CS 318 Principles of Operating Systems

Fall 2018

Lecture 17: File System Crash Consistency

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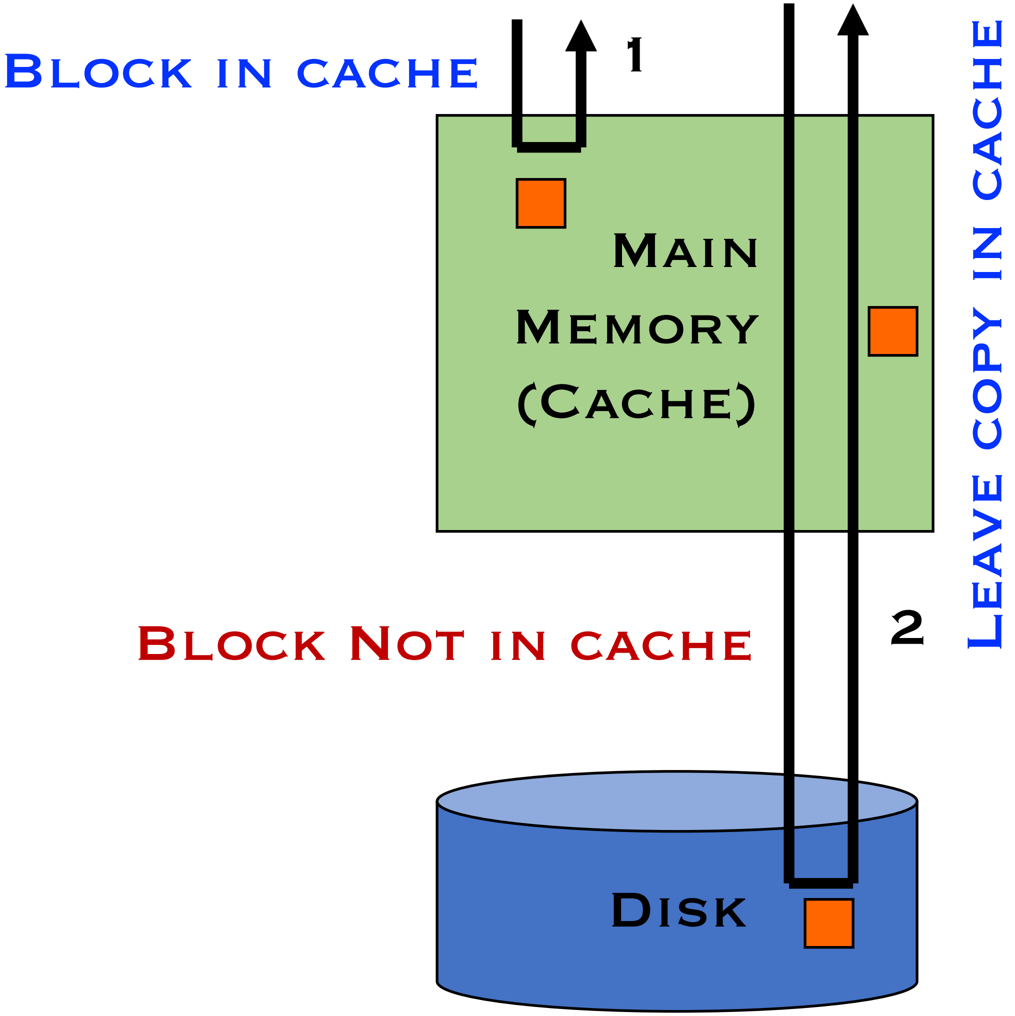
Administrivia

- **Lab 3**
- **Extra office hour**
  - Wednesday 4:30-6pm

Review: File I/O Path (Reads)

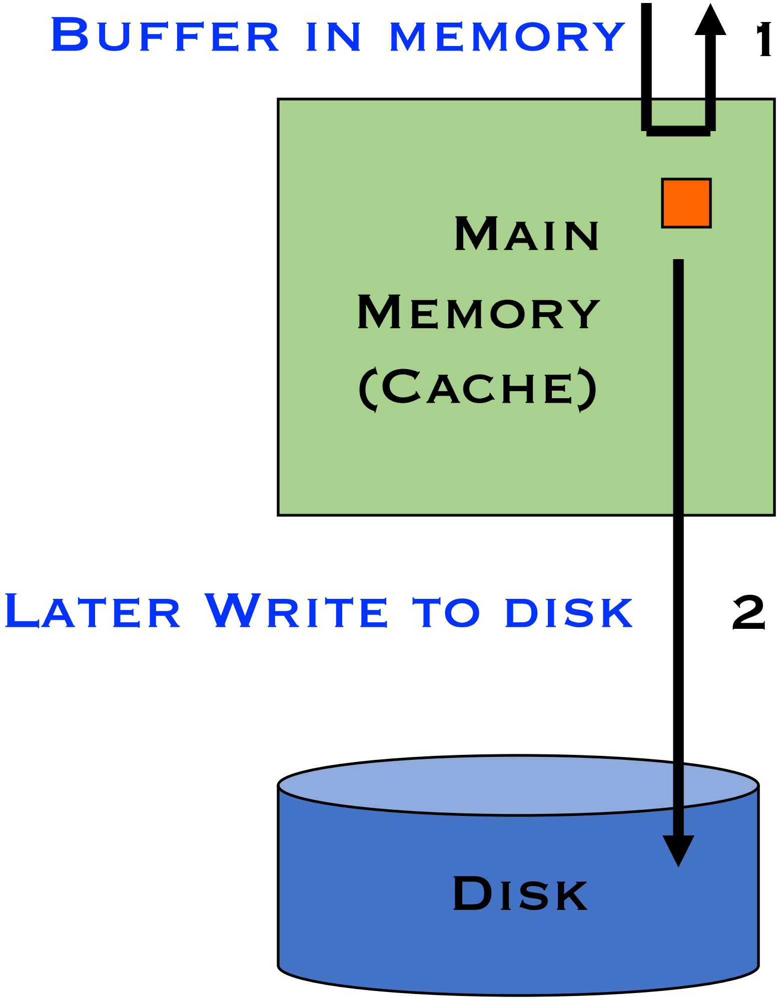
- **`read()` from file**
  - Check if block is in cache
  - If so, return block to user [1 in figure]
  - If not, read from disk, insert into cache, return to user [2]



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

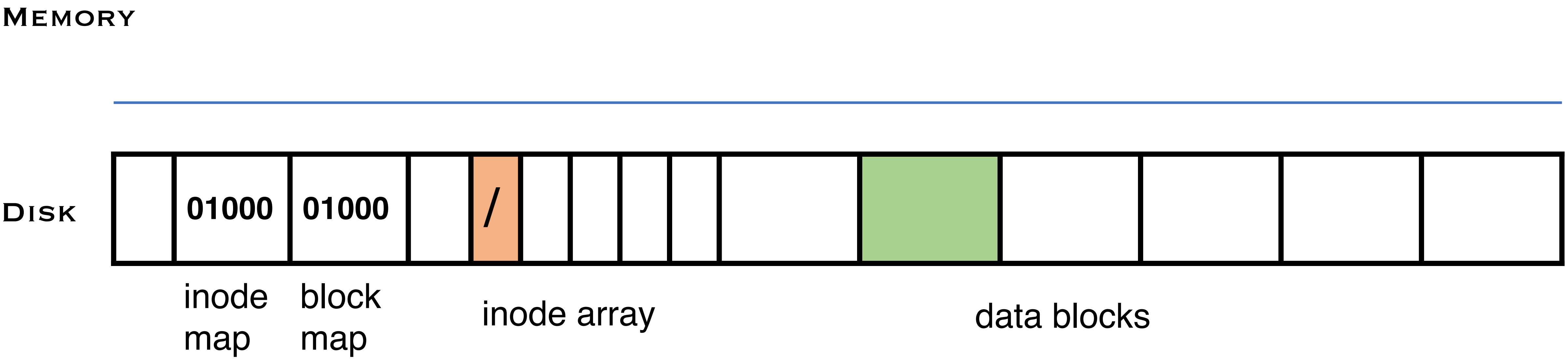


The Consistent Update Problem

- **Atomically update file system from one consistent state to another, which may require modifying several sectors, despite that the disk only provides atomic write of one sector at a time**
  - What do we mean by consistent state?

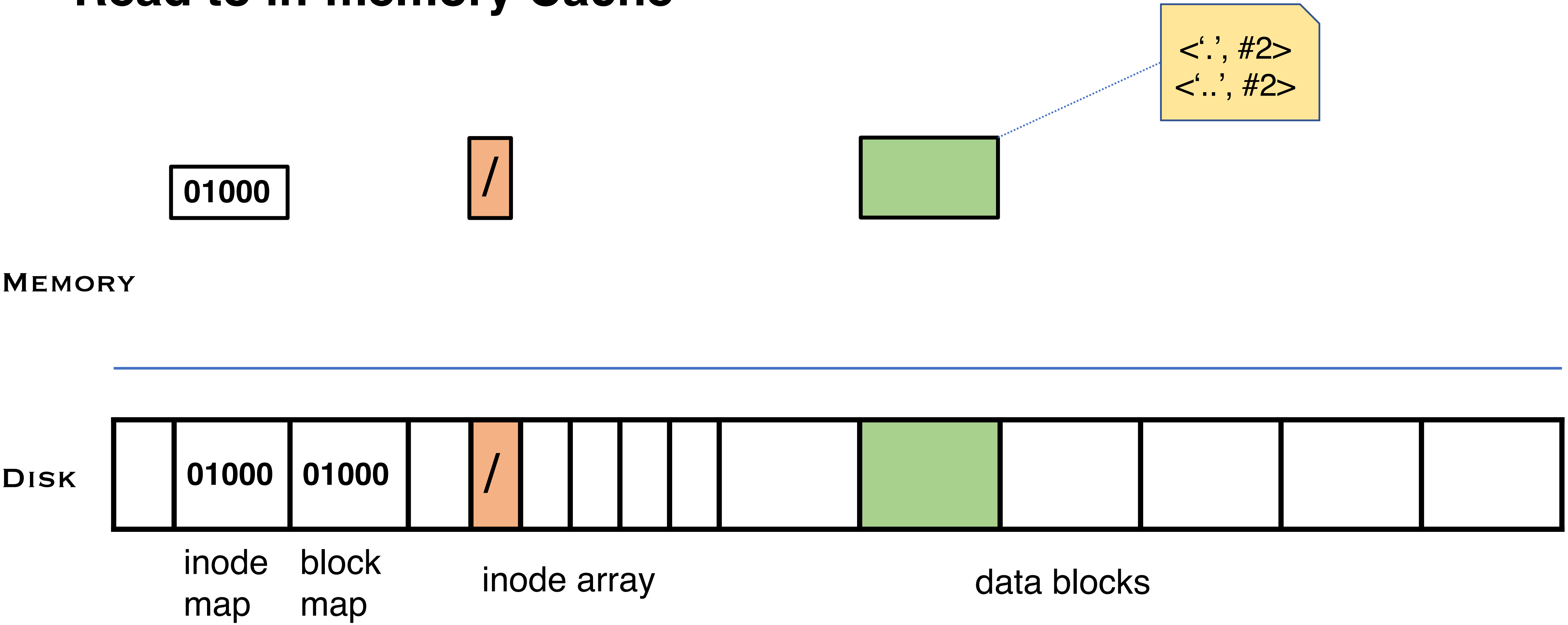
Example: File Creation

- **Initial state**



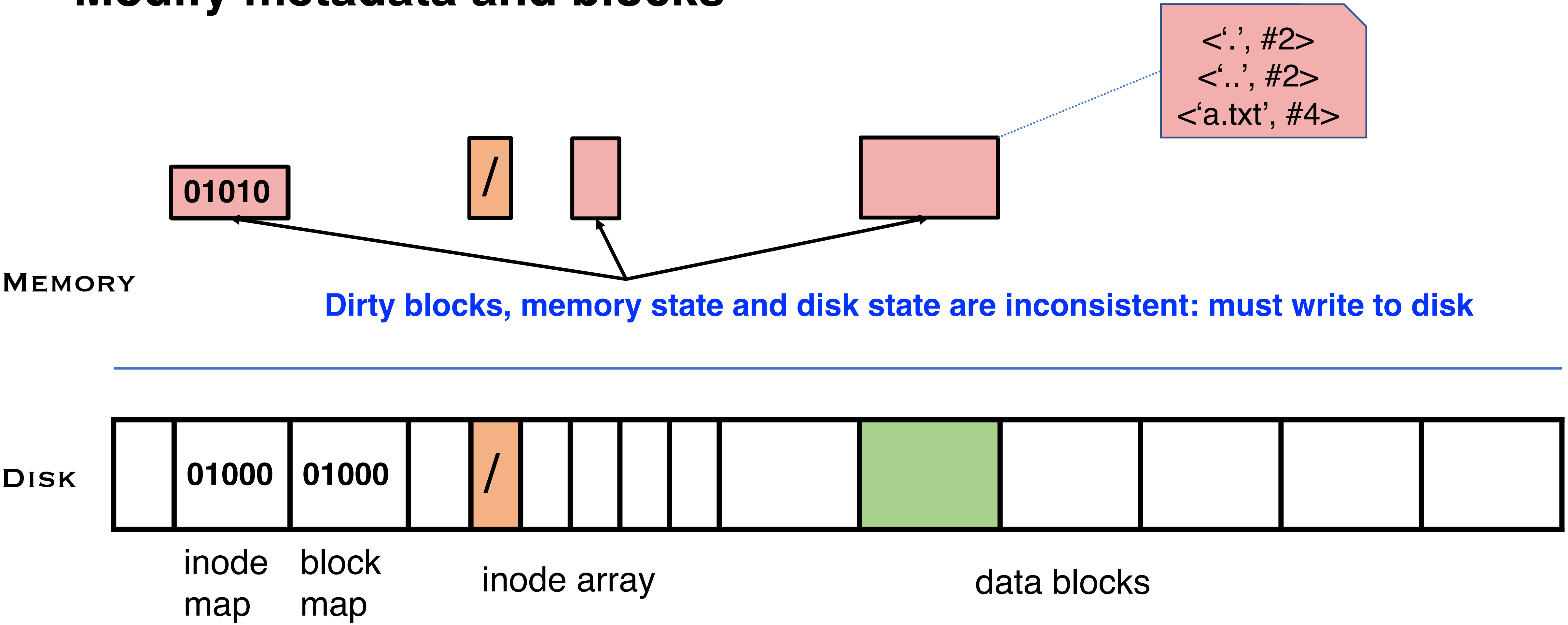
Example: File Creation

- **Read to in-memory Cache**



Example: File Creation

- **Modify metadata and blocks**



Dirty blocks, memory state and disk state are inconsistent: must write to disk

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’

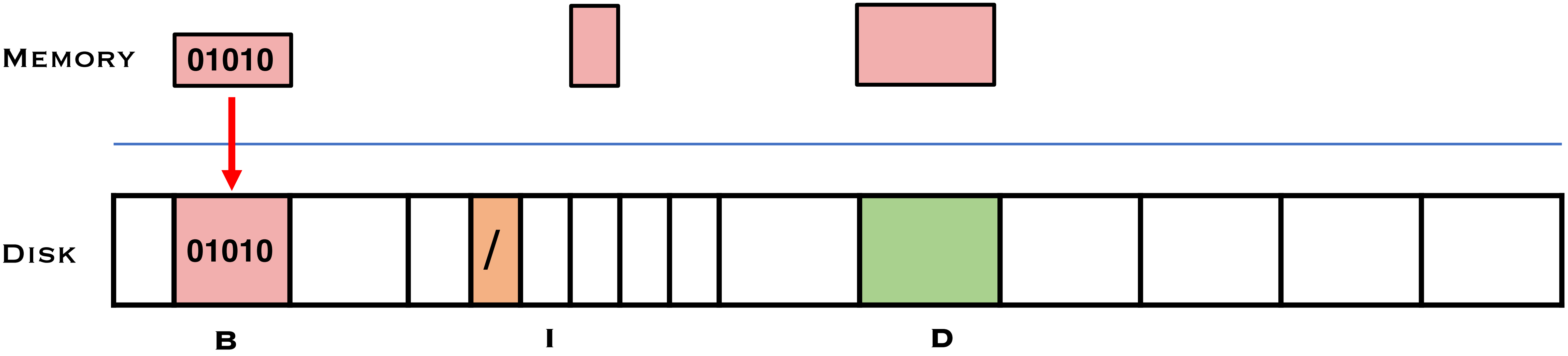
The General Problem

- **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

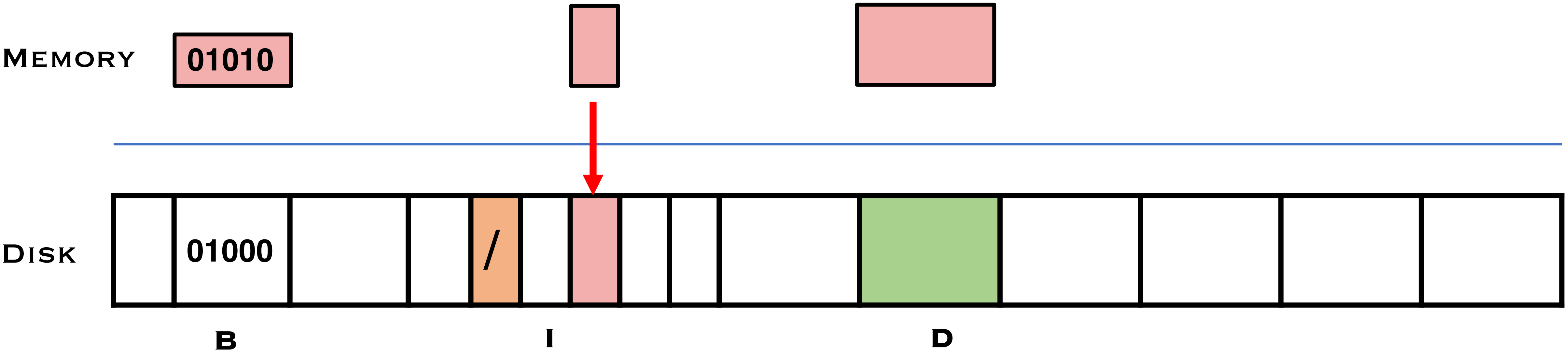
- **Result?**



Example: Inode First

- **Write Ordering: Bitmap (B), Inode (I), Data (D)**
  - But CRASH after I has reached disk, before B or D

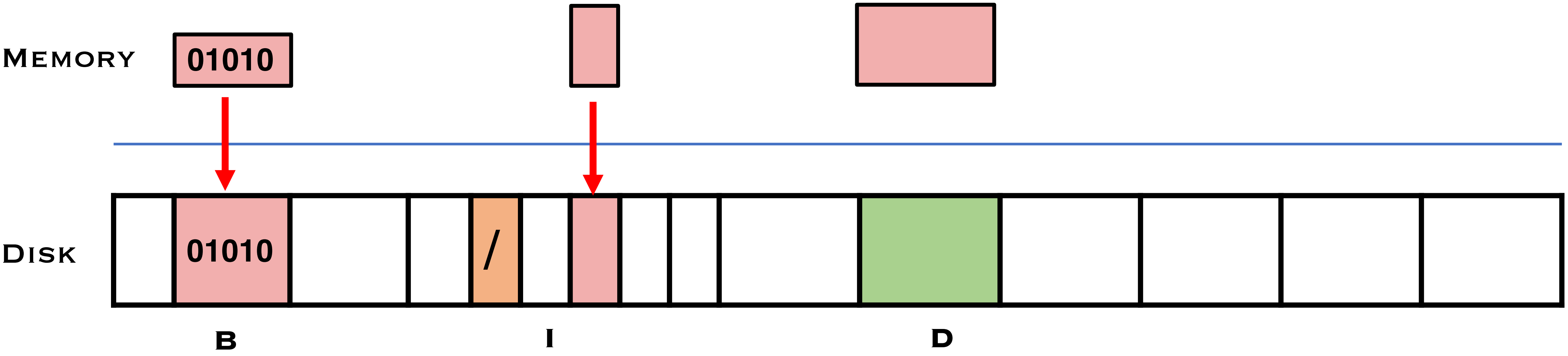
- **Result?**



Example: Inode First

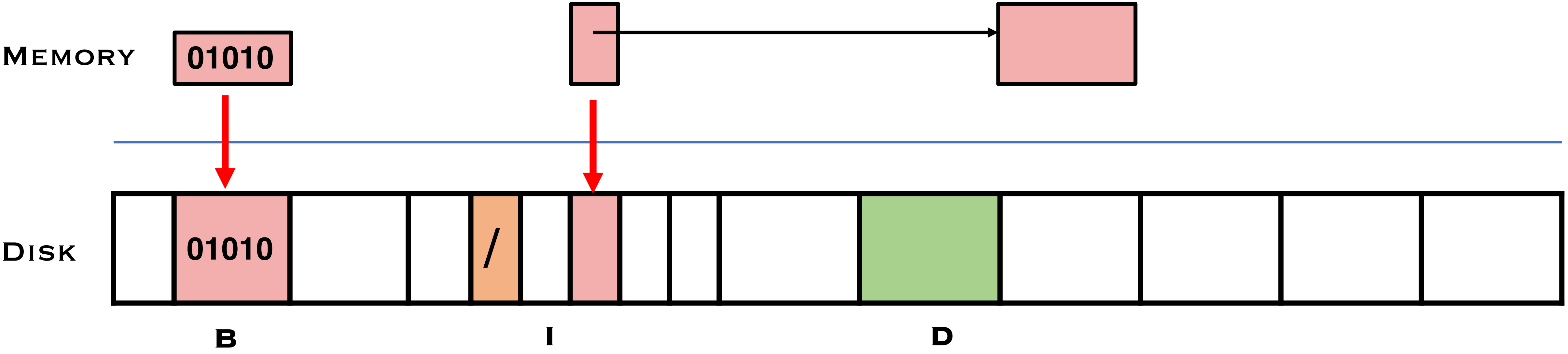
- **Write Ordering: Bitmap (B), Inode (I), Data (D)**
  - But CRASH after I AND B have reached disk, before D

- **Result?**



Example: Inode First

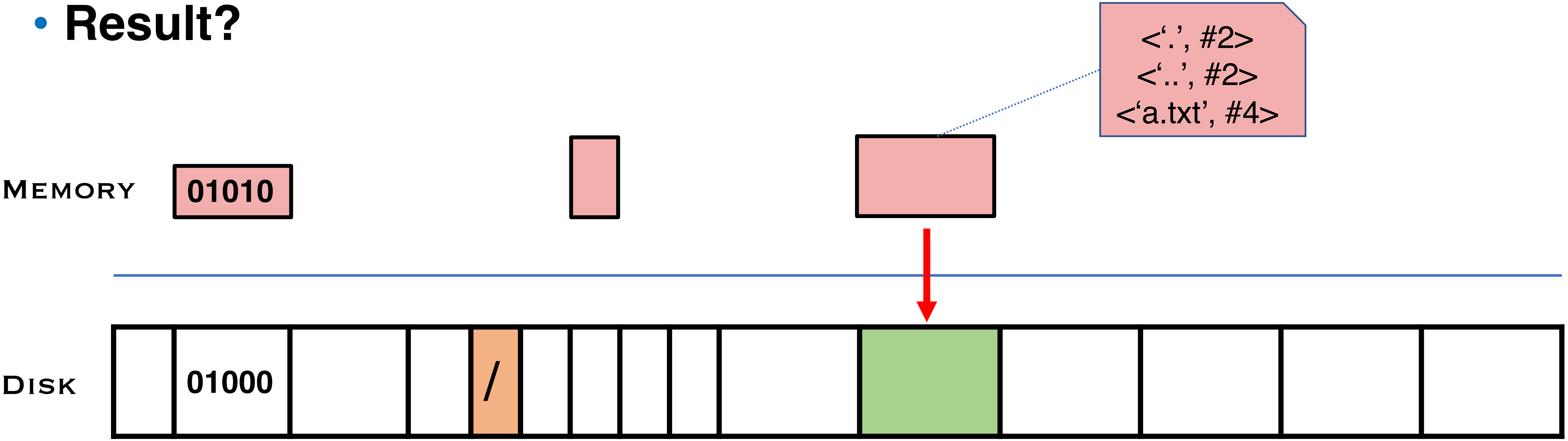
- **Write Ordering: Bitmap (B), Inode (I), Data (D)**
  - But CRASH after I AND B have reached disk, before D
- **Result?**
  - What if data block is a new block for the new file (i.e., create file with data)



Example: Data First

- **Write Ordering: Data (D) , Bitmap (B), Inode (I)**
  - CRASH after D has reached disk, before I or B

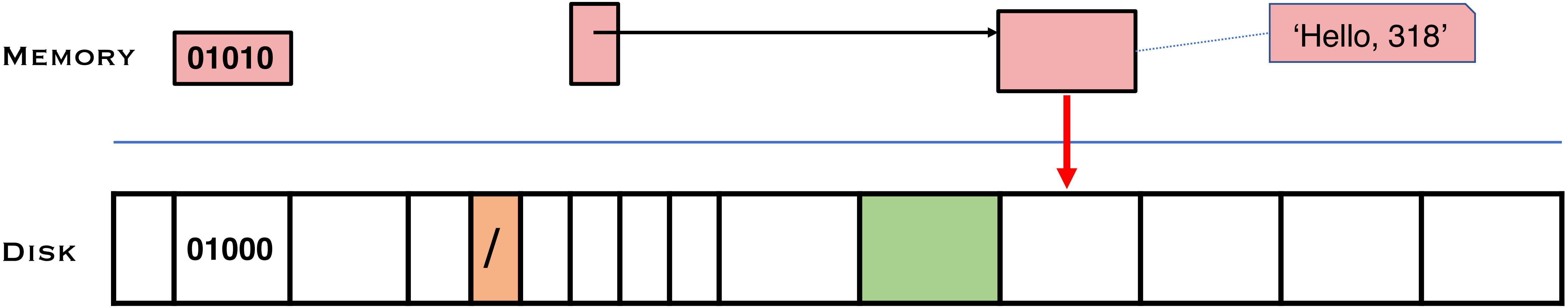
- **Result?**



Example: Data First

- **Write Ordering: Data (D) , Bitmap (B), Inode (I)**
  - CRASH after D has reached disk, before I or B

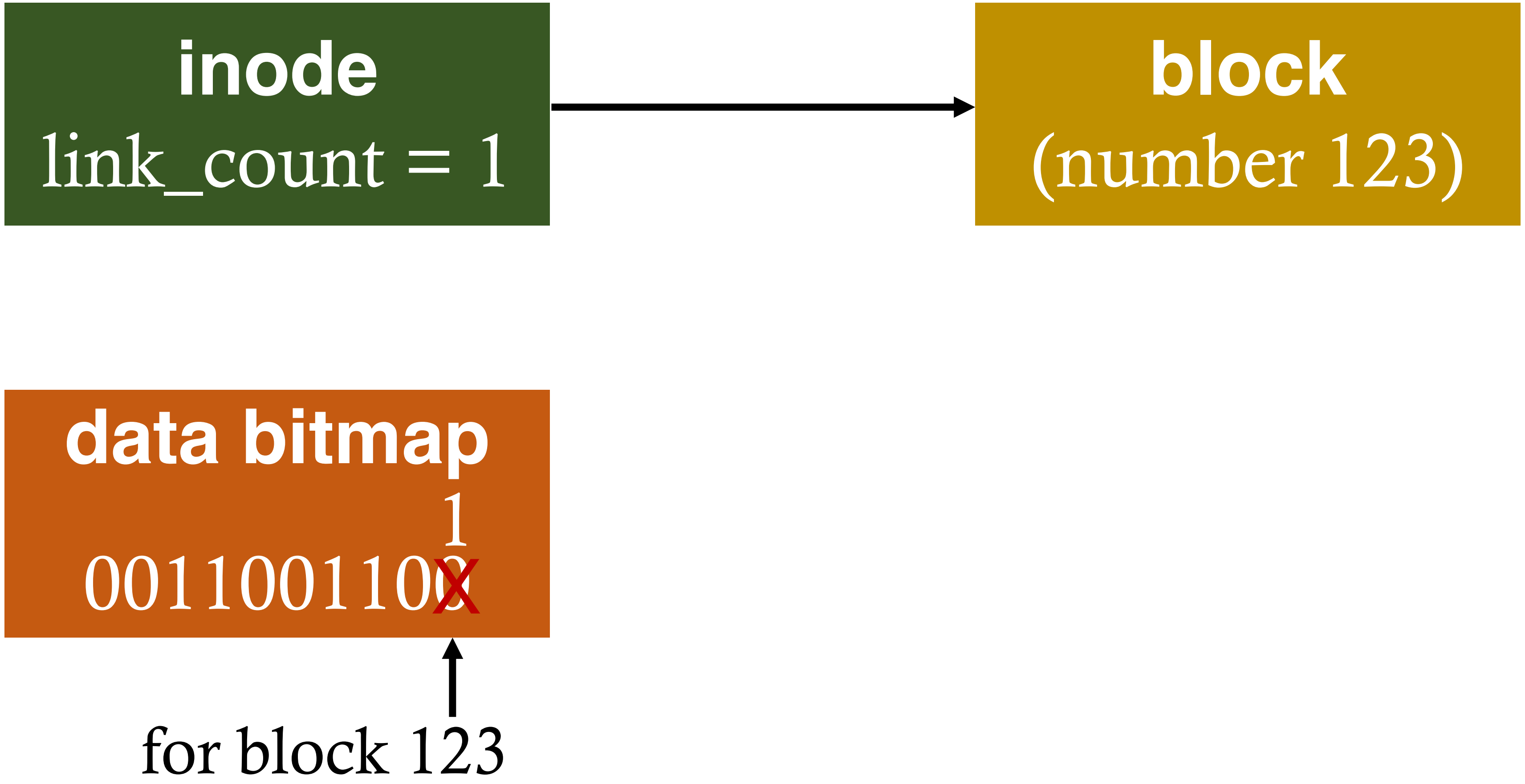
- **Result?**
  - What if data block is a new block for the new file (i.e., create file with data)



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



inode

link_count = 1

block

(number 123)

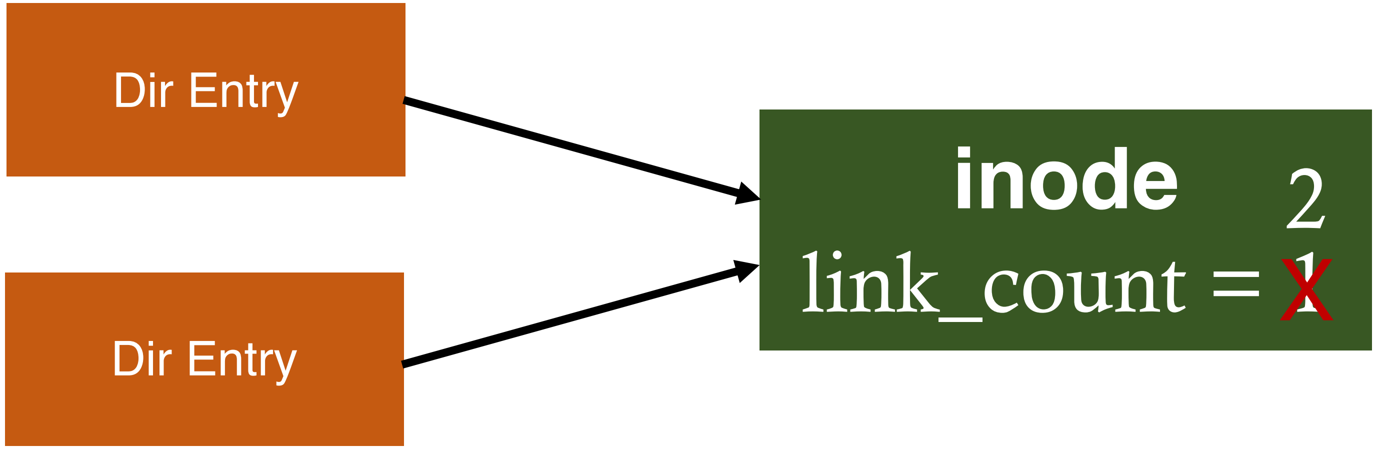
data bitmap

1

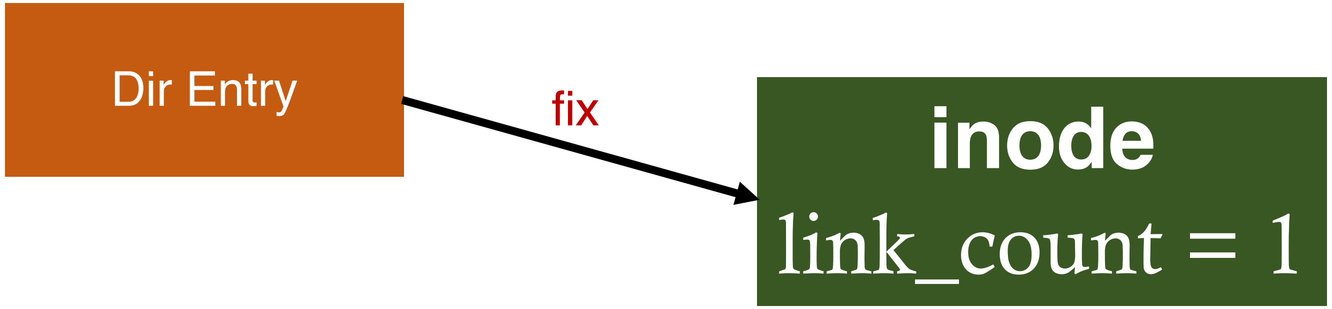
001100110~~0~~

for block 123

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/
...
```

Traditional Solution: FSCK

- **FSCK: “file system checker”**

- **When system boots:**
  - Make multiple passes over file system, looking for inconsistencies
  - Try to fix automatically or punt to admin
    - Example: B’ I D, B I’ D

- **Problem:**
  - Cannot fix all crash scenarios
    - Can B’ I D’ be fixed?
  - Performance
    - Sometimes takes hours to run on large disk volumes
    - Does fsck have to run upon every reboot?
  - Not well-defined consistency

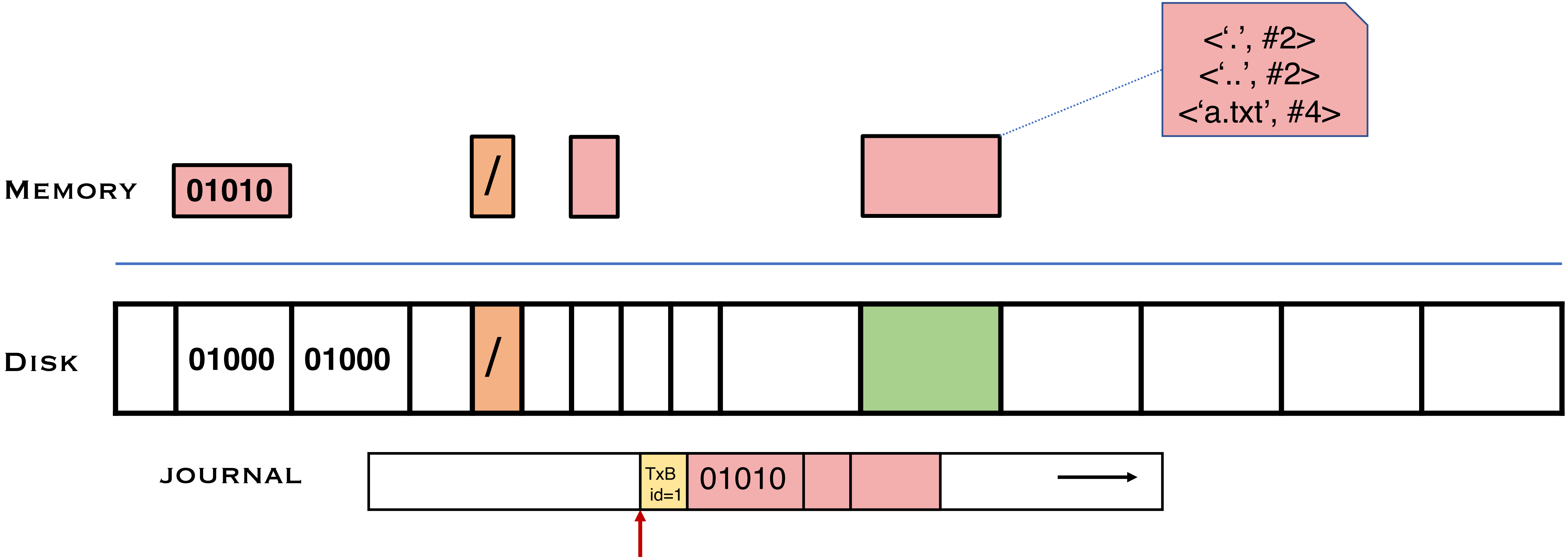
Another Solution: Journaling

- **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”

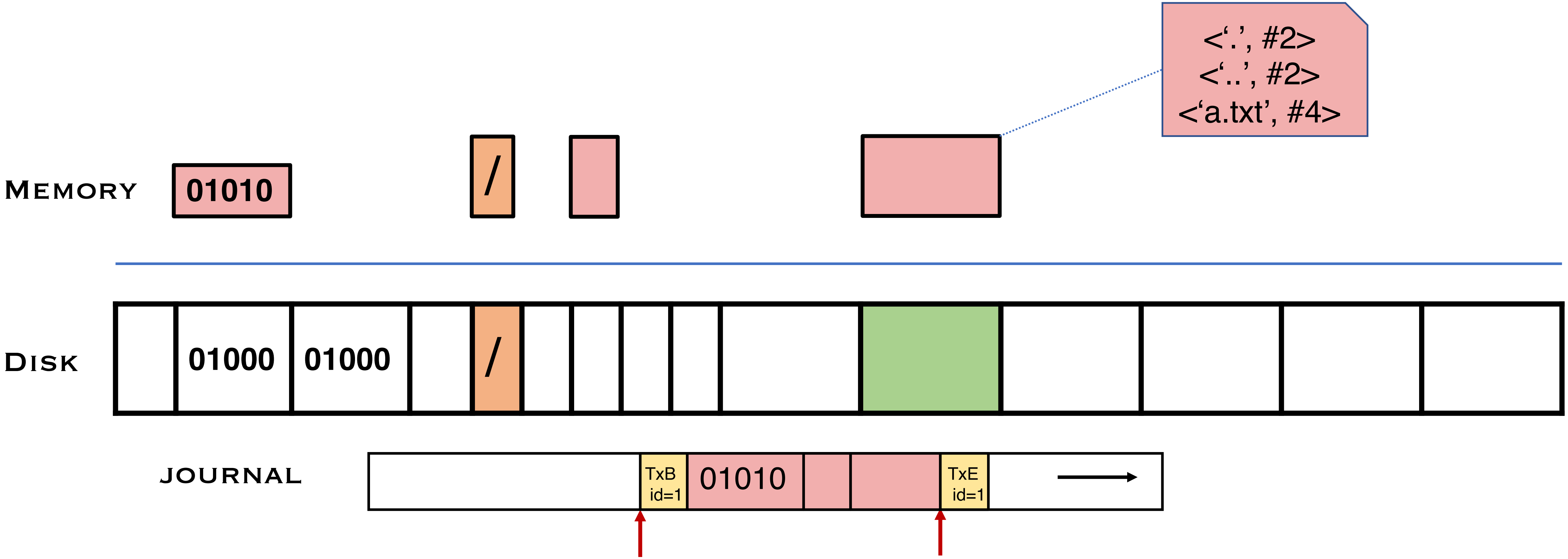
Case Study: Linux Ext3

- **Physical journaling: write real block contents of the update to log**
  - Four totally ordered steps
    - Commit dirty blocks to journal as one transaction (`TxBegin`, I, B, D blocks)
    - Write commit record (`TxEnd`)
    - Copy dirty blocks to real file system (checkpointing)
    - Reclaim the journal space for the transaction
- **Logical journaling: write logical record of the operation to log**
  - "Add entry F to directory data block D"
  - Complex to implement
  - May be faster and save disk space

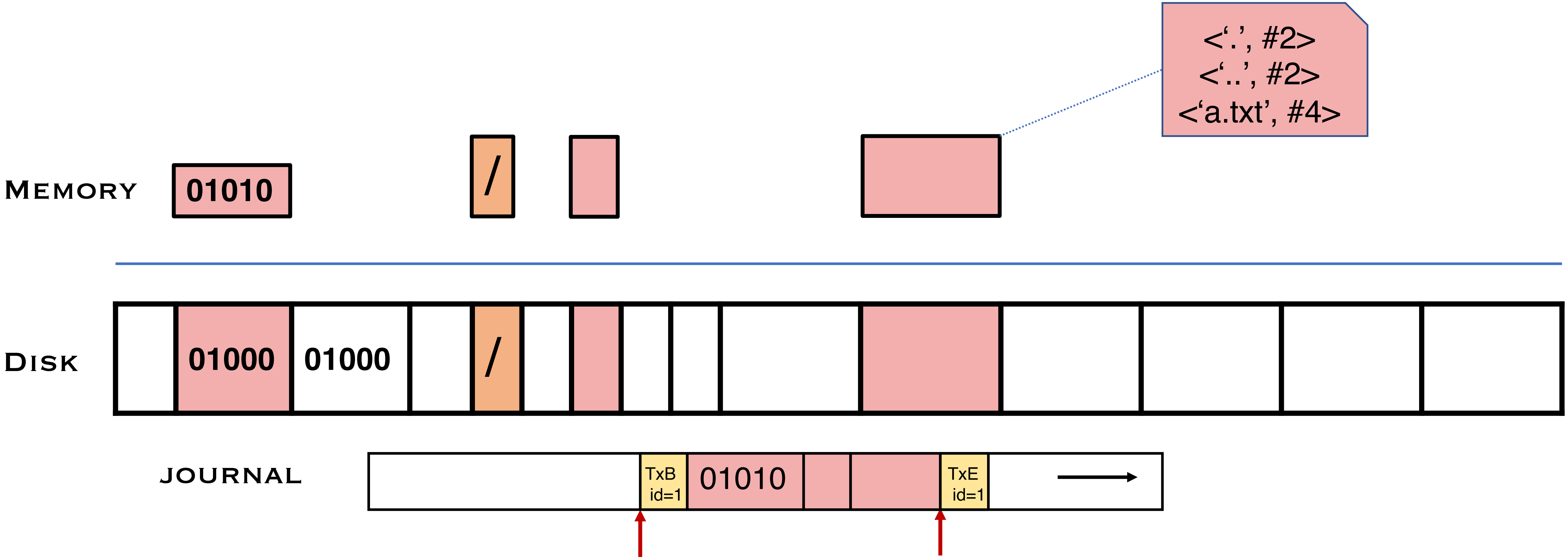
Step 1: Write Blocks to Journal



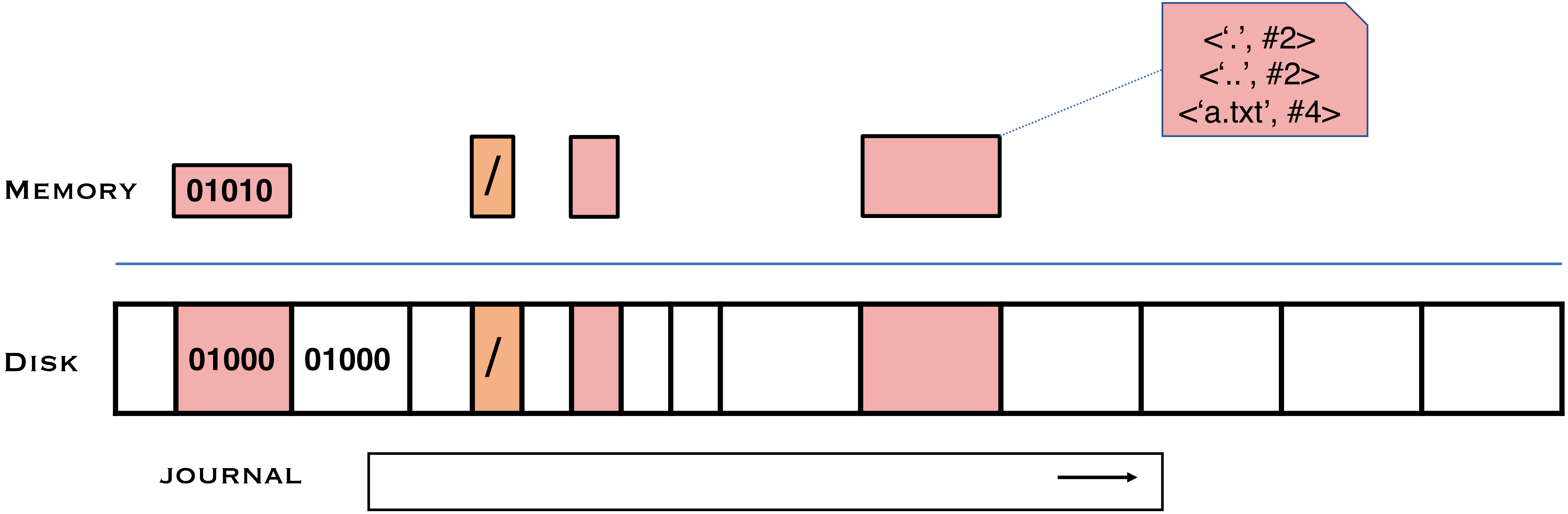
Step 2: Write Commit Record



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 I, B, and D have not yet been checkpointed?
    - How could this happen?
    - Why don’t we merge step 2 and step 1?
  - What if Tx is in log, I, B, D have been checkpointed, but Tx has not been 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)

Next Time…

- **Read Appendix B**