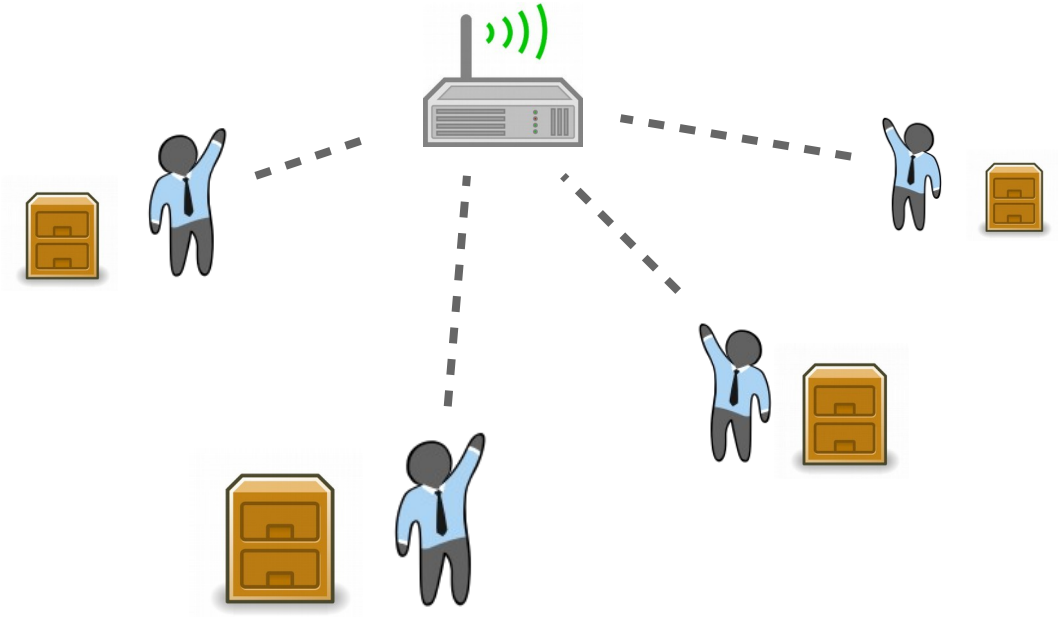
CS 470
Spring 2024

Mike Lam, Professor



Distributed Web and File Systems

A.K.A. “alternative emphases of CS 470”

Content taken from the following:

"Distributed Systems: Principles and Paradigms" by Andrew S. Tanenbaum and Maarten Van Steen (Chapters 11 and 12)

Various online sources

Distributed systems

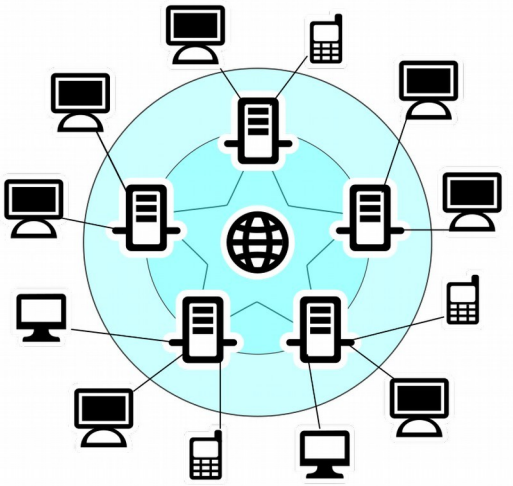
Web Systems

Relevant courses:

- **CS 343. Application Development**
- **CS 347. Web Development**

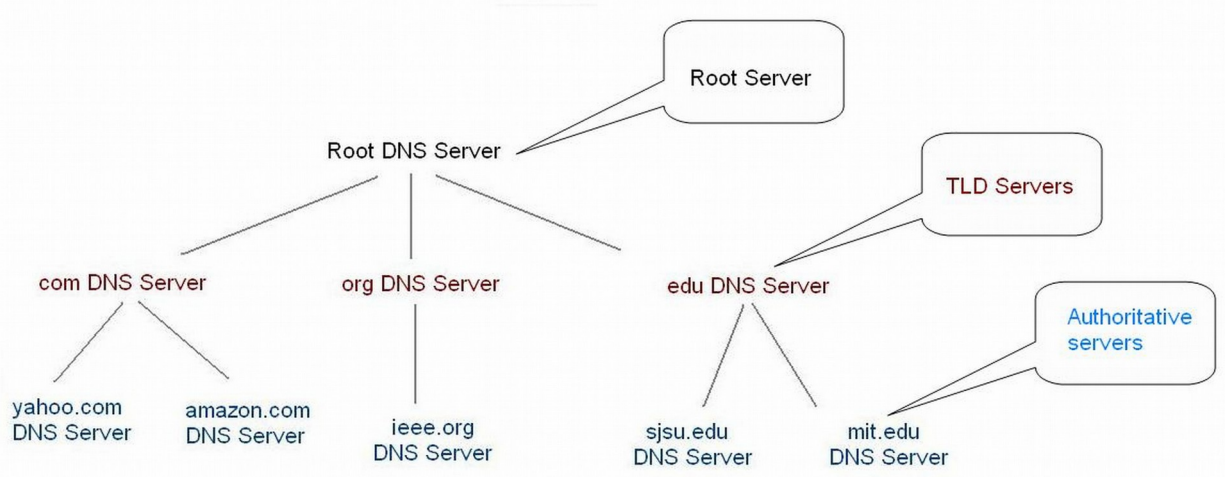
The "Internet"

- World Wide Web (WWW)
  - System for sharing information via hyperlinked documents
  - Started as a CERN project by Tim Berners-Lee; now a massive distributed system built on a worldwide network (the "Internet")
- Issues:
  - Naming
  - Security
  - Consistency
  - Replication



Naming

- IPv4 and IPv6 addresses for hosts
- Uniform Resource Locator (URL)
  - Unique worldwide name of a document
  - Domain + hierarchical path
- Domain Name Service (DNS)
  - Distributed, hierarchical IP address lookup protocol



Naming

- What do URLs and DNS names have in common?
  - A. They both address individual files on the web.
  - B. They are both hierarchical.
  - C. They are resolved by queries to the same server.
  - D. They both address hostnames.
  - E. They are both controlled by CERN.

Security

- Secure Socket Layer (SSL) and Transport Layer Security (TLS)
  - Public-key authentication, symmetric end-to-end encryption
  - Certificate Authority (CA) provides centralized key checking
    - Examples: Comodo/Sectigo, Symantec, and Let's Encrypt

- HyperText Transfer Protocol (HTTP)
  - Protocol for browser-server communication
  - Request and response model w/ headers and status codes
  - HTTPS is HTTP over SSL/TLS

- Common Gateway Interface (CGI)
  - Standardized program execution protocol
  - Somewhat similar to remote procedure calls (RPCs)

- Denial-of-Service (DoS) or Distributed DoS (DDoS) attacks
  - Often executed by botnets of virus-infected personal computers

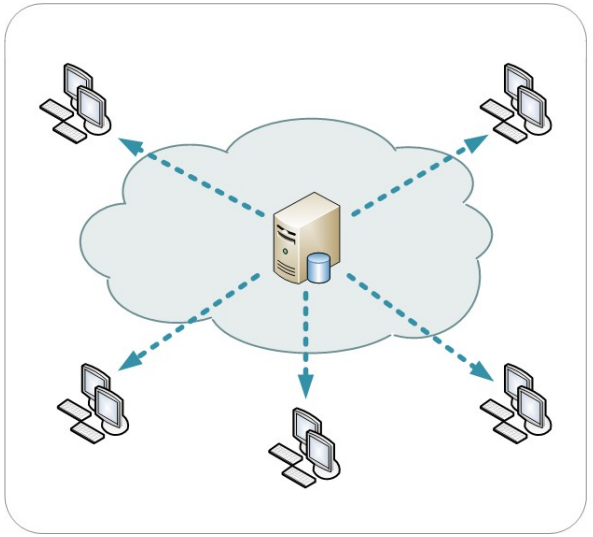
Interchange formats

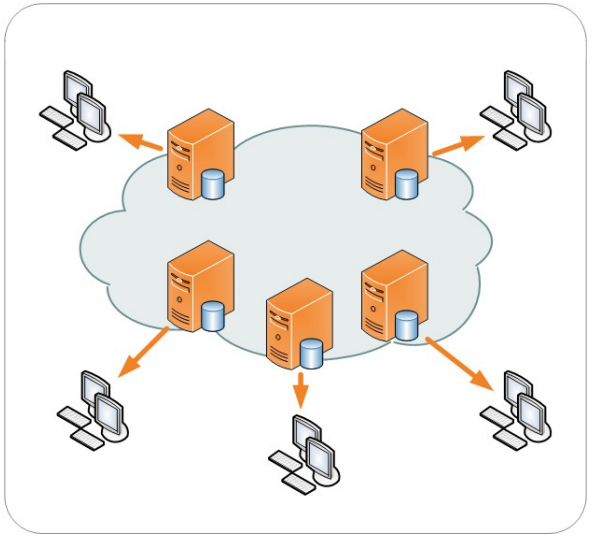
- The internet is a **very** heterogeneous distributed system
  - Exchanging information can be a challenge
- HyperText Markup Language (HTML)
  - Document format for WWW; also SHTML w/ server side includes
- eXtensible Markup Language (XML)
  - Generalized HTML; generic data-interchange format
- Multipurpose Internet Mail Exchange (MIME)
  - Encoding formats for email messages; facilitates public-key crypto
- Simple Object Access Protocol (SOAP)
  - Web services data format
- JavaScript Object Notation (JSON)
  - Lightweight data-interchange format

Consistency

- Content Delivery Networks (e.g. Akamai)
  - Globally-distributed network of proxy servers
  - Goal: improve data locality
  - Peer-to-peer and private CDNs
- Firefox / Chrome / Safari / Edge
  - Graphical interface for HTTP connections
  - Often caches website components locally

Traditional model





CDN model

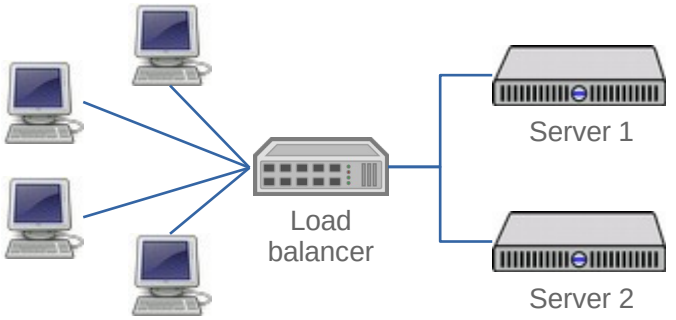
https://en.wikipedia.org/wiki/Content_delivery_network

Consistency

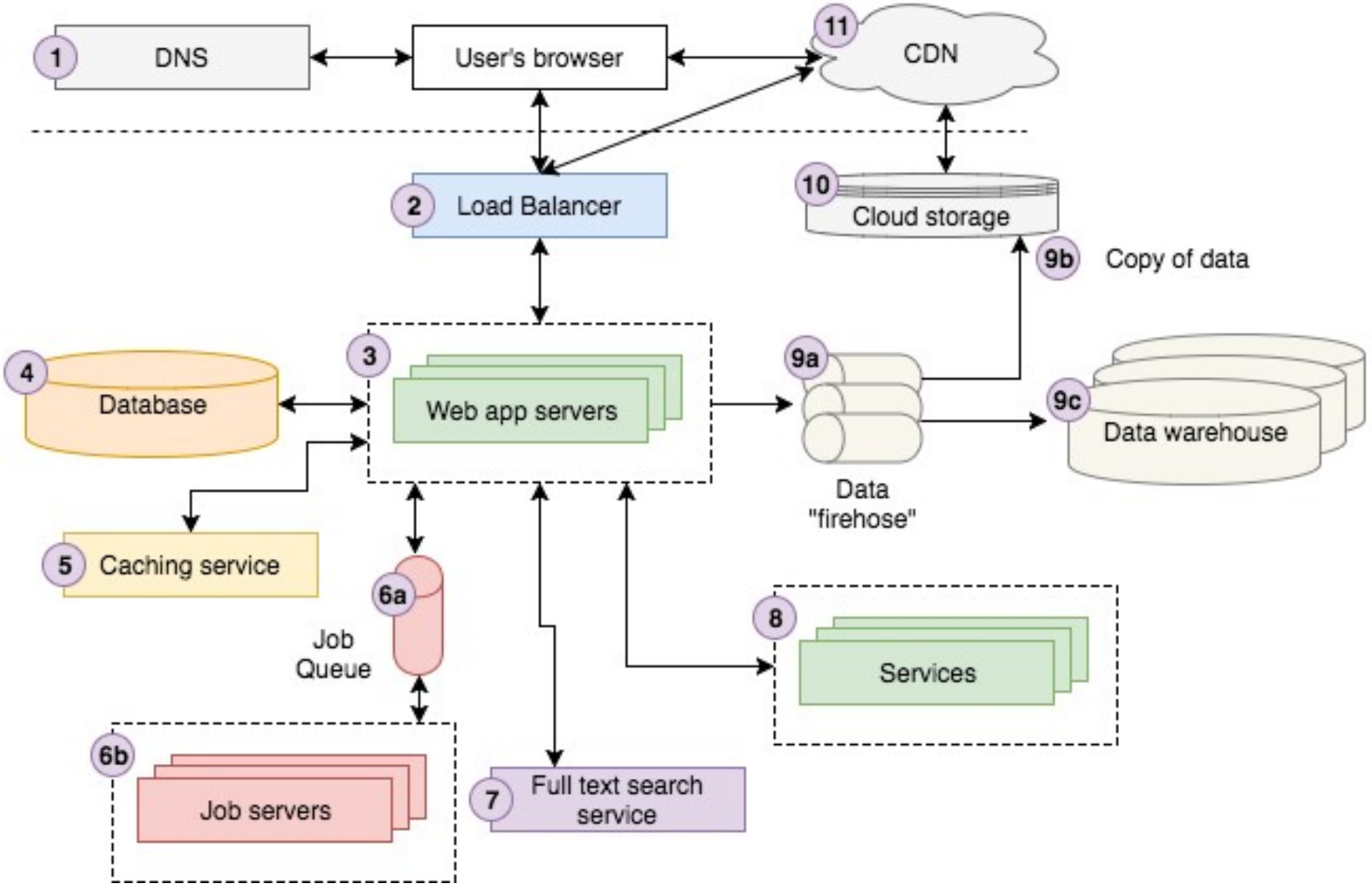
- What is the most accurate consistency model for the web?
  - A. Strict consistency
  - B. Sequential consistency
  - C. Causal consistency
  - D. Eventual consistency
  - E. No consistency

Replication

- Apache - Open-source extensible web server
  - LAMP: Linux, Apache, MySQL/MariaDB/MongoDB, PHP/Perl/Python
  - Other web servers: Nginx & Microsoft IIS
- Load balancing
  - Large websites require multiple servers w/ replicated data to provide availability to a massive number of users
  - Load balancers ensure that the traffic is distributed evenly



Web systems architecture

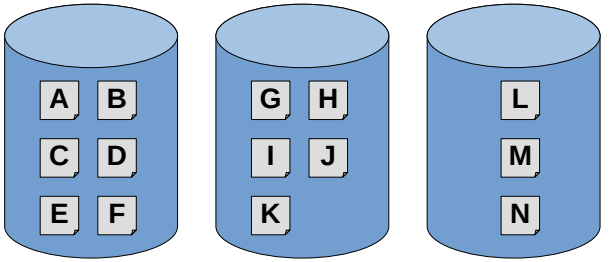


https://engineering.videoblocks.com/web-architecture-101-a3224e126947

File Systems

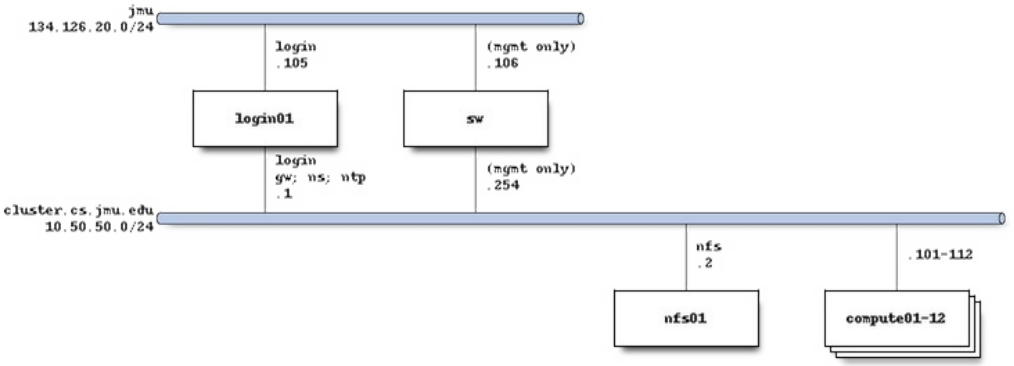
File systems

- File system: manages storage of structured data in files
- Networked file system: **centralized** storage with export/mount sharing
- Distributed file system: **distributed** storage with communication protocol
- Centralized vs. decentralized
  - Asymmetric (client/server) vs. symmetric
- Issues:
  - Naming
  - Security
  - Consistency
  - Replication



Networked file systems

- Networked file system: **centralized** storage with export/mount sharing
- Export: a file system that is made available to another host
- Mount: link to a remote file system in the local file system
  - File systems table (fstab) configuration
  - Static vs. automatic mounting



/etc/fstab on (old) cluster

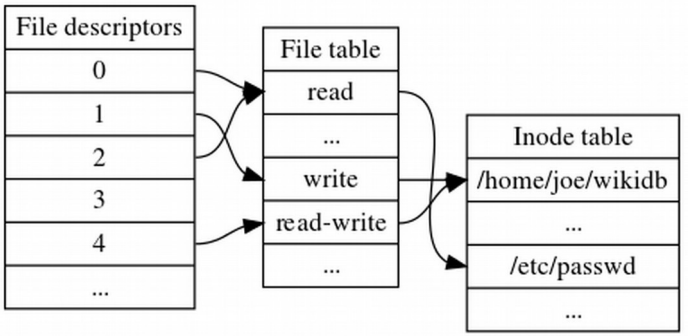
```
/dev/mapper/rhel_login01-root          /              xfs     defaults
/dev/mapper/rhel_login01-swap          swap           swap    defaults

nfs.cluster.cs.jmu.edu:/nfs/home       /nfs/home      nfs     rw
nfs.cluster.cs.jmu.edu:/nfs/scratch    /scratch       nfs     rw
nfs.cluster.cs.jmu.edu:/nfs/shared     /shared        nfs     rw,acl
```

Question

- The key/value store from P3 is a
  - A. Networked file system
  - B. Distributed file system
  - C. Both networked and distributed
  - D. None of these

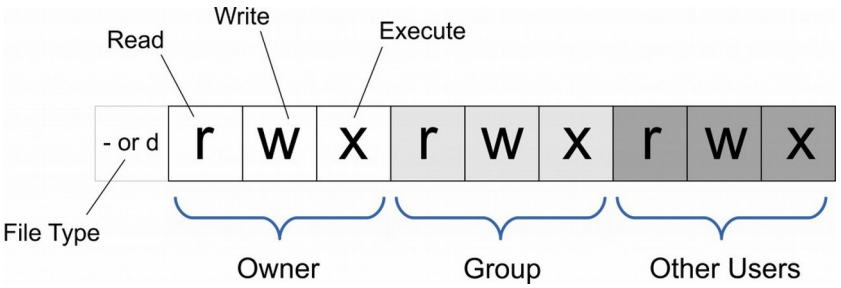
Naming

- Hierarchical file names
  - Filesystem Hierarchy Standard on Unix/Linux-based machines
- File descriptors / handles
  - Abstract identifier for an open file
  - In POSIX, positive integers:
    - Standard input: 0
    - Standard output: 1
    - Standard error: 2
- In distributed file systems:
  - Data-centric names
  - Location-centric names
  - Name servers (lookup) vs. file servers (access)



Security

- Authentication
  - UIDs, LDAP, Kerberos, Active Directory
- Access control (authorization)
  - Unix file permissions
  - Access control lists (e.g., POSIX)
  - Client vs. server permissions
- Encryption: security vs. performance tradeoff



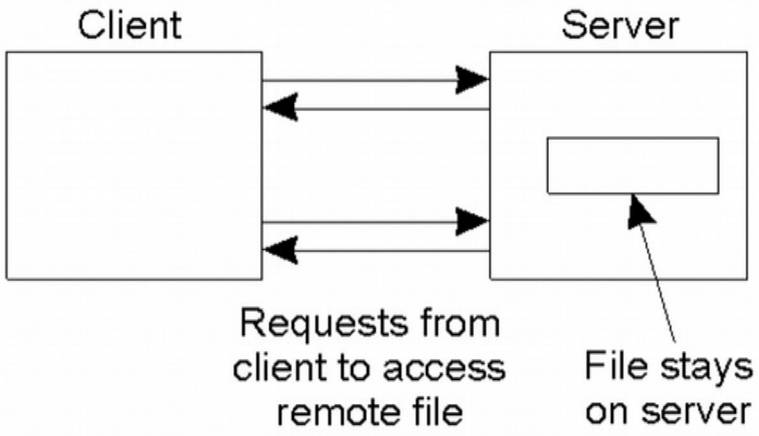
Unix file permissions

```
Alice:  read,write;
Bob:    read;
Admins: read,write;
```

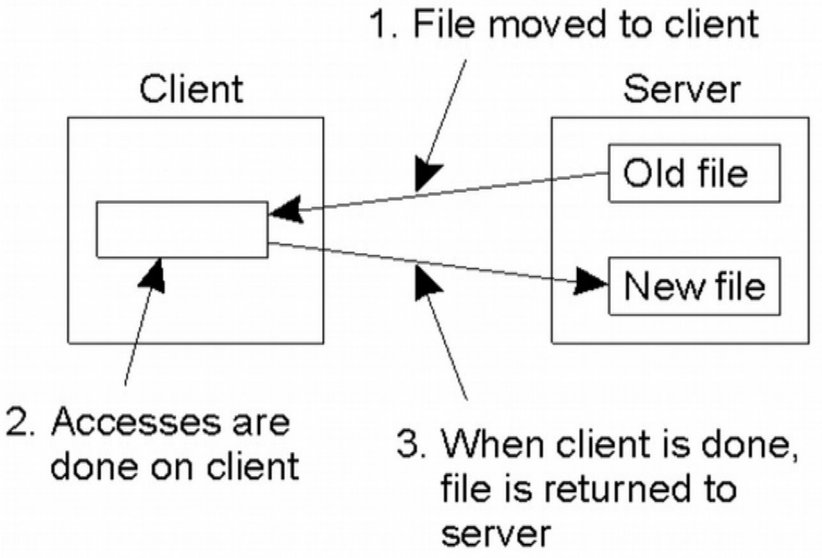
Access control list

Consistency

- Remote-write vs. local-write model
  - Forward updates immediately vs. buffer and send periodically
  - Also called remote access vs. upload/download
  - Tradeoff: consistency vs. performance



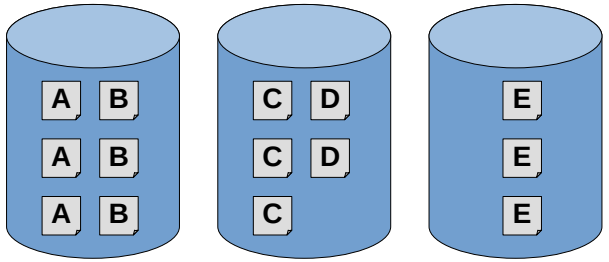
Remote-write



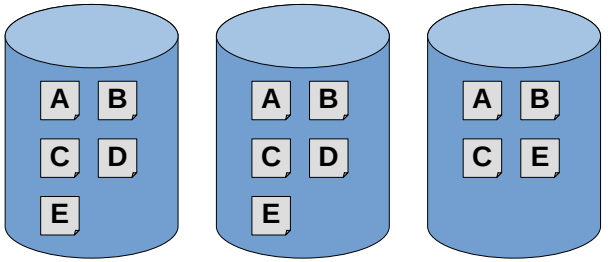
Local-write

Replication

- Client-side replication (caching)
  - Provides continued functionality while offline
  - Causes synchronization / consistency problems
  - Callback system for updating other clients
- Server-side replication (mirroring)
  - Provides fault tolerance
  - Striping: splitting a file's blocks across multiple servers



no striping



w/ striping

Replication

- Which configuration makes the most sense in the context of a distributed system where clients must disconnect from the system for significant periods of time?
  - A. Remote-write with client-side replication
  - B. Remote-write with server-side replication
  - C. Local-write with client-side replication
  - D. Local-write with server-side replication
  - E. None of these are appropriate

Peer-to-peer file systems

- Characterized by direct communication between clients
  - Centralized (e.g., Napster) vs. decentralized (e.g., Bittorrent)
  - Anonymized (e.g., Freenet) via large-scale distributed caching with encryption and hash-based keys to locate data
- Raises many social and ethical issues
  - Censorship, activism, and free speech
  - Privacy and security
  - Illegal activity and law enforcement

(Particular) File Systems

Network File System (NFS)

- Basic file sharing protocol for local networks
  - Based on remote procedure calls (RPCs)
  - Provides shared storage and reliability in presence of failures

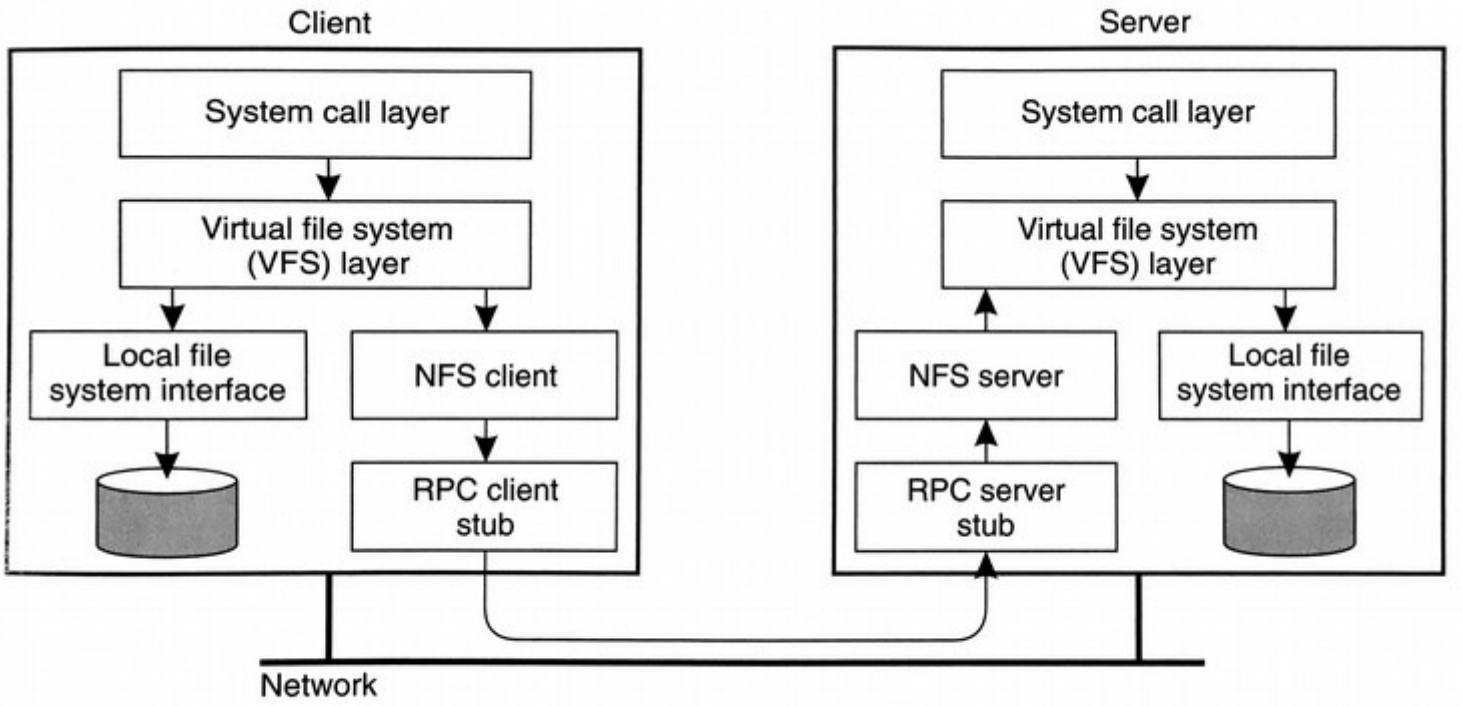


Figure 11-2. The basic NFS architecture for UNIX systems.

from Tanenbaum and Van Steen (Ch.11)

Network File System (NFS)

- Developed by Sun in 1984
  - Originally an in-house solution (v.1), now an open standard
- NFSv2 released in 1989
  - UDP-based stateless protocol
  - No built-in locking
- NFSv3 released in 1995
  - 64-bit and TCP support
- NFSv4 released in 2000
  - Adds stateful protocol and compound RPCs
  - Better access control (finer granularity)
  - New security features (including encrypted traffic)
  - pNFS: scalable access to files distributed on multiple servers

Andrew File System (AFS)

- Developed at CMU in early 1980s
  - (Named after Andrew Carnegie and Andrew Mellon)
- Improved on NFS in terms of scalability and security
- Weak consistency model
  - Each file is locked when opened
  - Modifications are performed and buffered locally
  - Updates are only sent to the server when a file is closed
  - Server uses callbacks to update other clients
- Kerberos-based access control lists
  - Lookup / insert / delete / administer
  - Read / write / lock
- Heavily influenced development of NFSv4

NFSv4

- Access control lists
  - Type: **A** = allow, **D** = deny, **U** = audit, **L** = alarm
  - Flags: **g** = group, **d** = directory-inherit, **f** = file-inherit
  - Permissions: **r** = read, **w** = write, **a** = append, **x** = execute, **d** = delete
  - Permissions (cont.): **c** = read-ACL, **C** = write-ACL, **o** = write-owner
  - Policy of "default-deny"

```
A::OWNER@:rwatTnNcCy
A::alice@nfsdomain.org:rxtncy
A::bob@nfsdomain.org:rwadtTnNcCy
A:g:GROUP@:rtncy
D:g:GROUP@:waxTC
A::EVERYONE@:rtncy
D::EVERYONE@:waxTC
```

(Particular)
Parallel File Systems

Google File System (GFS)

- Reliable asymmetric distributed file system on commodity hardware
  - Each file is split into chunks with unique chunk IDs (chunks can be replicated)
  - Master stores metadata tracking each file and its chunks (and where they are)
  - Basis for BigTable, backing store for the original MapReduce

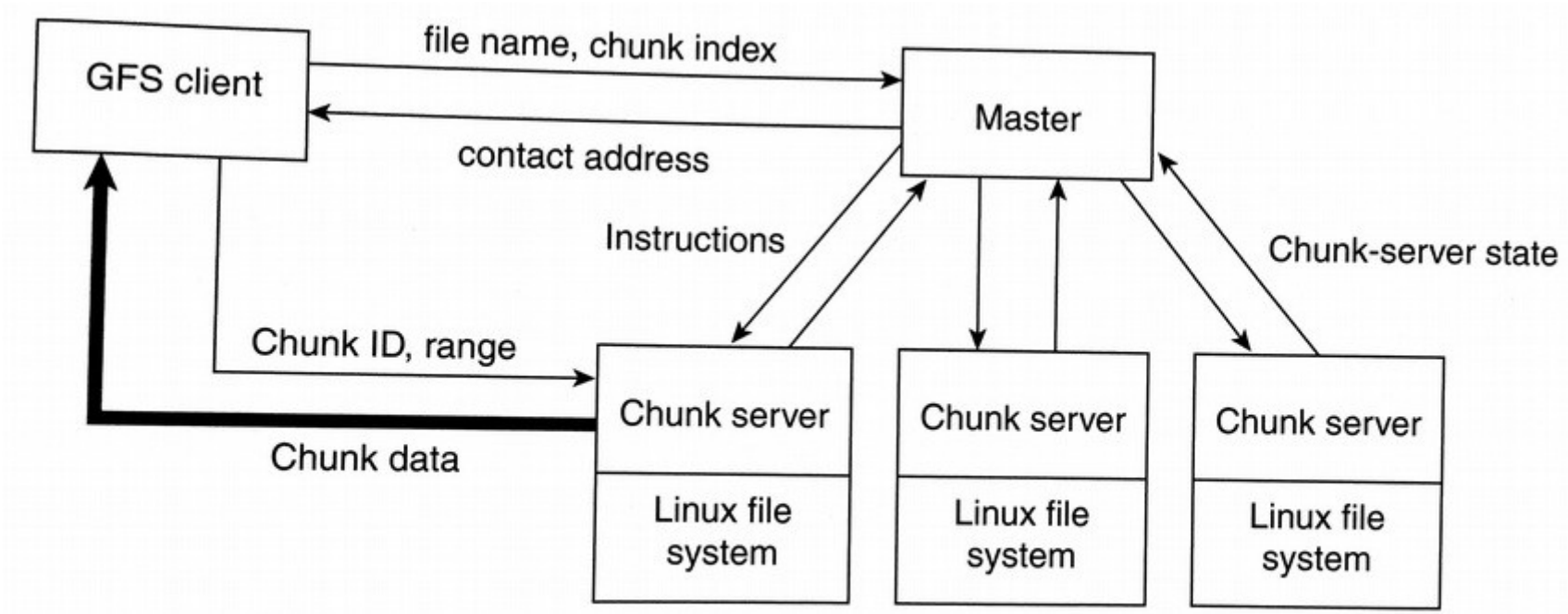


Figure 11-5. The organization of a Google cluster of servers.

from Tanenbaum and Van Steen (Ch.11)

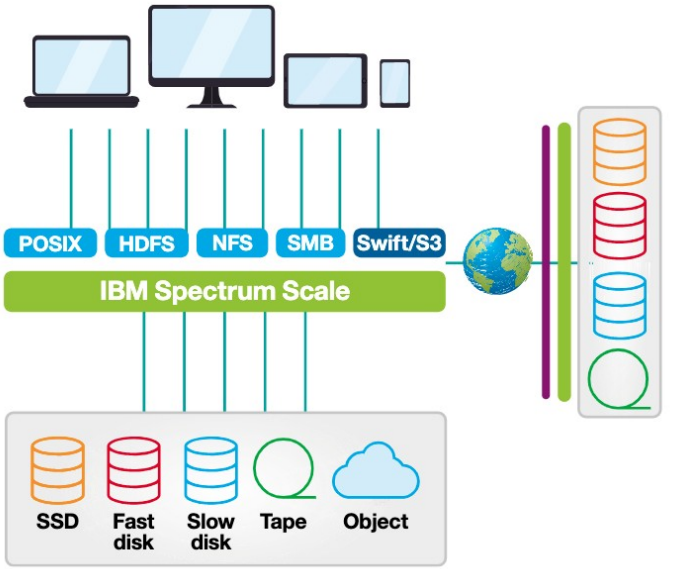
Lustre

- High-performance parallel file system
  - Initially a research project; later owned by Sun/Oracle
  - Now open source, maintained by a collection of organizations
  - Multiple lower-level interconnects: Ethernet, Infiniband
  - Used by many supercomputer installations
    - E.g., Sequoia and Titan
- Three functional units
  - Metadata server (MDS) – names, layout, permissions
  - Object storage server (OSS) – stores file data
  - Clients – connect to servers

GPFS / Spectrum Scale

- The General Parallel File System (GPFS) was developed by IBM and released in 1998
  - Re-branded as IBM Spectrum Scale in 2015
  - Used in many supercomputer installations
    - E.g., Sierra and Summit

- Industrial HPC file system
  - Reads and writes happen in parallel
  - Distributed metadata; no single point of failure
  - Availability and fault tolerance mechanisms
  - Full POSIX, NFS, and SMB compatibility
  - Multiple backing stores



https://www.ibm.com/downloads/cas/GQN4XN15

Question

- Which of the following is true of all three previously-discussed HPC file systems?
  - A) Files split into “chunks” with unique IDs
  - B) Metadata stored separately from data
  - C) Full POSIX and SMB compatibility
  - D) Source code is open and available
  - E) None of these is true of all three