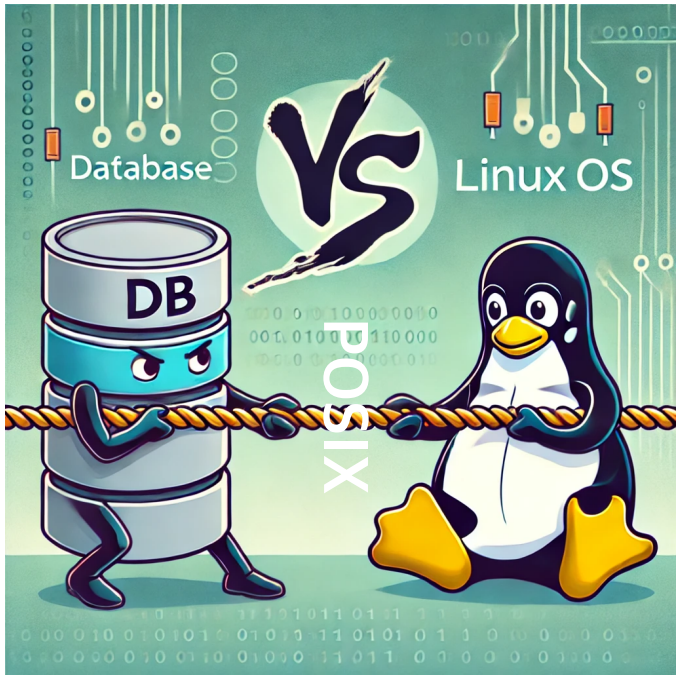
Practical DB-OS Co-Design with Privileged Kernel-Bypass

Xinjing Zhou, Viktor Leis, Jinming Hu, Xiangyao Yu, Michael Stonebraker

MIT CSAIL, TUM, DolphinDB Inc, UW-Madison, MIT CSAIL

DB-OS Interface Mismatch

Performance
Hardware control



Security
Multiplexes hardware
Resource efficiency

DBMS Reimplements a lot of OS Features

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- File/Storage caching

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- User-space task scheduling and I/O scheduling

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- File/Storage caching
- Snapshotting
- User-space task scheduling and I/O scheduling
- But DBMS, being unprivileged, does not have powers that OS has
  - Page Table, MMU
  - Hardware interrupts
  - TLB flush instructions
  - Only exposed through slow POSIX interfaces (mmap, madvise, signals)

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Async-fork: Mitigating Query Latency Spikes Incurred by the Fork-based Snapshot Mechanism from the OS Level

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Are You Sure You Want to Use MMAP in Your Database Management System?

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Virtual-Memory Assisted Buffer Management

Preprint accepted for publication at SIGMOD 2023

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TYPES OF DATABASE PAPER

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Case Study: Virtual Memory Snapshotting

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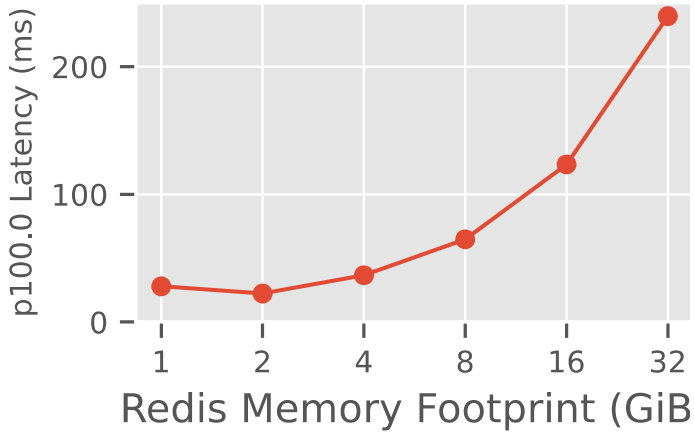
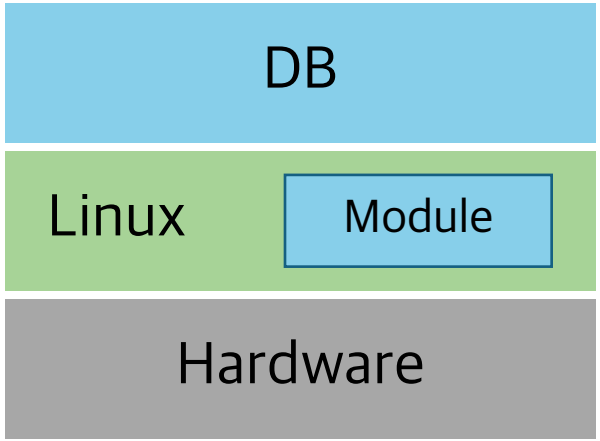
Redis p100 Query Latency during Checkpointing



Co-Design Paradigms for this Problem



Customized Linux Kernel
- **Security**
- **Maintainability**

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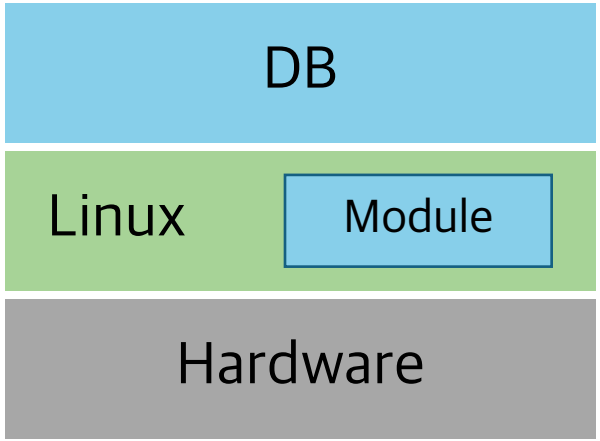

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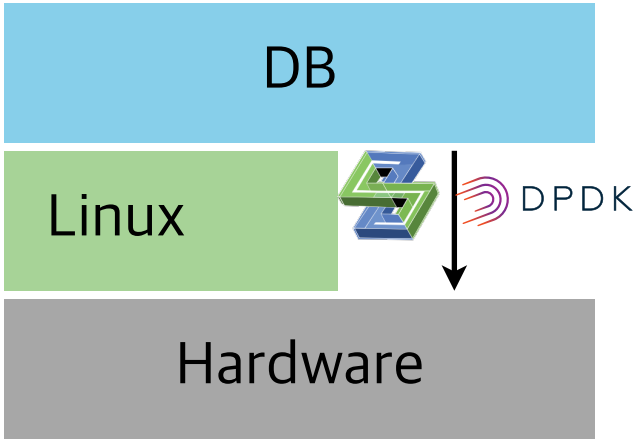

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- **No direct control on MMU & Page Table**
- **Limited Design Space**

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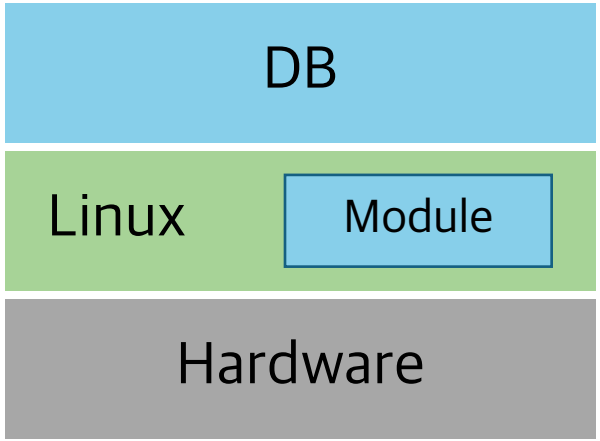

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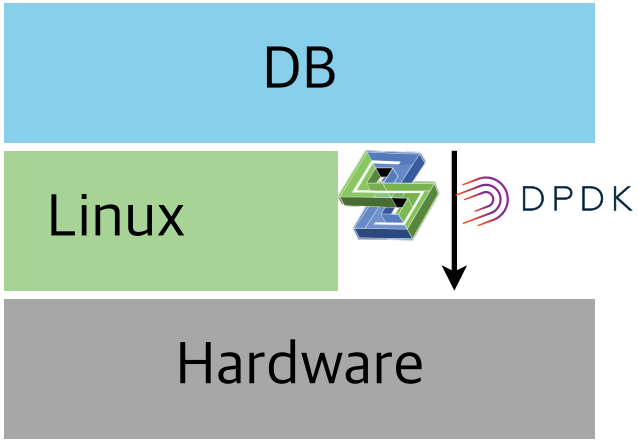

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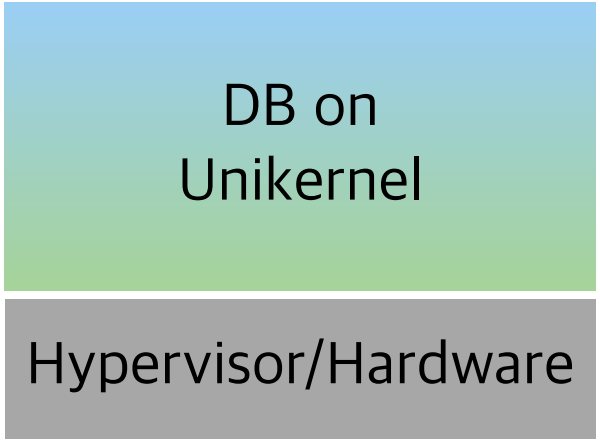
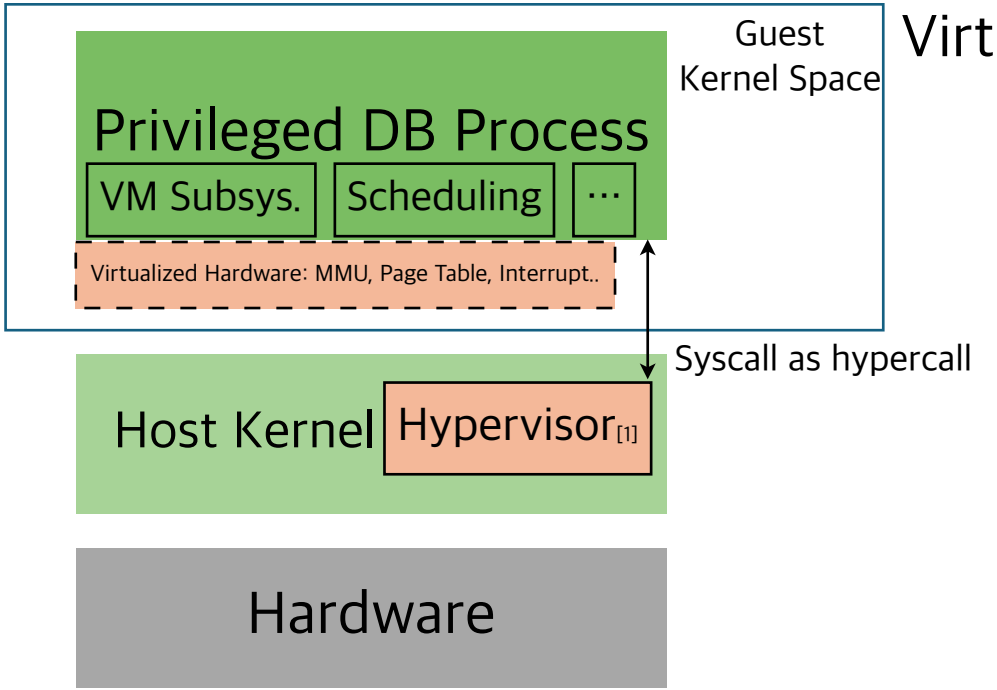


DB-Unikernel
- **All-or-nothing**
- **Throwing baby(ecosystem) out with bathwater(POSIX)**

How to allow DBMS complete freedom to specialize subsystems while minimizing impact on security, eco-system, and compatibility ?

Making DB Process Privileged with Virtualization



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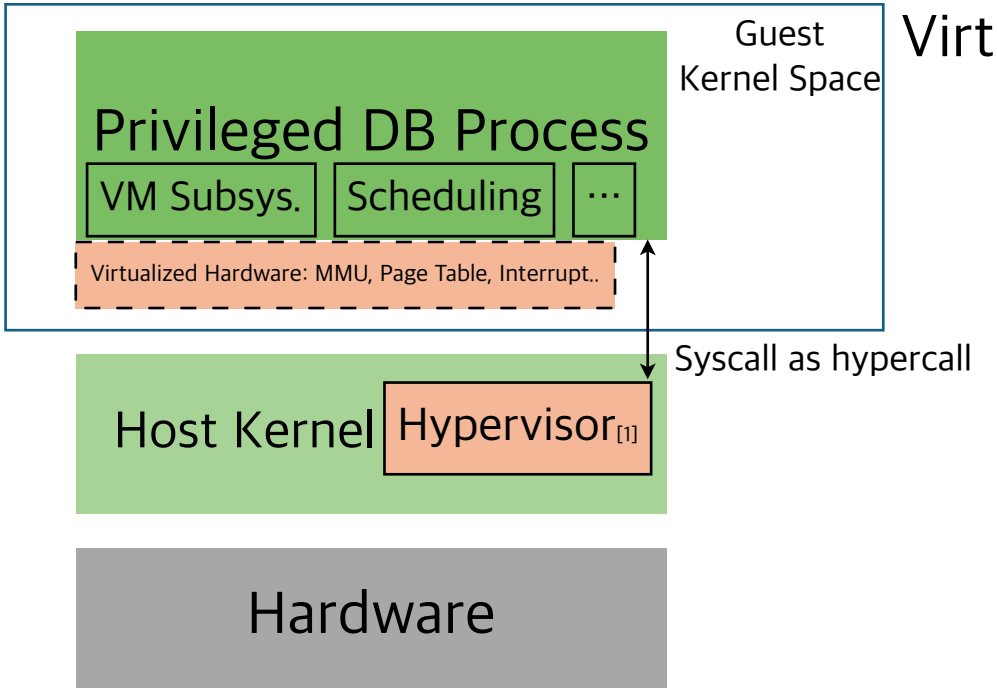

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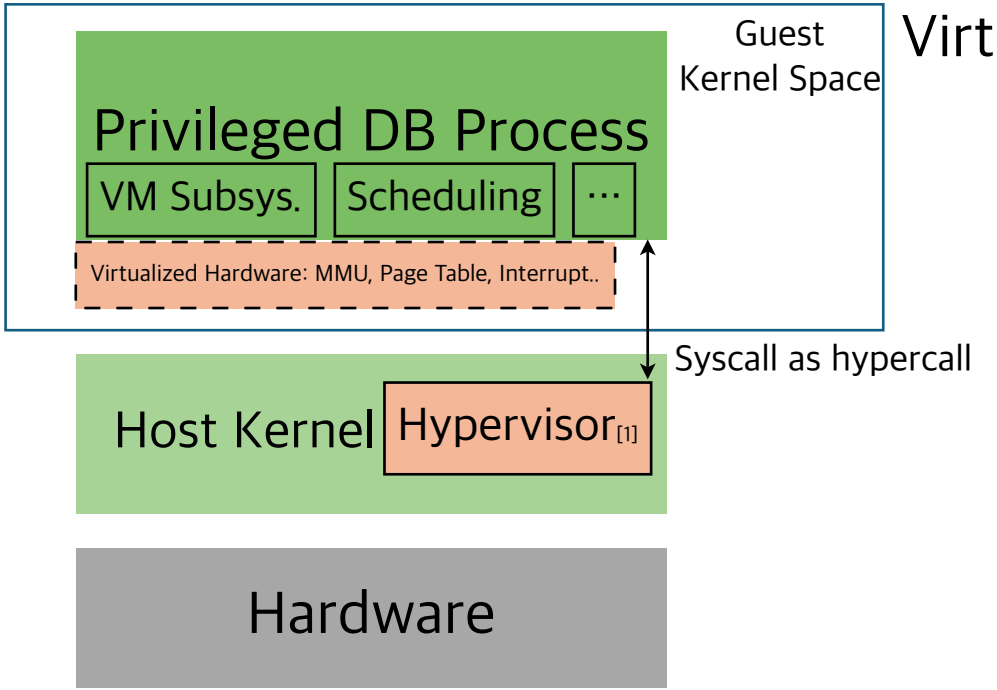

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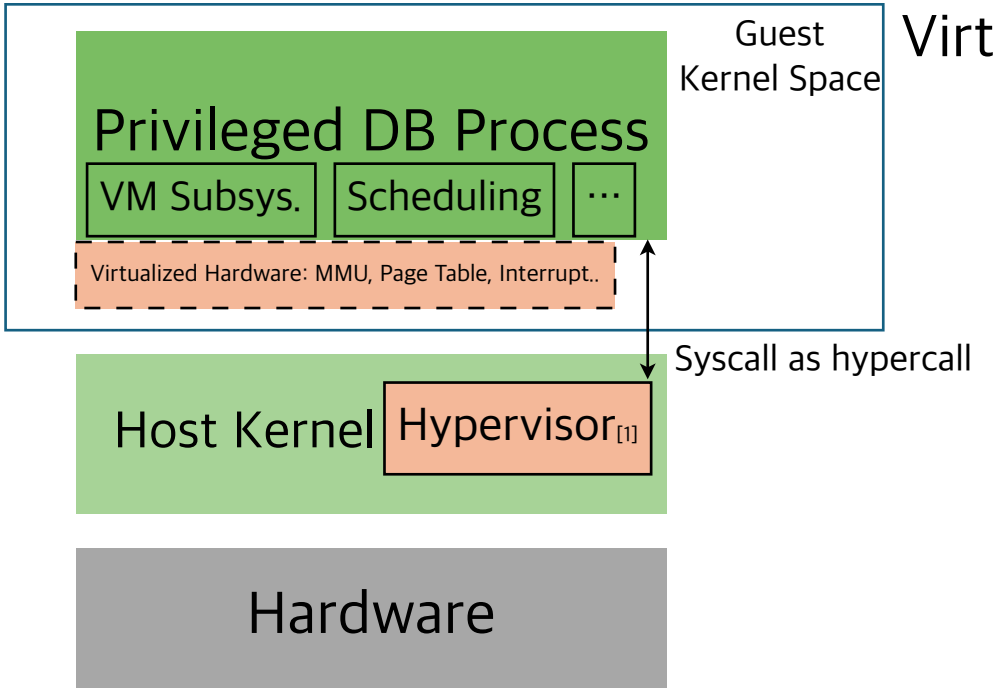

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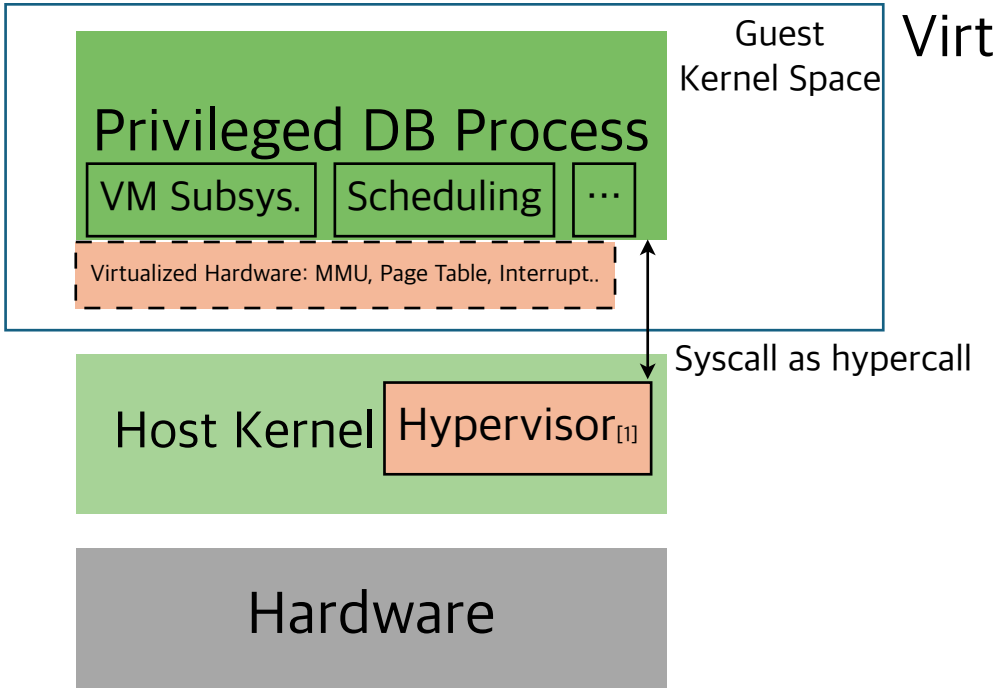

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- Not throwing the baby out with bathwater

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Privileged Kernel-Bypass vs. Kernel-Bypass for DBMS

	Kernel Bypass	**Privileged Kernel Bypass**
DBMS runs in	User Space	Guest Kernel Space
Specializes	Network/Storage	Virtual Memory/Scheduler/Interrupt /Network/Storage

This paper

- **Instantaneous snapshotting. ←**
- “Perfect” virtual-memory-assisted buffer manager **[see paper]**

Linux fork Bottleneck Analysis

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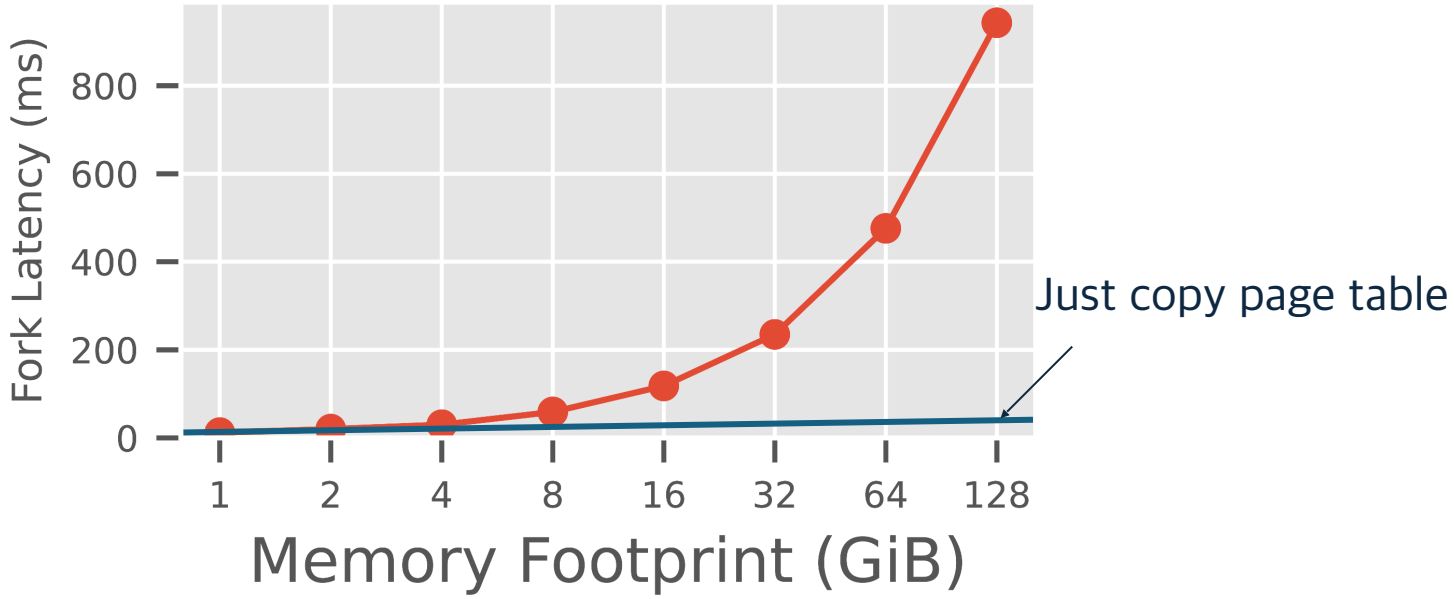

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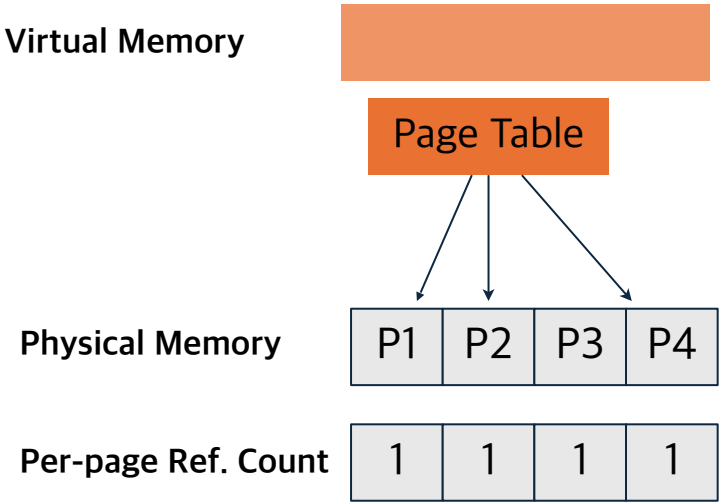

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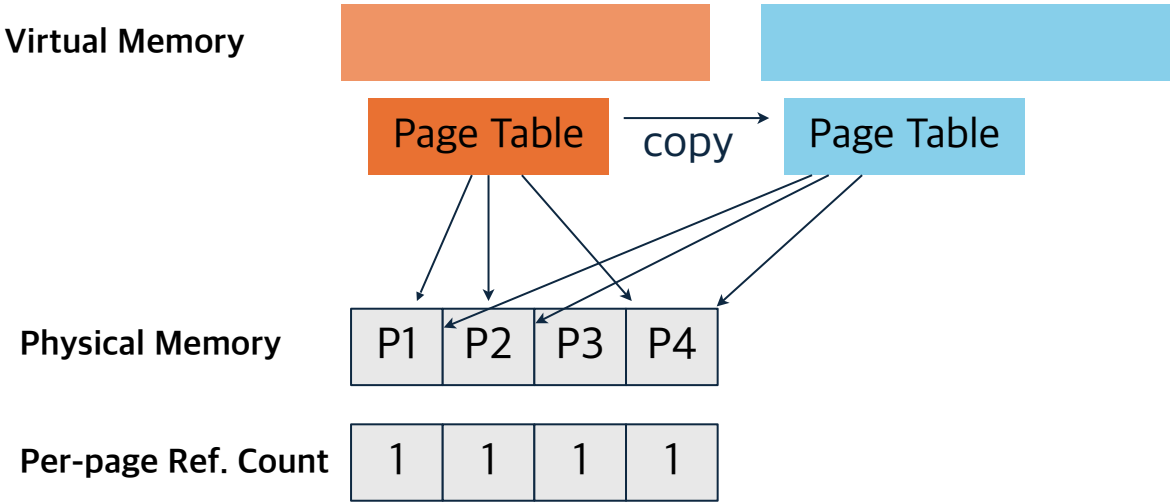

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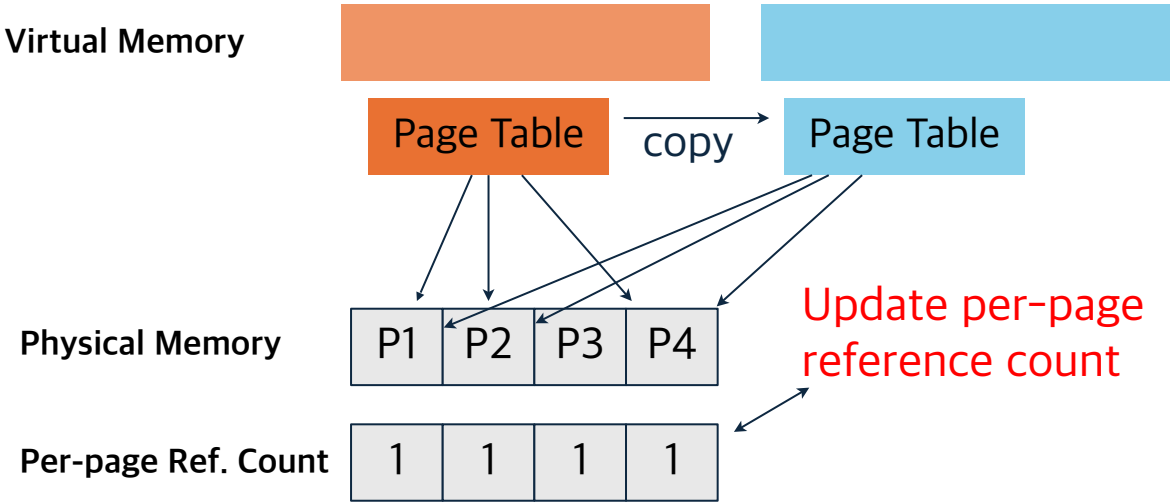

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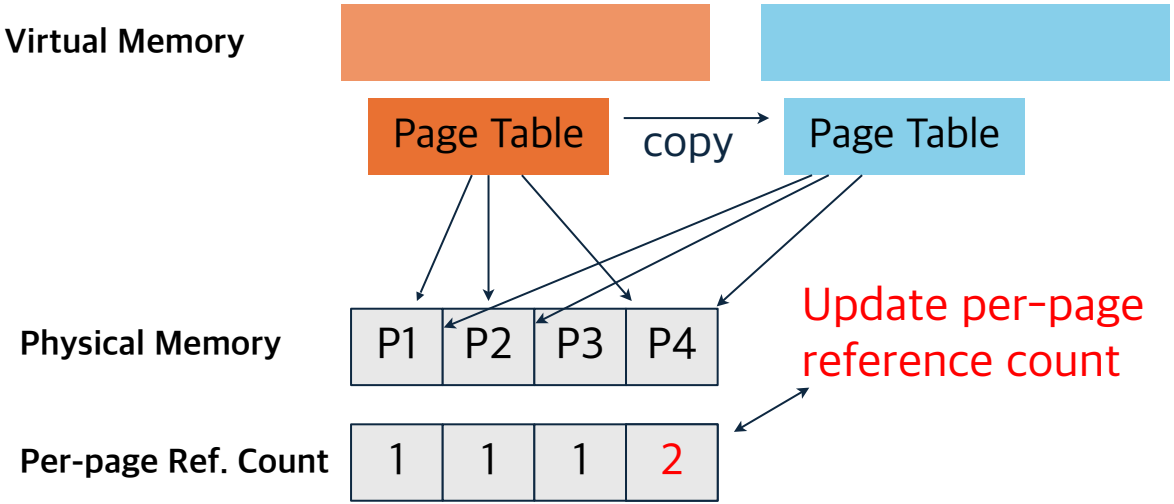

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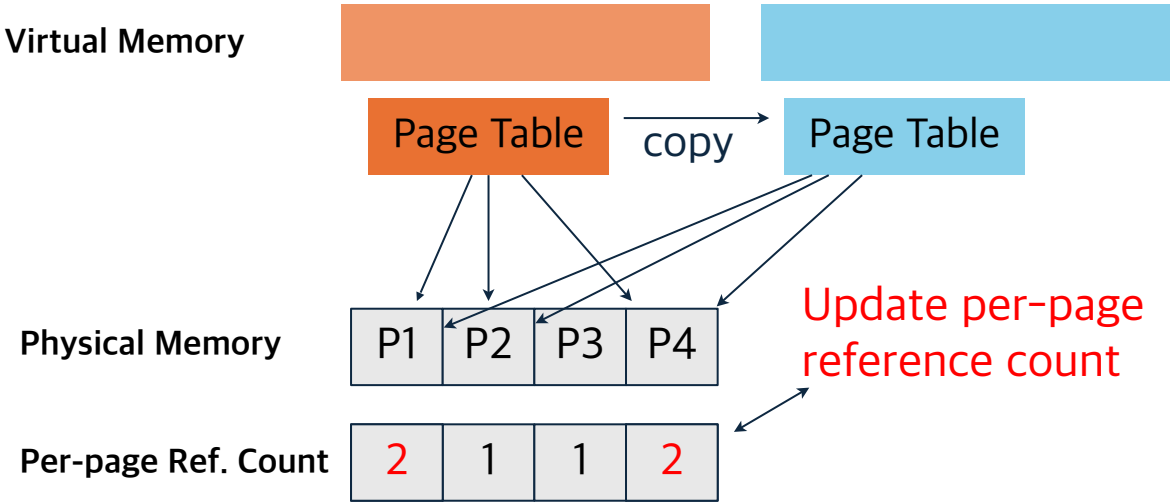

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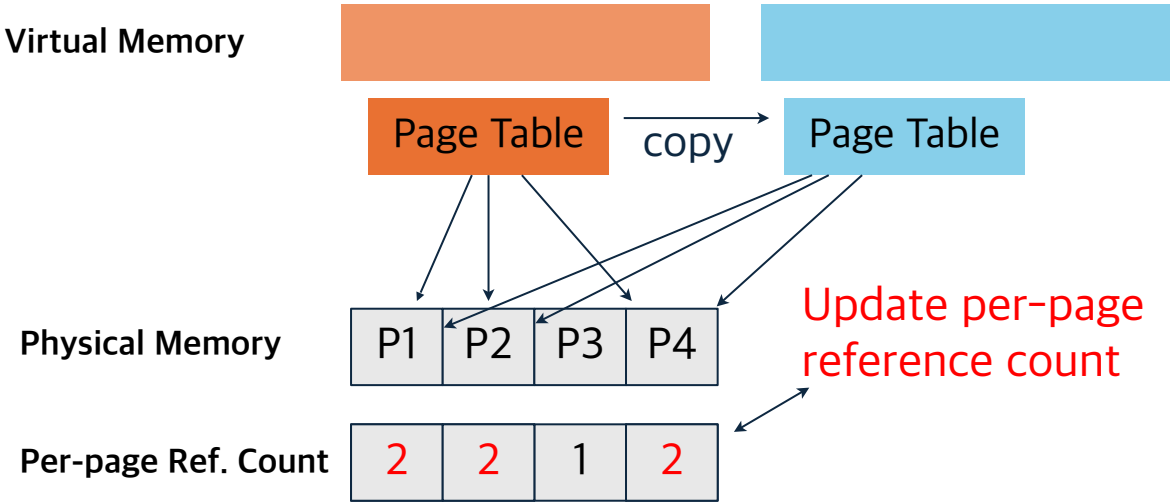

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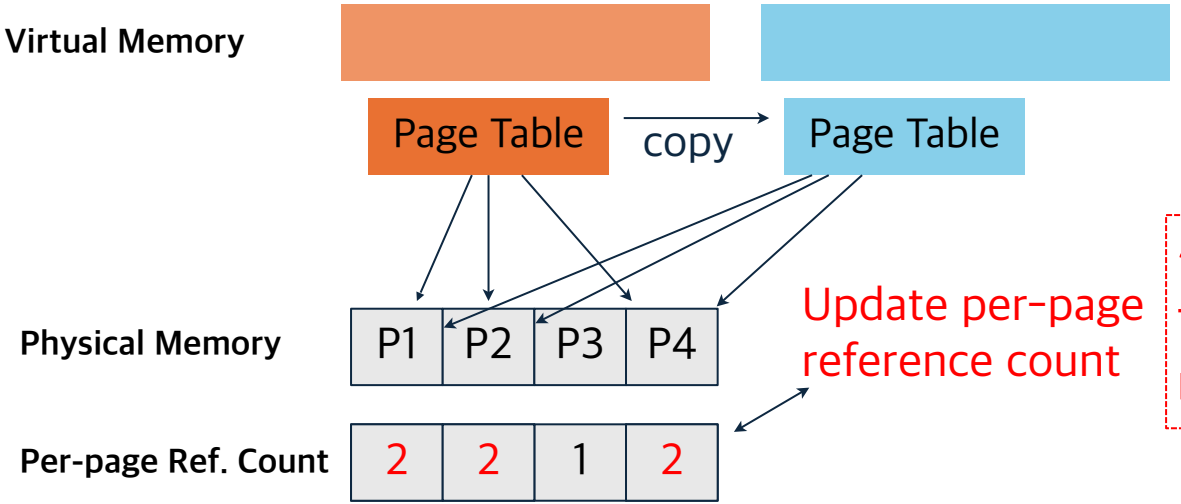

~90% CPU cycles due to cache misses and random accesses

Fast Snapshotting with Privileged Kernel Bypass

- We can make many simplifying assumptions
- Specialize a simple VM/snapshotting system in the privileged DB process
  - No reference counting for physical pages – DB is the only user
  - No support for shared-memory, page cache, memory-mapped files…
  - No nested snapshot – Redis/KeyDB/Hyper use cases
- Challenge: how to safely reclaim physical pages without reference count?

Safely Reclaiming Physical Pages with Timestamp

- Lifecycle of page/snapshot tracked with timestamps – akin to epoch-based reclamation
- A page is reclaimed when there are no references from any page tables.
  - No overlap between the lifetime of active page tables and physical page
- Pages are periodically examined for garbage collection in batches

Main Page Table

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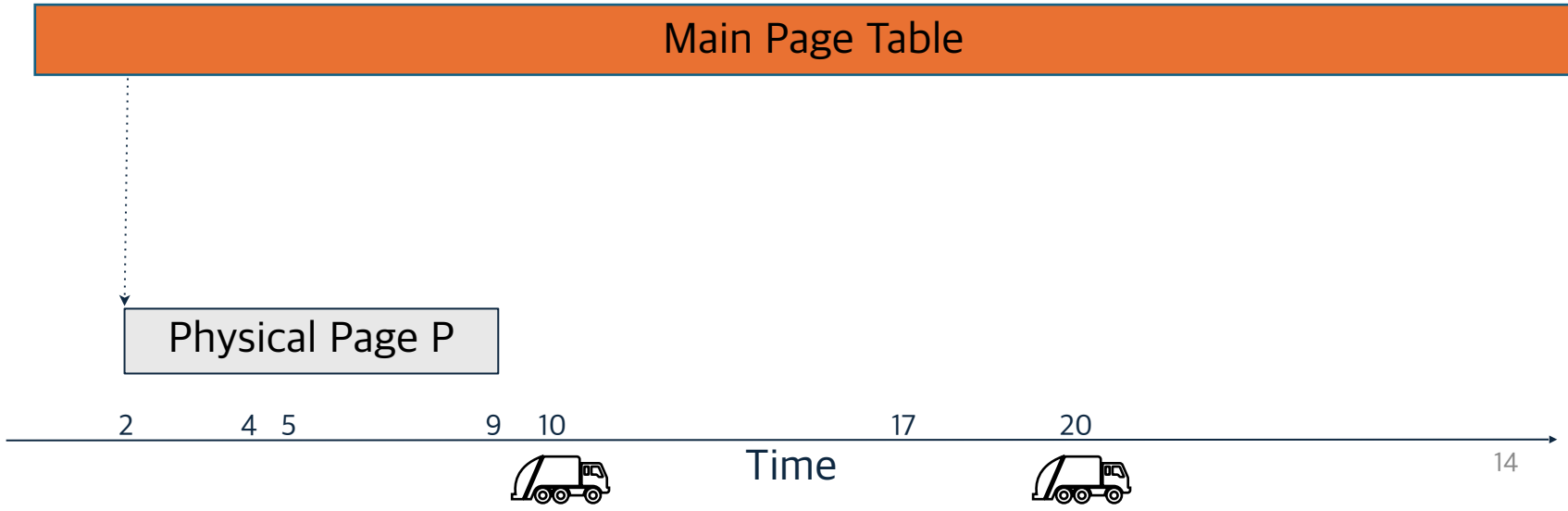

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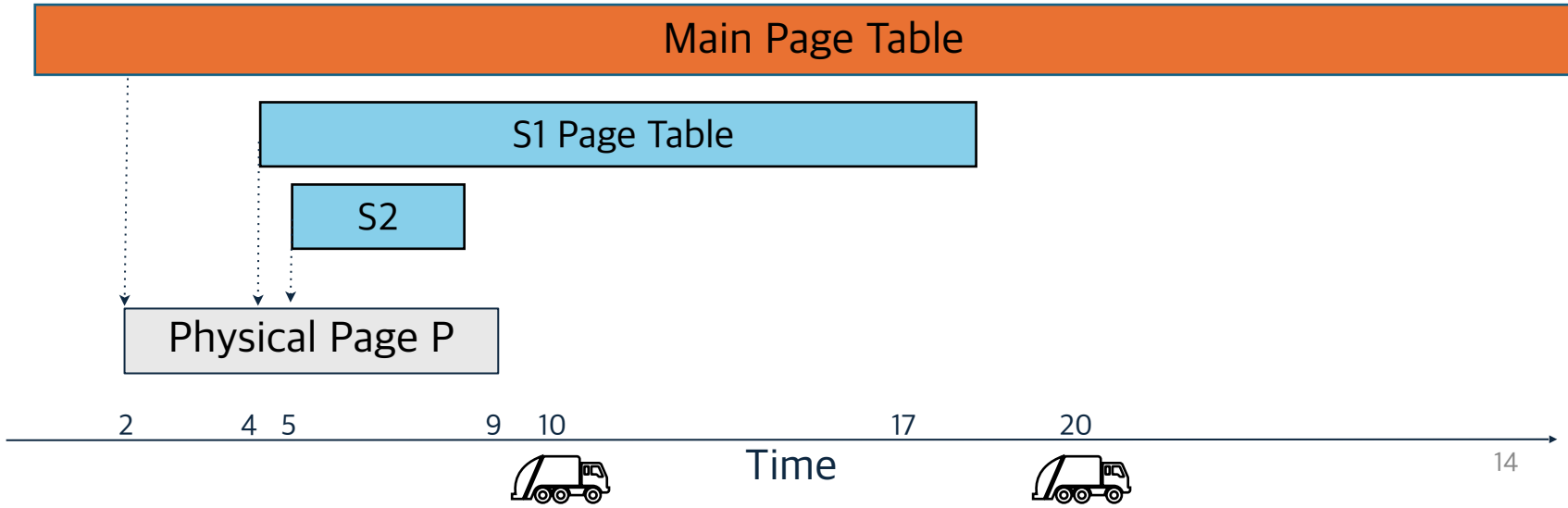

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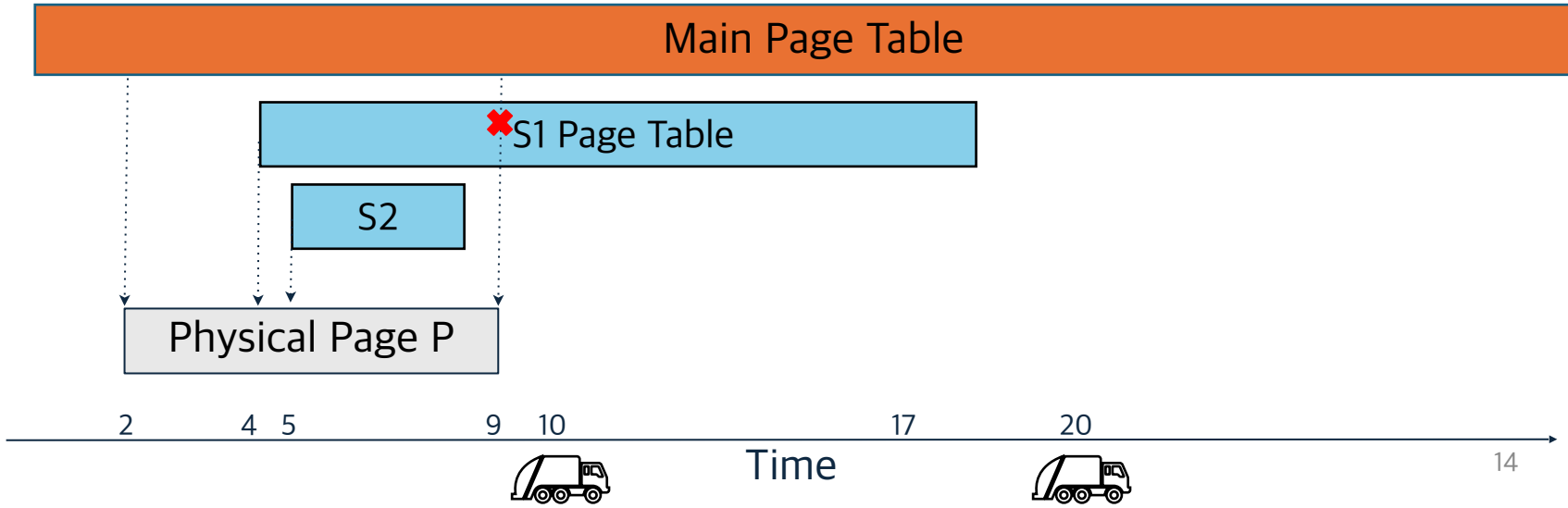

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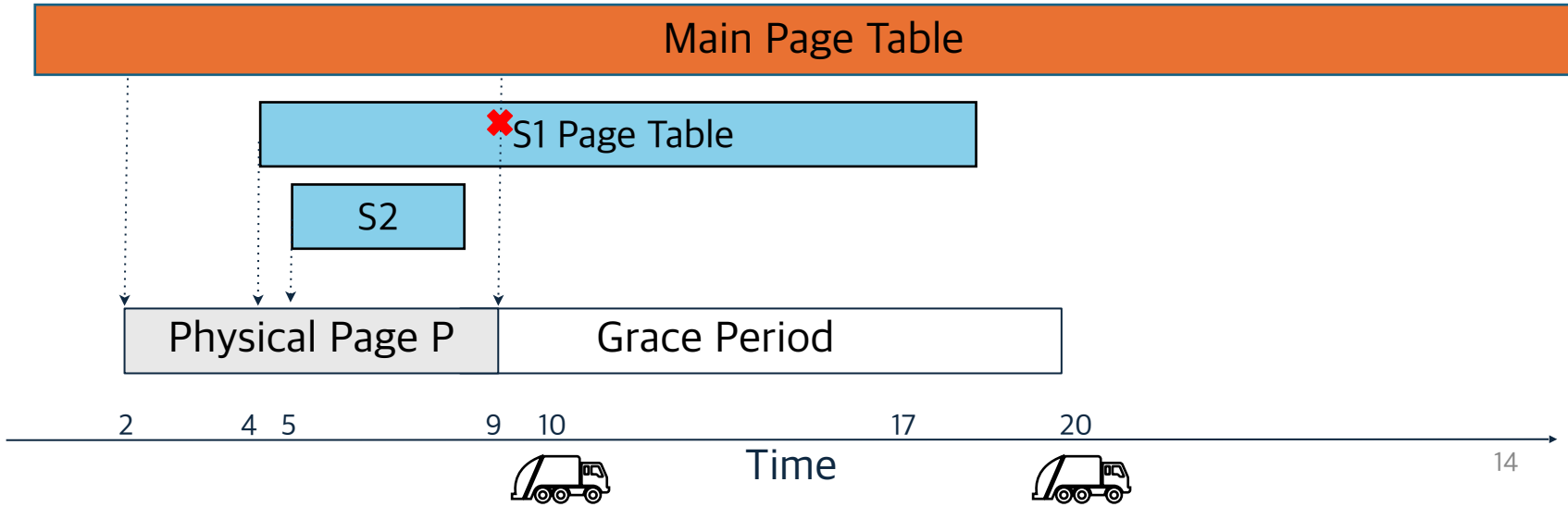

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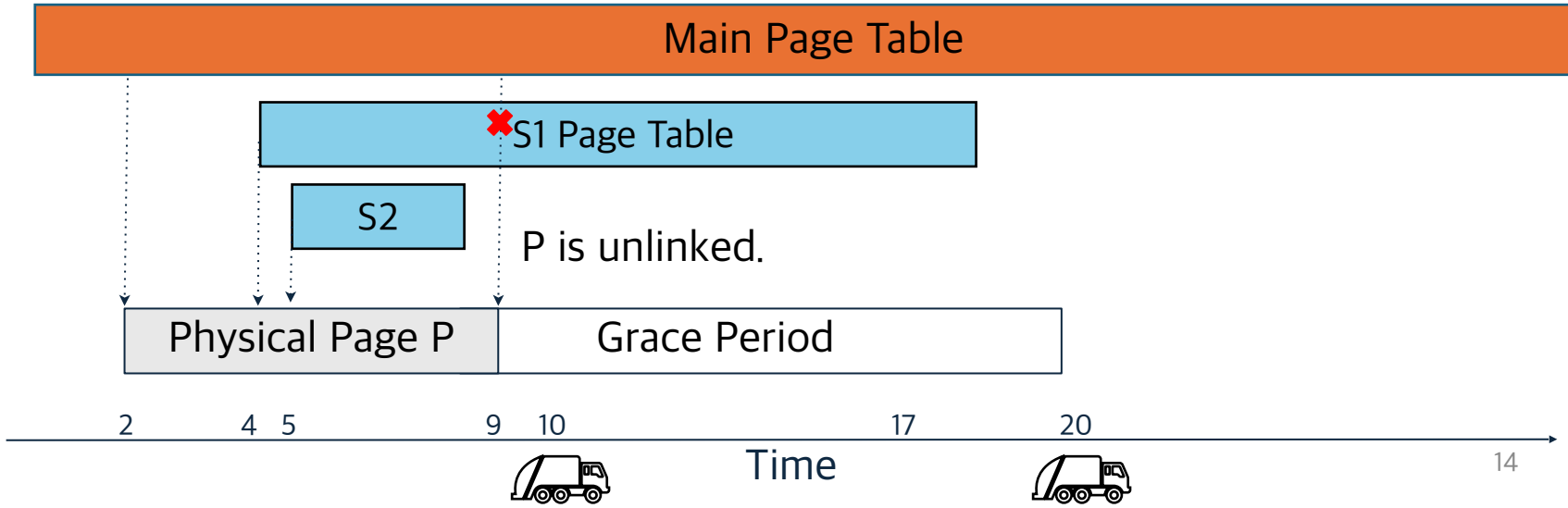

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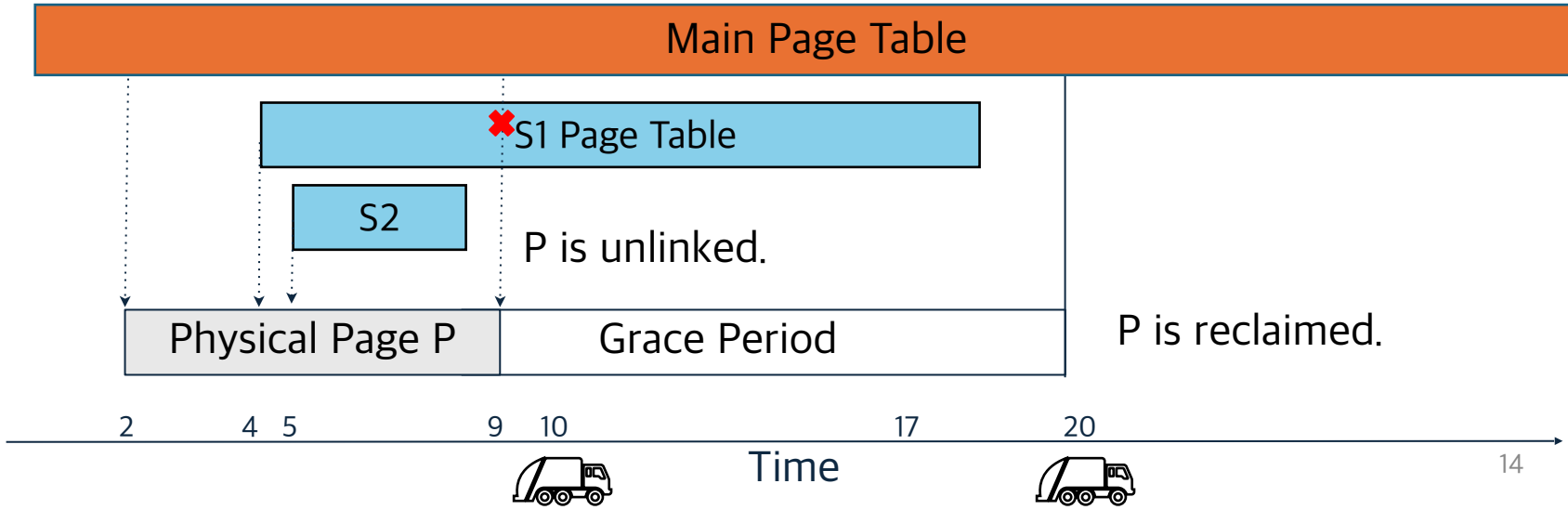
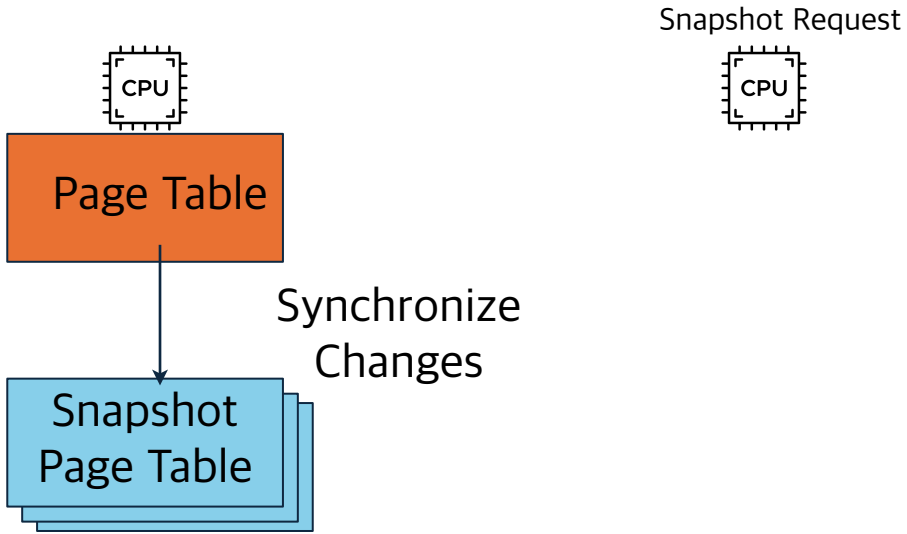


Instant Snapshotting via Pre-Creation

- Asynchronously maintain a set of ready-to-go snapshot page tables
- Completely hide the copy latency, making the snapshot creation appear instant



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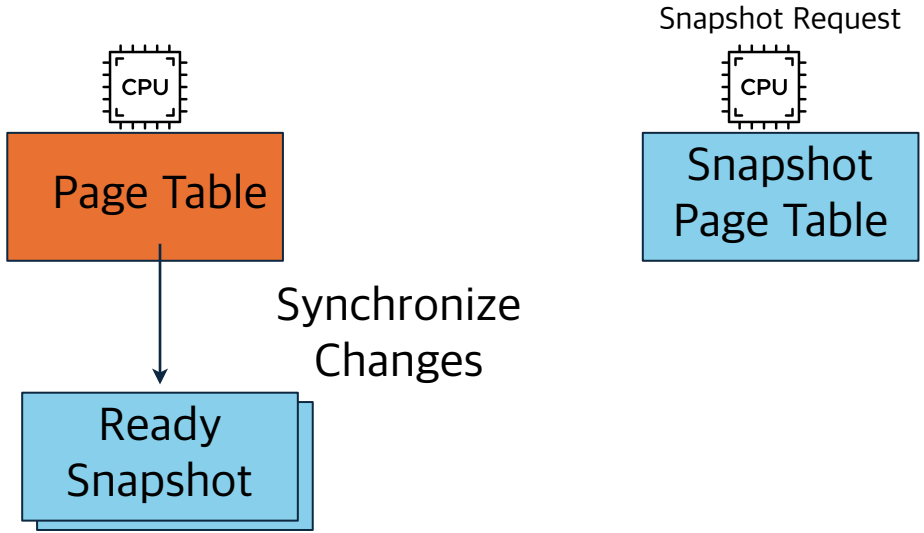
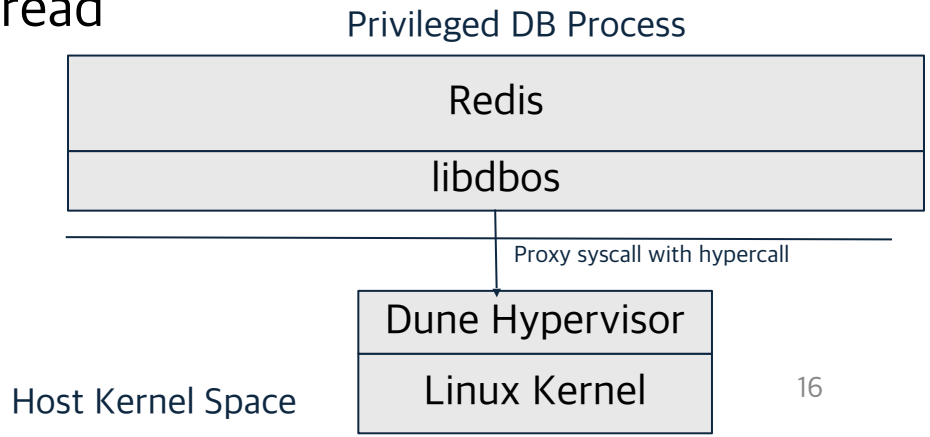


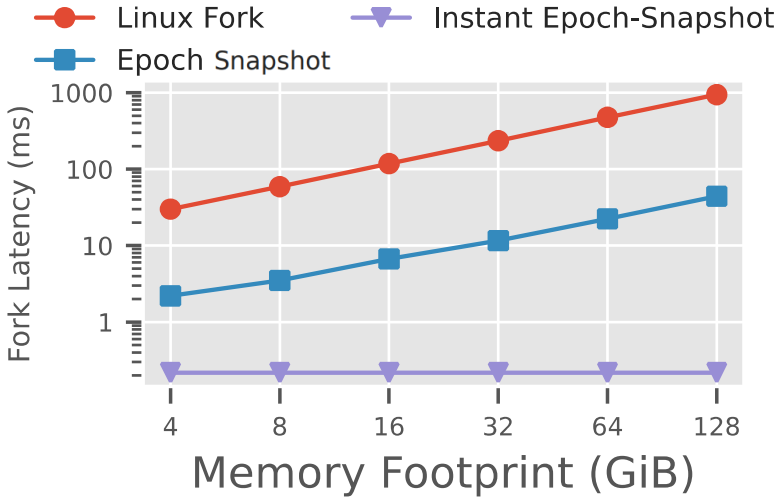
Implementation

- The snapshot mechanism is implemented (~1K LOC) in a guest kernel called **libdbos** on top of Dune hypervisor
  - Linux virtual memory subsystem 110K LOC
- Physical memory backing and system call proxy are done by the hypervisor
- Evaluated on Redis by replacing fork with this snapshot mechanism
  - Checkpoint process runs in a thread

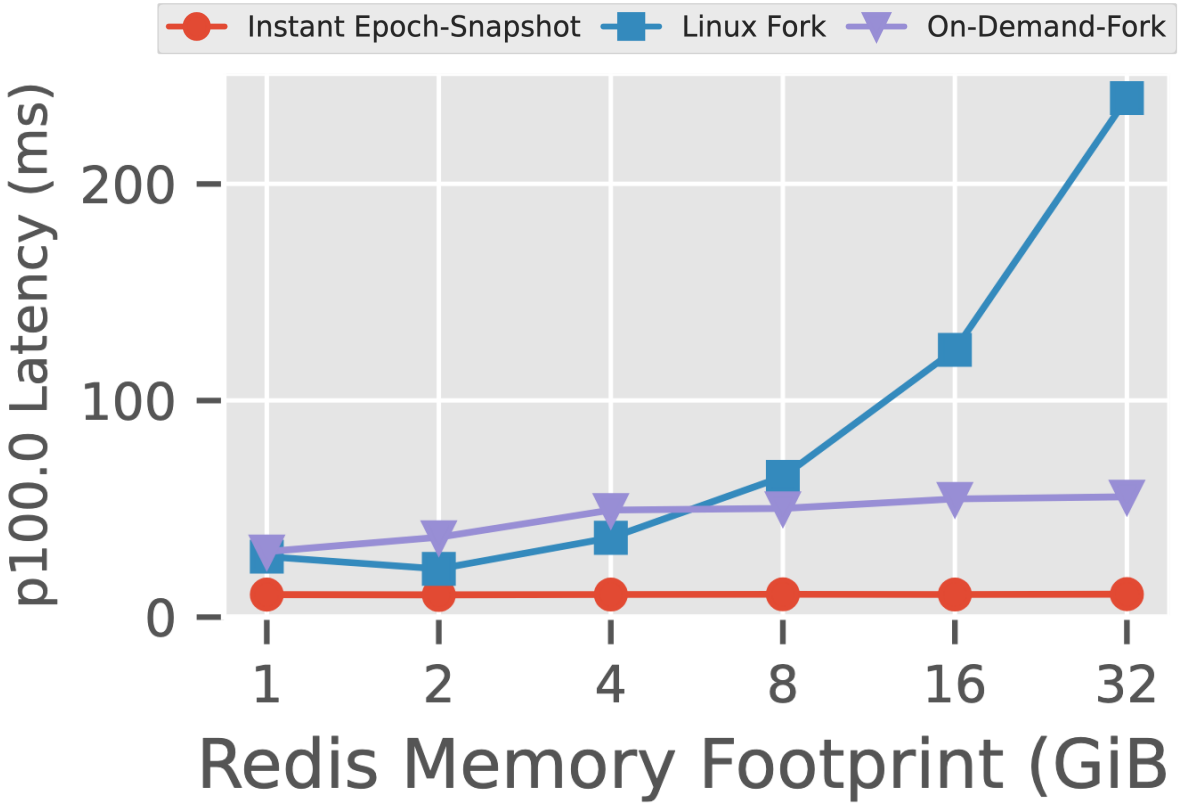


Microbenchmark

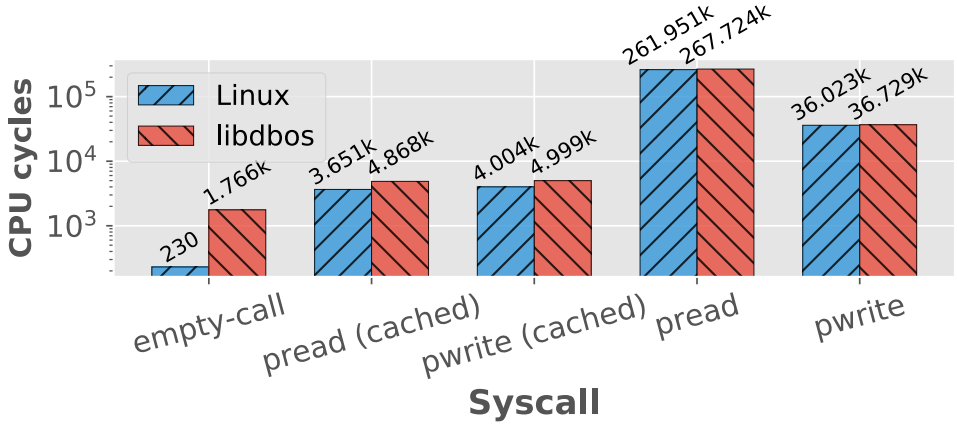
- ~20x reduction in snapshot latency
  - Snapshot 128GB memory in 40ms without parallelization
- Async copy completely hides fork latency if snapshot frequency > page table copy time



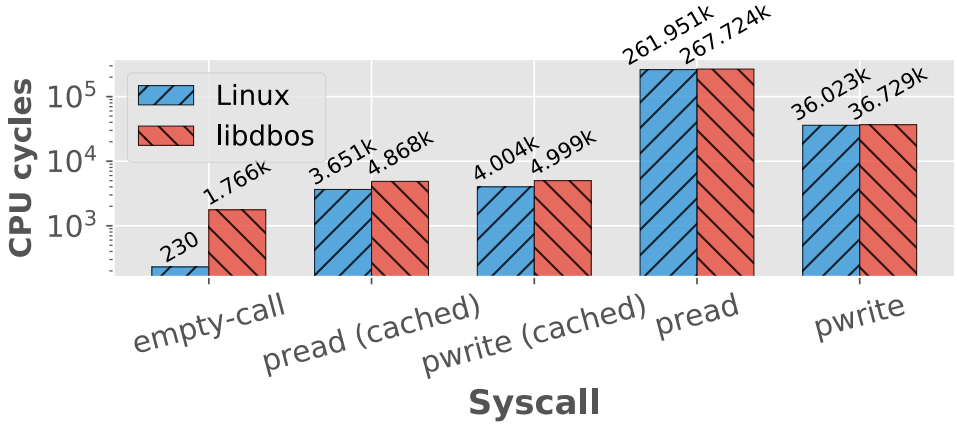
Tail Latency of Redis **SET** Query during Checkpoint

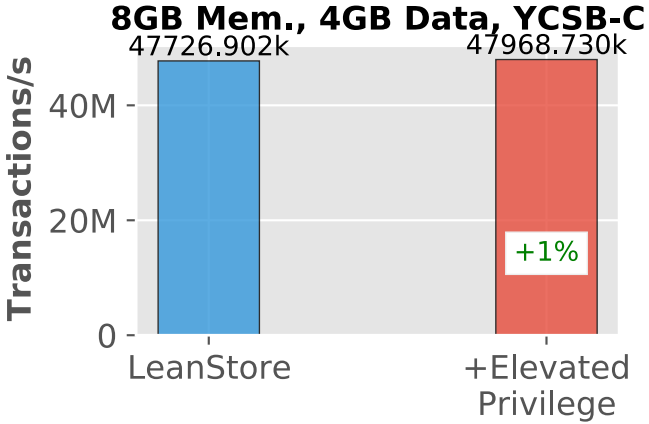


Cost of Virtualization

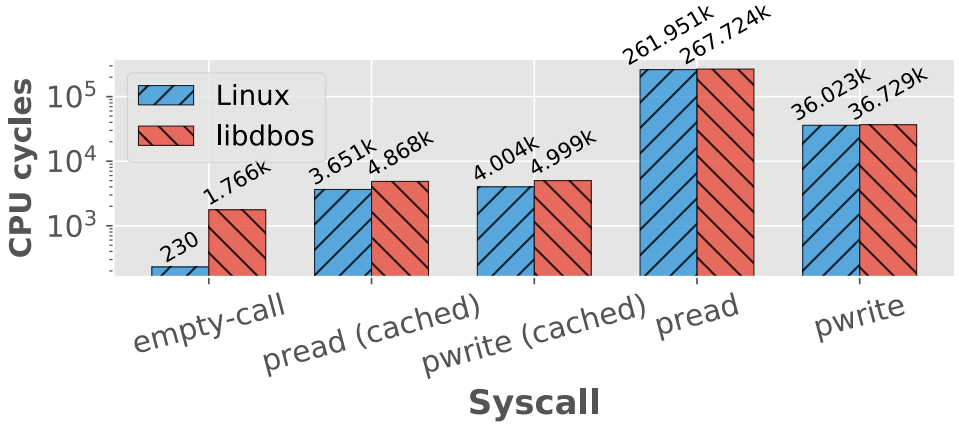


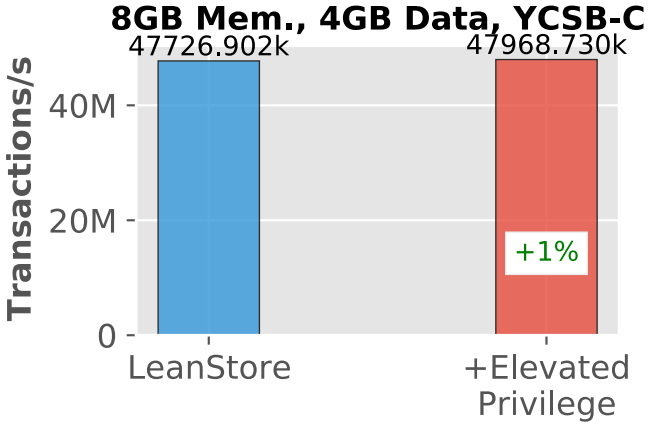
Cost of Virtualization

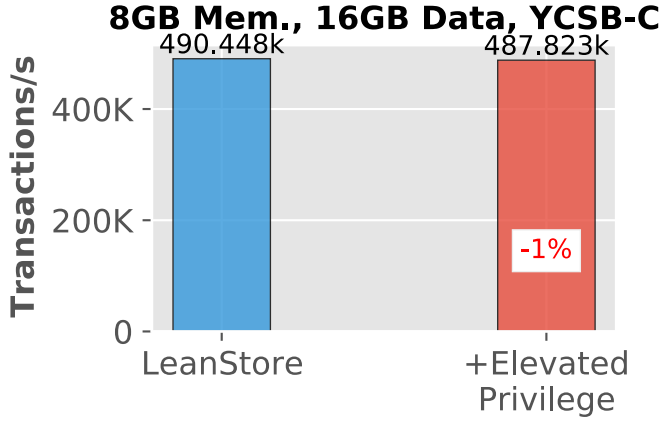




Cost of Virtualization



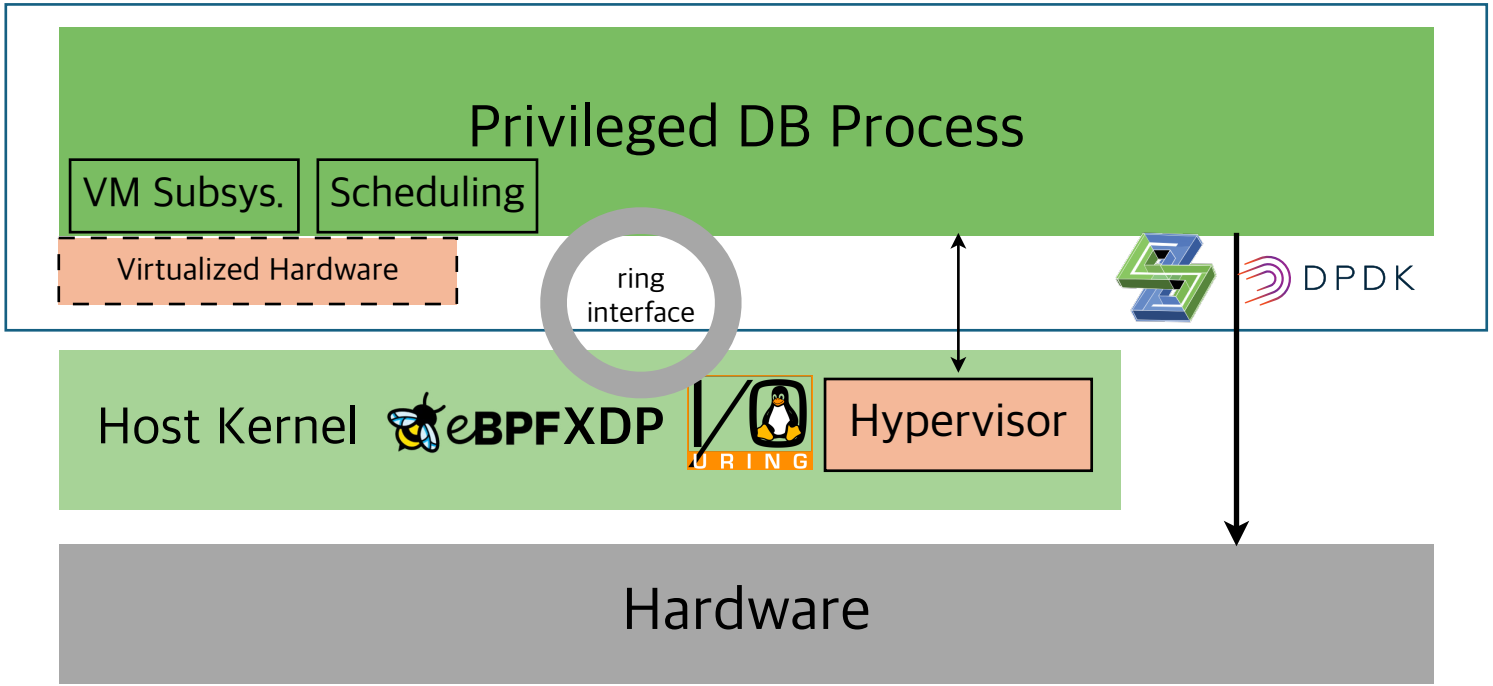




Numerous Possibilities

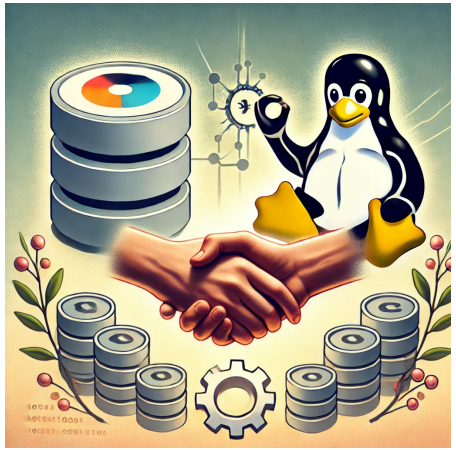
- Virtual Memory
  - “Perfect” virtual-memory-assisted buffer manager
  - Faster memory-rewiring for DBMS query processing and indexing
  - Faster memory allocation
  - …
- Scheduling
  - Robust lightweight task scheduling with preemption
  - Transaction-priority-aware lightweight task scheduling
  - …
- Hypervisor Interface
  - DBMS-assisted memory ballooning

Compatible with Modern Linux Data-Path Interfaces



Conclusions

- With **privileged kernel-bypass**, we can address the mismatch problem while
  - minimizing impact on kernel security and stability
  - providing complete design freedom to DBMS
  - preserving ecosystem
- DBMS deserves to be to **privileged!**



Paper