PERSISTENCE: FILE API AND FILE SYSTEMS

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CS 537, Spring 2019

ADMINISTRIVIA

Mid-semester grades: All regrades are done!?

Project 4b: Due next week ~~4/9~~ 4/16 AM

Project 5: One project 9%. Updated due dates on website

Discussion this week: Review worksheet, More Q&A for 4b

↳ Part of midterm

AGENDA / LEARNING OUTCOMES

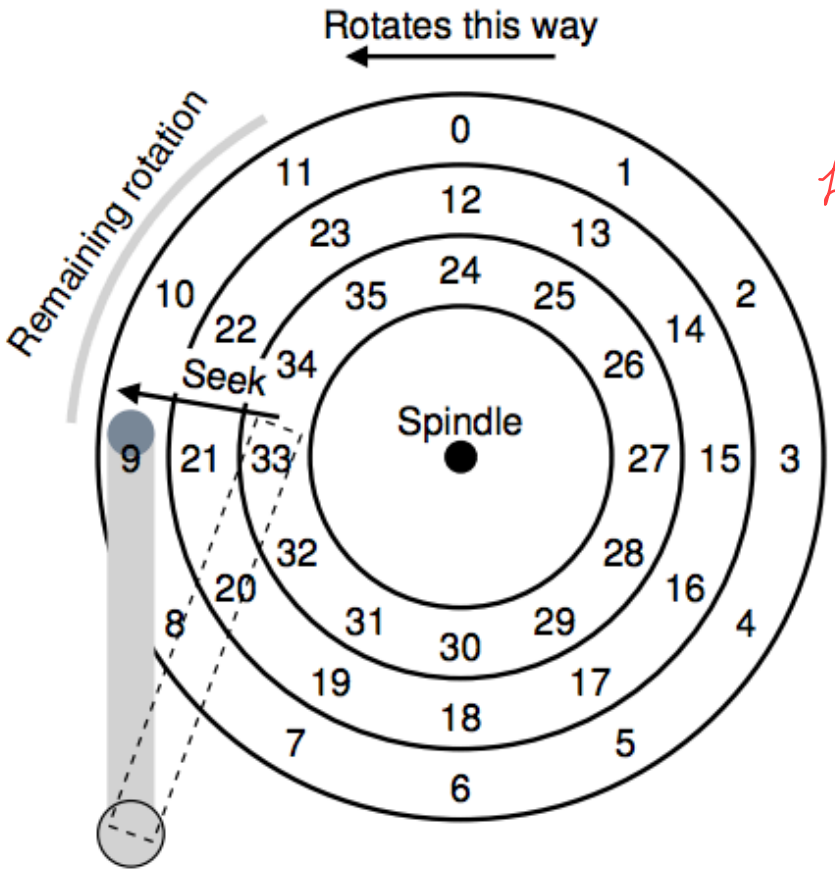
What are the API to create/modify directories?

How does file system represent files, directories?

What steps must reads/writes take?

RECAP

READING DATA FROM DISK



Latency of read →

Seek Time

Rotational delay

RAID COMPARISON

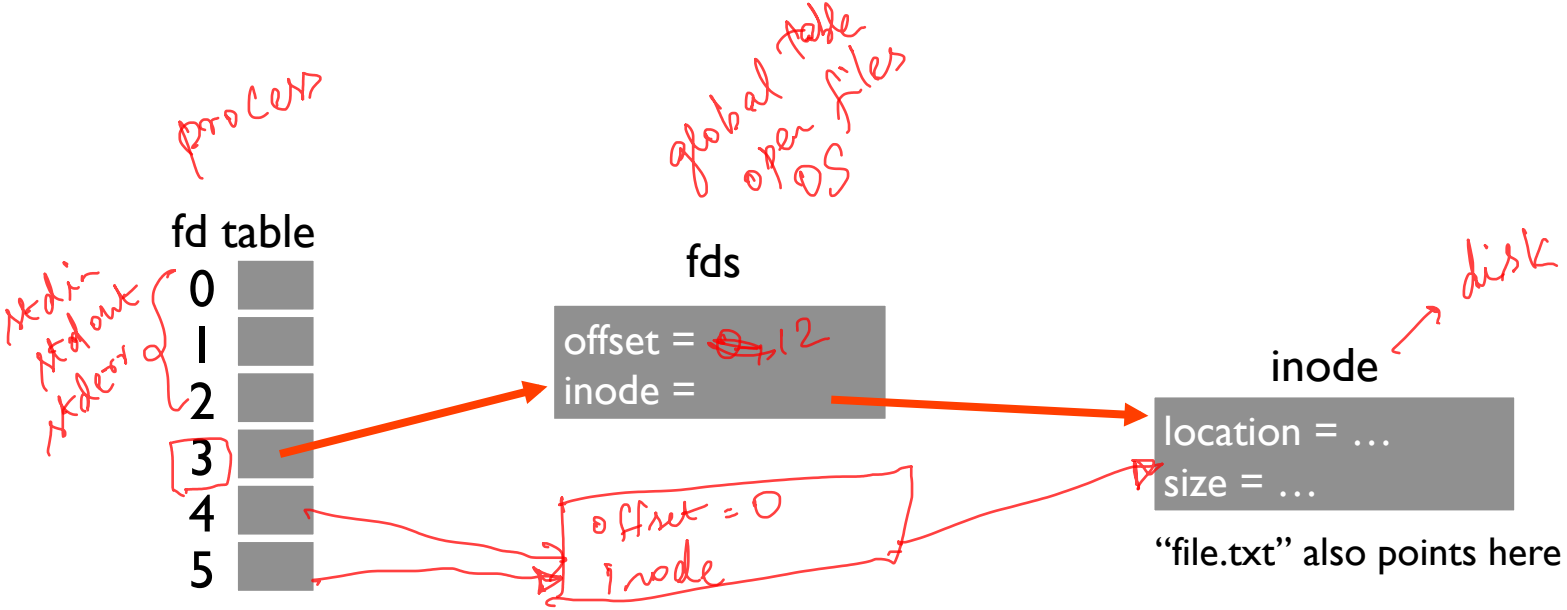
	RAID-0	RAID-1	RAID-4	RAID-5
Capacity	$N \cdot B$	$(N \cdot B)/2$	$(N-1) \cdot B$	$(N-1) \cdot B$
Reliability	0	1 (for sure) $\frac{N}{2}$ (if lucky)	1	1
Throughput				
Sequential Read	$N \cdot S$	$(N/2) \cdot S$	$(N-1) \cdot S$	$(N-1) \cdot S$
Sequential Write	$N \cdot S$	$(N/2) \cdot S$	$(N-1) \cdot S$	$(N-1) \cdot S$
Random Read	$N \cdot R$	$N \cdot R$	$(N-1) \cdot R$	$N \cdot R$
Random Write	$N \cdot R$	$(N/2) \cdot R$	$\frac{1}{2} \cdot R$	$\frac{N}{4} R$
Latency				
Read	T	T	T	T
Write	T	T	$2T$	$2T$

FILE API WITH FILE DESCRIPTORS

```
int fd = open(char *path, int flag, mode_t mode)
read(int fd, void *buf, size_t nbyte)
write(int fd, void *buf, size_t nbyte)
close(int fd)
```

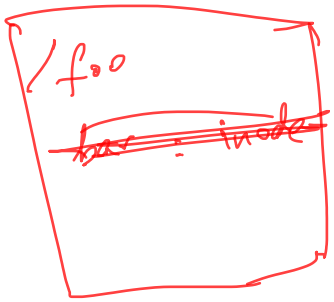
advantages:

- string names → open uses a string name
- hierarchical → /foo/bar
- traverse once → only happens on open | cache fd
- offsets precisely defined → same file can be opened multiple times




```
int fd1 = open("file.txt"); // returns 3
read(fd1, buf, 12);
int fd2 = open("file.txt"); // returns 4
int fd3 = dup(fd2);         // returns 5
```

DELETING FILES



There is no system call for deleting files!

rm /foo/bar

Inode (and associated file) is **garbage collected** when there are no references

Paths are deleted when: `unlink()` is called

removes file from the directory

FDs are deleted when: `close()` or process quits

file may still be accessible even after calling unlink

open()
unlink()
:
read()

temporary files

COMMUNICATING REQUIREMENTS: FSYNC

File system keeps newly written data in memory for awhile

Write buffering improves performance (why?)

buffer data in-memory

fewer disk

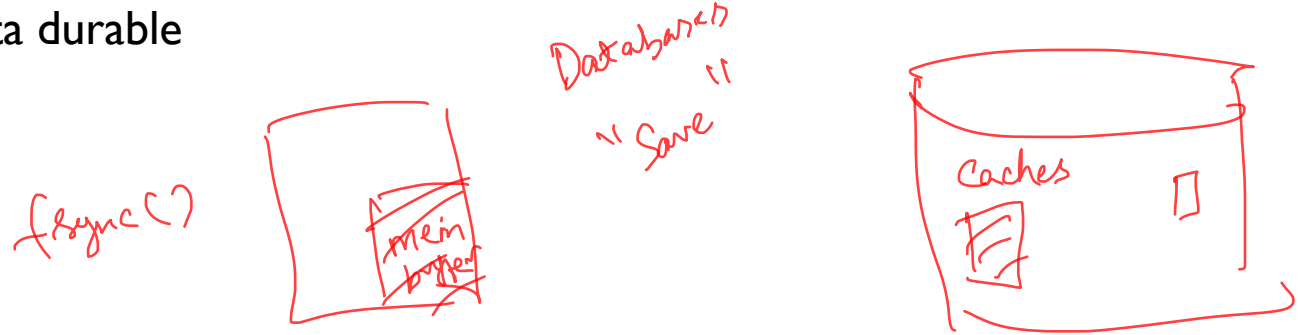
But what if system crashes before buffers are flushed?

lose data !!!

fsync(int fd) forces buffers to flush to disk, tells disk to flush its write cache

Makes data durable

Database "Save"



RENAME

rename(char *old, char *new):

- deletes an old link to a file
- creates a new link to a file

Just changes name of file, does not move data

Even when renaming to new directory

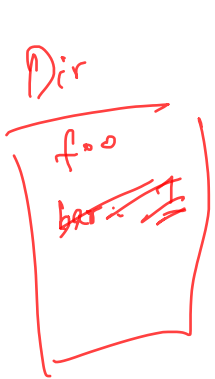
Atomicity guaranteed by OS!

either old file exists or new file exists

mv command implemented using rename

/foo/bar

/bar/foo



ATOMIC FILE UPDATE

Say application wants to update file.txt atomically

If crash, should see only old contents or only new contents

we have many changes to file.txt ≡ ATOMIC

1. write new data to file.txt.tmp file ≡ copy file.txt file.txt.tmp
2. fsync file.txt.tmp — edits /writes to flush buffers in background.
3. rename file.txt.tmp over file.txt, replacing it

→ Atomicity gaurentee

DIRECTORY FUNCTIONS, LINKS

DIRECTORY CALLS

mkdir: create new directory

readdir: read/parse directory entries

Why no writedir?

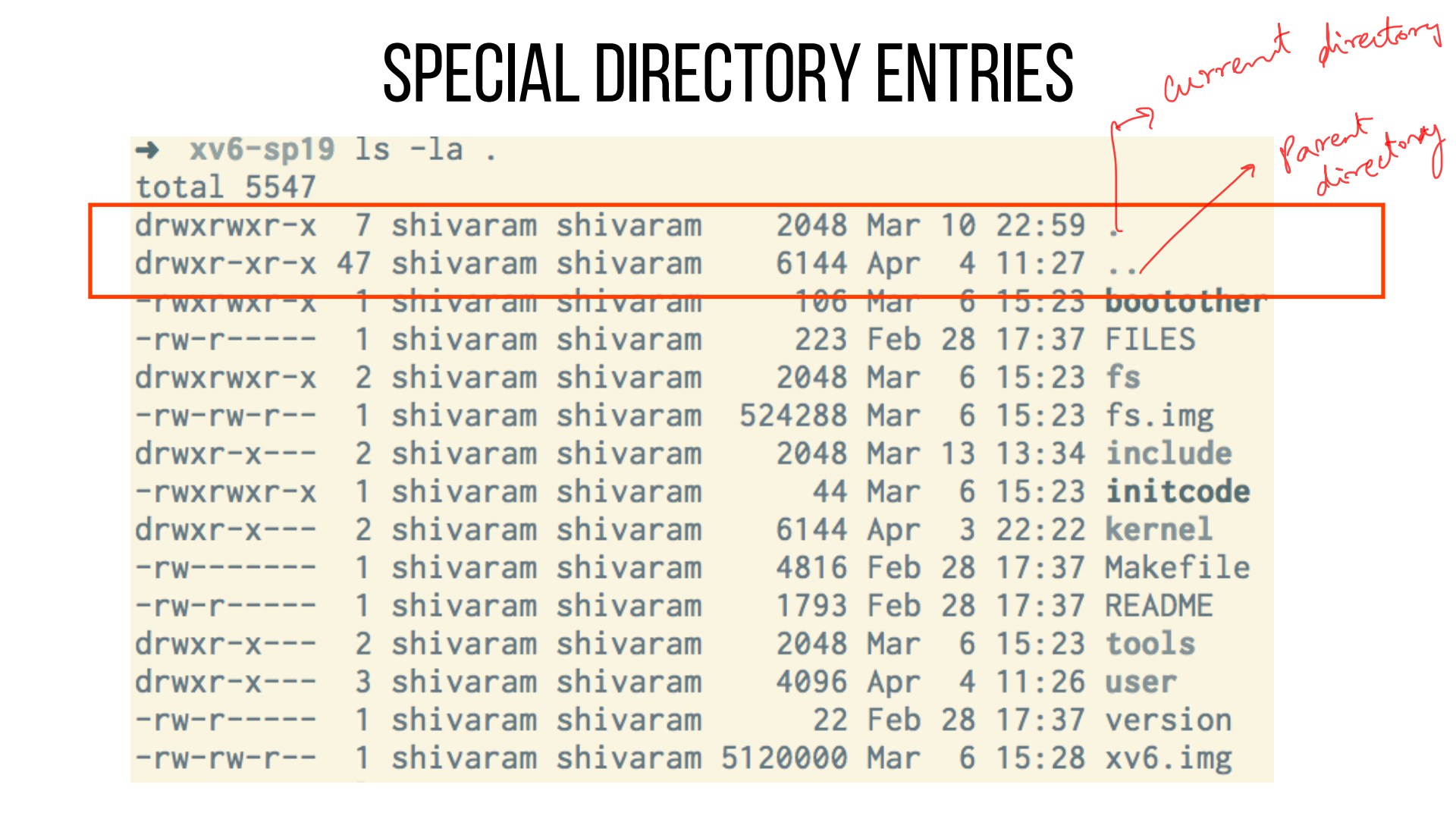
mkdir /foo same commandline

stat, f_stat

↳ ls can be implemented using readdir

↳ Is rename() or unlink() enough? or open()

SPECIAL DIRECTORY ENTRIES




```
➜  xv6-sp19 ls -la .
total 5547
drwxrwxr-x  7 shivaram shivaram    2048 Mar 10 22:59 .
drwxr-xr-x 47 shivaram shivaram    6144 Apr  4 11:27 ..
-rwxrwxr-x  1 shivaram shivaram     106 Mar  6 15:23 bootother
-rw-r-----  1 shivaram shivaram     223 Feb 28 17:37 FILES
drwxrwxr-x  2 shivaram shivaram    2048 Mar  6 15:23 fs
-rw-rw-r--  1 shivaram shivaram  524288 Mar  6 15:23 fs.img
drwxr-x---  2 shivaram shivaram    2048 Mar 13 13:34 include
-rwxrwxr-x  1 shivaram shivaram      44 Mar  6 15:23 initcode
drwxr-x---  2 shivaram shivaram    6144 Apr  3 22:22 kernel
-rw-------  1 shivaram shivaram    4816 Feb 28 17:37 Makefile
-rw-r-----  1 shivaram shivaram    1793 Feb 28 17:37 README
drwxr-x---  2 shivaram shivaram    2048 Mar  6 15:23 tools
drwxr-x---  3 shivaram shivaram    4096 Apr  4 11:26 user
-rw-r-----  1 shivaram shivaram      22 Feb 28 17:37 version
-rw-rw-r--  1 shivaram shivaram 5120000 Mar  6 15:28 xv6.img
```

LINKS

Hard links: Both path names use same inode number

File does not disappear until all removed; cannot link directories

```
echo “Beginning…” > file1
ln file1 link
cat link
ls -li
echo “More info” >> file1
mv file1 file2
rm file2
```

SOFT LINKS

Soft or symbolic links: Point to second path name; can softlink to dirs

"Shortcut"

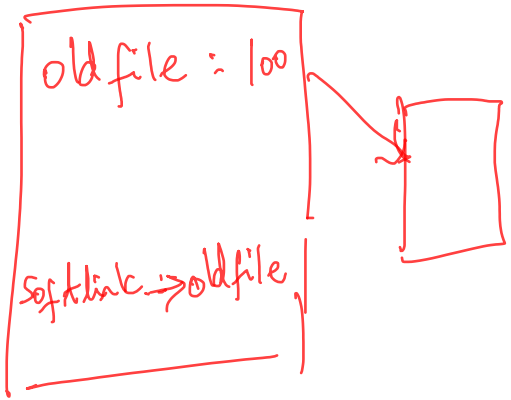
source dest.

```
ln -s oldfile softlink
```

rm oldfile ; cat softlink

Confusing behavior: "file does not exist"!

Confusing behavior: "cd linked_dir; cd ..; in different parent!



PERMISSIONS, ACCESS CONTROL

```
➜  xv6-sp19 ls -la .
total 5547
drwxrwxr-x  7 shivaram shivaram    2048 Mar 10 22:59 .
drwxr-xr-x 47 shivaram shivaram    6144 Apr  4 11:27 ..
-rwxrwxr-x  1 shivaram shivaram     106 Mar  6 15:23 bootother
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drwxrwxr-x  2 shivaram shivaram    2048 Mar  6 15:23 fs
-rw-rw-r--  1 shivaram shivaram  524288 Mar  6 15:23 fs.img
```

Owner rwx | Group rwx | others rwx

read write execute

```
➜  xv6-sp19 fs la .
Access list for . is
Normal rights:
  system:administrators rlidwka
  system:anyuser l
  shivaram rlidwka
```

775

l → list

AFS home dir

rwx → 1, 2, 4

=7 all set

=4 read

=2 write

=6 read+W

=0 no access

MANY FILE SYSTEMS

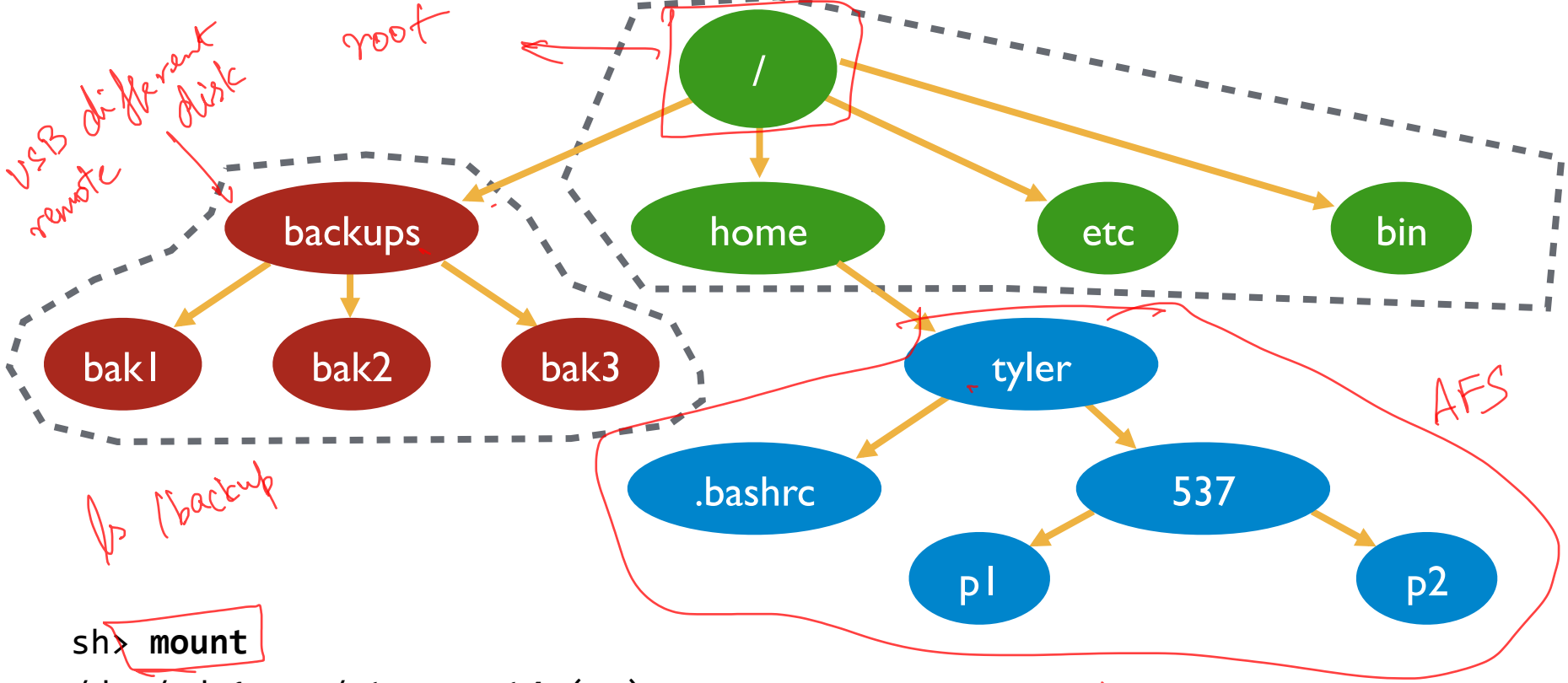
Users often want to use many file systems

For example:

- main disk
- backup disk
- AFS
- thumb drives
- CD / external HDD

remote

Idea: stitch all the file systems together into a super file system!




```
sh> mount
/dev/sda1 on / type ext4 (rw)
/dev/sdb1 on /backups type ext4 (rw)
AFS on /home type afs (rw)
```

no hard links across mount points

BUNNY 14

https://tinyurl.com/cs537-sp19-bunny14

BUNNY 14

Consider the following code snippet:

https://tinyurl.com/cs537-sp19-bunny14

```
1 echo "hello" > oldfile
2 ln -s oldfile link1
3 ln oldfile link2
4 rm oldfile
```

What will be the output of `cat link1`

"File not found"

soft link

What will be the output of `cat link2`

"hello" → Hard link

What is the file permission to only give current user read, write, execute access?

700

4 + 2 + 1

111

FILE API SUMMARY

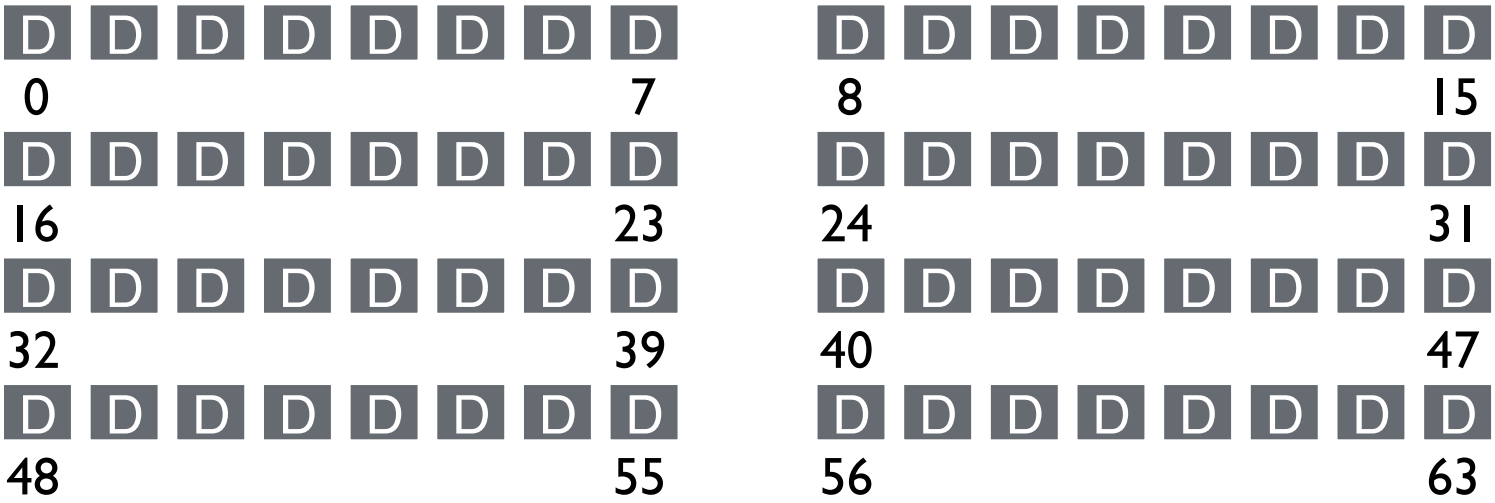
Using multiple types of name provides convenience and efficiency

Mount and link features provide flexibility.

Special calls (fsync, rename) let developers communicate requirements to file system

FILESYSTEM DISK STRUCTURES

FS STRUCTS: EMPTY DISK

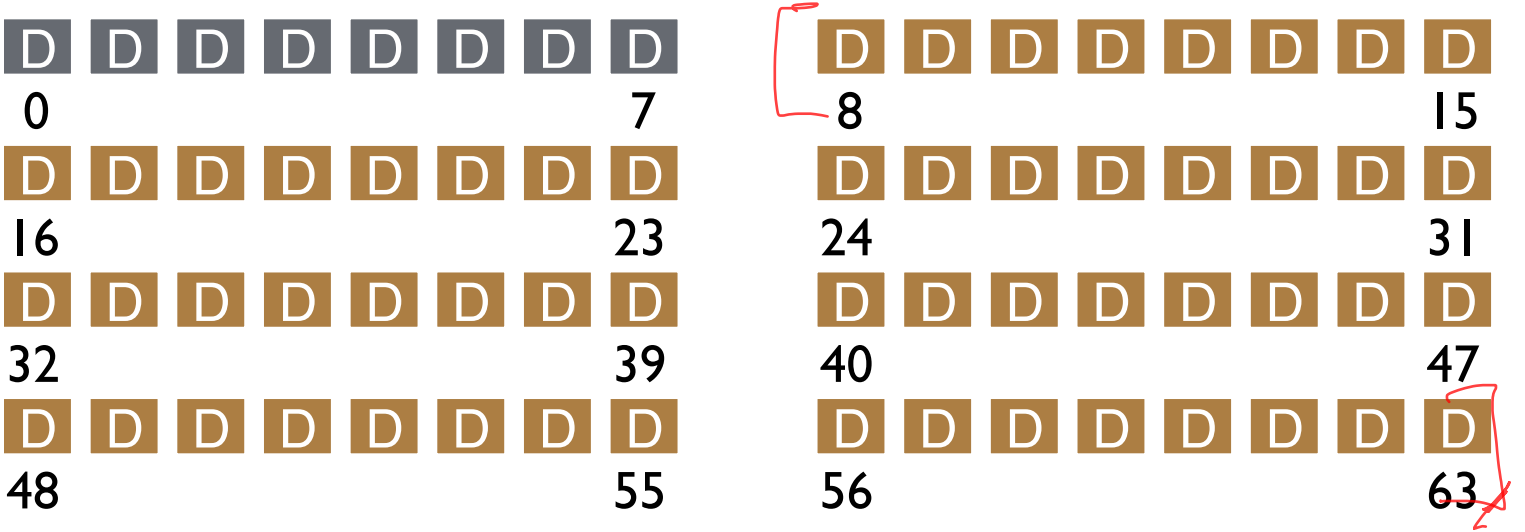


Assume each block is 4KB = block size

Virtual memory = Page

FS STRUCTS: DATA BLOCKS

block 8 - block 63 contain data blocks



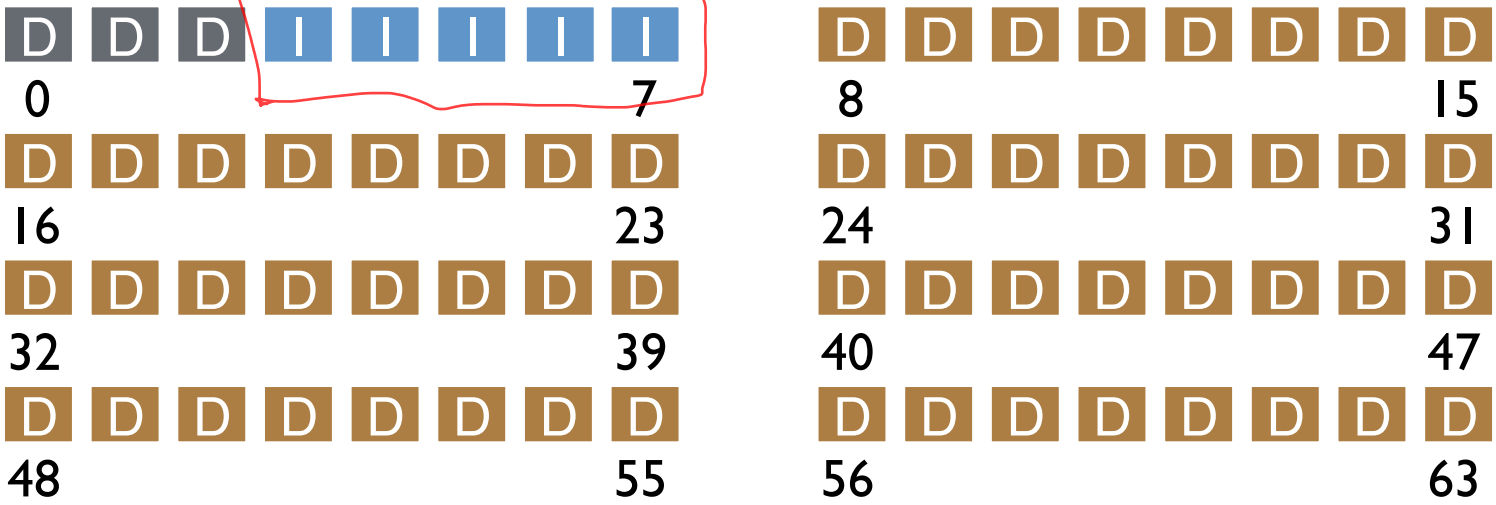
Simple layout → Very Simple File System

FS persistent! metadata → disk

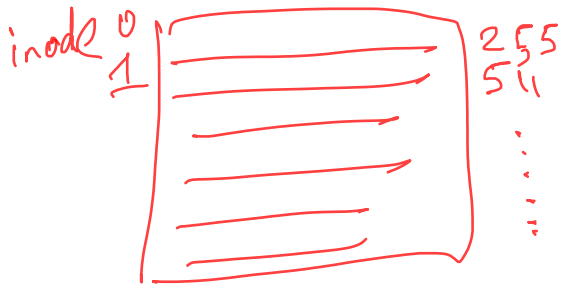
INODE POINTERS

5 blocks

inode



ONE INODE BLOCK



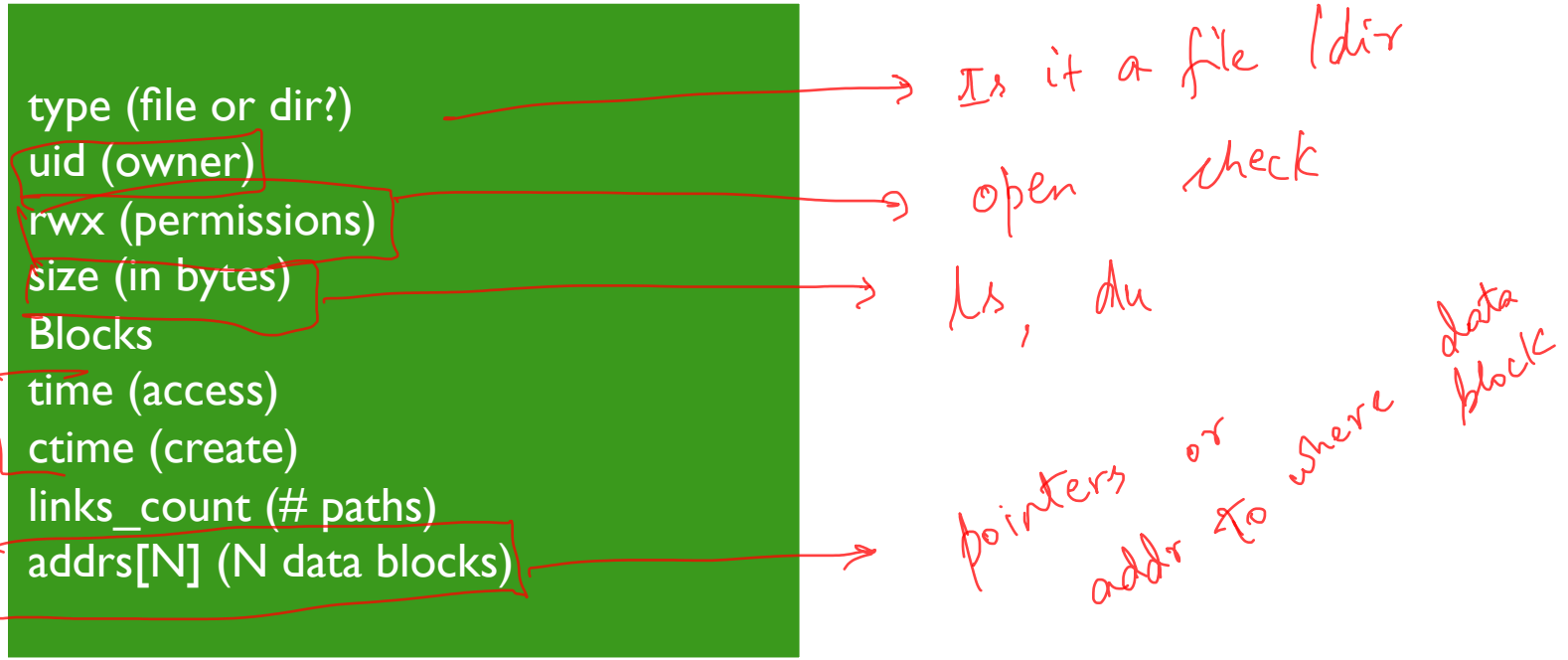
Each inode is typically 256 bytes (depends on the FS, maybe 128 bytes)

4KB disk block

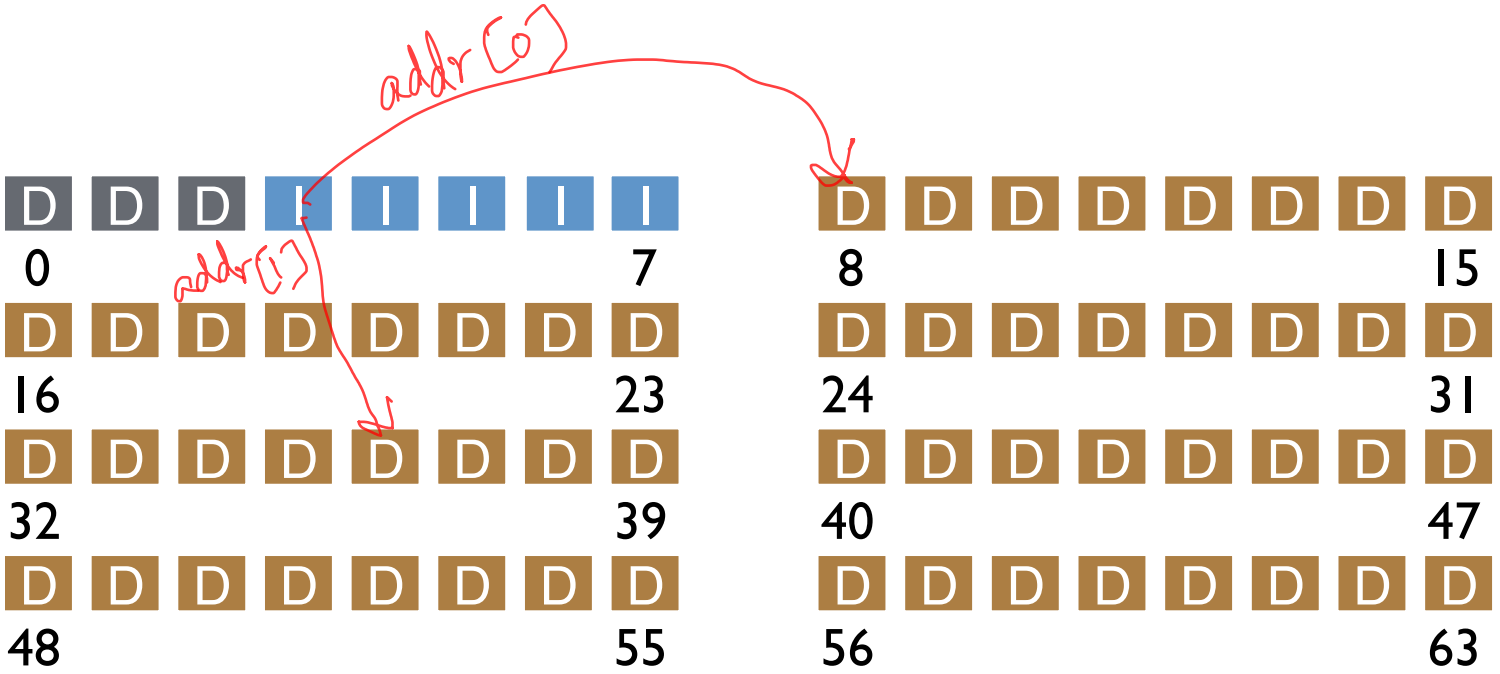
16 inodes per inode block.

inode 16	inode 17	inode 18	inode 19
inode 20	inode 21	inode 22	inode 23
inode 24	inode 25	inode 26	inode 27
inode 28	inode 29	inode 30	inode 31

INODE


type (file or dir?)
uid (owner)
rwx (permissions)
size (in bytes)
Blocks
time (access)
ctime (create)
links_count (# paths)
addrs[N] (N data blocks)
Is it a file / dir
open check
ls, du
pointers or addr to where data block

FS STRUCTS: INODE DATA POINTERS



INODE

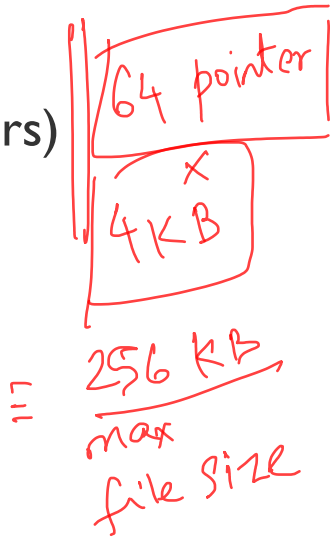
type (file or dir?)
uid (owner)
rwx (permissions)
size (in bytes)
Blocks
time (access)
ctime (create)
links_count (# paths)
addrs[N] (N data blocks)

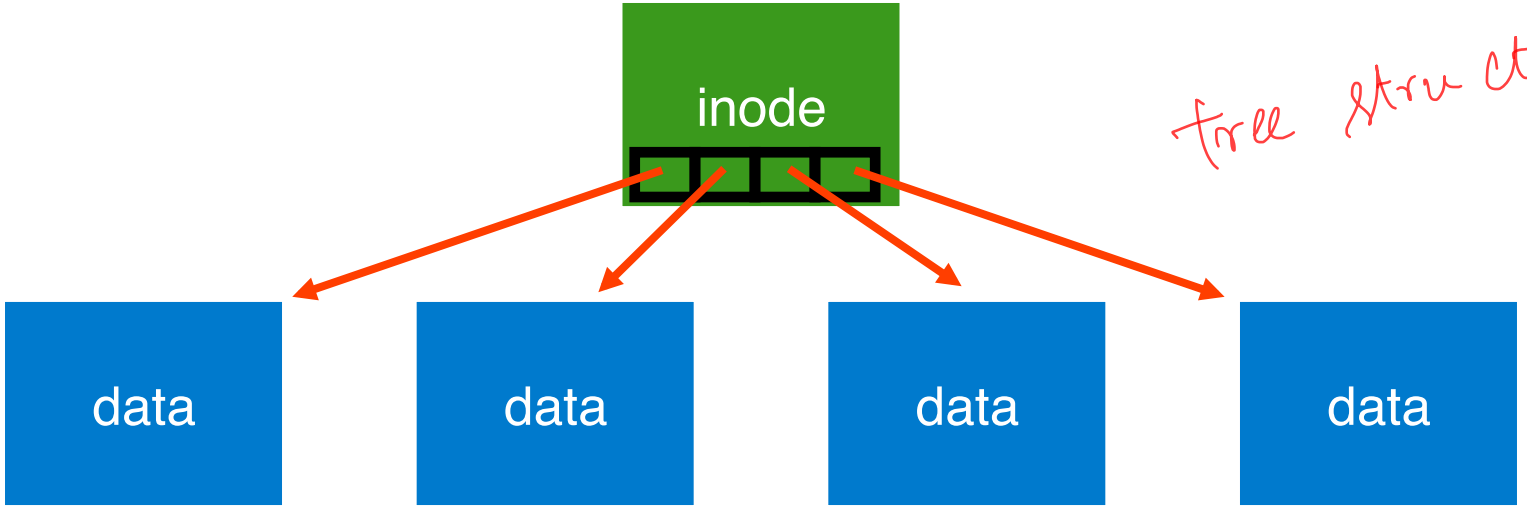
Assume single level (just pointers to data blocks)

What is max file size?

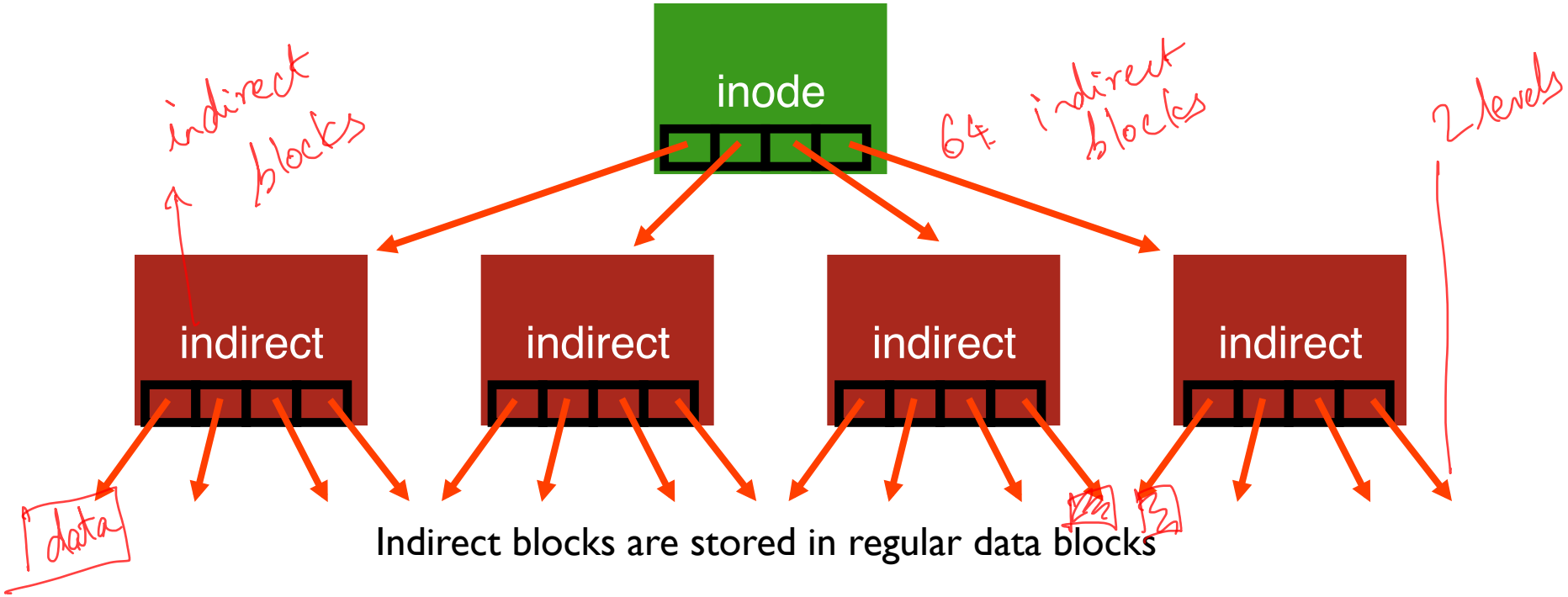
Assume 256-byte inodes
(all can be used for pointers)
Assume 4-byte addrs

How to get larger files?





free structure



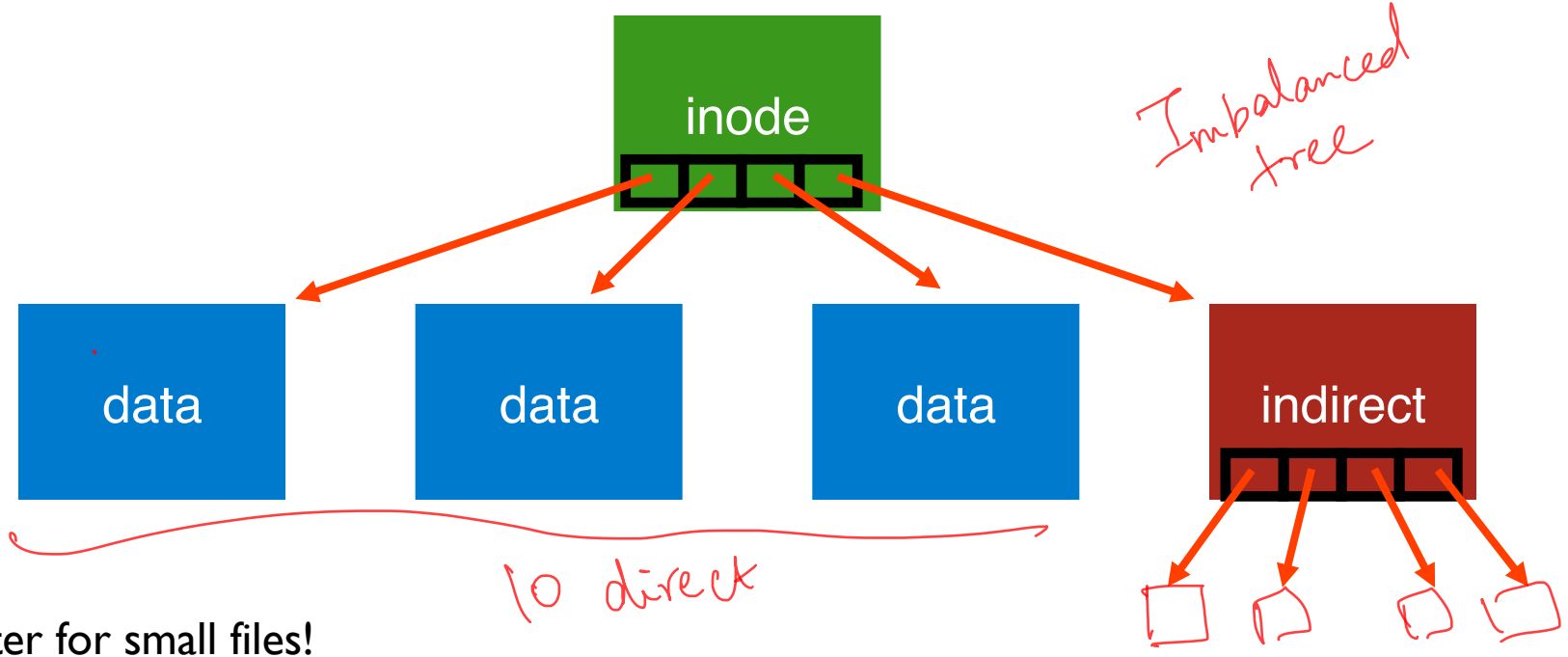
Indirect blocks are stored in regular data blocks

Largest file size with 64 indirect blocks?

$= 64 \times [64 \times 4\,KB] = 4096 \times 4B$

$= 16\,MB$?

Any Cons?



Better for small files!

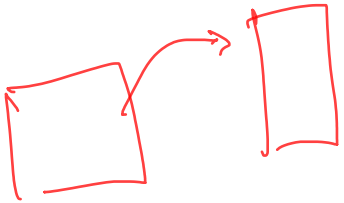
How to handle even larger files?

Double indirect blocks

Adding more levels to tree

for small files data can go in direct block

OTHER APPROACHES



Extent-based

Linked (File-allocation Tables) ⇒ FAT-32 file system

Multi-level Indexed → ext-2 | ext-3

Questions

- Amount of fragmentation (internal and external)
- Ability to grow file over time?
- Performance of sequential accesses (contiguous layout)?
- Speed to find data blocks for random accesses?
- Wasted space for meta-data overhead (everything that isn't data)?
  Meta-data must be stored persistently too!

BUNNY 15

https://tinyurl.com/cs537-sp19-bunny15

BUNNY 15

Assume 256 byte inodes (16 inodes/block).
What is the offset for inode with number 0?

https://tinyurl.com/cs537-sp19-bunny15

What is the offset for inode with number 0?

What is the offset for inode with number 0?

DIRECTORIES

File systems vary

Common design:

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

Various formats could be used

- lists
- b-trees

SIMPLE DIRECTORY LIST EXAMPLE

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

unlink(“foo”)

ALLOCATION

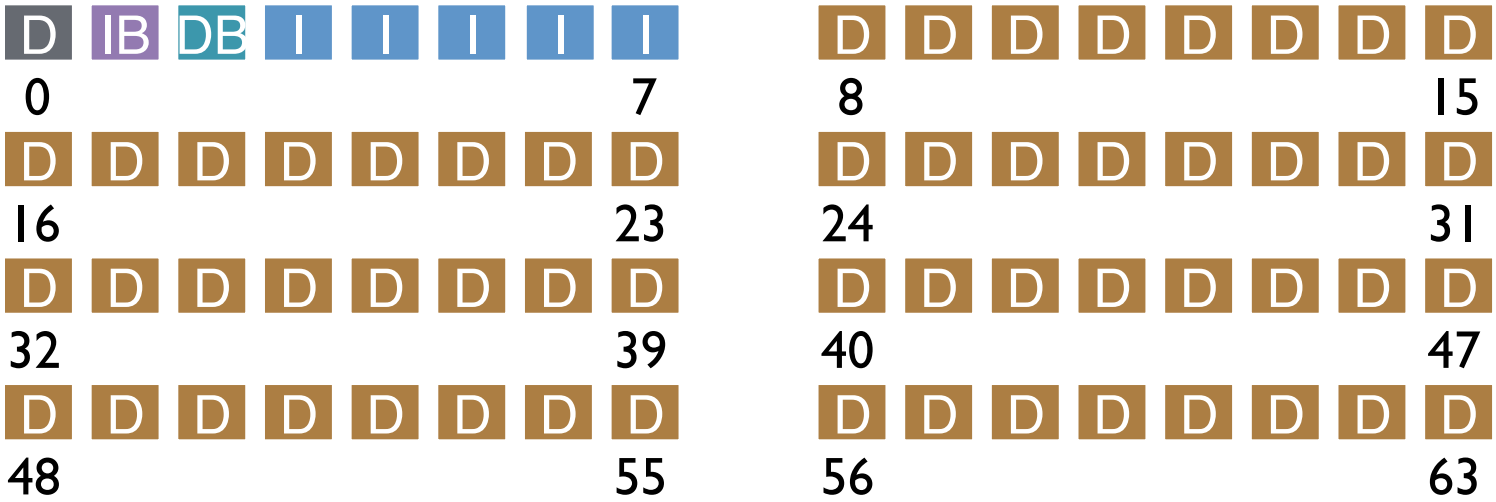
How do we find free data blocks or free inodes?

Free list

Bitmaps

Tradeoffs in next lecture…

FS STRUCTS: BITMAPS



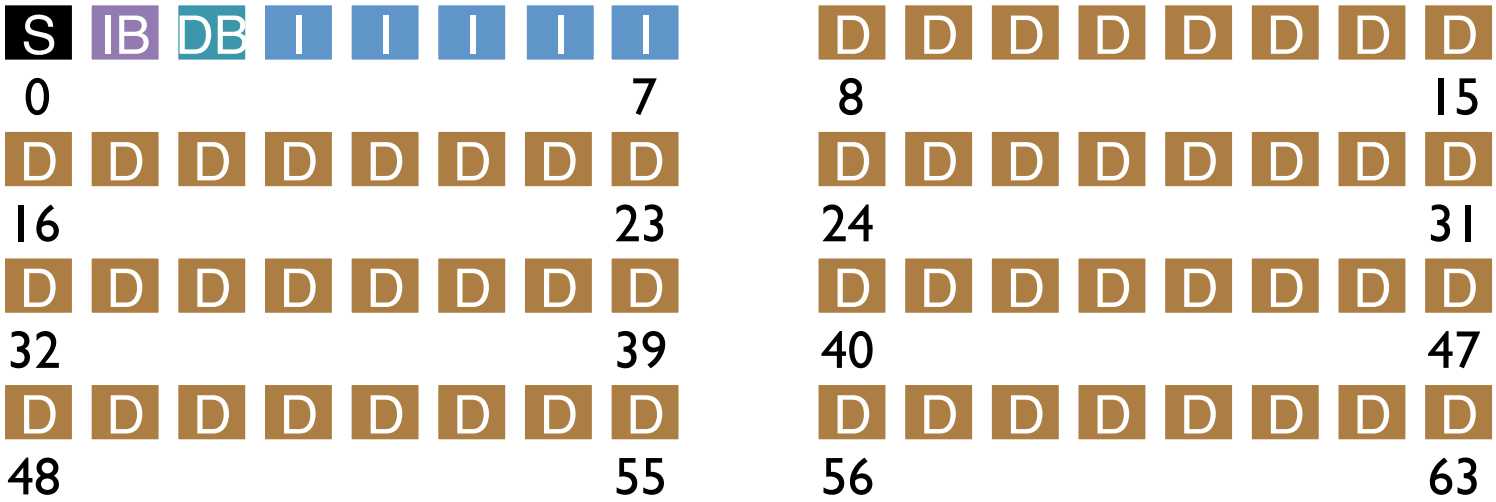
SUPERBLOCK

Need to know basic FS configuration metadata, like:

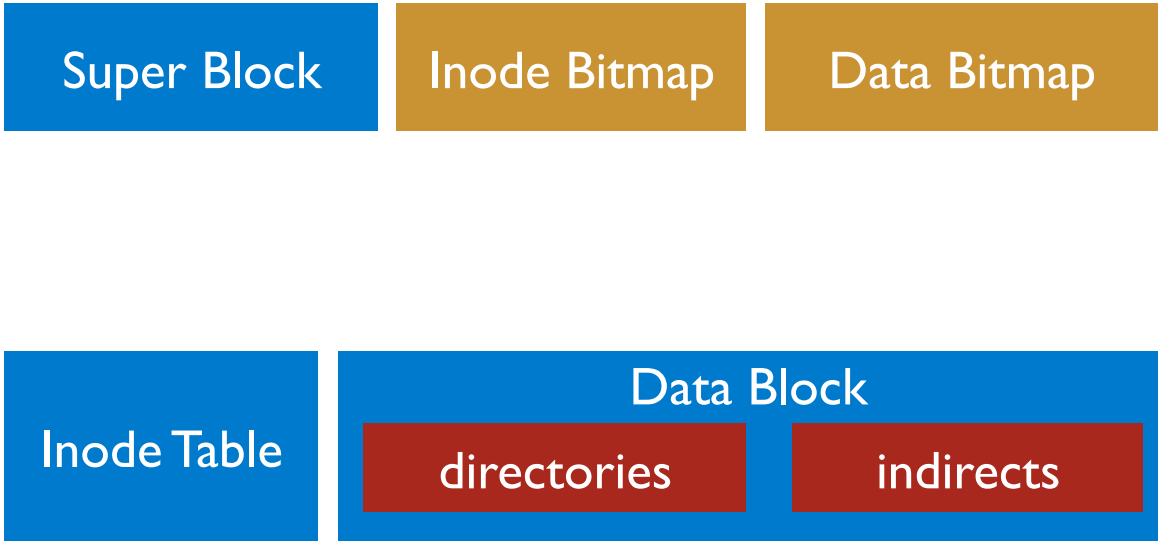
- block size
- # of inodes

Store this in superblock

FS STRUCTS: SUPERBLOCK



SUMMARY


Super Block
Inode Bitmap
Data Bitmap
Inode Table
Data Block
directories
indirects

PART 2 : OPERATIONS

- create file
- write
- open
- read
- close

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			

What needs to be read and written?

open /foo/bar

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

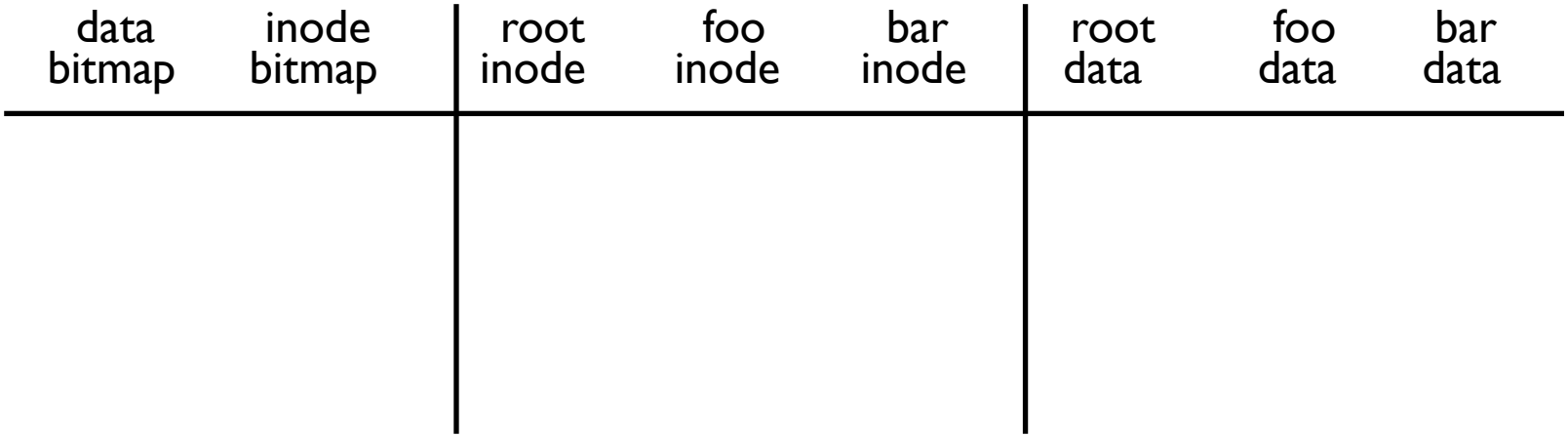
write to /foo/bar (assume file exists and has been opened)

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

read /foo/bar – assume opened

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

close /foo/bar



nothing to do on disk!

EFFICIENCY

How can we avoid this excessive I/O for basic ops?

Cache for:

- reads
- write buffering

WRITE BUFFERING

Why does procrastination help?

Overwrites, deletes, scheduling

Shared structs (e.g., bitmaps+dirs) often overwritten.

We decide: how much to buffer, how long to buffer…

- tradeoffs?

NEXT STEPS

Next class: UNIX Fast-File System