Strata:
A Cross Media File System

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Let’s build a fast server

NoSQL store, Database, File server, Mail server …

Requirements

- Small updates (1 Kbytes) dominate
- Dataset scales up to 10 TB
- Updates must be crash consistent

Storage diversification

	Latency	$/GB
DRAM	100 ns	8.6
NVM (soon)	300 ns	4.0
SSD	10 us	0.25
HDD	10 ms	0.02

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Byte-addressable: cache-line granularity IO

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Large erasure blocks need to be sequentially written
Random writes: **5~6x slowdown** due to **GC [FAST'15]**

A fast server on today's file system

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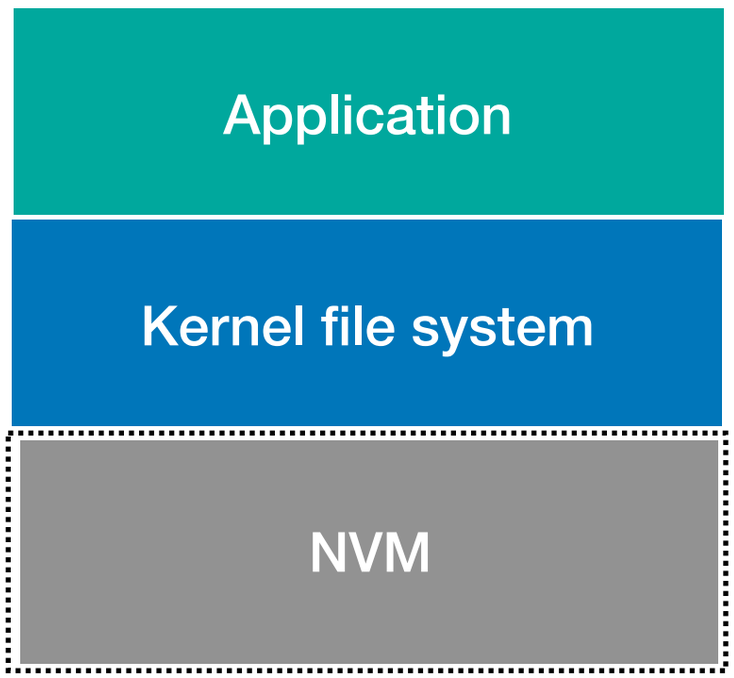

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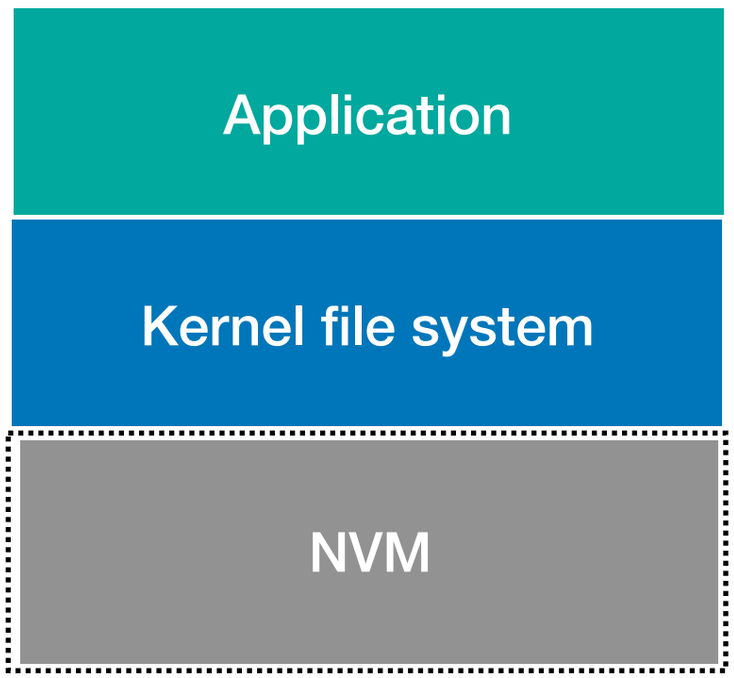

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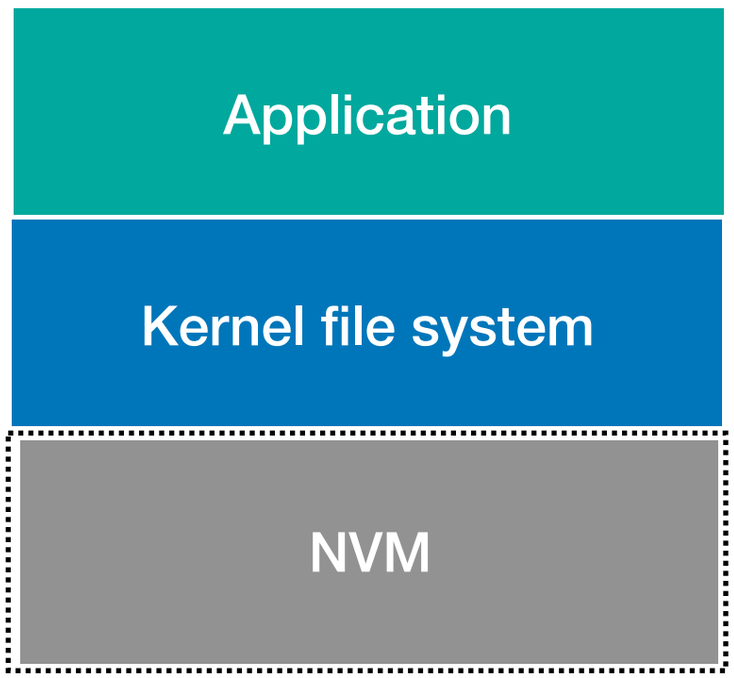

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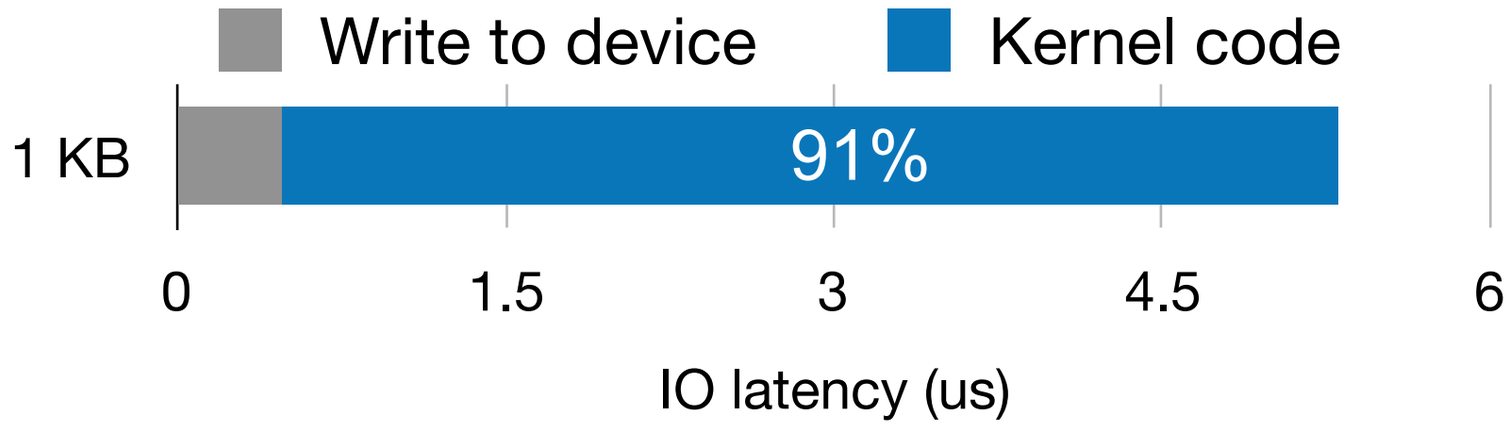

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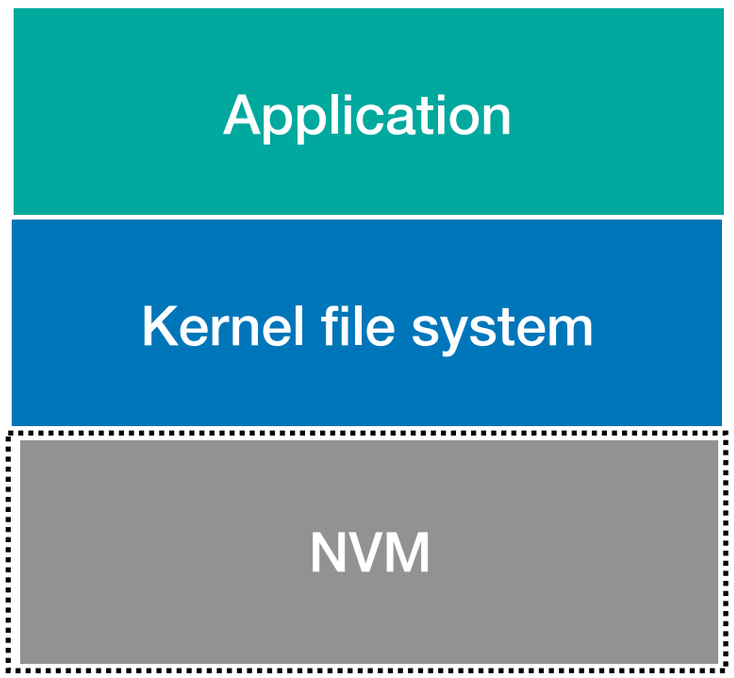

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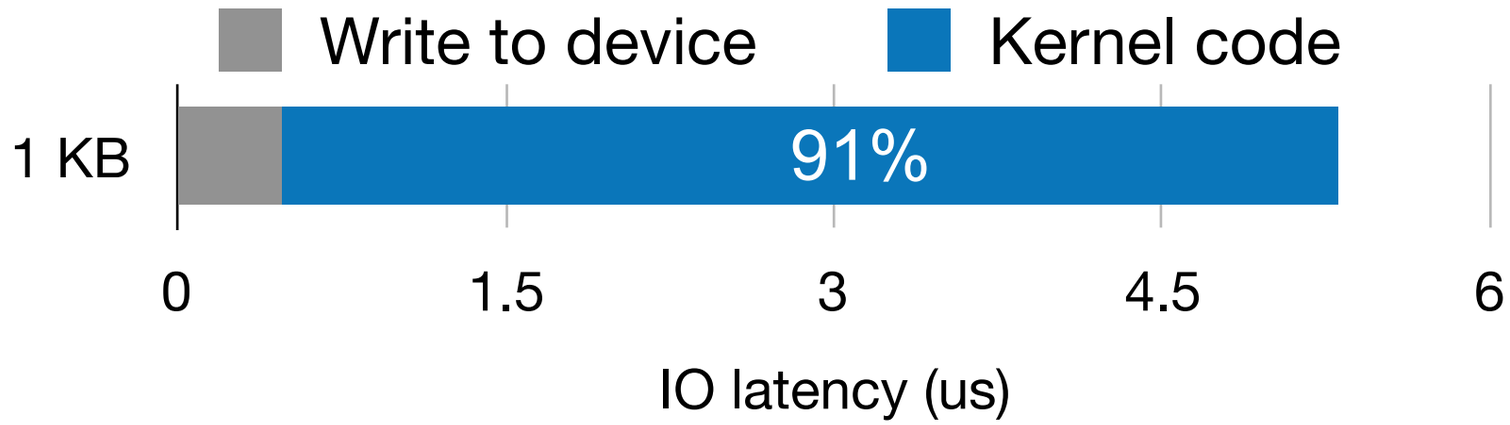

NVM is so fast that kernel is the bottleneck

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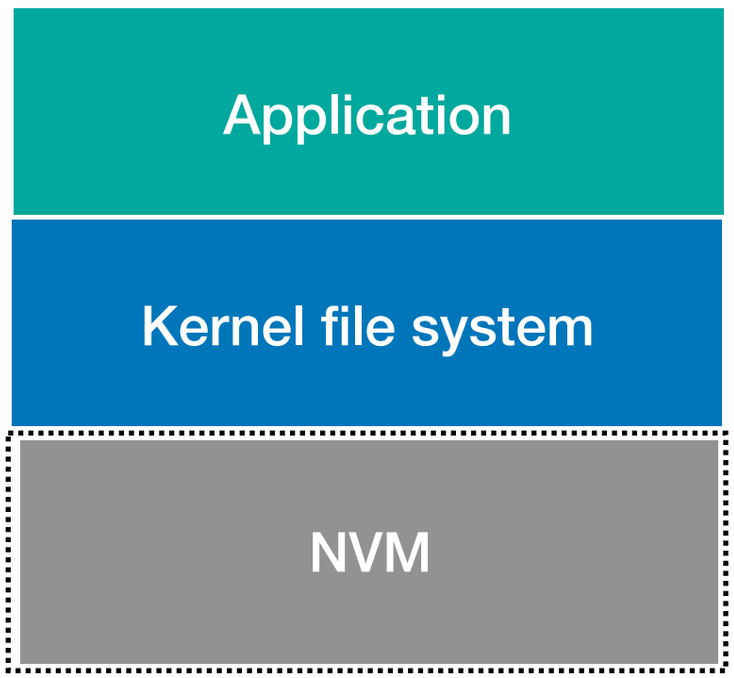

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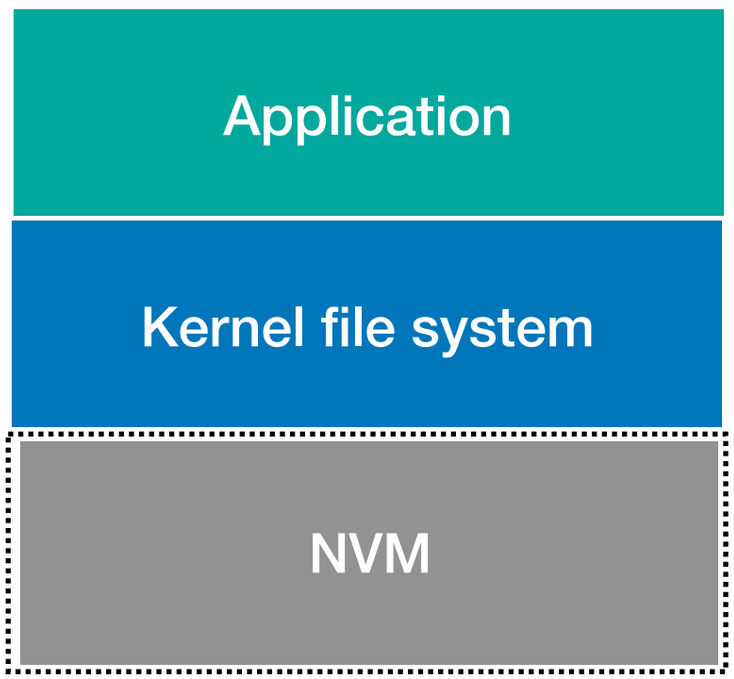

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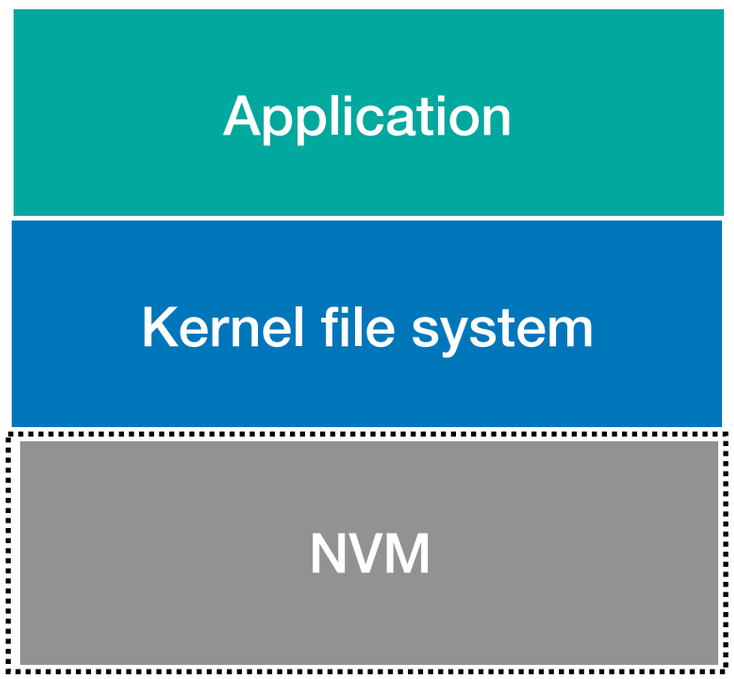

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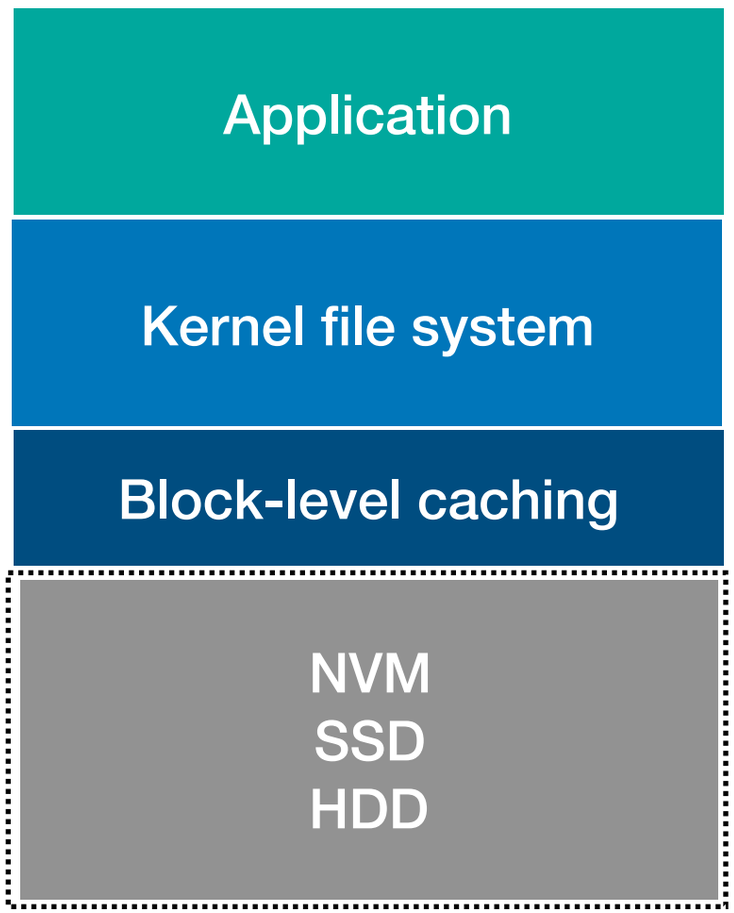

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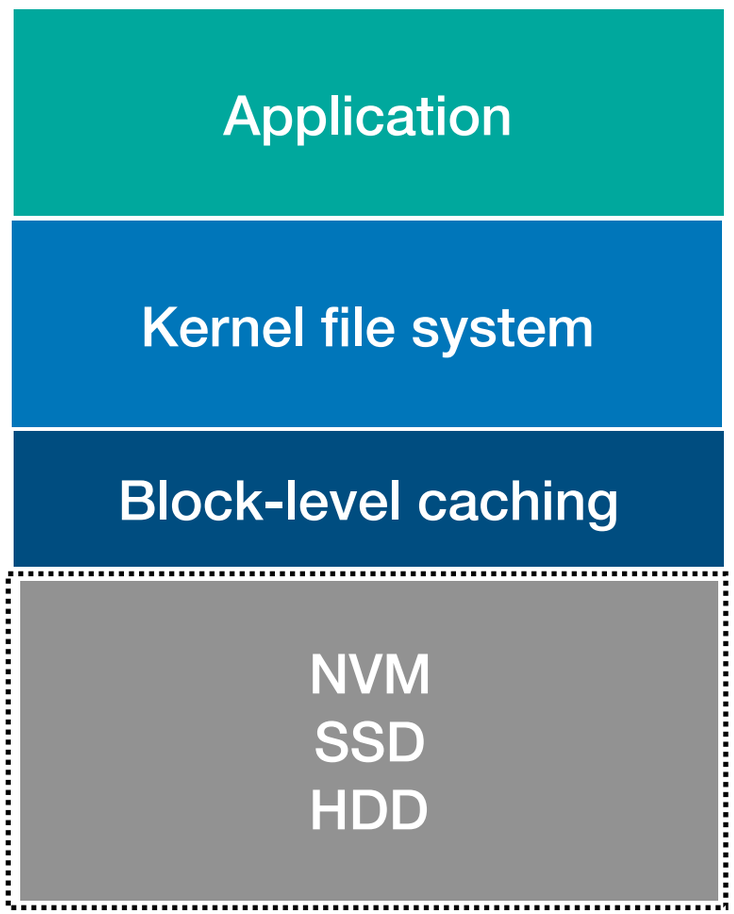

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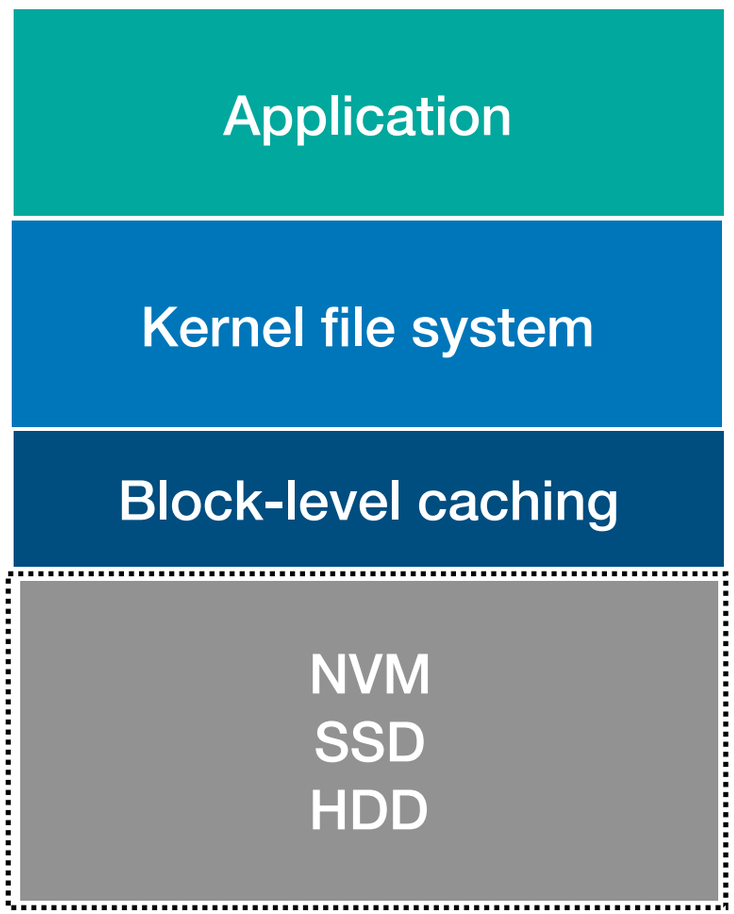

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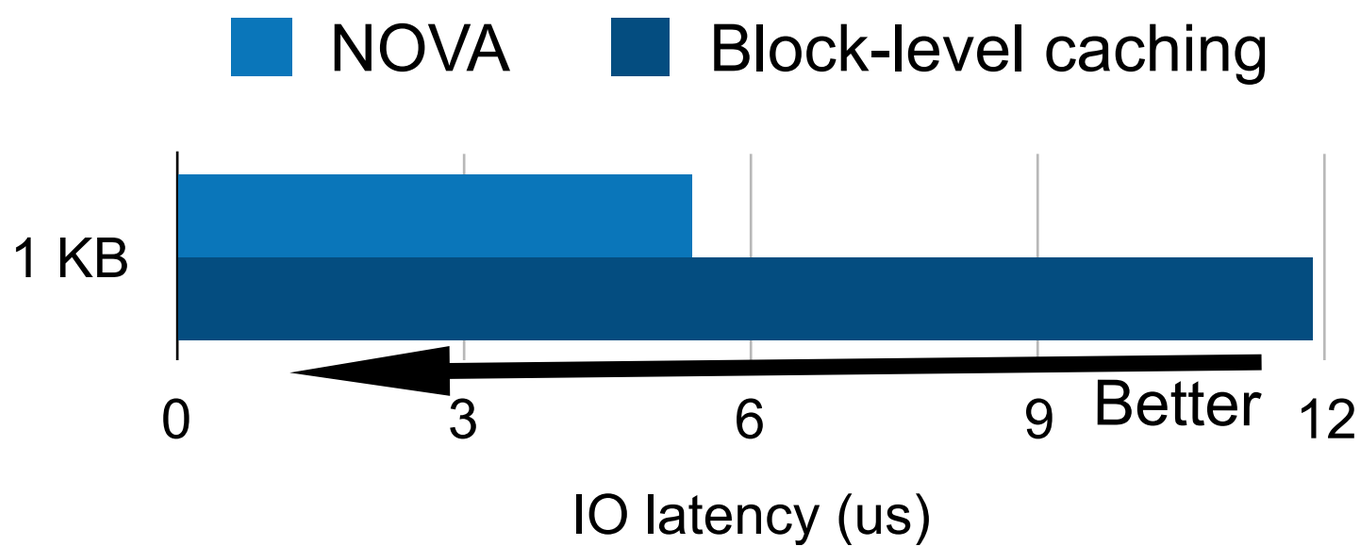

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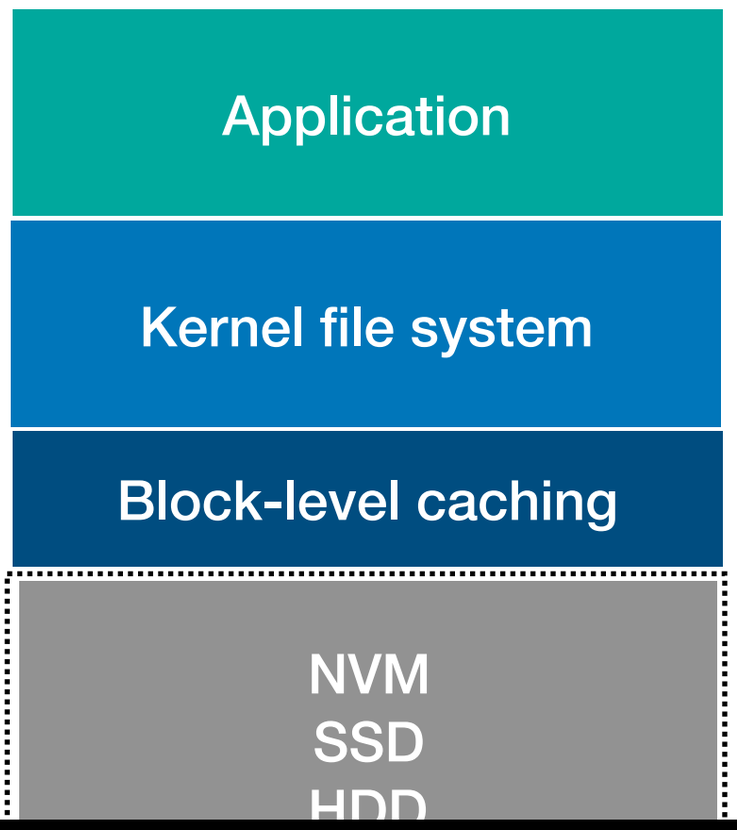

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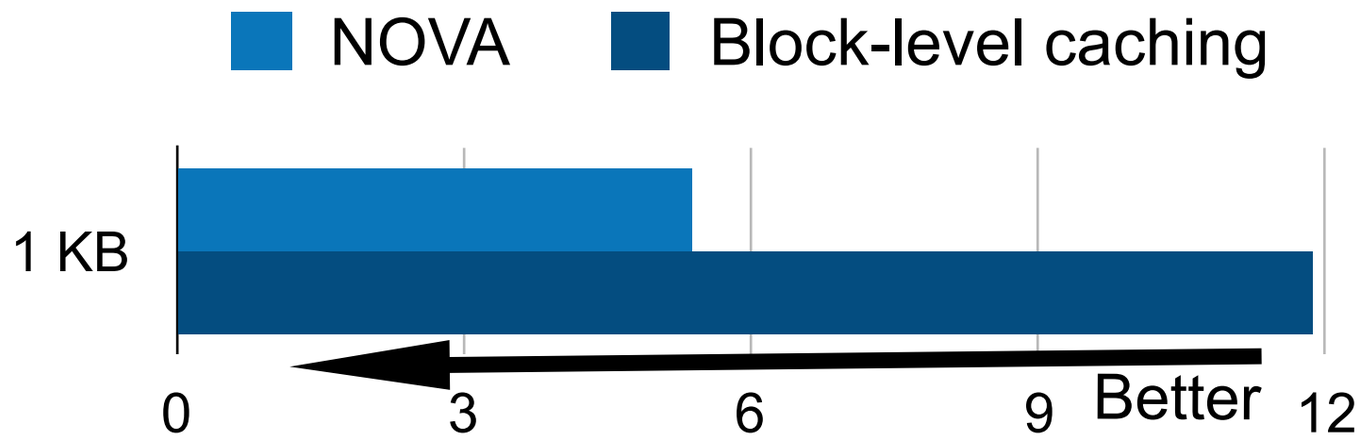

Block-level caching is too slow

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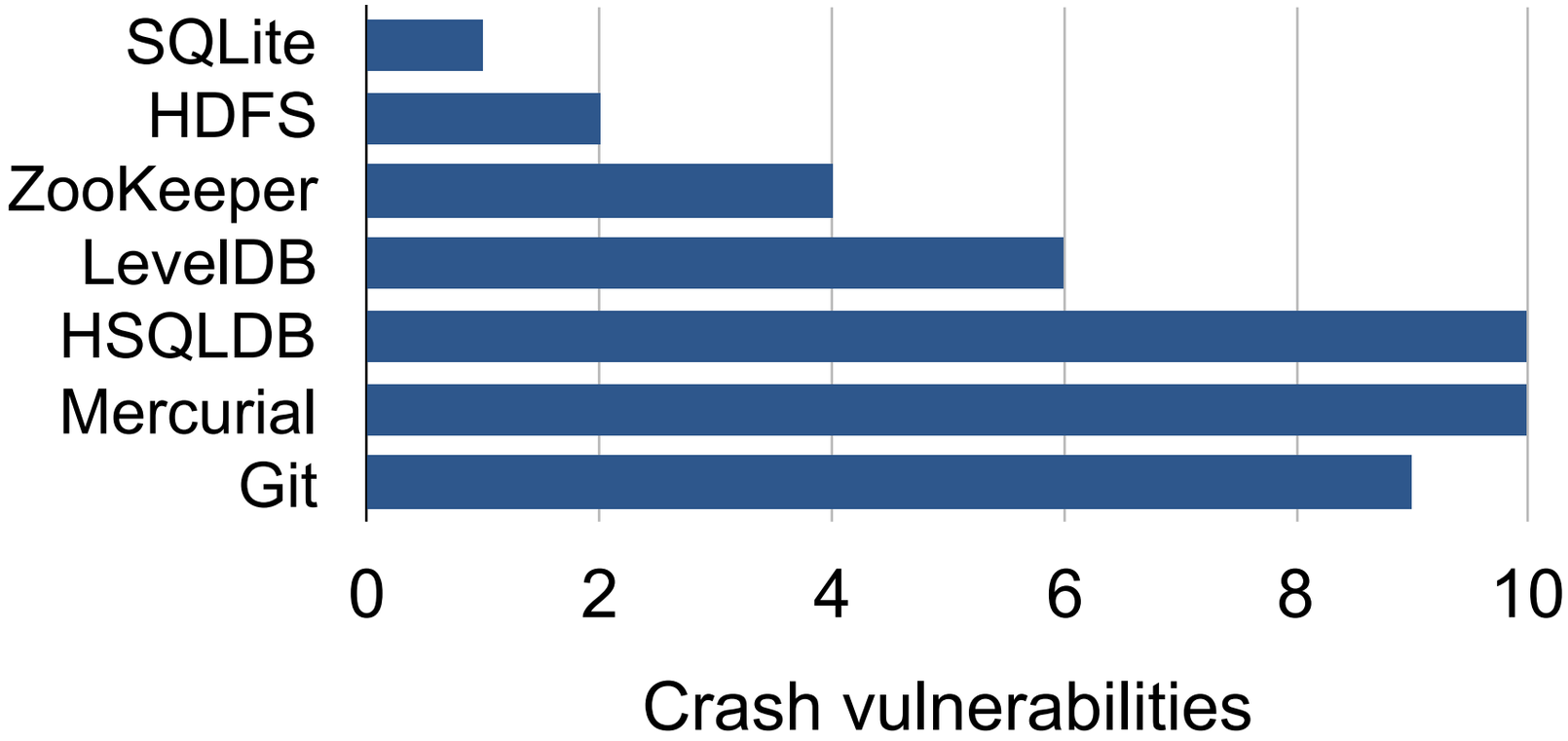

Pillai et al., OSDI 2014

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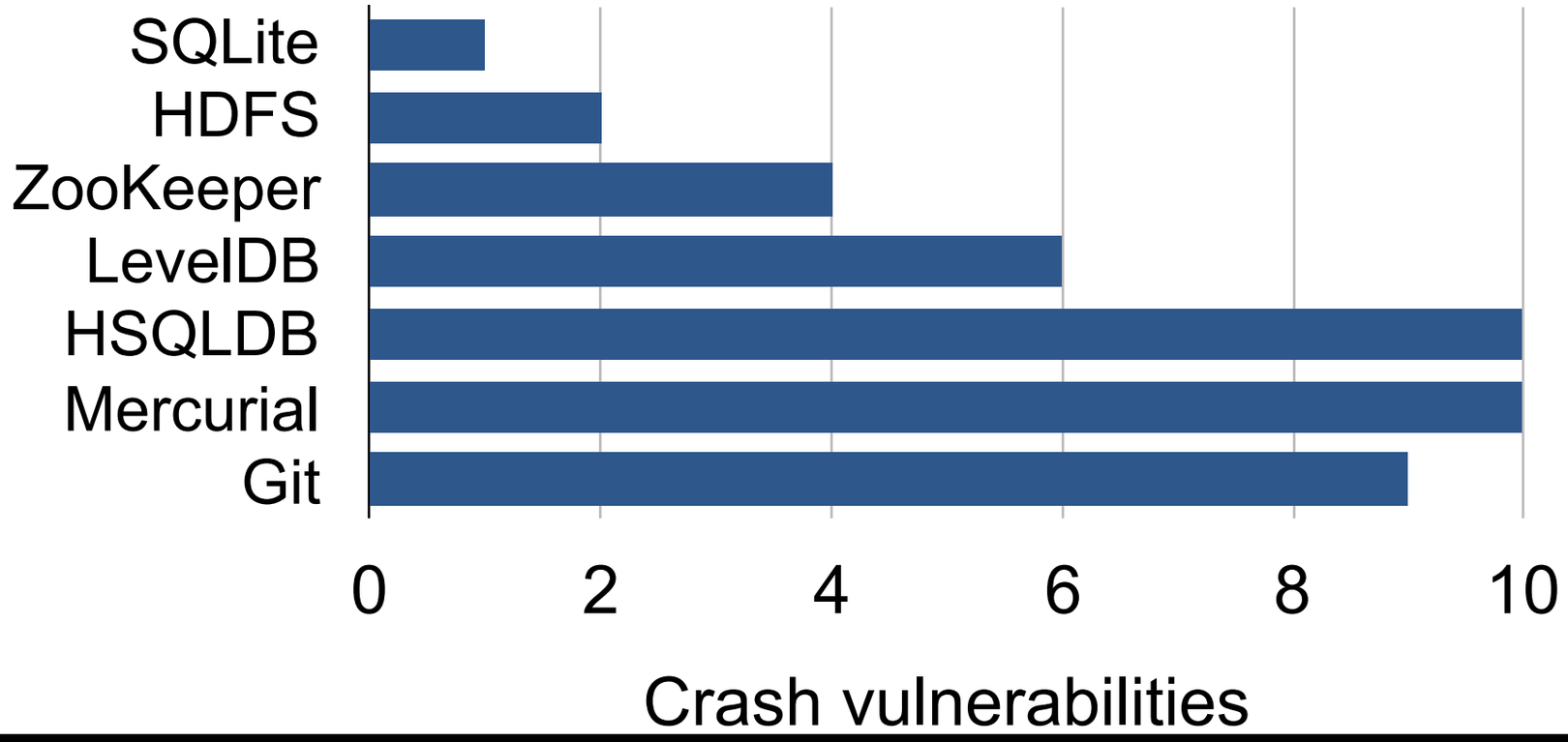

Applications struggle for crash consistency

Problems in today's file systems

- Kernel mediates every operation
  NVM is so fast that kernel is the bottleneck

- Tied to a single type of device
  For low-cost capacity with high performance, must leverage multiple device types
  NVM (soon), SSD, HDD

- Aggressive caching in DRAM,
  write to device only when you must (fsync)
  Applications struggle for crash consistency

Strata:
A Cross Media File System

Performance: especially small, random IO

- Fast user-level device access

Low-cost capacity: leverage NVM, SSD & HDD

- Transparent data migration across different storage media
- Efficiently handle device IO properties

Simplicity: intuitive crash consistency model

- In-order, synchronous IO
- No fsync() required

Strata: main design principle

Log operations to NVM at user-level

Digest and migrate data in kernel

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LibFS Log operations to NVM at user-level

Performance: Kernel bypass, but private

Simplicity: Intuitive crash consistency

KernelFS Digest and migrate data in kernel

Apply log operations to shared data

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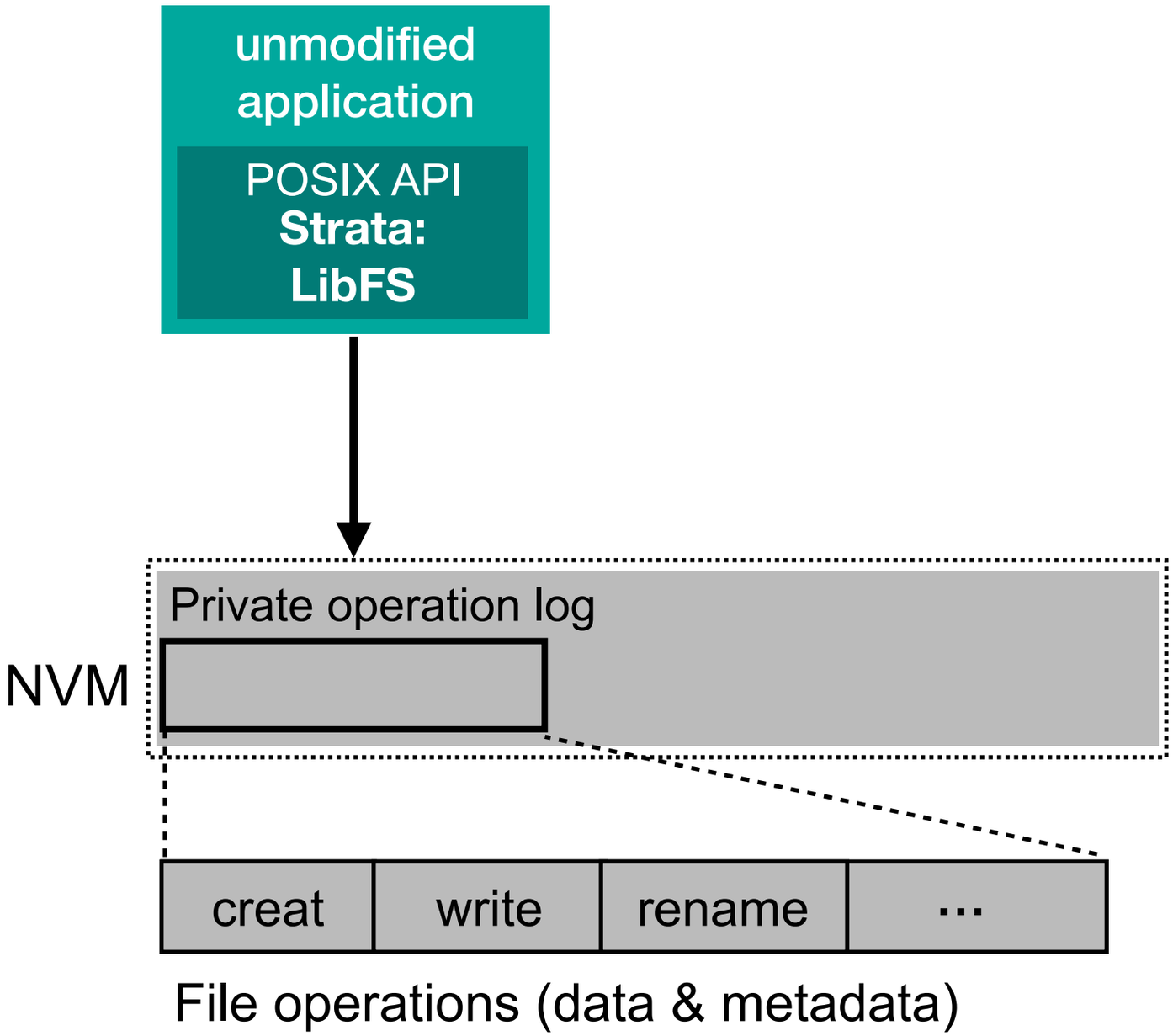
Outline

- **LibFS:** Log operations to NVM at user-level
  - Fast user-level access
  - In-order, synchronous IO
- **KernelFS:** Digest and migrate data in kernel
  - Asynchronous digest
  - Transparent data migration
  - Shared file access
- **Evaluation**

Log operations to NVM at user-level



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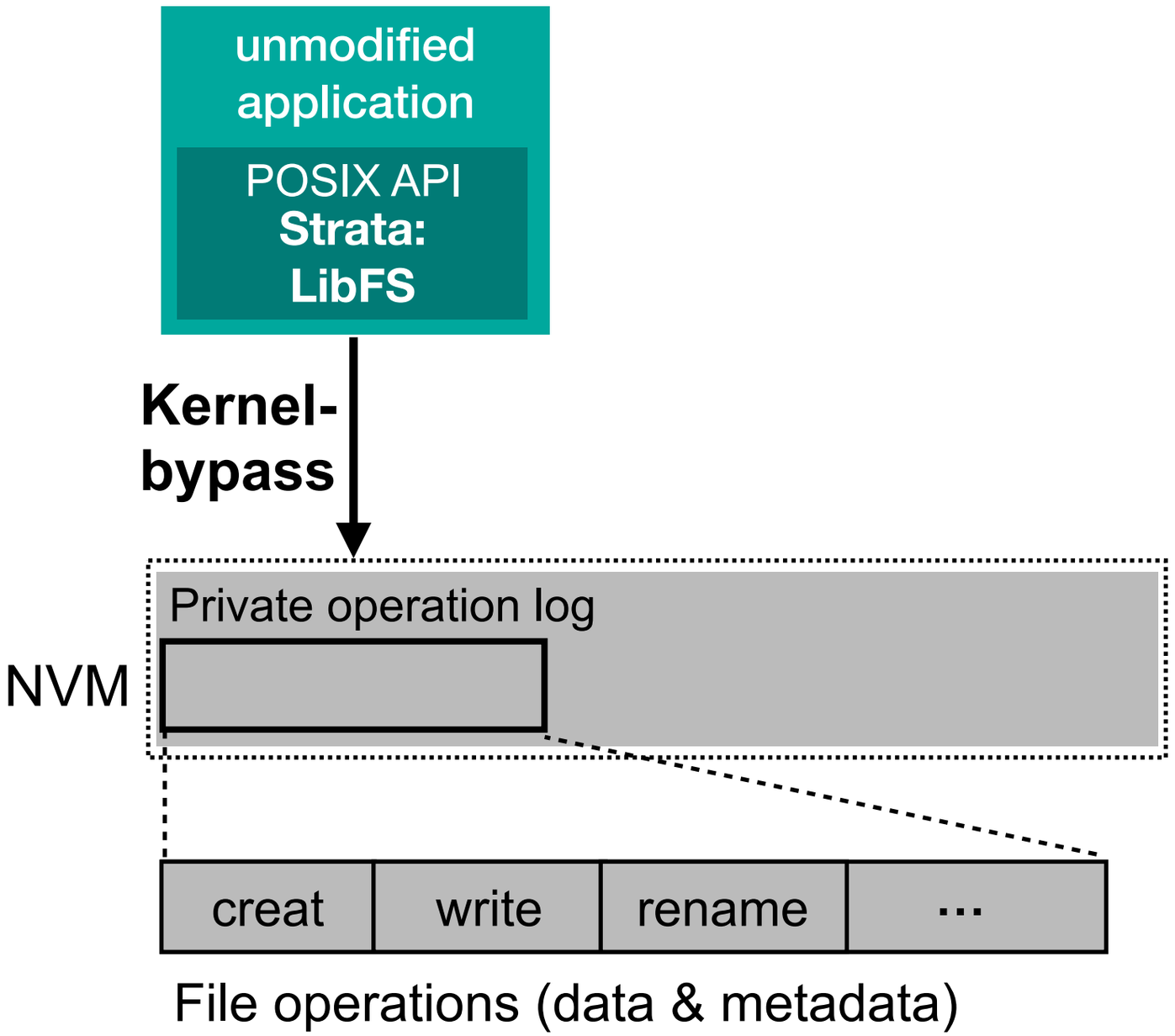

- Fast writes
  - Directly access fast NVM
  - Sequentially append data
  - Cache-line granularity
  - Blind writes

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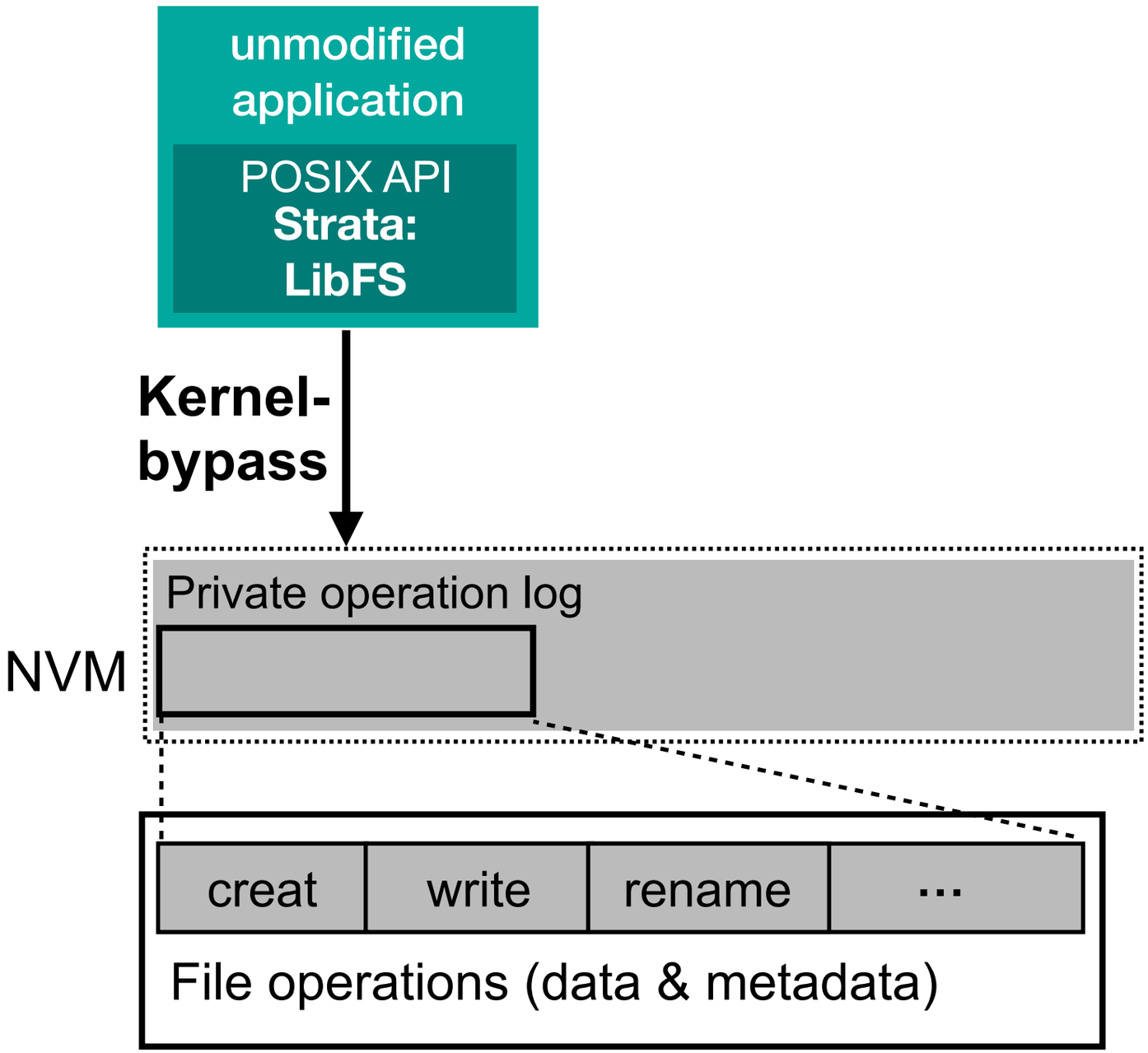

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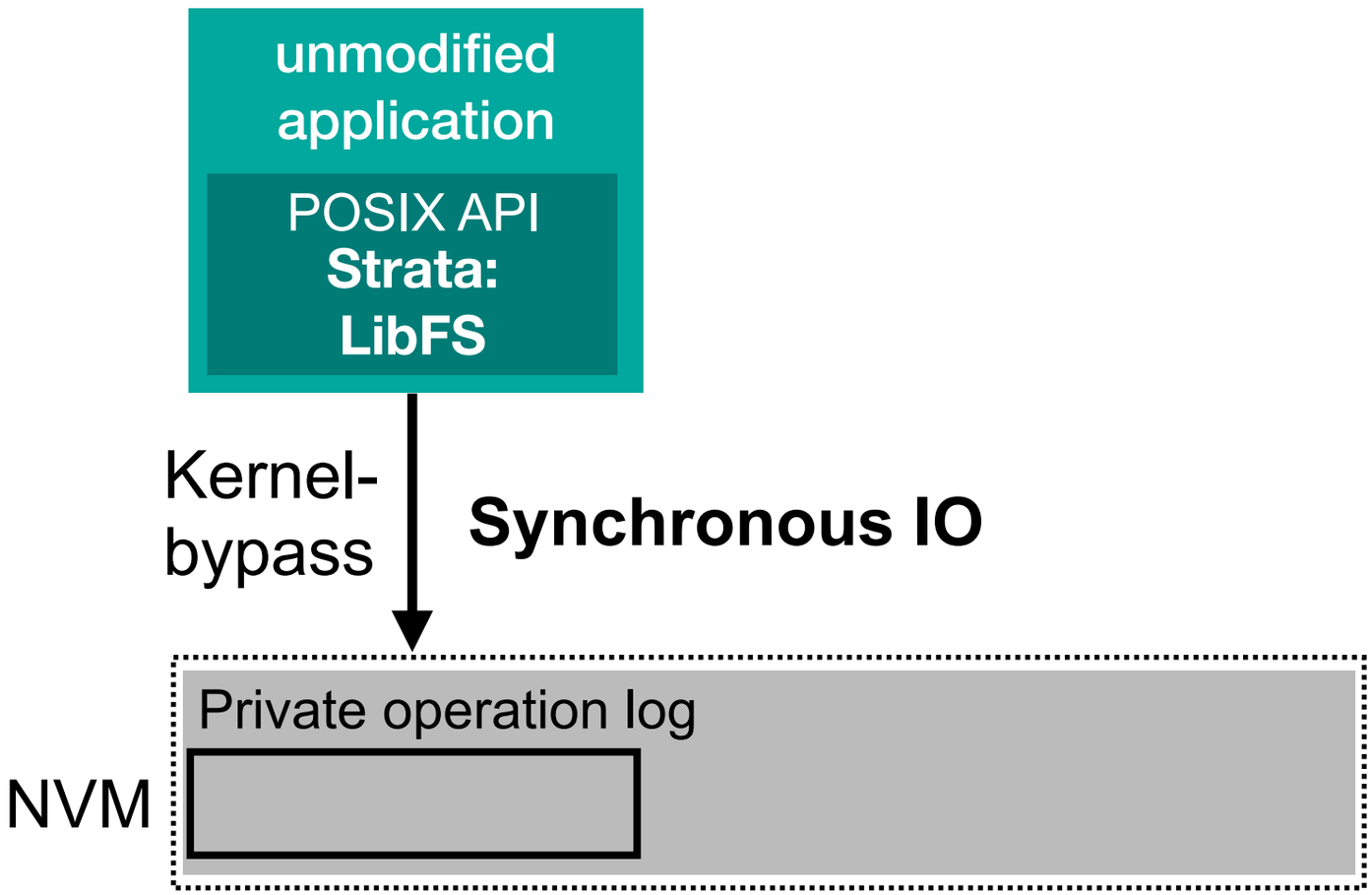
- Crash consistency
  - On crash, kernel replays log

Intuitive crash consistency



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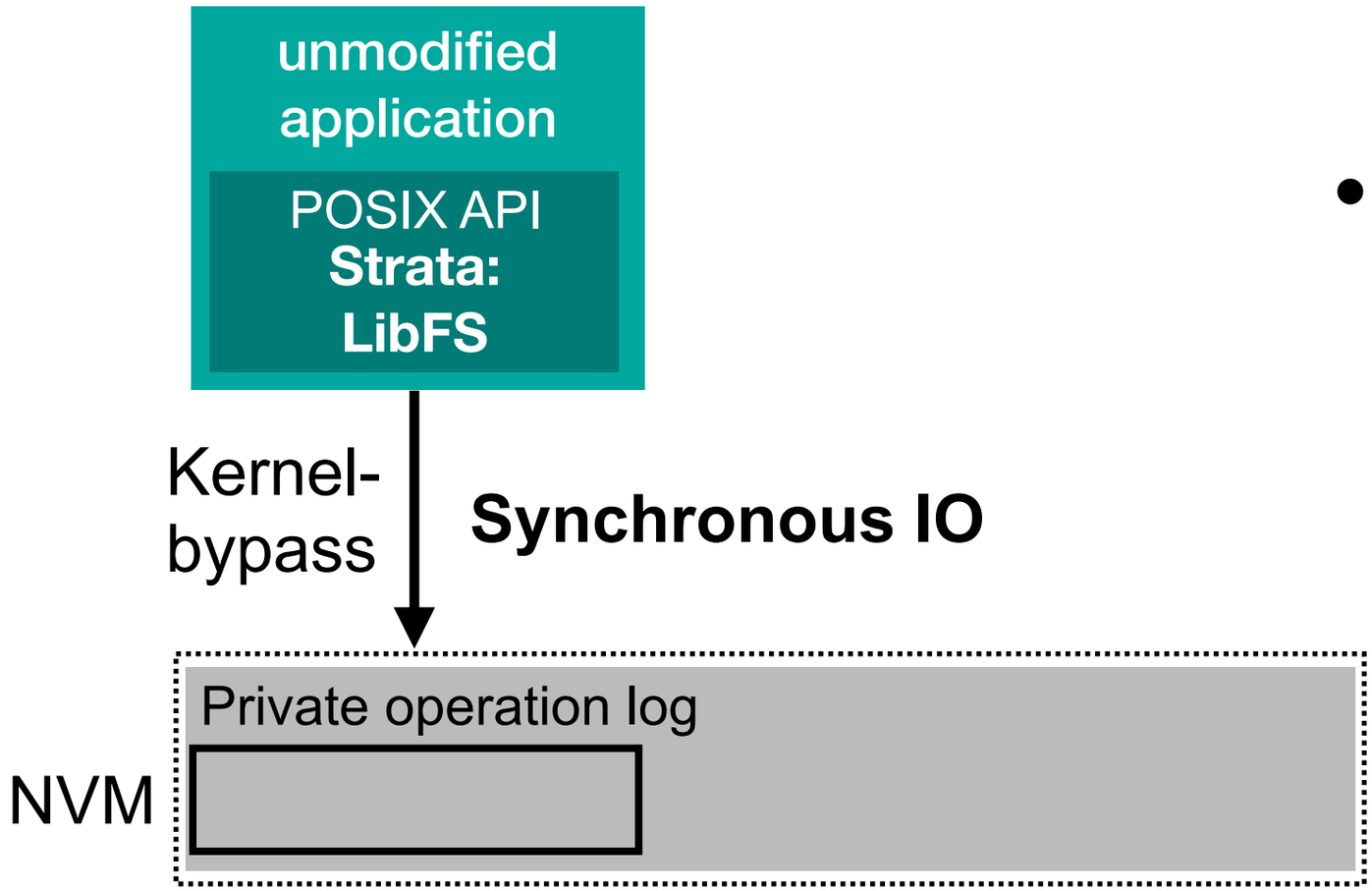

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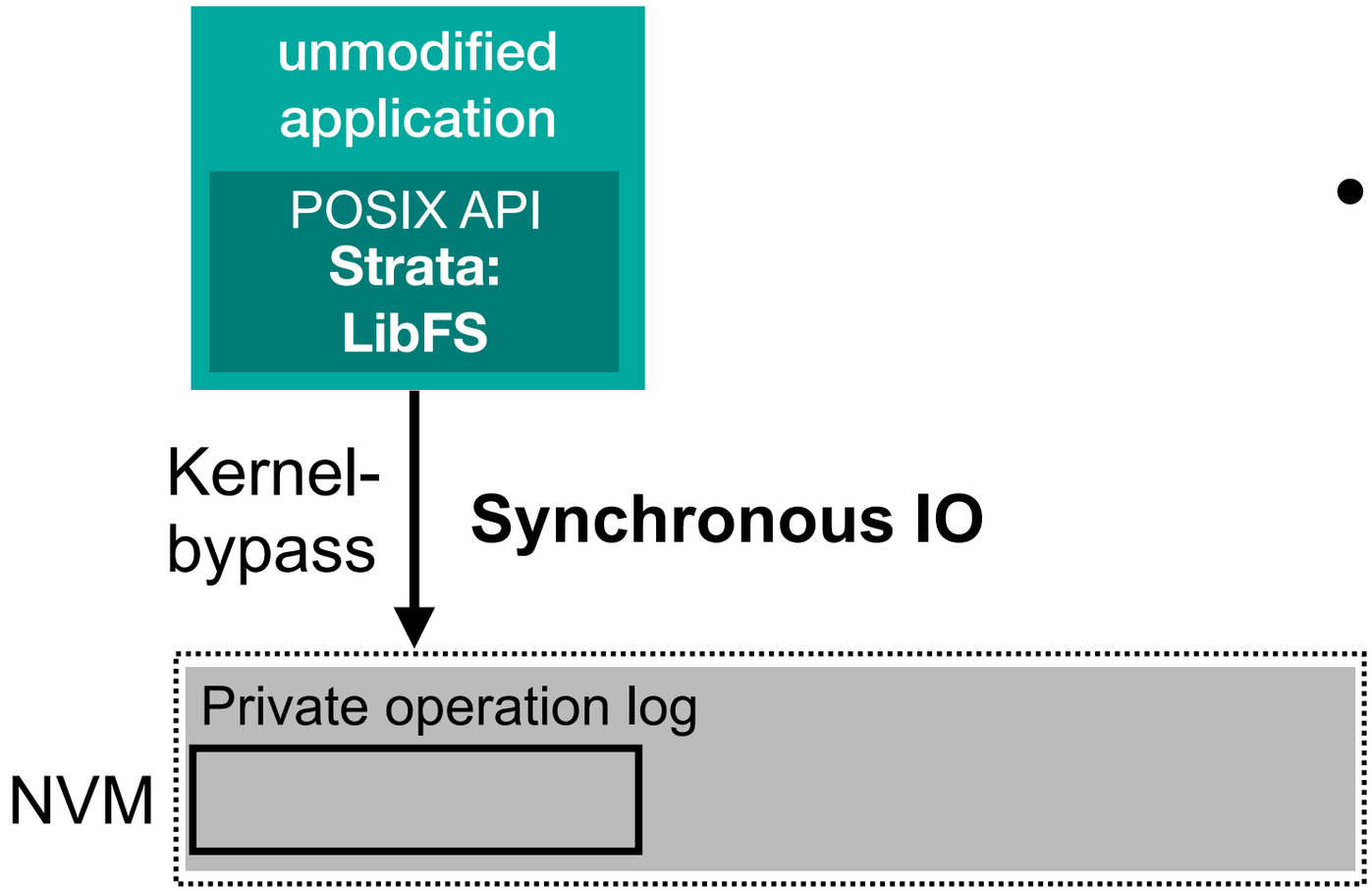

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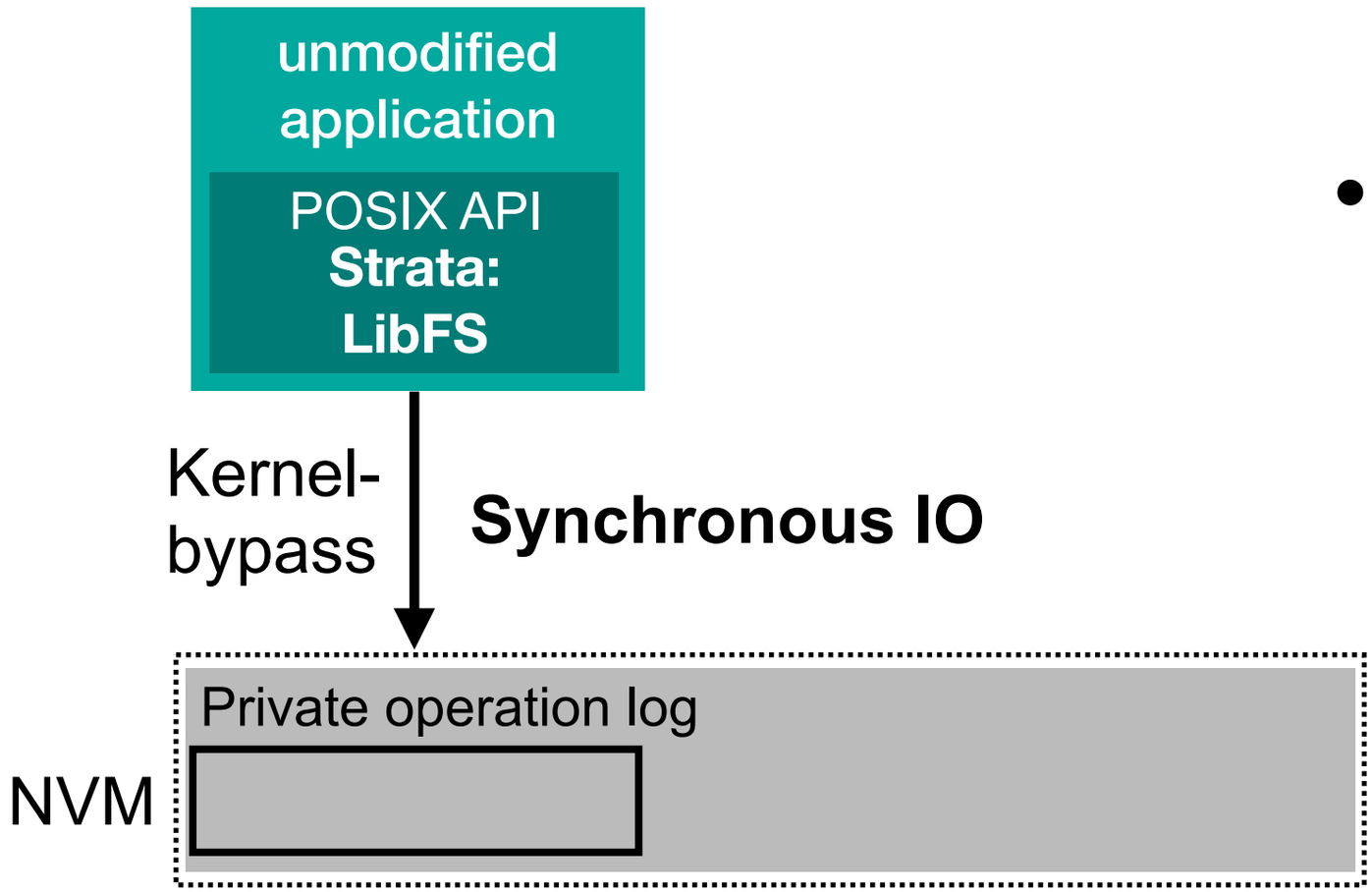

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Fast synchronous IO: NVM and kernel-bypass

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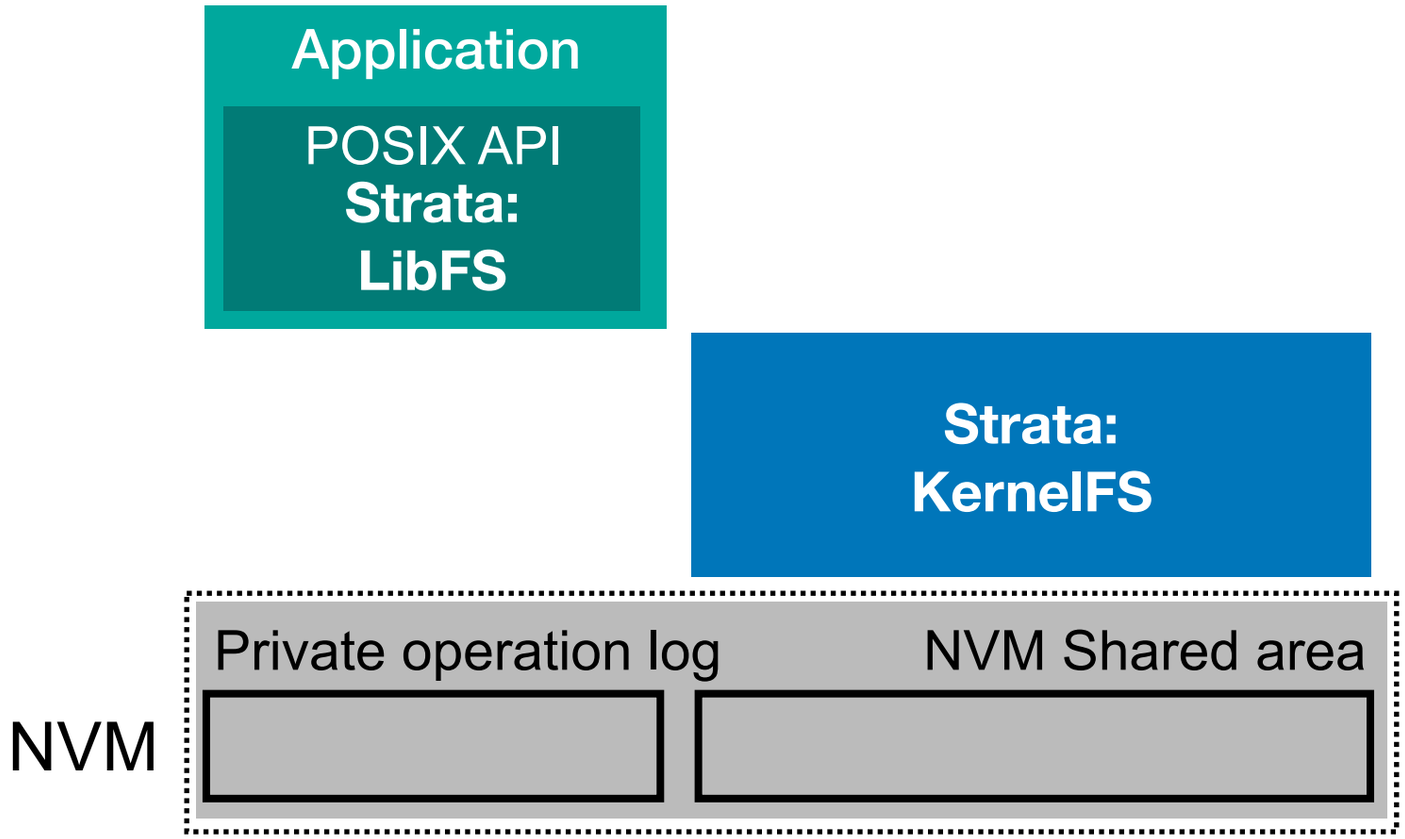
Digest data in kernel



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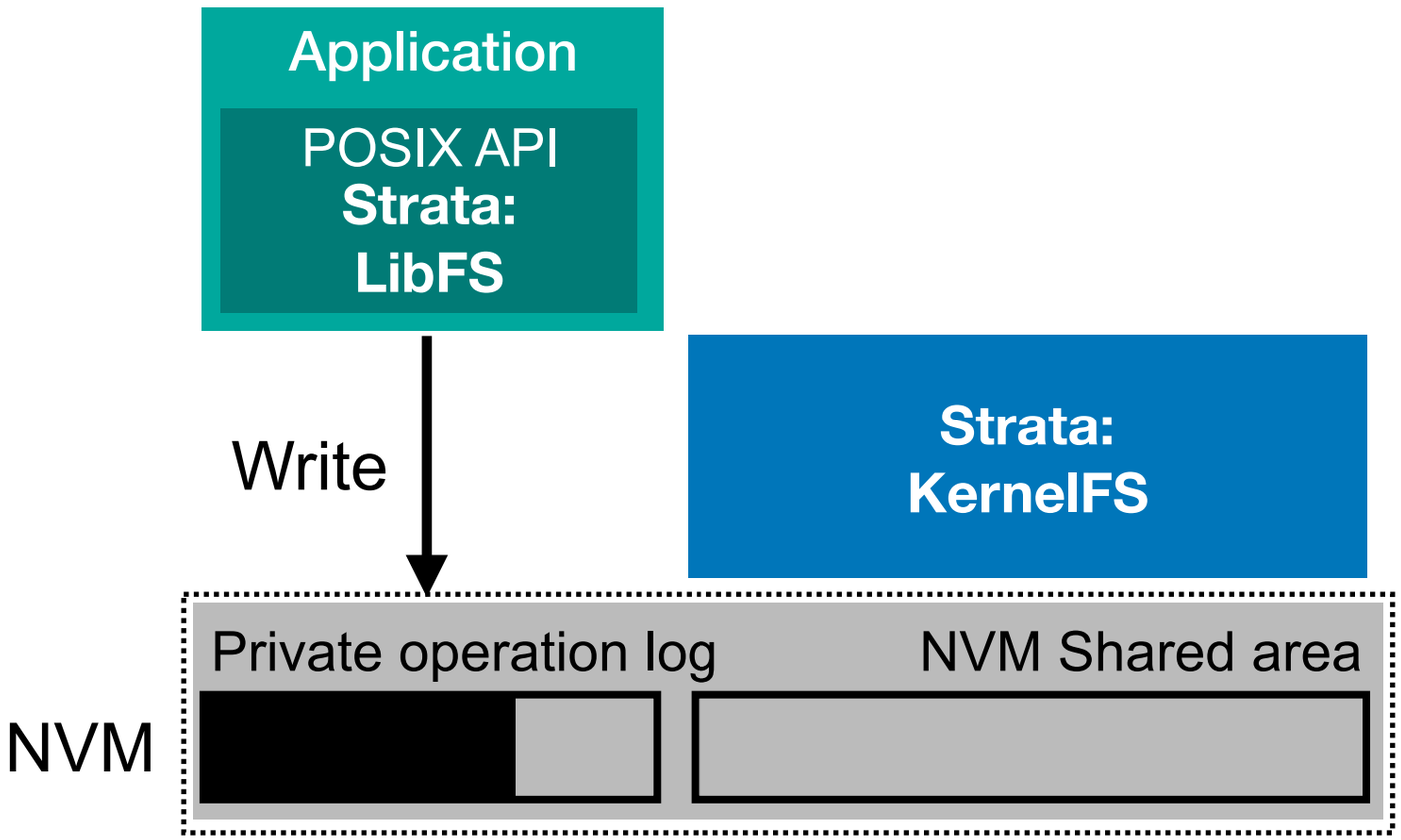

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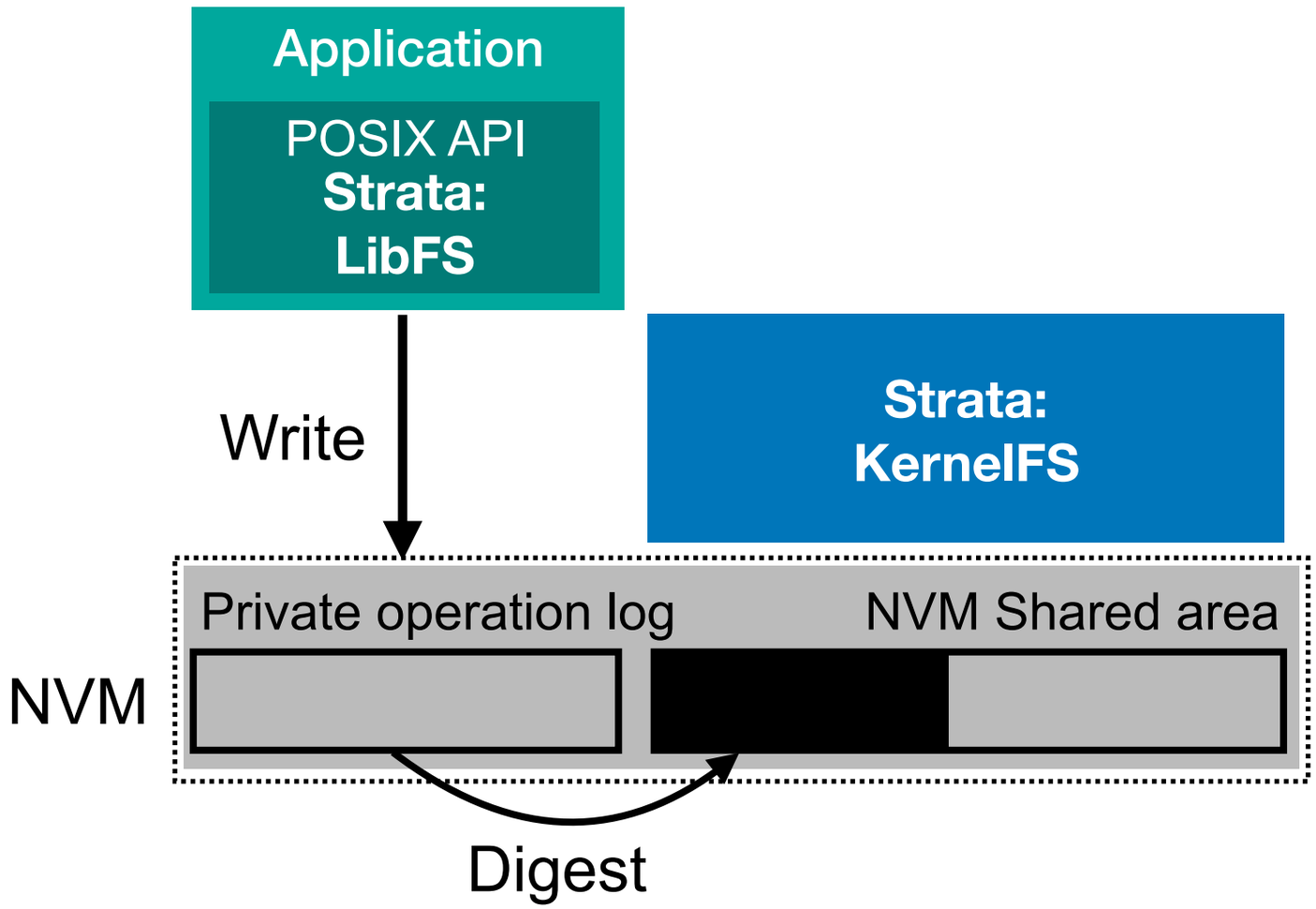

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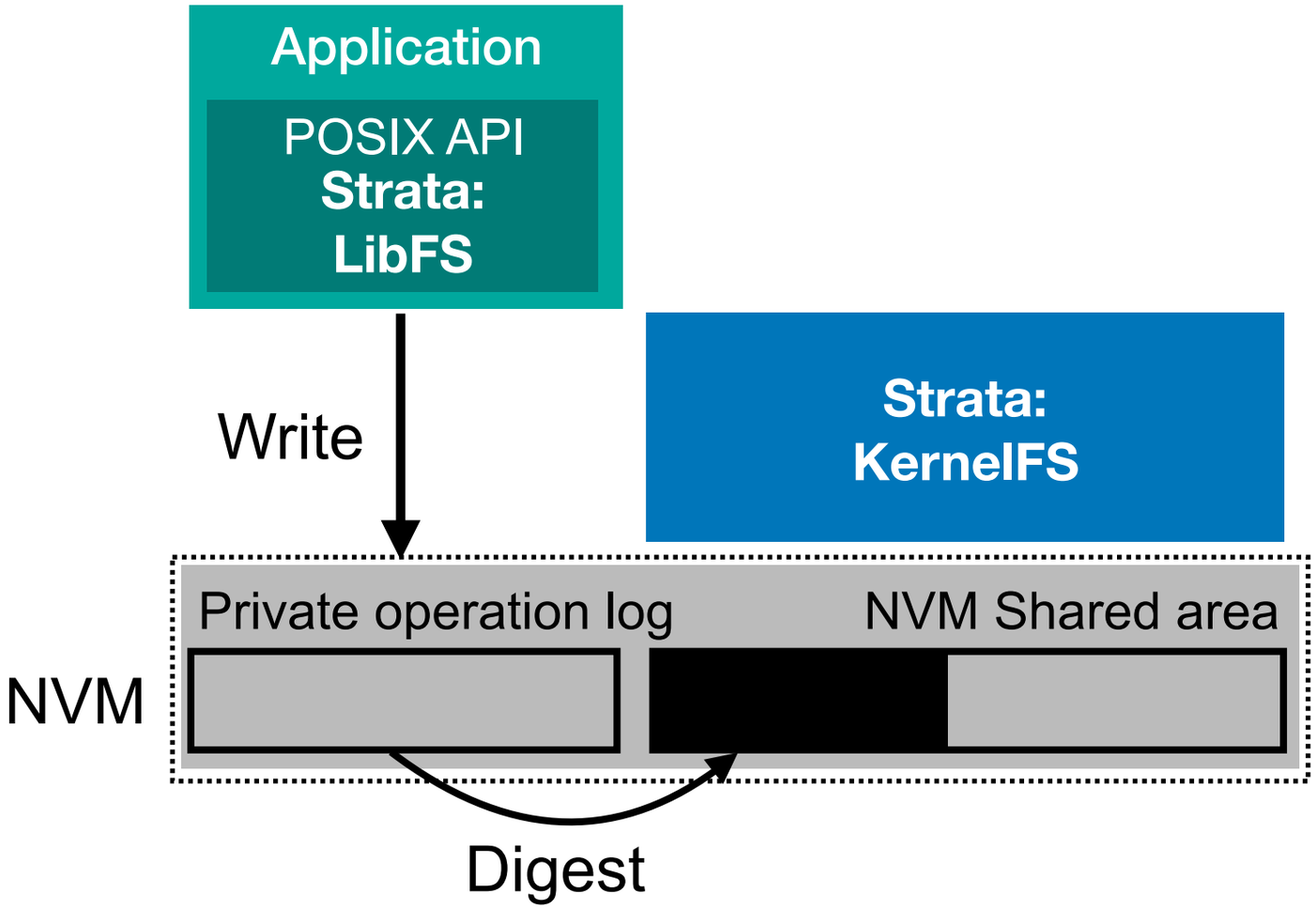
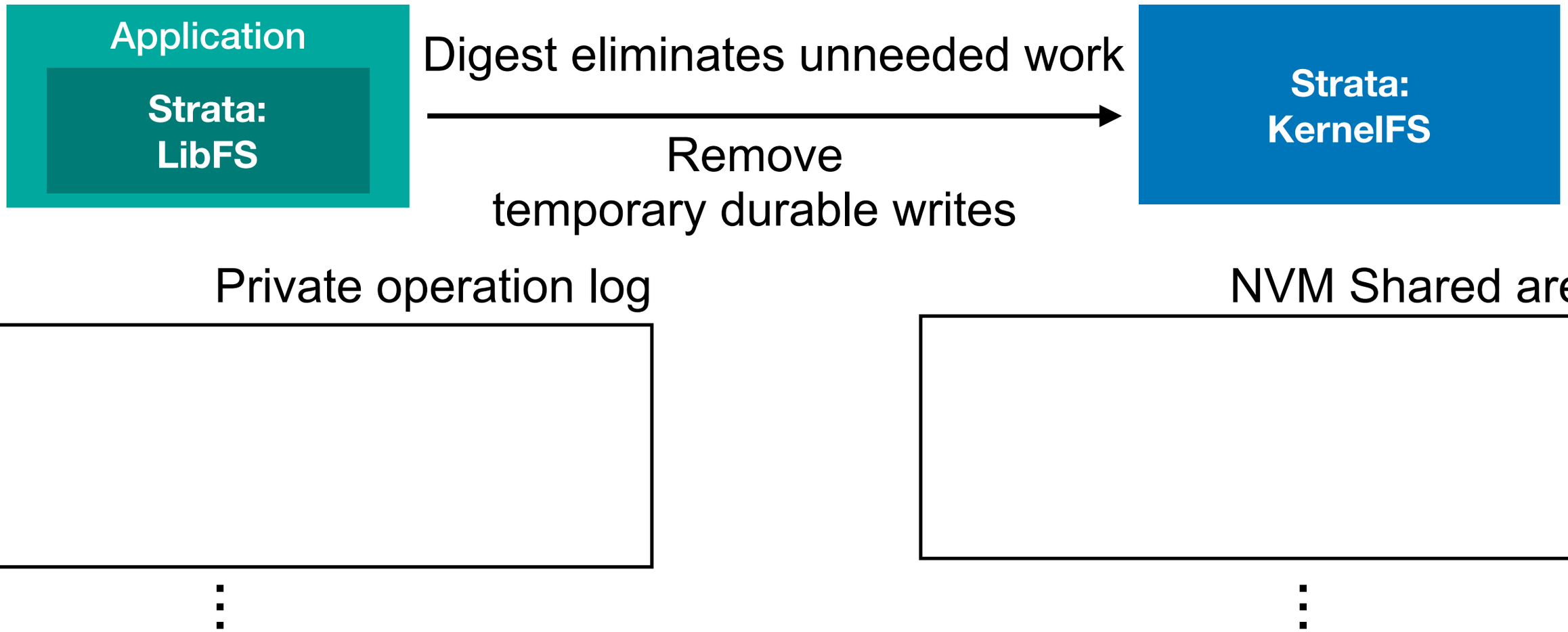


- **Visibility:**
  make private log visible to other applications
- **Data layout:**
  turn write-optimized to read-optimized format (extent tree)
- Large, batched IO
  - Coalesce log

Digest optimization: Log coalescing

SQLite, Mail server: crash consistent update using write ahead logging



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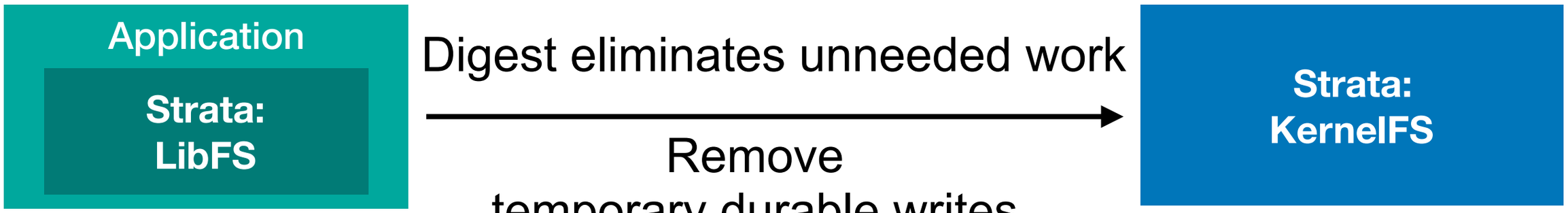

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⋮

NVM Shared area

⋮

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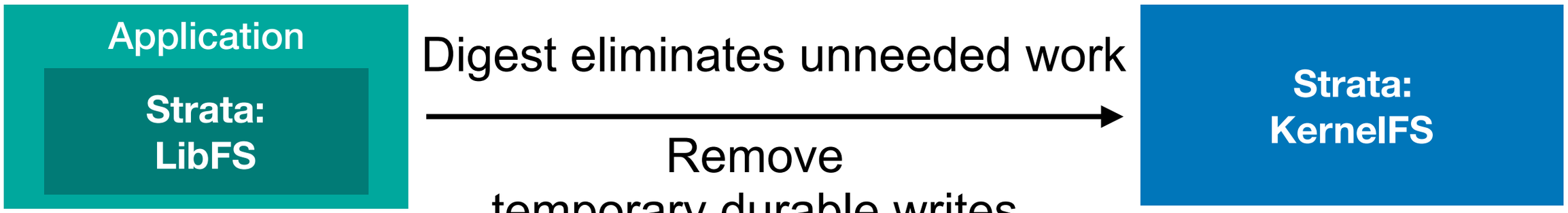

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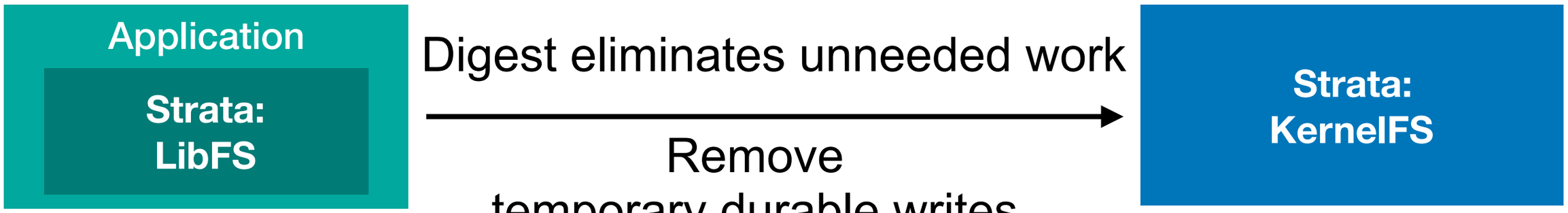

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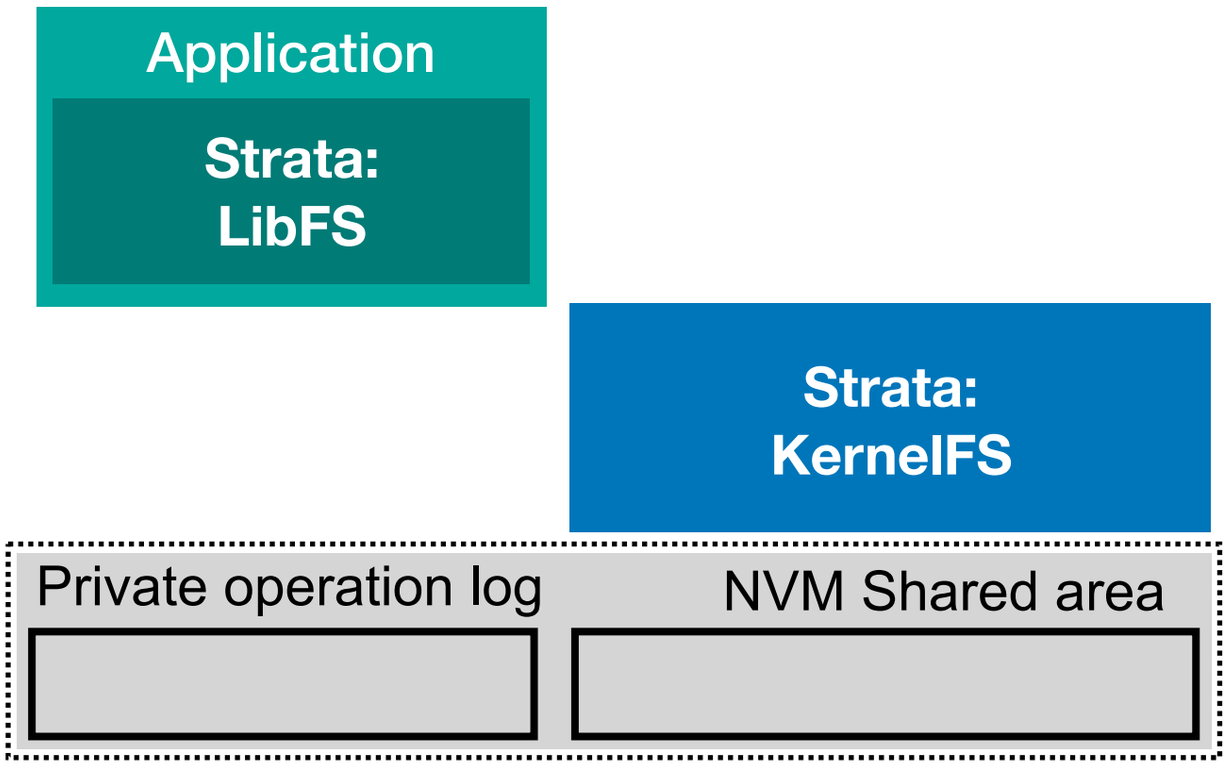
Throughput optimization: Log coalescing saves IO while digesting

Digest and migrate data in kernel



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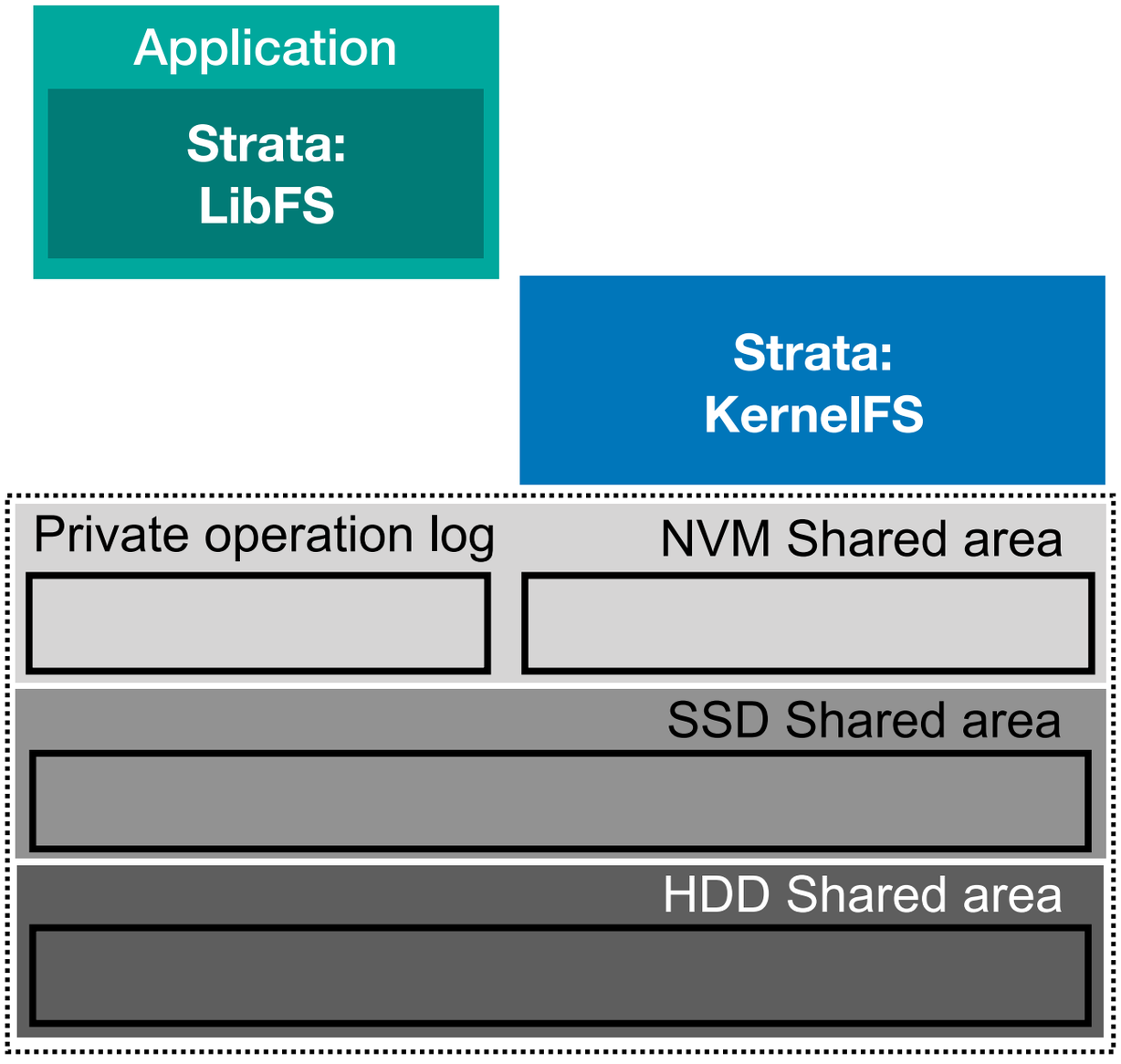

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  - KernelFS migrates cold data to lower layers

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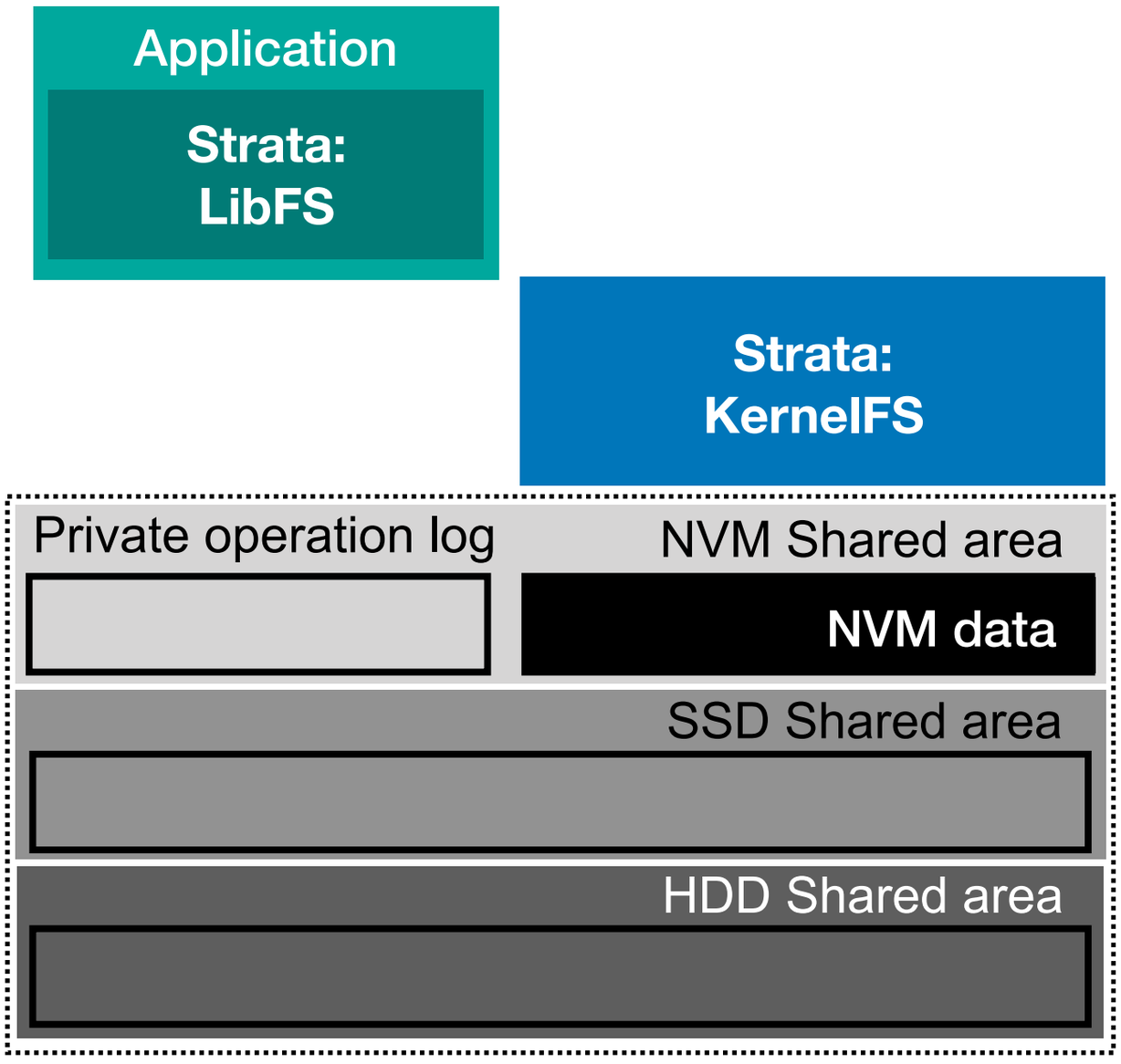

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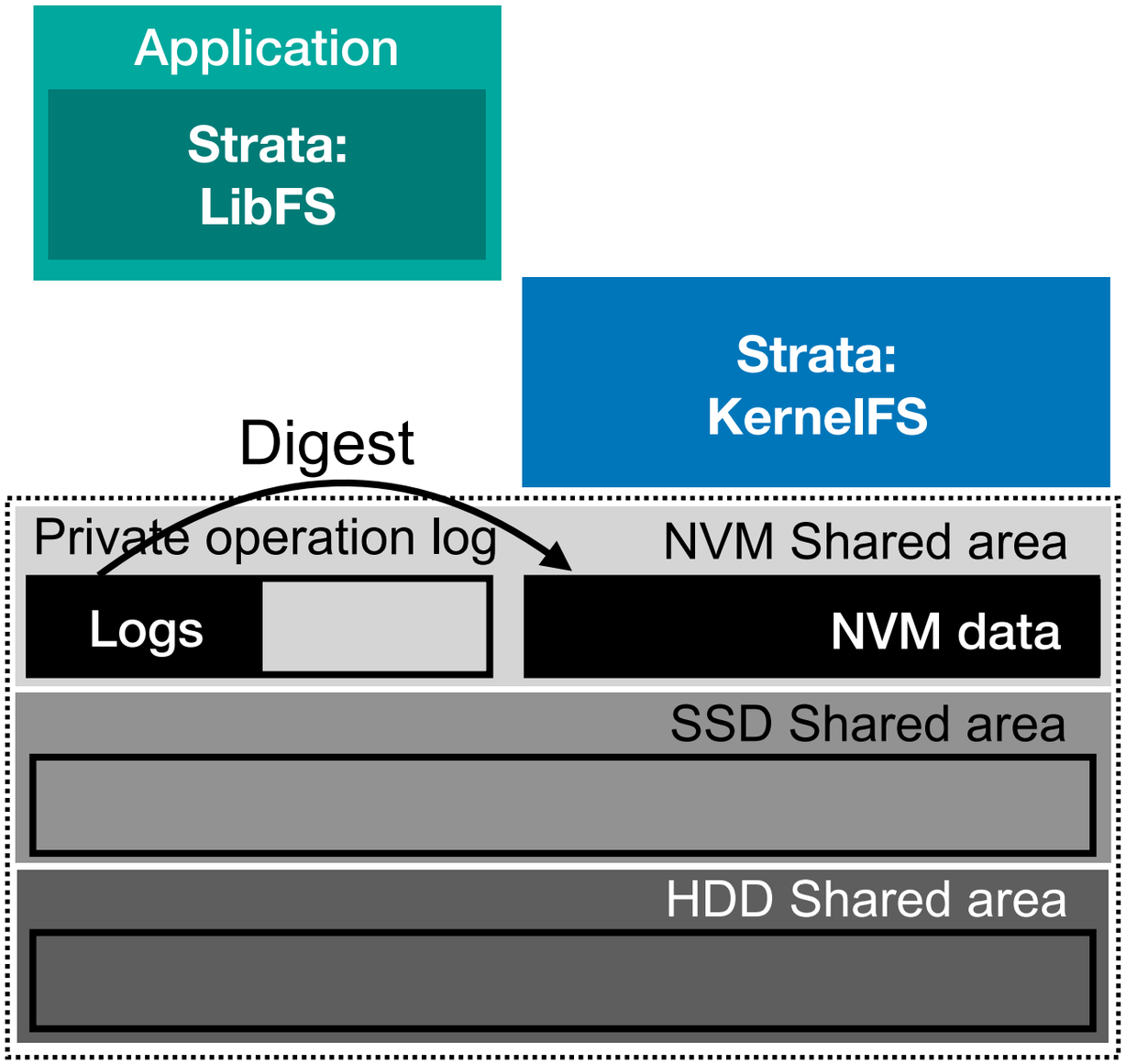

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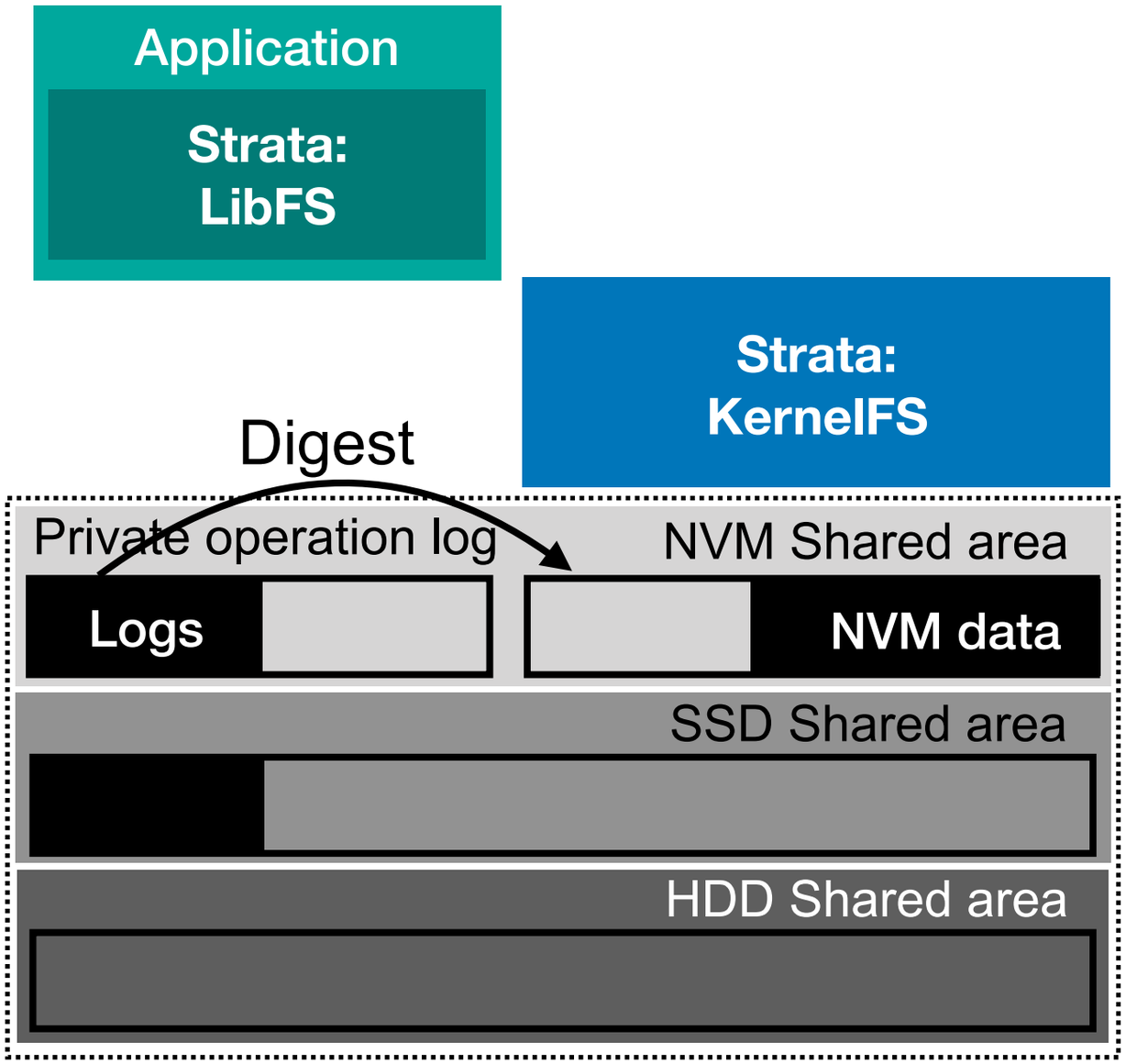

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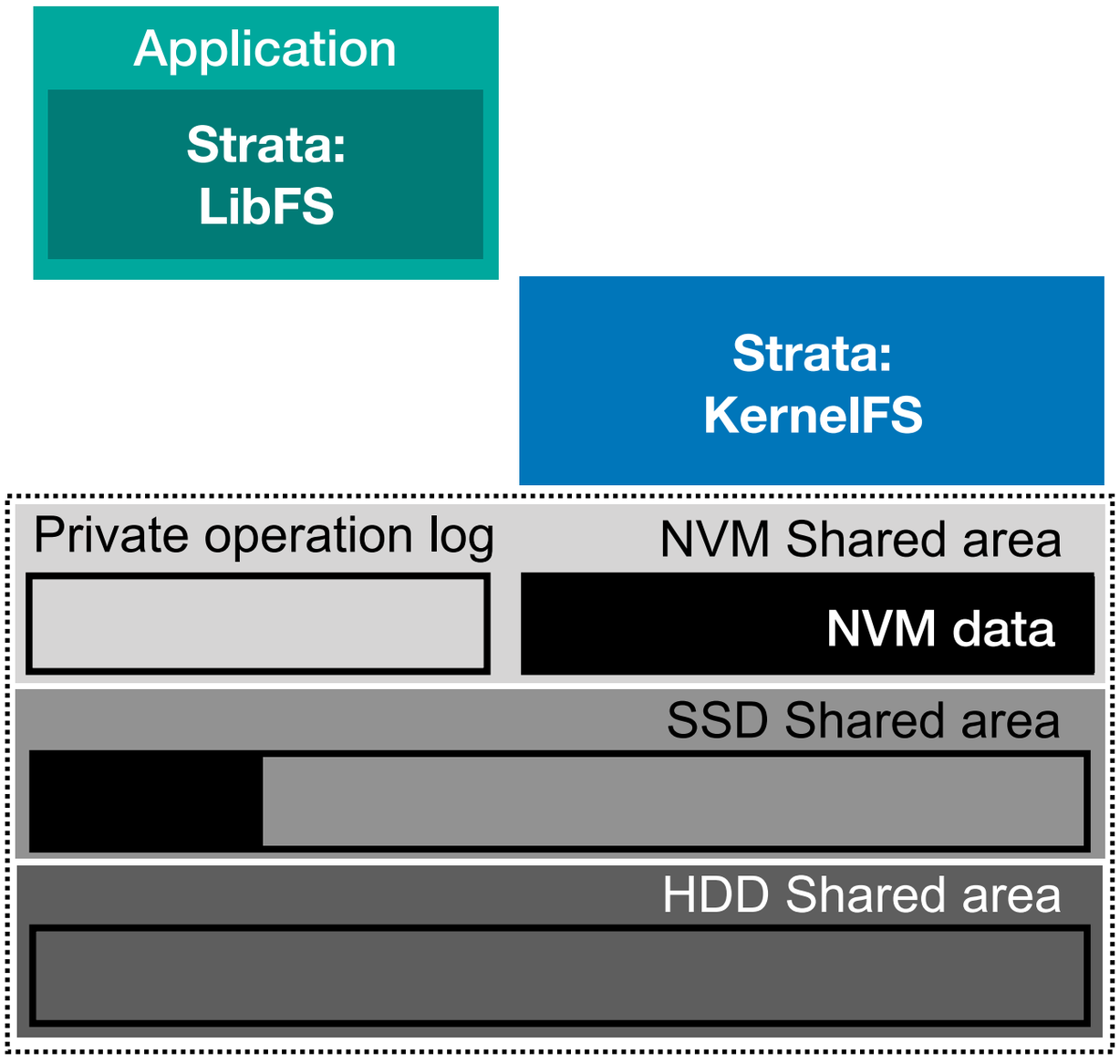

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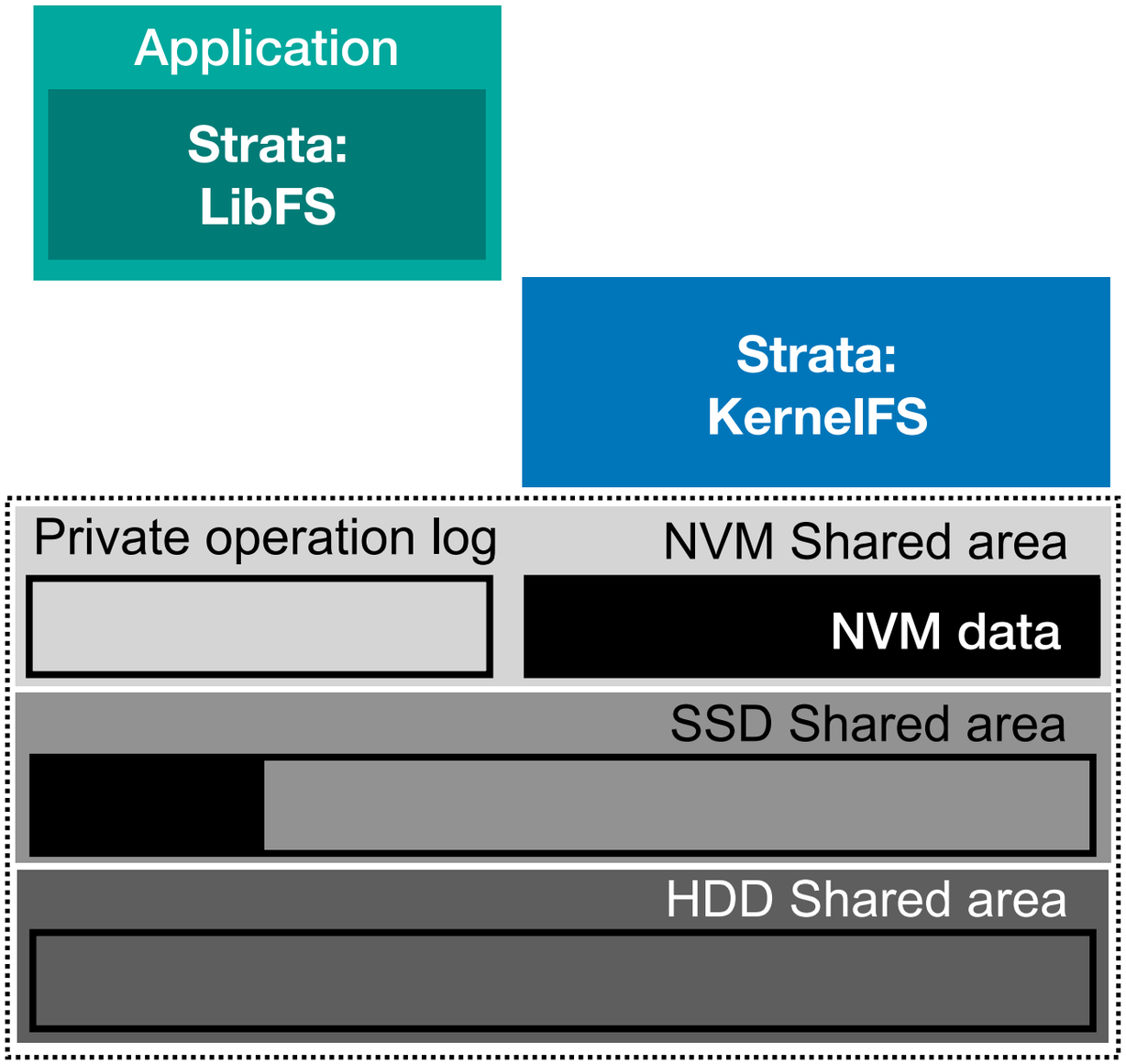

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  - Migrate 1 GB blocks
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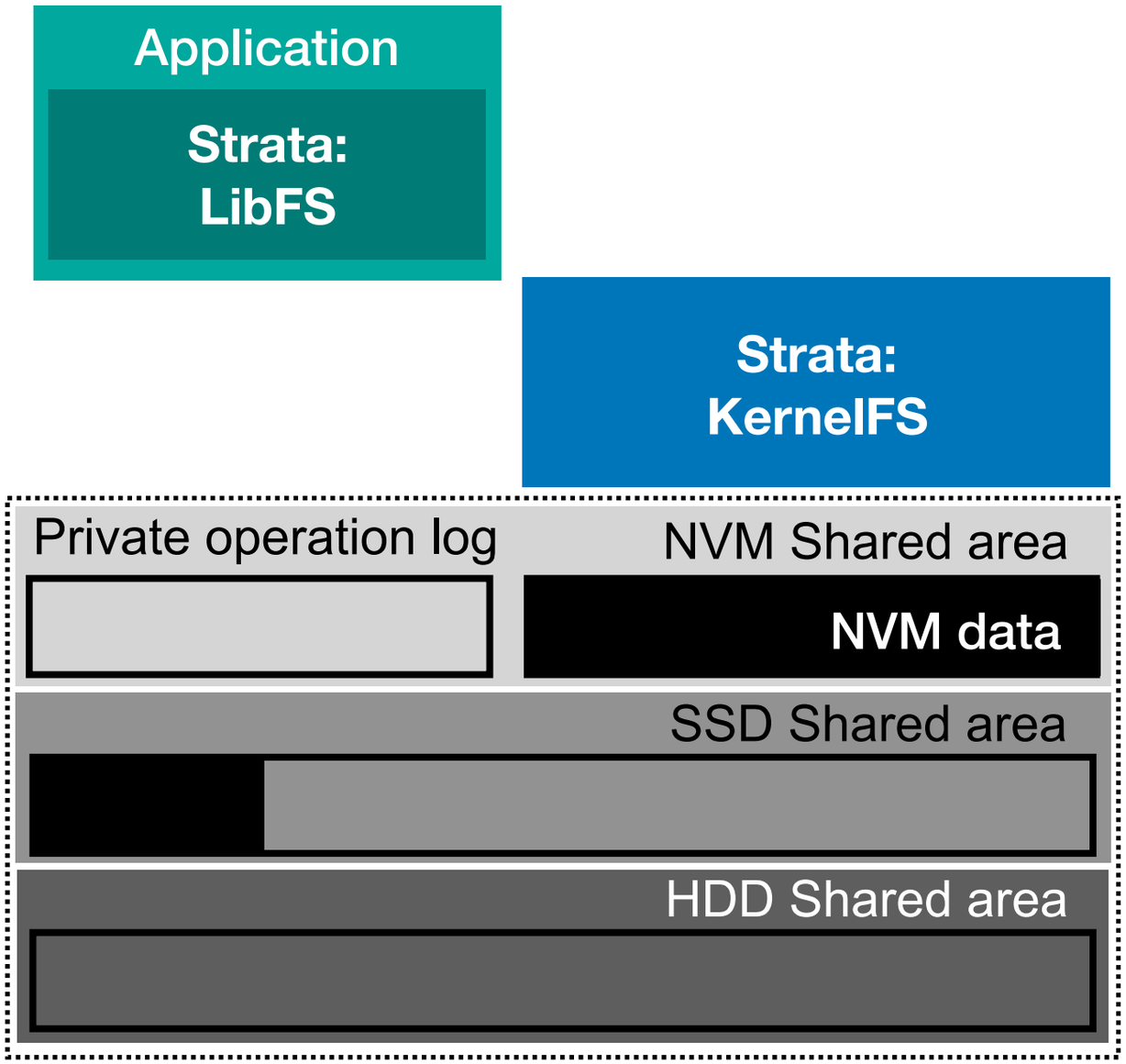

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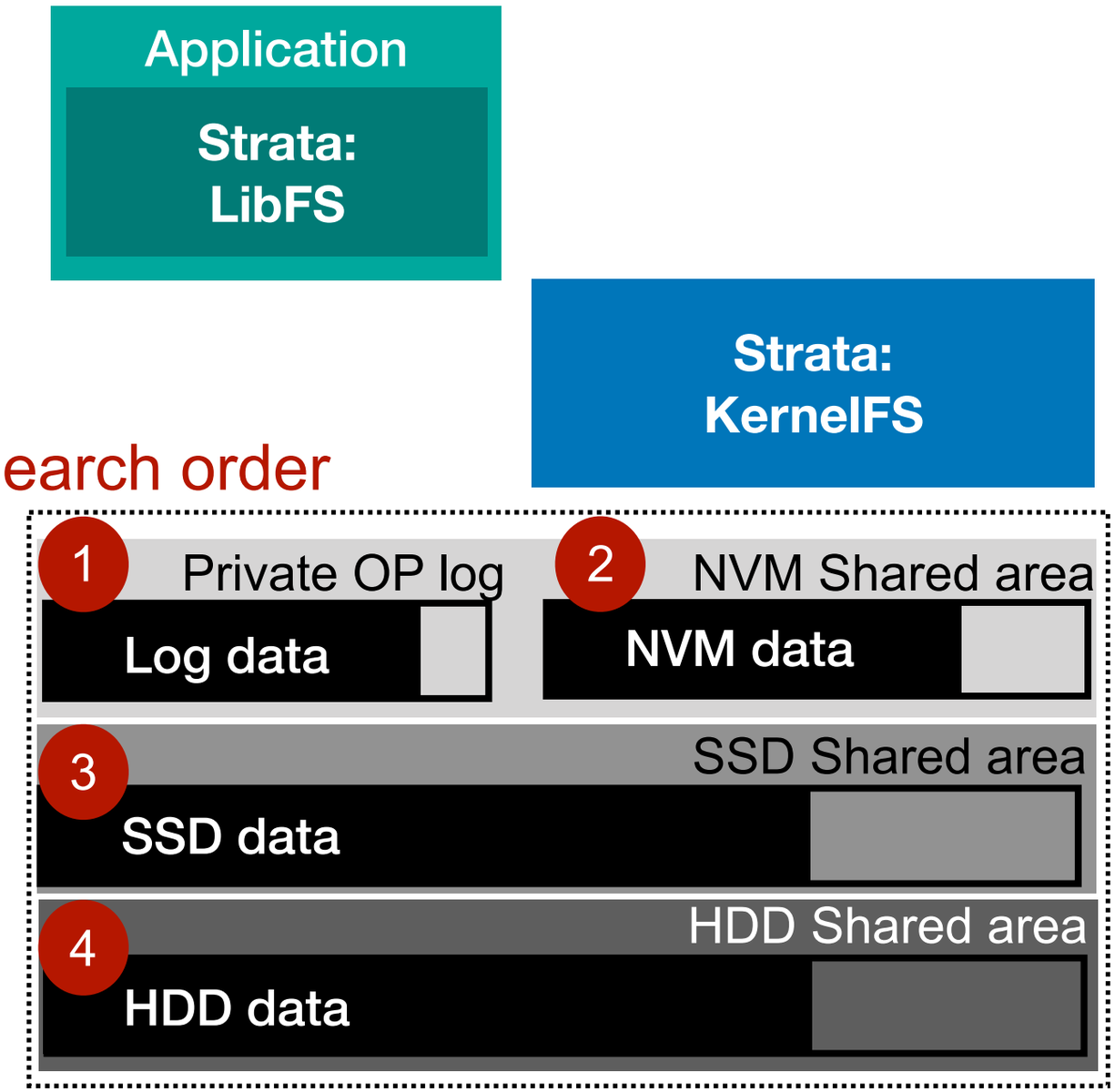
Resembles log-structured merge (LSM) tree

Read: hierarchical search



Shared file access

- **Leases** grant access rights to applications [SOSP'89]
  - Required for files and directories
  - Function like lock, but revocable
  - Exclusive writer, shared readers

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- On revocation, LibFS digests leased data
  - Private data made public before losing lease

- **Leases serialize concurrent updates**

Outline

- **LibFS**: Log operations to NVM at user-level
  - Fast user-level access
  - In-order, synchronous IO
- **KernelFS**: Digest and migrate data in kernel
  - Asynchronous digest
  - Transparent data migration
  - Shared file access
- **Evaluation**

Experimental setup

- 2x Intel Xeon E5-2640 CPU, 64 GB DRAM
  - 400 GB NVMe SSD, 1 TB HDD
- Ubuntu 16.04 LTS, Linux kernel 4.8.12

- Emulated NVM
  - Use 40 GB of DRAM
  - Performance model [Y. Zhang et al. MSST 2015]
    - Throttle latency & throughput in software

Evaluation questions

- **Latency:**
  - Does Strata efficiently support small, random writes?
  - Does asynchronous digest have an impact on latency?
- **Throughput:**
  - Strata writes data twice (logging and digesting). Can Strata sustain high throughput?
  - How well does Strata perform when managing data across storage layers?

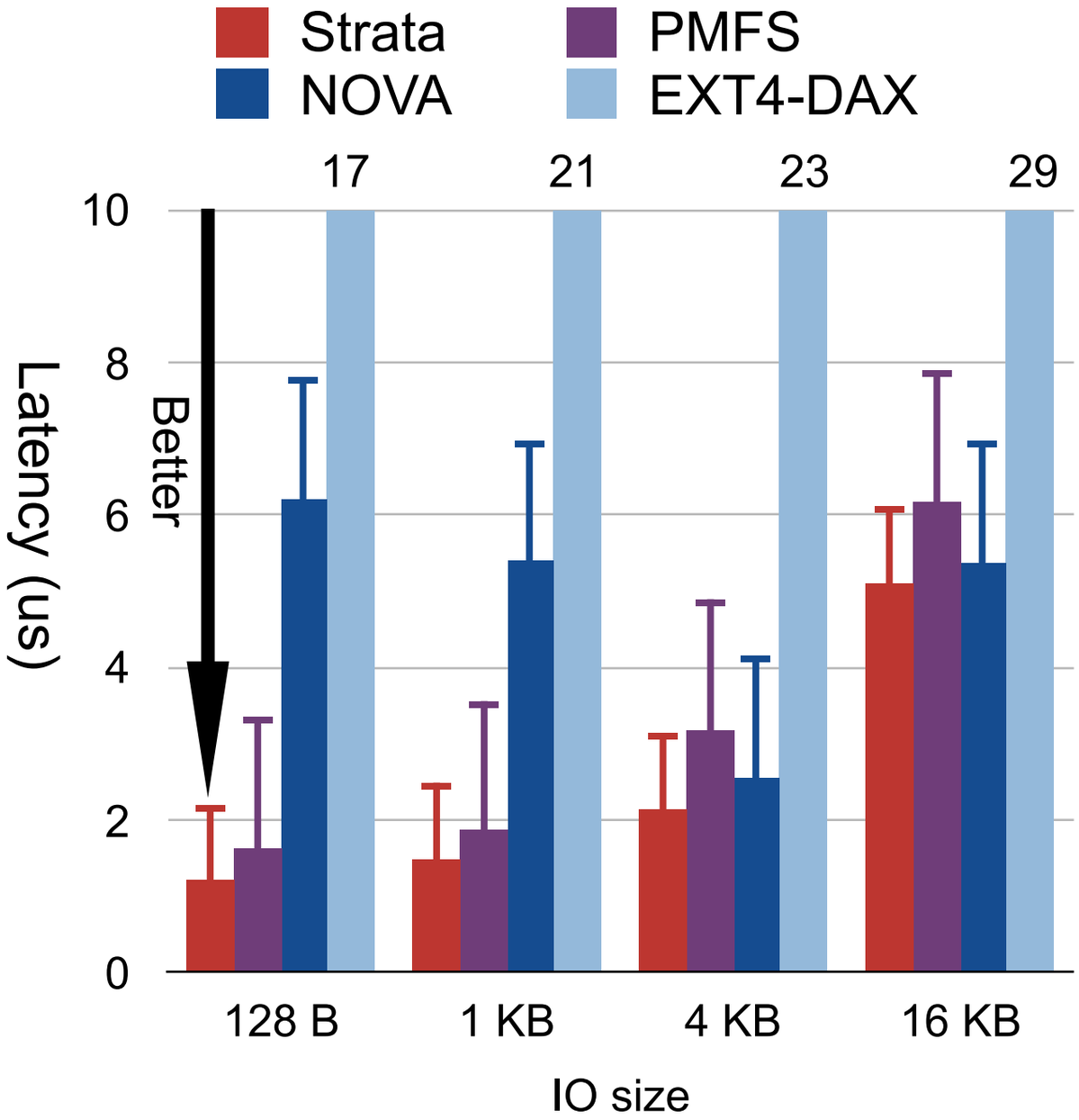
Related work

- **NVM file systems**
  - PMFS[EuroSys 14]: In-place update file system
  - NOVA[FAST 16]: log-structured file system
  - EXT4-DAX: NVM support for EXT4

- **SSD file system**
  - F2FS[FAST 15]: log-structured file system

Microbenchmark: write latency

- Strata logs to NVM
  - Compare to NVM kernel file systems:
    PMFS, NOVA, EXT4-DAX
- Strata, NOVA
  - In-order, synchronous IO
  - Atomic write
- PMFS, EXT4-DAX
  - No atomic write



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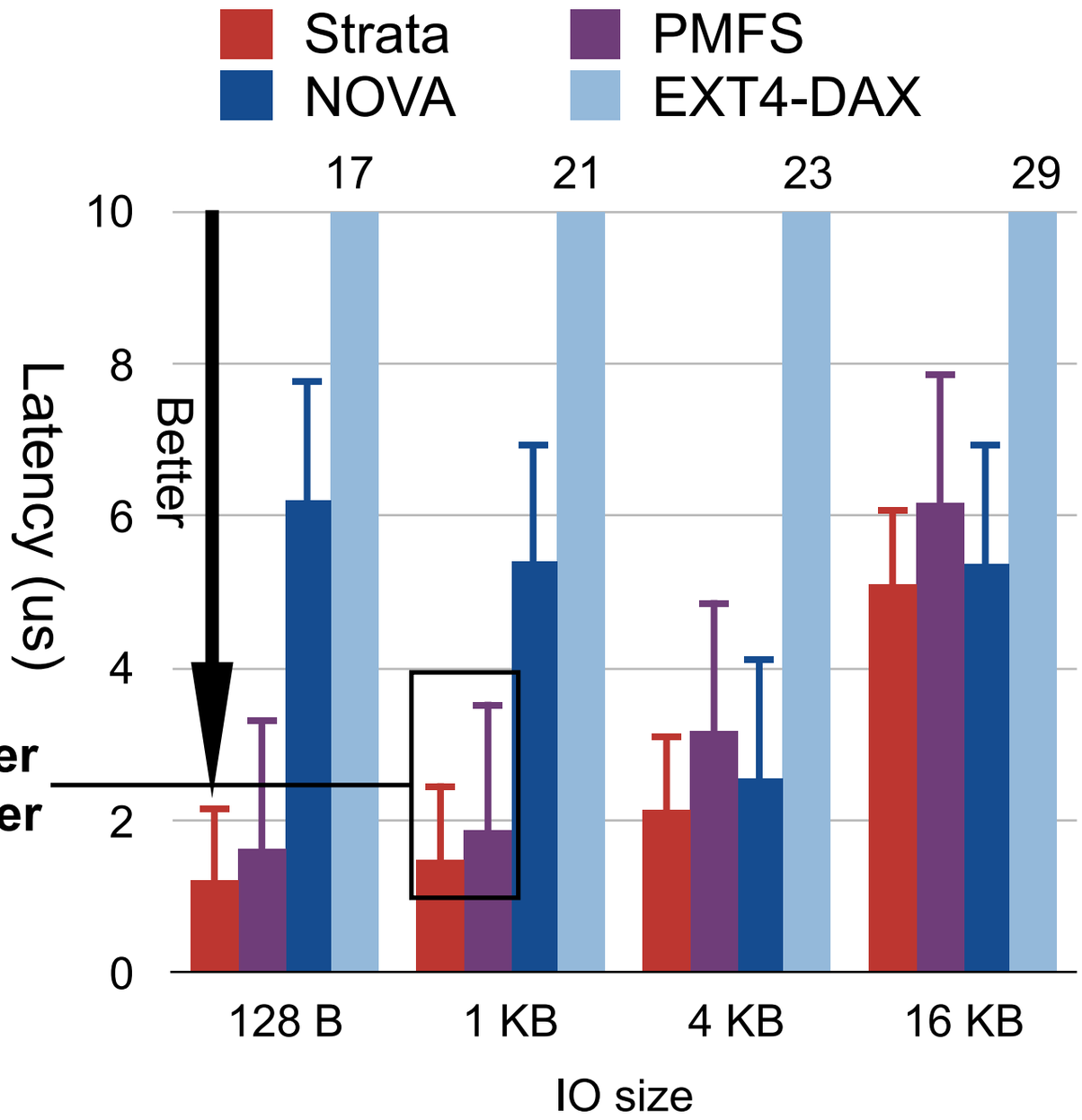
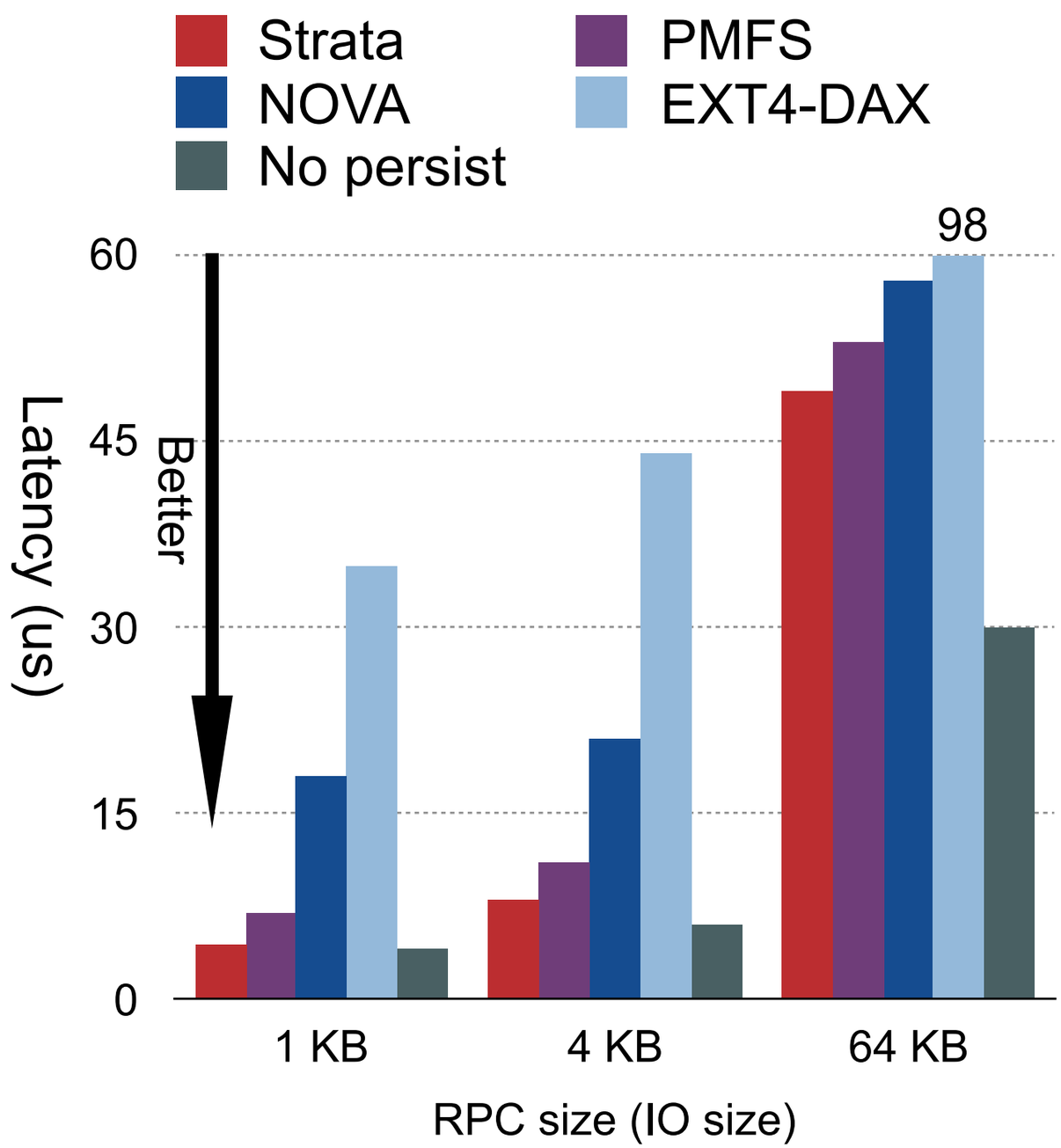


Avg.: 26% better
Tail : 43% better

Latency: persistent RPC

- Foundation of most servers
  - Persist RPC data before sending ACK to client
- RPC over RDMA
  - 40 Gb/s Infiniband NIC
- For small IO (1 KB)
  - 25% slower than No persist
  - 35% faster than PMFS
    7x faster than EXT4-DAX



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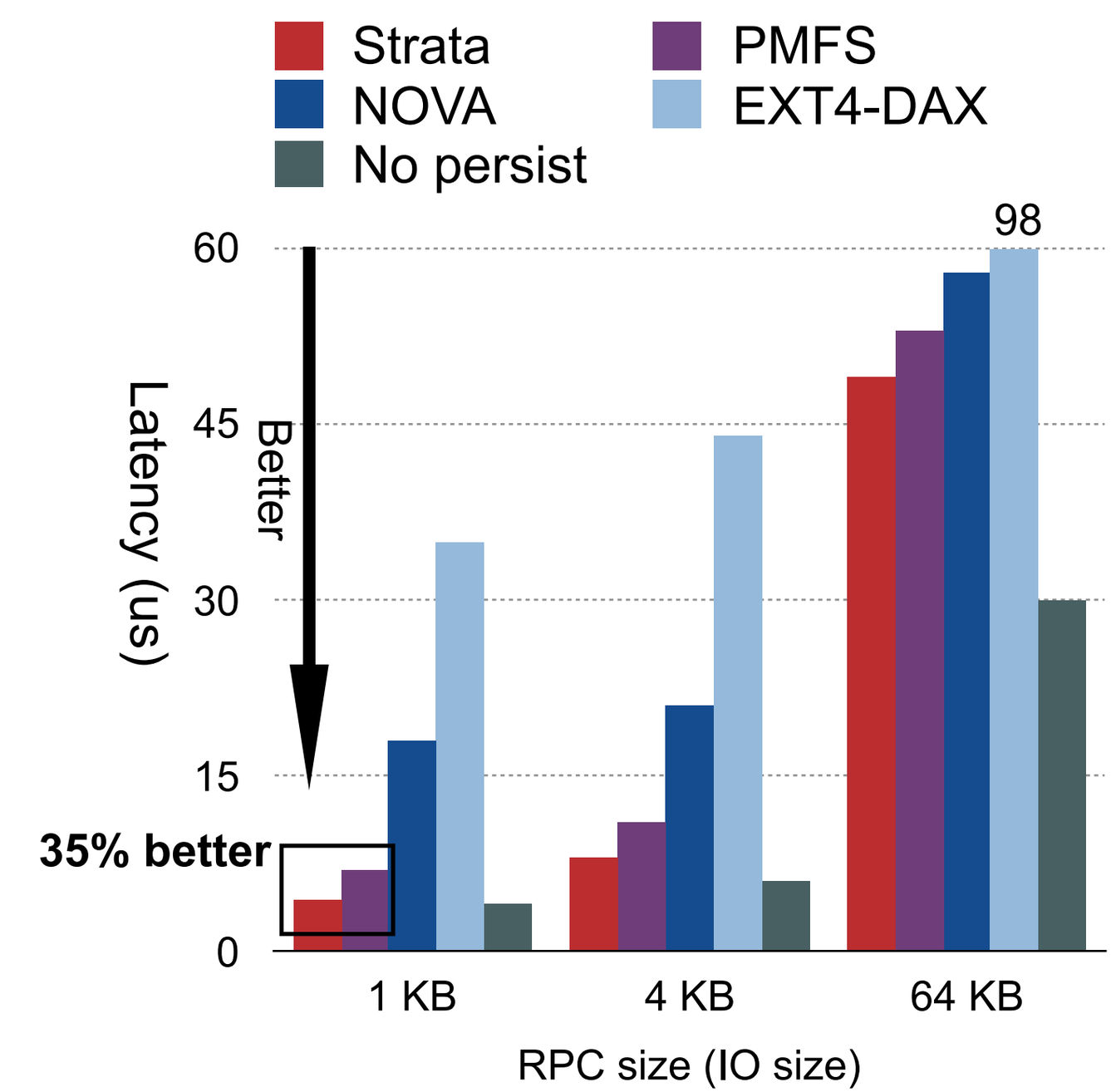

Latency: LevelDB

- LevelDB (NVM)
  - Key size: 16 B
  - Value size: 1 KB
  - 300,000 objects

- **Workload causes asynchronous digests**

- Fast user-level logging
  - Random write
    - 25% better than PMFS
  - Random read
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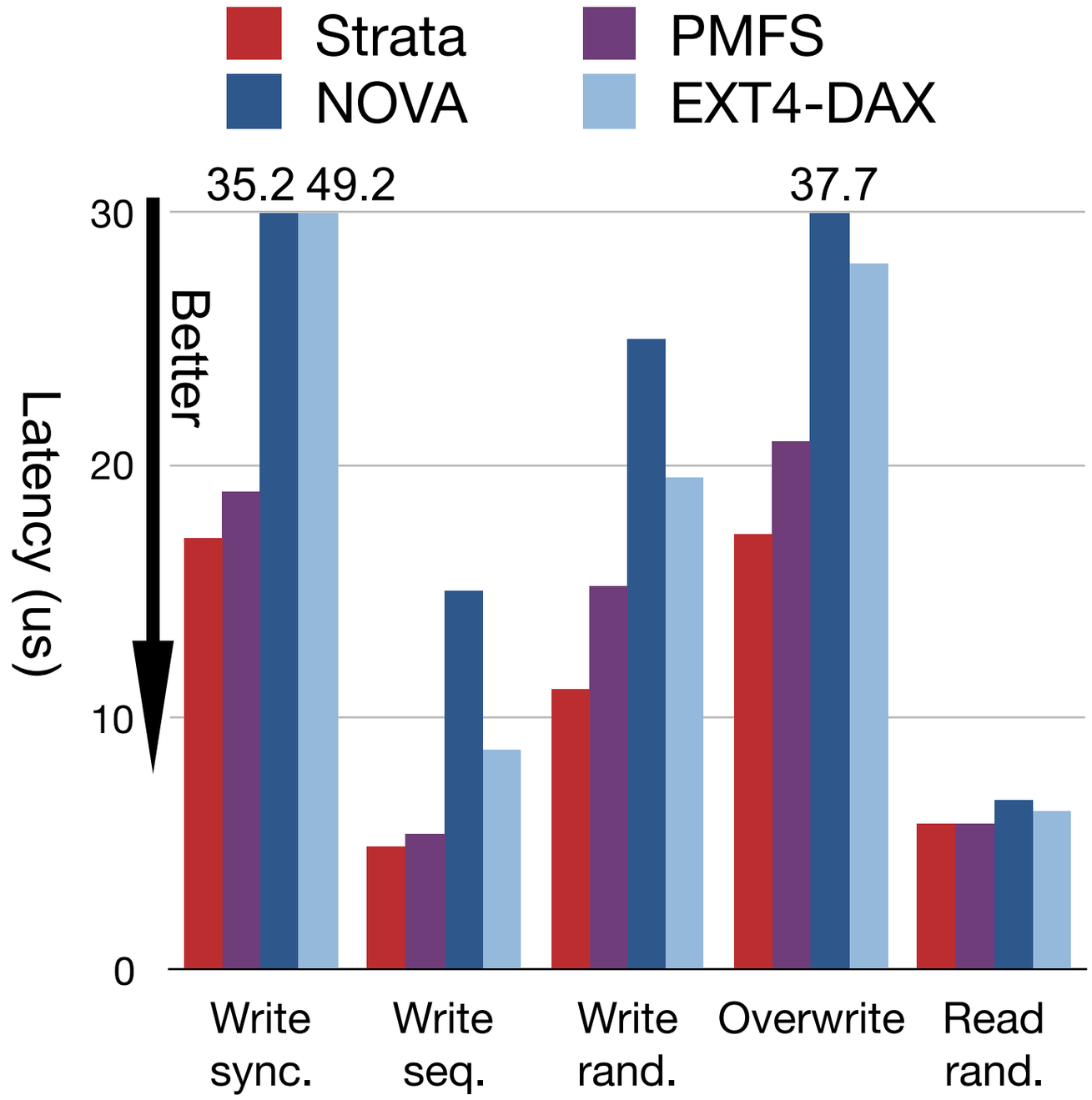

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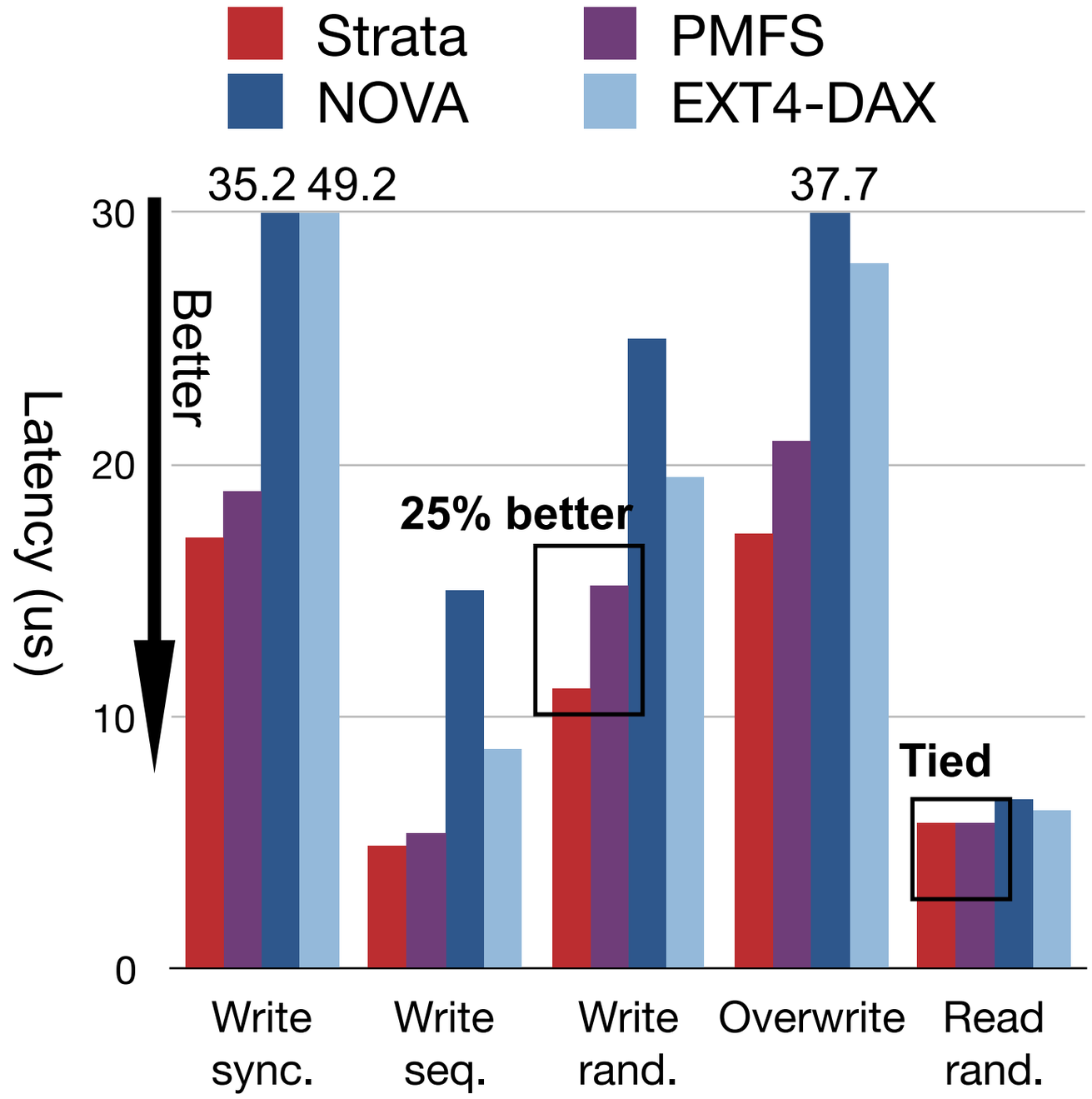

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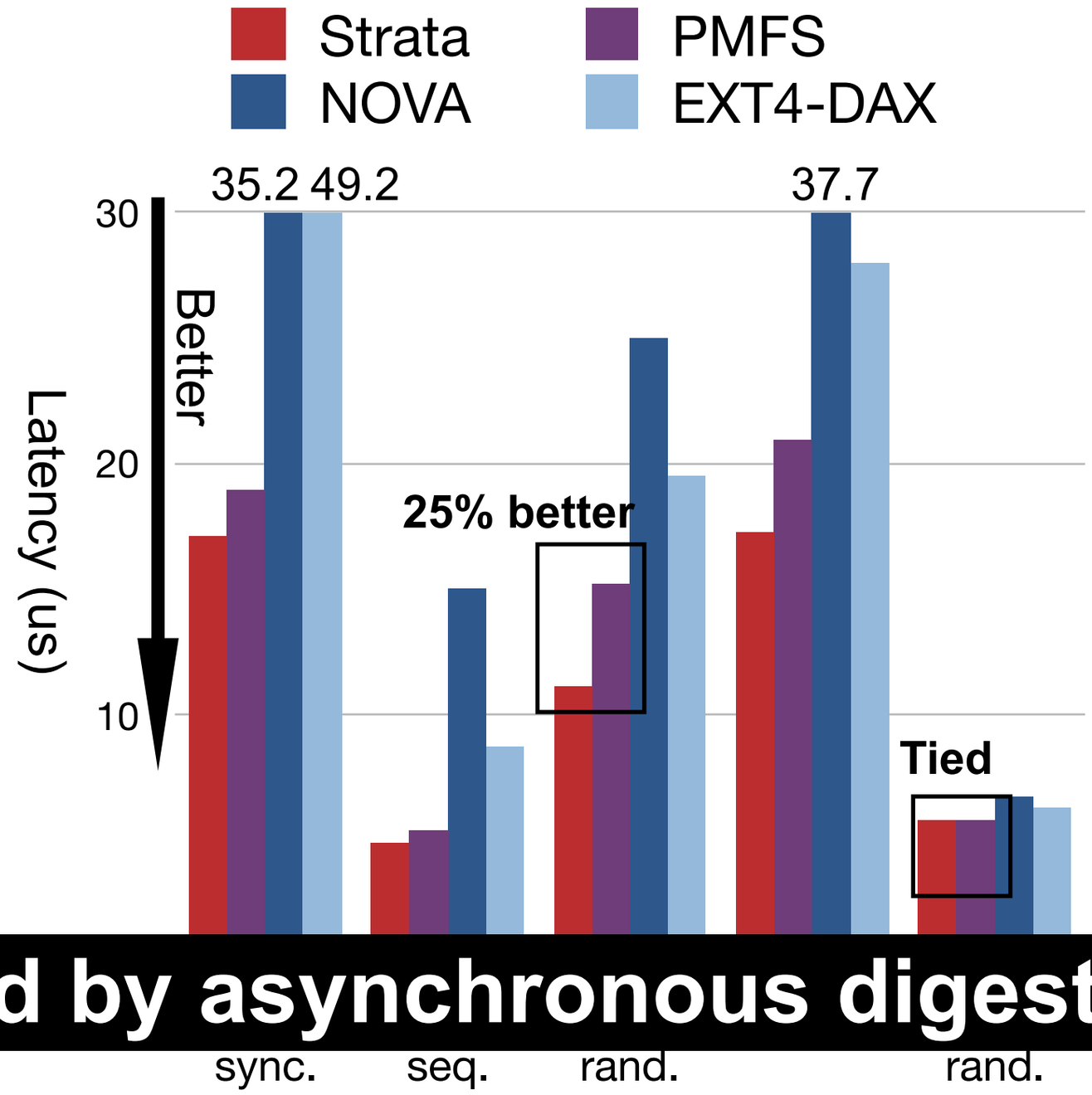

IO latency not impacted by asynchronous digest

Evaluation questions

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- **Throughput:**
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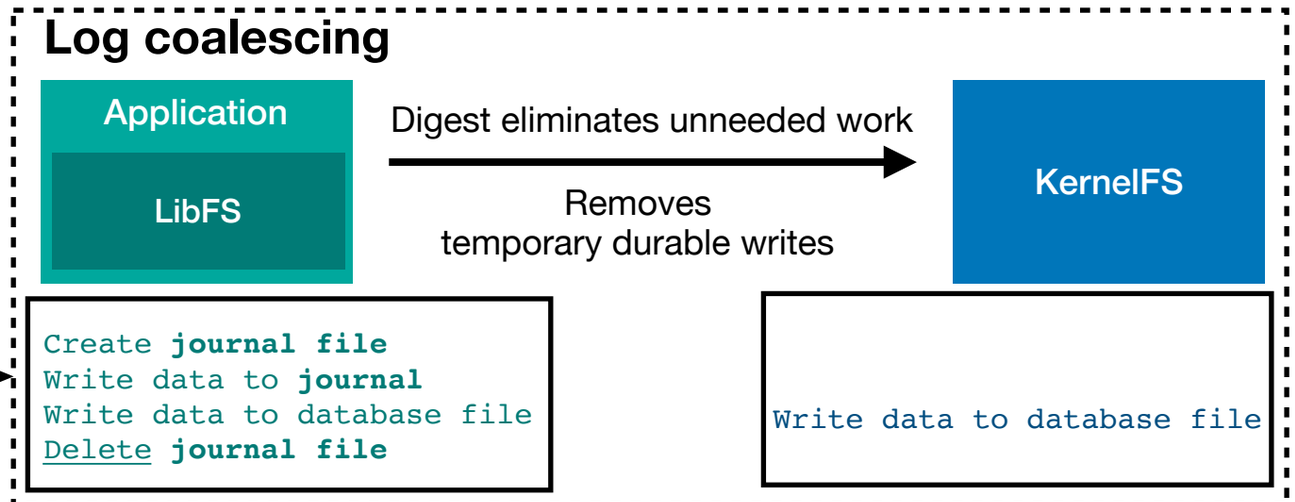
Throughput: Varmail

Mail server workload from Filebench

- Using only NVM
- 10000 files
- Read/Write ratio is 1:1
- **Write-ahead logging**



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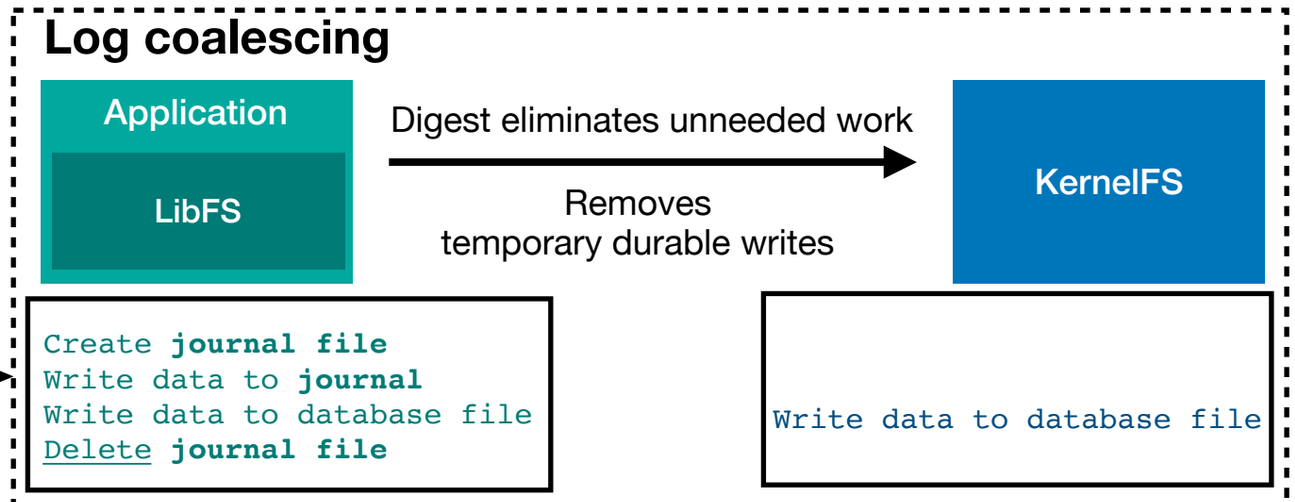

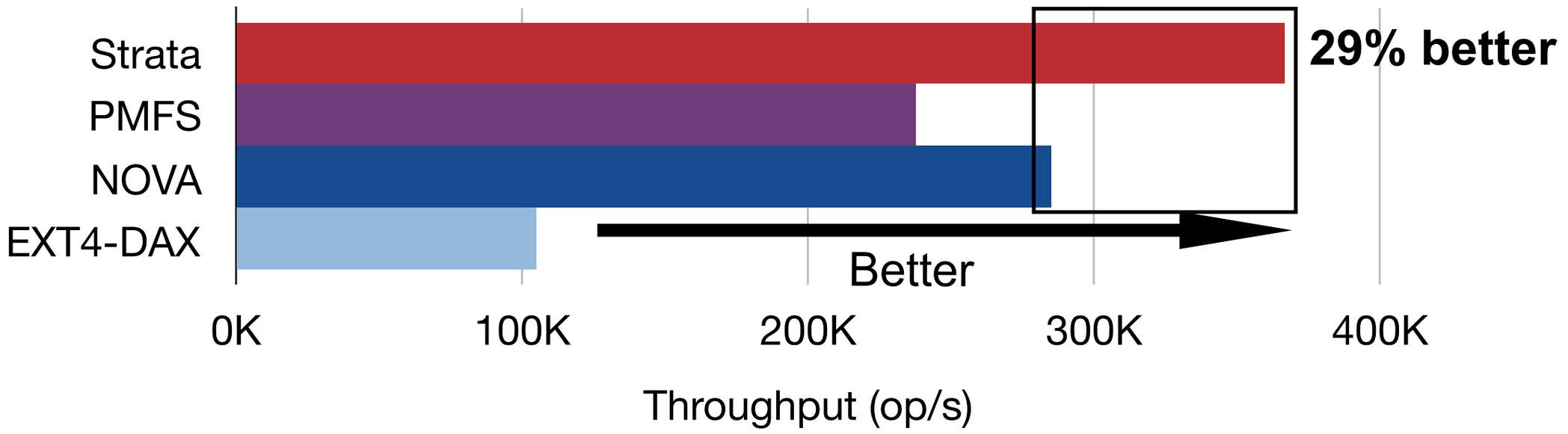

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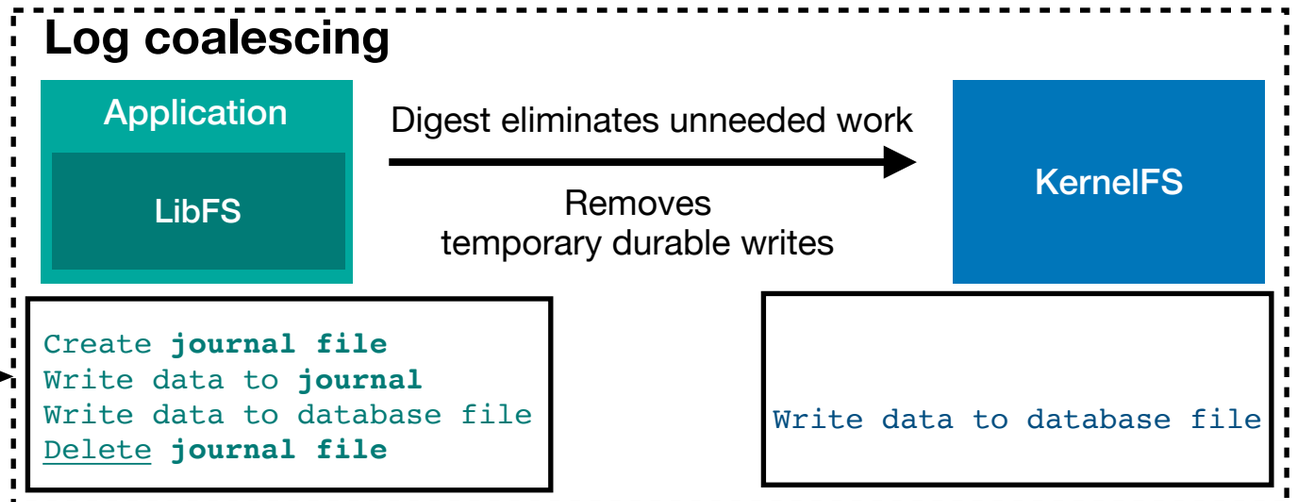
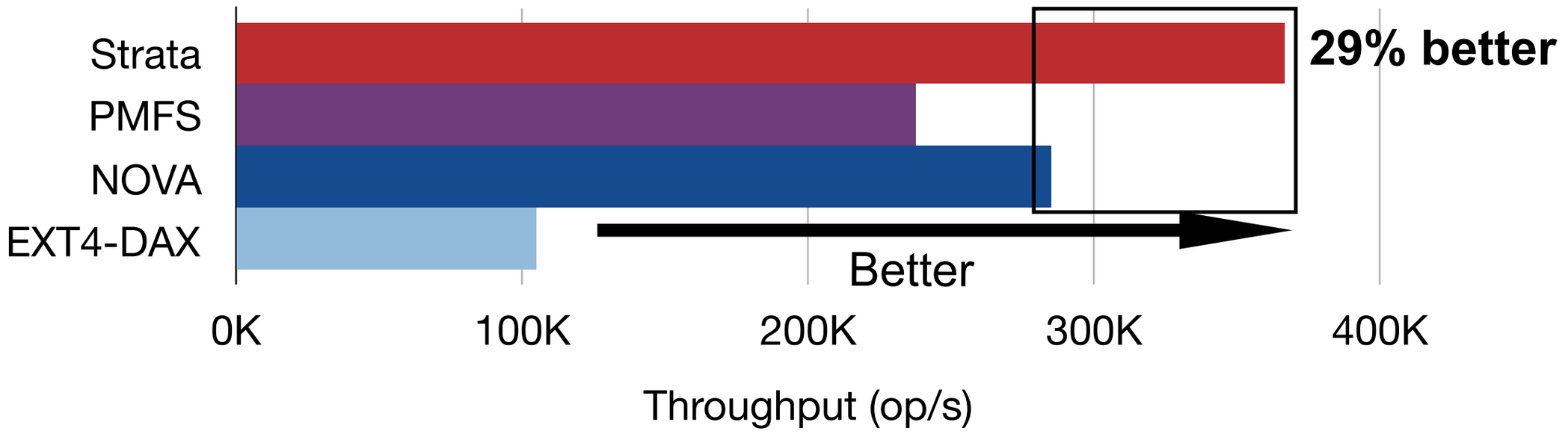




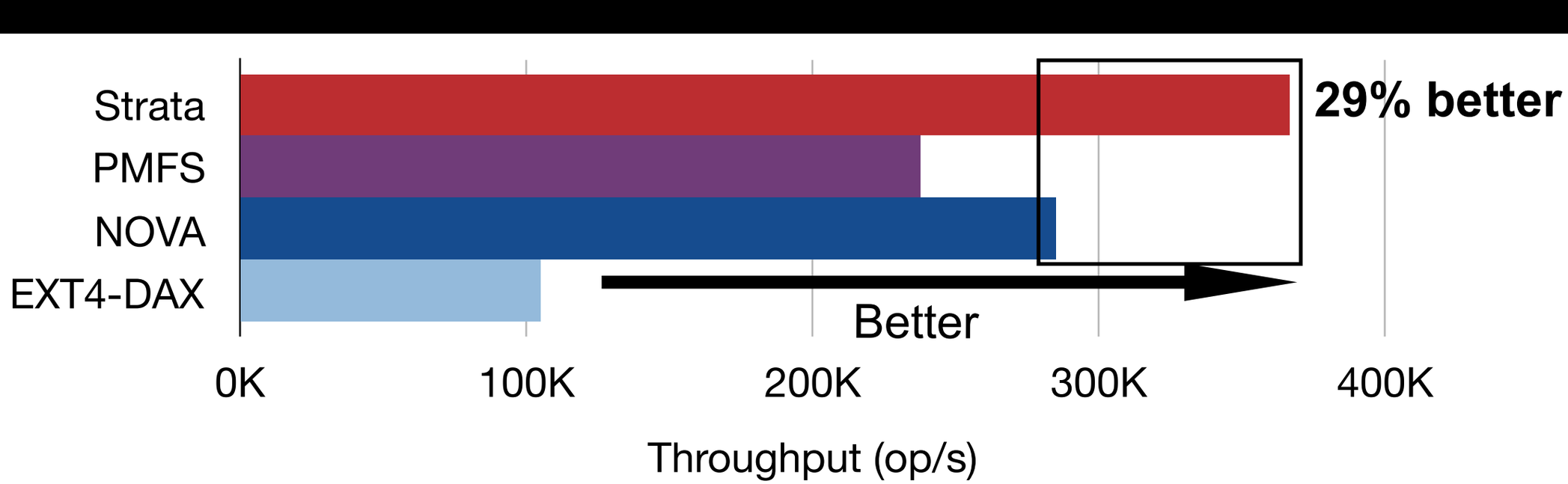
Log coalescing eliminates 86% of log entries, saving 14 GB of IO

Throughput: Varmail

No kernel file system has both low latency and high throughput:

- PMFS: better latency
- NOVA: better throughput

Strata achieves both low latency and high throughput



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Throughput: data migration

File server workload from Filebench

- Working set starts at NVM, grows to SSD, HDD
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User-level migration

- LRU: whole file granularity
- Treat each file system as a black-box
- NVM: NOVA, SSD: F2FS, HDD: EXT4

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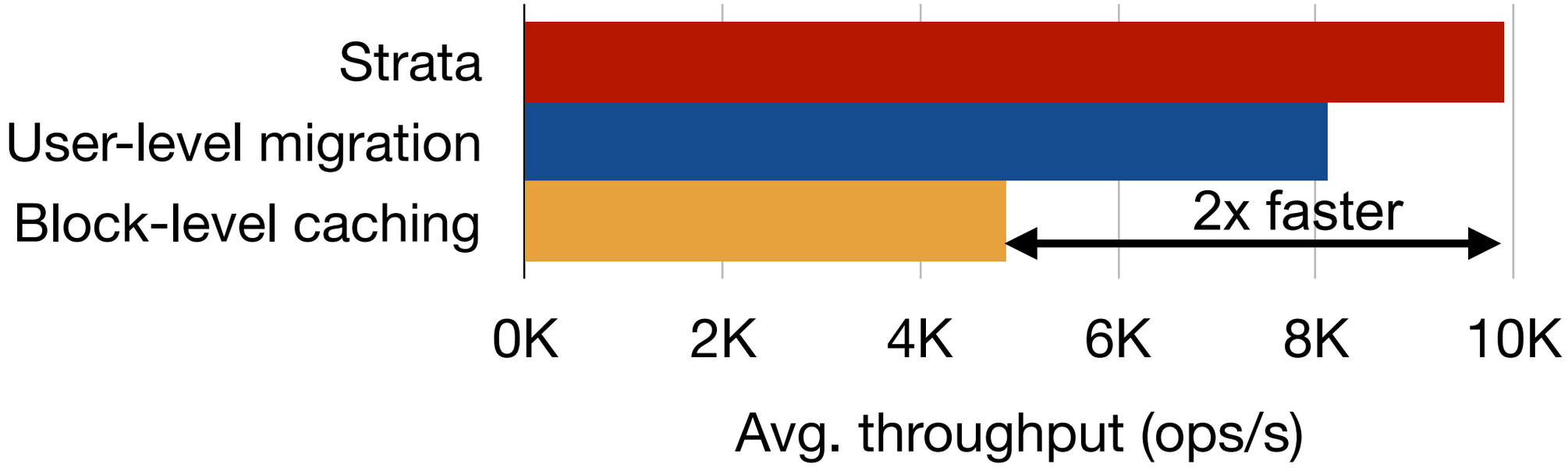

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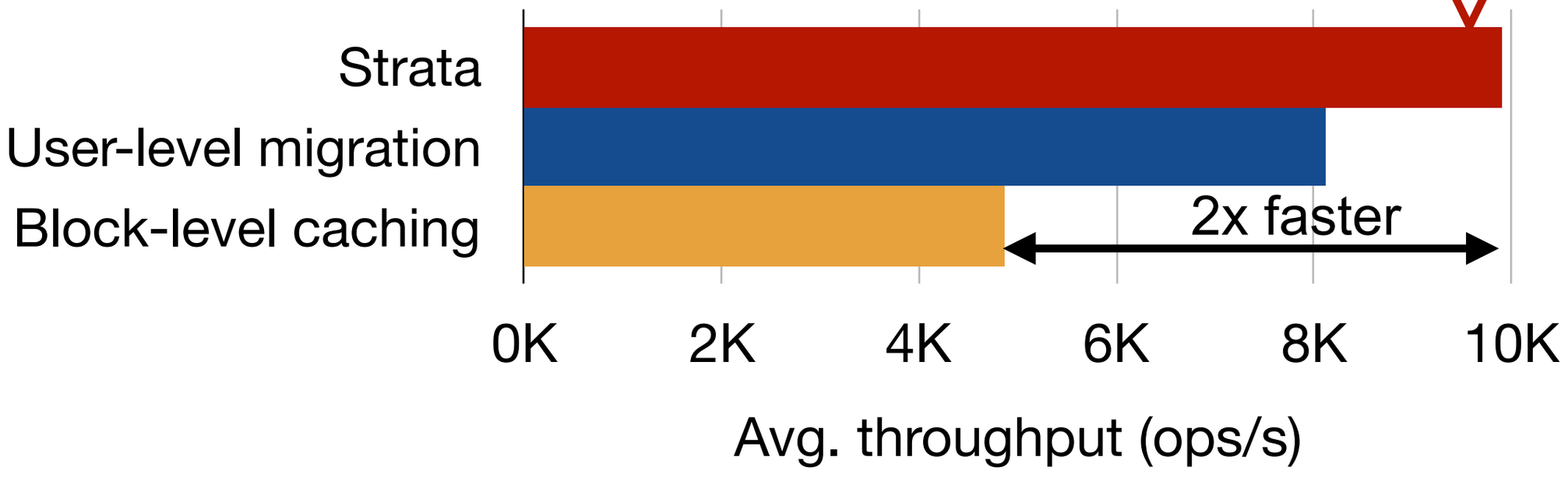
22% faster than user-level migration

Cross layer optimization: placing hot metadata in faster layers



Conclusion

Server applications need fast, small random IO on vast datasets with intuitive crash consistency

Strata, a cross media file system, addresses these concerns

Performance: low latency, high throughput

- Novel split of LibFS, KernelFS
- Fast user-level access

Low-cost capacity: leverage NVM, SSD & HDD

- Asynchronous digest
- Transparent data migration with large, sequential IO

Simplicity: intuitive crash consistency model

- In-order, synchronous IO

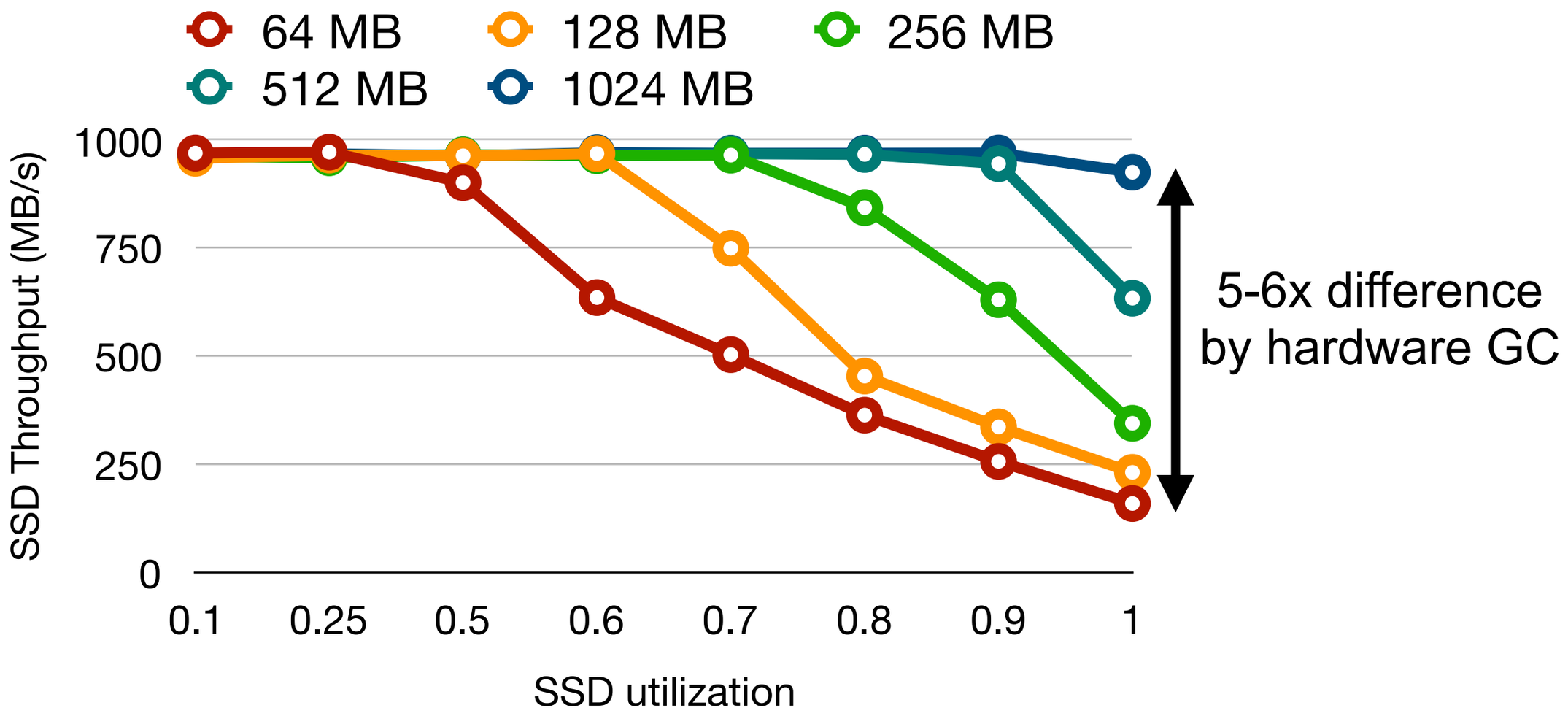
Source code is available at
https://github.com/ut-osa/strata

Backup

Device management overhead

SSD, HDD prefer large sequential IO

For example, SSD **Random** write:



Sequential writes avoid management overhead