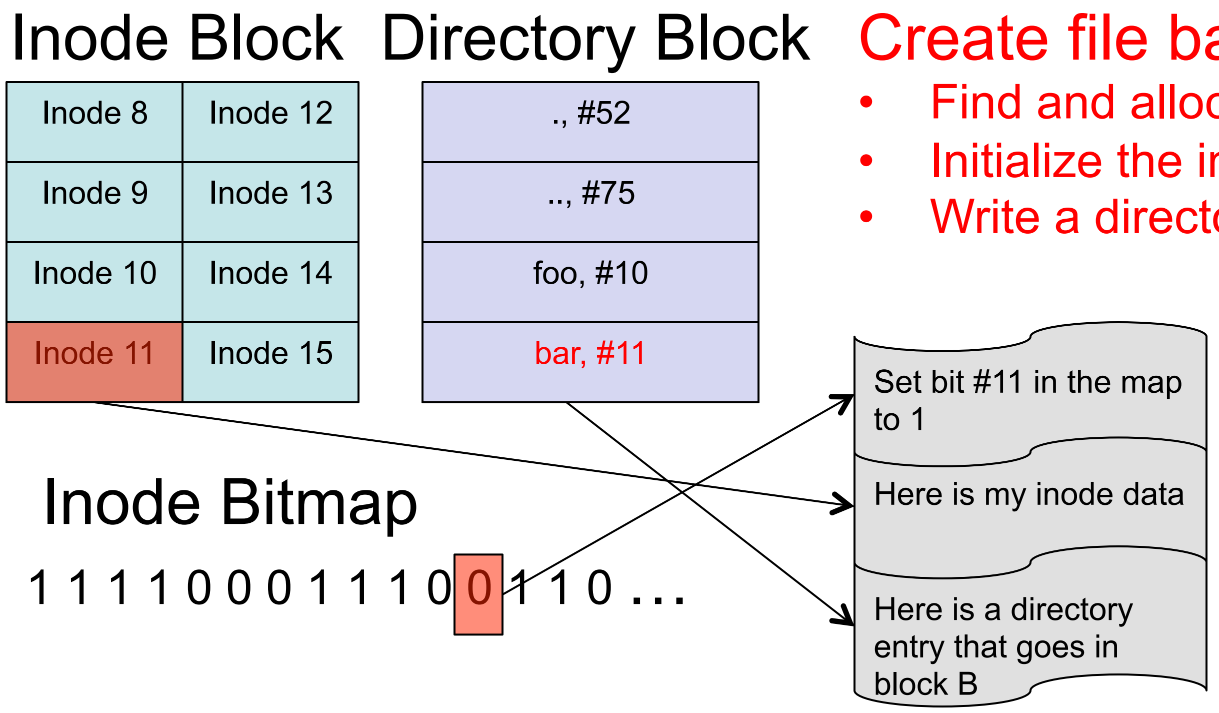
Journaling File Systems

- Learning Objectives
  - Explain log journaling/logging can make a file system recoverable.
  - Discuss tradeoffs inherent in journaling.
  - Identify shortcomings in journaling file systems
- Topics
  - Notes we leave to help us recovery a file system: a log
  - Different approaches to logging
  - Checkpointing

Log Records

- Log records are “notes” that the running file system leaves for the recovery process.



Create file bar

- Find and allocate an inode
- Initialize the inode
- Write a directory entry

What do we do after a crash?

- Read the notes:
  - Use the notes to figure out what you need to do to make the file system consistent after the crash.
  - Might need to undo some operations; why/when?
  - Might need to redo some other operations; why/when?
- Using database parlance, we call these “notes” a log.
  - The act of reading the log and deciding what to do is called recovery.
  - Backing out an operation is called undoing it.
  - Re-applying the operation is called redoing it.

Is this a good idea?

- Why is this logging and recovery better than simply writing the data synchronously?
  - Synchronous writes can appear anywhere on disk.
  - The log is typically a contiguous region of disk, so writing to it is usually quite efficient.
  - You can buffer data in memory longer.

Journaling File Systems: A Rich History

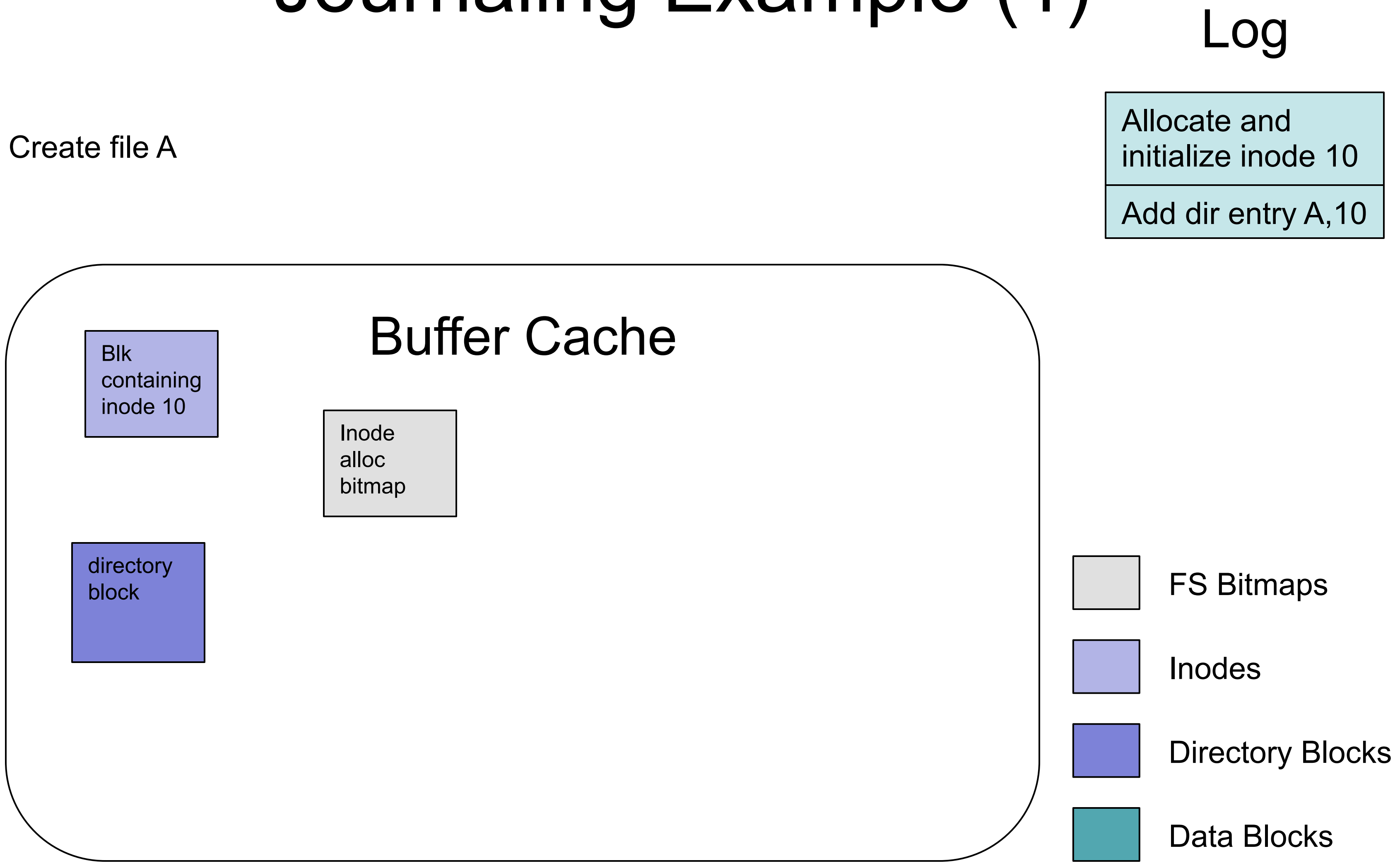
- The Database Cache (1984)
  - Write data to a sequential log.
  - Lazily transfer data from the sequential log to actual file system.
- The Cedar File System (1987)
  - Log meta-data updates.
  - Log everything twice to recover from any single block failure.
  - Data is not logged.
- IBM's JFS (1990)
  - Log meta-data to a 32 MB log.
  - Also uses B+ tree for directories and extent descriptors.
- Veritas VxFS (1990 or 1991)
  - Maintain and intent log of all file system data structure changes.
  - Data is not logged.
- Many journaling file systems today; some log meta-data only; some log data too; some make data logging optional
  - Ext3
  - Reiser
  - NTFS
  - ZFS
  - BTRFS
  - …

Journaling/Logging

- Motivation
  - Sequential writes are fast; random writes are slow.
  - Meta-data operations typically require multiple writes to different data structures (e.g., inodes and directories).
  - Logging/Journaling converts random I/Os to sequential ones.
- How a journaling file system works
  - Before writing data structure changes to disk, write a log record that describes the change.
  - Log records typically contain either or both:
    - REDO Information: describes how to apply the update in case the data does not make it to disk.
    - UNDO: Information: describes how to back out the update in case the data gets to disk but shouldn't (because some other update never made it to the disk or the log).
  - Make sure that log records get to disk before the data that the log record describes (write-ahead logging or WAL).
  - After a system crash, replay the log and redo/undo operations as appropriate to restore file system to a consistent state.

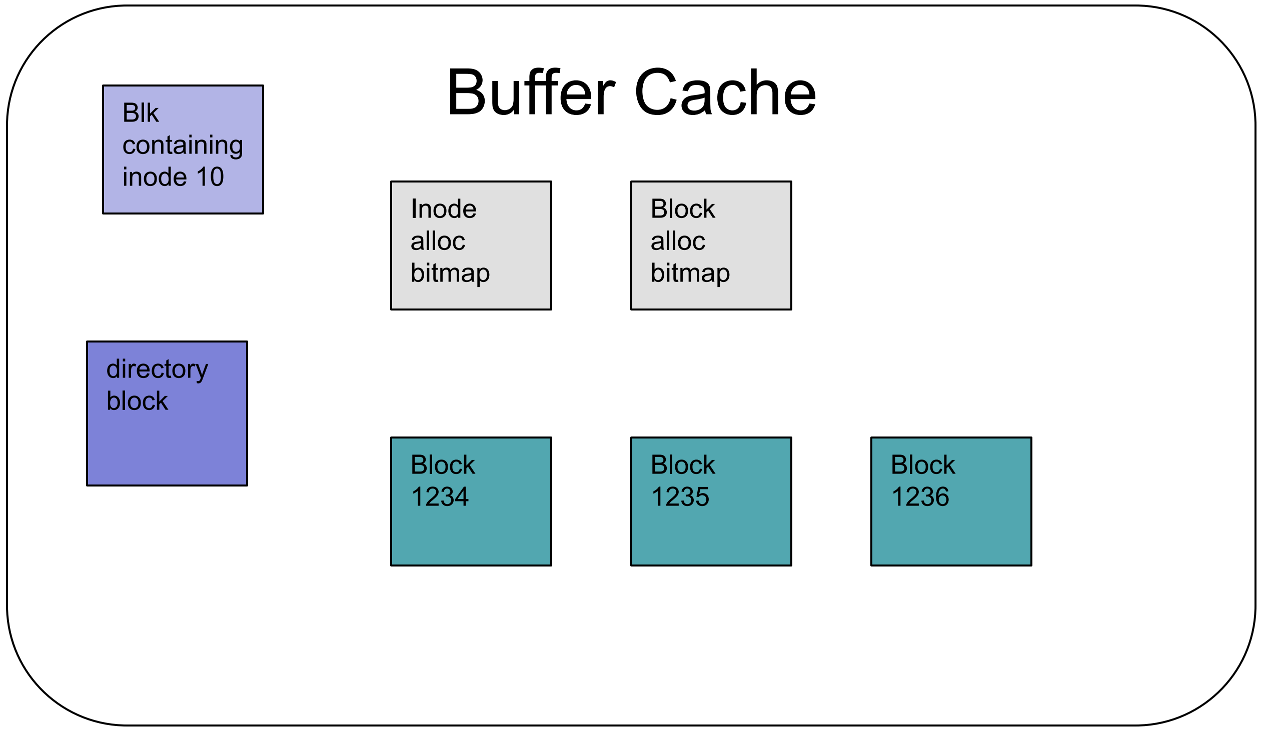
Journaling Example (1)

Create file A



Journaling Example (2)

Create file A
Write blocks 0-2 to file A



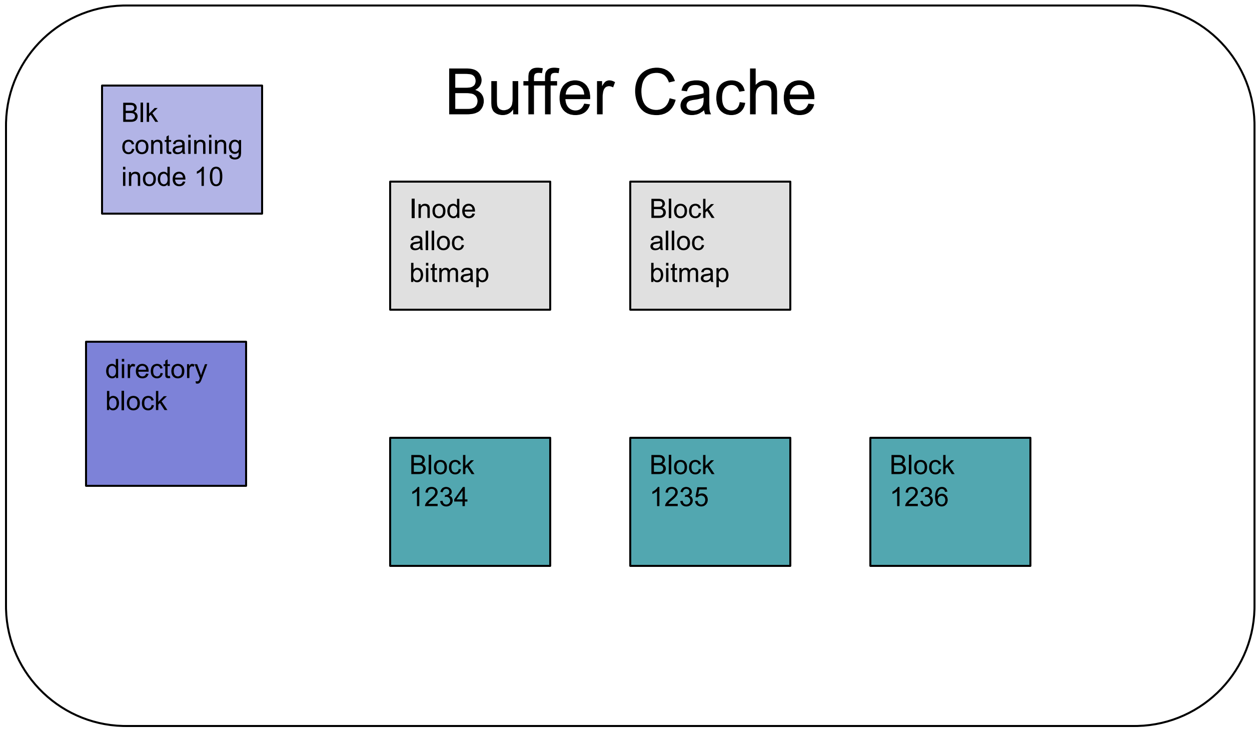
Log

Allocate and initialize inode 10
Add dir entry A,10
Alloc block 1234 to inode 10; lbn 0
Alloc block 1235 to inode 10; lbn 1
Alloc block 1236 to inode 10; lbn 2

⬜	FS Bitmaps
🟪	Inodes
🟦	Directory Blocks
🟩	Data Blocks

Journaling Example (3)

Create file a
Write blocks 0-2 to file A
Delete file A



Log

Remove directory entry A,10
Free block 1234
Free block 1235
Free block 1236
Clear inode 10
Deallocate inode 10

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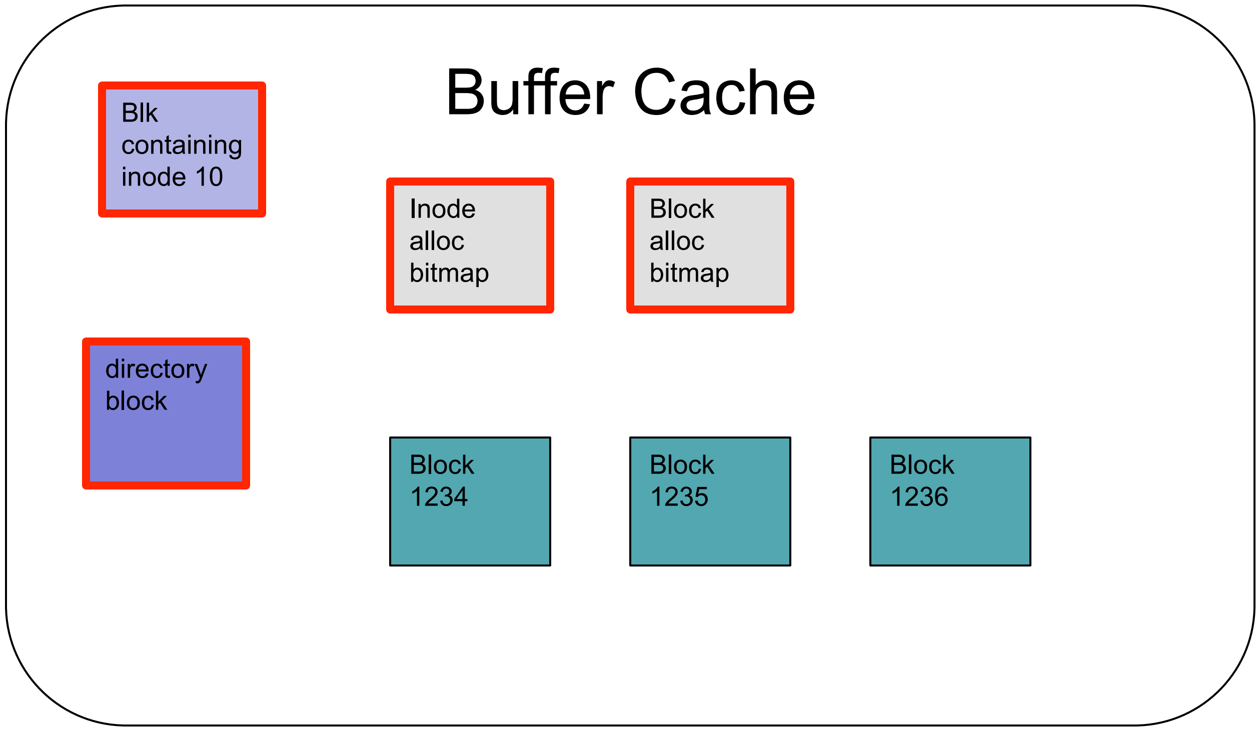
Journaling Example (4)

Create file a
Write blocks 0-2 to file A
Delete file A



Log

- Remove directory entry A,10
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Operations versus Transactions

- Notice that a single file system API call consists of multiple operations:
  - API call: create file A
  - Operations:
    - Allocate inode
    - Initialize inode
    - Create directory entry
- There are a number of different ways that one could record this information in a log record…

Approaches to Logging: Granularity

- Logical logging
  - Write a single high level record that describes an entire API call: allocate inode 10, initialize it, and create a new directory entry in directory D that names inode 10 “a”
- Physical logging
  - Write a log record per physical block modified:
    - (inode allocation) Here is the old version of page 100; here is the new version (they differ by one bit)
    - (initialize inode) Here is the old version of a block of inodes; here is the new version.
    - (directory entry) Here is a the old version of a block of a directory; here is the new version.
- Operation logging
  - Write a log describing a modification to a data structure:
    - “Allocate inode 10” or “change bit 10 on page P from 0 to 1”
    - “Write the following values into inode 10” or “change bytes 0-31 from these old values to these new values”
    - Add the directory entry <a, 10> into directory D or “change bytes N-M from these old values to these new values”

“Big Records” vs “Small Records”

- The fundamental difference between high level logical logging and low level operation logging is whether each API call translates into one or more records.
- One record:
    - You can consider the operation done once you have successfully logged that record.
- Multiple records:
    - You may generate records, but not get all the way to the end of the sequence of records and then experience a failure: in that case, even though you have some log records, you can’t finish the complete whatever you were doing, because you don’t have all the information.
    - A partial sequence must be treated as a failure during recovery.

Transactions

- We call the sequence of operations comprising a single logical operation (API call) a transaction.
- Transactions come from the database world where you want to apply multiple transformations to a data collection, but have all the operations appear atomically (either all appear or non appear).
- In the database world, we use the ACID acronym to describe transactions:
  - A: Atomic: either all the operations appear or none do
  - C: Consistent: each transaction takes the data from one consistent state to another.
  - I: Isolation: each transactions behaves as if it's the only one running on the system.
  - D: Durable: once the system responds to a commit request, the transaction is complete and must be complete regardless of any failures that might happen.

File System Transactions

- File systems typically abide by the ACI properties, but may not guarantee durability.
  - Example: we might want the write system call to follow the ACI properties, but we may not require a disk write and might tolerate some writes not being persistent after a failure.
- Transactions:
  - Are an elegant way to deal with error handling (just abort the transaction).
  - Let you recover after a failure: roll forward committed transactions; roll back uncommitted ones.

Transaction APIs

- Begin transaction
- Commit transaction: make all the changes appear
- Abort transaction: make all the changes disappear (as if the transaction never happened).
- Prepare (used for distributed transactions, but we don’t need it here).

- For recovery purposes, any transaction that does not commit is aborted.

What to log: Undo/Redo

- Undo information lets you back out things during recovery.
  - Under what conditions might you want to back out things?
  - Assuming that we only use the log to recover after a failure, under what conditions would you never need UNDO records?
- Redo information lets you roll a transaction forward.
  - Under what conditions might you need to do this?
  - Under what conditions would you never need REDO records?

What to log: Undo/Redo

- Undo information lets you back out things during recovery.
  - Under what conditions might you want to back out things?
    - An API call did not finish, but has started modifying some data.
  - Assuming that we only use the log to recover after a failure, under what conditions would you never need UNDO records?
    - If any data in an active transactions is never allowed to go to disk.
- Redo information lets you roll a transaction forward.
  - Under what conditions might you need to do this?
    - A transaction completed, but not all the data got written to disk.
  - Under what conditions would you never need REDO records?
    - Part of the commit required writing all the changes to disk.

Managing Log Space

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  - Allocate more?
  - Reuse space?

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  - Reuse space?
    - How?

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    - How? Circular buffer
    - What conditions must we enforce?

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  - Reuse space?
    - How? Circular buffer
    - What conditions must we enforce?
      - The log records we're overwriting must not be necessary any more.
      - Log records become unnecessary when the data they describe is safely on the disk.
    - Desirable properties:
      - It would be nice if we never actually ran out of disk space and had to block until we forced a bunch of data to disk.

Checkpointing

- The process of delineating parts of the log that are still required for recovery and parts that are no longer required.
- Checkpointing services two purposes:
  - Lets you reclaim disk space
  - Bounds recovery time
- A checkpoint typically marks a specific place in the log, indicating that updates described before the checkpoint have been safely written to disk, so log space can be reclaimed.
- It also marks the point from which recovery starts.

Types of Checkpoints (1)

- Stop-the-world
  - Stop accepting new operations.
  - Flush all dirty buffers.
  - After dirty buffers are all written, write a checkpoint record to the log.
  - Challenges:
    - What about partially completed transactions?
    - Doesn't this cause a big performance hit?

Types of Checkpoints (2)

- Fuzzy checkpointing
  - Identify a point in the log before which there are no active transactions. (Call that point, C.)
  - Start writing all dirty buffers to disk. *
  - When all the writes complete, write a log record that indicates that a checkpoint for point C is complete.

  * Technically, you need only flush buffers with updates described in log records prior to C; sometimes it's difficult to identify those.

Types of Checkpoints (3)

- Static Checkpointing
  - Divide the log into some number of chunks (probably >= 3).
  - We're going to take checkpoints on a chunk basis.
  - When you fill up a chunk, begin writing all the dirty blocks associated with that chunk.
  - When those writes complete, the chunk can be reused. *
  - Challenges:
    - What if an operation spans multiple chunks?
    - What if a single operation requires more space than can fit in a chunk?
    - Speaking of that – what if a single operation consumes more space than the entire log?
    - Which operation do you think might consume the greatest amount of log space?
    - And how will you handle it?

A4 Implementation Details

- We provide:
  - A log container into which you can write records and from which you can read and iterate over records during recovery. You will want to become familiar with the APIs to this code.
- We require:
  - Operation logging
  - Log only metadata: your goal is to make sure that the meta data of the file system is consistent after recovery; you need not guarantee that all the data is intact.
- We recommend:
  - UNDO/REDO logging
  - Thinking carefully about when you can force the log to disk and when you must force the log to disk.