Distributed Systems
Fall 2024

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Today's Agenda

File system basics

Distributed File systems

- Network File System (NFS)
- Andrew File System (AFS)

Next Class Tuesday (19/11)

Coursework Deadline (18/11) @ Noon

Coursework Submission

File System Basics

File System APIs

File System On-Disk Structures

File System Operations

What is a File?

Array of persistent bytes that can be read/written

Two interpretations of file system

- Collection of files (file system image)
- Part of OS that manages those files
  - Many local file systems: ext2, ext3, ext4, xfs, zfs, brtfs, f2fs, etc.
  - Files are common abstraction across all

Files need names so we can access correct one

- Three types of names – Inode number (unique id), path, file descriptor

Inode Number

Each file has exactly one inode number

Inodes are unique (at a given time) within file system image

Different file systems may use the same number

Numbers may be recycled after deletes

See inodes via “ls -i”

- See inode number incrementing as we create new files

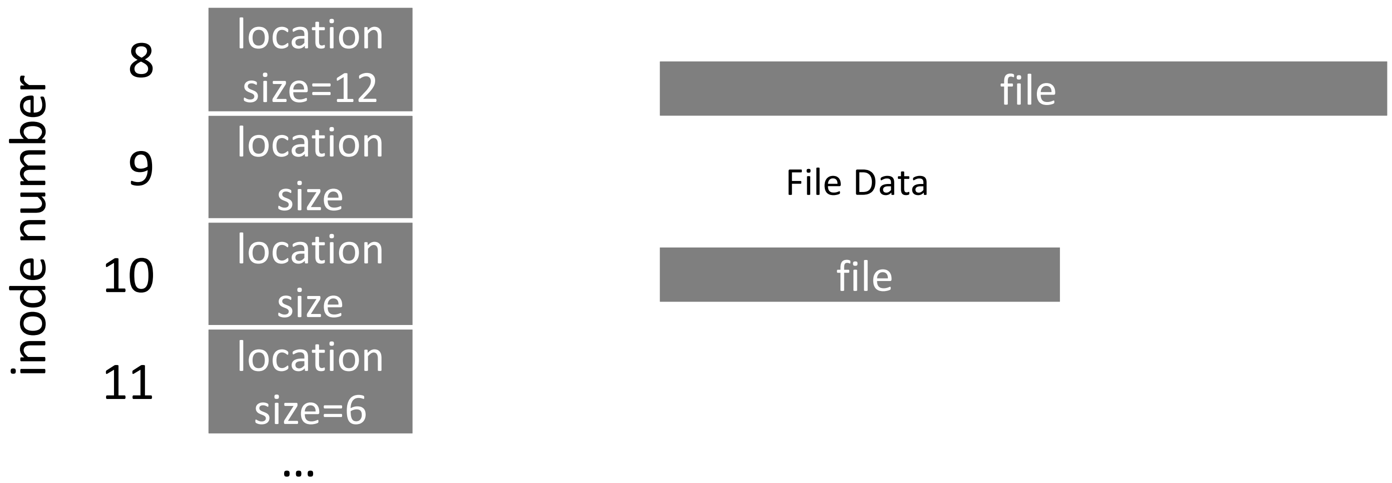
```
yuvraj@iMac temp % ls -li
19656510 drwxr-xr-x  2 yuvraj  staff  64 Jul 19 18:34 dir1
19656511 -rw-r--r--  1 yuvraj  staff   0 Jul 19 18:34 file1
```

Finding Inodes

Inodes stored in known, fixed block location on disk

Ondisk structure is called Inode file

Simple math to determine location of particular inode



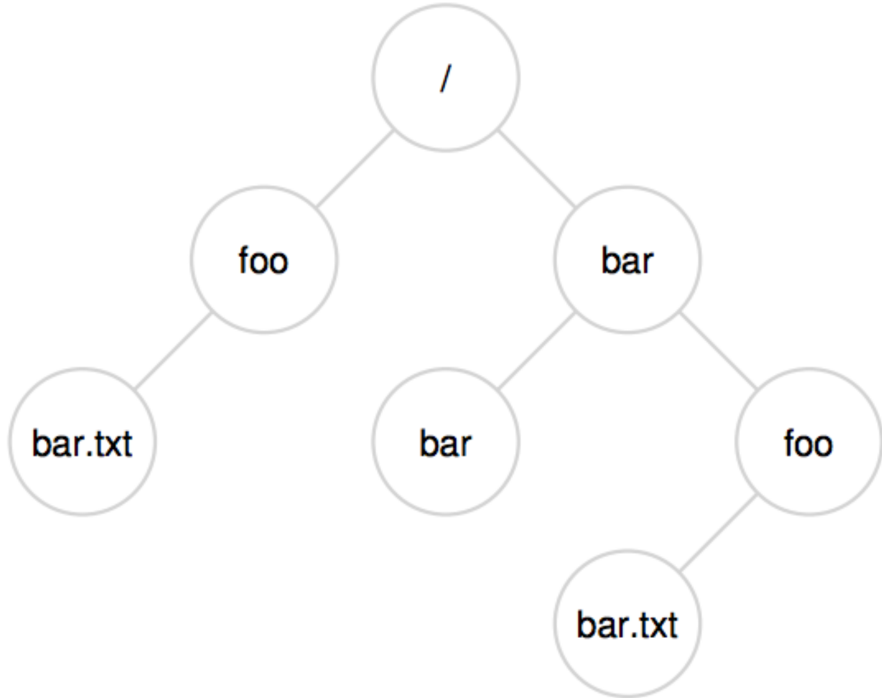
Directory

Directory is special file that contains files

Directories are stored very similarly to files

Add a bit to inode to designate if data is for “file” or “directory”

All files within a directory called as directory entries



Special Directory Entries

```
yuvraj@iMac / % cd /; ls -lia
                   2 drwxr-xr-x  20 root  wheel   640 Jan  1  2020 .
                   2 drwxr-xr-x  20 root  wheel   640 Jan  1  2020 ..
            12450924 drwxrwxr-x  23 root  admin   736 Jul 17 17:17 Applications
            12428142 drwxr-xr-x  67 root  wheel  2144 May 26 00:24 Library
1152921500311879701 drwxr-xr-x@  9 root  wheel   288 Jan  1  2020 System
               21338 drwxr-xr-x   6 root  admin   192 Jan  1  2020 Users
               23589 drwxr-xr-x   3 root  wheel    96 Jul 19 10:06 Volumes
```

Accessing Files using API

Multiple sys-calls to access the files

- open() – Open a file for reading, writing, or both
  - fd = open (const char* *Path*, int *flags*);
- read() – Reads the specified amount of bytes cnt of input into the memory area indicated by buf
  - size_t read (int *fd*, void* *buf*, size_t *cnt*);
- close() – Close a file; Cannot access file after close
  - int close(int fd);

...

File Descriptor

While opening file, do expensive path traversal

Store the inode in descriptor object (kept in memory)

Do reads/writes via descriptor, which tracks offset

Each process has a file-descriptor table that contains pointers to open file descriptors

Integers used for file I/O are indexes into the per-process table

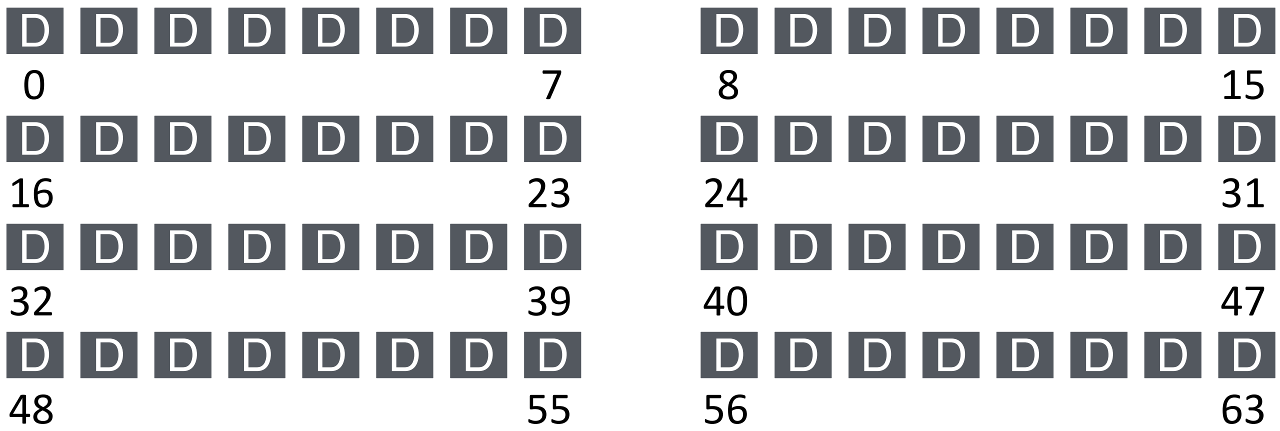
- stdin:0, stdout:1, stderr:2

On close(), the descriptor object is removed

File Descriptor in Action


```
int fd1 = open("file.txt"); // returns 3
read(fd1, buf, 12);
int fd2 = open("file.txt"); // returns 4
read(fd2, buf1, 16);
```

File System Empty Disk



Assume each block is 4KB

File System On-Disk Structures

Data stored in multiple on-disk structures

- Data block
- Indirect Block
- Inode Table
- Directories
- Data Bitmap
- Inode Bitmap
- Superblock

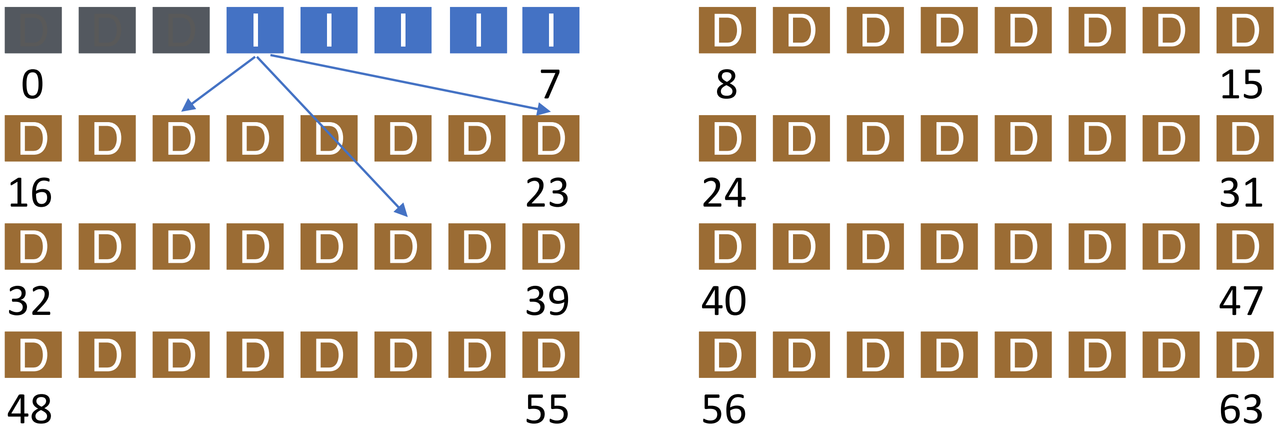
Inode Table & Inode Block

Each inode is typically 256 bytes (depends on the file system, maybe 128 bytes)

Inode block – 4 KB disk block to store inodes

In a single 4 KB block, we can store 16 inodes

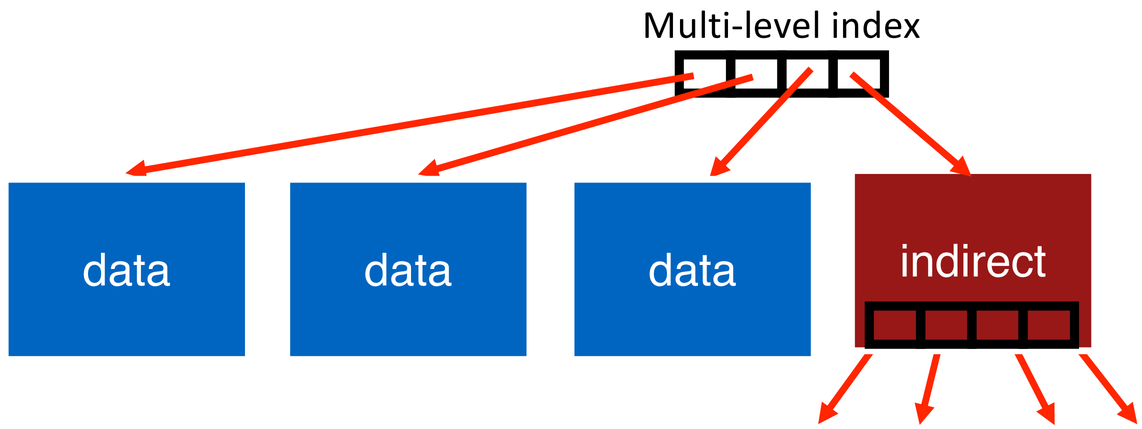
Inode blocks combine to become the Inode Table



Inode, Data and Indirect Blocks

Inode represents a file and stores its data and metadata

type (file or dir?)
uid (owner)
rwx (permissions)
size (in bytes)
Blocks
time (access)
ctime (create)
links_count (# paths)
addrs[N] (N data blocks)



Example:

12 direct pointers + 1 single indirect + 1 double indirect

Block size of 4 KB and 4-byte pointers

$$(12 + 1024 + 1024*1024\ ) \times 4\ \text{KB}) = 4\ \text{GB}$$

Better for small files!

For larger files, rely on double and triple indirect blocks

Directory

Format of how data stored varies

Common design

- Store directory entries in data blocks
- Large directories use multiple data blocks
- Use bit in inode to distinguish directories from files

Various formats for directories could be used to store directory entries

- List with fixed-sized elements to store filenames
- List with variable sized elements to store filenames
- B-Trees to store filenames

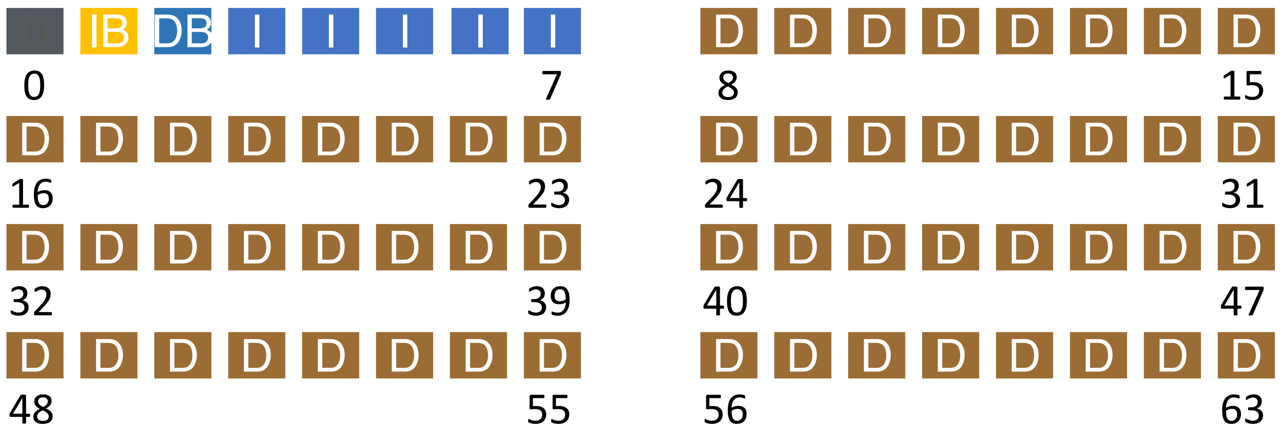
valid	name	inode
1	.	134
1	..	35
1	foo	80
1	bar	23

Data Bitmap & Inode Bitmap File

How do we find free data blocks and free inodes?

Use bitmaps to represent free and used blocks/inodes

- One bit designates state of each block/inode
- Set to 1 if allocated, 0 if free

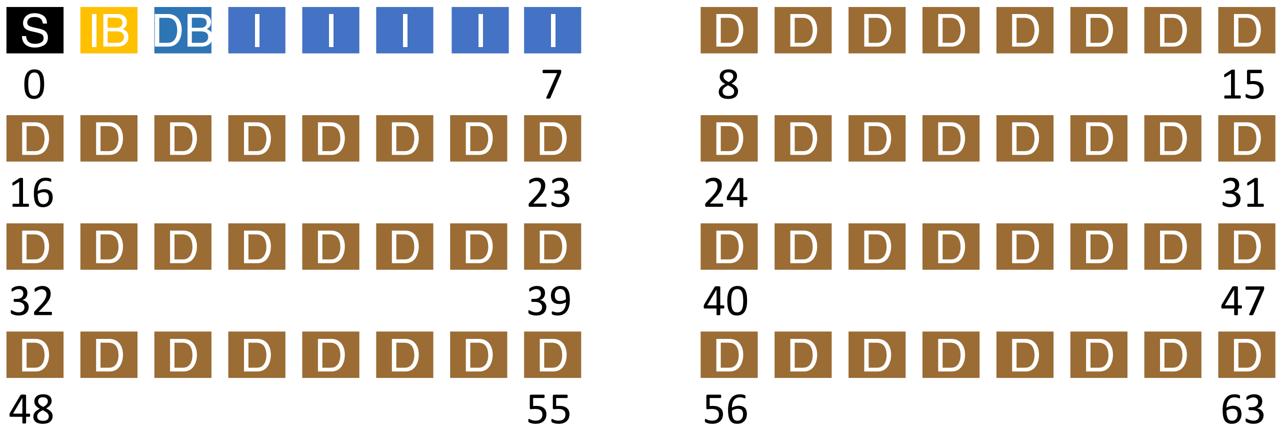


Superblock

Superblock is the starting point that stores important information about the file system

- # of blocks
- # of inodes
- Block size

…. and many more



create() Flow

create /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data
		read				
					read	
			read			
						read
	read					
	write					
						write
				read		
				write		
			write			

open() Flow

open /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
		read					
					read		
			read				
						read	
				read			

read() Flow

read /foo/bar – assume opened

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
							read

write() Flow

write to /foo/bar (assume file exists and has been opened)

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
read							
write							
							write
				write			

close() Flow

close /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data

nothing to do on disk!

Types of File Systems

Local file systems (FFS, ext3, ext4, LFS, etc.)

- Processes on same machine access shared files on the machine

Network file systems (NFS, AFS, etc.)

- Processes on different machines access shared files on a different machine
- Many client connect with a nearby single server

Goals for Distributed File Systems

Fast + Simple crash recovery

- Both clients and file server may crash

Transparent access

- Can’t tell accesses are over the network
- Normal UNIX semantics

Reasonable performance

- Scale with number of clients

Building a Distributing File System

Virtual File System (VFS)

VFS is a virtual abstraction like local file system

- Provides virtual superblocks, inodes, files, and dentry
- Compatible with a variety of local and remote file systems

VFS helps in allowing the same system call interface to be used across different file systems

- Implementation related to how things work for each file system is different

Network File System (NFS)

Think of NFS as more of a protocol than a particular file system

Many companies have implemented NFS since 1980s

- Oracle/Sun, NetApp, EMC, IBM

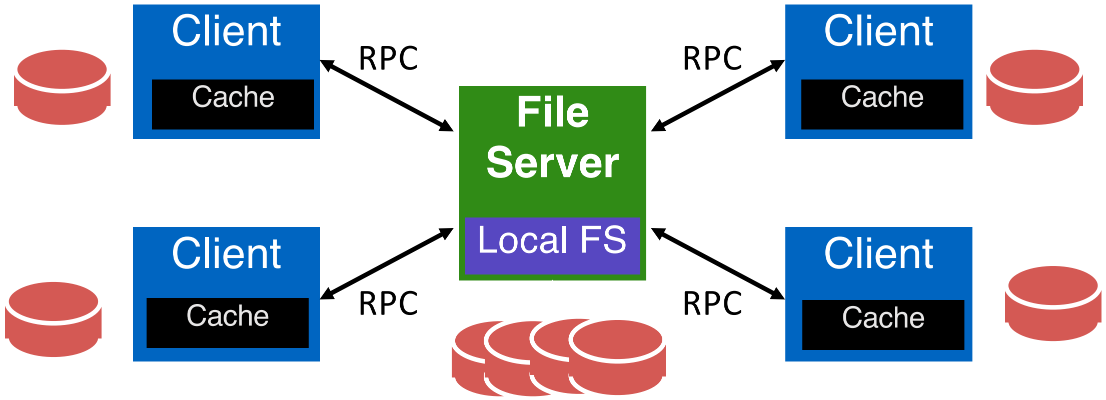
We are looking at NFSv2

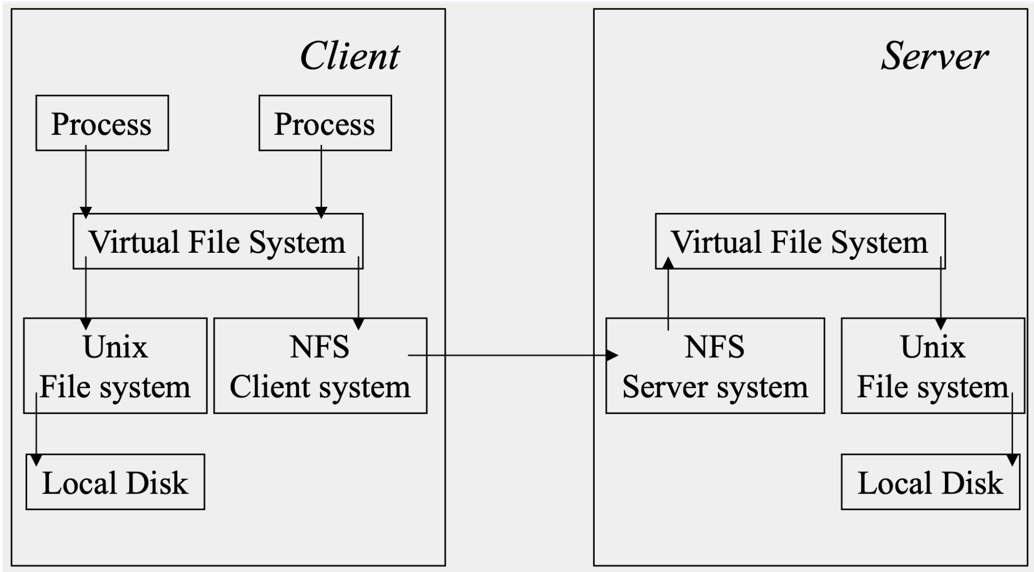
- Nfsv4 has many changes

Why look at an older protocol?

- Simpler, focused goals (simple crash recovery, stateless)

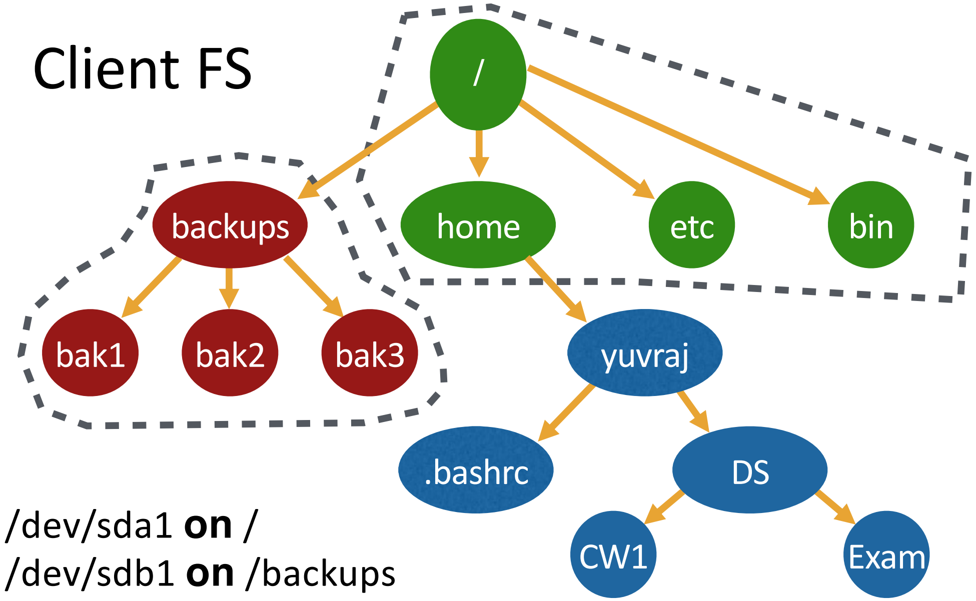
NFS Architecture





RPC: Remote Procedure Call
Cache individual blocks of NFS files

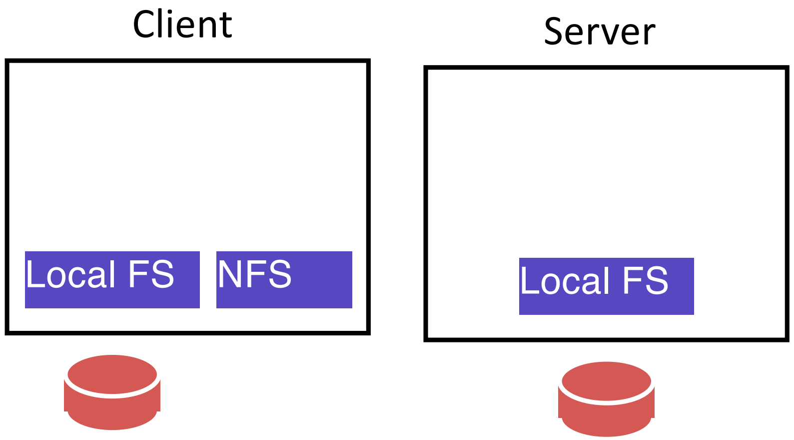
Exporting NFS



/dev/sda1 **on** /
/dev/sdb1 **on** /backups
NFS **on** /home/yuvraj

Where will read to /backups/bak1 go?

Where will read to /home/yuvraj/.bashrc go?

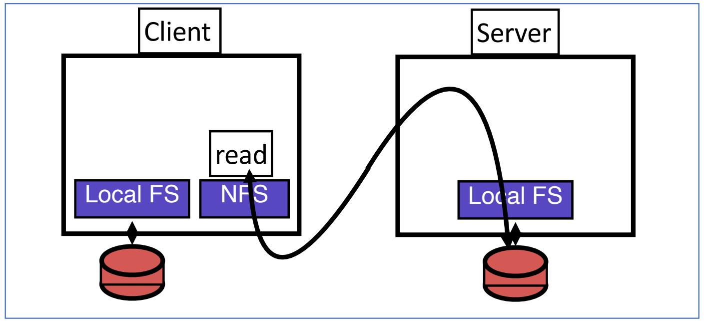


What do Clients Send to Server?

Strategy 1: Wrap regular UNIX system calls using RPC

- open() on client class open() on server
- open() on server returns fd back to client

- read(fd) on client calls read(fd) on server
- read(fd) on server returns data back to client

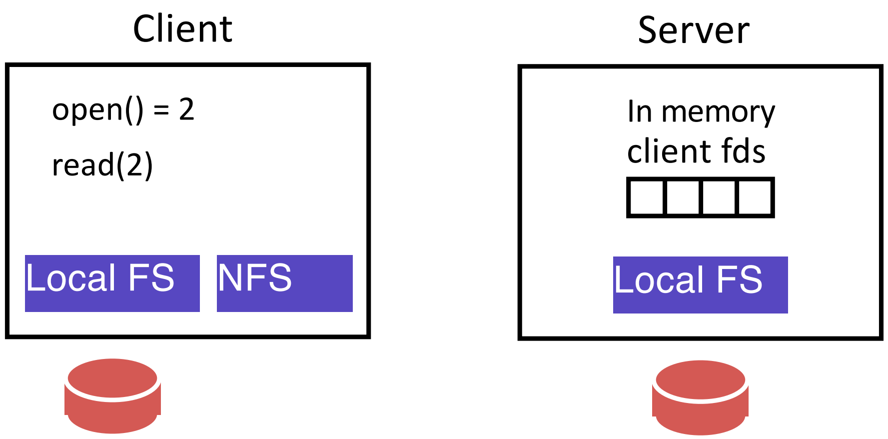


What do Clients Send to Server? (contd…)

Strategy 1: Wrap regular UNIX system calls using RPC

Problem: What about server crashes (and reboots)

```
int fd = open("foo", O_RDONLY);
read(fd, buf, MAX);
read(fd, buf, MAX);
… Server crash
read(fd, buf, MAX);
```



Recall: What is fd tracking?

What do Clients Send to Server? (contd…)

Strategy 1: Wrap regular UNIX system calls using RPC

Problem: What about server crashes (and reboots)

Potential Solutions

- Run some crash recovery protocol when server reboots
  - Complex
- Persist fds on server disk
  - Slow for disks
  - How long to keep fds? What if client crashes or misbehaves?

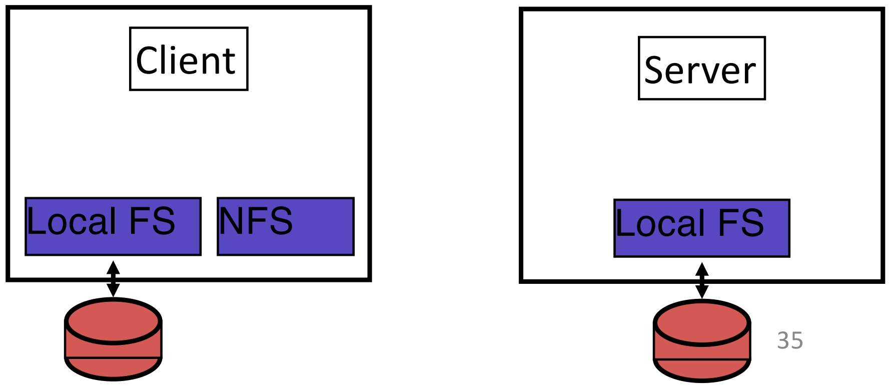
What do Clients Send to Server? (contd…)

Strategy 2: Every request from client completely describes desired operation

Use stateless protocol

- Server maintains no state about clients (that is necessary for correctness)
- Server can keep state only for performance (hints or cached copies)
- Can crash and reboot with no correctness problems (just slower performance)

Main idea of NFSv2



What do Clients Send to Server? (contd…)

Strategy 2: Stateless protocol

Need API change; Get rid of fds; One possibility:

pread(char *path, buf, size, offset);

pwrite(char *path, buf, size, offset);

Specify path and offset in each message

Server need not remember anything from clients

- Server can crash and reboot transparently to clients

Too many path lookups

What do Clients Send to Server? (contd...)

Strategy 3: Stateless protocol + Inode requests

```
inode =  open(char *path);
pread(inode, buf, size, offset);
pwrite(inode, buf, size, offset);
```

With some new interfaces on server for accessing by inode number

Correctness problem

- Inode not guaranteed to be unique over time
- If file is deleted, the inode could be reused

What do Clients Send to Server? (contd…)

Strategy 4: Stateless Protocol + File Handle

```
fh = open(char *path);
pread (fh, buf, size, offset);
pwrite(fh, buf, size, offset);
```

File Handle = <volume ID, inode #, generation #>

Opaque to client

- Client should not interpret internals

Generation count is incremented each time inode is allocated to new file/directory

What do Clients Send to Server? (contd…)

Final Strategy: Stateless Protocol + File Handle + Client Logic

Build normal UNIX API on client side on top of RPC-based APIs

Clients maintain their own file descriptors

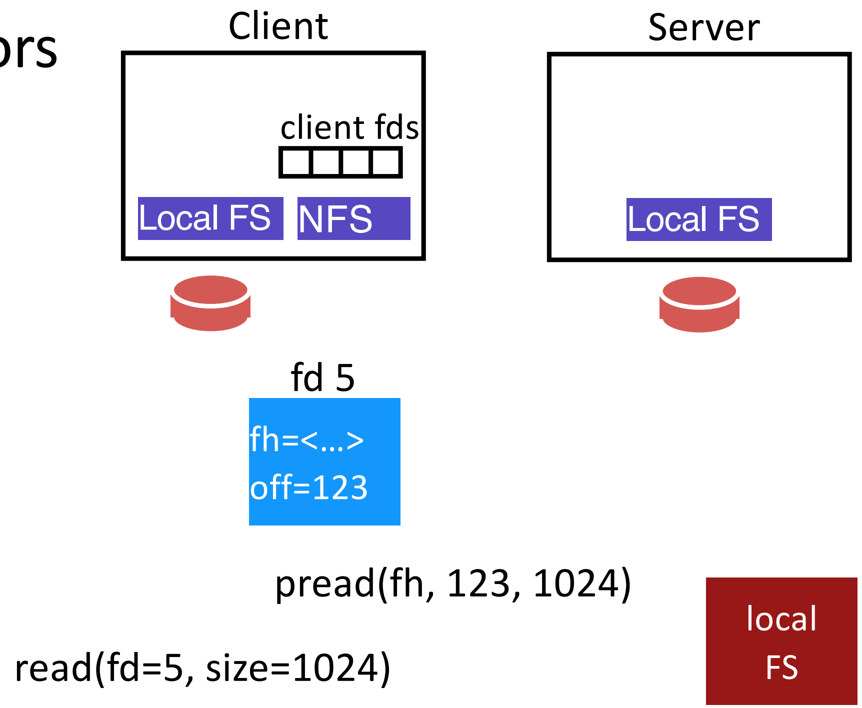
Client open() creates a local fd object

Local fd object contains

- File handle (returned by server)
- Current offset (maintained by client)

Client sends fh, offset, size to server

Server extracts inode from fh



Idempotent vs. Non-Idempotent Operations

Append operation adds content at the end of the file

append(fh, buf, size);

RPC often has “at-least-once” semantics

- May call procedure on server multiple times
- Implementing “exactly once” requires state on server, which we are trying to avoid

If RPC library replays messages, what happens when append() is retried on server?

- Could wrongly append() multiple times if server crashes and reboots

Idempotent vs. Non-Idempotent Operations

Idempotent Operations

- If f() is idempotent, f() has the same effect as f(); f(); …. f(); f();
- pwrite(), any read operation

Non-Idempotent Operations

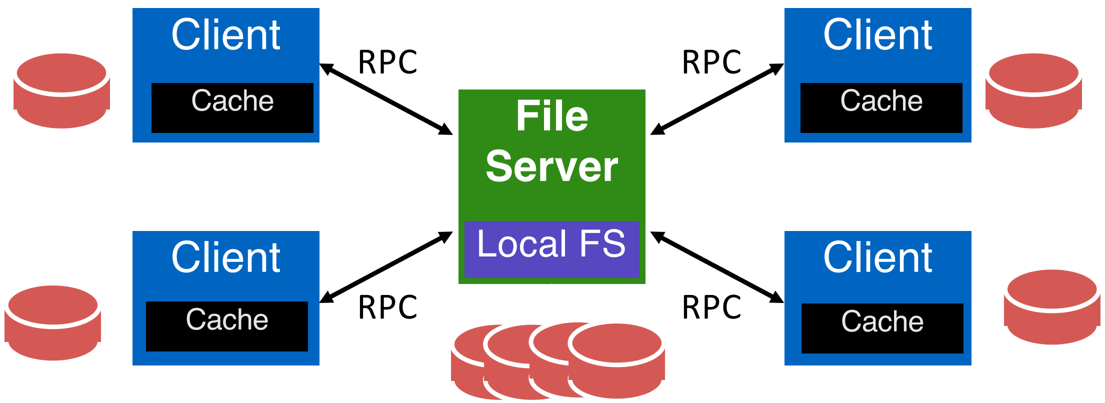
- Cannot be retried multiple times
- Append, mkdir, rmdir, creat

NFS Caching

With NFS, data can be cached in three places

- Server memory
- Client disk
- Client memory

How to make sure server and all client versions are in sync?

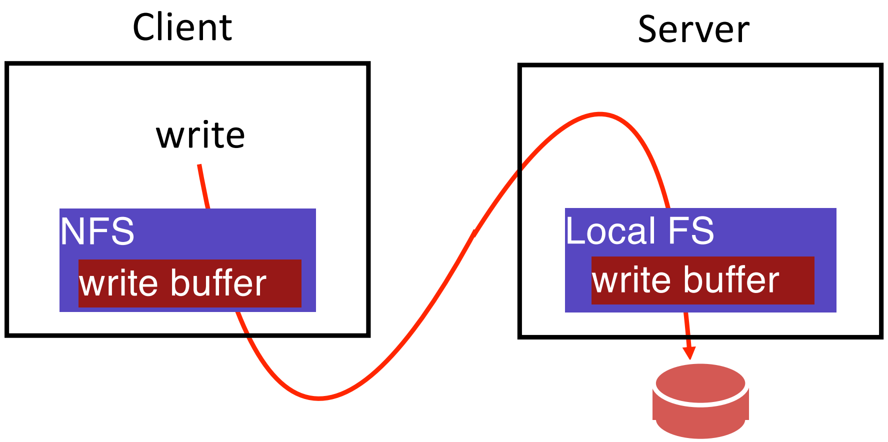


NFS Caching: Problem 1

NFS server often buffers writes to improve performance

Server might acknowledge write before pushed to disk

What happens if server crashes?



NFS Caching: Problem 1 (contd…)

NFS server often buffers writes to improve performance

Server might acknowledge write before pushed to disk

What happens if server crashes?

Solutions:

- Don’t use server write buffer (persist data to disk before acknowledging write) → Slow
- Use persistent memory → More expensive

NFS Caching: Problem 2

Clients must cache some data

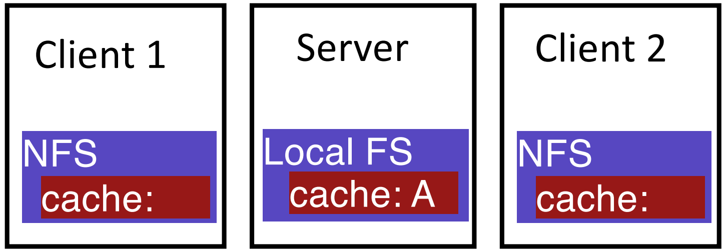
- Too slow to always contact server;
- Server would become severe bottleneck

Update visibility problem: Server doesn't have latest version

Some clients may see old version (different semantics than local file system)

When client buffers a write, how can server see update?

- Client flushes cache entry to server
- When should client perform flush?



NFS Caching: Problem 2 (contd…)

When should client perform flush?

Possibilities

- After every write (too slow)
- Periodically after some interval (odd semantics)

NFS Solution

- Flush on close()
- Other times optionally too – e.g., when low on memory

Problems not solved by NFS

- File flushes not atomic (one block of file at a time)
- Two clients flush at once can lead to mixed data

NFS Caching: Problem 3

“Stale Cache” Problem

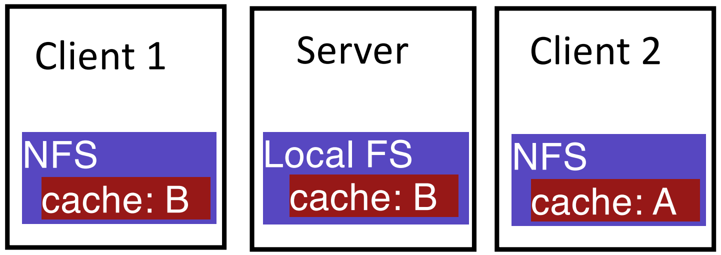
- Clients doesn’t have latest version from server
- Clients may see old version (different semantics than local FS)

How can it get latest update?

- Maintaining state – push update to relevant clients

Stateless solution

- Clients recheck if cached copy is current before using data
- Recheck faster than getting data



NFS Caching: Problem 3 (contd…)

Client cache records time when data block is fetched (t1)

Before using data block, clients sends file STAT request to server

- STAT gets last modified timestamp (t2) for this file

If t2 > t1, then refetch data block

NFS developers found server overloaded

- Found stat accounted for 90% of server requests

Fix

- Client caches result of stat (attribute cache)
- Make stat cache entries expire after a given time (3 seconds)
- Clients could read data that is up to 3 seconds old

Andrew File System (AFS)

Andrew File System: Developed at CMU in 1980s

Used in many universities (UoE home directories are AFS backed)

Goals

- More reasonable semantics for concurrent file access
- Improved scalability (many clients per server)
- Willing to sacrifice and statelessness

AFS Whole File Caching

Approach

- Measurements show most files are read in entirety
- open(): AFS client fetches whole file, storing in local memory or disk
- close(): Client flushes file to server if file was written

Convenient and intuitive semantics

- Use same version of file entire time between open() and close()

Performance advantages

- AFS needs to do work only for open/close (less load on server)
- Reads/writes are completely local

AFS Caching

AFS faces same problem as we discussed with NFS

Update Visibility

- How are updates sent to the server

Stale Cache

- How are other caches kept in sync with server?

AFS Caching – Update Visibility

AFS, like NFS, also flush on close

Buffer whole files on local disk; update file on server atomically

But what about concurrent writes?

- Last writer wins (i.e., the last file close wins)
- Newver get data mixed from multiple versions on server unlike NFS

AFS Caching: Stale Cache

Stateful solution unlike NFS' stateless solution

Server tells clients when data is overwritten

- Server must remember which clients have the file open right now

When clients cache data on open(), ask for "callback" from server if file changes

- Clients can use data during this open() without caching

Clients only verifies callback when open() file (not every read)

- May not refetch file on next open()
- Operate on same version of file from open to close

AFS Callbacks: Dealing with State

Callbacks are good to handle the stale cache issue.

What about client and server crashes?

AFS Callbacks: Dealing with State (contd…)

Client crash

- After reboot, cached data might be on client disk
- Might read stale data from the cached copy
- Solutions
  - Evict everything from cache
  - Recheck specific entries before using

Server crash

- Lose track of all clients who have file open
- Solution – Tell all clients to recheck all data before next open

NFS vs AFS Protocols

Time	Client A	Client B	Server Action?
0	fd = open("file A");		
10	read(fd, block1);		
20	read(fd, block2);		
30	read(fd, block1);		
31	read(fd, block2);		
40		fd = open("file A");	
50		write(fd, block1);	
60	read(fd, block1);		
70		close(fd);	
80	read(fd, block1);		
81	read(fd, block2);		
90	close(fd);		
100	fd = open("fileA");		
110	read(fd, block1);		
120	close(fd);		

NFS Protocol

Time	Client A	Client B	Server Action?
0	fd = open("file A"); Filehandle		Lookup for file A
10	read(fd, block1);		Read
20	read(fd, block2);		Read
30	read(fd, block1); Check cache; attr expired; call		Get_attr()
31	read(fd, block2); get_attr(); else use local copy	Latest attributes	Get_attr()
40		fd = open("file A"); Filehandle	Lookup for file A
50		write(fd, block1); Keep local	
60	read(fd, block1); Check cache; attr expired; call get_attr(); else use local copy	Latest attributes	Get_attr()
70		close(fd); Send data to server	Write to disk
80	read(fd, block1); Check cache; attr expired; call		Get_attr()
81	read(fd, block2); get_attr(); expired; flush cache; fresh read again	Latest attributes	Get_attr()
90	close(fd);		
100	fd = open("fileA"); Filehandle		Lookup for file A
110	read(fd, block1); Check cache; attr expired; call get_attr(); else use local copy	Latest attributes	Get_attr()
120	close(fd);		

AFS Protocol

Time	Client A	Client B	Server Action?
0	fd = open("file A");		Setup callback for A, send all of file A
10	read(fd, block1);		
20	read(fd, block2);		
30	read(fd, block1); Local read		
31	read(fd, block2);		
40		fd = open("file A");	Setup callback for A, send all of file A
50		write(fd, block1);	
60	read(fd, block1); Local read		
70		close(fd); Send back changes of A;	Server break call backs
80	read(fd, block1); Local read		
81	read(fd, block2); Local read		
90	close(fd);		
100	fd = open("fileA"); No callback; fetch file A again		Setup callback for A, send all of file A
110	read(fd, block1); Local read		
120	close(fd);		

When will server be contacted for NFS? For AFS?
What data will be sent? What will each client see?