

Operating Systems (Honor Track)

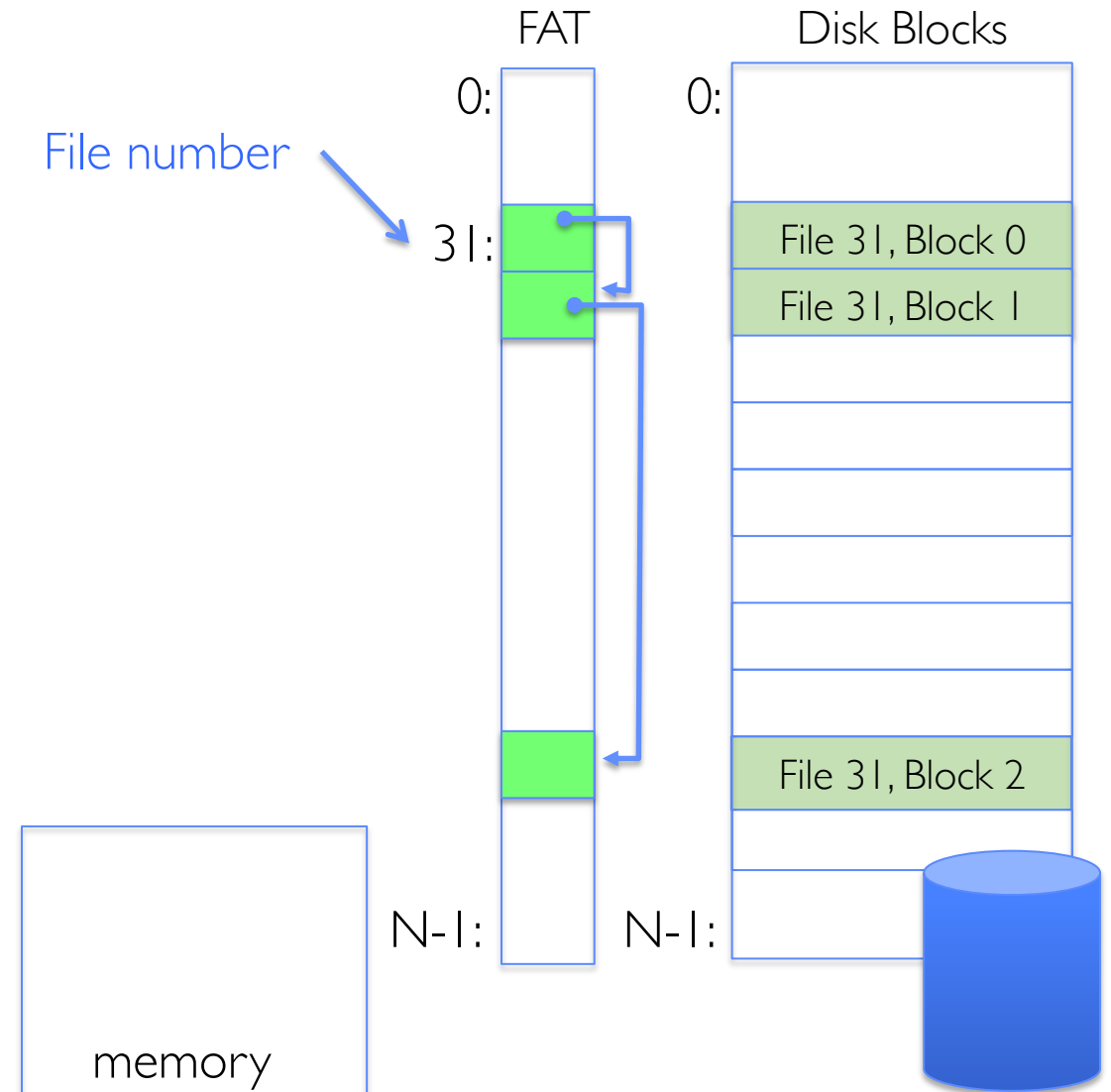
File System 3: Buffering, Reliability, and Transactions

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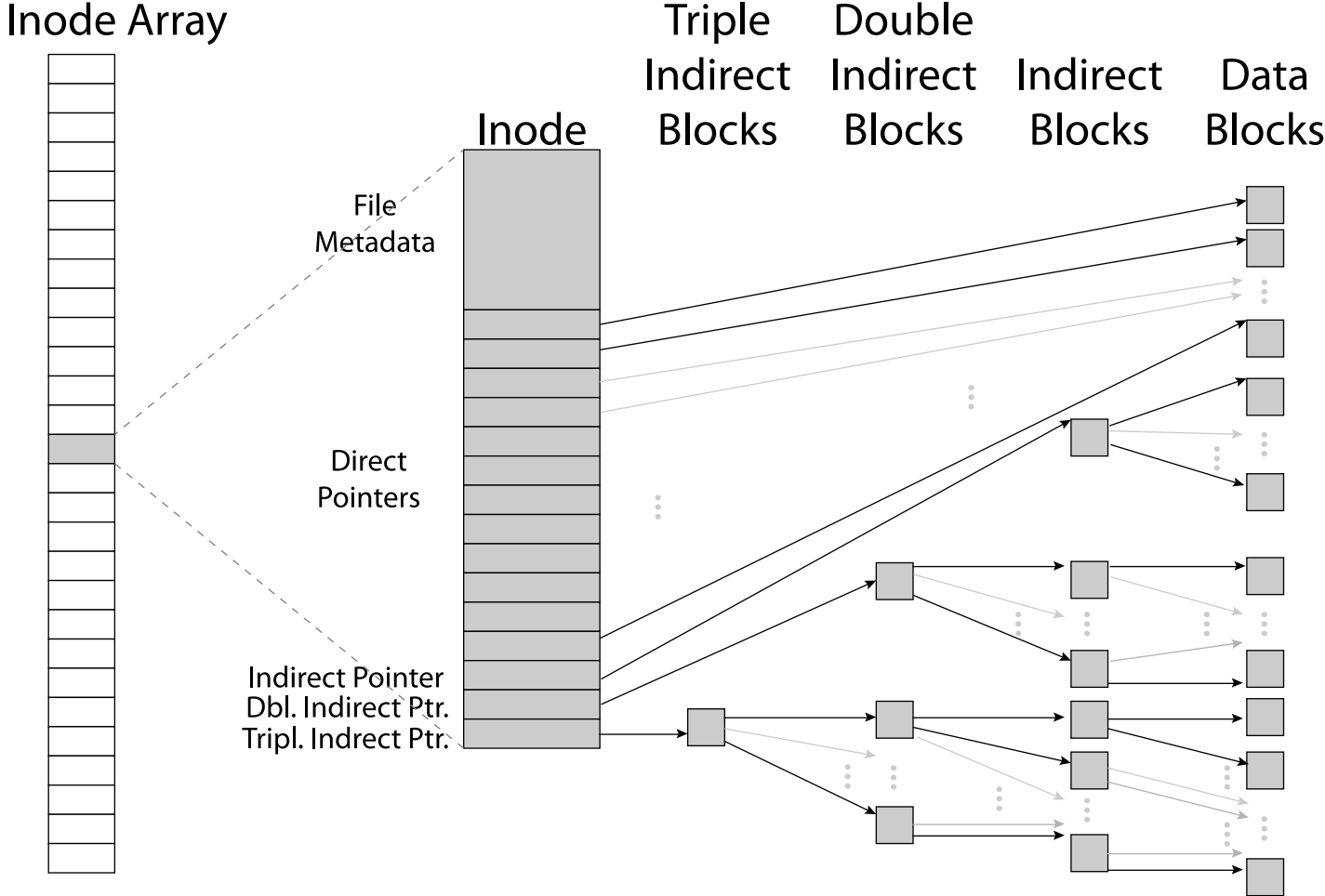
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Recap: FAT (File Allocation Table)

- Assume (for now) we have a way to translate a path to a “file number”
 - i.e., a directory structure
- Disk Storage is a collection of Blocks
 - Just hold file data (offset $o = \langle B, x \rangle$)
- Example: `file_read 31, < 2, x >`
 - Index into FAT with file number
 - Follow linked list to block
 - Read the block from disk into memory

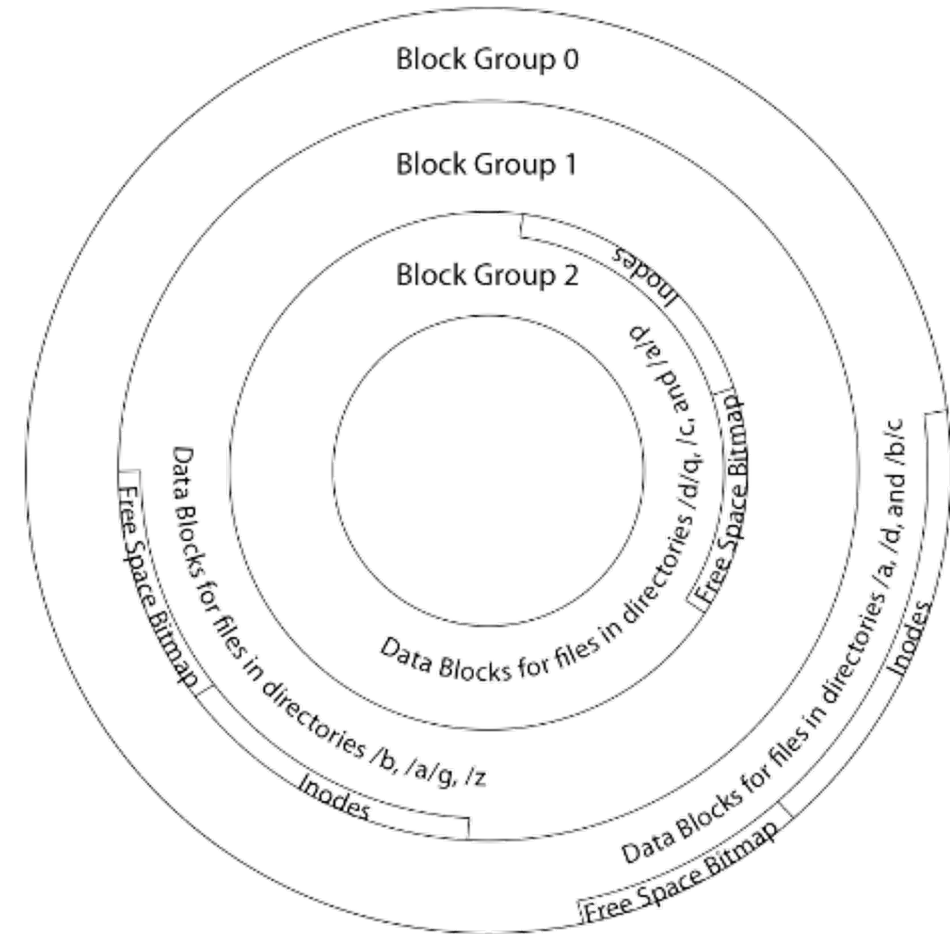


Recap: Inode Structure

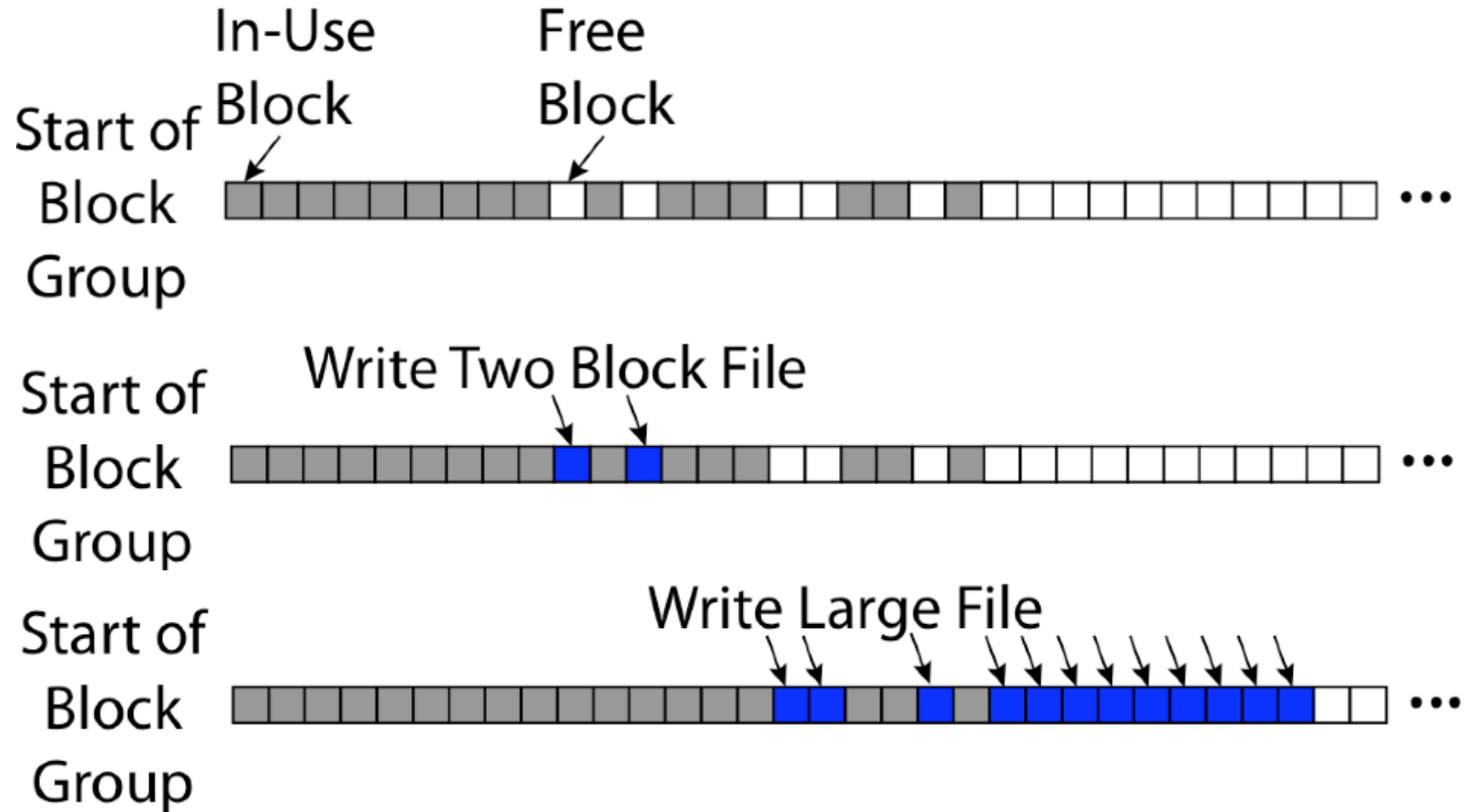


Recap: FFS Locality: Block Groups

- The UNIX BSD 4.2 (FFS) distributed the header information (inodes) closer to the data blocks
 - Often, inode for file stored in same “cylinder group” as parent directory of the file
 - makes an “ls” of that directory run very fast
- File system volume divided into set of block groups
 - Close set of tracks
- Data blocks, metadata, and free space interleaved within block group
 - Avoid huge seeks between user data and system structure
- Put directory and its files in common block group

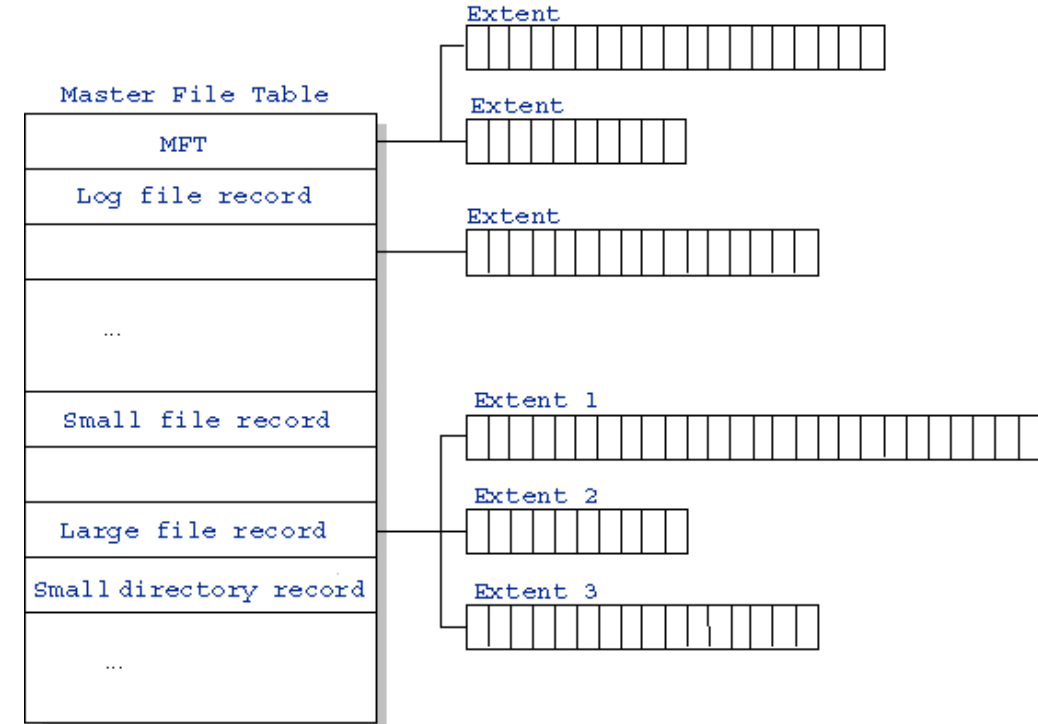


Recap: UNIX 4.2 BSD FFS First Fit Block Allocation

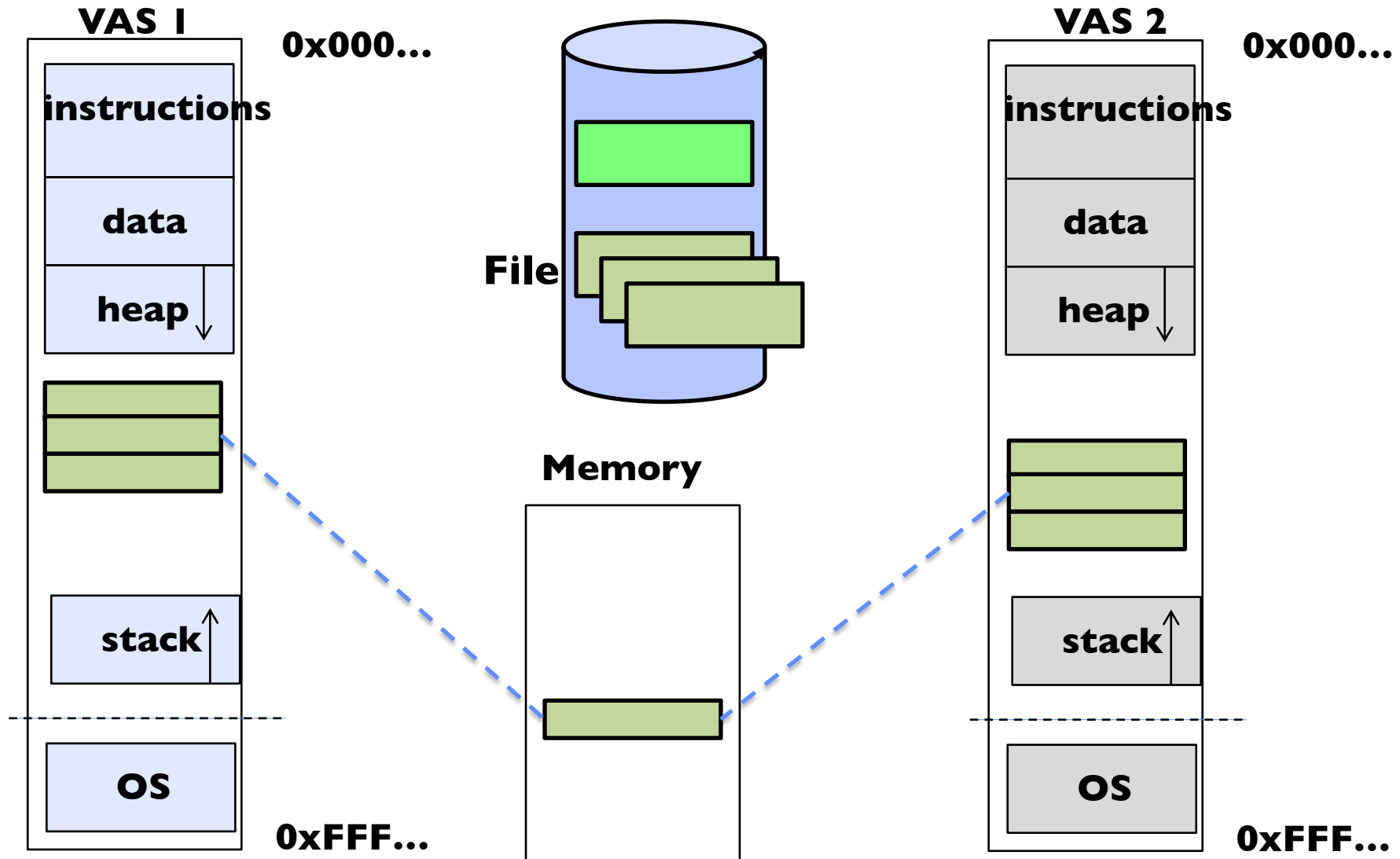


Recap: New Technology File System (NTFS)

- Default on modern Windows systems
- Variable length extents
 - Rather than fixed blocks
- Instead of FAT or inode array: Master File Table
 - Like a database, with max 1 KB size for each table entry
 - Everything (almost) is a sequence of <attribute:value> pairs
 - » Meta-data and data
- Each entry in MFT contains metadata and:
 - File's data directly (for small files)
 - A list of *extents* (start block, size) for file's data
 - For big files: pointers to other MFT entries with *more* extent lists



Recap: Sharing through Mapped Files



- Also: anonymous memory between parents and children
 - no file backing – just swap space

Recap: Buffer Cache

- Kernel *must* copy disk blocks to main memory to access their contents and write them back if modified
 - Could be data blocks, inodes, directory contents, etc.
 - Possibly dirty (modified and not written back)
- Key Idea: Exploit locality by caching disk data in memory
 - Name translations: mapping from paths → inodes
 - Disk blocks: mapping from block address → disk content
- **Buffer Cache:** Memory used to cache kernel resources, including disk blocks and name translations
 - Can contain “dirty” blocks (with modifications not on disk)

Recap: Buffer Cache Discussion

- Implemented entirely in OS software
 - Unlike memory caches and TLB
- Blocks go through transitional states between free and in-use
 - Being read from disk, being written to disk
- Blocks are used for a variety of purposes
 - inodes, data for dirs and files, freemap
 - OS maintains pointers into them
- Termination – e.g., process exit – open, read, write
- Replacement – what to do when it fills up?

File System Caching

- Replacement policy?
 - LRU. Can afford overhead for full LRU implementation.
 - Advantages:
 - » Works well in general as long as memory is big enough to accommodate a host's working set of files.
 - Disadvantages:
 - » Fails when some application scans through file system, thereby flushing the cache with data used only once
- Other replacement policies?
 - Some systems allow applications to request other policies
 - Example, 'Use Once':
 - » File system can discard blocks as soon as they are used

File System Caching (con't)

- Cache Size: How much memory should the OS allocate to the buffer cache vs virtual memory?
 - Too much memory to the file system cache \Rightarrow won't be able to run many applications
 - Too little memory to file system cache \Rightarrow many applications may run slowly (disk caching not effective)
 - Solution: adjust boundary dynamically so that the disk access rates for paging and file access are balanced

File System Prefetching

- **Read Ahead Prefetching:** fetch sequential blocks early
 - Key Idea: exploit fact that most common file access is sequential by prefetching subsequent disk blocks ahead of current read request
 - Elevator algorithm can efficiently interleave prefetches from concurrent applications
- How much to prefetch?
 - Too much prefetching imposes delays on requests by other applications
 - Too little prefetching causes many seeks (and rotational delays) among concurrent file requests

Delayed Writes

- Buffer cache is a writeback cache (writes are termed “**Delayed Writes**”)
- write() copies data from user space to kernel buffer cache
 - Quick return to user space
- read() is fulfilled by the cache, so reads see the results of writes
 - Even if the data has not reached disk
- When does data from a write syscall finally reach disk?
 - When the buffer cache is full (e.g., we need to evict something)
 - When the buffer cache is flushed periodically (in case we crash)

Delayed Writes (Advantages)

- Performance advantage: return to user quickly without writing to disk!
- Disk scheduler can efficiently order lots of requests
 - Elevator Algorithm can rearrange writes to avoid random seeks
- Delay block allocation:
 - May be able to allocate multiple blocks at same time for file, keep them contiguous
- Some files never actually make it all the way to disk
 - Many short-lived files!

Buffer Caching vs. Demand Paging

- Demand paging
 - LRU is infeasible; use approximation (like Clock)
 - Evict not-recently-used pages when memory is close to full
- Buffer Cache
 - LRU is OK
 - Buffer Cache: write back dirty blocks periodically, even if used recently
 - » Why? To minimize data loss in case of a crash

Dealing with Persistent State

- Buffer Cache: write back dirty blocks periodically, even if used recently
 - Why? To minimize data loss in case of a crash
 - Linux does periodic flush every 30 seconds
- **Not foolproof! Can still crash with dirty blocks in the cache**
 - What if the dirty block was for a directory?
 - » Lose pointer to file's inode (leak space)
 - » **File system now in inconsistent state** 😞

**Takeaway: File systems need
recovery mechanisms**

Important “ilities”

- **Availability:** the probability that the system can accept and process requests
 - Measured in “nines” of probability: e.g. 99.9% probability is “3-nines of availability”
 - Key idea here is independence of failures
- **Durability:** the ability of a system to recover data despite faults
 - This idea is fault tolerance applied to data
 - Doesn’t necessarily imply availability: data in disk is durable, but cannot be accessed when the machine is down
- **Reliability:** the ability of a system or component to perform its required functions under stated conditions for a specified period of time (IEEE definition)
 - Usually stronger than simply availability: means that the system is not only “up”, but also working correctly
 - Includes availability, security, fault tolerance/durability
 - Must make sure data survives system crashes, disk crashes, other problems

HOW TO MAKE FILE SYSTEMS MORE *DURABLE*?

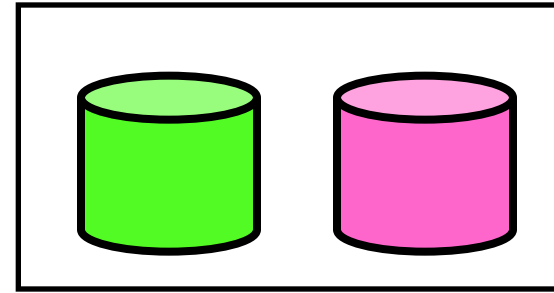
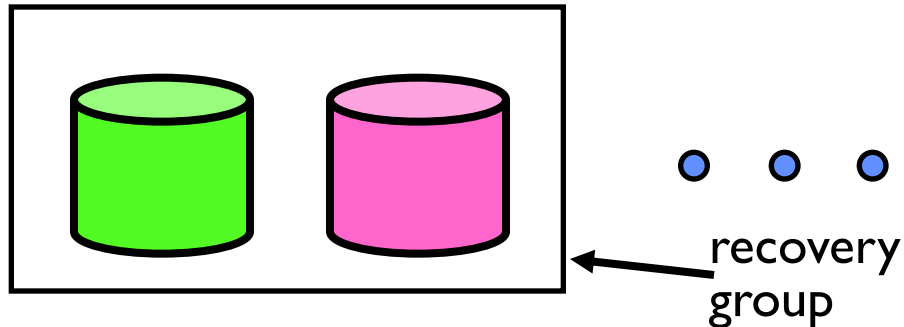
How to Make File Systems more Durable?

- Disk blocks contain Reed-Solomon error correcting codes (ECC) to deal with small defects in disk drive
 - Can allow recovery of data from small media defects
- Make sure writes survive in short term
 - Either abandon delayed writes or
 - Use special, battery-backed RAM (called non-volatile RAM or **NVRAM**) for dirty blocks in buffer cache
- Make sure that data survives in long term
 - Need to **replicate!** More than one copy of data!
 - Important element: **independence of failure**
 - » Could put copies on one disk, but if disk head fails...
 - » Could put copies on different disks, but if server fails...
 - » Could put copies on different servers, but if building is struck by lightning....
 - » Could put copies on servers in different continents...

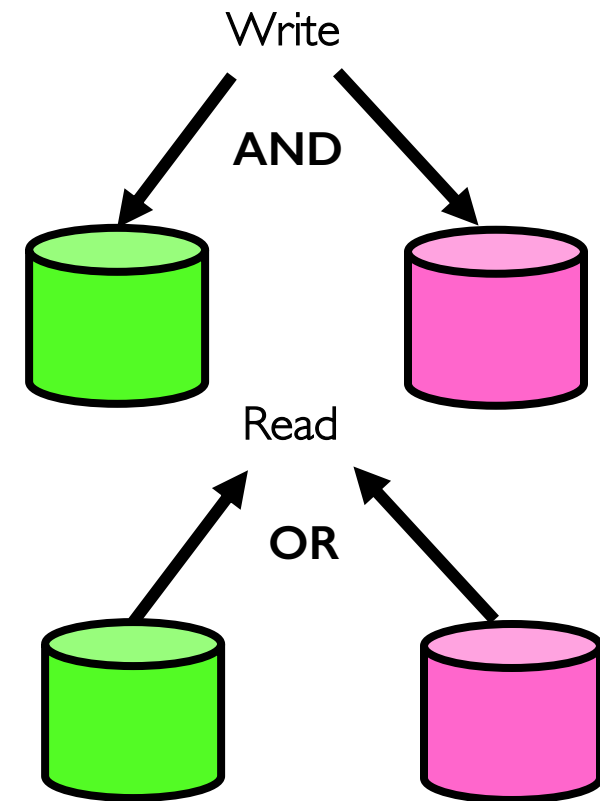
RAID

- RAID: Redundant array of inexpensive/independent disks
- Goal: reliability, performance, capacity
- Data storage virtualization
 - Build a logical disk drive from multiple physical disk drives
 - Better reliability, performance and capacity than a single physical drive

RAID 1: Disk Mirroring/Shadowing

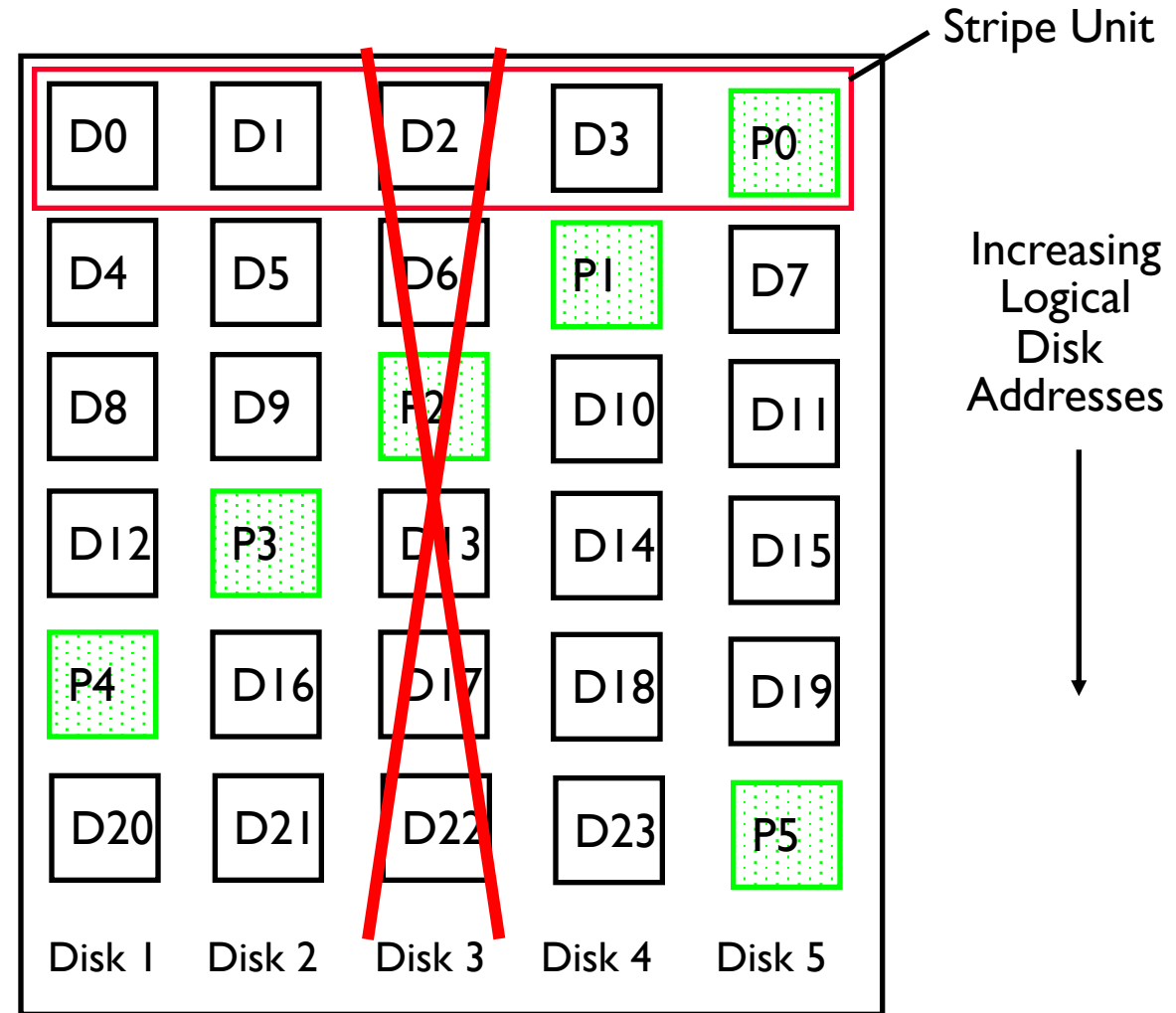


- Each disk is fully duplicated onto its “shadow”
 - For high I/O rate, high availability environments
 - Most expensive solution: 100% capacity overhead
- Bandwidth sacrificed on write:
 - Logical write = two physical writes
 - Highest bandwidth when disk heads and rotation synchronized (challenging)
- Reads may be optimized
 - Can have two independent reads to same data
- Recovery:
 - Disk failure \Rightarrow replace disk and copy data to new disk
 - Hot Spare: idle disk attached to system for immediate replacement



RAID 5: High I/O Rate Parity

- Data striped across multiple disks
 - Successive blocks stored on successive (non-parity) disks
 - Increased bandwidth over single disk
- Parity block (in green) constructed by XORing data blocks in stripe
 - $P_0 = D_0 \oplus D_1 \oplus D_2 \oplus D_3$
 - Can destroy any one disk and still reconstruct data
- Suppose Disk 3 fails, then can reconstruct:
 $D_2 = D_0 \oplus D_1 \oplus D_3 \oplus P_0$



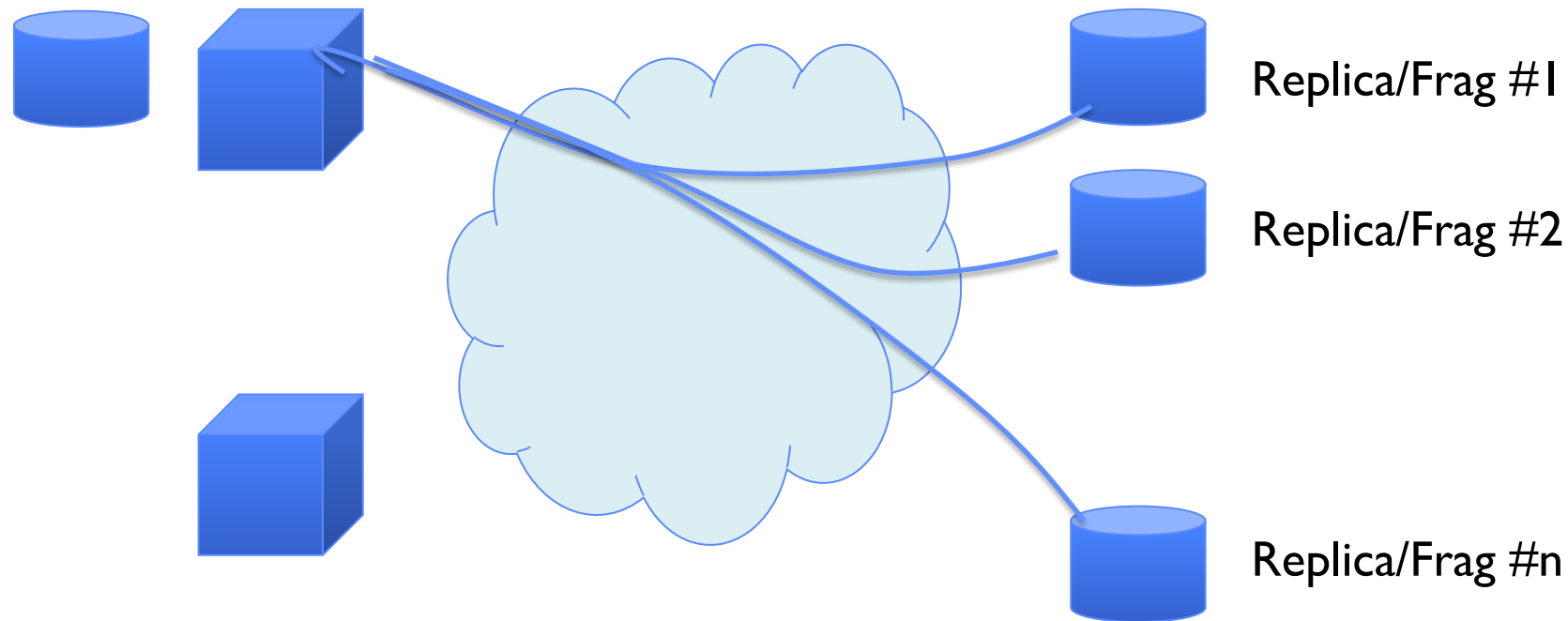
- Can spread information widely across internet for durability
 - RAID algorithms work over geographic scale

RAID 6 and other Erasure Codes

- In general: RAIDX is an “erasure code”
 - Must have ability to know which disks are bad
 - Treat missing disk as an “Erasure”
- Today, disks so big that: RAID 5 not sufficient!
 - Time to repair disk sooooo long, another disk might fail in process!
 - “RAID 6” – allow 2 disks in replication stripe to fail
 - Requires more complex erasure code, such as EVENODD code
- More general option for general erasure code: Reed-Solomon codes
 - m data fragments
 - generate $n - m$ extra fragments
 - can tolerate $n - m$ failures
- Erasure codes not just for disk arrays. For example, geographic replication
 - E.g., split data into $m = 4$ fragments, generate $n = 16$ fragments and distribute across Internet
 - Any 4 fragments can be used to recover the original data --- very durable!

Higher Durability through Geographic Replication

- Highly durable – hard to destroy all copies
- Highly available for reads
 - Simple replication: read any copy
 - Erasure coded: read m of n
- Low availability for writes
 - Can't write if any one replica is not up
 - Or – need relaxed consistency model
- Reliability? – availability, security, durability, fault-tolerance



HOW TO MAKE FILE SYSTEMS MORE *RELIABLE*?

File System Reliability: (Difference from Block-level reliability)

- What can happen if disk loses power or software crashes?
 - Some operations in progress may complete
 - Some operations in progress may be lost
 - Overwrite of a block may only partially complete
- Having RAID doesn't necessarily protect against all such failures
 - No protection against writing bad state
 - What if one disk of RAID group not written?
- File system needs durability (as a minimum!)
 - Data previously stored can be retrieved (maybe after some recovery step), regardless of failure
- But durability is not quite enough...!

Storage Reliability Problem

- Single logical file operation can involve updates to multiple physical disk blocks
 - inode, indirect block, data block, bitmap, ...
 - With sector remapping, single update to physical disk block can require multiple (even lower level) updates to sectors
- 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?

Threats to Reliability

- Interrupted Operation
 - Crash or power failure in the middle of a series of related updates may leave stored data in an inconsistent state
 - Example: transfer funds from one bank account to another
 - What if transfer is interrupted after withdrawal and before deposit?
- Loss of stored data
 - Failure of non-volatile storage media may cause previously stored data to disappear or be corrupted

Two Reliability Approaches

Careful Ordering and Recovery

- FAT & FFS + fsck
- Each step builds structure
- Data block \leftarrow inode \leftarrow free \leftarrow directory
- Last step links it in to rest of FS
- Recover scans structure looking for incomplete actions

Versioning and Copy-on-Write

- ZFS, ...
- Version files at some granularity
- Create new structure linking back to unchanged parts of old
- Last step is to declare that the new version is ready

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 by
 - FAT and FFS (fsck) to protect file system structure/metadata
 - Many app-level recovery schemes (e.g., Word, emacs autosaves)

Question

- Assume you need to store
 - A piece of data
 - A directory entry / pointer for the data
- Assume each of these operations is atomic
- Which one you should write first ? Data or Pointer ?

Berkeley FFS: Create a File

Normal operation:

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

Recovery:

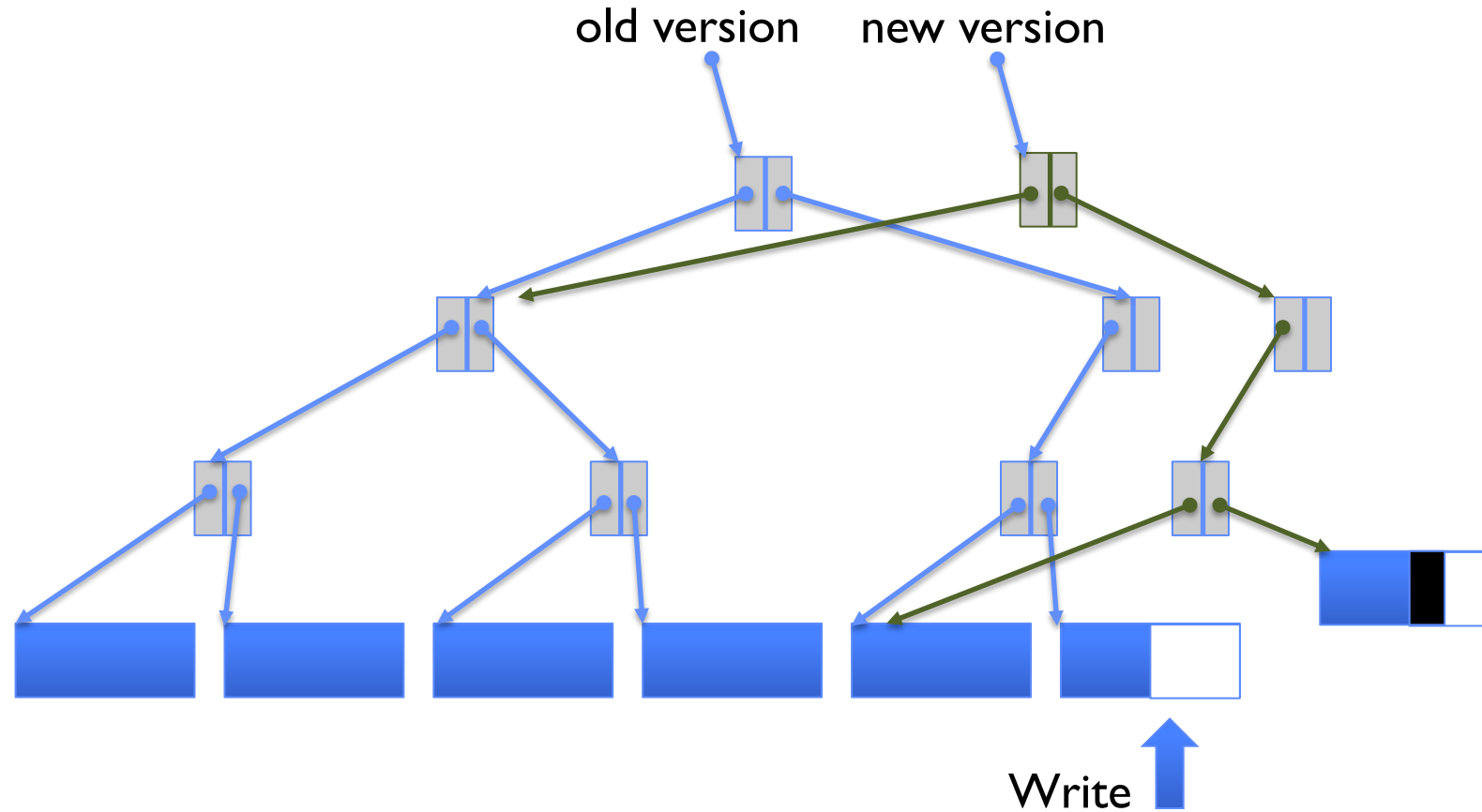
- Scan inode table
- If any unlinked files (not in any directory), delete or put in lost & found dir
- Compare free block bitmap against inode trees
- Scan directories for missing update/access times

Time proportional to disk size

Reliability Approach #2: Copy on Write File Layout

- Recall: multi-level index structure lets us find the data blocks of a file
- Instead of over-writing existing data blocks and updating the index structure:
 - Create a new version of the file with the updated data
 - Reuse blocks that don't change much of what is already in place
 - This is called: **Copy On Write (COW)**
- Seems expensive! But
 - Updates can be batched
 - Almost all disk writes can occur in parallel
- Approach taken in network file server appliances
 - NetApp's Write Anywhere File Layout (WAFL)
 - ZFS (Sun/Oracle) and OpenZFS

COW with Smaller-Radix Blocks



- If file represented as a tree of blocks, just need to update the leading fringe

Example: ZFS and OpenZFS

- Variable sized blocks: 512 B – 128 KB
- Symmetric tree
 - Know if it is large or small when we make the copy
- Store version number with pointers
 - Can create new version by adding blocks and new pointers
- Buffers a collection of writes before creating a new version with them
- Free space represented as tree of extents in each block group
 - Delay updates to free space (in log) and do them all when block group is activated

More General Reliability Solutions

- Use Transactions for atomic updates
 - Ensure that multiple related updates are performed atomically
 - i.e., if a crash occurs in the middle, the state of the systems reflects either all or none of the updates
 - Most modern file systems use transactions internally to update filesystem structures and metadata
 - Many applications implement their own transactions
- Provide Redundancy for media failures
 - Redundant representation on media (Error Correcting Codes)
 - Replication across media (e.g., RAID disk array)

Transactions

- Closely related to critical sections for manipulating shared data structures
- They extend concept of atomic update from memory to stable storage
 - Atomically update multiple persistent data structures
- Many ad-hoc approaches
 - FFS carefully ordered the sequence of updates so that if a crash occurred while manipulating directory or inodes the disk scan on reboot would detect and recover the error (fsck)
 - Applications use temporary files and rename

Key Concept: Transaction

- A *transaction* is an atomic sequence of reads and writes that takes the system from consistent state to another.



- Recall: Code in a critical section appears atomic to other threads
- Transactions extend the concept of atomic updates from *memory* to *persistent storage*

Typical Structure

- **Begin** a transaction – get transaction id
- Do a bunch of updates
 - If any fail along the way, **roll-back**
 - Or, if any conflicts with other transactions, **roll-back**
- **Commit** the transaction

“Classic” Example: Transaction

```
BEGIN;      --BEGIN TRANSACTION
UPDATE accounts SET balance = balance - 100.00 WHERE
  name = 'Alice';

UPDATE branches SET balance = balance - 100.00 WHERE
  name = (SELECT branch_name FROM accounts WHERE name
  = 'Alice');

UPDATE accounts SET balance = balance + 100.00 WHERE
  name = 'Bob';

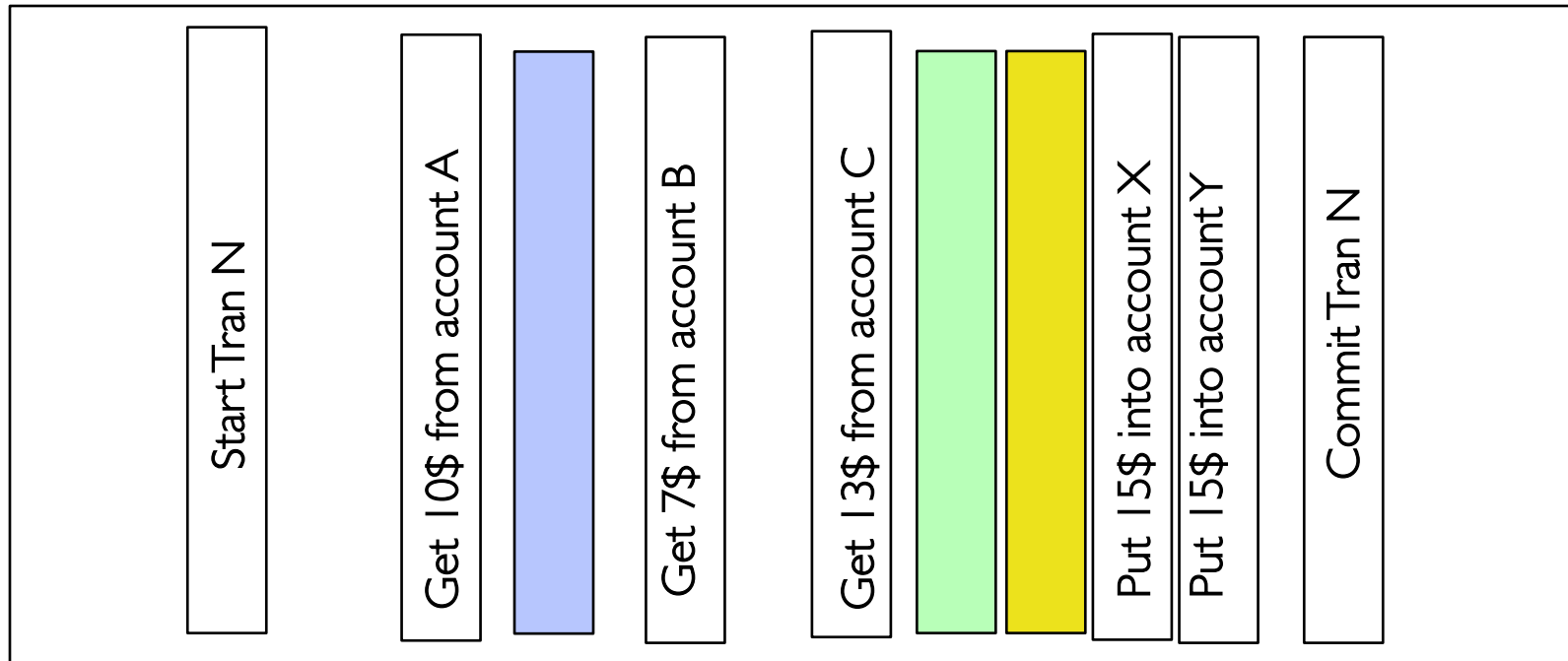
UPDATE branches SET balance = balance + 100.00 WHERE
  name = (SELECT branch_name FROM accounts WHERE name
  = 'Bob');

COMMIT;     --COMMIT WORK
```

Transfer \$100 from Alice's account to Bob's account

Concept of a log

- One simple action is atomic – write/append a basic item
- Use that to seal the commitment to a whole series of actions



Transactional File Systems

- Better reliability through use of log
 - Changes are treated as transactions
 - A transaction is committed once it is written to the log
 - » Data forced to disk for reliability
 - » Process can be accelerated with NVRAM
 - Although File system may not be updated immediately, data preserved in the log
- Difference between “Log Structured” and “Journaled”
 - In a Log Structured filesystem, data stays in log form
 - In a Journaled filesystem, Log used for recovery

File System Summary

- Buffer Cache: Memory used to cache kernel resources, including disk blocks and name translations
 - Can contain “dirty” blocks (blocks yet on disk)
- File system operations involve multiple distinct updates to blocks on disk
 - Need to have all or nothing semantics
 - Crash may occur in the midst of the sequence
- Traditional file system perform check and recovery on boot
 - Along with careful ordering so partial operations result in loose fragments, rather than loss
- Copy-on-write provides richer function (versions) with much simpler recovery
 - Little performance impact since sequential write to storage device is nearly free