SE3331-1 (2023 Fall)

Distributed file system

NFS & GFS

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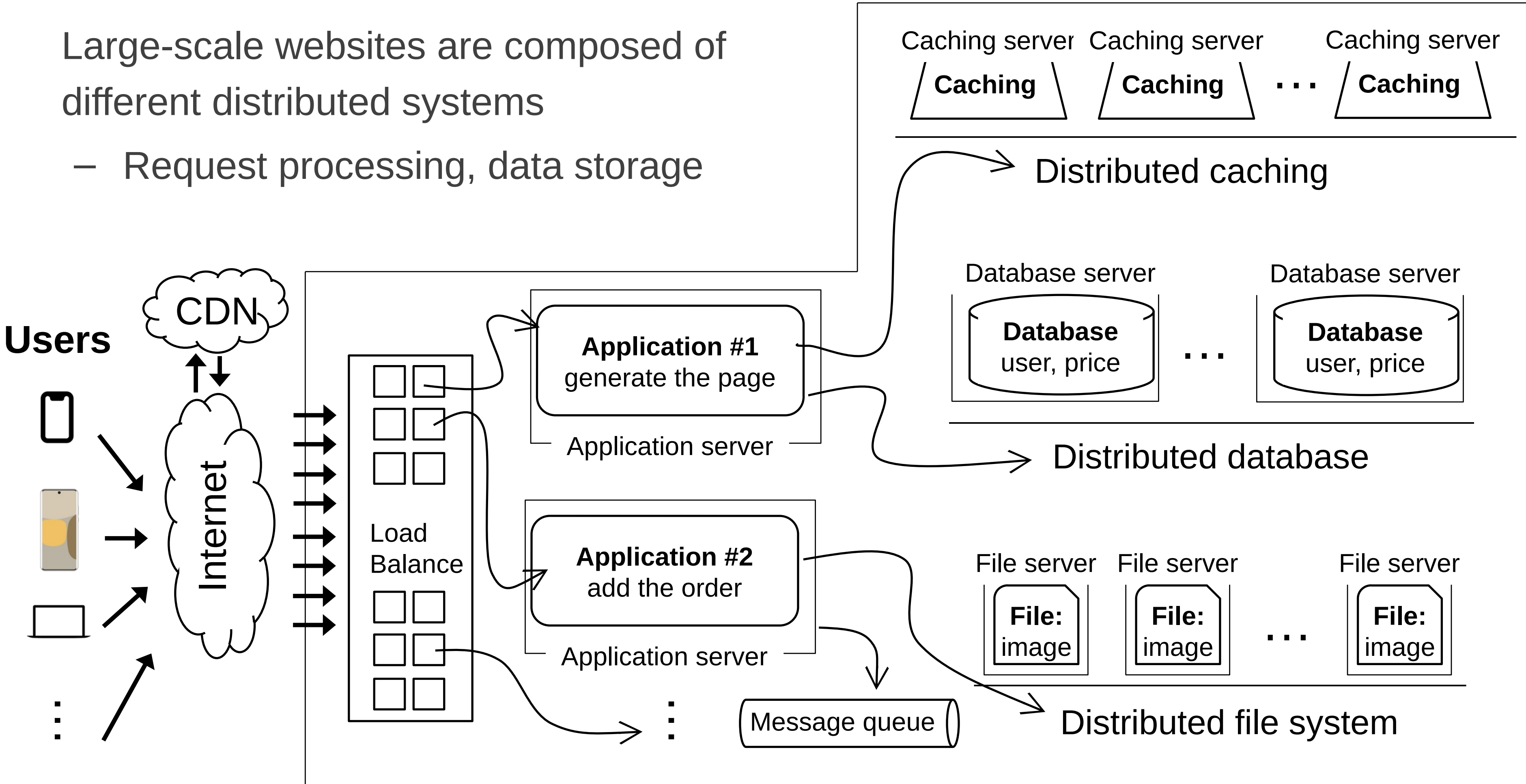
Large-scale website so-far

Large-scale websites are composed of different distributed systems

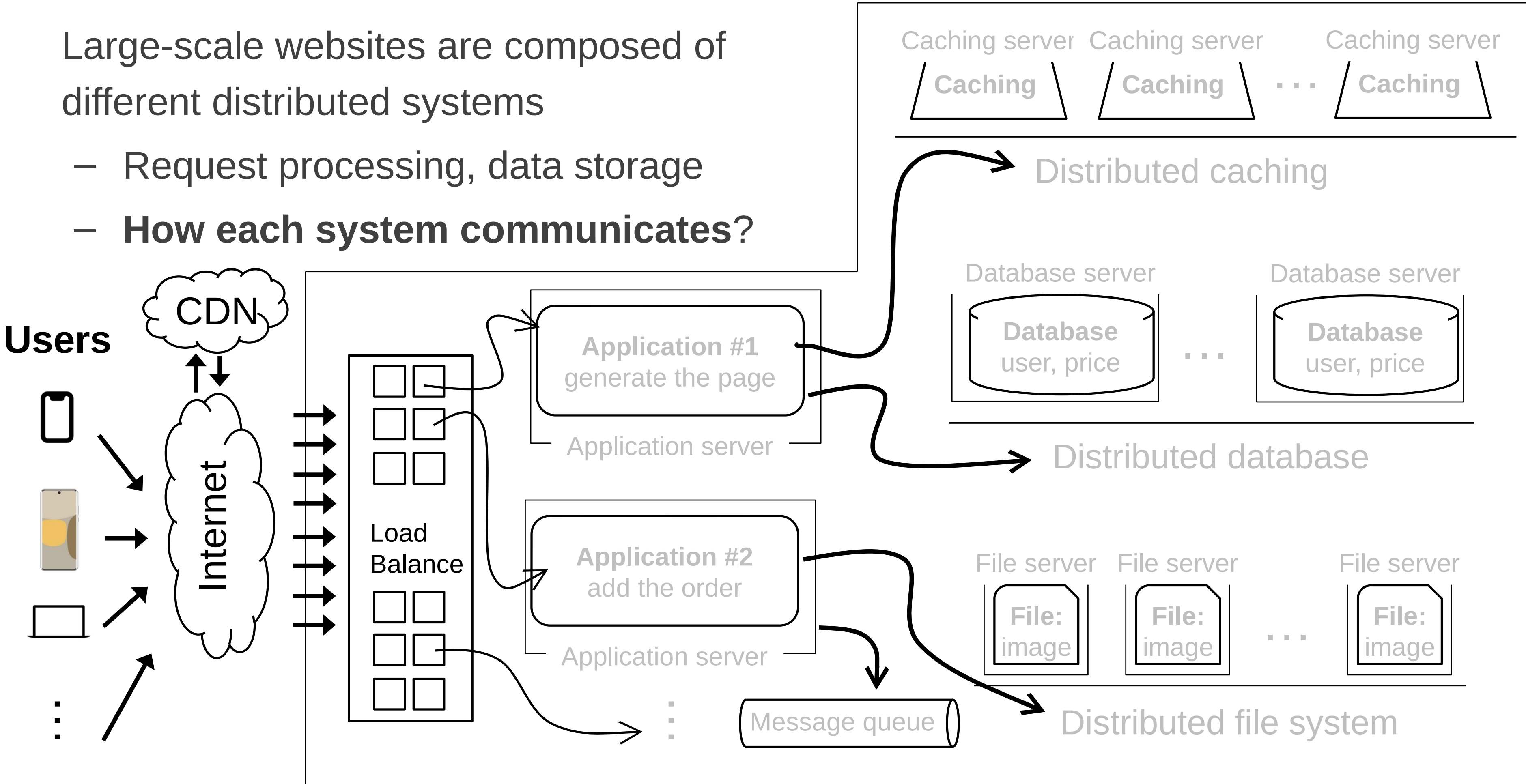
- Request processing, data storage



Large-scale website so-far

Large-scale websites are composed of different distributed systems

- Request processing, data storage
- **How each system communicates**?



Last lecture: Remote Procedure Call (RPC)

Allow a procedure to execute in another address space without coding the details for the remote interaction

RPC History

- Idea goes back in 1976

gRPC

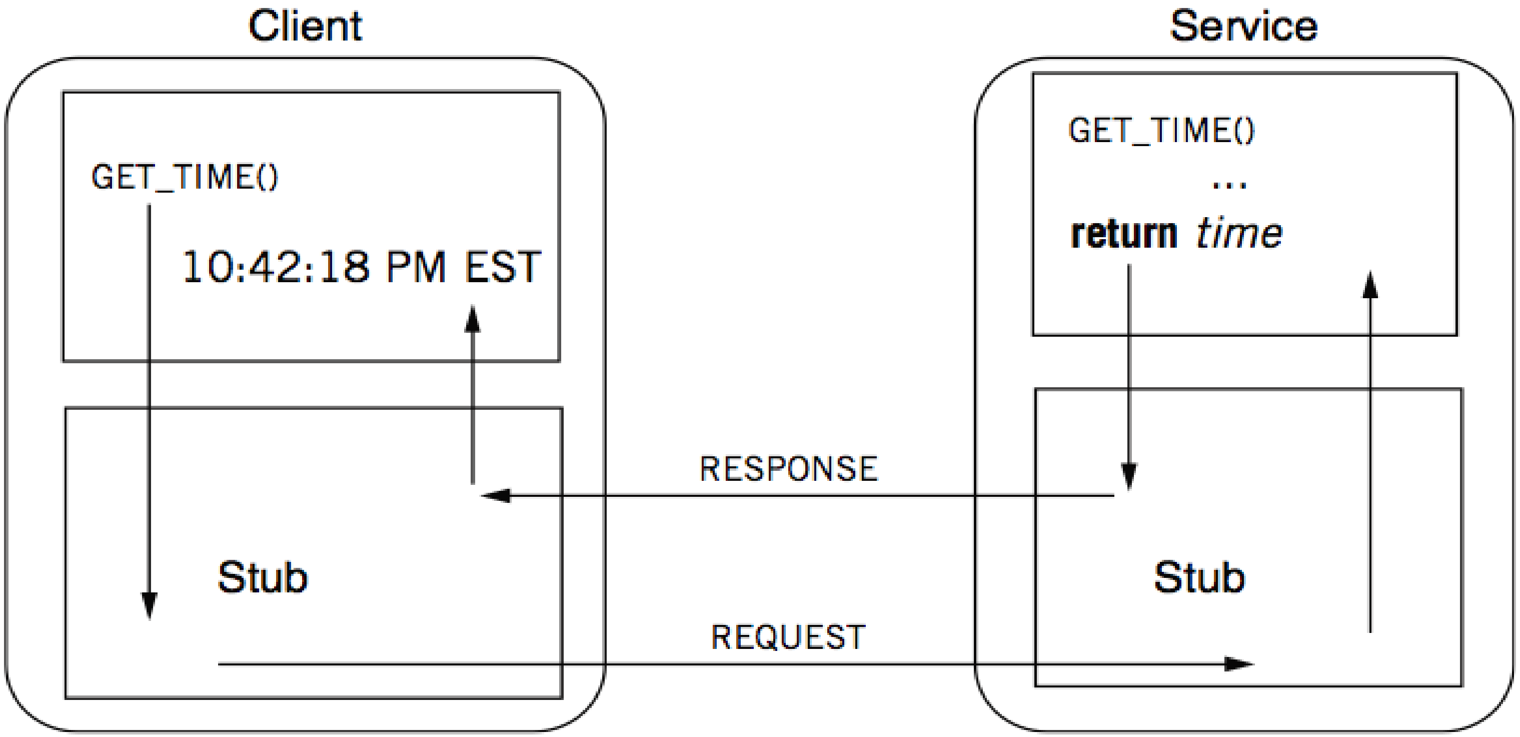
bRPC

RPC uses **stubs** to avoid handling argument **encoding/decoding** and send/receiving messages, message transports, etc.

How RPC handles **failures**?

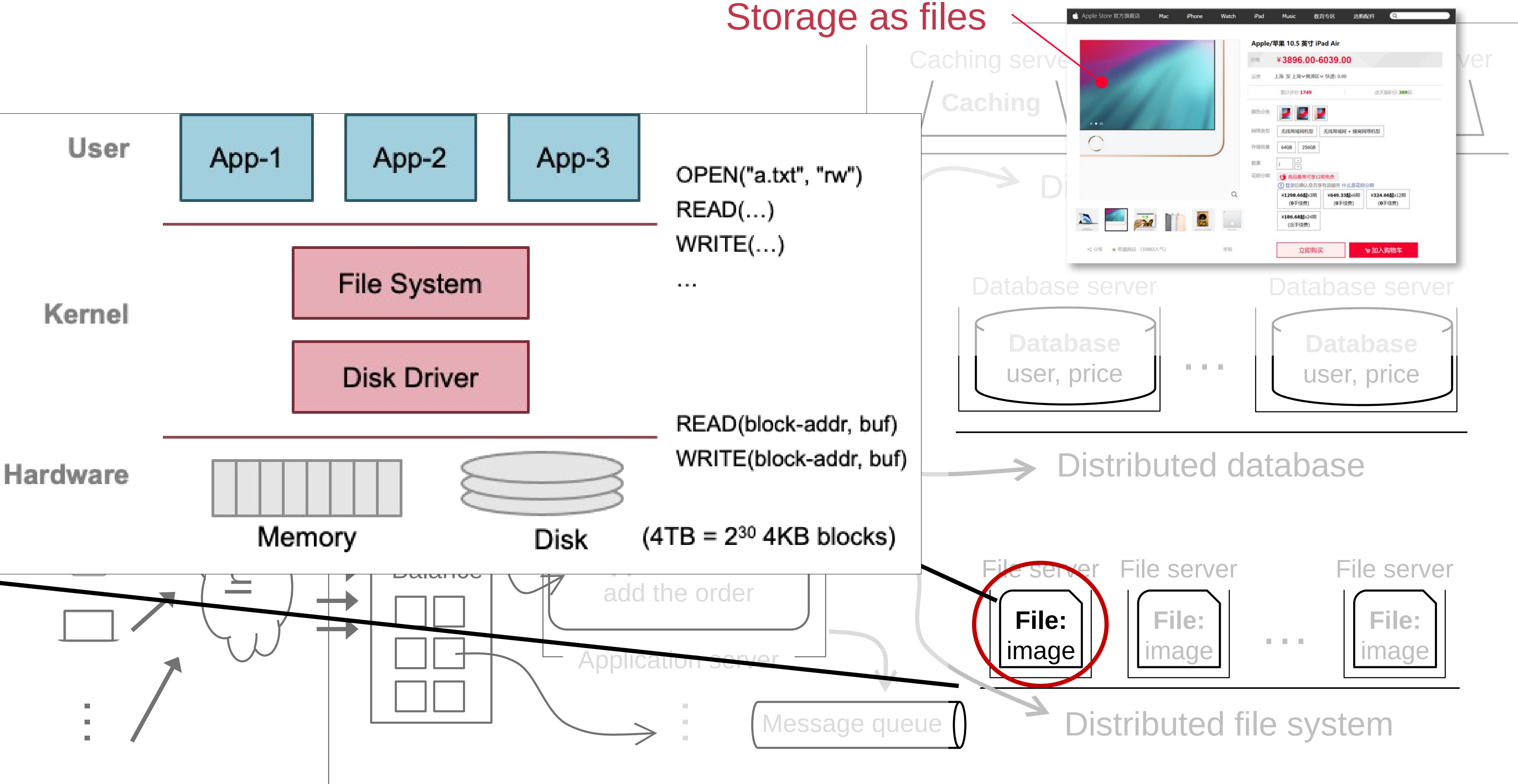
- Depends on the **semantic**: at-most-once, at-least-once & exactly-once

Review: RPC -- a complete calling process



Previous lecture: single-machine file system

Storage as files



OPEN("a.txt", "rw")
READ(…)
WRITE(…)
…

READ(block-addr, buf)
WRITE(block-addr, buf)

(4TB = 2^{30} 4KB blocks)

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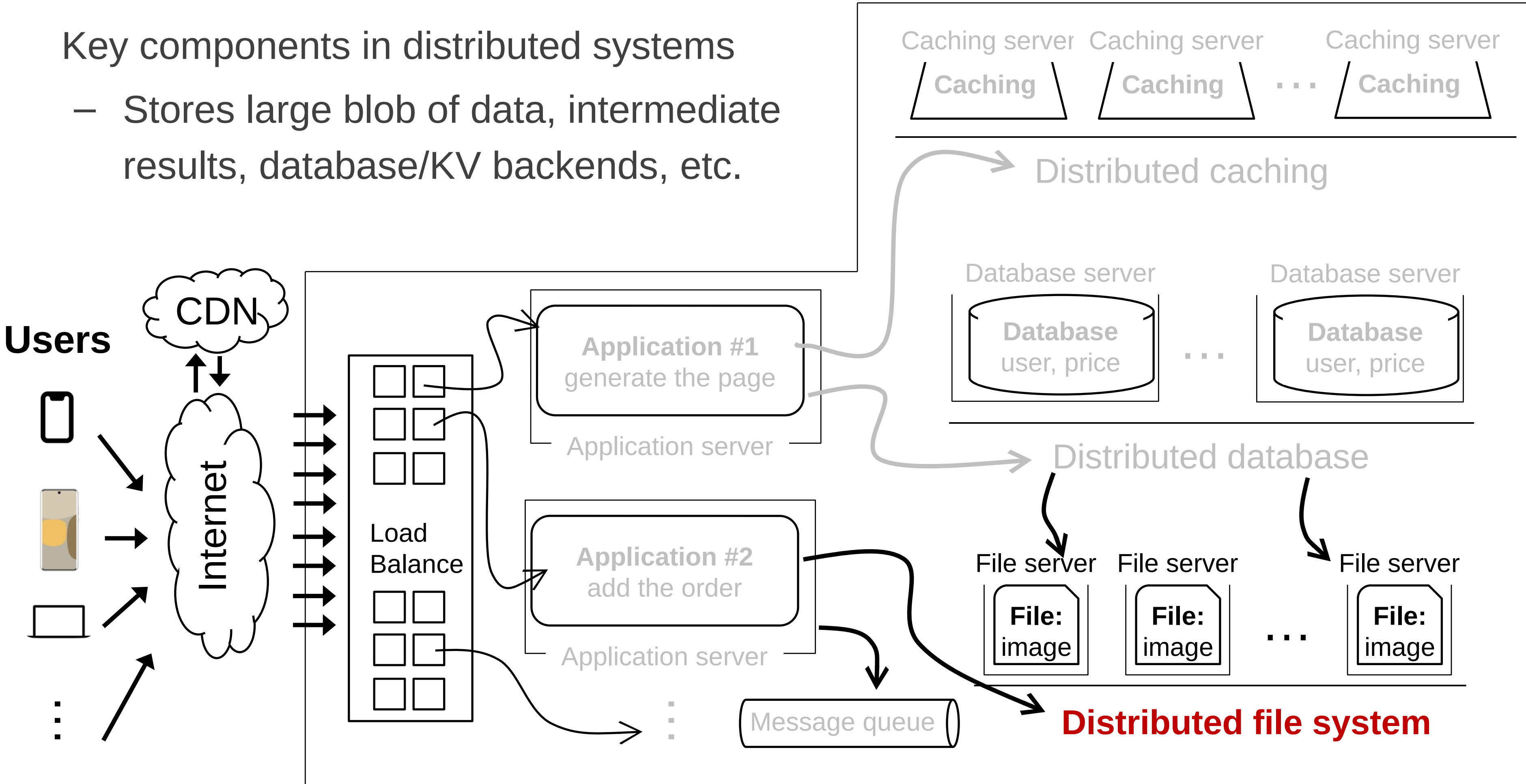
With the help of RPC

We can now build distributed file system!

Distributed file system

Key components in distributed systems

- Stores large blob of data, intermediate results, database/KV backends, etc.



Ways for accessing remote files

Many familiar ways, **FTP**, **telnet**, …

- Explicit access (knowing it is a distributed file system)
- User-directed connection to access remote resource

There is also transparent approach

- E.g., NFS, GFS, etc.
- Applications access the remote files like a local file

Distributed File Service Types

Upload/Download model

- Read file: copy file from server to client
- Write file: copy file from client to server

Advantage

- Simple

Problem

- **Wasteful** “what if client needs small pieces?”
- **Problematic** “what if client does not have enough space?”
- **Consistency** “what if others modify the same file?”

Distributed File Service Types

Remote access model

- File service provide functional interface with RPC (`create, delete, read, write`, etc.)

Advantage

- Client gets only what's needed
- Server can manage a consistent view of file system

Problem

- Possible server and network problem (e.g., congestion)
    - Servers are accessed for duration of file access
    - Same data may be requested repeatedly

NFS with RPC

NFS: Network File System

Design Goals (by Sun, 1980s, designed for workstations)

- Any machine can be a client or a server
- Support **diskless** workstations
- Support **Heterogeneous** deployment
  - Different HW, OS, underlying file system
- Access **transparency**
  - Use remote access model
- Recovery from **failure**
  - Stateless, UDP, client retries
- High **performance**
  - Use caching and read-ahead

RPC used in NFS

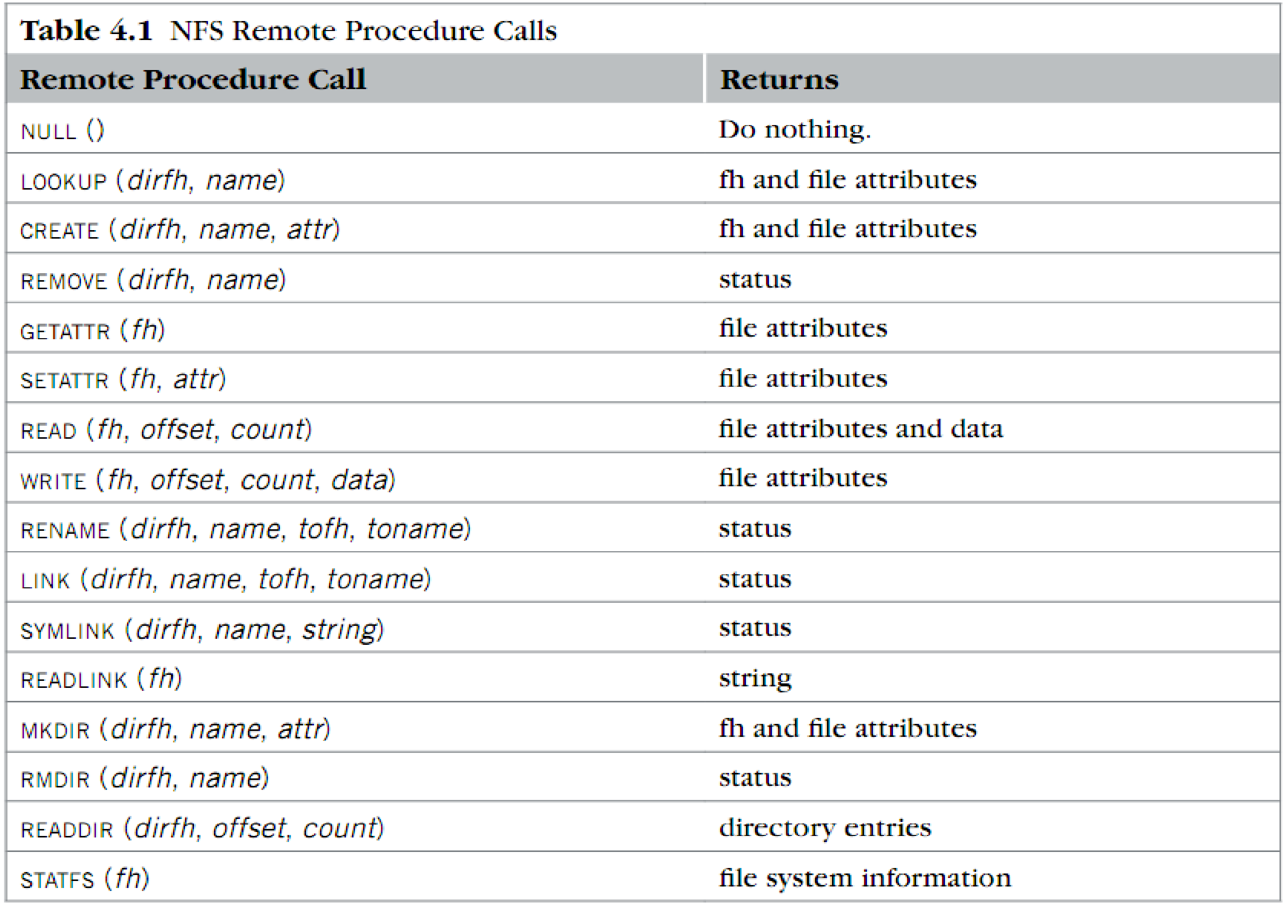


Table 4.1 NFS Remote Procedure Calls

Remote Procedure Call	Returns
NULL ()	Do nothing.
LOOKUP (*dirfh, name*)	fh and file attributes
CREATE (*dirfh, name, attr*)	fh and file attributes
REMOVE (*dirfh, name*)	status
GETATTR (*fh*)	file attributes
SETATTR (*fh, attr*)	file attributes
READ (*fh, offset, count*)	file attributes and data
WRITE (*fh, offset, count, data*)	file attributes
RENAME (*dirfh, name, tofh, toname*)	status
LINK (*dirfh, name, tofh, toname*)	status
SYMLINK (*dirfh, name, string*)	status
READLINK (*fh*)	string
MKDIR (*dirfh, name, attr*)	fh and file attributes
RMDIR (*dirfh, name*)	status
READDIR (*dirfh, offset, count*)	directory entries
STATFS (*fh*)	file system information

Where is OPEN and CLOSE?

NFS Protocols: Mount

Protocol:

- Request access to exported directory tree
    - Requests **permission** to access contents

Client: parses **pathname**
contacts server for file **handle**

- Server returns **file handle (fh)**

Client: create in-memory VFS **inode** (vnode) at
mount point internally points to remote files
(client keeps state, not the server)

NFS Protocols: `Mount`

Static mounting

- mount request contacts server

Server: add list of shared directories to /etc/exports

Client:

```
mount 192.168.1.100:/users/paul /home/paul
```

NFS Protocols: `Lookup/READ/WRITRE...`

Directory and File **Access** Protocol:

- Access files and directories (`read, mkdir`, ...)

First, perform a lookup RPC

- Returns file handle and attributes

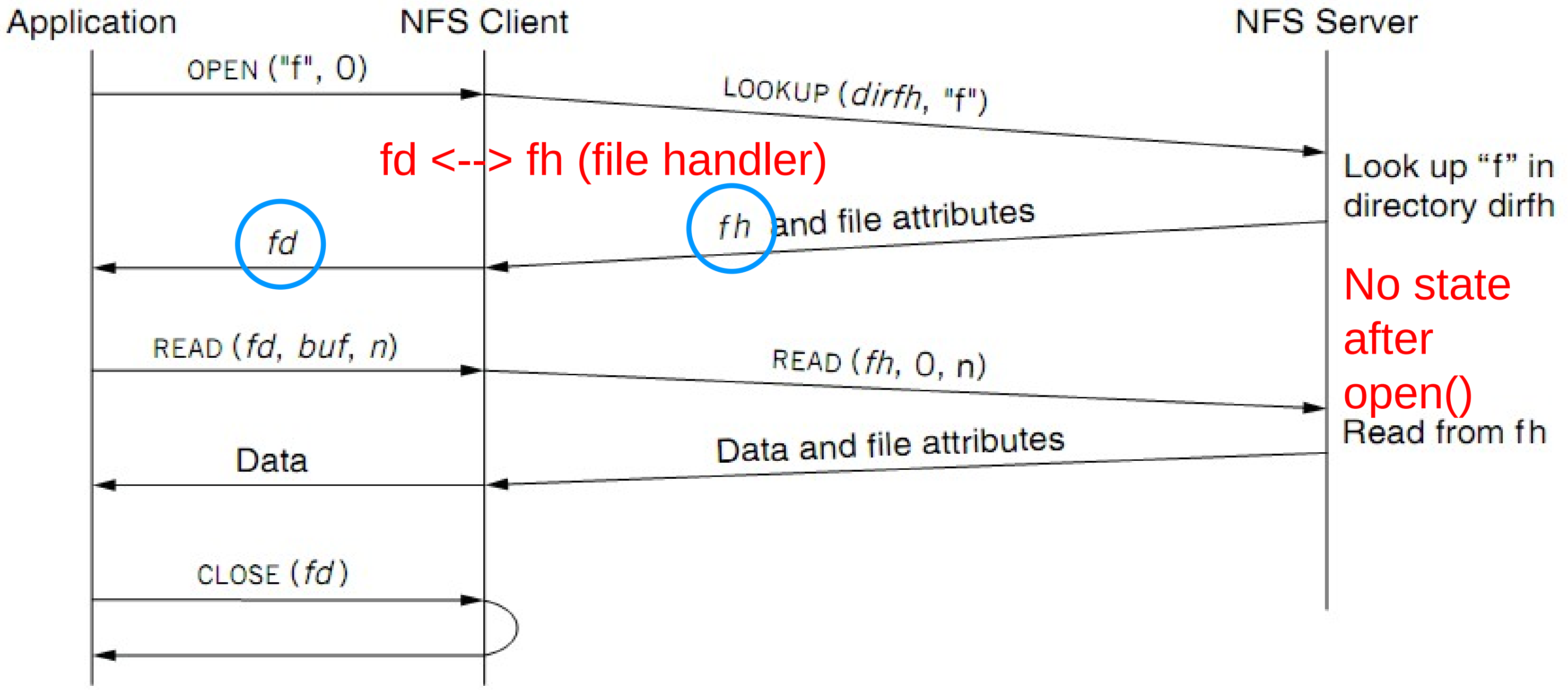
`lookup` is not like `open`

- Establish state on the client **only** (no information on server)
- Call the **NFS** lookup function

The **handle** passed as a parameter for other file access function

- e.g., `read(handle, offset, count)`

Read a file of NFS



fd <--> fh (file handler)

No state after open()

NFS Protocols: Lookup/READ/WRITRE...

NFS has 16 functions (version 2)

null
lookup

create
remove
rename

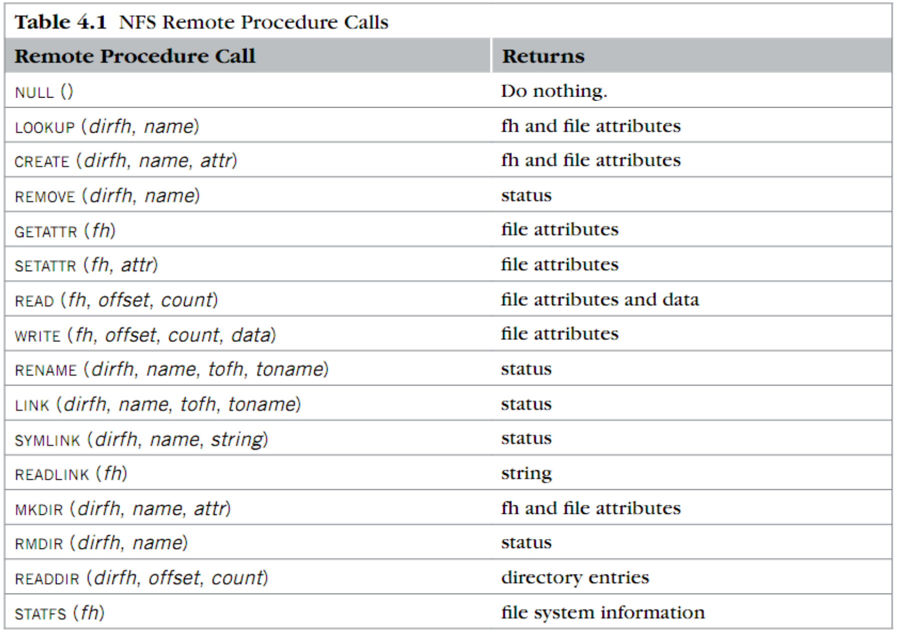
read
write

link
symlink
readlink

mkdir
rmdir
readdir

getattr
setattr

statfs



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RENAME (*dirfh, name, tofh, toname*)	status
LINK (*dirfh, name, tofh, toname*)	status
SYMLINK (*dirfh, name, string*)	status
READLINK (*fh*)	string
MKDIR (*dirfh, name, attr*)	fh and file attributes
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STATFS (*fh*)	file system information

File Handler for a Client

File handler contains three parts

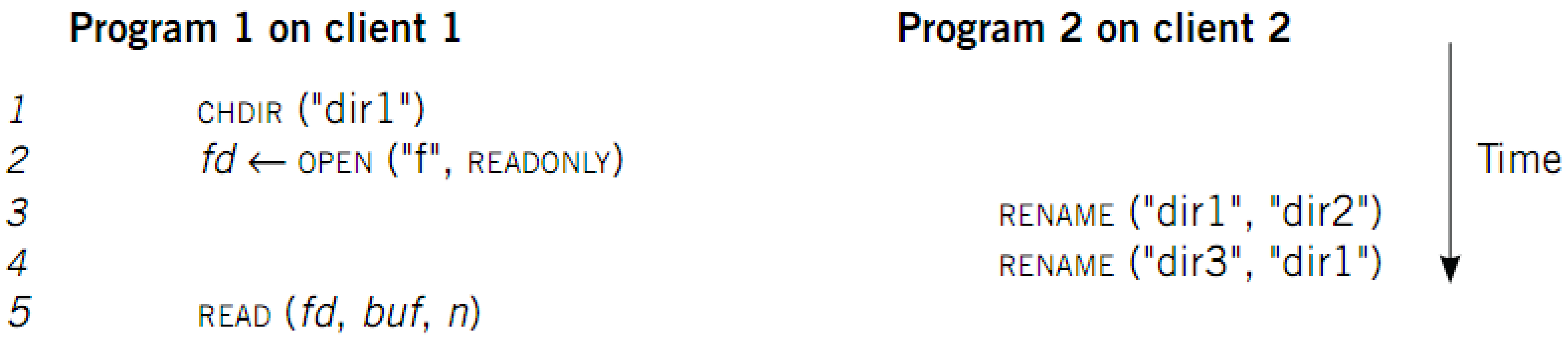
- **File system identifier**: for server to identify the file system
- **inode number**: for server to locate the file
- **Generation number**: for server to maintain consistency of a file

Can still work across server failures

- E.g., server reboot

Q: Why not put path name in the handle?

Case 1: Rename After Open



	Program 1 on client 1	Program 2 on client 2
1	CHDIR ("dir1")	
2	*fd* ← OPEN ("f", READONLY)	
3		RENAME ("dir1", "dir2")
4		RENAME ("dir3", "dir1")
5	READ (*fd*, *buf*, *n*)	

UNIX Spec:

- Program 1 should read "dir2/f"
- NFS should keep the spec

Stateless on NFS server

Stateless on NFS server

- Each RPC contains all the information

Q: What about states like file cursor?

- Client maintains the states, including the file cursor

Client can repeat a request until it receives a reply (at least once)

- Server may execute the same request twice
- Solution: each RPC is tagged with a transaction number, and server maintains some "soft" state: reply cache
- **Q**: What if the server fails between two same requests?

Case 2: Delete After Open

	Program 1 on client 1	Program 2 on client 2
1		*fd* ← OPEN ("f", READONLY)
2	UNLINK ("f")	
3	*fd* ← OPEN ("f", CREATE)	
4		READ (*fd*, *buf*, *n*)

UNIX spec:

- On local FS, program 2 will read the old file

How to avoid program 2 reading new file?

- Generation number
- "stale file handler"

Not the same as UNIX spec! It's a tradeoff...

NFS performance

Usually **slower** than local

- Question: depends on what?

File server performance & network speed

Optimization: **caching** at client

- **Goal**: reduce number of remote ops
- Caching: `read, readlink, getattr, lookup, readdir`
  1. Cache file data at client (buffer cache)
  2. Cache file attribute information at client
  3. Cache pathname bindings for faster lookup

Server side

- Caching is “automatic” via buffer cache
- All NFS writes are write-through to disk

Problem: cache coherence

Type-1: <u>Read/write coherence</u>

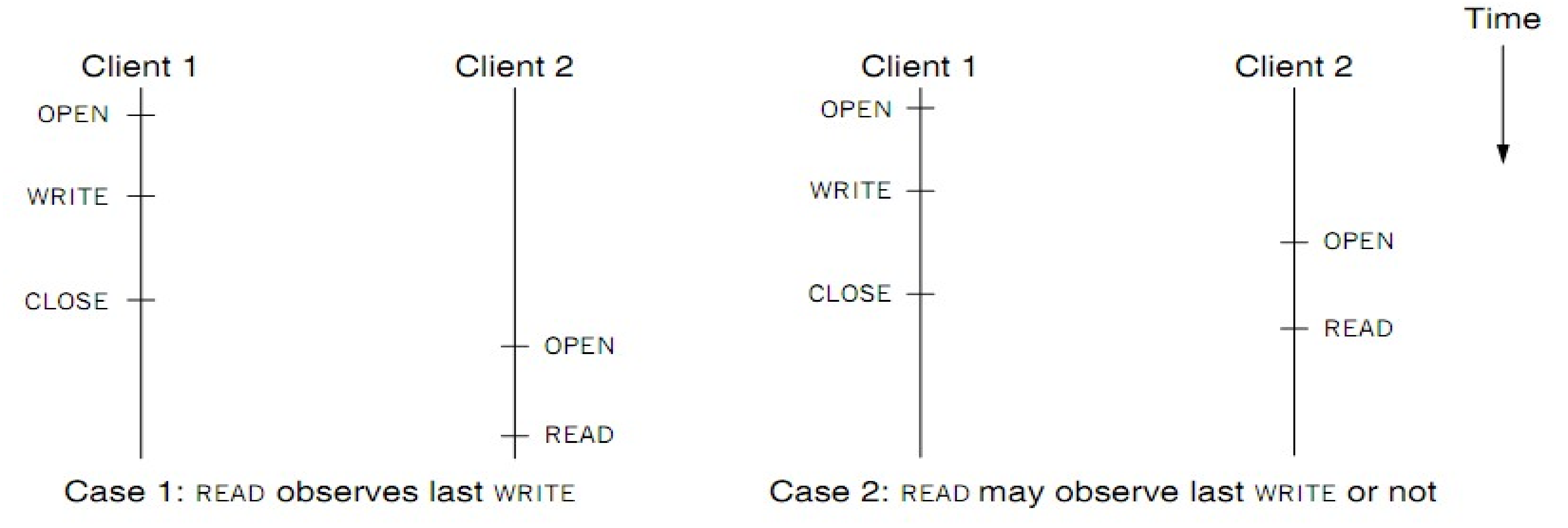
- On local file system, **READ** gets newest data
- On NFS, client has cache
- NFS could guarantee read/write coherence for every operation, or just for certain operation

Type-2: <u>Close-to-open consistency</u>

- Higher data rate
- **GETATTR** when **OPEN**, to get last modification time
- Compare the time with its cache
- When **CLOSE**, send cached writes to the server

Coherence

Two cases of close-to-open consistency



More contents of consistency in later lectures

VFS: Extend the inode-based FS to support NFS

Vnode

- Abstract whether a file or directory is local or remote
- In volatile memory (why?)
- Support several different local file system
- Where should vnode layer be inserted?

Vnode API

- Same as we learnt: OPEN, READ, WRITE, CLOSE…
- Code of fd_table, current dir, file name lookup, can be moved up to the file system call layer

Validation

Inconsistencies may arise in NFS

Resolve **inconsistencies** with **validation**

Both server and client save **timestamp** of files

When file opened or server contacted for new

1. Compare last modification time
2. If remote is more recent, invalidate cached data

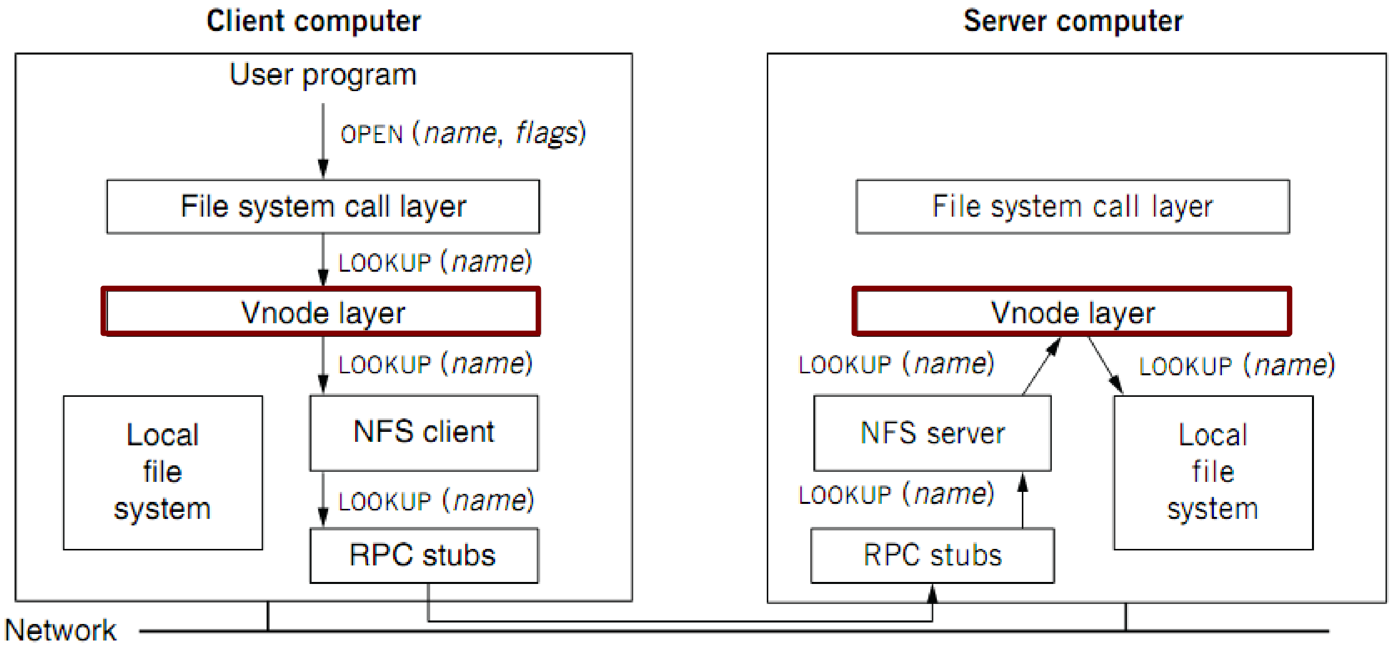
Always **invalidate** data after some time

– `open` files (3 sec), `directories` (30 sec)

If data block is modified, it is:

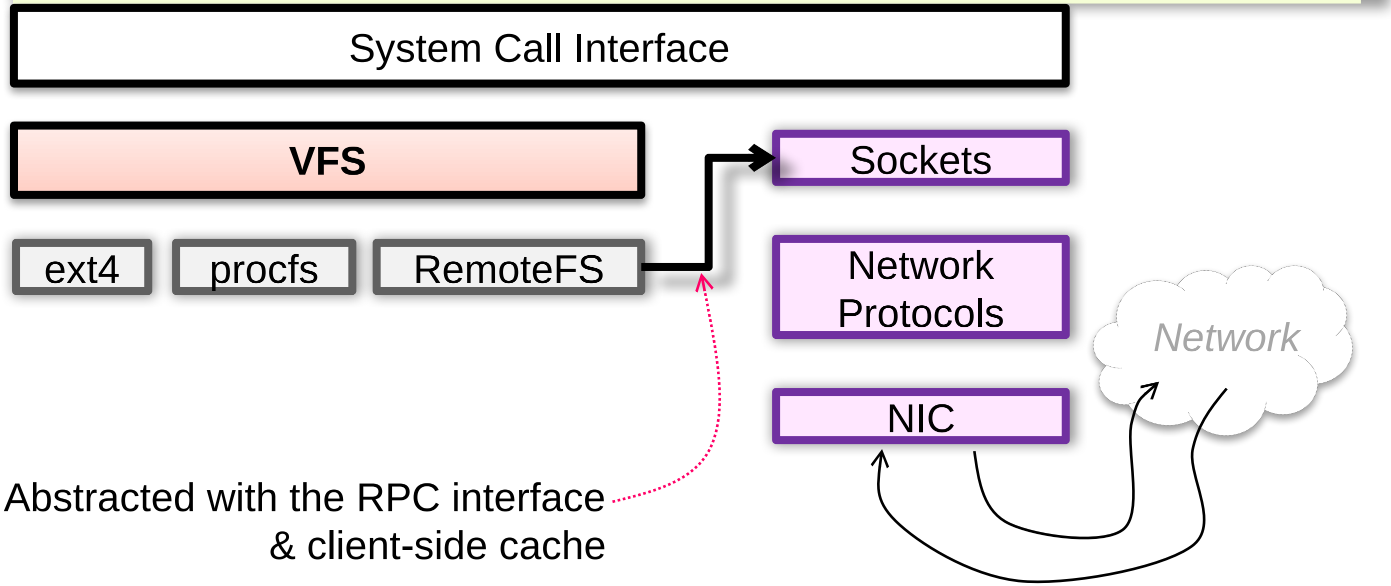
– Marked **dirty**, then flushed on file `close`

VFS: Extend the inode-based FS to support NFS



Accessing Remote Files

Implement the client module as a FS under VFS



Abstracted with the RPC interface
& client-side cache

Improving Read Performance

Transfer data in large chunks

- 8KB default

Read-ahead

- Optimize for sequential file access
- Send requests to read disk blocks before they are requested by the applications

NFS is continuously improving

Version 3

User-level lock manager

NVRAM support

Adjust RPC retries dynamically

Client-side disk caching

Support 64-bit file sizes

TCP support and large-block transfers

Commit operation

…

Version 4

More state: control of caching, notify of file changes

Server export a single name space (pseudo file system)

Compound RPC support

Extended attribute and ACL

Negotiate security mechanism on mount

…

Reference Materials

RFC 1831: RPC Specification

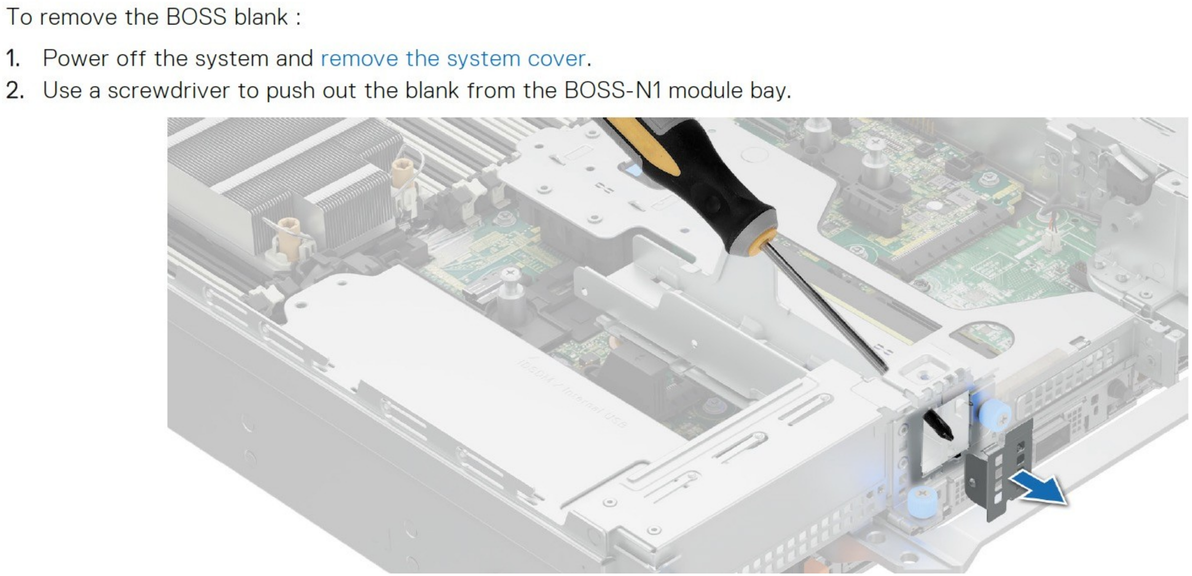
- http://www.ietf.org/rfc/rfc1831.txt?number=1831

RFC 1832: XDR Specification

- http://www.ietf.org/rfc/rfc1832.txt?number=1832

Drawback of NFS

1. **Capacity**
   - Can only disks on a single server, which has a limited capacity to insert disks



To remove the BOSS blank :

1. Power off the system and remove the system cover.
2. Use a screwdriver to push out the blank from the BOSS-N1 module bay.

Drawback of NFS

1. **Capacity**

   – Can only disks on a single server, which has a limited capacity

2. **Reliability**

   – If the server crashes, the remote files are unavailable

3. **Performance**

   – The file performance is limited to a single file (and a single network bandwidth)

Observation: plenty of available servers in a datacenter

Plenty of machines in a datacenter

- E.g., much cheaper than a high-end server

Idea: utilis multiple machines to form a single, large distributed file system

- We can leverage the aggregated capacity of all the machines!

Naïve solution: do manual partitioning

- User decides which files / directories are stored on which server
- Not so good: dates back to the FTP case ⏪

Design goal: transparent remote file accesses

We don’t want the developers to manage which file store on which server

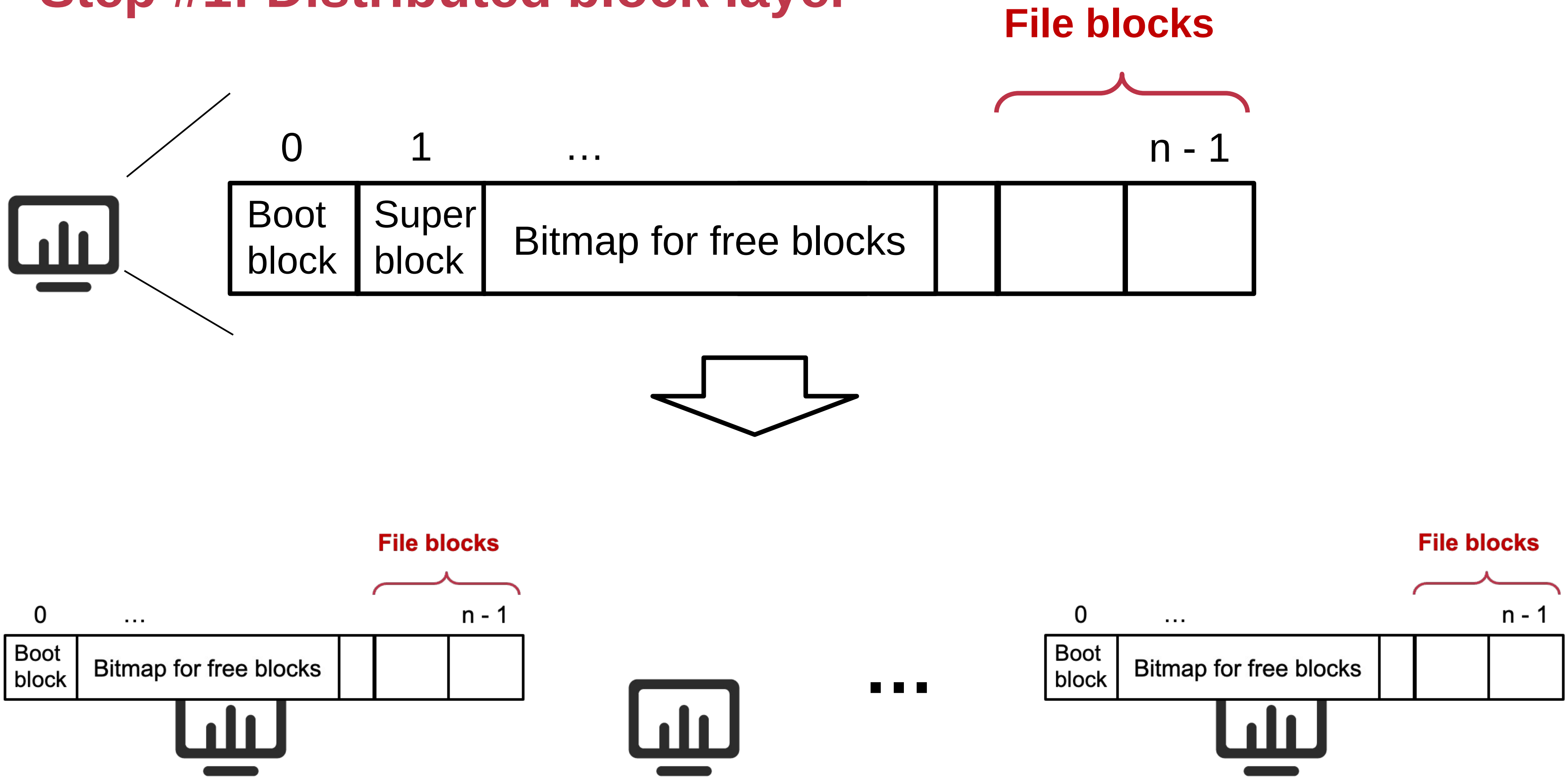
- It is difficult to the developers
- Also, does not support existing applications

But, it means that we cannot reuse the inode-based filesystem implementations

- Nevertheless, the overall principles are the same, e.g., we still needs things like block layer, inode layer, etc.

We will see many challenges faced by distributed systems during our journal ⏪

Step #1: Distributed block layer



Step #1: Distributed block layer

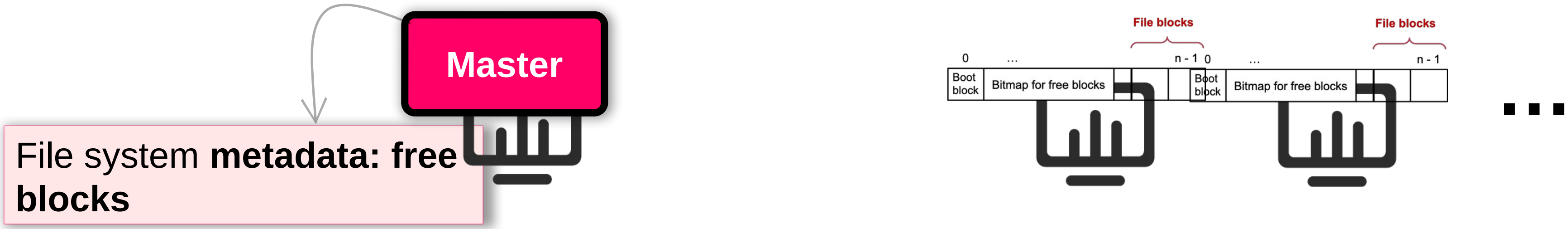
File (inode)	Block num	Disk Block

Q1. How to access the block in a distributed setting?

- Simple, we can extend the block_id to <mac_id, block_id>

Q2. Second, how can a client know which machine has a free block?

- Sol#1. select a random server; if it has free block, then we are done; if not, retry until we can find one.
- Sol#2. use a master server to record the free blocks at each machine, and all the block allocation & deallocation go to the master



File system **metadata: free blocks**

L2: File Layer: do we need a redesign?

File (inode)	Block num	Disk Block

Recall: Given an inode, can map a block index number (of a file) to a block number (of a disk)

- Index number: e.g., the 3rd block of a file is number 78

No need for now for now for functionality, since we can access the blocks

- With our previous designed distributed layer

There are some other issues, e.g., performance, reliability, consistency, etc.

- We will back to these example later

L3: Distributed inode Number Layer

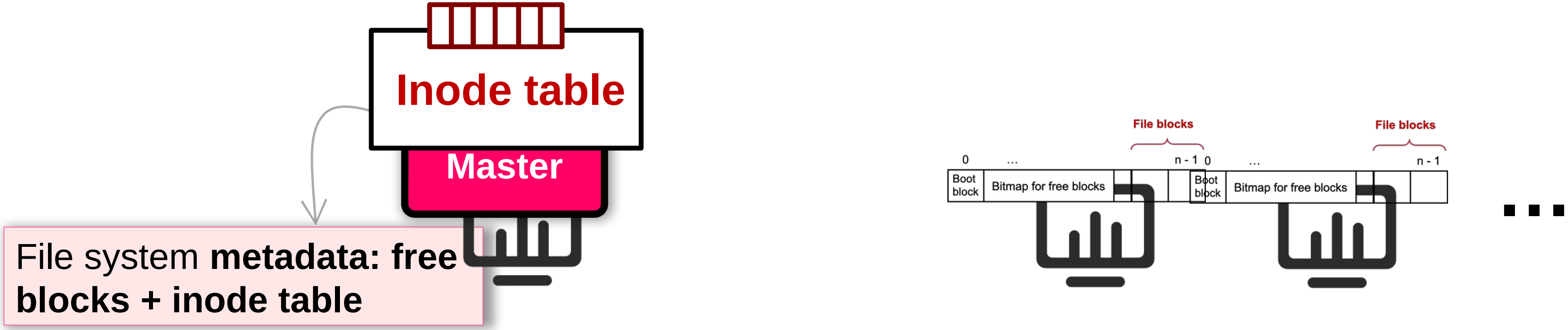
Inode num	File (inode)	Block num	Disk Block

Mapping: **inode number -> inode**

inode table: at a fixed location on storage

- inode number is the index of inode table
- Track which inode number are in use, e.g. free list, a field in inode

Distributed inode number layer: store the inode table at the master!



File system **metadata: free blocks + inode table**

L4: File Name Layer

File name	Inode num	File (inode)	Block num	Disk Block

File name

- Hide metadata of file management
- Files and I/O devices

```
struct inode
  integer block_nums[N]
  integer size
  integer type
```

Mapping

- Mapping table is saved in directory
- Default context: **current working directory**
  - Context reference is an inode number
  - The current working directory **is also a file**

Overview of inode content

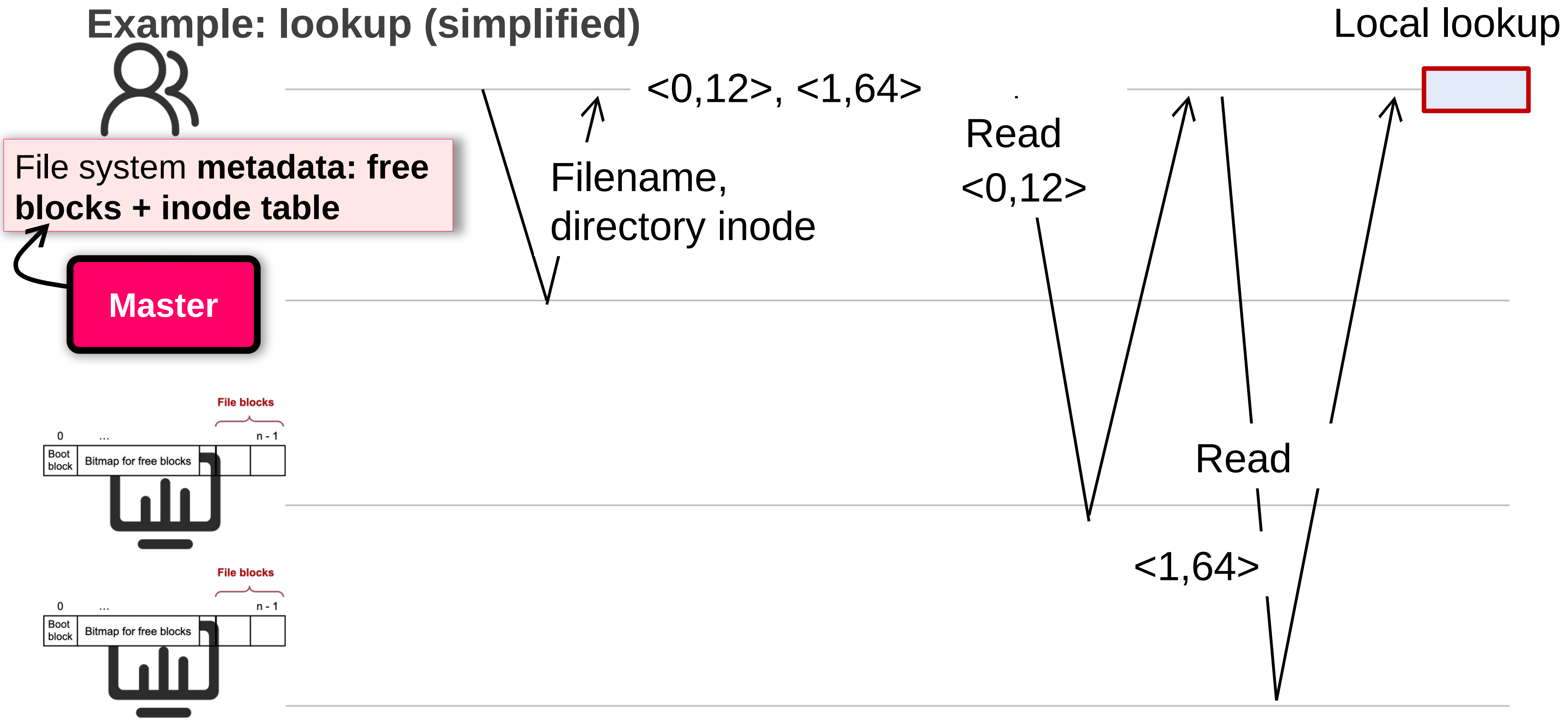
File name	inode num
helloworld.txt	12
cse2021.md	73

Question

- Do we need to extend it to a distributed setup? So far, so good!

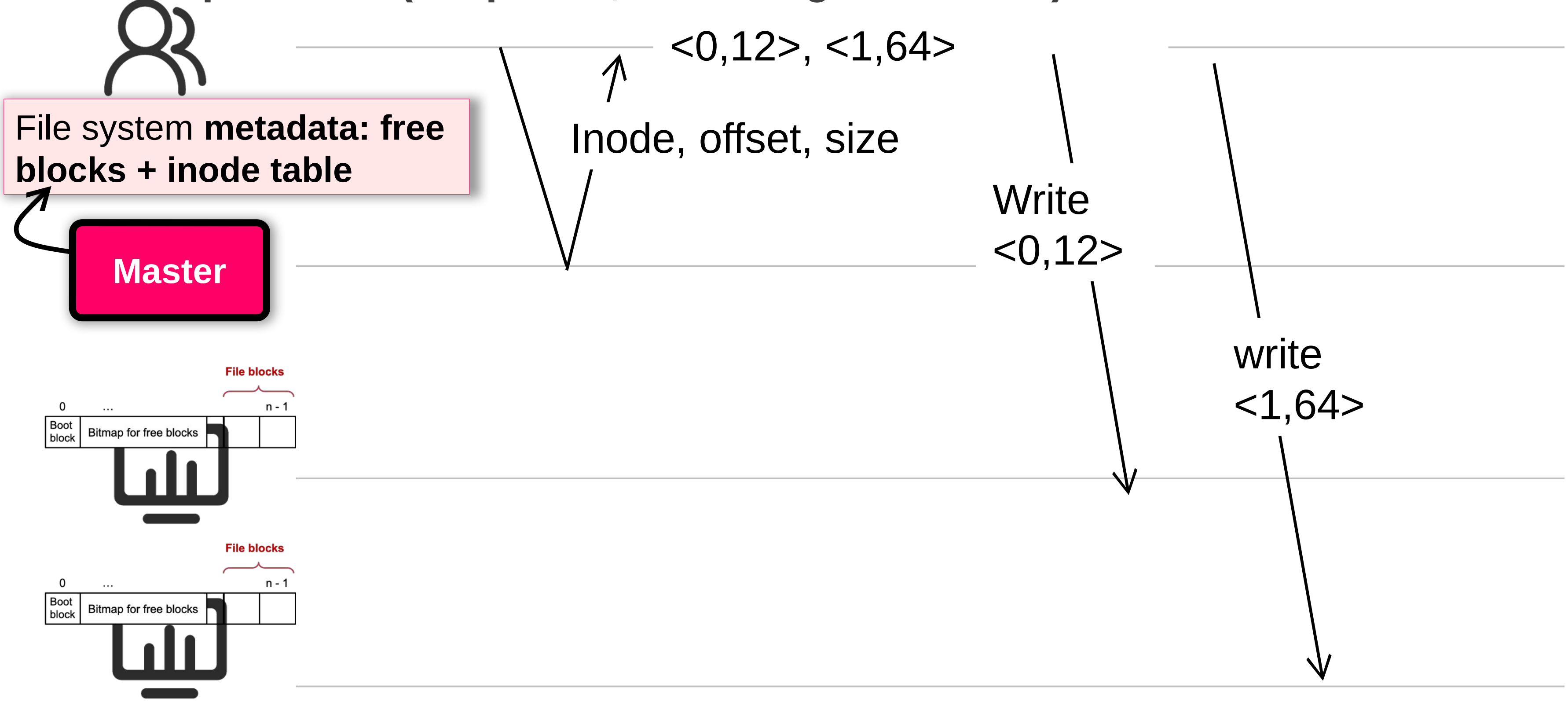
Put the distributed file layers so far together

Example: lookup (simplified)



Put the distributed file layers so far together

Example: write (simplified, assuming no blocks)



File system **metadata: free blocks + inode table**

Master

Inode, offset, size

<0,12>, <1,64>

Write <0,12>

write <1,64>

L5: Path Name Layer

Path name	File name	Inode num	File (inode)	Block num	Disk Block

Hierarchy of directories and files

- Structured naming: E.g. "projects/paper"

```
procedure PATH_TO_INODE_NUMBER(string path, integer dir)-> integer
    if PLAIN_NAME(path) return NAME_TO_INODE_NUMBER(path,dir)
    else
        dir <- LOOKUP(FIRST(path), dir)
        path <- REST(path)
        return PATH_TO_INODE_NUMBER(path,dir)
```

Context: the working directory **`dir`**

If we have the lookup, then we can also do the path lookup ⏪

Issues of our naïve design so far

Performance

- E.g., path lookup is slow due to multiple RTTs
- Though we can use cache, like we have done in NFS ⏪
- But, what about data in a file? If the read is large, it uses many blocks, so many servers needed to be communicated

Reliability

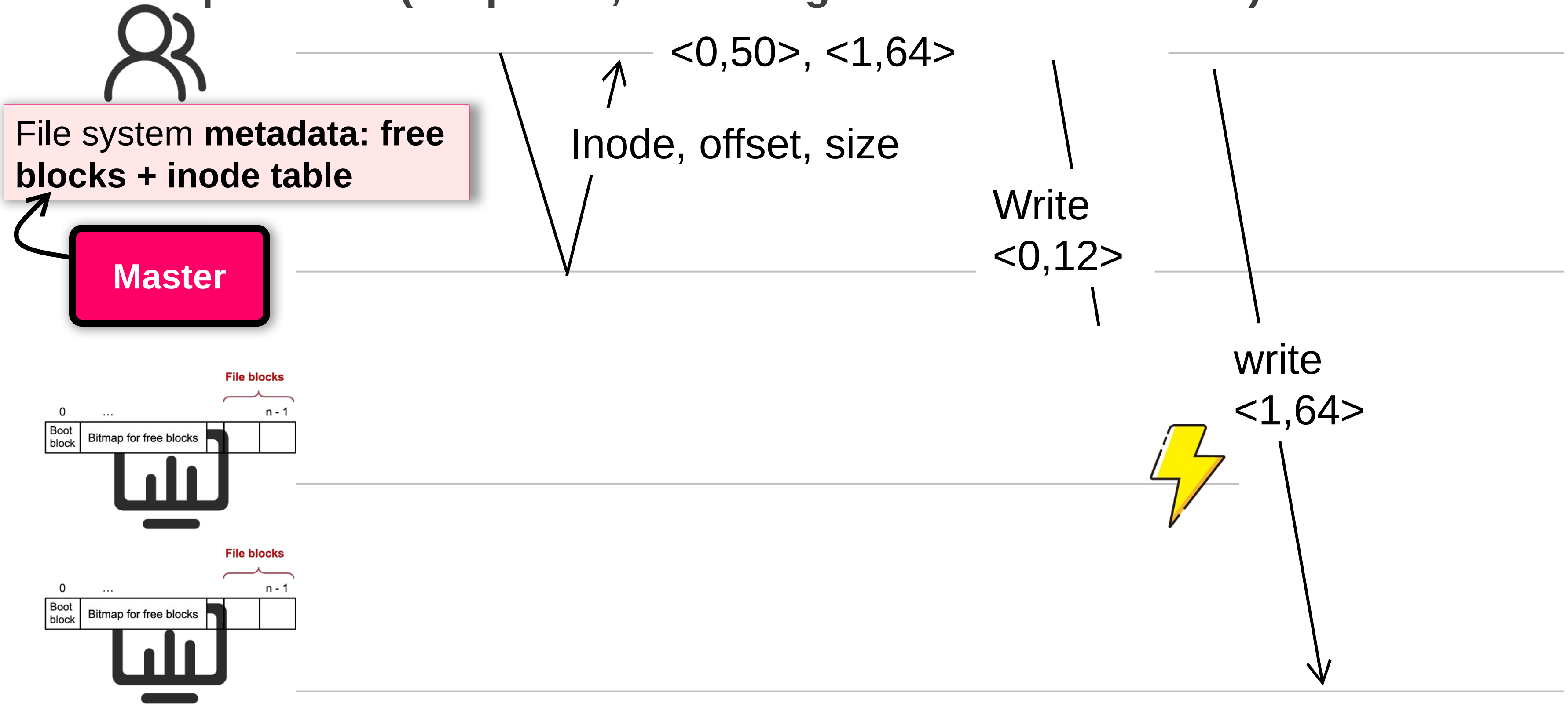
- E.g., what if the master fails?
- E.g., what if some servers that store the blocks fail?

Correctness

- If a failure happens, the overall system states will be corrupted!

Correctness broken under failure: example

Example: write (simplified, assuming no blocks allocation)



File system **metadata: free blocks + inode table**

Master

Inode, offset, size

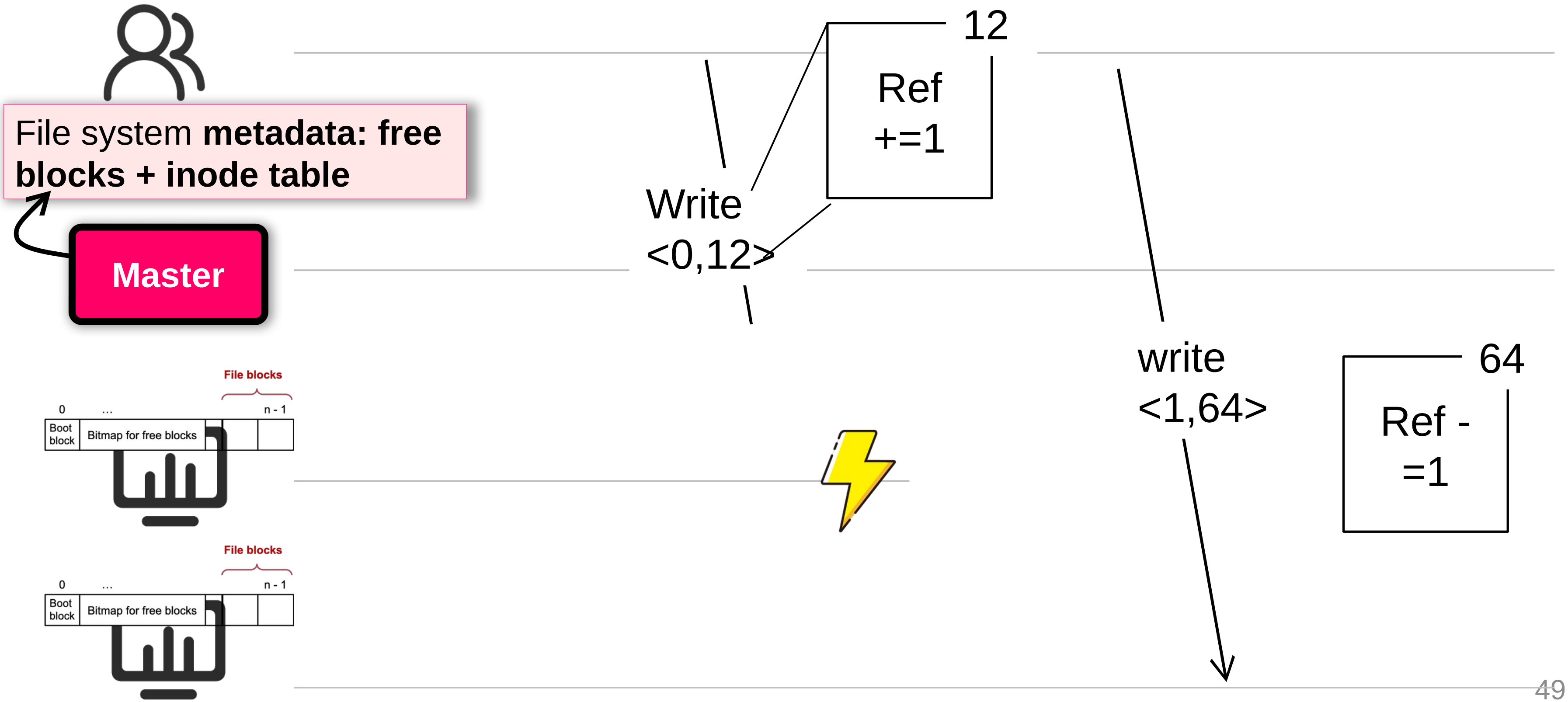
<0,50>, <1,64>

Write <0,12>

write <1,64>

Correctness broken under failure: example

Example: rename (simplified with only reference counters operations)



File system **metadata: free blocks + inode table**

Master

Failure is a subtle issue & can even happens under in inode-base filesystem

We will talk about the issues in later lectures

We need more “weapons” to cope w/ the above issues

Performance

- E.g., path lookup is slow due to multiple RTTs
- Though we can use cache, like we have done in NFS ⏪

Reliability **=> we need data replication**

- E.g., what if the master fails?
- E.g., what if some servers that store the blocks fail?

Correctness **=> we need to define what is correct & how to achieve so** ⏪

- If a failure happens, the overall system states will be corrupted!

Case study: GFS

The Google File System

Sanjay Ghemawat, “The Google File System”. SOSP, **2003**

GFS design goals

Scalable distributed file system

- E.g., Can NFS stores a very large file?

Designed for large **data-intensive** applications

- Essential for distributed computing frameworks, e.g., MapReduce

Fault-tolerant; runs on commodity hardware

- E.g., what if a server crashes, in the case of NFS?

Delivers **high performance** to a large number of clients

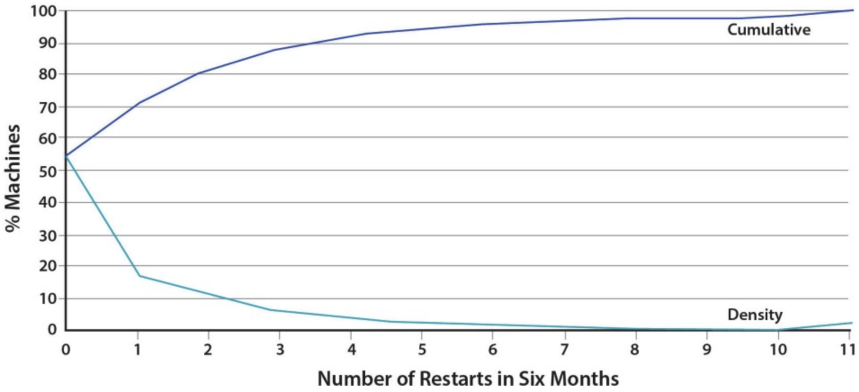
Design Assumptions

Assumptions for **conventional** file systems **don’t work**

- E.g., “most files are small”, “short lifetimes”

Component **failures** are the **norm**, not an exception

- File system = thousands of storage machines
- Some % not working at any given time (recall from lecture2)



Machine failures at Google. Source: An Introduction to the Design of Warehouse-Scale Machines

Design Assumptions: environments

Assumptions for **conventional** file systems **don’t work**

- E.g., “most files are small”, “short lifetimes”

Component **failures** are the **norm**, not an exception

- File system = thousands of storage machines
- Some % not working at any given time (recall from lecture2)

Files are huge: n-GB/TB files are the norm, e.g., large web index

- I/O ops and block size choices are affected

More Design Assumptions: File Access

Most files are **appended**, not overwritten (why? E.g., add new web pages to the Google’s global store)

- **Random** writes within a file are **rare**
  - Means we need to provide efficient **appends**

Workload is mostly:

- mostly reads: large streaming reads;
  - Once created, files are **mostly read**; often **sequential** (e.g., read a previous archived page)

We should designing the **FS API** with the design of **apps** benefits the system

GFS interface

GFS does **not** have a **standard OS-level API**

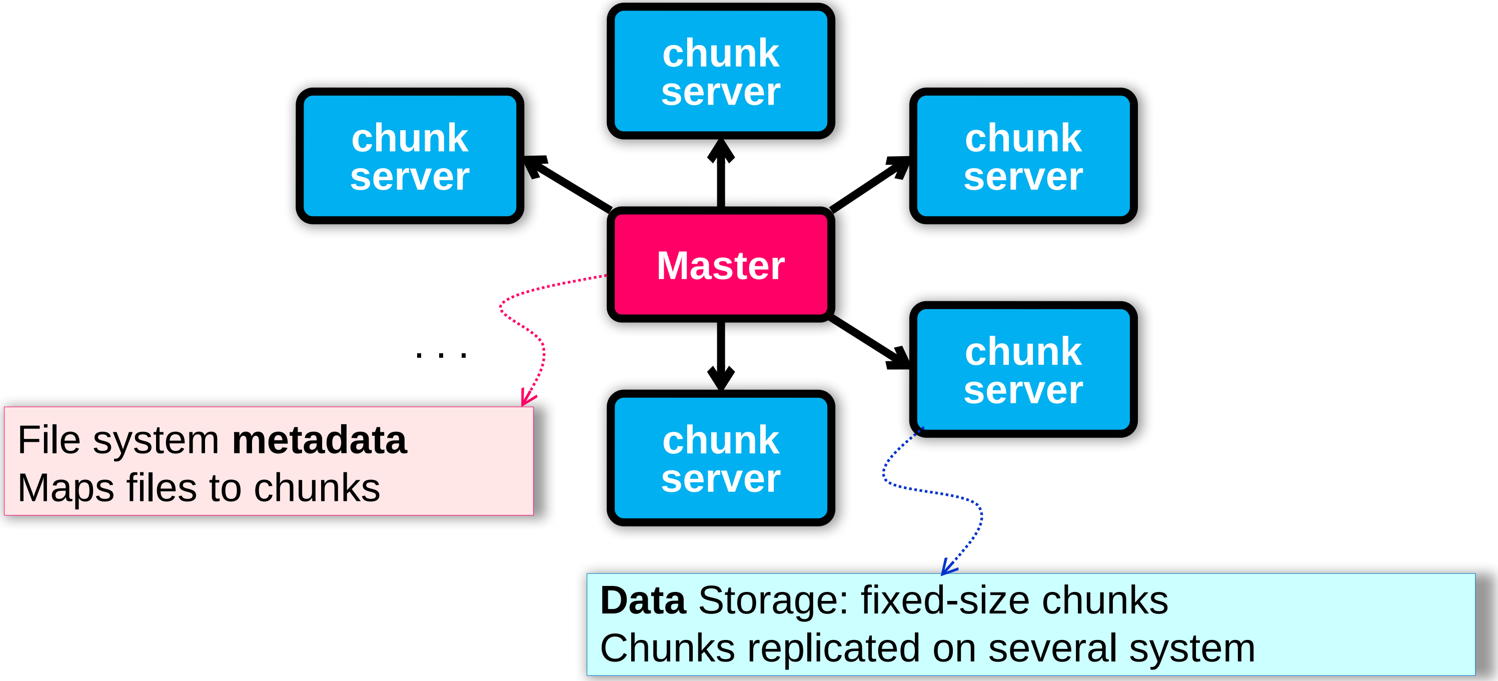
- No POSIX API
- No kernel/VFS implementation
- It provides user-level API

Operations

- Basic ops: `create/delete/open/close/read/write`
- Additional ops: `snapshot/append`
- Not supported ops: `link, symlink, rename`
- Why not rename? As I illustrated before, hard to ensure consistency under failures (no mature distributed TX---see later lectures---at that time)

GFS architecture

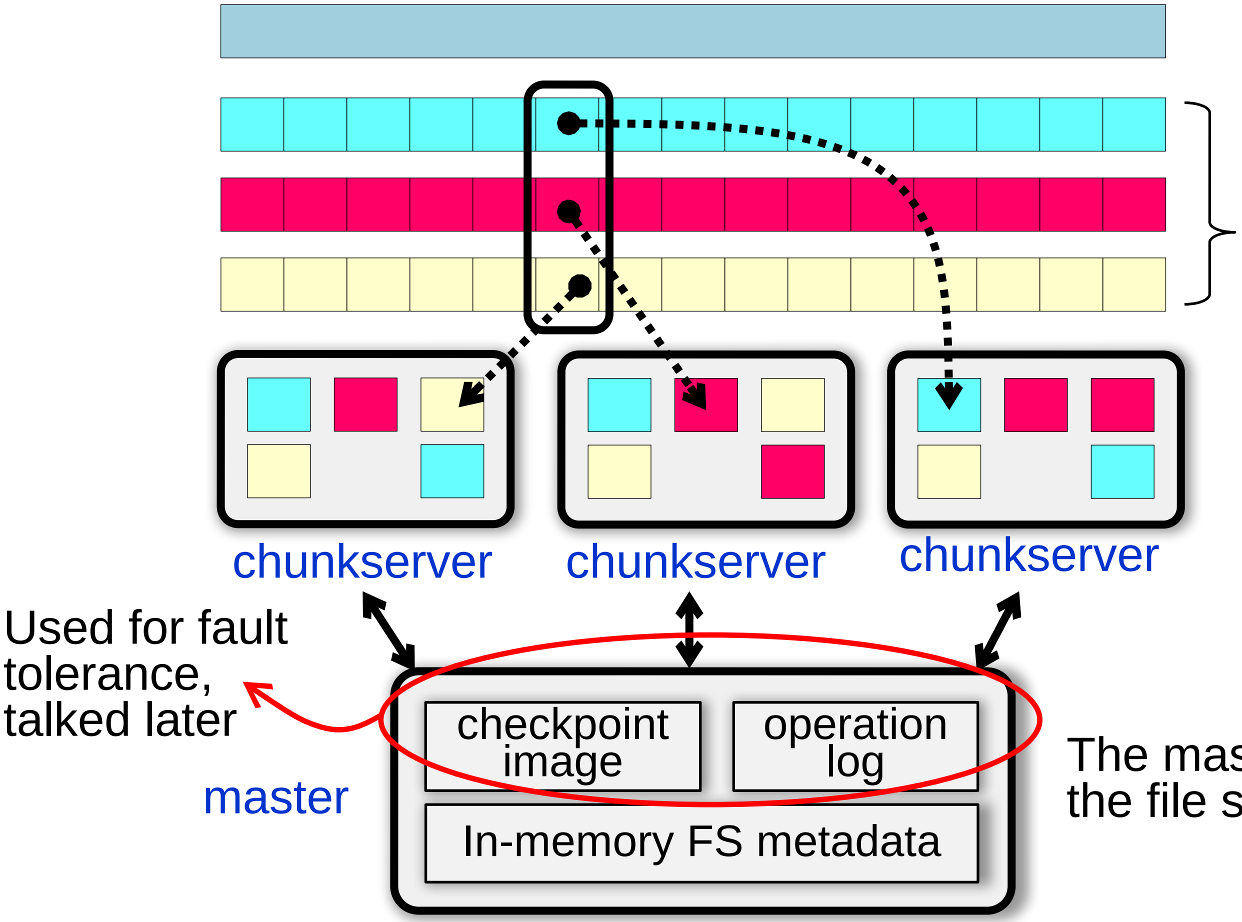
A GFS cluster = **1 Master** (Distributed inode layer) + **N Chunkservers** (Distributed blocks layer + replication)



File system **metadata**
Maps files to chunks

Data Storage: fixed-size chunks
Chunks replicated on several system

GFS files



A File is made of 64MB chunks, possibly spawn multiple machines

That are replicated for fault-tolerance

Chunks live on chunkservers

chunkserver

chunkserver

chunkserver

Used for fault tolerance, talked later

master

checkpoint image

operation log

In-memory FS metadata

The master manages the file system namespace

Chunks (Blocks) and Chunkservers

Chunk size **= 64 MB** (default)

- 32-bit checksum with each chunk

Chunk **handle**

- Globally unique 64-bit number
- Assigned by the master when creation

Chunks are stored on local disk as Linux files (aka. file system overlay)

Each chunk is **replicated** on multiple nodes

- Three replicas (default)
- More replicas for popular files to avoid **hotspots**

Why Large Chunks?

Default chunks size = 64MB

- Compare to Linux ext4 block size: 4KB~1MB

Benefits:

- **Reduce** the need for **frequent communication** with master for chunk location info
- Makes it feasible to keep a **TCP connection** open for an extended time
  - Establishing a TCP connect can be costly (two-way handshake, see later lectures)
- Master stores all **metadata** in memory

GFS Master

Maintains all file system metadata

- Access control info, filename to chunks mappings, current locations of chunks

Manages

- ~~Chunk **leases** (locks), **garbage** collection, chunk **migration**~~ (not the focus of this lecture)

Master replicates its data for fault-tolerance

- A large topic also not the focus of today’s lecture

Questions: differences from our naïve filesystem?

1. **Master stores current locations of chunks (blocks)**
    1. Unlike naïve distributed file, which store the locations in the inode block
    2. Why? For performance
2. **Master replicates its data for fault-tolerance**
    1. Our previous design does not replicate the data

GFS uses one master, why? Make the design simple

All metadata stored in master's memory

- Super-fast access

Name-to-chunk maps (e.g., using an in-memory tree)

- Stored in **memory**
- Also persist in **an operation log** on the disk (talk about in later chapters)

Don't store chunk location persistently

- This is queried from all the chunkservers at startup
- Can keep up-to-date: master controls all the management
- Benefits: simpler for consistency management

Client-GFS interaction model

GFS client code linked into each app

- No **OS-level** API
- Interacts with **master** for metadata-related ops
- Interacts **directly with chunkservers** for data
  - Master is not a point of congestion

No caching: neither clients nor chunkservers cache data

- Except for the system buffer cache

Clients cache metadata

- e.g., location of a file’s chunks

Reading a file in GFS (very similar to the naïve DFS)

Reading a file is simple in GFS

1. Contact the **master**

2. Get file’s **metadata**: chunk handles

3. Get the **location** of each of the chunk handles
   – Multiple replicated chunkservers per chunk

4. Contact any **available** chunkserver for chunk

Writing a File in GFS (More complicated due to replication)

Less frequent than reading

- But is more complex, because we need to deal with the consistency issues
- GFS adopts a **relaxed consistency model (see later lectures)**
- E.g, may have inconsistency state, but work well for their apps
- Benefits: simple & efficient to implement

Master grants a chunk lease to one of the replicas

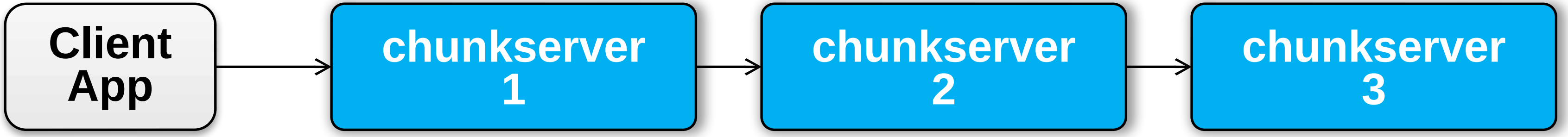
- This replica will be the **primary** chunkserver
  - The only one that can modify the chunk
- Primary can request extensions (of lease), if needed
  - Master increases the chunk version number and informs replicas

Writing a File in GFS: Two-phases

Phase 1: send data

Deliver data but **don't write** to the file

- A client is given a list of replicas
    - Identifying the primary and secondaries
- Client writes to the closest replica
    - Pipeline forwarding
- Chunkservers store this data in a cache (in memory)

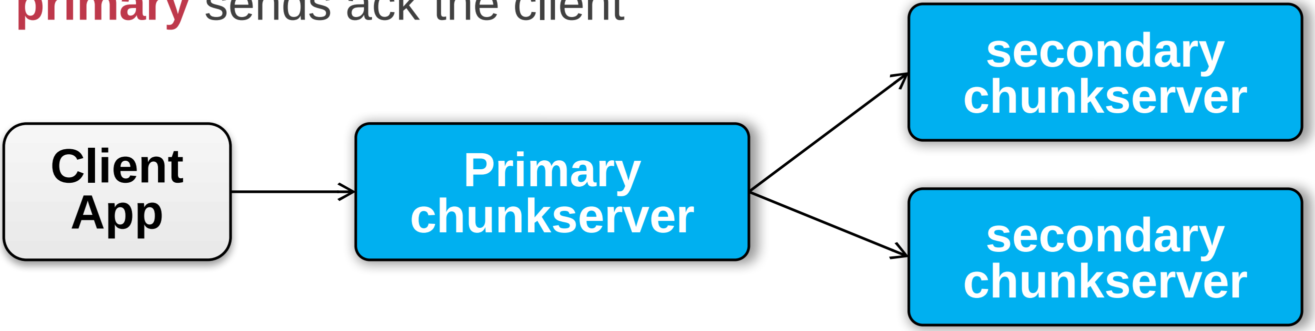


Writing a File in GFS: Two-phases

Phase 2: write data

Add the data to the file (commit)

- Client waits for replicas' ack of receiving data
- Send a **write** request to the **primary**
- The **primary** is responsible for serialization of writes (applying then forwarding)
- Once all acks have been received
  - ✉ The **primary** sends ack the client



Writing a File in GFS: Two-phases

Data flow (phase 1) is different from **control flow** (phase 2)

Data flow

- Client ✉ chunkserver ✉ chunkserver ✉ ...
- Order does not matter

Control flow

- Client ✉ primary ✉ all secondaries
- Order maintained (also for concurrent writes from multiple clients)

Chunk version numbers are used to detect if any replica has stale data

- Is maintained by the primary chunkserver
- If a replica has stale data, it shall be replaced

Naming in GFS: simple flat naming

No per-directory data structure like most file systems

- E.g., directory file contains names of all files in the directory

No aliases (i.e., no hard or symbolic links)

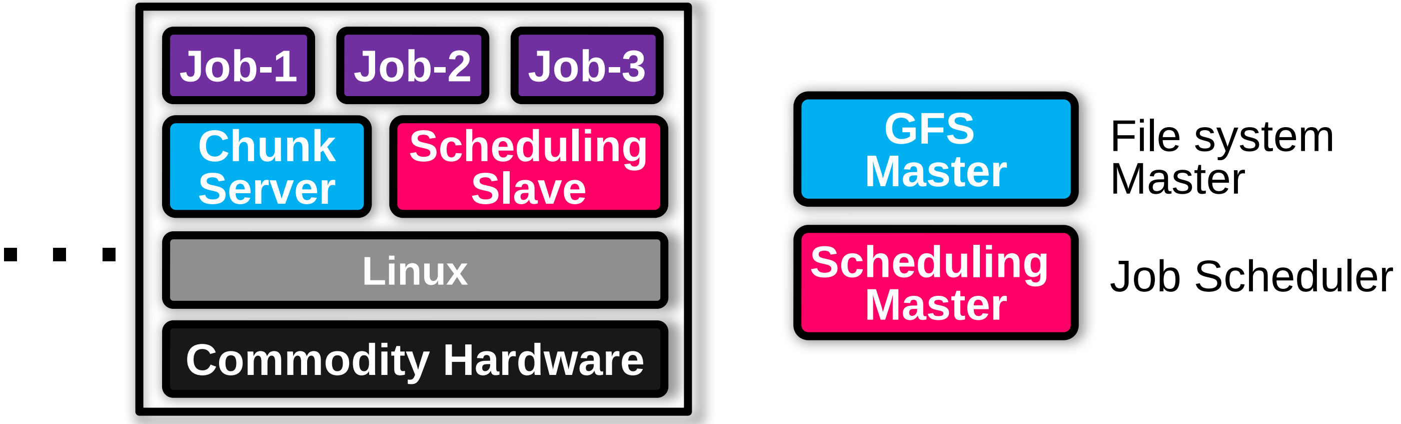
Namespace is a single lookup table

- Maps pathnames to metadata

Summary: GFS in Google cluster

Google cluster environment

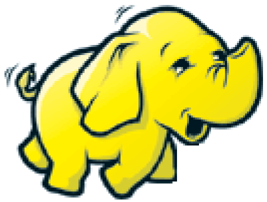
- Core services: GFS + cluster scheduling system
- Typically, 100s to 1000s of active jobs
- 200+ clusters, many with 1000s of machines
- Pools of 1000s of clients
- 4+ PB filesystems, 40GB/s read/write loads



HDFS: another popular (open-source) DFS

Hadoop **D**istributed **FS**

Primary storage system for **Hadoop** apps



A framework that allows for the distributed processing of large data sets across clusters of computers

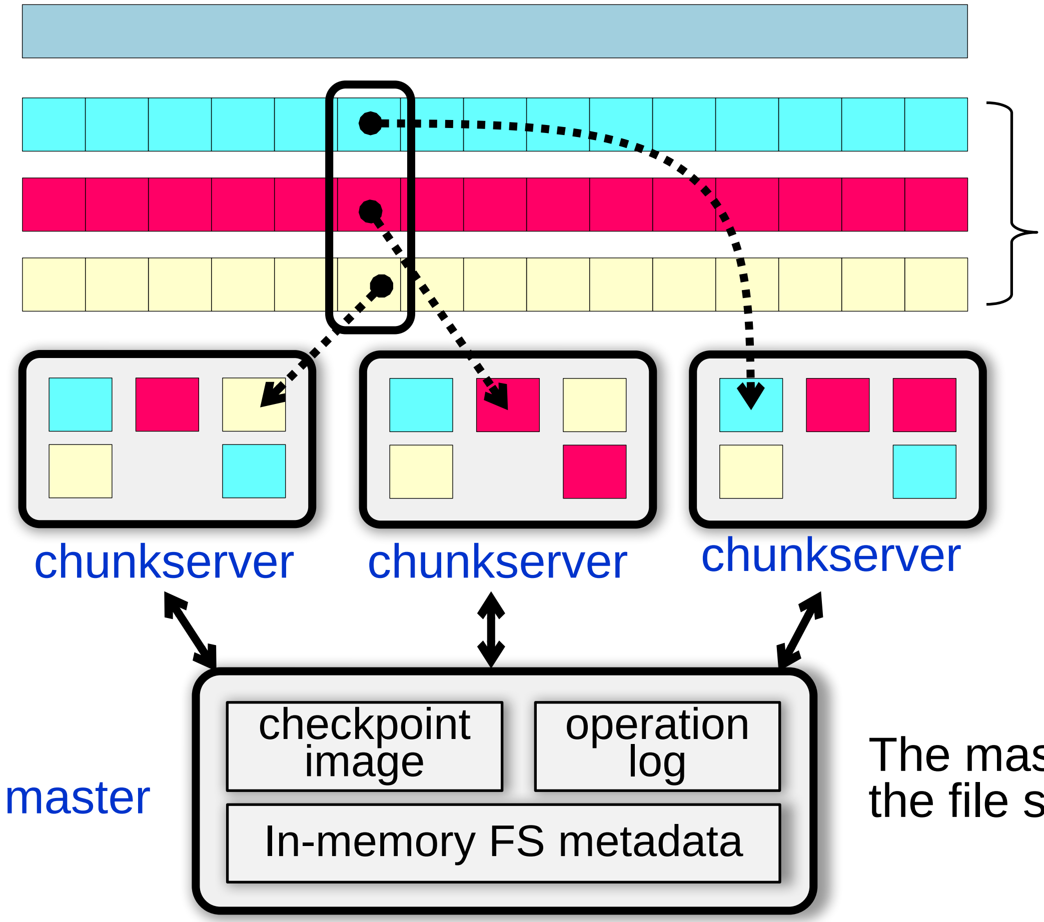
Design Goals & Assumptions of HDFS

HDFS is an open source (Apache) implementation inspired by GFS design

Similar goals as GFS

- Run on commodity hardware
- Highly fault tolerant
- High throughput & large-scale deployments
- …

Recall GFS files



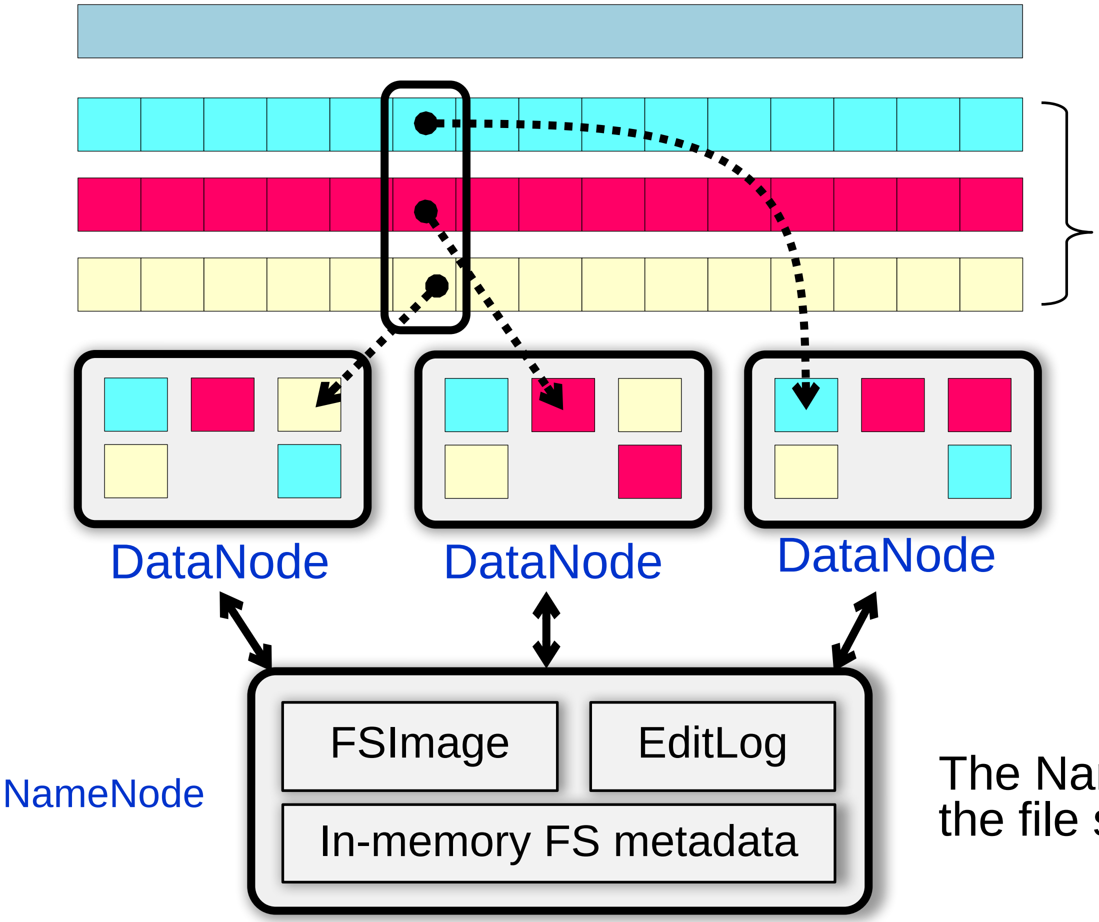
A File is made of 64MB chunks, possibly spawn multiple machines

That are replicated for fault-tolerance

Chunks live on chunkservers

The master manages the file system metadata

HDFS files



DataNode

DataNode

DataNode

NameNode

FSImage

EditLog

In-memory FS metadata

A File is made of 64MB blocks, possibly spawn multiple machines

That are replicated for fault-tolerance

Blocks live on DataNodes

The NameNode manages the file system metadata

Summary

Designing distributed file system (DFS) is not simply

- Single-node file system + RPC

Many design choices for performance, consistency model & failure handling

- Interface
- Caching
- Access model

Two case studies

- **NFS**: transparent access files on a remote server
- **GFS**: highly-scalable & fault-tolerant DFS optimized for Google’s workload

GFS or NFS are not Perfect

NFS

- Can **not scale**
- Is **not fault-tolerant**
- But is well-enough for many workloads, e.g., sharing the data for experiments in our lab ⏪

GFS

- **Relaxed consistency model**: the results of concurrent mutations are undefined
- Single-node master: single point of failures (though next-generation of GFS refines this, with more advanced techniques developed later)
- Work well in Google’s datacenter workloads

GFS or NFS are not Perfect

NFS

- Can **not scale**
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GFS

- **Relaxed consistency model**: the results of concurrent mutations are undefined
- Single-node master: single point of failures (though next-generation of GFS refines this)
- Work well in Google's datacenter workloads

We will see system principles to cope with them in future lectures.

For other workloads (e.g., Database) may not sufficient.