Towards Application Driven Storage

Optimizing RocksDB for Open-Channel SSDs

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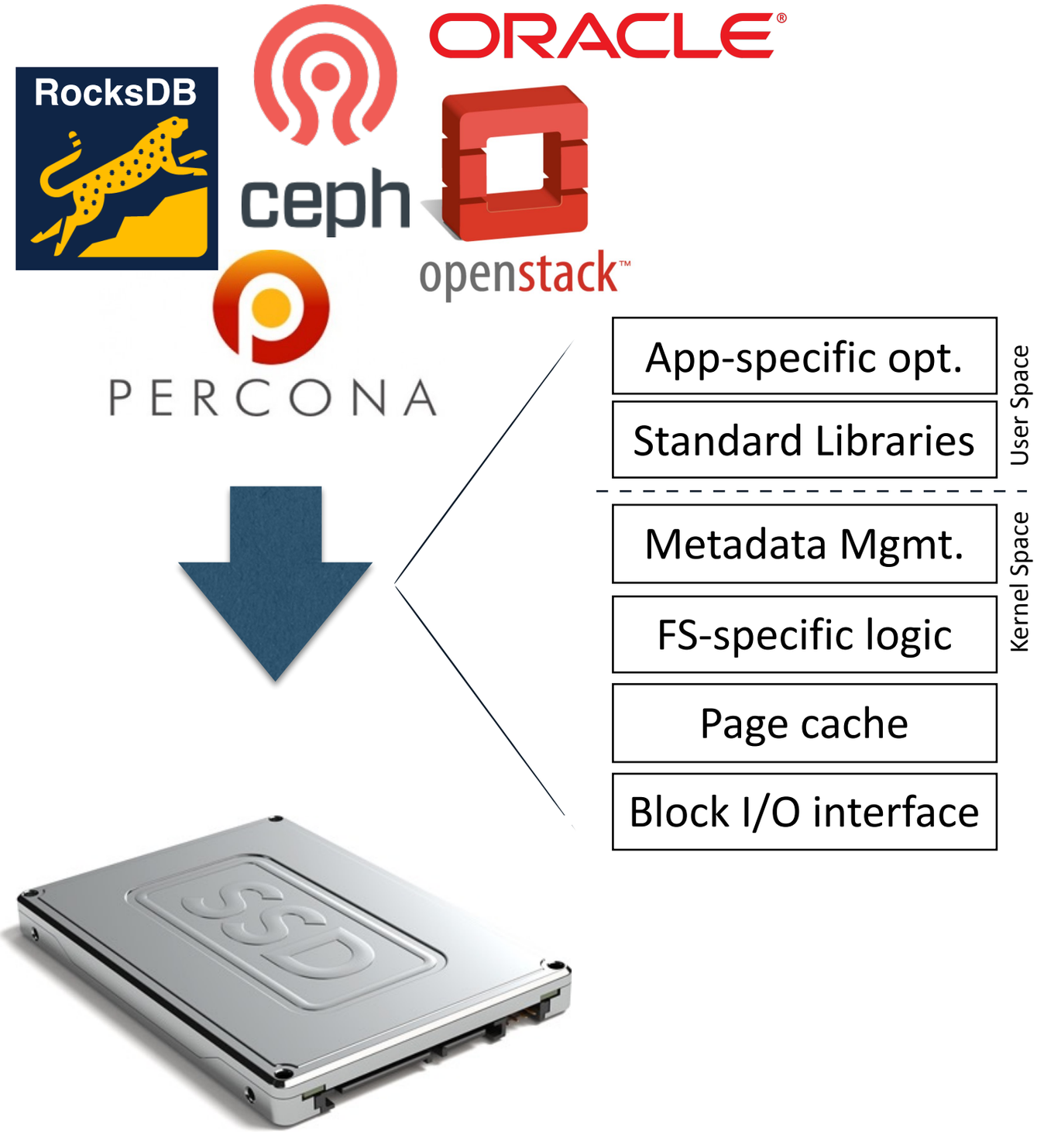
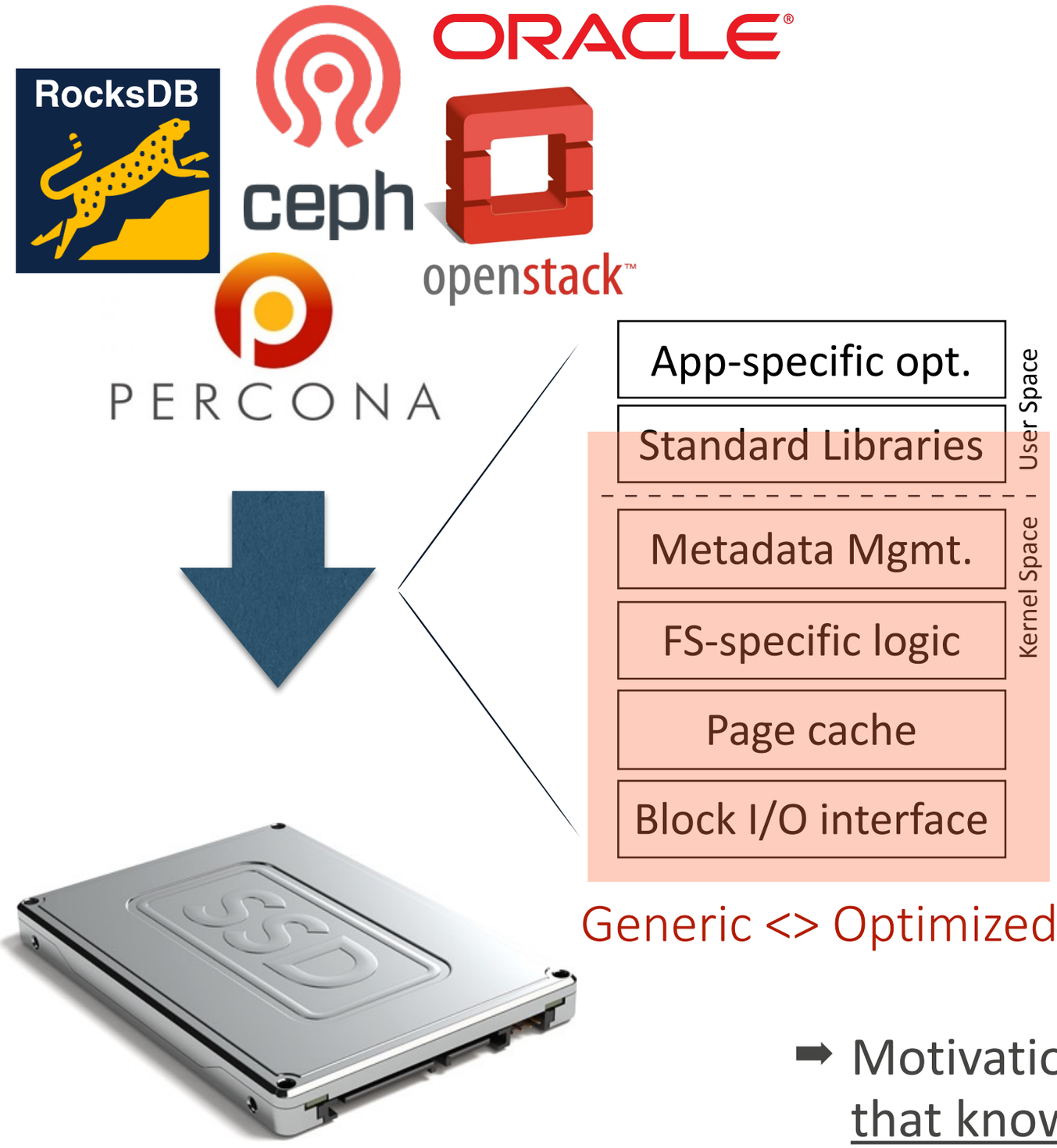
LinuxCon Europe 2015

Application Driven Storage: What is it?



Application Driven Storage: What is it?



Generic <> Optimized

- Application Driven Storage
  - Avoid multiple (redundant) translation layers
  - Leverage optimization opportunities
  - Minimize overhead when manipulating persistent data
  - Make better decisions regarding latency, resource utilization, and data movement (compared to best-effort techniques today)

➡ Motivation: Give the tools to the applications that know how to manage their own storage

Application Driven Storage Today

- Arrakis (https://arrakis.cs.washington.edu)
  - Remove the OS kernel entirely from normal application execution
- Samsung multi stream
  - Let the SSD know from where “I/O streams” emerge to make better decisions
- Fusion I/O
  - Dedicated I/O stack to support a specific type of hardware
- Open-Channel SSDs
  - Expose SSD characteristics to the host and give it full control over its storage

Traditional Solid State Drives

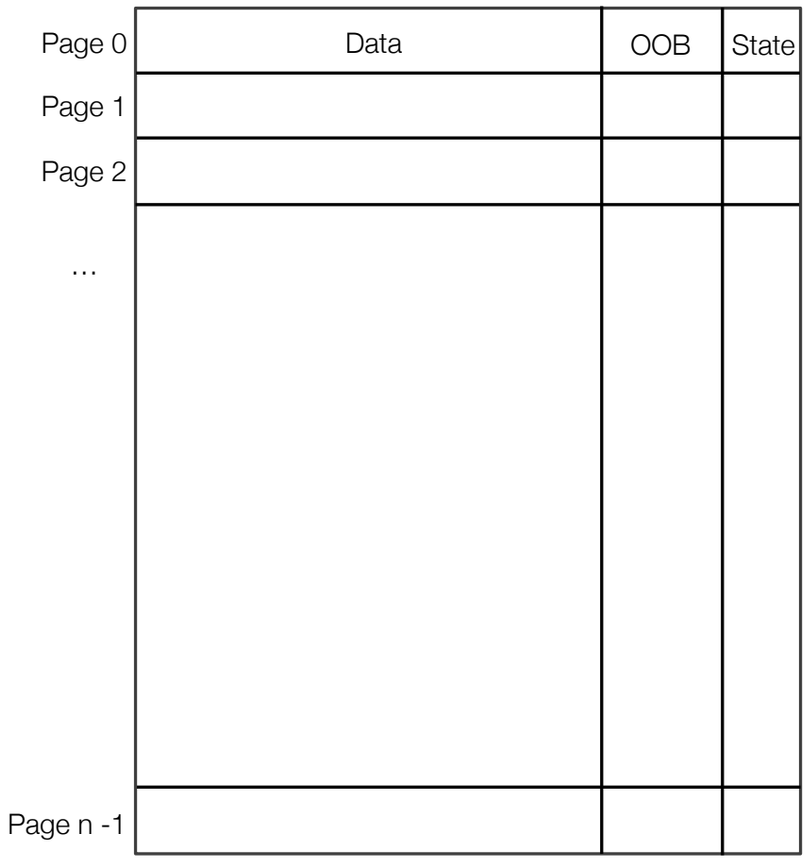
High throughput + Low latency

Parallelism + Controller

- Flash complexity is abstracted away form the host by an embedded Flash Translation Layer (FTL)
  - Maps logical addresses (LBAs) to physical addresses (PPAs)
  - Deals with flash constrains (next slide)
  - Has enabled adoption by making SSDs compliant with the existing I/O stack

Flash memory 101

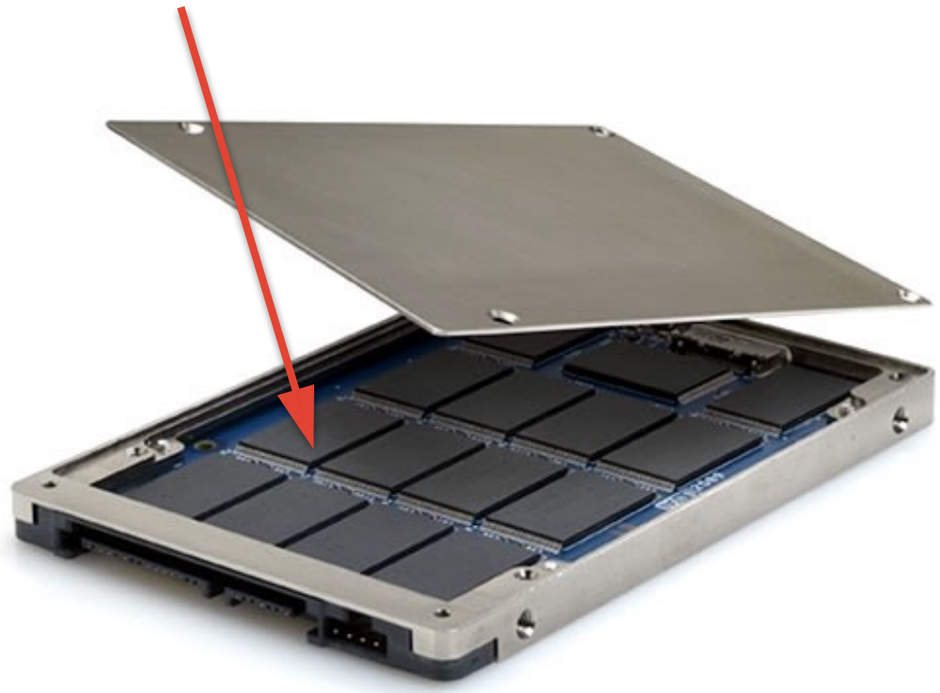
- Flash constrains:
  - Write at a page granularity
    - Page state: Valid, invalid, erased
  - Write sequentially in a block
  - Write always to an erased page
    - Page becomes valid
  - Updates are written to a new page
    - Old pages become invalid - need for GC
  - Read at a page granularity (seq./random reads)
  - Erase at a block granularity (all pages in block)
    - Garbage collection (GC):
      - Move valid pages to new block
      - Erase valid and invalid pages -> erased state



Open-Channel SSDs: Overview

- Open Channel SSDs share control responsibilities with the Host in order to implement and maintain features that typical SSDs implemented strictly in the SSD device firmware

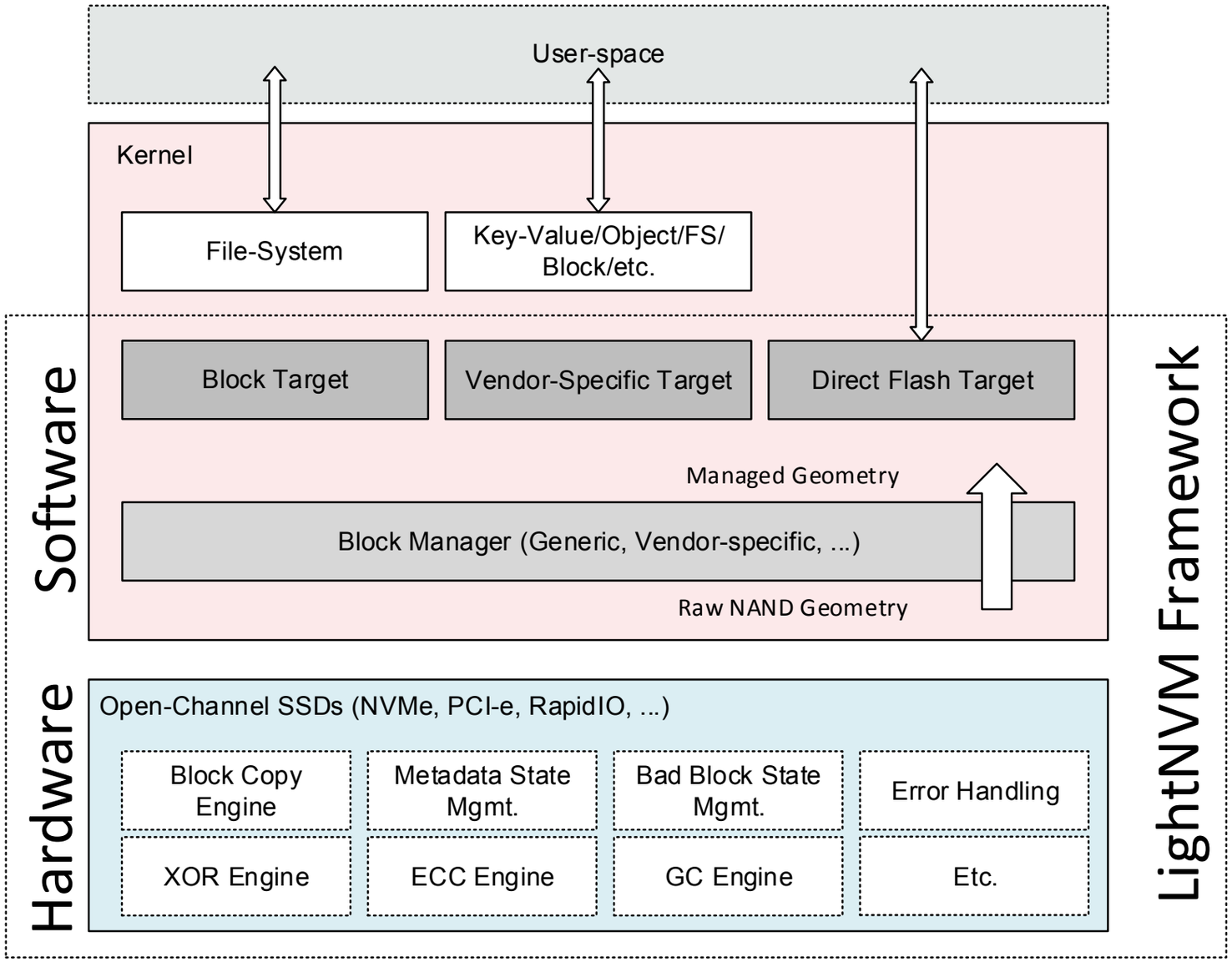
Physical flash exposed to the host (Read, Write, Erase)



- Host-based FTL manages:
  - Data placement
  - I/O scheduling
  - Over-provisioning
  - Garbage collection
  - Wear-leveling
- Host needs to know:
  - SSD features & responsibilities
  - SSD geometry
    - NAND media idiosyncrasies
    - Die geometry (blocks & pages)
    - Channels, timings, etc.
    - Bad blocks & ECC

Host manages physical flash → **Application Driven Storage**

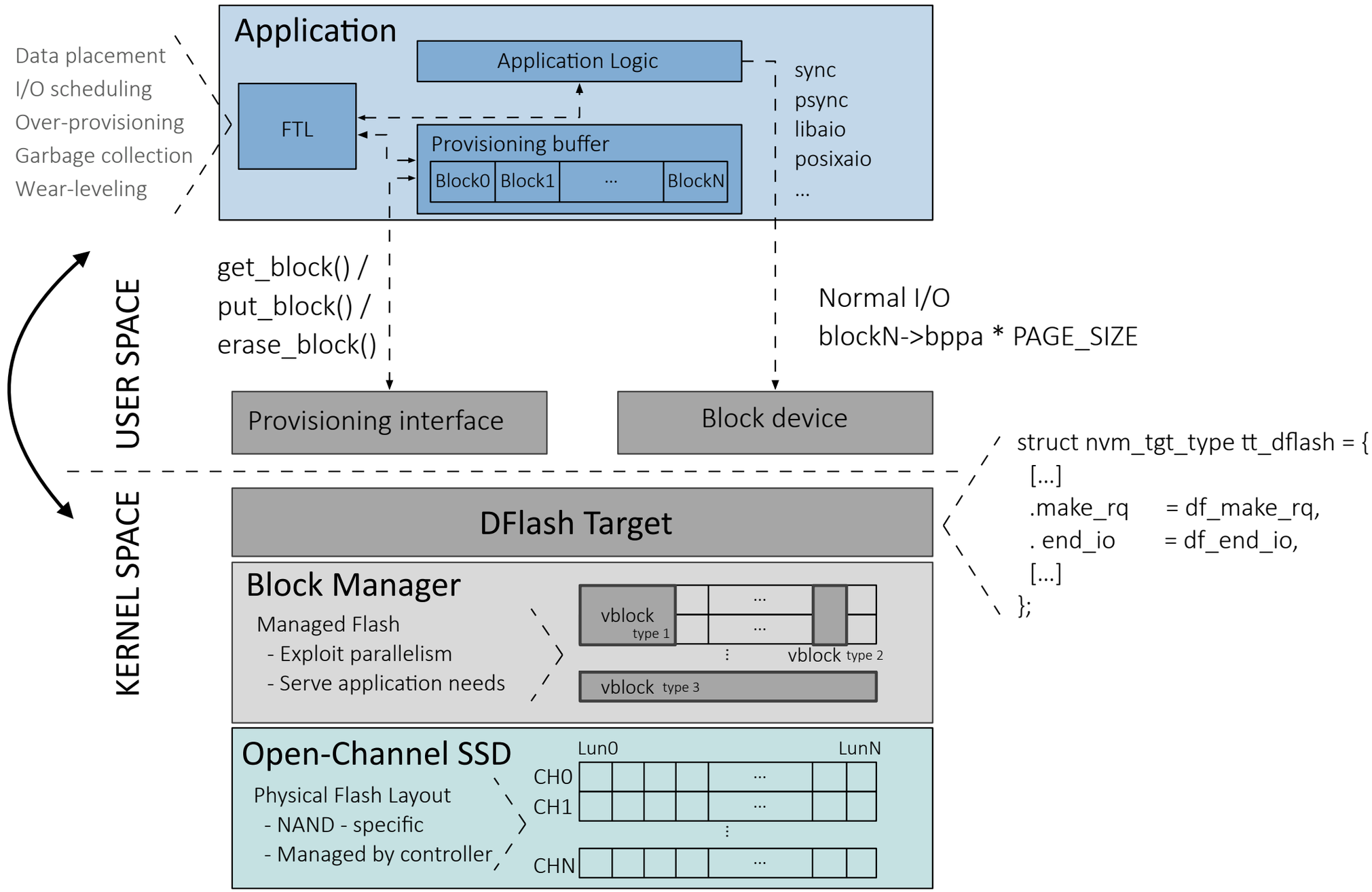
Open-Channel SSDs: LightNVM



- Targets
  - Expose physical media to user-space
- Block Managers
  - Manage physical SSD characteristics
  - Evens out wear-leveling across all flash
- Open-Channel SSD
  - Responsibility
  - Offload engines

LightNVM's DFlash: Application FTL

```
struct vblock {
  uint64_t id;
  uint64_t owner_id;
  uint64_t nppas;
  uint64_t ppa_bitmap
  sector_t bppa;
  uint32_t vlun_id;
  uint8_t flags
};
```



➡ DFlash is the LightNVM target supporting application FTLs

Open-Channel SSDs: Challenges

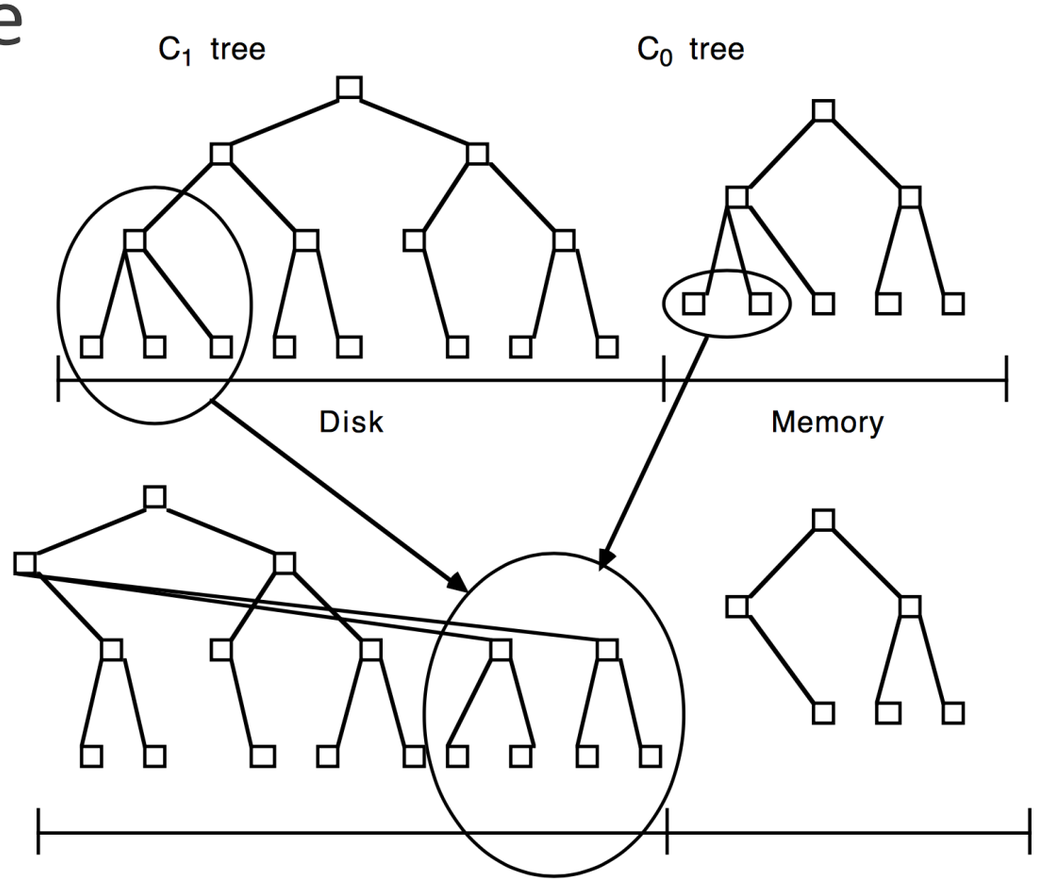
1. Which classes of applications would benefit most from being able to manage physical flash?
   - Modify storage backend (i.e., no posix)
   - Probably no file system, page cache, block I/O interface, etc.
2. Which changes do we need to make on these applications?
   - Make them work on Open-Channel SSDs
   - Optimize them to take advantage of directly using physical flash (e.g., data structures, file abstractions, algorithms).
3. Which interfaces would (i) make the transition simpler, and (ii) simultaneously cover different classes of applications?

➡ New paradigm that we need to explore in the whole I/O stack

RocksDB: Overview

- Embedded Key-Value persistent store
- Based on Log-Structured Merge Tree
- Optimized for fast storage
- Server workloads
- Fork from LevelDB
- Open Source:
  - https://github.com/facebook/rocksdb

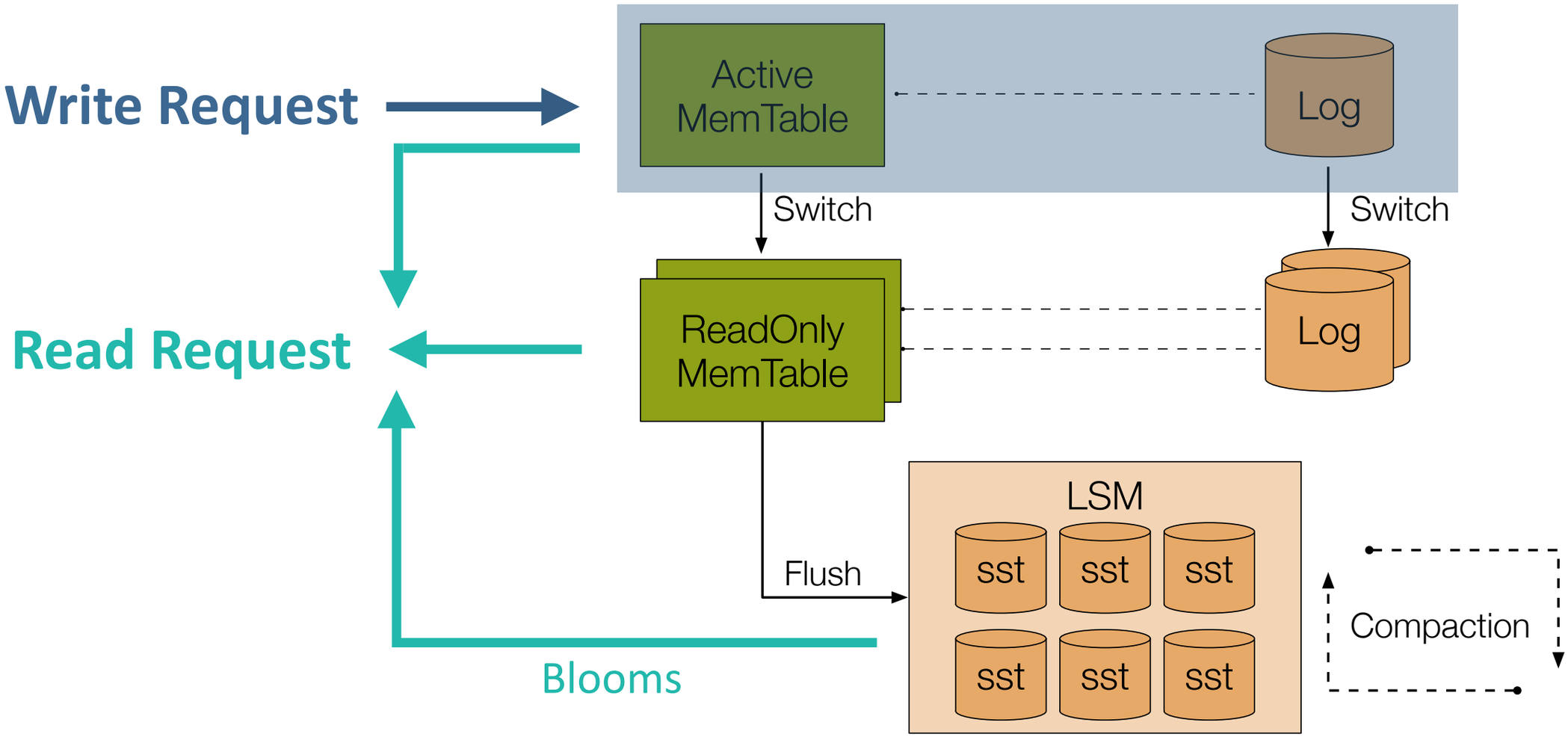
- RocksDB is not:
  - Not distributed
  - No failover
  - Not highly available



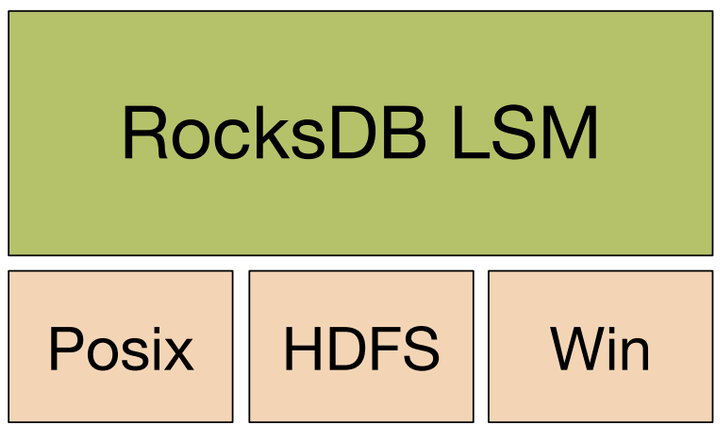
The Log-Structured Merge-Tree, Patrick ***O'Neil, Edward Cheng Dieter Gawlick, Elizabeth O'Neil.*** Acta Informatica, 1996.

RocksDB Reference: The Story of RocksDB, ***Dhruba Borthakur and Haobo Xu*** (link)

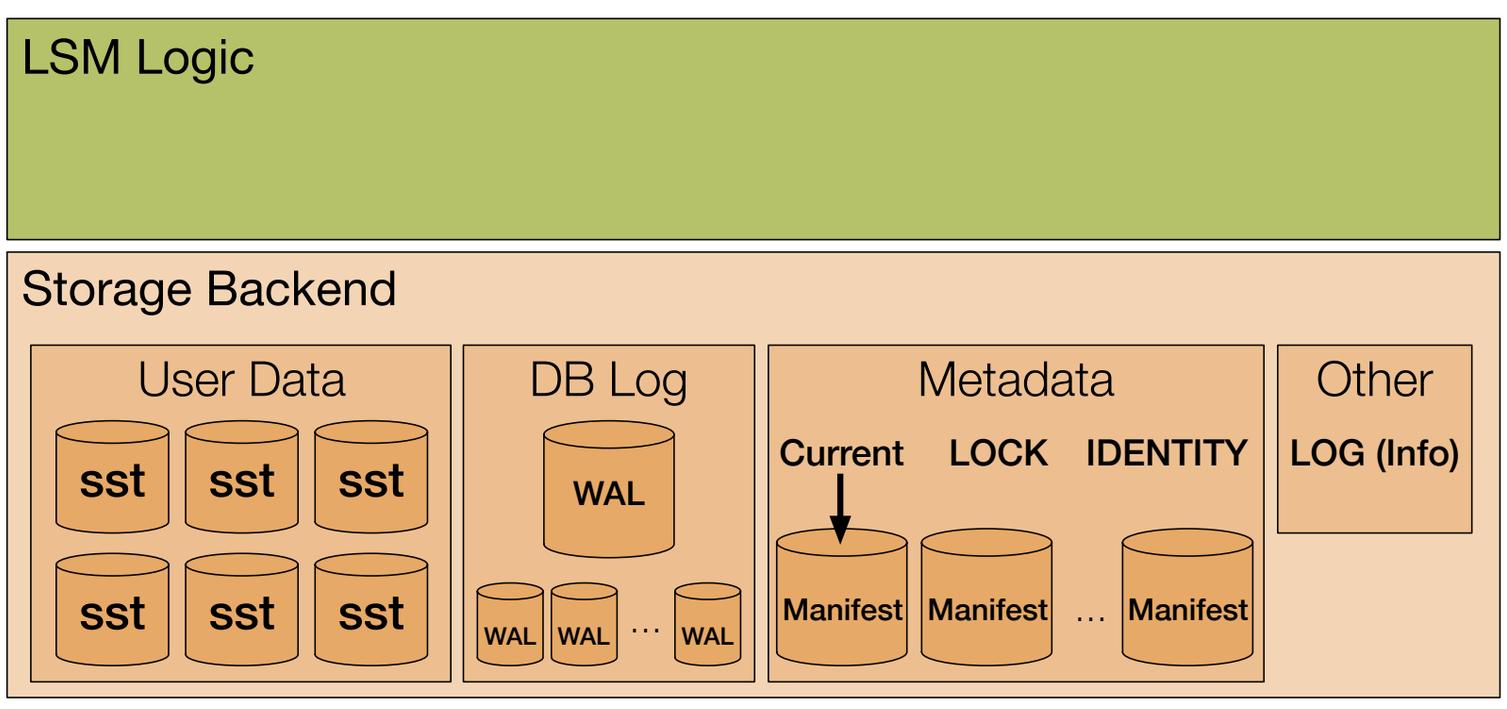
RocksDB: Overview



Problem: RocksDB Storage Backend



- Storage backend decoupled from LSM
  - WritableFile(): Sequential writes -> Only way to write to secondary storage
  - SequentialFile() -> Sequential reads. Used primarily for sstable user data and recovery
  - RandomAccessFile() -> Random reads. Used primarily for metadata (e.g., CRC checks)



- **Sstable:** Persistent memtable
- **DB Log:** Write-Ahead Log (WAL)
- **MANIFEST:** File metadata
- **IDENTITY:** Instance ID
- **LOCK:** use_existing_db
- **CURRENT:** Superblock
- **Info Log:** Log & Debugging

RocksDB: LSM using Physical Flash

- Objective: Fully optimize RocksDB for Flash memories
  - Control data placement:
    - User data in sstables is close in the physical media (same block, adjacent blocks)
    - Same for WAL and MANIFEST
  - Exploit Parallelism:
    - Define virtual blocks based on file write patters in the storage backend
    - Get blocks from different luns based on RocksDB's LSM write patters
  - Schedule GC and minimize over-provisioning
    - Use LSM sstable merging strategies to minimize (and ideally remove) the need for GC and over-provisioning on the SSD
  - Control I/O scheduling
    - Prioritize I/Os based on the LSM persistent needs (e.g., L0 and WAL have higher priority than levels used for compacted data to maximize persistency in case of power loss)

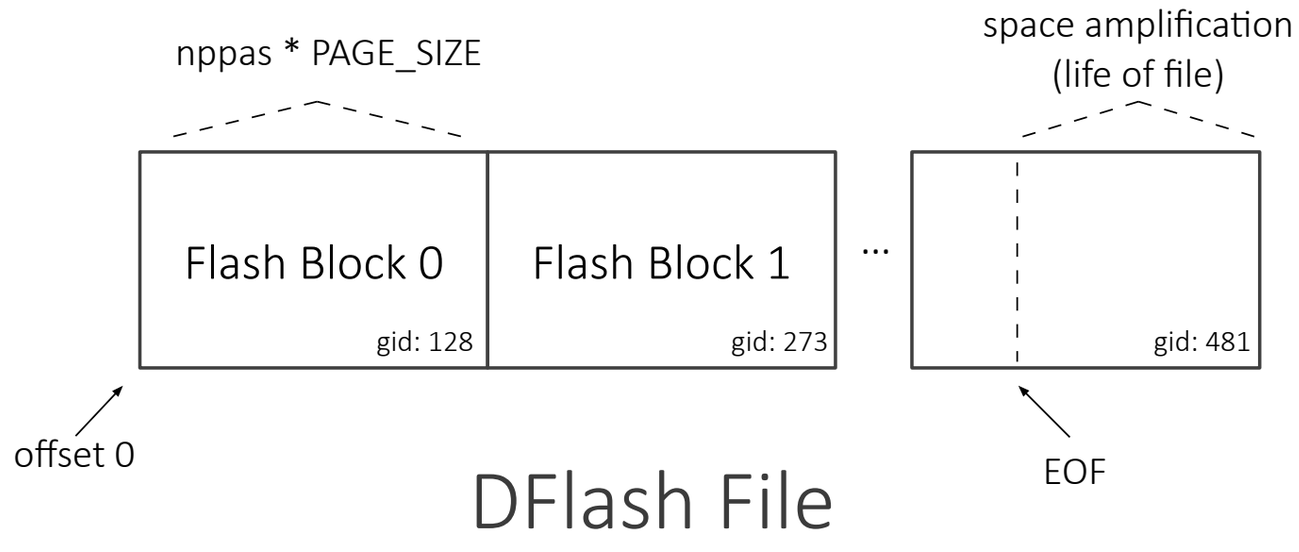
➡ Implement an FTL optimized for RocksDB, which can be reused for similar applications (e.g., LevelDB, Cassandra, MongoDB)

RocksDB + DFlash: Challenges

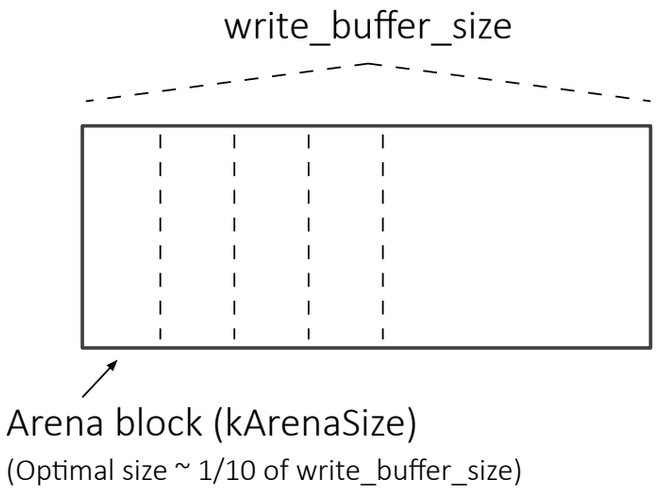
- Sstables (persistent memtables)
  - P1: Fit block sizes in L0 and further level (merges + compactions)
    - No need for GC on SSD side - RocksDB merging as GC (less write and space amplification)
  - P2: Keep block metadata to reconstruct sstable in case of host crash
- WAL (Write-Ahead Log) and MANIFEST
  - P3: Fit block sizes (same as in sstables)
  - P4: Keep block metadata to reconstruct the log in case of host crash
- Other Metadata
  - P5: Keep superblock metadata and allow to recover the database
  - P6: Keep other metadata to account for flash constrains (e.g., partial pages, bad pages, bad blocks)
- Process
  - P7: Follow RocksDB architecture - upstreamable solution

P1, P3: Match flash block size

- WAL and MANIFEST are reused in future instances until replaced
  - **P3:** Ensure that WAL and MANIFEST replace size fills up most of last block



- Sstable sizes follow a heuristic - MemTable::ShouldFlushNow()

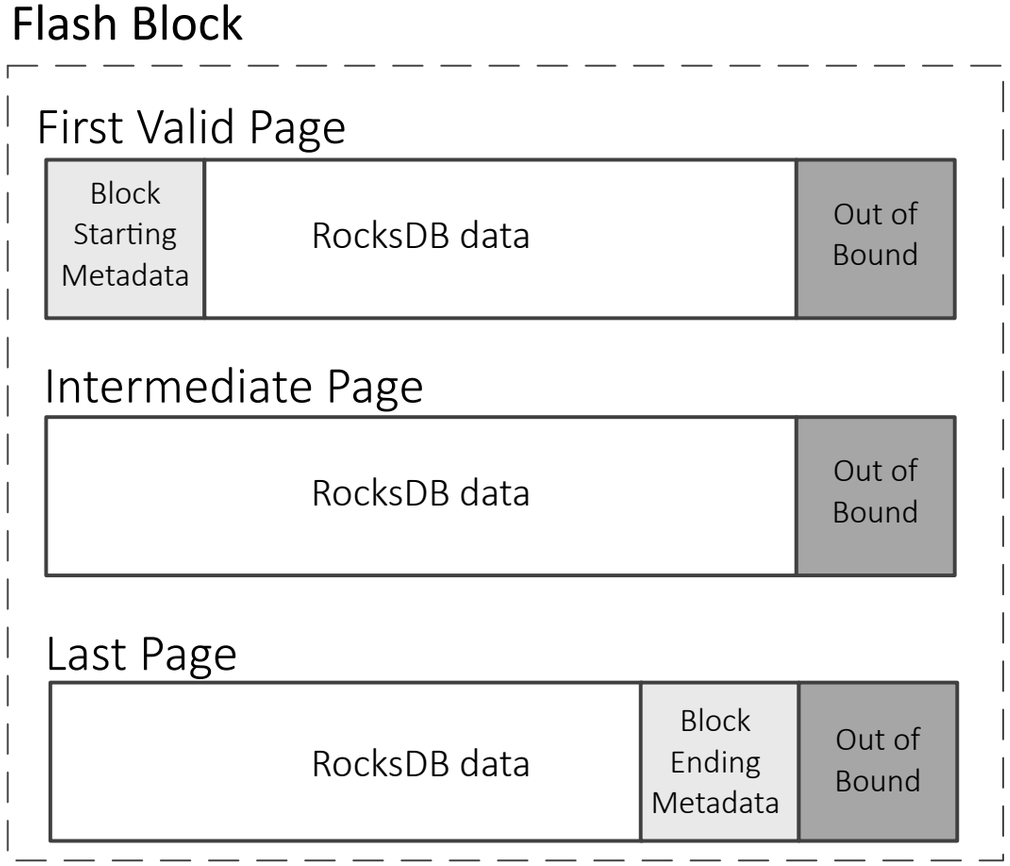


P1:

- kArenaBlockSize = sizeof(block)
- Conservative heuristic in terms of overallocation
  - Few lost pages is better than allocating a new block
- Flash block size becomes a “static” DB tuning parameter that is used to optimize “dynamic” ones

➡ Optimize RocksDB bottom up (from storage backend to LSM)

P2, P4, P6: Block Metadata



Out of Bound

```
struct vpage_meta {
  size_t valid_bytes;       // Valid bytes from offset 0
  uint8_t flags;            // State of the page
};
```

Block Starting Metadata

```
struct vblock_init_meta {
  char filename[100];       // RocksDB file GID
  uint64_t owner_id;        // Application owning the block
  size_t pos;               // relative position in block
};
```

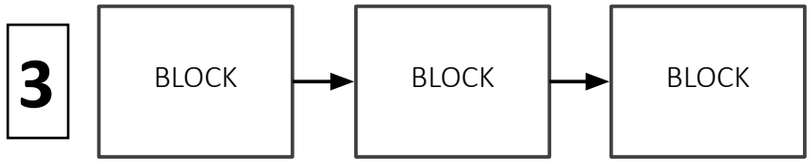
Block Ending Metadata

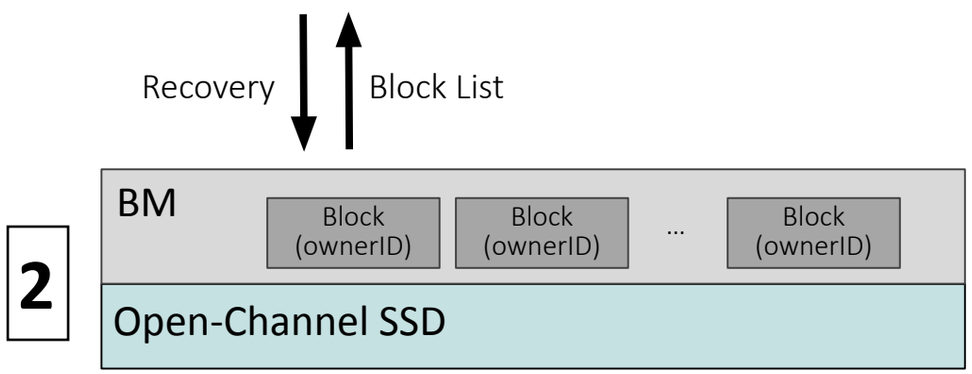
```
struct vblock_close_meta {
  size_t written_bytes;     // Payload size
  size_t ppa_bitmap;        // Updated valid page bitmap
  size_t crc;               // CRC of the whole block
  unsigned long next_id;    // Next block ID (0 if last)
  uint8_t flags;            // Vblock flags
};
```

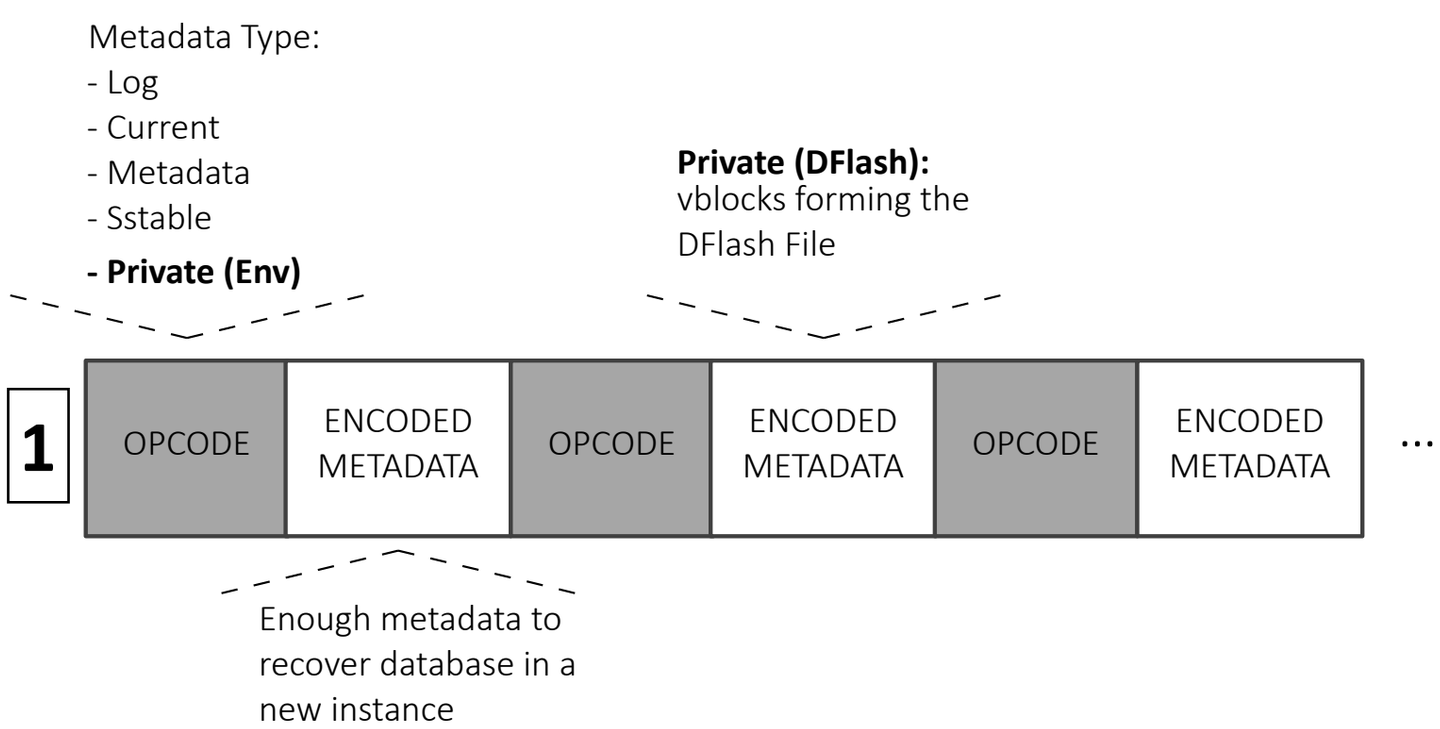
- Blocks can be checked for integrity
- New DB instance can append; padding is maintained in OOB (**P6**)
- Closing a block updates bad page & bad block information (**P6**)

P2, P4, P6: Crash Recovery

- A DFlash file can be reconstructed from individual blocks (**P2, P4**)
  1. Metadata for the blocks forming a DFlash file is stored in MANIFEST
     - The last WAL is not guaranteed to reach the MANIFEST -> RECOVERY metadata for DFLASH
  2. On recovery, LightNVM provides an application with all its valid blocks
  3. Each block stores enough metadata to reconstruct a DFLash file





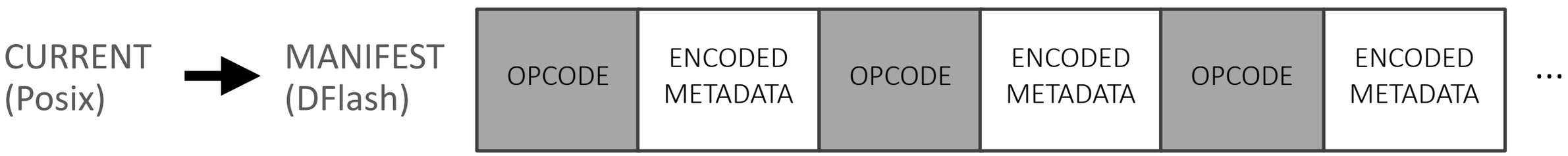


P5: Superblock

- CURRENT is used to store RocksDB “superblock”
  - Points to current MANIFEST, which is used to reconstruct the DB when creating a new instance. We append the block metadata that points to the blocks forming the current MANIFEST (**P5**)

Metadata Type:
- Log
- Current
- Metadata
- Sstable
- **Private (Env)**

Private (DFlash):
vblocks forming the DFlash File



Normal Recovery

Enough metadata to recover database in a new instance

P7: Work upstream

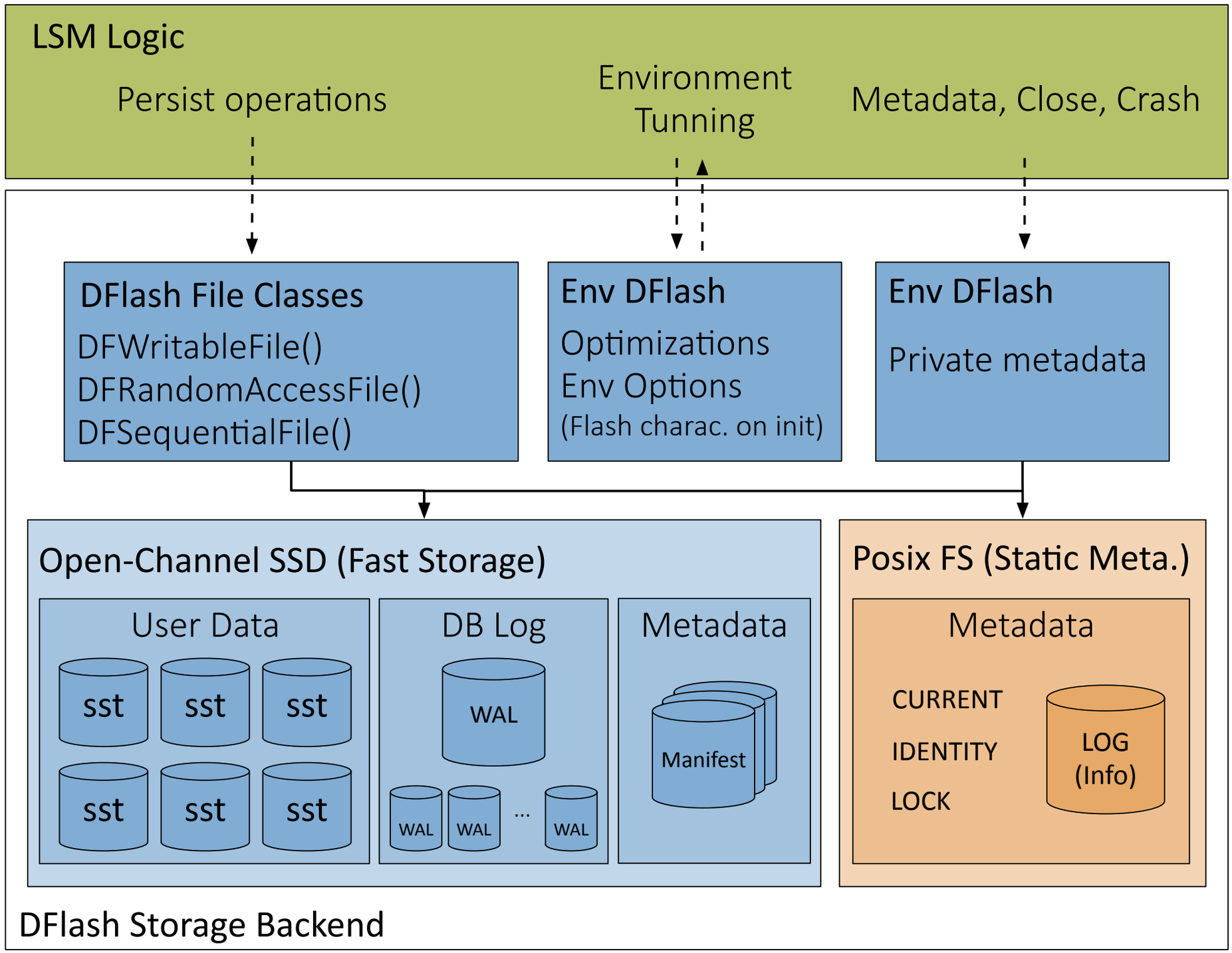
RocksDB + DFlash: Prototype (1/2)

- Optimize RocksDB for Flash storage
  - Implement a user space append-only FS that deals with flash constrains
    - Append-only: Updates are re-written and old data invalidated -> LSM understands this logic
    - Page cache implemented in user space; use Direct I/O
    - Only “sync” complete pages, and prefer closed blocks.
    - In case of write failure, write to a new block (or mark bad page and re-try)
  - Implement RocksDB’s file classes for DFlash:
    - WritableFile(): Sequential writes -> Only way to write to secondary storage
    - SequentialFile() -> Used primarily for sstable user data and recovery
    - RandomAccessFile() -> Used primarily for metadata (e.g., CRC checks)
- Use flash block as the central piece for storage optimizations
  - The Open-Channel SSD fabric is configured at first
    - Define block size - across luns and channels to exploit parallelism
    - Define different types of luns with different block features
  - RocksDB is configured with standard parameters (e.g., write buffer, cache)
    - DFlash backend tunes these parameters based on the type of lun and block

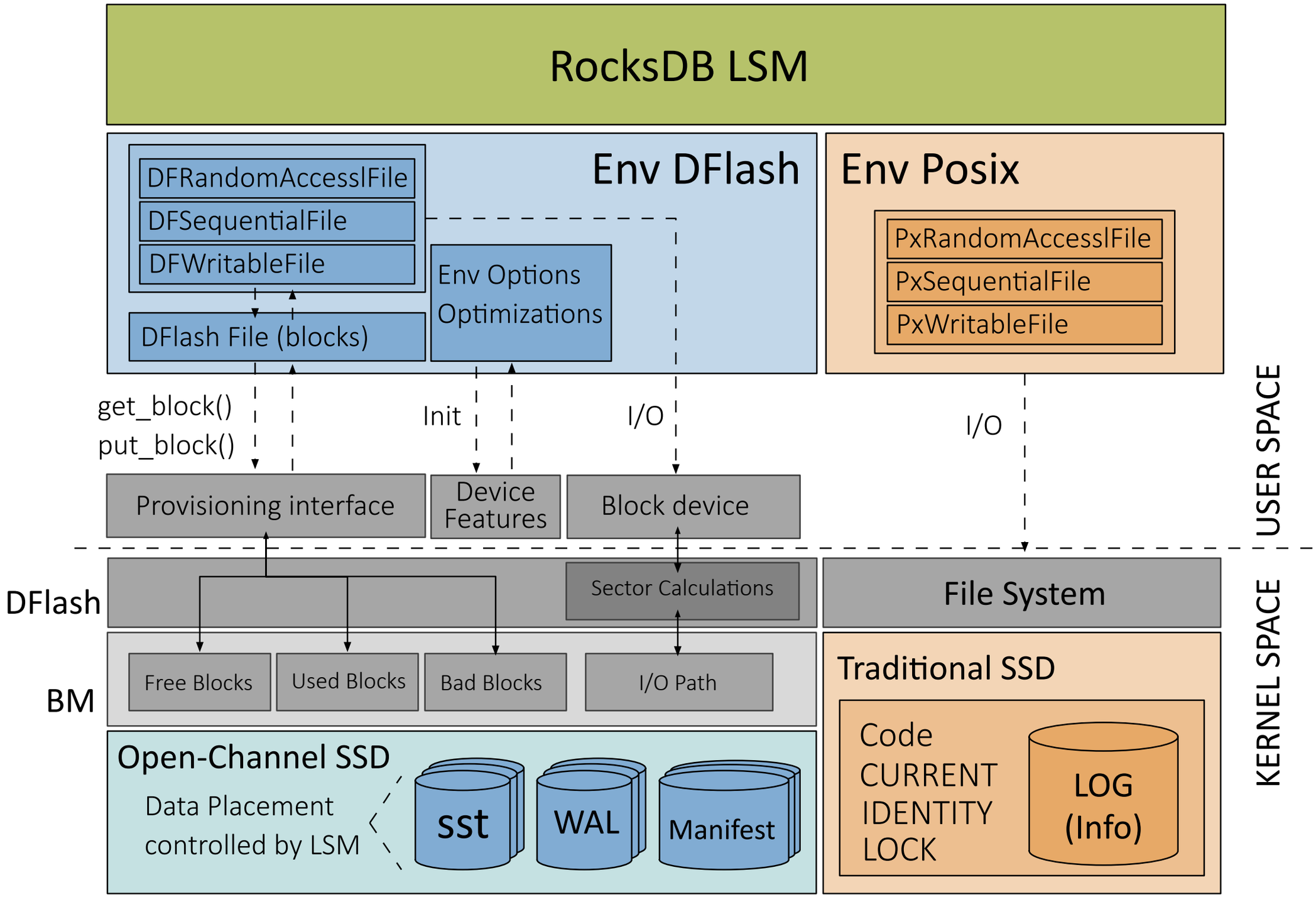
RocksDB + DFlash: Prototype (2/2)

- Use LSM merging strategies as perfect garbage collection (GC)
  - All blocks in a DFlash file are either active or inactive -> no need to GC in SSD
  - Reduce over-provisioning significantly (~5%)
  - Predictable latency -> SSD is in stable state from the beginning
- Reuse RocksDB concepts and abstractions as much as possible
  - Store private metadata in MANIFEST
  - Store superblock in CURRENT
  - Minimize the amount of “visible” metadata - use OOB, Root FS, etc.
- Separate persistent (meta)data between “fast” and “static”
  - Fast data is all user data (i.e., sstables) and the WAL
  - Fast metadata that follows user data rates (i.e., MANIFEST)
  - Static metadata is written once and seldom updated
    - CURRENT: Superblock for MANIFEST
    - LOCK and IDENTITY

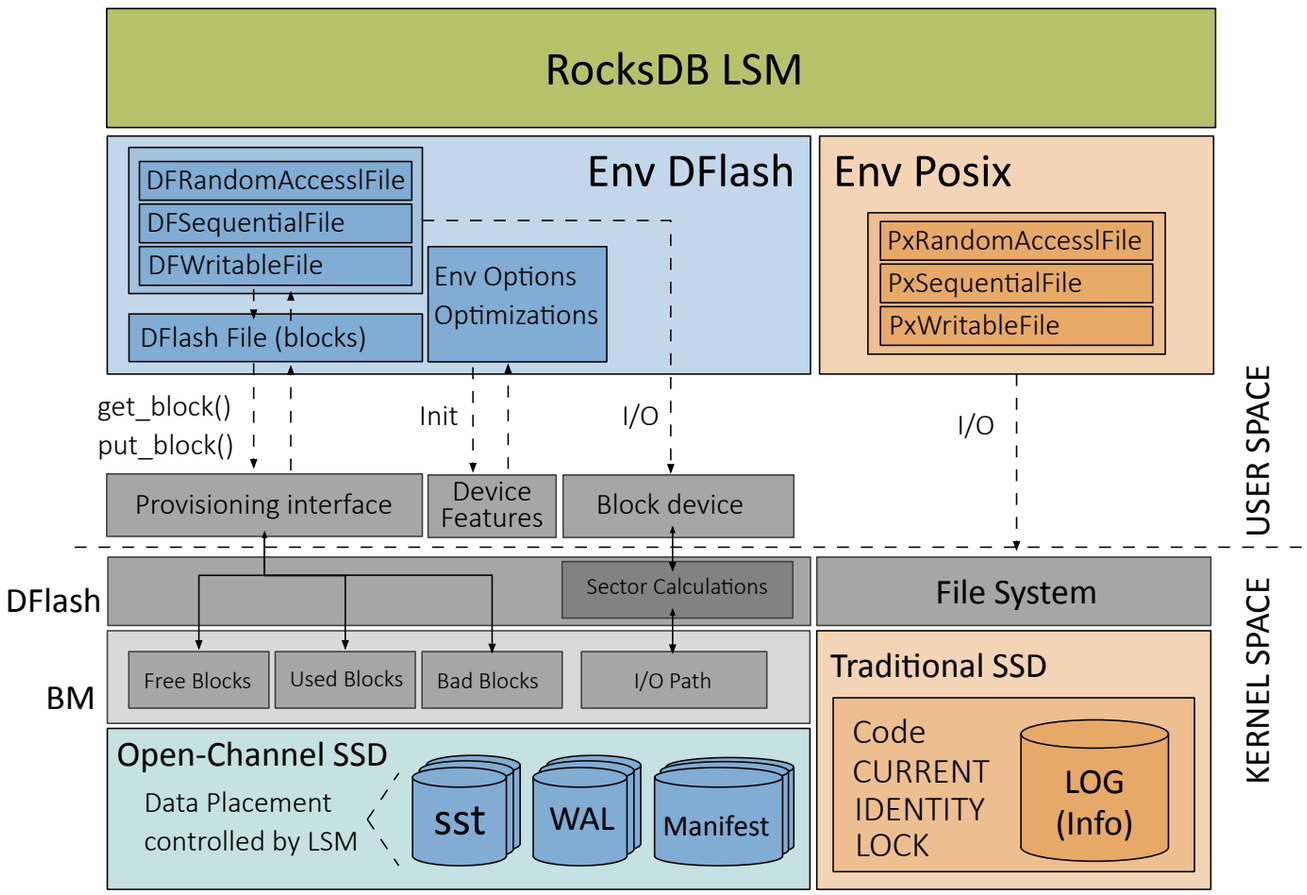
Architecture: RocksDB with DFlash



Architecture: DFlash + LightNVM



Architecture: DFlash + LightNVM



- LSM is the FTL
  - DFlash target and RocksDB storage backend take care of provisioning flash blocks
- Optimized critical I/O path
  - Sstables, WAL, and MANIFEST are stored in the Open-Channel SSD, where we can provide QoS
- Enable a RocksDB distributed architecture
  - BM abstracts the storage fabric (e.g., NVM) and can potentially provide blocks from different drives -> single address space

QEMU Evaluation: Writes

RocksDB make release	ENTRY KEYS with 4 threads	DFLASH (1 LUN)	POSIX
WRITES	10000 keys	70MB/s	25MB/s
	100000 keys	40MB/s	25MB/s
	1000000 keys	25MB/s	20MB/s

Bare Metal: ~180MB/s

Page-aligned write buffer

- DFlash write page cache + Direct I/O + flash page aligned write buffer is better optimized than best effort techniques and top-down optimizations (RocksDB parameters). Write buffer required by RocksDB due to small WAL writes
- If we manually tune buffer sizes with Posix, we obtain similar results. However, it requires lots of experimentation for each configuration

QEMU Evaluation: Reads

RocksDB make release	ENTRY KEYS	DFLASH (1 LUN)	POSIX
READ	10000 keys	5MB/s	300MB/s
	100000 keys	5MB/s	500MB/s
	1000000 keys	5MB/s	570MB/s

No page cache support

- Without a DFLASH page cache we need to issue an I/O for each read!
  - Sequential 20 byte-reads in same page would issue different PAGE_SIZE I/Os

QEMU Evaluation: “Fixing” Reads

RocksDB make release	ENTRY KEYS	DFLASH (1 LUN)	DFLASH (1 LUN) (+ simple page cache)	POSIX
READ	10000 keys	5MB/s	160MB/s	300MB/s
	100000 keys	5MB/s	280MB/s	500MB/s
	1000000 keys	5MB/s	300MB/s	570MB/s

Simple page cache for reads

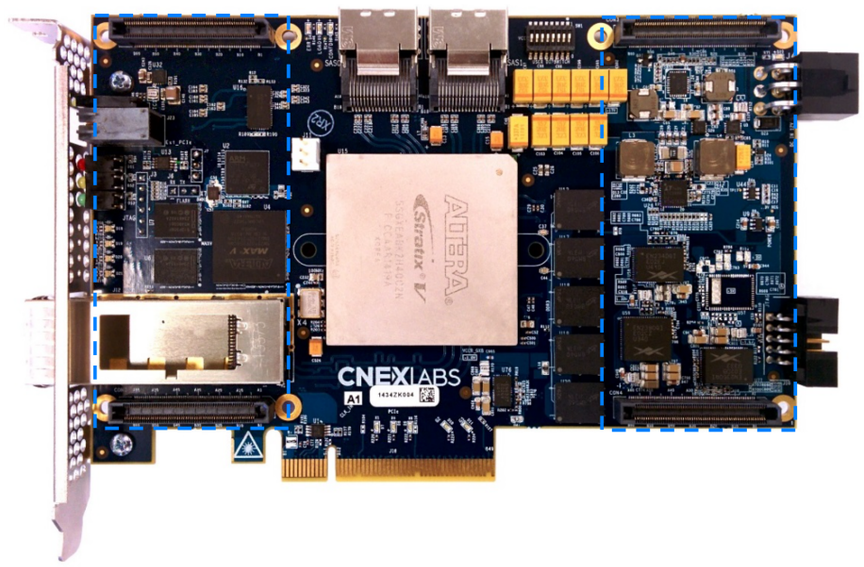
- Posix + buffered I/O using Linux’s page cache is still better, but we have confirmed our hypothesis.

➡ User-space page cache is a necessary optimization when the generic OS page cache is on the way. Other databases use this technique (e.g., Oracle, MySQL)

QEMU Evaluation: Insights

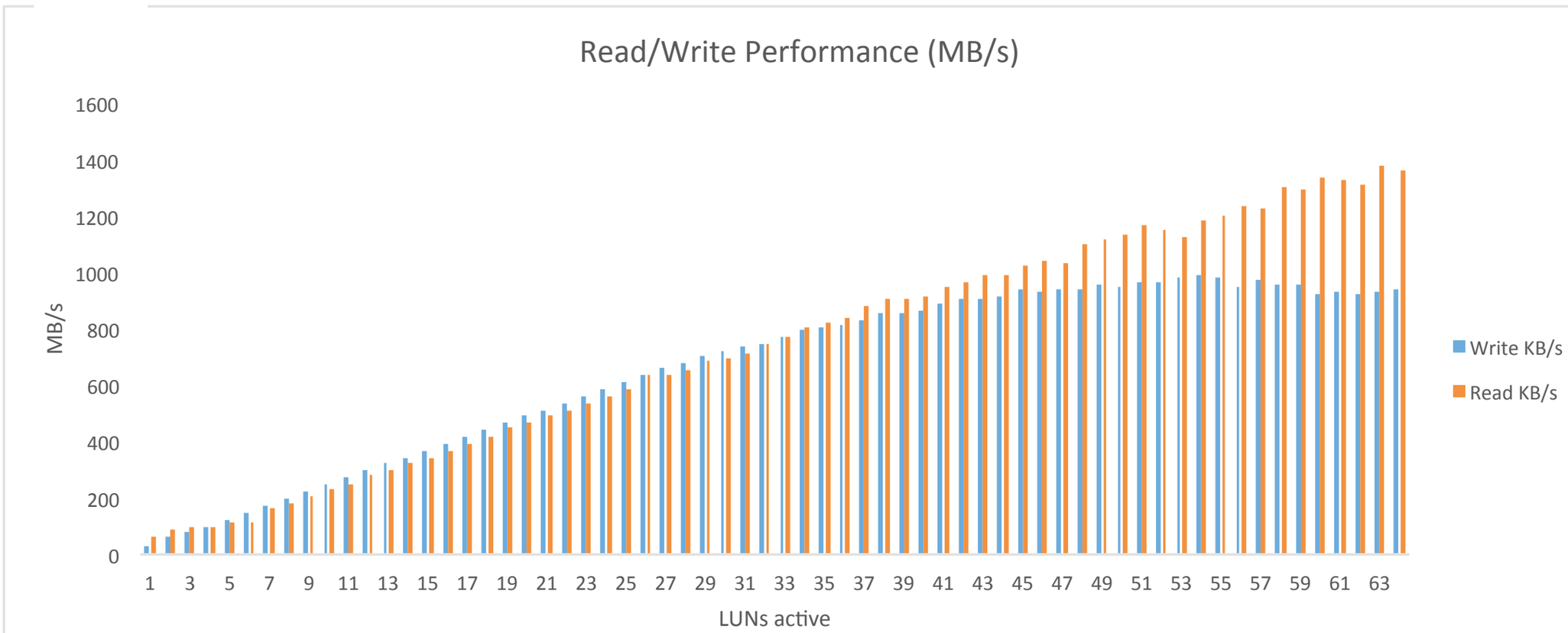
- Posix backend and DFlash backend (with 1 lun) should achieve very similar throughput for reads/writes when using same page cache and write buffer optimizations
- But…
  - DFlash allows to optimize buffer and cache sizes based on Flash characteristics
  - DFlash knows which file class is calling - we can do prefetching for sequential reads (DFSequentialFile) at block granularity
  - DFlash designed to implement a Flash optimized page cache using Direct I/O
- If the Open-Channel SSD exposes several LUNs, we can exploit parallelism within DFlash and RocksDB's LSM write/read patterns
  - How many luns and their characteristics are organized is controller specific

CNEX WestLake SDK: Overview



FPGA Prototype Platform before ASIC:

- PCIe G3x4 or PCI G2x8
- 4x10GE NVMoE
- 40 bit DDR3
- 16 CH NAND



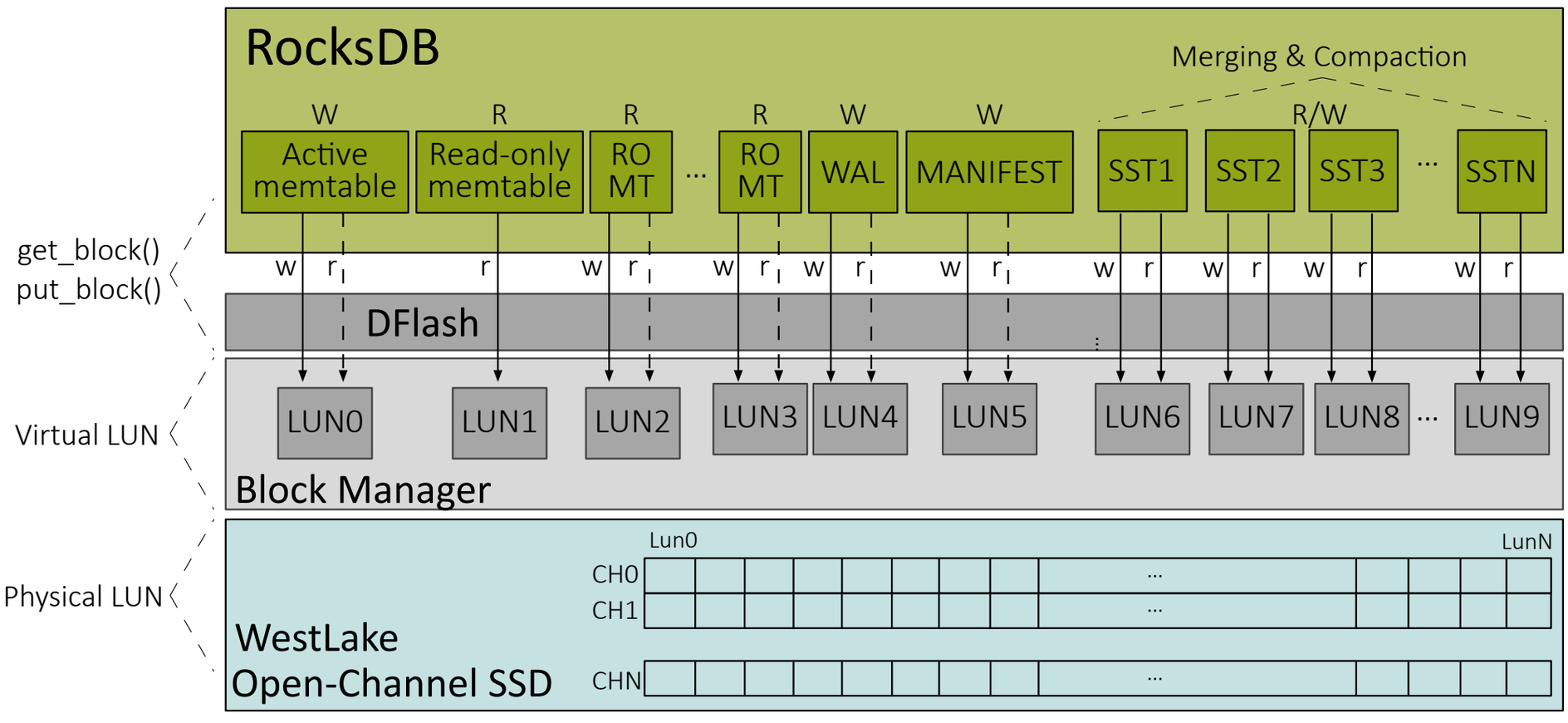
CNEX WestLake Evaluation

RocksDB make release	ENTRY KEYS with 4 threads	WRITES (1 LUN)	READS (1 LUN)	WRITES (8 LUNS)	READS (8 LUNS)	WRITES (64 LUNS)	READS (64 LUNS)
RocksDB DFLASH	10000 keys	21MB/s	40MB/s	X	X	X	X
	100000 keys	21MB/s	40MB/s	X	X	X	X
	1000000 keys	21MB/s	40MB/s	X	X	X	X
Raw DFLASH (with fio)		32MB/s	64MB/s	190MB/s	180MB/s	920MB/s	1,3GB/s

- We focus on a single I/O stream for first prototype -> 1 LUN

CNEX WestLake Evaluation: Insights

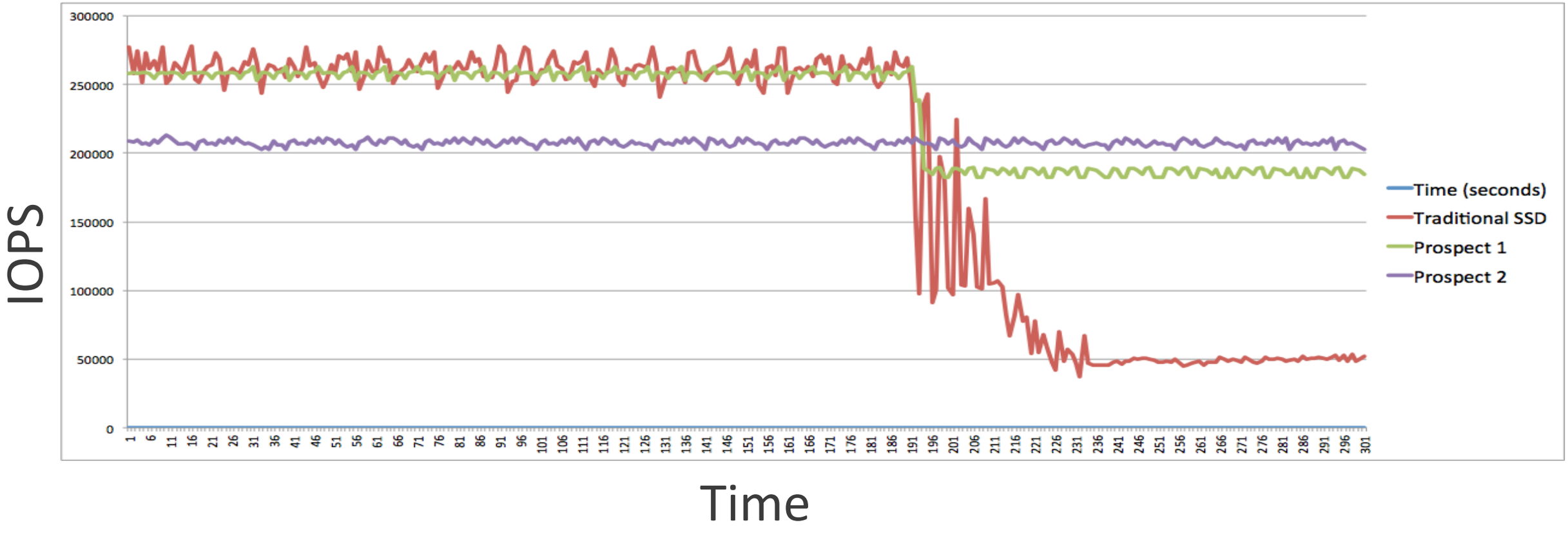
- RocksDB checks for sstable integrity on writes (intermittent reads)
  - We pay the price of not having an optimized page cache also on writes
  - Reads and writes are mixed in one single lun
- Ongoing work: Exploit parallelism in RocksDB's I/O patters



- Do not mix R/W
- Different VLUN per path
- Different VLUN types
- Enabling I/O scheduling
- Block pool in DFlash (prefetching)

CNEX WestLake Evaluation: Insights

- Also, in *any* Open-Channel SSD
  - DFlash will not get a performance hit when the SSD triggers GC - RocksDB does GC when merging sstables in LSM > L0
    - SSD steady state is improved (and reached from the beginning)
    - We achieve predictable latency



Status and ongoing work

- Status:
  - get_block/put_block interface (first iteration) through the DFlash target
  - RocksDB DFlash target that plugs into LightNVM. Source code to test in available (RocksDB, Kernel, and QEMU). Working on WestLake upstreaming
- Ongoing:
  - Implement functions to increase the synergy between the LSM and the storage backend (i.e., tune write buffer based on block size) -> Upstreaming
  - Support libaio to enable async I/O in DFlash storage backend
    - Need to deal with RocksDB design decisions (e.g., Get() assumes sync IO)
  - Exploit device parallelism within RockDB internal structures
  - Define different types of virtual luns and expose them to the application
  - Other optimizations: double buffering, aligned memory in LSM, etc.
  - Move RocksDB DFlash's logic to **liblightnvm** -> append-only FS for Flash

Conclusions

- Application Driven Storage
  - Demo working on real hardware:
    - (RocksDB -> LightNVM -> WestLake-powered SSD)
  - QEMU support for testing and development
  - More Open-Channel SSDs coming soon.
- RocksDB
  - DFlash dedicated backend -> append-only FS optimized for Flash
  - Set the basis for moving to a distributed architecture while guaranteeing performance constrains (specially in terms of latency)
  - Intention to upstream the whole DFlash storage backend
- LightNVM
  - Framework to support Open-Channel SSDs in Linux
  - DFlash target to support application FTLs

Questions?

Towards Application Driven Storage

Optimizing RocksDB on Open-Channel SSDs with LightNVM

- Open-Channel SSD Project: https://github.com/OpenChannelSSD
- LightNVM: https://github.com/OpenChannelSSD/linux
- RocksDB: https://github.com/OpenChannelSSD/rocksdb

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