# Algorithms and Data Structures for Efficient Free Space Reclamation in WAFL

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# WAFL: 25+ Years!

- Technology trends
  - MHz -> GHz cores, 1 core -> 40+ cores
  - HDDs (5k->15k rpm, MB->TB), SSDs (100GiB->32TiB+), Cloud, SCM
  - Max file system size: 28 GiB -> 400 TiB
- Applications
  - NFS/SMB file sharing -> LUNs with FC/iSCSI access
  - Virtualization over block & file access
- Many data management features
  - snapshots, clones, replication, dedupe, compression, mobility, encryption, etc.
- Mixed workload deployment
  - ONTAP node: 100's of WAFL file systems, 100's TiB, 1000's of LUNs, etc.

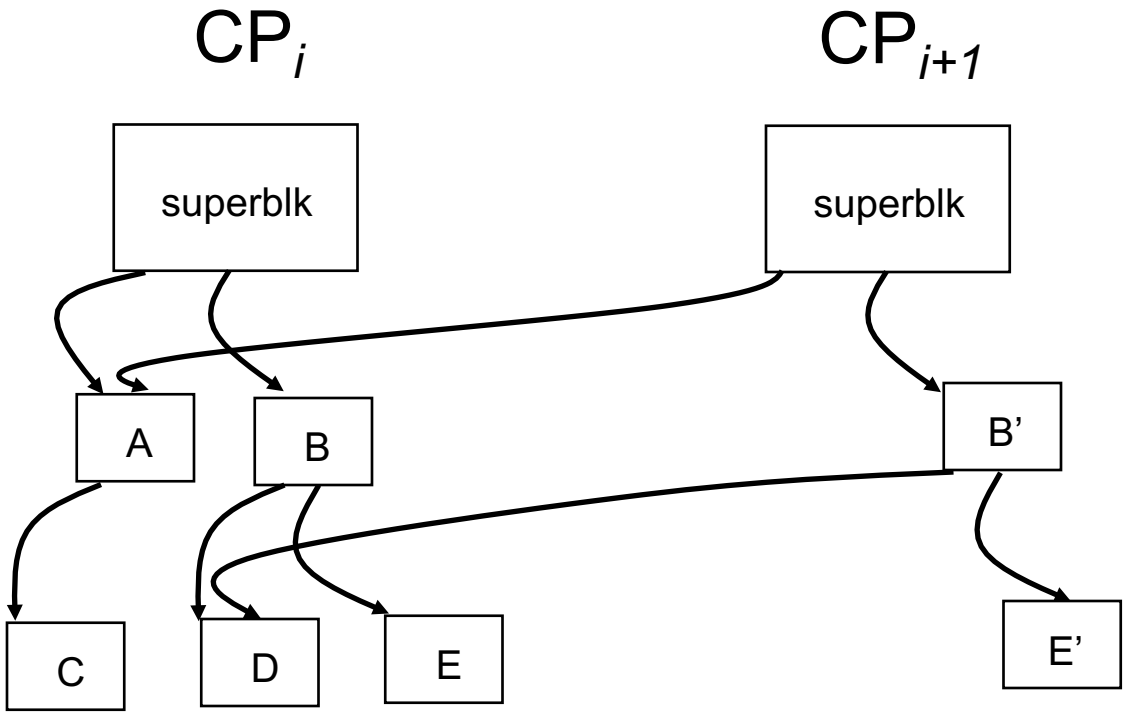
# Free Space Metadata

- Reasons for tracking free space:
  - find & allocate blocks for new writes
  - report usage for provisioning/purchasing decisions
- Design dimensions:
  - in-memory vs persistent
  - lazy vs contemporaneous
- Consistent performance is key: balanced resource usage
  - user ops vs free space management (& other backend work)
  - CPU, I/O, memory, etc.

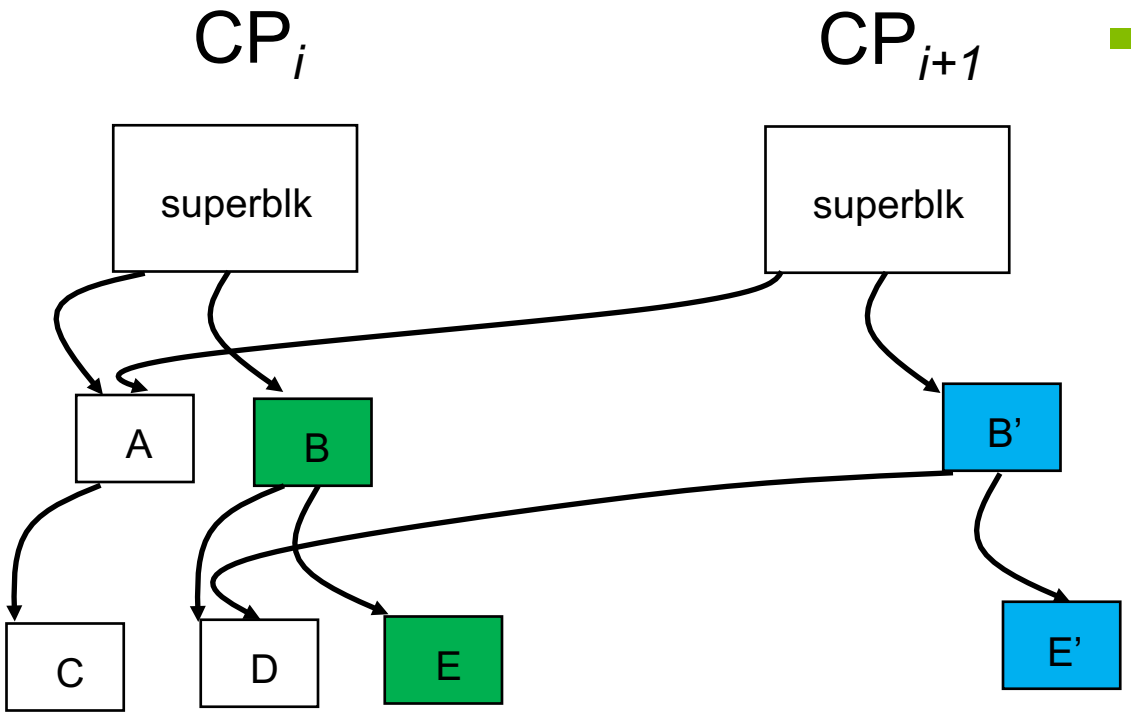
# WAFL: Layout & Transactional Model

- File system is a tree of blocks
  - everything is a file, including metadata
- Log-structured & copy-on-write
  - each *dirty* buffer written to a newly allocated block
  - except the superblock
- Large atomic transactions: ~GB worth of dirty buffers
  - ~2s to 5s long
  - persistent file system always self-consistent
  - *consistency point* (CP)

# Atomic Update of the Persistent File System



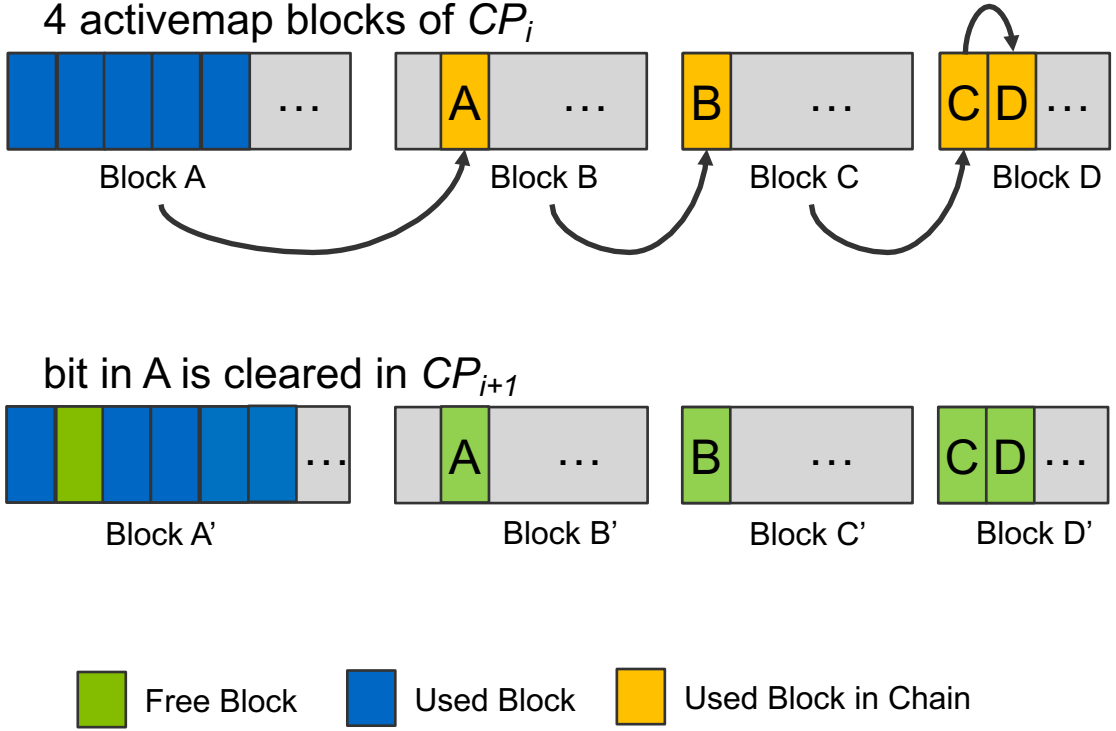
# Atomic Update of the Persistent File System




- 1 GB/s writes need
  - 1 GB/s allocations of new blocks
  - 1 GB/s frees of unused blocks

# Activemap Bits: used(1) -> free(0)

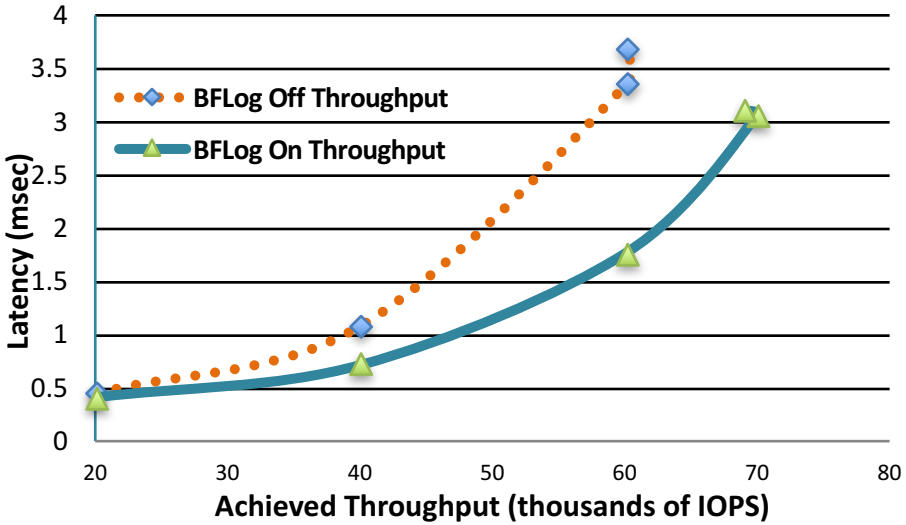
- Long CPs due to:
  - random frees -> more dirty activemap blocks
  - long activemap chains
- Long CPs hurt write throughput

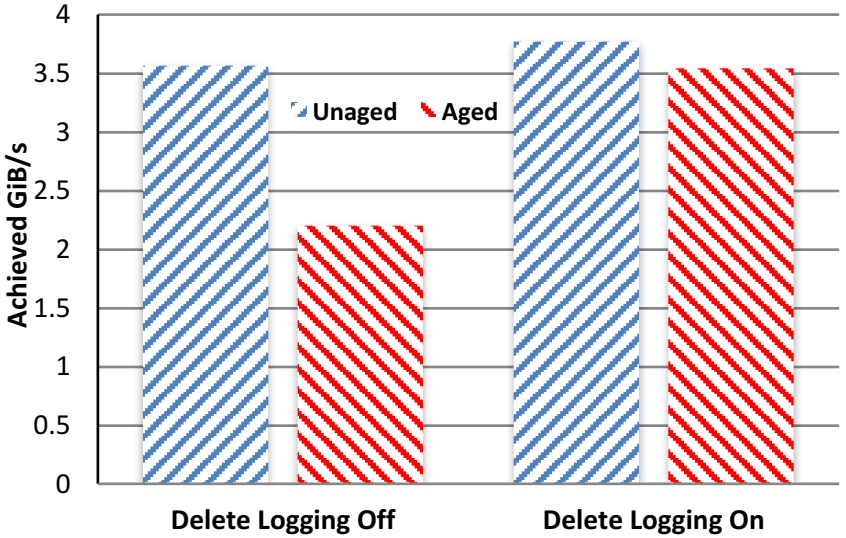


# Append Log using $L_1$s of a File

- Delay updates of activemap to avoid the chaining problem
- Convert several random to few batched
  - TLog('08): binary sort tree using $L_1$s of log file
    - dropped due to unpredictable performance
  - BFLog('12): 3 files - active, inactive (sorting), sorted
    - predictably pace sorting and freeing activity
- Log sized to ~0.5% of file system provides sufficient batching
- Blocks freed by file/LUN deletions, SCSI hole-punching

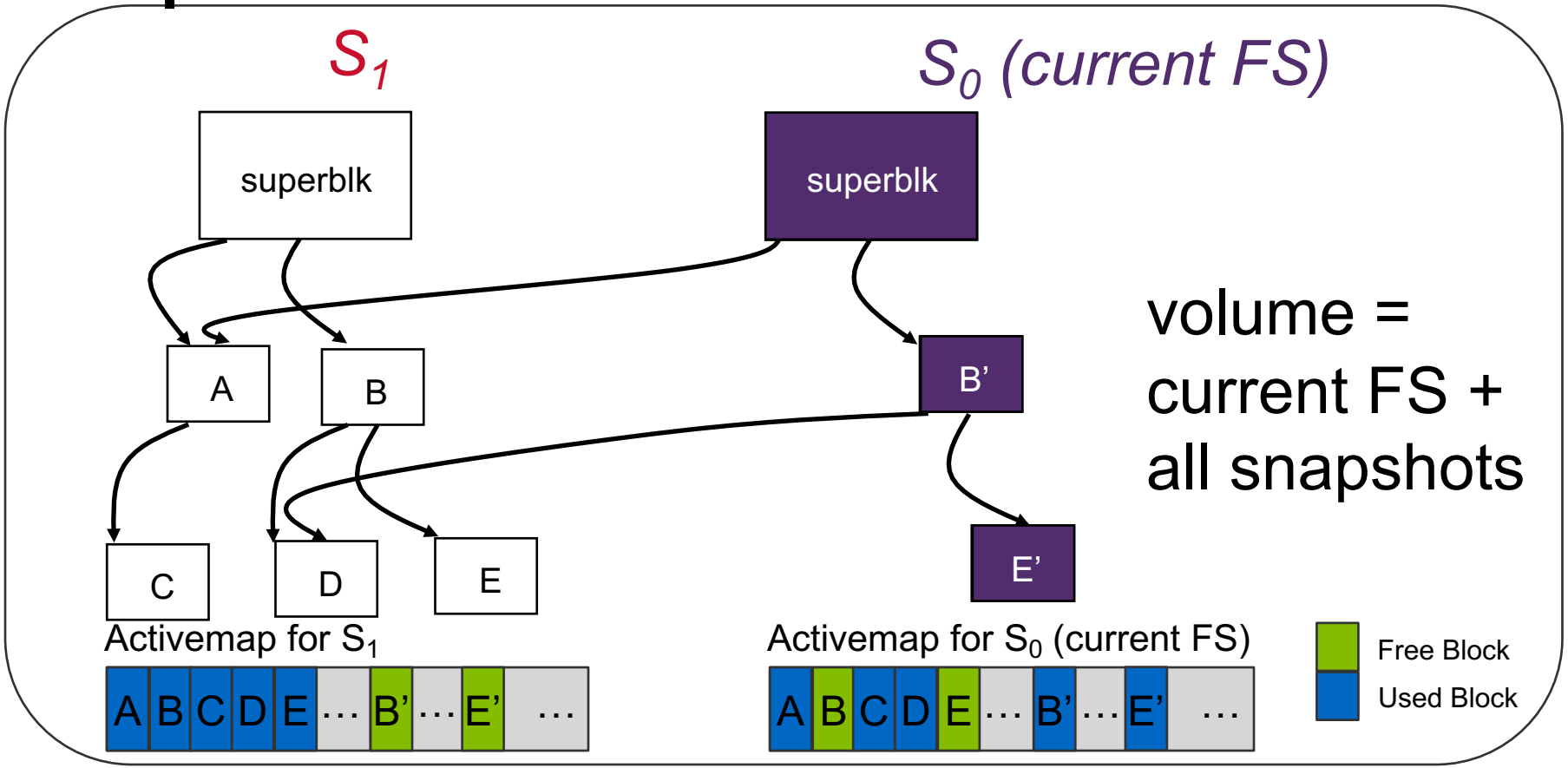
# Logging Results




- 17% higher write throughput at 34%-48% lower latency
- 6% to 60% (unaged v aged) raw deletion throughput
- Much higher delete throughput with little interference (not shown)

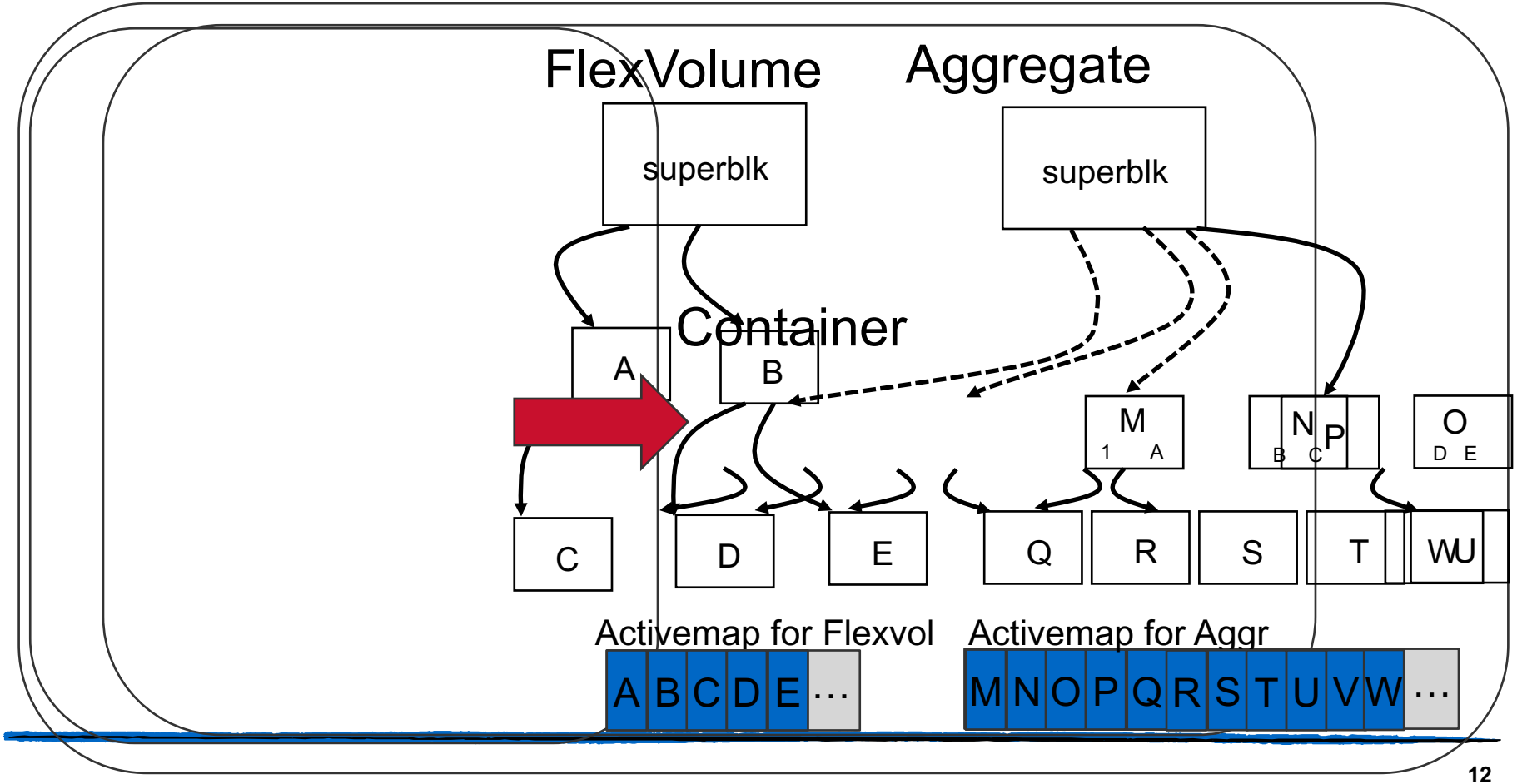
# Snapshots


$S_1$
$S_0$ (current FS)
superblk
superblk
A
B
B'
C
D
E
E'
volume = current FS + all snapshots
Activemap for $S_1$
A B C D E … B' … E' …
Activemap for $S_0$ (current FS)
A B C D E … B' … E' …
Free Block
Used Block

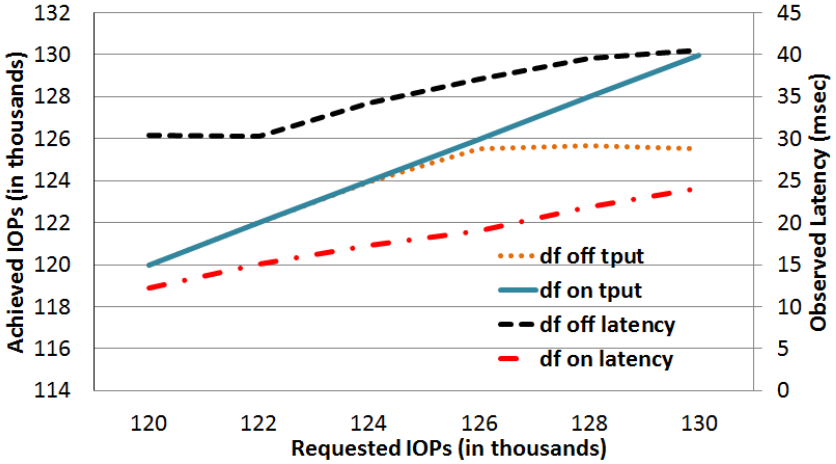
# Summary Map

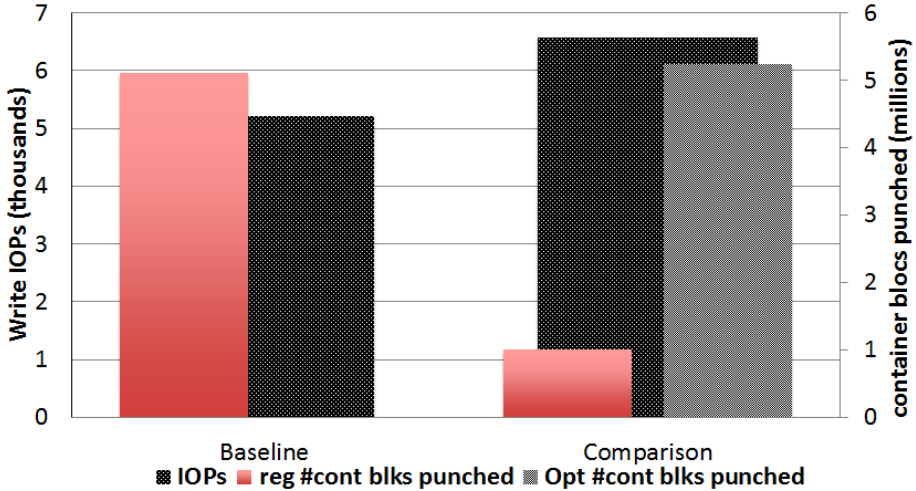
- Block is free iff every activemap says it is free
- Summary Map = Bit-OR of snapshots' activemaps
  - metafile in the current file system
- Block is free iff active & summary bits are both 0
- Summary can become stale:
  - snapshot creation, deletion, etc.
  - sequential scan to fixup summary
  - correctness is preserved while scan is in progress
- Fast reclamation of space without impacting other operations

# WAFL Layering: FlexVol & Aggregates



# Bunched Delayed Frees & Logging Interaction




- Bunched delayed frees: 60% lower latency at any load & higher saturation point
- Optimized processing via FlexVol Log: 84% of the container blocks punched out in optimized mode -> 26% higher throughput

# Conclusion

- WAFL has evolved over 2+ decades
  - deployments, media/hardware trends, applications/workloads
- Free space reclamation has also evolved
  - handle the changing requirements
  - interaction with dozens of features
- Consistent & predictable performance
  - with low latency and high throughput