CE 440 Introduction to Operating System

Lecture 20: File System Crash Consistency
Fall 2025

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Slides courtesy of Manuel Egele, Ryan Huang and Baris Kasikci

Administrivia

Lab 3a

- Due today (12/01) 11:59 pm
- If you design lab 3a well, 3b is relatively easy

Midterm 2

- Next Wednesday (12/10) in class
- Same format as midterm 1

More on Midterm 2

Covers material in the second half of the class

- Most questions about lecture 10 to lecture 17
- A few basic questions for lecture 18 to lecture 20

Closed book, two double-sided 8.5”x11” pages of notes

Can use a calculator but no other electronic devices

Based upon lecture (textbook), homework, and project

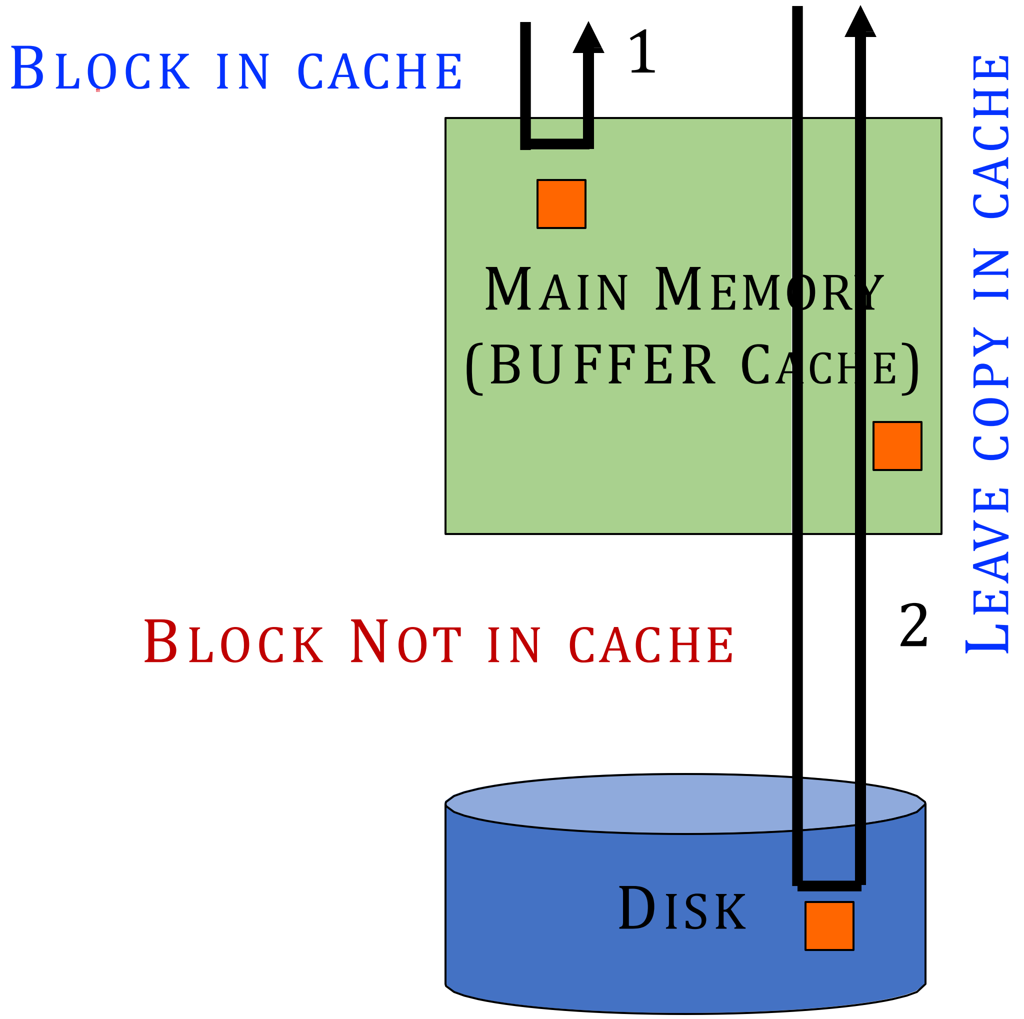
- Do the homework to practice for the exam

Review: File I/O Path (Reads)

File system uses buffer cache to speed up I/O

read() **from file**

- Check if block is in cache
- If so, return block to user [1 in figure]
- If not, read from disk, insert into cache, return to user [2]



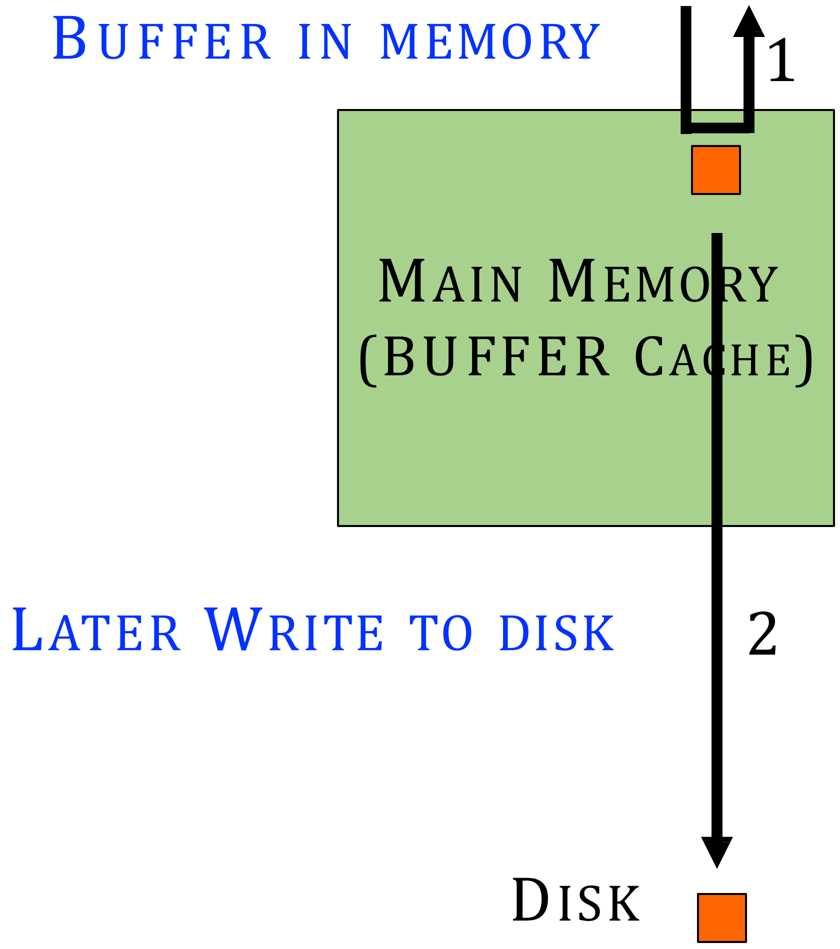
Review: File I/O Path (Writes)

write() **to file**

- Write is buffered in memory ("write behind") [1]
- Sometime later, OS decides to write to disk [2]
- Periodic flush or fsync call

Why delay writes?

- Implications for performance
- Implications for reliability



The Consistent Update Problem

Goal:

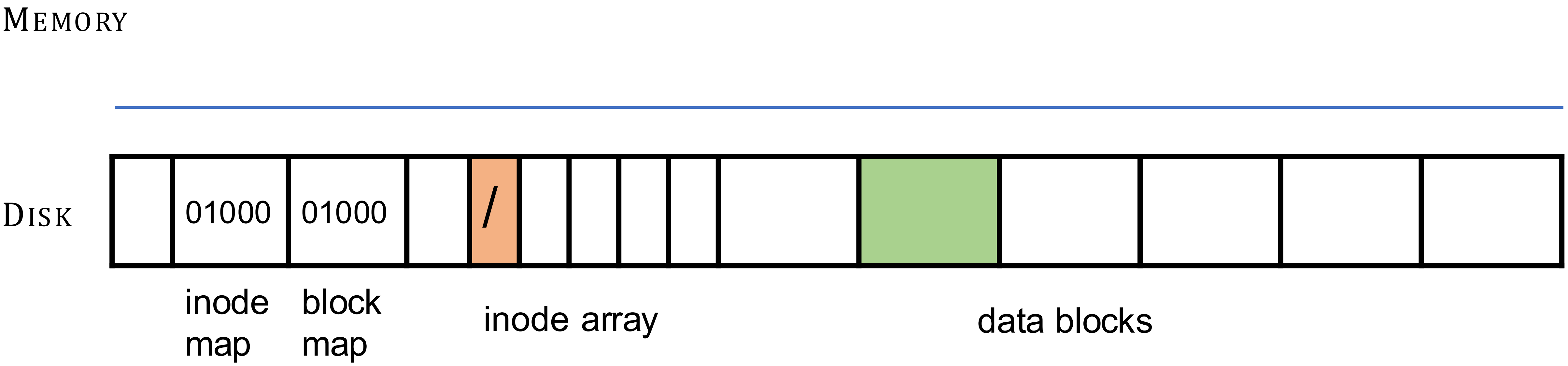
- Atomically update file system from one consistent state to another
- What do we mean by consistent state?

Challenge:

- An update may require modifying several sectors, despite that the disk only provides atomic write of one sector at a time

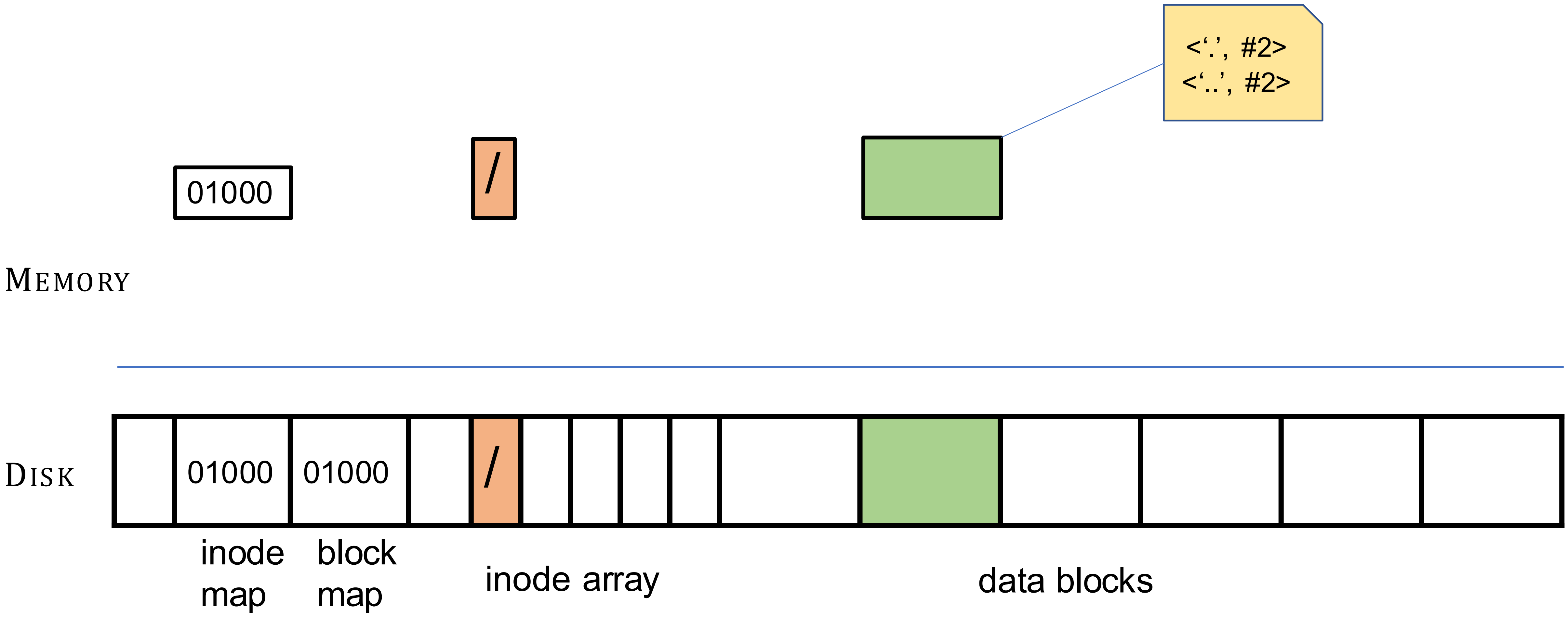
Example: File Creation of /a.txt

Initial state



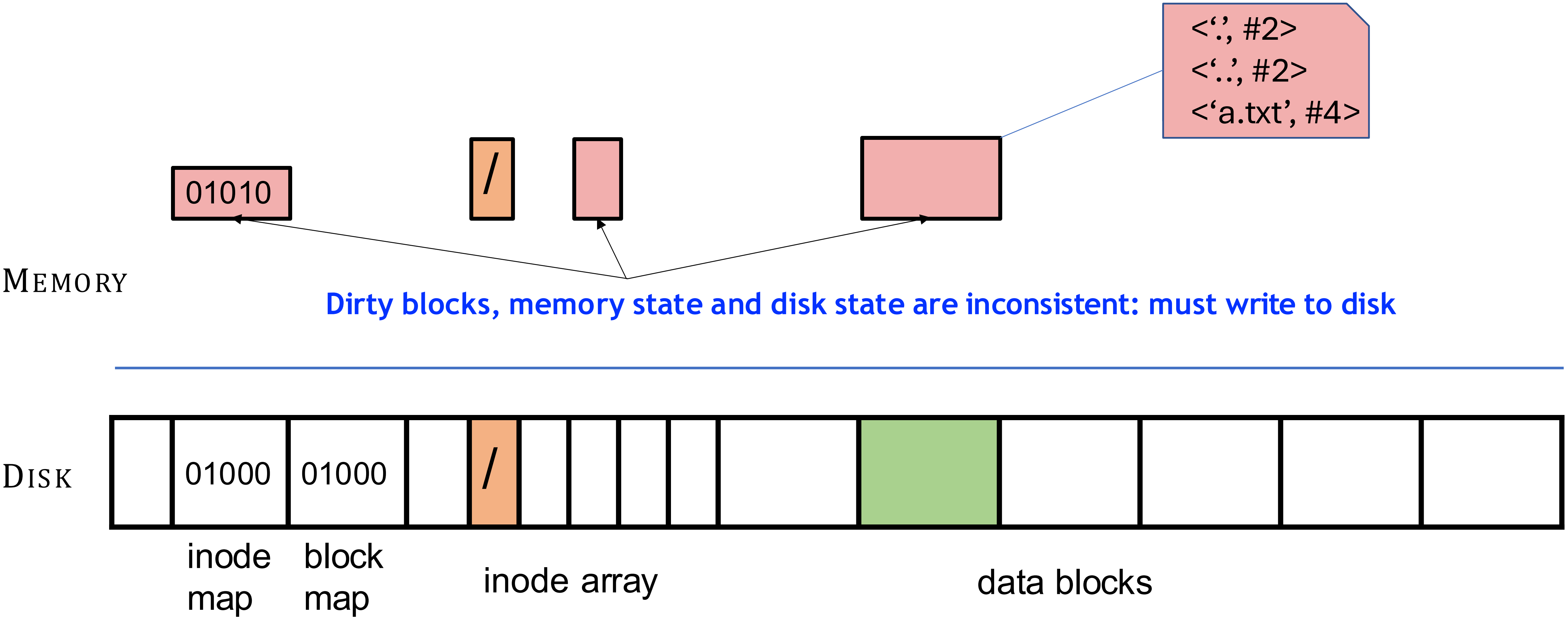
Example: File Creation of /a.txt

Read to in-memory Cache



Example: File Creation of /a.txt

Modify metadata and blocks



Crash?

Disk: atomically write one sector

- Atomic: if crash, a sector is either completely written, or none of this sector is written

An FS operation may modify multiple sectors

Crash → FS partially updated

Possible Crash Scenarios

File creation dirties three blocks

- inode bitmap (B)
- inode for new file (I)
- parent directory data block (D)

Old and new contents of the blocks

- B = 01000 B’ = 01010
- I = free I’ = allocated, initialized
- D = {} D’ = {<‘a.txt’, 4>}

Possible Crash Scenarios

Crash scenarios: any subset can be written

- B I D
- B’ I D
- B I’ D
- B I D’
- B’ I’ D
- B’ I D’
- B I’ D’
- B’ I’ D’

The General Problem

Writes: Have to update disk with N writes

- Disk does only a single write atomically

Crashes: System may crash at arbitrary point

- Bad case: In the middle of an update sequence

Desire: To update on-disk structures atomically

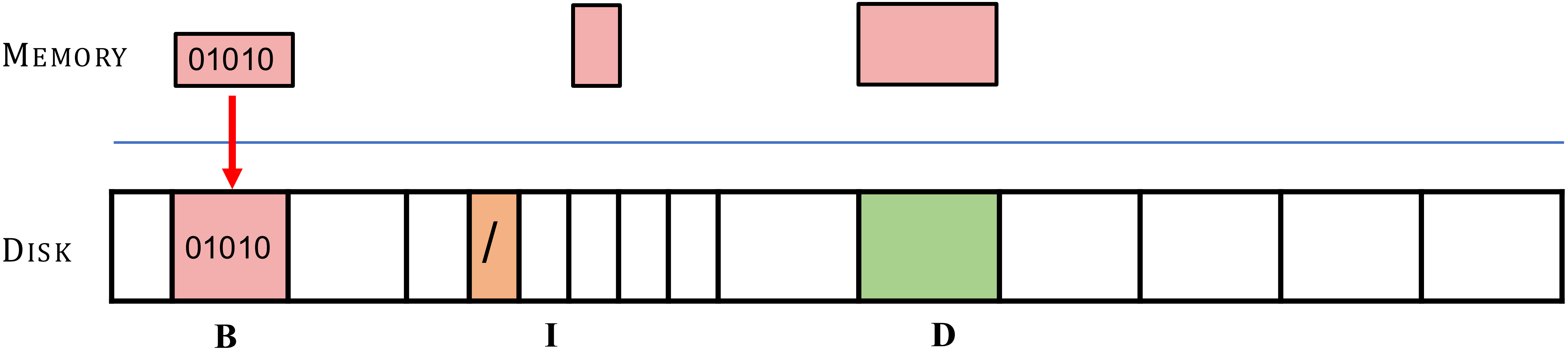
- Either all should happen or none

Example: Bitmap First

Write Ordering: Bitmap (B), Inode (I), Data (D)

- But CRASH after B has reached disk, before I or D

Result?

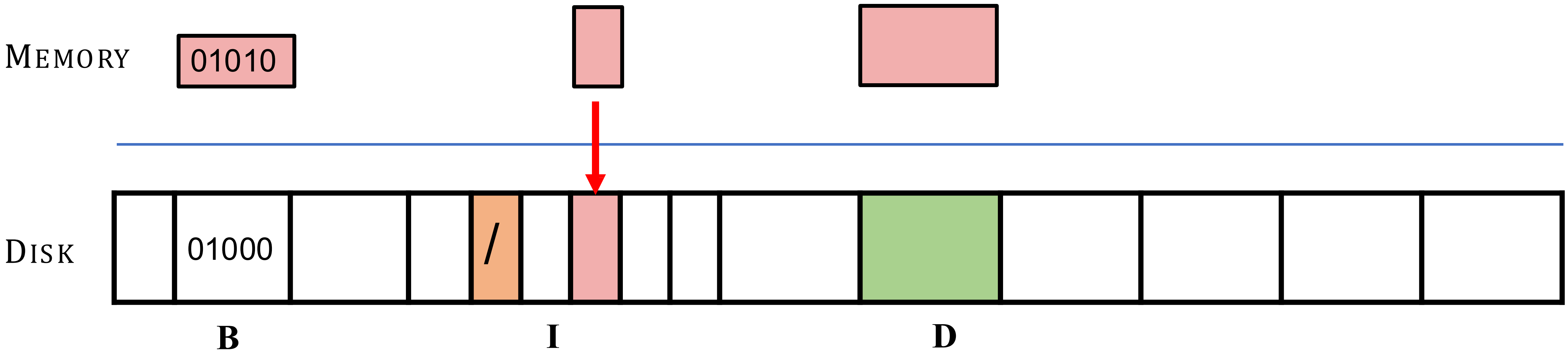


Example: Inode First

Write Ordering: Inode (I), Bitmap (B), Data (D)

- But CRASH after I has reached disk, before B or D

Result?

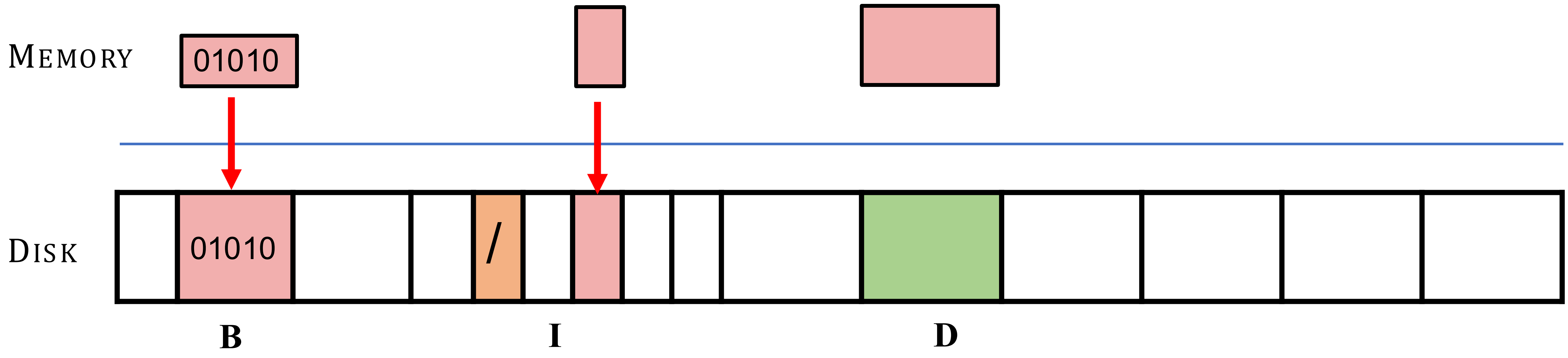


Example: Inode First

Write Ordering: Inode (I), Bitmap (B), Data (D)

- But CRASH after I AND B have reached disk, before D

Result?



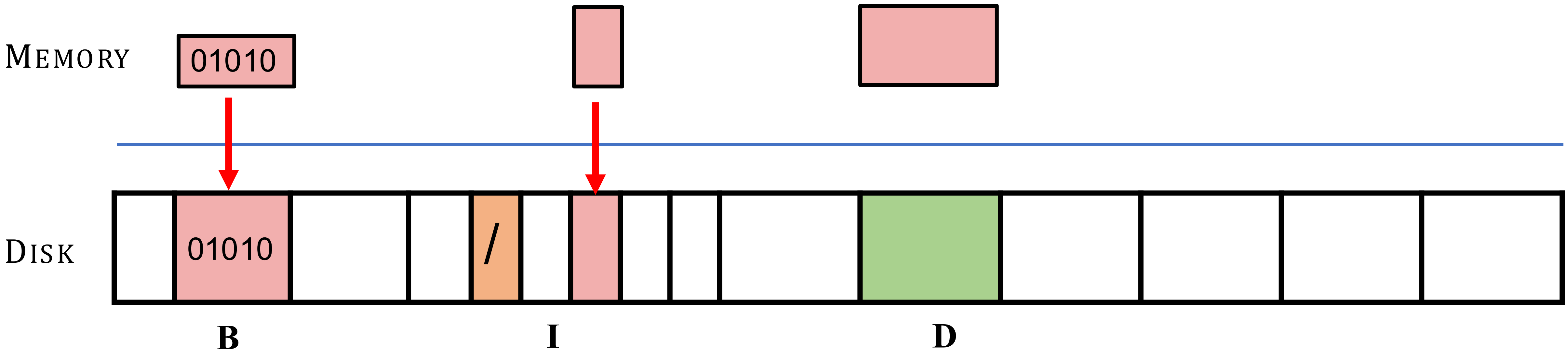
Example: Inode First

Write Ordering: Inode (I), Bitmap (B), Data (D)

- But CRASH after I AND B have reached disk, before D

Result?

- What if data block is a new block for the new file (i.e., create file with data)

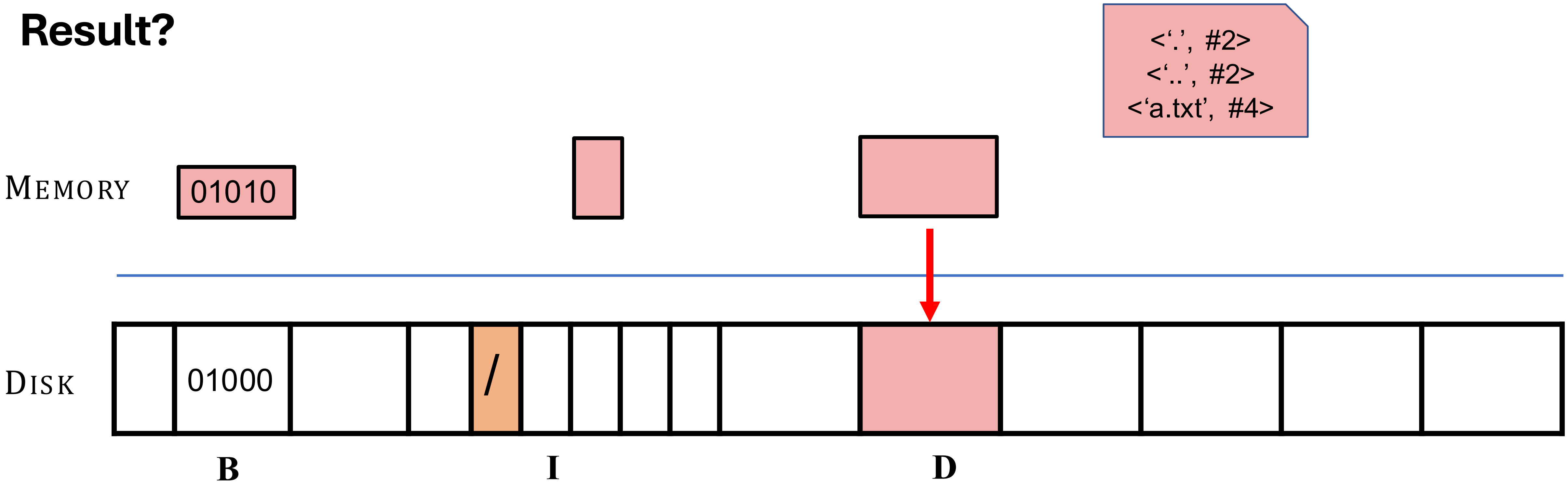


Example: Data First

Write Ordering: Data (D) , Bitmap (B), Inode (I)

- CRASH after D has reached disk, before I or B

Result?



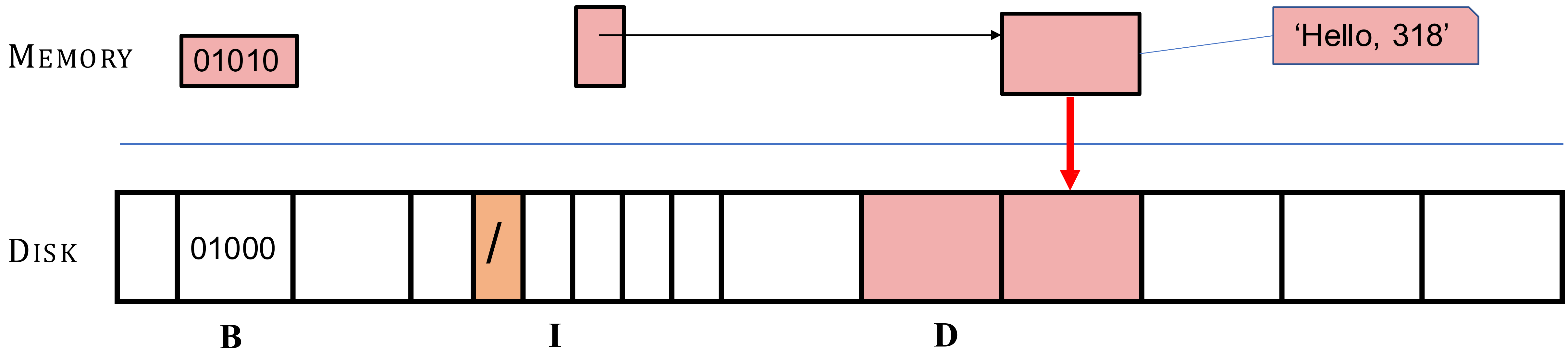
Example: Data First

Write Ordering: Data (D) , Bitmap (B), Inode (I)

- CRASH after D has reached disk, before I or B

Result?

- What if data block is a new block for the new file (i.e., create file with data)



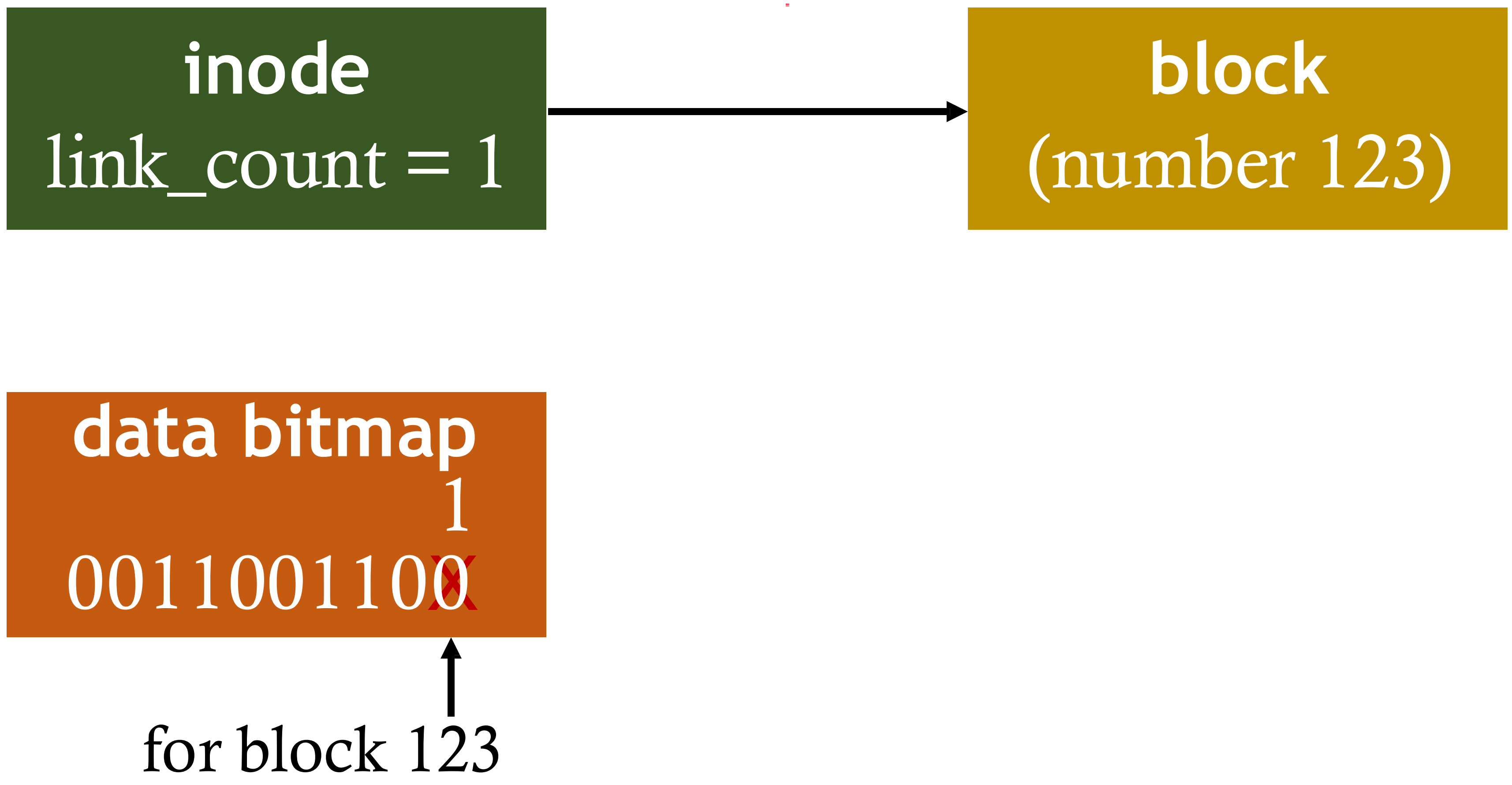
Traditional Solution: fsck

FSCK: "file system checker"

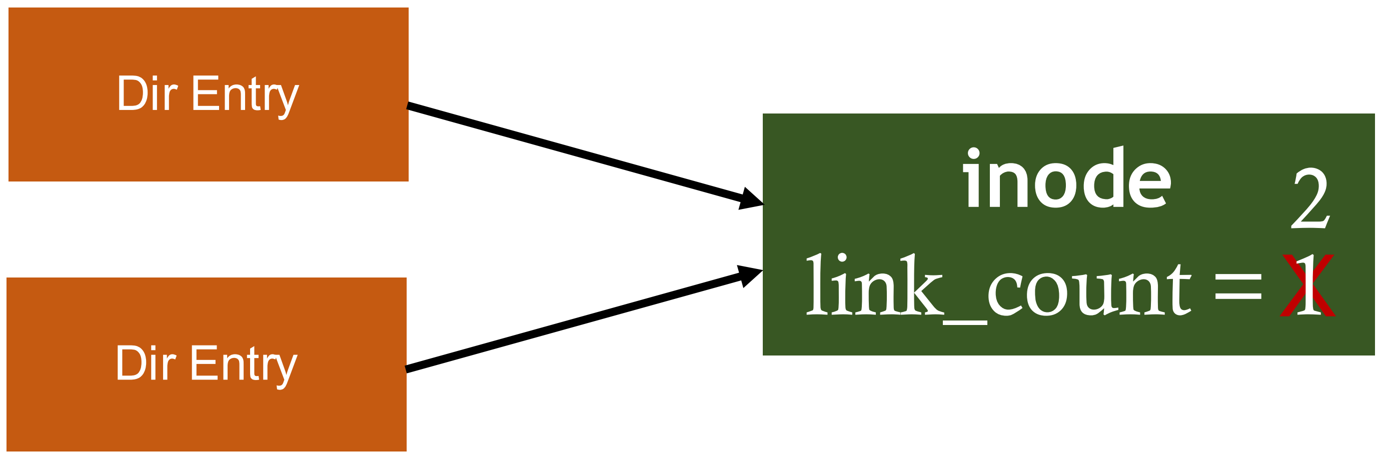
When system boots:

- Make multiple passes over file system, looking for inconsistencies
  - e.g., inode pointers and bitmaps, directory entries and inode reference counts
- Try to fix automatically

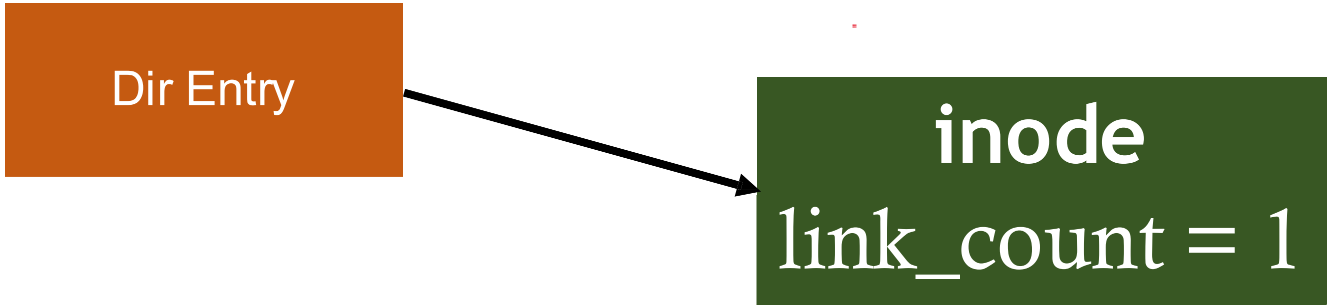
FSCK Example 1



FSCK Example 2

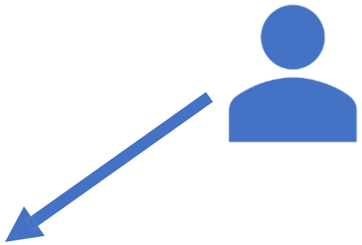


FSCK Example 3

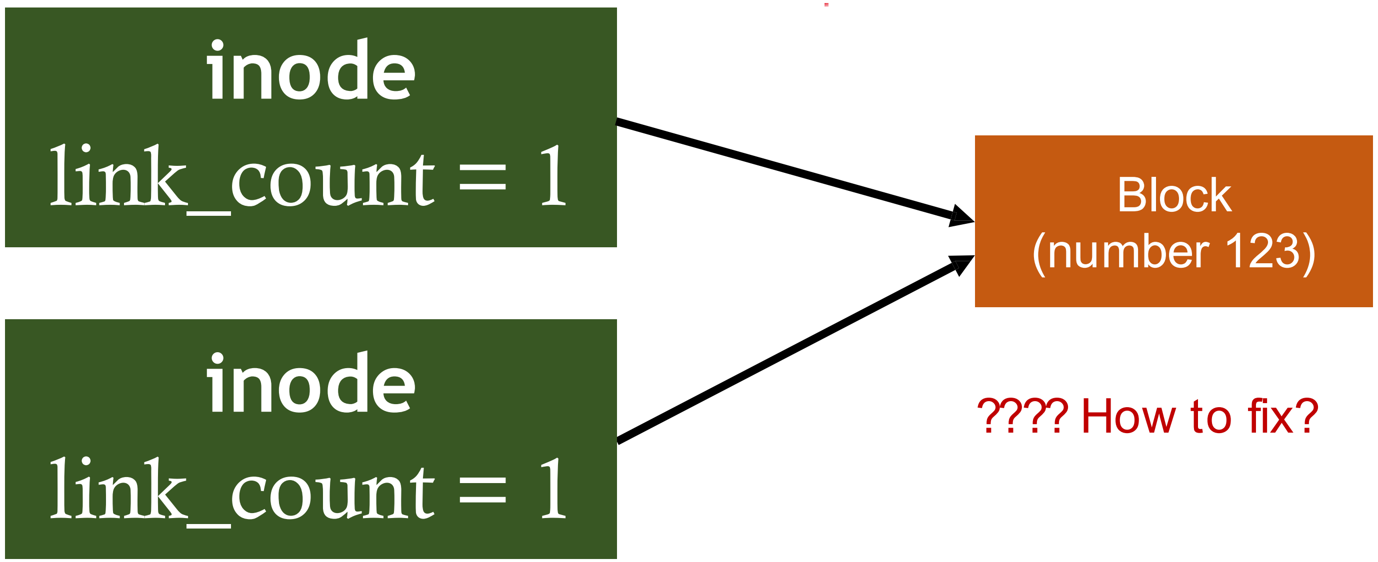


???? How to fix?

```
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/
...
```

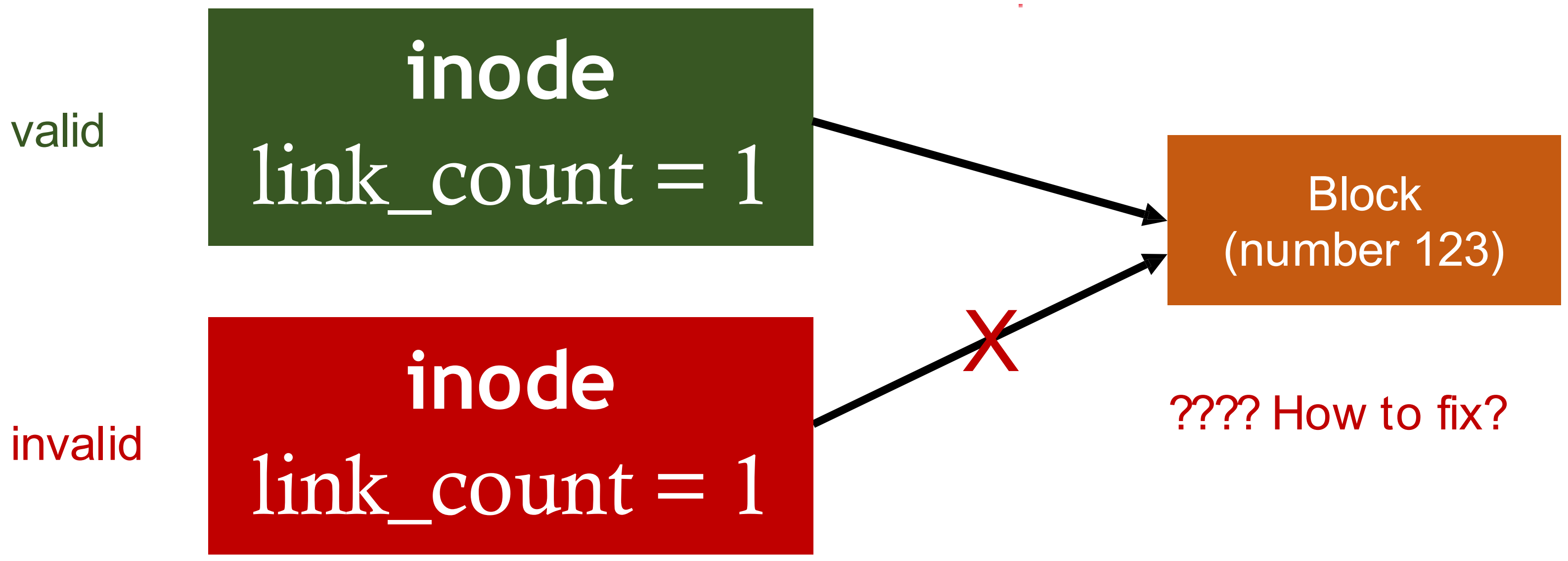


FSCK Example 4

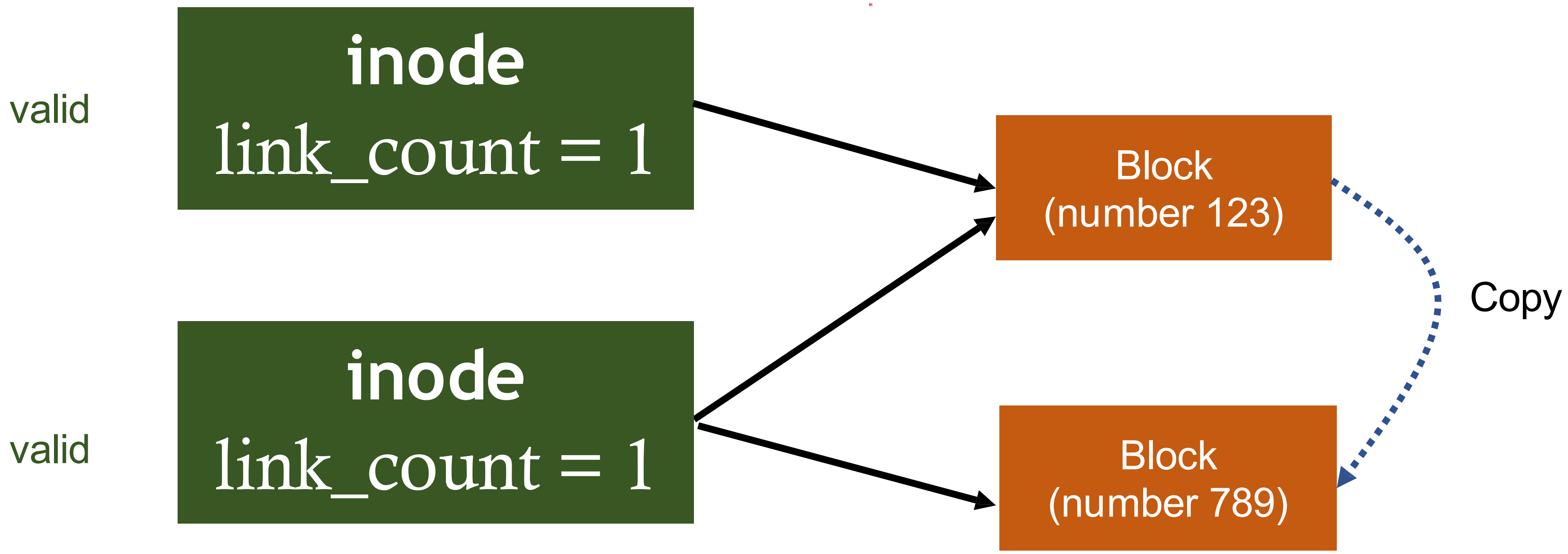


???? How to fix?

FSCK Example 4.a



FSCK Example 4.b



Traditional Solution: FSCK

FSCK: “file system checker”

When system boots:

- Make multiple passes over file system, looking for inconsistencies
- Try to fix automatically
  - Example: B’ I D, B I’ D
- Or punt to admin
- Check lost+found, manually put the missing-link files to the correct place

Traditional Solution: FSCK

Problem:

- Cannot fix all crash scenarios
  - Can B’ I D’ be fixed?
- Performance
  - Sometimes takes hours to run
    - Checking a 600GB disk takes ~70 minutes
  - Does fsck have to run upon every reboot?
- Not well-defined consistency

Another Solution: Journaling

Idea: Write "intent" down to disk before updating file system

- Called the "Write Ahead Logging" or "journal"
- Originated from database community

When crash occurs, look through log to see what was going on

- Use contents of log to fix file system structures
  - Crash before "intent" is written → no-op
  - Crash after "intent" is written → redo op
- The process is called "recovery"

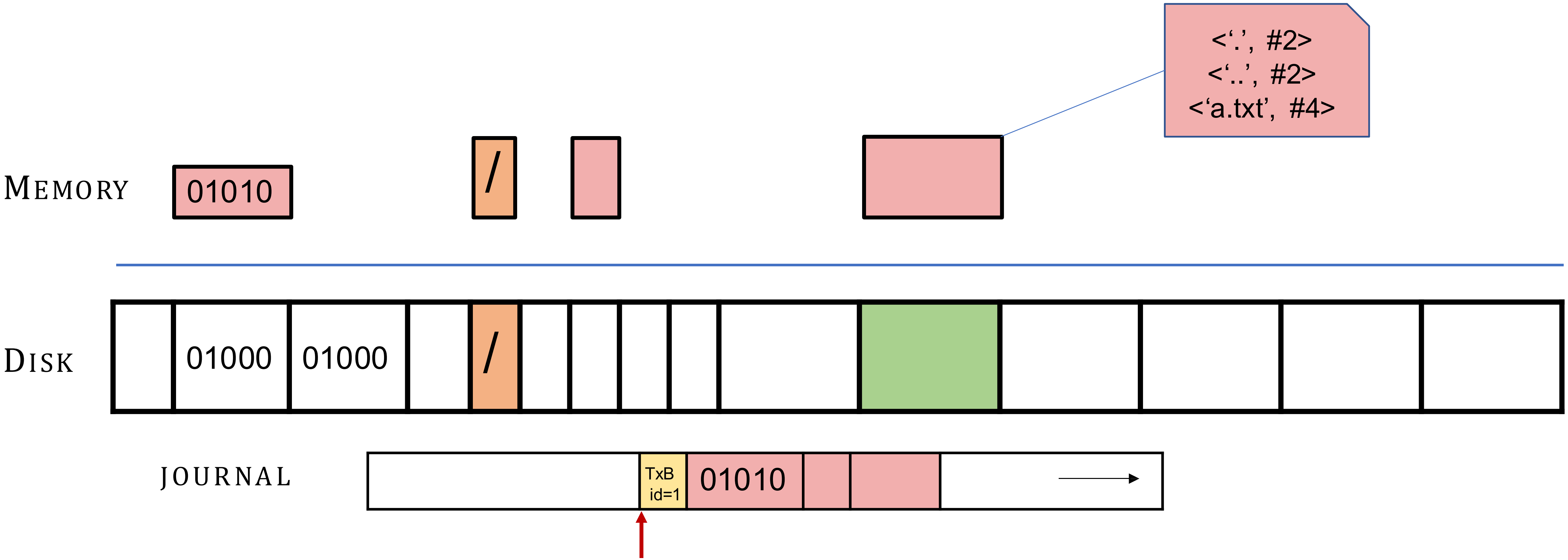
Case Study: Linux Ext3

Write real block contents of the update to log

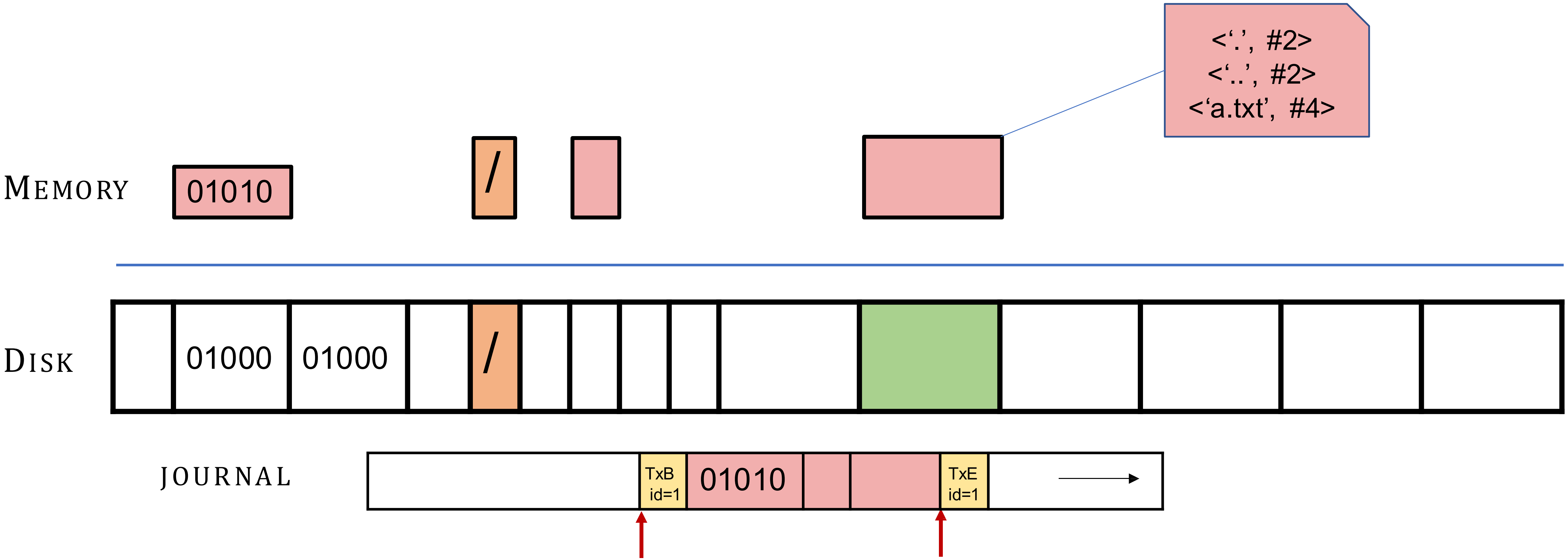
- Four totally ordered steps:

1. Commit dirty blocks to journal as one transaction (TxBegin, I, B, D blocks)
2. Write commit record (TxEnd)
3. Copy dirty blocks to real file system (checkpointing)
4. Reclaim the journal space for the transaction

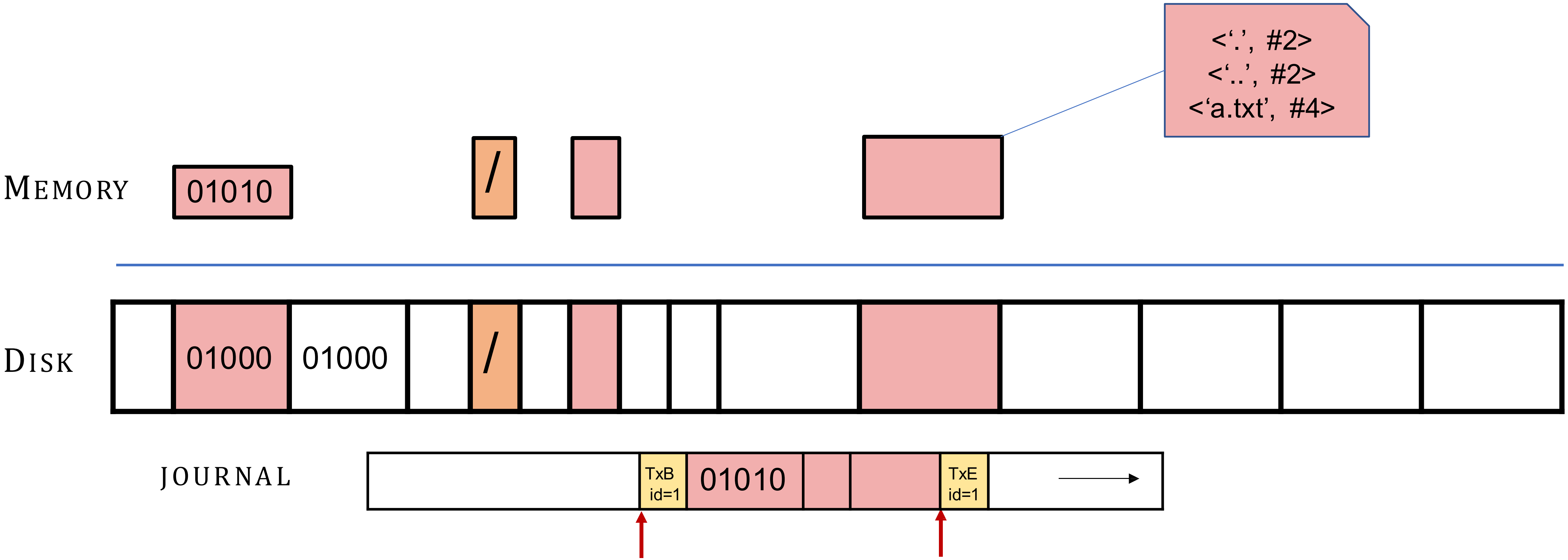
Step 1. Write Blocks to Journal



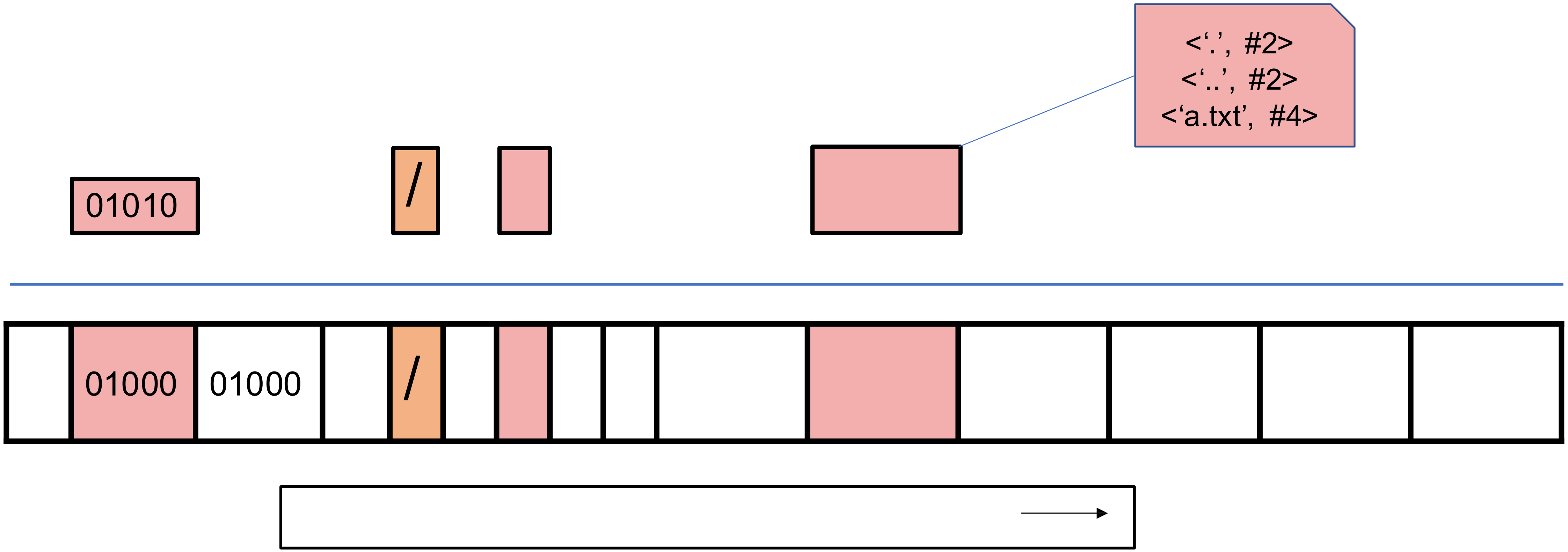
Step 2. Write Commit Record



Step 3: Copy Dirty Blocks to Real FS



Step 4: Reclaim Journal Space

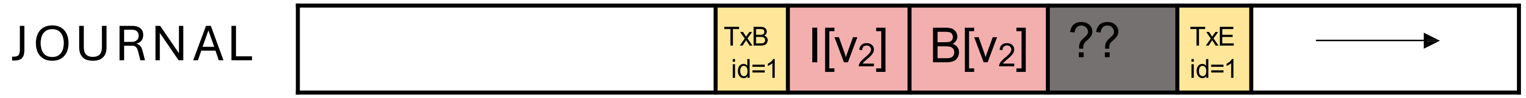


What If There Is A Crash?

Recovery: Go through log and "redo" operations that have been successfully committed to log

What if ...

- TxBegin but not TxEnd in log?
- TxBegin through TxEnd are in log, but D has not reached the journal?



- How could this happen?
- Why don't we merge step 2 and step 1?

- Tx in log, I, B, D have been checkpointed, but Tx is not freed from log?

Summary of Journaling Write Orders

Journal writes < FS writes

- Otherwise, crash → FS broken, but no record in journal to patch it up

FS writes < Journal clear

- Otherwise, crash → FS broken, but record in journal is already cleared

Journal writes < commit record write < FS writes

- Otherwise, crash → record appears committed, but contains garbage

Ext3 Journaling Modes

Journaling has cost

- one write = two disk writes, two seeks

Several journaling modes balance consistency and performance

Data journaling: journal all writes, including file data

- Problem: expensive to journal data

Metadata journaling: journal only metadata

- Used by most FS (IBM JFS, SGI XFS, NTFS)
- Problem: file may contain garbage data

Ordered mode: write file data to real FS first, then journal metadata

- Default mode for ext3
- Problem: old file may contain new data

Summary

The consistent update problem

- Example of file creation and different crash scenarios

Two approaches to crash consistency

- FSCK: slow, not well-defined consistency
- Journaling: well-defined consistency, different modes

Other approach

- Soft updates (advanced OS topics)