ANNOUNCEMENTS

P4 graded: In Learn@UW by end of day

P5: Available - File systems

- Can work on both parts with project partner
- Fill out form BEFORE tomorrow (WED) morning for match
- Watch videos; discussion section
- Part a : file system checker NOT in xv6 code base

Read as we go along!

- Chapter 42

UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

Andrea C. Arpaci-Dusseau
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PERSISTENCE: CRASH CONSISTENCY

Questions answered in this lecture:

What benefits and complexities exist because of data **redundancy?**

What can go wrong if disk blocks are not updated consistently?

How can file system be **checked and fixed** after crash?

How can **journaling** be used to obtain **atomic updates**?

How can the **performance** of journaling be improved?

DATA REDUNDANCY

Definition:
if *A* and *B* are two pieces of data,
and knowing *A* eliminates some or all values *B* could be,
there is redundancy between *A* and *B*

RAID examples:

- mirrored disk (complete redundancy)
- parity blocks (partial redundancy)

File system examples:

- **Superblock**: field contains total blocks in FS
- **Inodes**: field contains pointer to data block
- Is there redundancy across these two fields?
  Why or why not?

FILE SYSTEM REDUNDANCY EXAMPLE

Superblock: field contains total number of blocks in FS

DATA = N

Inode: field contains pointer to data block; possible DATA?

DATA in {0, 1, 2, …, N - 1}

Pointers to block N or after are invalid!

Total-blocks field has redundancy with inode pointers

QUESTION FOR YOU…

Give 5 examples of redundancy in FFS (or file systems in general)

- Dir entries AND inode table
- Dir entries AND inode link count
- Data bitmap AND inode pointers
- Data bitmap AND group descriptor
- Inode file size AND inode/indirect pointers

…

PROS AND CONS OF REDUNDANCY

Redundancy may improve:

- reliability
  - RAID-5 parity
  - Superblocks in FFS
- performance
  - RAID-1 mirroring (reads)
  - FFS group descriptor
  - FFS bitmaps

Redundancy hurts:

- capacity
- consistency
  - Redundancy implies certain combinations of values are illegal
  - Illegal combinations: inconsistency

CONSISTENCY EXAMPLES

Assumptions:

Superblock: field contains total blocks in FS.
DATA = 1024
Inode: field contains pointer to data block.
DATA in {0, 1, 2, …, 1023}

Scenario 1: Consistent or not?

Superblock: field contains total blocks in FS.
DATA = 1024
Inode: field contains pointer to data block.
DATA = 241
Consistent

Scenario 2: Consistent or not?

Superblock: field contains total blocks in FS.
DATA = 1024
node: field contains pointer to data block.
DATA = 2345
Inconsistent

WHY IS CONSISTENCY CHALLENGING?

File system may perform several disk writes to redundant blocks

If file system is interrupted between writes,
may leave data in inconsistent state

What can interrupt write operations?

- power loss

- kernel panic

- reboot

System (file system and disk) can even REORDER some writes for better performance

append to /foo/bar

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

QUESTION FOR YOU…

File system is appending to a file and must update 3 blocks:

- inode
- data bitmap
- data block

What happens if crash after only updating some blocks?

a) **bitmap**: lost block

b) **data**: nothing bad

c) **inode**: point to garbage (what?), **another file may use**

d) **bitmap** and **data**: lost block

e) **bitmap** and **inode**: point to garbage

f) **data** and **inode**: **another file may use same data block**

How can file system fix inconsistencies?

Solution #1:

FSCK = file system checker

Strategy:

After crash, scan whole disk for contradictions and "fix" if needed

Keep file system off-line until FSCK completes

For example, how to tell if data bitmap block is consistent?

Read every valid inode+indirect block
If pointer to data block, the corresponding bit should be 1; else bit is 0

FSCK checks

Hundreds of types of checks over different fields…

Do superblocks match?

Do directories contain "." and ".."?

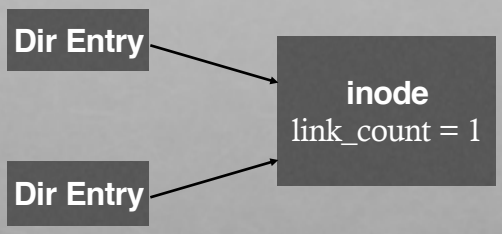
Do number of dir entries equal **inode link counts**?

Do different inodes ever point to **same block**?

…

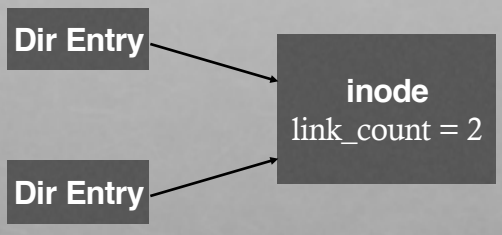
How to repair problems? Look at last two checks…

LINK COUNT (EXAMPLE 1)



How to fix to have consistent file system?

LINK COUNT (EXAMPLE 1)



Simple fix!

LINK COUNT (EXAMPLE 2)

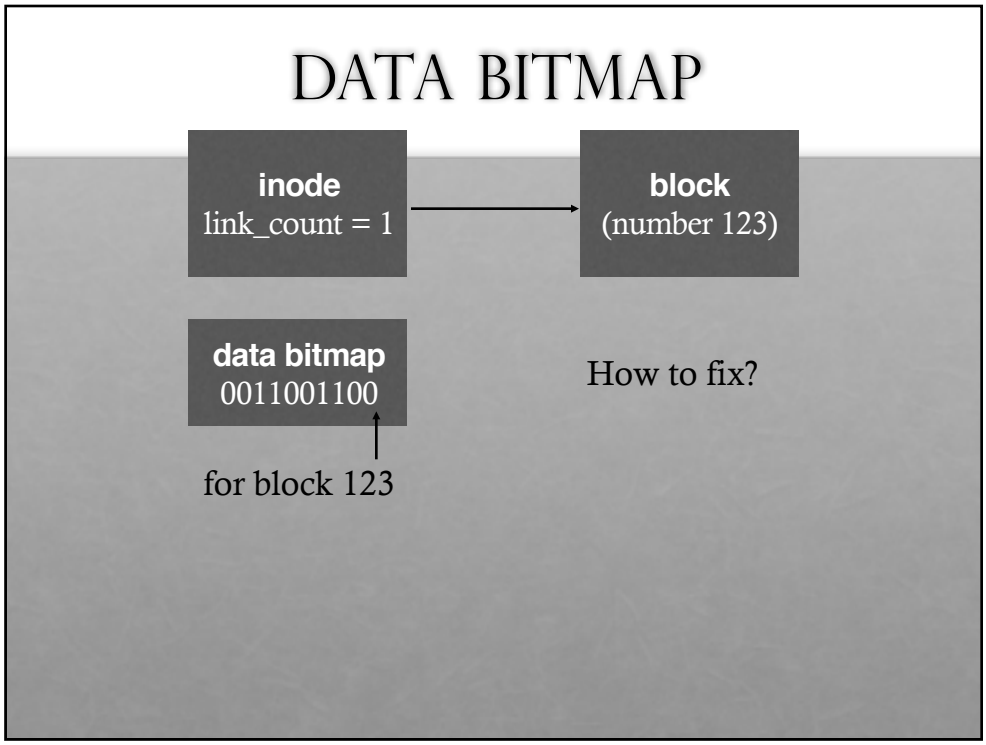
inode
link_count = 1

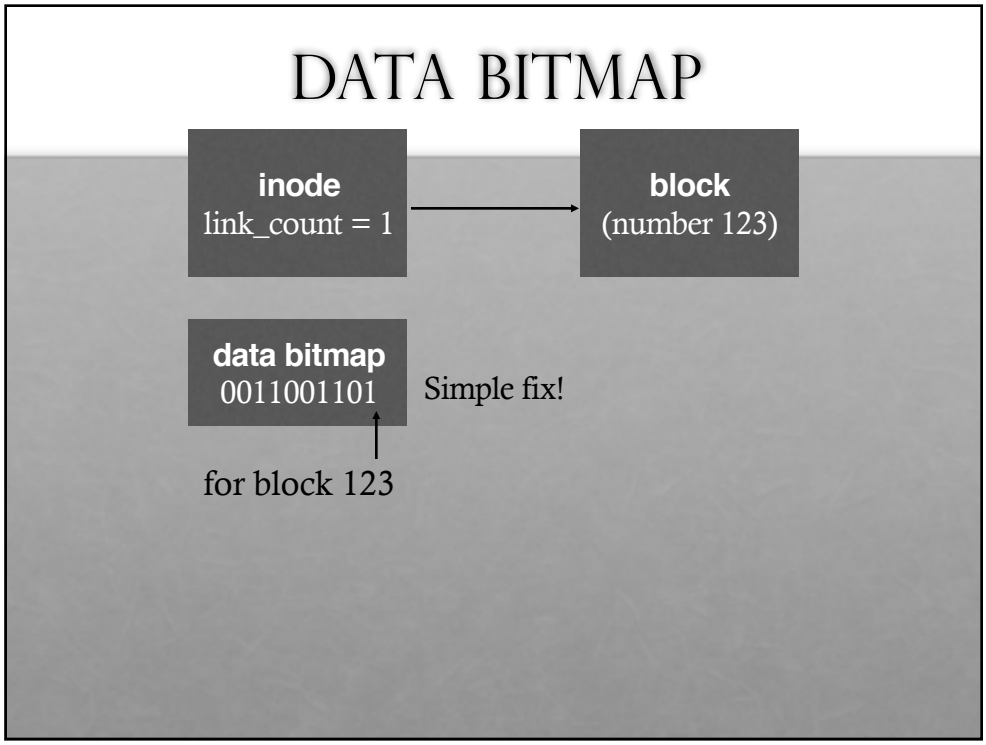
How to fix???

LINK COUNT (EXAMPLE 2)

Dir Entry → fix! → **inode** link_count = 1

```
ls -l /
total 150
drwxr-xr-x  401 18432 Dec 31  1969 afs/
drwxr-xr-x.   2 4096  Nov  3 09:42 bin/
drwxr-xr-x.   5 4096  Aug  1 14:21 boot/
dr-xr-xr-x.  13 4096  Nov  3 09:41 lib/
dr-xr-xr-x.  10 12288 Nov  3 09:41 lib64/
drwx------.   2 16384 Aug  1 10:57 lost+found/
...
```


DATA BITMAP
inode
link_count = 1
block
(number 123)
data bitmap
0011001100
How to fix?
for block 123


DATA BITMAP
inode
link_count = 1
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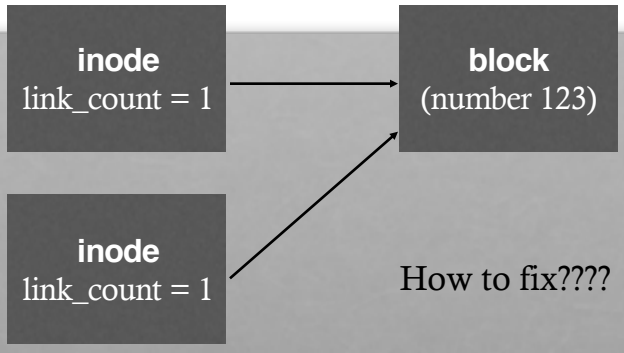
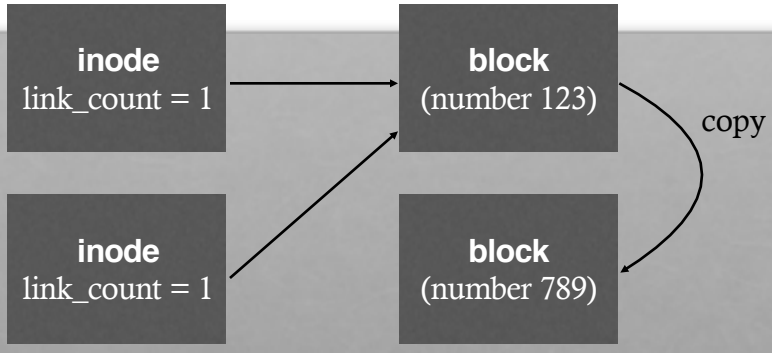
0011001101
Simple fix!
for block 123

DUPLICATE POINTERS

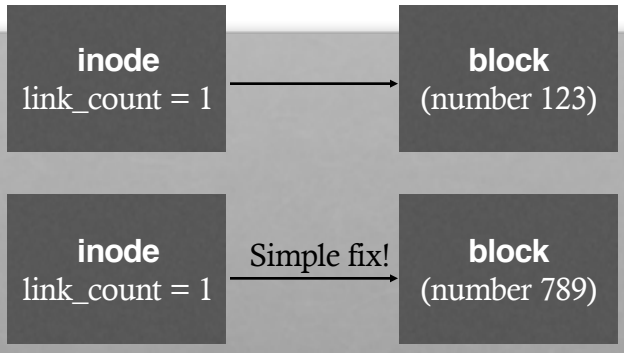


How to fix????

DUPLICATE POINTERS

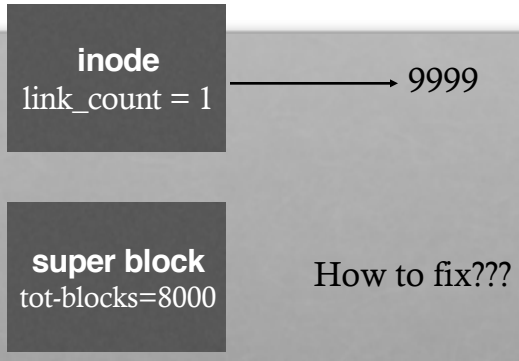


DUPLICATE POINTERS



But is this correct?

BAD POINTER



How to fix???

BAD POINTER

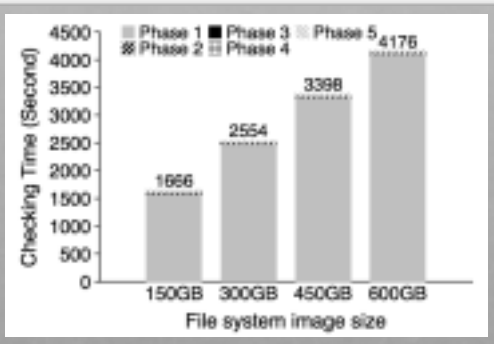
Remove pointer to non-existent data
Simple fix! (But is this correct?)

PROBLEMS WITH FSCK

Problem 1:

- Not always obvious how to fix file system image
- Don't know "correct" state, just consistent one
- Easy way to get consistency: reformat disk!

PROBLEM 2: FSCK IS VERY SLOW



Checking a 600GB disk takes ~70 minutes

ffsck: The Fast File System Checker

Ao Ma, EMC Corporation and University of Wisconsin—Madison; Chris Dragga, Andrea C. Arpaci-Dusseau, and Remzi H. Arpaci-Dusseau, University of Wisconsin—Madison

CONSISTENCY SOLUTION #2: JOURNALING

Goals

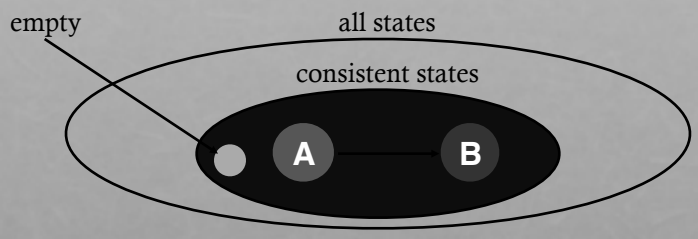
- Do some **recovery work** after crash, but don't read entire disk
- Don't move fs to just any consistent state, get **correct** state

Strategy: Atomicity

- Definition of atomicity for **concurrency**
  - operations in critical sections are not interrupted by operations on related critical sections
- Definition of atomicity for **persistence**
  - collections of writes are not interrupted by crashes; either (all new) or (all old) data is visible

CONSISTENCY VS CORRECTNESS

Say a set of writes moves the disk from state A to B



fsck just gives consistency
Atomicity gives A or B.

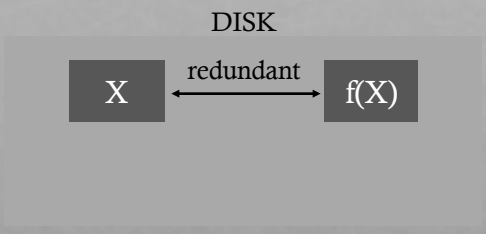
JOURNALING GENERAL STRATEGY

Never delete ANY old data, until ALL new data is safely on disk

Ironically, add redundancy to fix the problem caused by redundancy

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. Original:



FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. Original:

Good time to crash?
good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. Original:

DISK

Y f(X)

Good time to crash?
bad time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. Original:

DISK

Y f(Y)

Good time to crash?
good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. **With journal:**

DISK

X

f(X)

Good time to crash?

good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. With journal:

DISK

X

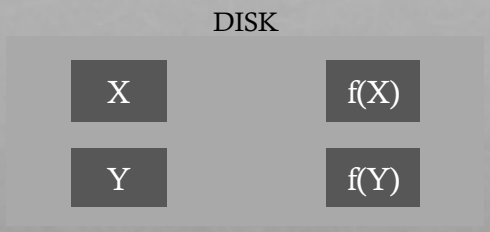
f(X)

Y

good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. With journal:



good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. With journal:

good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. With journal:

good time to crash

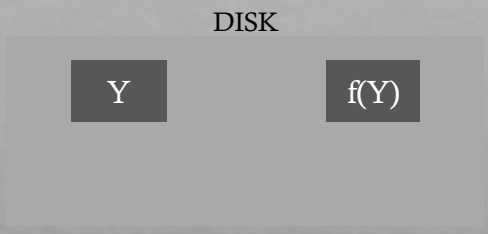
FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. With journal:

good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

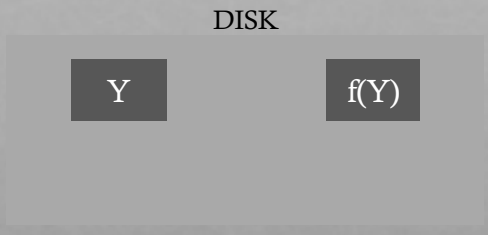
Want to replace X with Y. With journal:



good time to crash

FIGHT REDUNDANCY WITH REDUNDANCY

Want to replace X with Y. With journal:



With journaling, it's always a good time to crash!

Challenge after crash: what version to read?

BREAK

- What was the best thing you did over Thanksgiving Break?
- What was the best thing about this past semester for you?

QUESTION FOR YOU…

Develop algorithm to atomically update two blocks:
Write 10 to block 0; write 5 to block 1

Assume these are the only blocks in file system…

Time	Block 0	Block 1	extra	extra	extra	
1	12	3	0	0	0	
2	12	5	0	0	0	don't crash here!
3	10	5	0	0	0	

Usage Scenario: Block 0 stores Alice's bank account;
Block 1 stores Bob's bank account; transfer $2 from Alice to Bob

Wrong algorithm leads to inconsistent states
(non-atomic updates)

INITIAL SOLUTION: JOURNAL NEW DATA

Time	Block 0	Block 1	0'	1'	valid
1	12	3	0	0	0
2	12	3	10	0	0
3	12	3	10	5	0
4	12	3	10	5	1
5	10	3	10	5	1
6	10	5	10	5	1
7	10	5	10	5	0

Crash here?
→ Old data

Crash here?
→New data

Note: Understand behavior if crash after each write…

```
void update_accounts(int cash1, int cash2) {
        write(cash1 to block 2) // Alice backup
        write(cash2 to block 3) // Bob backup
        write(1 to block 4)     // backup is safe
        write(cash1 to block 0) // Alice
        write(cash2 to block 1) // Bob
        write(0 to block 4)     // discard backup
}

void recovery() {
        if(read(block 4) == 1) {
                write(read(block 2) to block 0) // restore Alice
                write(read(block 3) to block 1) // restore Bob
                write(0 to block 4)             // discard backup
        }
}
```

TERMINOLOGY

Extra blocks are called a "journal"

Writes to journal are "journal transaction"

Last valid bit written is "journal commit block"

PROBLEM WITH INITIAL APPROACH: JOURNAL SIZE

Disadvantages?

- slightly < half of disk space is usable
- transactions copy all the data (1/2 bandwidth!)

FIX #1: SMALL JOURNALS

Still need to first write all new data elsewhere before overwriting new data

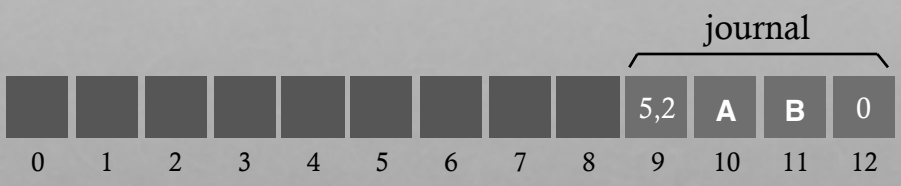
Goal:

- Reuse small area as backup for any block

How?

- Store block numbers in a transaction header

NEW LAYOUT



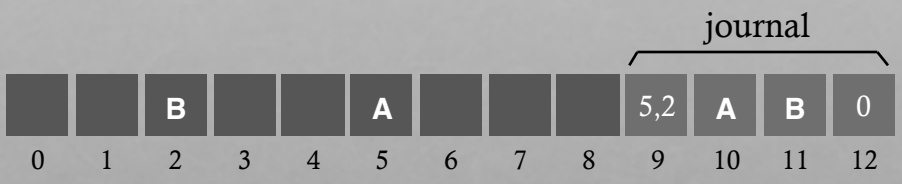
transaction: write A to block 5; write B to block 2

NEW LAYOUT

transaction: write A to block 5; write B to block 2

Checkpoint: Writing new data to in-place locations

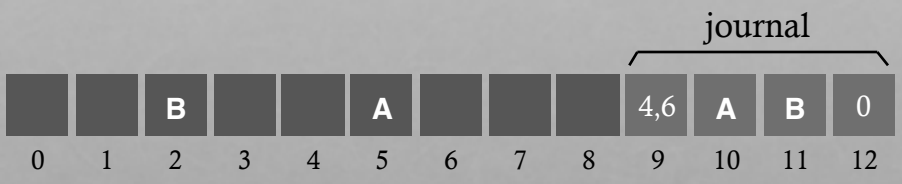
NEW LAYOUT



NEW LAYOUT

transaction: write C to block 4; write T to block 6

NEW LAYOUT

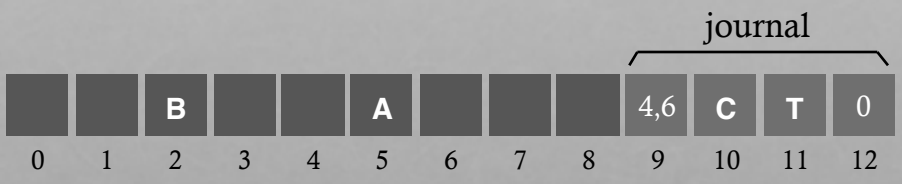


transaction: write C to block 4; write T to block 6

NEW LAYOUT

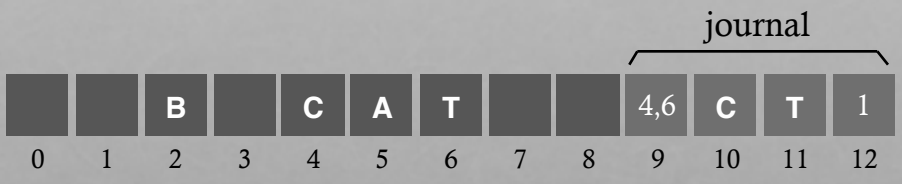
transaction: write C to block 4; write T to block 6

NEW LAYOUT



transaction: write C to block 4; write T to block 6

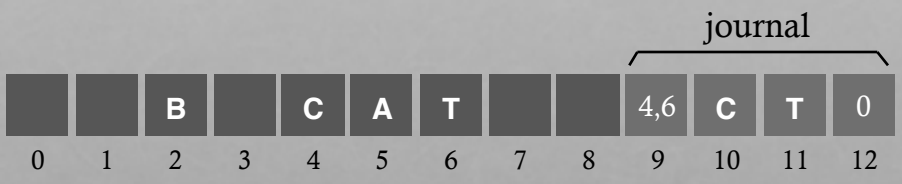
NEW LAYOUT



transaction: write C to block 4; write T to block 6

Checkpoint: Writing new data to in-place locations

NEW LAYOUT

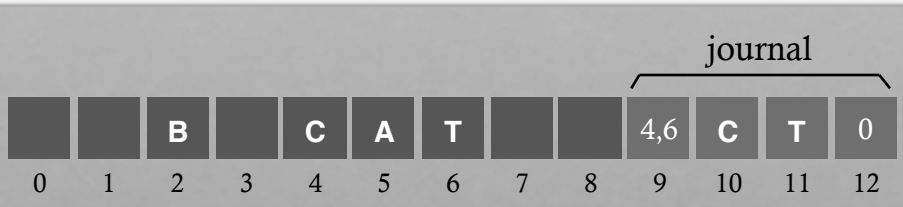


transaction: write C to block 4; write T to block 6

OPTIMIZATIONS

1. Reuse small area for journal
2. Barriers
3. Checksums
4. Circular journal
5. Logical journal

CORRECTNESS DEPENDS ON ORDERING



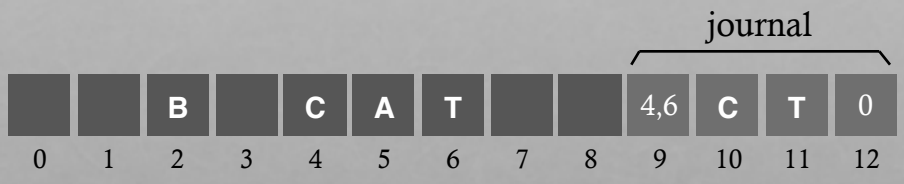
transaction: write C to block 4; write T to block 6

write order: 9, 10, 11, 12, 4, 6, 12

Enforcing total ordering is inefficient. Why?
Random writes

Instead: Use barriers w/ disk cache flush at key points (when??)

ORDERING



transaction: write C to block 4; write T to block 6

write order: 9,10,11 | 12 | 4,6 | 12

Use barriers at key points in time:
1) Before journal commit, ensure journal transaction entries complete
2) Before checkpoint, ensure journal commit complete
3) Before free journal, ensure in-place updates complete

OPTIMIZATIONS

1. Reuse small area for journal
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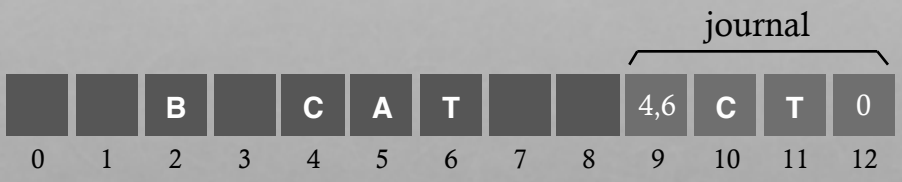
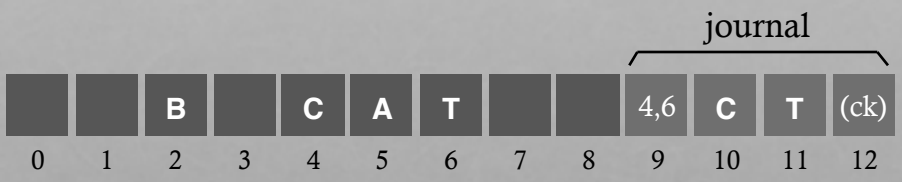
CHECKSUM OPTIMIZATION



write order: 9,10,11 | 12 | 4,6 | 12

How can we get rid of barrier between (9, 10, 11) and 12 ???

CHECKSUM OPTIMIZATION



write order: 9,10,11,12 | 4,6 | 12

In last transaction block, store checksum of rest of transaction
12 = Cksum(9, 10, 11)
During recovery:
If checksum does not match transaction, treat as not valid

OPTIMIZATIONS

1. Reuse small area for journal
2. Barriers
3. Checksums
4. Circular journal
5. Logical journal

WRITE BUFFERING OPTIMIZATION

Note: after journal write, there is no rush to checkpoint

- If system crashes, still have persistent copy of written data!

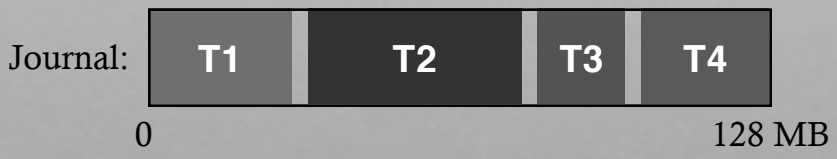
Journaling is sequential (fast!), checkpointing is random (slow!)

Solution? Delay checkpointing for some time

Difficulty: need to reuse journal space

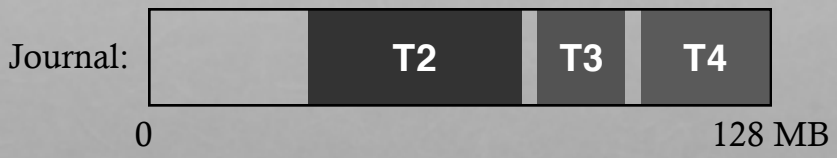
Solution: keep many transactions for un-checkpointed data

CIRCULAR BUFFER



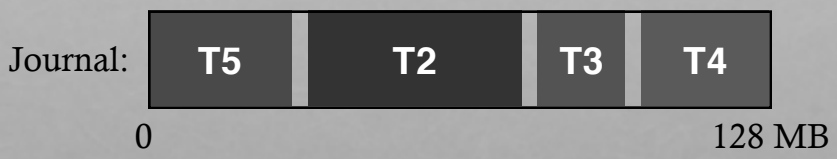
Keep data also in memory until checkpointed on disk

CIRCULAR BUFFER



checkpoint and cleanup

CIRCULAR BUFFER



transaction!

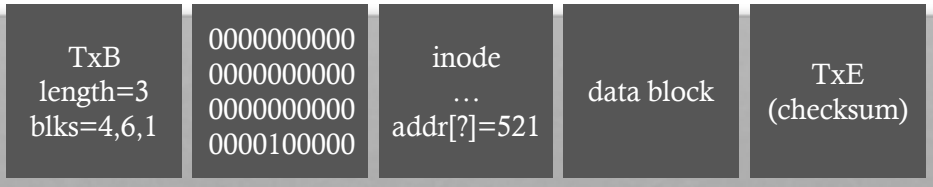
CIRCULAR BUFFER

checkpoint and cleanup

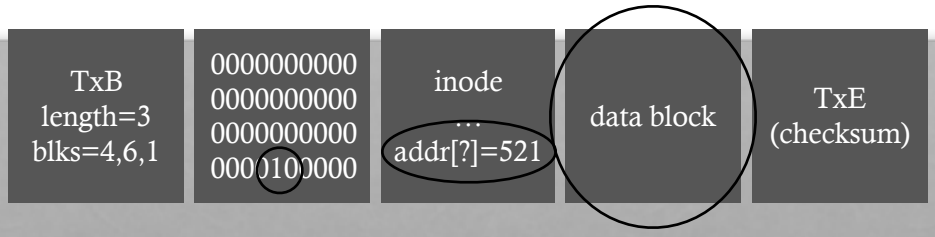
OPTIMIZATIONS

1. Reuse small area for journal
2. Barriers
3. Checksums
4. Circular journal
5. Logical journal

PHYSICAL JOURNAL



PHYSICAL JOURNAL



Actual changed data is much smaller!

LOGICAL JOURNAL

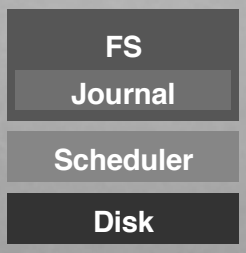
Logical journals record changes to bytes, not contents of new blocks

On recovery:
Need to read existing contents of in-place data and (re-)apply changes

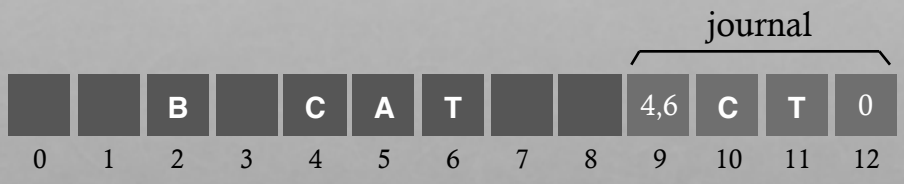
OPTIMIZATIONS

1. Reuse small area for journal
2. Barriers
3. Checksums
4. Circular journal
5. Logical journal

FILE SYSTEM INTEGRATION



REVIEW: ORDERING

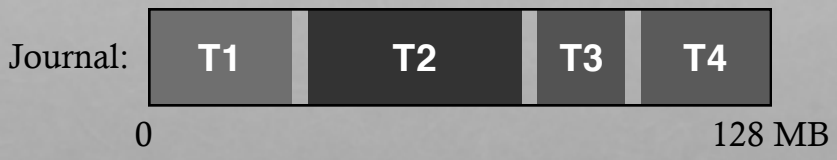


transaction: write C to block 4; write T to block 6

write order: 9,10,11 | 12 | 4,6 | 12

Use I/O **barriers** (wait for disk to complete write) at key points:
1) Before journal commit, ensure journal transaction entries complete
2) Before checkpoint, ensure journal commit completes
3) Before free journal, ensure in-place updates complete

REVIEW: CIRCULAR JOURNAL



Keep data also in memory until checkpointed on disk

HOW TO AVOID WRITING ALL DISK BLOCKS TWICE?

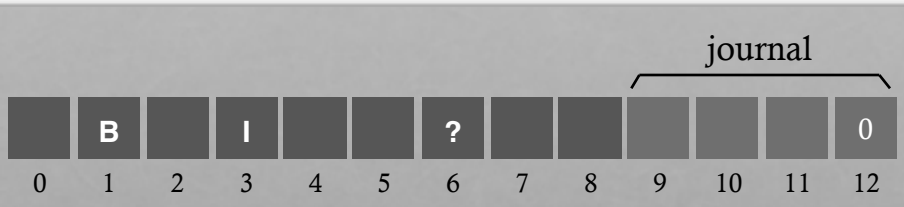
Observation:
Some disk blocks (e.g., user data) are less important

Strategy:

Journal only metadata, including:
superblock, bitmaps, inodes, indirect blocks, directories
- Guarantees metadata is consistent even if crash occurs
- Won't leak blocks or re-allocate blocks to multiple files

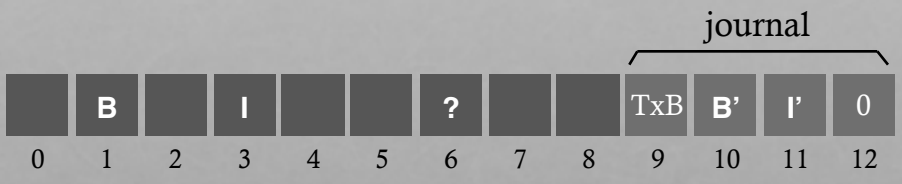
Regular data, write it to in-place locations whenever convenient
- Files may contain garbage if crash and recover

APPROACH 1: WRITEBACK JOURNAL



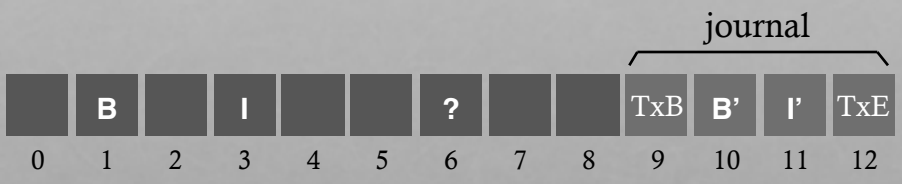
transaction: append data to file with inode I

WRITEBACK JOURNAL



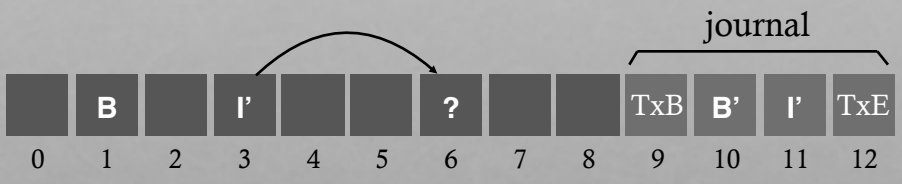
transaction: append data to file with inode I

WRITEBACK JOURNAL



transaction: append data to file with inode I

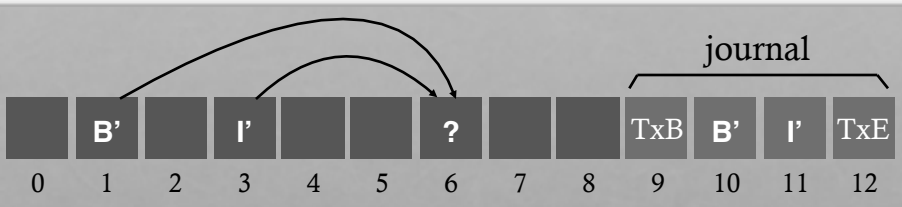
WRITEBACK JOURNAL



transaction: append data to file with inode I

Update in-place copy of I'

WRITEBACK JOURNAL



transaction: append data to file with inode I

Update in-place copy of B'

what if we crash now?
Solutions?

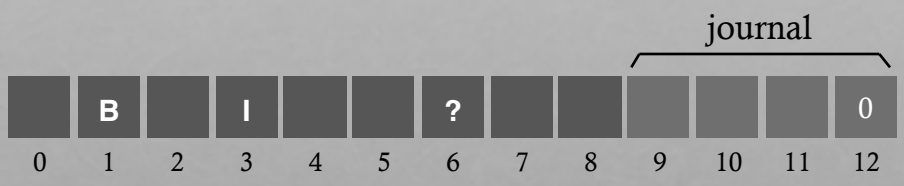
APPROACH 2: ORDERED JOURNALING

Still only journal metadata

But write data **before** the transaction

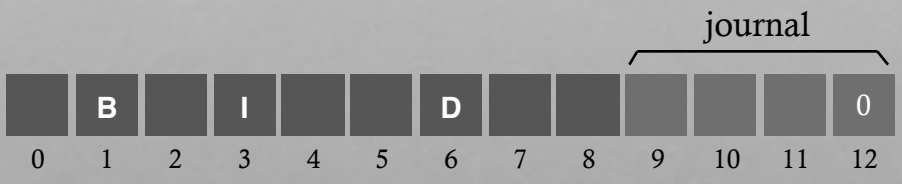
No leaks of sensitive data!

ORDERED JOURNAL



transaction: append to inode I

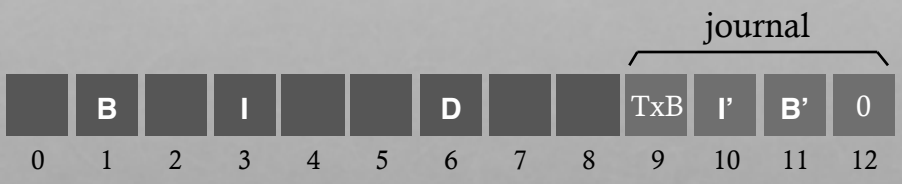
ORDERED JOURNAL



transaction: append to inode I

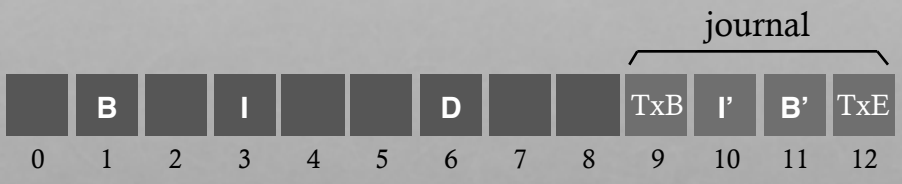
What happens if crash now?
B indicates D currently free, I does not point to D;
Lose D, but that might be acceptable

ORDERED JOURNAL



transaction: append to inode I

ORDERED JOURNAL

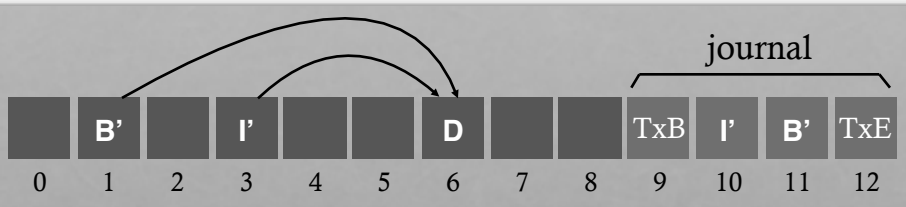


transaction: append to inode I

ORDERED JOURNAL

transaction: append to inode I

ORDERED JOURNAL



transaction: append to inode I

CONCLUSION

Most modern file systems use journals

- ordered-mode for meta-data is very popular (default mode)

FSCK is still useful for weird cases

- bit flips
- FS bugs

Some file systems don't use journals, but still (usually) write new data before deleting old (copy-on-write file systems)