COS 318: Operating Systems

File Caching and Reliability

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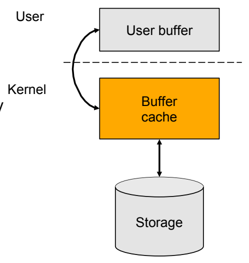
(http://www.cs.princeton.edu/courses/cos318/)

Topics

- Motivating the Problem: File buffer cache
- Possible Solutions

File Buffer Cache

- A large cache in kernel
- Read: check if the block is in
  - Yes: Copy block to user buffer
  - No: Read from storage to buffer cache and copy to user buffer
- Write: check if the block is in
  - Yes: Update it with user buffer
  - No: Copy block to buffer cache (may replace a block). Write the block.
- Usual questions
  - What to cache?
  - How to size the cache?
  - What to prefetch?
  - How and what to replace?
  - Which write policies?

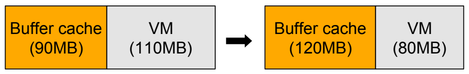


What to Cache?

- For different kinds of blocks
  - i-nodes
  - Indirect blocks
  - Directories
  - Data blocks
- Issues
  - Are all blocks equal?

Buffer Cache Size

- Competition
  - Competes with VM and the rest of the system for memory
- Two approaches
  - Fixed size
  - Variable size
- How to adjust buffer cache size?
  - Users make decisions
  - Working set idea with dynamic adjustments within thresholds



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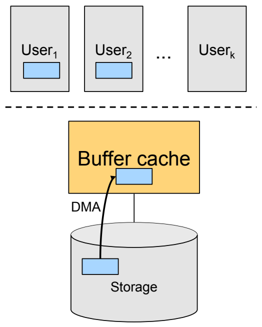
Why in the Kernel?

- DMA
  - DMA works with "pinned" physical memory
- Multiple user processes
  - Share the buffer cache
- Typical replacement strategy
  - Global LRU
  - Working set for each process



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What to Prefetch?

- Optimal
  - Prefetch in just enough time to use them
- Good news: file accesses have locality
  - Temporal locality
  - Spatial locality
- Common strategies
  - Prefetch next k blocks together
  - Discard unreferenced blocks
  - Layout consecutive blocks to the same cylinder group
  - Fetch directory and i-nodes together
- Advanced strategy
  - Prefetch all small files of a directory
  - Prefetch beginning portions of large files

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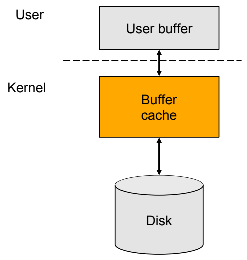
Write Policies

- Write through
  - Write to storage immediately
  - Cache is consistent
  - Simple, but cause more I/Os
- Write back
  - Update a block in buffer cache and mark it as dirty write to storage later
  - Fast writes, absorbs writes, and enables batching
  - So, what's the problem?



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Write Back Complications

- Tension
  - On crash, all modified data in cache is lost.
  - Postpone writes ⇒ better performance but more damage
- When to write back
  - When a block is evicted
  - When a file is closed
  - On an explicit flush
  - When a time interval elapses (30 seconds in Unix)
- Issues
  - These options have no guarantees about written data being lost

File System Reliability

- What if disk loses power or machine crashes?
  - Some operations in progress may complete
  - Some operations in progress may be lost
  - Overwrite of a block may be only partially complete
- File system wants durability (as a minimum)
  - Data previously stored can be retrieved (maybe after some recovery step), regardless of failure

Multiple Updates

- If multiple updates needed to perform some operations, a crash can occur between them
  - Moving a file between directories:
    - Delete file from old directory
    - Add file to new directory
  - Create new file
    - Allocate space on disk for header, data
    - Write new header to disk
    - Add the new file to directory
- What if there is a crash in the middle?
- Problems even with write-through cache

Storage Reliability Problem

- Single logical file operation can involve updates to multiple physical disk blocks
  - inode, indirect block, data block, bitmap, …
- At a physical level, operations complete one at a time
  - But we want higher level concurrent operations for performance
- How do we guarantee consistency regardless of when crash occurs?

Approaches

- Throw everything away and start over
  - Done for most things (e.g., make again)
  - What about your email?
- Check, and recover what you can when stuff gets corrupted: Reconstruction
  - Try to fix things after a crash (e.g. "fsck")
  - Figure out where you are, make file system consistent

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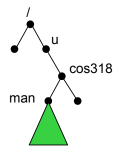
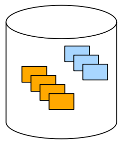
Reconstruction: File Recovery Tools

- Physical backup (dump) and recovery
  - Dump disk block by block to a backup system
  - Backup only changed blocks since the last backup as an incremental
  - Recovery tool is made accordingly
- Logical backup (dump) and recovery
  - Traverse the logical structure from the root
  - Selectively dump what you want to backup
  - Verify logical structures as you backup
  - Recovery tool selectively move files back
- Consistency check (e.g. fsck)
  - Start from the root i-node
  - Traverse the whole tree and mark reachable files
  - Verify the logical structure
  - Unreachable blocks are free
  - Lots of other consistency checks on superblocks, inodes, data blocks etc.





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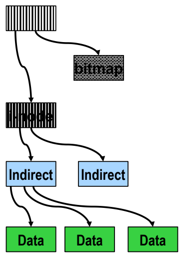
Recovery from Disk Block Failures

- Boot block
  - Create a utility to replace the boot block
  - Use a flash memory to duplicate the boot block and kernel
- Super block
  - If there is a duplicate, remake the file system
- Free block data structure
  - Search all reachable blocks from the root
  - Unreachable blocks are free



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Approaches

- Throw everything away and start over
  - Done for most things (e.g., make again)
  - What about your email?
- Check, and recover what you can when stuff gets corrupted: Reconstruction
  - Try to fix things after a crash (e.g. "fsck")
  - Figure out where you are, make file system consistent
- Try to not let stuff get corrupted:
  1. Careful ordering to make consistent updates
  2. Copy on Write
  3. Logging and transactions

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Careful Ordering: Write Metadata First

- Modify /u/cos318/foo
  - Traverse to /u/cos318/

Crash Consistent

  - Allocate data block

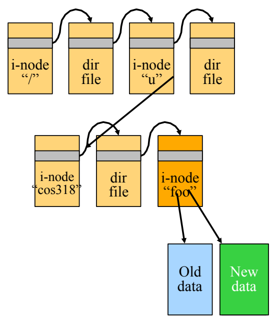
Crash Consistent

  - Write pointer into i-node

Crash Inconsistent

  - Write new data to foo

Crash Consistent



Writing metadata first can cause inconsistency

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Write Data First

- Modify /u/cos318/foo
  - Traverse to /u/cos318/

Crash Consistent

  - Allocate data block

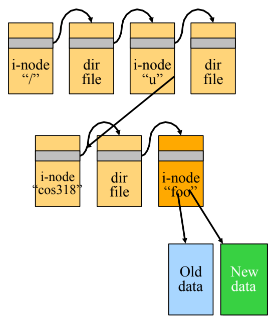
Crash Consistent

  - Write new data to foo

Crash Consistent

  - Write pointer into i-node

Crash Consistent



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1. Consistent Updates: Bottom-Up Order

- The general approach is to use a "bottom up" order
  - File data blocks, file i-node, directory file, directory i-node, …
- What about file buffer cache
  - Write back all data blocks
  - Update file i-node and write it to disk
  - Update directory file and write it to disk
  - Update directory i-node and write it to disk (if necessary)
  - Continue until no directory update exists
- Solve the write back problem?
  - Updates are consistent but leave garbage blocks around
  - May need to run fsck to clean up once a while
- Ideal approach: consistent update without leaving garbage

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Careful Ordering in General

- Sequence operations in a specific order
  - Careful design to allow sequence to be interrupted safely
- Post-crash recovery
  - Read data structures to see if there were any operations in progress
  - Clean up/finish as needed
- Approach taken in FAT, FFS (fsck), and many app-level recovery schemes (e.g., Word)

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Careful ordering

- Pros
  - Works with minimal support in the disk drive
  - Works for most multi-step operations
- Cons
  - Can require time-consuming recovery after a failure
  - Difficult to reduce every operation to a safely interruptible sequence of writes
  - Difficult to achieve consistency when multiple operations occur concurrently
  - Garbage left around that needs to be collected

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2: Copy-on-Write

- Never update in place
  - To update file system, write a new version of the blocks/data structures containing the update
  - Reuse existing unchanged disk blocks
- Seems expensive. But:
  - Updates can be batched
  - Almost all disk writes can occur in parallel
- Approach taken in network file server appliances (WAFL, ZFS)

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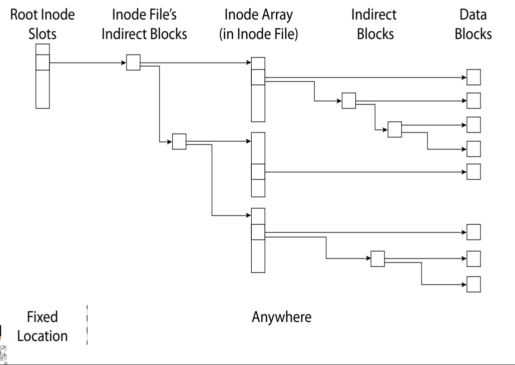
Copy on Write



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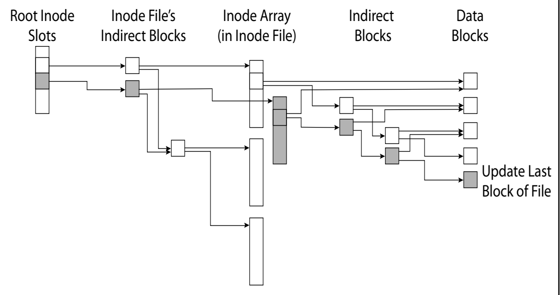
Copy on Write


Root Inode Slots
Inode File's Indirect Blocks
Inode Array (in Inode File)
Indirect Blocks
Data Blocks
Update Last Block of File

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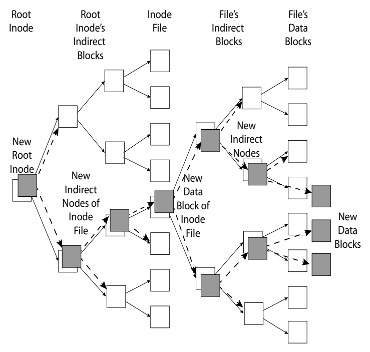
Copy on write batch update



Copy-on-Write Garbage Collection

- For write efficiency, want contiguous sequences of free blocks
  - Spread across all block groups
  - Updates leave dead blocks scattered
- For read efficiency, want data read together to be in the same block group
  - Write anywhere leaves related data scattered

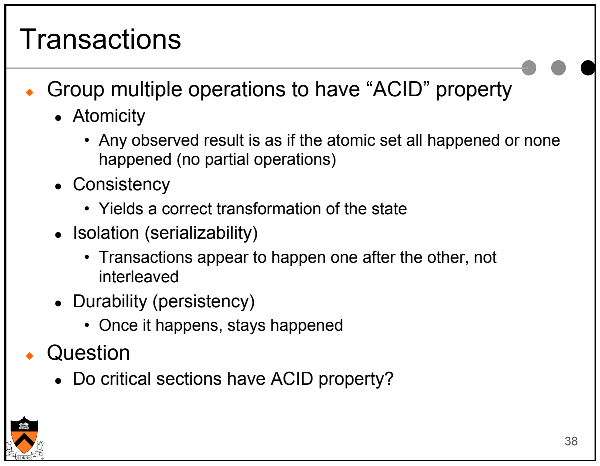
=> Background coalescing of live/dead blocks

Copy-on-Write

- Pros
  - Consistent behavior regardless of failures
  - Fast recovery (root block array)
  - High throughput (best if updates are batched)
- Cons
  - Potential for high latency
  - Small changes require many writes
  - Garbage collection essential for performance
    - Updates leave dead blocks scattered, but want contiguous free blocks and grouped related data

3: Logging and Transactions

- Instead of modifying data structures on disk directly, write changes to a journal/log
  - Intention list: set of changes we intend to make
  - Log/Journal is **append-only**
- Once changes are on log, safe to apply changes to data structures on disk
  - If there is a crash, recovery can read log to see what changes were intended
- Once changes are copied, safe to remove log



Transactions

- Group multiple operations to have "ACID" property
  - Atomicity
    - Any observed result is as if the atomic set all happened or none happened (no partial operations)
  - Consistency
    - Yields a correct transformation of the state
  - Isolation (serializability)
    - Transactions appear to happen one after the other, not interleaved
  - Durability (persistency)
    - Once it happens, stays happened
- Question
  - Do critical sections have ACID property?

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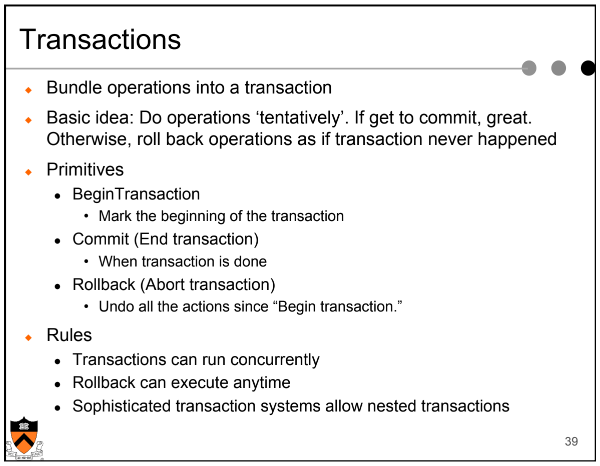

Transactions

- Bundle operations into a transaction
- Basic idea: Do operations 'tentatively'. If get to commit, great. Otherwise, roll back operations as if transaction never happened
- Primitives
  - BeginTransaction
    - Mark the beginning of the transaction
  - Commit (End transaction)
    - When transaction is done
  - Rollback (Abort transaction)
    - Undo all the actions since "Begin transaction."
- Rules
  - Transactions can run concurrently
  - Rollback can execute anytime
  - Sophisticated transaction systems allow nested transactions

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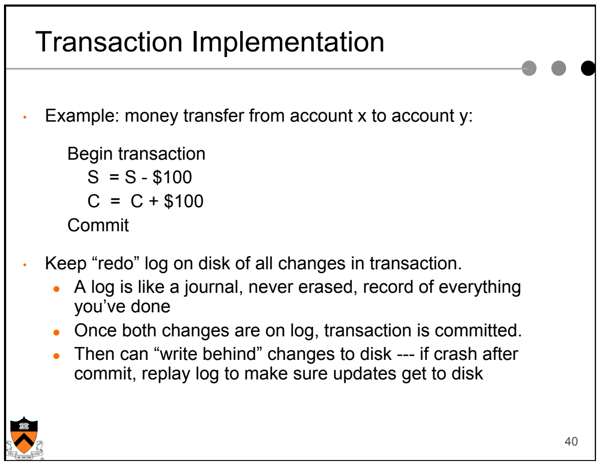

Transaction Implementation

- Example: money transfer from account x to account y:

  Begin transaction
    S = S - $100
    C = C + $100
  Commit

- Keep "redo" log on disk of all changes in transaction.
  - A log is like a journal, never erased, record of everything you've done
  - Once both changes are on log, transaction is committed.
  - Then can "write behind" changes to disk --- if crash after commit, replay log to make sure updates get to disk

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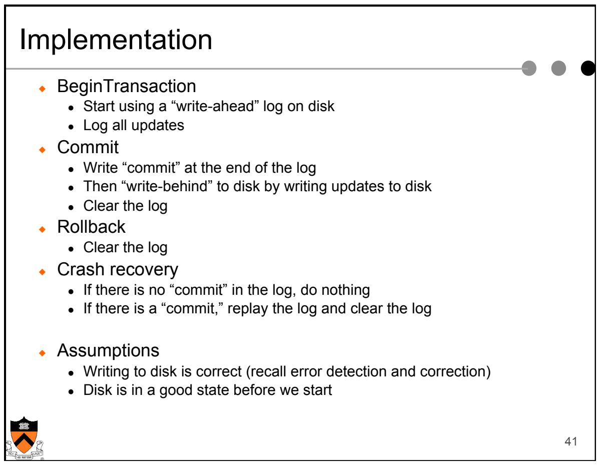

Implementation

- BeginTransaction
  - Start using a "write-ahead" log on disk
  - Log all updates
- Commit
  - Write "commit" at the end of the log
  - Then "write-behind" to disk by writing updates to disk
  - Clear the log
- Rollback
  - Clear the log
- Crash recovery
  - If there is no "commit" in the log, do nothing
  - If there is a "commit," replay the log and clear the log
- Assumptions
  - Writing to disk is correct (recall error detection and correction)
  - Disk is in a good state before we start

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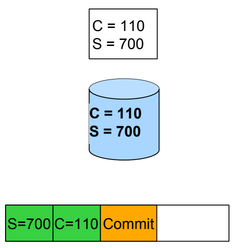
An Example: Atomic Money Transfer

- Move $100 from account S to C (1 thread):

```
BeginTransaction
   S = S - $100;
   C = C + $100;
Commit
```

- Steps:
  1: Write new value of S to log
  2: Write new value of C to log
  3: Write commit
  4: Write S to disk
  5: Write C to disk
  6: Clear the log and reclaim space
- Possible crashes
  - After 1
  - After 2
  - After 3 before 4 and 5



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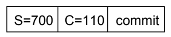
Transaction implementation (cont'd)



1. Write new value of S to log
2. Write new value of C to log
3. Write commit
4. Write S to disk
5. Write C to disk
6. Reclaim space on log

- What if we crash after 1?
  - No commit, nothing on disk, so just ignore changes
- What if we crash after 2? Ditto
- What if we crash after 3 before 4 or 5?
  - Commit written to log, so replay those changes back to disk
- What if we crash while we are writing "commit"?
  - As with concurrency, we need some primitive atomic operation or else can't build anything. (e.g., writing a single sector on disk is atomic)

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Revisit The Implementation

- BeginTransaction
  - Start using a "write-ahead" log on disk
  - Log all updates
- Commit
  - Write "commit" at the end of the log
  - Single disk write to make transaction durable
  - Then "write-behind" to disk by writing updates to disk
  - Clear the log
- Rollback
  - Clear the log
- Crash recovery
  - If there is no "commit" in the log, do nothing
  - If there is "commit," replay the log and clear the log
- Question: What if there is a crash during the recovery?

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Performance

- Log written sequentially
  - Often kept in flash storage
- Asynchronous write back
  - Any order as long as all changes are logged before commit, and all write backs occur after commit
- Can process multiple transactions
  - Transaction ID in each log entry
  - Transaction completed iff its commit record is in log

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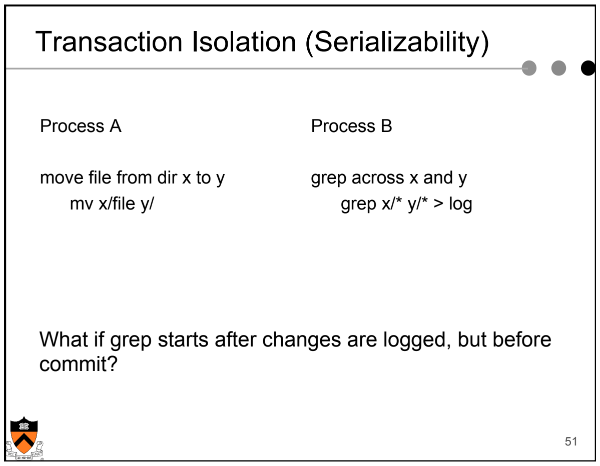

Transaction Isolation (Serializability)

Process A	Process B
move file from dir x to y	grep across x and y
mv x/file y/	grep x/* y/* > log

What if grep starts after changes are logged, but before commit?

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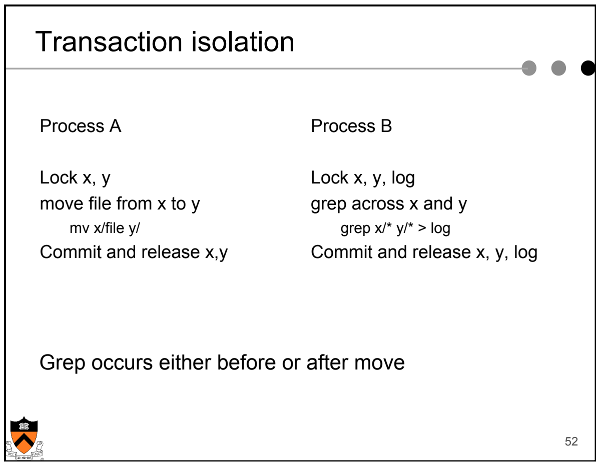

Transaction isolation

Process A	Process B
Lock x, y	Lock x, y, log
move file from x to y	grep across x and y
mv x/file y/	grep x/* y/* > log
Commit and release x,y	Commit and release x, y, log

Grep occurs either before or after move

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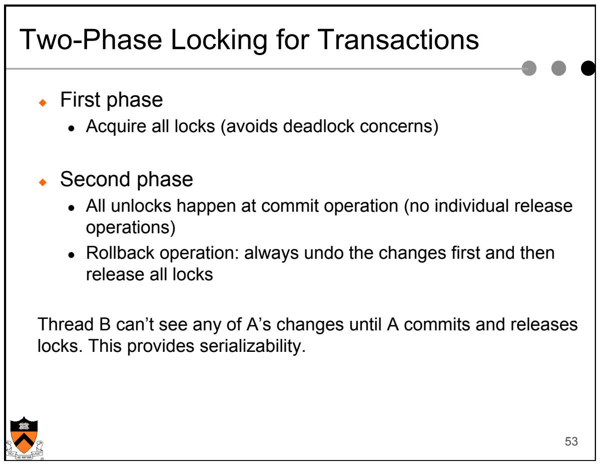

Two-Phase Locking for Transactions

- First phase
  - Acquire all locks (avoids deadlock concerns)
- Second phase
  - All unlocks happen at commit operation (no individual release operations)
  - Rollback operation: always undo the changes first and then release all locks

Thread B can't see any of A's changes until A commits and releases locks. This provides serializability.

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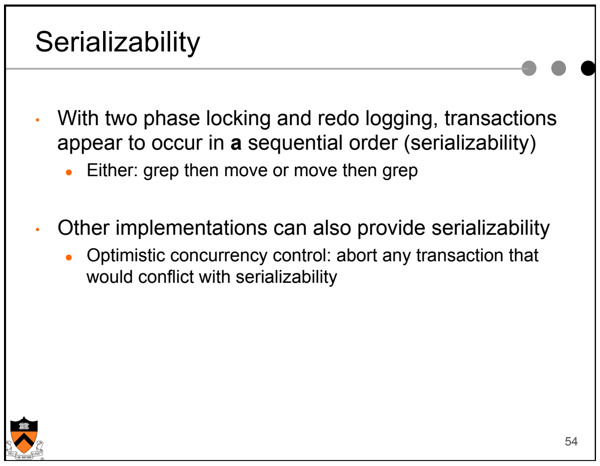

Serializability

- With two phase locking and redo logging, transactions appear to occur in **a** sequential order (serializability)
  - Either: grep then move or move then grep
- Other implementations can also provide serializability
  - Optimistic concurrency control: abort any transaction that would conflict with serializability

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Use Transactions in File Systems

- Make a file operation a transaction
  - Create a file
  - Move a file
  - Write a chunk of data
  - …
- Make arbitrary number of file operations a transaction
  - Make sure logging is idempotent
  - Recovery by replaying the log
  - Called "logging file system" or "journaling file system"

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Performance Issue with Logging

- For every disk write, we now have two disk writes
  - They are on different parts of the disk!
- Performance tricks
  - Changes made in memory and then logged to disk
  - Log writes are sequential
  - Merge multiple writes to the log with one write
  - Use NVRAM (Non-Volatile RAM) to keep the log

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Log Management

- How big is the log?
- Observation
  - Log what's needed for crash recovery
- Method
  - Checkpoint operation: flush the buffer cache to disk
  - After a checkpoint, we can truncate log and start again
  - Log needs to be big enough to hold changes
- Question
  - If you only log metadata (file descriptors and directories) and not data blocks, are there any problems?

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Summary

- File buffer cache
  - True LRU is possible
  - Simple write back is vulnerable to crashes
- Disk block failures and file system recovery tools
  - Individual recovery tools
  - Top down traversal tools
- Consistent updates
  - Transactions and ACID properties
  - Logging or Journaling file systems

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