Crash Consistency

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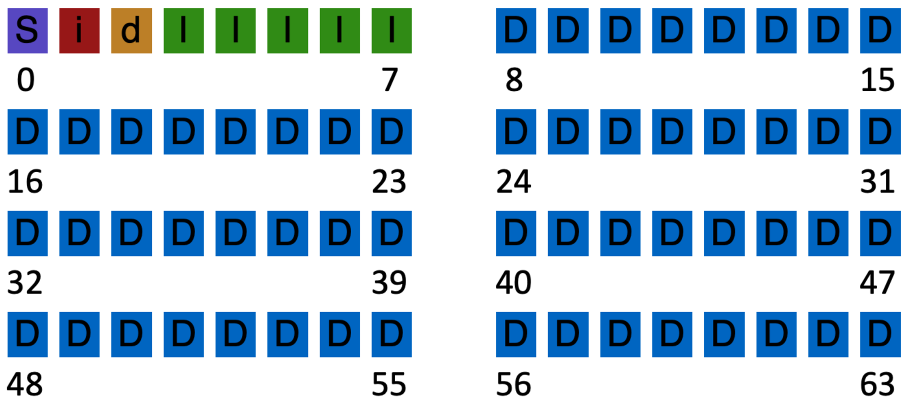


Inconsistency: a result of redundancy (non-independence)

Knowing A limits the possible values of B.

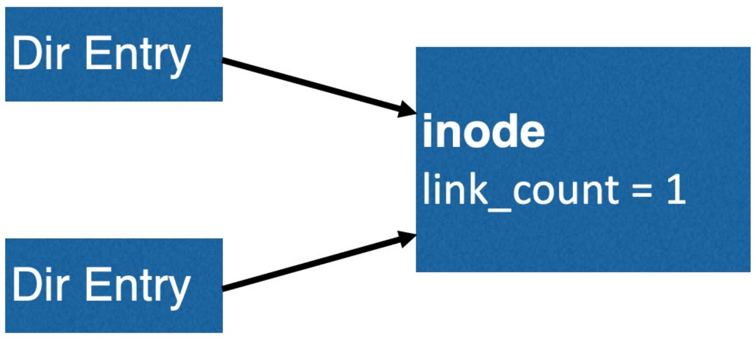
Inode pointer
Data block bitmap

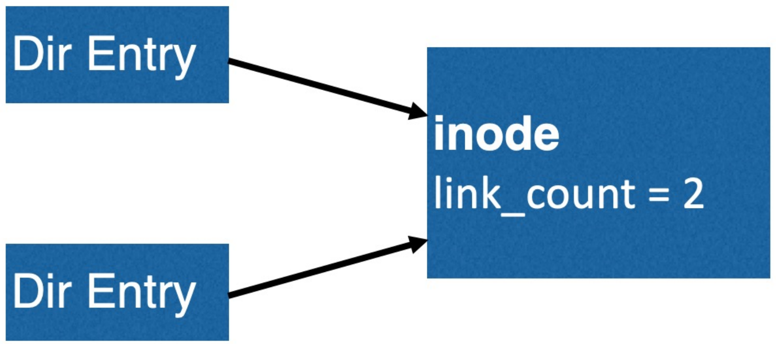
Inode link count
Directory entry

Superblock total block count
Inode pointer

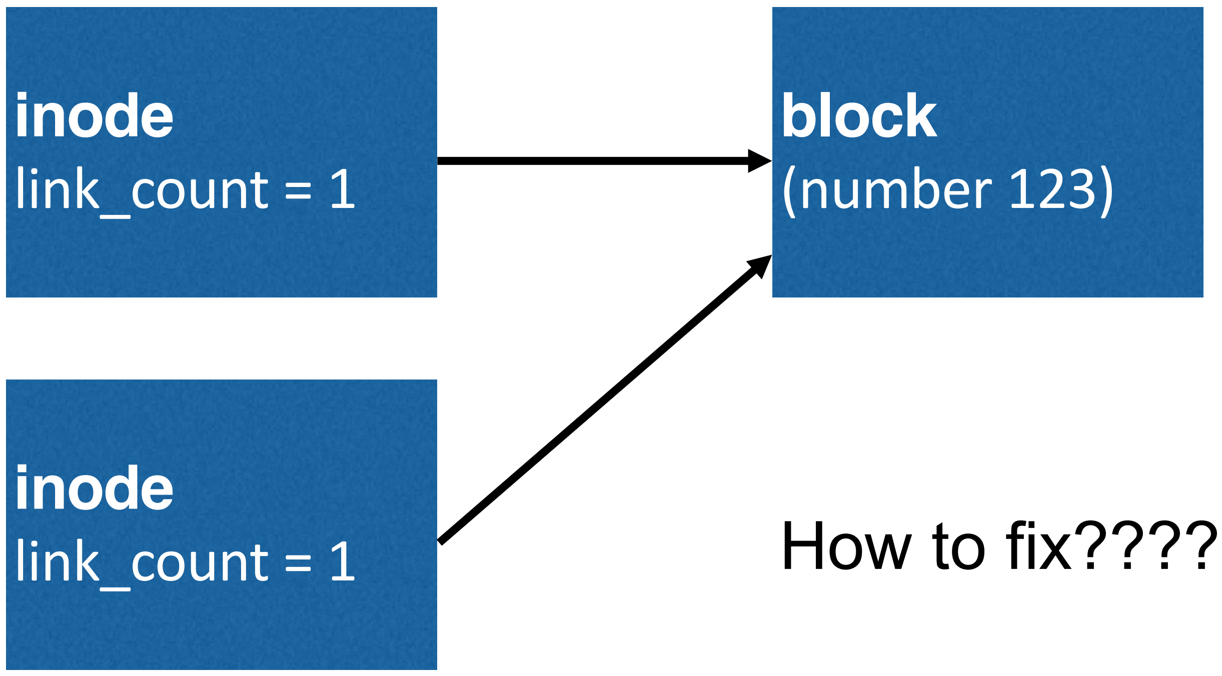
Filesystem checker: after a crash, look at data structures on disk, and make them consistent.

100s of checks & fixes



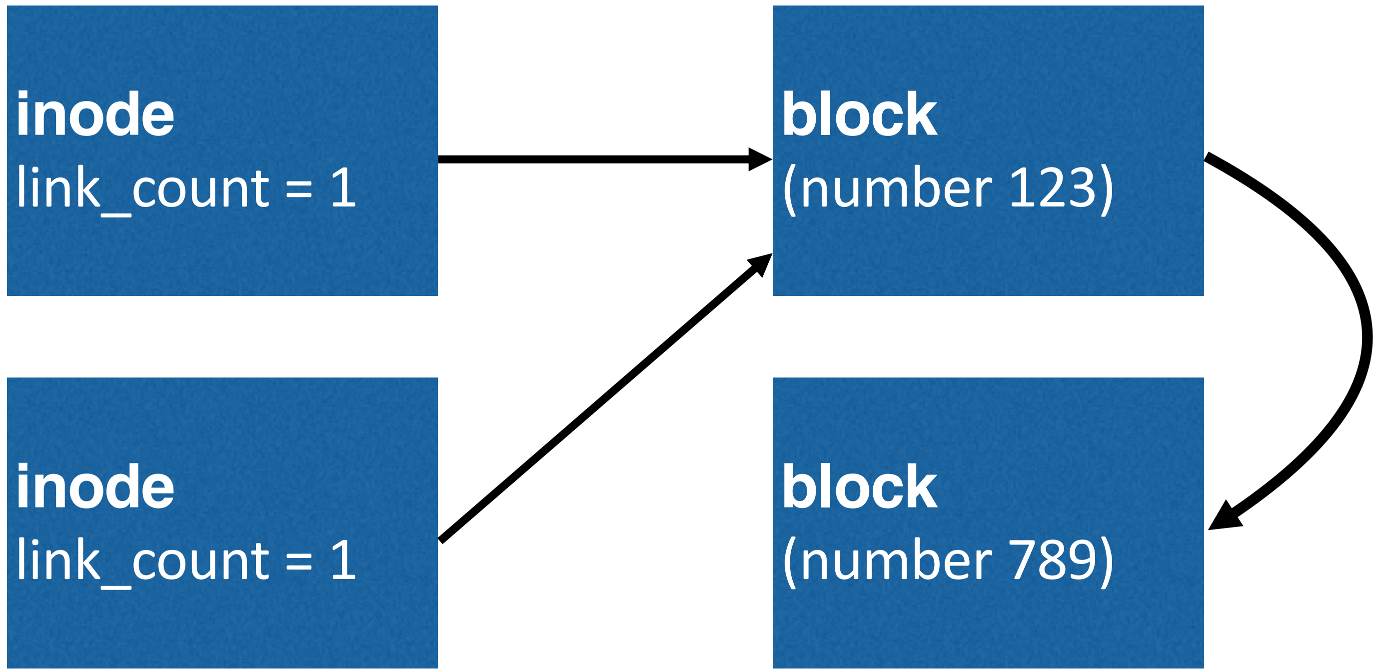


Duplicate Pointers



How to fix????

Duplicate Pointers



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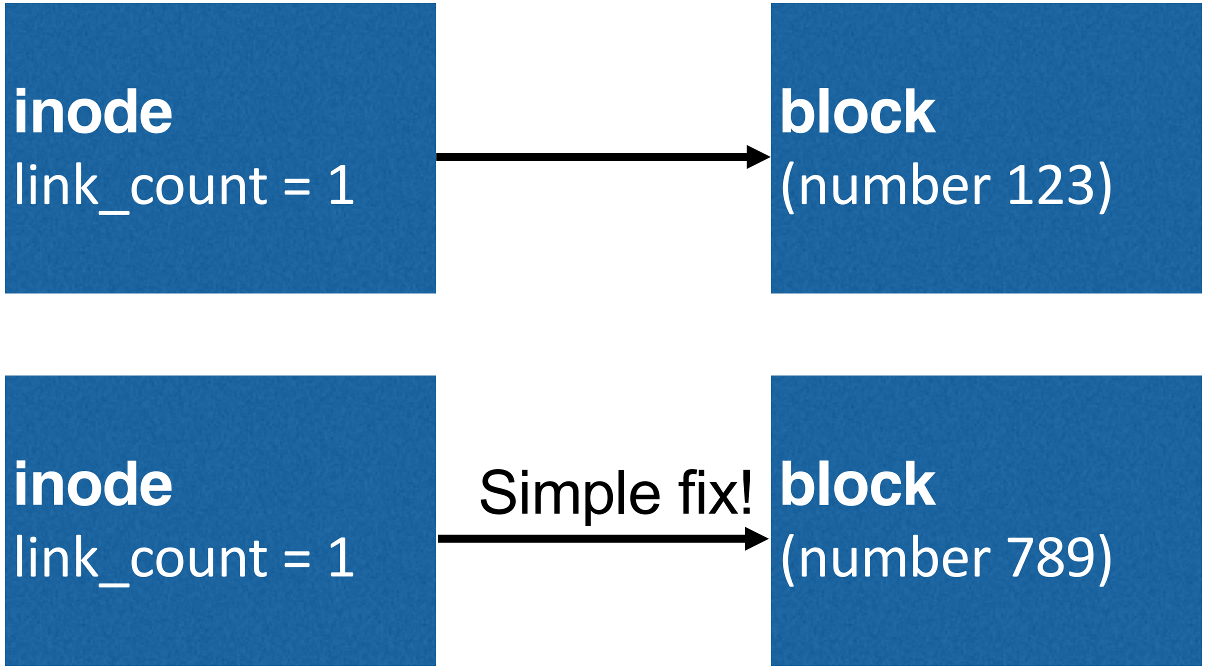
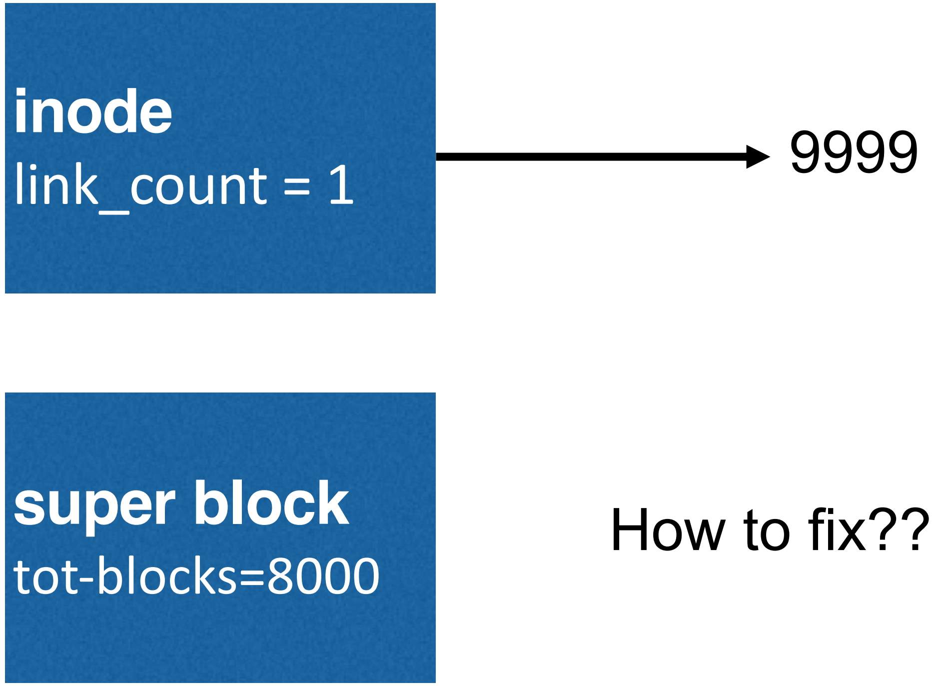


But is this correct?

Bad Pointer



How to fix???

Bad Pointer

inode
link_count = 1

Simple fix! (But is this correct?)

super block
tot-blocks=8000

Problems with fsck

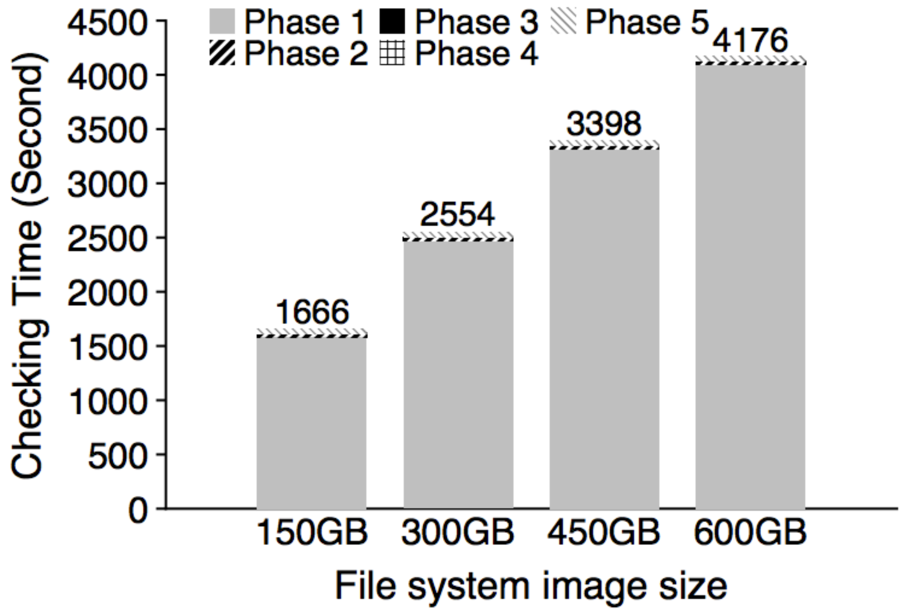
Problem 1:

- Not always obvious how to fix file system image

- Don’t know “correct” state, just a 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

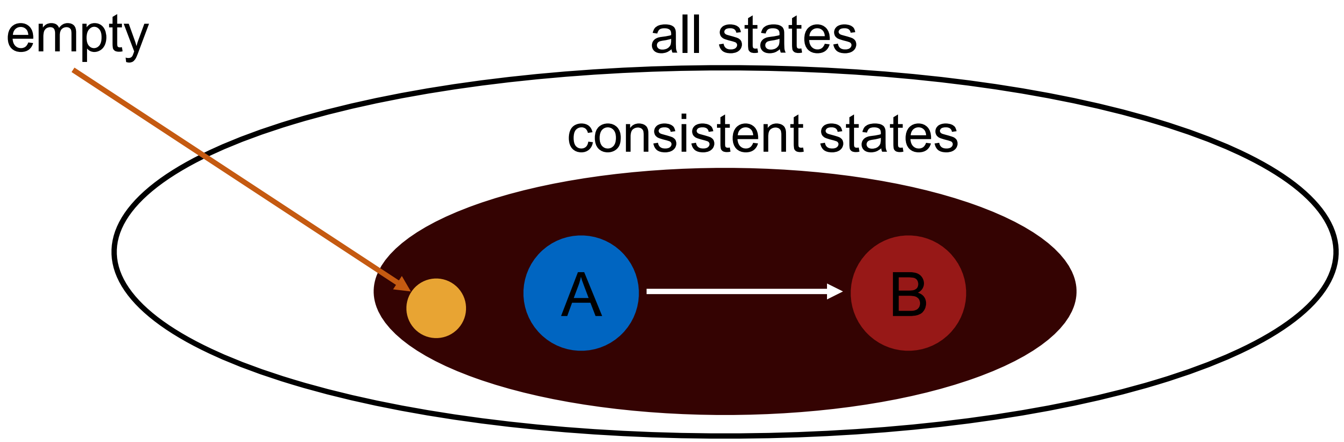
- Ok to do some **recovery work** after crash, but not to read entire disk
- Don't move file system to just any consistent state, get **correct** state (in most cases)

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 gives consistency
Atomicity gives A or B.

Journaling: General Strategy

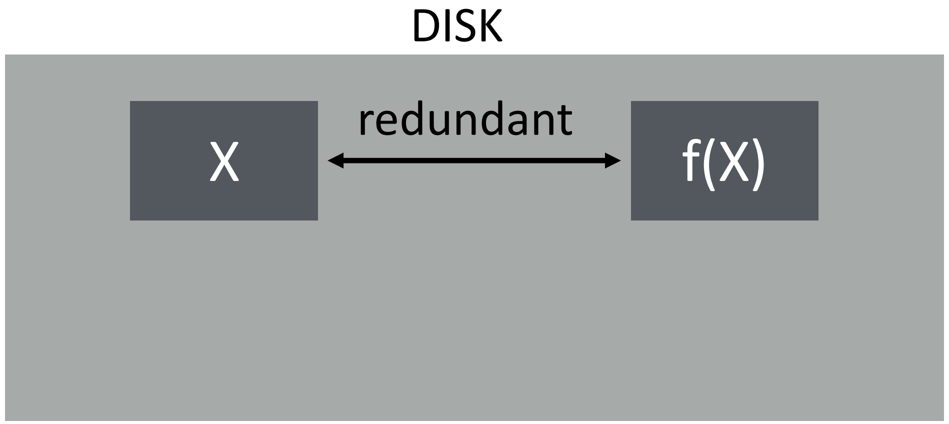
Never delete ANY old data, until, ALL new data is safely on disk

Ironically, adding redundancy to fix the problem caused by redundancy.

Do a little extra work during regular operation, to avoid A LOT OF extra work during recovery

Fight Redundancy with Redundancy

Want to replace X with Y. Original:



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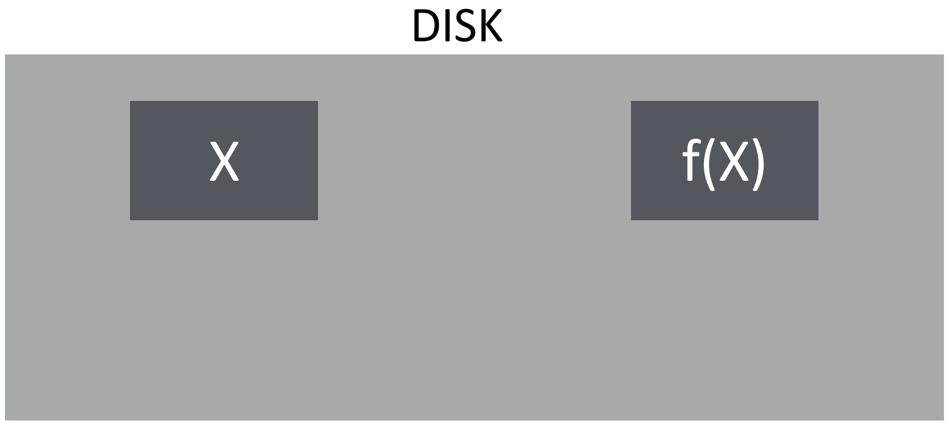

Good time to crash?

Yes, good time to crash

Fight Redundancy with Redundancy

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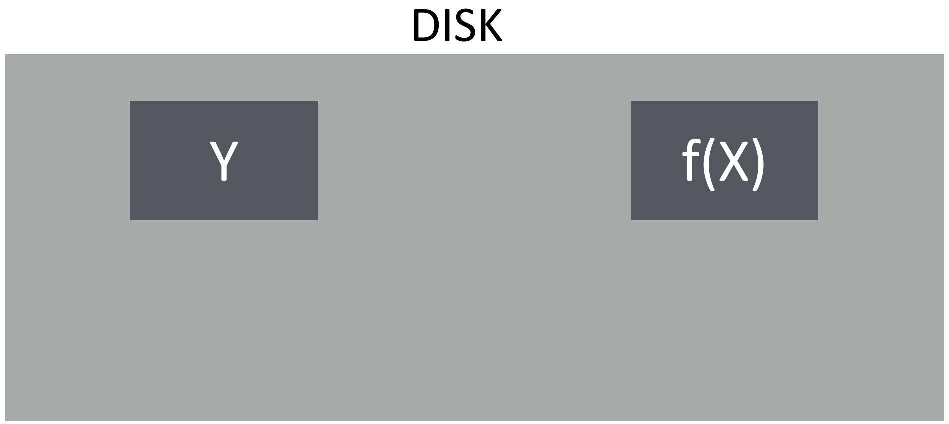
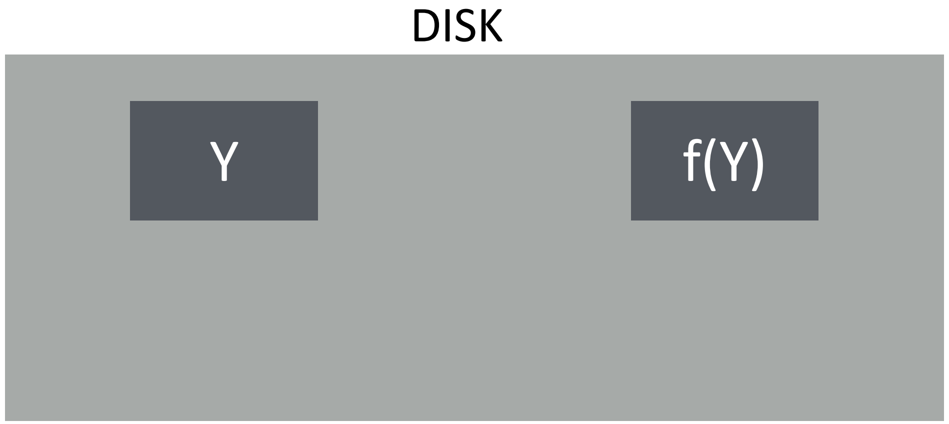


Good time to crash?

bad time to crash

Fight Redundancy with Redundancy

Want to replace X with Y. Original:

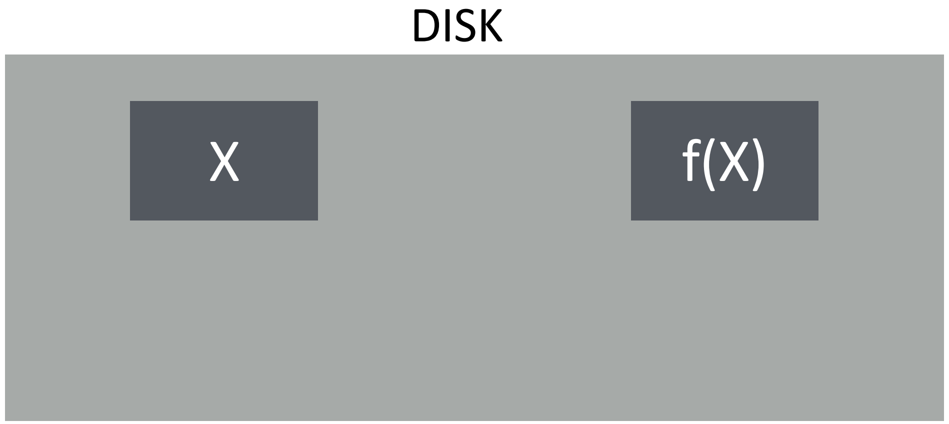


Good time to crash?

good time to crash

Fight Redundancy with Redundancy

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



Good time to crash?

good time to crash

Fight Redundancy with Redundancy

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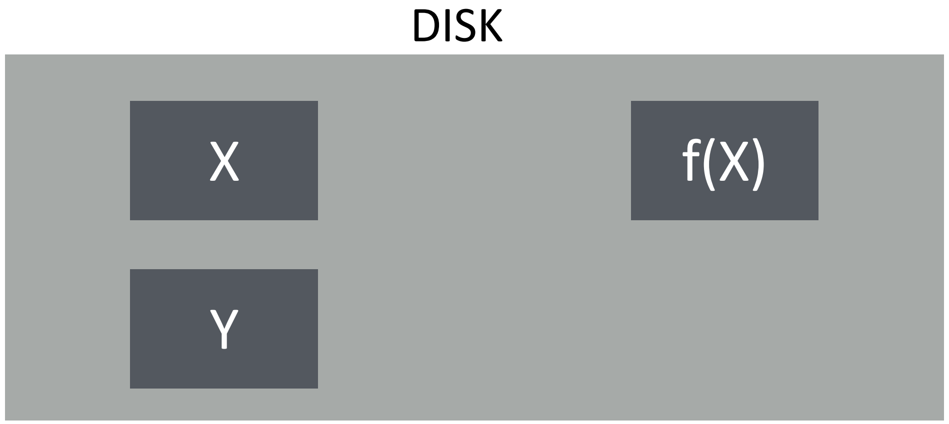

good time to crash

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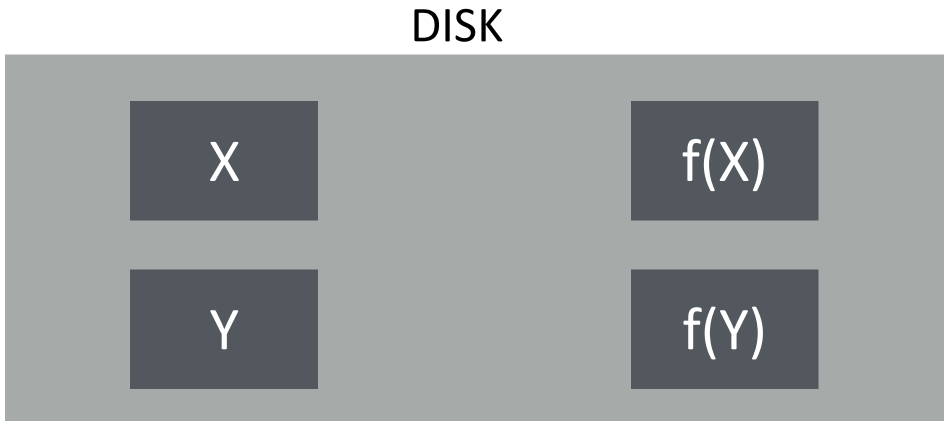

good time to crash

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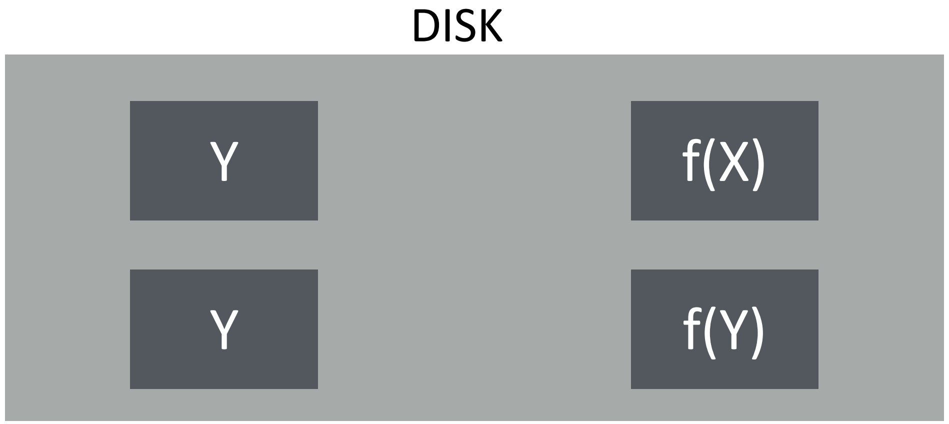

good time to crash

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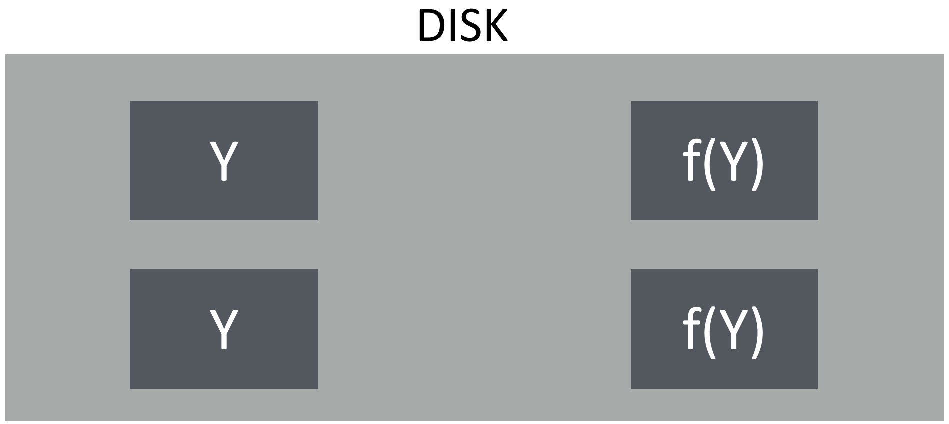

good time to crash

Fight Redundancy with Redundancy

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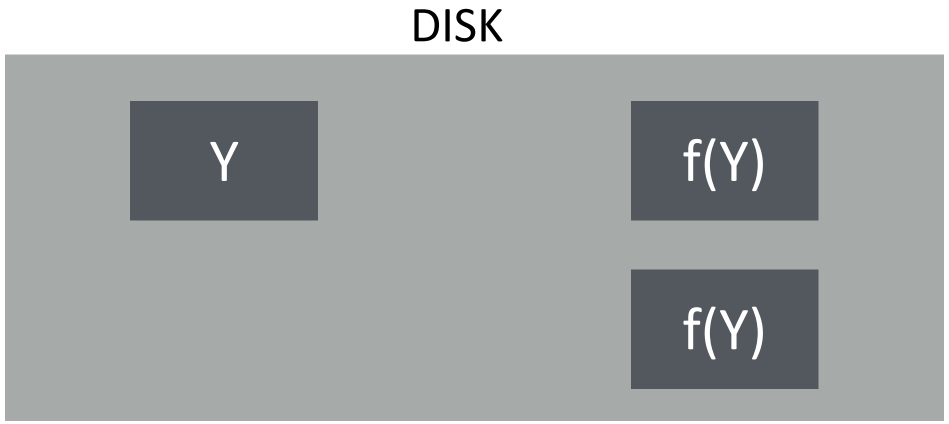

good time to crash

Fight Redundancy with Redundancy

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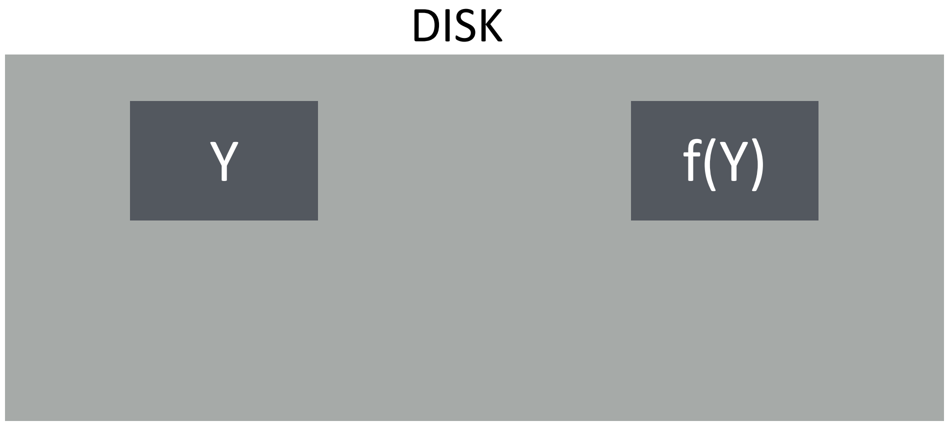

good time to crash

Fight Redundancy with Redundancy

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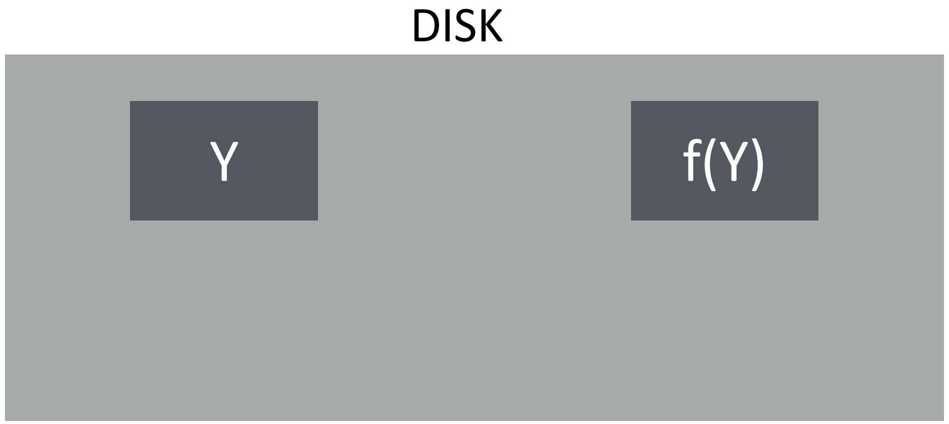


With journaling, it's always a good time to crash!

Inconsistency: how do we fix it?

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

Assume these are only blocks in file system.

Assume: only 1 block, not multiple, can be written in one shot

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

Time	**Block 0**	**Block 1**
1	12	3
2	12	5
3	10	5

don't crash here!

A wrong update algorithm can leads to inconsistent states
(non-atomic updates)

Initial Solution: Journal New Data

Suppose we make a copy of each block first

Time	Block 0	Block 1	J:2	J:3	J:valid:4
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

Let's understand behavior if crash occurs after each write

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

```
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

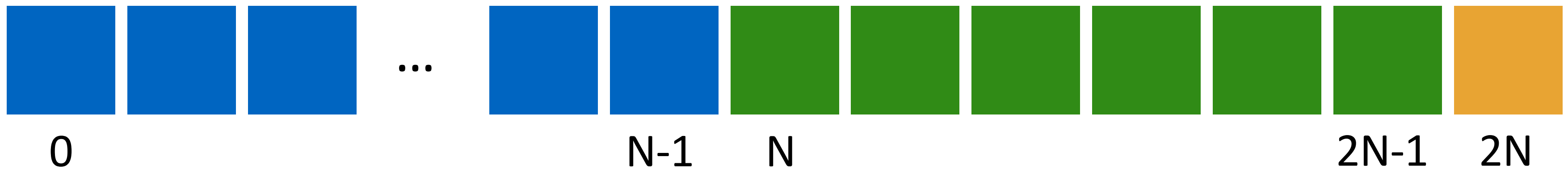
Extra blocks are called a journal

The writes to the journal are a journal transaction

The last valid bit written is a journal commit block

The actual writes of data is called checkpoint

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

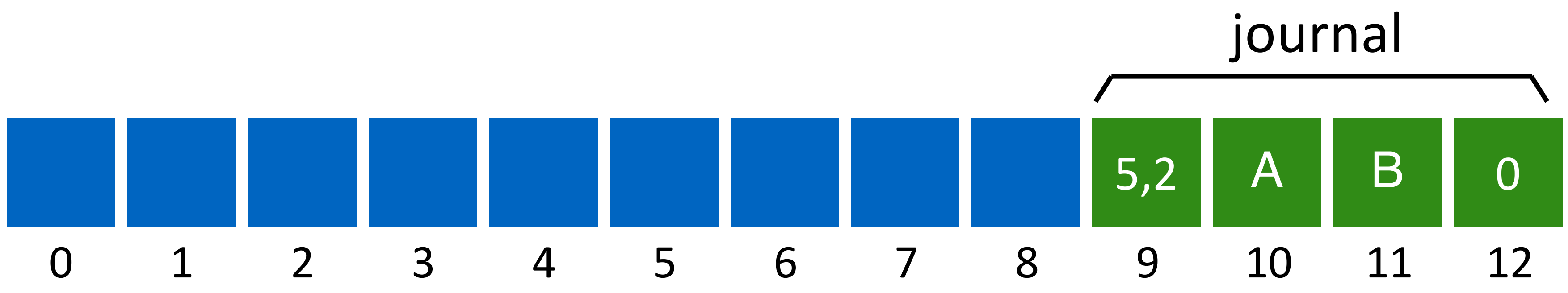
Goal:

- Reuse small area as backup for any block

How?

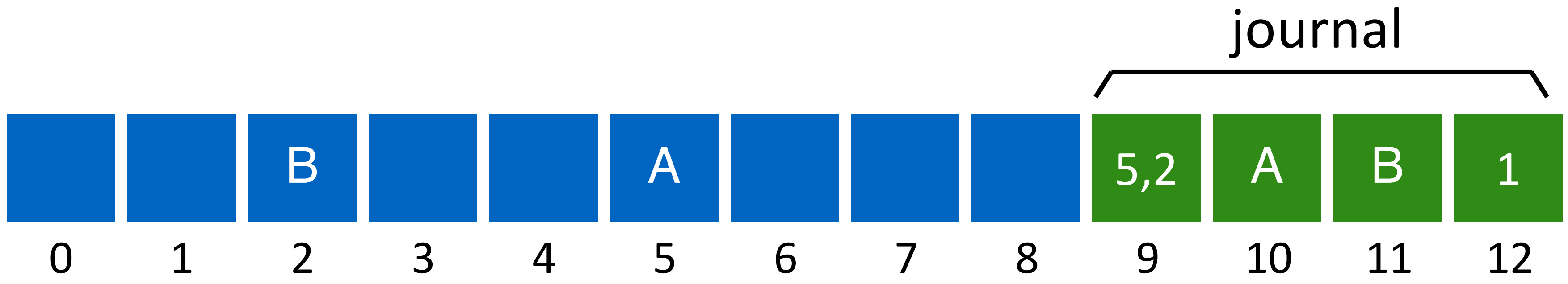
- Store block numbers in a transaction header

New Layout



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

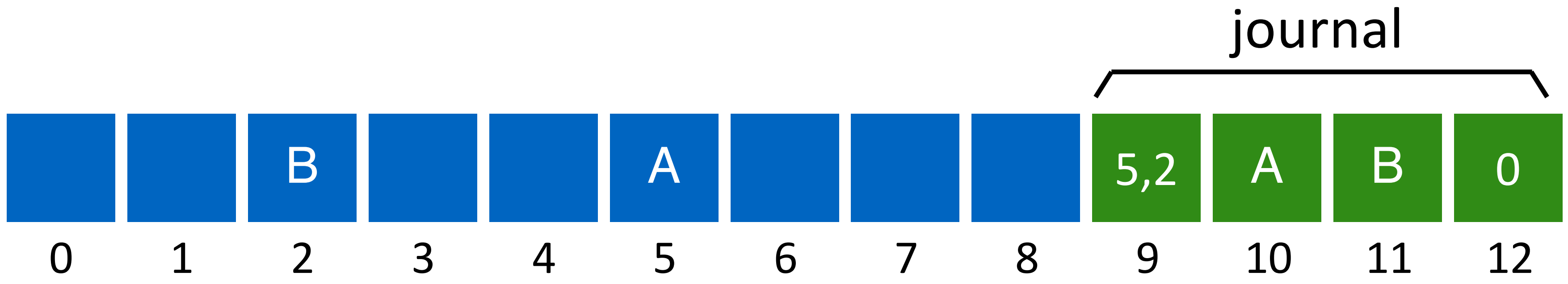
New Layout



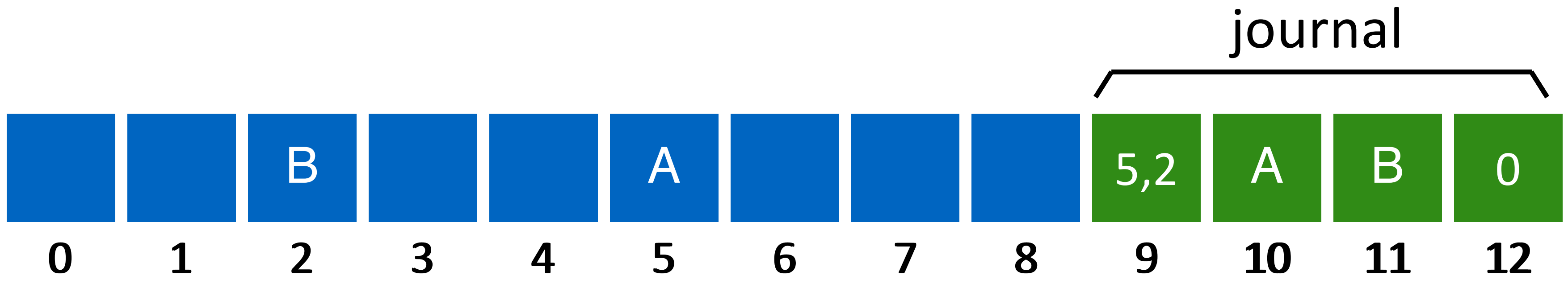
transaction: write A to block 5; write B to block 2

Checkpoint: Writing new data to in-place locations

New Layout

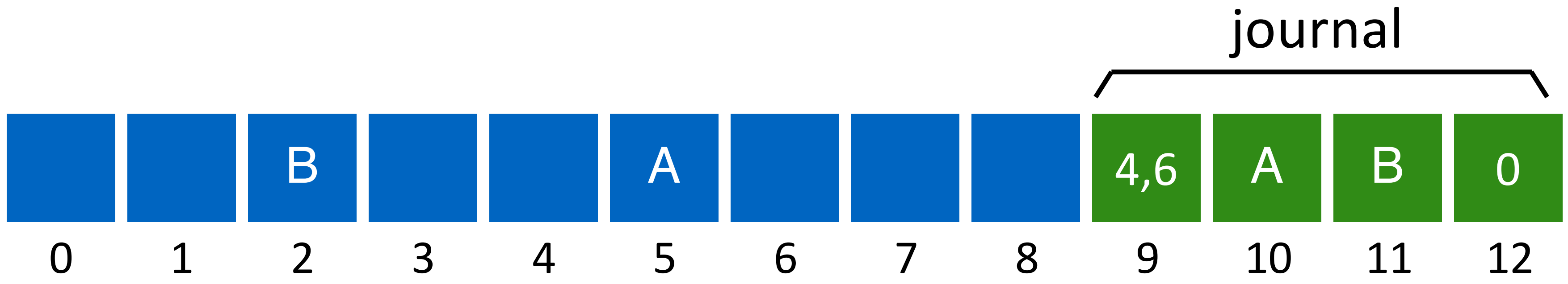


New Layout



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

New Layout



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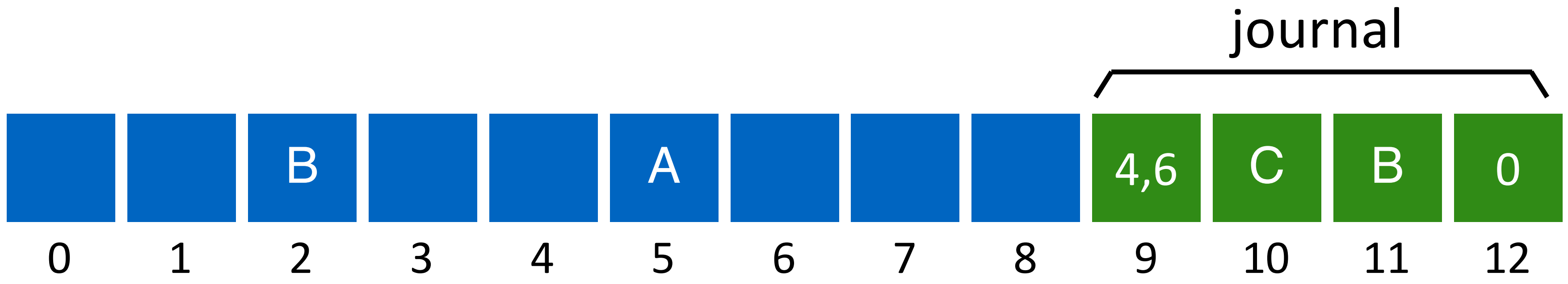

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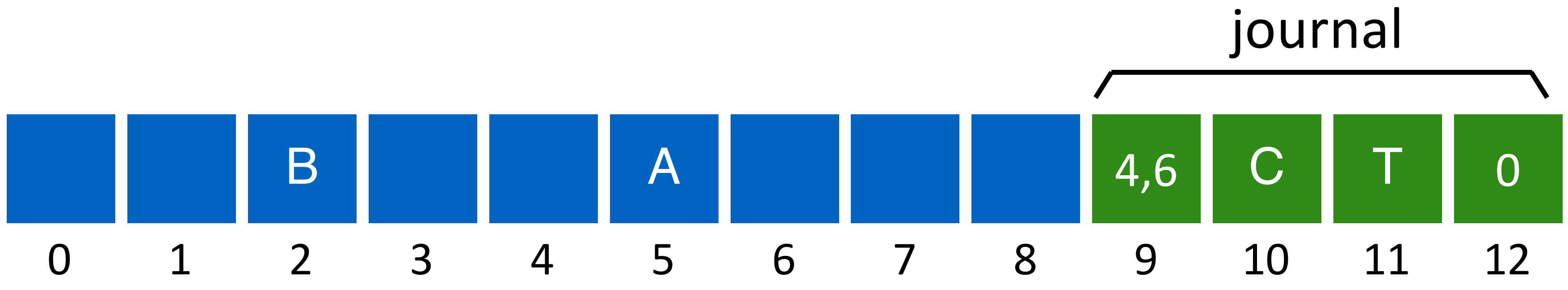

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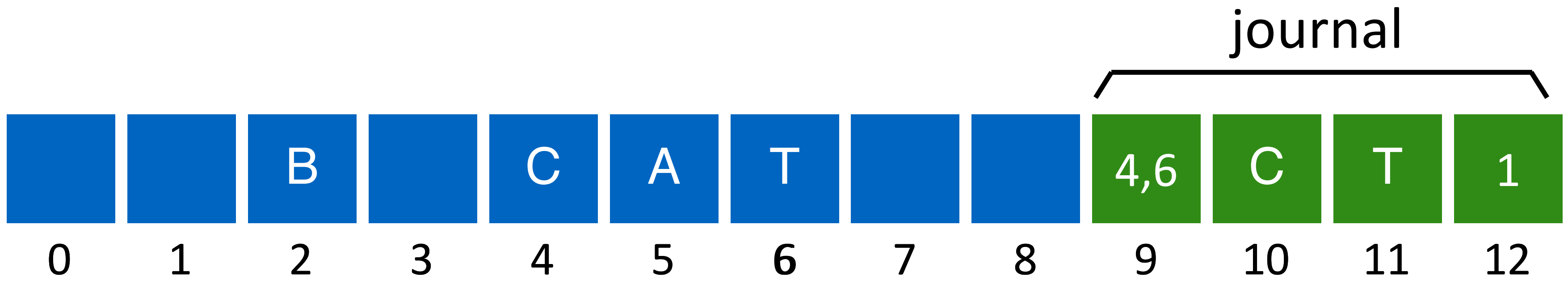

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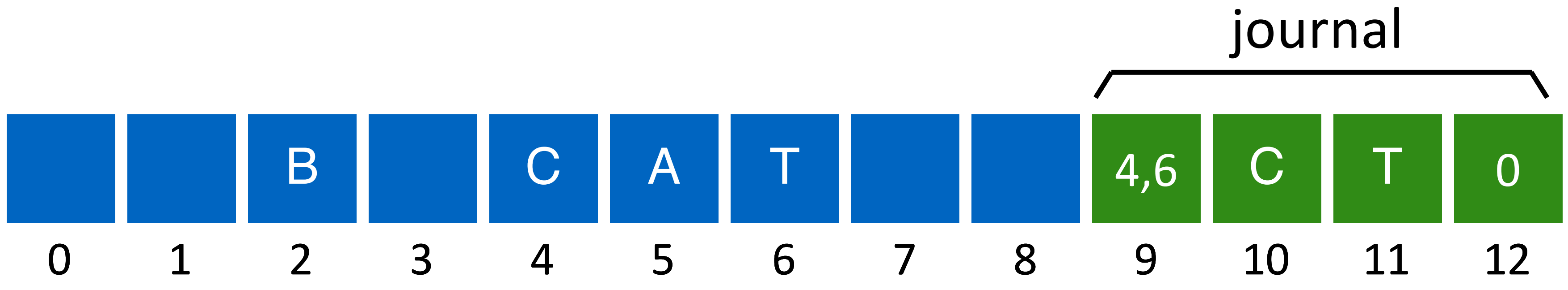
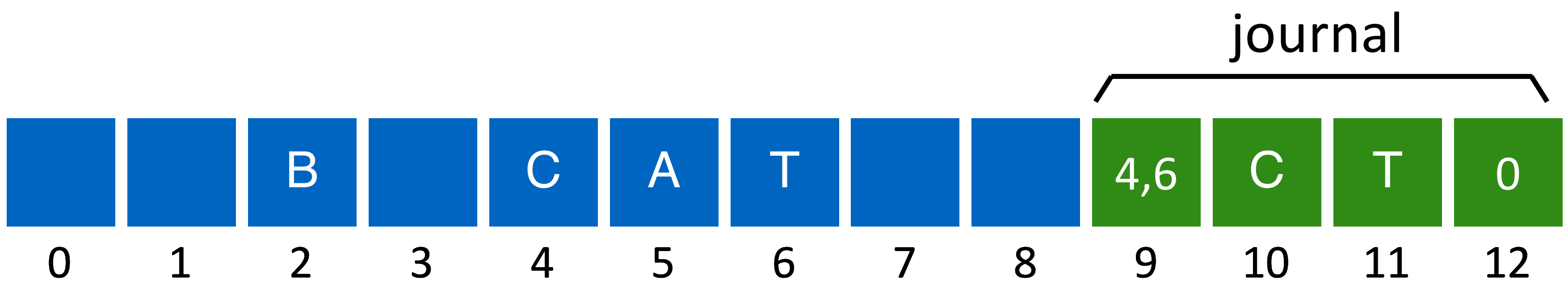


transaction: write C to block 4; write T to block 6

Optimizations

1. Reuse small area for journal
2. Barriers - (fsync)
3. Checksums
4. Circular journal
5. Logical journal

Correctness depends on Ordering



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

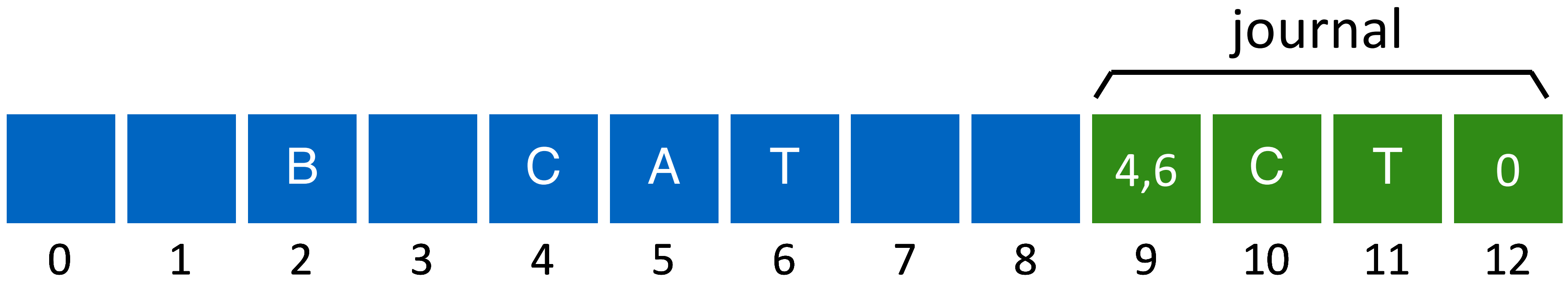
write order: 9, 10, 11, 12, 4, 6, 12

Enforcing total ordering among these writes 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

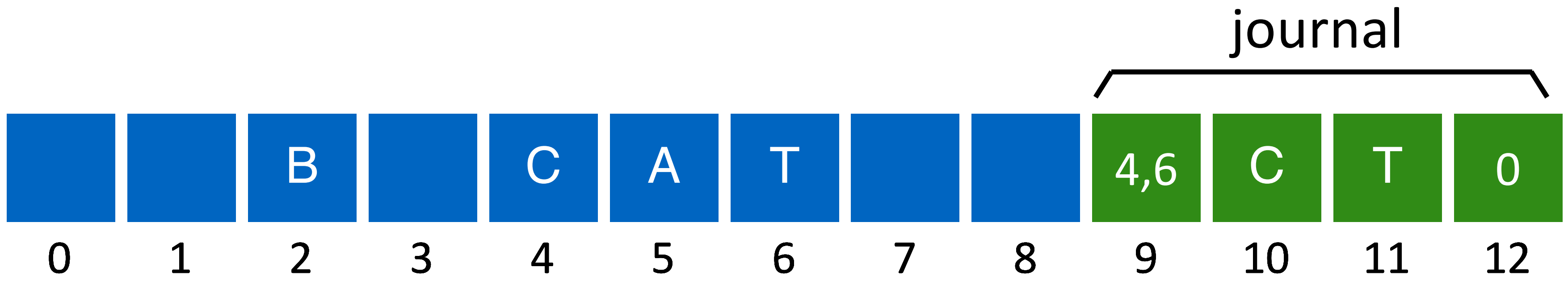
write order: 9,10,11 | 12 | 4,6 | 12

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
Force disk controller to commit data through fsync/sync

Optimizations

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

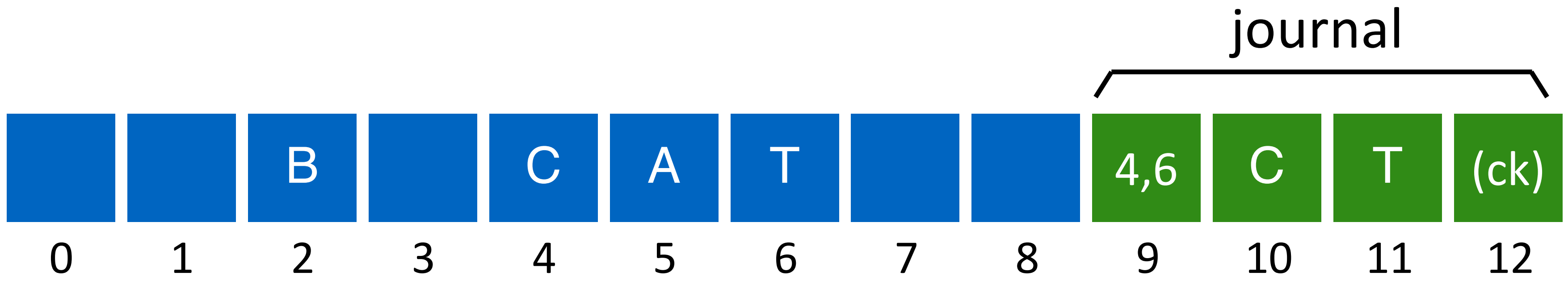
Checksums to avoid txn commit barrier



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

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

Checksums to avoid txn commit barrier



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

In last transaction block, store checksum of rest of transaction

data in 12 = checksum(9, 10, 11)

During recovery:

If checksum does not match transaction, treat txn 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, checkpointing is random

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

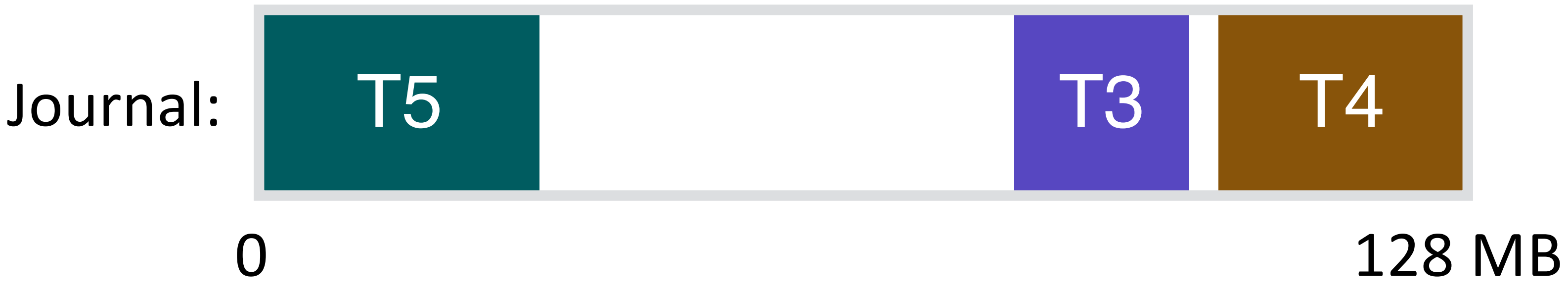
Circular Buffer

checkpoint and cleanup

Circular Buffer

New transaction reuses cleaned-up space

Circular Buffer



checkpoint and cleanup

Optimizations

1. Reuse small area for journal
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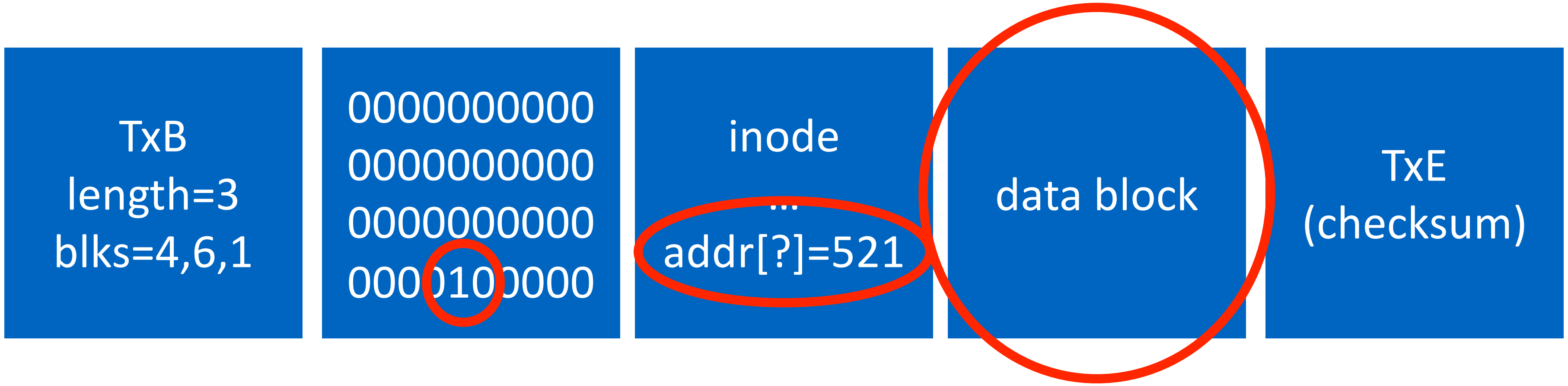
5. Logical journal

Physical Journal

TxB length=3 blks=4,6,1	0000000000 0000000000 0000000000 0000100000	inode … addr[?]=521	data block	TxE (checksum)

Physical Journal



Logical Journal

TxB length=1	list of changes	TxE (checksum)

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

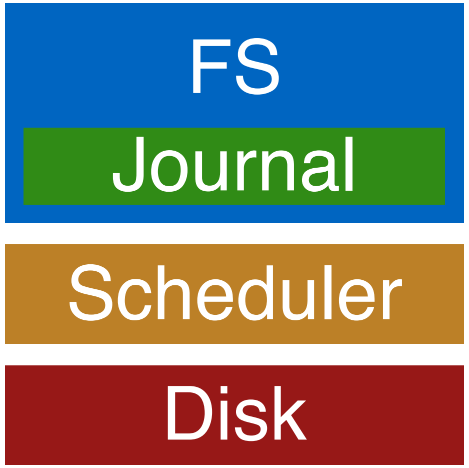
Tradeoff: More work upon recovery!
Need to read existing contents of in-place data and (re-)apply changes

Metadata journaling

Optimizations

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

File System Integration



How to avoid writing all disk blocks twice?

Observation: some blocks (e.g., user data) could be considered less important

Strategy: journal all metadata, including:

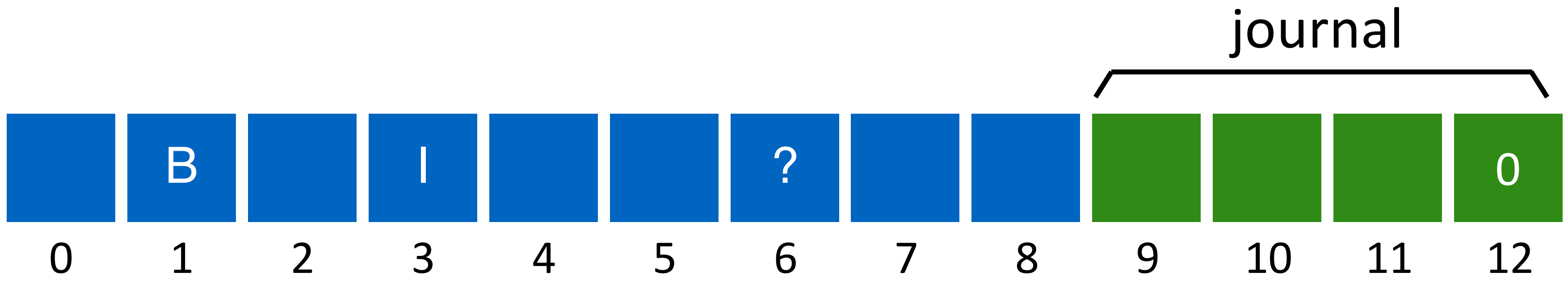
superblock, bitmaps, inodes, indirects, directories

For regular data, write it back whenever convenient.

Problem? Of course, files may contain garbage if fail before writing the data.

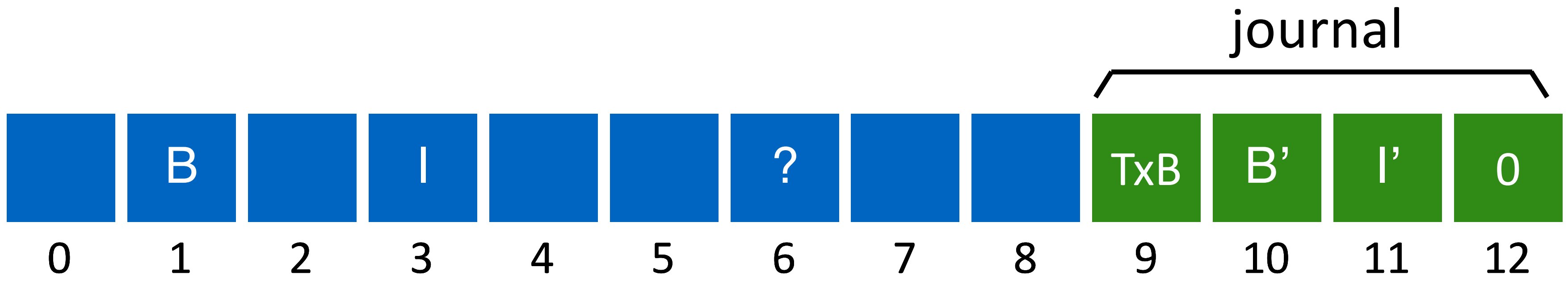
Unordered metadata journaling

Writeback Journal



transaction: append to inode I

Writeback Journal



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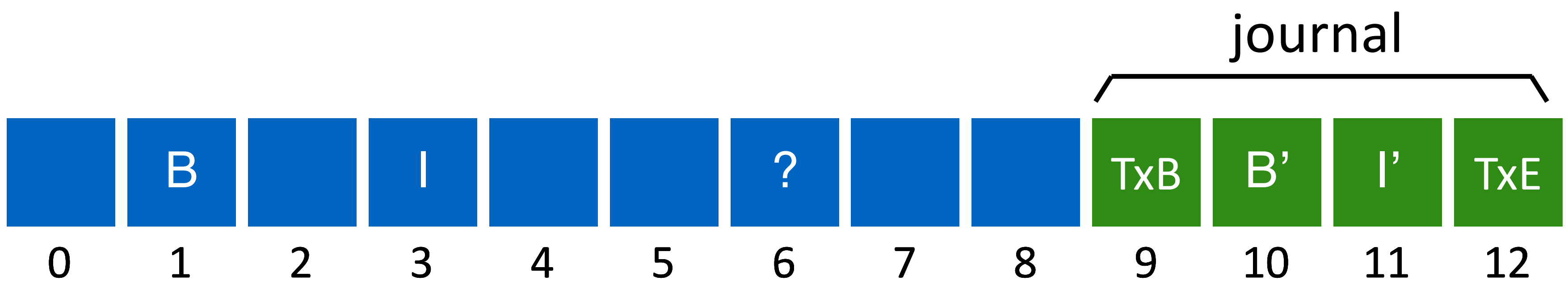

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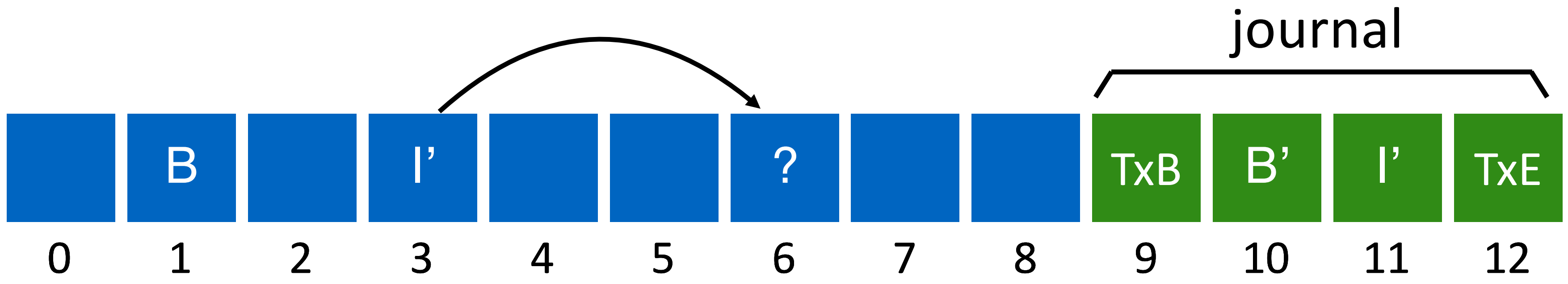

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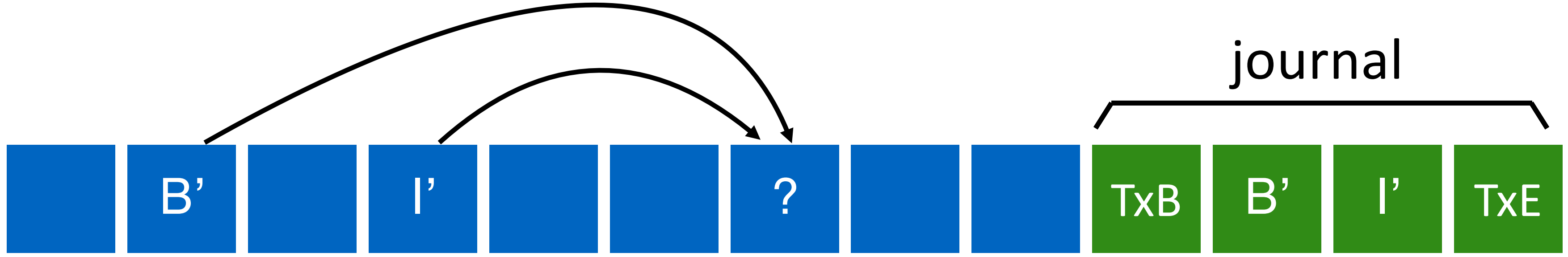


transaction: append to inode I

what if we crash now?

Point to garbage data?
Possibly leak sensitive data?

Solutions?

Ordered Metadata Journaling

Still only journal metadata

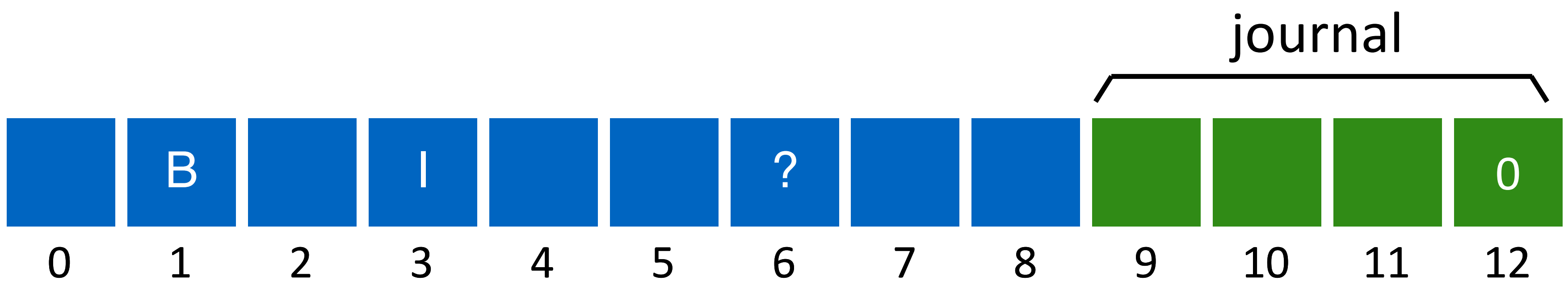
But write data **before** the transaction

No leaks of sensitive data or data loss if metadata consistent

Tip: write the “pointed-to” thing first before writing the pointer

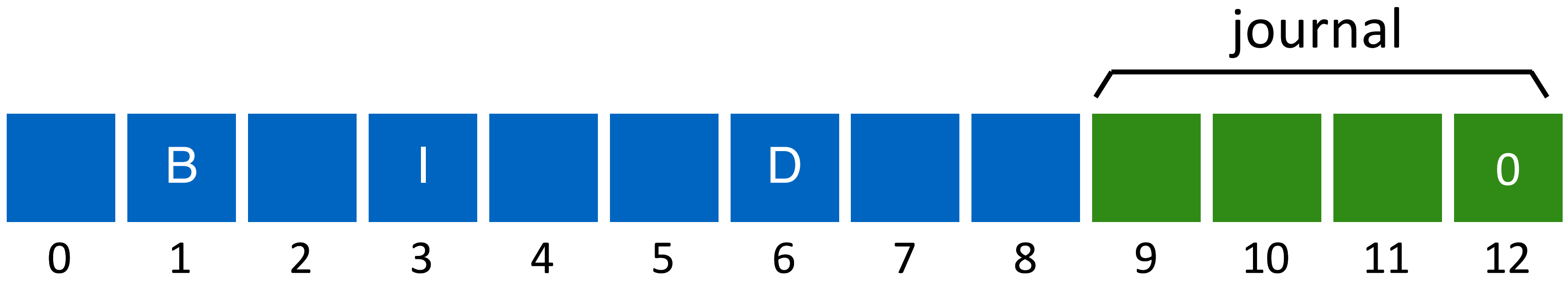
(A generally applicable tip in many contexts!)

Ordered Journal



transaction: append to inode I

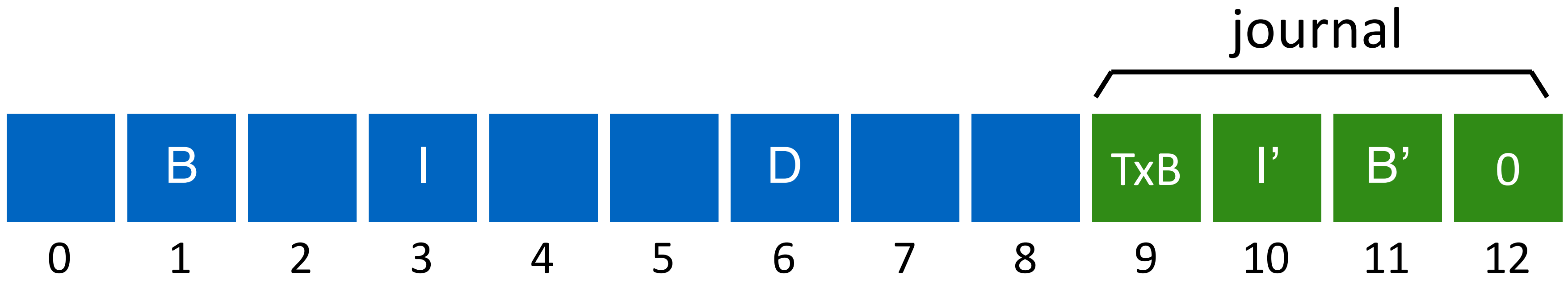
Ordered Journal



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



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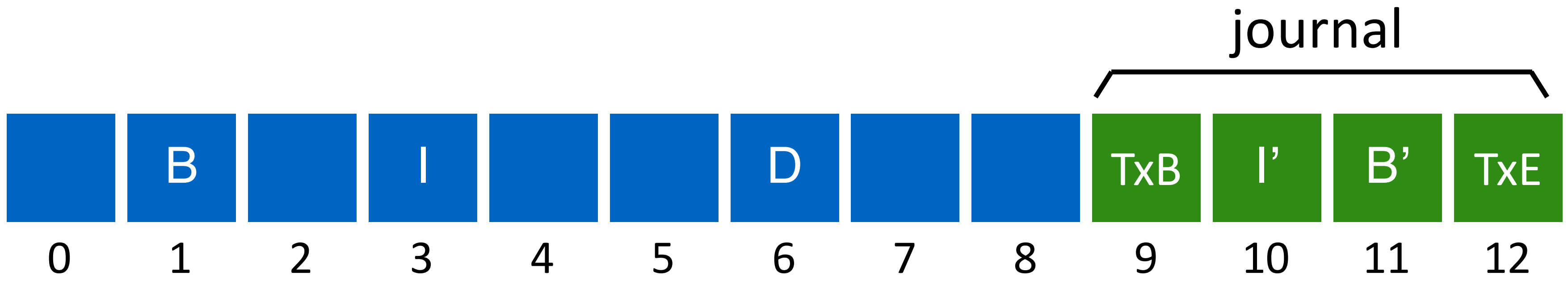

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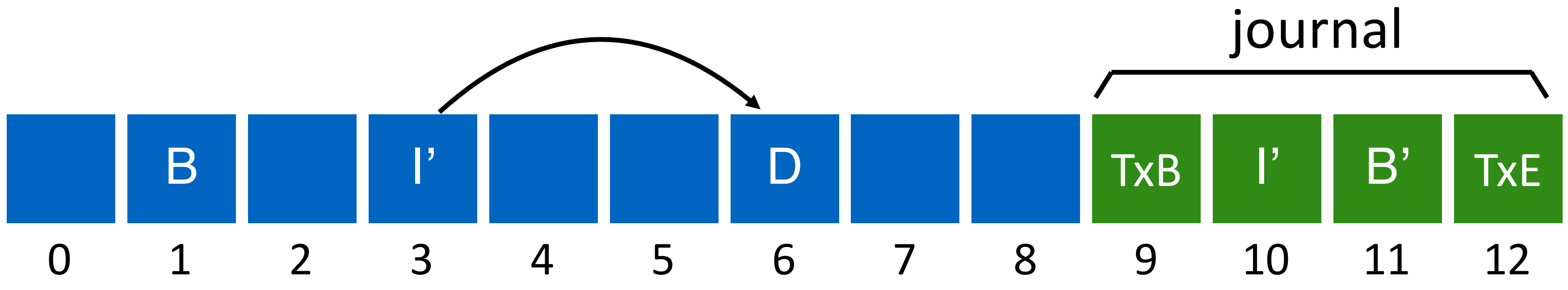

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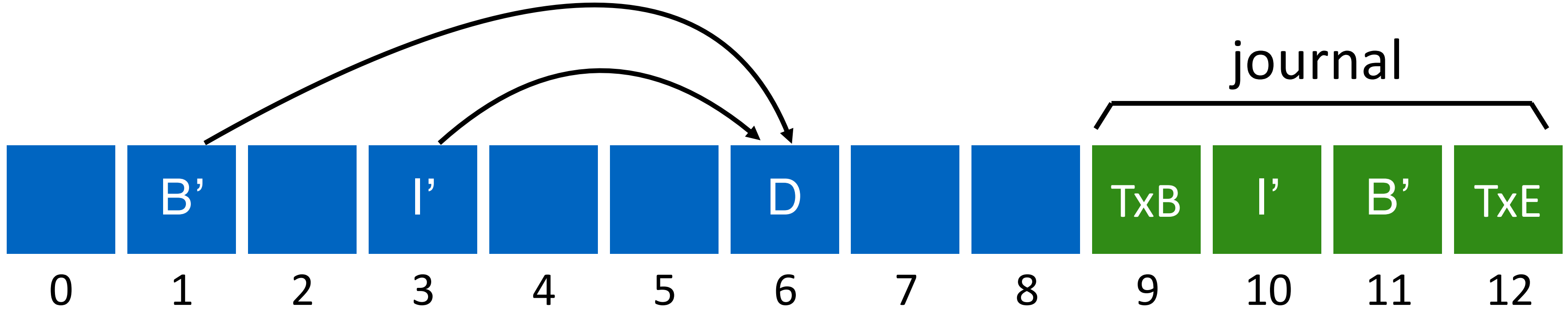

transaction: append to inode I

Summary

Most modern file systems use journals

- Ordered metadata journaling mode is popular

FSCK is still useful for weird cases: bit flips, filesystem bugs, …

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

Crash consistency makes persistent memory different from physical (main) memory

Operating Systems

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Outro

Summary

- An OS is a set of abstractions, mechanisms, policies to access your machine hardware

- OS work with, rely on, and support hardware capabilities
  - When hardware changes, OS support must change

- Virtualization: getting an app to use machine as if it's own
- Concurrency: doing things simultaneously on a machine
- Persistence: accessing and storing data that remains after failure

OK, now what?

Go about life as usual (1/3)

- But live with a deeper appreciation of how your machines work
- Example: When you buy more memory, what do you expect to run faster, and what won't?
- What does your machine hardware guarantee? What isn't?

Put your OS knowhow to use (tech work: 2/3)

- You've programmed significantly in this course. In future:
- Become a power-user of the machine
- Debug functionality and optimize performance for your software
  - Why is ML inference slow? Why does my system run out of memory?
- How do you design a complex system? What are the foundational problems?
- What principles should you use to organize functionality? What functionality goes where?

Go one level deeper (3/3)

- Use your knowledge to solve a problem you care about

- Learn more about computer systems
  - Rutgers CS curriculum: CS 552, 519, 545, …

- Push the boundaries of systems
  - Talk to me about research

Thanks & all the best!