ctFS:

Replacing File Indexing with Hardware Memory Translation through Contiguous File Allocation for Persistent Memory

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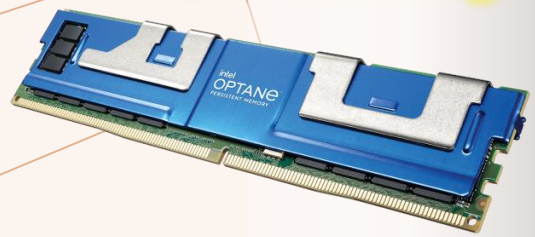
Persistent Memory

-Future of Computer Storage

LOW Latency



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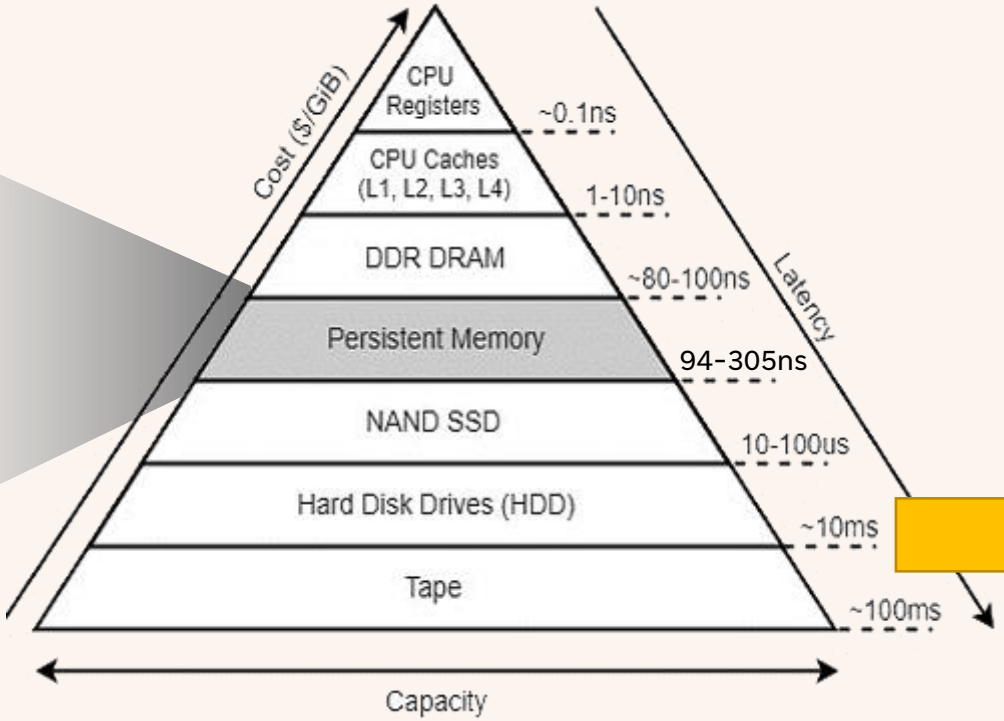

Access Time Breakdown

Source: https://docs.pmem.io/persistent-memory/getting-started-guide/introduction

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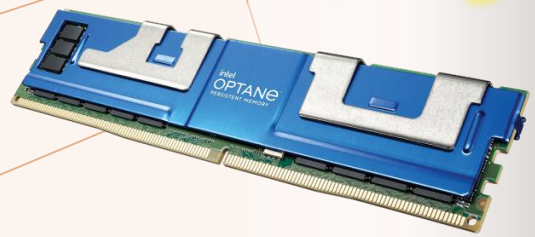

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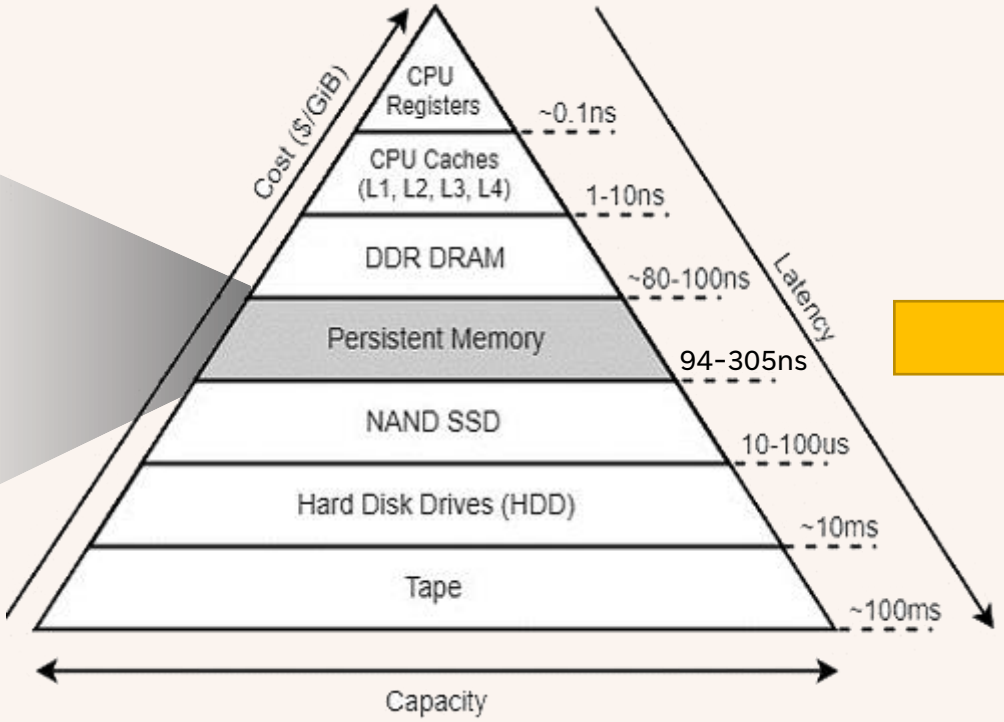

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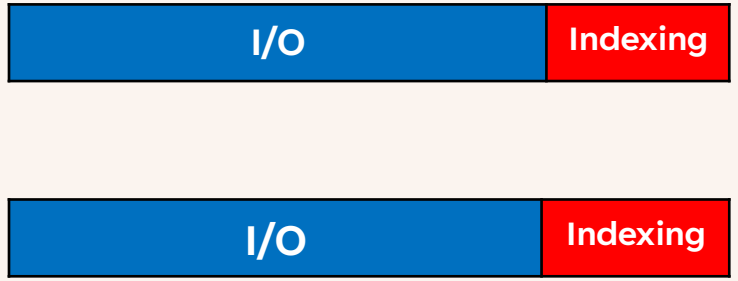

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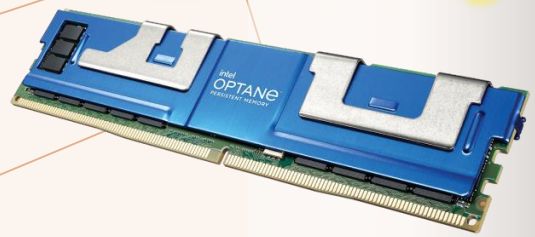

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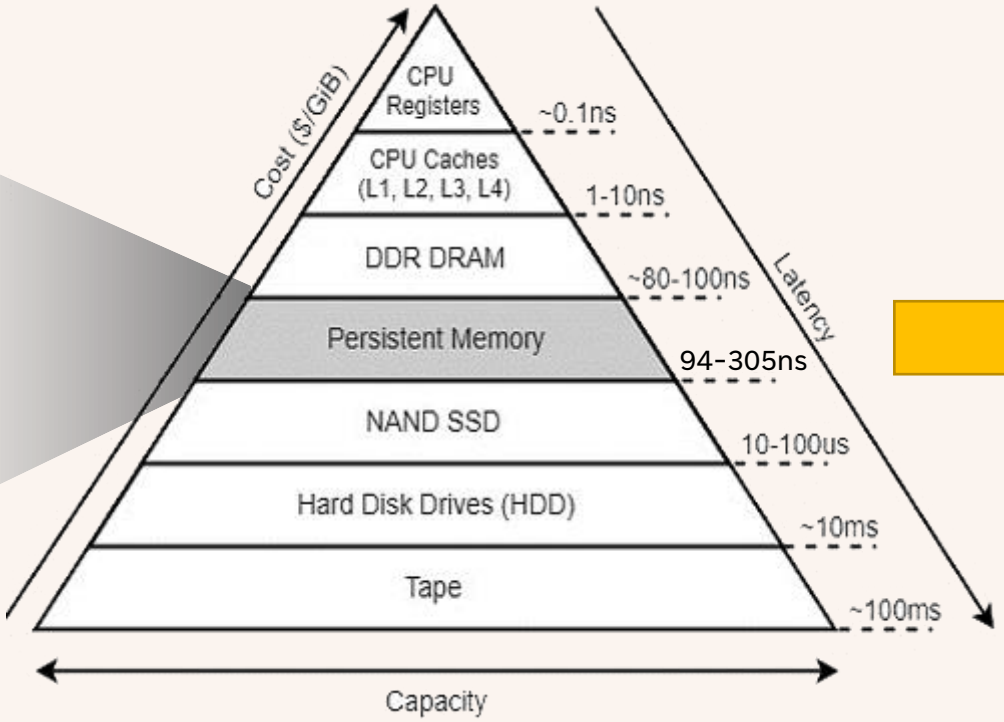

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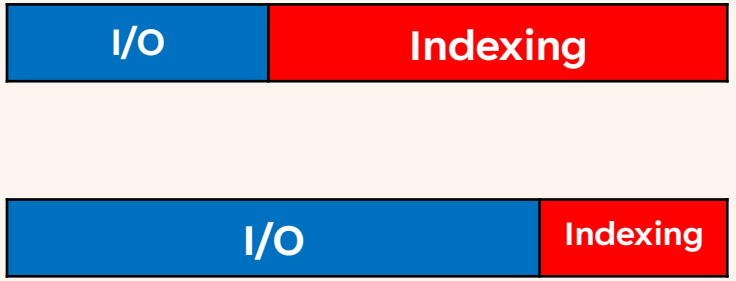

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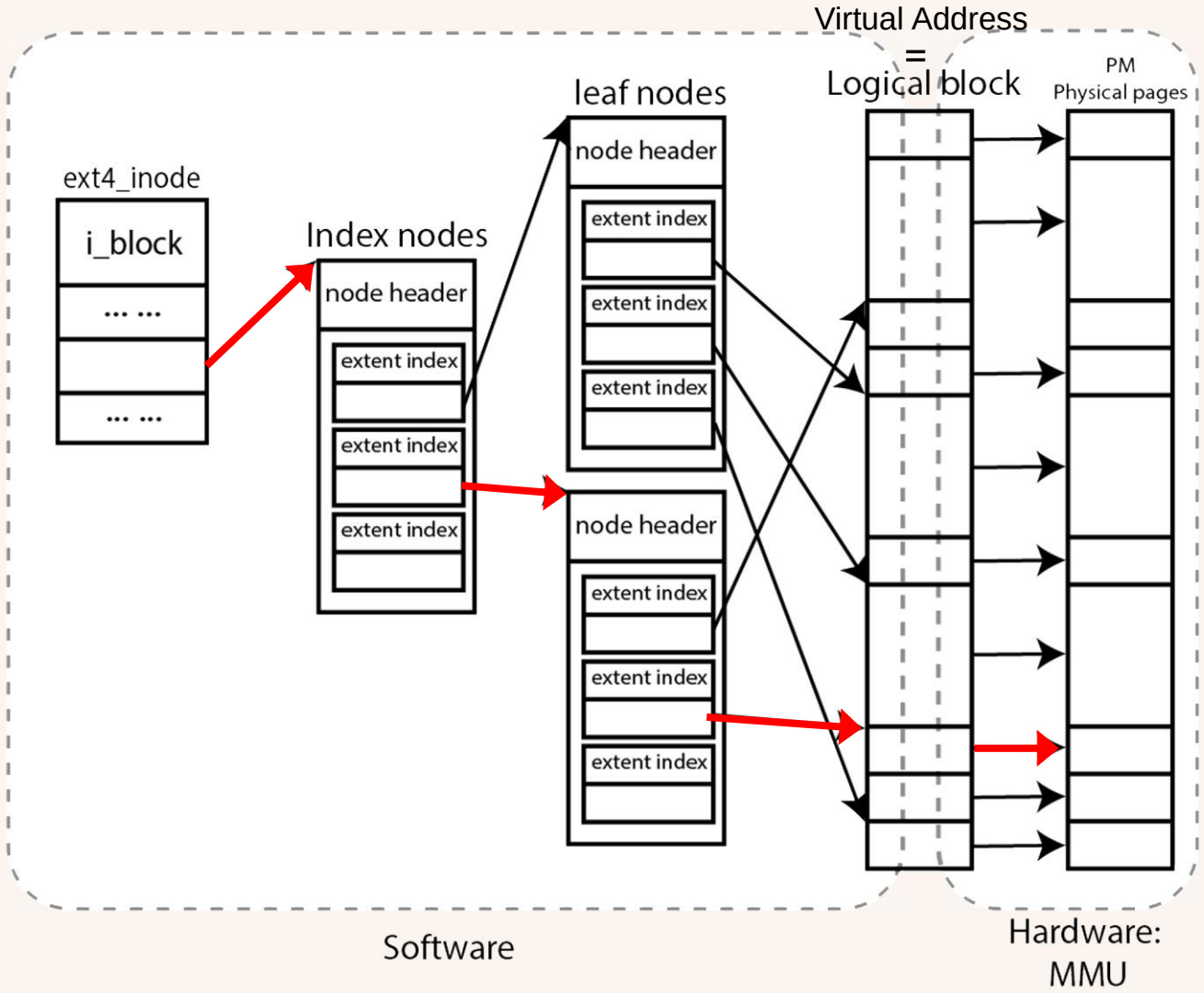
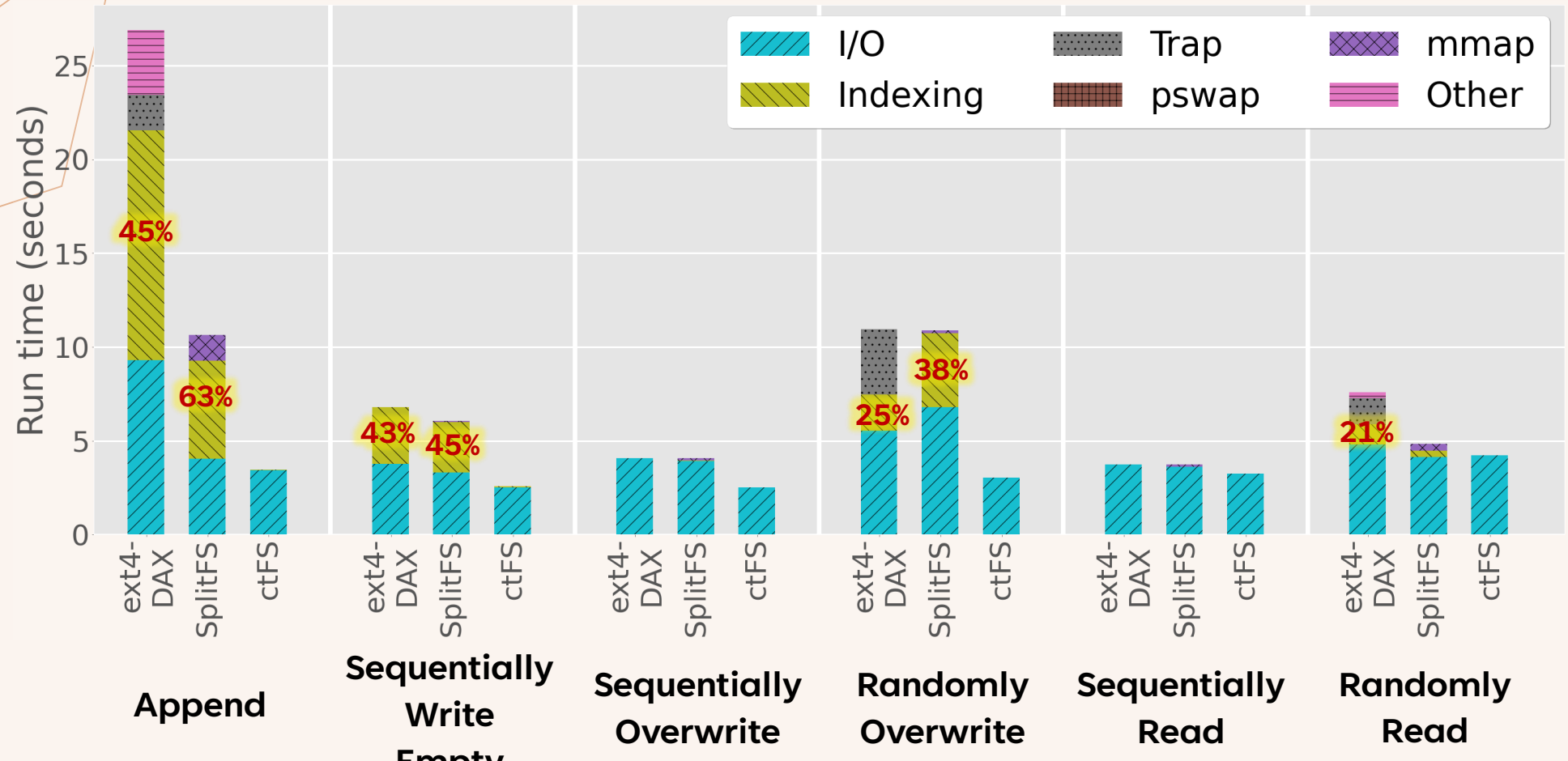
Ext4-DAX Indexing Path is COMPLEX!



*Top is lower address

Software Indexing is Slow!



*10GB Total Workload for each test
*Lower is better

Source: SplitFS[SOSP19]. Rohan Kadekodi, et al.

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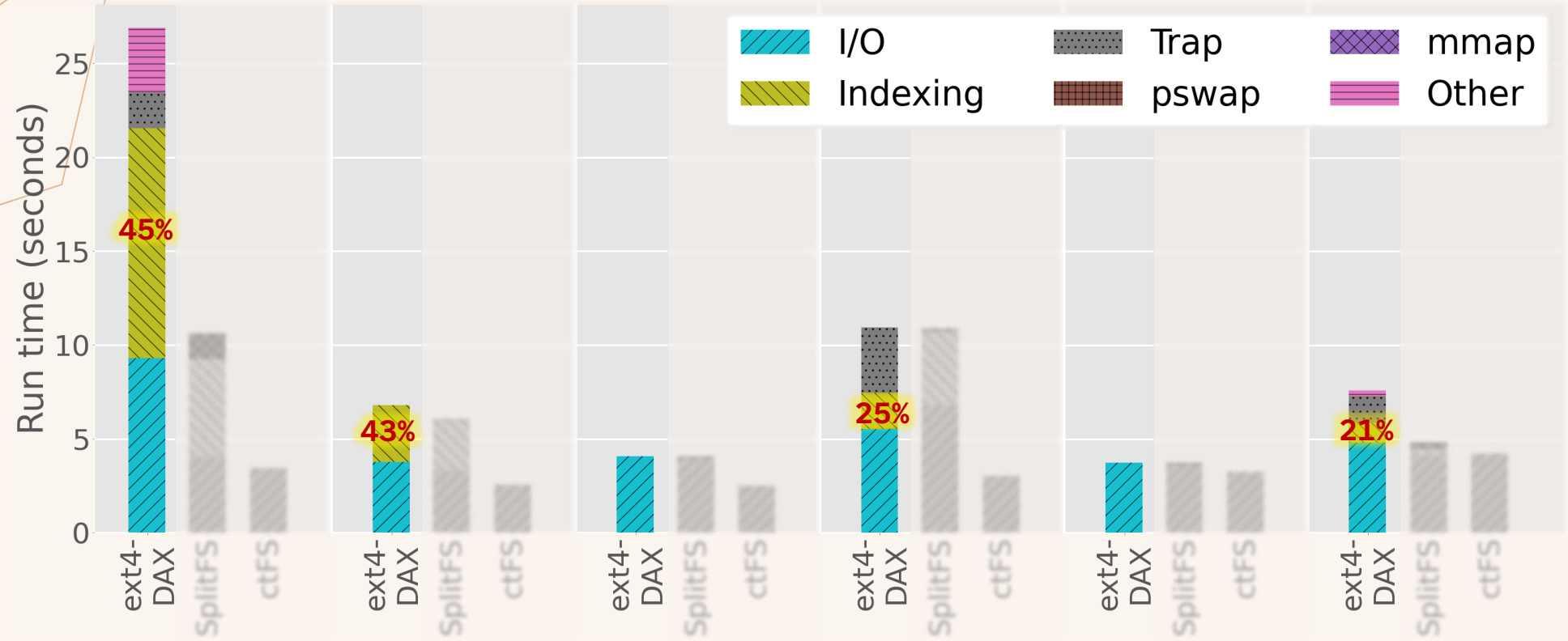

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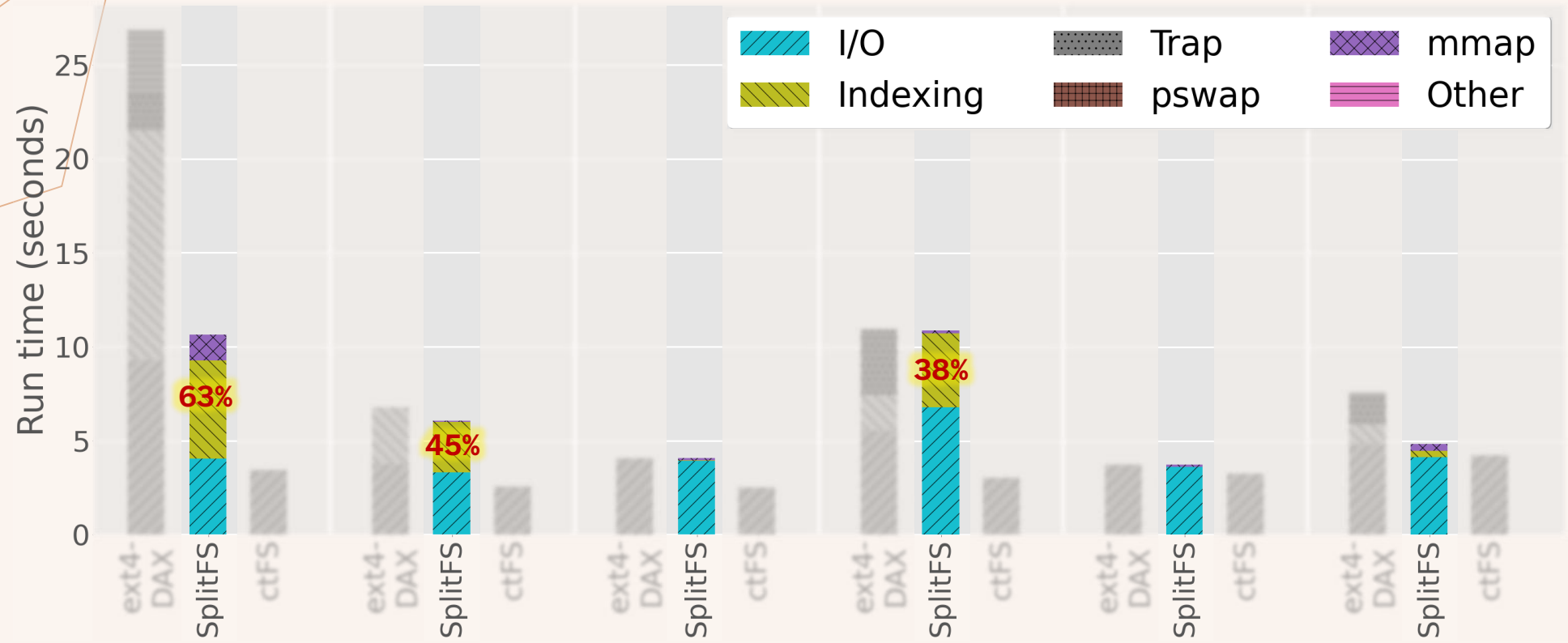

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OTHER RELATED WORKS

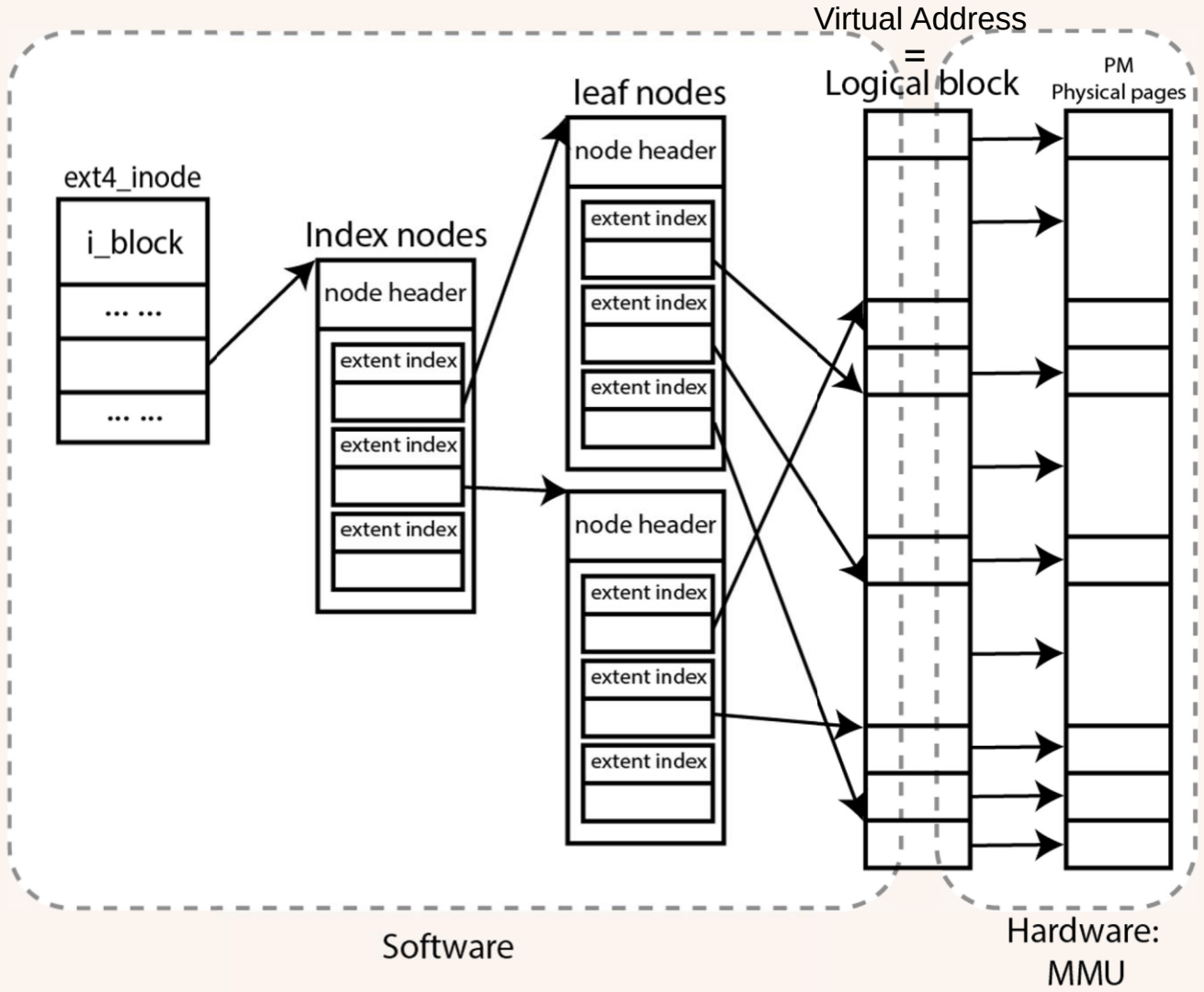
HashFS [FAST ’21] Neal, et al.

Use hash table for indexing, built on Strata

KUCO [FAST ’21] Chen, et al.

Offload some of the indexing job to user level, based on ext2-style block mapping

RETHINK Indexing!



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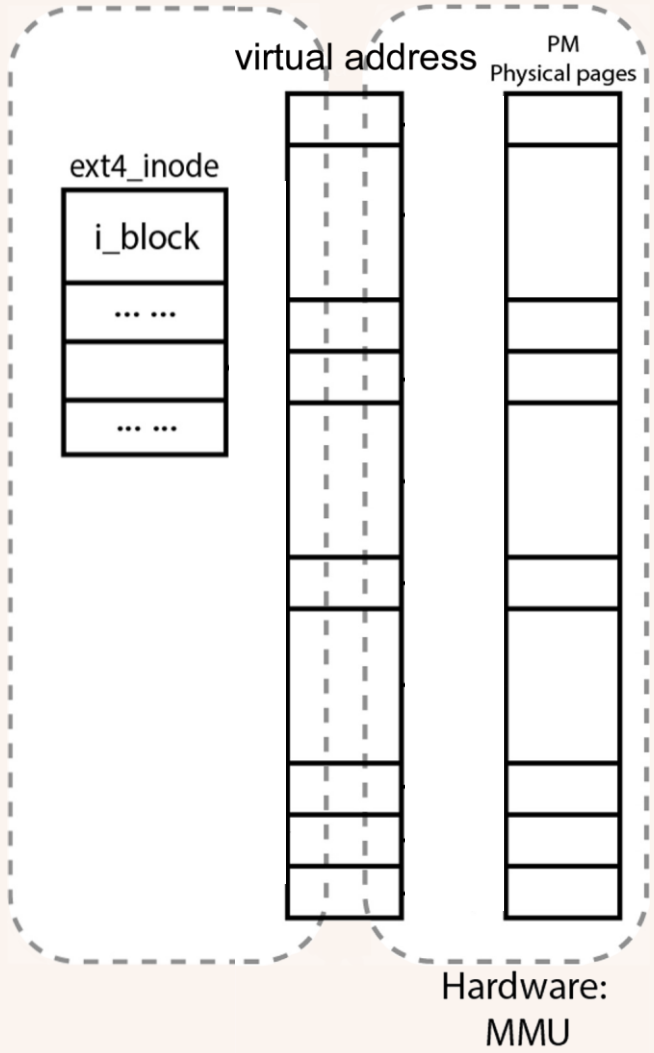

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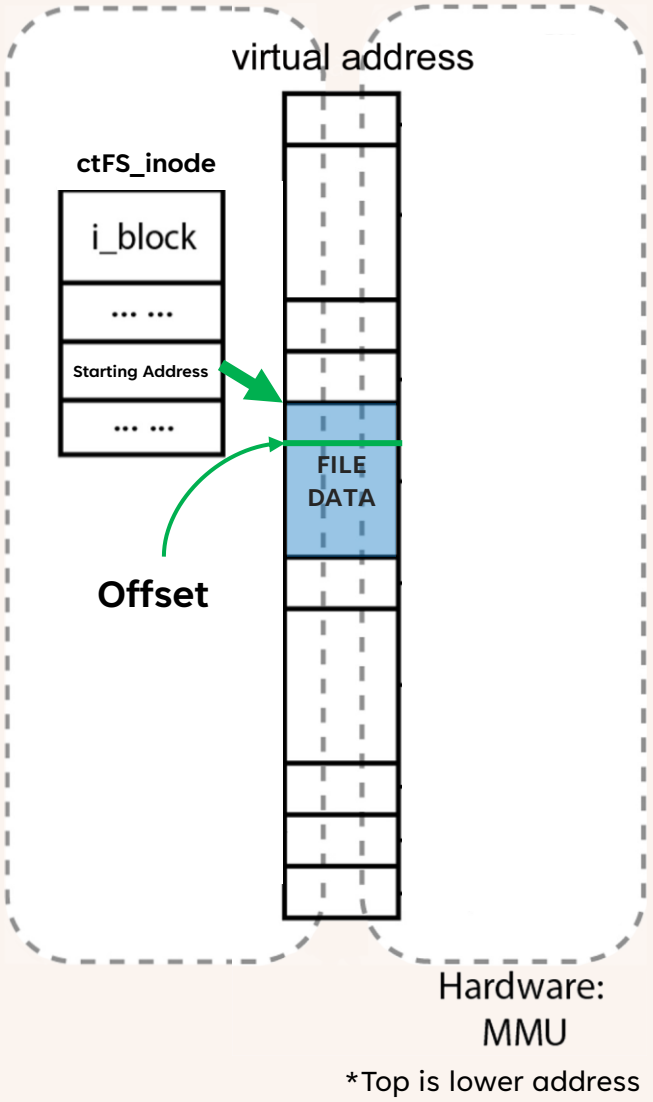
Replace Software Indexing With MMU Translation

Treat PM as Memory

Instead of Disks

ctFS: Replace Indexing with Hardware Memory Translation



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- Files are **Contiguously** Allocated in **Virtual** Address Space
  - Only store Starting Address in inode
  - File access -> start + offset

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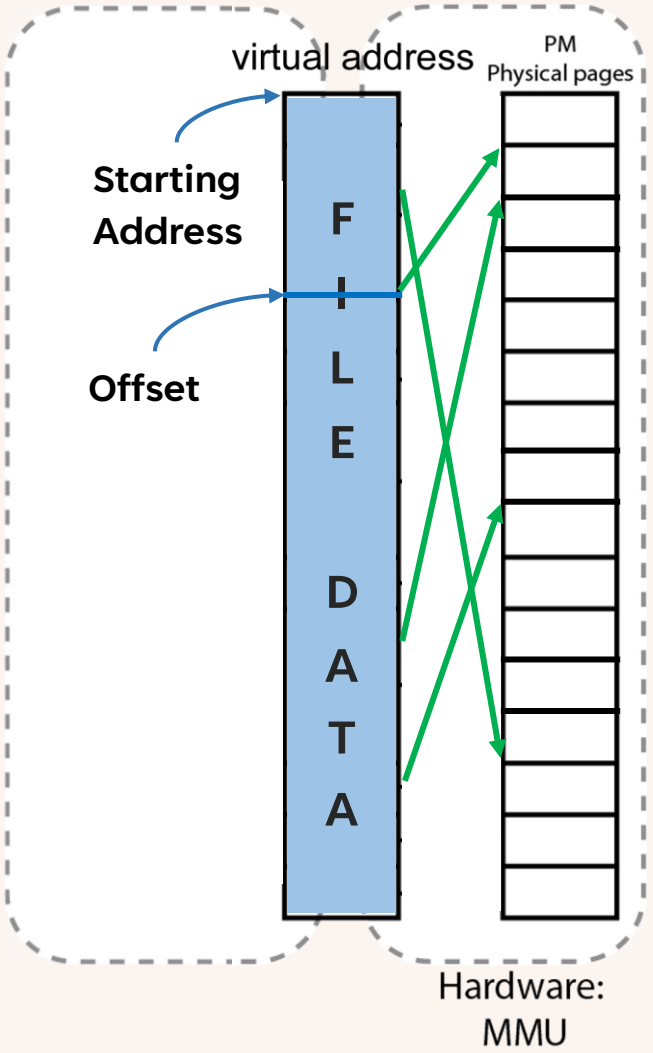

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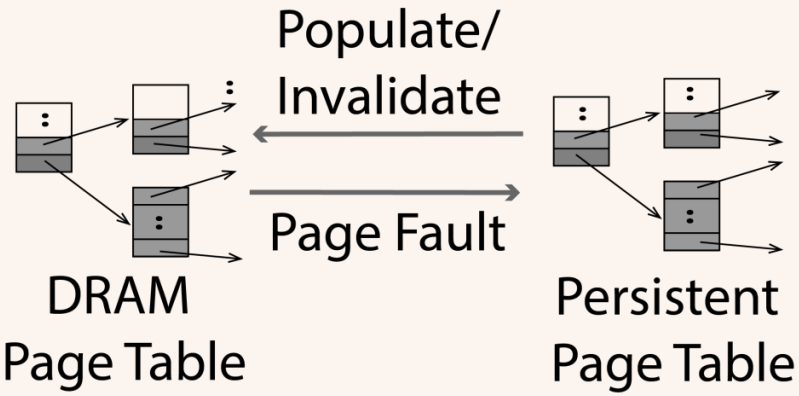
- Virtual to physical mapping is managed by **Persistent Page Tables**
  - Copy to DRAM on page fault
  - Demand Paging



ctFS: Replace Indexing with Hardware Memory Translation

ctU: User Part

FS Functionalities

File System APIs

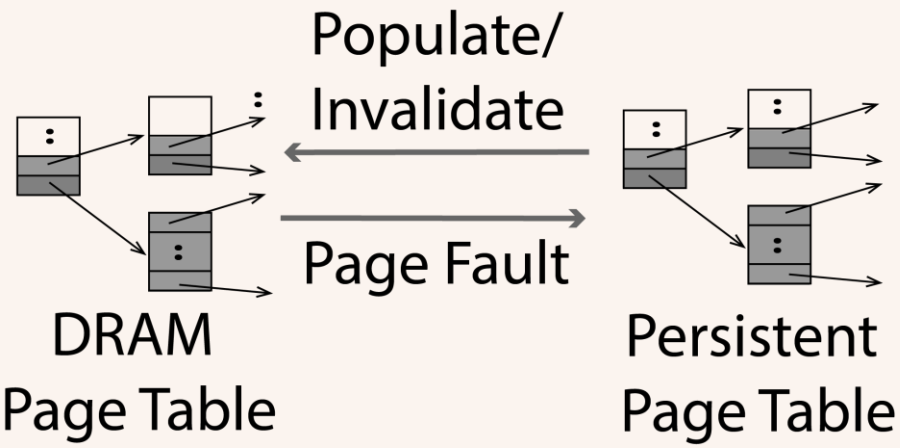
File Layout

ACID Guarantees

⋮

ctK: Kernel Part

Memory Abstractions

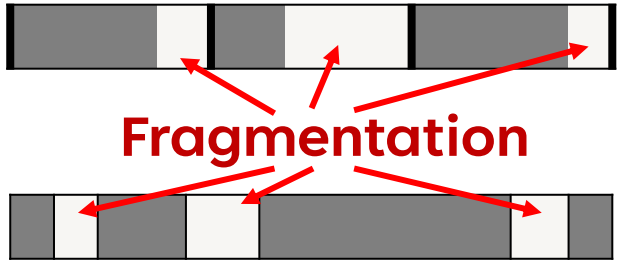


Challenges of being Contiguous

Occupied

Free

Allocate?



- Fixed-size Partition: Internal Fragmentation
- Variable-size Partition: External Fragmentation and Garbage Collection

Hierarchical Layout

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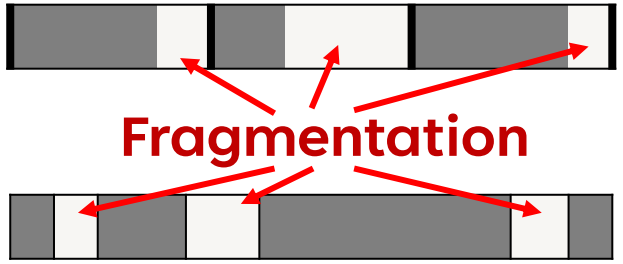

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Resize?

- A file grows and conflicts with another
- Need Migration

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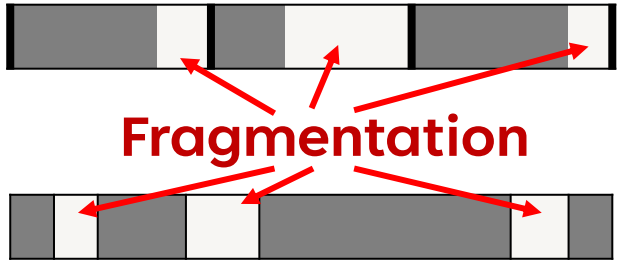

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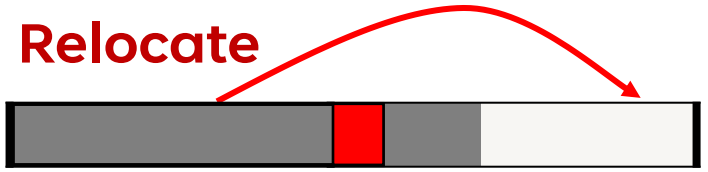
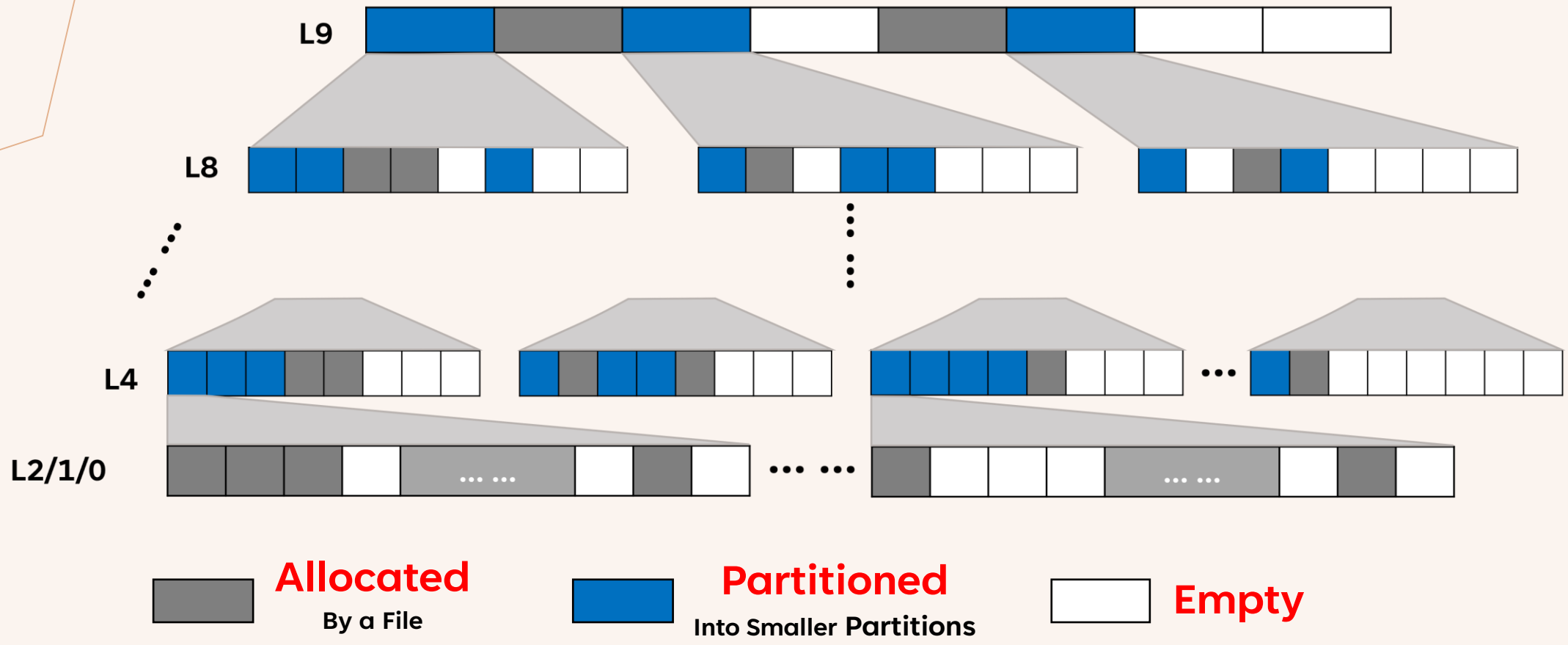


- A file grows and conflicts with another
- Need Migration

New Syscall: pswap()

ctFS: Hierarchical File System Layout

L9 512GB
L8 64GB
L7 8GB
L6 1GB
L5 128MB
L4 16MB
L3 2MB
L2 256KB
L1 32KB
L0 4KB



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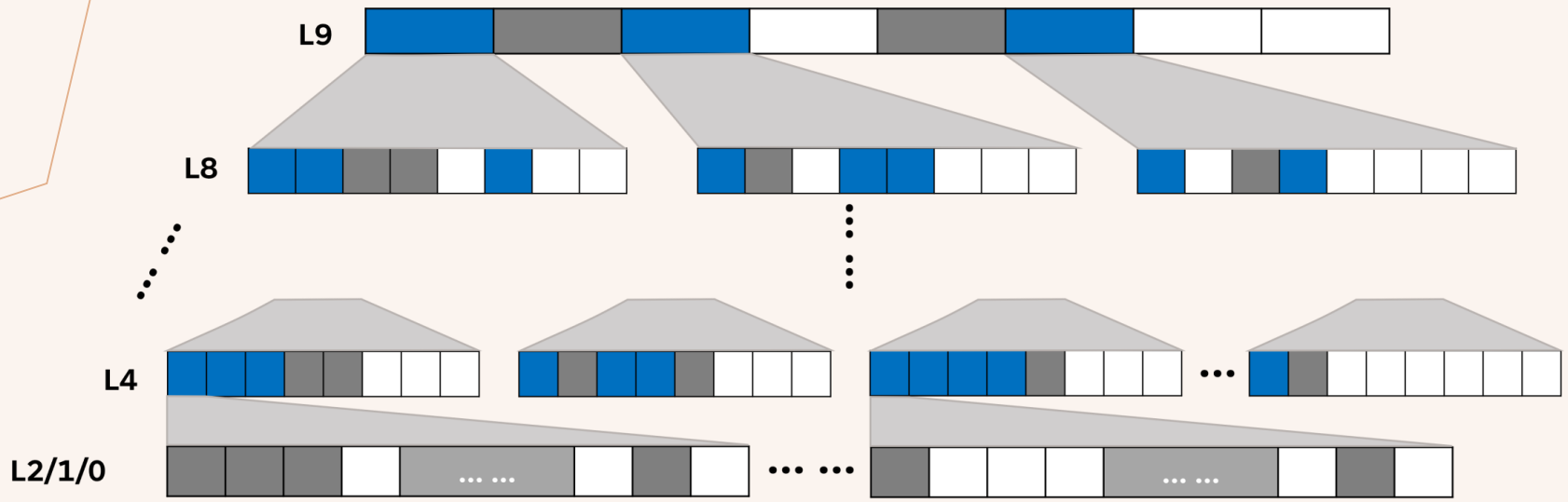

Allocated
By a File

Partitioned
Into Smaller Partitions

Empty

- Partition of different levels
- Size is **8x** between levels
- Starting Address is **Aligned** to its size

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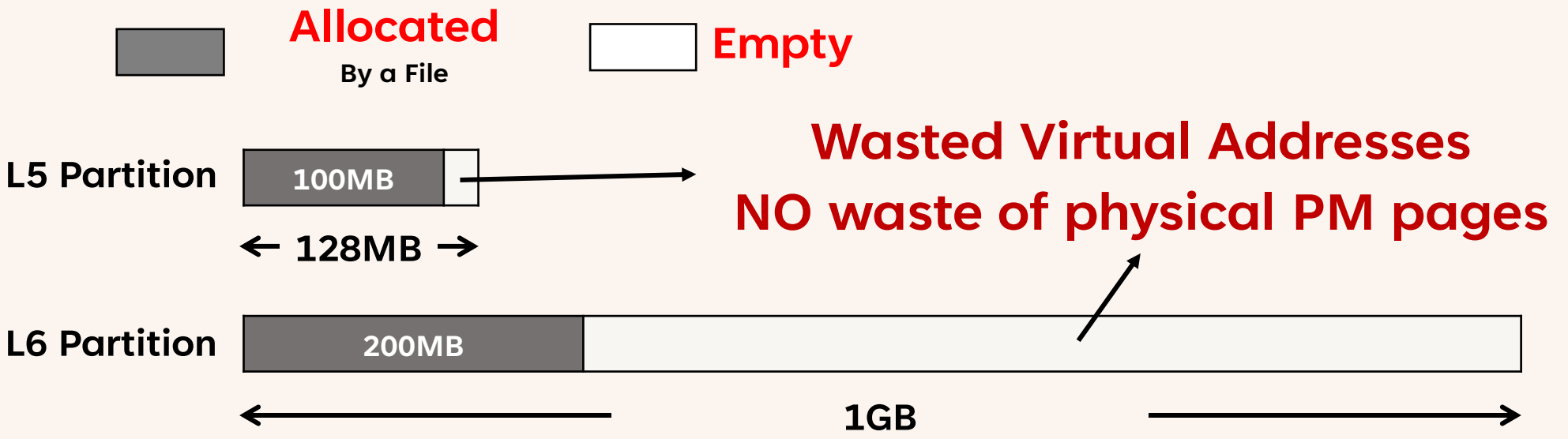
ctFS: **Hierarchical** File System Layout

- **One** file **One** partition
- Occupied by a file: **Allocated**



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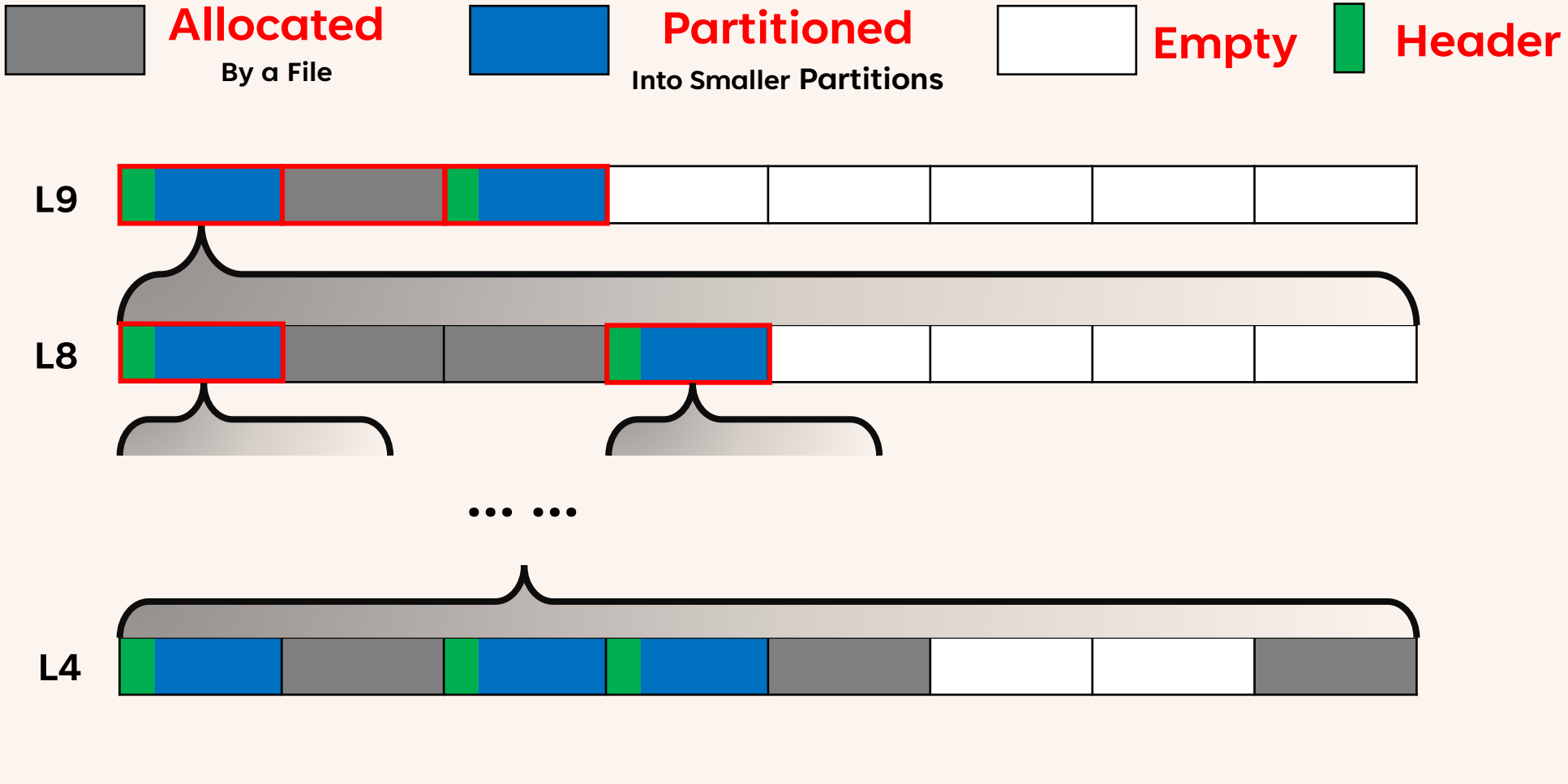

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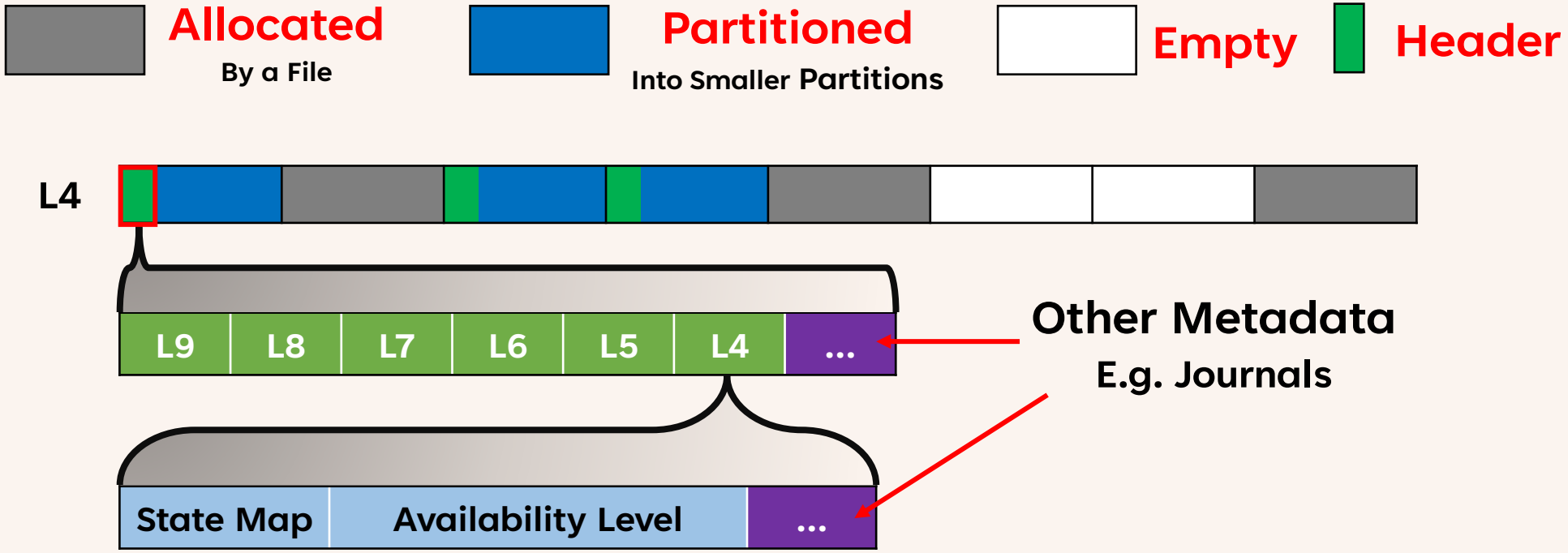

Header Layout

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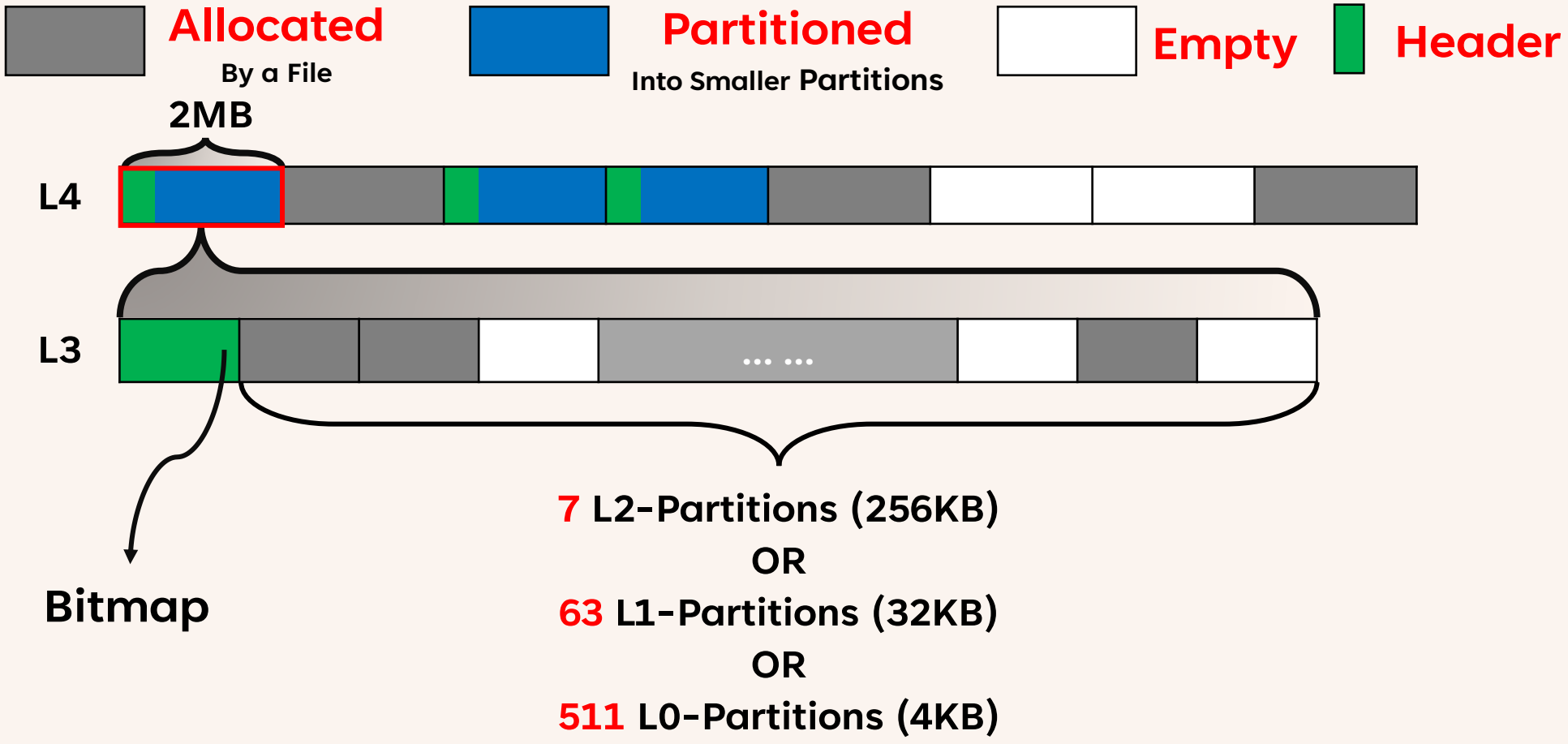
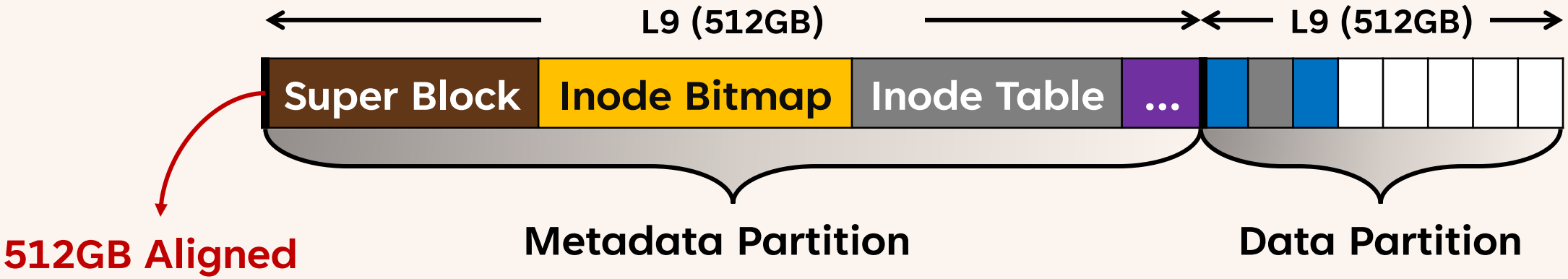


ctFS: Hierarchical File System Layout

- Highest Level ≥ 2 x PM Capacity
  - E.g. 256GB PM needs L9
- Two highest level partitions are reserved
  - Metadata Partition and Data Partition
  - E.g. Two L9-Partitions reserved below



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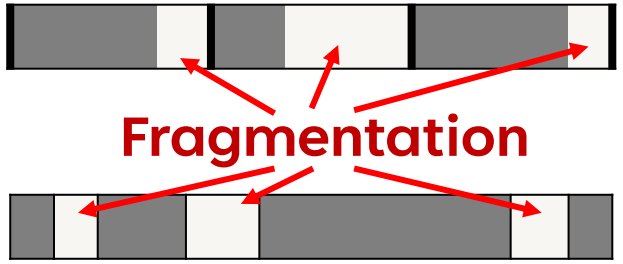

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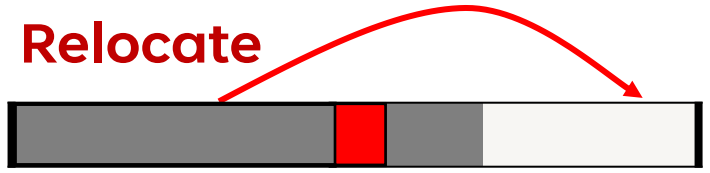

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New Syscall: pswap()

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int pswap(void* A, void* B, unsigned int N, ...);
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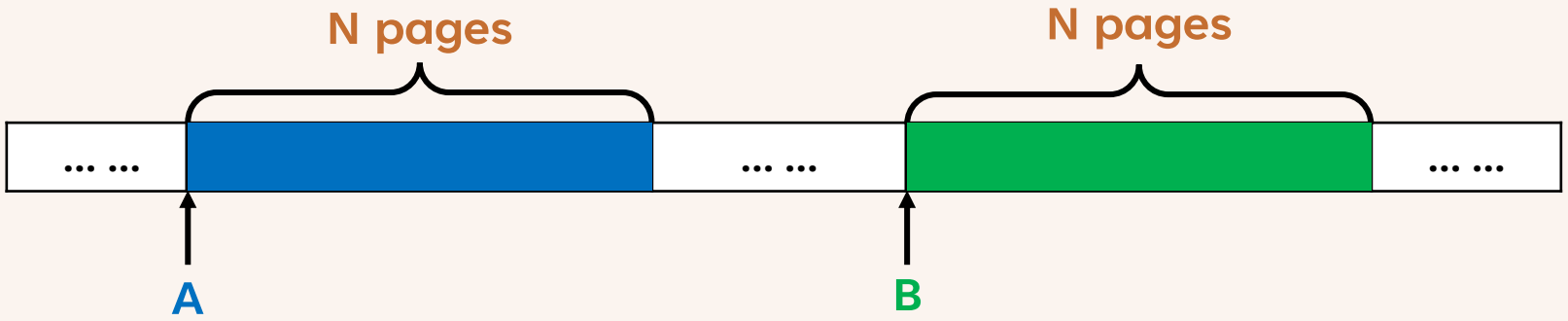
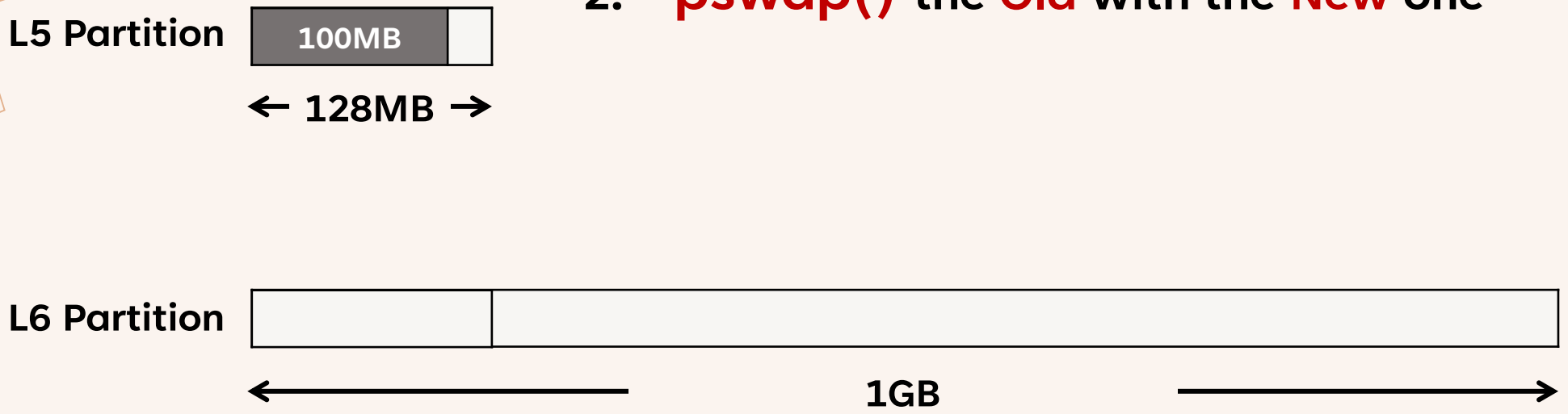


- Atomically swap the mapping of two **Same-Sized Contiguous** sequences of virtual pages
- Crash consistency guaranteed using REDO log

Use pswap() To Resize

```
int pswap(void* A, void* B, unsigned int N, int* flag);
```

1. Allocate an Empty Higher-Level Partition
2. pswap() the Old with the New one



Use pswap() To Resize

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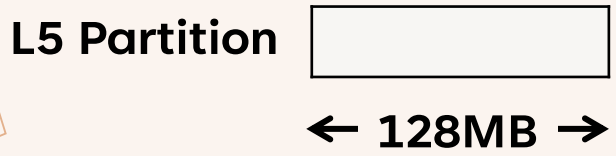
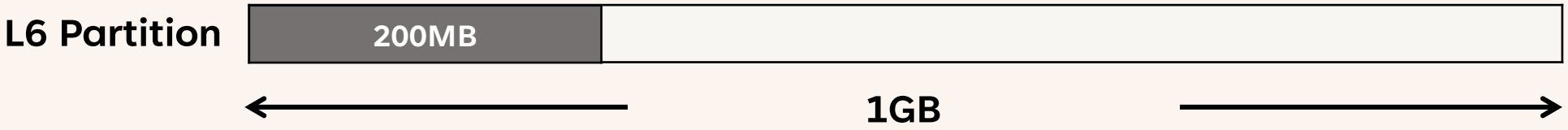
1. Allocate an **Empty** Higher-Level Partition
2. **pswap()** the **Old** with the **New** one
3. Write the **Extra Data** and Alter the Metadata





pswap()'s Key to Efficiency

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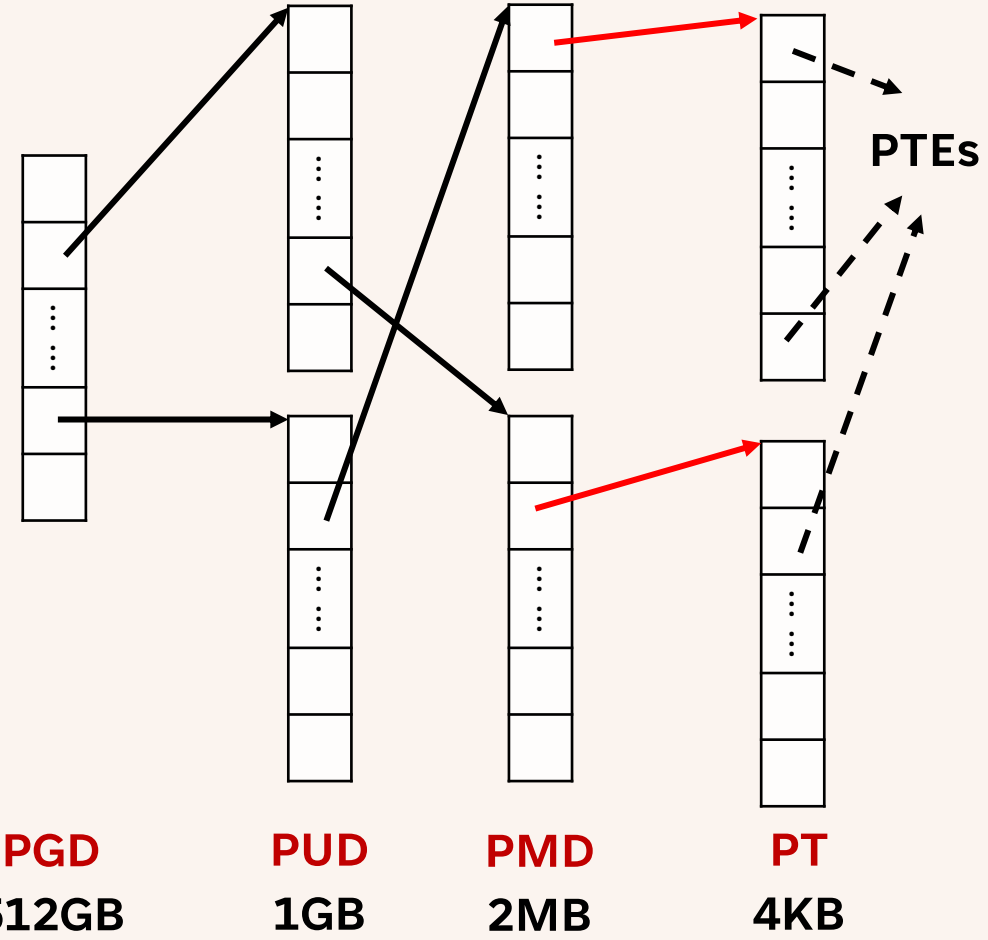

- pswap() 128MB:
  - *64* pairs of PMD entries instead of *32k* PT entries
- Perfect only when Aligned
  - ctFS partitions are strictly size Aligned

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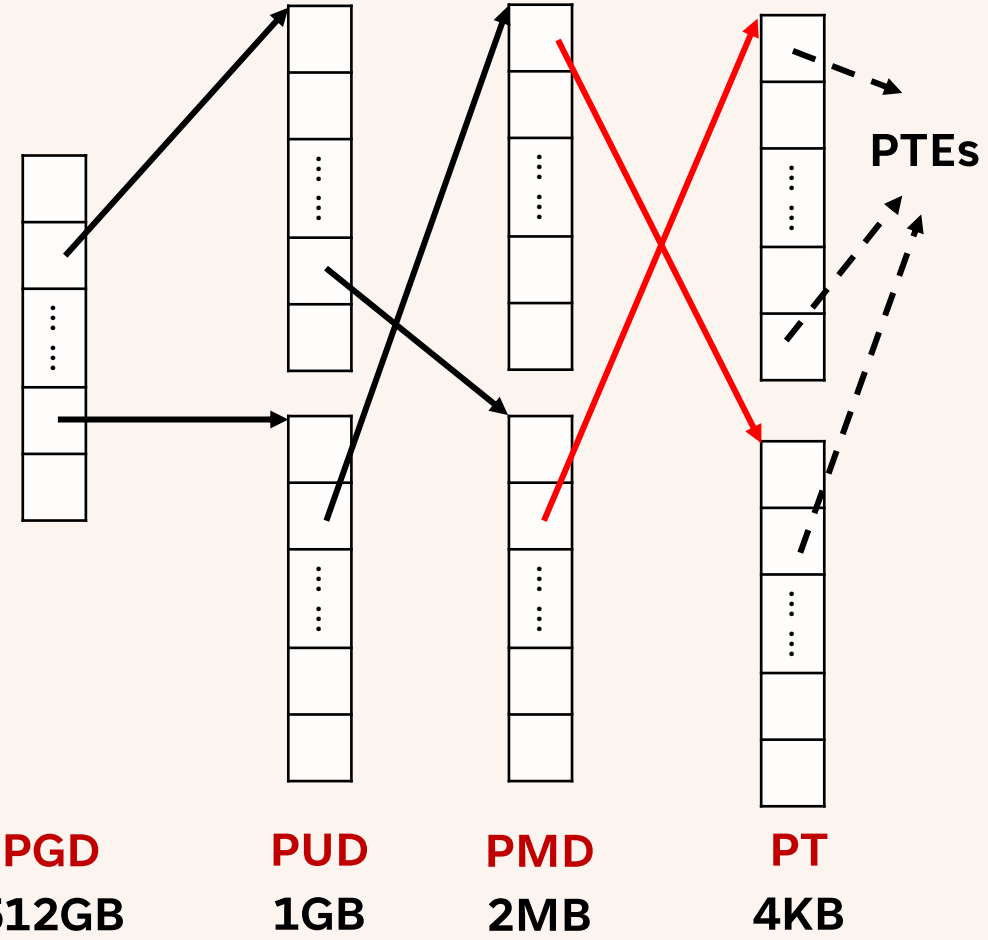

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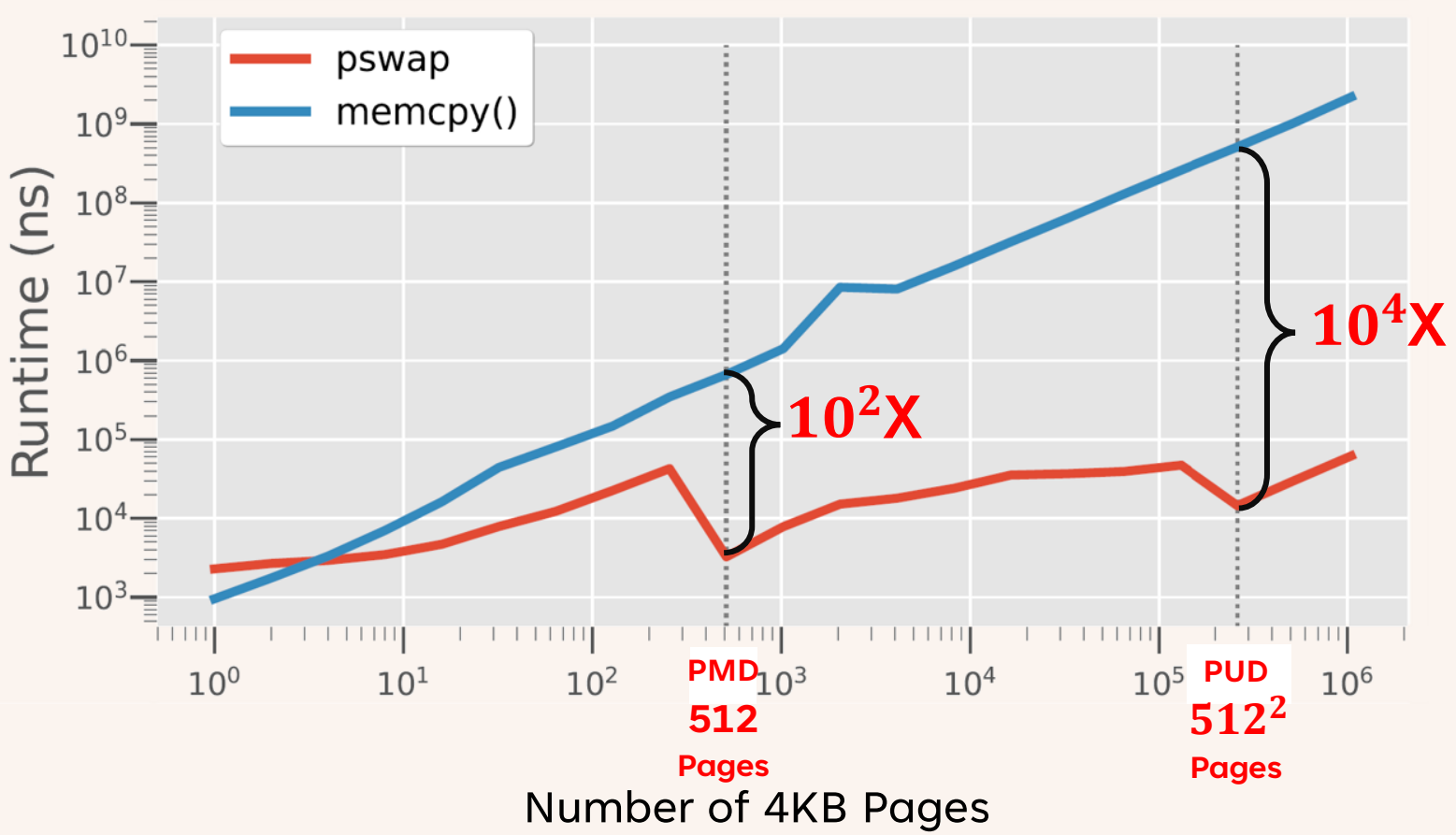

Atomic Write Powered By pswap()

1. Allocate a staging partition
2. Write new data to staging partition
3. Copy the data fragment to the new partition if the write is not page-aligned
4. Call pswap() to atomically swap affected pages

- Used in ctFS's Strict Mode

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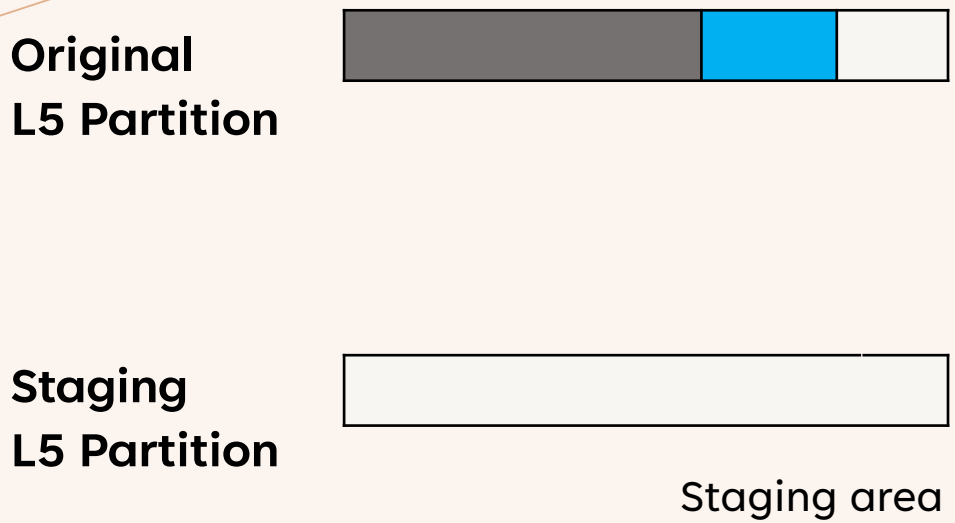

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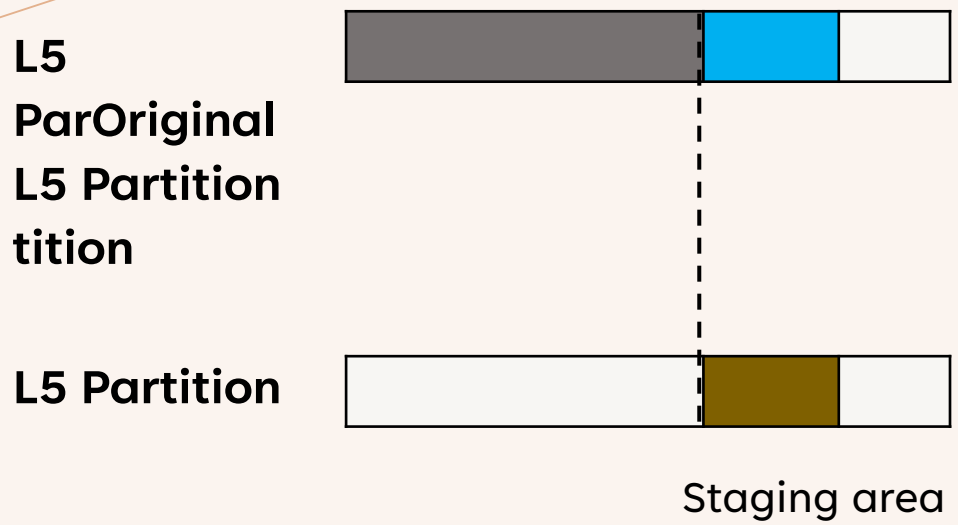

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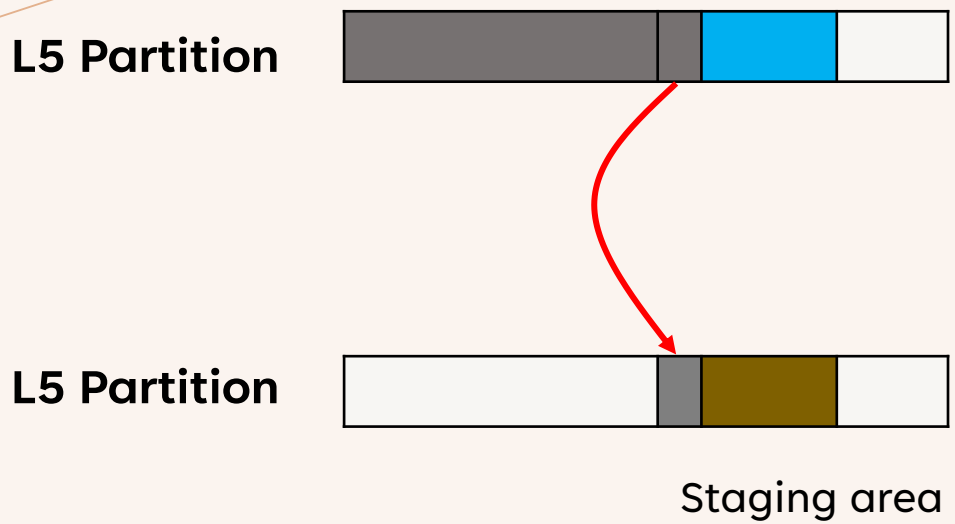

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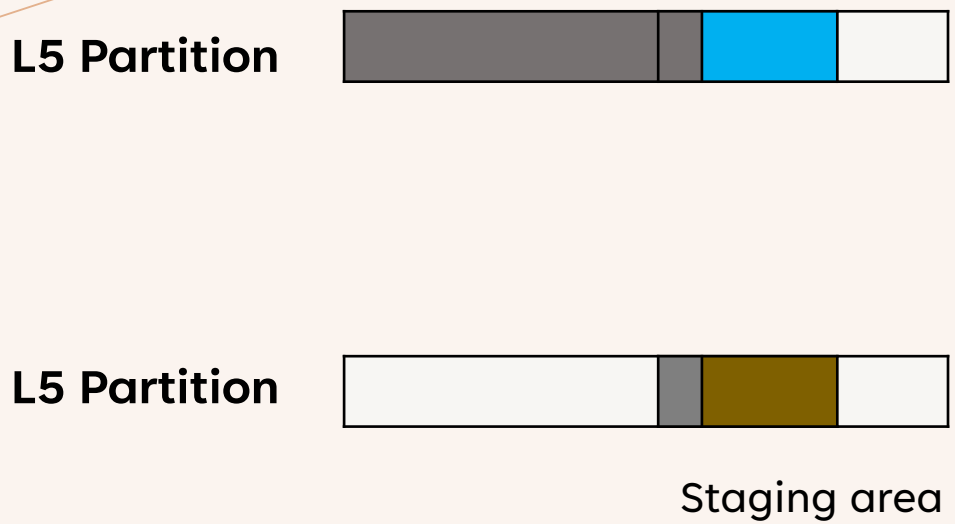

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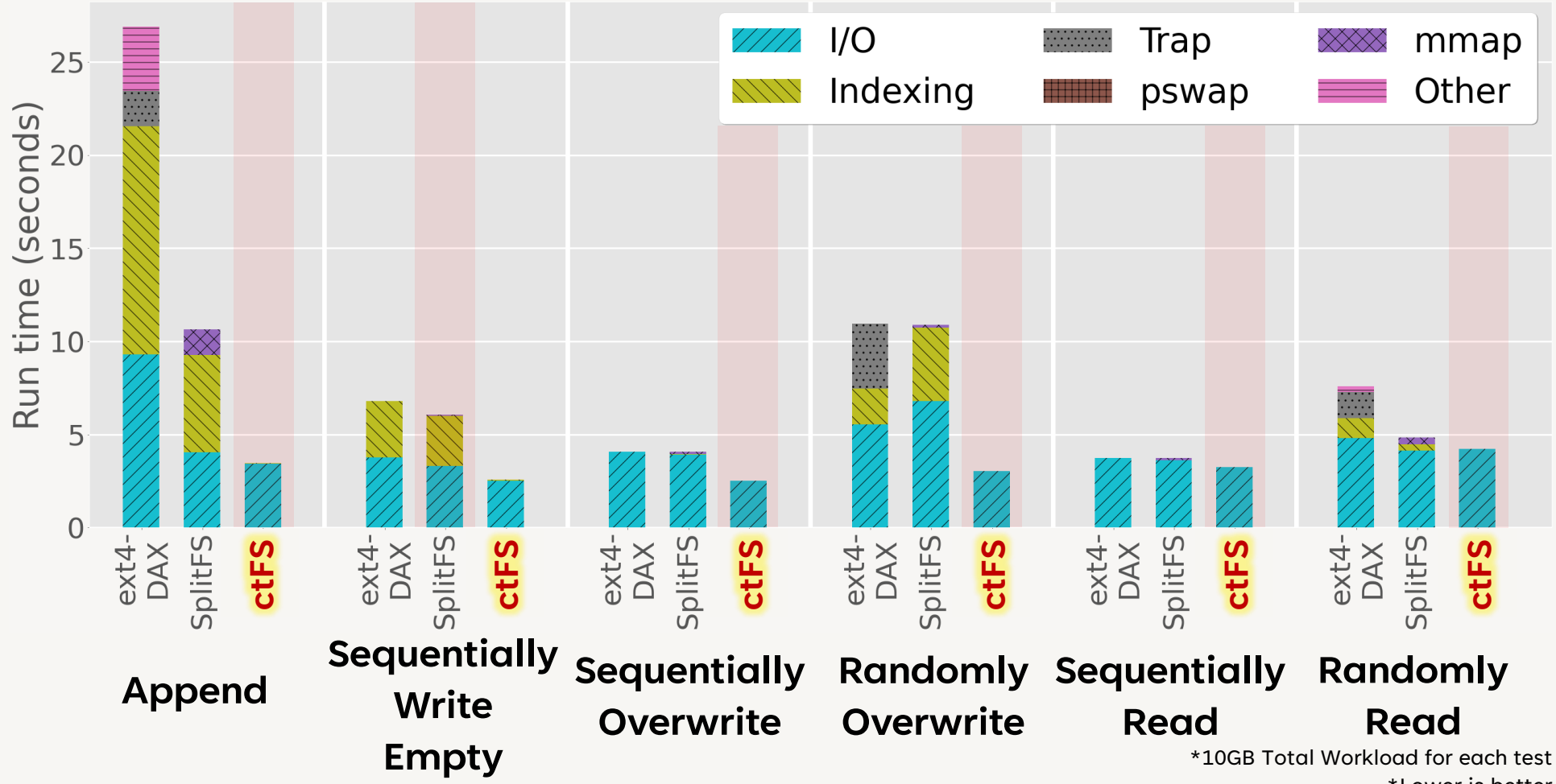
Evaluation

- Micro Benchmarks
- Application Evaluation
- All tests are conducted in the following setup:
  - CPU: 8-core Intel Xeon 4215 CPU @2.5 GHz
  - DRAM: 96GB DDR4 RDIMM
  - PM: 2 X 128GB Intel Optane NVDIMM
  - OS: Ubuntu 20.04 LTS
  - Kernel: Linux Version v5.7.0-rc7+

Microbenchmarks: Indexing Cost **Eliminated**



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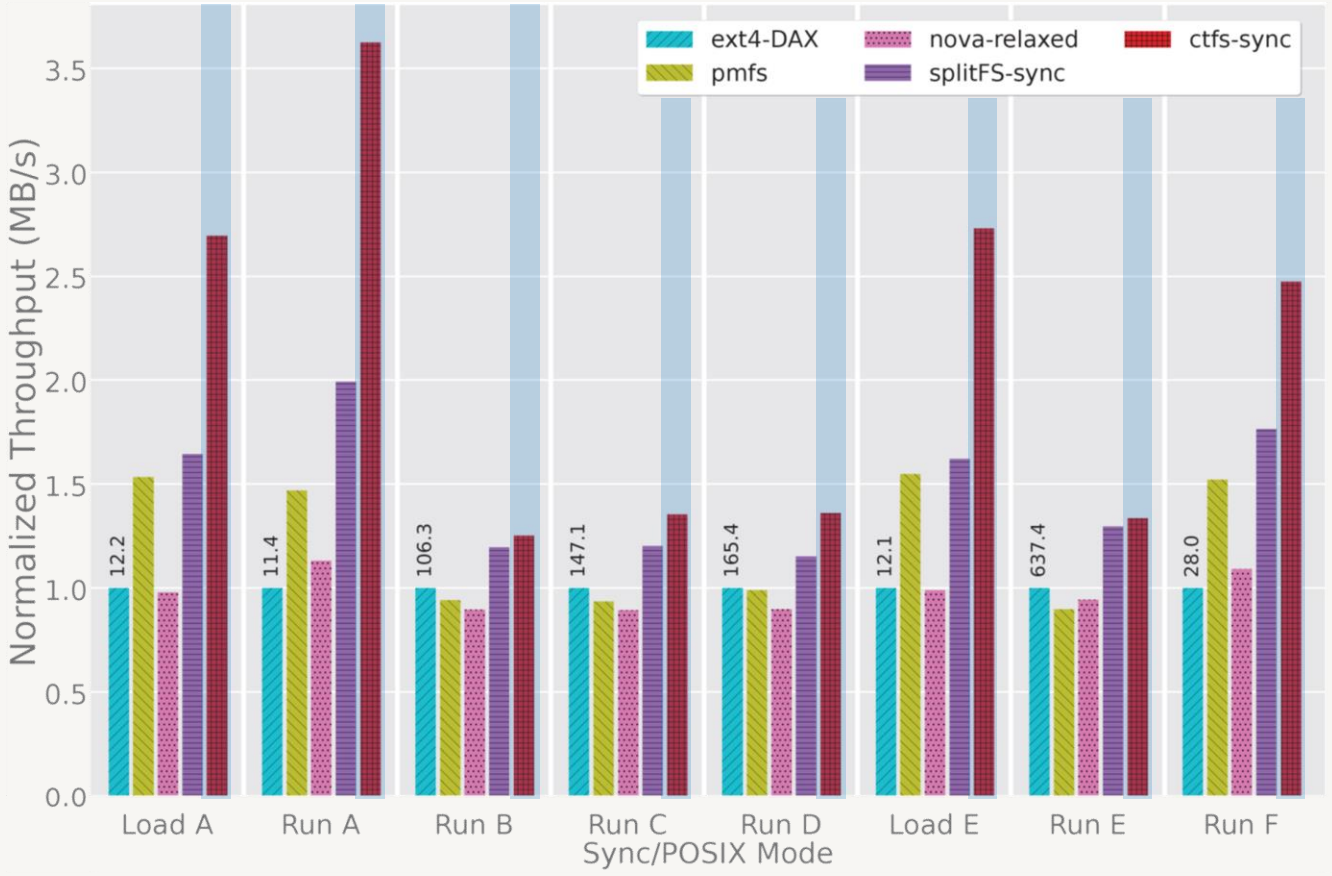
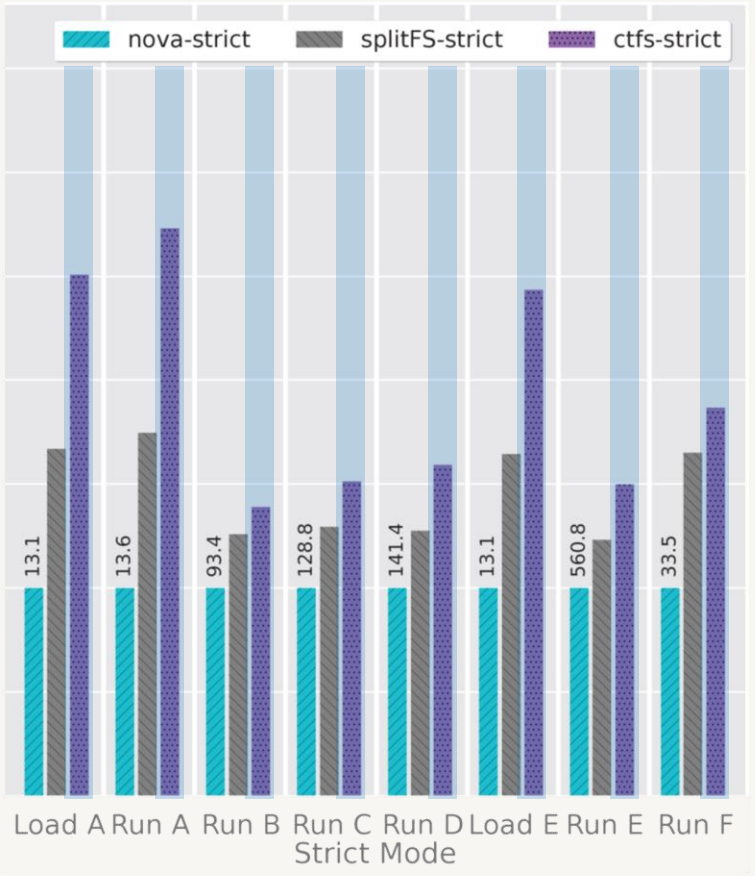
LevelDB on YCSB:





*Higher is better

Protection Issue

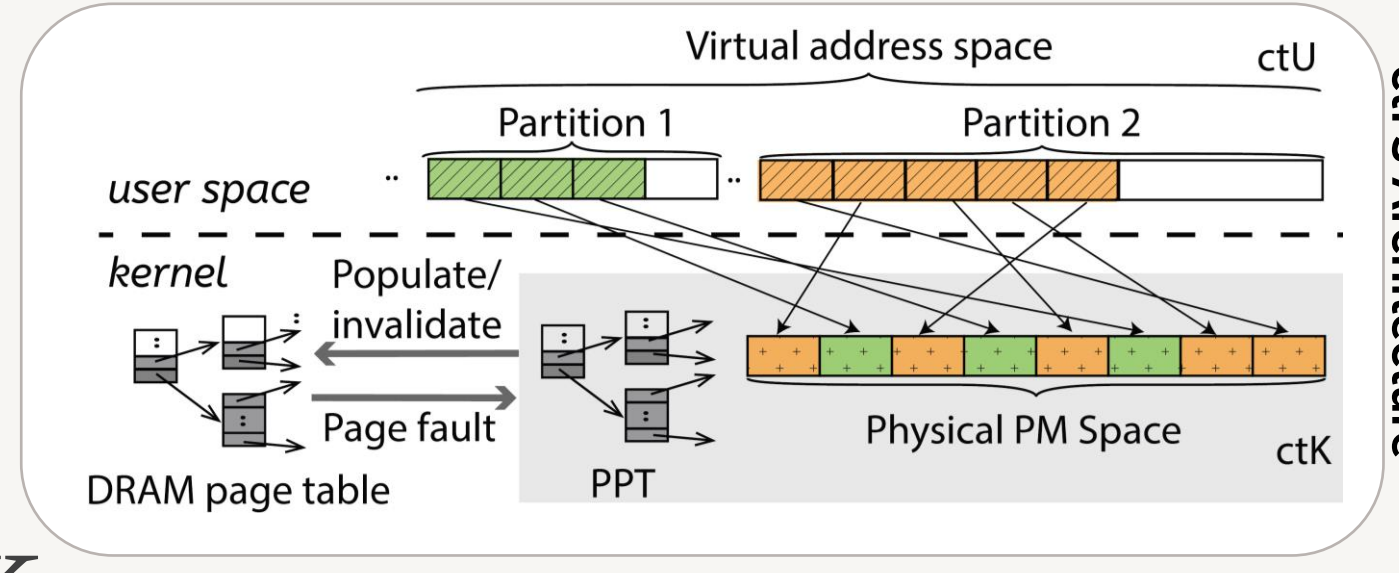
- Weak Protection
  - Due to user-level meta-data handling
  - MPK used to prevent corruption from memory bugs
  - May be vulnerable to intentional attacks
- If it’s a concern
  - One ctFS instance for each application
  - Migration to the kernel in progress

Paper

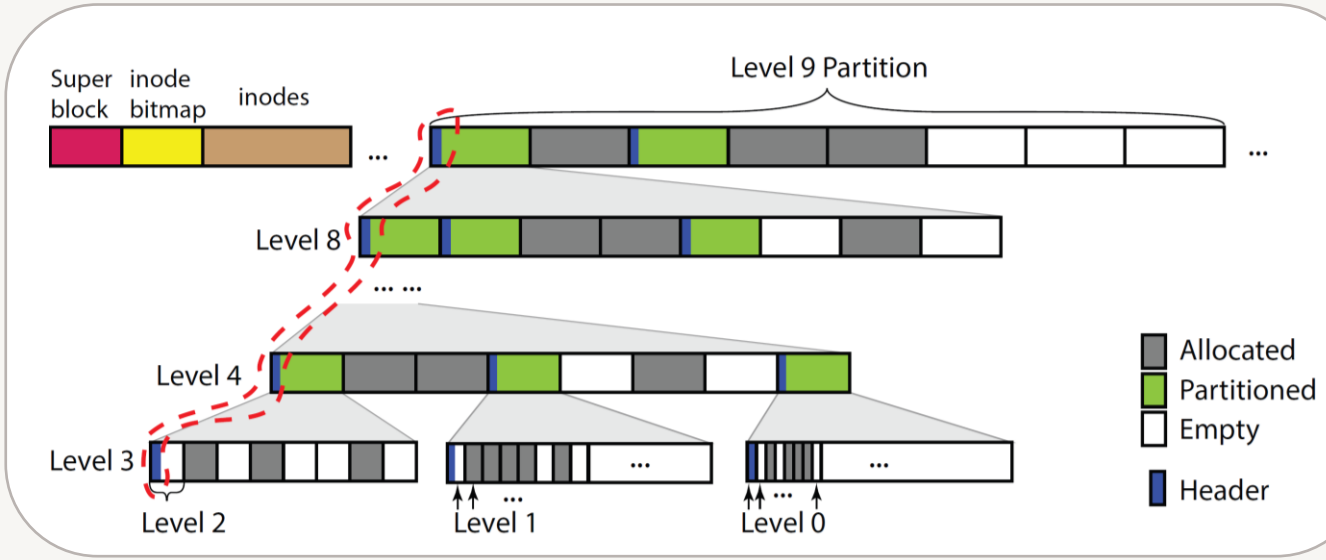
THANK YOU :)

GitHub

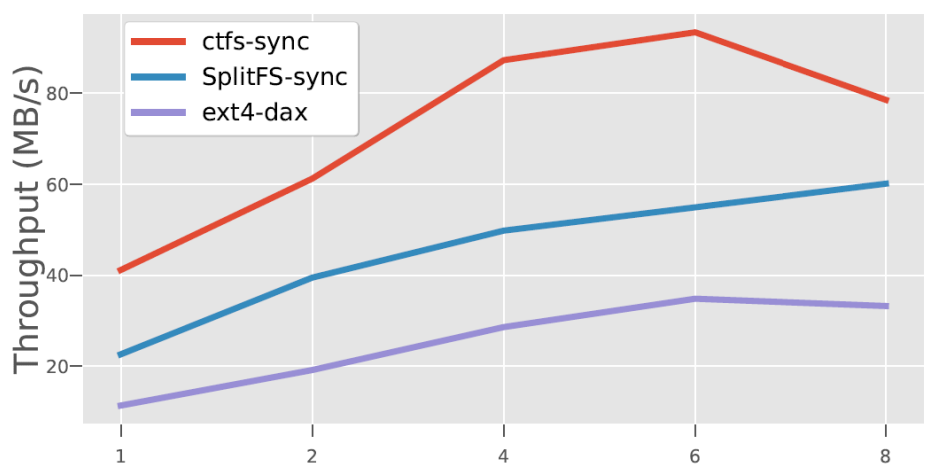
ctFS Architecture



Hierarchical Allocator

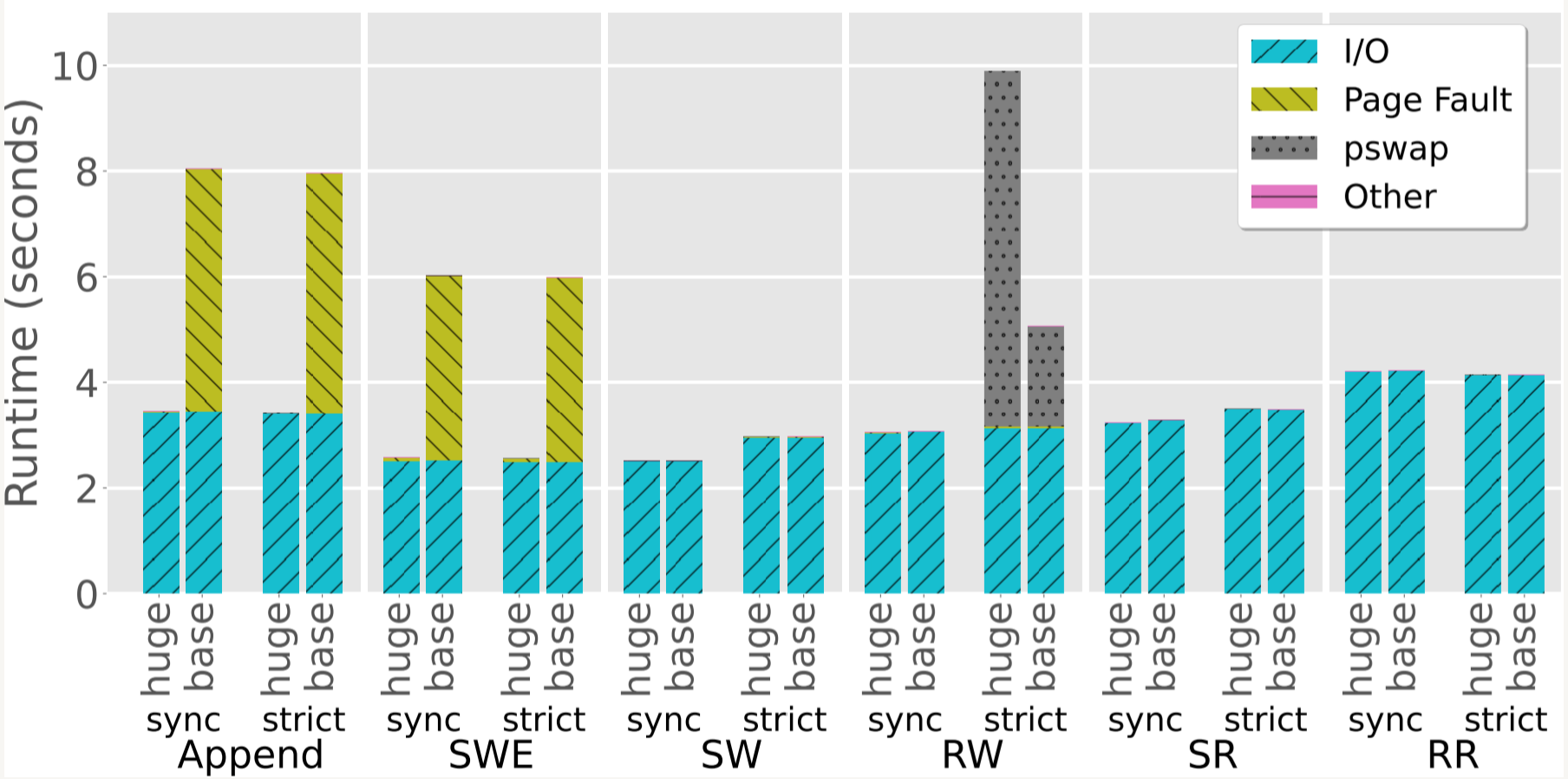


Scalability & Resource Usage



	SplitFS		Ext4-Dax	ctFS
	sync	strict		
Bootstrap (µs)	1.4×10^6	1.1×10^6	0	5
open (create) (µs)	40	40	15	2
open (existing) (µs)	4	10	4	2
unlink (µs)	32	43	31	1.6
DRAM usage (MB)	198	572	N/A	0.516
Space available after format (GB)	230.69		230.69	248.05
Space consumed after YCSB LoadA (MB)	5486.3		5336.7	5378.1

ctFS runtime breakdown & huge page impact



Internal Fragmentation

- Manageable
  - Max waste: < 7x of file size
  - Physical space is not wasted
- Virtual Memory space is HUGE
  - Currently in use: 2^{48}B (256 TB)
  - Now supporting: 2^{57}B (128 EB)