Changelog

12 April 2022: change xv6 file sizes slide to correct block pointer size

last time

FAT filesystem

header — global/general information

divide disk into clusters (possibly larger than sector)

files+directory 'data' stored in one+ whole clusters

linked list identifies clusters making up file/directory

file allocation table — one number per (potential data) cluster

- next pointers for linked list
- indicate which clusters are free

directory entries

- 'data' for directories
- starting location, name, etc. about file/dir in directory

on debugging issues

having better tests for paging/protection helped less than I hoped

too many students not getting to the point of looking at tests

tests not good enough at diagnosing certain types of memory corruption

- e.g. freeing non-heap pages incorrectly

probably should have discouraged students from modifying kfree()

- more elegant/less code, but harder to debug than other options

on office hour queues

too much OH time per student given number waiting

- we can't spend 15 uninterrupted minutes/student with one TA + 15 students waiting
- TAs/I sometimes have trouble switching away from students (e.g. while they're gathering debugging info, when they get to a new problem)
- adjusting the queue ordering can't really fix this issue

we can be more useful with better problems

- we're less useful when student has done less investigation of what ran before crash/etc.

need faster switching between students

- ideally can help other students while waiting for student to add debugging/etc.
- in practice: especially on Discord, doesn't happen as much as I hoped

xv6 filesystem

xv6's filesystem similar to modern Unix filesytems

better at doing contiguous reads than FAT

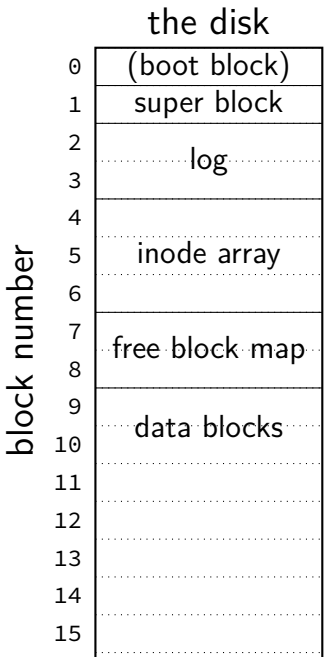
better at handling crashes

supports *hard links*

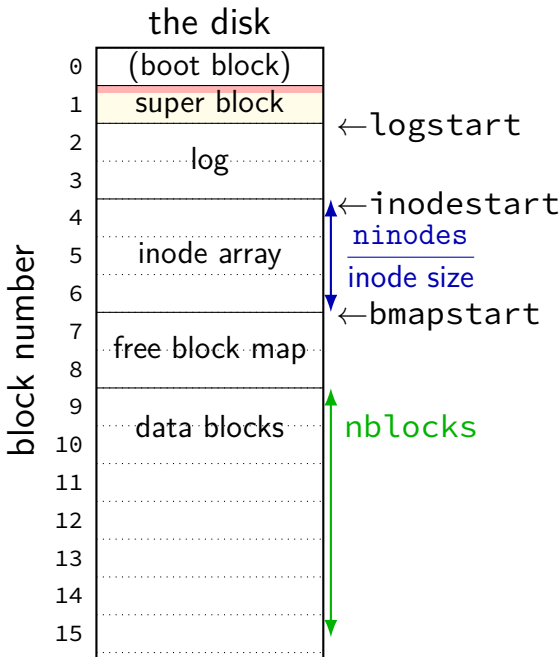
divides disk into *blocks* instead of clusters

file block numbers, free blocks, etc. in different tables

xv6 disk layout



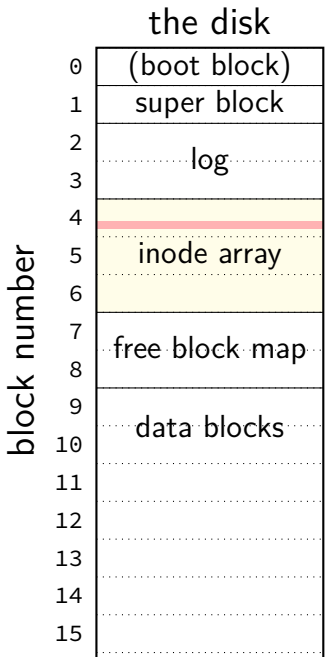
xv6 disk layout



superblock — "header"

```
struct superblock {
  uint size;
    // Size of file system image (b
  uint nblocks;
    // # of data blocks
  uint ninodes;
    // # of inodes
  uint nlog;
    // # of log blocks
  uint logstart;
    // block # of first log block
  uint inodestart;
    // block # of first inode block
  uint bmapstart;
    // block # of first free map bl
};
```

xv6 disk layout



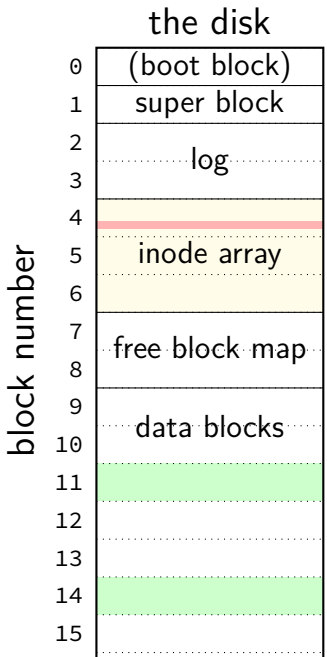
inode — file information

```
struct dinode {
  short type;  // File type
    // T_DIR, T_FILE, T_DEV

  short major; short minor; // T_DEV only

  short nlink;
    // Number of links to inode in file syst
  uint size;   // Size of file (bytes)
  uint addrs[NDIRECT+1];
    // Data block addresses
};
```

xv6 disk layout



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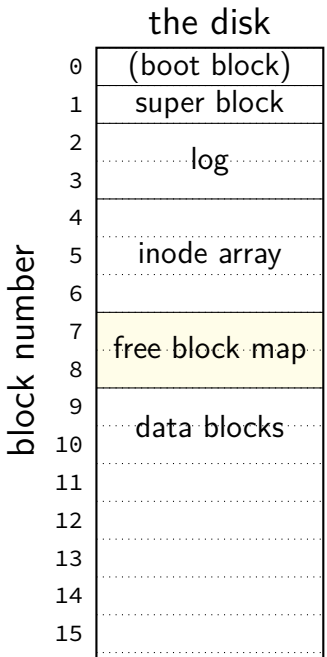
```

location of data as block numbers:
e.g. addrs[0] = 11; addrs[1] = 14;
special case for larger files

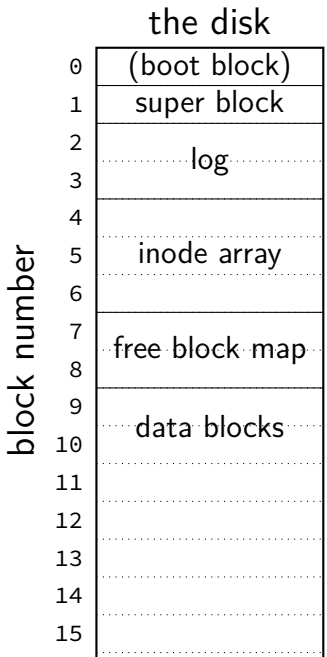
xv6 disk layout



free block map — 1 bit per data block
1 if available, 0 if used

allocating blocks: scan for 1 bits
contiguous 1s — contigous blocks

xv6 disk layout



what about finding free inodes
xv6 solution: scan for type = 0

typical Unix solution: separate free inode map

xv6 directory entries

```
struct dirent {
  ushort inum;
  char name[DIRSIZ];
};
```

inum — index into inode array on disk

name — name of file or directory

each directory reference to inode called a *hard link*

- multiple hard links to file allowed!

xv6 allocating inodes/blocks

need new inode or data block: linear search

simplest solution: xv6 always takes the first one that's free

xv6 FS pros versus FAT

support for reliability — log

- more on this later

possibly easier to scan for free blocks

- more compact free block map

easier to find location of kth block of file

- element of addrs array

file type/size information held with block locations

- inode number = everything about open file
- easier to read/modify file info all at once?

missing pieces

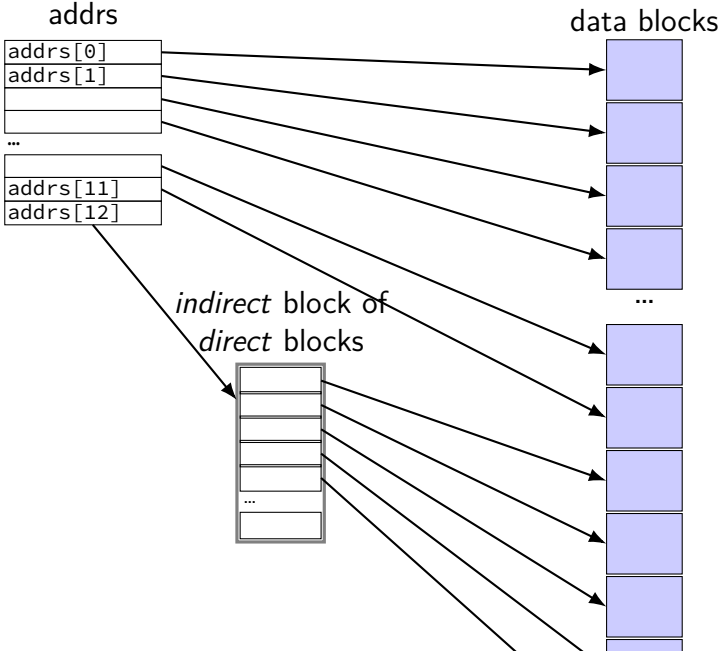
what's the log? (more on that later)

other file metadata?

creation times, etc. — xv6 doesn't have it

not good at taking advantage of HDD architecture

xv6 inode: direct and indirect blocks



xv6 file sizes

512 byte blocks

2-byte block pointers: 256 block pointers in the indirect block

256 blocks = 131072 bytes of data referenced

12 direct blocks @ 512 bytes each = 6144 bytes

1 indirect block @ 131072 bytes each = 131072 bytes

maximum file size = 6144 + 131072 bytes

Linux ext2 inode

```
struct ext2_inode {
    __le16 i_mode;              /* File mode */
    __le16 i_uid;               /* Low 16 bits of Owner Uid */
    __le32 i_size;              /* Size in bytes */
    __le32 i_atime;     /* Access time */
    __le32 i_ctime;     /* Creation time */
    __le32 i_mtime;     /* Modification time */
    __le32 i_dtime;     /* Deletion Time */
    __le16 i_gid;               /* Low 16 bits of Group Id */
    __le16 i_links_count;       /* Links count */
    __le32 i_blocks;    /* Blocks count */
    __le32 i_flags;     /* File flags */
    ...
    __le32 i_block[EXT2_N_BLOCKS]; /* Pointers to blocks */
    ...
};
```

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```

type (regular, directory, device)
and permissions (read/write/execute for owner/group/others)

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```

owner and group

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    __le32 i_block[EXT2_N_BLOCKS]; /* Pointers to blocks */
    ...
};
```

whole bunch of times

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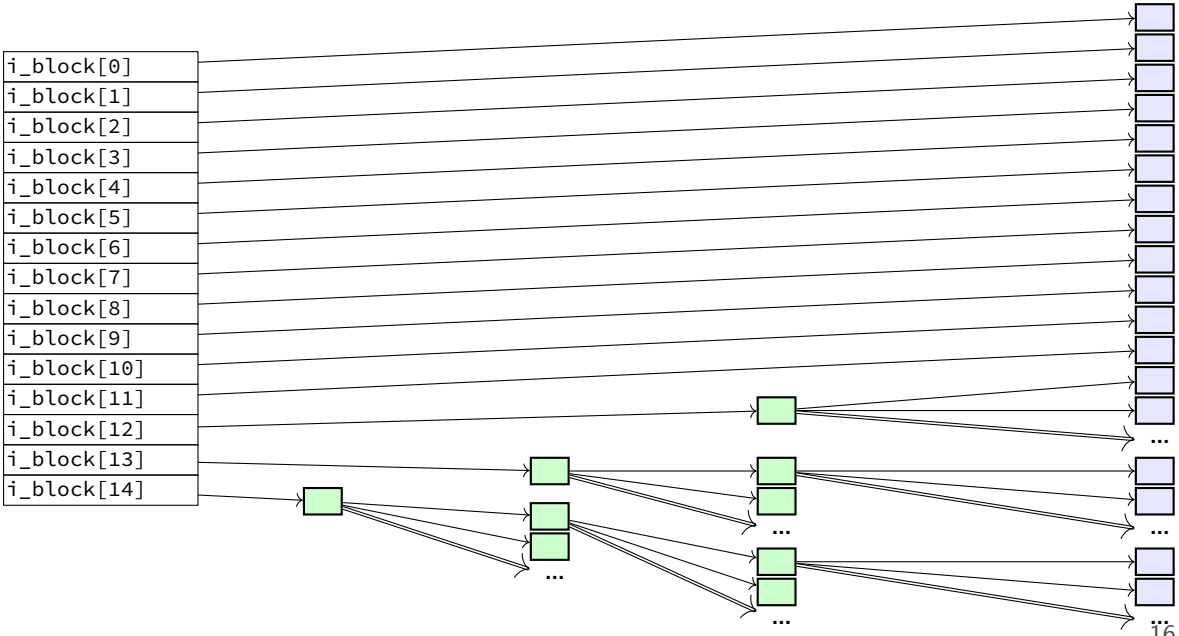
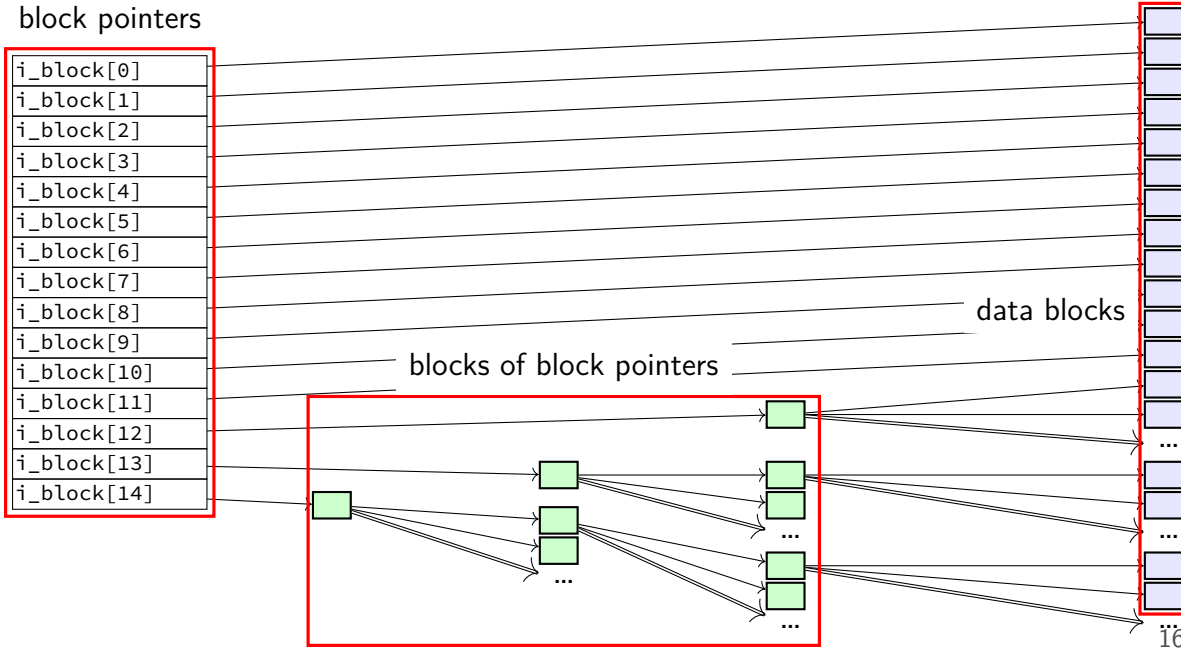
    ...
};
```

similar pointers like xv6 FS — but more indirection

double/triple indirect



double/triple indirect



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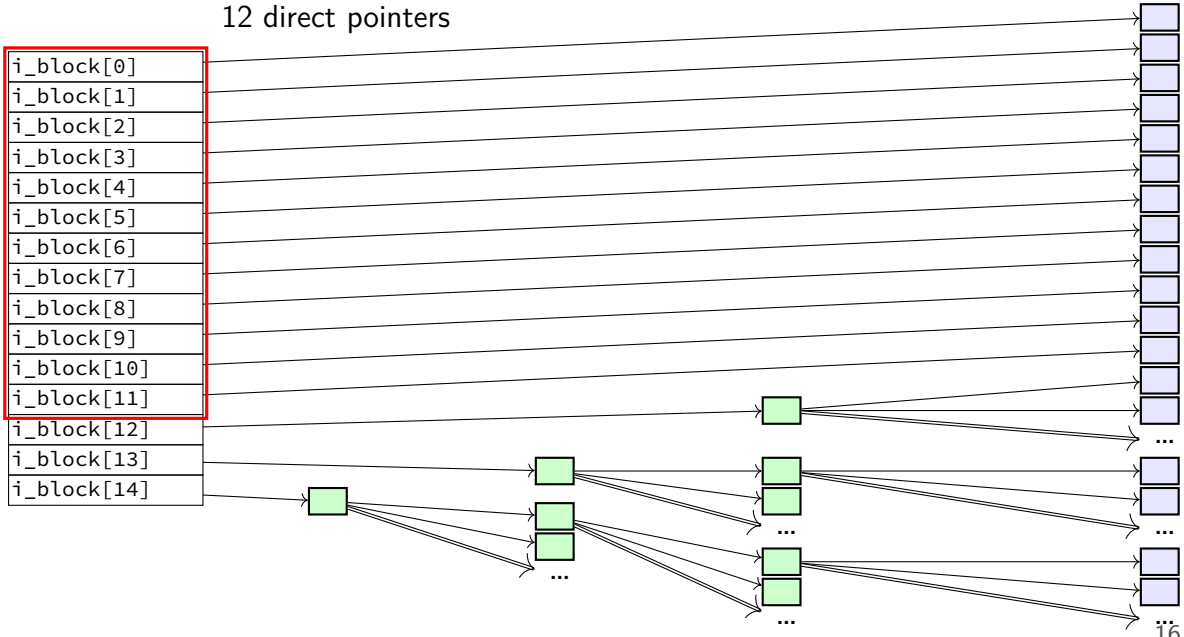

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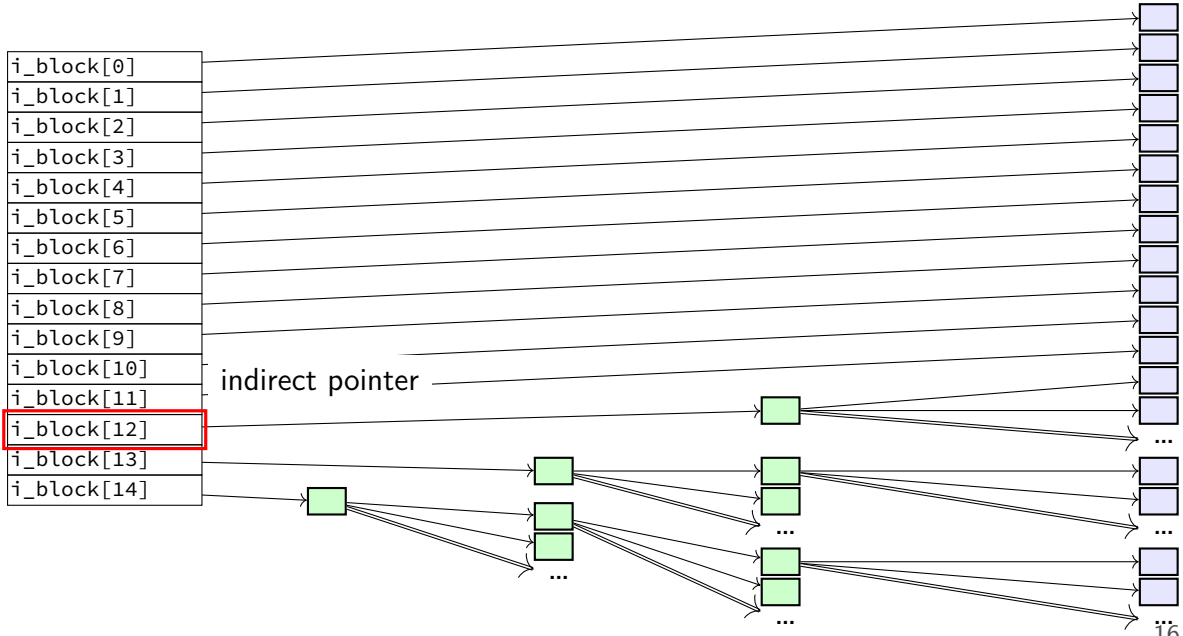

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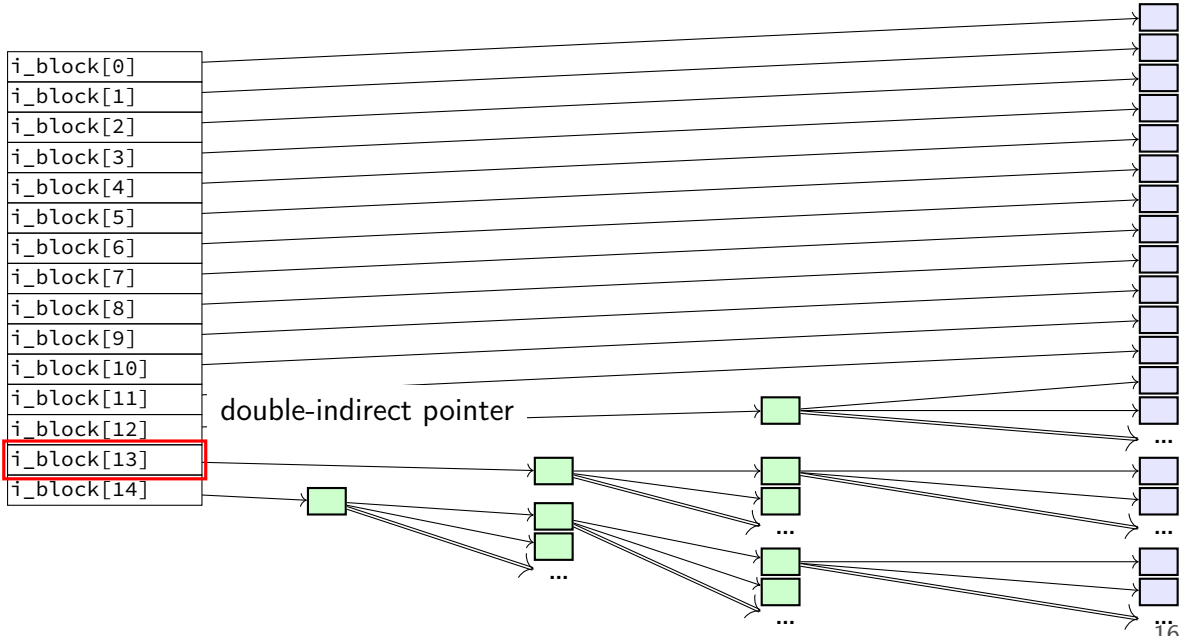

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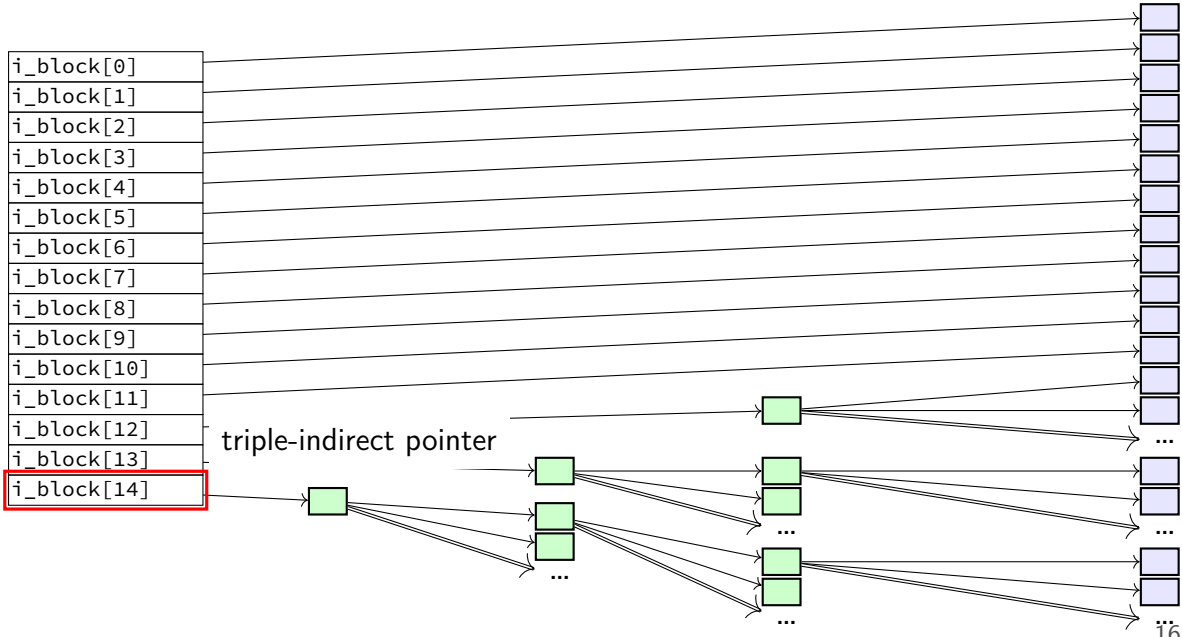

ext2 indirect blocks (1)

12 direct block pointers

1 indirect block pointer

- pointer to block containing more direct block pointers

1 double indirect block pointer

- pointer to block containing more indirect block pointers

1 triple indirect block pointer

- pointer to block containing more double indirect block pointers

ext2 indirect blocks (1)

12 direct block pointers

1 indirect block pointer

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1 triple indirect block pointer

- pointer to block containing more double indirect block pointers

exercise: if 1K blocks, 4 byte block pointers, how big can a file be?

ext2 indirect blocks (solution)

12 direct pointers: first 1K (block size) $\times$ 12 bytes of data

1 indirect pointer:

- points to block with 1K (block size)/4 byte (pointer size) = 256 pointers
- 256 pointers point to 1K blocks
- next 256KB of data

1 double indirect pointer

- points to block with 1K (block size)/4 byte (pointer size) = 256 pointers
- 256 pointers point to pointers that each are like an indirect pointer
- 256KB per indirect pointer $\rightarrow$ next $256 \cdot 256$ KB of data

1 triple indiret

- next $256 \cdot 256 \cdot 256$ KB of data

total size: $12 + 256 + 256^2 + 256^3$ KB = 16843020 KB $\approx$ 16GB

ext2 indirect blocks (2)

12 direct block pointers

1 indirect block pointer

1 double indirect block pointer

1 triple indirect block pointer

exercise: if 1K (2^{10} byte) blocks, 4 byte block pointers,
how does OS find byte 2^{15} of the file?

(1) using indirect pointer or double-indirect pointer in inode?
(2) what index of block pointer array pointed to by pointer in inode?

ext2 indirect blocks (2) (solution)

byte 2^{15} = 32KB into file

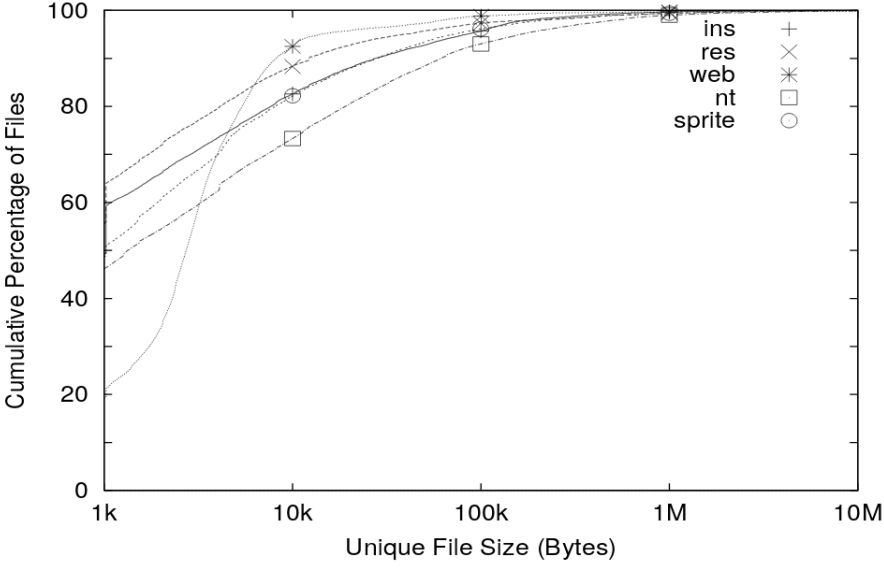
12 direct pointers: first 1K (block size) $\times$ 12 bytes of data

1 indirect pointer:

- points to block with 1K (block size)/4 byte (pointer size) = 256 pointers
- 256 pointers point to 1K blocks
- next 256KB of data

going to be (32 - 12)th element

empirical file sizes



typical file sizes

most files are small

- sometimes 50+% less than 1kbyte
- often 80-95% less than 10kbyte

doens't mean large files are unimportant

- still take up most of the space
- biggest performance problems

extents

large file? lists of many thousands of blocks is awkward

- ...and requires multiple reads from disk to get

solution: store extents: (start disk block, size)

- replaces or supplements block list

Linux's ext4 and Windows's NTFS both use this

allocating extents

challenge: finding contiguous sets of free blocks

NTFS: scan block map for "best fit"

- look for big enough chunk of free blocks
- choose smallest among all the candidates

don't find any? okay: use more than one extent

seeking with extents

challenge: finding byte X of the file

with block pointers: can compute index

with extents: need to scan list?

filesystem reliability

a crash happens — what's the state of my filesystem?

hard disk atomicity

interrupt a hard drive write?

write whole disk sector or corrupt it

hard drive/SSD stores checksum for each sector

write interrupted? — checksum mismatch

- hard drive/SSD returns read error

reliability issues

is the filesystem in a consistent state?

- do we know what blocks are free?
- do we know what files exist?
- is the data for files actually what was written?

also important topics, but won't spend much time on these:

what data will I lose if storage fails?

- mirroring, erasure coding (e.g. RAID) — using multiple storage devices
- idea: if one storage device fails, other(s) still have data

what data will I lose if I make a mistake?

- filesystem can store *multiple versions*
- "snapshots" of what was previously there

several bad options (1)

suppose we're moving a file from one directory to another on xv6

steps:

A: write new directory entry

B: overwrite (remove) old directory entry

several bad options (1)

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if we do A before B and crash happens after A:

- can have extra pointer of file
- problem: if old directory entry removed later, will get confused and free the file!

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steps:

A: write new directory entry

B: overwrite (remove) old directory entry

if we do A before B and crash happens after A:

- can have extra pointer of file
- problem: if old directory entry removed later, will get confused and free the file!

if we do B before A and crash happens after B:

- the file disappeared entirely!

beyond ordering

recall: updating a sector is atomic

- happens entirely or doesn't

can we make filesystem updates work this way?

beyond ordering

recall: updating a sector is atomic

- happens entirely or doesn't

can we make filesystem updates work this way?

yes — 'just' make updating one sector do the update

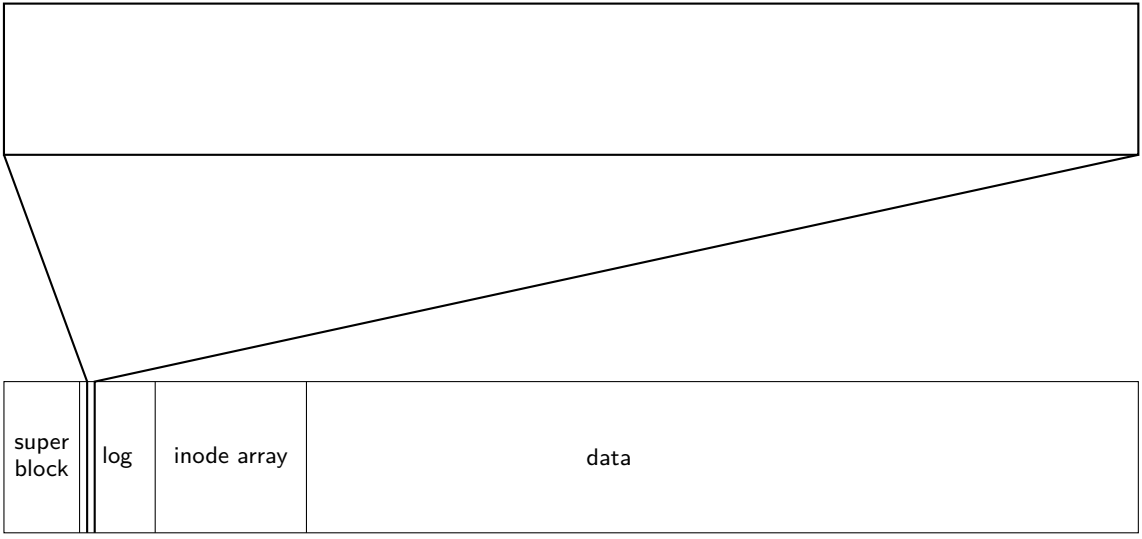
concept: transaction

transaction: bunch of updates that happen all at once

implementation trick: one update means transaction "commits"

- update done — whole transaction happened
- update not done — whole transaction did not happen

redo logging: file creation



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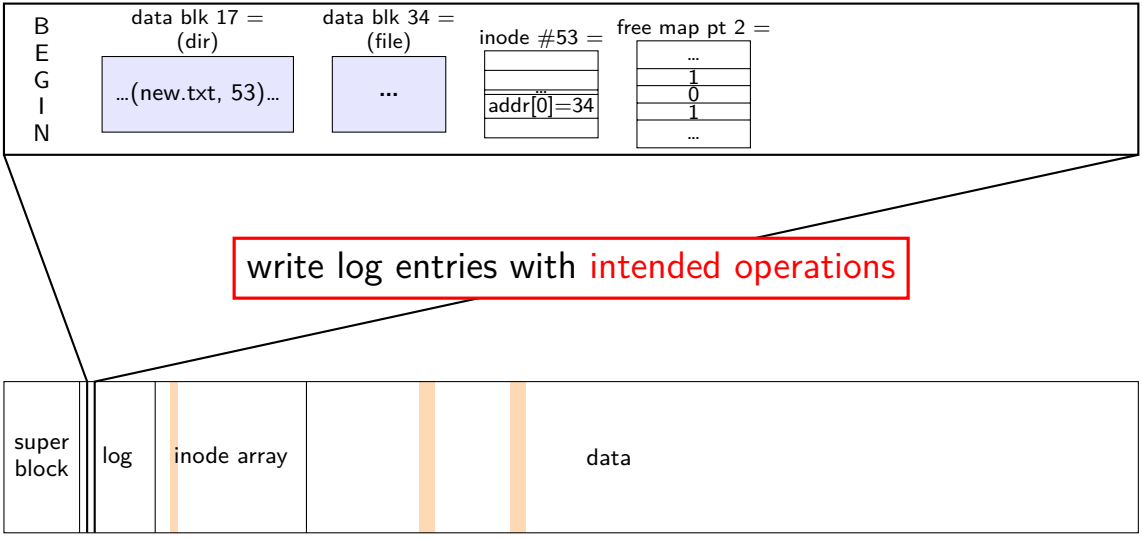

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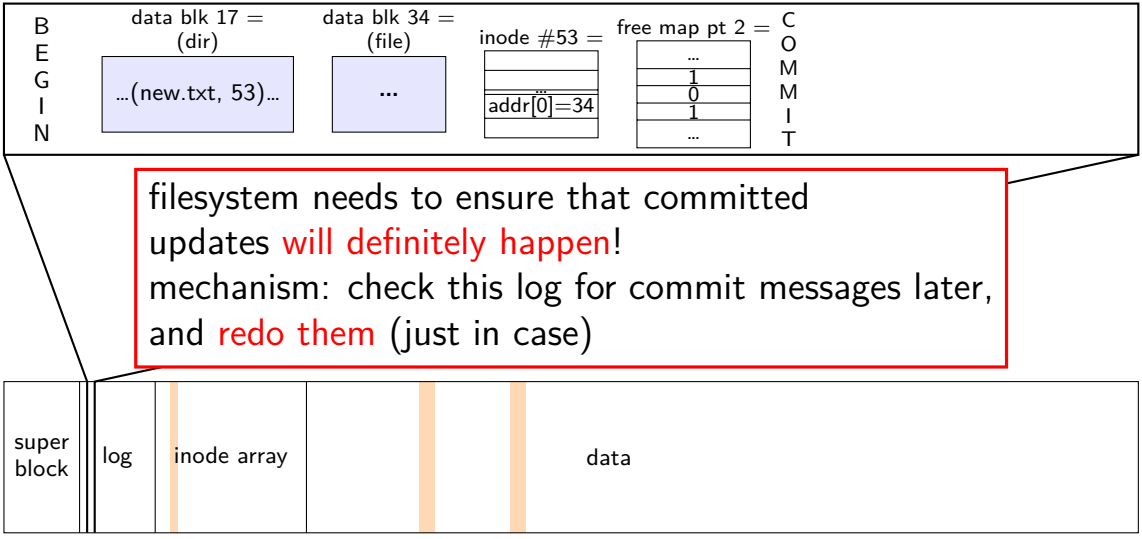

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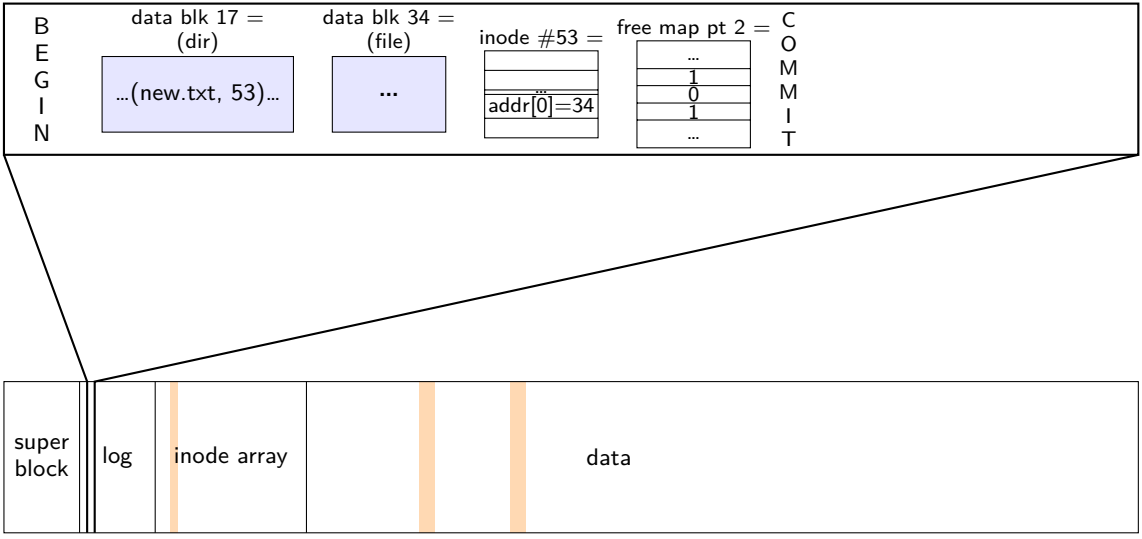

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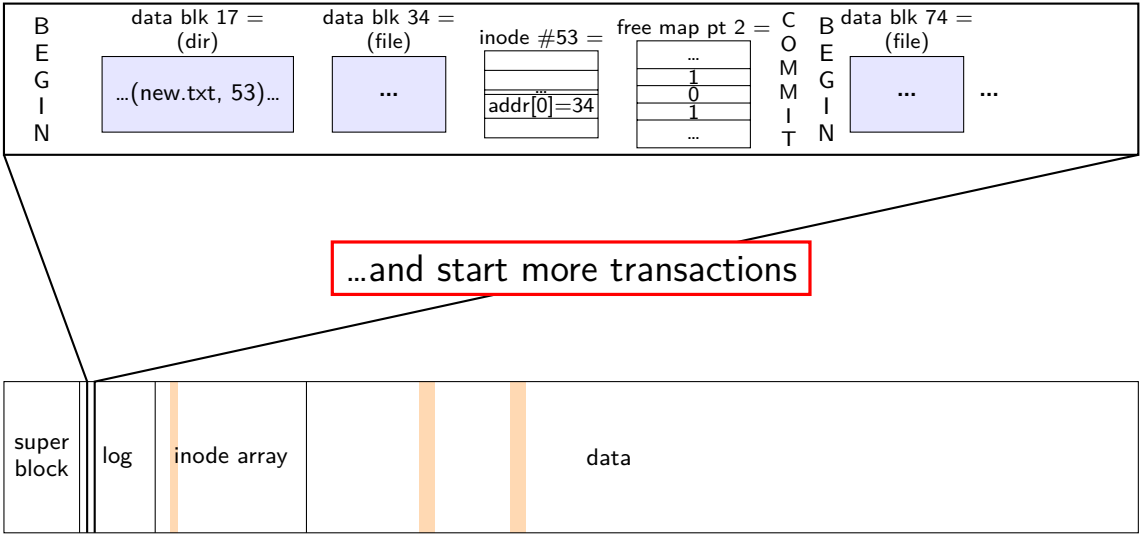

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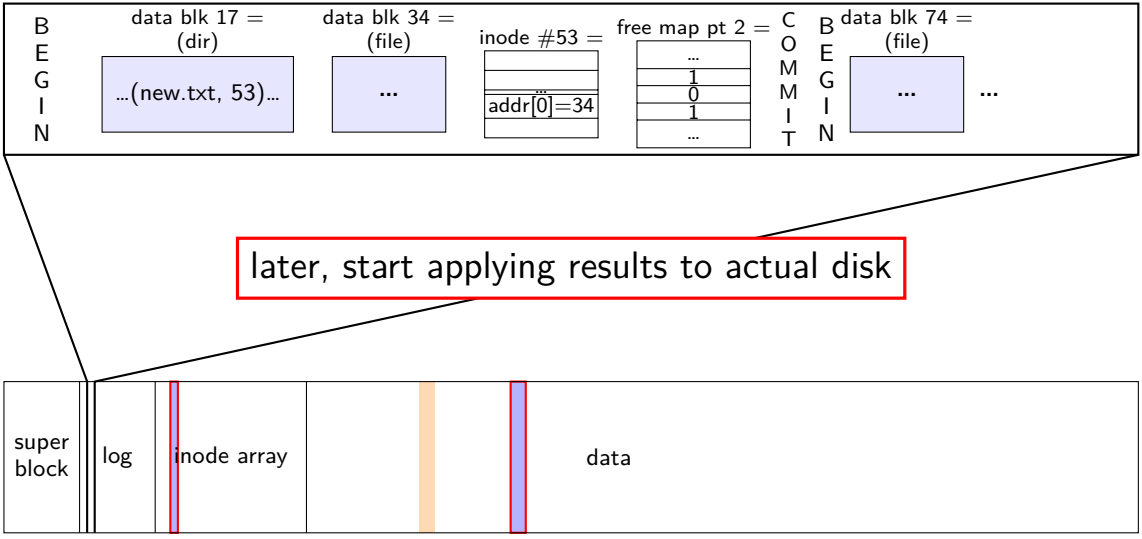

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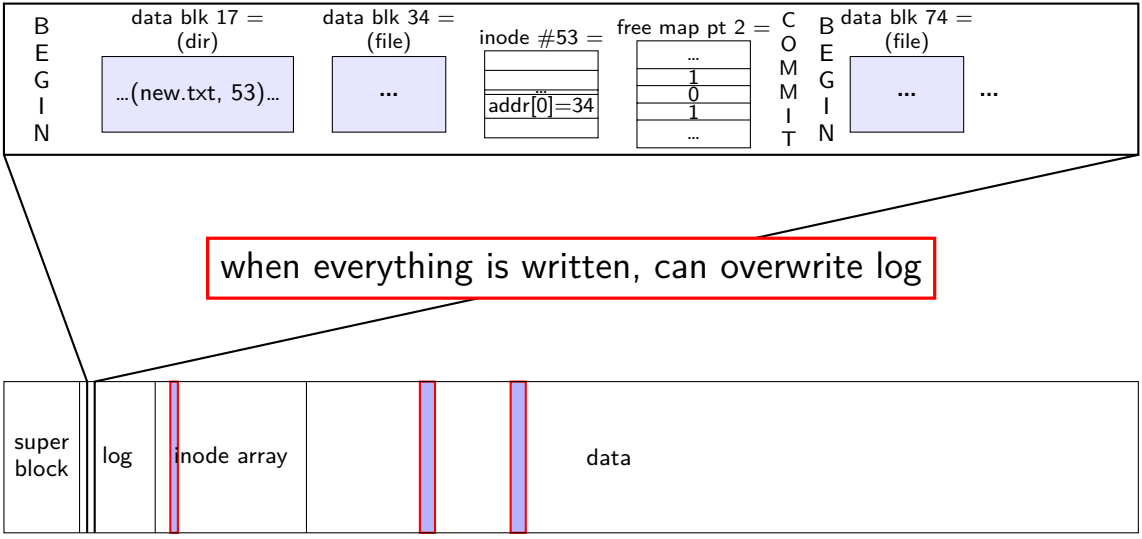

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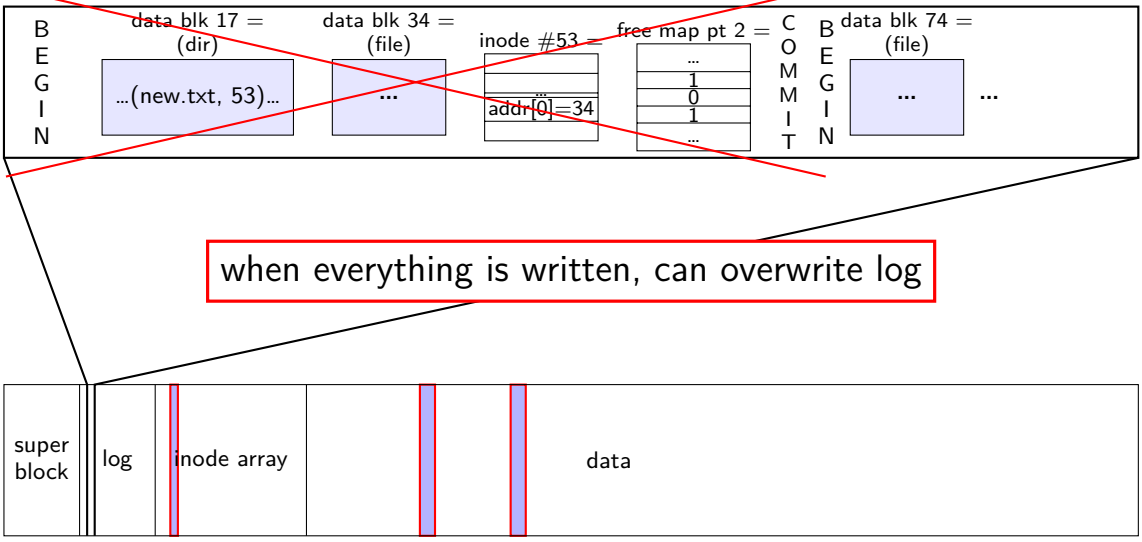

redo logging: file creation

normal operation

write to log transaction steps:

- data blocks to create
- direcotry entry, inode to write
- directory inode (size, time)
- update

write to log "commit transaction"

in any order:

- update file data blocks
- update directory entry
- update file inode
- update directory inode

reclaim space in log

- "garbage collection"

redo logging: file creation

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crash before *commit*?
file not created
no partial operation to real data

redo logging: file creation

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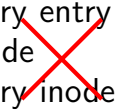

reclaim space in log

- "garbage collection"

crash after *commit*?

file created

promise: will perform logged updates

(after system reboots/recovers)

redo logging: file creation

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reclaim space in log

- "garbage collection"

recovery

read log and...

ignore any operation with no "commit"

redo any operation with "commit"

- already done? — okay, setting inode twice

reclaim space in log

idempotency

logged operations should be *okay to do twice* = *idempotent*

good example: set inode link count to 4

bad example: increment inode link count

good example: overwrite inode number X with new value

as long as last committed inode value in log is right...

bad example: allocate new inode with particular contents

good example: overwrite data block with new value

bad example: append data to last used block of file

redo logging summary

write intended operation to the log

- before ever touching 'real' data
- in format that's safe to do twice

write marker to commit to the log

- if exists, the operation *will be done eventually*

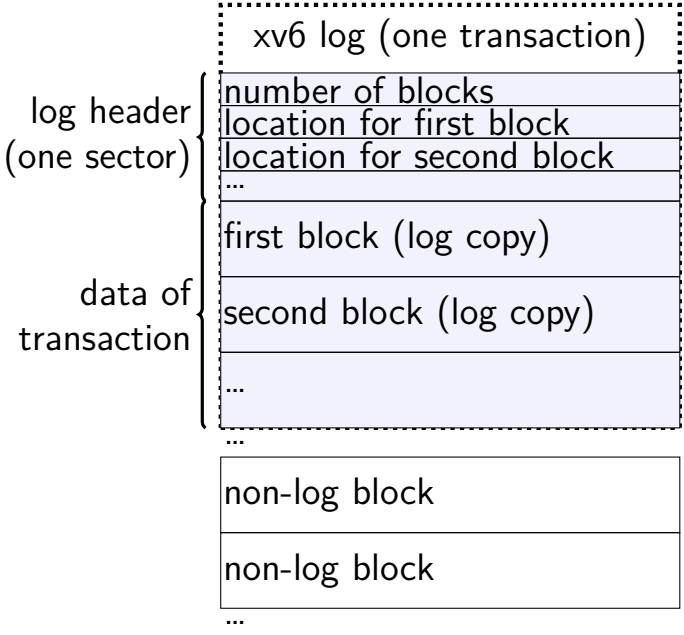
actually update the real data

redo logging and filesystems

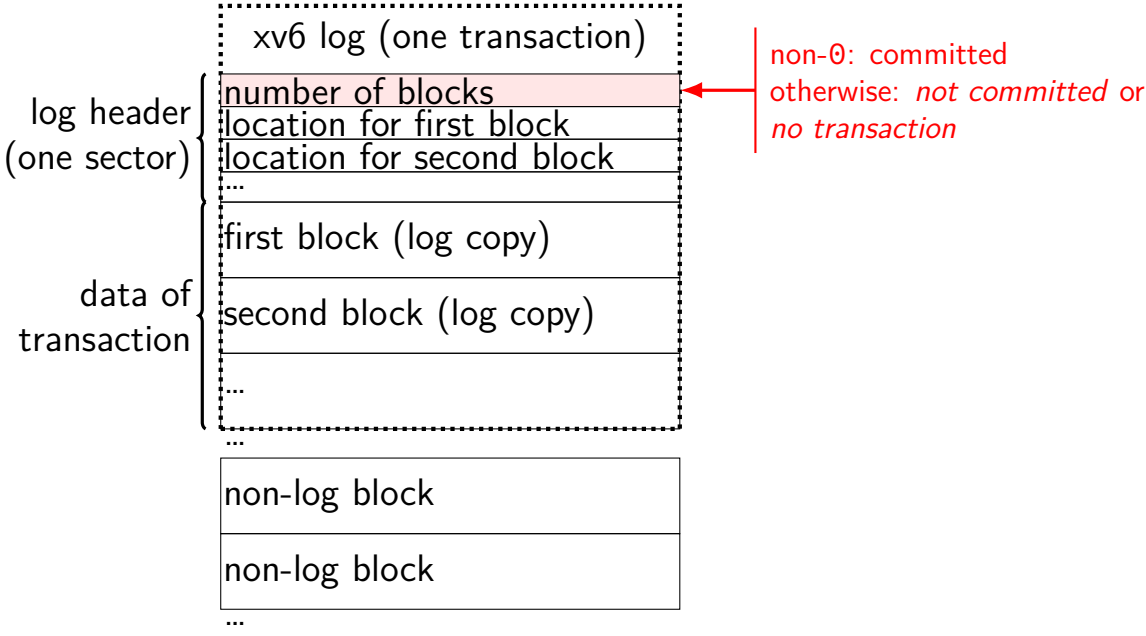
filesystems that do redo logging are called *journalling filesystems*

backup slides

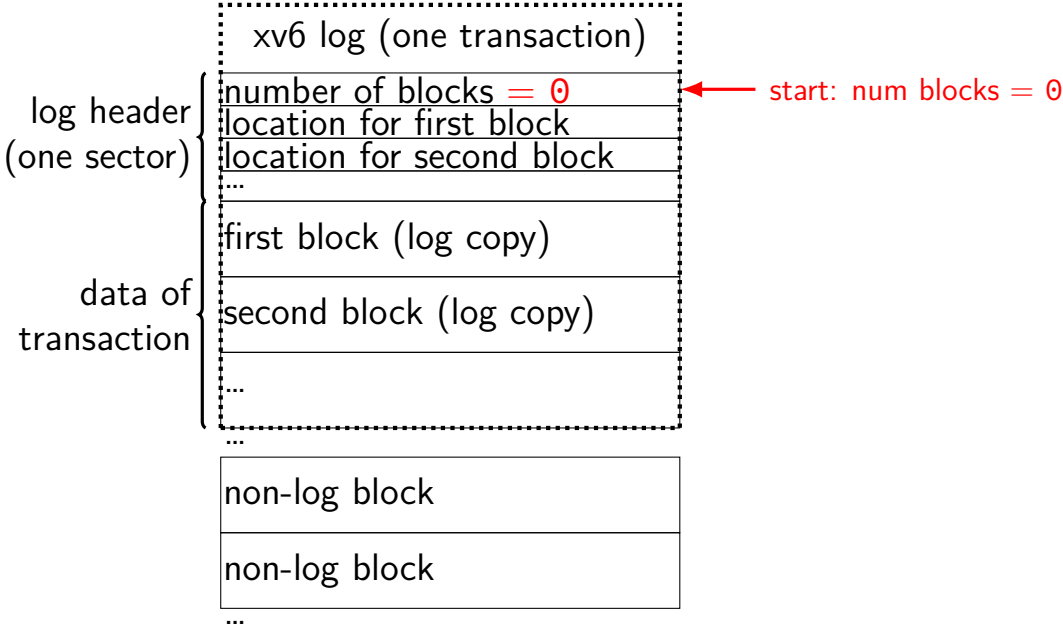
the xv6 journal



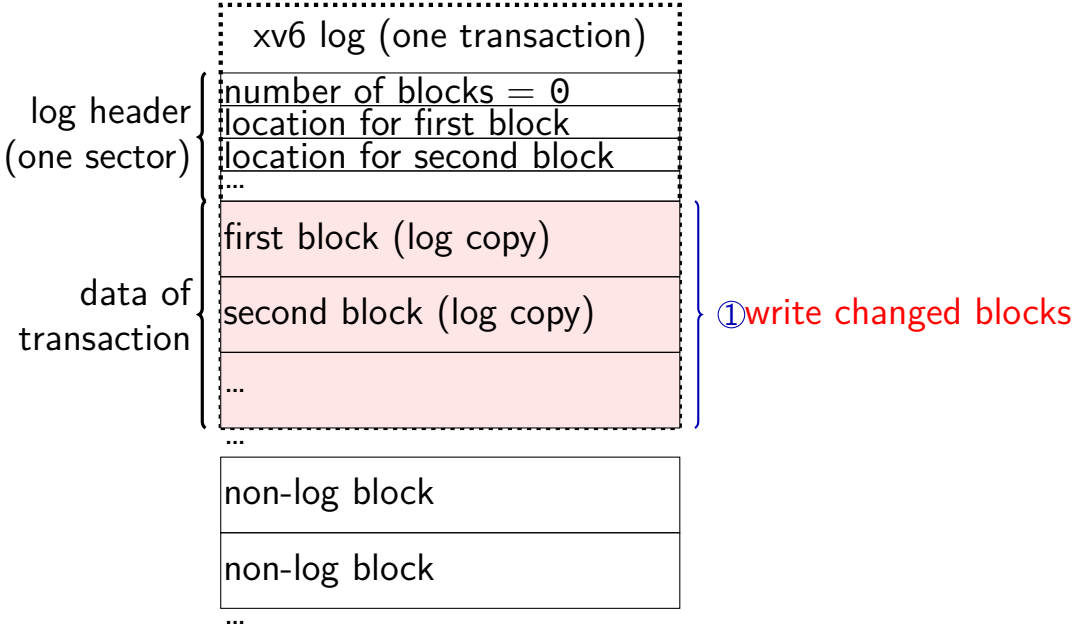
the xv6 journal



the xv6 journal



the xv6 journal



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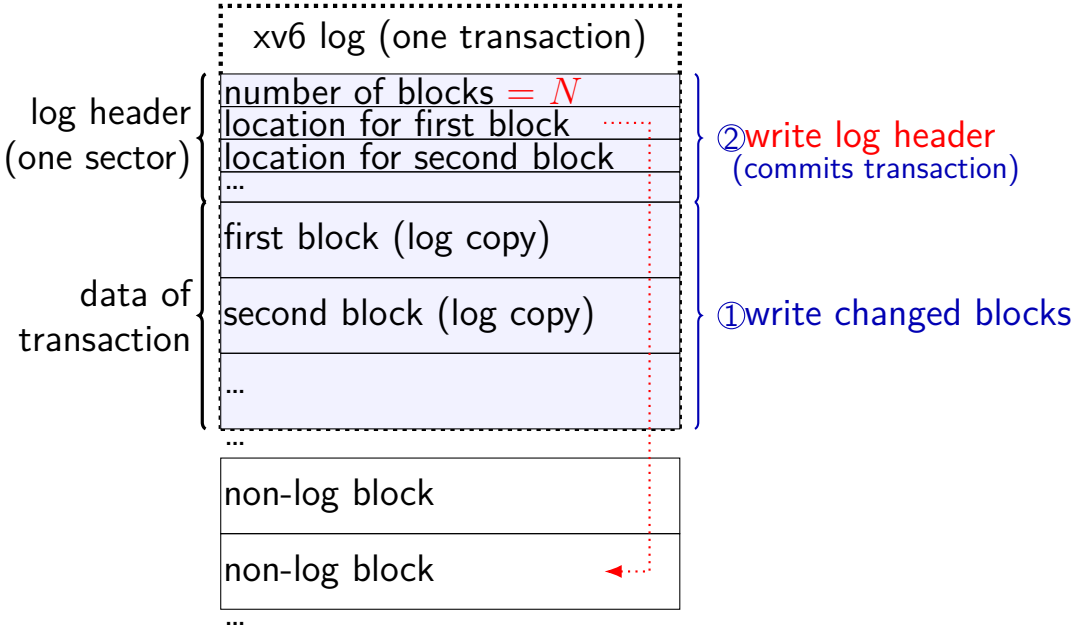

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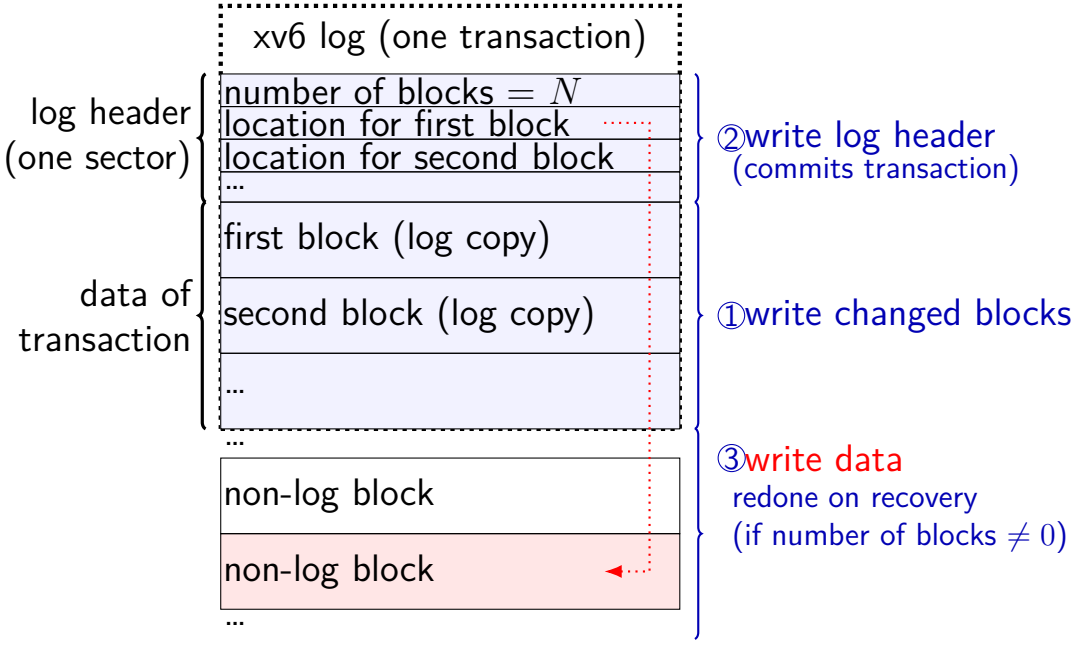

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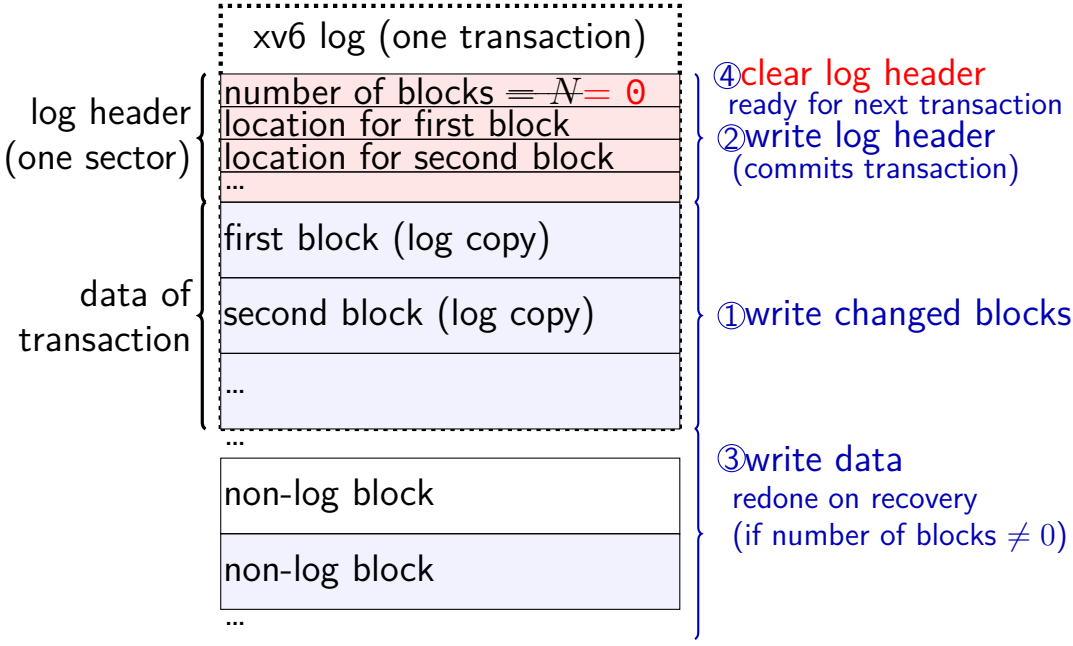

what is a transaction?

so far: each file update?

faster to do batch of updates together

- one log write finishes lots of things
- don't wait to write

xv6 solution: combine lots of updates into one transaction

only commit when...

- no active file operation, *or*
- not enough room left in log for more operations

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mounting filesystems

Unix-like system

root filesystem appears as /

other filesystems *appear as directory*

e.g. lab machines: my home dir is in filesystem at /net/zf15

directories that are filesystems look like normal directories

`/net/zf15/..` is `/net` (even though in different filesystems)

mounts on a dept. machine

```
/dev/sda1 on / type ext4 (rw,errors=remount-ro)
proc on /proc type proc (rw,noexec,nosuid,nodev)
...
udev on /dev type devtmpfs (rw,mode=0755)
devpts on /dev/pts type devpts (rw,noexec,nosuid,gid=5,mode=0620)
tmpfs on /run type tmpfs (rw,noexec,nosuid,size=10%,mode=0755)
...
/dev/sda3 on /localtmp type ext4 (rw)
...
zfs1:/zf2 on /net/zf2 type nfs (rw,hard,intr,proto=udp,nfsvers=3,
                                noacl,sloppy,addr=128.143.136.9)
zfs3:/zf19 on /net/zf19 type nfs (rw,hard,intr,proto=udp,nfsvers=3,
                                  noacl,sloppy,addr=128.143.67.236)
zfs4:/sw on /net/sw type nfs (rw,hard,intr,proto=udp,nfsvers=3,
                               noacl,sloppy,addr=128.143.136.9)
zfs3:/zf14 on /net/zf14 type nfs (rw,hard,intr,proto=udp,nfsvers=3,
                                  noacl,sloppy,addr=128.143.67.236)
...
```

kernel FS abstractions

Linux: *virtual file system* API

object-oriented, based on FFS-style filesystem

to implement a filesystem, create object types for:

- superblock (represents "header")
- inode (represents file)
- dentry (represents cached directory entry)
- file (represents *open file*)

common code handles directory traversal

- and caches directory traversals

common code handles file descriptors, etc.

exercise

say xv6 filesystem with:

- 64-byte inodes (12 direct + 1 indirect pointer)
- 16-byte directory entries
- 512 byte blocks
- 2-byte block pointers

how many blocks (not storing inodes) is used to store a directory of 200 30464B ($29 \cdot 1024 + 256$ byte) files?

- remember: blocks could include blocks storing data or block pointers or directory enties

how many blocks is used to store a directory of 2000 3KB files?

fragments

Linux FS: a file's last block can be a *fragment* — only part of a block

each block split into approx. 4 fragments

- each fragment has its own index

extra field in inode indicates that last block is fragment

allows one block to store data for several small files

beyond mirroring

mirroring seems to waste a lot of space

10 disks of data? mirroring $\rightarrow$ 20 disks

10 disks of data? how good can we do with 15 disks?

best possible: lose 5 disks, still okay

- can't do better or it wasn't really 10 disks of data

schemes that do this based on *erasure codes*

- erasure code: encode data in way that handles parts missing (being erased)

erasure code example

store 2 disks of data on 3 disks

recompute original 2 disks of data from any 2 of the 3 disks

extra disk of data: some formula based on the original disks

- common choice: bitwise XOR

common set of schemes like this: RAID

- Redundant Array of Independent Disks

snapshots

filesystem snapshots

idea: filesystem keeps old versions of files around

- accidental deletion? old version stil there
- eventually discard some old versions

can access *snapshot* of files at prior time

snapshots

filesystem snapshots

idea: filesystem keeps old versions of files around

- accidental deletion? old version stil there
- eventually discard some old versions

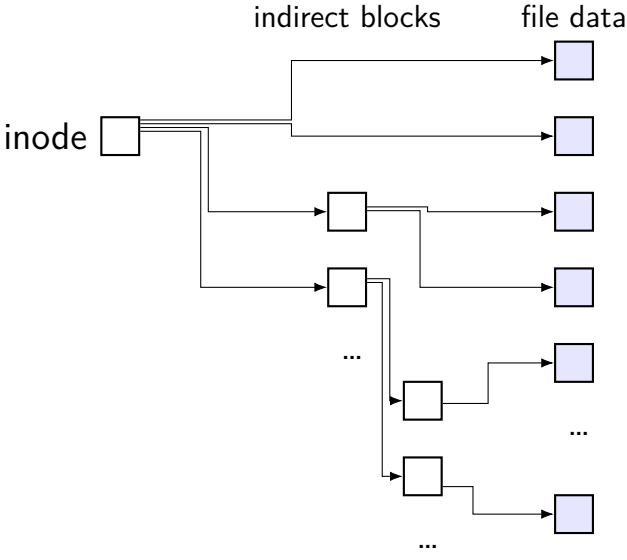
can access *snapshot* of files at prior time

mechanism: copy-on-write

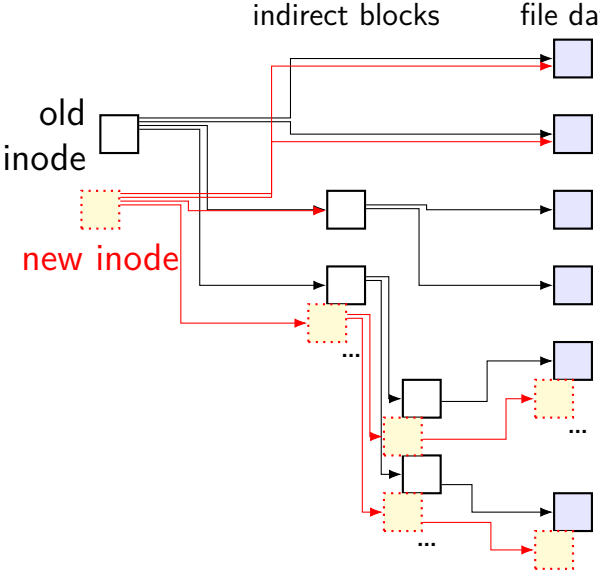
changing file makes new copy of filesystem

common parts shared between versions

inode and copy-on-write



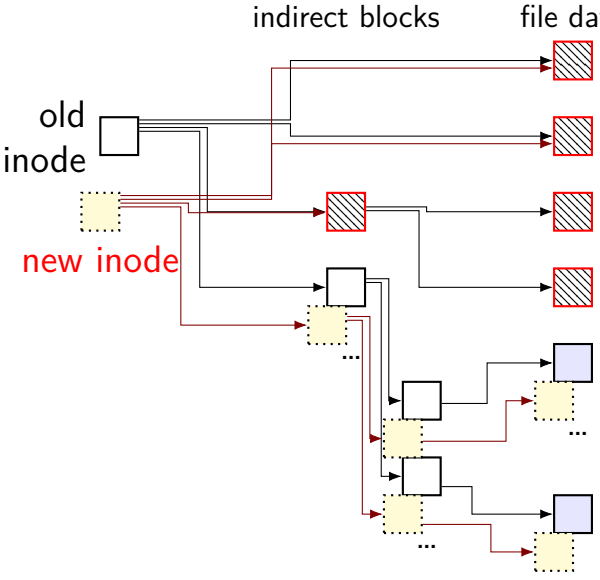
inode and copy-on-write



update: new data blocks
+ new indirect blocks
+ new inode

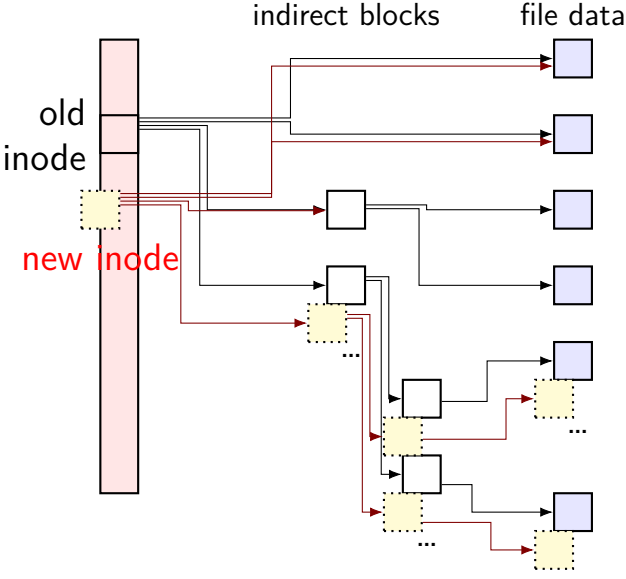
both old+new inode valid

inode and copy-on-write



unchanged parts of file shared

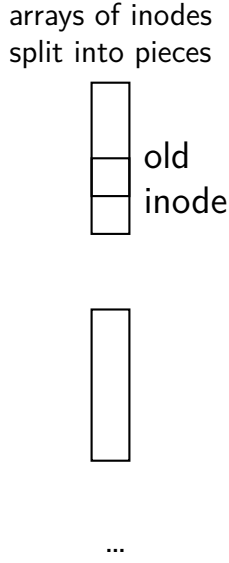
inode and copy-on-write



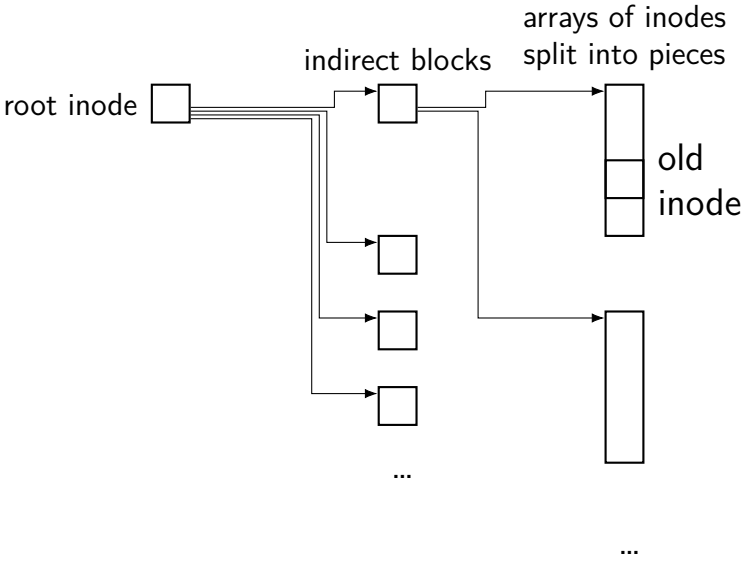
challenge: FFS/xv6/ext2 design has big array of inodes

don't want to write new copy of *entire inode array*

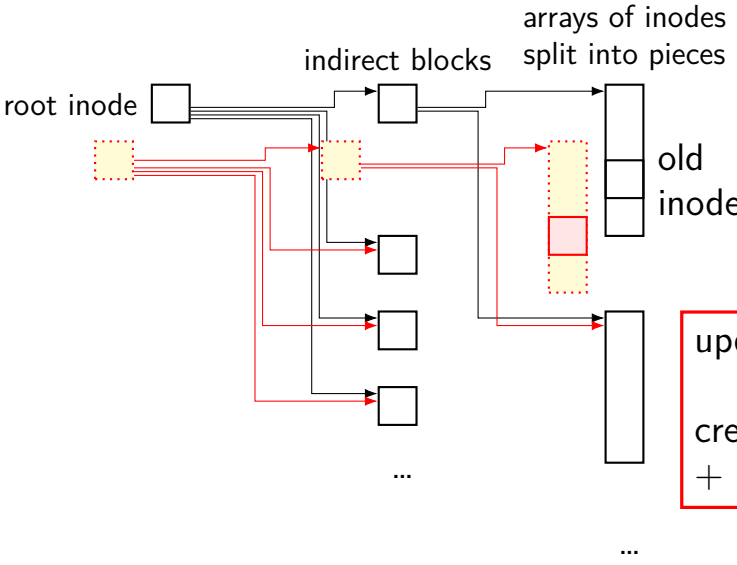
extra indirection for inode array



extra indirection for inode array



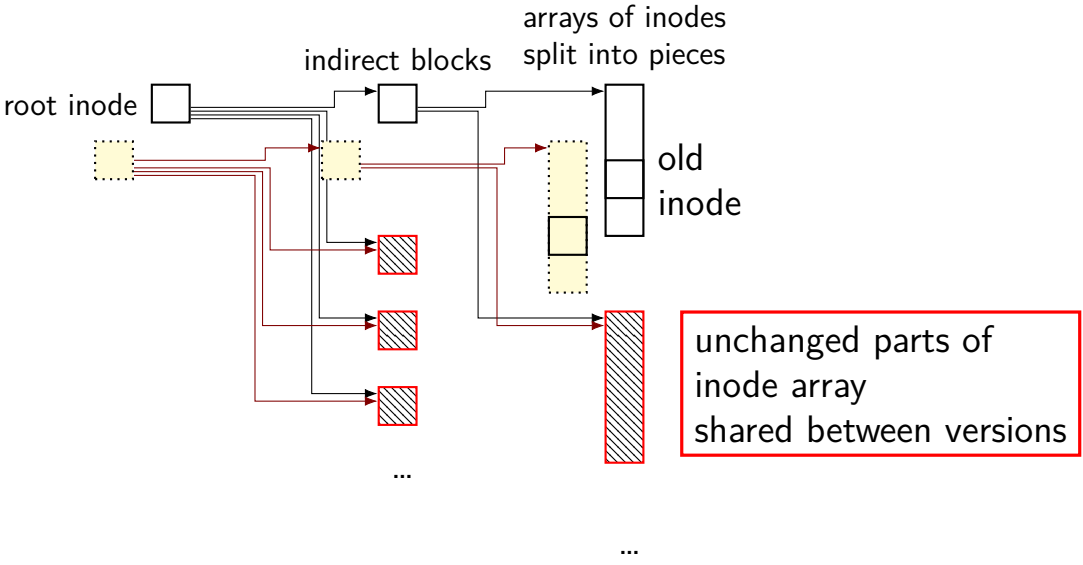
extra indirection for inode array



update one inode?

create new root inode
+ pointers

extra indirection for inode array



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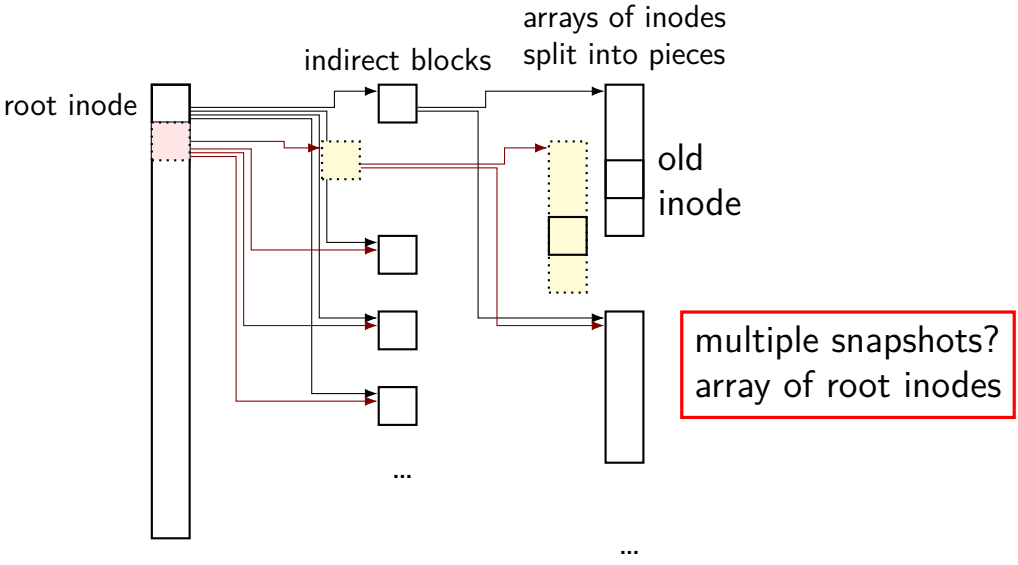


multiple snapshots?
array of root inodes

copy-on-write indirection

file update = replace with new version

array of versions of entire filesystem

only copy modified parts

keep reference counts, like for paging assignment

lots of pointers — only change pointers where modifications happen

snapshots in practice

ZFS supports this (if turned on)

example: `.zfs/snapshots/11.11.18-06` pseudo-directory

contains contents of files at 11 November 2018 6AM

multiple copies

FAT: multiple copies of file allocation table and header

in inode-based filesystems: often multiple copies of superblocks

if part of disk's data is lost, have an extra copy

- always update both copies
- hope: disk failure to small group of sectors

hope: enough to recover most files on disk failure

- extra copy of metadata that is important for all files
- but won't recover specific files/directories whose data was lost

aside: FAT date encoding

seperate date and time fields (16 bits, little-endian integers)

bits 0-4: seconds (divided by 2), 5-10: minute, 11-15: hour

bits 0-4: day, 5-8: month, 9-15: year (minus 1980)

sometimes extra field for 100s(?) of a second

Fast File System

the Berkeley Fast File System (FFS) 'solved' some of these problems

- McKusick et al, "A Fast File System for UNIX" `https://people.eecs.berkeley.edu/~brewer/cs262/FFS.pdf`
- avoids long seek times, wasting space for tiny files

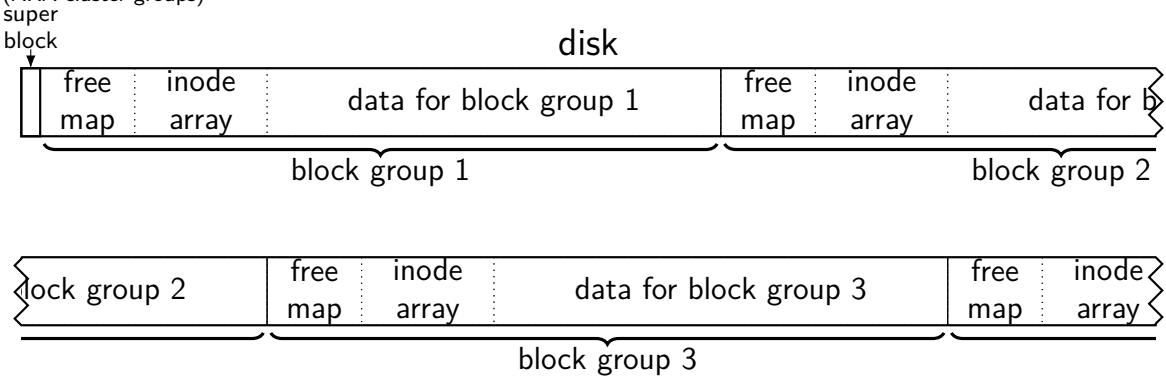
Linux's ext2 filesystem based on FFS

some other notable newer solutions (beyond what FFS/ext2 do)

- better handling of very large files
- avoiding linear directory searches

block groups

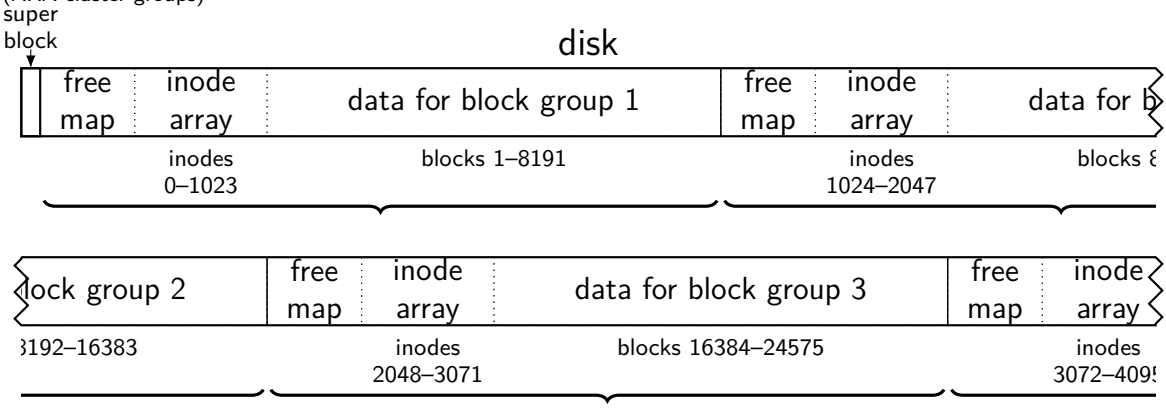
(AKA cluster groups)



split disk into block groups
each block group like a mini-filesystem

block groups

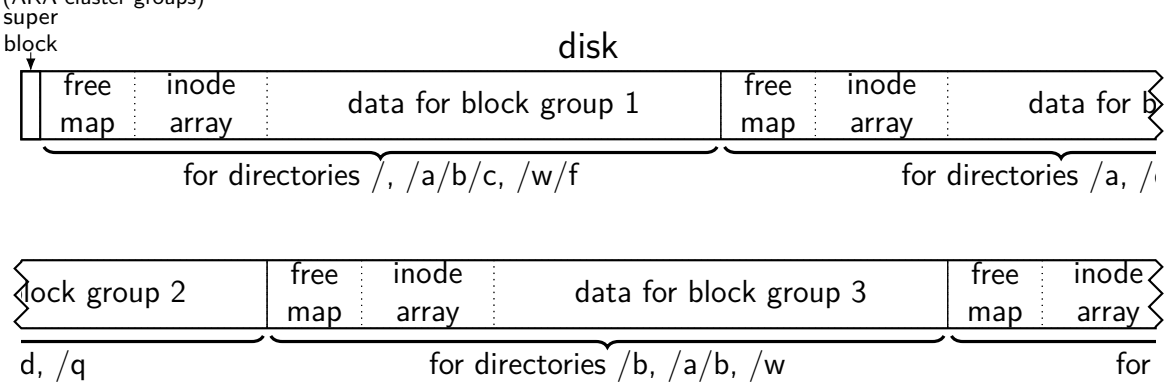
(AKA cluster groups)



split block + inode numbers across the groups
inode in one block group can reference blocks in another
(but would rather not)

block groups

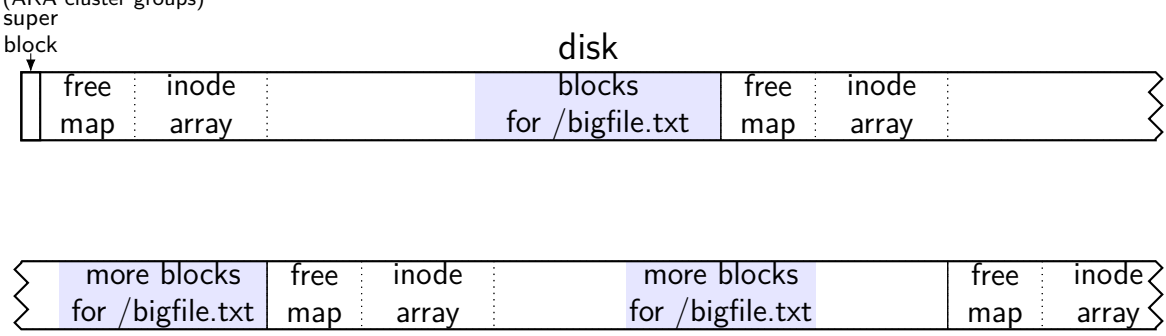
(AKA cluster groups)



goal: *most data* for each directory within a block group
directory entries + inodes + file data close on disk
lower seek times!

block groups

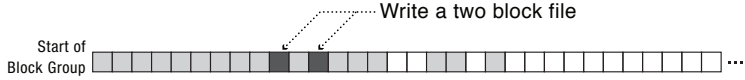
(AKA cluster groups)



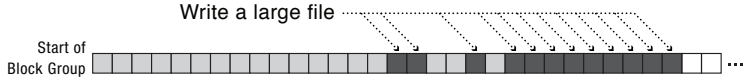
large files might need to be split across block groups

allocation within block groups

Expected typical arrangement.



Small files fill holes near start of block group.



Large files fill holes near start of block group and then write most data to sequential range blocks.

FFS block groups

making a subdirectory: new block group

- for inode + data (entries) in different

writing a file: same block group as directory, first free block

- intuition: non-small files get contiguous groups at end of block
- FFS keeps disk deliberately underutilized (e.g. 10% free) to ensure this

can wait until dirty file data flushed from cache to allocate blocks

- makes it easier to allocate contiguous ranges of blocks

several bad options (2)

suppose we're creating a new file

A: mark blocks as used in free block map

B: write inode for file

C: write directory entry for file

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if we do A before B+C and crash happens after A:

have blocks we can't use (not free), but which are unused

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C: write directory entry for file

if we do A before B+C and crash happens after A:

have blocks we can't use (not free), but which are unused

if we do B before A+C and crash happens after B:

have inode we can't use (not free), but which is not really used

several bad options (2)

suppose we're creating a new file

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B: write inode for file

C: write directory entry for file

if we do A before B+C and crash happens after A:
have blocks we can't use (not free), but which are unused

if we do B before A+C and crash happens after B:
have inode we can't use (not free), but which is not really used

if we do C before A+B and crash happens after C:
have directory entry that points to junk — will behave weirdly

xv6 filesystem performance issues

inode, block map stored far away from file data

- long seek times for reading files

unintelligent choice of file/directory data blocks

- xv6 finds *first free block/inode*
- result: files/directory entries scattered about

blocks are pretty small — needs lots of space for metadata

- could change size? but waste space for small files
- large files have giant lists of blocks

linear searches of directory entries to resolve paths

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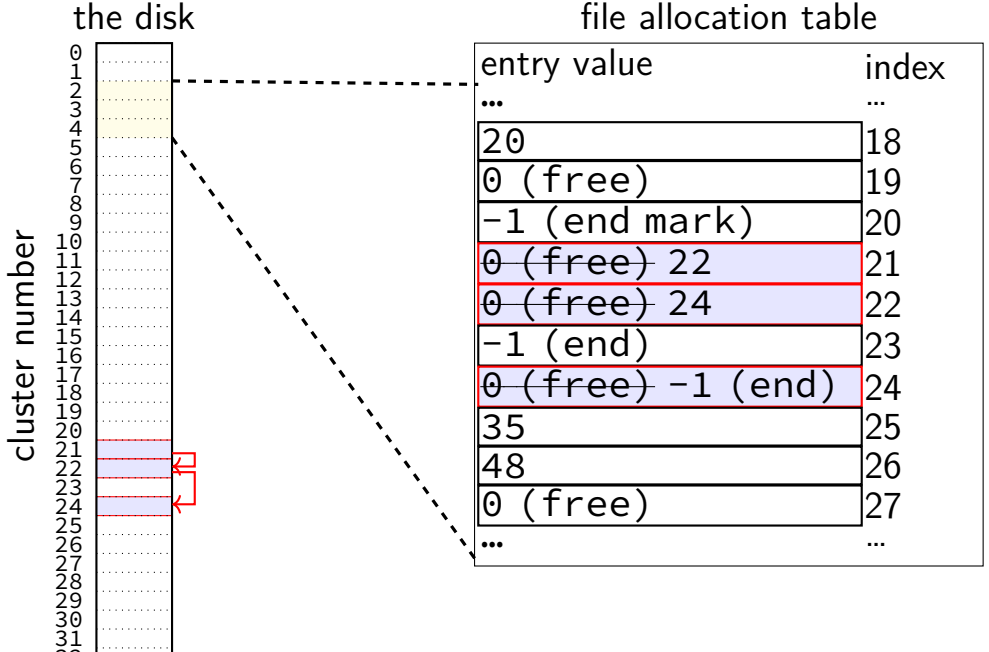
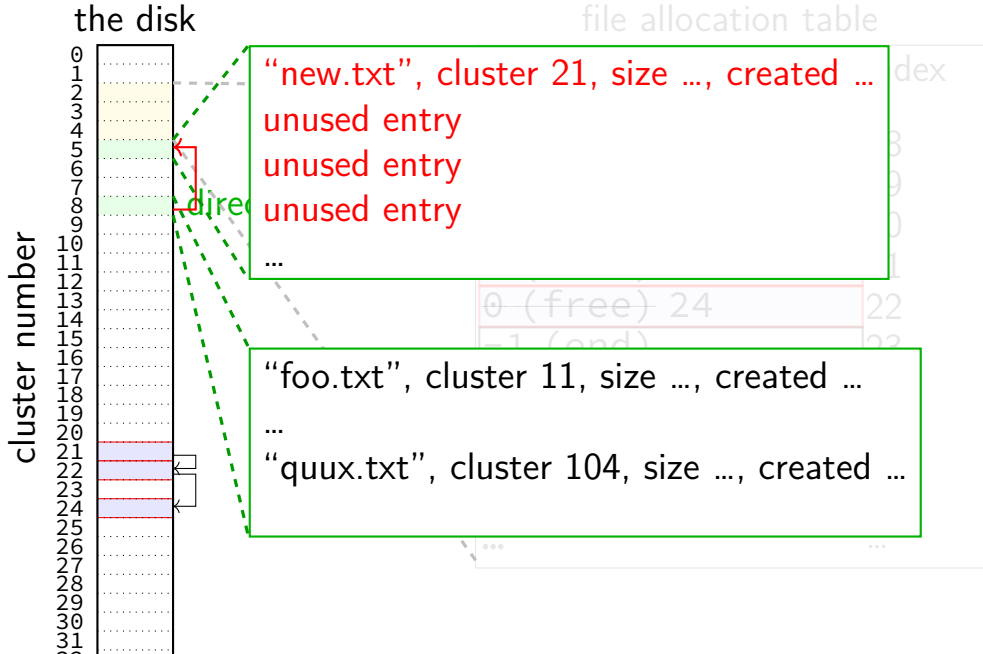
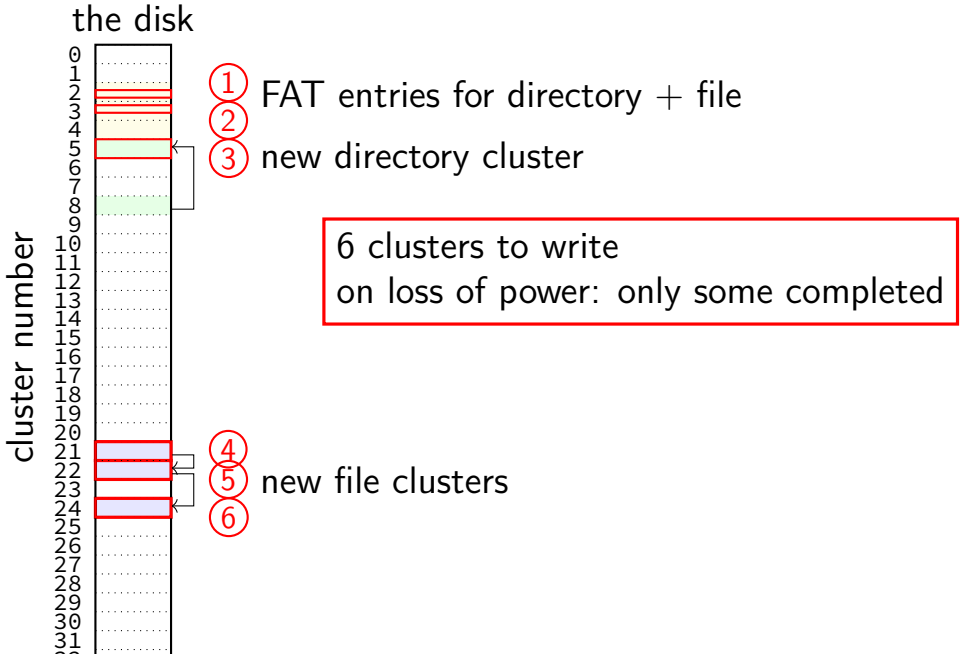
recall: FAT: file creation (1)



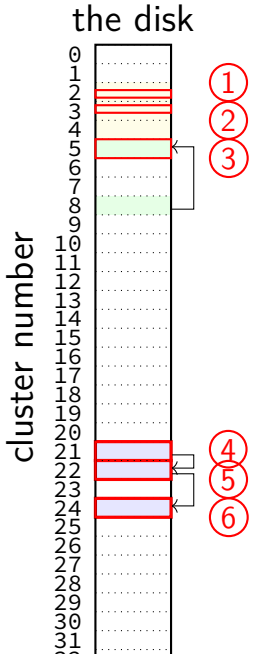
recall: FAT: file creation (2)



exercise: FAT file creation



exercise: FAT file creation



1. FAT entries for directory + file
2.
3. new directory cluster

6 clusters to write
on loss of power: only some completed

exercise: what happens if only 1, 2 complete?
everything but 3?

4.
5. new file clusters
6.

exercise: FAT ordering

(creating a file that needs new cluster of direntries)

1. FAT entry for extra directory cluster
2. FAT entry for new file clusters
3. file clusters
4. file's directory entry (in new directory cluster)

what ordering is best if a crash happens in the middle?

A. 1, 2, 3, 4
B. 4, 3, 1, 2
C. 1, 3, 4, 2
D. 3, 4, 2, 1
E. 3, 1, 4, 2

exercise: xv6 FS ordering

(creating a file that neeeds new block of direntries)

1. free block map for new directory block
2. free block map for new file block
3. directory inode
4. new file inode
5. new directory entry for file (in new directory block)
6. file data blocks

what ordering is best if a crash happens in the middle?

A. 1, 2, 3, 4, 5, 6
B. 6, 5, 4, 3, 2, 1
C. 1, 2, 6, 5, 4, 3
D. 2, 6, 4, 1, 5, 3
E. 3, 4, 1, 2, 5, 6

r

inode-based FS: careful ordering

mark blocks as allocated before referring to them from directories

write data blocks before writing pointers to them from inodes

write inodes before directory entries pointing to it

remove inode from directory before marking inode as free

or decreasing link count, if there's another hard link

idea: better to waste space than point to bad data

recovery with careful ordering

avoiding data loss → can 'fix' inconsistencies

programs like `fsck` (filesystem check), `chkdsk` (check disk)

run manually or periodically or after abnormal shutdown

inode-based FS: creating a file

normal operation

allocate data block

write data block

update free block map

update file inode

update directory entry

filename+inode number

update direcotry inode

modification time

inode-based FS: creating a file

normal operation

allocate data block

write data block

update free block map

update file inode

update directory entry
- filename+inode number

update direcotry inode
- modification time

general rule:
better to waste space
than point to bad data

mark blocks/inodes used before writing

inode-based FS: creating a file

normal operation

- allocate data block
- write data block
- update free block map
- update file inode
- update directory entry
  - filename+inode number
- update direcotry inode
  - modification time

recovery (`fsck`)

- read all directory entries
- scan all inodes
- free unused inodes
  - unused = not in directory
- free unused data blocks
  - unused = not in inode lists
- scan directories for missing update/access times

inode-based FS: exercise: unlink

what order to remove a hard link (= directory entry) for file?

1. overwrite directroy entry for file
2. decrement link count in inode (but link count still > 1 so don't remove)

assume not the last hard link

inode-based FS: exercise: unlink

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2. mark inode as free (link count = 0 now)
3. mark inode's data blocks as free

assume is the last hard link

inode-based FS: exercise: unlink last

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1. overwrite last directroy entry for file
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3. mark inode's data blocks as free

assume is the last hard link

what does recovery operation do?

fsck

Unix typically has an `fsck` utility

- Windows equivalent: `chkdsk`

checks for *filesystem consistency*

- is a data block marked as used that no inodes uses?
- is a data block referred to by two different inodes?
- is a inode marked as used that no directory references?
- is the link count for each inode = number of directories referencing it?
- ...

assuming careful ordering, can fix errors after a crash without loss

maybe can fix other errors, too

fsck costs

my desktop's filesystem:
2.4M used inodes; 379.9M of 472.4M used blocks

recall: check for data block marked as used that no inode uses:

- read blocks containing all of the 2.4M used inodes
- add each block pointer to a list of used blocks
- if they have indirect block pointers, read those blocks, too
- get list of all used blocks (via direct or indirect pointers)
- compare list of used blocks to actual free block bitmap

pretty expensive and slow

running fsck automatically

common to have “clean” bit in superblock

last thing written (to set) on shutdown

first thing written (to clear) on startup

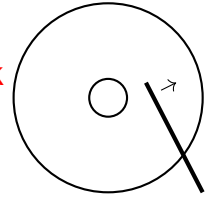
on boot: if clean bit clear, run fsck first

ordering and disk performance

recall: seek times

would like to order writes based on locations on disk

- write many things in one pass of disk head
- write many things in cylinder in one rotation



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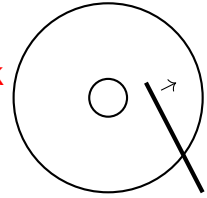


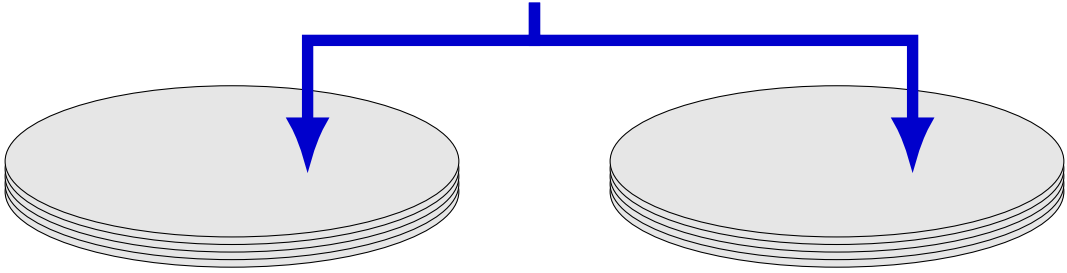
ordering constraints make this hard:

free block map for file (start), then file blocks (middle), then...

file inode (start), then directory (middle), ...

mirroring whole disks

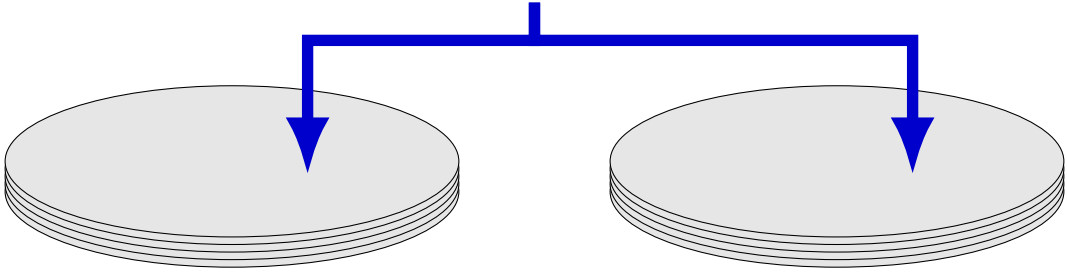
alternate strategy: write everything to two disks



mirroring whole disks

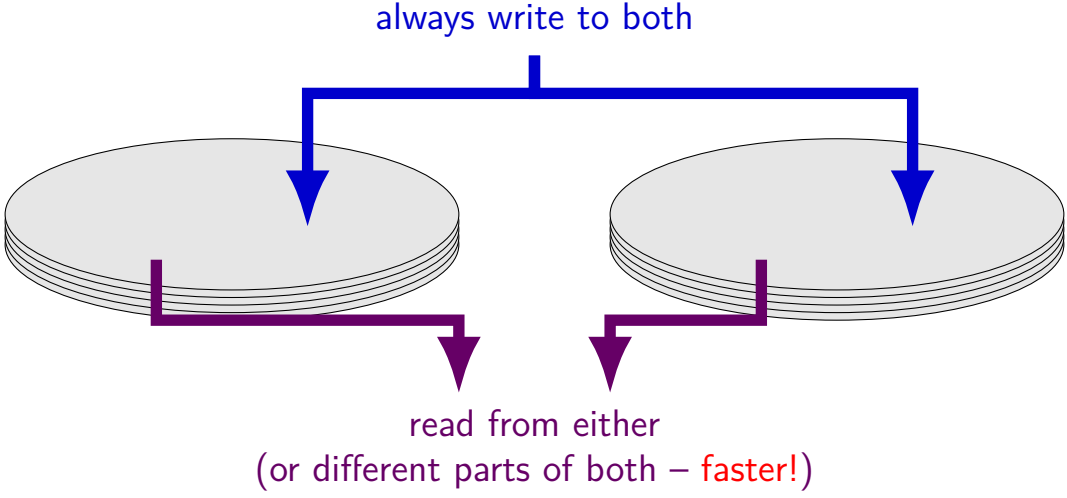
alternate strategy: write everything to two disks

always write to both



mirroring whole disks

alternate strategy: write everything to two disks



beyond mirroring

mirroring seems to waste a lot of space

10 disks of data? mirroring $\rightarrow$ 20 disks

10 disks of data? how good can we do with 15 disks?

best possible: lose 5 disks, still okay

- can't do better or it wasn't really 10 disks of data

schemes that do this based on *erasure codes*

- erasure code: encode data in way that handles parts missing (being erased)

erasure code example

store 2 disks of data on 3 disks

recompute original 2 disks of data from any 2 of the 3 disks

extra disk of data: some formula based on the original disks

- common choice: bitwise XOR

common set of schemes like this: RAID

- Redundant Array of Independent Disks

exericse

filesystem has:

- root directory with 2 subdirectories
- each subdirectory contains 3 512B files, 2 4MB files
- (1MB = 1024KB; 1KB = 1024B)
- 32B directory entries
- 4B block pointers
- 4KB blocks
- inode: 12 direct pointers, 1 indirect pointer, 1 double-indirect, 1 triple-indirect

(a) how many inodes used?

(b) how many blocks (outside of inodes) with 1KB fragments? [minimum w/partial blocks]

(c) how many blocks (outside of inodes) with block pointers replaced by 8B extents (no fragments)? [compute minimum]

inodes used

per each of 2 subdirectories: 5 files + 1 inode for subdirectory = 6

plus 1 for root directory itself

$= 12 + 1 = 13$

blocks with fragments

each of 6 512B files uses a single 1KB fragment

wastes 512Bs of it

each of 2 subdirectory needs $32\text{B} \cdot 5 \ll 1\text{KB}$ (1 fragment)

(5 directory entries; probably also additional entries for `..`)

root directory needs $32\text{B} \cdot 2 \ll 1\text{KB}$ (1 fragment)

9 1KB fragments $\rightarrow$ minimum 3 (4KB) blocks

each of 4 4MB file uses 1024 data blocks

1 indirect block for blocks 13-(1024+13) [last 12 pointers unused]

$= 4096$ blocks (4MB files data) $+ 4$ (4MB file indirects) $+ 3$ (for fragments)
$= 4103$ blocks

blocks with extents

each of 6 512B files uses a single 4KB block

extent specifying block

each of 2 subdirectory needs $32\text{B} \cdot 5 \ll 4\text{KB}$ (1 block)

root directory needs $32\text{B} \cdot 2 \ll 4\text{KB}$ (1 block)

each of 2 4MB file uses 2048 data blocks

no indirect blocks assuming 2048 data blocks are contiguous (one extent in inode)

$= 4096$ blocks (4MB files data) $+ 6$ (small files) $+ 3$ (directory entries) $=$ 4105 blocks

redo logging problems

doesn't the log get infinitely big?

writing everything twice?

redo logging problems

doesn't the log get infinitely big?

writing everything twice?

limiting log size

once transaction is written to real data, can discard

sometimes called "garbage collecting" the log

may sometimes need to block to free up log space

- perform logged updates before adding more to log

hope: usually log cleanup happens "in the background"

redo logging problems

doesn't the log get infinitely big?

writing everything twice?

lots of writing?

entire log can be written sequentially

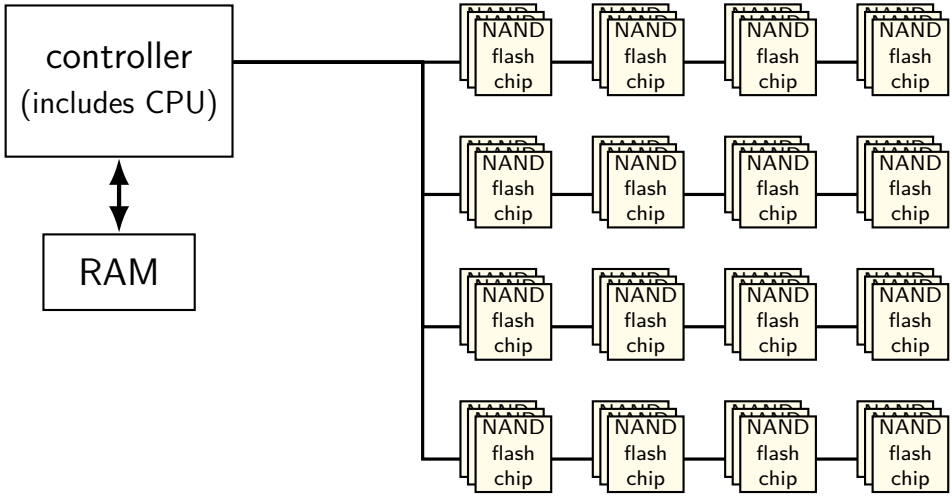
- ideal for hard disk performance
- also pretty good for SSDs

no waiting for 'real' updates

- application can proceed while updates are happening
- files will be updated even if system crashes

often better for performance!

solid state disk architecture



flash

no moving parts

- no seek time, rotational latency

can read in sector-like sizes ("pages") (e.g. 4KB or 16KB)

write once between erasures

erasure only in large *erasure blocks* (often 256KB to megabytes!)

can only rewrite blocks order tens of thousands of times

- after that, flash starts failing

SSDs: flash as disk

SSDs: implement hard disk interface for NAND flash

- read/write sectors at a time
- sectors much smaller than erasure blocks
- sectors sometimes smaller than flash 'pages'
- read/write with use sector numbers, not addresses
- queue of read/writes

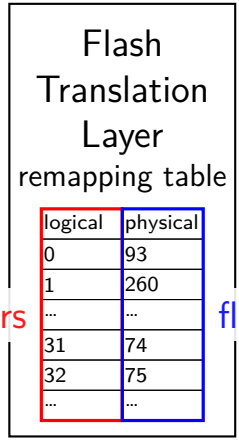
need to hide erasure blocks

- trick: block remapping — move where sectors are in flash

need to hide limit on number of erases

- trick: wear levening — spread writes out

block remapping



OS sector numbers

flash locations

block remapping

Flash Translation Layer

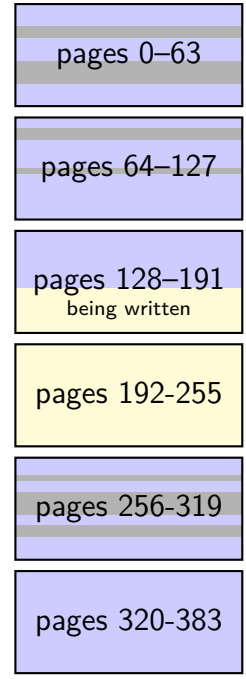
remapping table

logical	physical
0	93
1	260
...	...
31	74
32	75
...	...

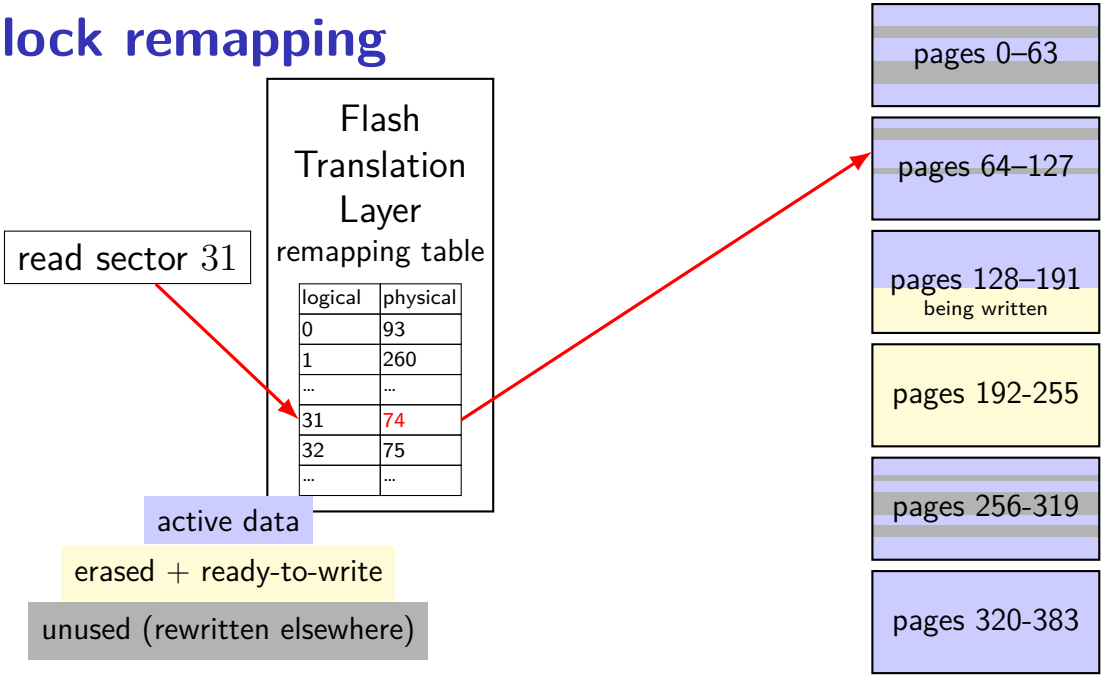
active data

erased + ready-to-write

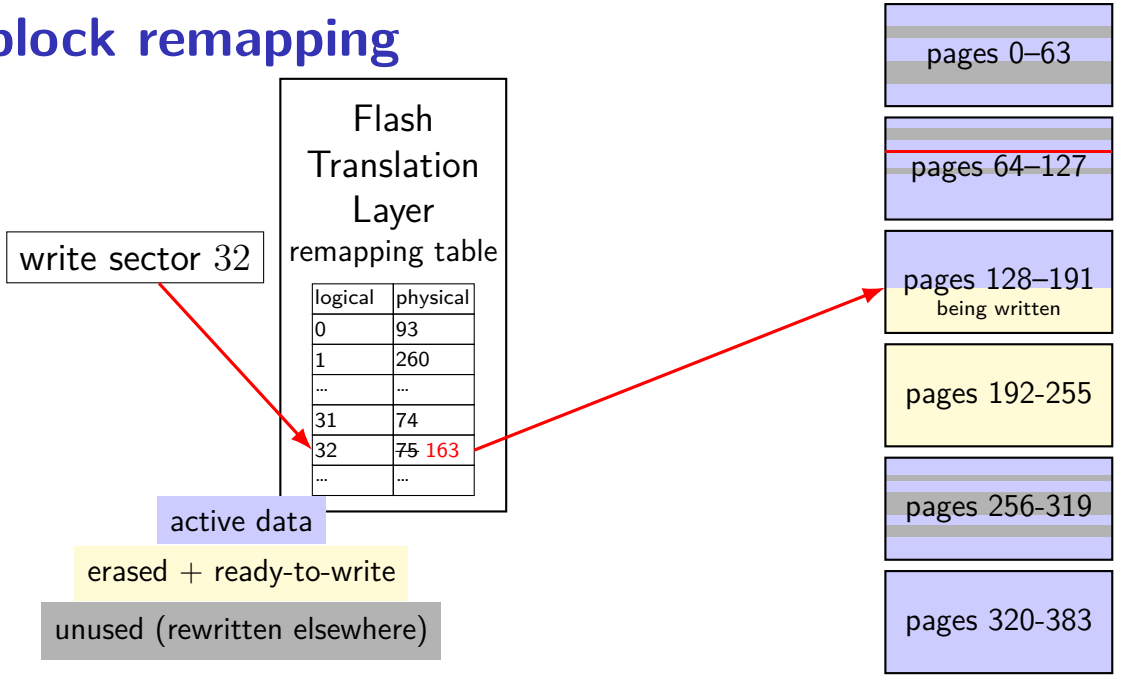
unused (rewritten elsewhere)



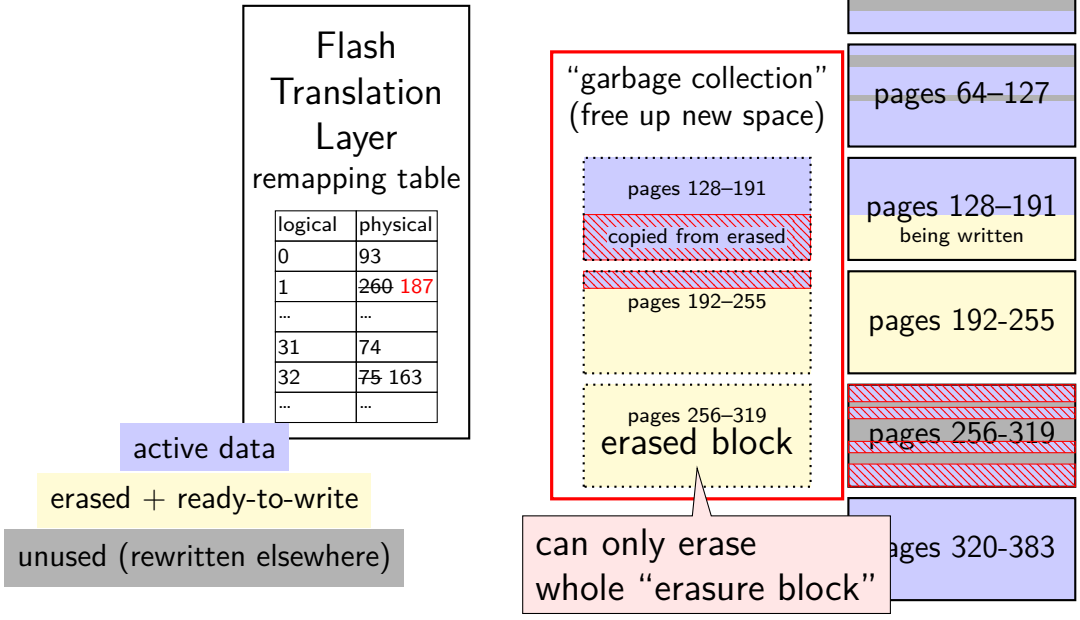
block remapping



block remapping



block remapping



block remapping

controller contains mapping: sector $\rightarrow$ location in flash

on write: write sector to *new location*

eventually do *garbage collection* of sectors

> if erasure block contains some replaced sectors and some current sectors...
> copy current blocks to new locationt to reclaim space from replaced sectors

doing this efficiently is very complicated

SSDs sometimes have a 'real' processor for this purpose

exercise

Assuming a FAT-like filesystem on an SSD, which of the following are likely to be stored in the same (or very small number of) erasure block?

[a] the clusters of a set of log file all in one directory written continuously over months by a server and assigned a contiguous range of cluster numbers

[b] the data clusters of a set of images, copied all at once from a camera and assigned a variety of cluster numbers

[c] all the entires of the FAT (assume the OS only rewrites a sector of the FAT if it is changed)

SSD performance

reads/writes: sub-millisecond

contiguous blocks don't really matter

can depend a lot on the controller

- faster/slower ways to handle block remapping

writing can be slower, especially when almost full

- controller may need to move data around to free up erasure blocks
- erasing an erasure block is pretty slow (milliseconds?)

extra SSD operations

SSDs sometimes implement non-HDD operations

on operation: TRIM

way for OS to mark sectors as unused/erase them

SSD can remove sectors from block map

- more efficient than zeroing blocks
- frees up more space for writing new blocks

aside: future storage

emerging non-volatile memories...

slower than DRAM ("normal memory")

faster than SSDs

read/write interface like DRAM but persistent

capacities similar to/larger than DRAM

backup slides