Persistence: Journaling

CS 537: Introduction to Operating Systems

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Administrivia

- Project 5 due Nov 19 @ 11:59pm
- Exam 2 regrade form

Review File System Implementation

- Data Structures
  - Superblock, inode and data bitmap, inode table, data blocks, directory entries
- Access Methods
  - How does a call like `open()`, `read()`, or `write()` get mapped onto the data structures of the disk?

Review Fast File System

- Treat the disk like it's a disk
  - Divide disk into **groups**
  - Each group gets superblock, block bitmap, inode bitmap, inode table, and data blocks
- *Keep related stuff together, keep unrelated stuff far apart*
  - Place directories in group with low number of directories but high number of free inodes
  - Place files (both data and inode) in group with directory
- Large File Exception

Quiz 17 Fast File System

https://tinyurl.com/cs537-fa24-q17

This lecture: crash consistency

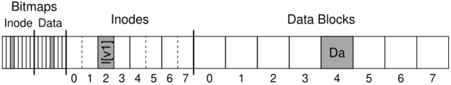
A crash could interrupt the system between any two writes.
How to **update the file system safely** despite this?

fsck and Journaling

- Crash Consistency Problem
- Solution 1: fsck
- Solution 2: Journaling
  - Data Journaling, Recovery, Metadata Journaling
- Solution 3: Other Approaches

Consistency in File System

The file system consists of several data structures which need to be **consistent with each other**.



```
owner       : remzi
permissions : read-write
size        : 1
pointer     : 4
pointer     : null
pointer     : null
pointer     : null
```

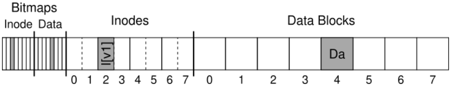
Consistency in File System

Consider the case of appending a single data block to an existing file. The following changes must occur:

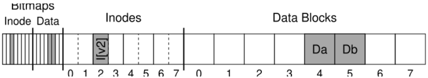
- Update block bitmap to acquire a free block
- Update inode to *I[v2]* and point to new data block
- Write data *Db* to new data block

If a crash happens after one or two of these writes have taken place, but not all three, the file system could be left in an **inconsistent state**.

Before:



After:



3 Crash Scenarios

- **Just the data block (Db) is written to disk**
  - Since the inode and data bitmap are not updated, the block is not attached to the file and could still be allocated.
  - FS is consistent but does not contain the new data in Db.
- **Just the updated inode (I[v2]) is written to disk**
  - Since inode is updated but data was not written to Db, garbage is attached to the end of the file
  - Since data bitmap was not modified, block could be allocated to a different file (**file system inconsistency**)
- **Just the updated bitmap is written to disk**
  - data block has not been attached to the file, resulting in a **space leak**

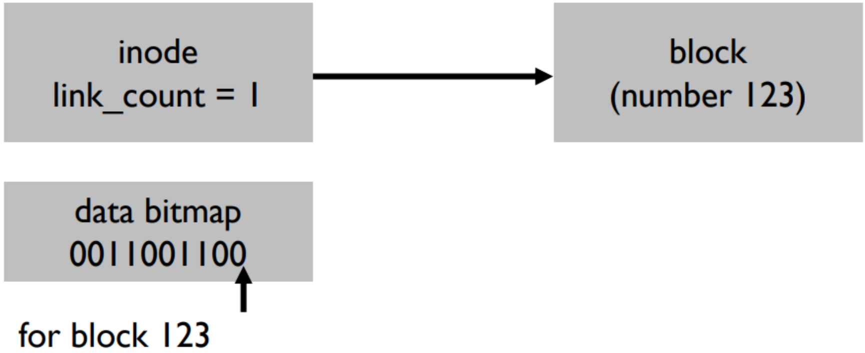
We want file system updates to happen **atomically** from one consistent state to another.

Solution #1: The File System Checker: `fsck`

Let inconsistencies happen, then fix by running `fsck`:

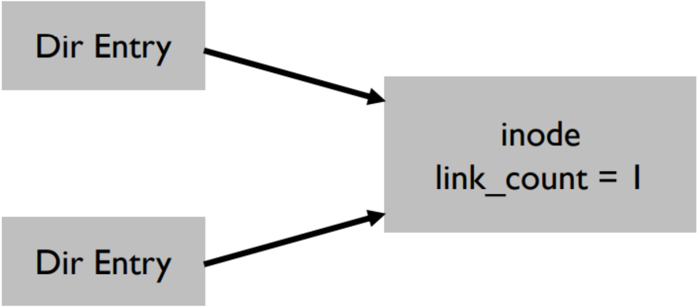
- First check **superblock**, that it looks reasonable.
- **Free blocks**: scan the inodes, direct blocks, indirect blocks, etc., to build a list of allocated and free data blocks. Compare this list with the data bitmap. Do the same for the inode bitmap compared to the inode table.
- **Inode state**: check for corruption, e.g. valid type field.
- **Inode links**: verify the link count
- **Duplicates**: Check for duplicate pointers to same data blocks
- **Bad Blocks**: Check for pointers outside range of valid data blocks
- **Directory Checks**: Integrity check (each directory contains a `.` and `..` pointer to proper values, inodes exist, each directory linked to once).

Free Blocks Example



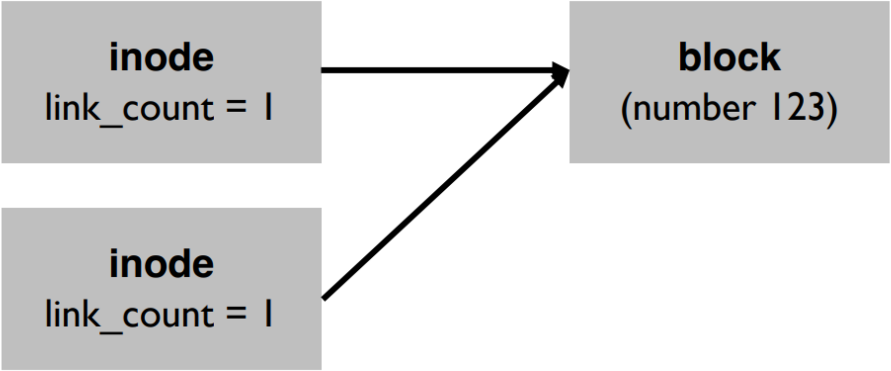
Block is unallocated but in inode

Link Count Example



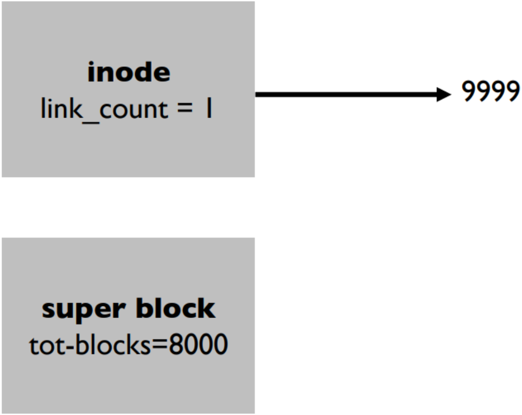
Link count is wrong

Duplicate Pointers



Block is in two inodes

Bad Pointer

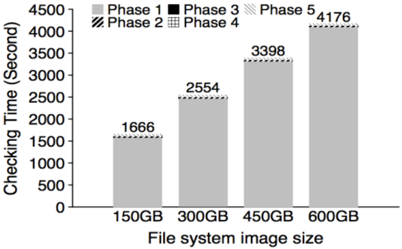


Pointer is to invalid block number

Problems with fsck

- Not always obvious how to fix
- Don't know "correct" state, just consistent state

Fundamental problem with fsck: too slow



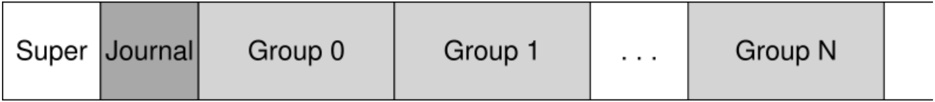
Checking a 600GB disk takes ~70 minutes

ffsck: fast file system checker
Ao Ma, Chris Dragga, Andrea C. Arpaci-Dusseau, and Remzi H. Arpaci-Dusseau

Solution #2: Journaling (or Write-Ahead Logging)

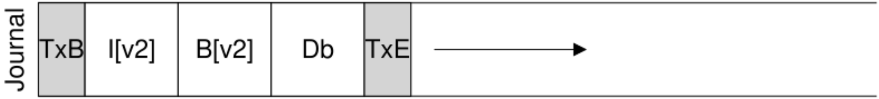
Before updating the disk, first write down a little note (in the **journal** on disk) describing what you are about to do.

On a crash during update, go back and look at the journal.



Adds a bit of work during update but greatly reduces work required during recovery

Data Journaling



1. **Journal write** – Write out TxB, I[v2], B[v2], and Db, wait for these to complete
2. **Journal commit** – Write out TxE, wait for this to complete, transaction is **committed**
3. **Checkpoint** – Write the contents of the update to their final on-disk locations

The TxB block contains information about the pending update (e.g. final addresses for blocks and a **transaction identifier**)
The disk guarantees any 512-byte write is atomic – the TxE is a single 512-bytes.

Recovery

Crashes can occur at any time:

- If occurs before the commit, the update is skipped
- If occurs after the commit but before the checkpoint finishes:
  - On boot, scan the log and look for committed transactions and **replay** them in order: called **redo logging**
  - In the worse case, a transaction might be performed again

Data journaling timeline

	Journal			File System	
TxB	Contents		TxE	Metadata	Data
	(metadata)	(data)			
issue	**issue**	**issue**			
complete					
	complete				
		complete			
			issue		
			complete		
				issue	**issue**
					complete
				complete	

Data Journaling

- Note the **write issue**s which can occur simultaneously
- Completion time is determined by the I/O subsystem, which may reorder writes to improve performance
- Horizontal dashed lines representing barriers waiting for completion of writes are enforced by FS for protocol correctness

Batching Log Updates

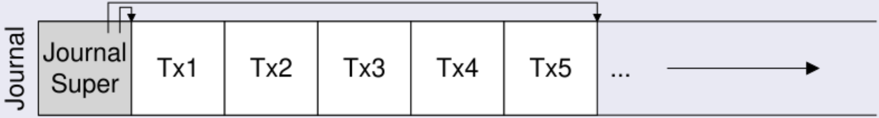
- This journaling protocol adds a lot of extra disk traffic
- Some FS do not commit each update one at a time, rather buffer all updates into a **global transaction**

Making Log Finite

Journaling file systems treat the log as a **circular log** adds a 4th step to protocol:

4. **Free**: some time later, mark the transaction free in the journal by updating the journal superblock

Journal Superblock keeps track of portion of journal with non-checkpointed transactions.



Metadata Journaling

Data journaling has high cost: each data block is written twice

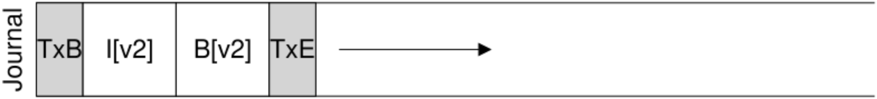
Ordered journaling or **metadata journaling** only puts metadata in journal

More complicated to get right

Metadata Journaling Protocol

By forcing data write first, a file system can guarantee that a pointer will never point to garbage – commonly used technique.

1. **Data write:** Write data to final location; wait for completion (optional)
2. **Journal metadata write:** Write the begin block and metadata to log; wait for completion
3. **Journal commit:** Write the transaction commit block (containing TxE)
4. **Checkpoint metadata:** Write the contents of the metadata to final locations
5. **Free:** Later, mark the transaction free in journal superblock



Tricky Case: Block Reuse

- User creates a file in directory `foo`. FS journal has a write to `foo`'s inode and its block 1000.
- User deletes `foo`, FS frees block 1000.
- User creates a new file which FS gives block 1000. FS directly writes to block 1000.

On crash, replay write to block 1000 with old `foo` contents, but these are now owned by a file

Linux's `ext` FS has **revoke** entries in log. Replaying first checks for these entries and doesn't replay entries that are revoked

Metadata journaling

Metadata Journaling

	Journal		File System	
TxB	Contents (metadata)	TxE	Metadata	Data
issue	**issue**			**issue**
				complete
complete				
	complete			
		issue		
		complete		
			issue	
			complete	

- Data is written once
- ext4 doesn't wait for data to be written - tricky to get right

Solution #3: Other Approaches / Ideas

- **Copy-On-Write (COW)**
  - Never overwrite in place: write new data, then point to it
  - Basis of **Log File System** (lecture next time), and ZFS and btrfs
- **Soft Updates**
  - Carefully order all writes to the FS
  - Requires intricate knowledge of each FS data structure
- **Backpointer-based Consistency (BBC)**
  - Developed here at UW
  - Every block contains a back-pointer, so data blocks point to the inode they belong to.
  - Consistency can be checked between the forward pointers in the inode with the backpointers

Summary

- Crash consistency is a key problem in file systems
- Journaling is a key technique to make crash consistency easy