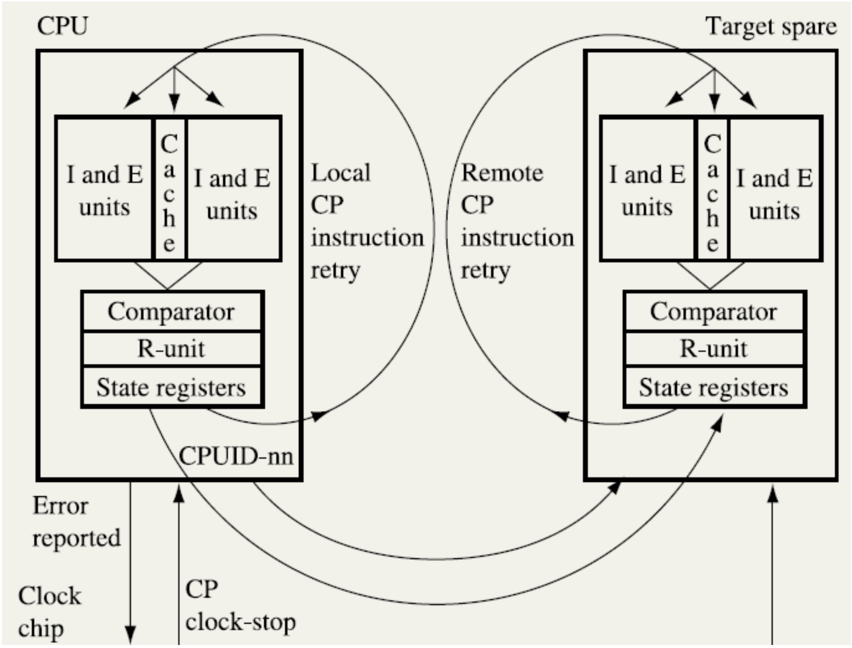
Replication is Old News



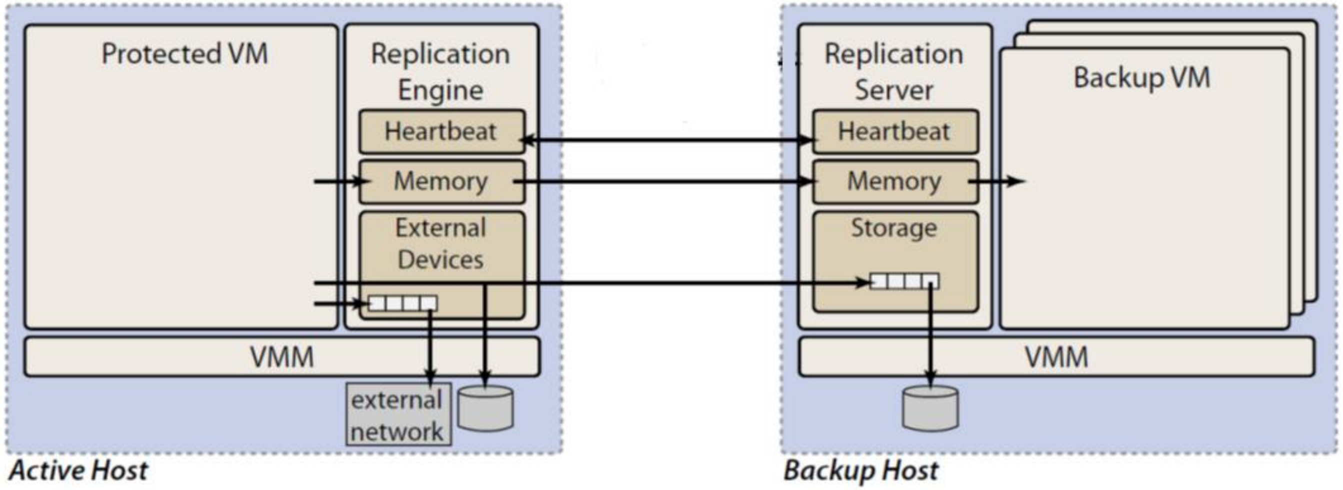
Bell Systems No. 1 ESS (1964)

Stratus/32 multiprocessor node (1983)





IBM G5/G6 Processing Unit (1999)



Remus: Virtual Machine Replication (2008)

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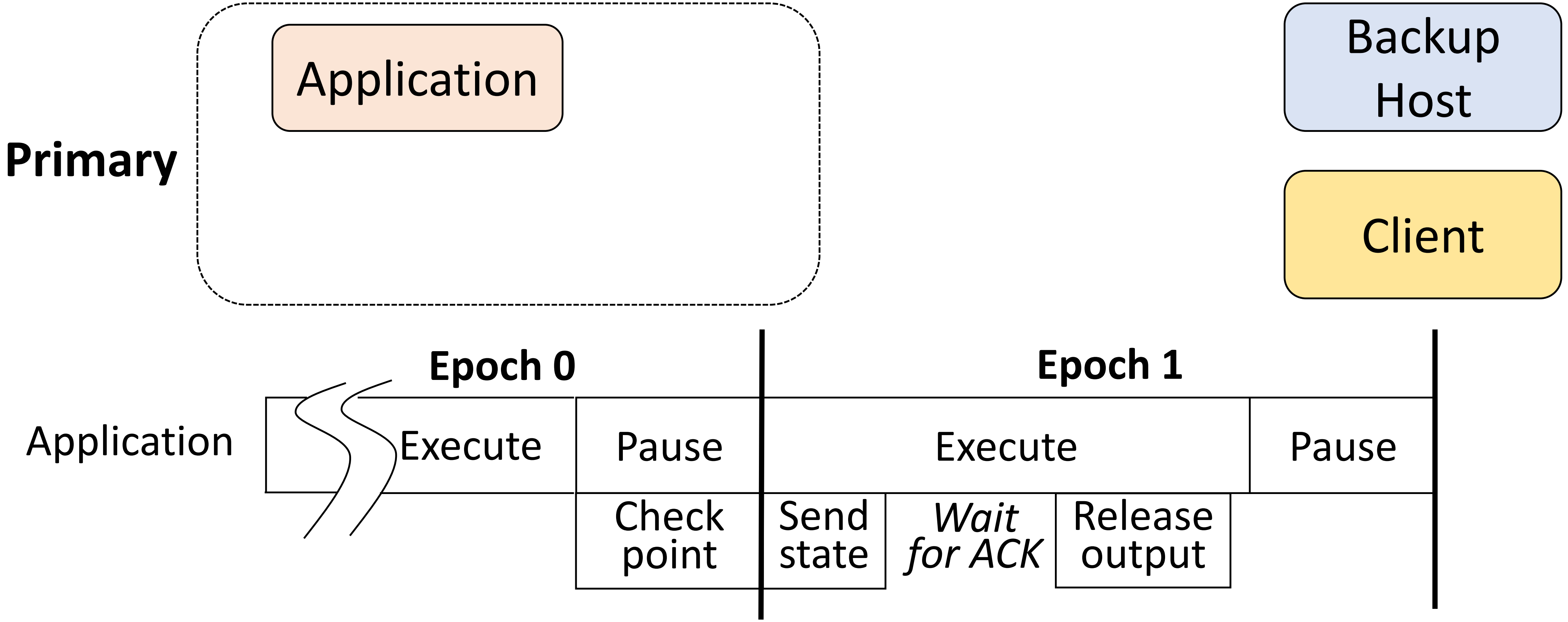
RRC overcomes limitations by **decoupling** replication-related operations from normal operations

Talk Outline

- Preface
- **Motivation**
- RRC overview
- Overcoming design and implementation challenges
- Evaluation

Passive Backup: Checkpointing-Based Mechanisms



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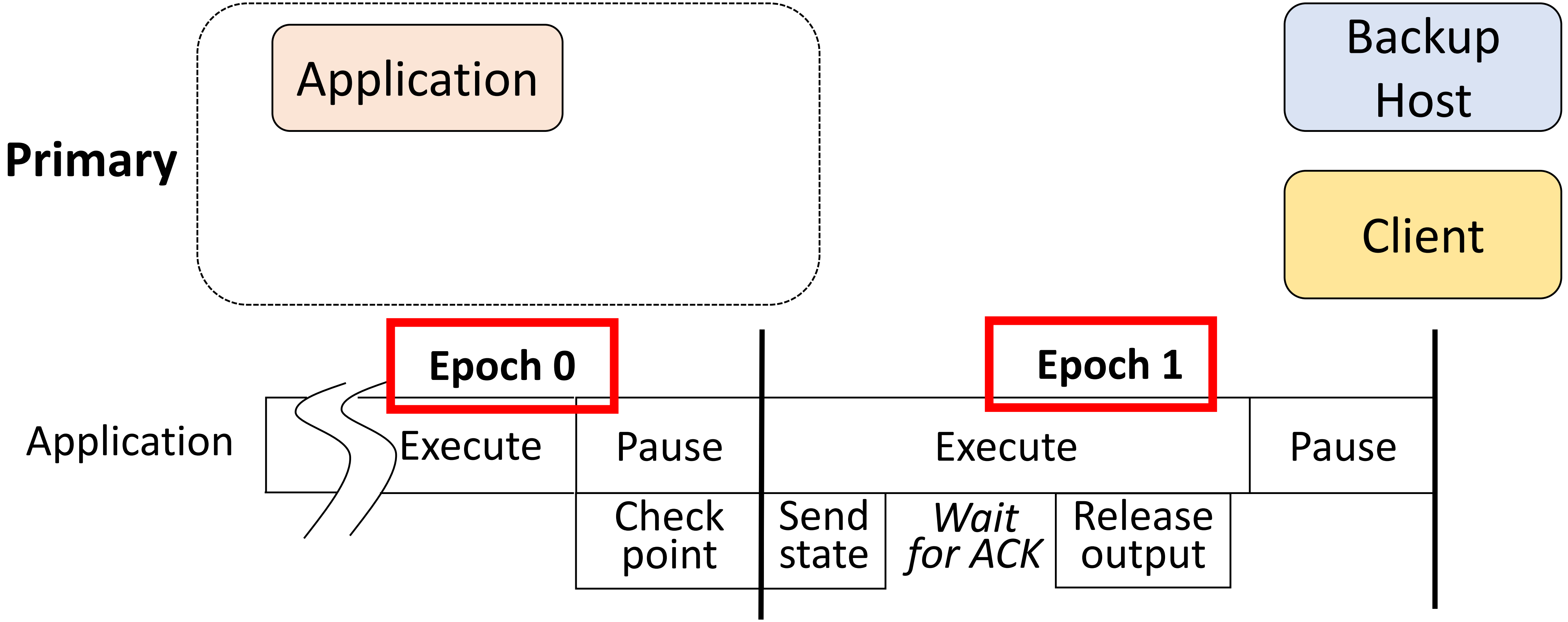

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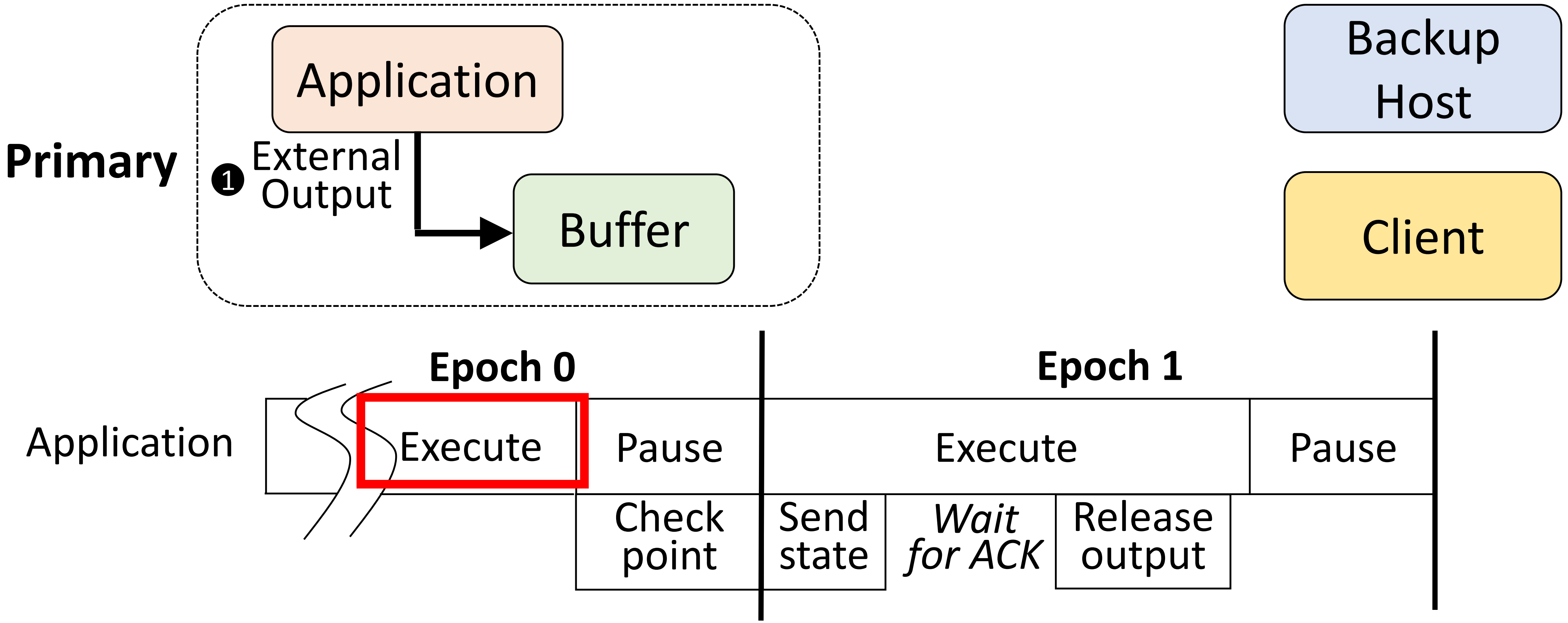

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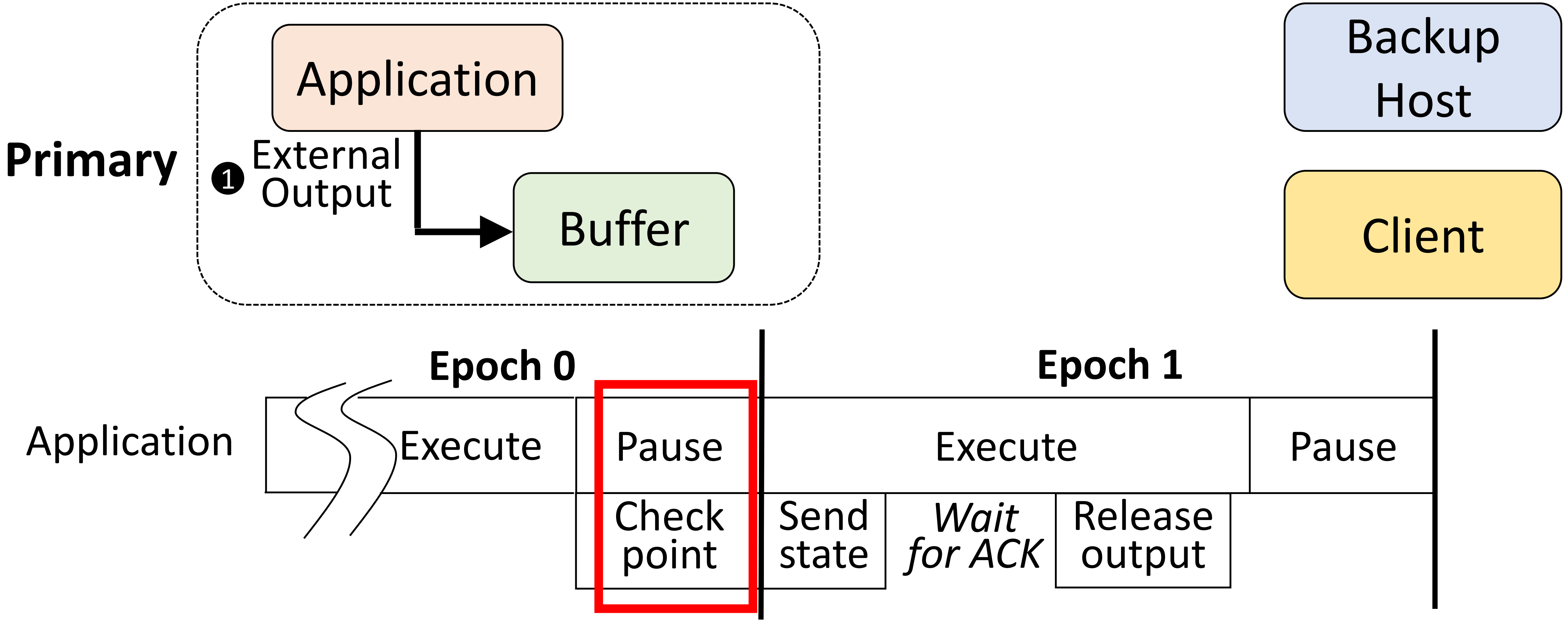

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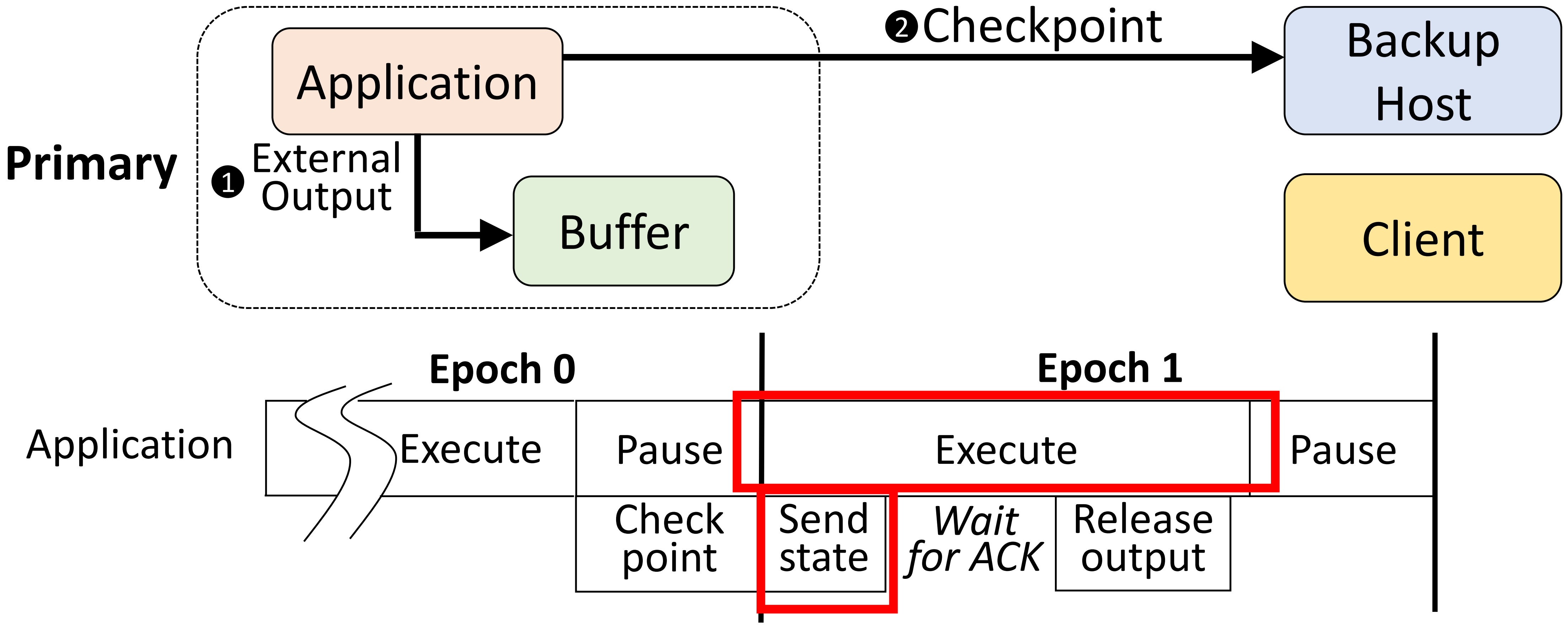

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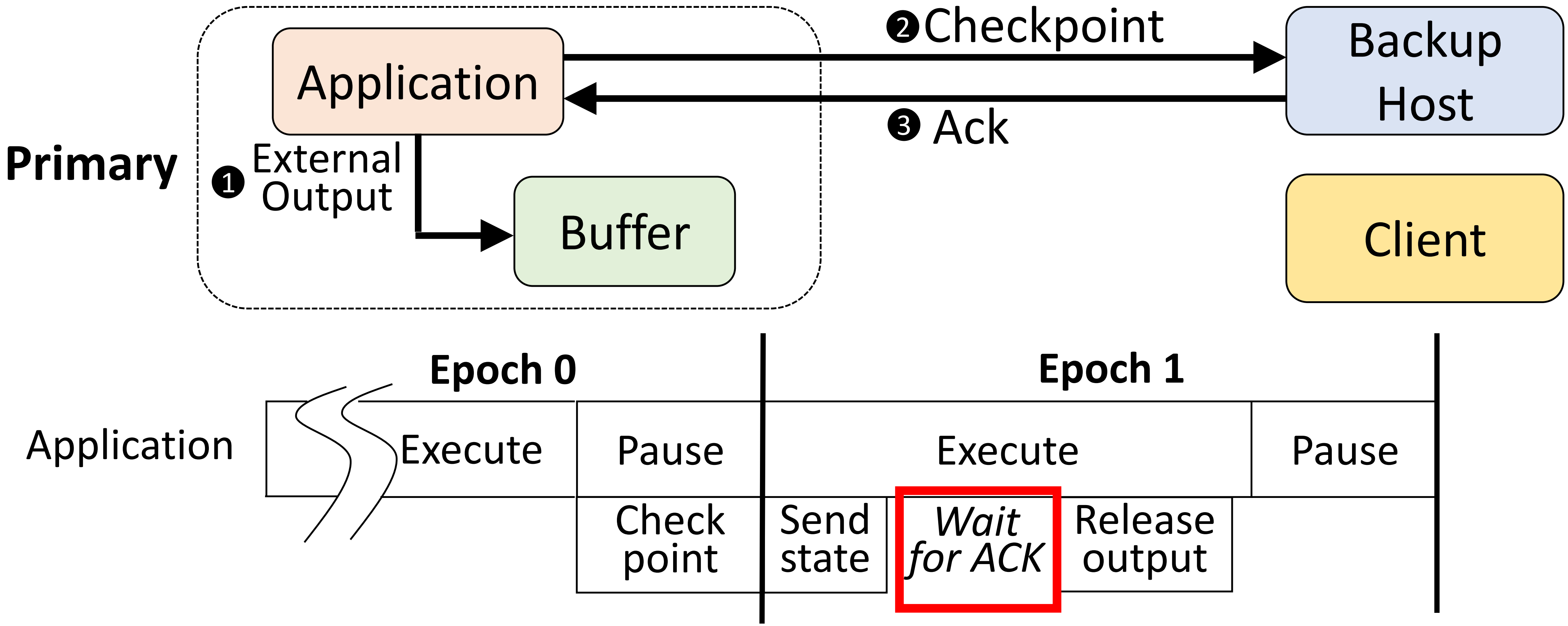

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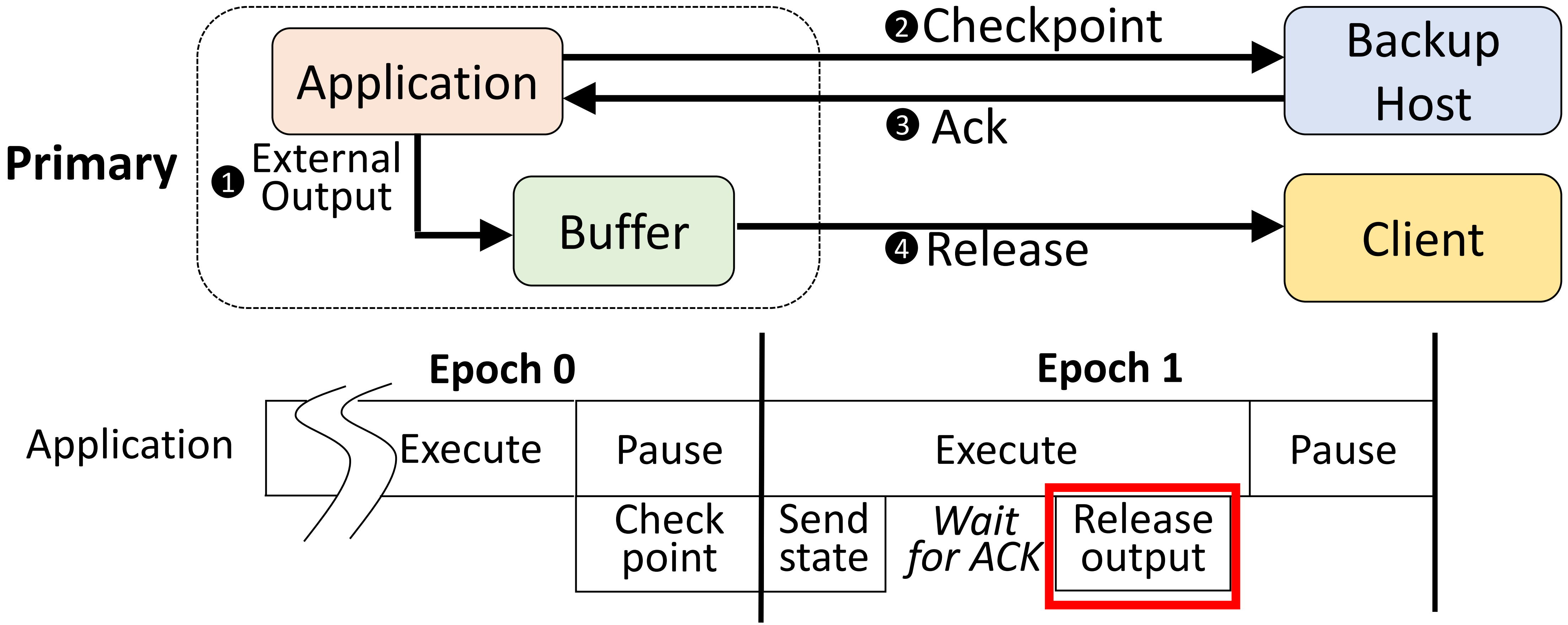

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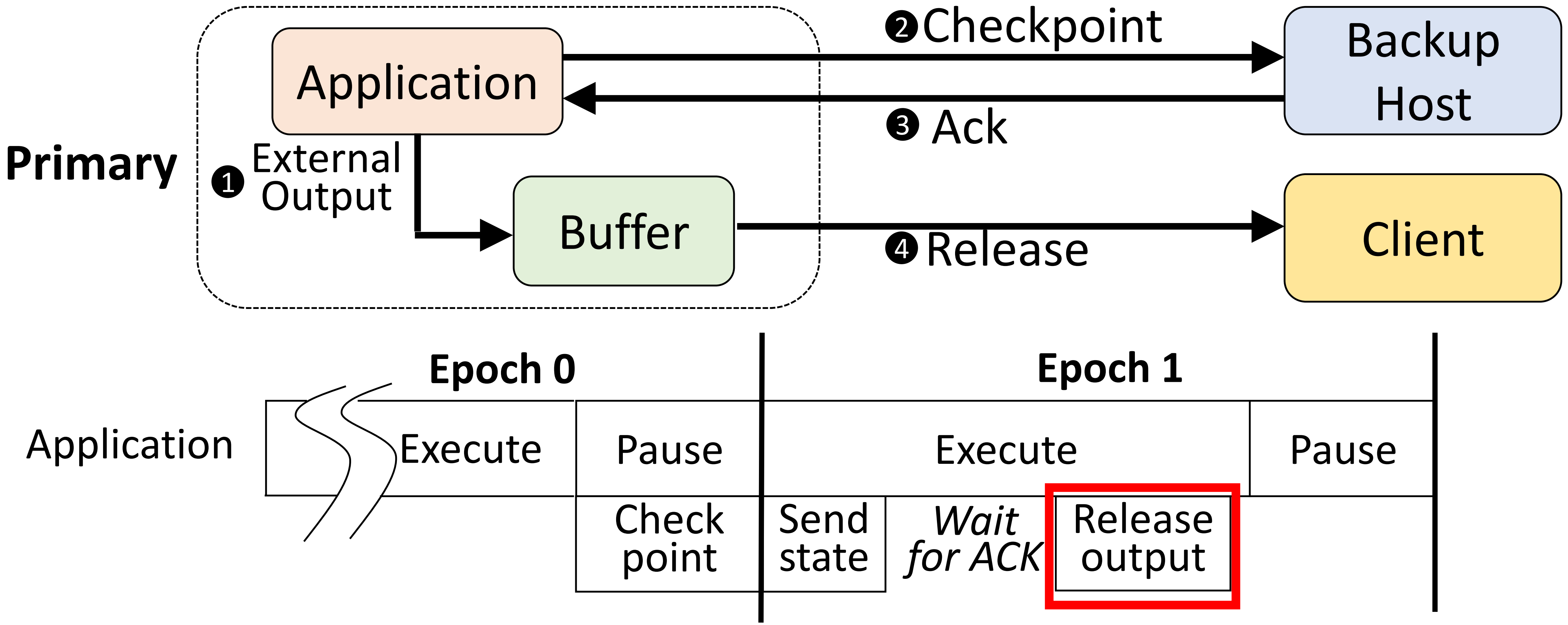
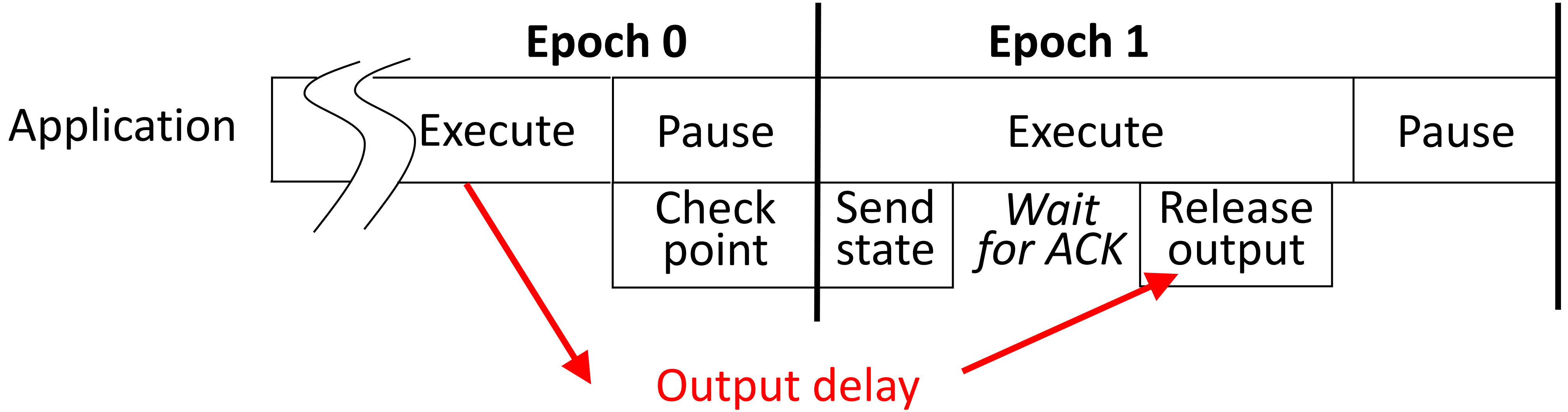


Why delayed output:

Backup needs to restore state consistent with clients

Checkpointing-Based Mechanisms → High latency Overhead



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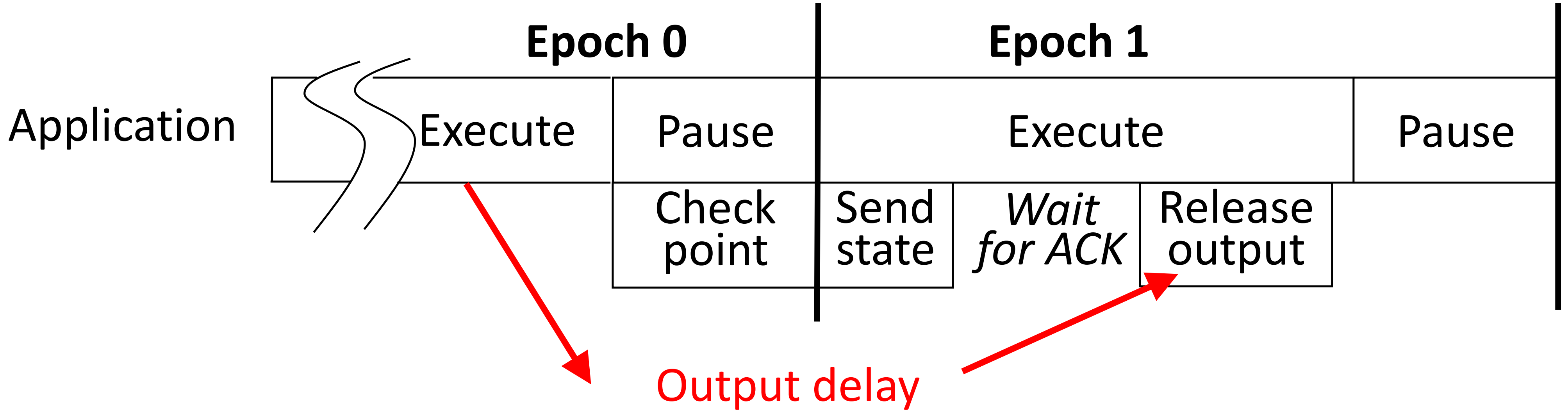

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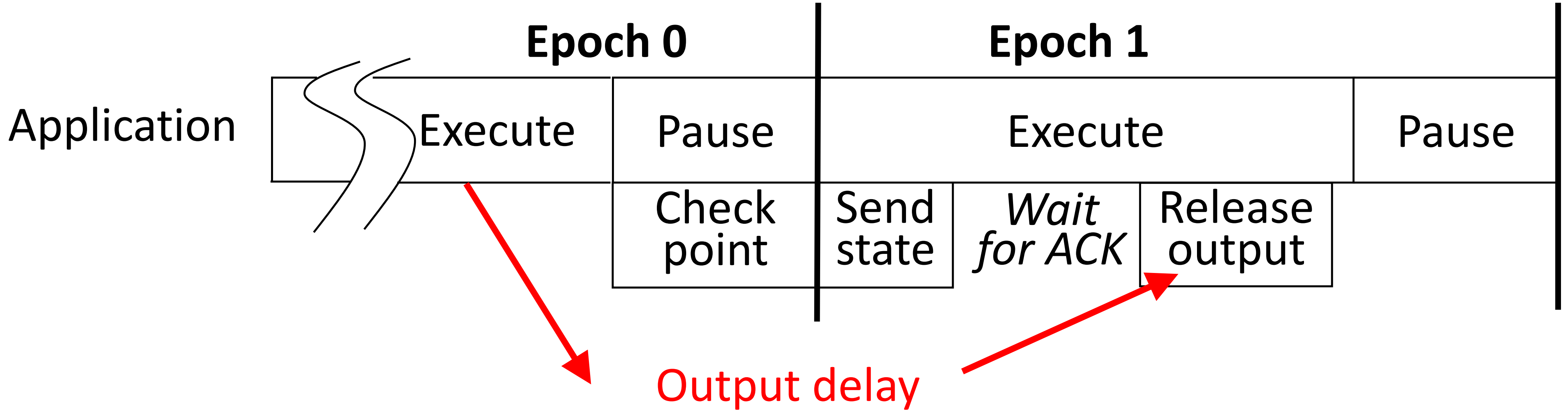

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In practice: 10s of milliseconds interval → 10s of milliseconds latency

→ Unacceptably high latency overhead

Active Backup: Mechanisms based on Active Replication

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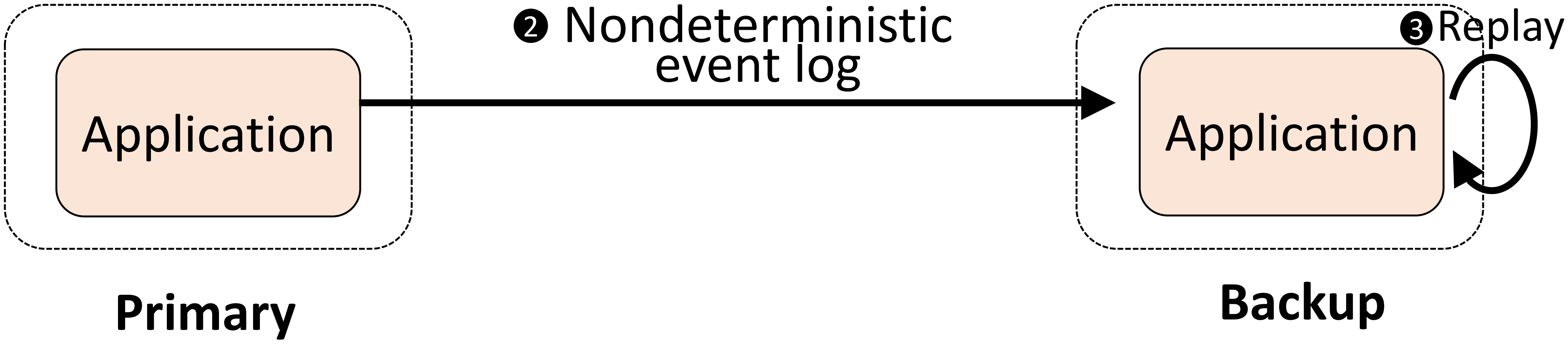

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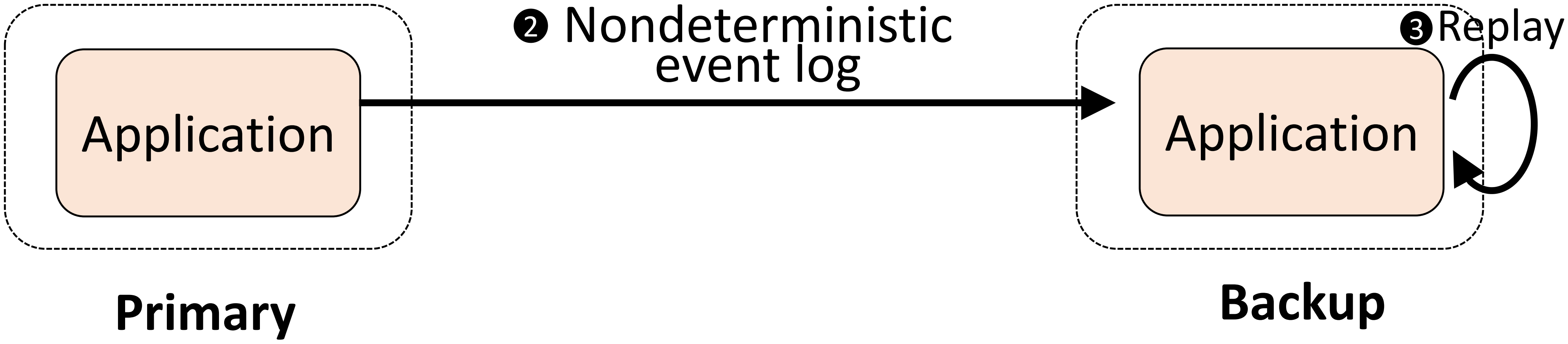
- Primary sends outcomes of nondeterministic events to backup
- Backup enforces outcome of nondeterministic events to match execution

Disadvantages of Active Backup Mechanisms



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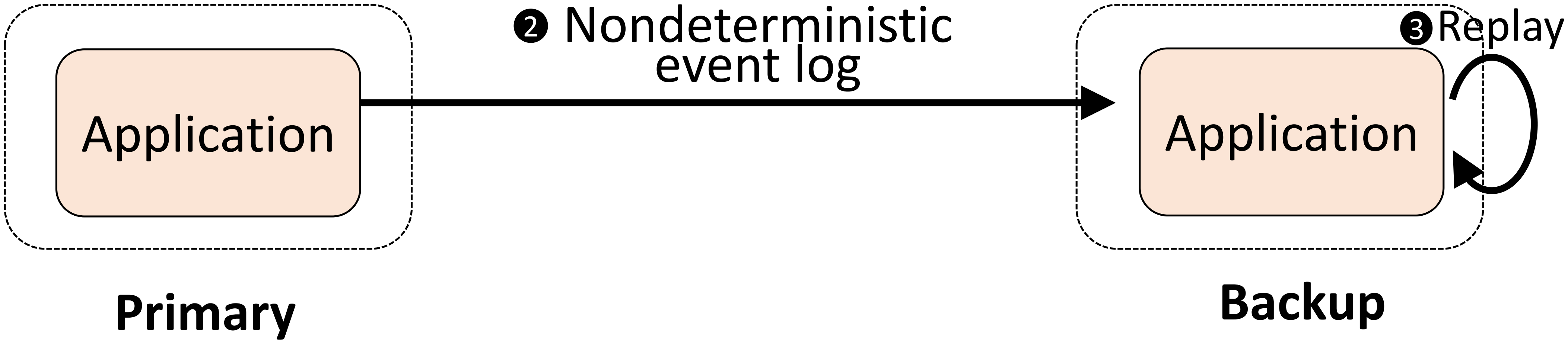

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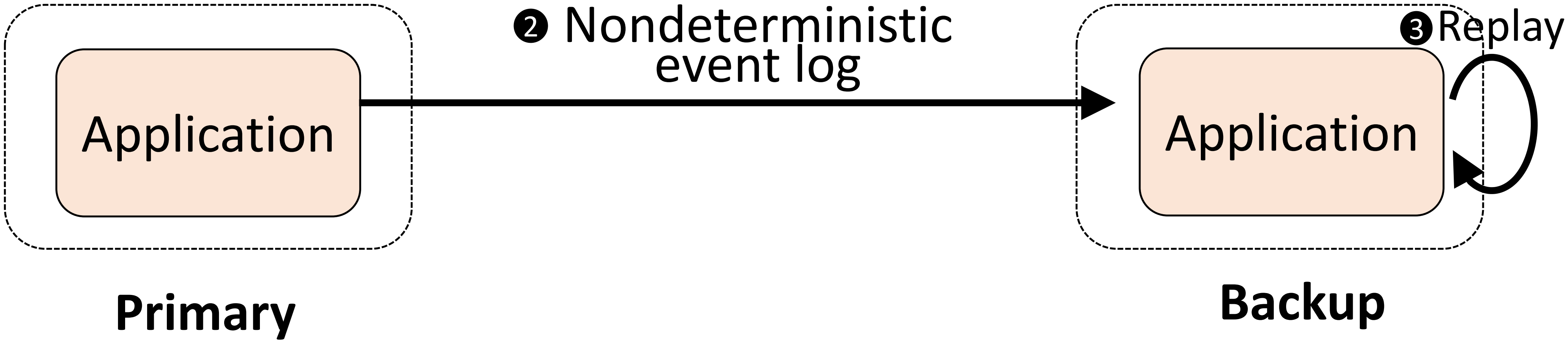

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- Performance limited by tight coupling between replicas
- Resource overhead **lower bound** = 100%

Undesirable Couplings in Current Mechanisms

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RRC breaks these couplings

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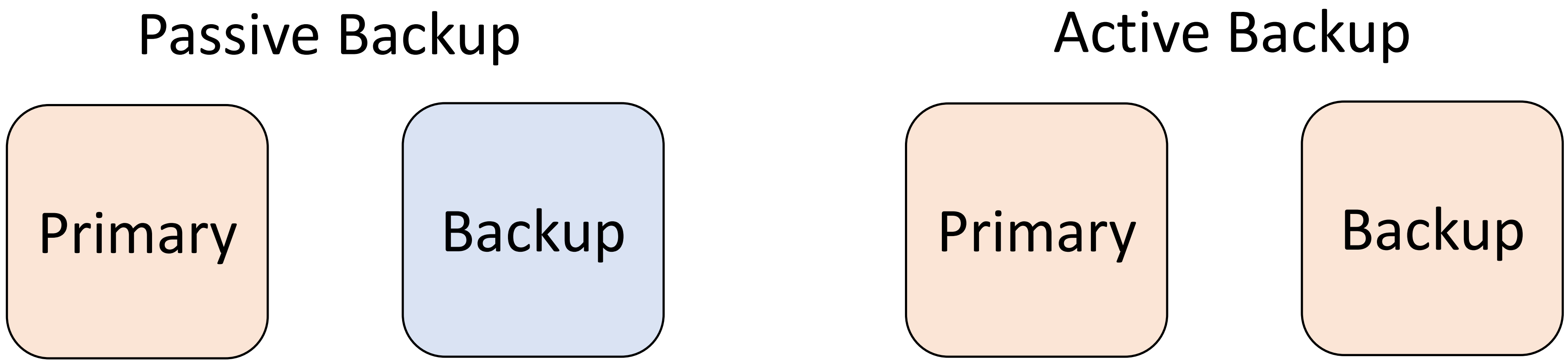
Passive Backup as the Starting Point



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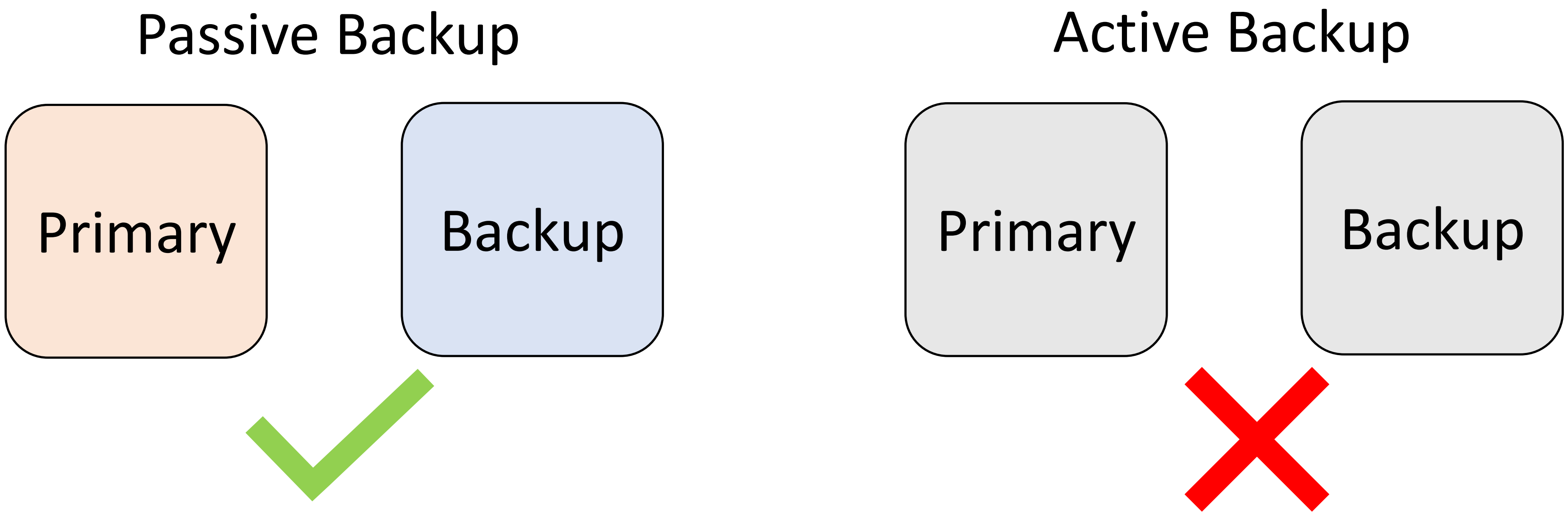

- Avoid vulnerability to nondeterminism
- Avoid coupling performance of primary with backup
- Reduce resource overhead

Decoupling Latency Overhead from Checkpoint Interval Using hybrid replication

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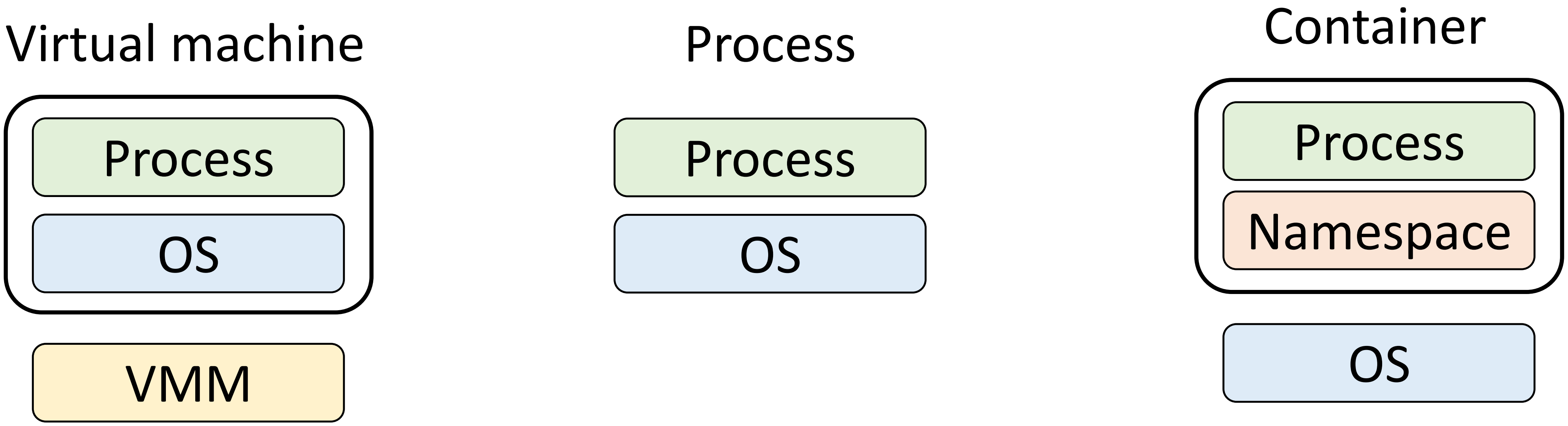
Solution: Hybrid replication – combine checkpointing with execution replay

- Outputs release decoupled from checkpoint commitment
- On primary failure
  - Restore the last checkpoint on backup
  - Backup replays primary execution up to the last released outputs

Choice of Granularity of Replication



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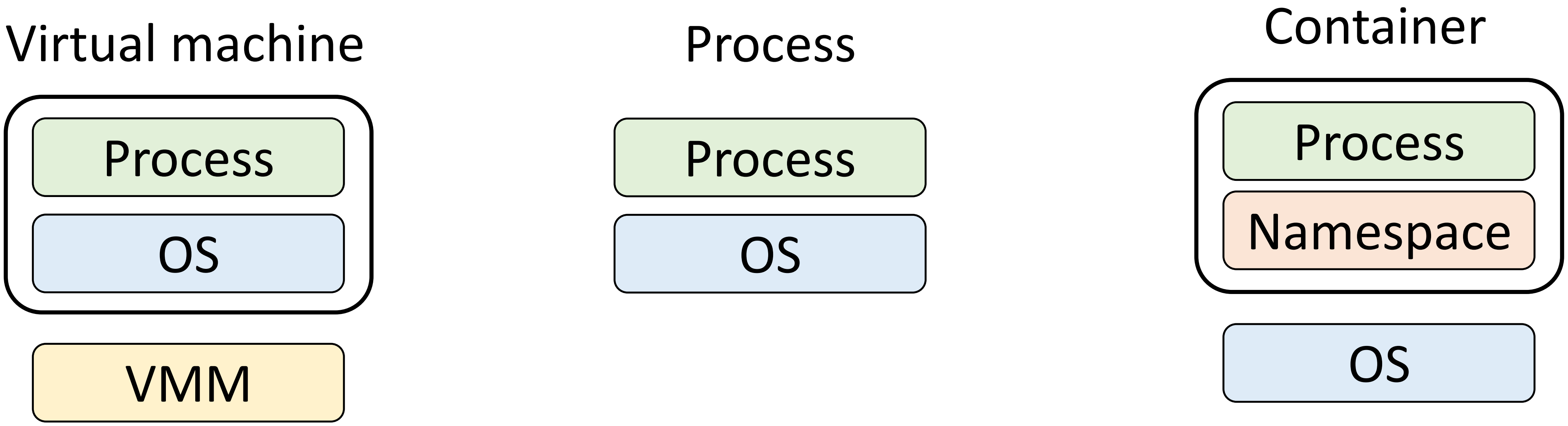
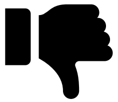
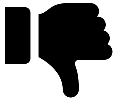



High runtime overheads


Tracking OS nondeterministic events

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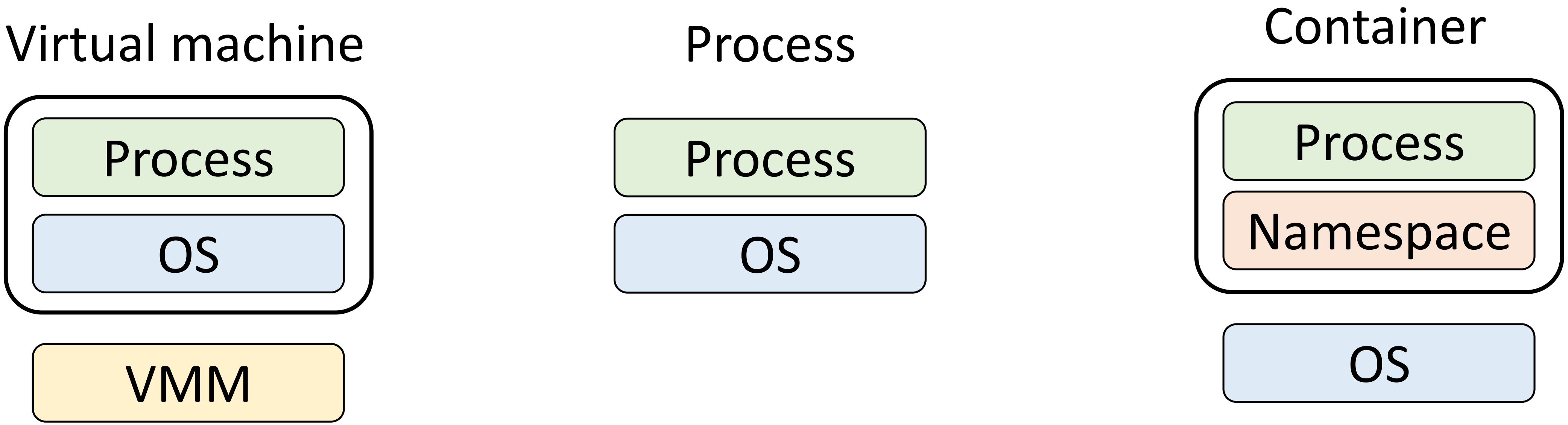

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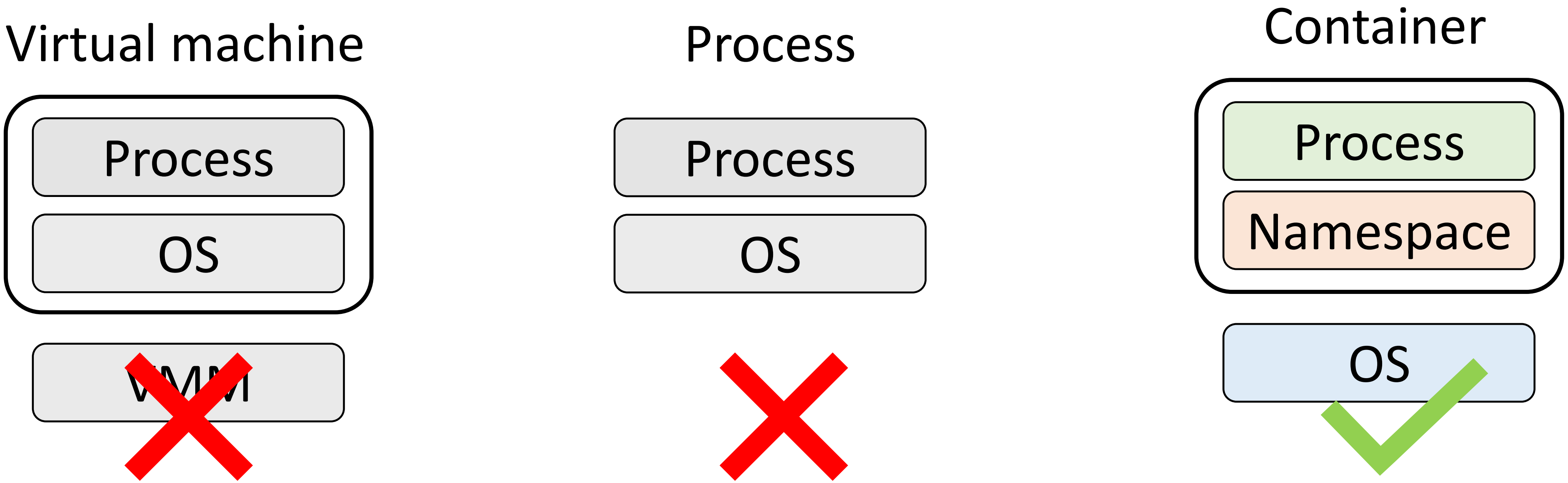

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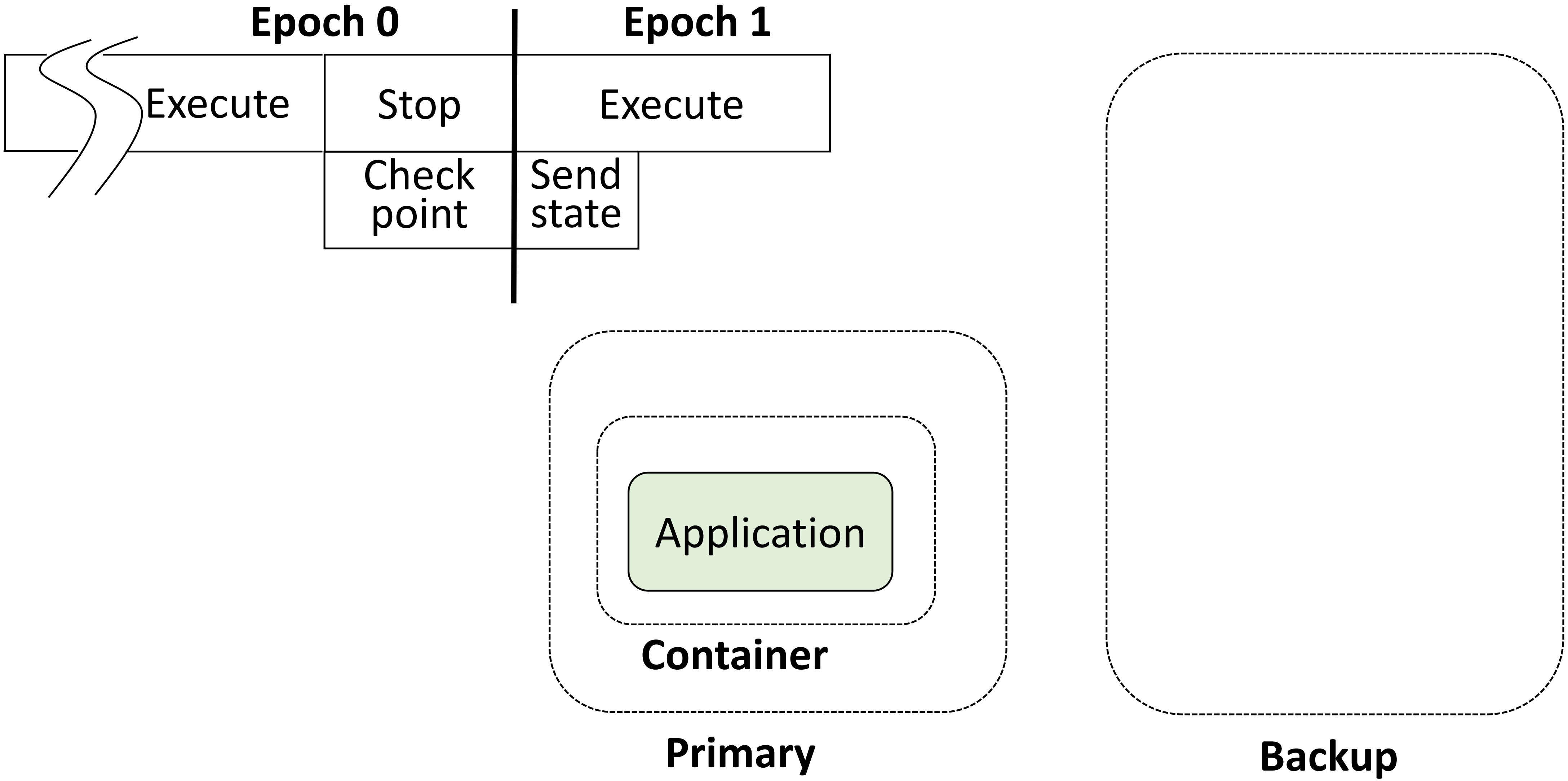
- Naming conflicts e.g., process ID

- Resolves limitations of processes/ VMs

Normal operation



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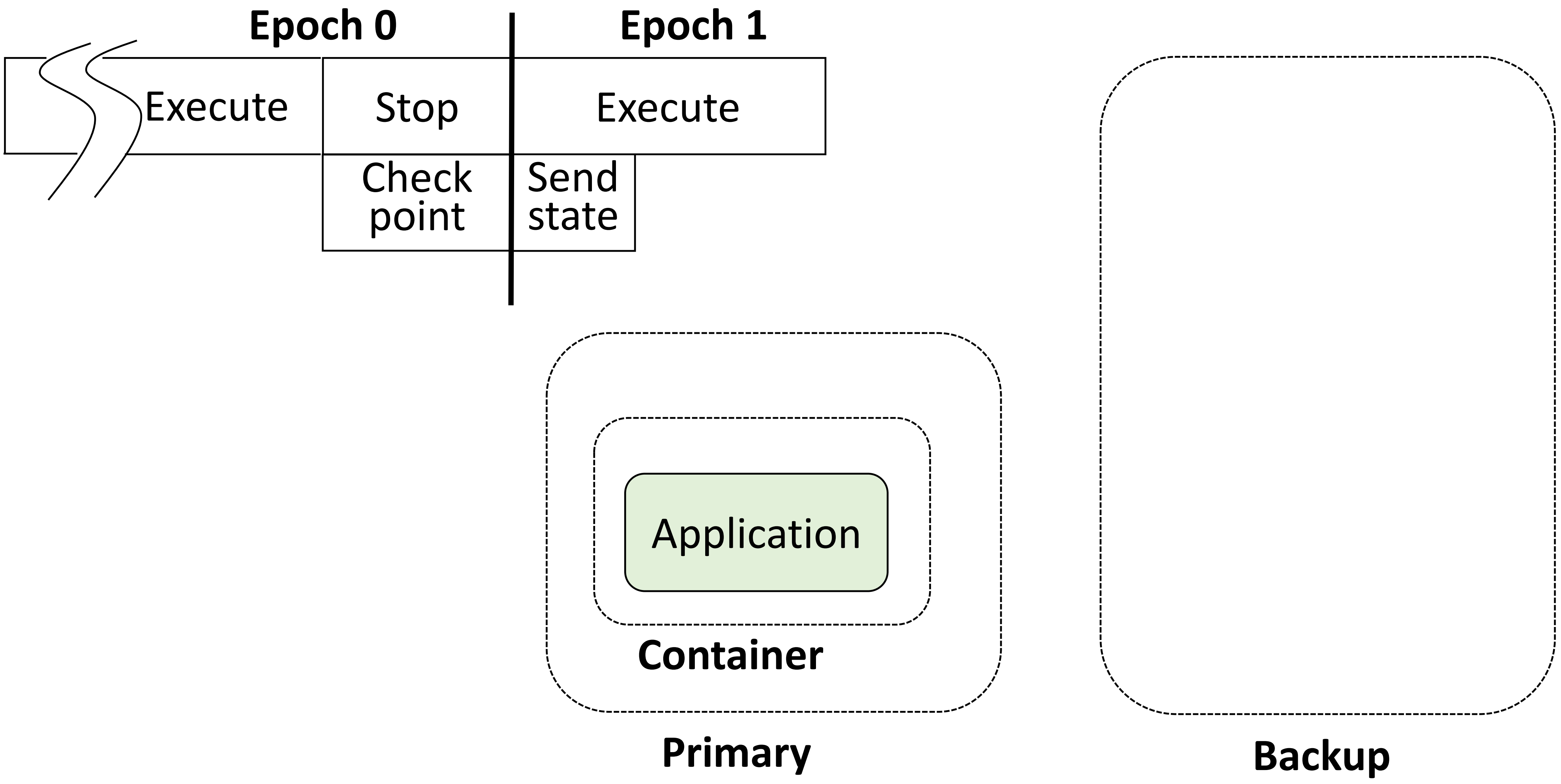

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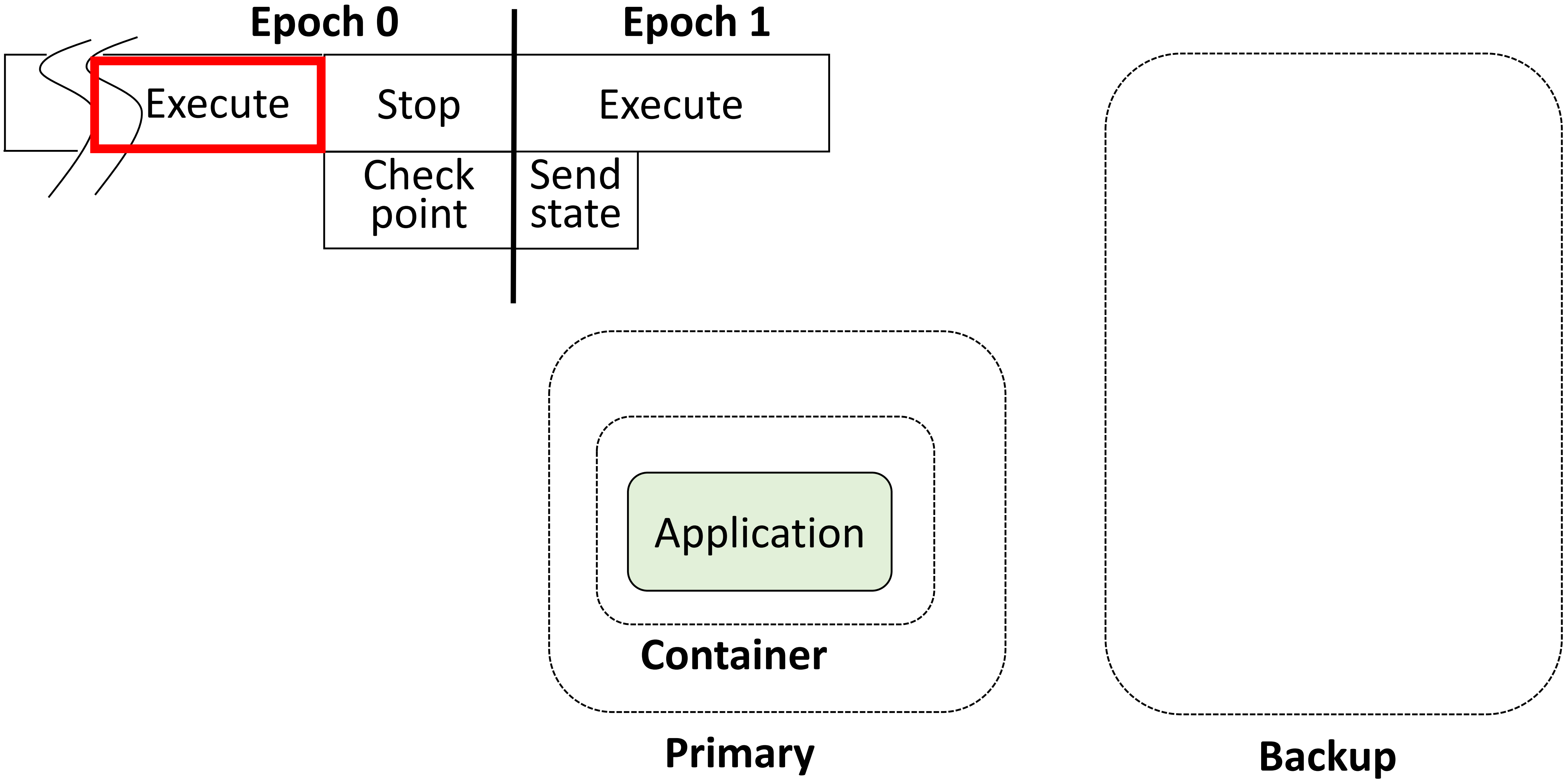

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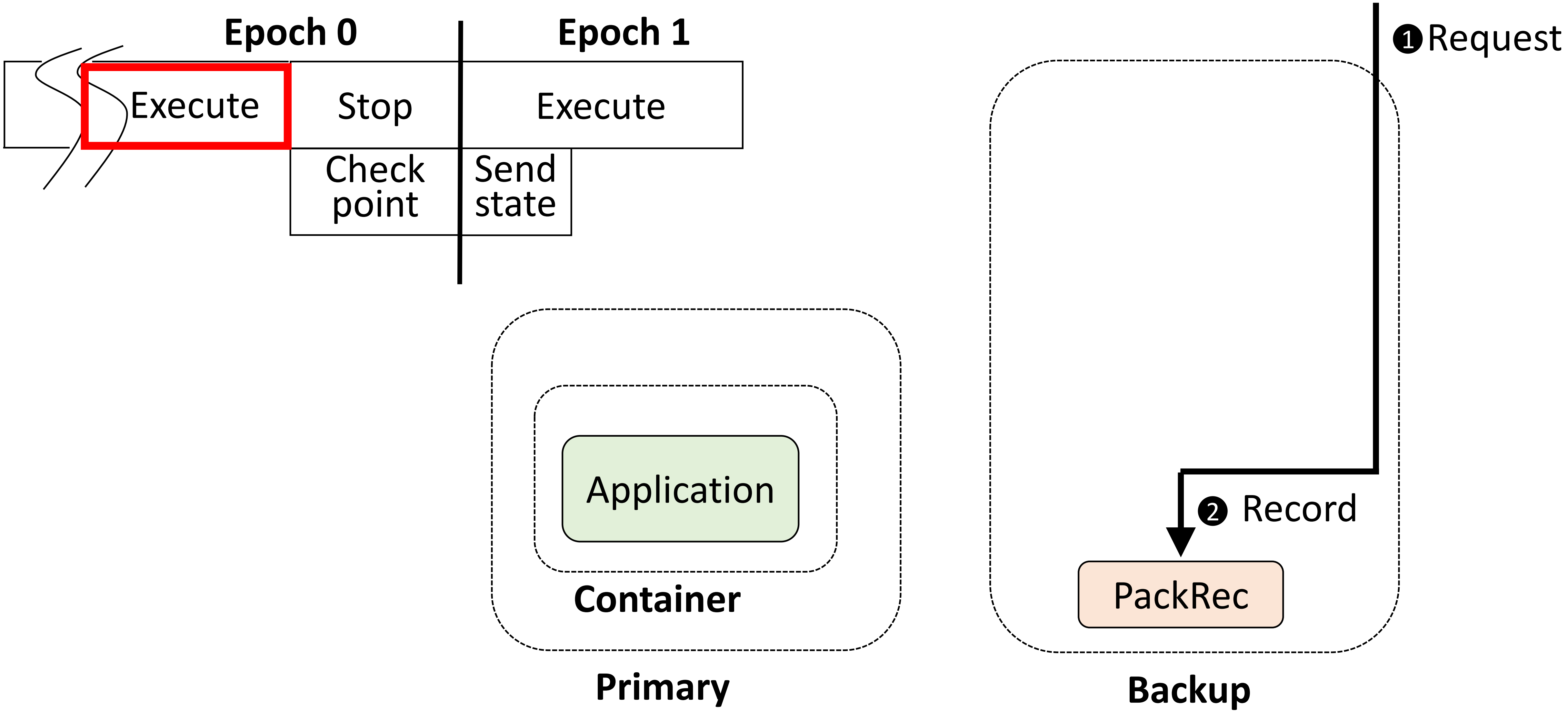

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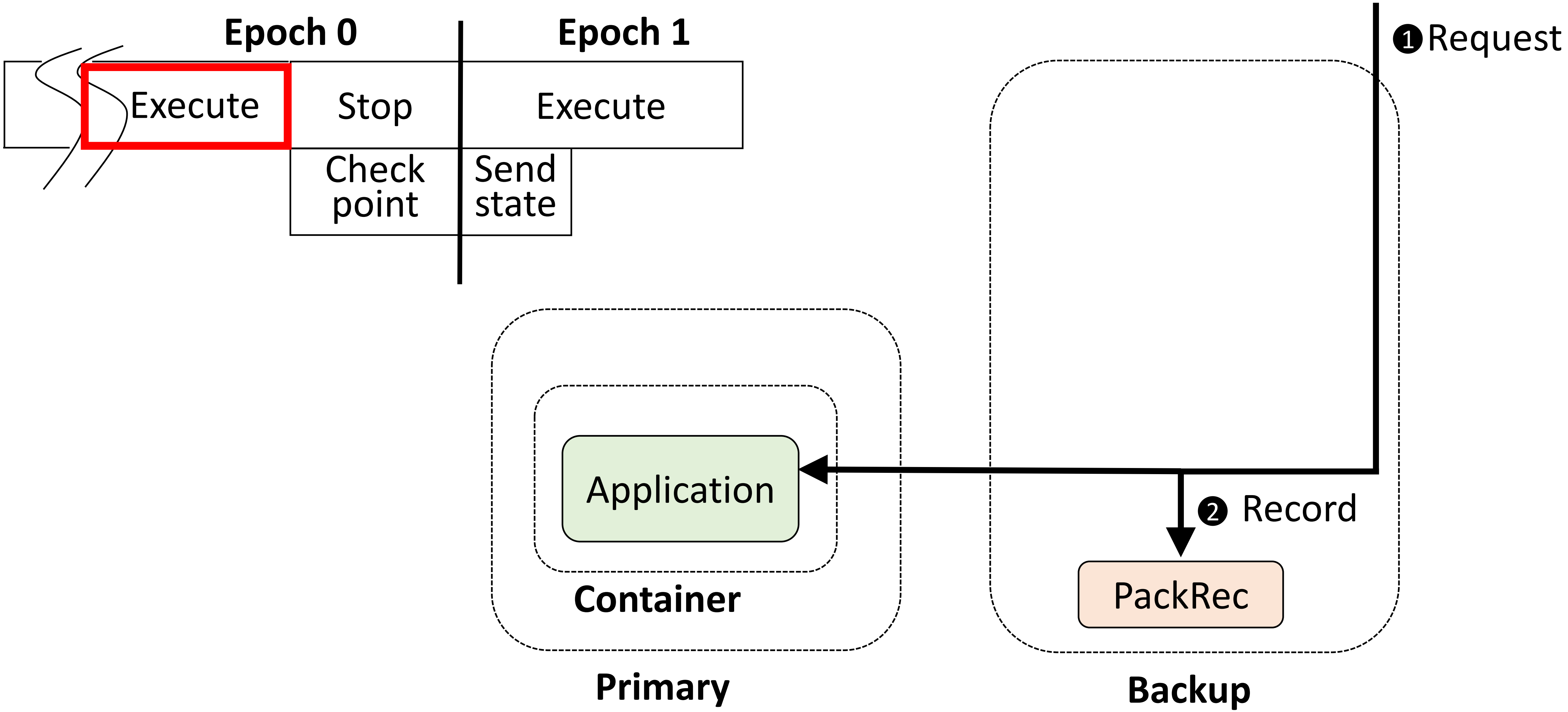

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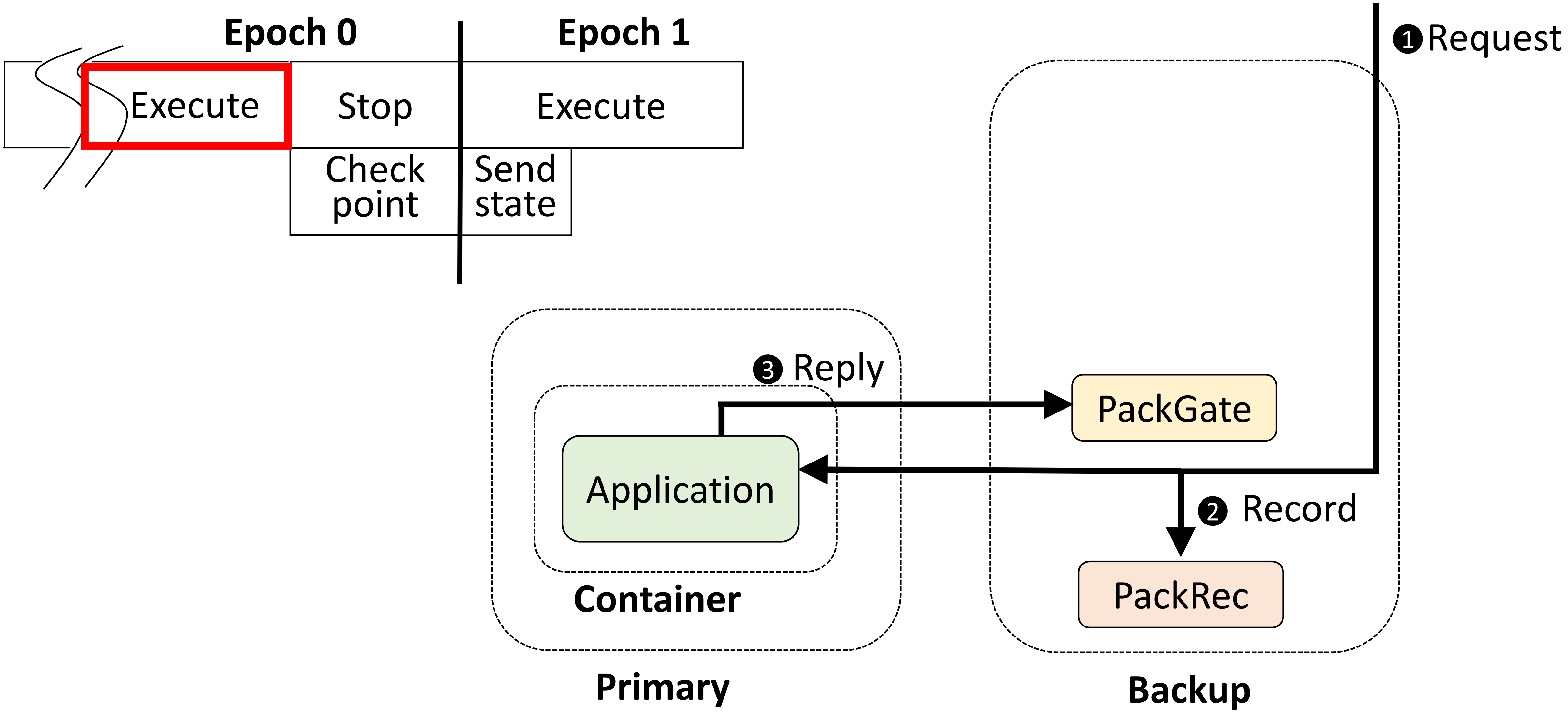

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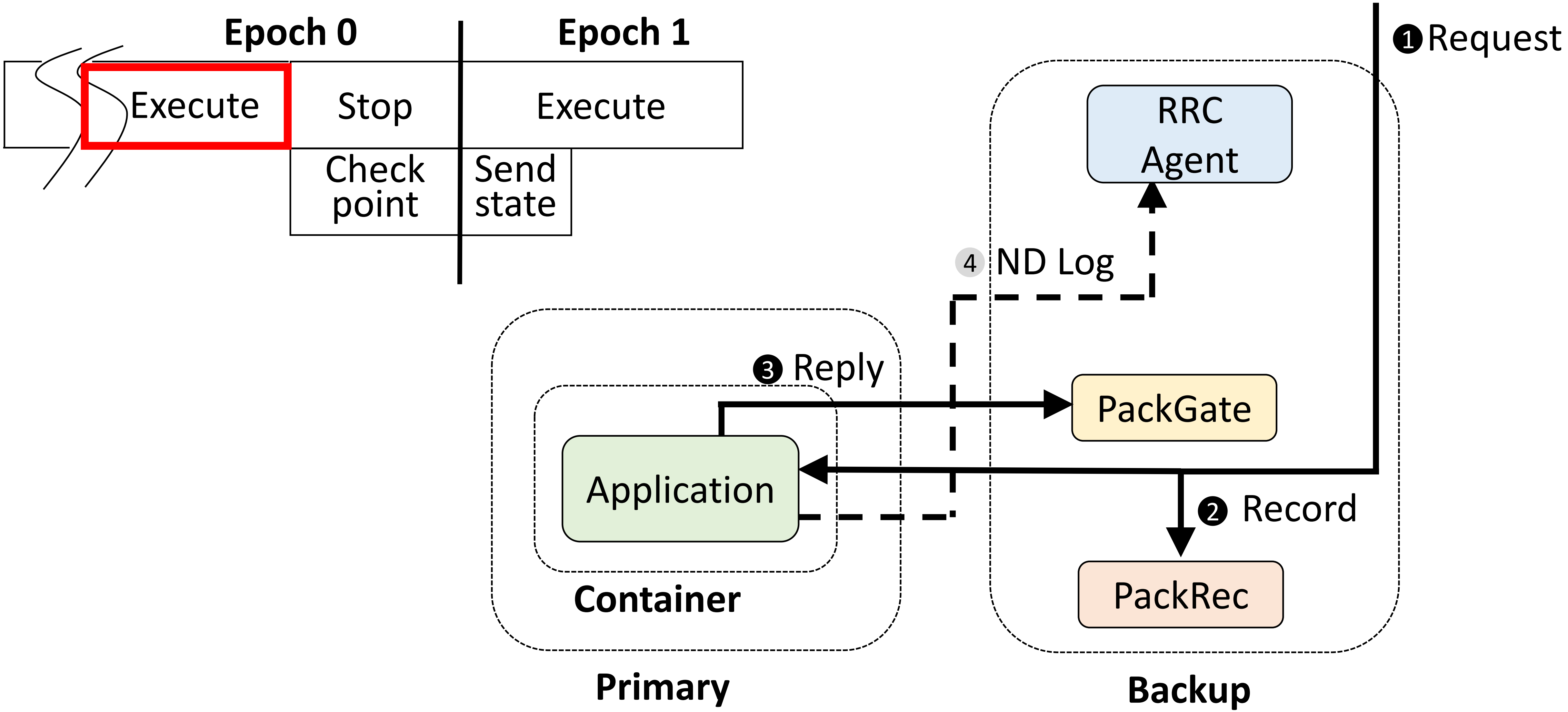

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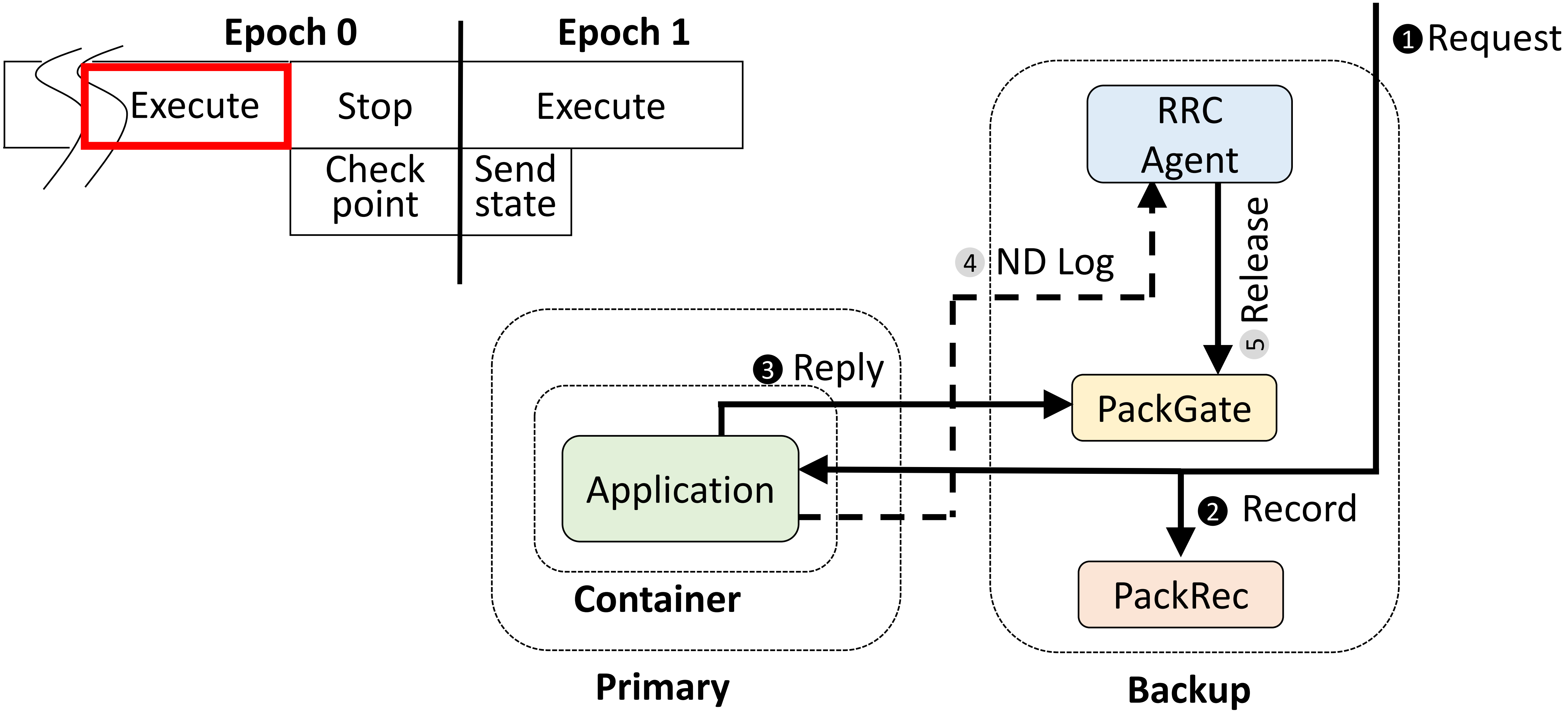

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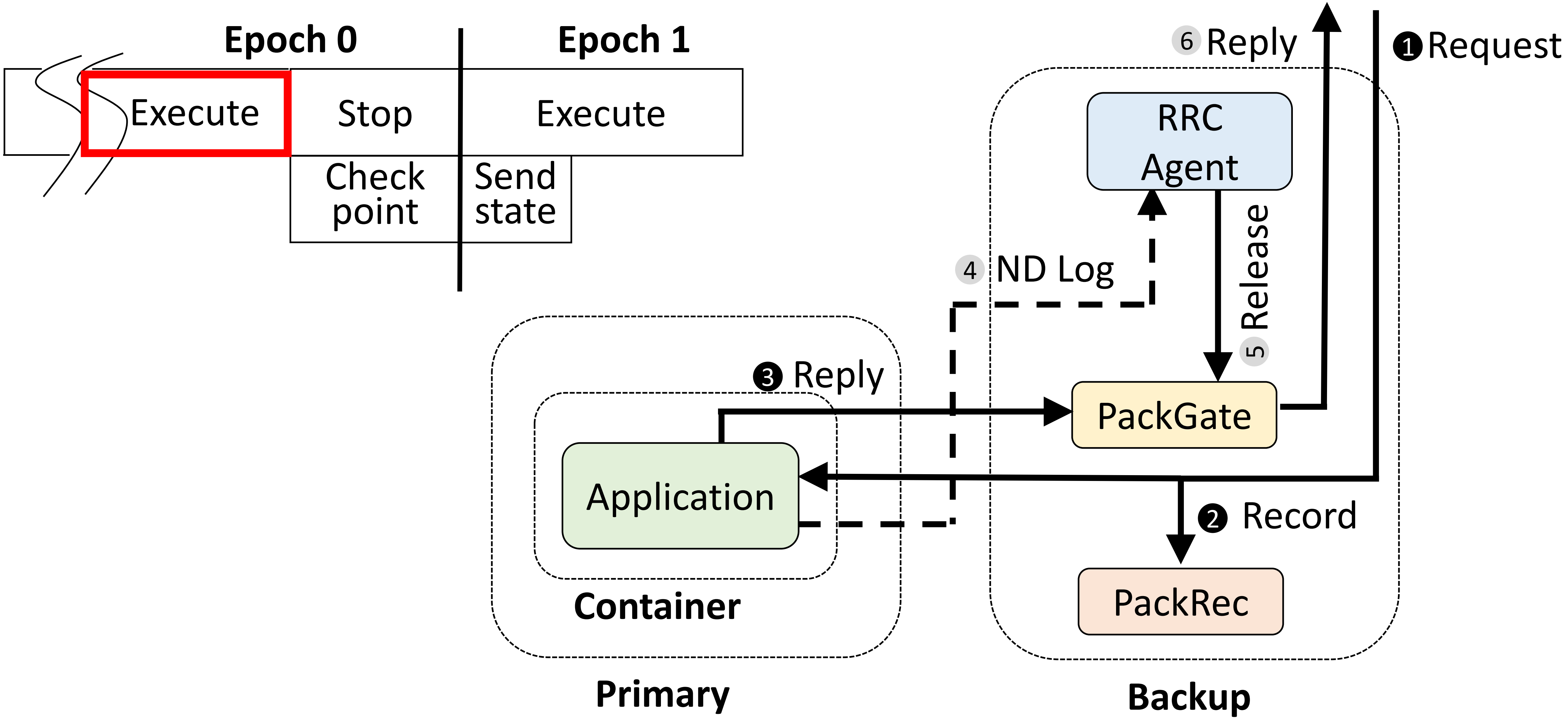

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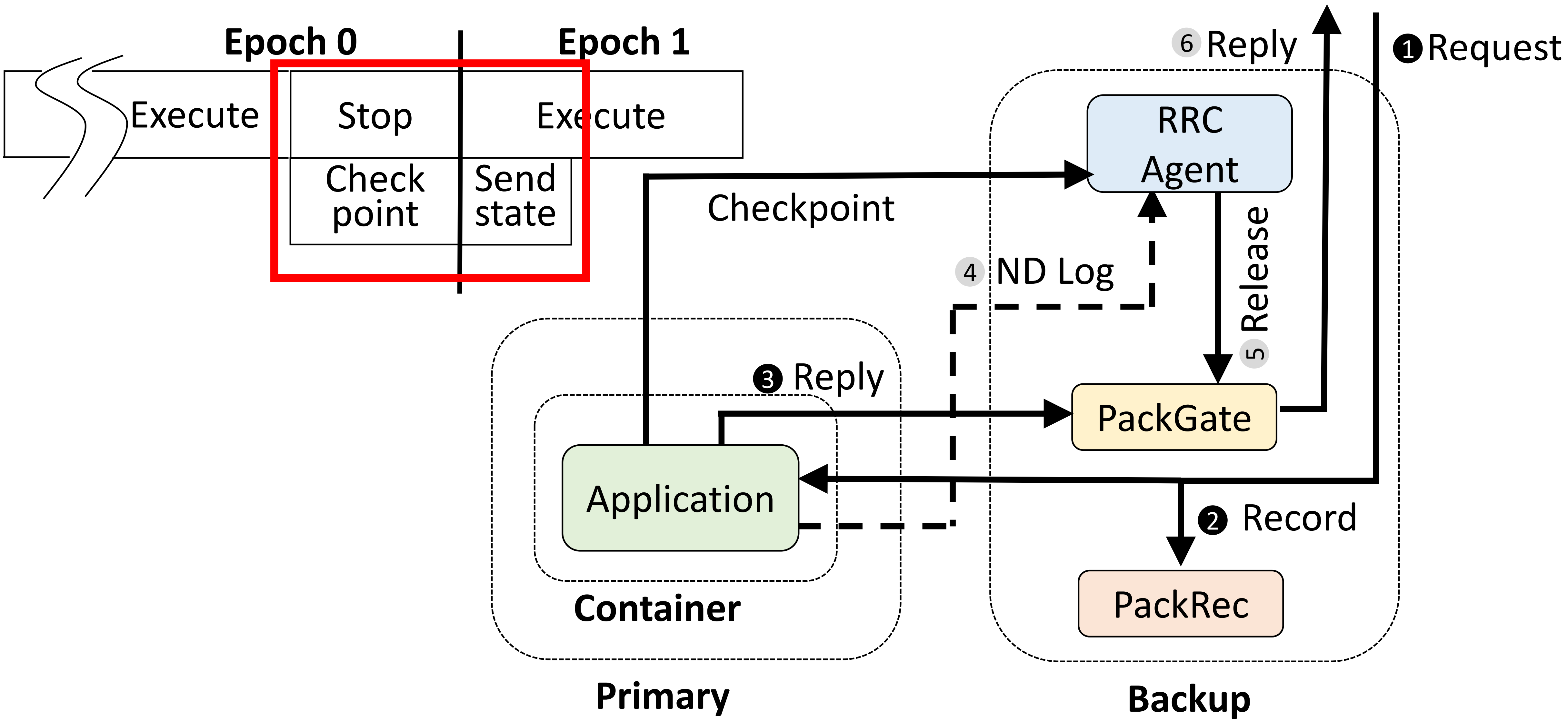
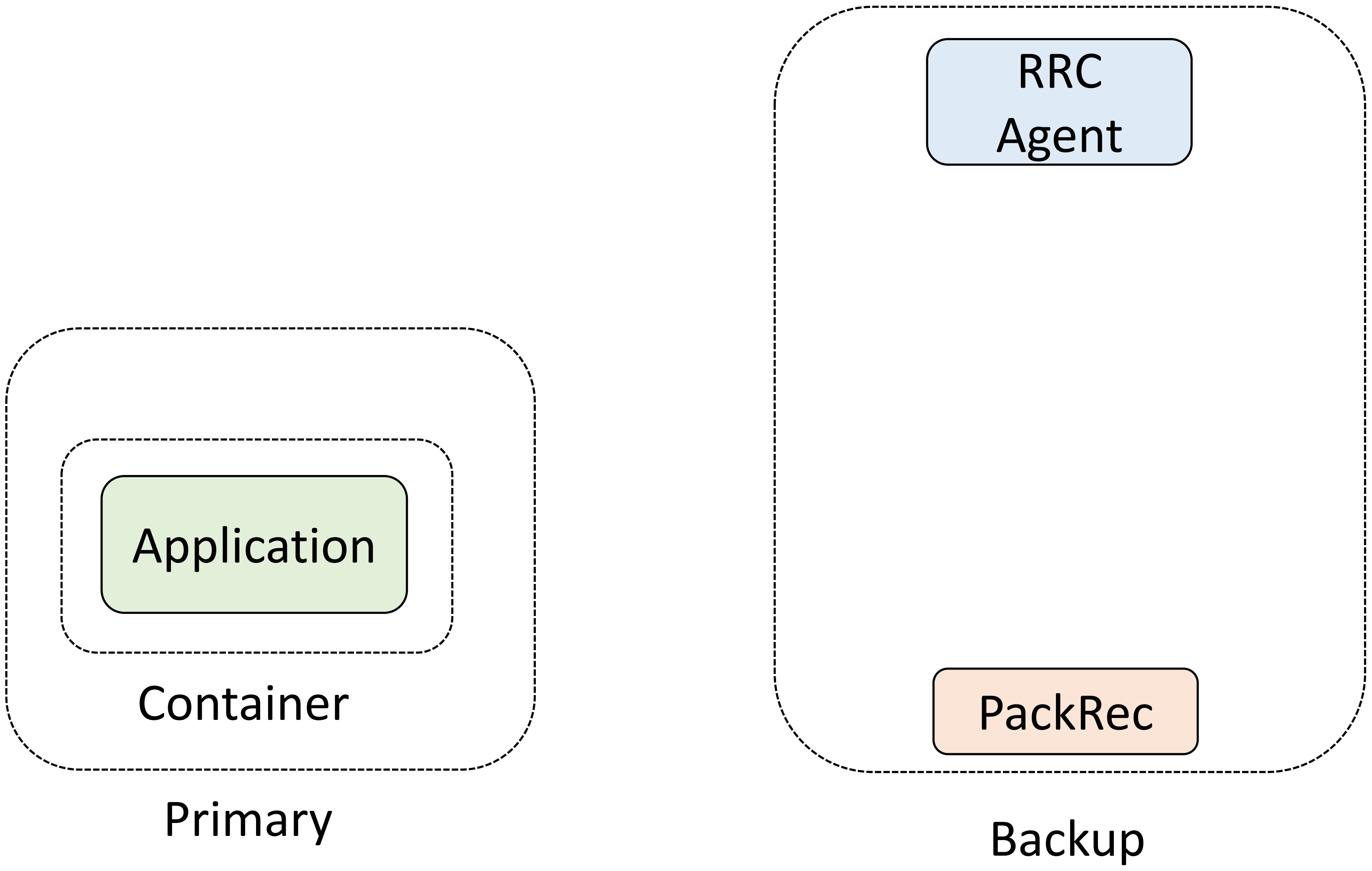


Handling Primary Failure



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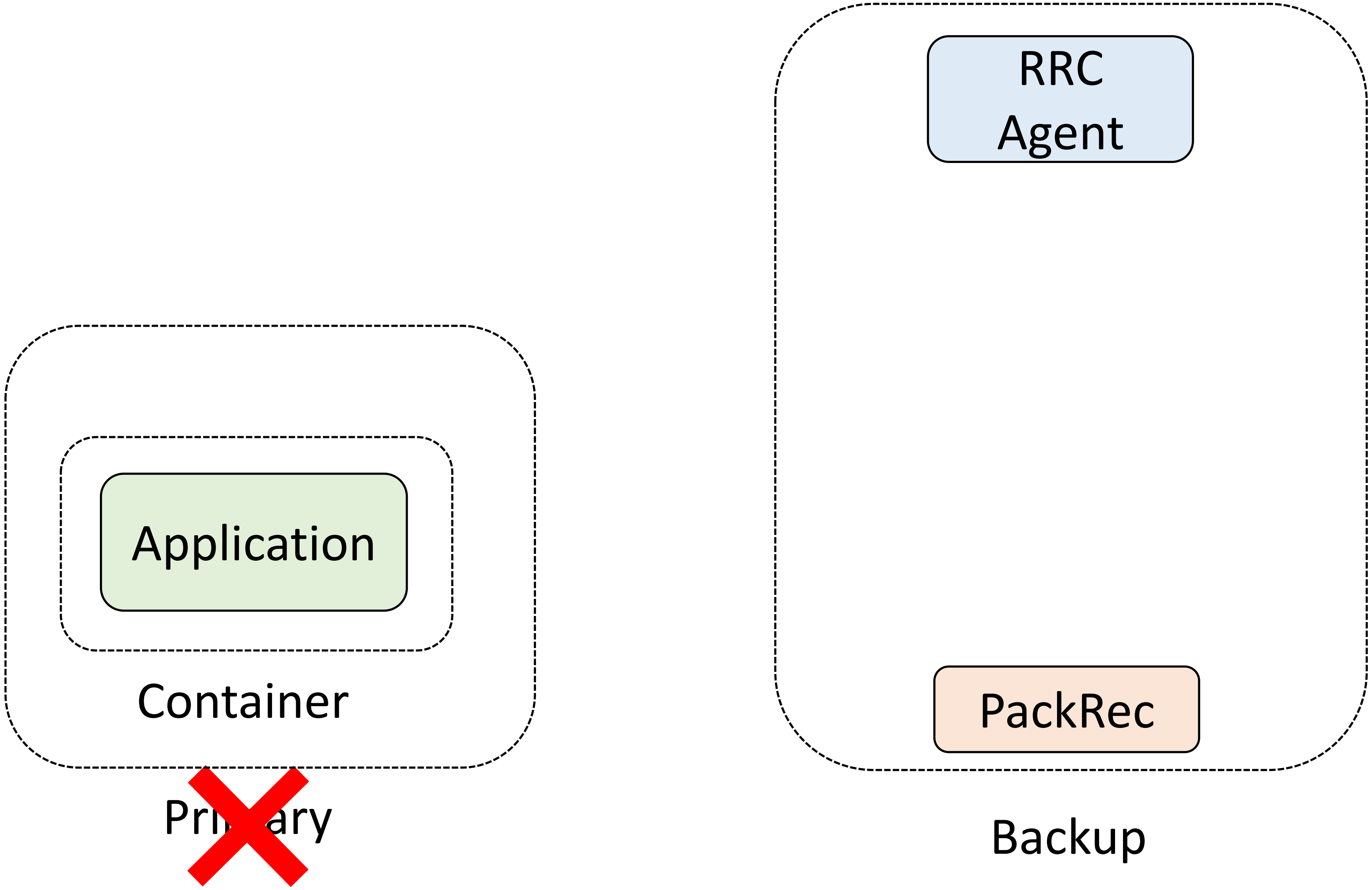

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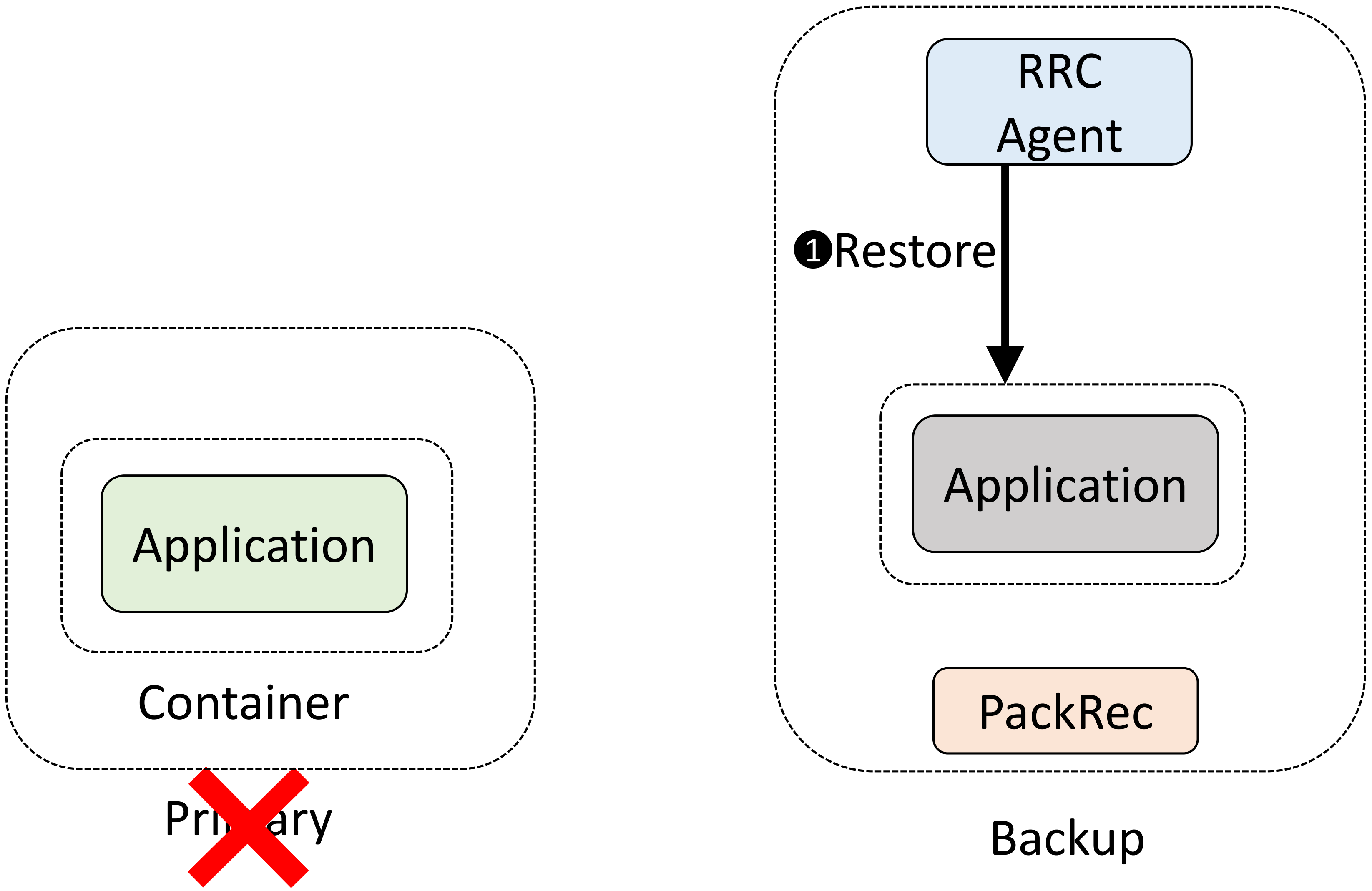

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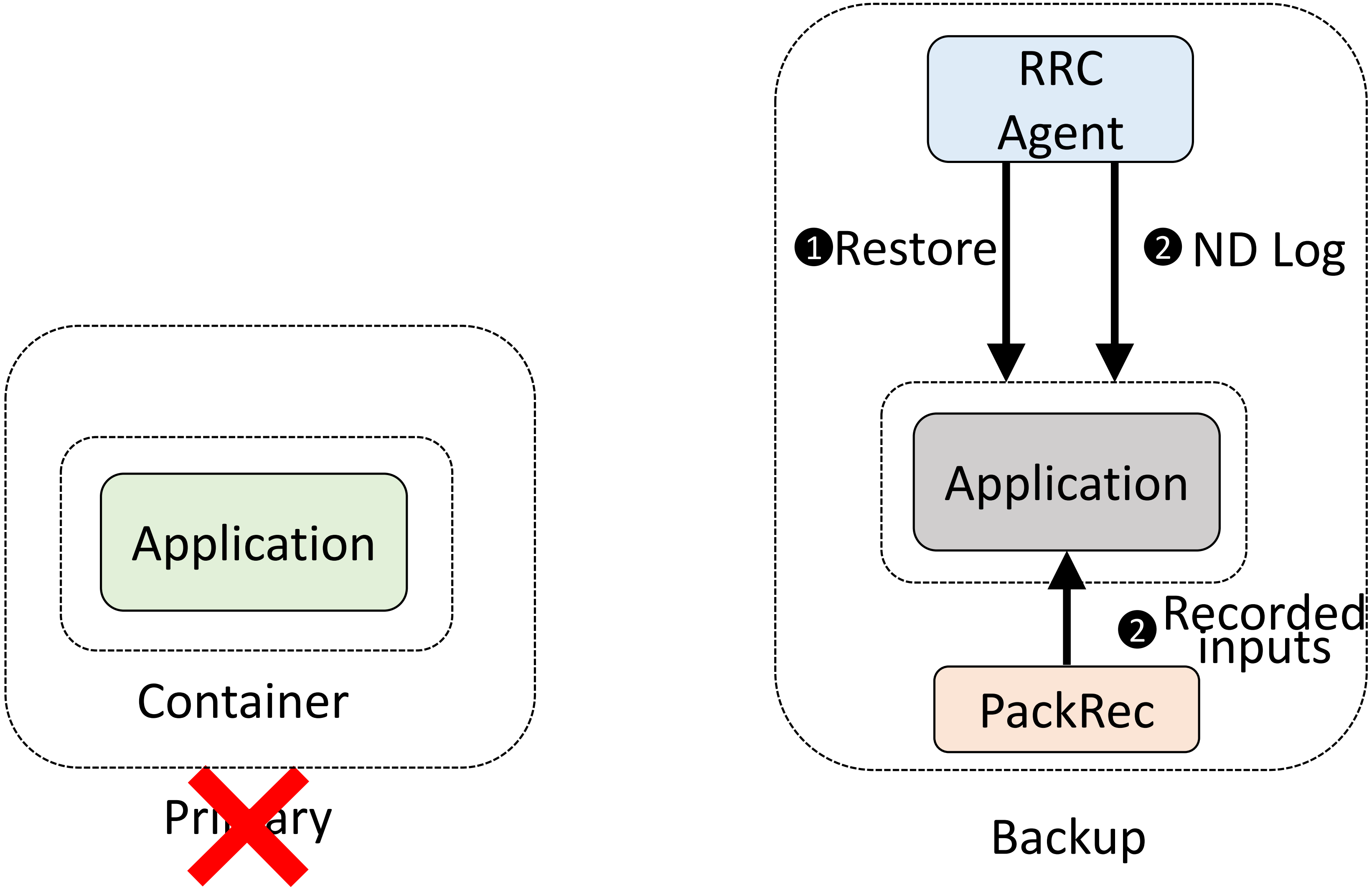

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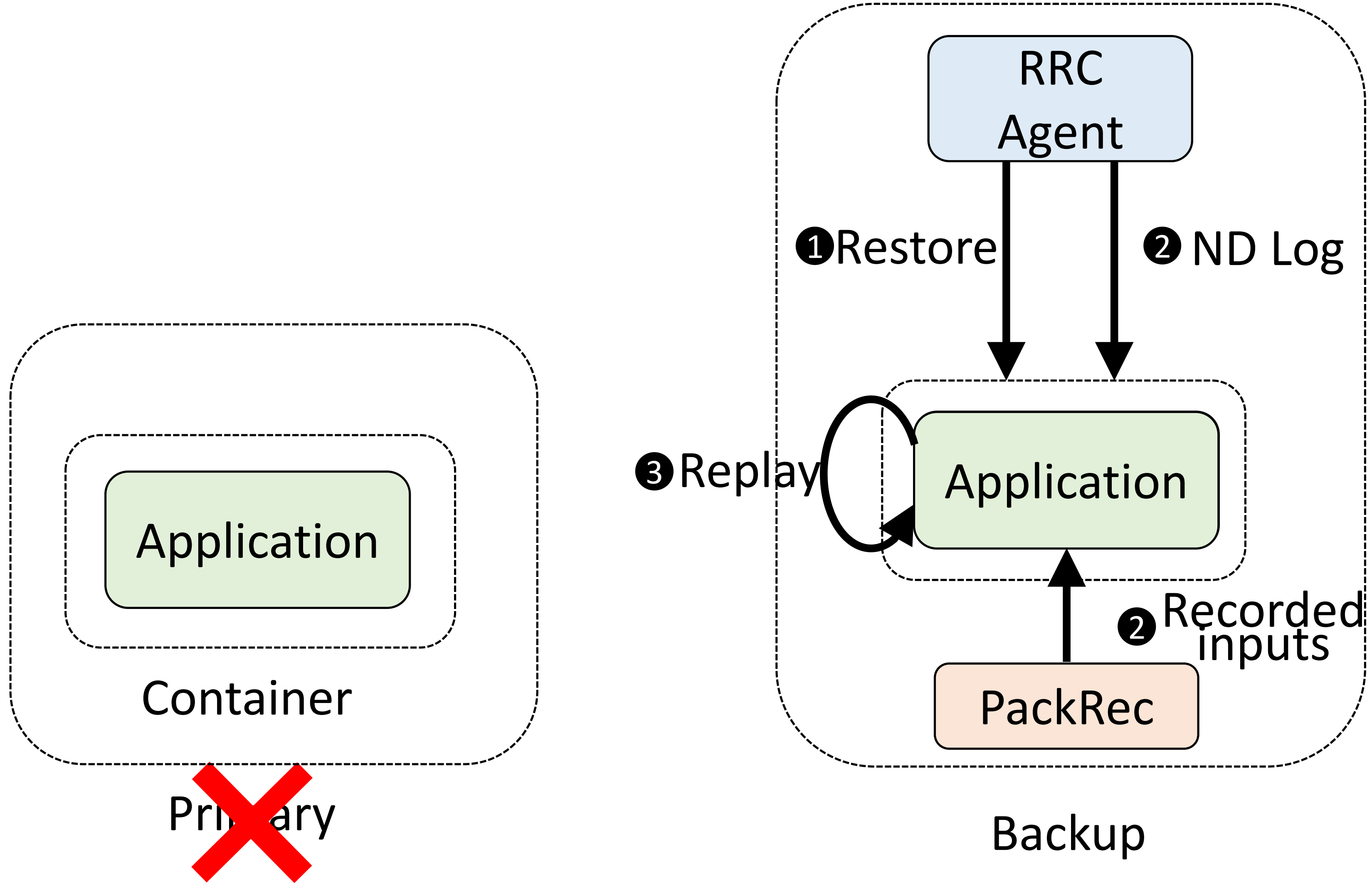

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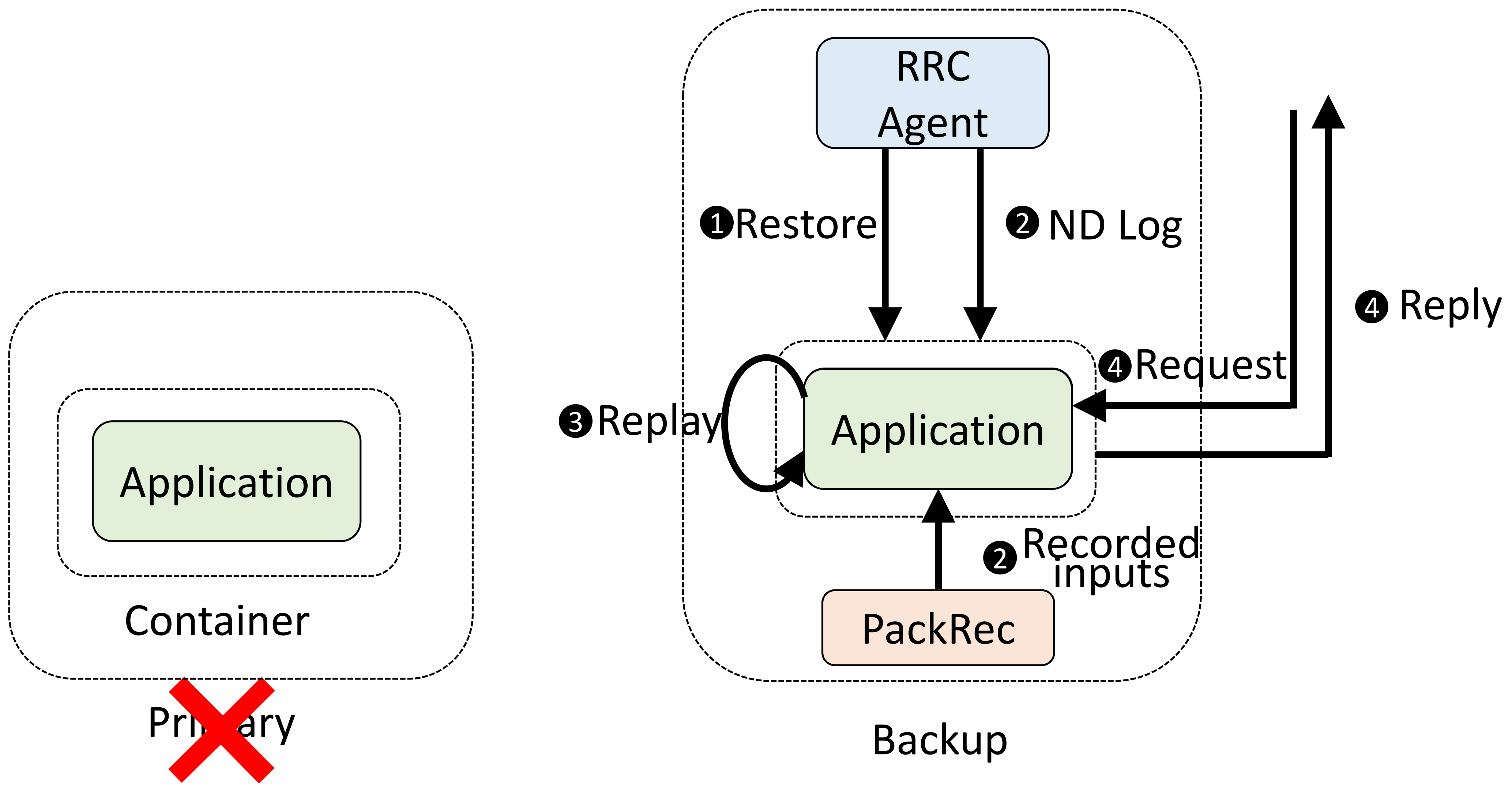
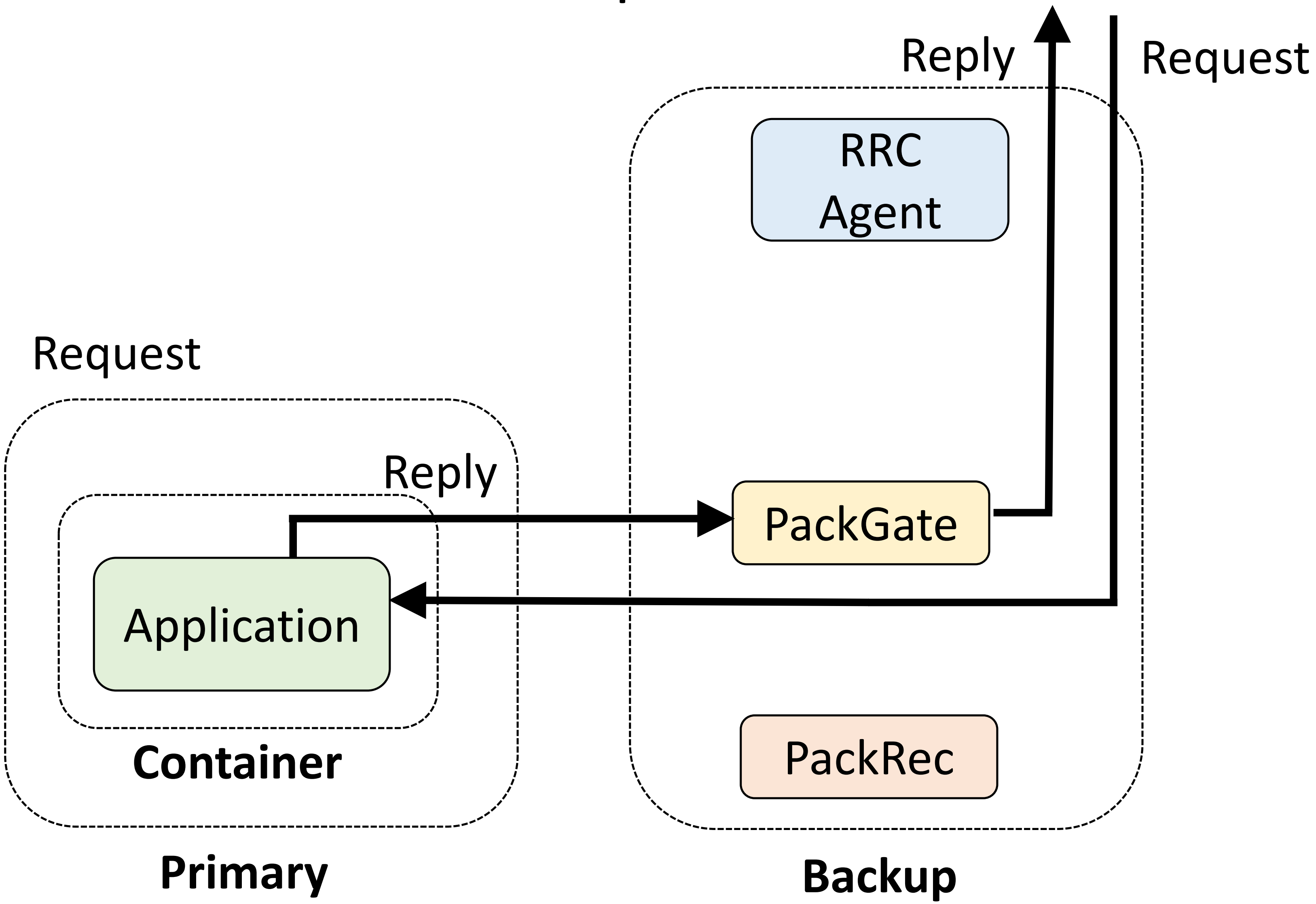


RRC: Backup Failure



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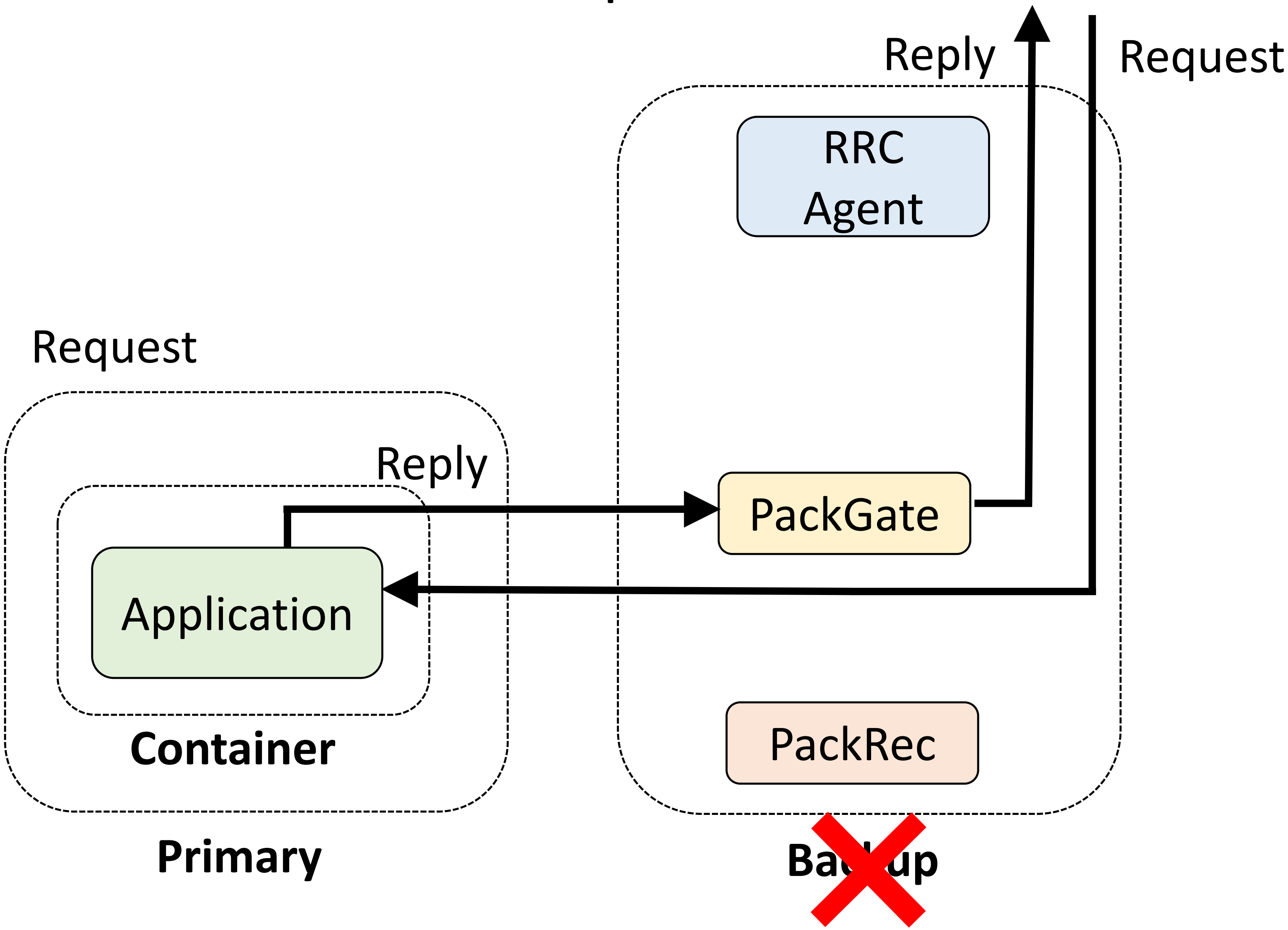

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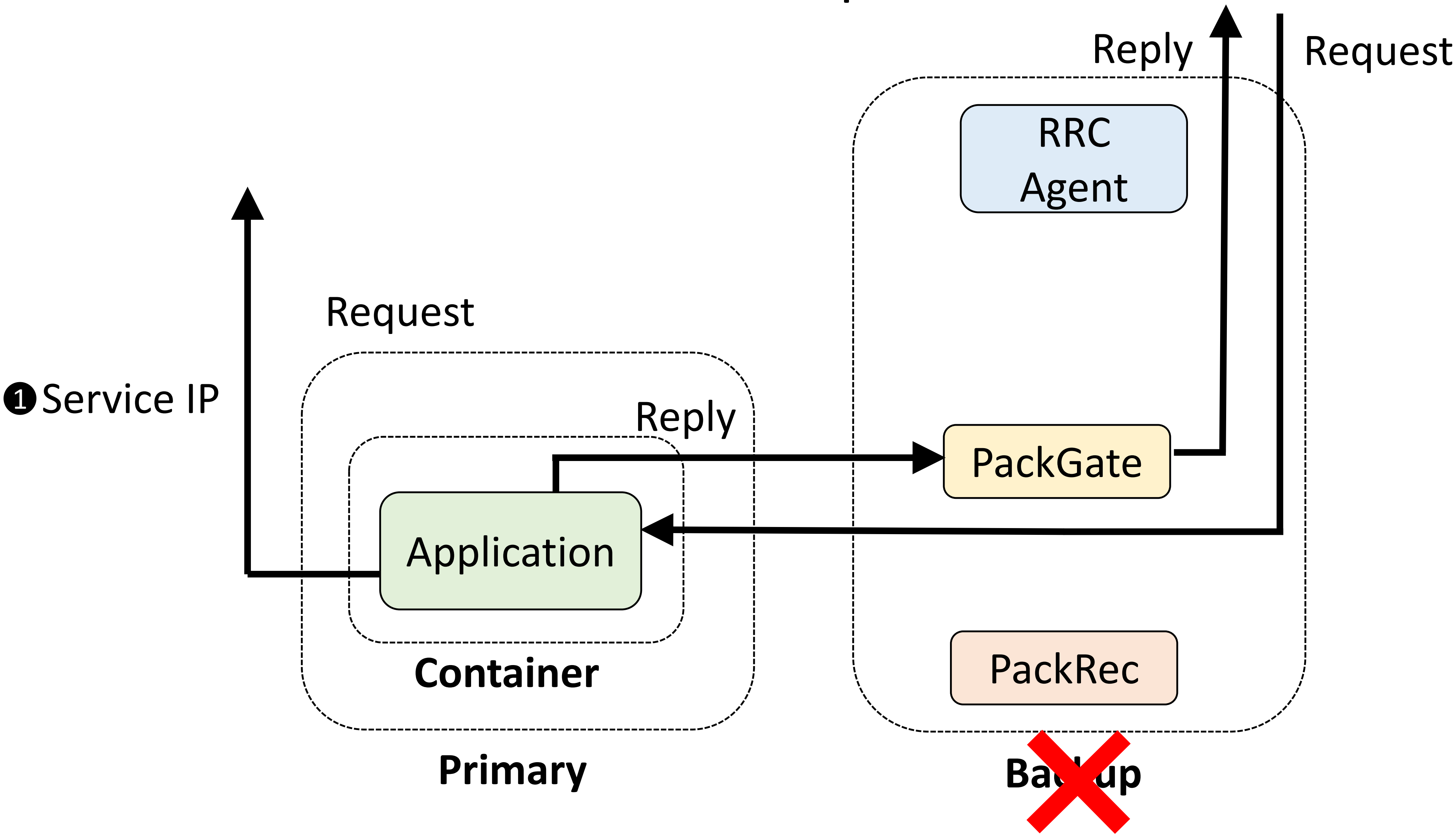

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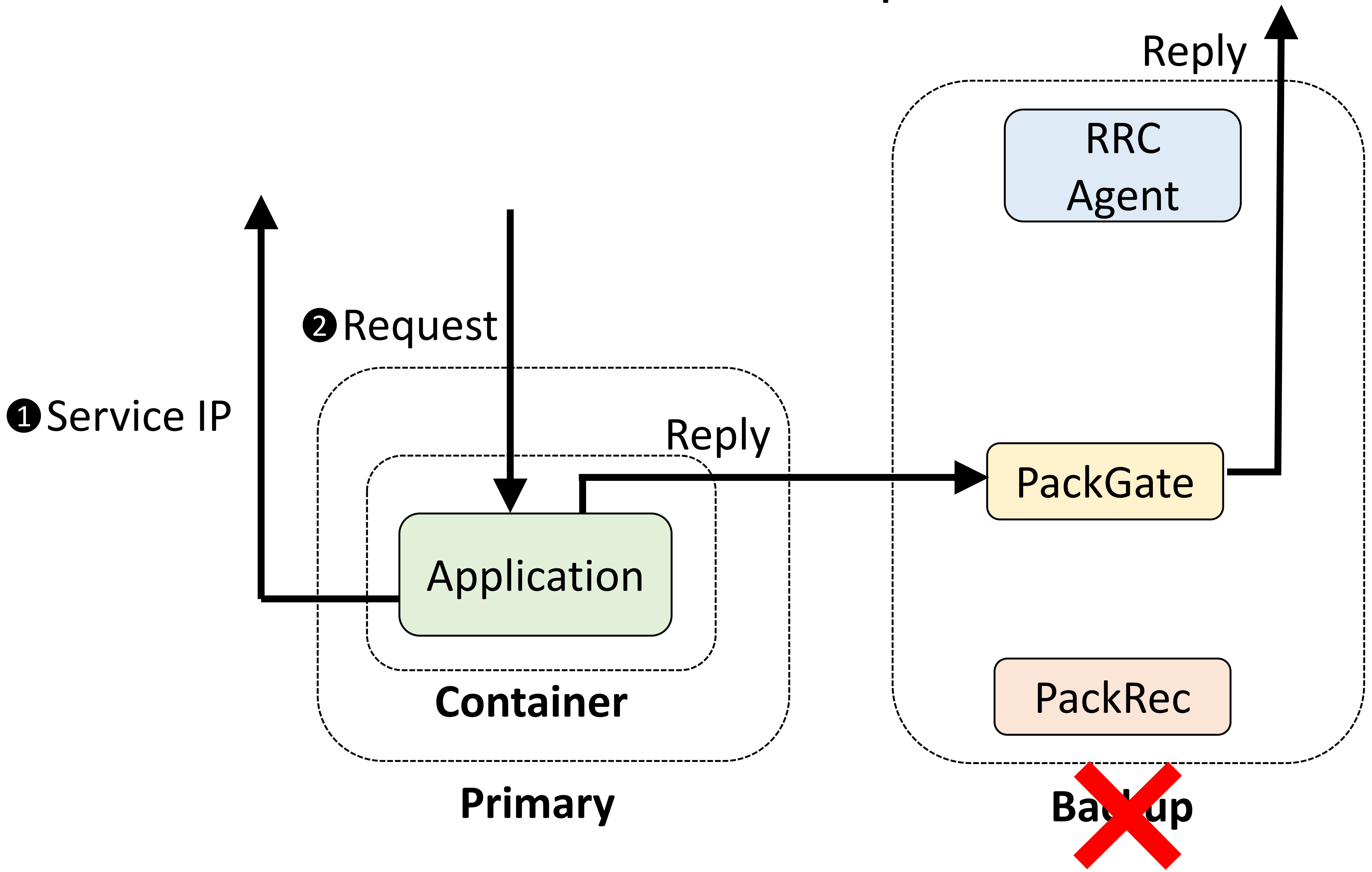

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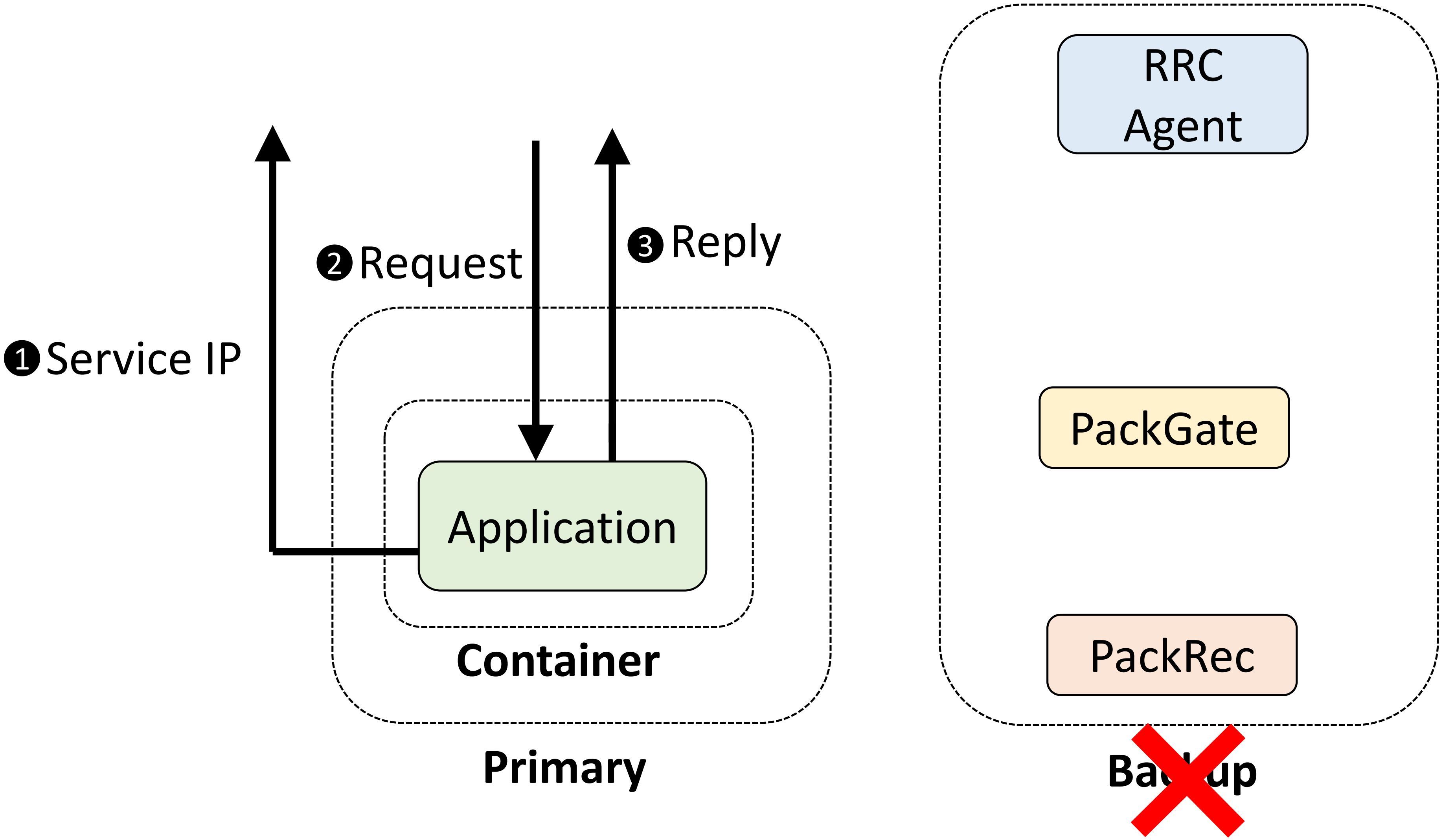

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Key Design and Implementation Challenges

- Minimizing pause time during checkpointing
- Handling untracked nondeterministic events
- Robust integration of asynchronous checkpointing and recording of nondeterministic events
- Minimizing the overhead for collection and transfer of nondeterministic event logs
- Integration of TCP failover with replay during recovery

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Container: tight state coupling with the underlying kernel

→ Significant in-kernel container state must be checkpointed

→ Retrieving the in-kernel container state is slow**: thousands of syscalls**

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→ Retrieving the in-kernel container state is slow**: thousands of syscalls**

Checkpointing a container is **slow**

Service Pause during Container Checkpointing

Checkpointing requires saving a **consistent** state

→ Execution must pause during checkpointing

→ Service pause time during checkpointing

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Challenge: minimize the pause time despite slow checkpointing

Minimizing Service Pause Using Container Fork

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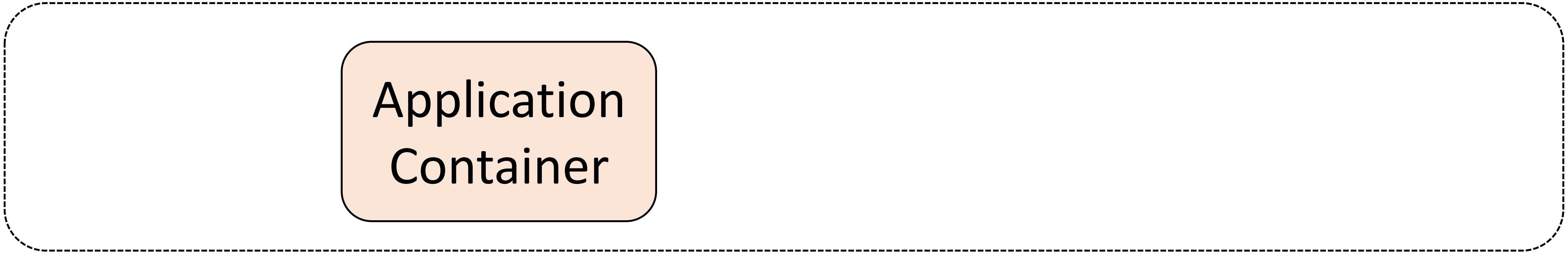
Primary Host



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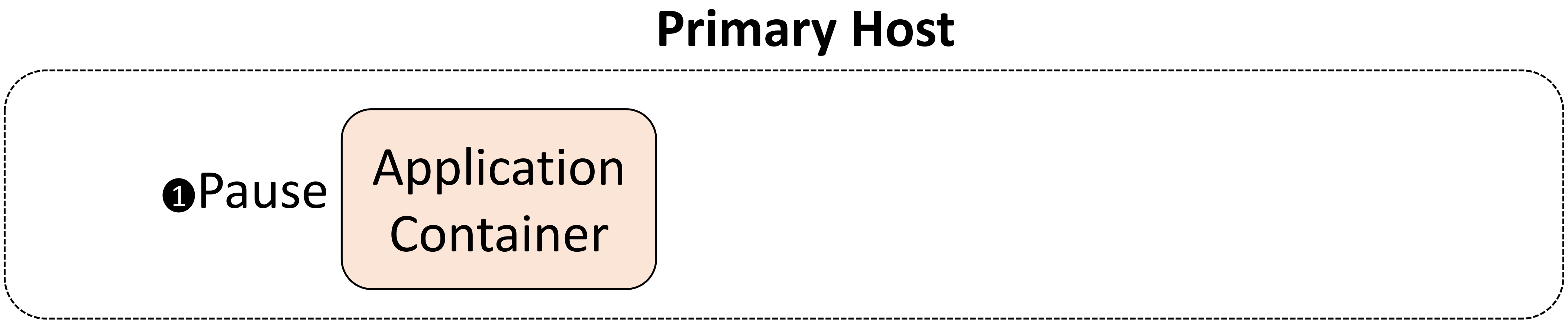

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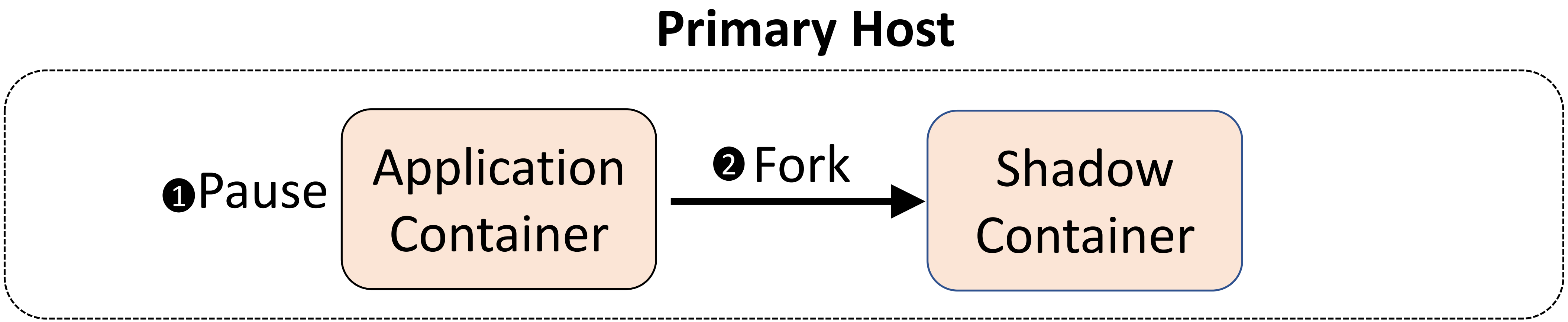

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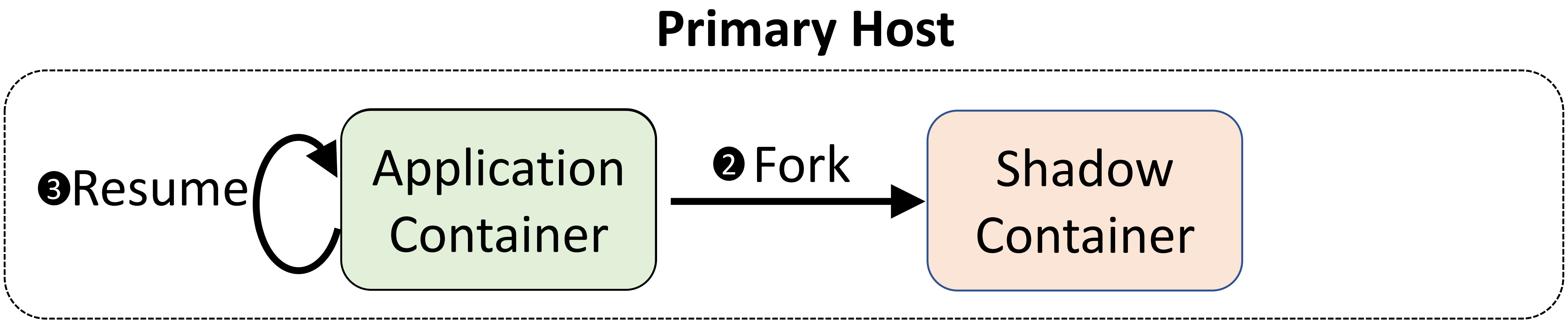

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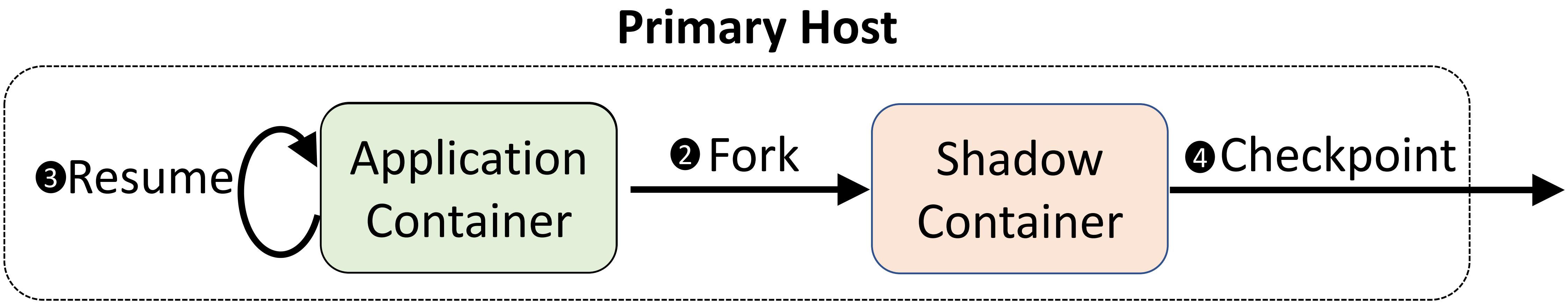

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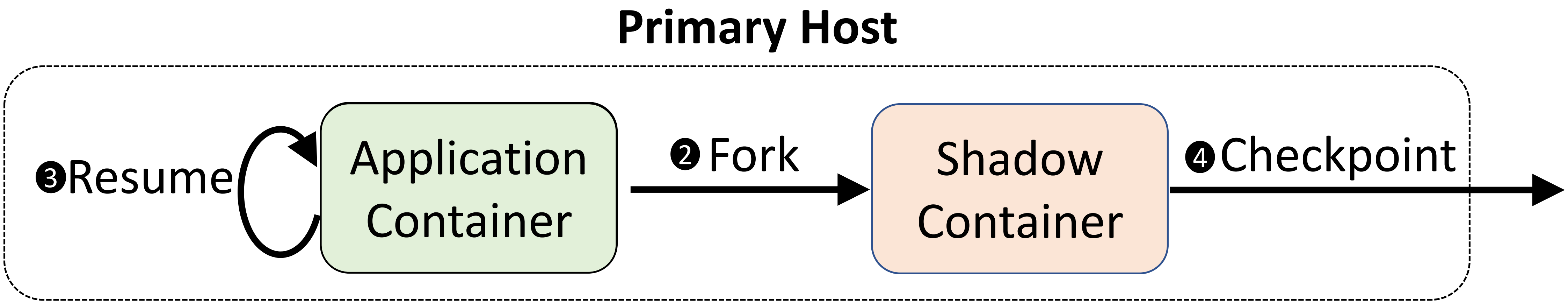

Result: Service Pause time [5.9ms - 42.9ms] → [0.5ms - 3.2ms]

Nondeterministic events and the Challenge of Data Races

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Execution replay **only** during recovery

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Solution:

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  → Unacceptably high overhead
- Record the outcomes of synchronization operations
  → Challenge: data races – unsynchronized memory accesses

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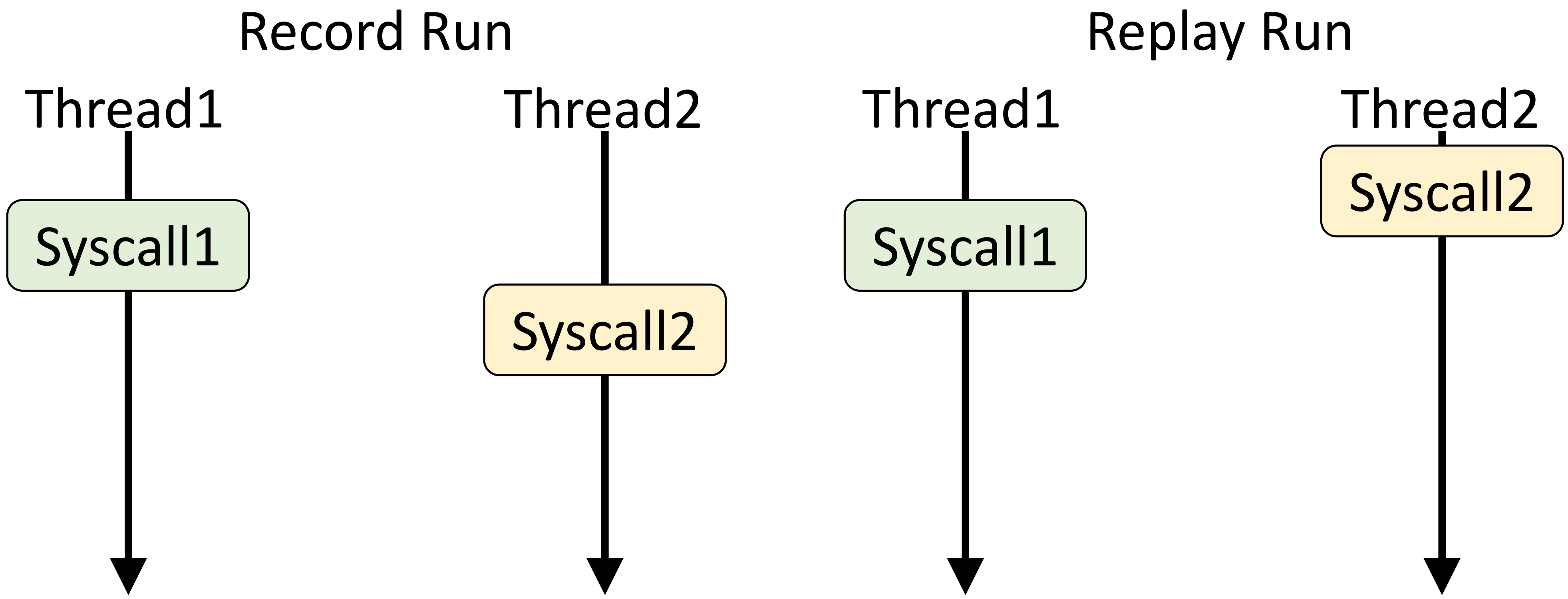
→ RRC focuses on **infrequently-manifested** data races

The Potential Impact of Data Races



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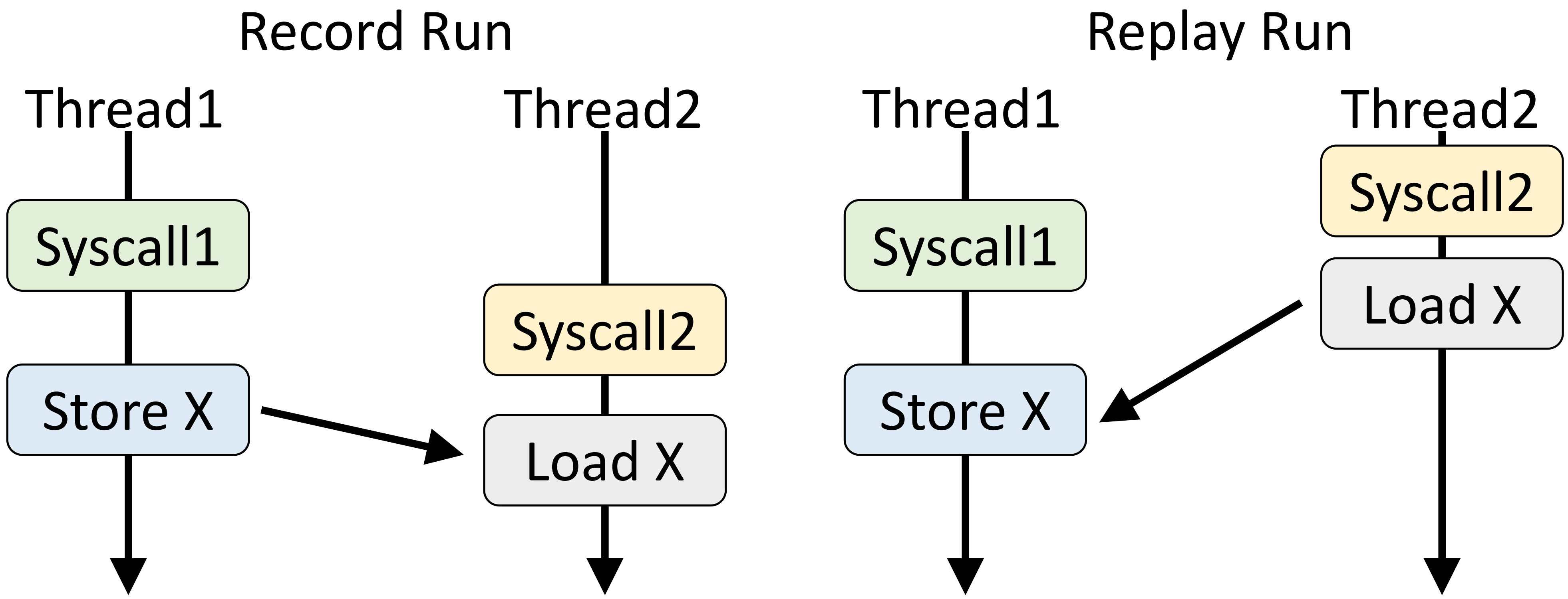

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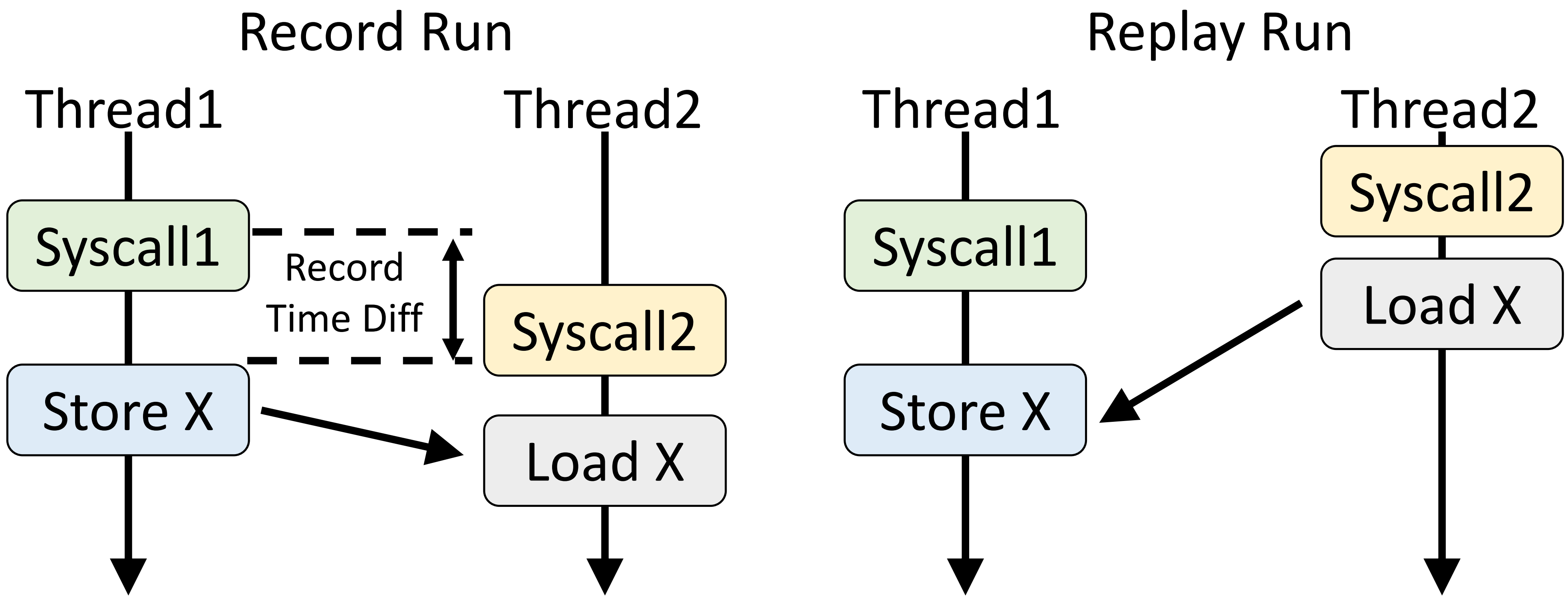
    → Outcomes of data races
      → Different outcomes of replay

RRC’s Mitigation of the Impact of Data Races



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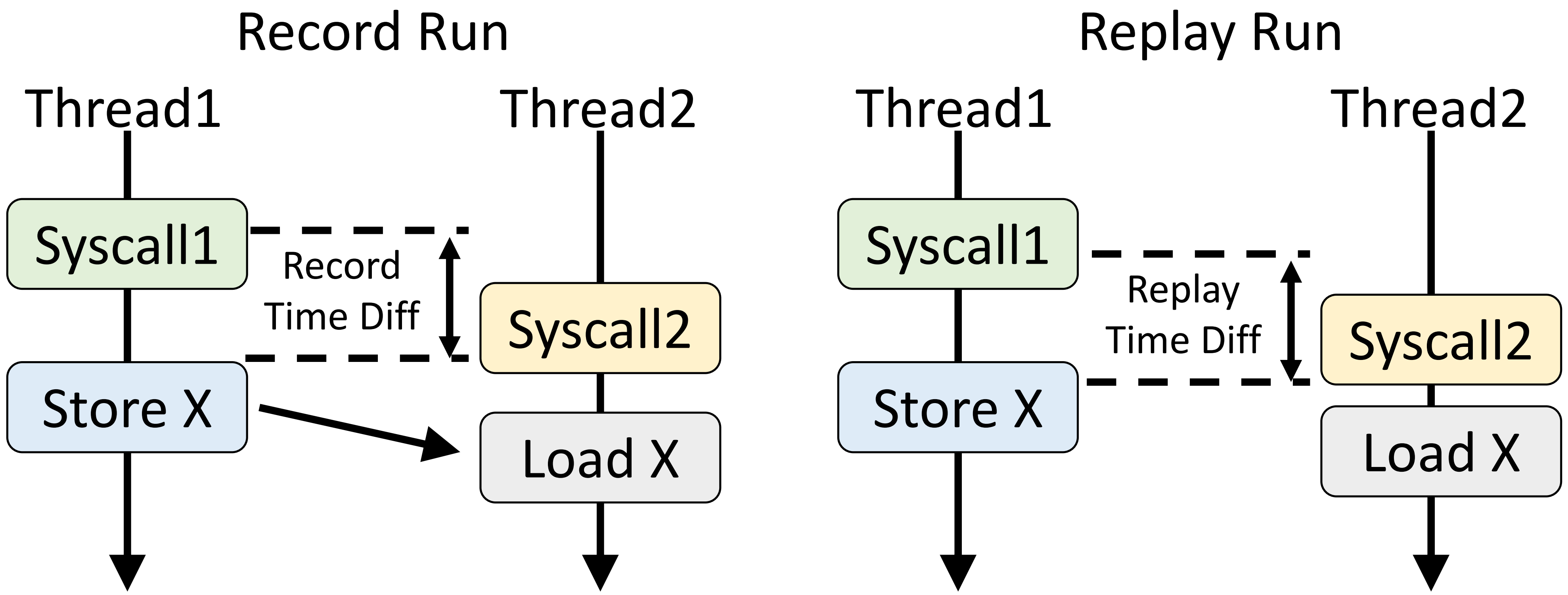

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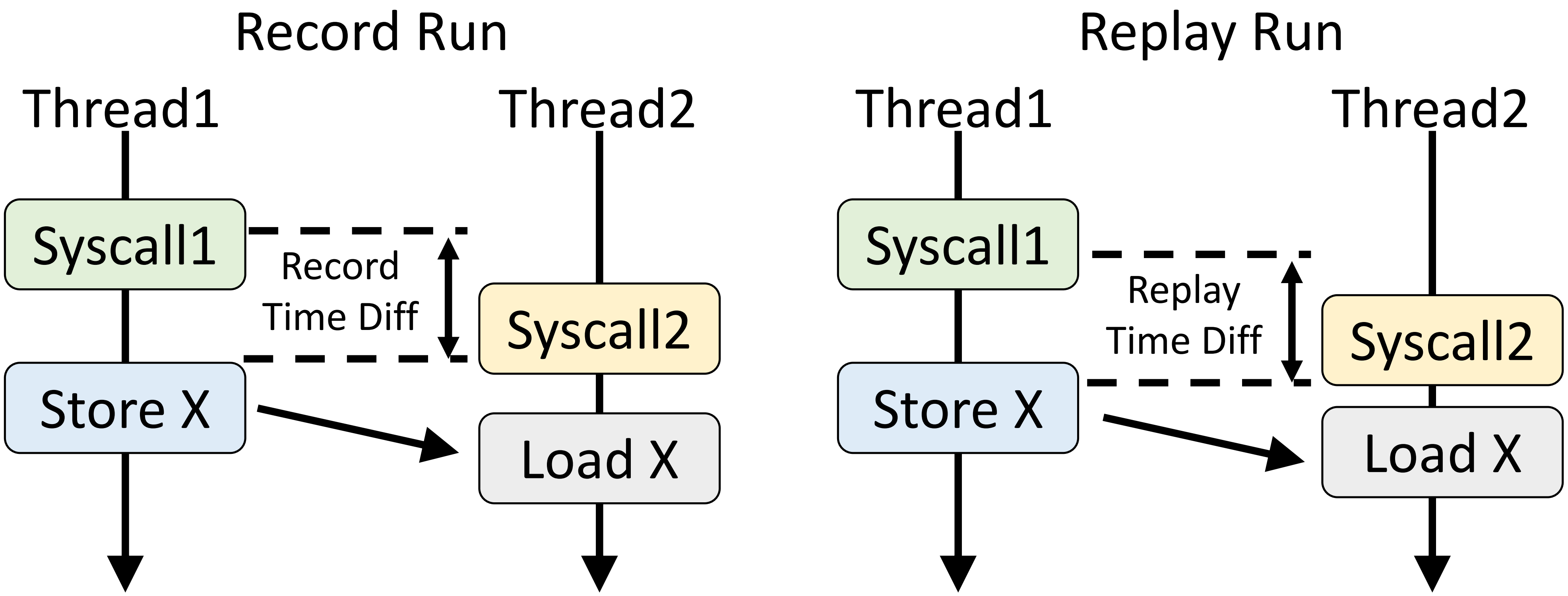

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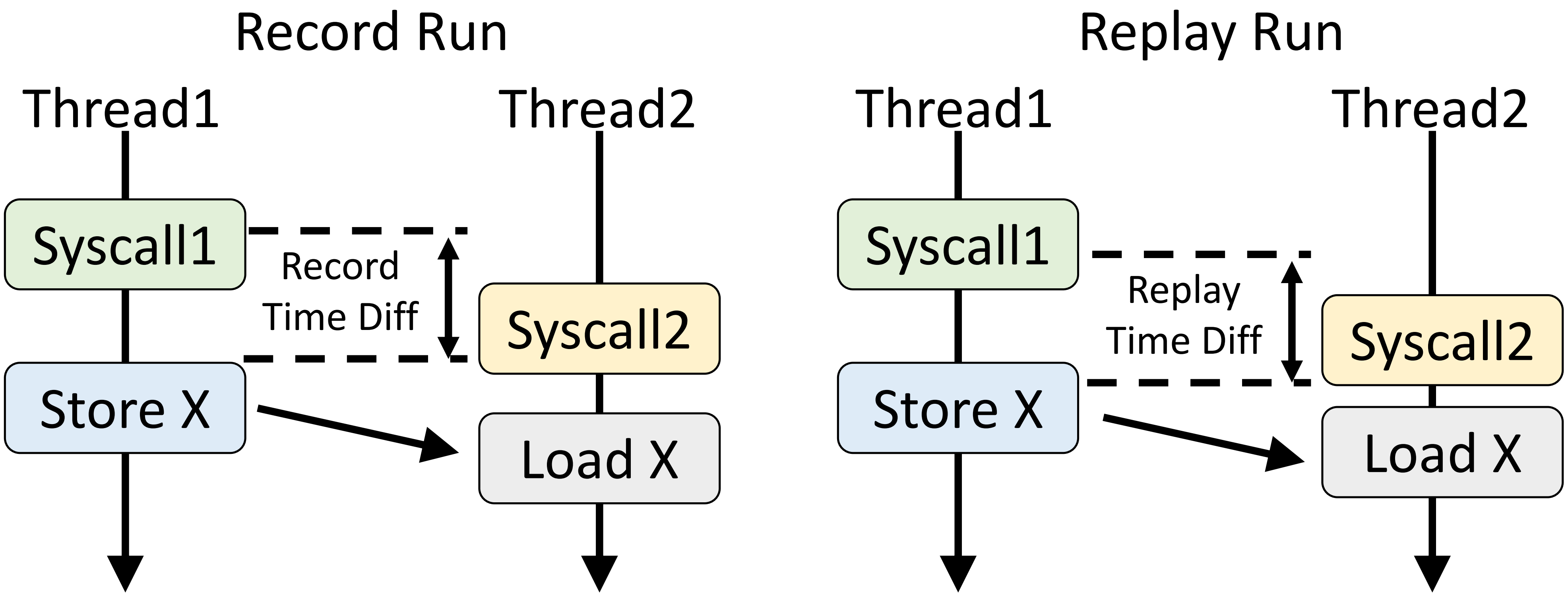

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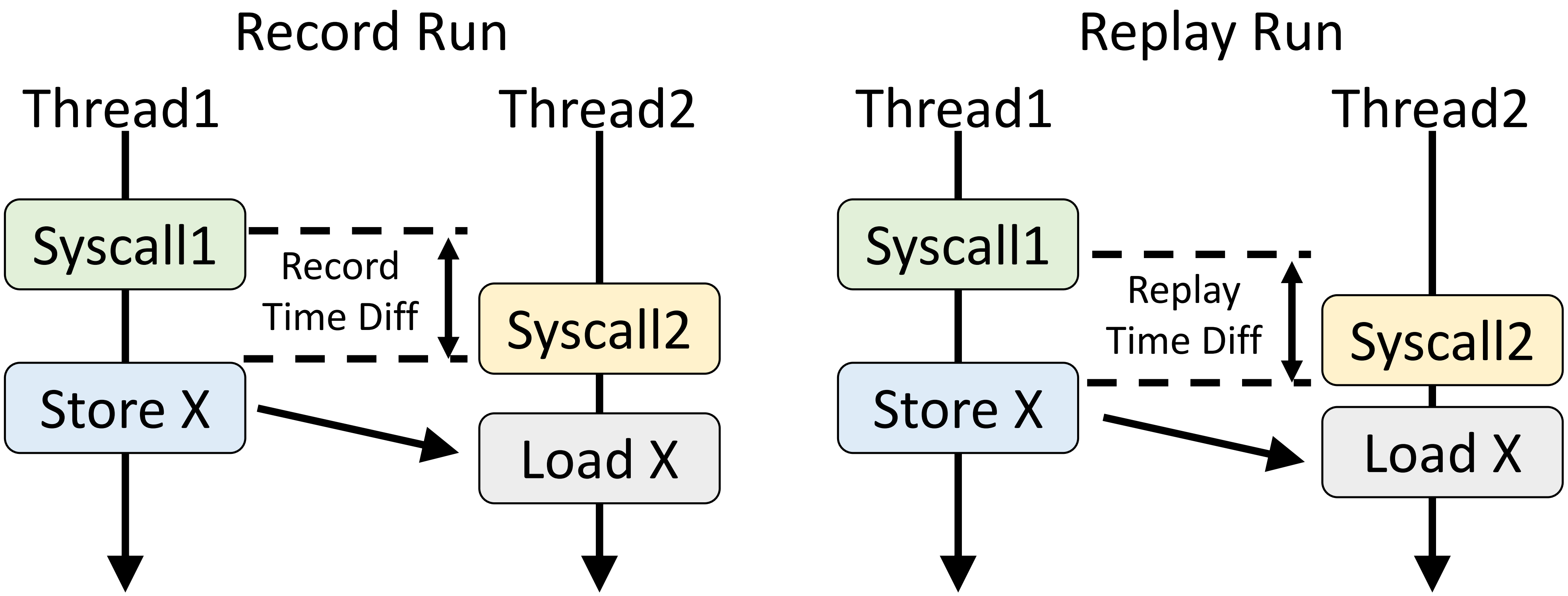

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Recovery success rate with infrequent data races: {35%, 51%} → > 99%

Talk Outline

- Preface
- Motivation
- RRC overview
- Overcoming design and implementation challenges
- **Evaluation**

Key design and implementation challenges

- Latency overhead
- Throughput overhead
- Recovery success rate
- Impact of data races
- CPU utilization overhead
- Pause time
- Recovery latency
- Impact of checkpoint interval
- Impact of workload footprint size and working set size
- Comparison with custom application-specific mechanisms

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- RRC configuration:
  - 100ms checkpointing interval

Latency Overhead: RRC vs. NiLiCon

Average Latency Overhead

	Lig	Redis	Taran	SSDB	Mem$	Aero
RRC	144µs	198µs	211µs	263µs	169µs	290µs
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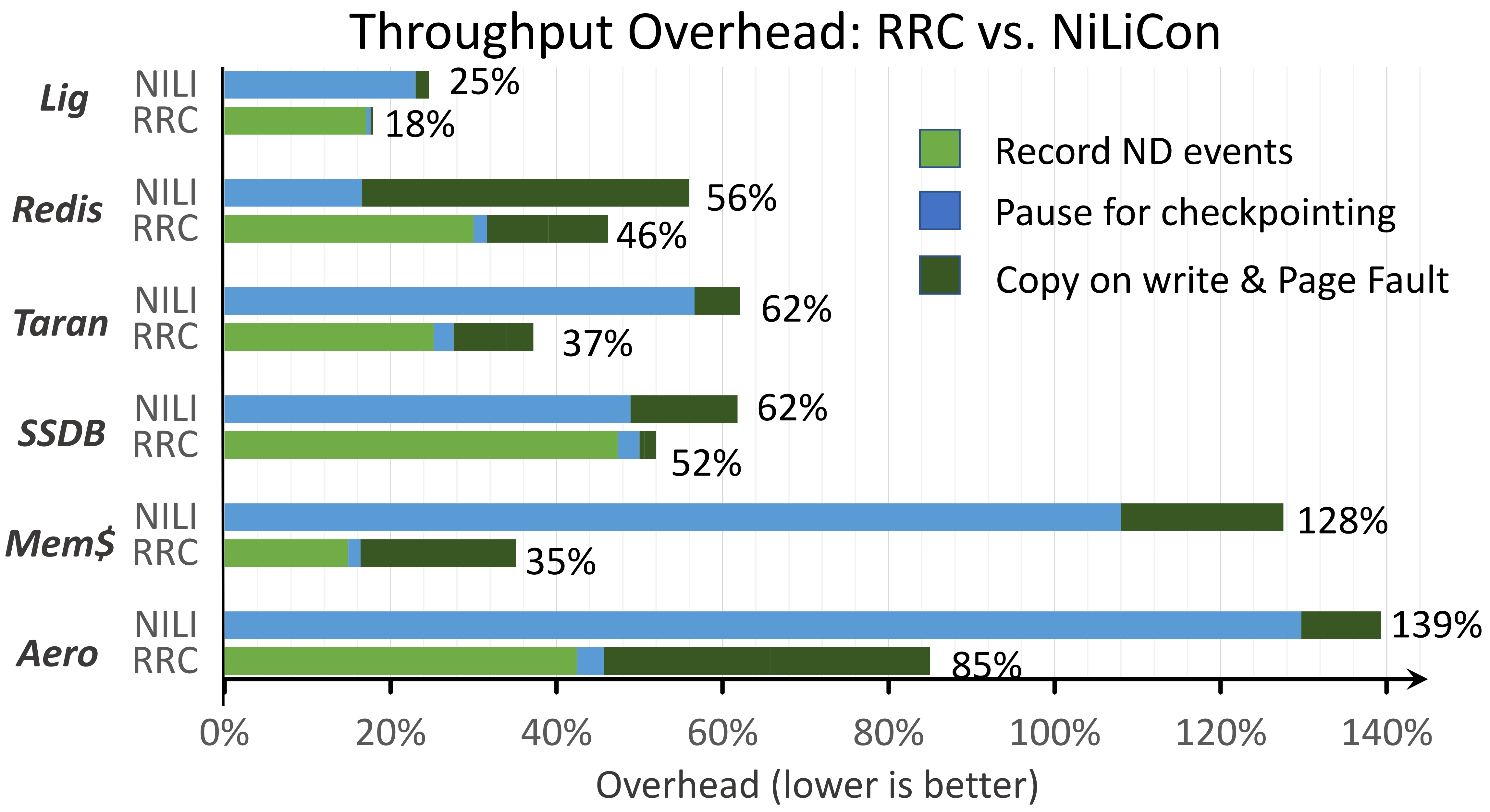
RRC: Hybrid replication + Container fork →
two orders of magnitude lower latency overhead



Throughput Overhead: RRC vs. NiLiCon
Lig
NILI
25%
RRC
18%
Redis
NILI
56%
RRC
46%
Taran
NILI
62%
RRC
37%
SSDB
NILI
62%
RRC
52%
Mem$
NILI
128%
RRC
35%
Aero
NILI
139%
RRC
85%
Record ND events
Pause for checkpointing
Copy on write & Page Fault
0%
20%
40%
60%
80%
100%
120%
140%
Overhead (lower is better)

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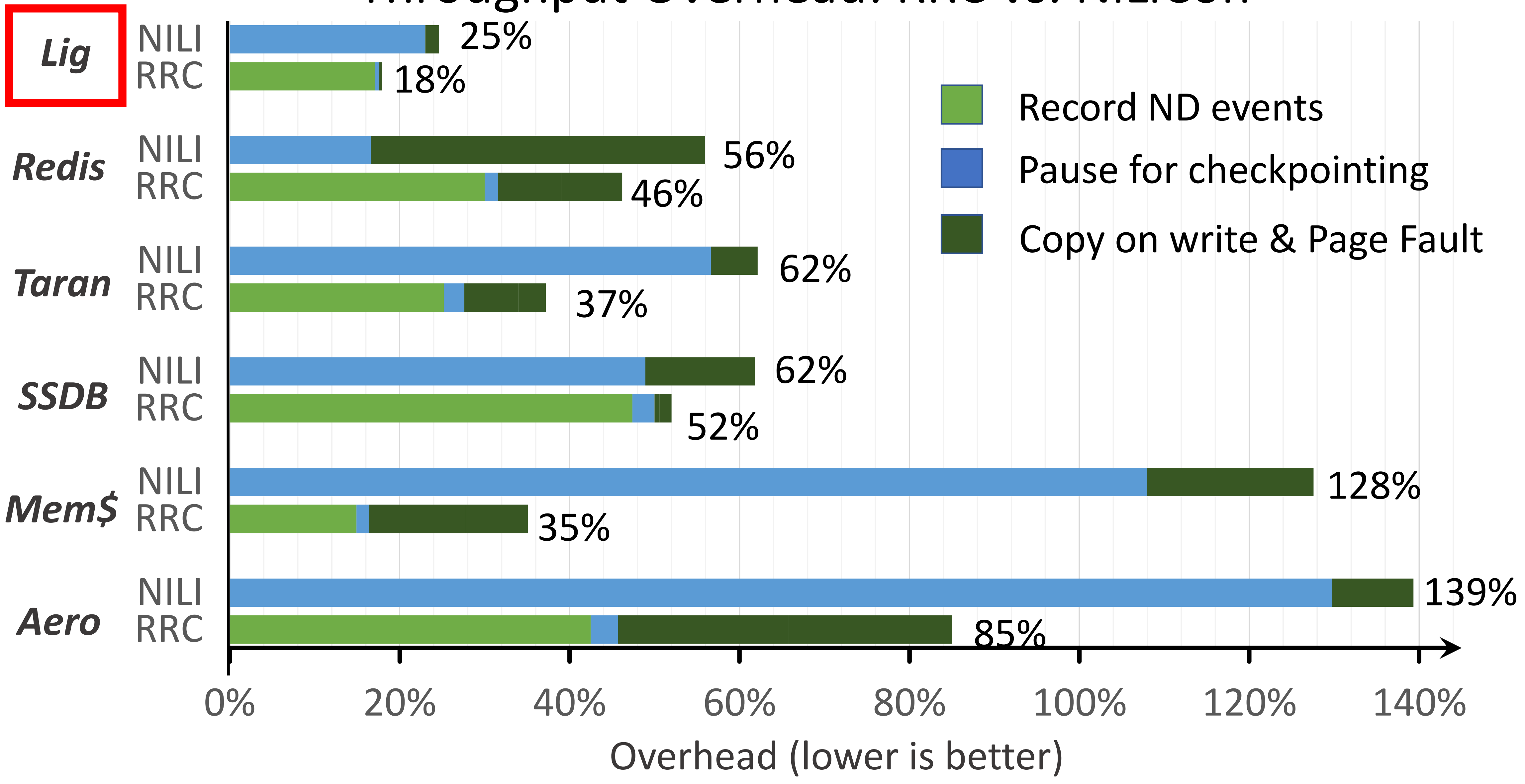

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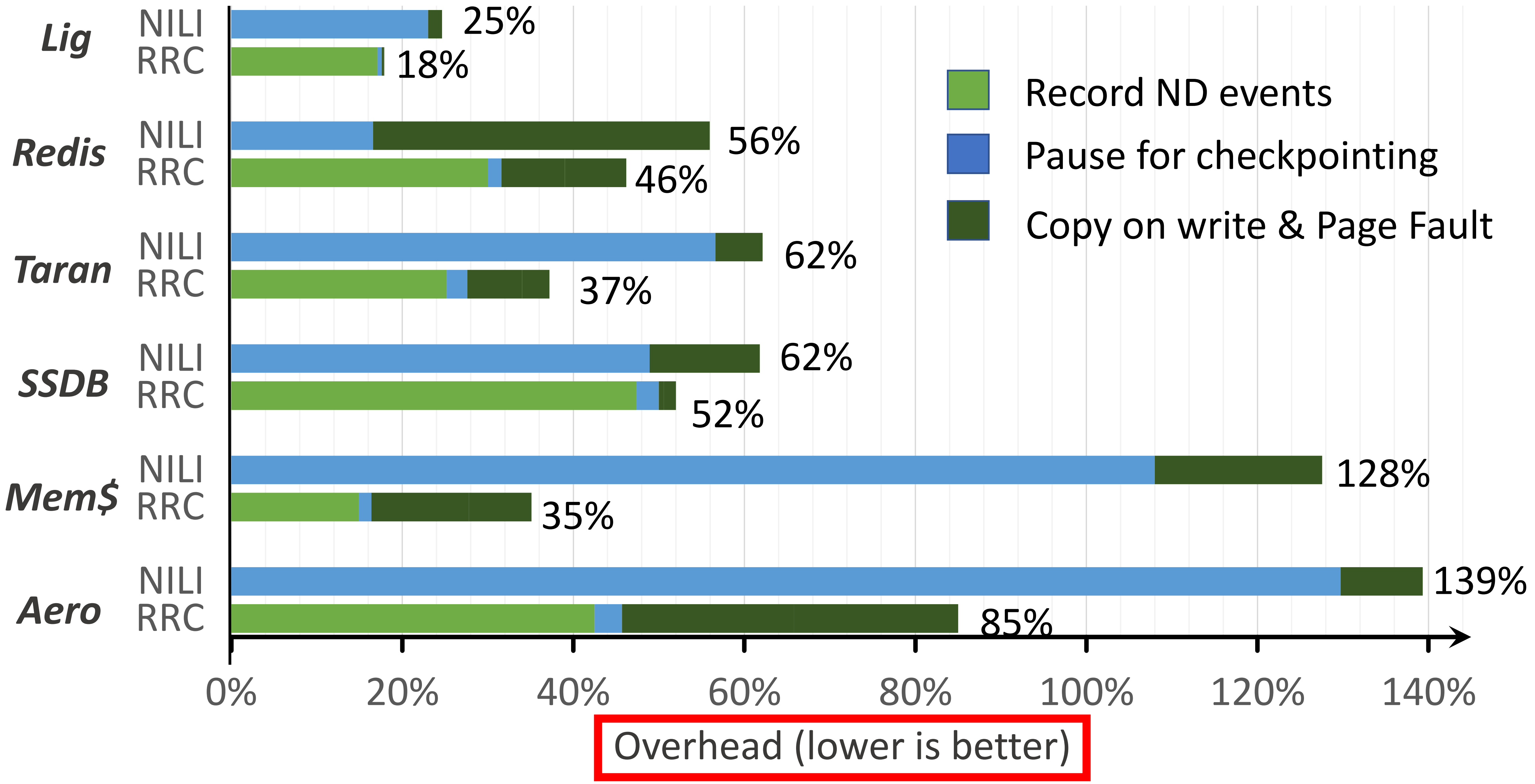

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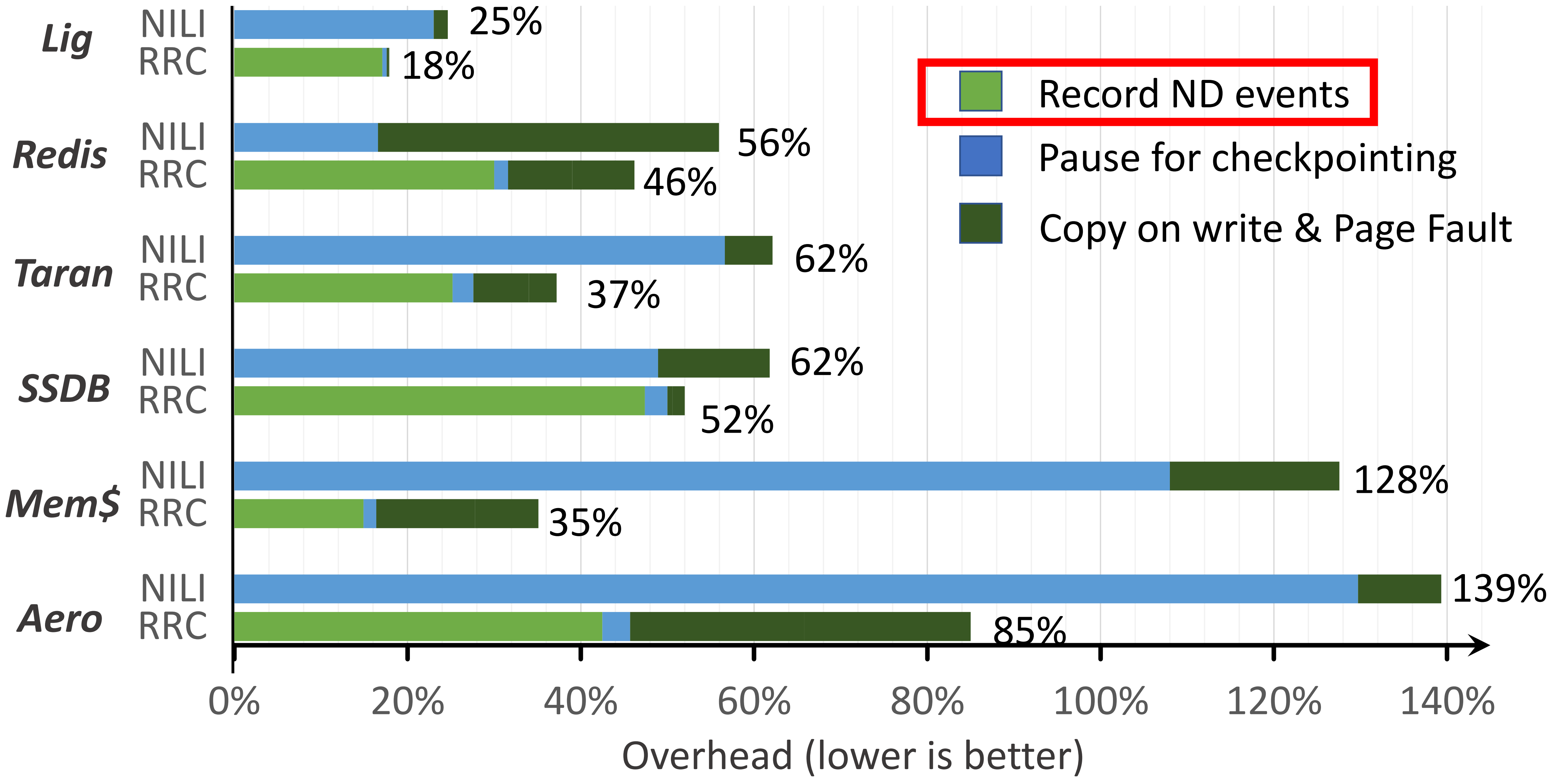

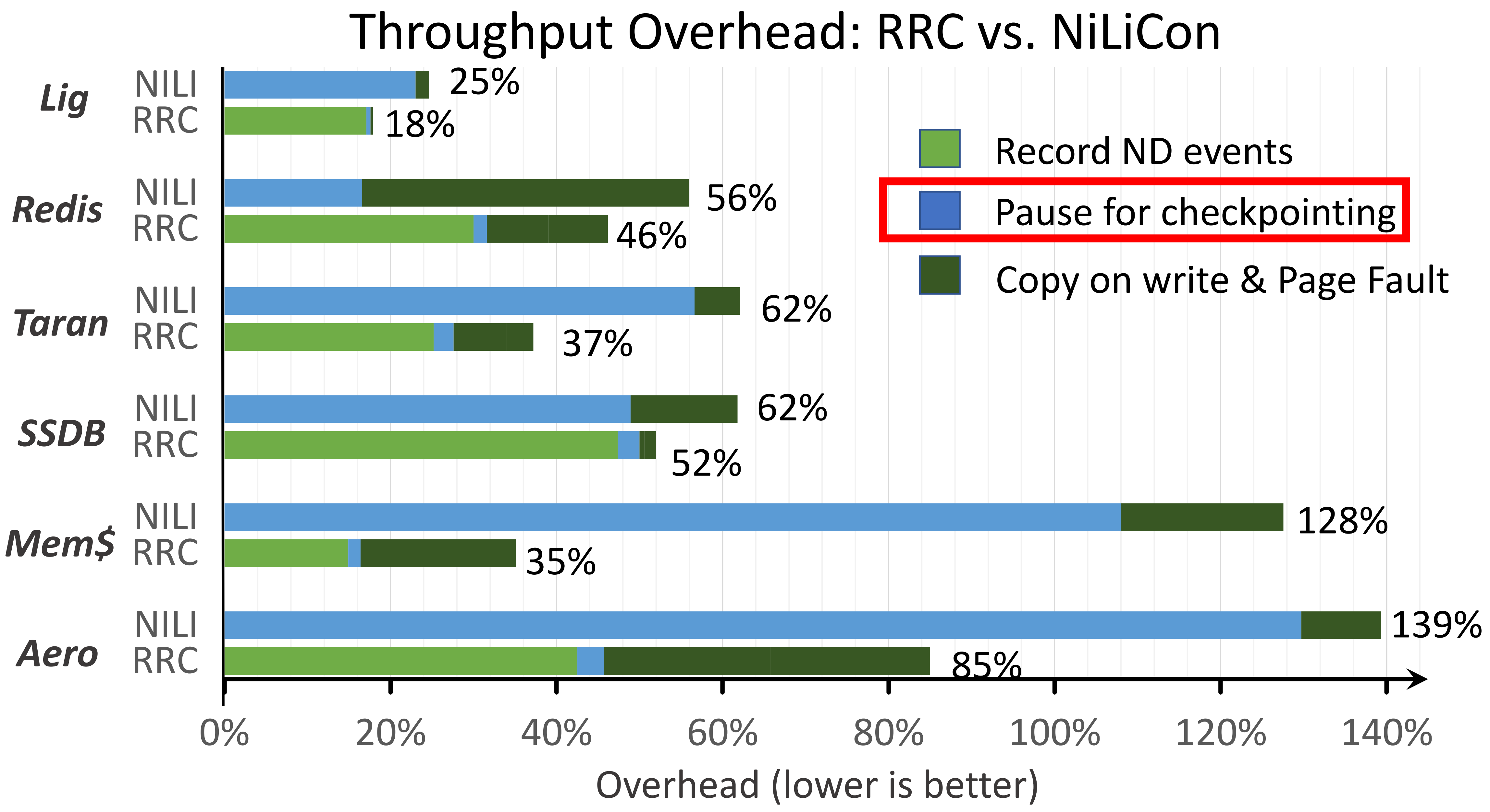

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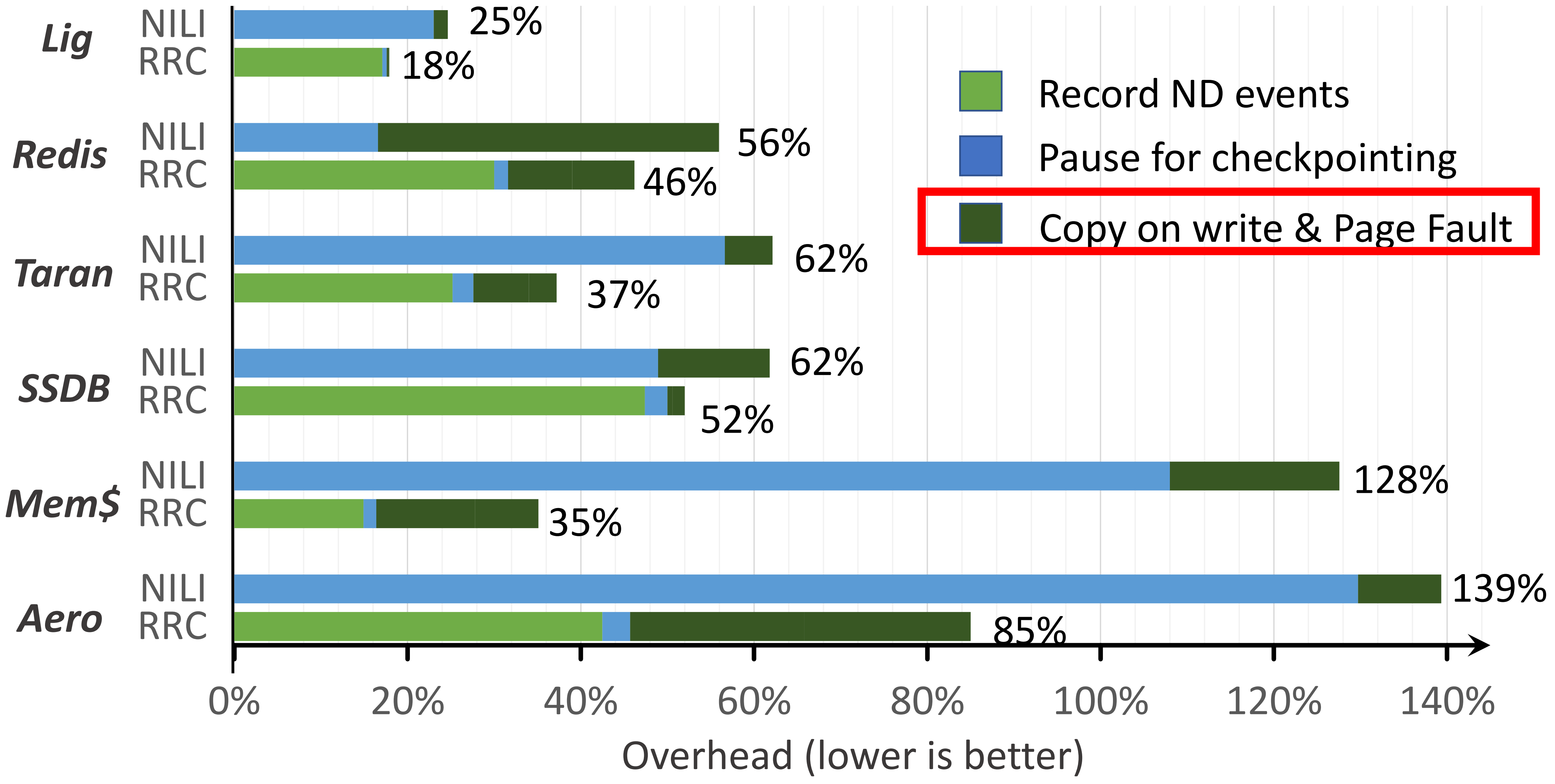

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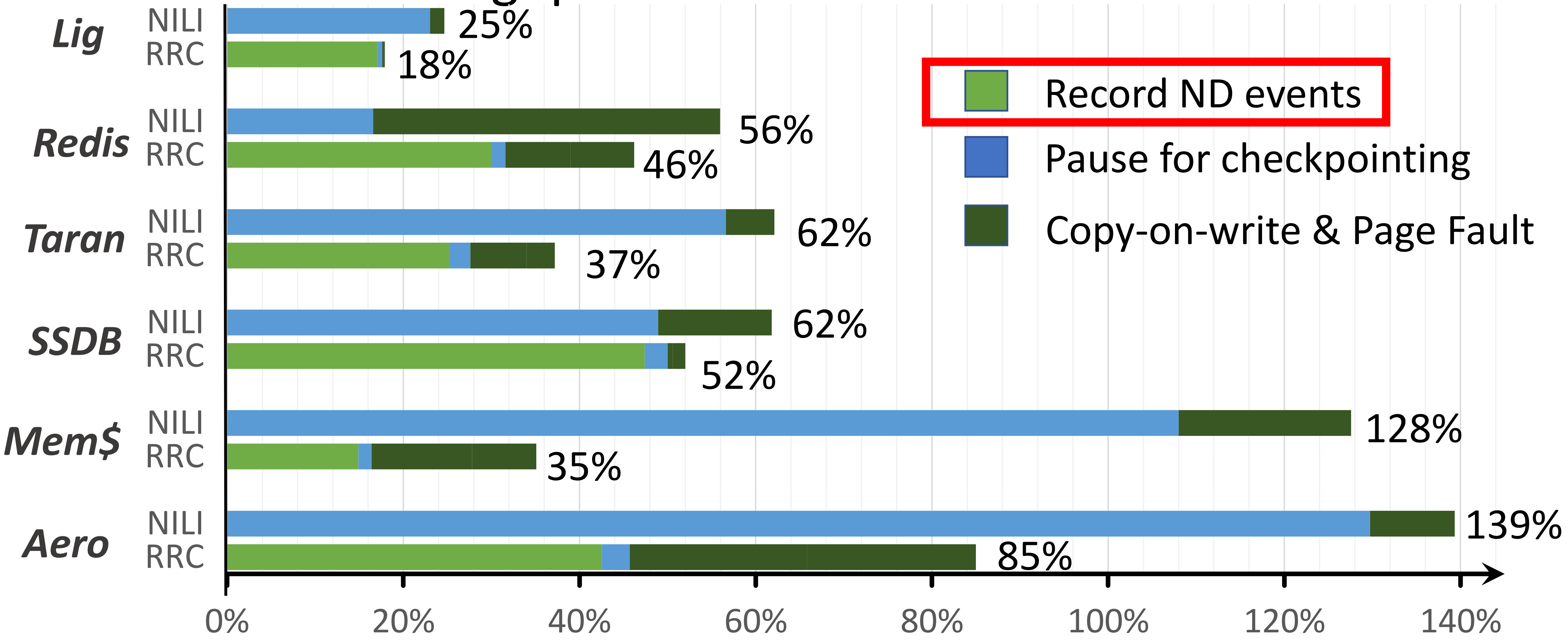

Recording overhead: RRC: 14% - 47% NiLiCon: 0%

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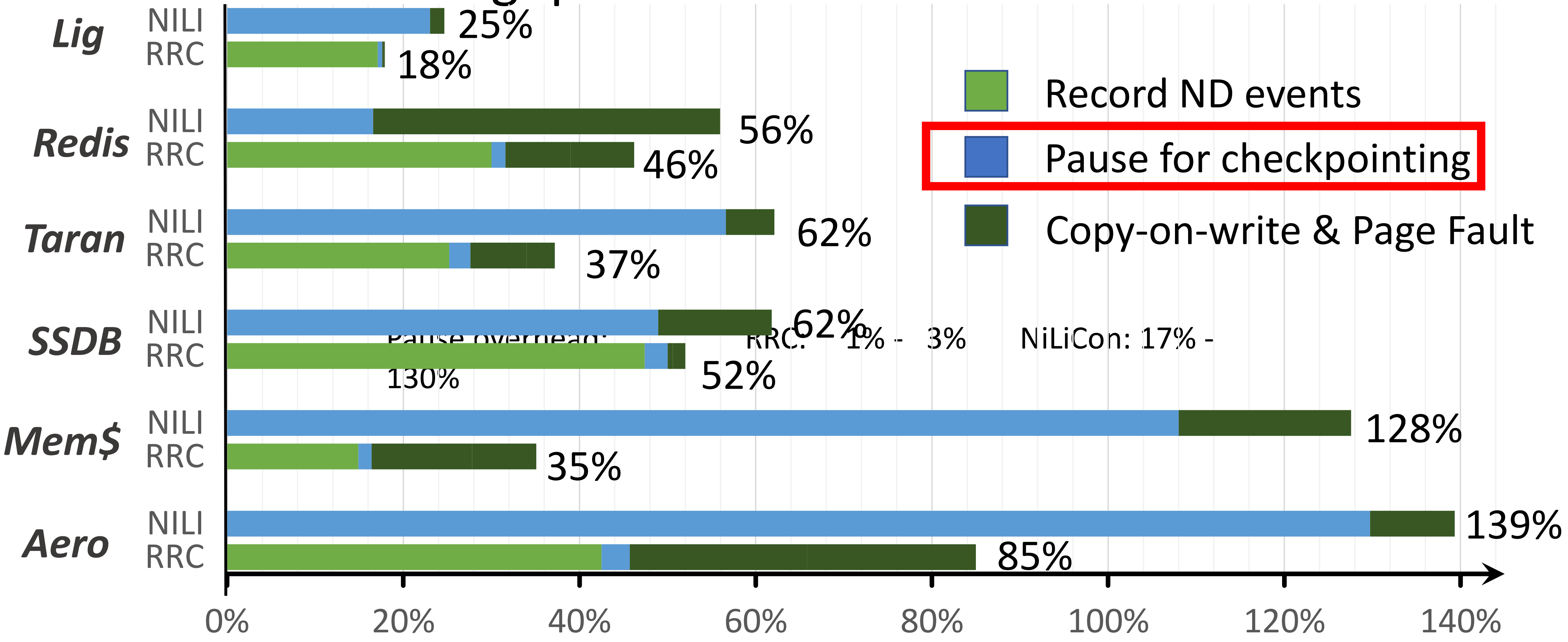

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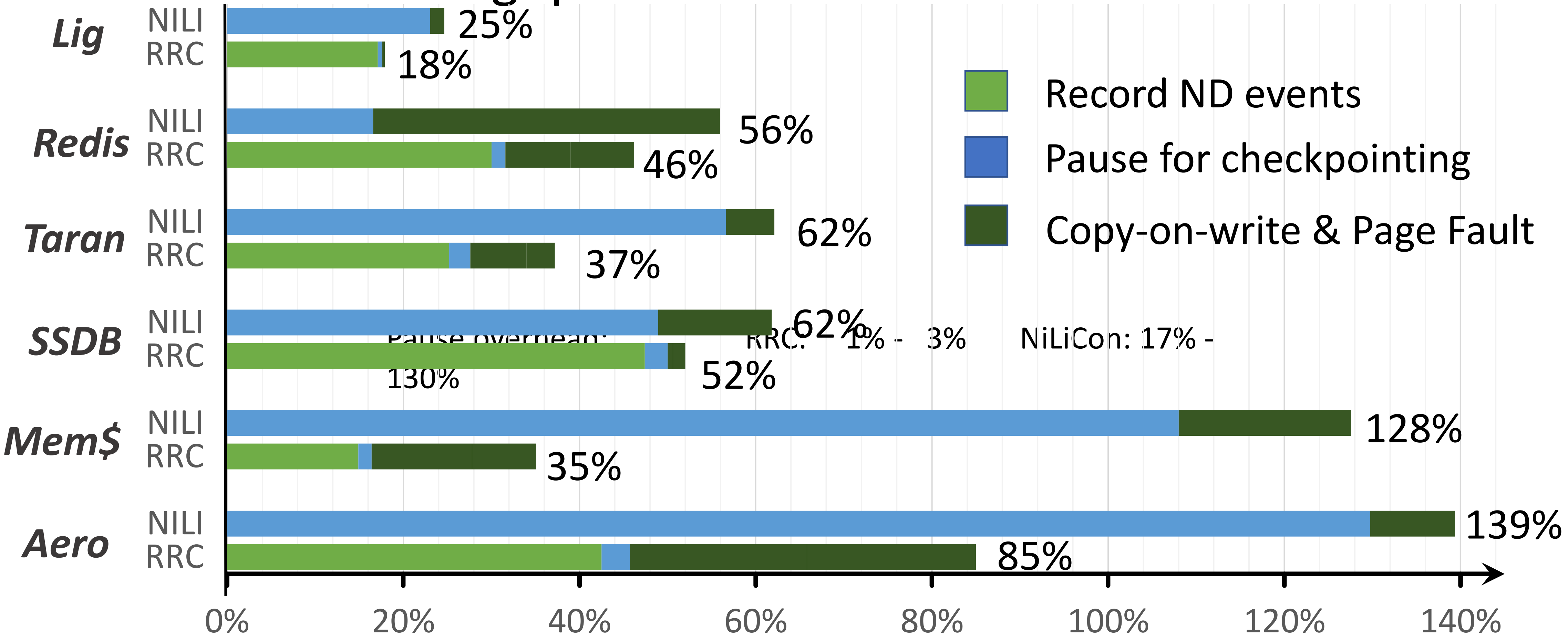

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Overall: RRC: 18% - 85% NiLiCon: 25% - 139%

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  throughput overhead < 85% vs. < 139% with passive backup
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Support for Deterministic Replay

Requirement:

- Record nondeterministic events on the primary
- Transfer the log to the backup
- Replay the log for recovery on the backup

Nondeterministic events:

- External inputs – e.g., network packets from the clients
- Synchronization operations – e.g., lock acquire/release
- Certain local operations -- e.g., gettimeofday()