IndexFS: Scaling File System Metadata Performance with Stateless Caching and Bulk Insertion

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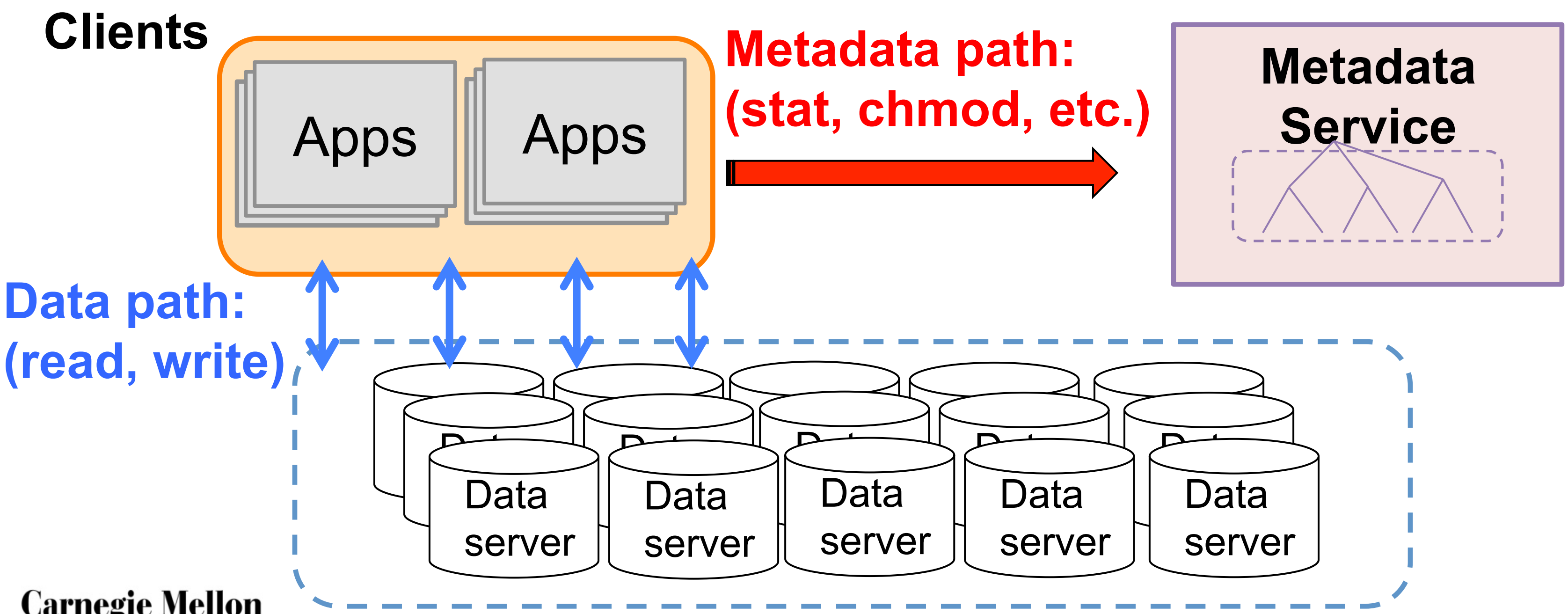
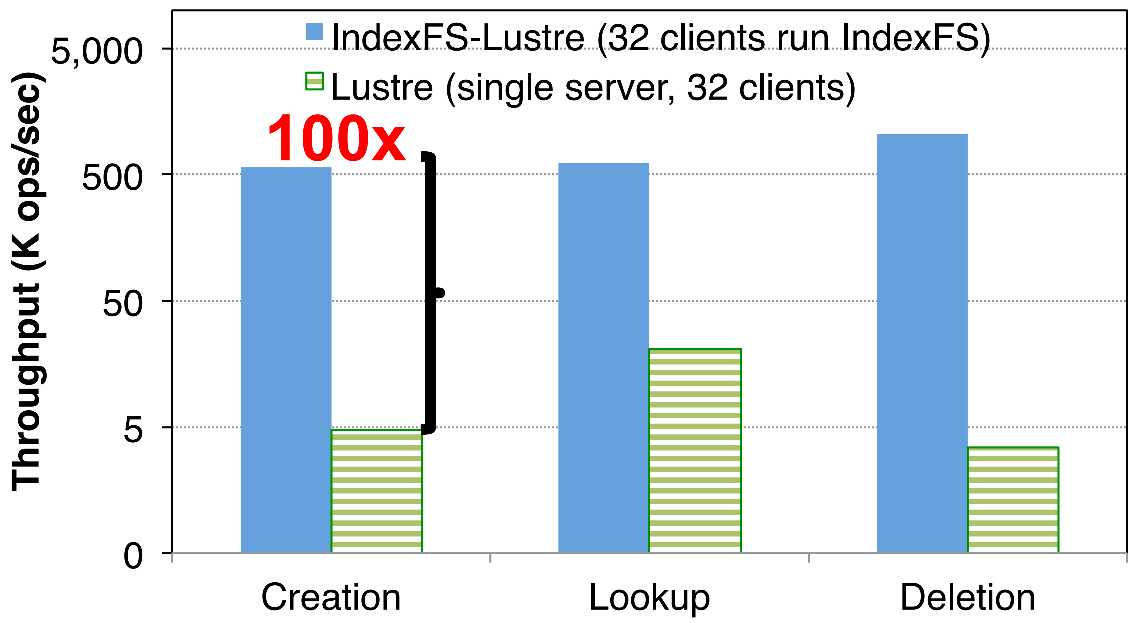
Why Scalable Metadata Service

- Many cluster file systems don't scale MDS well
  - Single metadata server (e.g. Lustre/HDFS)
  - Flat object name space (e.g. Amazon S3)
  - Static partition namespace (e.g. Fed. HDFS/Lustre 2.4)



Why Scalable Metadata Service

- Need a scalable, automatically load balanced, distributed metadata service
- IndexFS:
  - A middleware solution that provides metadata performance scaling for existing file systems

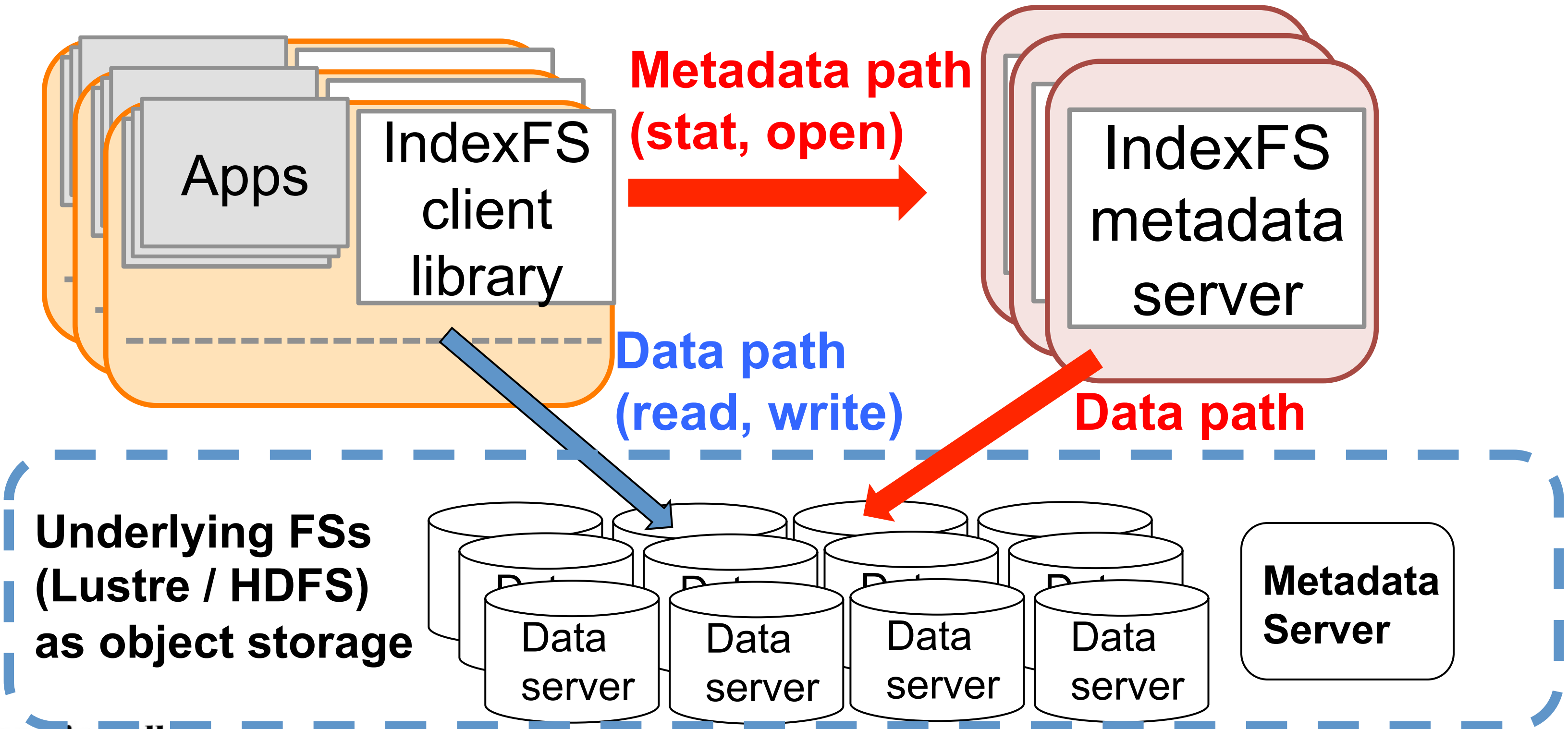


Outline

- Motivation
- ✓ IndexFS: Distributed Metadata Service
  - Architecture
  - Namespace Distribution
  - Hotspot Mitigation with Storm-free Caching
  - Column-style Table and Bulk Insertion
- Summary

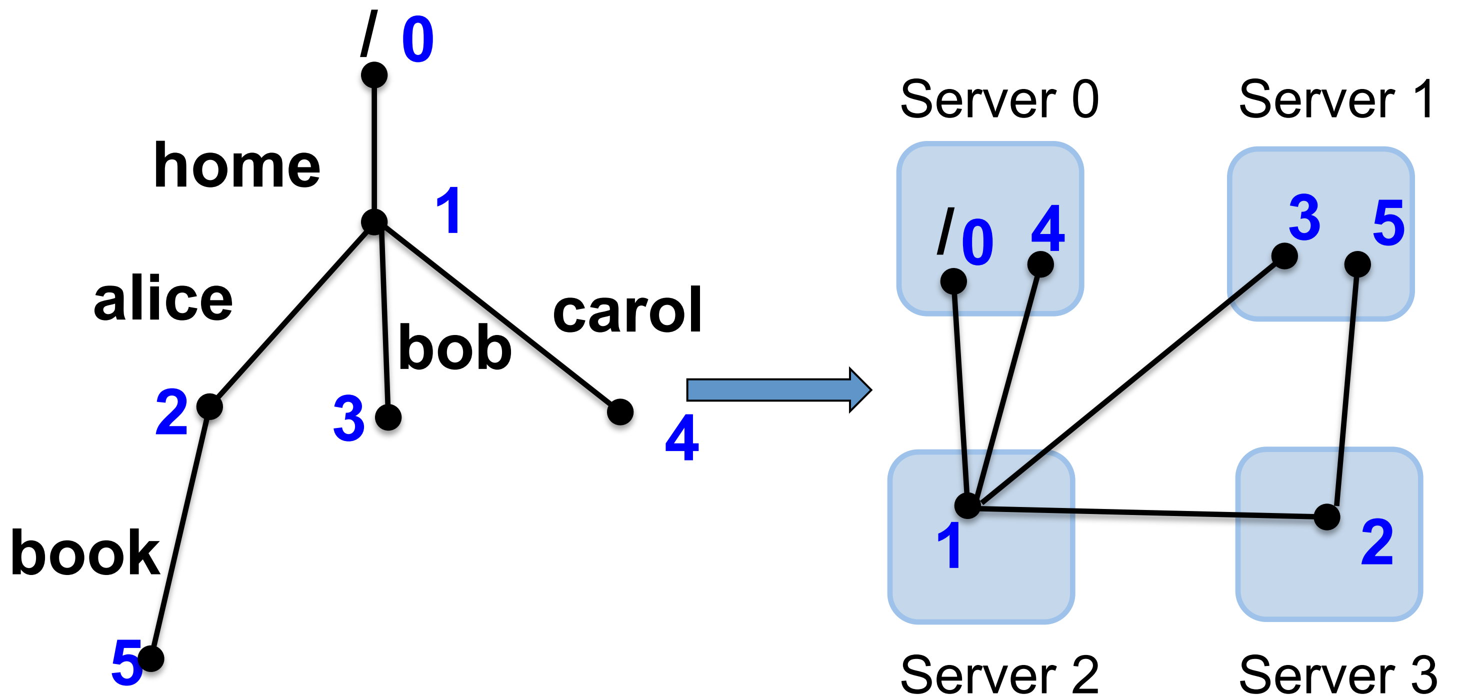
Middleware Design

- IndexFS is layered on top of original DFSs
  - Provide a scalable metadata path for existing file systems such as HDFS, PVFS and Lustre



IndexFS Directory Distribution

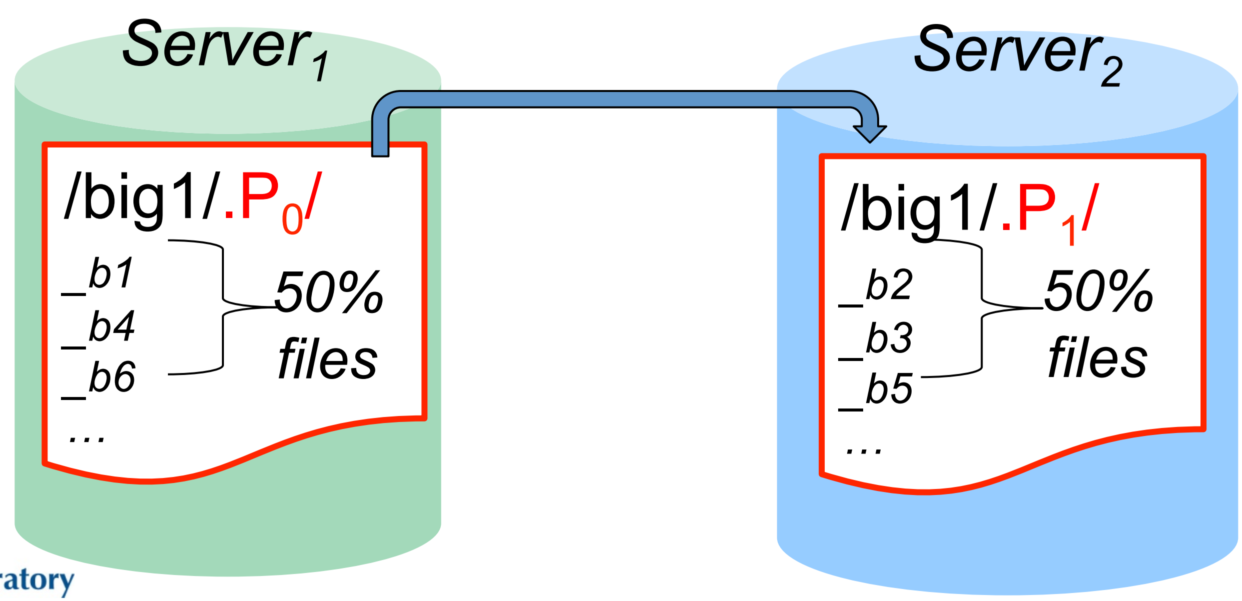
- Randomly assign directory to servers at creation
  - Load balance small directory working set



Dynamically Split Large Directories

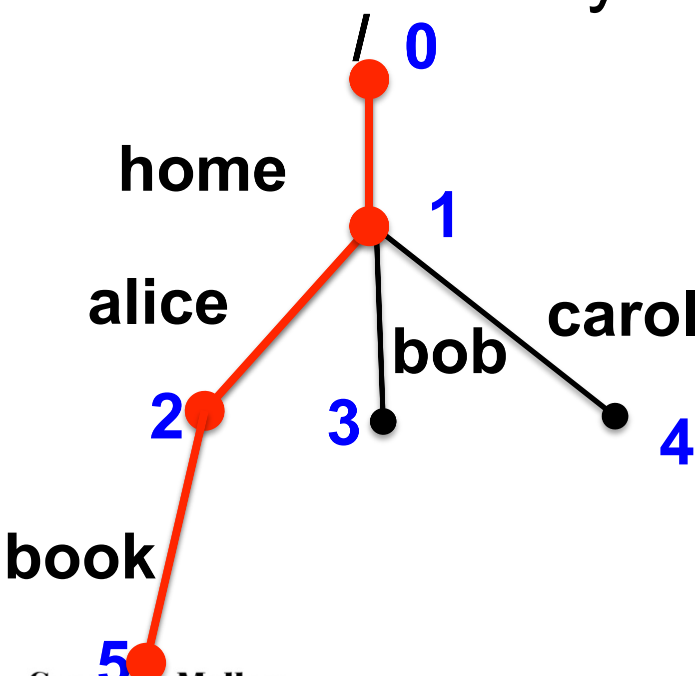
- Use GIGA+ for incremental growth [Patil11]
  - Binary split a partition when its size exceeds a threshold until each server has the same work
  - Load balance giant directories

Binary split a large directory



Efficient Per-Node Metadata Table

- Represent directory / file as a key-value pair
- Key:<parent directory's inode number, filename>
- Value: attributes, file data or file pointer
- Stored in a key value store : LevelDB [Dean11]

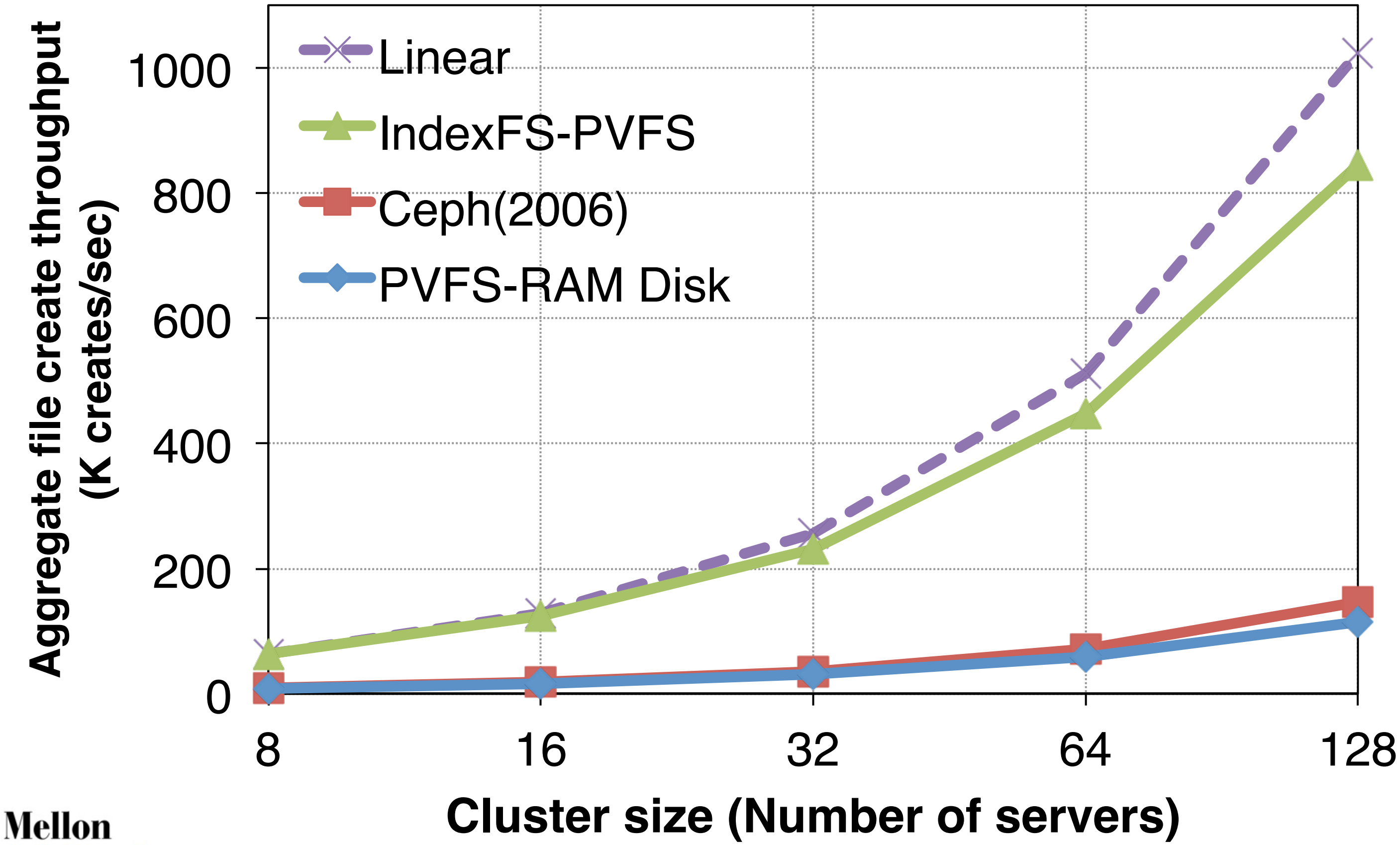


Lexicographic order

Key	Value
<0, *home*>	1, attributes
<1, *alice*>	2, attributes
<1, *bob*>	3, attributes
<1, *carol*>	4, attributes
<2, *book*>	5, attributes, small file data

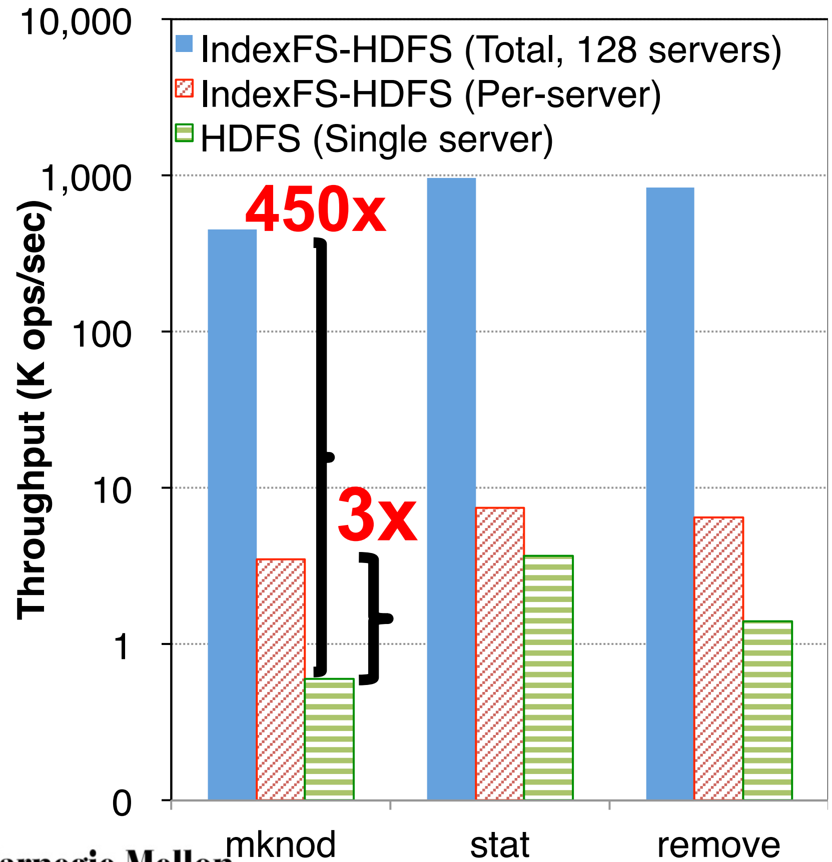
Basic MDS Scalability: File Creation

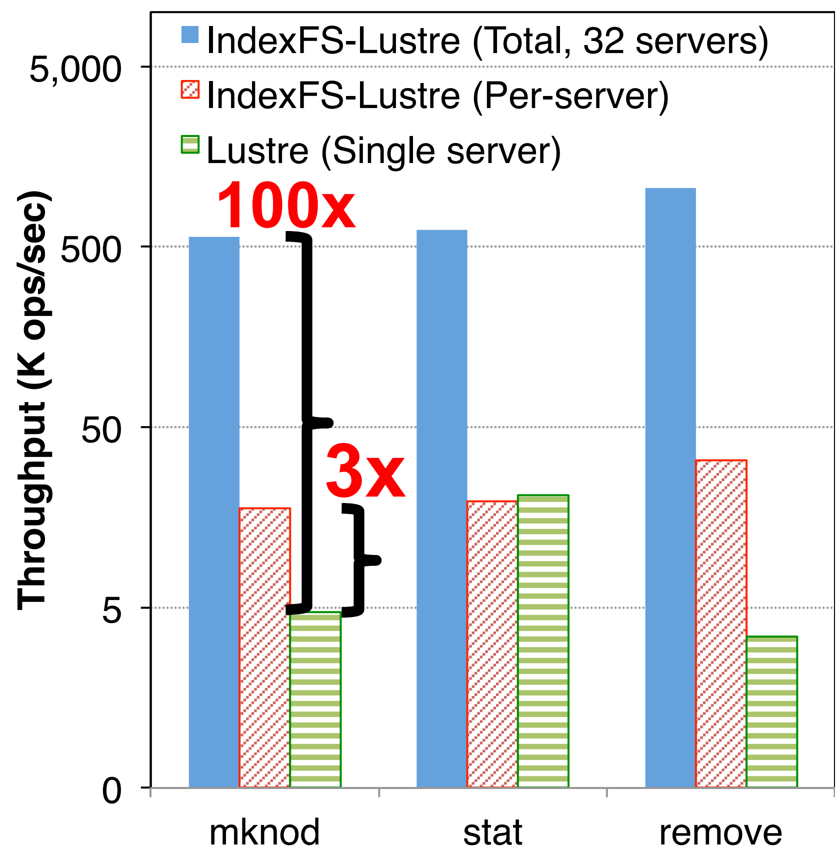
- Workloads: clients create files in one directory
- Use NFS PRObE Kodiak (8-yr old LANL hardware)



100-450X Faster For HDFS & Lustre

- Run mdtest on IndexFS layered on top of HDFS in PRObE Kodiak and Lustre in LANL Smog clusters





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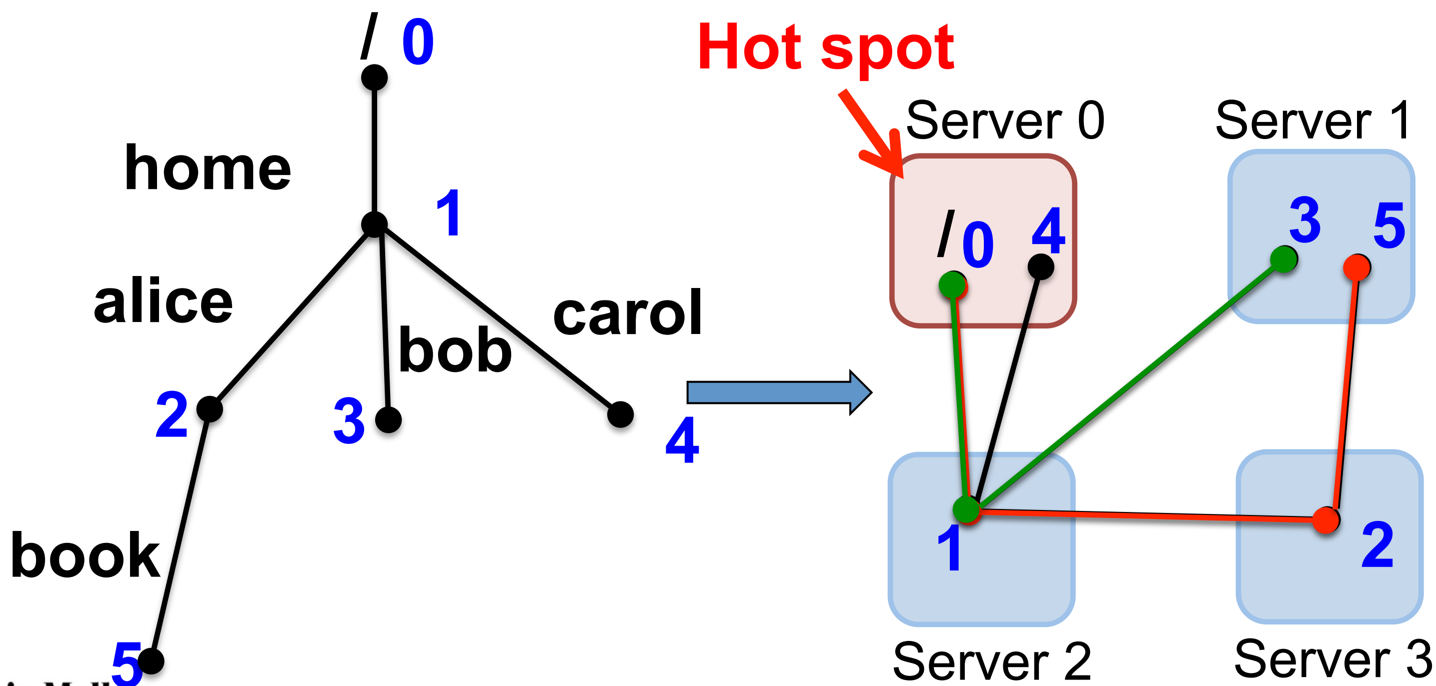
Hot Spot: Server with Root Directories

- Every lookup starts with the root directory
  - Path traversal needs to visit each ancestor
  - Retrieve inode number and access permissions
  - Early IndexFS was defeated by this hot spot



How To Mitigate Hot Spots?

- Client caches directory entry in many FSs
- Problem with invalidation callbacks at scale
  - Cache invalidation waits for responses of all clients
    - Clients may fail / may cause invalidation storm
  - Many parallel file systems disable cache when busy

- Idea: let the “clock” do the invalidation

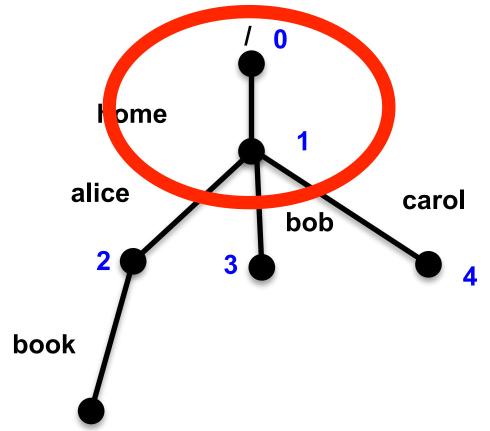
How To Mitigate Hot Spots?

- Client caches directory entry in many FSs
- Problem with invalidation callbacks at scale

- Idea: let the “clock” do the invalidation
  - Clients use ***read-only*** cache for directory entries
  - Servers remember only ***expiration deadline***
  - Assume ***clock synchronization*** within data center
  - Directory mutations wait for expiration
    - *rmdir*, *rename*, *chmod* can be slow

Timeout Based Lease

- Inspiration:
  - Hot spots at top of tree has few changes



- Explored two expiration time choices:
  - tree depth: fixed duration *K* / depth
  - rate based: *L**read rate / (read rate+write rate)

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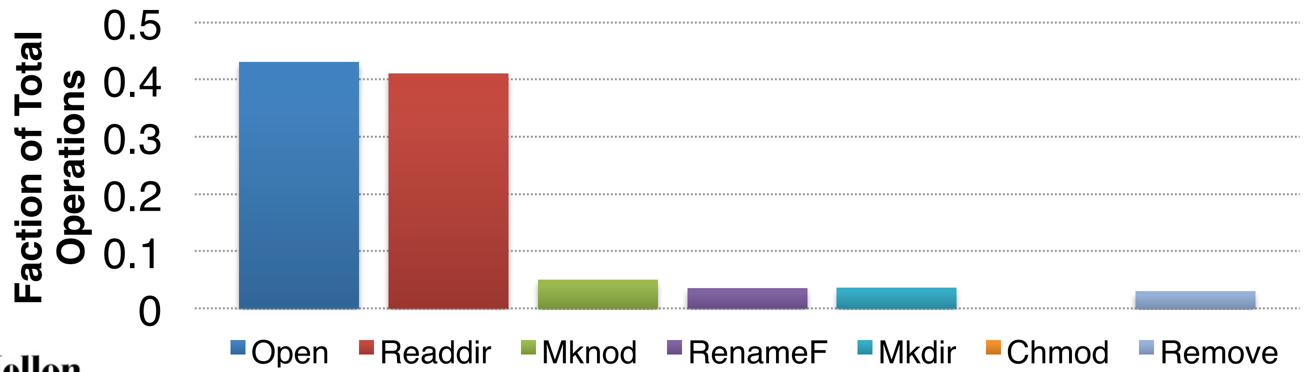
Trace Replay Experiment

- IndexFS run on top of a 128-node PVFS cluster
  - All metadata and data stored in PVFS as files
- Workload:
  - Replay 1 million ops/server from LinkedIn trace
  - Pre-create namespace in the empty file system
  - One day trace:10M objects and 130M operations
  - Distribution: 90% reads, 10% mutations



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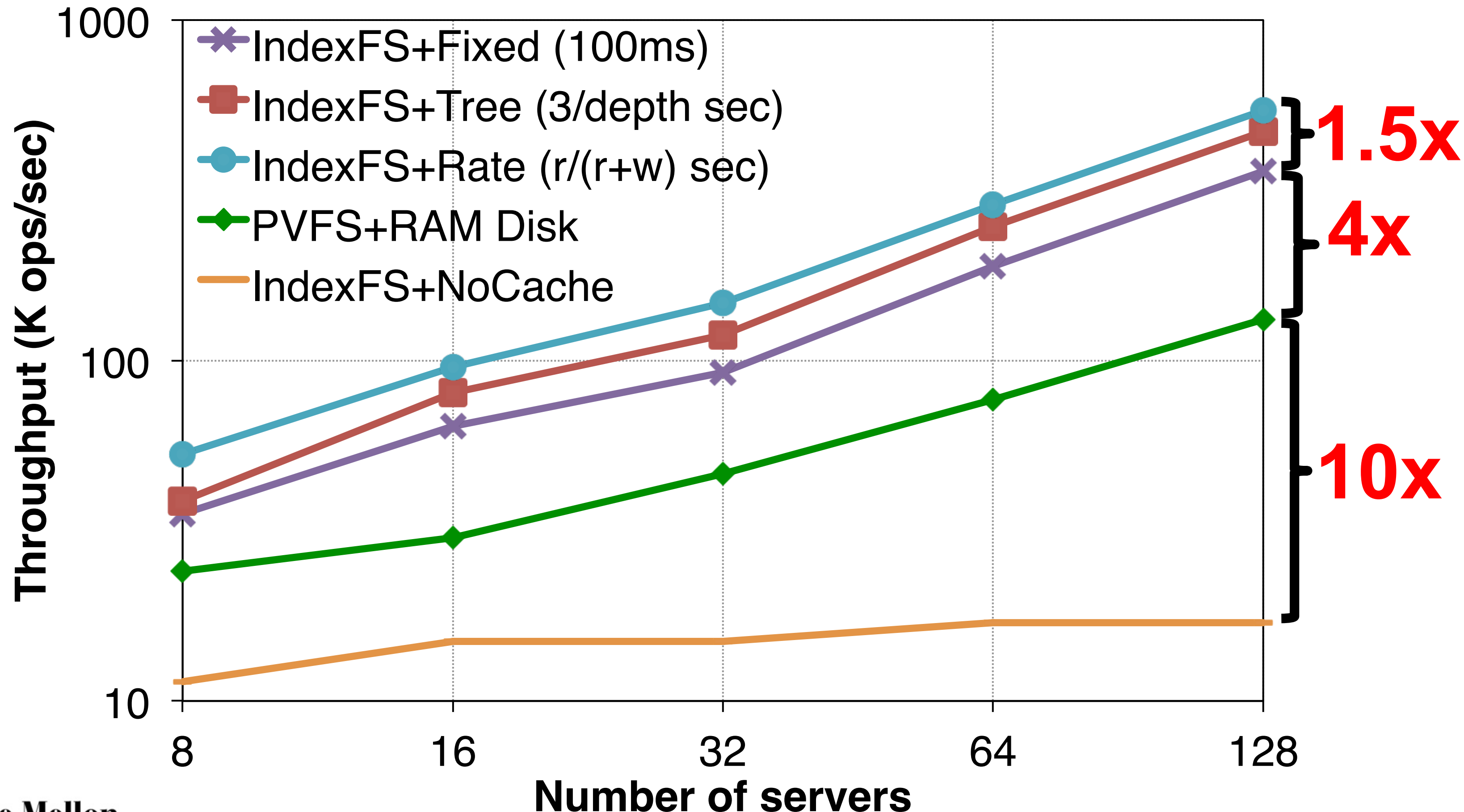
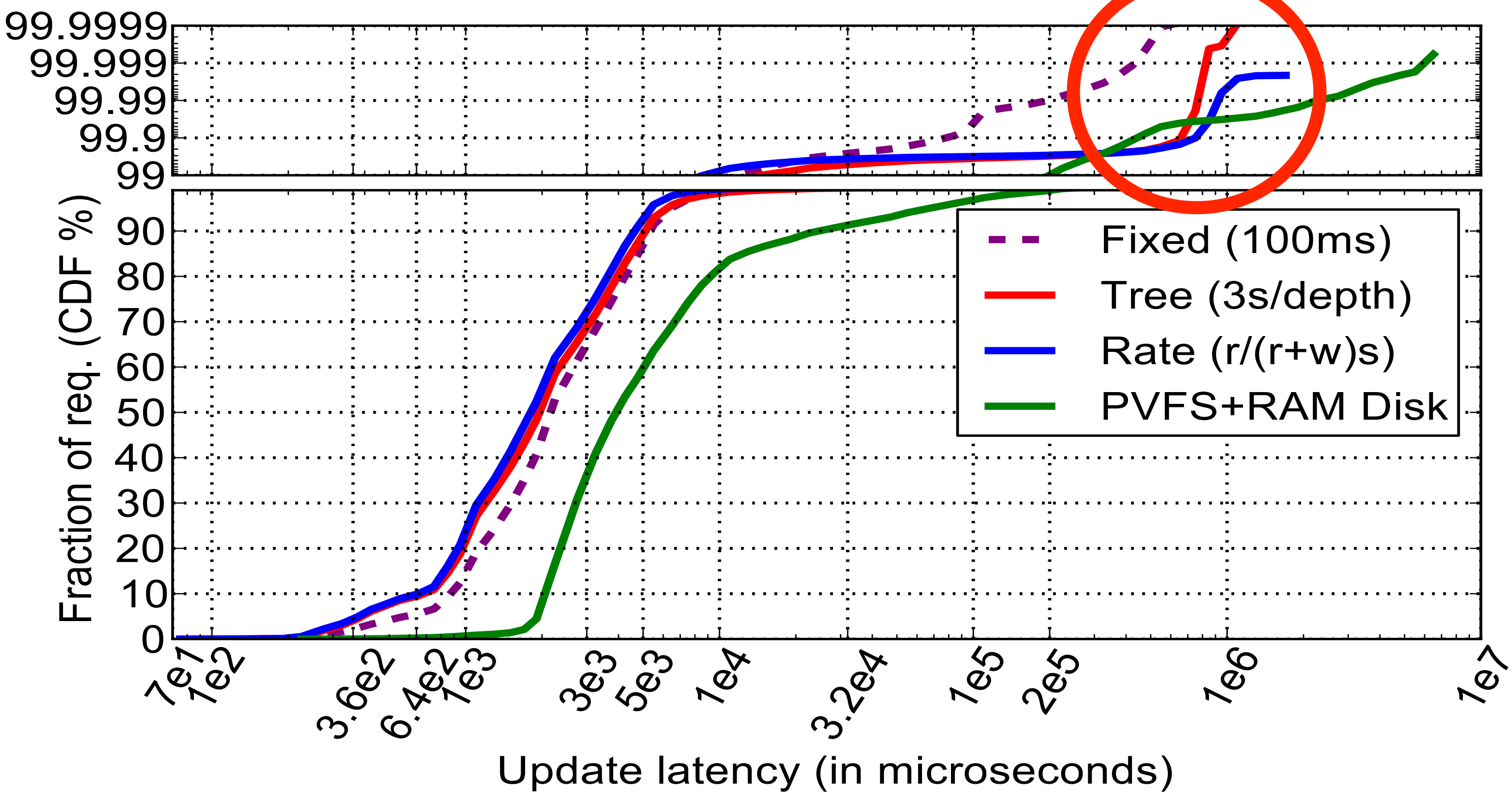
Replay Result: Throughput

- Directory entry cache mitigates hot spots



Replay Result: Chmod Latency

- Fixed duration lease gets the lowest tail latency
  - Trade-off between tail latency and throughput



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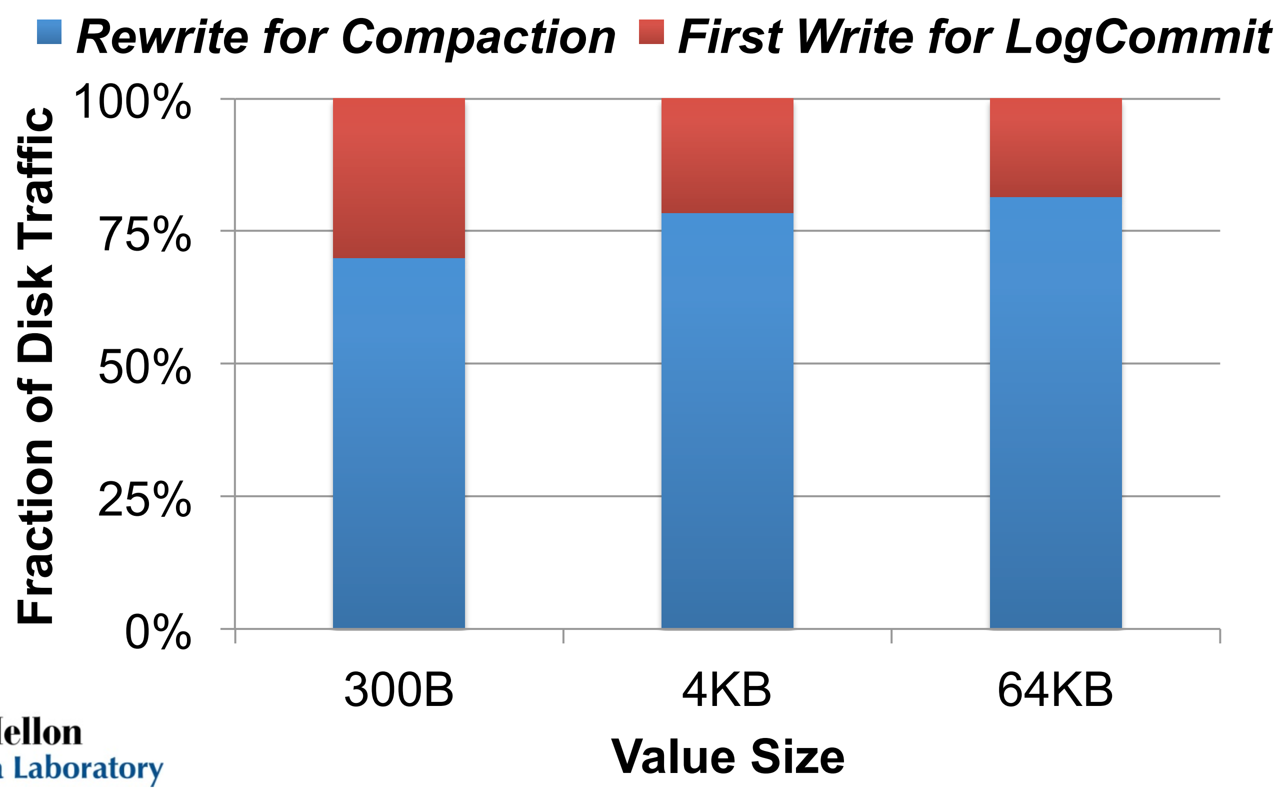
Bulk File Creations

- Some applications want faster file creations
  - e.g. HPC checkpoint applications

- IndexFS removes two main bottlenecks:
  - LevelDB's background compaction
    - **Column-style storage schema**
  - Too many RPC round trips
    - **Bulk insertion**

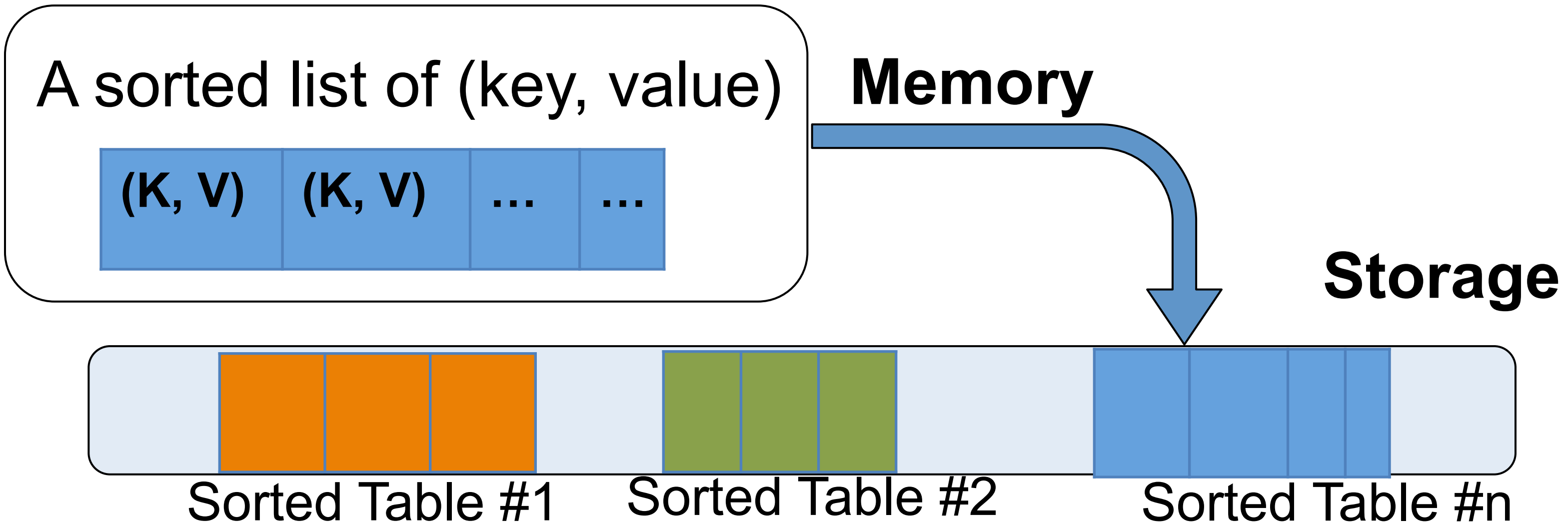
1st Bottleneck: Compaction in LevelDB

- Slow insertion for storing all metadata and data file
  - 75% of insertion disk traffic caused by compaction
  - Compaction of larger values wastes more bandwidth



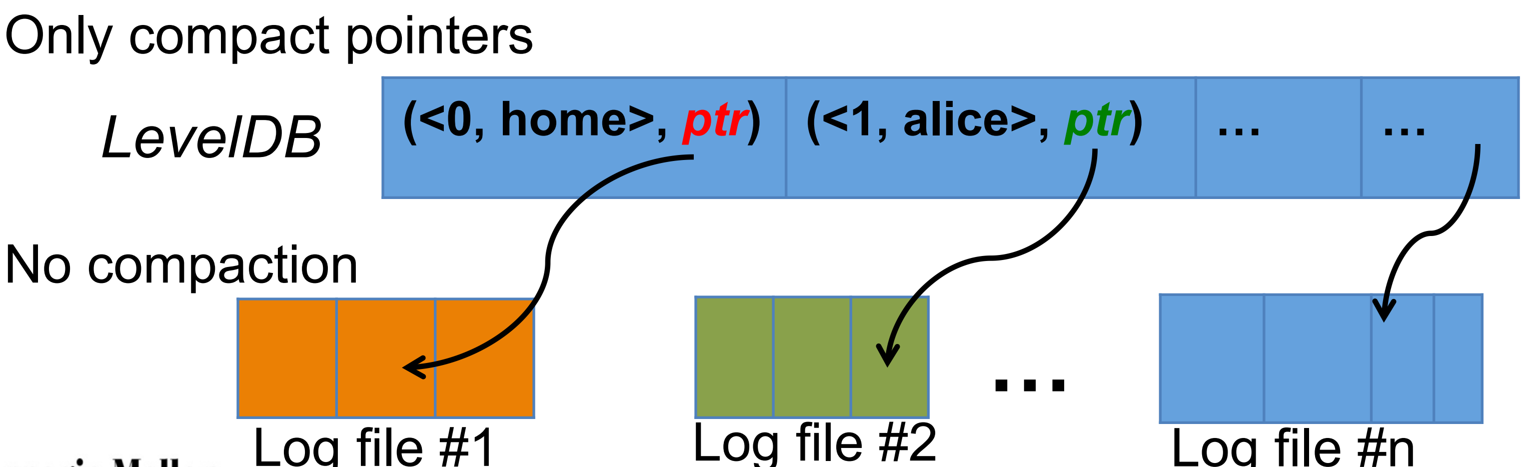
Background: LevelDB Internal

- LevelDB (LSM Tree): Insert and update ops:
  - Buffer and sort recent inserts/updates in memory
  - Flush buffer to generate immutable sorted tables
  - Perform compaction to reduce #tables for searching
- Want to avoid rewrites while having fast lookup



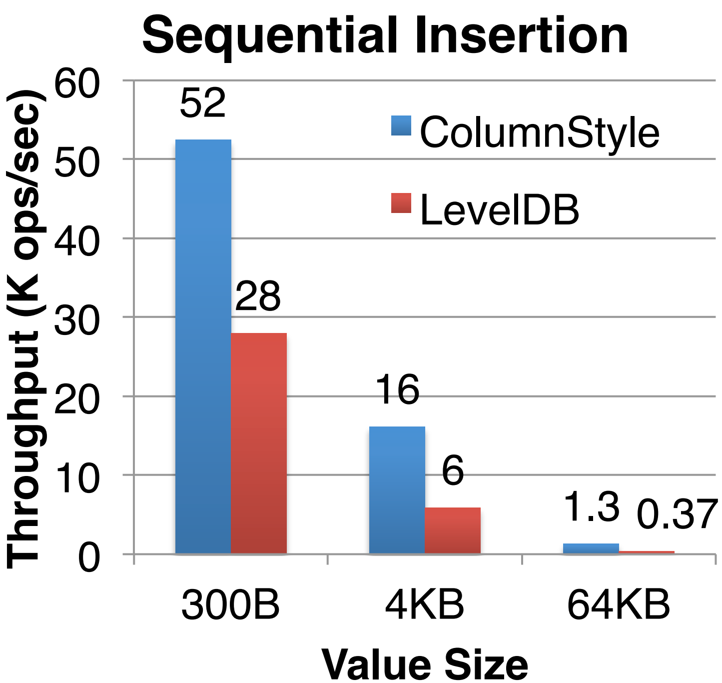
Column-Style Metadata Schema

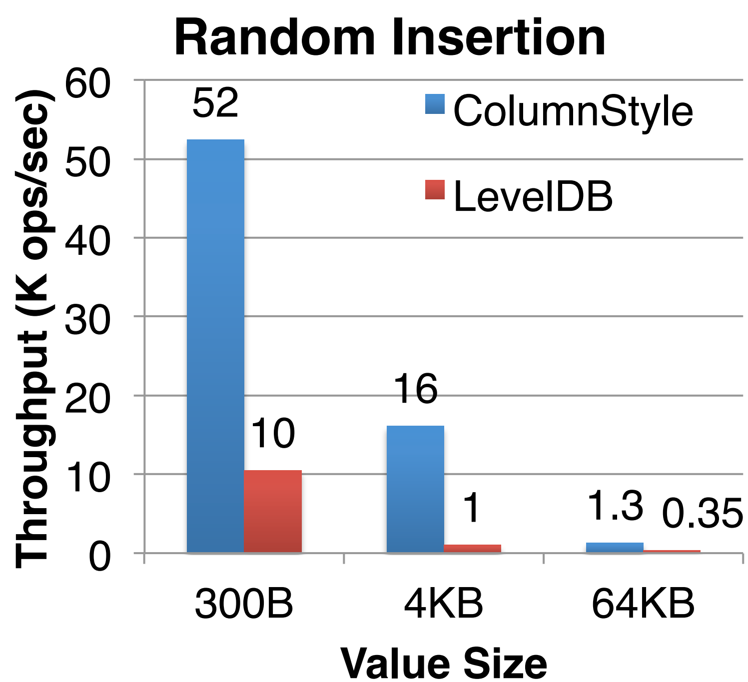
- Column-style approach:
  - Metadata/small files appended to non-LevelDB log files
  - LevelDB stores only pointers to metadata
  - Don't compact the metadata
    - – Delay space reclamation for deleted/over-written values since metadata are small



Speed Up Ingestion Rate

- Insert 30M entries sequentially or randomly
  - Limit memory to 350 MB, using single SATA disk
- About 2 to 15 times faster insertion



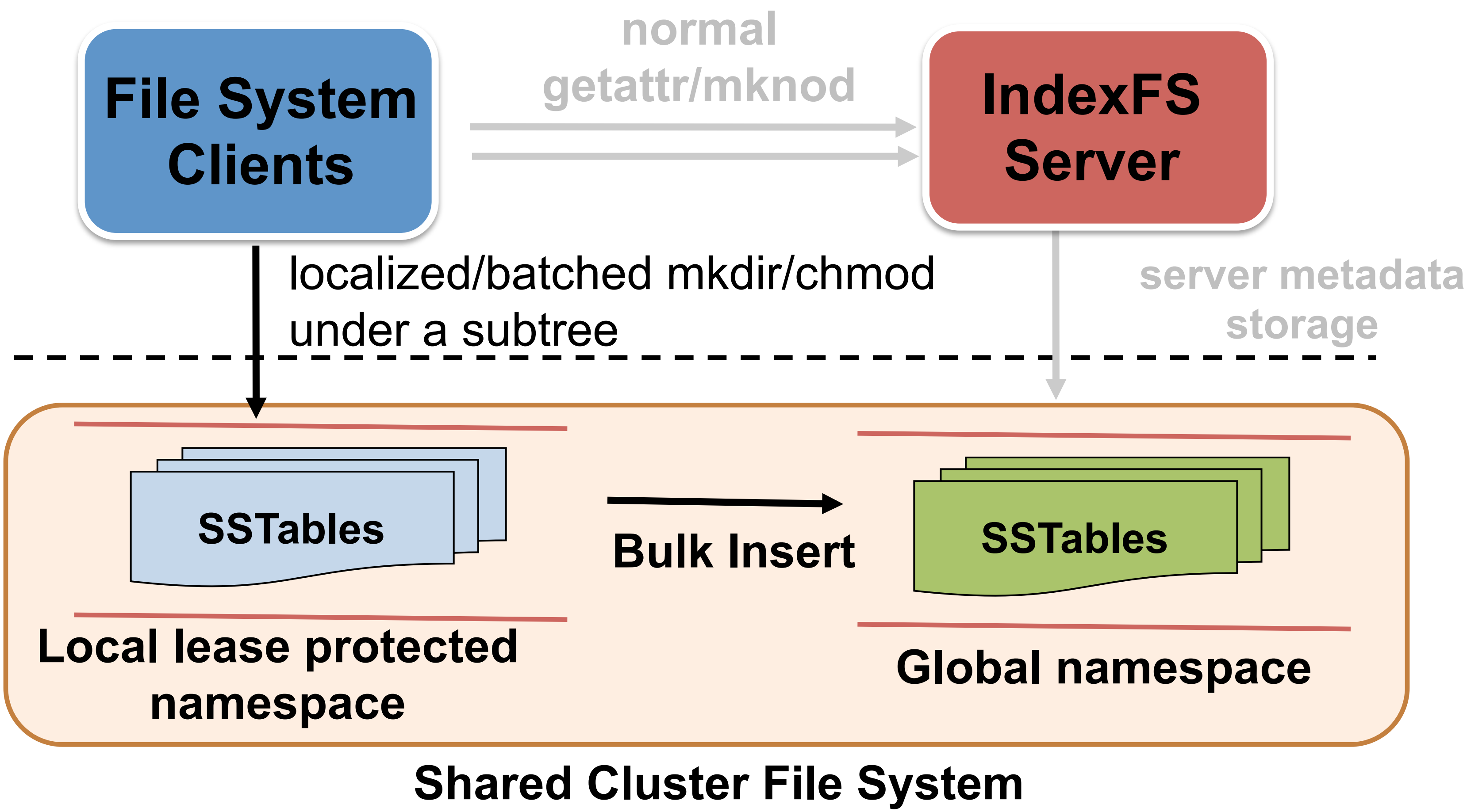


Fix 2nd Bottleneck: Bulk Insertion

- Extend client cache to support write-back
  - No RPC overheads per metadata operation
  - Avoids constant synchronization at servers
  - Better utilization of the underlying bandwidth

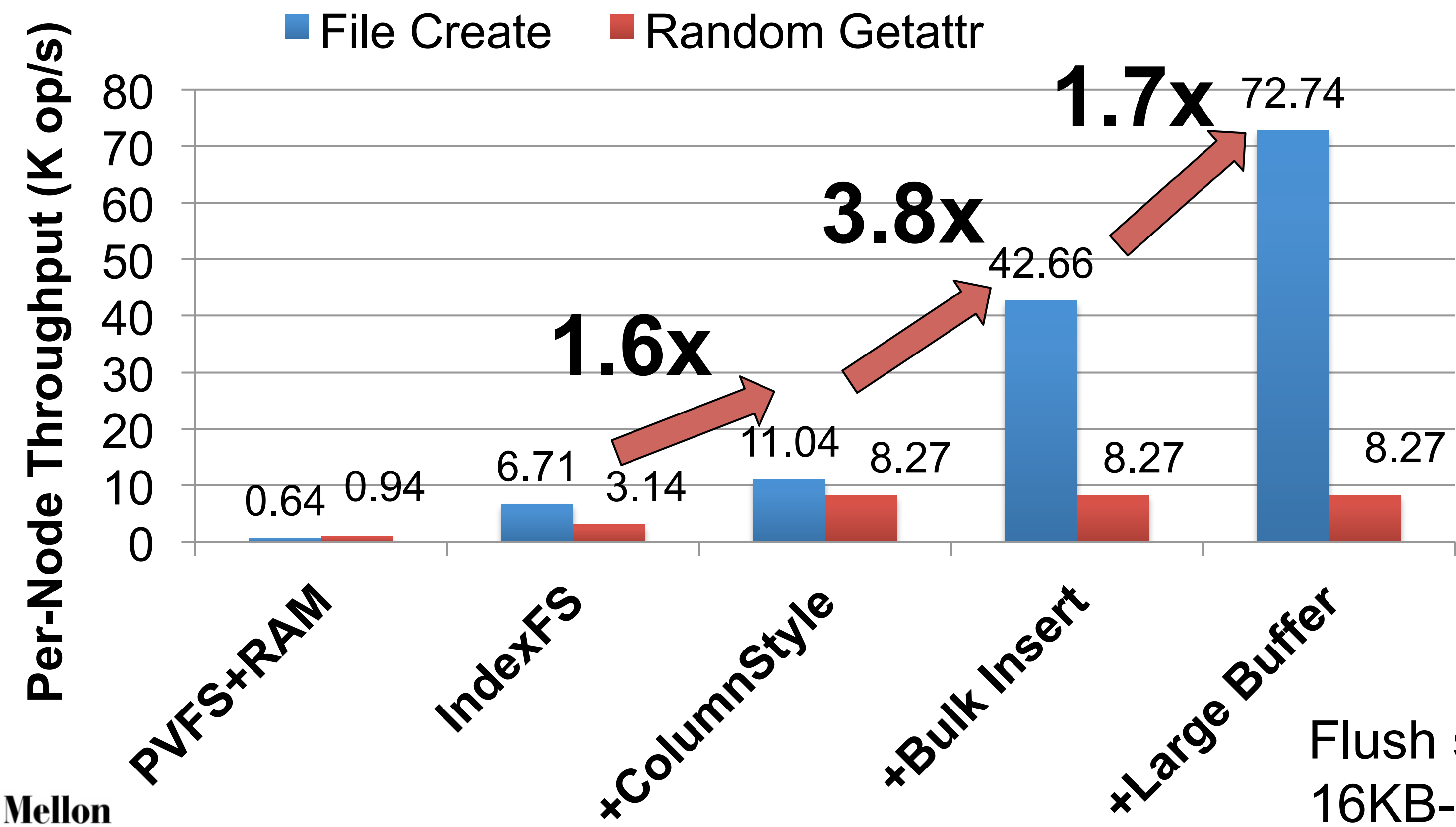
- Assumptions
  - Clients have access to backend storage nodes
  - Only possible for clients to insert new subtrees
    - No namespace conflicts
  - Asynchronous error reporting is acceptable

Bulk Insertion Implementation



Bulk Insertion: Factor Analysis

- Evaluation bulk insertion on top of PVFS
  - Perform random insertion and stat in one directory



Flush size: 16KB->64KB

Summary

- IndexFS: a **middleware** approach to scale metadata path, portable to HDFS, Lustre, PVFS

- Scale out: **partition tree on directory basis**
  - GIGA+ for incremental partition of giant directories.
  - Read-only consistent caching without per-client state
- Scale up: **optimize log-structured merge tree**
  - Column-style schema reduces compaction overhead
  - Bulk insertion to avoid server coordination

- Code available: http://www.pdl.cmu.edu/indexfs

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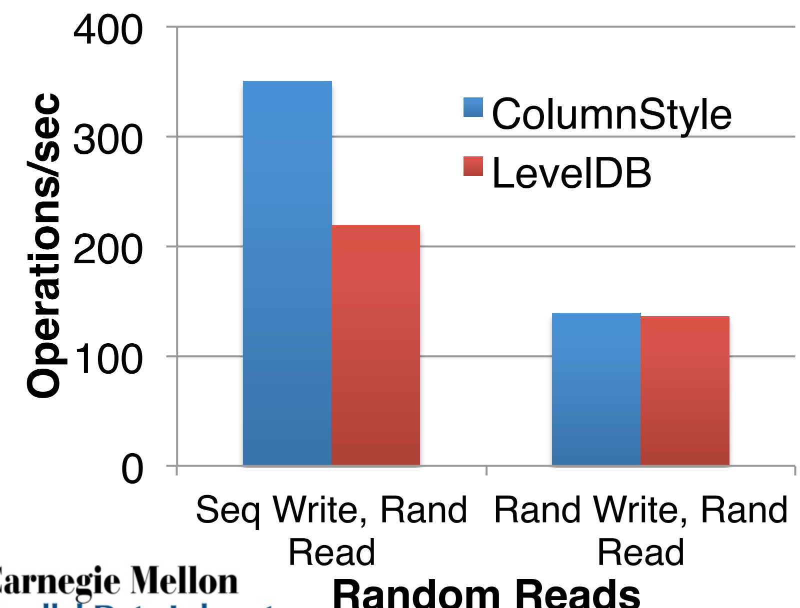
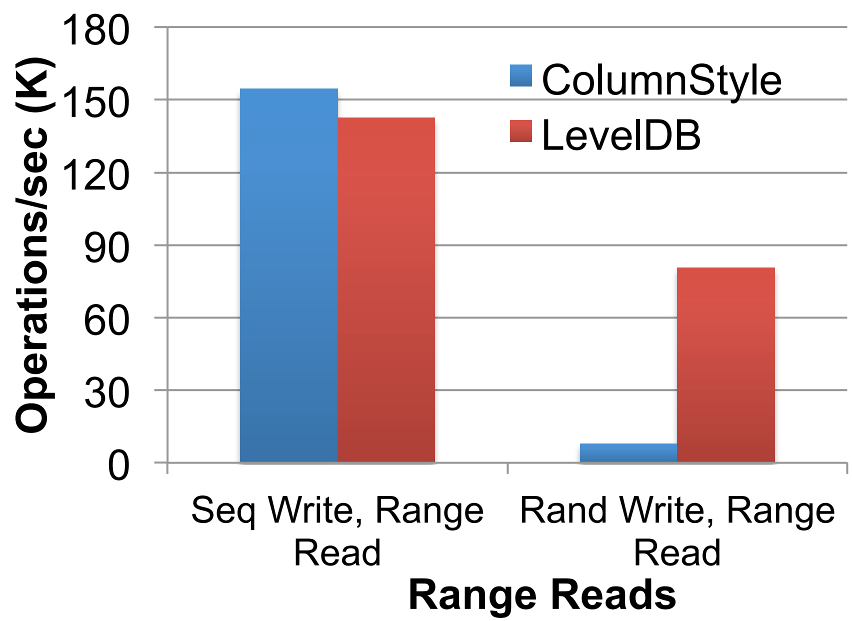
Comparable Read Throughput

- Read after rand./seq. insertion of 4KB entries
  - *Random Read*: read randomly over all entries
  - *Range Read*: read randomly in 1% adjacent range
- No compaction, so no clustering for range read
  - Only use compaction for workload-specific prefetch





Cluster Specification

- PRObE Kodiak
  - CPU: AMD Opteron 252, Dual core, 2.6GHz
  - Memory: 8GB
  - Network: 1GE NIC
  - Storage: Western Digital 1TB hard drive
  - OS: Ubuntu 12.10 Kernel 3.6.6 x86-64
- LANL Smog
  - CPU: AMD Opteron 6136, 16-core, 2.4GHz
  - Memory: 32GB
  - Network: Torus 3D, bandwidth: 4.7GB/s
  - Storage: Hardware RAID array, bandwidth 8GB/s
  - OS: Cray Linux
  - Lustre version: 1.8.6