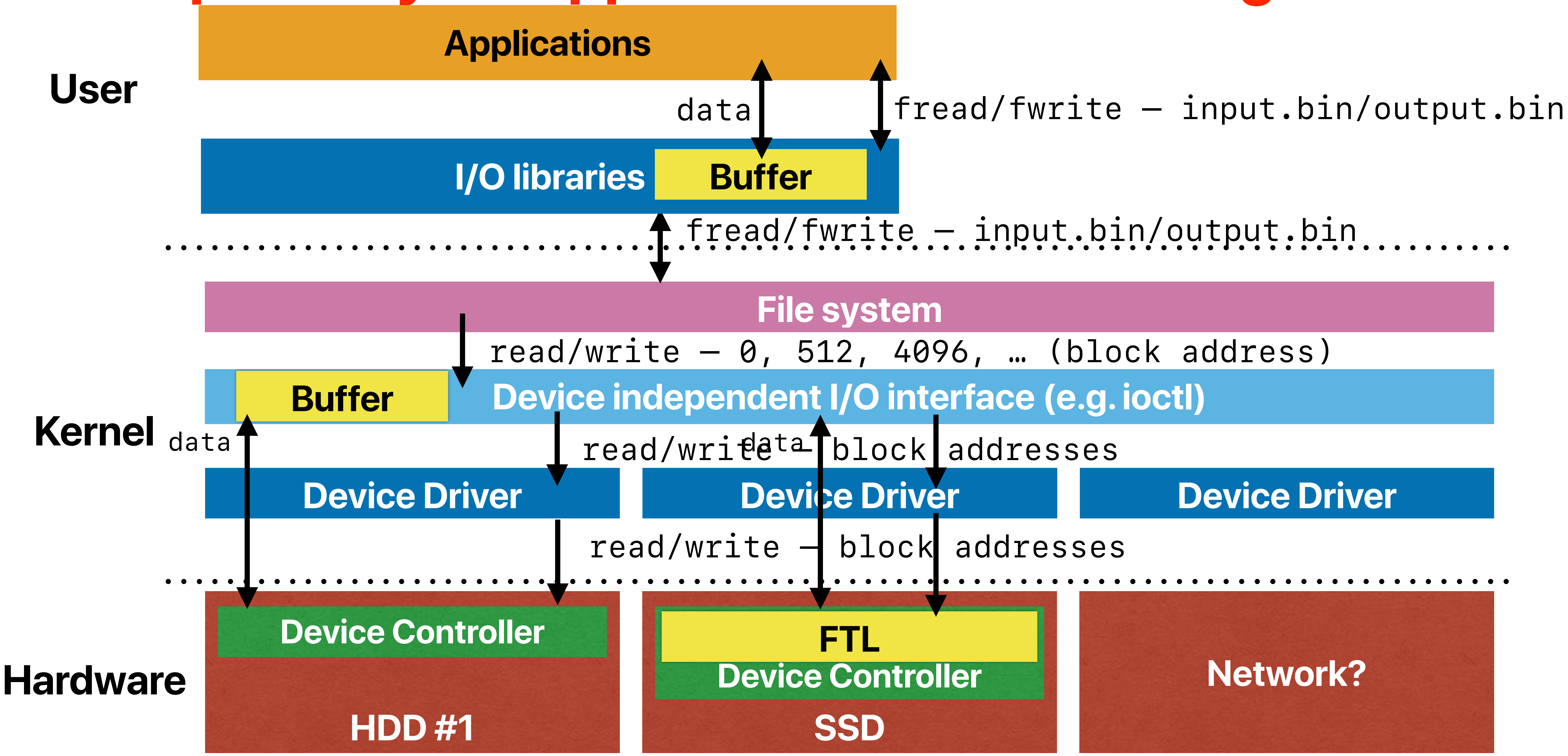
File systems over the network

Hung-Wei Tseng

Recap: How your application reaches storage device



Recap: File systems on a computer

- Unix File System
  - Hierarchical directory structure
  - File — metadata (inode) + data
  - Everything is files
- BSD Fast File System — optimize for reads
  - Cylinder group — Layout data carefully with device characteristics, replicated metadata
  - Larger block size & fragments to fix the drawback
  - A few other new features
- Sprite Log-structured File System — optimize for small random writes
  - Computers cache a lot — reads are no more the dominating traffic
  - Aggregates small writes into large sequential writes to the disk
  - Invalidate older copies to support recovery

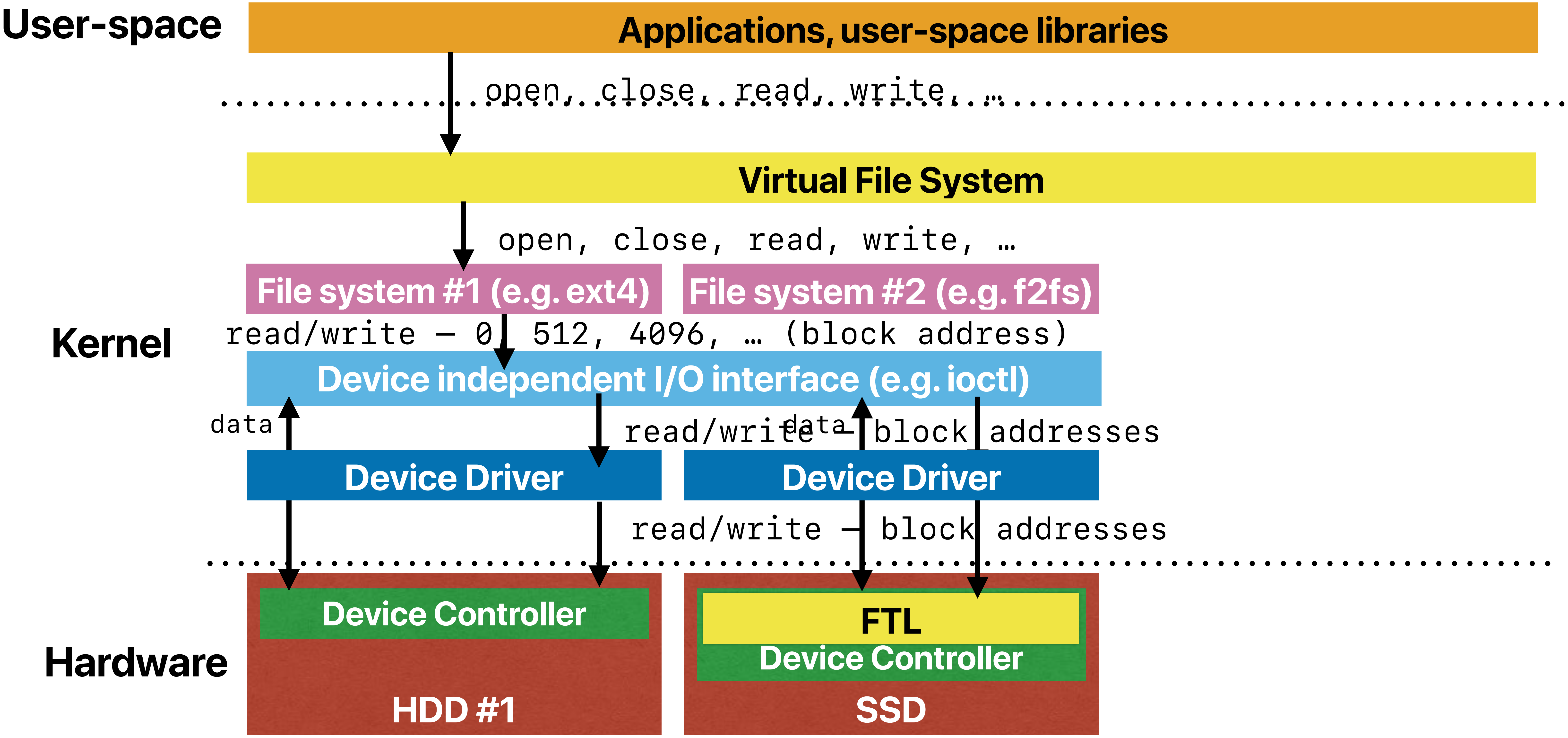
Recap: Extent file systems — ext2, ext3, ext4

- Basically optimizations over FFS + Extent + Journaling (write-ahead logs)
- Extent — consecutive disk blocks
- A file in ext file systems — a list of extents
- Journal
  - Write-ahead logs — performs writes as in LFS
  - Apply the log to the target location when appropriate
- Block group
  - Modern H.D.Ds do not have the concept of “cylinders”
  - They label neighboring sectors with consecutive block addresses
  - Does not work for SSDs given the internal log-structured management of block addresses

Recap: flash SSDs, NVM-based SSDs

- Asymmetric read/write behavior/performance
- Wear-out faster than traditional magnetic disks
- Another layer of indirection is introduced
  - Intensify log-on-log issues
  - We need to revise the file system design

The introduction of virtual file system interface


User-space
Applications, user-space libraries
open, close, read, write, …
Virtual File System
open, close, read, write, …
Kernel
File system #1 (e.g. ext4)
File system #2 (e.g. f2fs)
read/write — 0, 512, 4096, … (block address)
Device independent I/O interface (e.g. ioctl)
data
read/write — block addresses
data
Device Driver
Device Driver
read/write — block addresses
Hardware
Device Controller
HDD #1
FTL
Device Controller
SSD

Current scoreboard

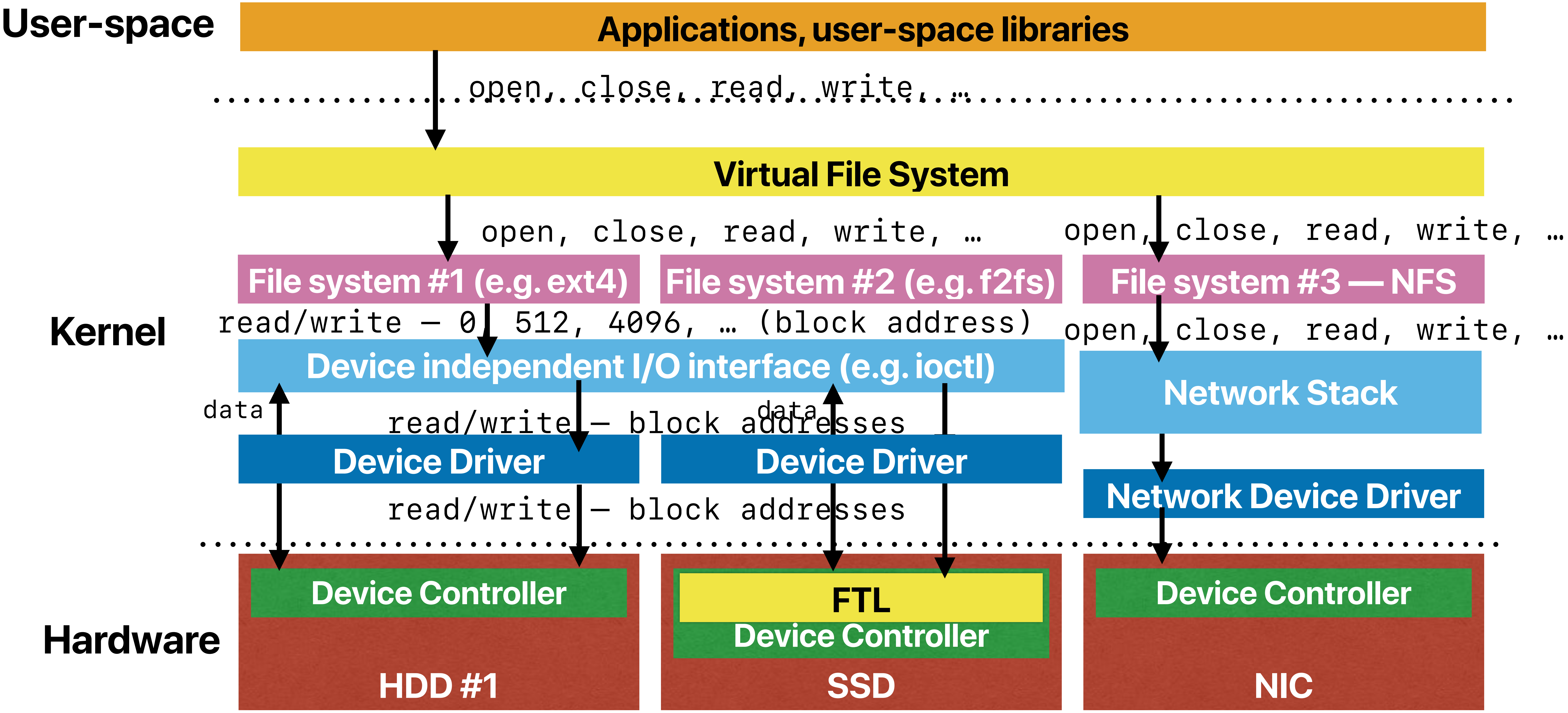
Red	Blue
20	18

Outline

- NFS
- Google file system

Network File System

The introduction of virtual file system interface



User-space

Applications, user-space libraries

`open, close, read, write, …`

Kernel

Virtual File System

`open, close, read, write, …`

`open, close, read, write, …`

File system #1 (e.g. ext4)

File system #2 (e.g. f2fs)

File system #3 — NFS

`read/write — 0, 512, 4096, … (block address)`

`open, close, read, write, …`

Device independent I/O interface (e.g. ioctl)

Network Stack

`data`

`read/write — block addresses`

`data`

Device Driver

Device Driver

Network Device Driver

`read/write — block addresses`

Hardware

Device Controller

HDD #1

FTL

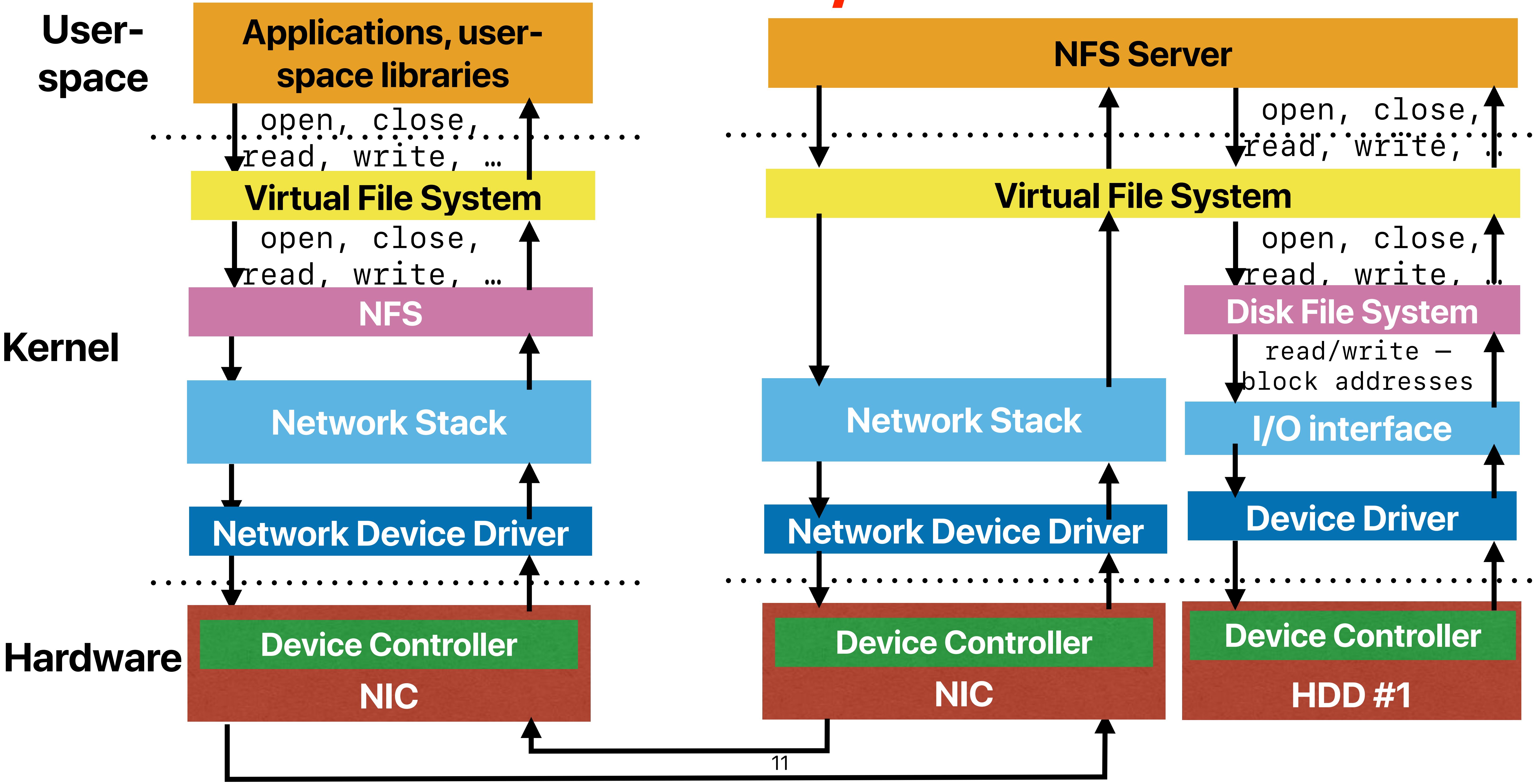
Device Controller

SSD

Device Controller

NIC

NFS Client/Server



How does NFS handle a file?

- The client gives it’s file system a tuple to describe data
  - Volume: Identify which server contains the file — represented by the mount point in UNIX
  - inode: Where in the server
  - generation numer: version number of the file
- The local file system forwards the requests to the server
- The server response the client with file system attributes as local disks

Poll close in 1:30

Number of network operations

- For a file /mnt/nfs/home/hungwei/foo.c , how many network sends/receives in total does NFS need to perform to fetch the actual file content in the worst case? (assume the file system is mounted to /mnt/nfs)
  A. 8
  B. 9
  C. 10
  D. 11
  E. 12

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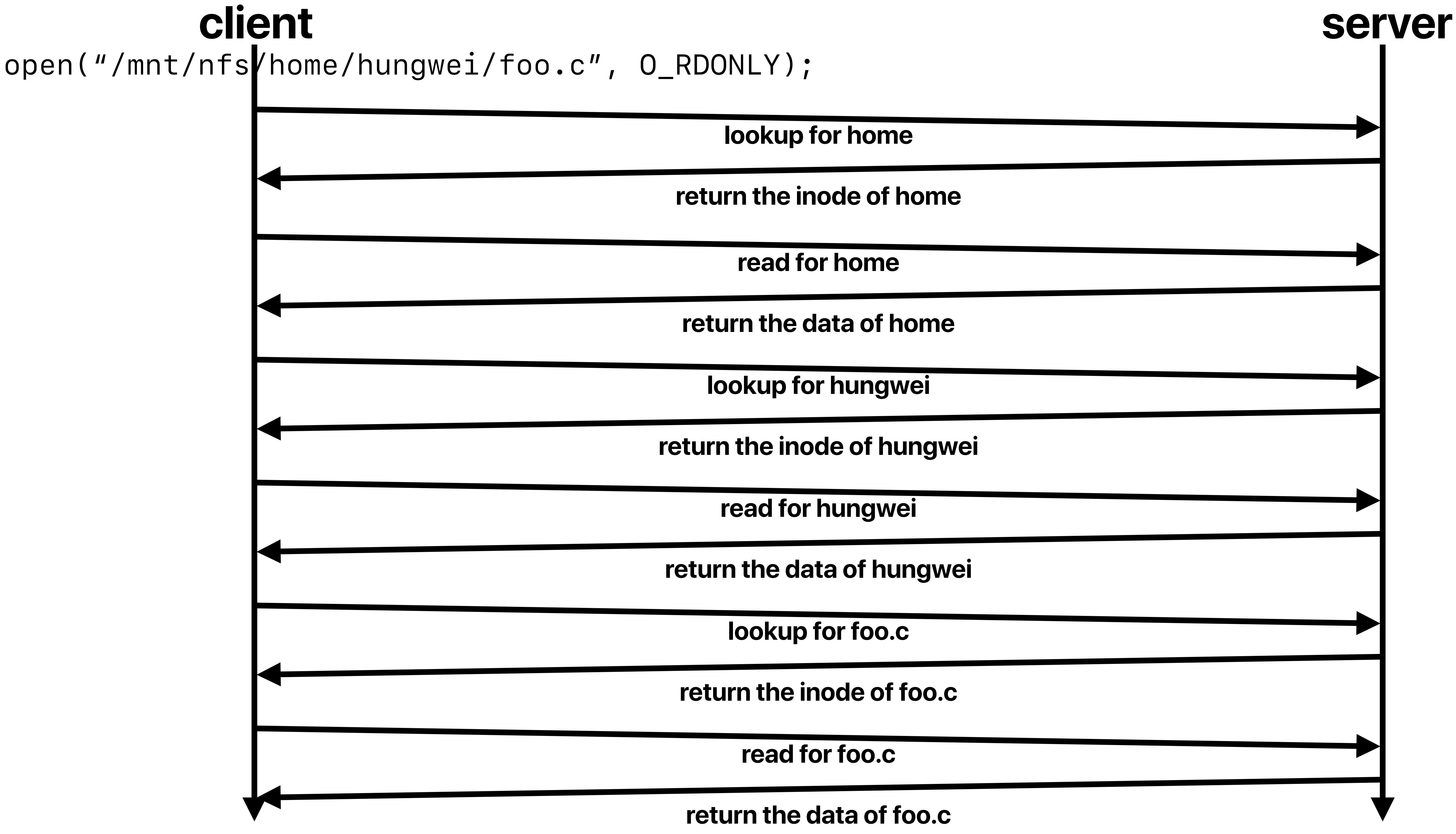
How open works with NFS



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Caching

- NFS operations are expensive
  - Lots of network round-trips
  - NFS server is a user-space daemon
- With caching on the clients
  - Only the first reference needs network communication
  - Later requests can be satisfied in local memory

Poll close in 1:30

Stateless NFS

- How many of the following statements fit the reason why NFS uses a stateless protocol, in which the protocol doesn't track any client state?
  ① Simplify the system design for recovery after server crashes
  ② Simplify the client design for recovery after client crashes
  ③ Easier to guarantee file consistency
  ④ Improve the network latency
  A. 0
  B. 1
  C. 2
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  ✓ ① Simplify the system design for recovery after server crashes

  If using stateful protocol, FDs on all clients are lost

  ✓ ② Simplify the client design for recovery after client crashes

  If using stateful protocol, server doesn't know client crashes and consider the file is open still

  ③ Easier to guarantee file consistency

  The server has no knowledge about who has the file

  ④ Improve the network latency

  Nothing to do with NFS

  A. 0

  B. 1

  [✓ C. 2]

  D. 3

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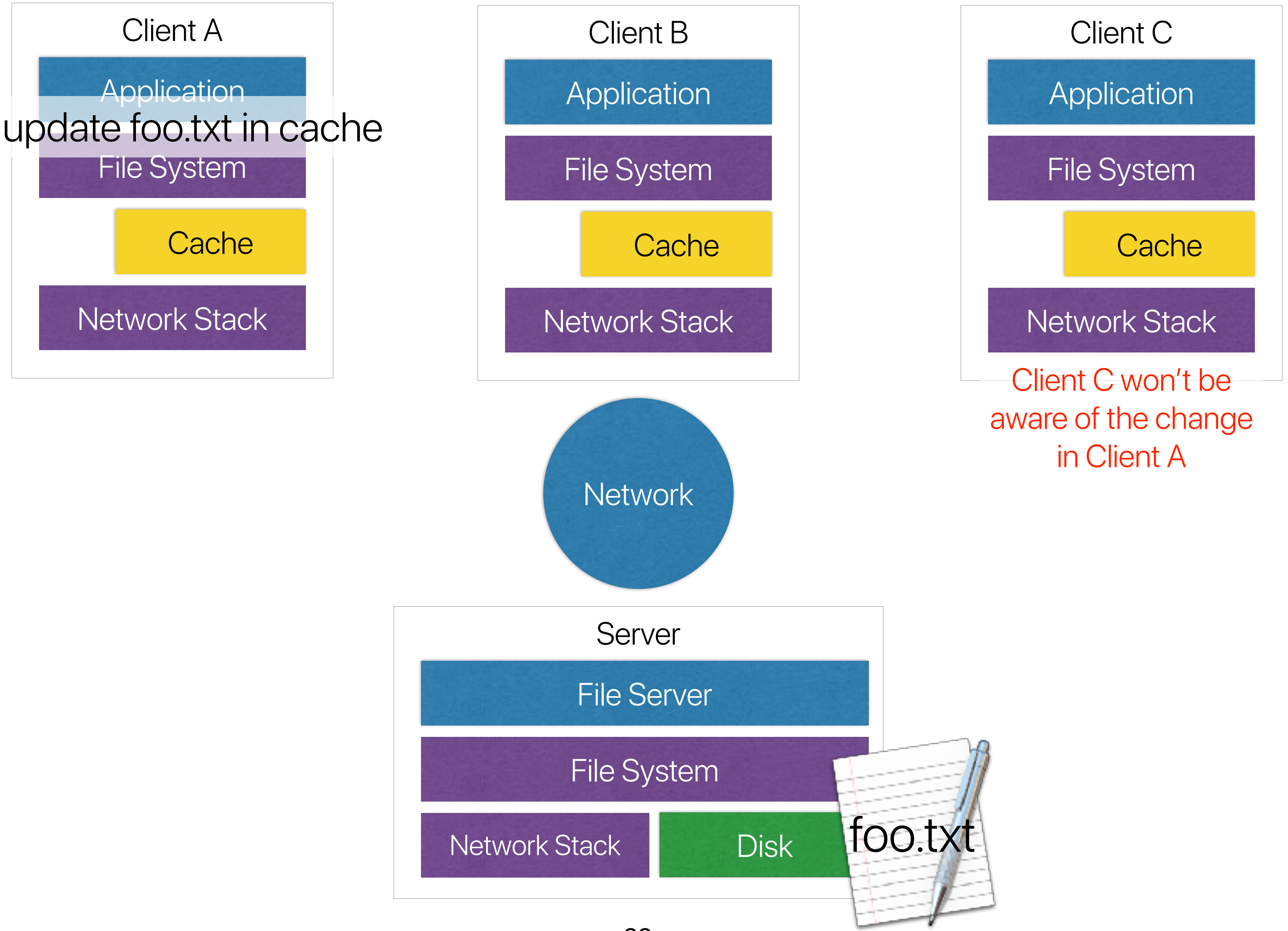
Idempotent operations

- Given the same input, always give the same output regardless how many times the operation is employed
- You only need to retry the same operation if it failed

Think about this



Client C won't be aware of the change in Client A

Solution

- Flush-on-close: flush all write buffer contents when close the file
  - Later open operations will get the latest content
- Force-getattr:
  - Open a file requires getattr from server to check timestamps
  - attribute cache to remedy the performance

The Google File System

Sanjay Ghemawat, Howard Gobioff, and
Shun-Tak Leung
Google

Poll close in 1:30

GFS

- How many of the following fit the optimization goals for GFS?
  ① Optimize for storing small files
  ② Optimize for fast, modern storage devices
  ③ Optimize for random writes
  ④ Optimize for access latencies
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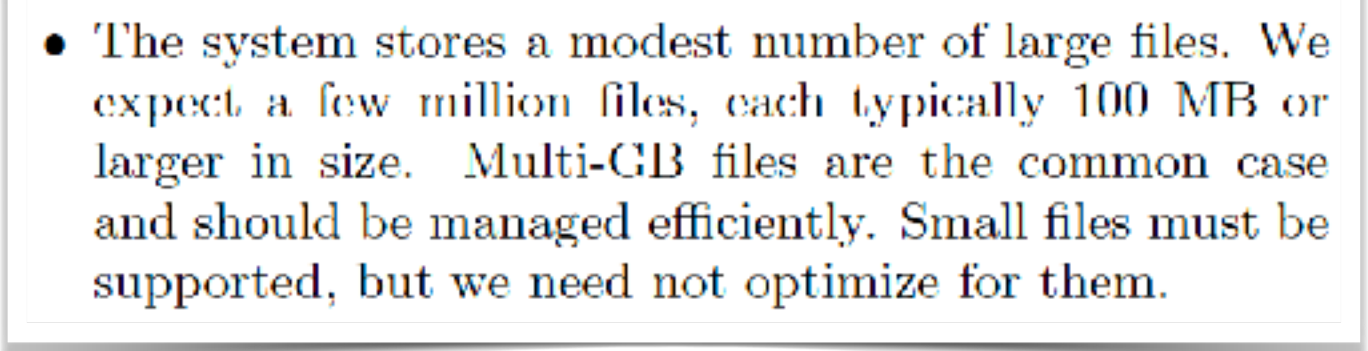
- The system stores a modest number of large files. We expect a few million files, each typically 100 MB or larger in size. Multi-GB files are the common case and should be managed efficiently. Small files must be supported, but we need not optimize for them.

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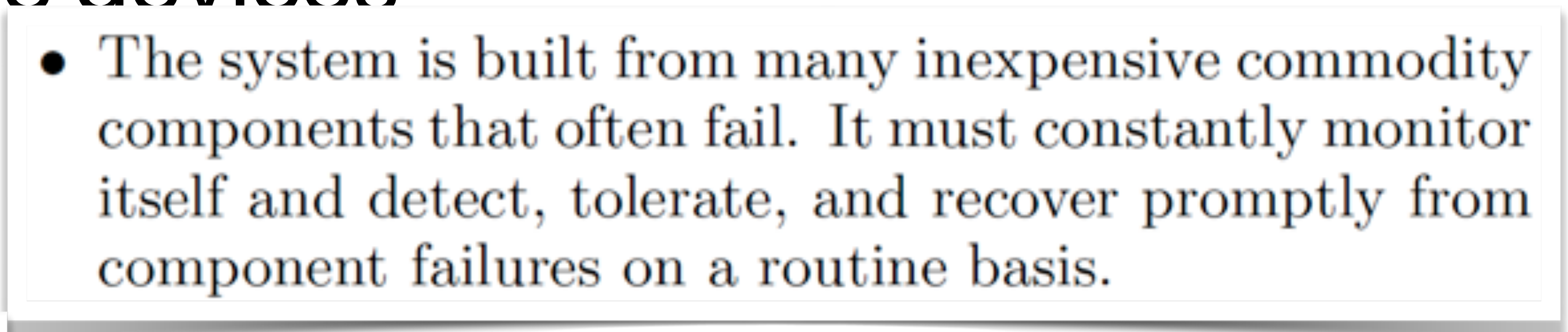
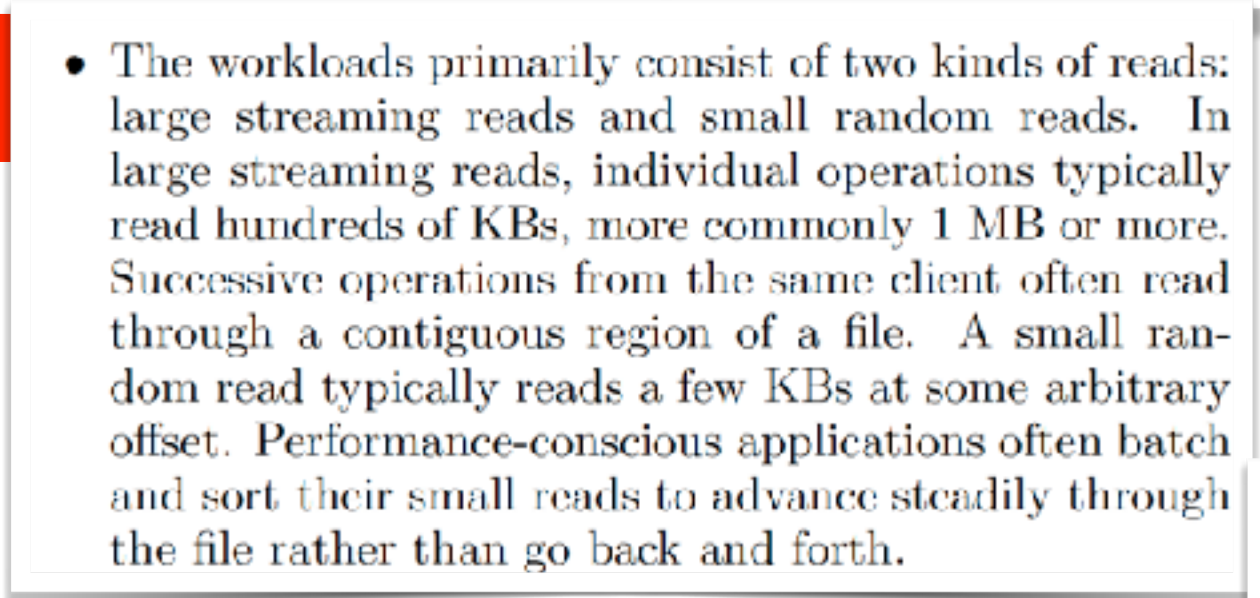
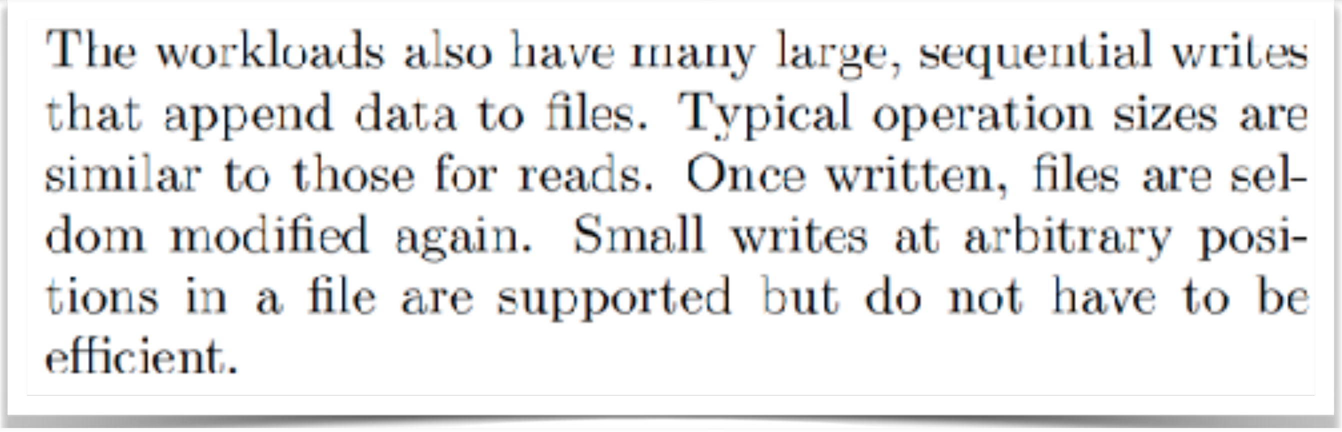
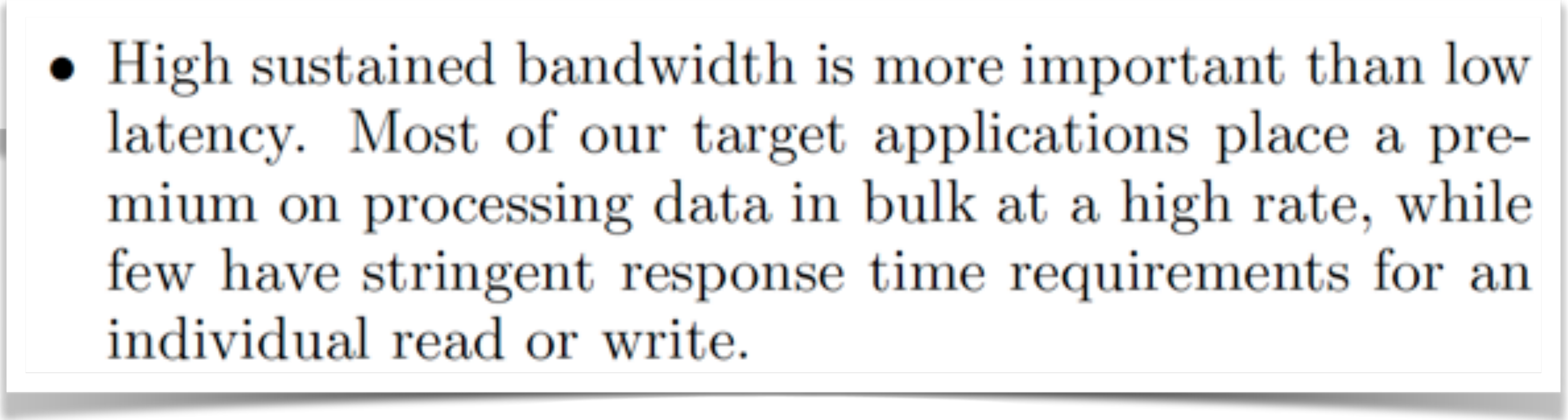

- The system is built from many inexpensive commodity components that often fail. It must constantly monitor itself and detect, tolerate, and recover promptly from component failures on a routine basis.


- The workloads primarily consist of two kinds of reads: large streaming reads and small random reads. In large streaming reads, individual operations typically read hundreds of KBs, more commonly 1 MB or more. Successive operations from the same client often read through a contiguous region of a file. A small random read typically reads a few KBs at some arbitrary offset. Performance-conscious applications often batch and sort their small reads to advance steadily through the file rather than go back and forth.


The workloads also have many large, sequential writes that append data to files. Typical operation sizes are similar to those for reads. Once written, files are seldom modified again. Small writes at arbitrary positions in a file are supported but do not have to be efficient.


- High sustained bandwidth is more important than low latency. Most of our target applications place a premium on processing data in bulk at a high rate, while few have stringent response time requirements for an individual read or write.

Why we care about GFS

- Conventional file systems do not fit the demand of data centers
- Workloads in data centers are different from conventional computers
  - Storage based on inexpensive disks that fail frequently
  - Many large files in contrast to small files for personal data
  - Primarily reading streams of data
  - Sequential writes appending to the end of existing files
  - Must support multiple concurrent operations
  - Bandwidth is more critical than latency

Data-center workloads for GFS

- Google Search (Web Search for a Planet: The Google Cluster Architecture, IEEE Micro, vol. 23, 2003)
- MapReduce (MapReduce: Simplified Data Processing on Large Clusters, OSDI 2004)
  - Large-scale machine learning problems
  - Extraction of user data for popular queries
  - Extraction of properties of web pages for new experiments and products
  - Large-scale graph computations
- BigTable (Bigtable: A Distributed Storage System for Structured Data, OSDI 2006)
  - Google analytics
  - Google earth
  - Personalized search

What GFS proposes?

- Maintaining the same interface
  - The same function calls
  - The same hierarchical directory/files
- Files are decomposed into large chunks (e.g. 64MB) with replicas
- Hierarchical namespace implemented with flat structure
- Master/chunkservers/clients

Poll close in 1:30

Large Chunks

- How many of the following datacenter characteristics can large chunks help address?
  - ① Storage based on inexpensive disks that fail frequently
  - ② Many large files in contrast to small files for personal data
  - ③ Primarily reading streams of data
  - ④ Sequential writes appending to the end of existing files
  - ⑤ Must support multiple concurrent operations
  - ⑥ Bandwidth is more critical than latency
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  - C. 3
  - D. 4
  - E. 5

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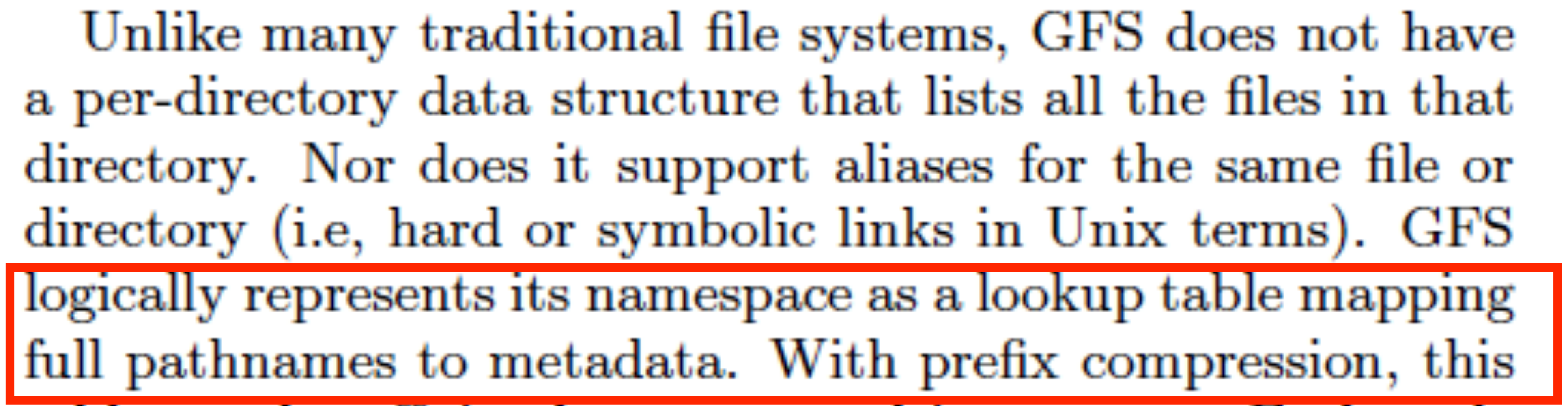
Latency Numbers Every Programmer Should Know

Operations	Latency (ns)	Latency (us)	Latency (ms)	
L1 cache reference	0.5 ns			~ 1 CPU cycle
Branch mispredict	5 ns			
L2 cache reference	7 ns			14x L1 cache
Mutex lock/unlock	25 ns			
Main memory reference	100 ns			20x L2 cache, 200x L1 cache
Compress 1K bytes with Zippy	3,000 ns	3 us		
Send 1K bytes over 1 Gbps network	10,000 ns	10 us		
Read 4K randomly from SSD*	150,000 ns	150 us		~1GB/sec SSD
Read 1 MB sequentially from memory	250,000 ns	250 us		
Round trip within same datacenter	500,000 ns	500 us		
Read 1 MB sequentially from SSD*	1,000,000 ns	1,000 us	1 ms	~1GB/sec SSD, 4X memory
Read 512B from disk	10,000,000 ns	10,000 us	10 ms	20x datacenter roundtrip
Read 1 MB sequentially from disk	20,000,000 ns	20,000 us	20 ms	80x memory, 20X SSD
Send packet CA-Netherlands-CA	150,000,000 ns	150,000 us	150 ms	

Flat file system structure

- Directories are illusions
- Namespace maintained like a hash table



Unlike many traditional file systems, GFS does not have a per-directory data structure that lists all the files in that directory. Nor does it support aliases for the same file or directory (i.e, hard or symbolic links in Unix terms). GFS logically represents its namespace as a lookup table mapping full pathnames to metadata. With prefix compression, this

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Announcement

- Reading quizzes due next Thursday
- Office hour
    - M 3p-4p and Th 9a-10a
    - Use the office hour Zoom link, not the lecture one
- Piazza
    - One of the most efficient ways of getting responses
    - Feel free to discuss your project — just don't discuss code directly
- Project
    - Due 3/2
    - No late submission is allowed
- EE260 (CRN: 64597, by Hung-Wei Tseng)
    - Quantum Computing and Computer Architecture
    - Seminar-style. You will present once is the quarter. 2-page research proposal.

Computer
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