DIST. FILE SYSTEMS

CS435 Distributed Systems

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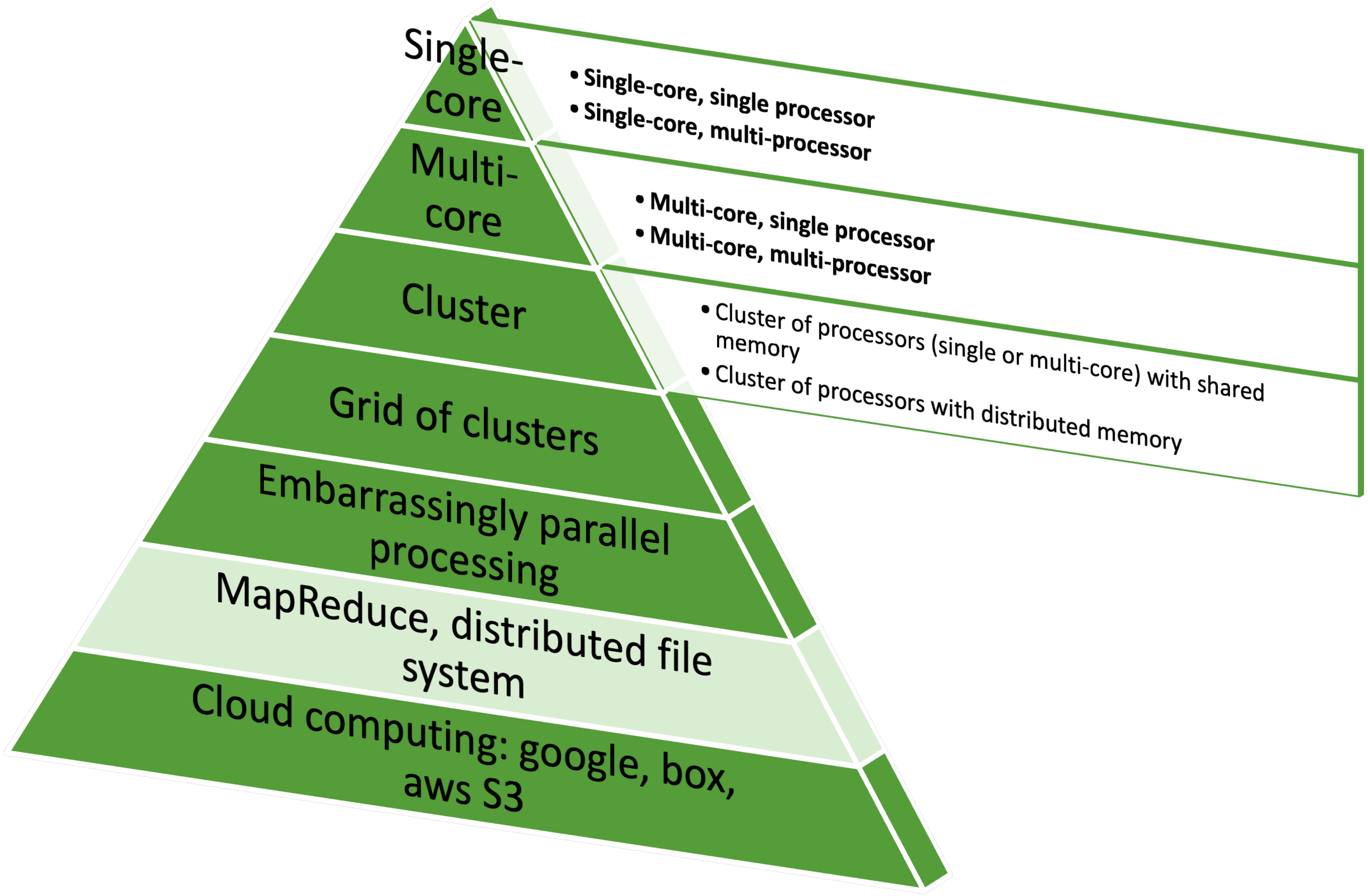
TOPICS

- What is a file system?
- Big data and storage?
- Dist File Systems
- Google File System
- Hadoop Dist File System

A FILE SYSTEM

WHAT IS A FILE SYSTEM?



WHAT IS A FILE SYSTEM?

A file system is a method or structure that a computer operating system uses to organize, store, retrieve, and manage files and data on storage devices.

Off system/online storage/ secondary memory	File system abstraction/ Databases	Offline/ tertiary memory/ DFS
RAID: Redundant Array of Inexpensive Disks	NAS: Network Accessible Storage	SAN: Storage area networks

WHAT IS A FILE SYSTEM?

File System Modules

Directory module:	relates file names to file IDs
File module:	relates file IDs to particular files
Access control module:	checks permission for operation requested
File access module:	reads or writes file data or attributes
Block module:	accesses and allocates disk blocks
Device module:	disk I/O and buffering

File Attribute Record

File length
Creation timestamp
Read timestamp
Write timestamp
Attribute timestamp
Reference count
Owner
File type
Access control list

WHAT IS A FILE SYSTEM?

UNIX file system operations

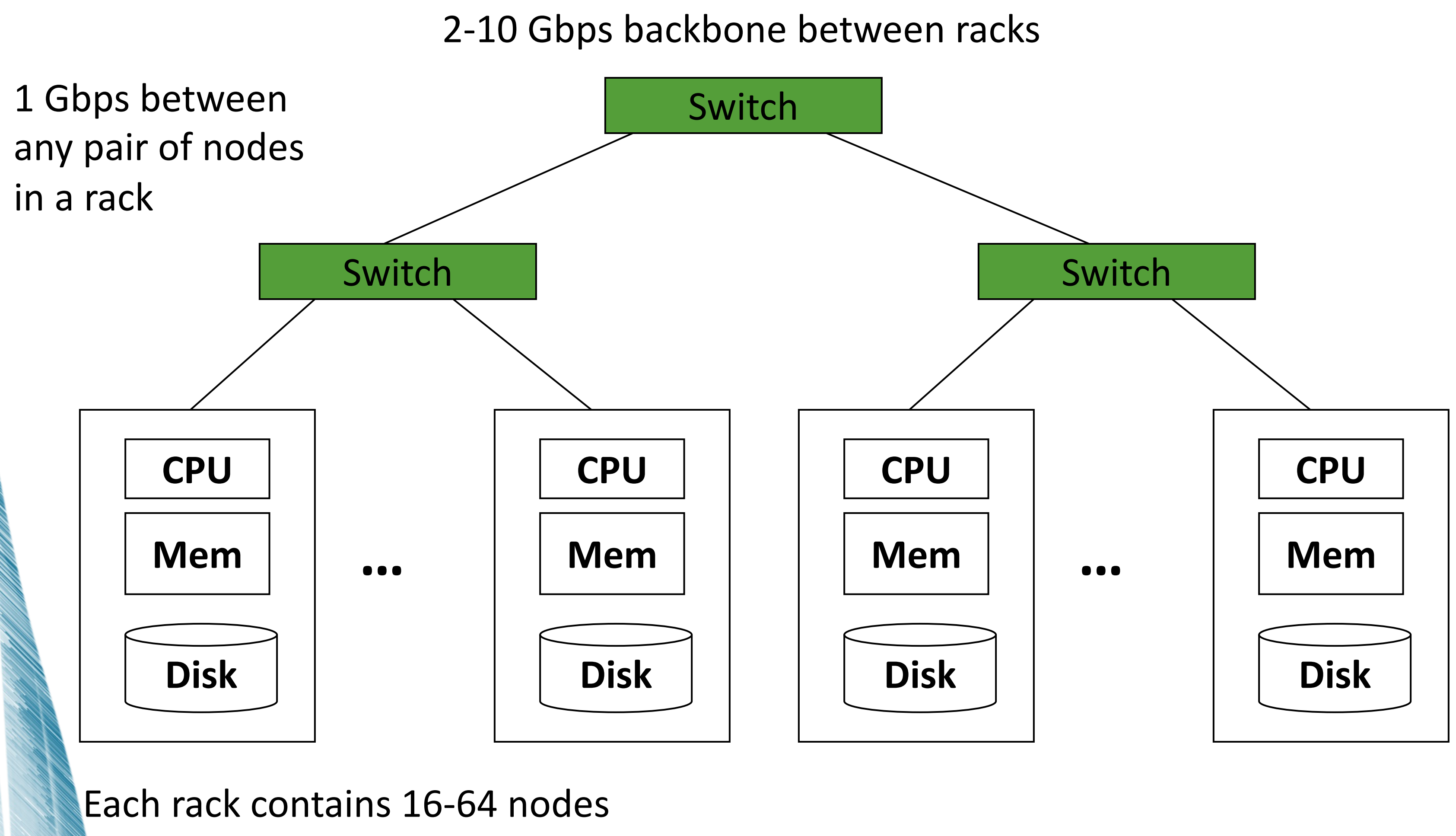
filedes = open(name, mode) *filedes = creat(name, mode)*	Opens an existing file with the given *name*. Creates a new file with the given *name*. Both operations deliver a file descriptor referencing the open file. The *mode* is *read*, *write* or both.
status = close(filedes)	Closes the open file *filedes*.
count = read(filedes, buffer, n) *count = write(filedes, buffer, n)*	Transfers *n* bytes from the file referenced by *filedes* to *buffer*. Transfers *n* bytes to the file referenced by *filedes* from buffer. Both operations deliver the number of bytes actually transferred and advance the read-write pointer.
pos = lseek(filedes, offset, whence)	Moves the read-write pointer to offset (relative or absolute, depending on *whence*).
status = unlink(name)	Removes the file *name* from the directory structure. If the file has no other names, it is deleted.
status = link(name1, name2)	Adds a new name (*name2*) for a file (*name1*).
status = stat(name, buffer)	Gets the file attributes for file *name* into *buffer*.

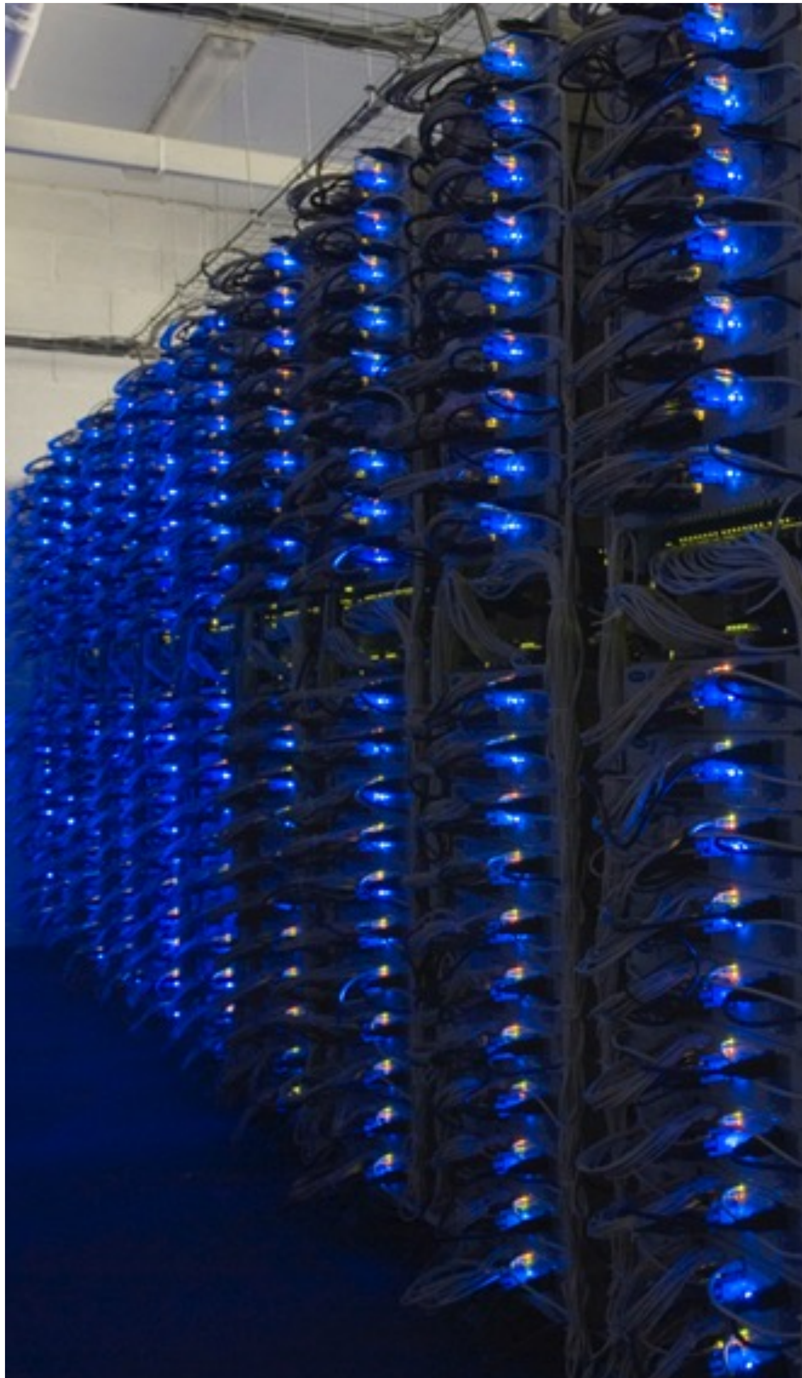
BIG DATA AND STORAGE

BIG DATA AND STORAGE

- 20+ billion web pages x 20KB = 400+ TB
- 1 computer reads 30-35 MB/sec from disk
  - ~4 months to read the web
- ~1,000 hard drives to store the web
- Takes even more to **do** something useful with the data!
- **Today, a standard architecture for such problems is emerging:**
  - Cluster of commodity Linux nodes
  - Commodity network (ethernet) to connect them

BIG DATA AND STORAGE





BIG DATA AND STORAGE

- **Large-scale computing** for **data mining** problems on **commodity hardware**
- **Challenges:**
  - **How do you distribute computation?**
  - **How can we make it easy to write distributed programs?**
  - **Machines fail:**
    - One server may stay up 3 years (1,000 days)
    - If you have 1,000 servers, expect to loose 1/day
    - People estimated Google had ~1M machines in 2011
      - 1,000 machines fail every day!

BIG DATA AND STORAGE

- **Problem:**
  - If nodes fail, how to store data persistently?
- **Answer:**
  - **Distributed File System:**
    - Provides global file namespace
    - Google GFS; Hadoop HDFS;
- **Typical usage pattern**
  - Huge files (100s of GB to TB)
  - Data is rarely updated in place
  - Reads and appends are common

DISTRIBUTED FILE SYSTEMS

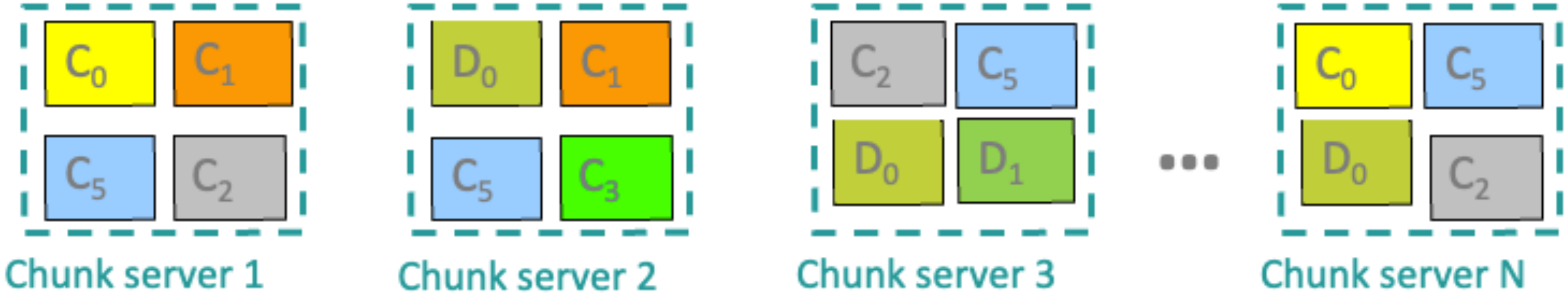
DISTRIBUTED FILE SYSTEMS

- **Present a single view of all files across multiple computers**
  - Shared directory structure
  - Shared files
- **Chunk servers**
  - File is split into contiguous chunks
  - Typically each chunk is 16-64MB
  - Each chunk replicated (usually 2x or 3x)
  - Try to keep replicas in different racks
- **Master node**
  - a.k.a. Name Node in Hadoop’s HDFS
  - Stores metadata about where files are stored
  - Might be replicated
- **Client library for file access**
  - Talks to master to find chunk servers
  - Connects directly to chunk servers to access data

DISTRIBUTED FILE SYSTEMS

Reliable distributed file system

- Data kept in “chunks” spread across machines
- Each chunk **replicated** on different machines
  - Seamless recovery from disk or machine failure



Bring computation directly to the data!

Chunk servers also serve as compute servers

DISTRIBUTED FILE SYSTEMS

Desirable Properties from a DFS perspective

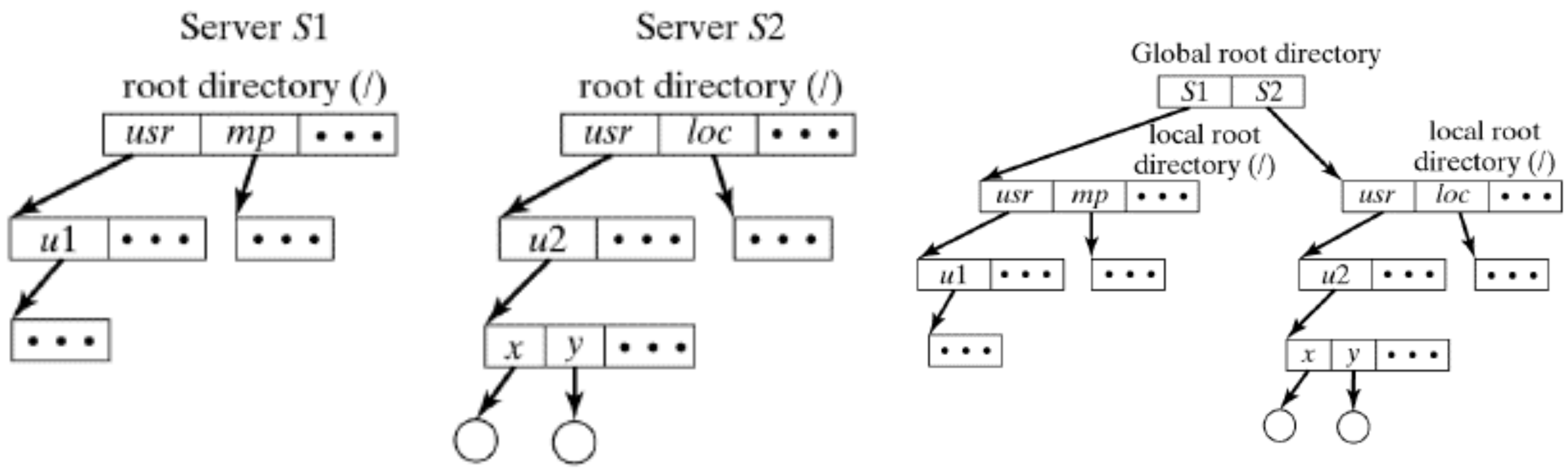
- Files are stored on a server machine
  - Client machine(s) do RPCs to server to perform operations on file
- Transparency: client accesses DFS files as if it were accessing local (say, Unix) files
  - Same API as local files, i.e., client code doesn't change
  - Need to make **location**, **replication**, etc. invisible to client
- Support **concurrent** clients
  - Multiple client processes reading/writing the file concurrently
- Replication: for fault-tolerance
- **One-copy update semantics**: when file is replicated, its contents, as visible to clients, are no different from when the file has exactly 1 replica

DISTRIBUTED FILE SYSTEMS

- Directory structures differentiated by:
  - Global *vs* Local naming:
    - Single global structure or different for each user?
  - Location transparency:
    - Does the path name reveal anything about machine or server?
  - Location independence
    - When a file moves between machines, does its path name change?

GLOBAL DIRECTORY STRUCTURE

- Combine local directory structures under a new common root



GLOBAL DIRECTORY STRUCTURE

- Problem with “Combine under new common root:”
  - Using / for new root invalidates existing local names
- Solution (Unix United):
  - Use / for local root
  - Use `..` to move to new root
  - Example: reach `u1` from `u2`: can use either

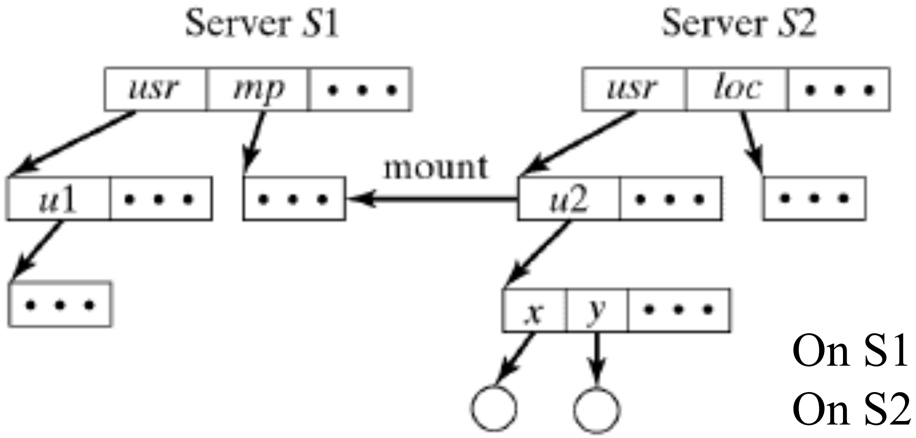
    `../../../S1/usr/u1`

    or

    `/../S1/usr/u1`
  - Names are *not* location transparent

LOCAL DIRECTORY STRUCTURES

- Mounting
  - Subtree on one machine is *mounted* over/in-the-place-of a directory on another machine (called the *mount point*)
  - Original contents of mount point are invisible during mount (so usually an empty directory is chosen)
  - Structure changes dynamically
  - Each user has own view of FS

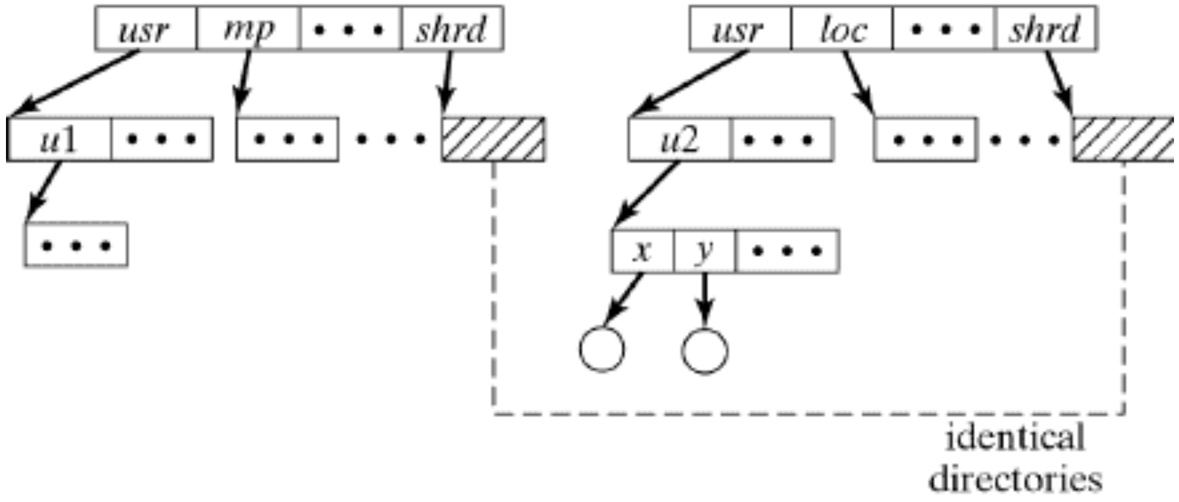


On S1: **/mp**
On S2: **/usr**

On S1: **/mp/u2/x**
On S2: **/usr/u2/x**

SHARED DIRECTORY SUBSTRUCTURE

- Each machine has local file system
- One subtree is shared by all machines

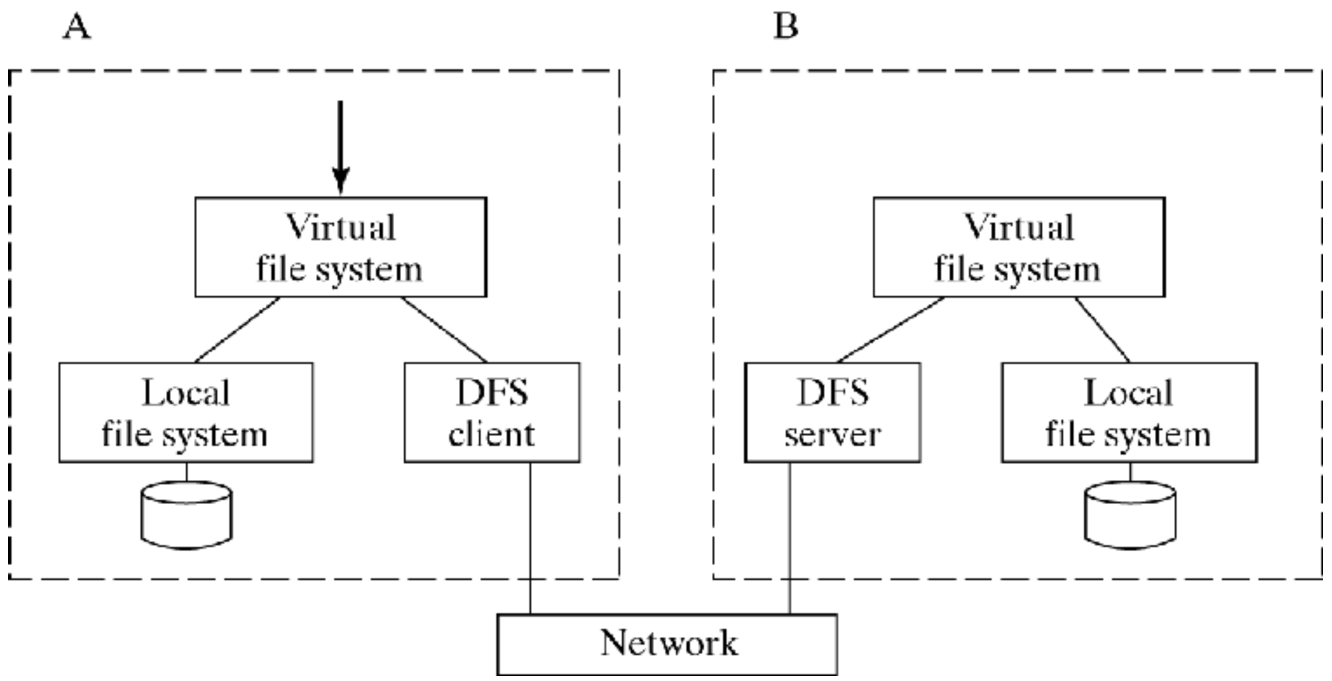


SEMANTICS OF FILE SHARING

- Unix semantics
  - All updates are immediately visible
  - Generates a lot of network traffic
- Session semantics
  - Updates visible when file closes
  - Simultaneous updates are unpredictable (lost)
- Transaction semantics
  - Updates visible at end of transaction
- Immutable-files semantics
  - Updates create a new version of file
  - Now the problem is one of version management

IMPLEMENTING DFS

- Basic Architecture
  - Client/Server Virtual file system (cf., Sun's NFS):
    - If file is local, access local file system
    - If file is remote, communicate with remote server



IMPLEMENTING DFS

- Caching reduces
  - Network delay
  - Disk access delay
- Server caching - simple
  - No disk access on subsequent access
  - No cache coherence problems
  - But network delay still exists
- Client caching - more complicated
  - When to update file on server?
  - When/how to inform other processes when files is updated on server?

IMPLEMENTING DFS

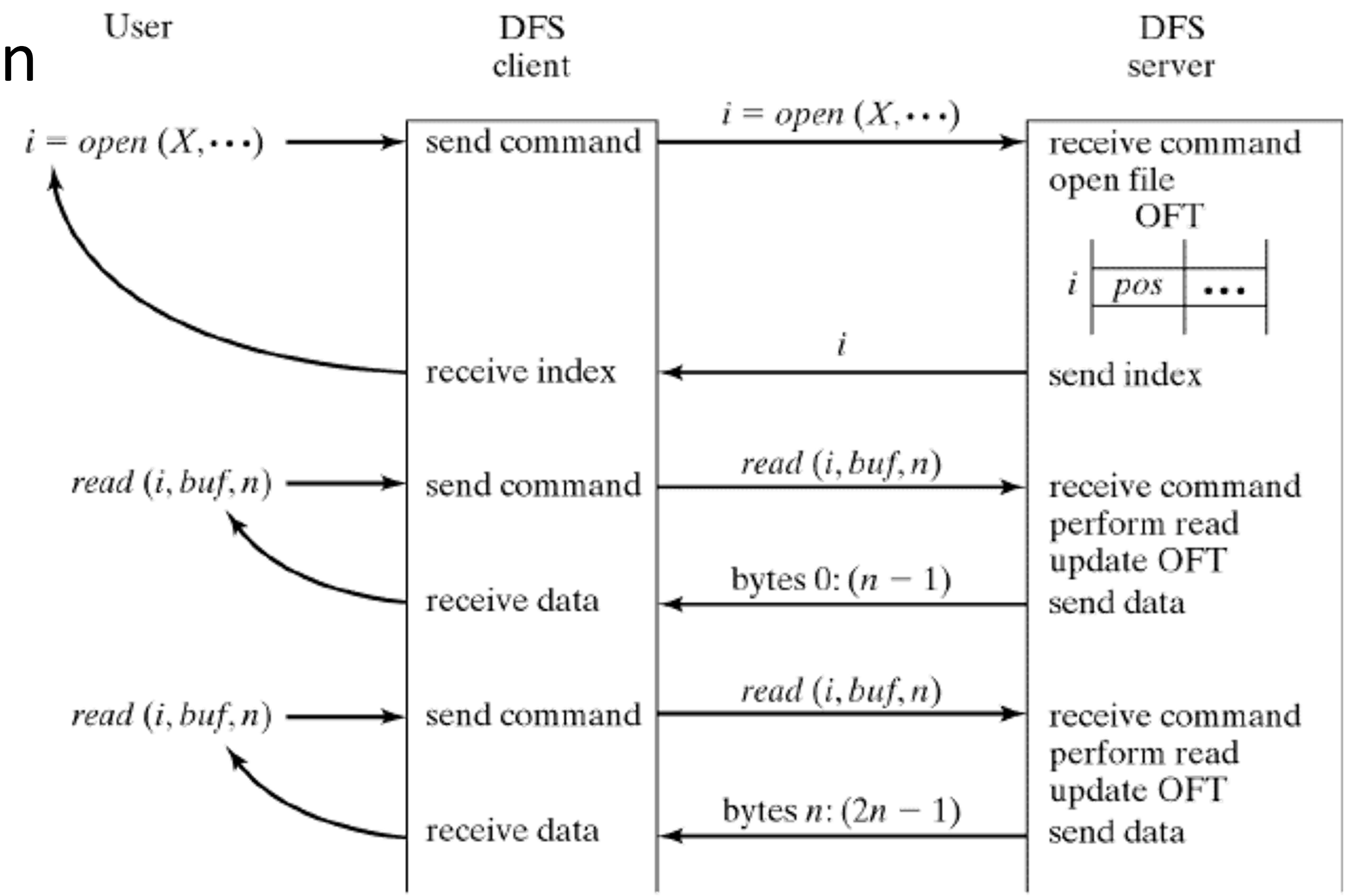
- When to update file on server?
  - Write-through
    - Allows Unix semantics but overhead is significant
  - Delayed writing
    - Requires weaker semantics
      - Session semantics: only propagate update when file is closed
      - Transaction semantics: only propagate updates at end of transactions
- How to propagate changes to other caches?
  - Server initiates/informs other processes
    - Violates client/server relationship
  - Clients check periodically
    - Checking before each access defeats purpose of caching
    - Checking less frequently requires weaker semantics
      - Session semantics: only check when opening the file

IMPLEMENTING DFS

- Stateless vs. Stateful Server
- Stateful = Maintain state of open files
- Client passes commands & data between user process & server

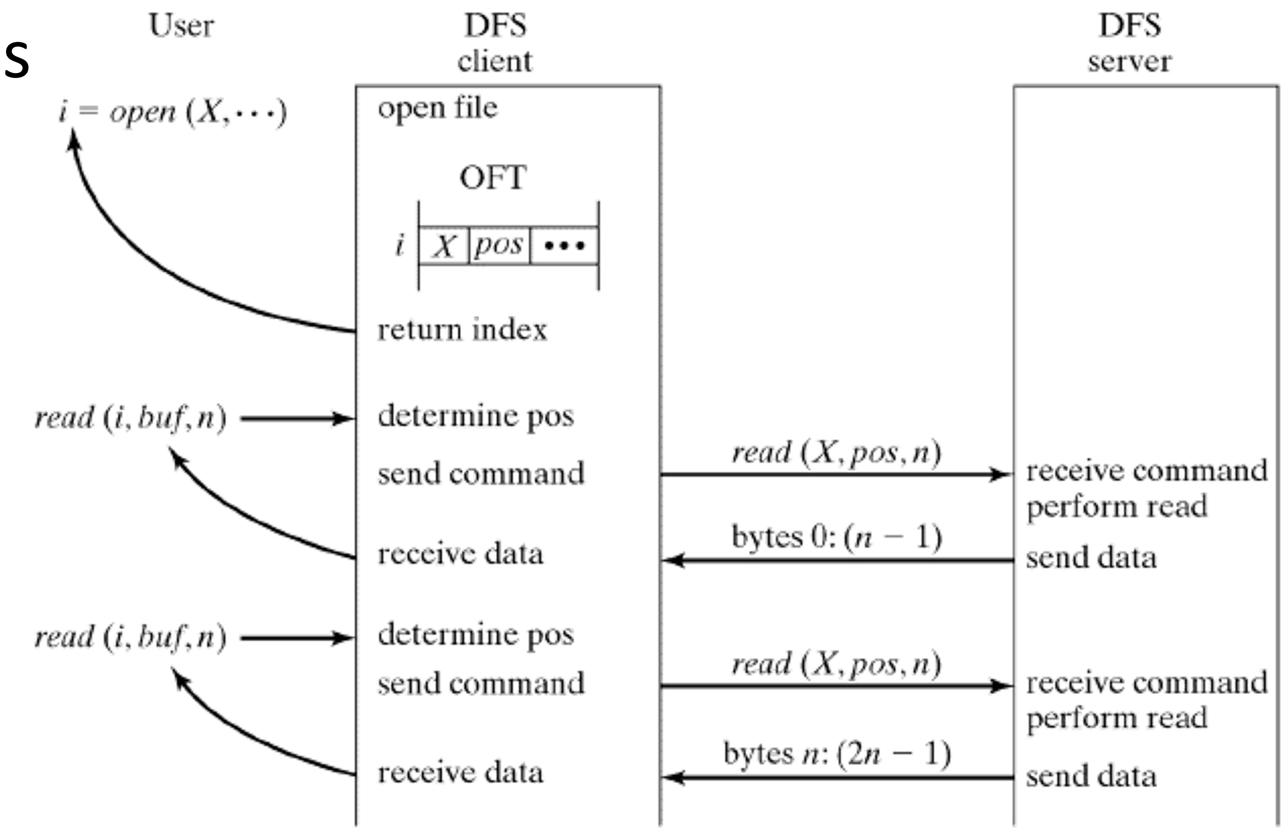
Problem when server crashes:

- State of open files is lost
- Client must restore state when server recovers



IMPLEMENTING DFS

- Stateless Server (e.g., NFS) = Client maintains state of open files
- (Most) commands are *idempotent* (can be repeated). (File deletion and renaming aren't) When server crashes:
  - Client waits until server recovers
  - Client reissues read/write commands

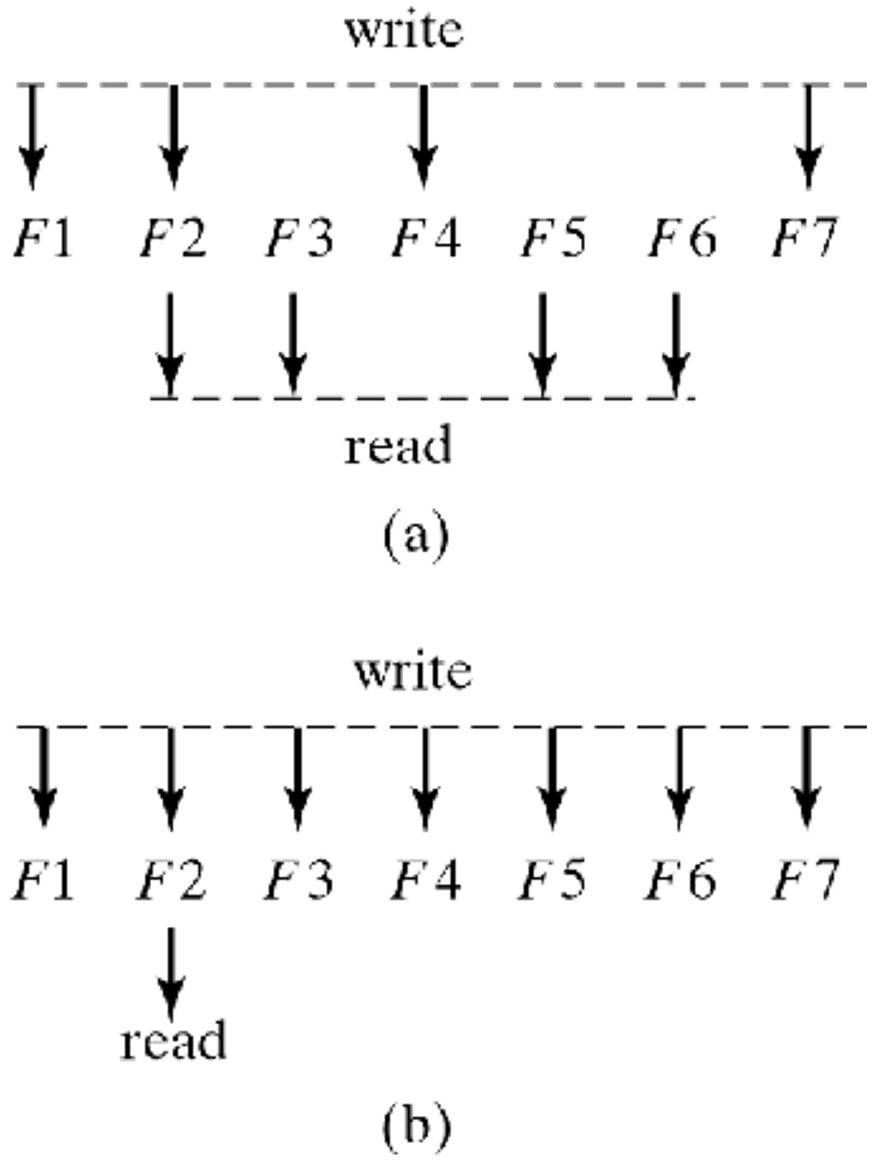


IMPLEMENTING DFS

- File replication improves
  - Availability
    - Multiple copies available
  - Reliability
    - Multiple copies help in recovery
  - Performance
    - Multiple copies remove bottlenecks and reduce network latency
  - Scalability
    - Multiple copies reduce bottlenecks

IMPLEMENTING DFS

- Problem: File copies must be consistent
- Replication protocols
  - Read-Any/Write-All
    - Problem: What if a server is temporarily unavailable?
  - Quorum-Based Read/Write
    - N copies; r = read quorum; w = write quorum
    - r+w > N and w > N/2
    - Any read sees at least one current copy
    - No disjoint writes



GOOGLE FILE SYSTEM

The following slides are taken from Virginia Tech

Google Disk Farm

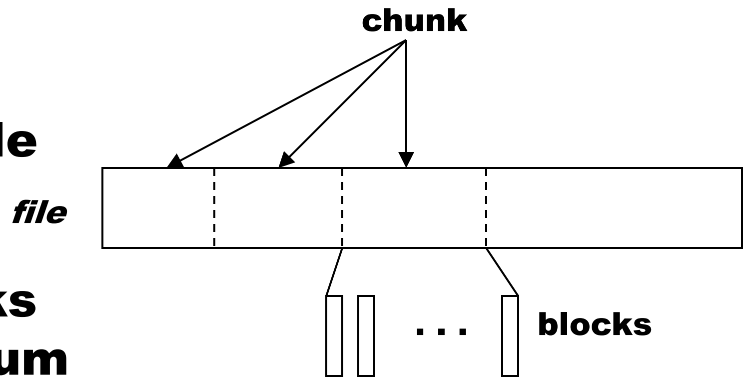
Early days…

…today

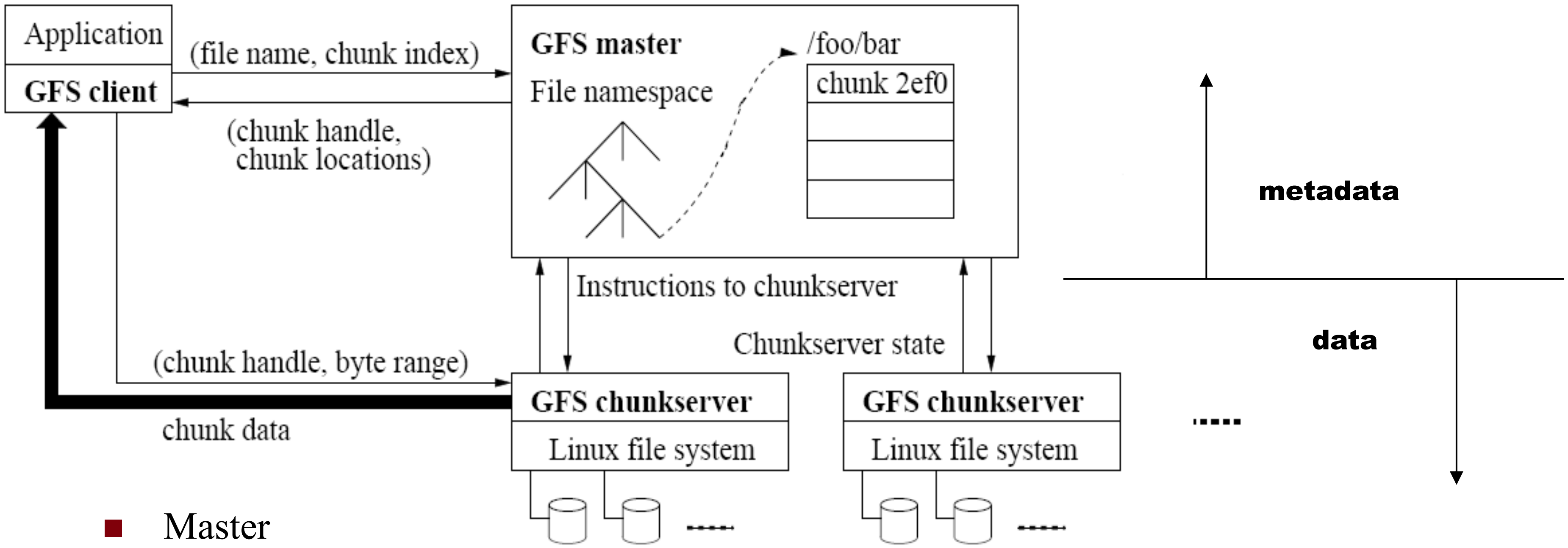
Design

- Design factors
  - **Failures are common (built from inexpensive commodity components)**
  - **Files**
    - large (multi-GB)
    - mutation principally via appending new data
    - low-overhead atomicity essential
  - **Co-design applications and file system API**
  - **Sustained bandwidth more critical than low latency**

- File structure
  - **Divided into 64 MB chunks**
  - **Chunk identified by 64-bit handle**
  - **Chunks replicated (default 3 replicas)**
  - **Chunks divided into 64KB blocks**
  - **Each block has a 32-bit checksum**



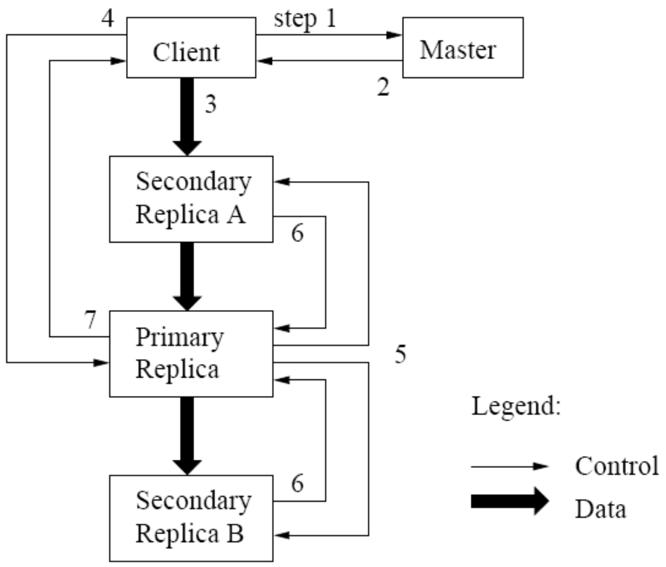
Architecture



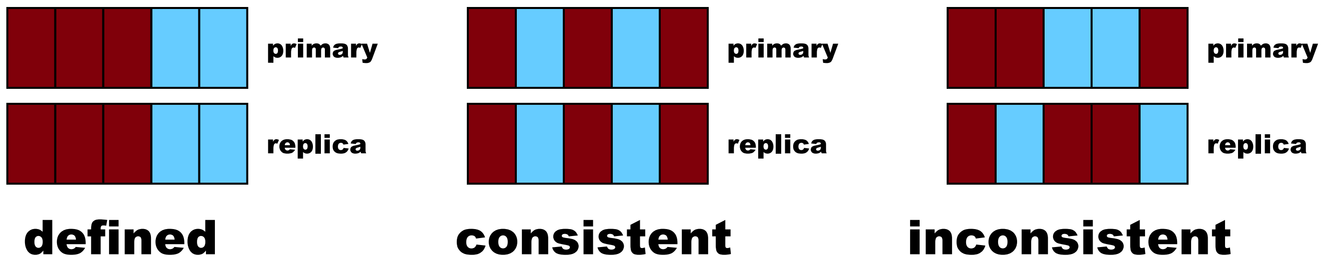
- Master
  - Manages namespace/metadata
  - Manages chunk creation, replication, placement
  - Performs snapshot operation to create duplicate of file or directory tree
  - Performs checkpointing and logging of changes to metadata
- Chunkservers
  - Stores chunk data and checksum for each block
  - On startup/failure recovery, reports chunks to master
  - Periodically reports sub-set of chunks to master (to detect no longer needed chunks)

Mutation operations

- Primary replica
  - **Holds lease assigned by master (60 sec. default)**
  - **Assigns serial order for all mutation operations performed on replicas**
- Write operation
  - **1-2: client obtains replica locations and identity of primary replica**
  - **3: client pushes data to replicas (stored in LRU buffer by chunk servers holding replicas)**
  - **4: client issues update request to primary**
  - **5: primary forwards/performs write request**
  - **6: primary receives replies from replica**
  - **7: primary replies to client**
- Record append operation
  - **Performed atomically (one byte sequence)**
  - **At-least-once semantics**
  - **Append location chosen by GFS and returned to client**
  - **Extension to step 5:**
    - If record fits in current chunk: write record and tell replicas the offset
    - If record exceeds chunk: pad the chunk, reply to client to use next chunk



Consistency Guarantees



- Write
  - **Concurrent writes may be consistent but undefined**
  - **Write operations that are large or cross chunk boundaries are subdivided by client into individual writes**
  - **Concurrent writes may become interleaved**
- Record append
  - **Atomically, at-least-once semantics**
  - **Client retries failed operation**
  - **After successful retry, replicas are defined in region of append but may have intervening undefined regions**
- Application safeguards
  - **Use record append rather than write**
  - **Insert checksums in record headers to detect fragments**
  - **Insert sequence numbers to detect duplicates**

	Write	Record Append
Serial success	*defined*	*defined* interspersed with *inconsistent*
Concurrent successes	*consistent* but *undefined*	
Failure	*inconsistent*	

Metadata management

Logical structure

pathname	lock	chunk list
/home	read	Chunk4400488,…
/save		Chunk8ffe07783,…
/home/user/foo	write	Chunk6254ee0,…
/home/user	read	Chunk88f703,…

- Namespace
  - **Logically a mapping from pathname to chunk list**
  - **Allows concurrent file creation in same directory**
  - **Read/write locks prevent conflicting operations**
  - **File deletion by renaming to a hidden name; removed during regular scan**
- Operation log
  - **Historical record of metadata changes**
  - **Kept on multiple remote machines**
  - **Checkpoint created when log exceeds threshold**
  - **When checkpointing, switch to new log and create checkpoint in separate thread**
  - **Recovery made from most recent checkpoint and subsequent log**
- Snapshot
  - **Revokes leases on chunks in file/directory**
  - **Log operation**
  - **Duplicate metadata (not the chunks!) for the source**
  - **On first client write to chunk:**
    - Required for client to gain access to chunk
    - Reference count > 1 indicates a duplicated chunk
    - Create a new chunk and update chunk list for duplicate

Chunk/replica management

- Placement
  - On chunkservers with below-average disk space utilization
  - Limit number of "recent" creations on a chunkserver (since access traffic will follow)
  - Spread replicas across racks (for reliability)
- Reclamation
  - Chunk become garbage when file of which they are a part is deleted
  - Lazy strategy (garbage college) is used since no attempt is made to reclaim chunks at time of deletion
  - In periodic "HeartBeat" message chunkserver reports to the master a subset of its current chunks
  - Master identifies which reported chunks are no longer accessible (i.e., are garbage)
  - Chunkserver reclaims garbage chunks
- Stale replica detection
  - Master assigns a version number to each chunk/replica
  - Version number incremented each time a lease is granted
  - Replicas on failed chunkservers will not have the current version number
  - Stale replicas removed as part of garbage collection

Performance

Cluster	A	B
Chunkservers	342	227
Available disk space	72 TB	180 TB
Used disk space	55 TB	155 TB
Number of Files	735 k	737 k
Number of Dead files	22 k	232 k
Number of Chunks	992 k	1550 k
Metadata at chunkservers	13 GB	21 GB
Metadata at master	48 MB	60 MB

Cluster	A	B
Read rate (last minute)	583 MB/s	380 MB/s
Read rate (last hour)	562 MB/s	384 MB/s
Read rate (since restart)	589 MB/s	49 MB/s
Write rate (last minute)	1 MB/s	101 MB/s
Write rate (last hour)	2 MB/s	117 MB/s
Write rate (since restart)	25 MB/s	13 MB/s
Master ops (last minute)	325 Ops/s	533 Ops/s
Master ops (last hour)	381 Ops/s	518 Ops/s
Master ops (since restart)	202 Ops/s	347 Ops/s

HADOOP DIST FILE SYSTEM

The following slides are taken from **Prasanth Kothuri**, CERN

Introduction to HDFS

Prasanth Kothuri, CERN

What’s HDFS

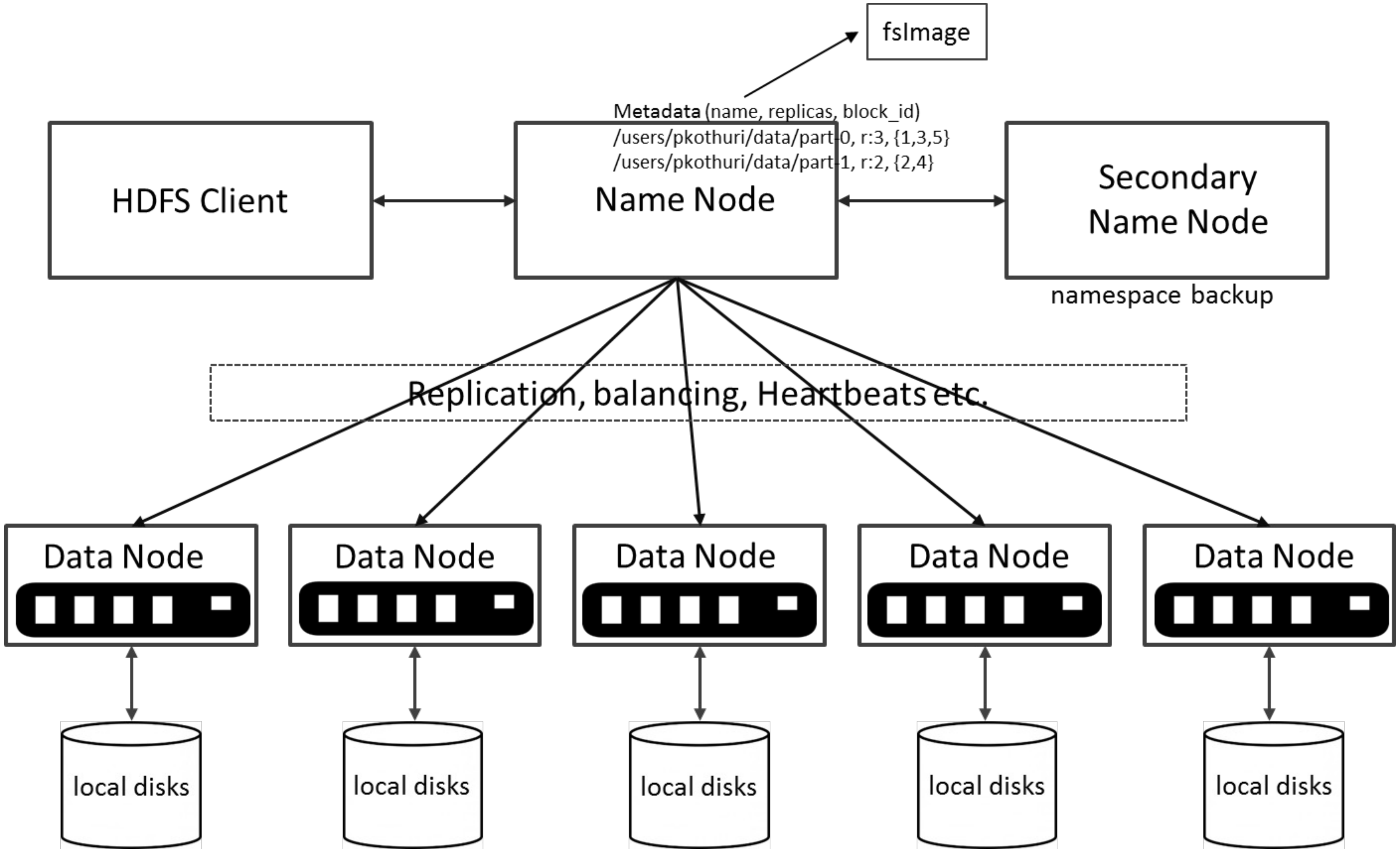
- HDFS is a distributed file system that is fault tolerant, scalable and extremely easy to expand.
- HDFS is the primary distributed storage for Hadoop applications.
- HDFS provides interfaces for applications to move themselves closer to data.
- HDFS is designed to ‘just work’, however a working knowledge helps in diagnostics and improvements.

Components of HDFS

There are two (*and a half*) types of machines in a HDFS cluster

- NameNode :– is the heart of an HDFS filesystem, it maintains and manages the file system metadata. E.g; what blocks make up a file, and on which datanodes those blocks are stored.
- DataNode :- where HDFS stores the actual data, there are usually quite a few of these.

HDFS Architecture



Unique features of HDFS

HDFS also has a bunch of unique features that make it ideal for distributed systems:

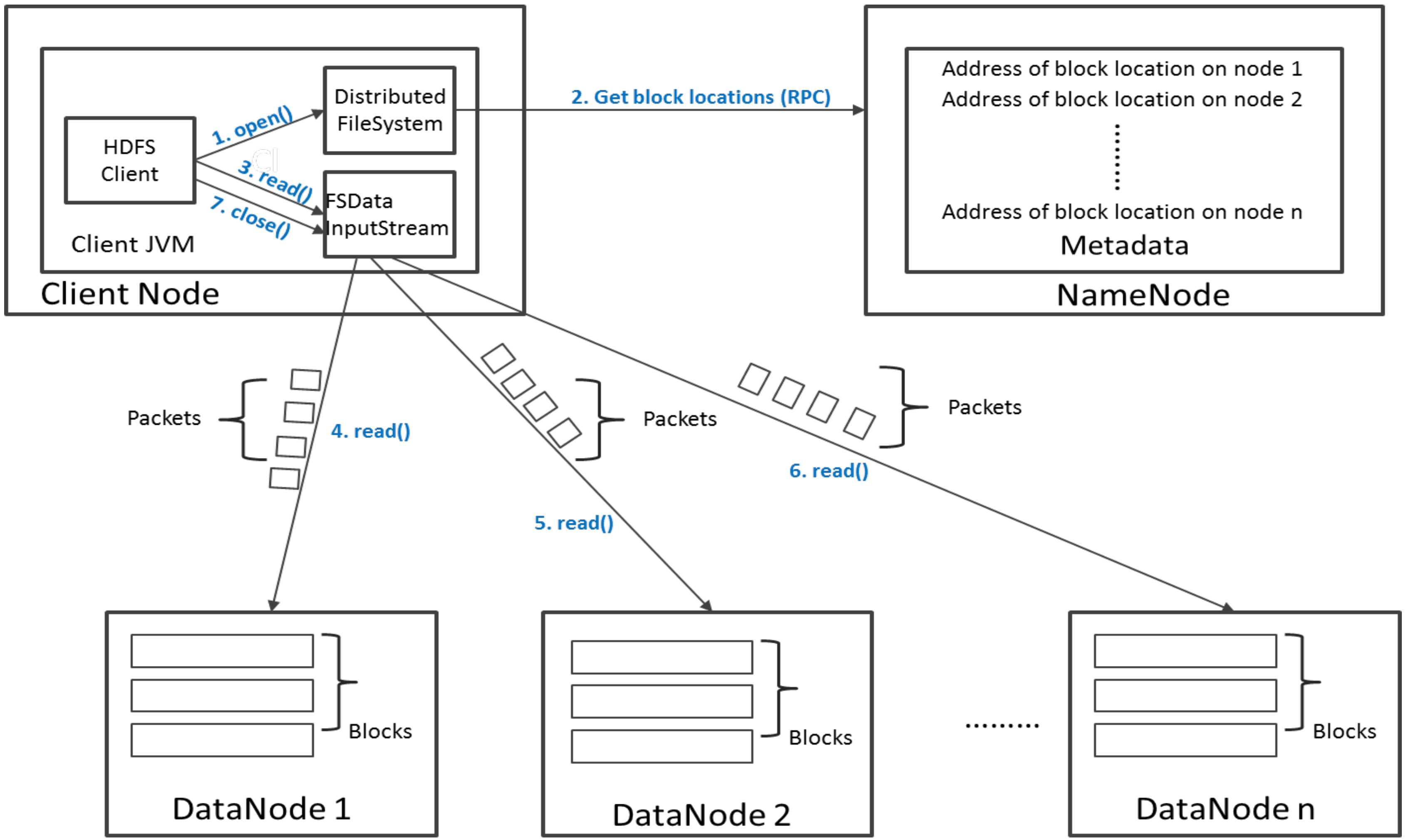
- Failure tolerant - data is duplicated across multiple DataNodes to protect against machine failures. The default is a replication factor of 3 (every block is stored on three machines).
- Scalability - data transfers happen directly with the DataNodes so your read/write capacity scales fairly well with the number of DataNodes
- Space - need more disk space? Just add more DataNodes and re-balance
- Industry standard - Other distributed applications are built on top of HDFS (HBase, Map-Reduce)

HDFS is designed to process large data sets with write-once-read-many semantics, it is not for low latency access

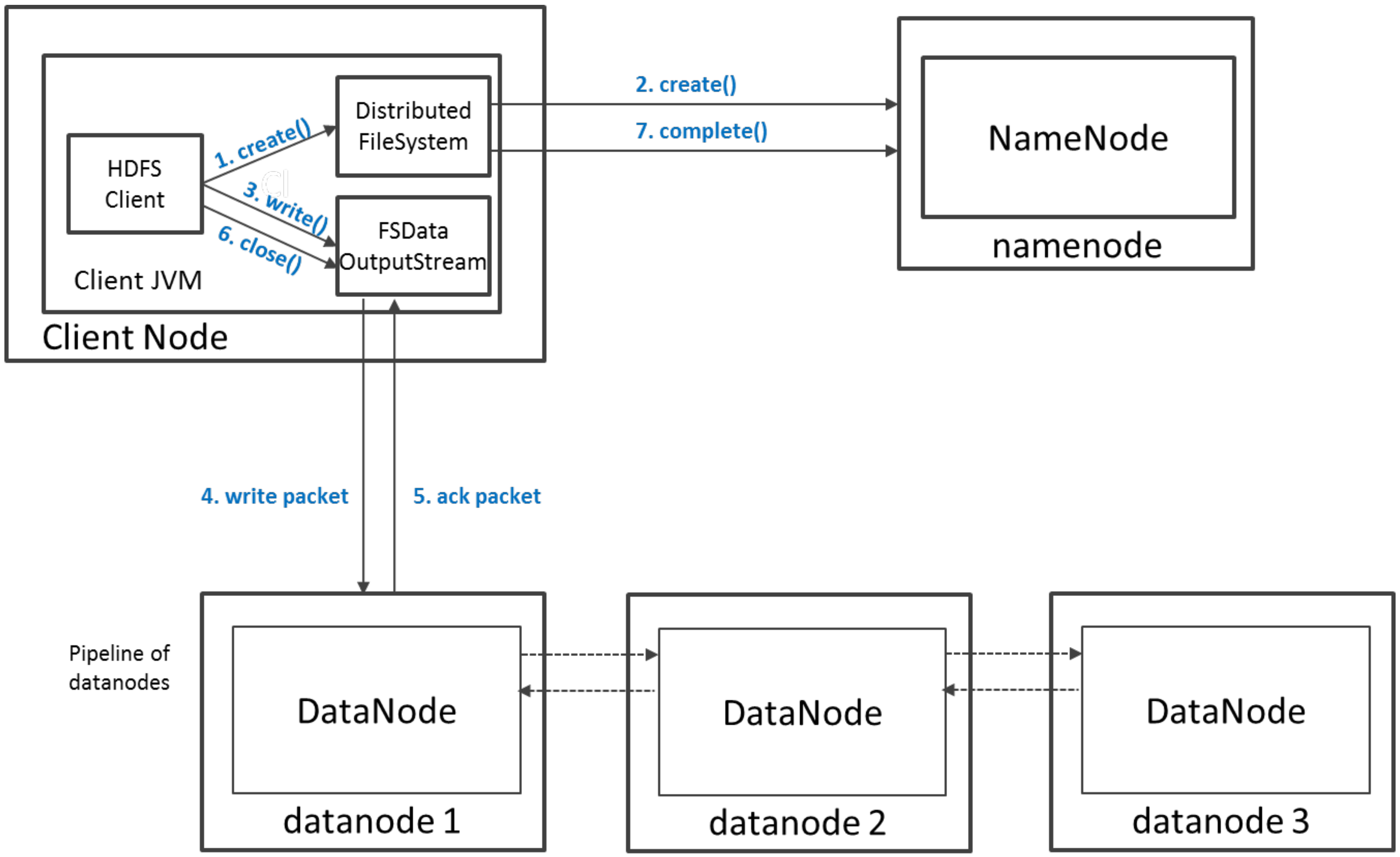
HDFS – Data Organization

- Each file written into HDFS is split into data blocks
- Each block is stored on one or more nodes
- Each copy of the block is called replica
- Block placement policy
  - First replica is placed on the local node
  - Second replica is placed in a different rack
  - Third replica is placed in the same rack as the second replica

Read Operation in HDFS



Write Operation in HDFS



HDFS Security

- Authentication to Hadoop
  - Simple – insecure way of using OS username to determine hadoop identity
  - Kerberos – authentication using kerberos ticket
  - Set by `hadoop.security.authentication=simple|kerberos`
- File and Directory permissions are same like in POSIX
  - read (r), write (w), and execute (x) permissions
  - also has an owner, group and mode
  - enabled by default (`dfs.permissions.enabled=true`)
- ACLs are used for implemention permissions that differ from natural hierarchy of users and groups
  - enabled by `dfs.namenode.acls.enabled=true`

HDFS Configuration

HDFS Defaults

- Block Size – 64 MB
- Replication Factor – 3
- Web UI Port – 50070

HDFS conf file - /etc/hadoop/conf/hdfs-site.xml

```
<property>
   <name>dfs.namenode.name.dir</name>
   <value>file:///data1/cloudera/dfs/nn,file:///data2/cloudera/dfs/nn</value>
</property>

<property>
   <name>dfs.blocksize</name>
   <value>268435456</value>
</property>

<property>
   <name>dfs.replication</name>
   <value>3</value>
</property>

<property>
   <name>dfs.namenode.http-address</name>
   <value>itracXXX.cern.ch:50070</value>
</property>
```

Interfaces to HDFS

- Java API (DistributedFileSystem)
- C wrapper (libhdfs)
- HTTP protocol
- WebDAV protocol
- Shell Commands

However the command line is one of the simplest and most familiar

HDFS – Shell Commands

There are two types of shell commands

User Commands

- `hdfs dfs` – runs filesystem commands on the HDFS
- `hdfs fsck` – runs a HDFS filesystem checking command

Administration Commands

- `hdfs dfsadmin` – runs HDFS administration commands

HDFS – User Commands (dfs)

List directory contents

```
hdfs dfs -ls
hdfs dfs -ls /
hdfs dfs -ls -R /var
```

Display the disk space used by files

```
hdfs dfs -du -h /
hdfs dfs -du /hbase/data/hbase/namespace/
hdfs dfs -du -h /hbase/data/hbase/namespace/
hdfs dfs -du -s /hbase/data/hbase/namespace/
```

HDFS – User Commands (dfs)

Copy data to HDFS

```
hdfs dfs -mkdir tdata
hdfs dfs -ls
hdfs dfs -copyFromLocal tutorials/data/geneva.csv tdata
hdfs dfs -ls –R
```

Copy the file back to local filesystem

```
cd tutorials/data/
hdfs dfs –copyToLocal tdata/geneva.csv geneva.csv.hdfs
md5sum geneva.csv geneva.csv.hdfs
```

HDFS – User Commands (acls)

List acl for a file

```
hdfs dfs -getfacl tdata/geneva.csv
```

List the file statistics – (%r – replication factor)

```
hdfs dfs -stat "%r" tdata/geneva.csv
```

Write to hdfs reading from stdin

```
echo "blah blah blah" | hdfs dfs -put - tdataset/tfile.txt
hdfs dfs -ls -R
hdfs dfs -cat tdataset/tfile.txt
```

HDFS – User Commands (fsck)

Removing a file

```
hdfs dfs -rm tdataset/tfile.txt
hdfs dfs -ls -R
```

List the blocks of a file and their locations

```
hdfs fsck /user/cloudera/tdata/geneva.csv -
files -blocks -locations
```

Print missing blocks and the files they belong to

```
hdfs fsck / -list-corruptfileblocks
```

HDFS – Adminstration Commands

Comprehensive status report of HDFS cluster

```
hdfs dfsadmin -report
```

Prints a tree of racks and their nodes

```
hdfs dfsadmin -printTopology
```

Get the information for a given datanode (like ping)

```
hdfs dfsadmin -getDatanodeInfo
localhost:50020
```

HDFS – Advanced Commands

Get a list of namenodes in the Hadoop cluster

```
hdfs getconf -namenodes
```

Dump the NameNode fsimage to XML file

```
cd /var/lib/hadoop-hdfs/cache/hdfs/dfs/name/current
hdfs oiv -i fsimage_0000000000000003388 -o
/tmp/fsimage.xml -p XML
```

The general command line syntax is

hdfs command [genericOptions] [commandOptions]

Other Interfaces to HDFS

HTTP Interface

```
http://quickstart.cloudera:50070
```

MountableHDFS – FUSE

```
mkdir /home/cloudera/hdfs
sudo hadoop-fuse-dfs dfs://quickstart.cloudera:8020
/home/cloudera/hdfs
```

Once mounted all operations on HDFS can be performed using standard Unix utilities such as 'ls', 'cd', 'cp', 'mkdir', 'find', 'grep',