File System Reliability

OSPP Chapter 14

Main Points

- Problem posed by machine/disk failures
- Transaction concept
- Reliability
  - Careful sequencing of file system operations
  - Copy-on-write
  - Journalling
  - Log structure (flash storage)
- Availability
  - RAID

File System Reliability

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

Storage Reliability Problem

- Single logical file operation can involve updates to multiple physical disk blocks
  - inode, indirect block, data block, bitmap, …
  - With remapping, single update to physical disk block can require multiple (even lower level) updates
- At a physical level, operations complete one at a time
  - Want concurrent operations for performance
- How do we guarantee consistency regardless of when crash occurs?

Transaction Concept

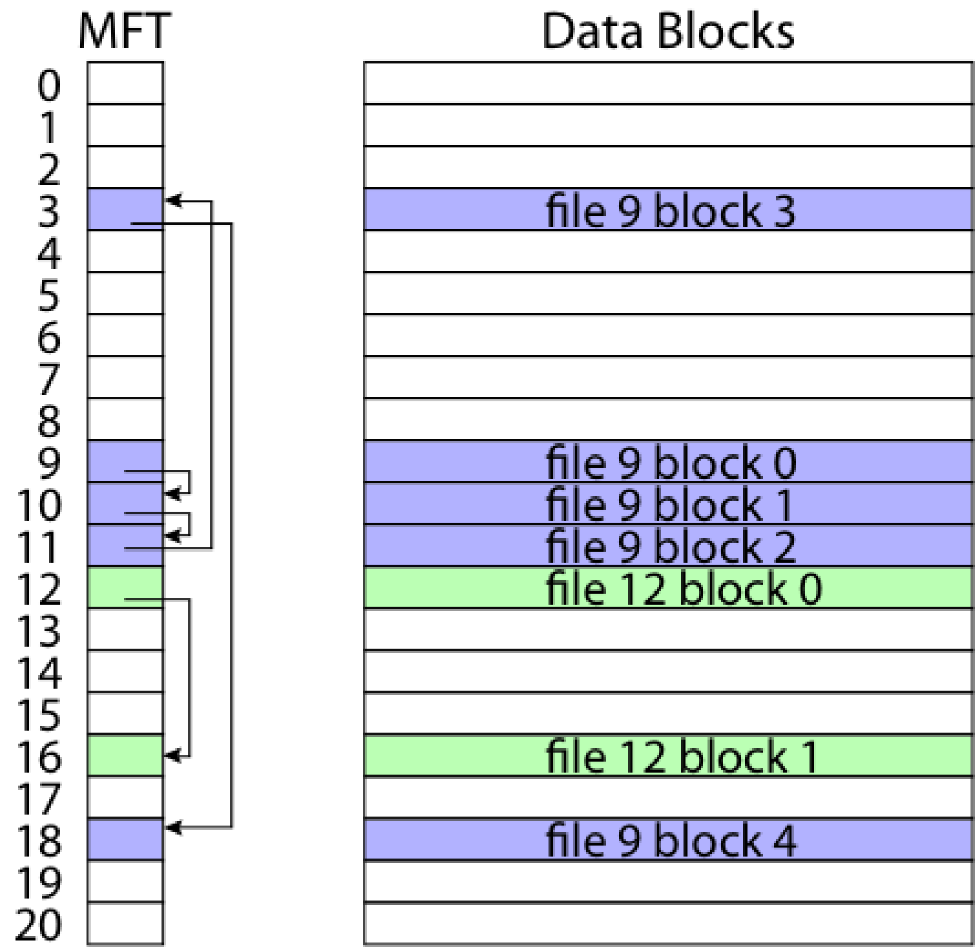
- Transaction is a group of operations (ACID)
  - Atomic: operations appear to happen as a group, or not at all (at logical level)
    - At physical level, only single disk/flash write is atomic
  - Isolation: other transactions do not see results of earlier transactions until they are committed
  - Consistency: sequential memory model (bit vague)
  - Durable: operations that complete stay completed
    - Future failures do not corrupt previously stored data

Reliability Approach #1: Careful Ordering

- 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)

FAT: Append Data to File

- Add data block
- Add pointer to data block
- Update file tail to point to new MFT entry
- Update access time at head of file



FAT: Append Data to File

Normal operation:

- Add data block
  - Crash here: why ok?
  - Lost storage block
- Add pointer to data block
  - Crash here: why ok?
  - Easy to re-create tail
- Update file tail to point to new MFT entry
  - Crash here: why ok?
  - Obtain time elsewhere
- Update access time at head of file

Recovery:

- Scan MFT
- If entry is unlinked, delete data block
- Reset file tail
- If access time is incorrect, update

FAT: Create New File

Normal operation:

- Allocate data block
- Update MFT entry to point to data block
- Update directory with file name -> file number
- Update modify time for directory

Recovery:

- Scan MFT
- If any unlinked files (not in any directory), delete
- Scan directories for missing update times

FFS: Create a File

Normal operation:

- Allocate data block
- Write data block
- Allocate inode
- Write inode block
- Update bitmap of free blocks
- Update directory with file name -> file number
- Update modify time for directory

Recovery:

- Scan inode table
- If any unlinked files (not in any directory), delete
- Compare free block bitmap against inode trees
- Scan directories for missing update/access times

Time proportional to size of disk

FFS: Move a File

Normal operation:

- Remove filename from old directory
- Add filename to new directory

Does this work (even if flipped)?

Recovery:

- Scan all directories to determine set of live files
- Consider files with valid inodes and not in any directory
  - New file being created?
  - File move?
  - File deletion?

Application Level (doc editing)

Normal operation:

- Write name of each open file to app folder
- Write changes to backup file
- Rename backup file to be file (atomic operation provided by file system)
- Delete list in app folder on clean shutdown

Recovery:

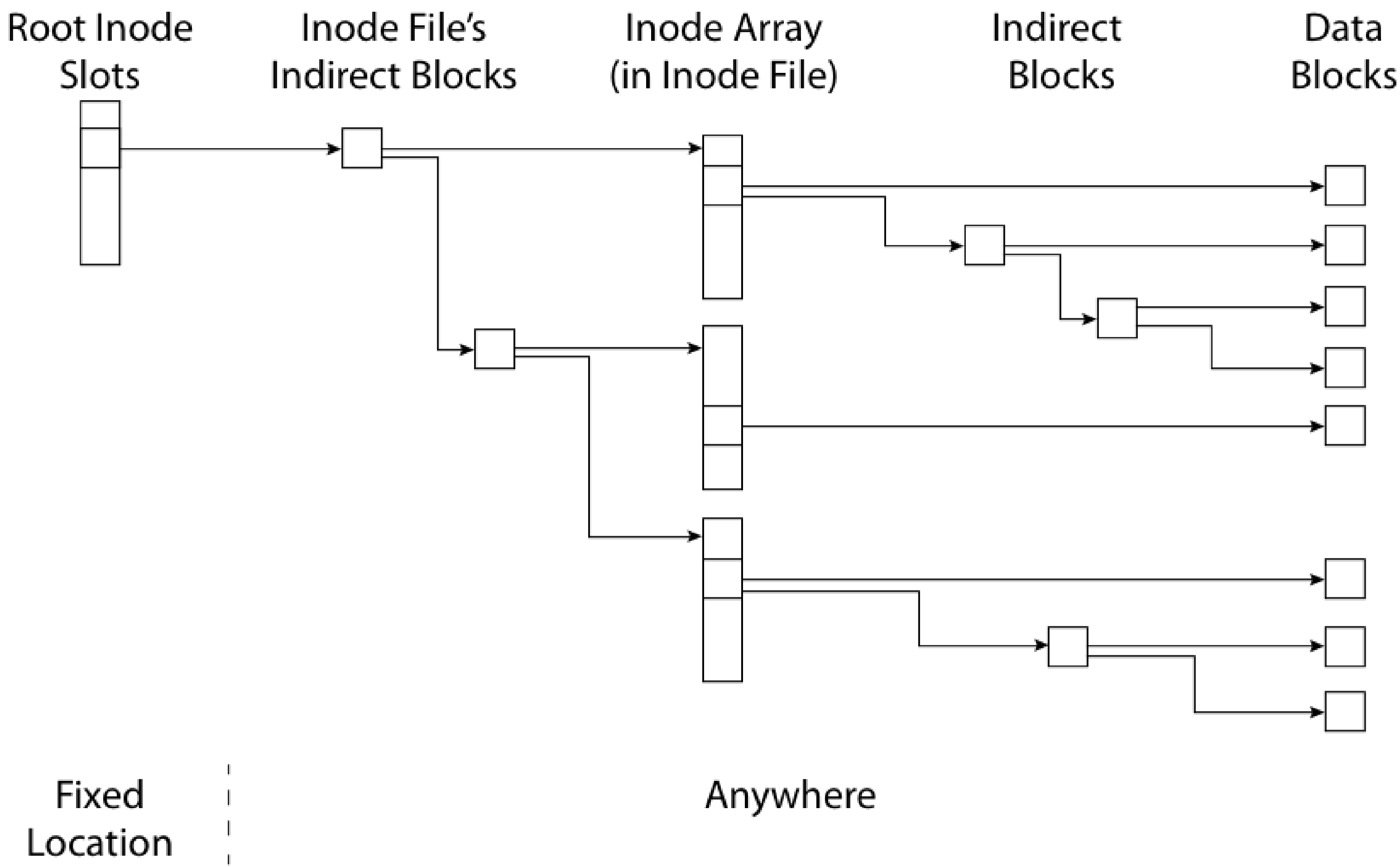
- On startup, see if any files were left open
- If so, look for backup file
- If so, ask user to compare versions

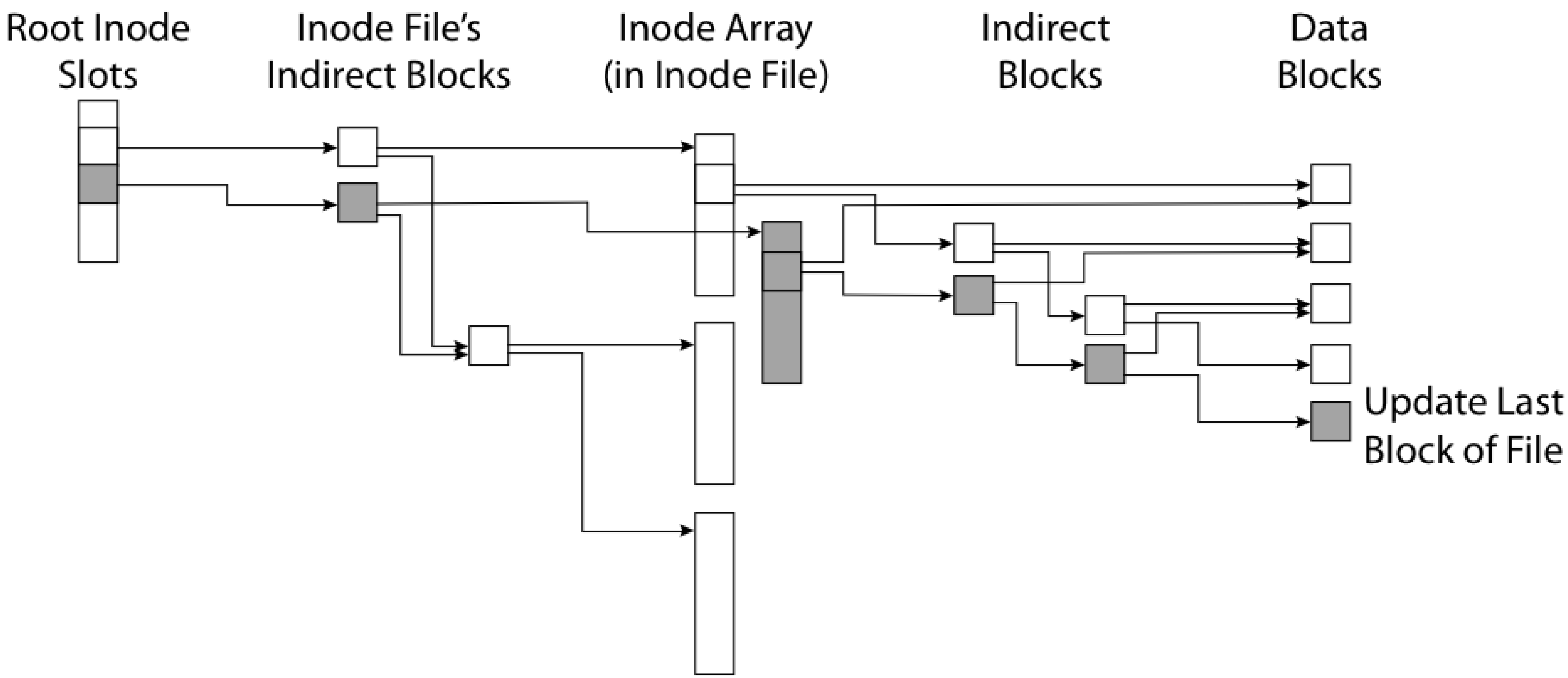
Careful Ordering

- Pros
  - Works with minimal support in the disk drive
  - Works for most multi-step operations
  - Fast
- Cons
  - Slow recovery
  - May not work alone (may need redundant info)

Reliability Approach #2: Copy on Write File Layout

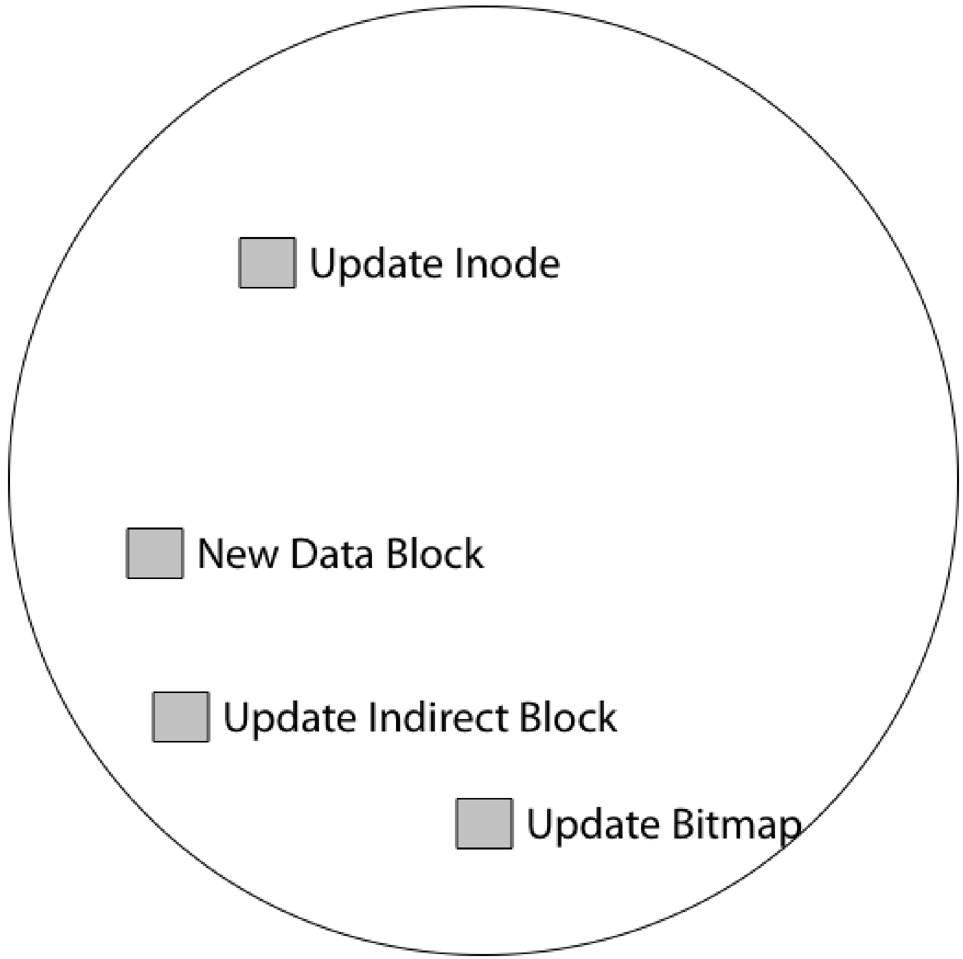
- To update file system, write a new version of the file system containing the update
  - Never update in place
- Seems expensive! But
  - Updates can be batched
  - Almost all disk writes can occur in parallel
- Approach taken in network file server appliances (WAFL, ZFS)


Root Inode
Slots
Inode File's
Indirect Blocks
Inode Array
(in Inode File)
Indirect
Blocks
Data
Blocks
Fixed
Location
Anywhere



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

FFS Update in Place



Copy On Write

- Pros
  - Correct behavior regardless of failures
  - Fast recovery (root block array)
  - High throughput (best if updates are batched)
- Cons
  - Small changes require many writes
  - Garbage collection essential for performance

File System Reliability

OSPP Chapter 14

Reliability options

- Write in place carefully
- Copy-on-write
- Write intention (log, journal) first

Logging File Systems

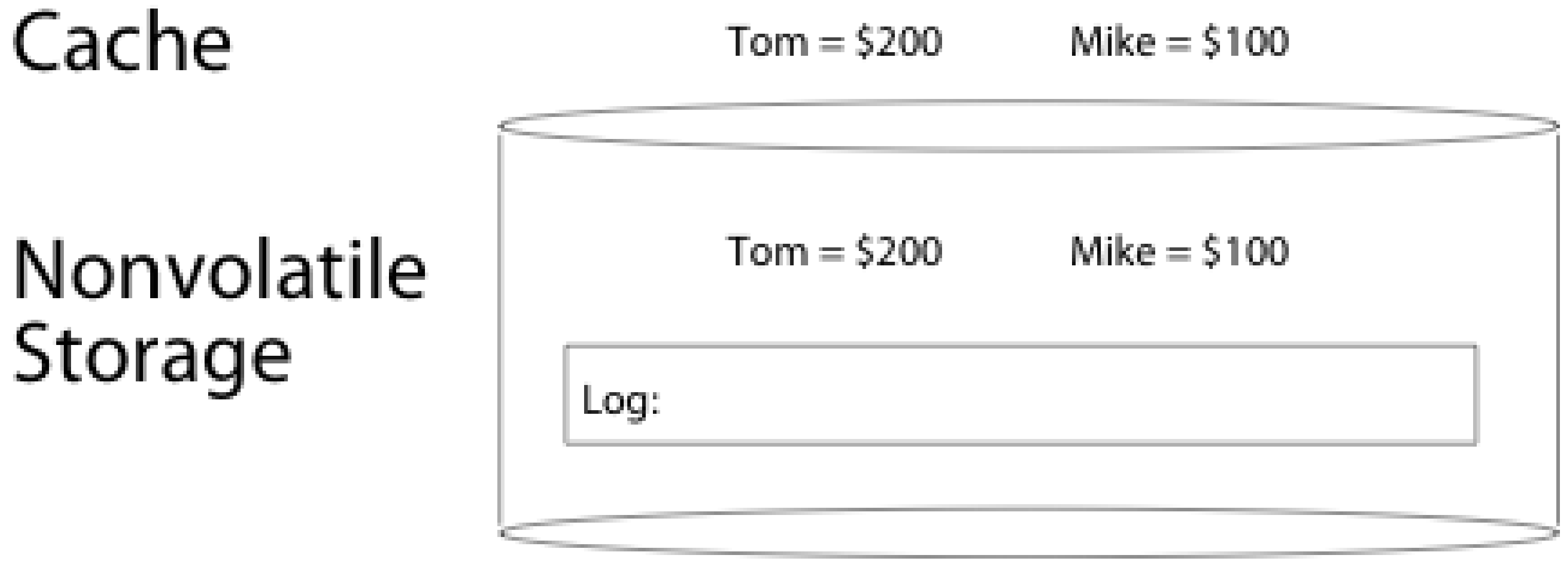
- Instead of modifying data structures on disk directly, write changes to a journal/log
  - Intention list: set of changes we intend to make
  - Log/Journal is **append-only**
  - Log: write data + meta-data
  - Journal: write meta-data only
- Once changes are on log, safe to apply changes to data structures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

Redo Logging

- Prepare
  - Write all changes (in transaction) to log
- Commit
  - Single disk write to make transaction durable
- Redo (write-back)
  - Copy changes to disk
- Garbage collection
  - Reclaim space in log
- Recovery
  - Read log
  - Redo any operations for committed transactions
  - Garbage collect log

Before Transaction Start

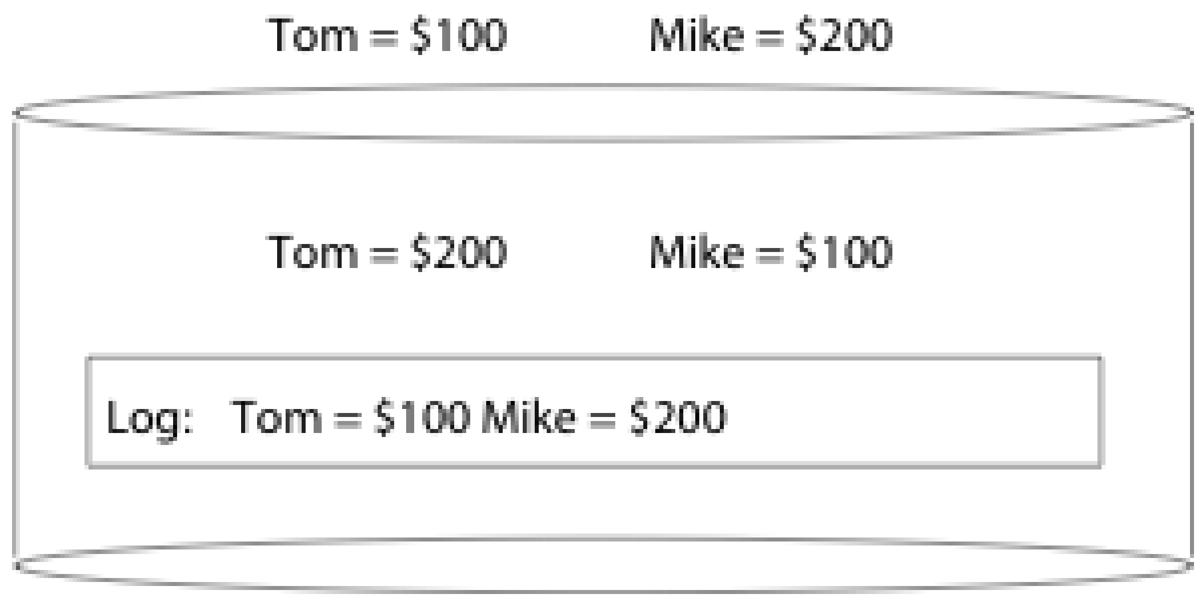
Example: transfer $100 from Tom to Mike



After Updates Are Logged

Cache

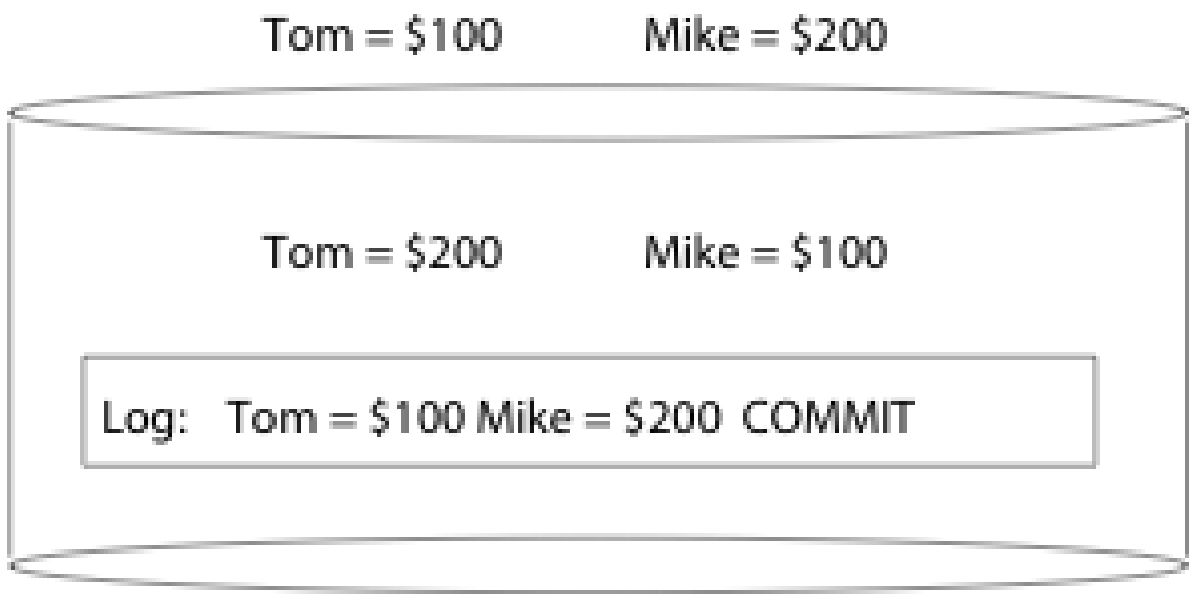
Nonvolatile Storage



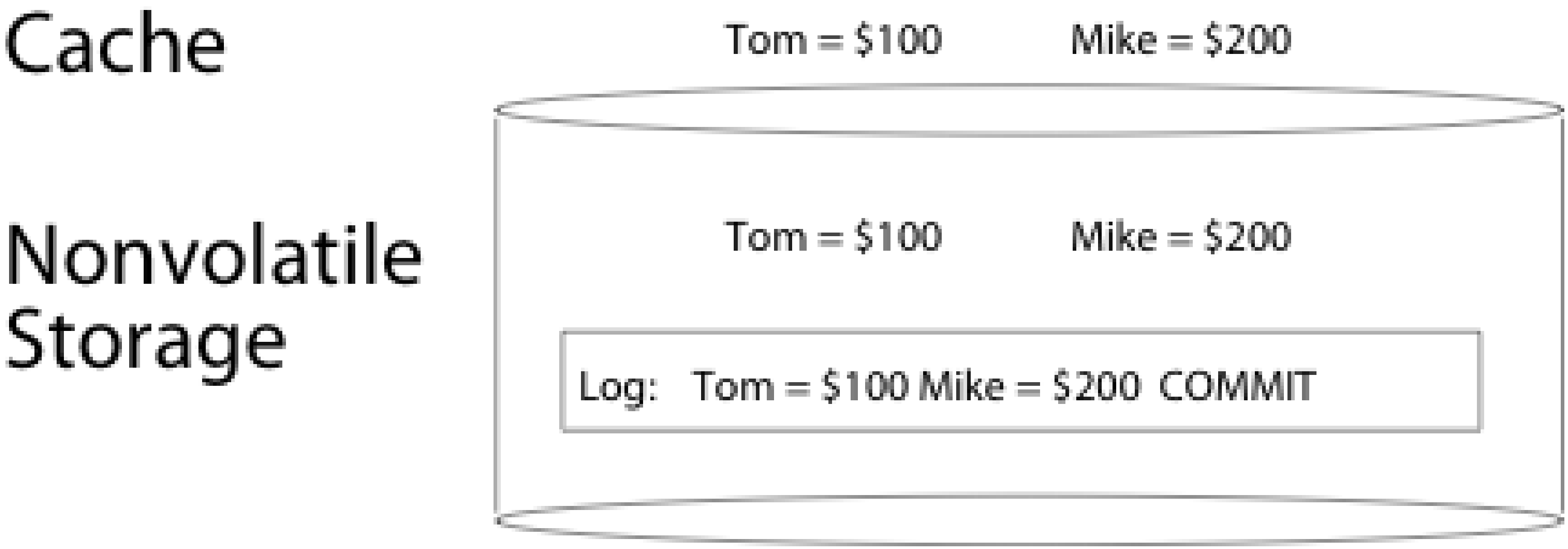
After Commit Logged

Cache

Nonvolatile Storage



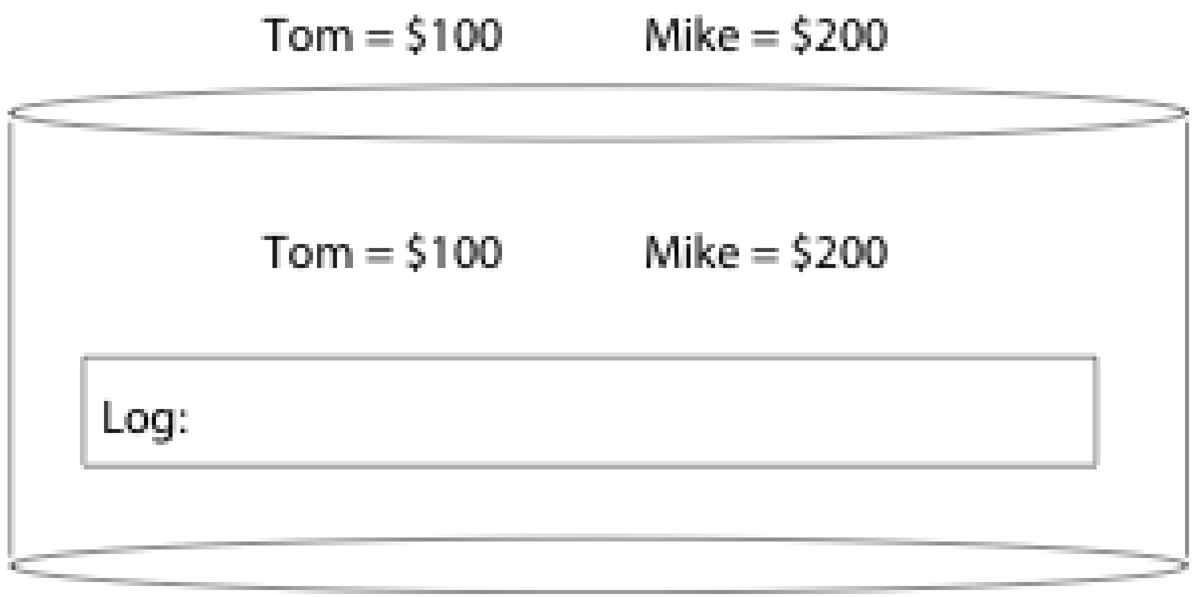
After Copy Back



After Garbage Collection

Cache

Nonvolatile
Storage



Redo Logging

- Prepare
  - Write all changes (in transaction) to log
- Commit
  - Single disk write to make transaction durable
- Redo
  - Copy changes to disk
- Garbage collection
  - Reclaim space in log
- Recovery
  - Read log
  - Redo any operations for committed transactions
  - Garbage collect log

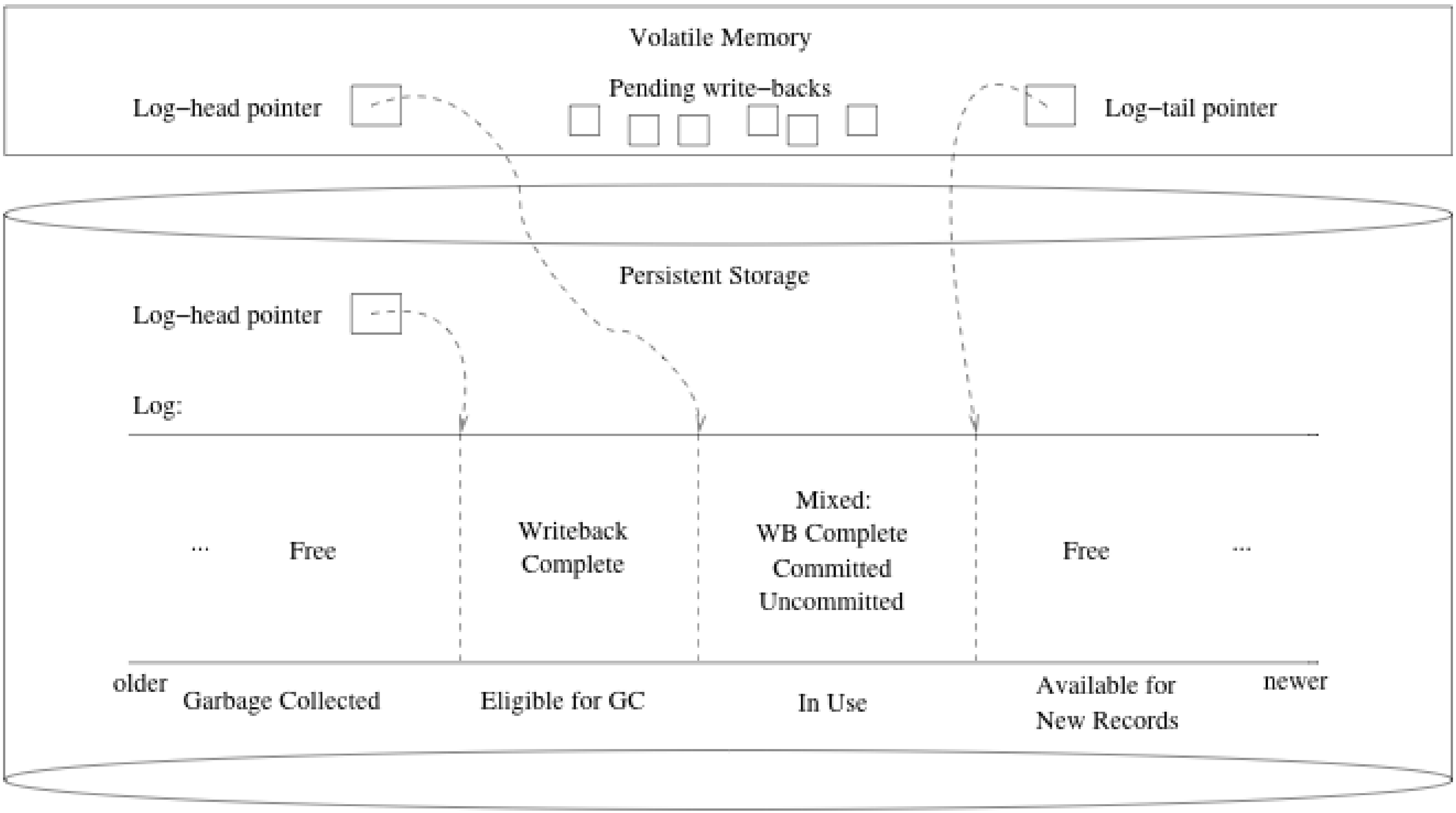
Questions

- What happens if machine crashes?
  – Before transaction start
  – After transaction start, before operations are logged
  – After operations are logged, before commit
  – After commit, before write back
  – After write back before garbage collection
- What happens if machine crashes during recovery?

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

Redo Log Implementation



Transaction Isolation

Process A

move file from x to y

mv x/file y/

Process B

grep across x and y

grep x/* y/* > log

Two Phase Locking

- Two phase locking: release locks only AFTER transaction commit
  - Prevents a process from seeing results of another transaction that might not commit

Transaction Isolation

Process A

Lock x, y

move file from x to y

```
mv x/file y/
```

Commit and release x,y

Why don't we log this?

Process B

Lock x, y, log

grep across x and y

```
grep x/* y/* > log
```

Commit and release x, y, log

Ensures `grep` occurs either before or after move

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
  - Isolation also achieved by multi-version concurrency control
  - Optimistic concurrency control: abort any transaction that would conflict with serializability

Question

- Do we need the copy back?
  - What if random disk update ~~in place~~ is very expensive?
  - Ex: flash storage, RAID

Log Structure

- Log is the data storage; no copy back
  - Storage split into contiguous fixed size segments
    - Flash: size of erasure block
    - Disk: efficient transfer size (e.g., 1MB)
  - Log new blocks into empty segment
    - Garbage collect dead blocks to create empty segments
  - Each segment contains extra level of indirection
    - Which blocks are stored in that segment
- Recovery
  - Find last successfully written segment

Storage Availability

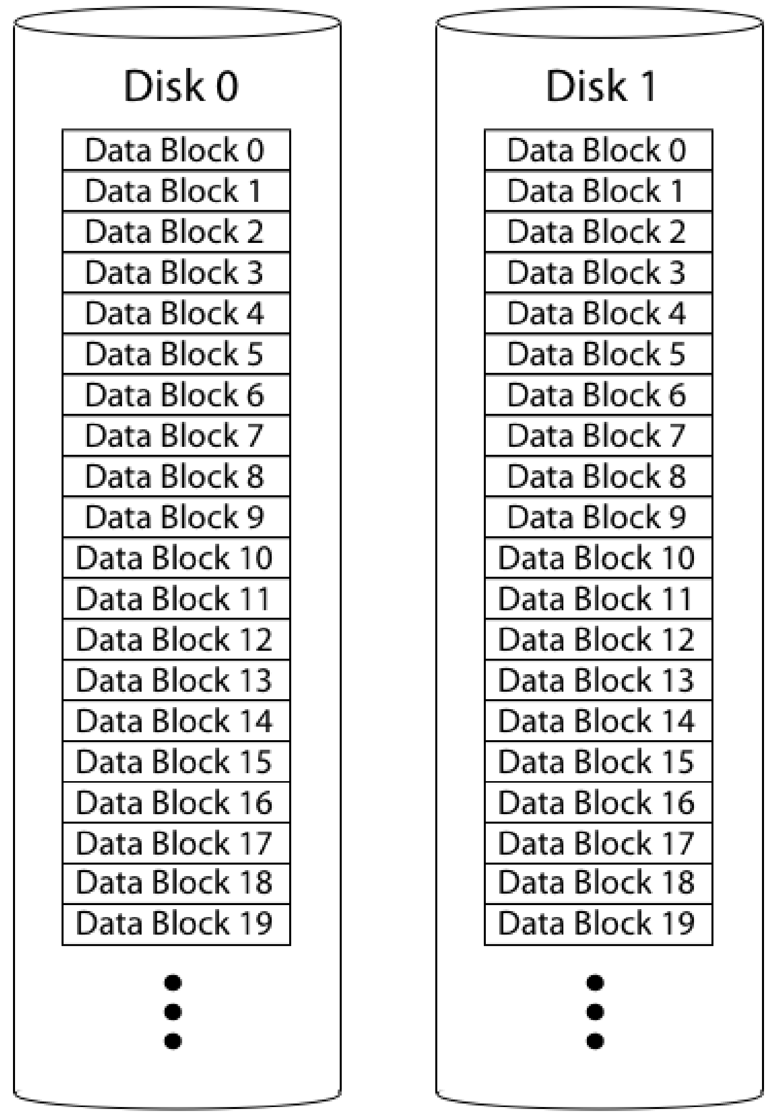
- Storage reliability: data fetched is what you stored
  - Transactions, redo logging, etc.
- Storage availability: data is there when you want it
  - More disks => higher probability of some disk failing
  - Data available ~ Prob(disk working)^k
    - If failures are independent and data is spread across k disks
  - For large k, probability that system works -> 0
    - .95 prob working, all k working .95^k, k=10 => 59%
    - k=50 => 8%!

RAID

- Replicate data for availability
  - RAID 0: no replication
  - RAID 1: mirror data across two or more disks
    - Google File System replicated its data on three disks, spread across multiple racks
  - RAID 5: split data across disks, with redundancy to recover from a single disk failure
  - RAID 6: RAID 5, with extra redundancy to recover from two disk failures

RAID 1: Mirroring

- Replicate writes to both disks
- Reads can go to either disk



Parity

- Parity block: Block1 xor block2 xor block3 …

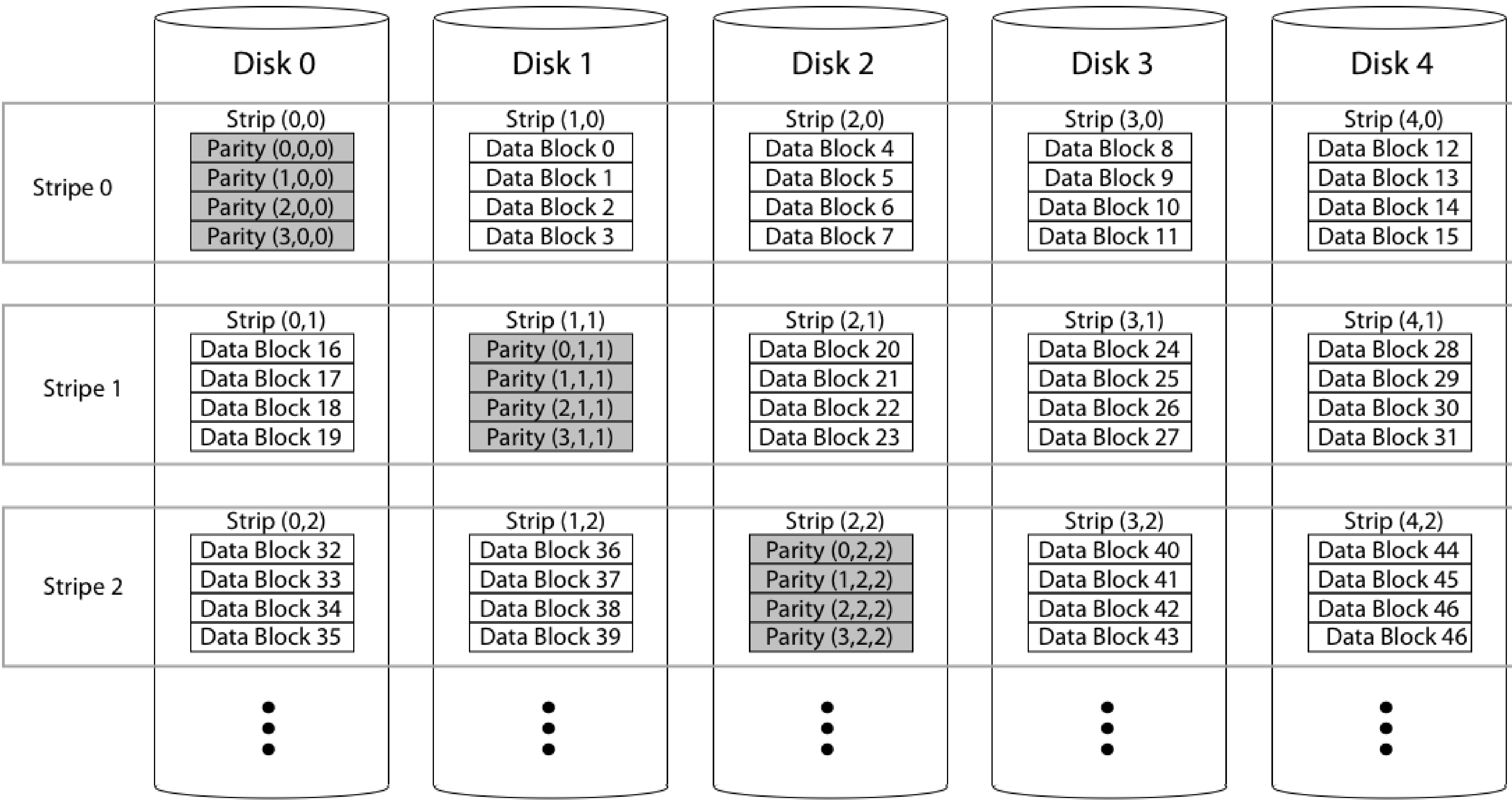
```
10001101      block1
01101100      block2
11000110      block3
--------------
00100111      parity block
```

- Can reconstruct any missing block from the others

RAID 5

- Stripe to increase bandwidth
- Strip is a sequential part of a stripe

RAID 5: Rotating Parity



RAID Update

- Mirroring
  - Write every mirror
- RAID-5: to write one block
  - Read old data block
  - Read old parity block
  - Write new data block
  - Write new parity block
    - Old data xor old parity xor new data
- RAID-5: to write entire stripe
  - Write data blocks and parity

Non-Recoverable Read Errors

- Disk devices can lose data
  - One sector per 10^15 bits read
  - Causes:
    - Physical wear
    - Repeated writes to nearby tracks
- What impact does this have on RAID recovery?

Read Errors and RAID recovery

- Example
  - 10 1 TB disks, and 1 fails
  - Read remaining disks to reconstruct missing data
- Probability of recovery =

  (1 – 10^15)^(9 disks * 8 bits * 10^12 bytes/disk)

  = 93%
- Solutions:
  - RAID-6: two redundant disk blocks
    - parity, linear feedback shift
  - Scrubbing: read disk sectors in background to find and fix latent errors