FalconFS: Distributed File System for Large-Scale Deep Learning Pipeline

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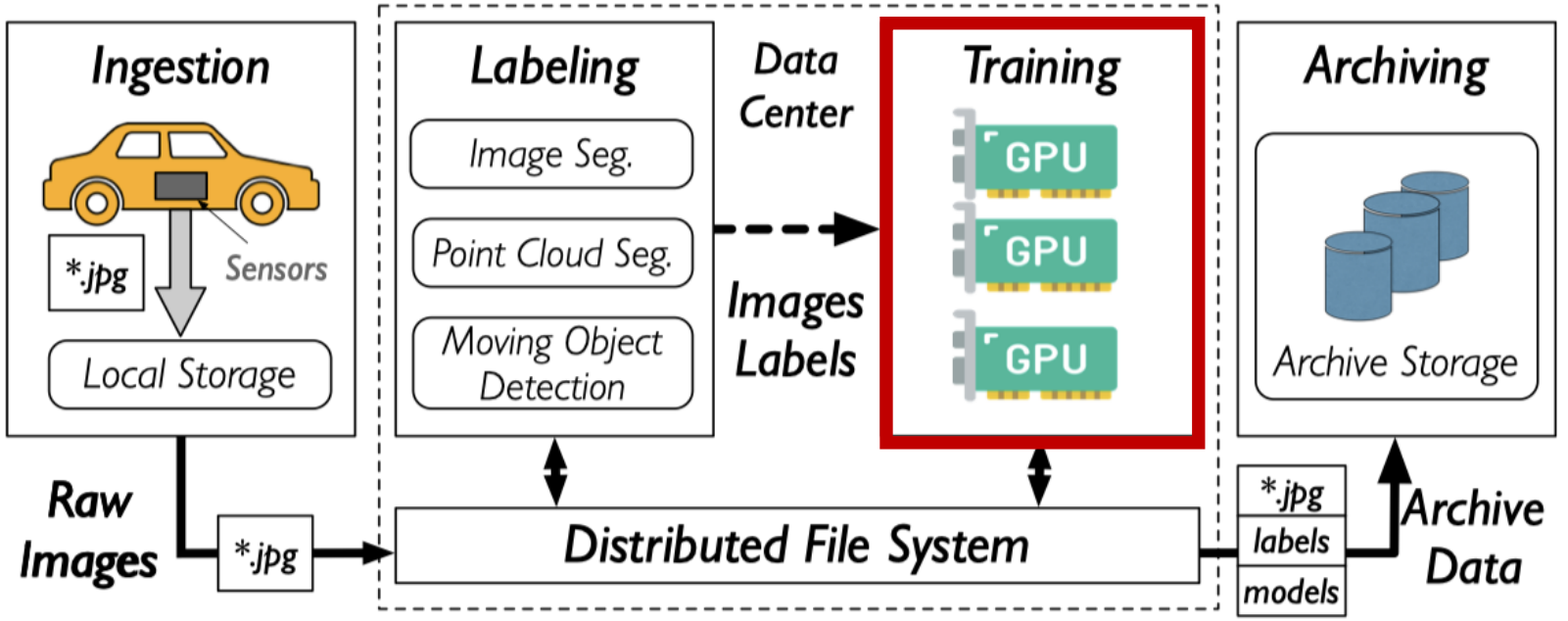
Metadata in Deep Learning Training Pipelines



Numerous Small Files

300 billion files, 1 billion directories

~300KB average file size

Poor Locality

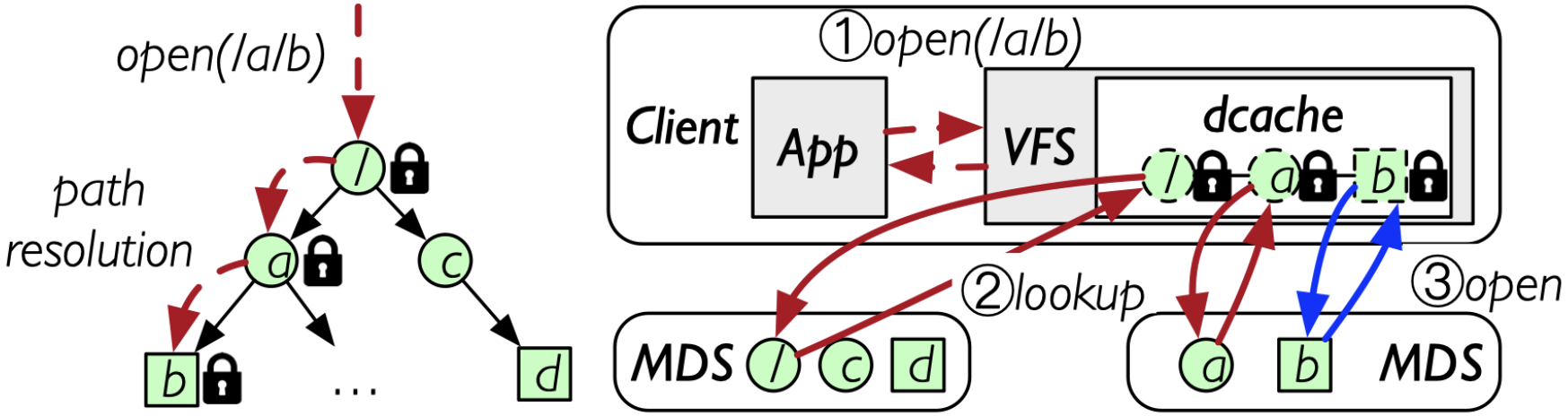
random file access

Challenges to the Underlying Distributed Filesystem

Numerous Small Files ⇒ **Significant Metadata Overhead**

~300KB average file size

~2.4 TB/s throughput ⟶ 8 million files/s



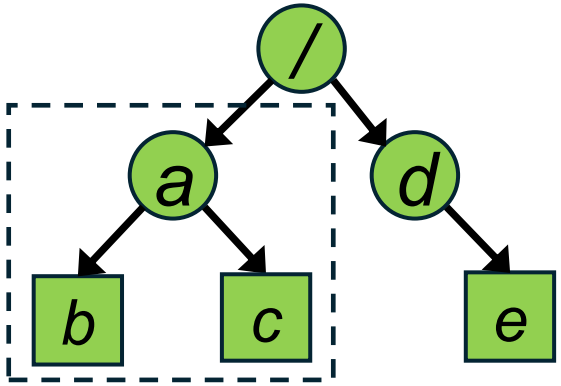
Main Source of Overhead

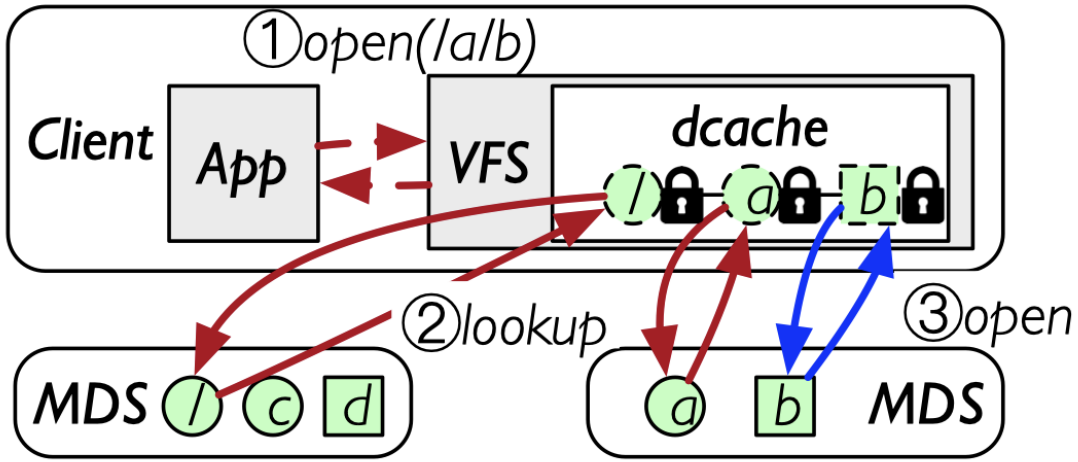
open(/a/b/c) incurs three lookup requests to */*, */a*, and */a/b*

Challenges to the Underlying Distributed Filesystem

Traditional Approach: Client Caching

Every cache hit eliminates one remote lookup





Assumption: Locality of Access

Clients access a small number of directories

High hit rate with low memory consumption

Challenges to the Underlying Distributed Filesystem

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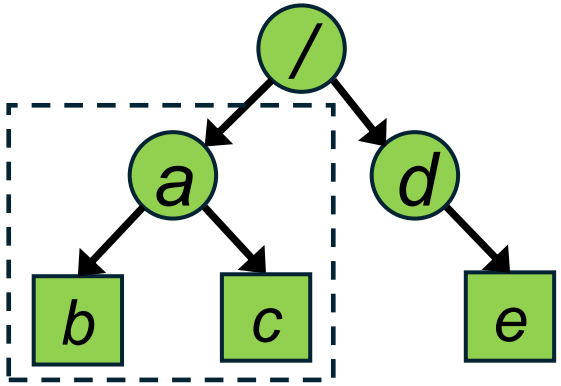
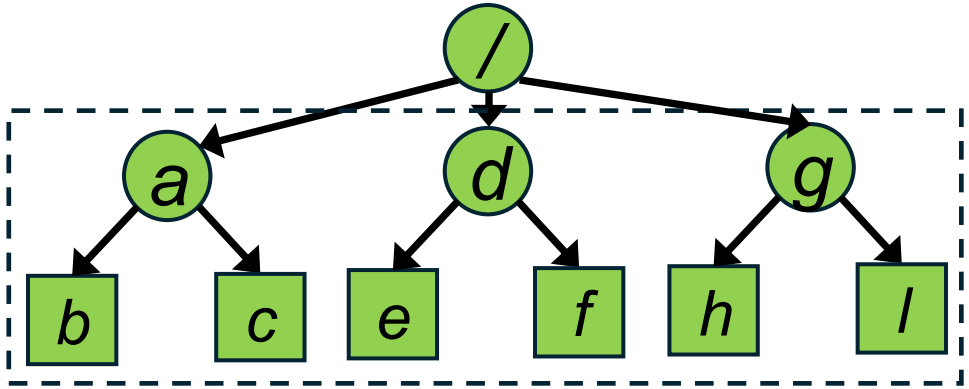




Assumption: Locality of Access

Clients access a small number of directories
High hit rate with low memory consumption

DL Workload: *Poor Locality*

Training tasks access files in random order
Low hit rate and high memory demand
Huawei ADS: > 100B files, 1B directories

Challenges to the Underlying Distributed Filesystem

Inherent Trade-Off: *Memory Consumption* & *Performance*

Memory Consumption

Cache billions of directories

⇓

Consume TBs of memory

Performance

Random accesses

⇓

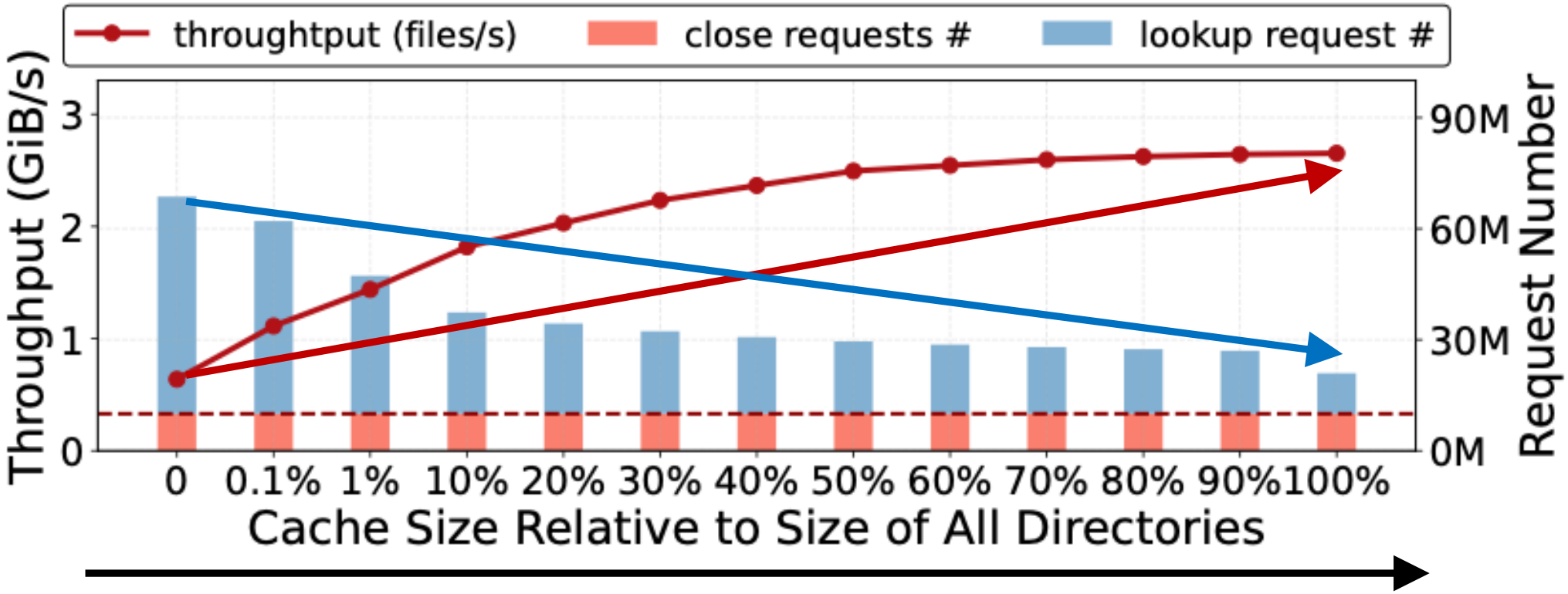
Cache miss rate is proportional to the number of not-cached directories

Client caching cannot solve the path resolution bottleneck

Challenges to the Underlying Distributed Filesystem

Inherent Trade-Off: *Memory Consumption* & *Performance*

Randomly read 10 million 64KB files in 1 million directories



Throughput Increases

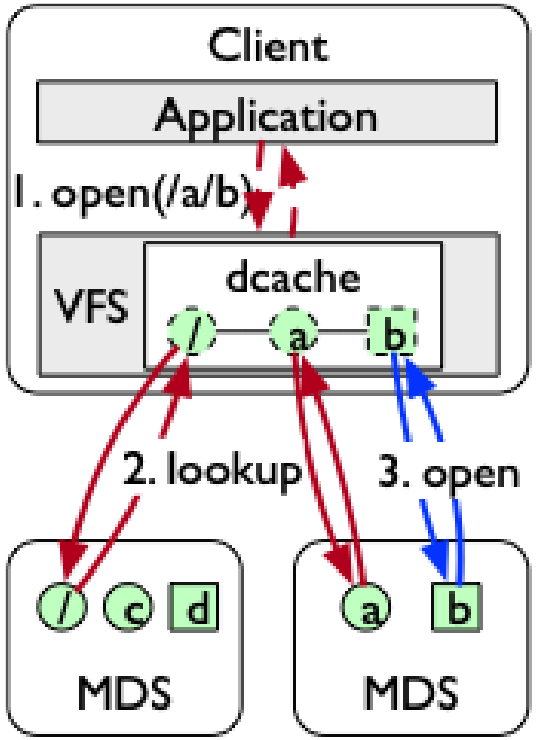
Request # Reduces

Cache Size Increases

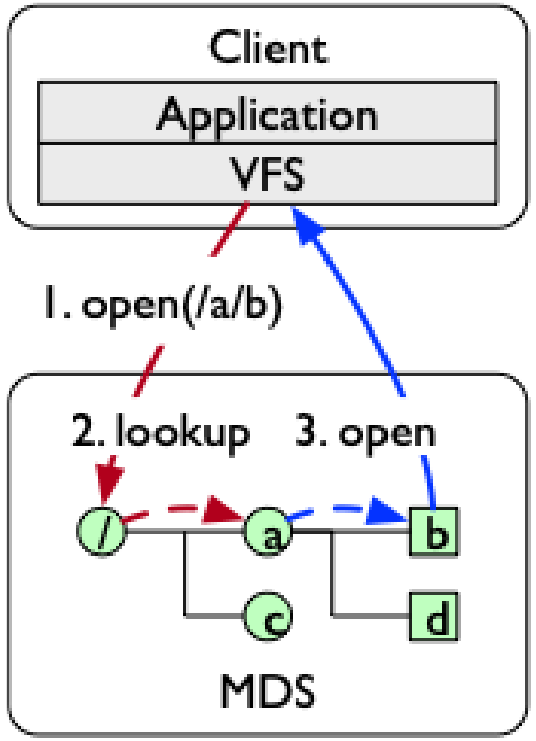
Our Solution

Key idea: make the client ***Stateless*** and offload path resolution to the servers

Client-Side Path Resolution



Server-Side Path Resolution



Why Stateless Client Architecture is Helpful

Client-Side Path Resolution

- Thousands of client nodes
- Kernel objects in VFS
- Colocate with training tasks

⇒

- Highly duplicated cache content
- Large object (800 bytes)
- High memory contention

Server-Side Path Resolution

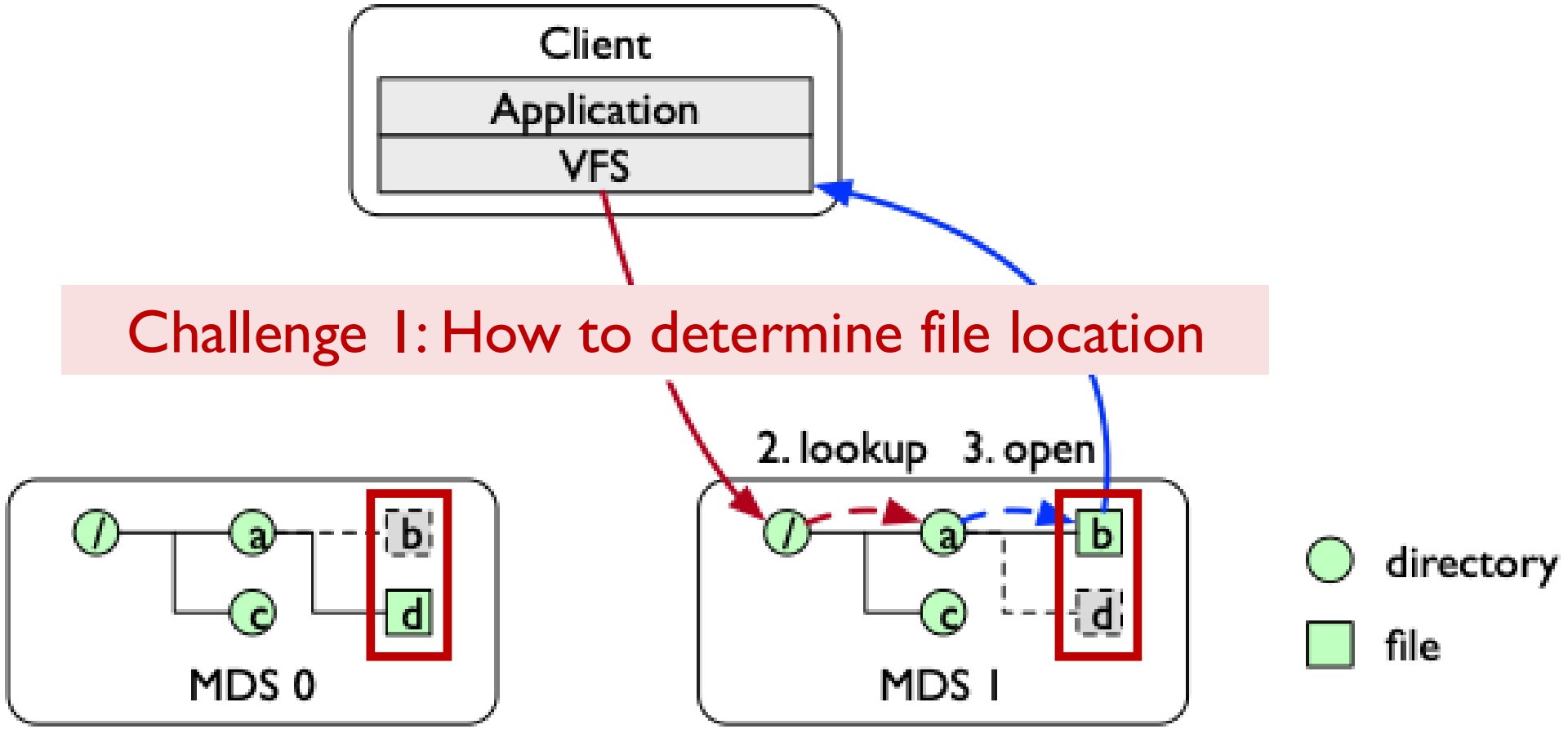
- Typically < 64 server nodes
- Customized metadata objects
- Standalone server processes

⇒

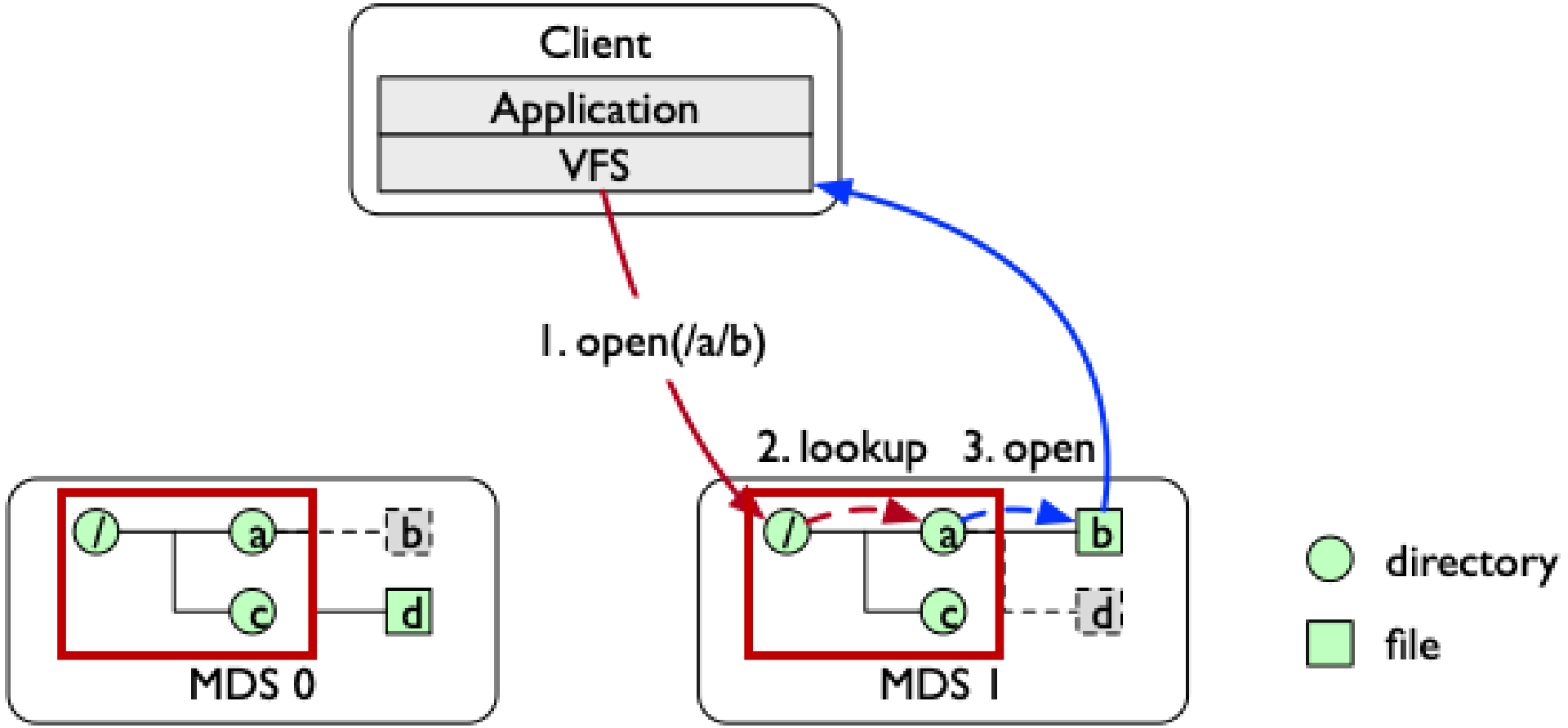
- Smaller total cache size
- Smaller objects (~100 bytes)
- Relatively abundant memory resources

Memory efficiency is higher on the server side

Challenges in Building the Stateless Client



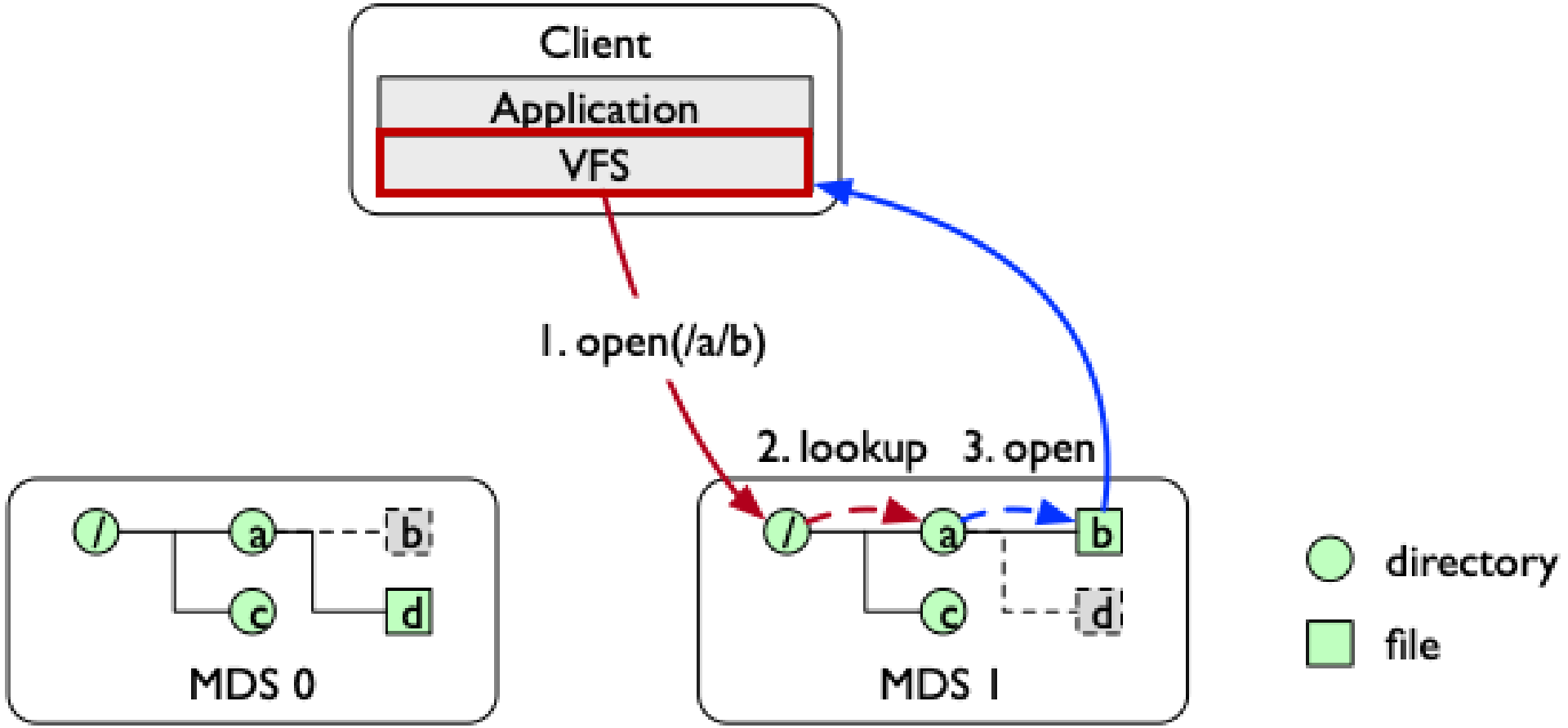
Challenges in Building the Stateless Client



Challenge 2: How to efficiently replicate the namespace

Challenges in Building the Stateless Client

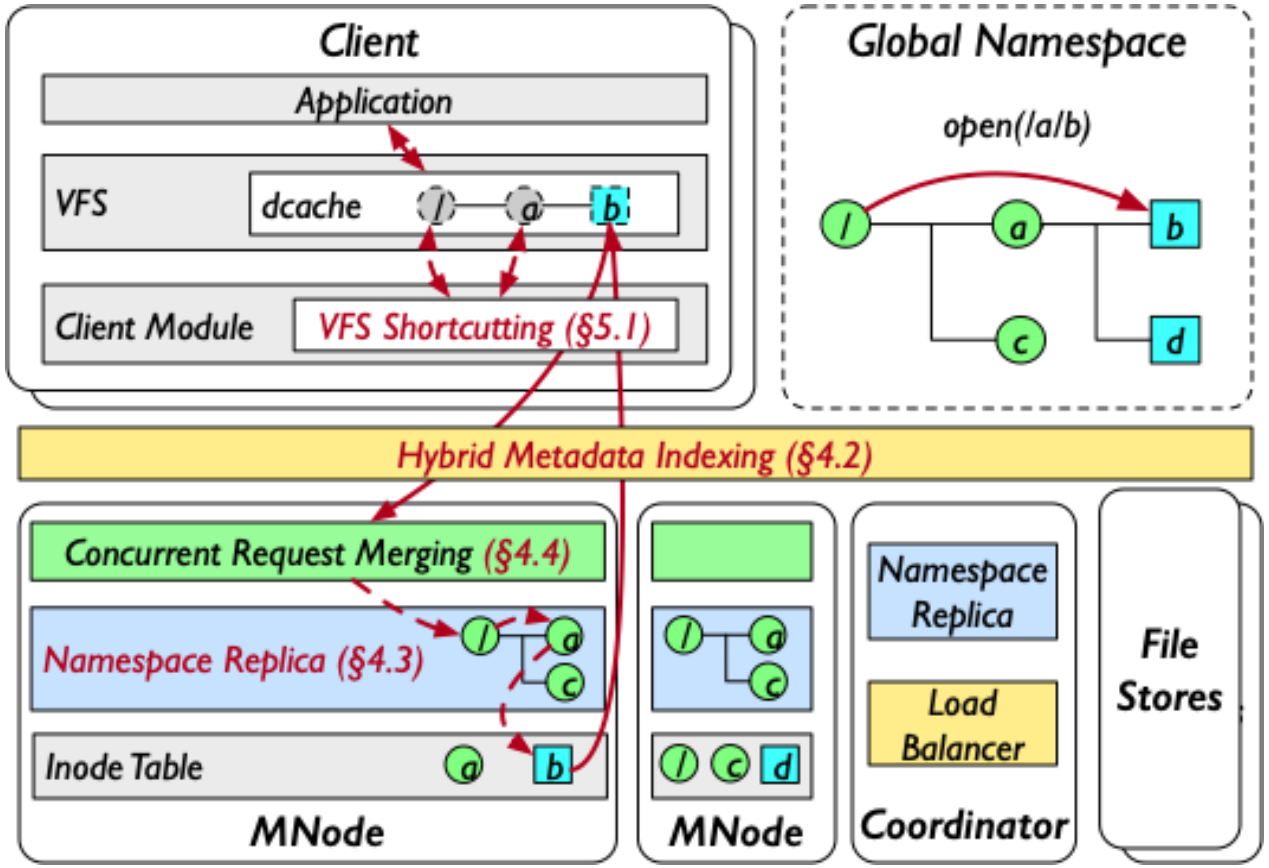
Challenge 3: How to preserve VFS compatibility



FalconFS Overview

Four Components:

- Client + MNode + Coordinator + File Stores



Metadata Schema:

	Key	Value	Organization
dentry	pid, name	id, perm	replicate
inode	pid, name	id, attr	partition

Namespace (dentry) replicated

Attributes (inode) partitioned

How to Locate File Inode?

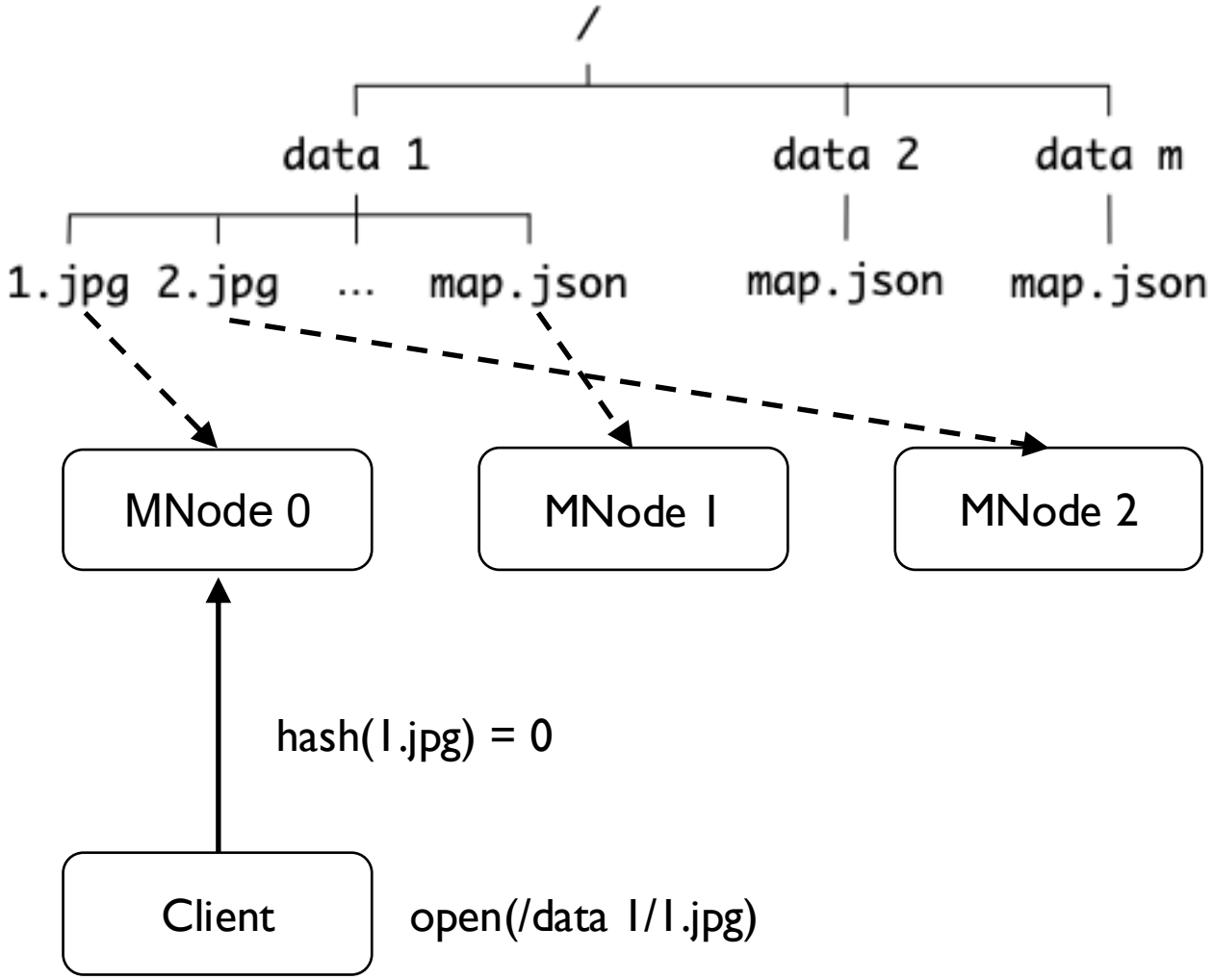
Common path: hash by filename

+

Directory size is typically far larger than the number of servers

⇓

Most files are distributed evenly 😄



How to Locate File Inode?

Common path: hash by filename

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Directory size is typically far larger than the number of servers

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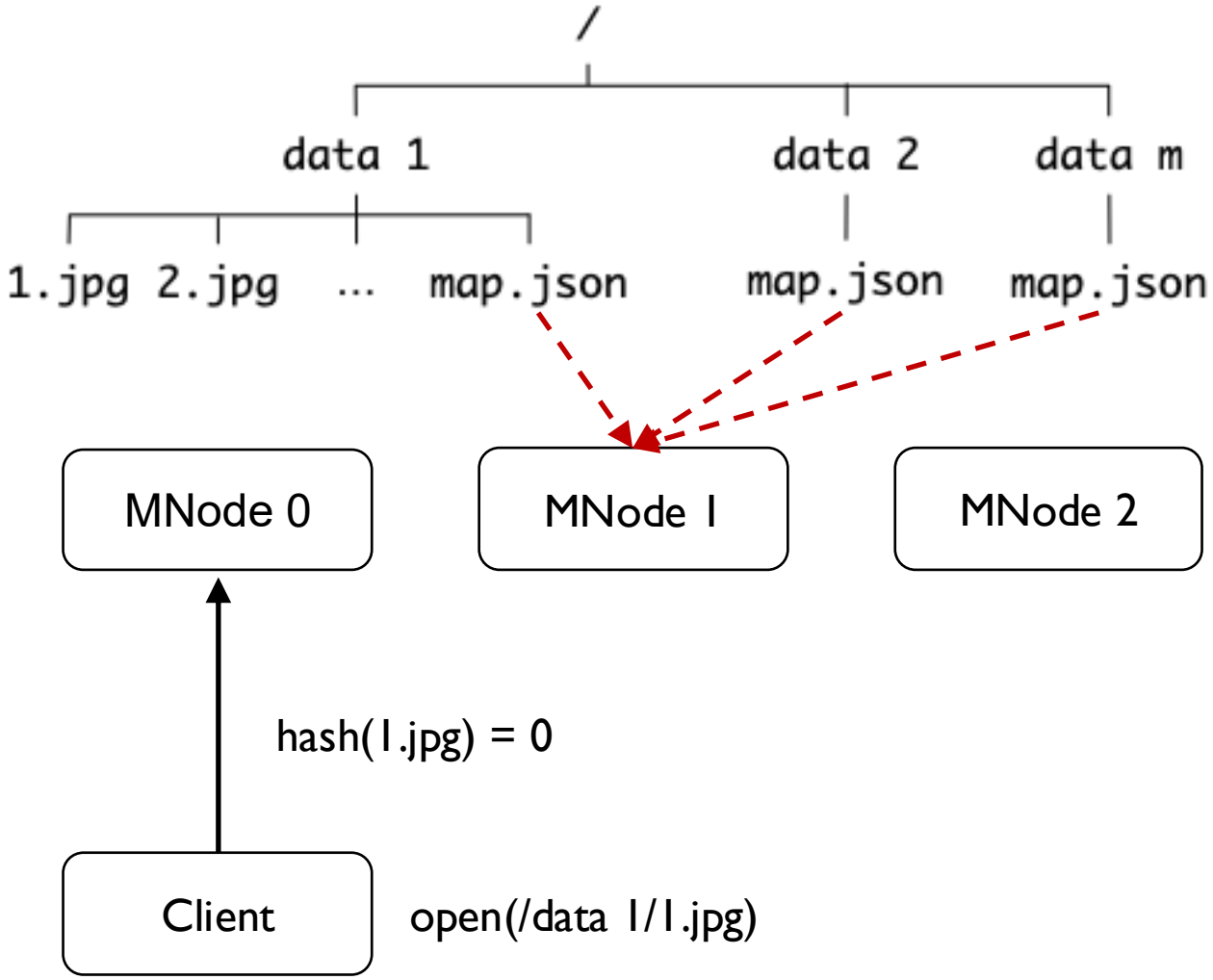
Most files are distributed evenly 😄

But

Same-name files can become hotspots ☹

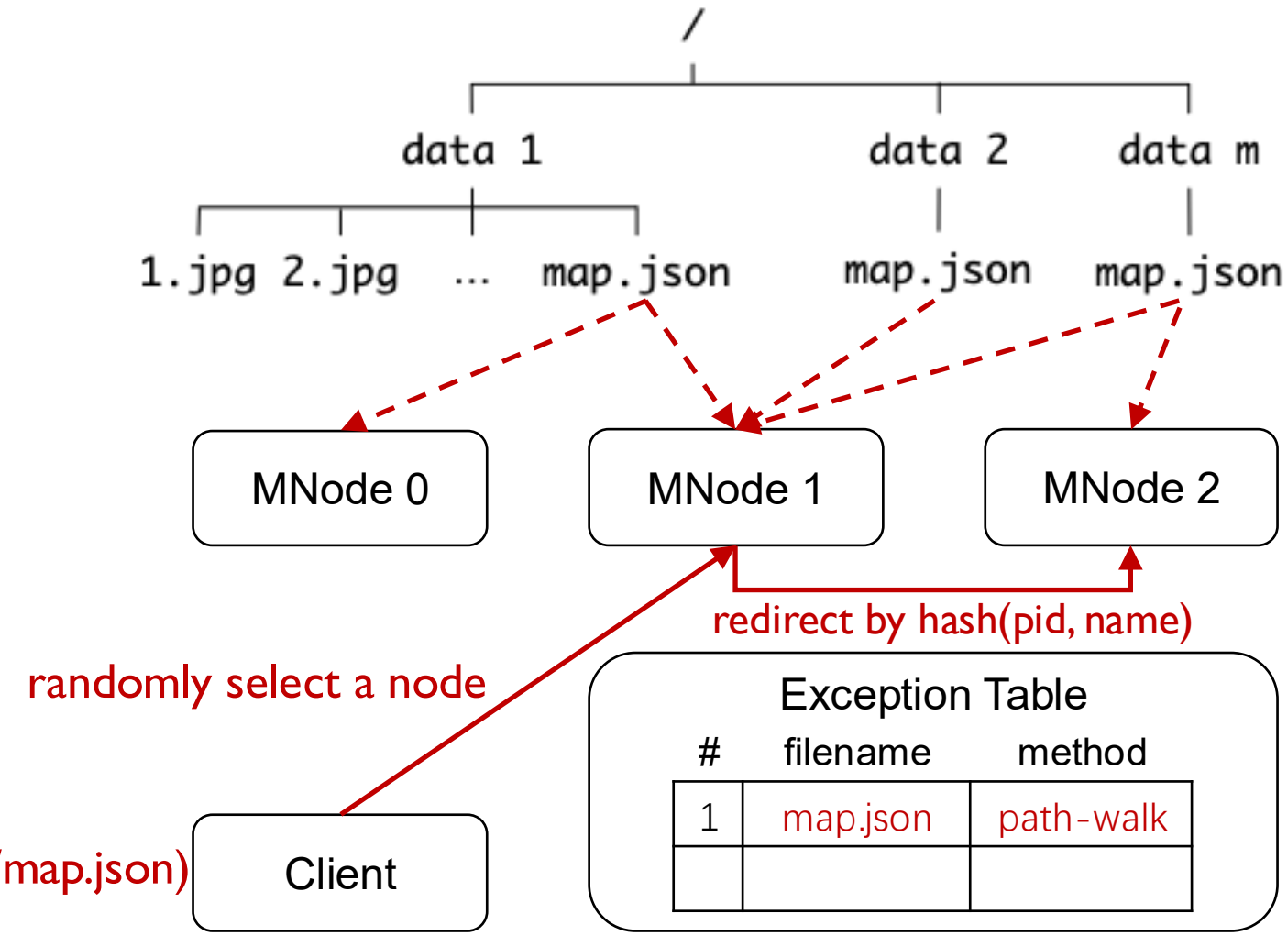


How to Locate File Inode?

Corner-case: selective redirection

Rule 1: path-walk redirection

- place inode by hash(pid, name)



How to Locate File Inode?

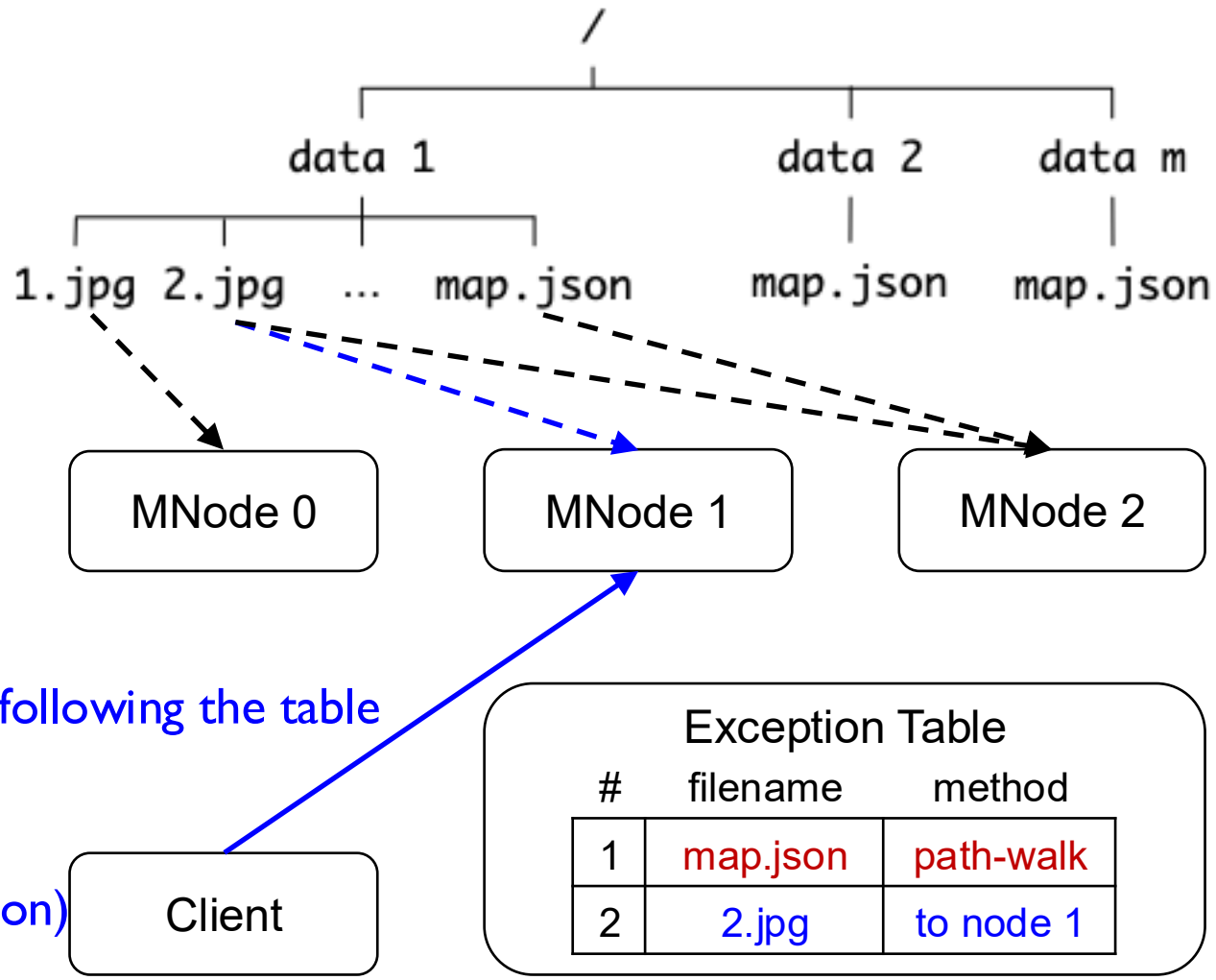
Corner-case: selective redirection

Rule 1: path-work redirection

- place inode by (pid, name)

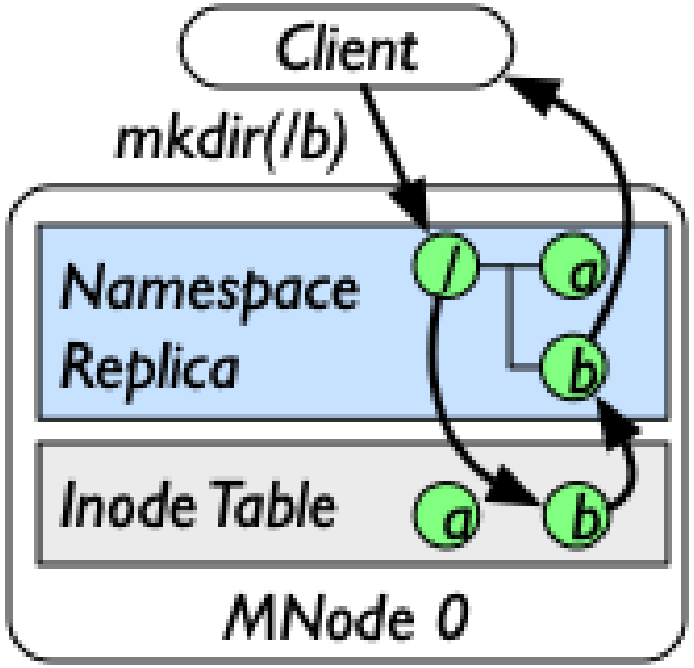
Rule 2: overriding redirection

- place inode according to table entry

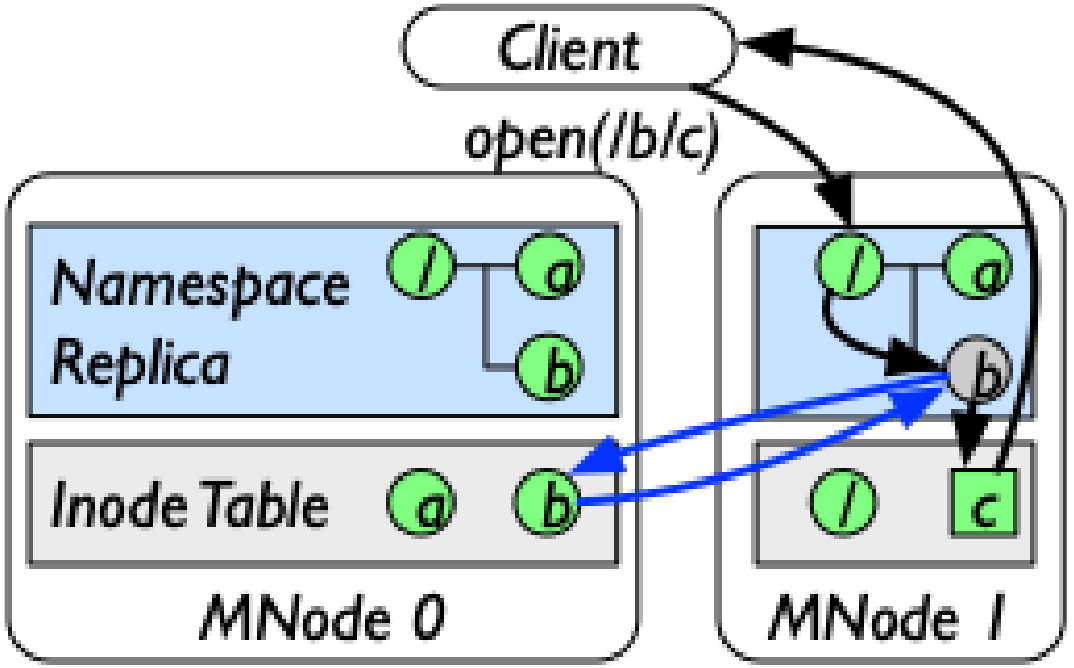


How to Manage Server-Side Namespace Replicas?

Create on a single node

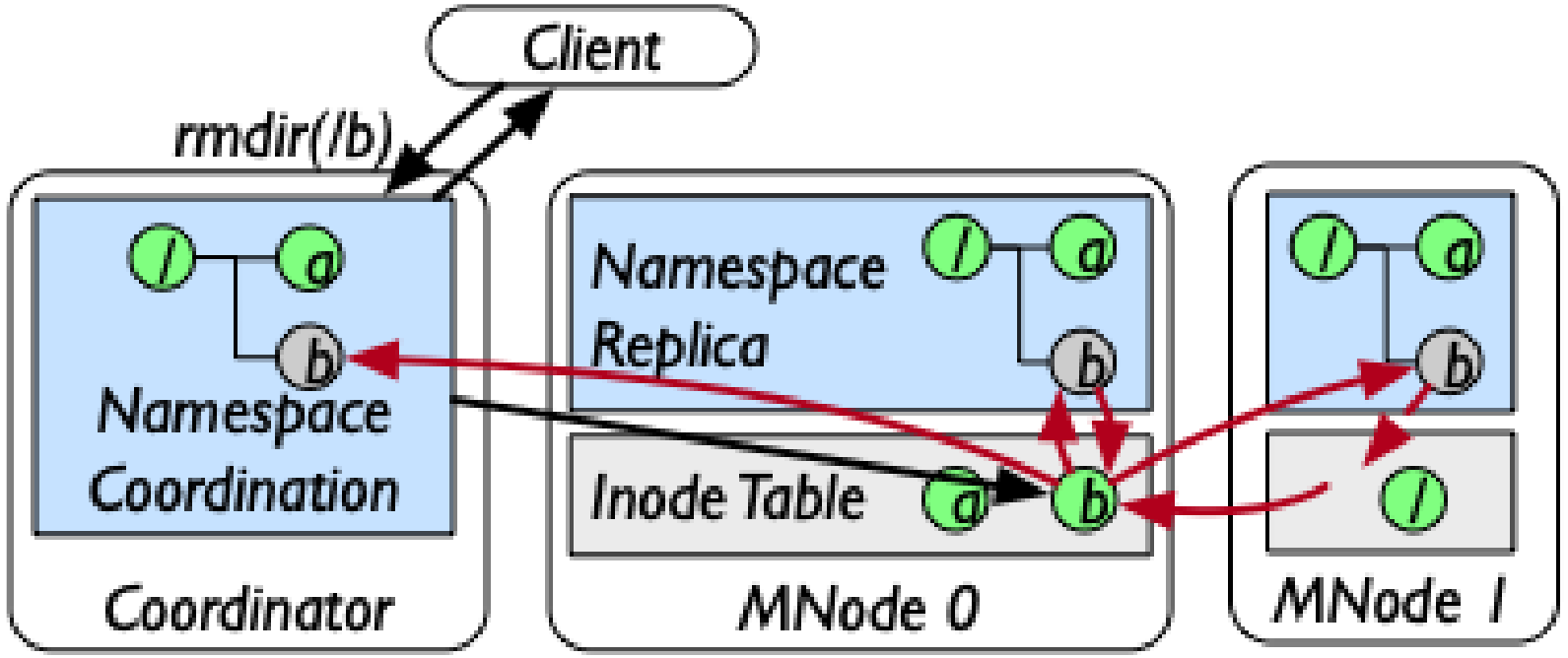


Replicate on lookup



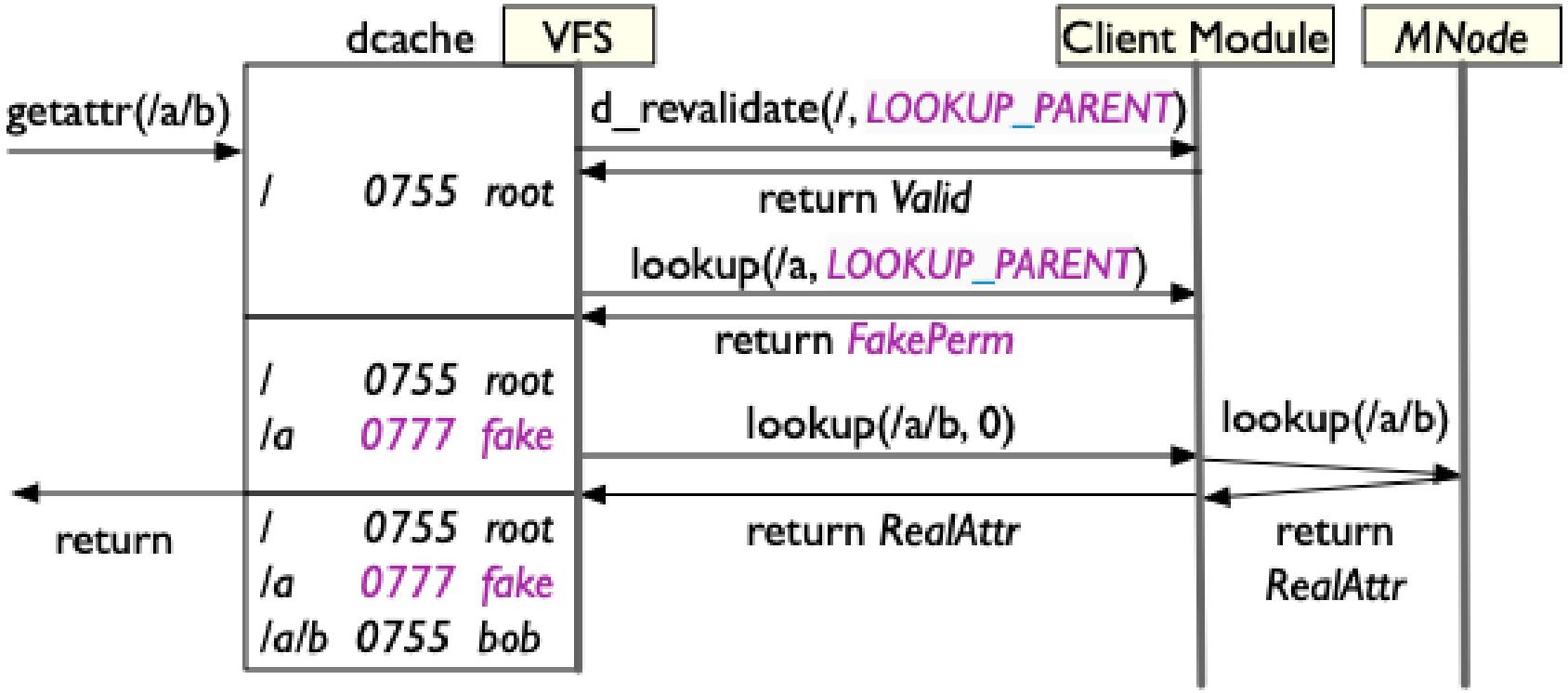
How to Manage Server-Side Namespace Replicas?

Invalidate replicas when updating the namespace



How to Implement VFS Compatibility?

- Distinguish lookups to the *intermediate* and the *last* components by leveraging *an existing flag*
- Return *FakePerm* for the intermediate lookups
- Construct the full path and perform remote lookup for the last lookups



Evaluation Setup

Hardware Platform

- 16 server nodes; 10 client nodes
- Each server node uses 4 cores

CPU	Intel Xeon Gold 5317 3.00GHz, 12 cores
Memory	8 × DDR4 2933MHz 16GB
Storage	Intel Optane Persistent Memory
Network	ConnectX-5 100GbE

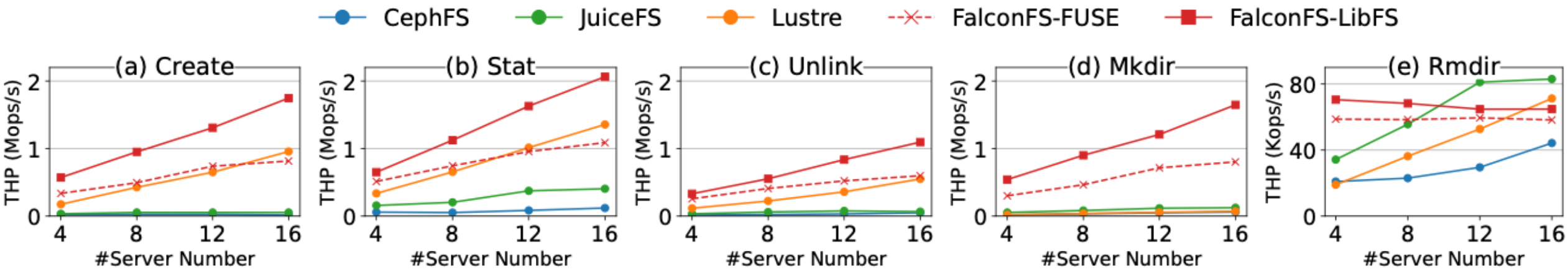
Compared Systems

- CephFS 12.2.13, JuiceFS 1.2.1, and Lustre 2.15.6
- Data and metadata replication disabled

Metadata Throughput

- Each client accesses its own private directories
- All directory lookups hit the (client-side) cache
- Saturate the performance by increasing the client thread number

Better

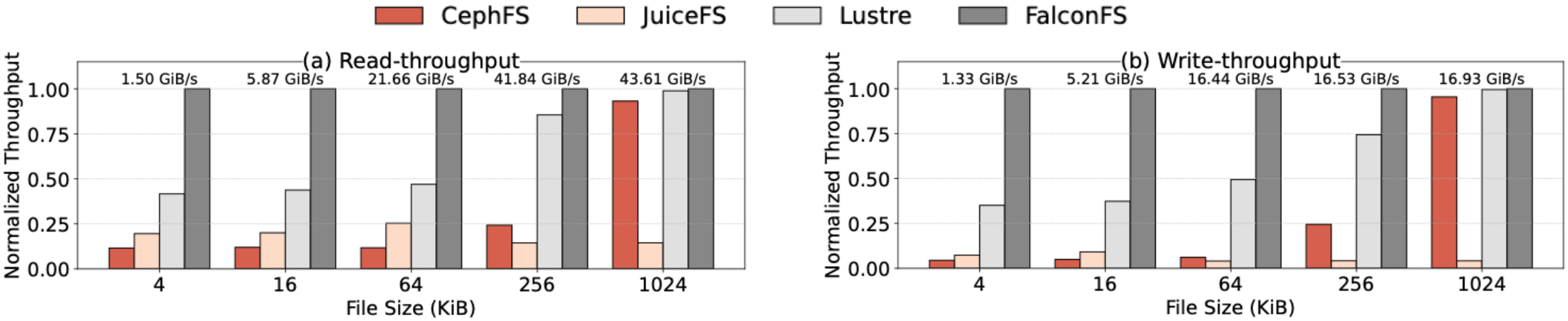


FalconFS has good basic metadata performance

Data Throughput

- Each client accesses 1024 files in its own private directories
- Saturate the performance with up to 2560 client threads
- Bypass page cache with O_DIRECT flag

Better



FalconFS's metadata advantage lead to better small file access performance

Load Balance in Real Workloads

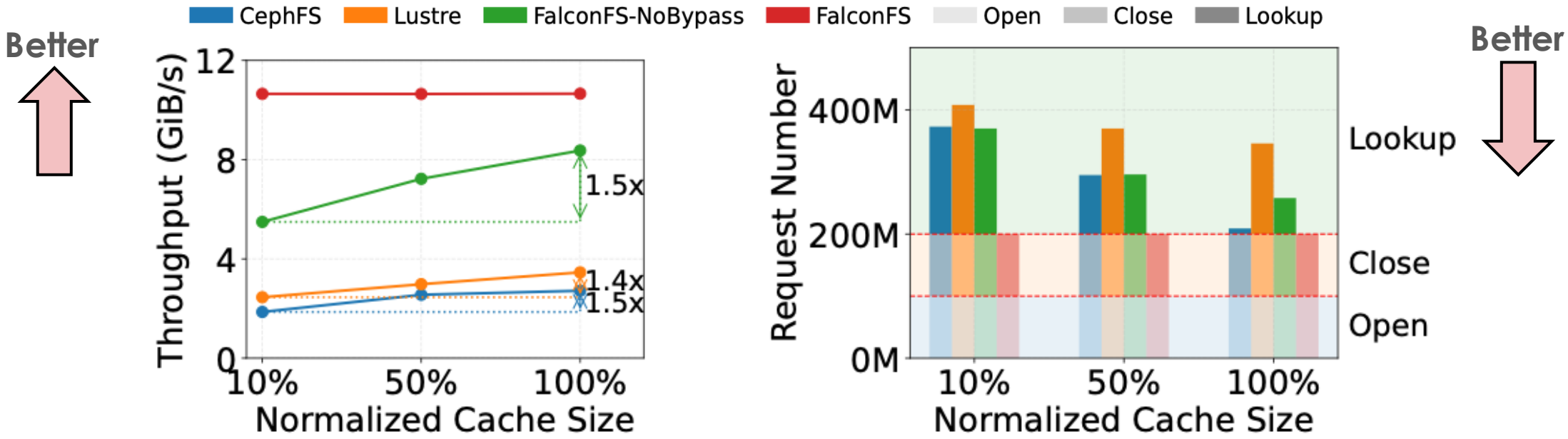
- Distribute the directory tree over 16 nodes
- In Linux-6.8 code, "Makefile" and "Kconfig" are path-walk redirected, accounting for 5.55% of all files in total
- In FSL homes, the most frequent filename accounts for 1.24% of all files

	inode #	inode distribution max	inode distribution min	exception entry # path-walk	exception entry # overriding
Labeling task	33320	6.99%	5.30%	0	0
ImageNet [17]	2027728	6.29%	6.21%	0	0
KITTI [13]	15003	7.01%	5.47%	0	0
Cityscapes [11]	20022	6.30%	6.22%	0	0
CelebA [27]	202599	6.54%	6.95%	0	0
SVHN [33]	33404	6.77%	5.76%	0	0
CUB-200-2011 [45]	12003	6.68%	5.95%	0	0
Linux-6.8 code	88936	6.49%	5.96%	2	0
FSL homes [41]	655177	6.83%	5.45%	1	0

In real workloads, FalconFS usually enjoys balanced load without redirection

Performance with Constrained Memory

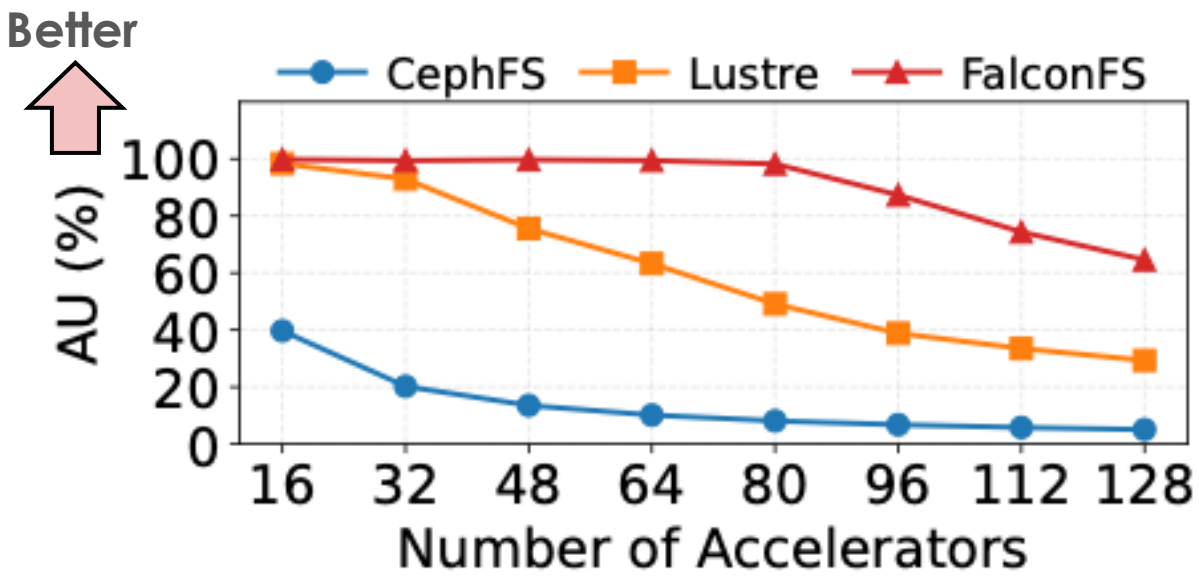
- Limit memory available to DFS client via cgroup v2 / CephFS config
- Randomly access 100 million files in 11.1 million directories

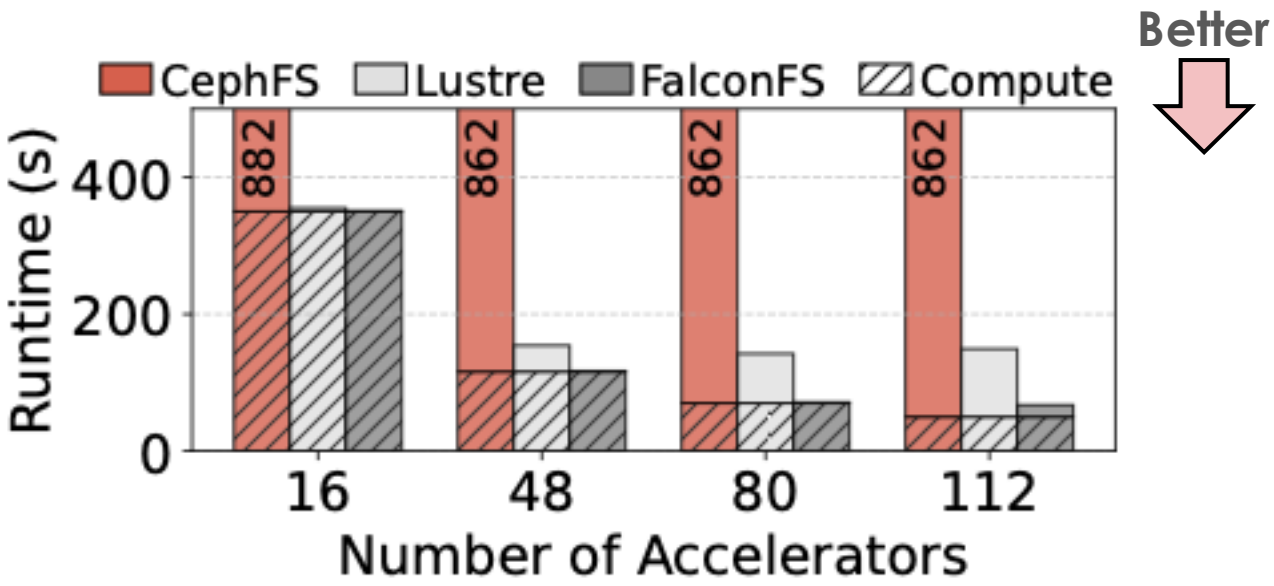


FalconFS has stably high performance when memory resources are constrained

End-to-End Evaluation

- Simulate training a ResNet-50 model
- Training set: 10 million 112 KiB files, in 1 million directories





FalconFS has stably high performance when memory resources are constrained

Conclusion

Problem

- Traditional path resolution architecture is a bottleneck for random file access

Key Techniques of FalconFS

- Hybrid metadata indexing
- Lazy namespace replication
- VFS shortcutting

Results

- Achieves stably high performance in numerous file random access workloads
- Deployed in Huawei ADS, reducing storage cost by >50%

Thanks & QA

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