Filesystems

Based on slides by Matt Welsh, Harvard

Announcements

- MP8 due tomorrow night
- Finals approaching, know your times and conflicts
  - Ours: Friday May 11, 1:30 – 4:30 pm
- Review material similar to midterm released by Friday
  - Topic outline
  - Practice final exam
- Review sessions
  - Vote on Piazza for times that work for you
  - Do this by midnight Tuesday; results announced Wed.
- Honors section demos
  - Vote on Piazza for times that work for you
  - Do this by Wednesday

Filesystems

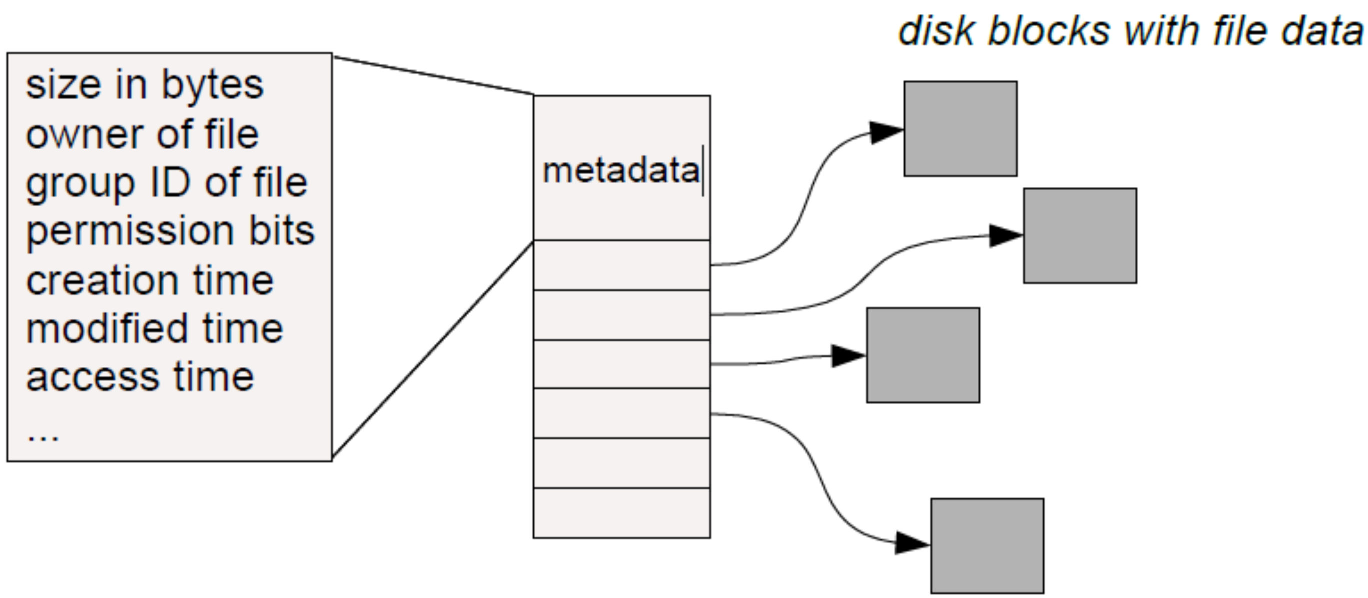
- A filesystem provides a high-level application access to disk
    - As well as CD, DVD, tape, floppy, etc...
  - Masks the details of low-level sector-based I/O operations
  - Provides structured access to data (files and directories)
  - Caches recently-accessed data in memory
- Hierarchical filesystems: Most common type
  - Organized as a tree of directories and files
- Byte-oriented vs. record-oriented files
  - UNIX, Windows, etc. all provide byte-oriented file access
    - May read and write files a byte at a time
  - Many older OS's provided only record-oriented files
    - File composed of a set of records; may only read and write a record at a time
- Versioning filesystems
  - Keep track of older versions of files
  - e.g., VMS filesystem: Could refer to specific file versions:foo.txt;1, foo.txt;2

Filesystem Operations

- Filesystems provide a standard interface to files and directories:
  - Create a file or directory
  - Delete a file or directory
  - Open a file or directory – allows subsequent access
  - Read, write, append to file contents
  - Add or remove directory entries
  - Close a file or directory – terminates access
- What other features do filesystems provide?
  - Accounting and quotas – prevent your classmates from hogging the disks
  - Backup – some filesystems have a "$HOME/.backup" containing automatic snapshots
  - Indexing and search capabilities
  - File versioning
  - Encryption
  - Automatic compression of infrequently-used files
- Should this functionality be part of the filesystem or built on top?
  - Classic OS community debate: Where is the best place to put functionality?

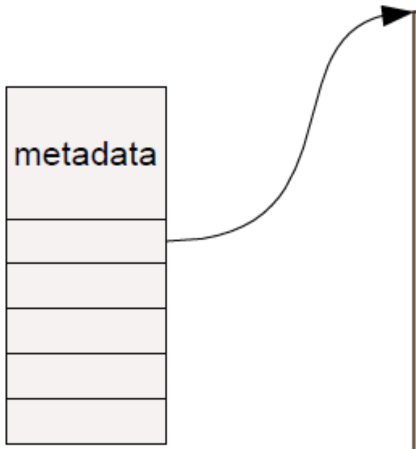
Basic Filesystem Structures

- Every file and directory is represented by an inode
  - Stands for "index node"
- Contains two kinds of information:
  - 1) Metadata describing the file's owner, access rights, etc.
  - 2) Location of the file's blocks on disk



Directories

- A directory is a special kind of file that contains a list of (filename, inode number) pairs

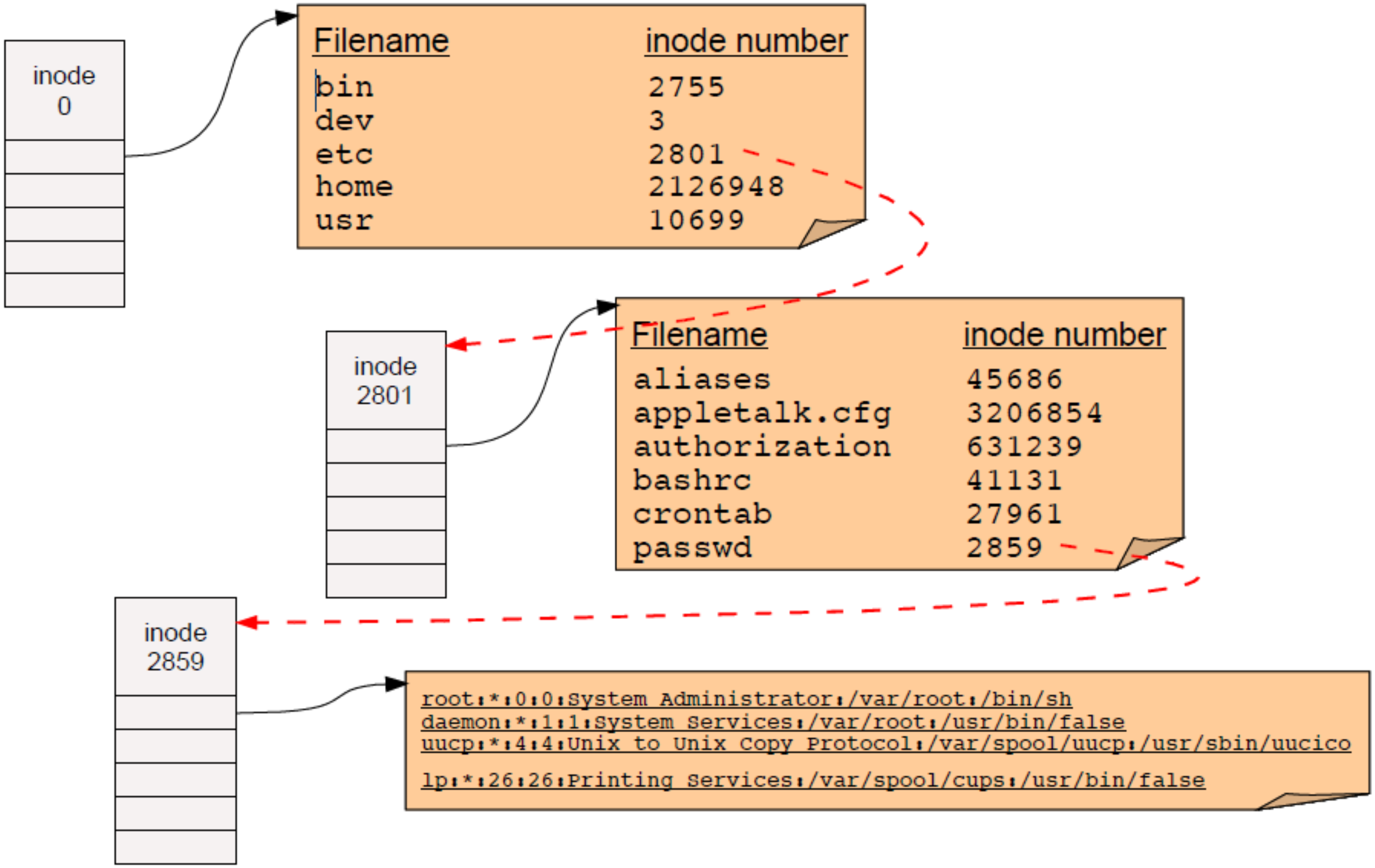


Filename	inode number
aliases	45686
appletalk.cfg	3206854
authorization	631239
bashrc	41131
crontab	27961
passwd	2859

  - These are the contents of the directory “file data” itself – NOT the directory's inode!
  - Filenames (in UNIX) are not stored in the inode at all!
- Two open questions:
  - How do we find the root directory (“ / “ on UNIX systems)?
  - How do we get from an inode number to the location of the inode on disk?

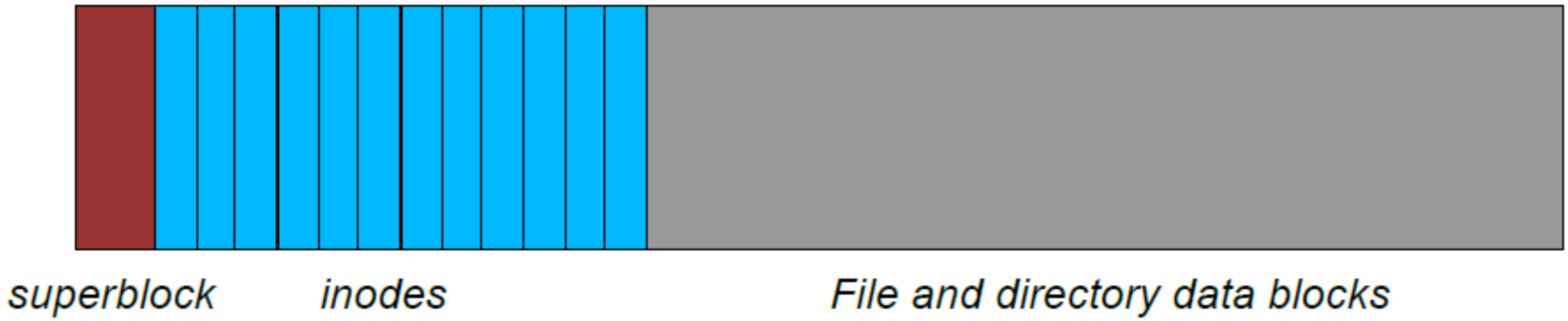
Pathname resolution

- To look up a pathname "/etc/passwd", start at root directory and walk down chain of inodes...



Locating inodes on disk

- All right, so directories tell us the inode number of a file.
  - How the heck do we find the inode itself on disk?
- Basic idea: Top part of filesystem contains *all* of the inodes!



  - inode number is just the "index" of the inode
  - Easy to compute the block address of a given inode:
    - block_addr(inode_num) = block_offset_of_first_inode + (inode_num * inode_size)
  - This implies that a filesystem has a fixed number of potential inodes
    - This number is generally set when the filesystem is created
  - The superblock stores important metadata on filesystem layout, list of free blocks, etc.

Stupid directory tricks

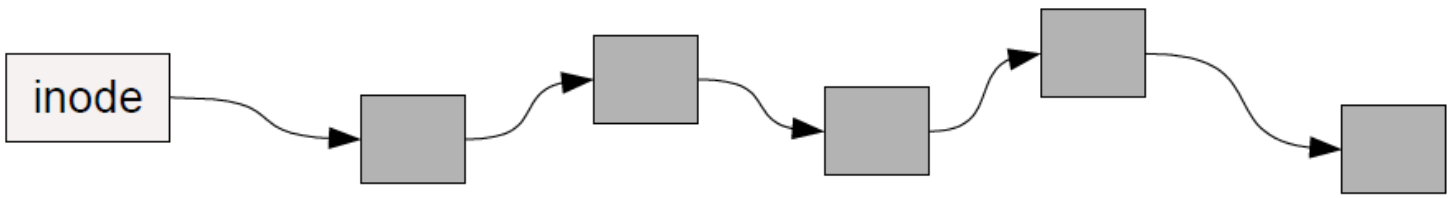
- Directories map filenames to inode numbers. What does this imply?
- We can create multiple pointers to the same inode in different directories
  - Or even the same directory with different filenames
- In UNIX this is called a "hard link" and can be done using "ln"

```
bash$ ls -i /home/foo
287663 /home/foo          (This is the inode number of "foo")
bash$ ln /home/foo /tmp/foo
bash$ ls -i /home/foo /tmp/foo
287663 /home/foo
287663 /tmp/foo
```

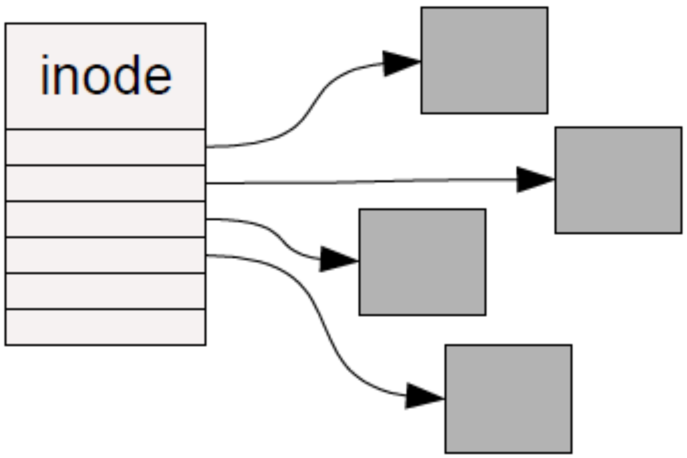
- "/home/foo" and "/tmp/foo" now refer to the same file on disk
  - Not a copy! You will always see identical data no matter which filename you use to read or write the file.
- Note: This is not the same as a "symbolic link", which only links one filename to another.

How should we organize blocks on a disk?

- Very simple policy: A file consists of linked blocks
  - inode points to the first block of the file
  - Each block points to the next block in the file (just a linked list on disk)
    - What are the advantages and disadvantages??

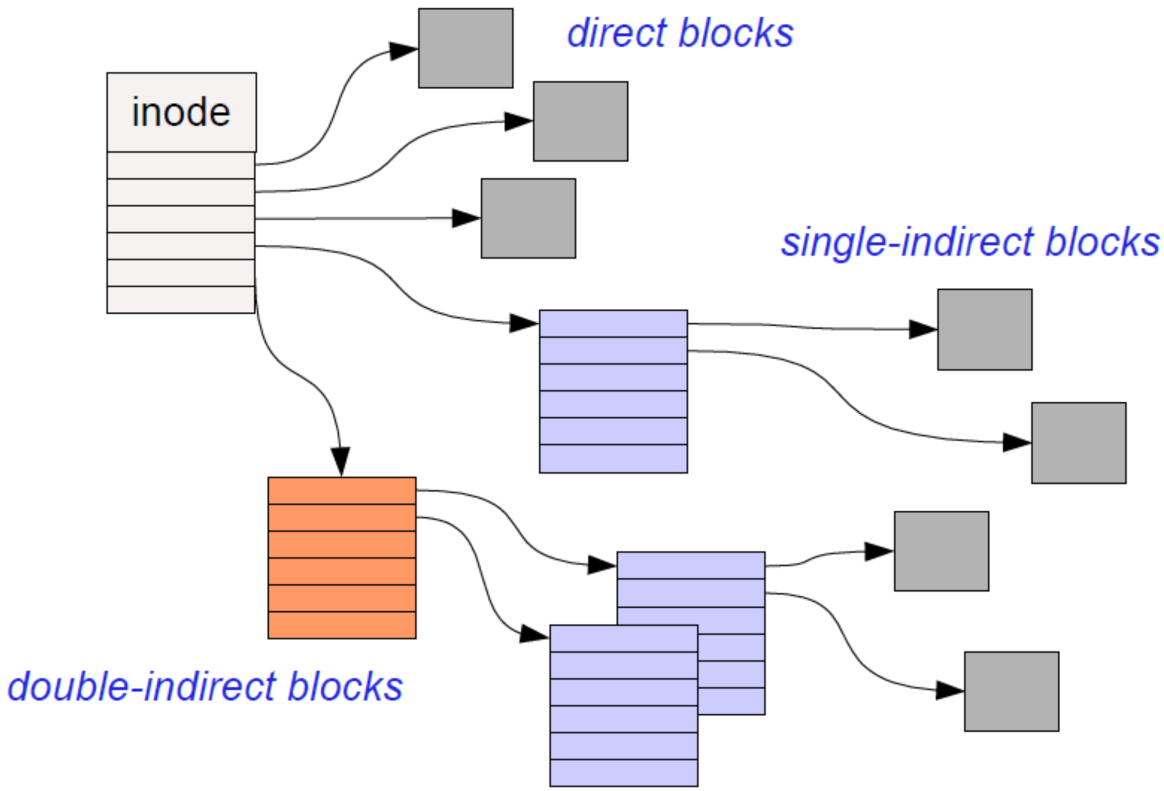


- Indexed files
  - inode contains a list of block numbers containing the file
  - Array is allocated when the file is created
    - What are the advantages and disadvantages??



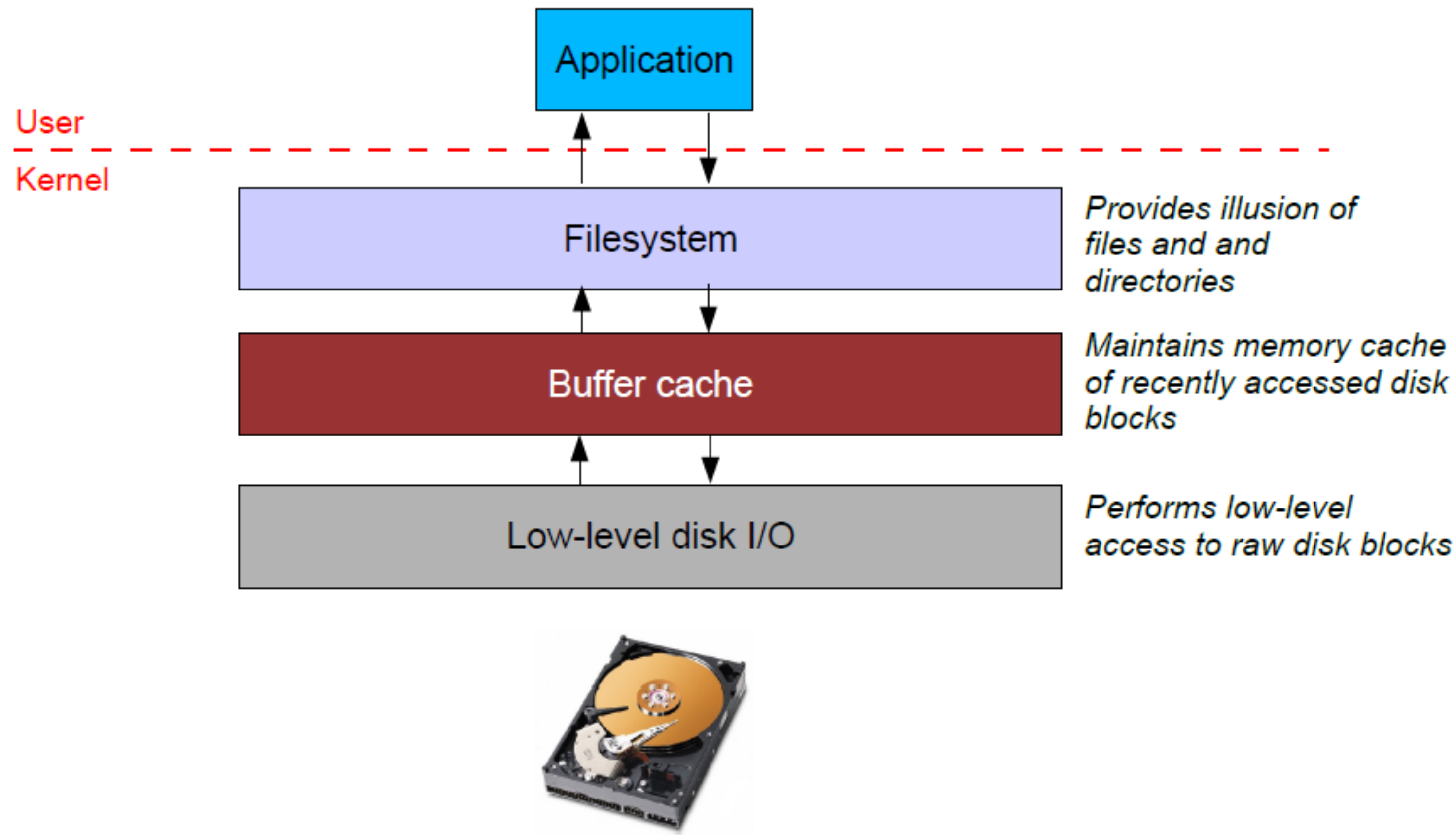
Multilevel indexed files

- inode contains a list of 10-15 direct block pointers
  - First few blocks of file can be referred to by the inode itself
- inode also contains a pointer to a single indirect, double indirect, and triple indirect blocks
  - Allows file to grow to be incredibly large!!!



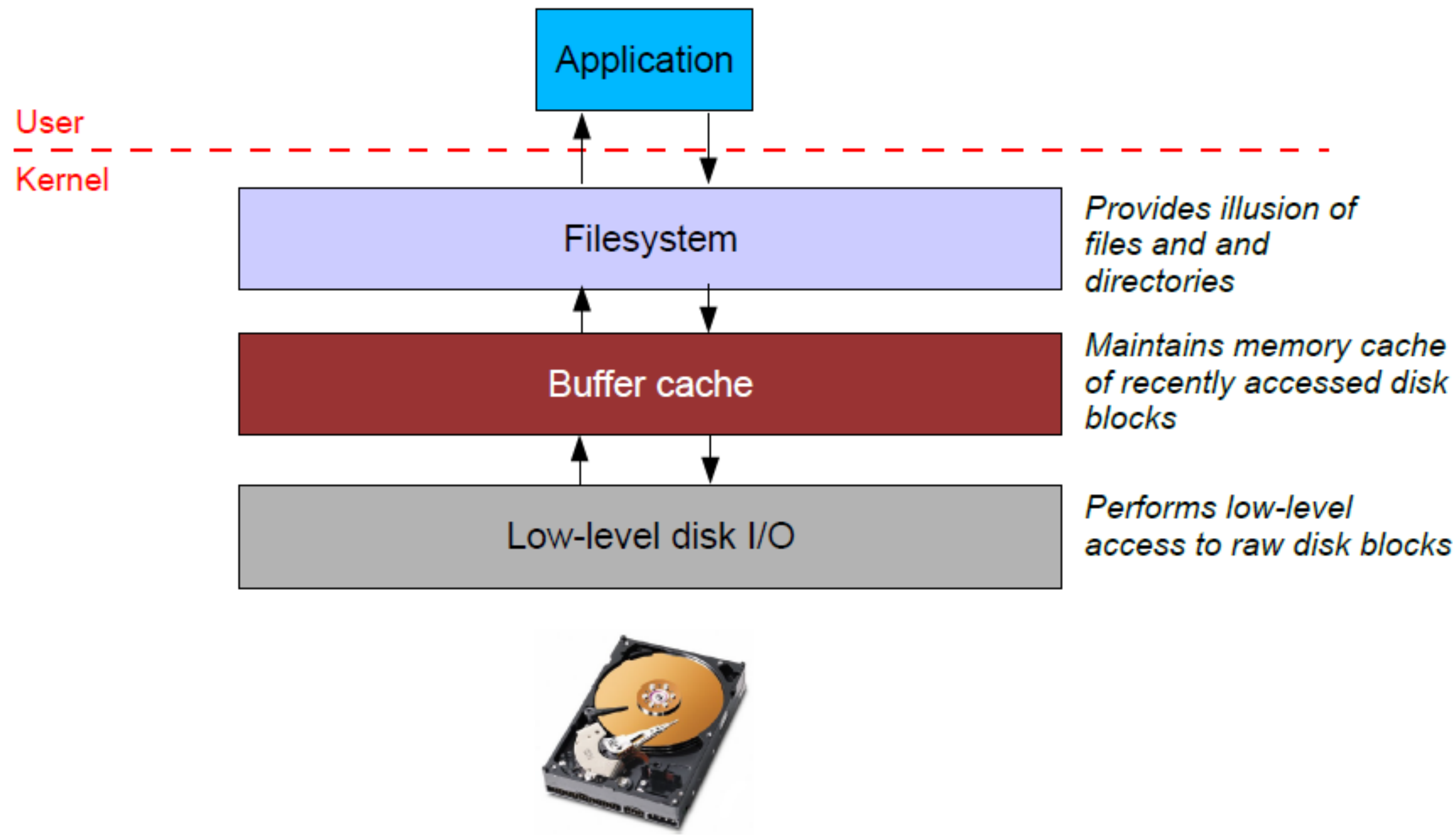
File system caching

- Most filesystems cache significant amounts of disk in memory
  - e.g., Linux tries to use all “free” physical memory as a giant cache
  - Avoids huge overhead for going to disk for every I/O



Caching issues

- Where should the cache go?
  - Below the filesystem layer: Cache individual disk blocks
  - Above the filesystem layer: Cache entire files and directories
  - Which is better??



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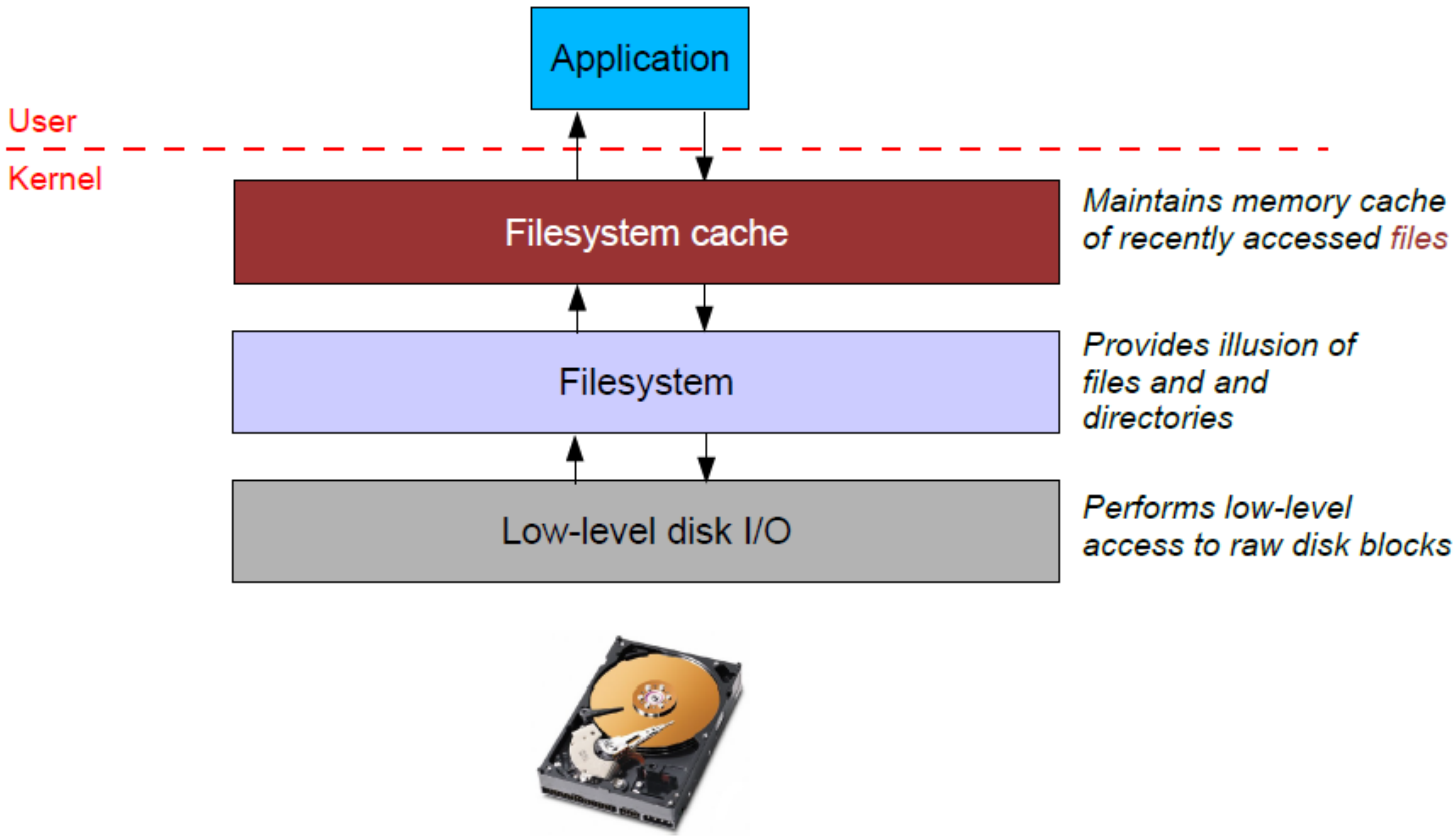
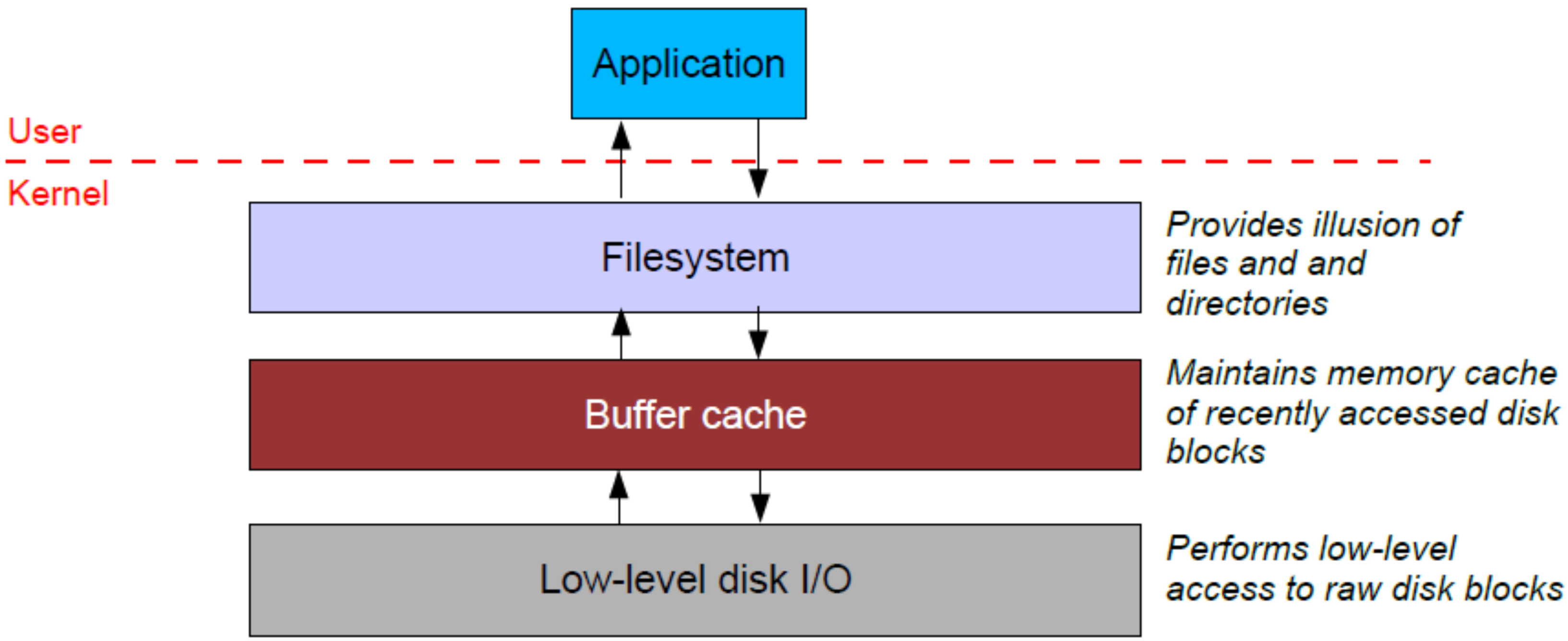


Caching issues (2)

- Reliability issues
  - What happens when you write to the cache but the system crashes?
  - What if you update some of the blocks on disk but not others?
    - Example: Update the inode on disk but not the data blocks?
  - Write-through cache: All writes immediately sent to disk
  - Write-back cache: Cache writes stored in memory until evicted (then written to disk)
    - Which is better for performance? For reliability?



Caching issues (2)

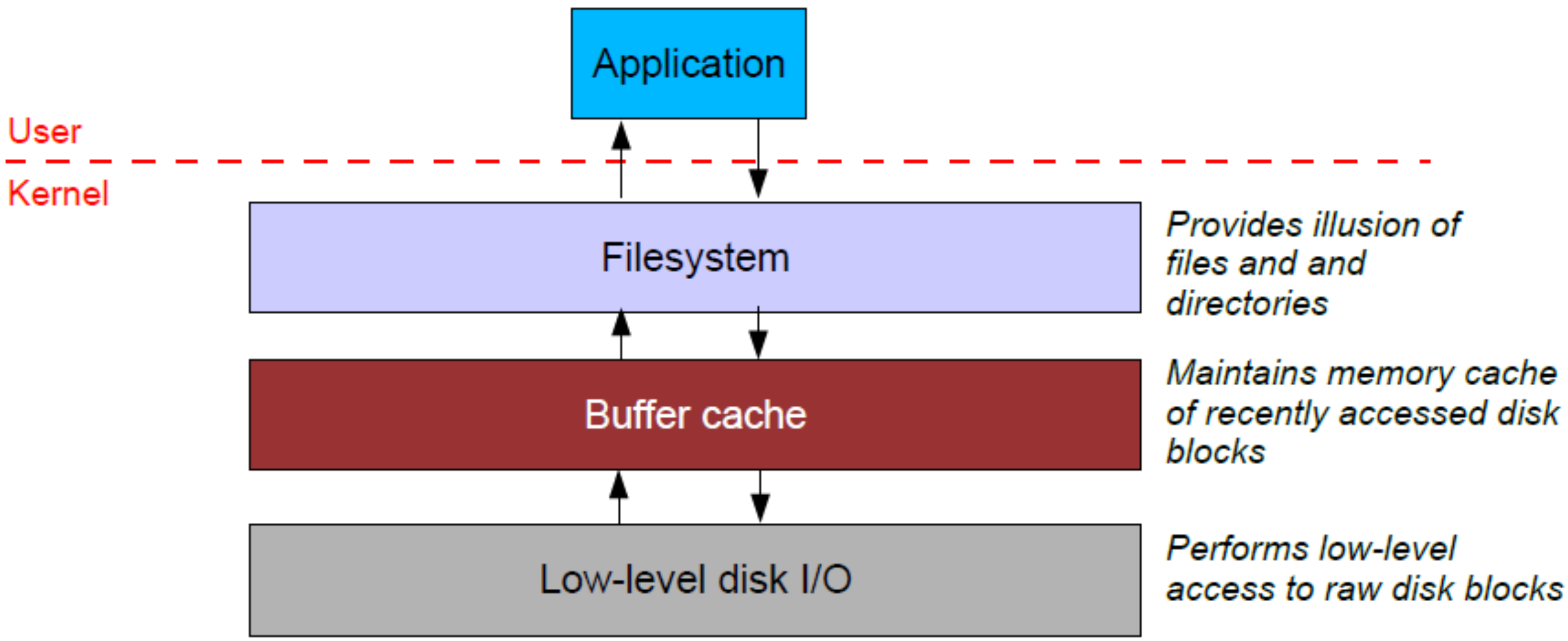
- "Syncing" a filesystem writes back any dirty cache blocks to disk
  - UNIX "sync" command achieves this.
  - Can also use fsync() system call to sync any blocks for a given file.
    - Warning – not all UNIX systems guarantee that after sync returns that the data has really been written to the disk!
    - This is also complicated by memory caching on the disk itself.
- Crash recovery
  - If system crashes before sync occurs, "fsck" checks the filesystem for errors
  - Example: an inode pointing to a block that is marked as free in the free block list
  - Another example: An inode with no directory entry pointing to it
    - These usually get linked into a "lost+found" directory
    - inode does not contain the filename so need the sysadmin to look at the file dataand guess where it might belong!

Caching and fsync() example

- Running the `copy` example from last time,
  - How fast is it the first time, vs. the second time you copy the same file?
  - What happens if we `fsync()` after each iteration?

Caching issues (3)

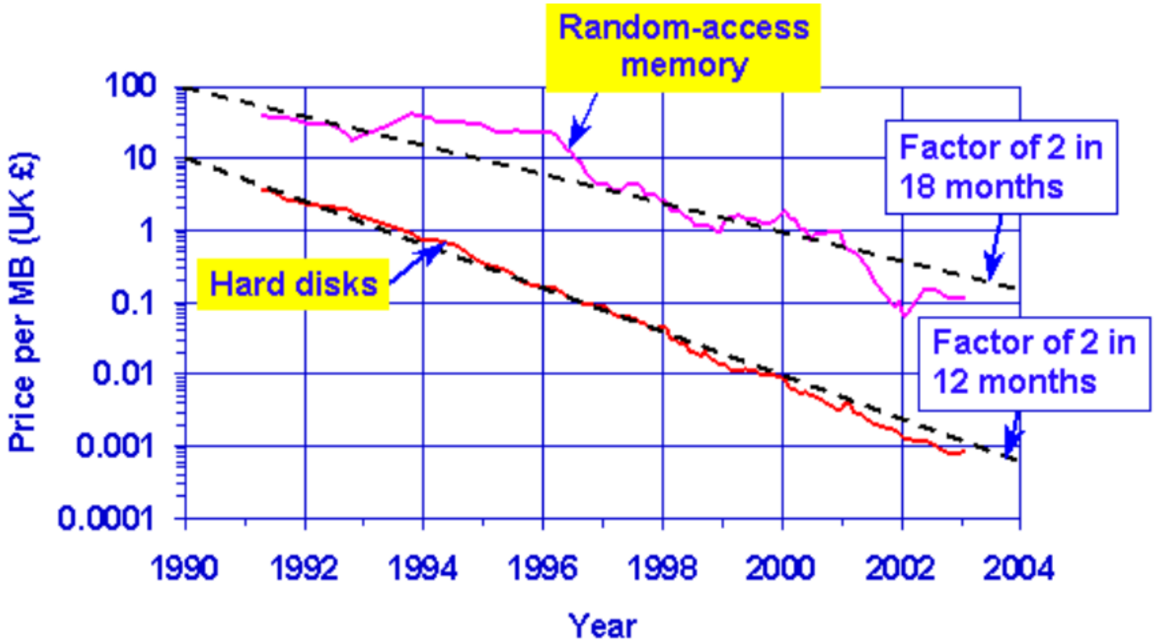
- Read ahead
  - Recall: Seek time dominates overhead of disk I/O
  - So, would ideally like to read multiple blocks into memory when you have a cache miss
    - Amortize the cost of the seek for multiple reads
  - Useful if file data is laid out in contiguous blocks on disk
    - Especially if the application is performing sequential access to the file



Making filesystems resilient: RAID

RAID Motivation

- Speed of disks not matching other components
  - Moore's law: CPU speed doubles every 18 months
  - SRAM speeds increasing by 40-100% a year
  - In contrast, disk seek time only improving 7% a year
    - Although greater density leads to improved transfer times once seek is done
- Emergence of PCs starting to drive down costs of disks
  - (This is 1988 after all)
  - PC-class disks were smaller, cheaper, and only marginally slower



RAID Motivation

- Basic idea: Build I/O systems as arrays of cheap disks
  - Allow data to be striped across multiple disks
  - Means you can read/write multiple disks in parallel – greatly improve performance
- Problem: disks are extremely unreliable
- Mean Time to Failure (MTTF)
  - MTTF (disk array) = MTTF (single disk) / # disks
  - Adding more disks means that failures happen more frequently..
  - An array of 100 disks with an MTTF of 30,000 hours = just under 2 weeks for the array's MTTF!

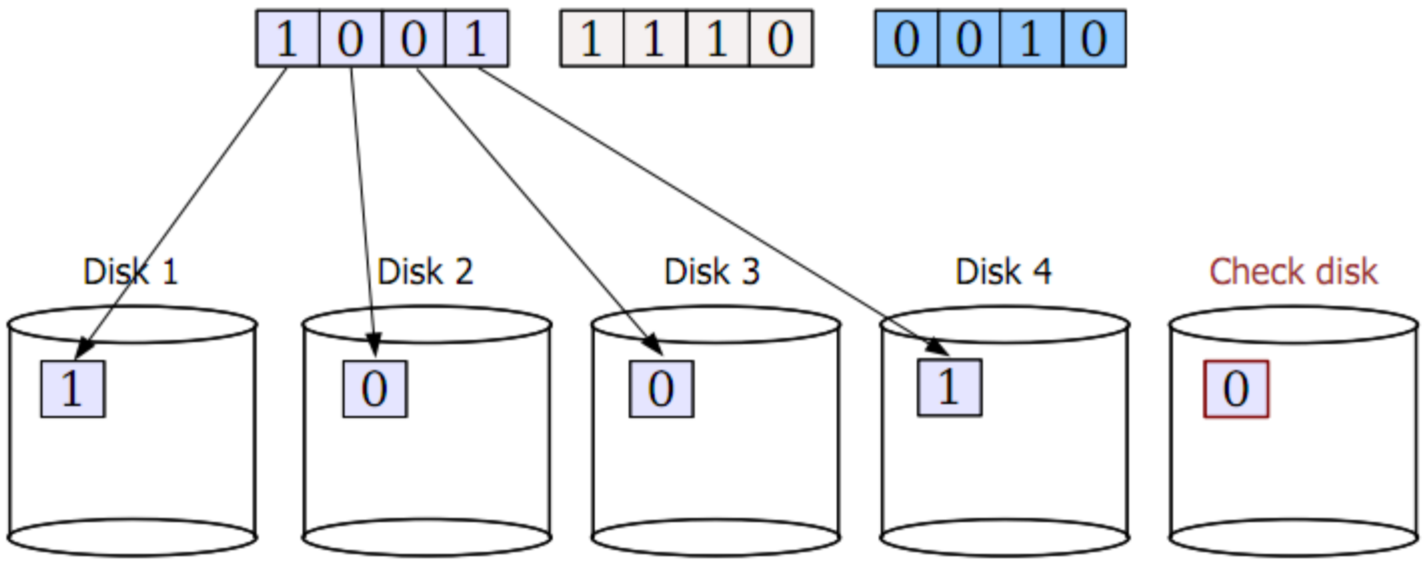
Increasing reliability

- Idea: Replicate data across multiple disks
  - When a disk fails, lost information can be regenerated from the redundant data
- Simplest form: Mirroring (also called "RAID 1")
  - All data is mirrored across two disks
- Advantages:
  - Reads are faster, since both disks can be read in parallel
  - Higher reliability (of course)
- Disadvantages:
  - Writes are slightly slower, since OS must wait for both disks to do write
  - Doubles the cost of the storage system!

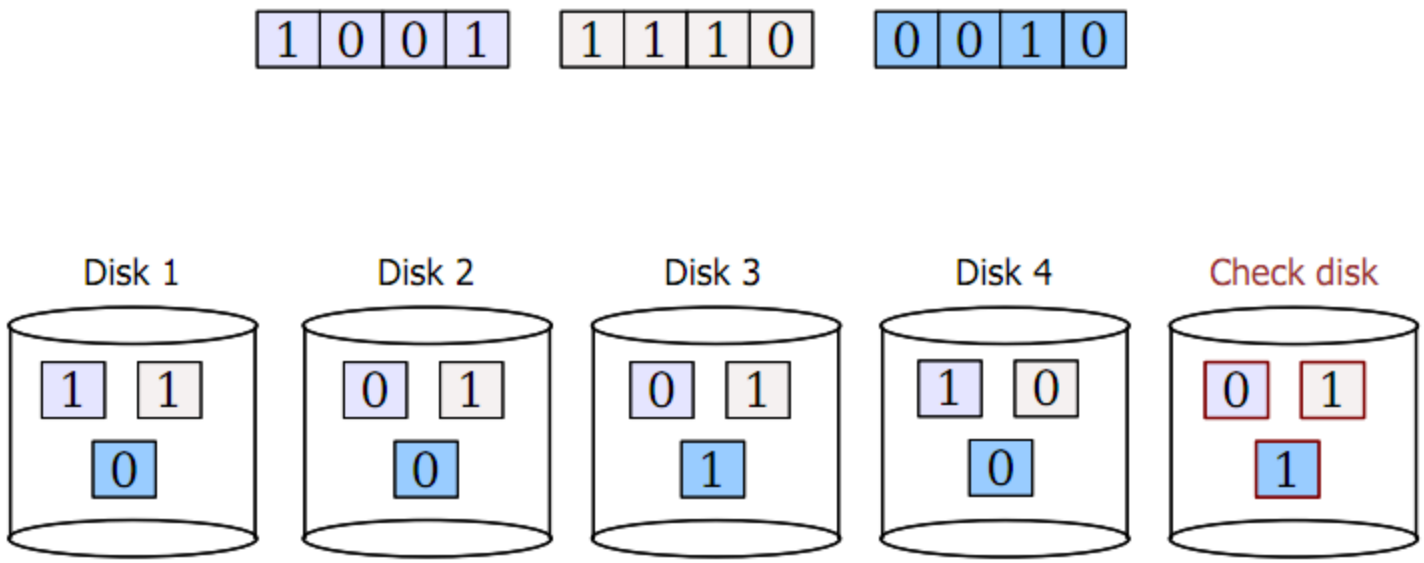
RAID 3

- Rather than mirroring, use parity codes
  - Given N bits $\{b_1, b_2, ..., b_N\}$, the parity bit P is the bit {0,1} that yields an even number of "1" bits in the set $\{b_1, b_2, ..., b_N, P\}$
  - Idea: If any bit in $\{b_1, b_2, ..., b_N\}$ is lost, can use the remaining bits (plus P) to recover it.
- Where to store the parity codes?
  - Add an extra "check disk" that stores parity bits for the data stored on the rest of the N disks
- Advantages:
  - If a single disk fails, can easily recompute the lost data from the parity code
  - Can use one parity disk for several data disks (reduces cost)
- Disadvantages:
  - Each write to a block must update the corresponding parity block as well

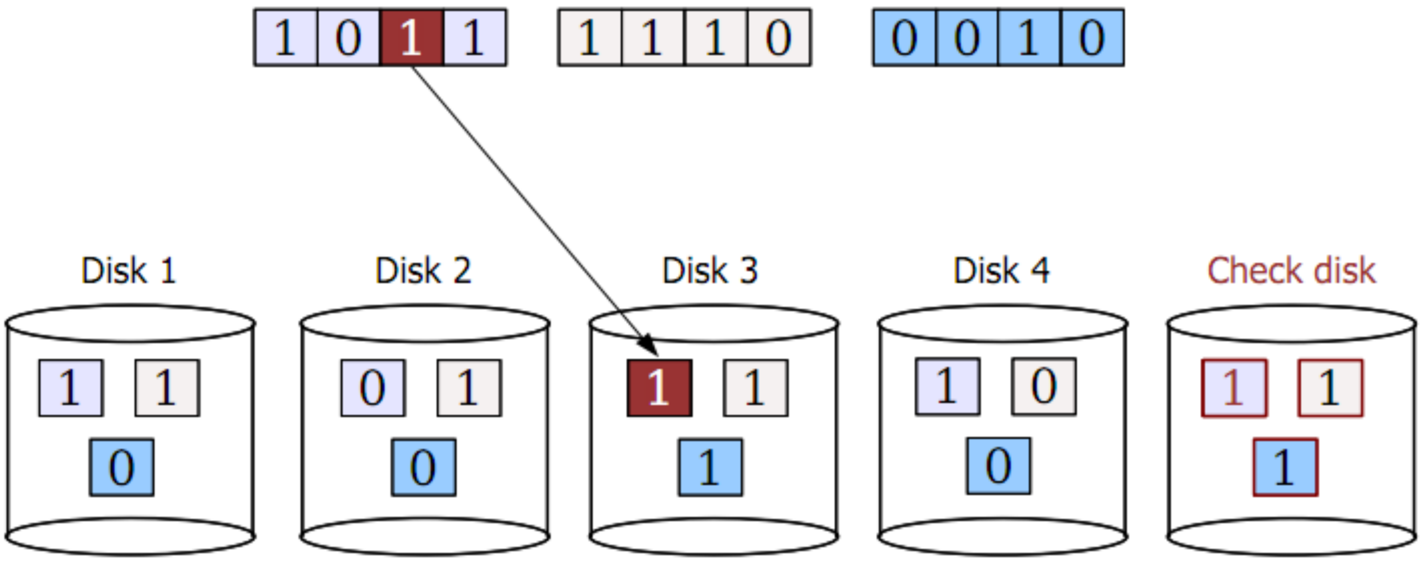
RAID 3 example



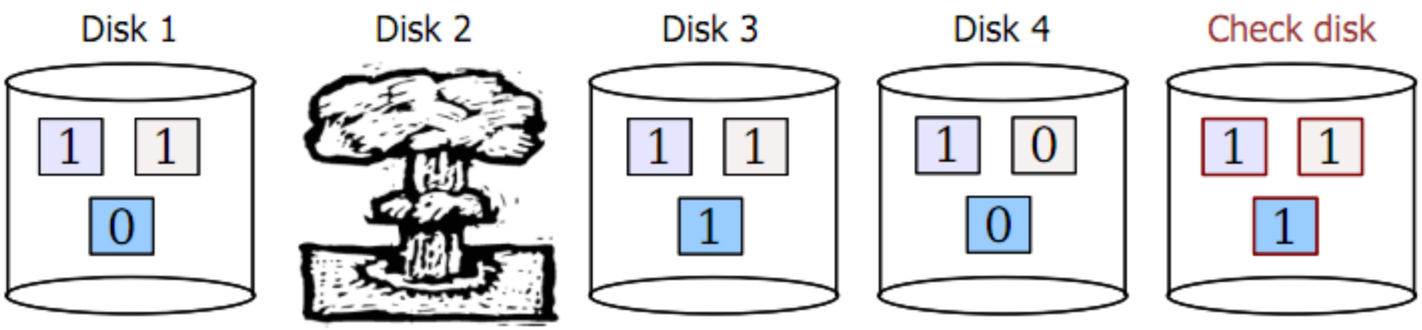
RAID 3 example



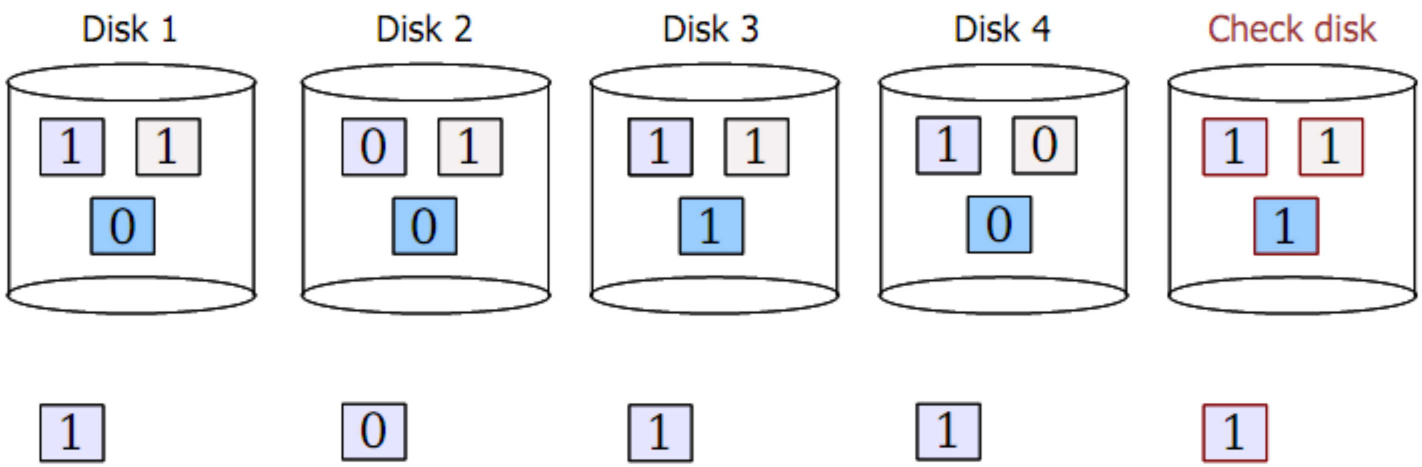
RAID 3 example



RAID 3 example



RAID 3 example



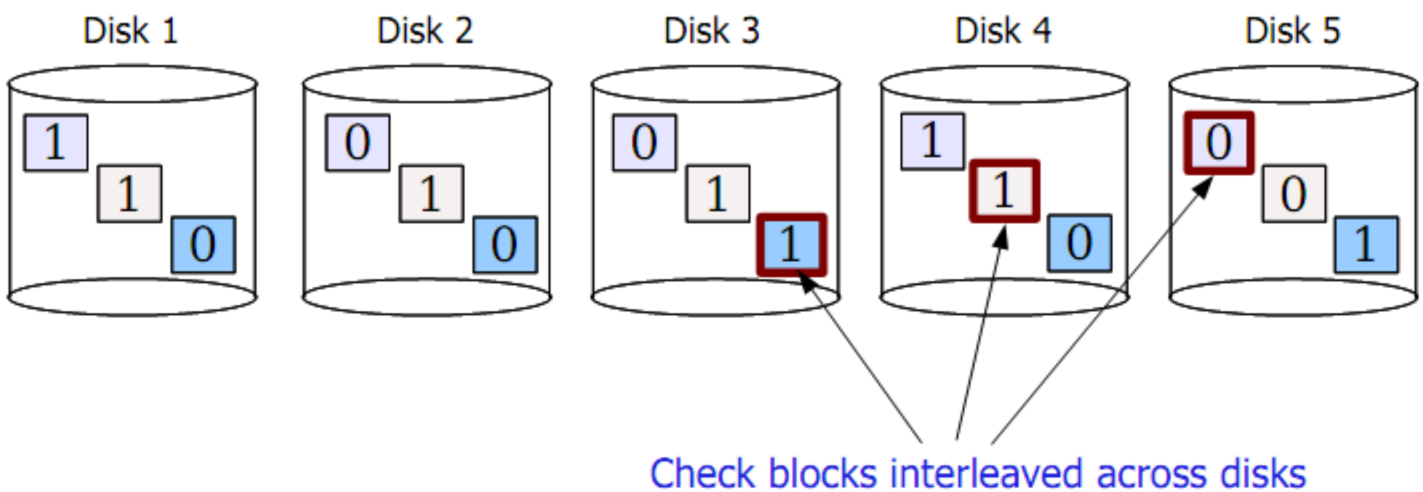
- 1. Read back data from other disks
- 2. Recalculate lost data from parity code
- 3. Rebuild data on lost disk

RAID 3 issues

- Terminology
  - MTTF = mean time to failure
  - MTTR = mean time to repair
- What is the MTTF of RAID?
  - Both RAID 1 and RAID 3 tolerate the failure of a single disk
  - As long as a second disk does not die while we are repairing the first failure, we are in good shape!
- So, what is the probability of a second disk failure?
- P(2nd failure) ≈ MTTR / (MTTF of one disk / # disks -1)
    - Assumes independent, exponential failure rates; see Patterson RAID paper for derivation
  - 10 disks, MTTF (disk) = 1000 days, MTTR = 1 day
    - P(2nd failure) ≈ 1 day / (1000 / 9) = 0.009
- What is the performance of RAID 3?
  - Check disk must be updated each time there is a write
  - Problem: The check disk is then a performance bottleneck
    - Only a single read/write can be done at once on the whole system!

RAID 5

- Another approach: Interleaved check blocks (“RAID 5”)
  - Rotate the assignment of data blocks and check blocks across disks
  - Avoids the bottleneck of a single disk for storing check data
  - Allows multiple reads/writes to occur in parallel (since different disks affected)



Reliable distributed storage

- Today, giant data stores distributed across 100s of thousands of disks across the world
  - e.g., your mail on gmail

- *"You know you have a large storage system when you get paged at 1 AM because you only have a few petabytes of storage left."*
  - – a "note from the trenches" at Google

Reliable distributed storage

- Issues
  - Failure is the common case
    - Google reports 2-10% of disks fail per year
    - Now multiply that by 60,000+ disks in a single warehouse...
  - Must survive failure of not just a disk, but a rack of servers or a whole data center
- Solutions
  - Simple redundancy (2 or 3 copies of each file)
    - e.g., Google GFS (2001)
  - More efficient redundancy (analogous to RAID 3++)
    - e.g., Google Colossus filesystem (~2010): customizable replication including Reed-Solomon codes with 1.5x redundancy
- More interesting tidbits: http://goo.gl/LwFIy

Today only!

Randy Katz
Distinguished Professor,
University of California at Berkeley

$2^{11213}-1$ IS PRIME

URBANA MAR 30 2009 ILL.

DONALD B. GILLIES MEMORIAL LECTURE

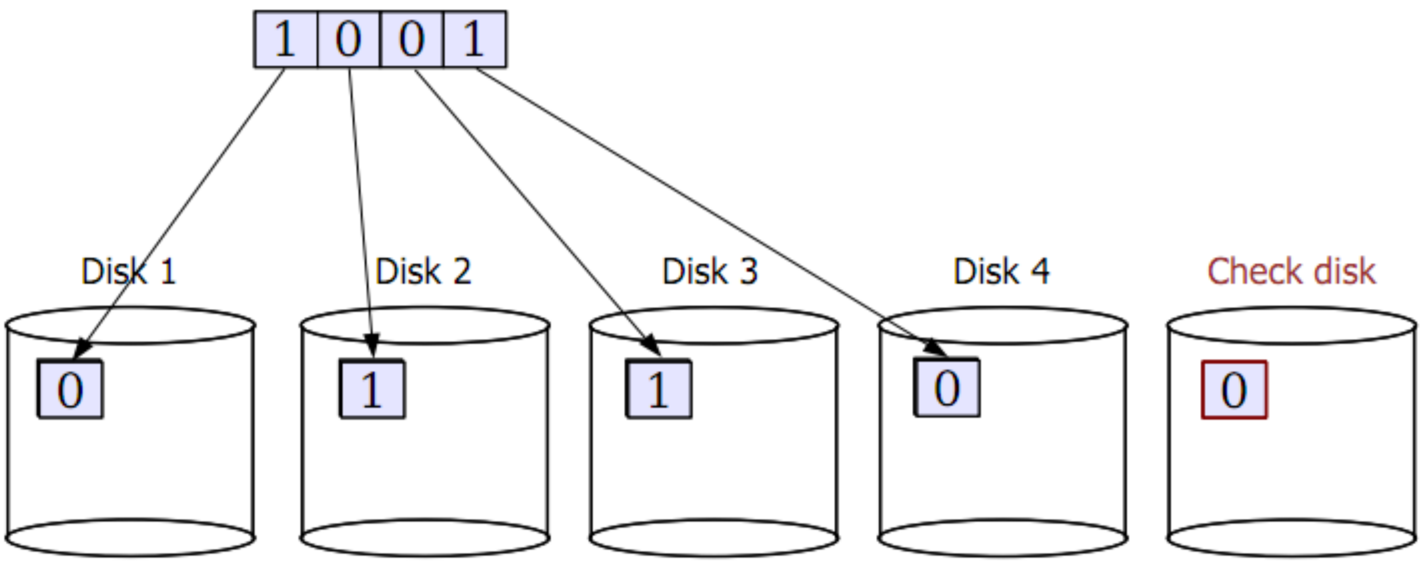
"Mesos: A Platform for Fine-Grained Resource Sharing in the Data Center"

4:00 p.m. Today
2405 Siebel Center

Bonus: Atomic write failures in RAID (not on exam)

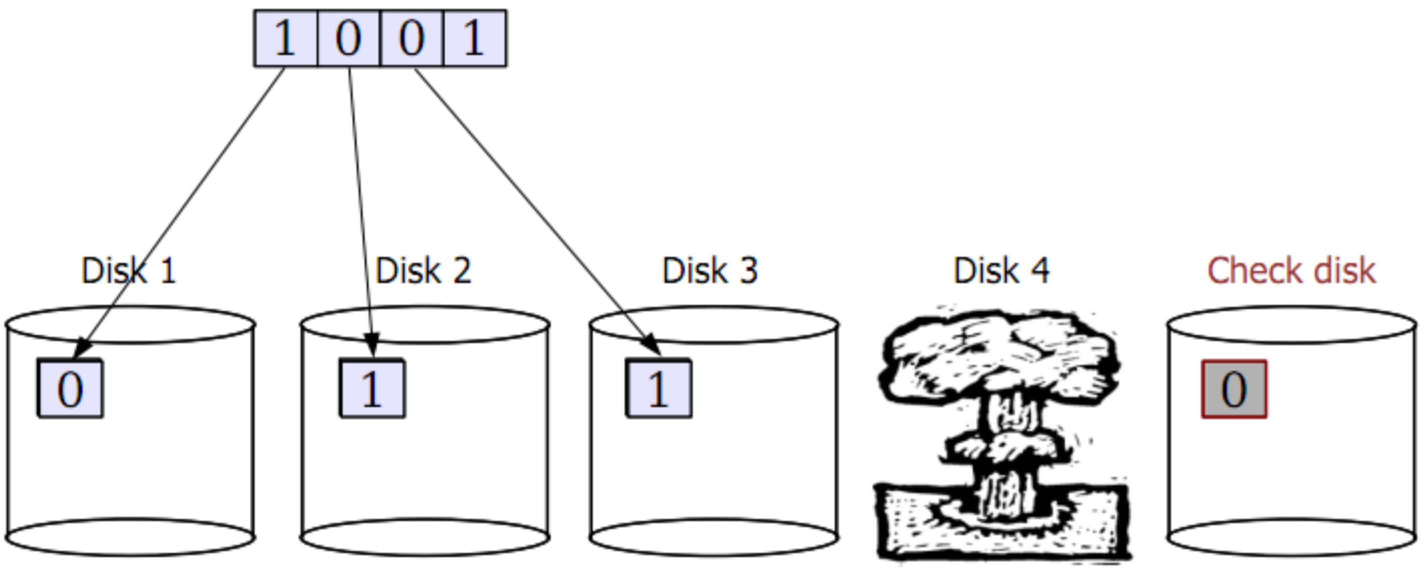
Atomic Write Failure

- Many applications perform "update in place"
  - They change a file on disk by overwriting it with a new version
- What happens with RAID?



Atomic Write Failure

- But is the complete write to all disks really atomic?
  - Generally, no!



Atomic Write Failure

- But is the complete write to all disks really atomic?
  - Generally, no!
- What does this mean?
  - Data can be left in an inconsistent state across the different disks!
  - Really hard to recover from this.
- Problem: Most applications assume the storage system has atomic write semantics.
- Possible fixes?
  - Use a journaling filesystem-like approach: Record changes to data objects transactionally.
    - Requires extensive changes to filesystem sitting on top of the RAID.
  - Battery-backed write cache:
    - RAID controller remembers all writes in a battery-backed cache
    - When recovery occurs, flush all writes out to the physical disks
    - Doesn't solve the problem in general but gives you some insurance.

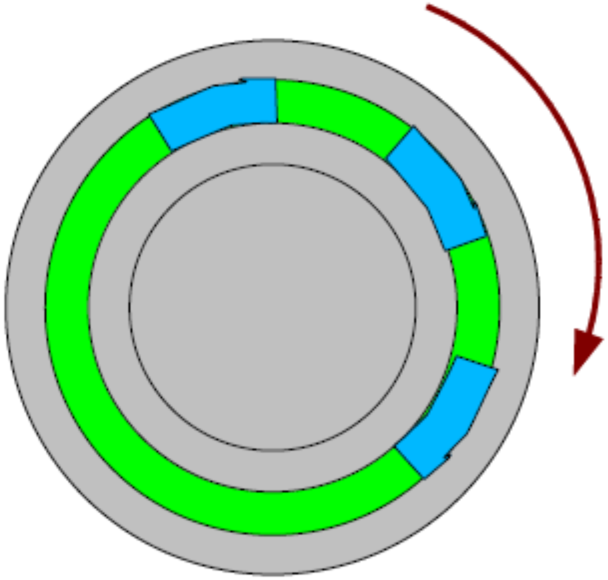
Bonus: Modern Filesystem techniques (not on exam)

Modern Filesystem Tricks

- Extents
- Pre-allocation
- Delayed allocation (Block remapping)
- Colocating inodes and directories
- Soft metadata updates
- Journaling
- These tricks are used by many modern filesystems
  - E.g., ext3 and ext4

Extent-based transfers

- One idea: a gap between sectors on a track
  - Try to take advantage of rotational latency for performing next read or write operation
  - Problem: Hurts performance for multi-sector I/O!
  - Cannot achieve the full transfer rate of the disk for large, contiguous reads or writes.
- Possible fix: Just get rid of the gap between sectors
  - Problem: "Dropped rotation" between consecutive reads or writes: have to wait for next sector to come around under the heads.



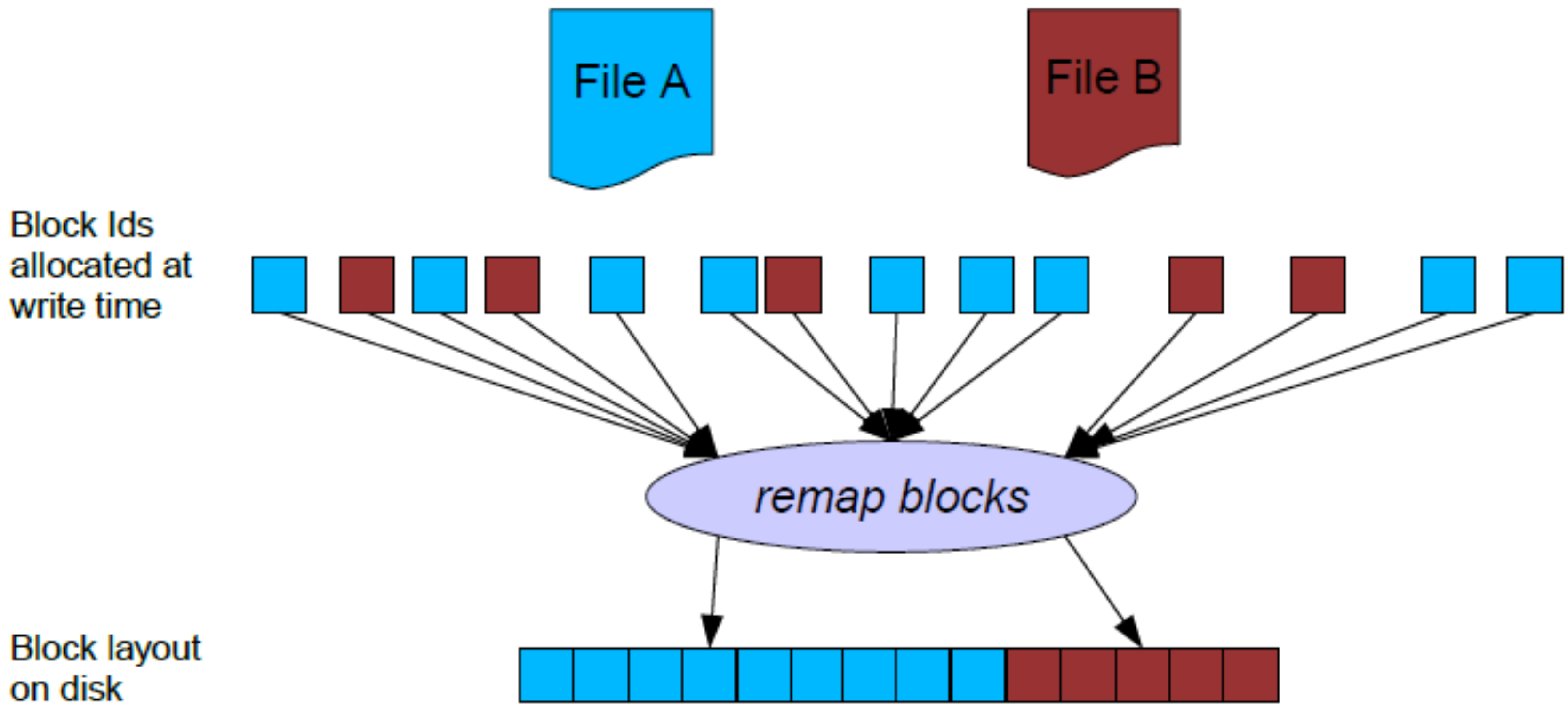
- Hybrid approach - "extents" [McVoy, USENIX'91]
  - Group blocks into "extents" or clusters of contiguous blocks
  - Try to do all I/O on extents rather than individual blocks
  - To avoid wasting I/O bandwidth, only do this when FS detects sequential access
    - Kind of like just increasing the block size...

Block remapping

- Problem: Block numbers are allocated when they are first written
  - FS maintains a free list of blocks and simply picks the first block off the list
    - No guarantee that these blocks will be contiguous for a large write!
  - A single file may end up with blocks scattered across the disk
- Why can't we maintain the free list in some sorted order?
  - Problem: Interleaved writes to multiple files may end up causing each file to be discontiguous.

Block remapping

- Idea: Delay determination of block address until cache is flushed
  - Hope that multiple block writes will accumulate in the cache
  - Can remap the block addresses for each file's writes to a contiguous set
    - This is kind of a hack, introduced "underneath" the FFS block allocation layer.
    - Meant fewer changes to the rest of the FFS code.
    - Sometimes building real systems means making these kinds of tradeoffs!



Colocating inodes and directories

- Problem: Reading small files is slow. Why?
  - What happens when you try to read all files in a directory (e.g., "ls -l" or "grep foo *") ?
  - Must first read directory.
  - Then read inode for each file.
  - Then read data pointed to by inode.
- Solution: Embed the inodes in the directory itself!
  - Recall: Directory just a set of <name, inode #> values
  - Why not stuff inode contents in the directory file itself?
- Problem #2: Must still seek to read contents of each file in the directory.
  - Solution: Pack all files in a directory in a contiguous set of blocks.

Synchronous metadata updates

- Problem: Some updates to metadata require synchronous writes
  - Means the data has to "hit the disk" before anything else can be done.
- Example #1: Creating a file
  - Must write the new file's inode to disk before the corresponding directory entry.
    - Why???
- Example #2: Deleting a file
  - Must clear out the directory entry before marking the inode as "free"
    - Why???

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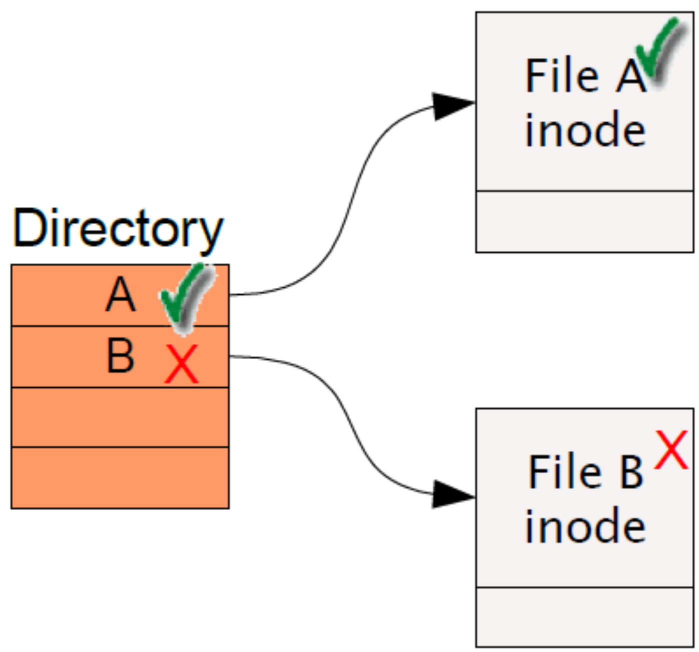
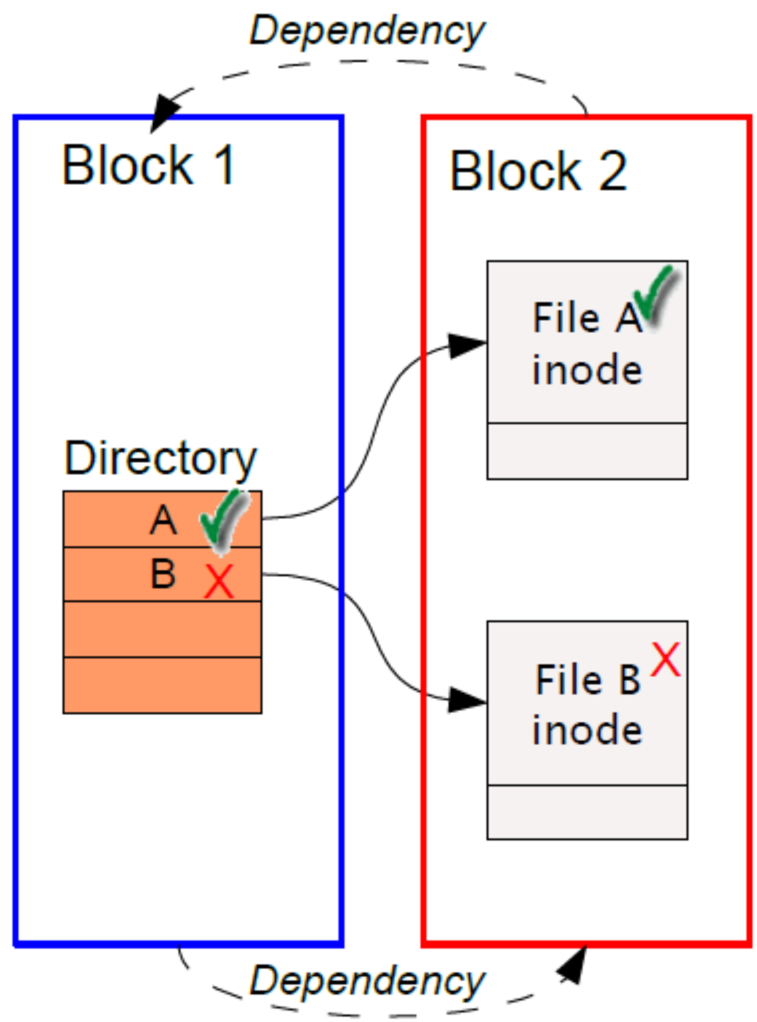


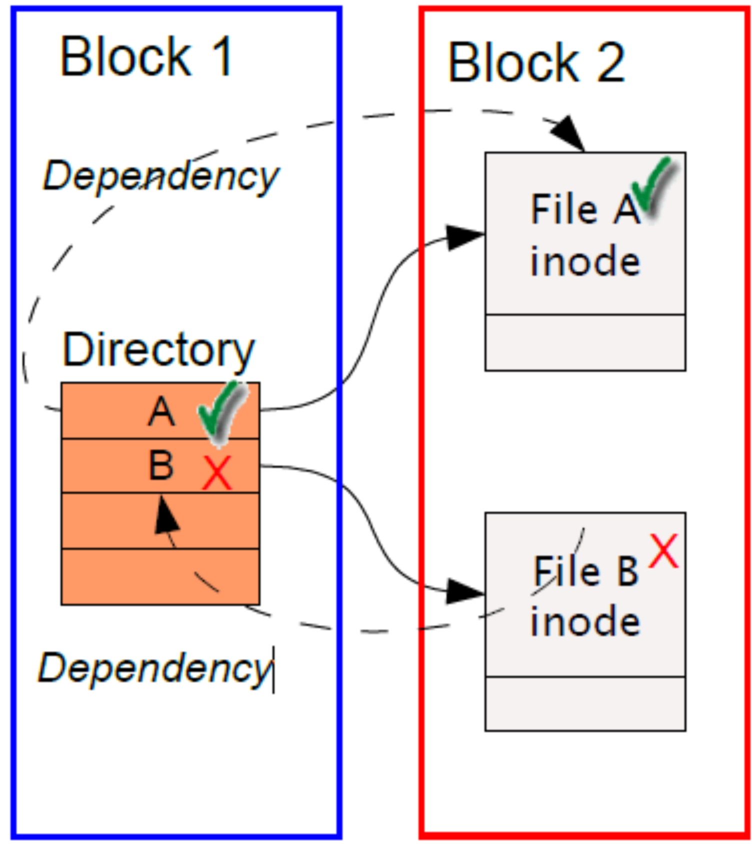
Synchronous metadata updates

- Say that ...
  - 1) Both inodes are in the same disk block.
  - 2) Both the file create and file delete have happened in the cache, but neither has hit the disk yet.
  - Given this, what order are we allowed to write the disk blocks out?
    - *We have a cyclic dependency here!!! Argggghhhh ....*



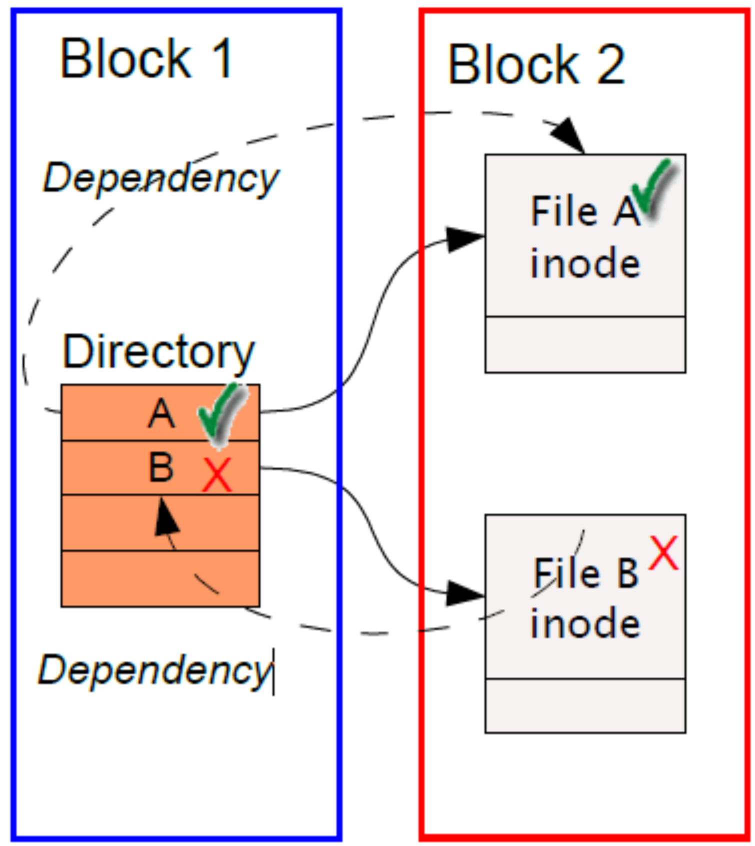
Solution: Soft Updates

- Idea: Keep track of dependencies on a finer granularity
  - Rather than at a block level, do this at a "data structure level"
  - Example: Track dependencies on individual inodes or directory entries.



Soft Updates - Example

- How to break the cyclic dependency?
  - "Roll back" one of the changes before writing the data out to disk!
- When flushing inode block (Block 2) to disk...
  - Undo the file delete operation (as if it never happened!)
  - Write out the inode block (Block 2) – still contains B!
  - Then write out the directory block (Block 1) – still contains entry for B!
  - Then redo the file delete operation ... can now proceed.



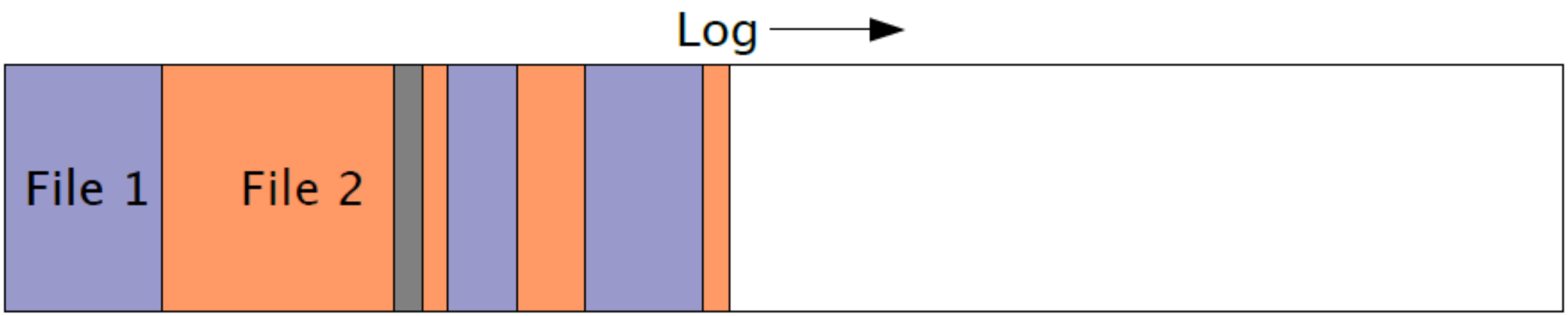
Log-structured Fileystems (LFS)

- Around '91, two trends in disk technology were emerging:
  - Disk bandwidth was increasing rapidly (over 40% a year)
  - Seek latency not improving much at all
  - Machines had increasingly large main memories
    - Large buffer caches absorb a large fraction of read I/Os
  - Can use for writes as well!
    - Coalesce several small writes into one larger write
- Some lingering problems with earlier filesystems...
  - Writing to file metadata (inodes) was required to be synchronous
    - Couldn't buffer metadata writes in memory
  - Lots of small writes to file metadata means lots of seeks!
- LFS takes advantage of both to increase FS performance
  - Started as a grad-school research project at Berkeley
  - Mendel Rosenblum and John Ousterhout

LFS: The basic idea

- Treat the entire disk as *one big append-only log for writes!*
  - Don't try to lay out blocks on disk in some predetermined order
  - Whenever a file write occurs, append it to the *end of the log*
  - Whenever file metadata changes, append it to the *end of the log*
- Collect pending writes in memory and stream out in one big write
  - Maximizes disk bandwidth
  - No "extra" seeks required (only those to move the end of the log)
- When do writes to the actual disk happen?
  - When a user calls sync() -- synchronize data on disk for whole filesystem
  - When a user calls fsync() -- synchronize data on disk for one file
  - When OS needs to reclaim dirty buffer cache pages
    - *Note that this can often be avoided, eg., by preferring clean pages*
- Sounds simple ...
  - But lots of hairy details to deal with!

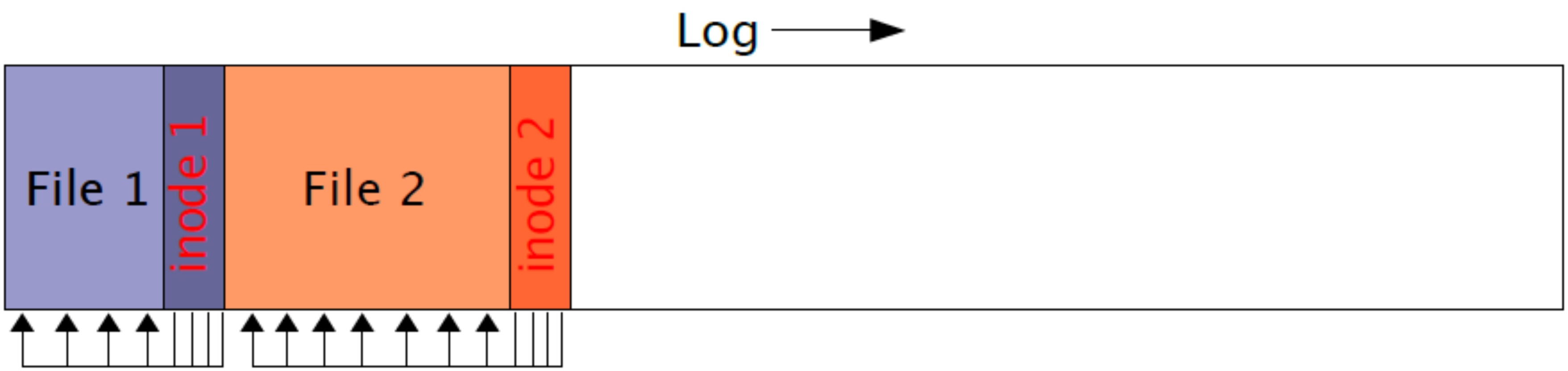
LFS Example



- Just append every new write that happens to the end of the log
  - Writing a block in the middle of the file just appends that block to the end of the log

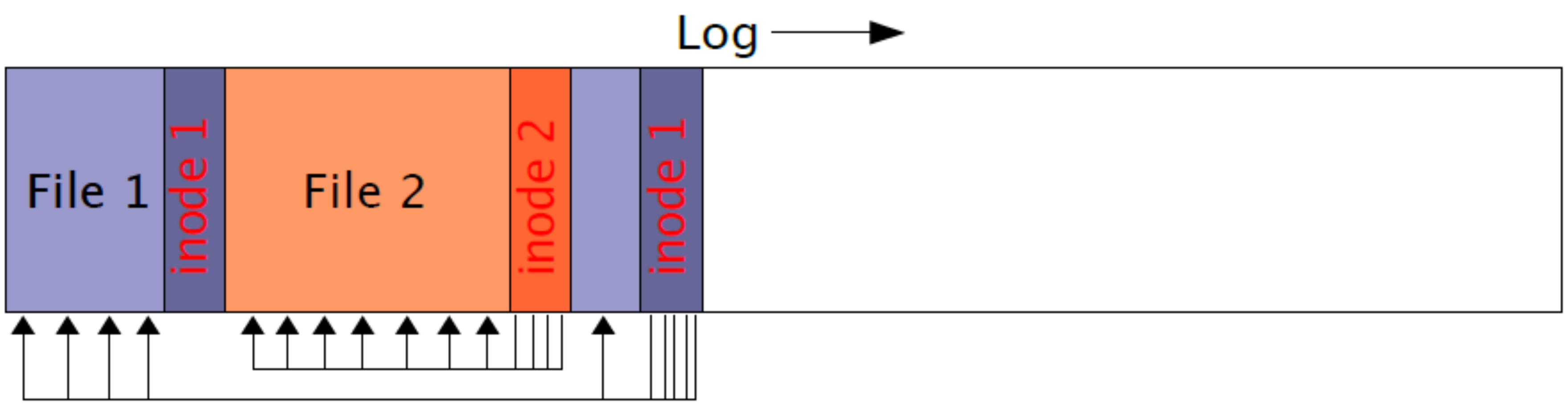
LFS and inodes

- How do you locate file data?
  - Sequential scan of the log is probably a bad idea ...
- Solution: Write the inodes to the tail of the log! (just like regular data)



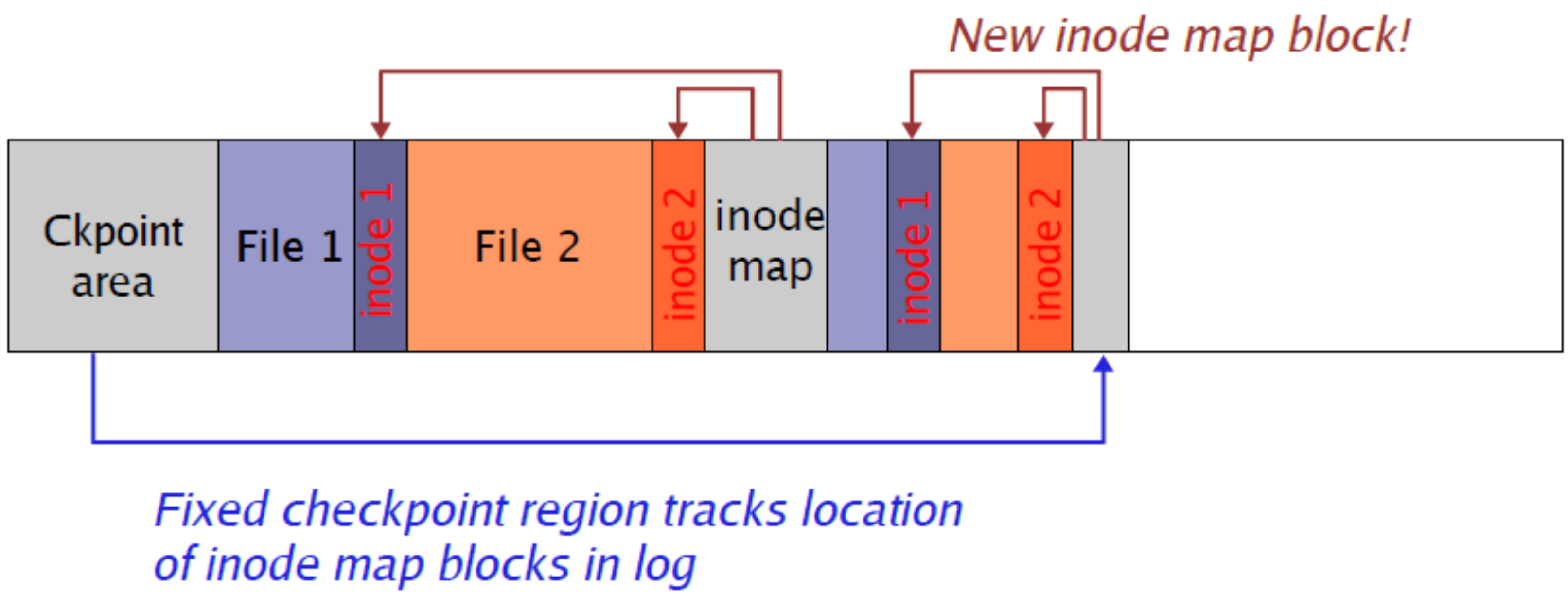
LFS and inodes

- How do you locate file data?
  - Sequential scan of the log is probably a bad idea ...
- Solution: Use FFS-style inodes!



inode map (this is getting fun)

- Well, now, how do you find the inodes??
  - Could also be anywhere in the log!
- Solution: *inode maps*
  - Maps "file number" to the location of its inode in the log
  - Note that inode map is *also written to the log!!!!*
  - Cache inode maps in memory for performance



Reading from LFS

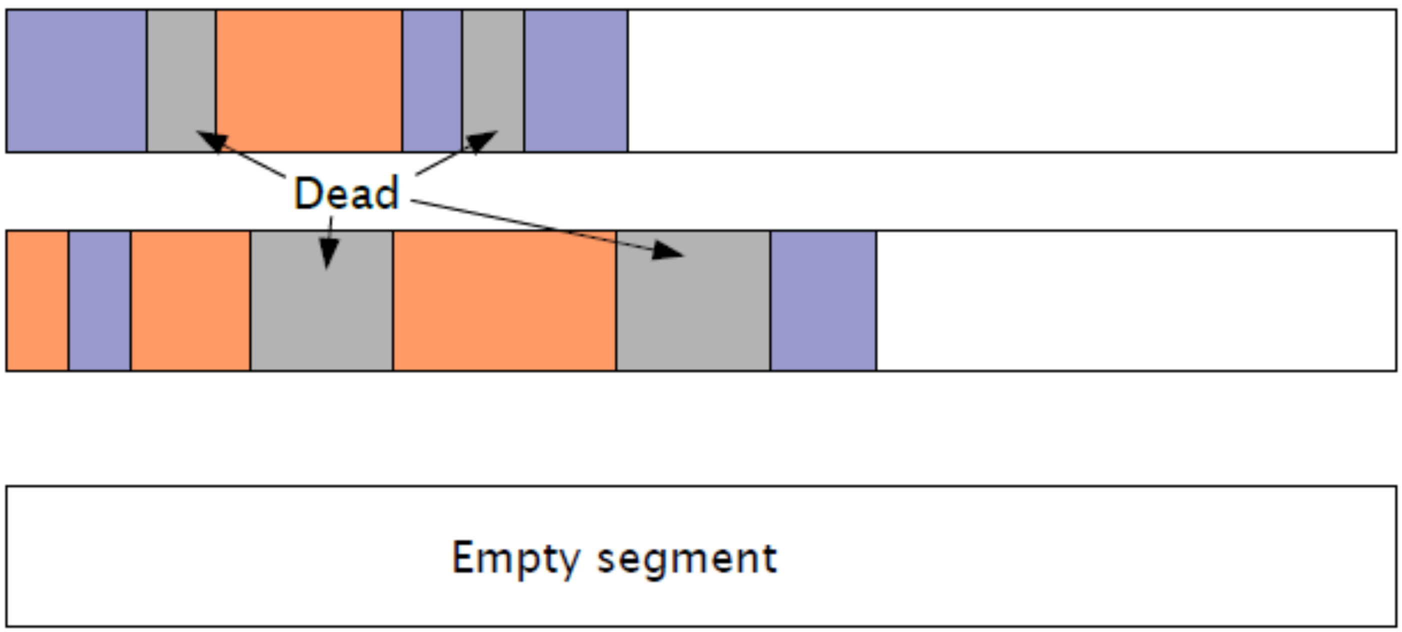
- But wait ... now file data is scattered all over the disk!
  - Seems to obviate all of the benefits of grouping data on common cylinders
- Basic assumption: Buffer cache will handle most read traffic
  - Or at least, reads will happen to data roughly in the order in which it was written
  - Take advantage of huge system memories to cache the heck out of the FS!

Log cleaner

- With LFS, eventually the disk will fill up!
  - Need some way to reclaim "dead space"
- What constitutes "dead space?"
  - Deleted files
  - File blocks that have been "overwritten"
- Solution: Periodic "log cleaning"
- Scan the log and look for deleted or overwritten blocks
  - Effectively, clear out stale log entries
- Copy *live data to the end of the log*
  - The rest of the log (at the beginning) can now be reused!

Log cleaning example

- LFS cleaner breaks log into *segments*
  - Each segment is scanned by the cleaner
  - Live blocks from a segment are copied into a new segment
  - The entire scanned segment can then be reclaimed



Log cleaning example

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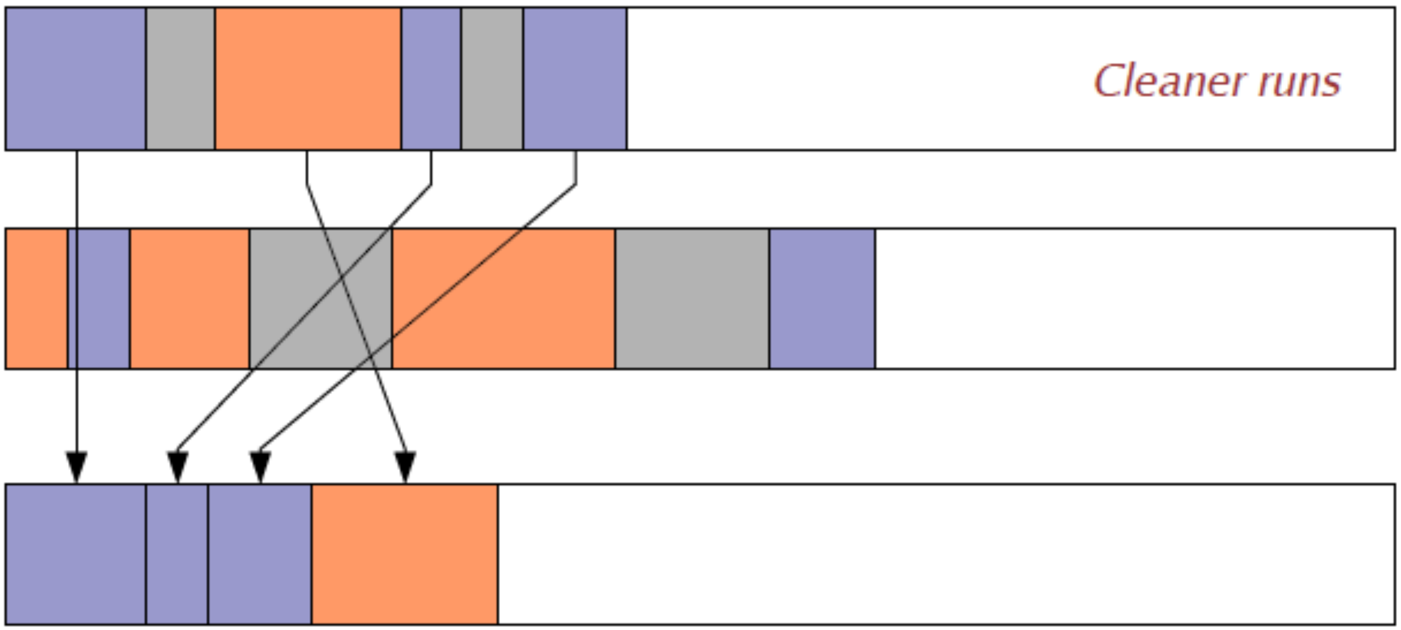

Log cleaning example

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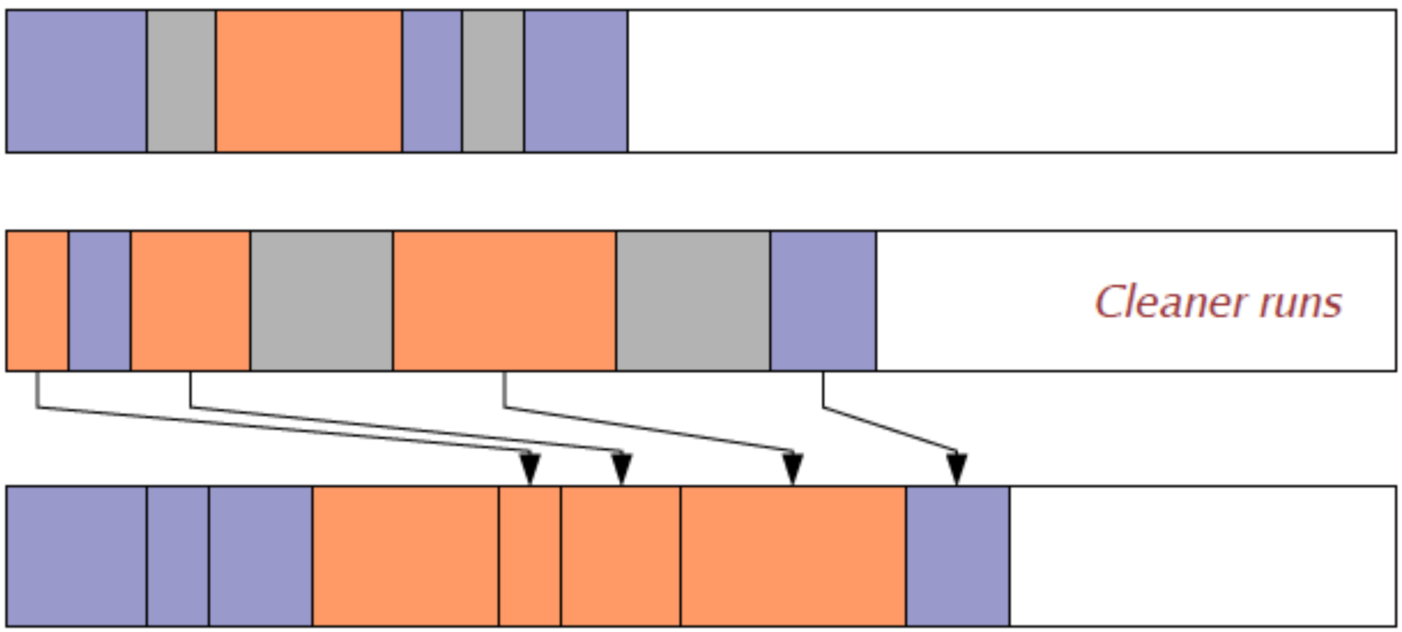


Log cleaning example

- LFS cleaner breaks log into *segments*
  - Each segment is scanned by the cleaner
  - Live blocks from a segment are copied into a new segment
  - The entire scanned segment can then be reclaimed

Properties of LFS

- Advantages
  - High write throughput
  - Few in-place writes
    - Some kinds of storage media have limited write/erase cycles per location (e.g., flash memory, CD-RW)
    - LFS prolongs life of media through write-leveling
- Disadvantages
  - Increases file fragmentation, can harm performance on systems with high seek times
  - Less throughputs on flash memory, where write fragmentation has much less of an impact on write throughput
- "Lies, damn lies, and benchmarks"
  - It is very difficult to come up with definitive benchmarks proving that one system is better than another
  - Can always find a scenario where one system design outperforms another

Filesystem corruption

- What happens when you are making changes to a filesystem and the system crashes?
  - Example: Modifying block 5 of a large directory, adding lots of new file entries
  - System crashes while the block is being written
  - The new files are "lost!"
- System runs `fsck` program on reboot
  - Scans through the entire filesystem and locates corrupted inodes and directories
  - Can typically find the bad directory, but may not be able to repair it!
  - *The directory could have been left in any state during the write*
- `fsck` can take a very long time on large filesystems
  - And, no guarantees that it fixes the problems anyway

Journaling filesystems

- Ensure that changes to the filesystem are made *atomically*
  - That is, a group of changes are made all together, or not at all
- Example: creating a new file
  - Need to write both the inode for the new file and the directory entry "together"
  - Otherwise, if a crash happens between the two writes, either..
    - 1) Directory points to a file that does not exist
    - 2) Or, file is on disk but not included in any directory

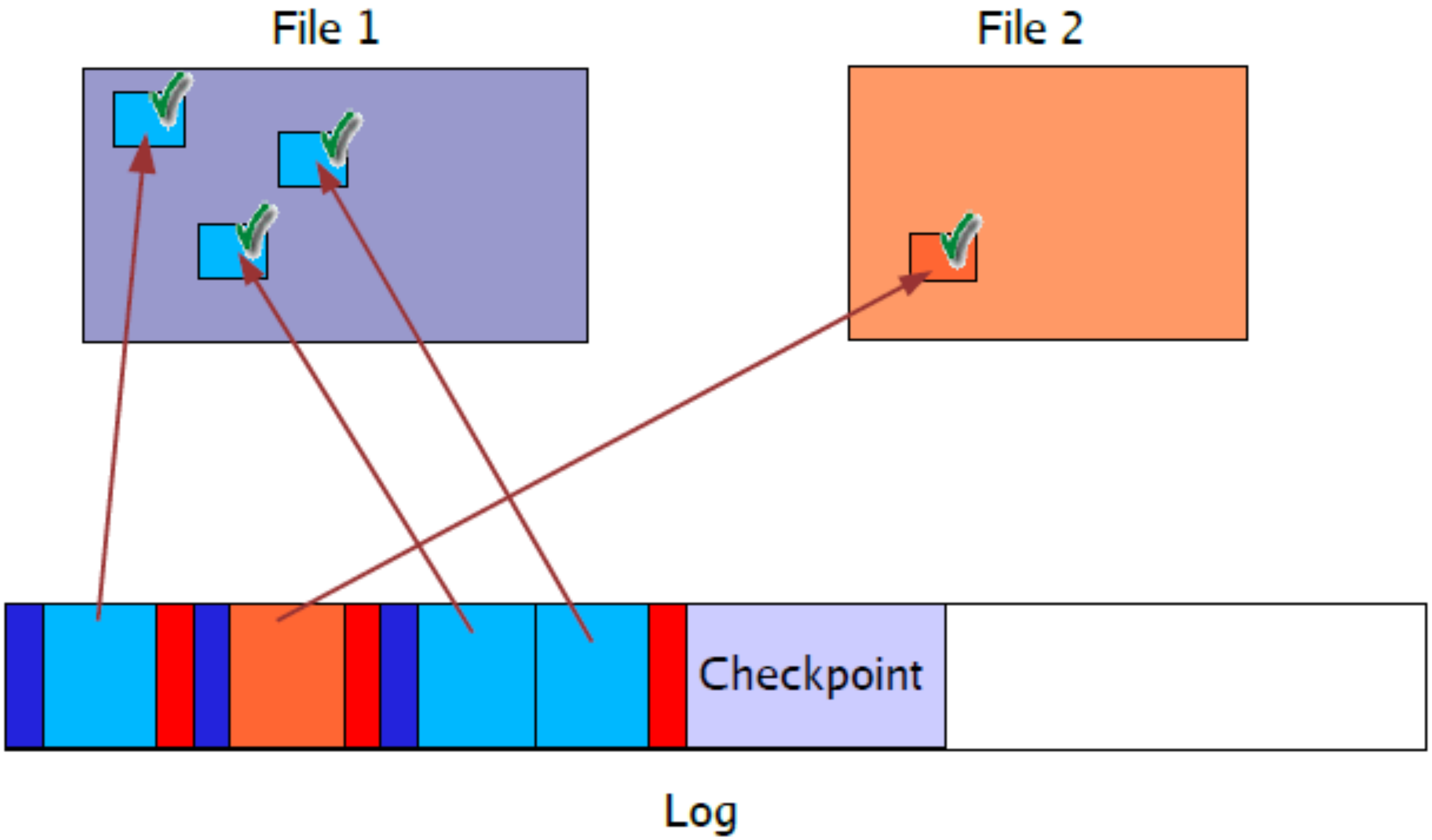
Journaling filesystems

- Goal: Make updates to filesystems appear to be atomic
  - The directory either looks exactly as it did **before the file was created**
  - Or the directory looks exactly as it did **after the file was created**
  - Cannot leave an FS entity (data block, inode, directory, etc.) in an intermediate state!
- Idea: Maintain a **log of all changes to the filesystem**
  - Log contains information on any operations performed to the filesystem state
  - e.g., "Directory 2841 had inodes 404, 407, and 408 added to it"
- To make a filesystem change:
  - 1. Write an *intent-to-commit record to the log*
  - 2. Write the appropriate **changes to the log**
    - *Do not modify the filesystem data directly!!!*
  - 3. Write a *commit record to the log*
- This is very similar to the notion of database *transactions*

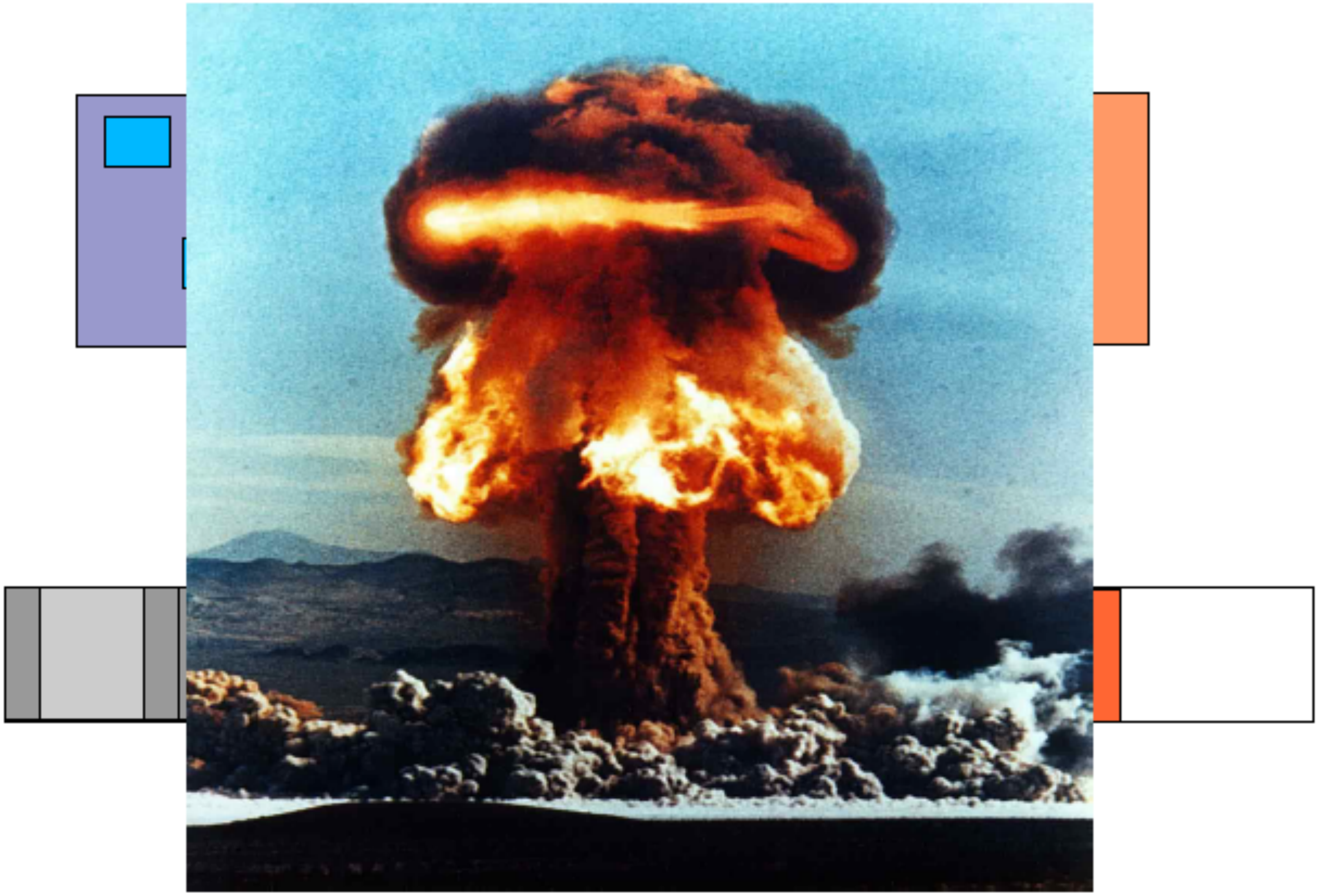
Journaling FS Recovery

- What happens when the system crashes?
  - Filesystem data has not actually been modified, just the log!
  - So, the FS itself reflects only what happened *before the crash*
- Periodically synchronize the log with the filesystem data
  - Called a *checkpoint*
  - Ensures that the FS data reflects all of the changes in the log
- No need to scan the entire filesystem after a crash...
  - Only need to look at the log entries **since the last checkpoint!**
- For each log entry, see if the commit record is there
  - If not, consider the changes incomplete, and don't try to make them

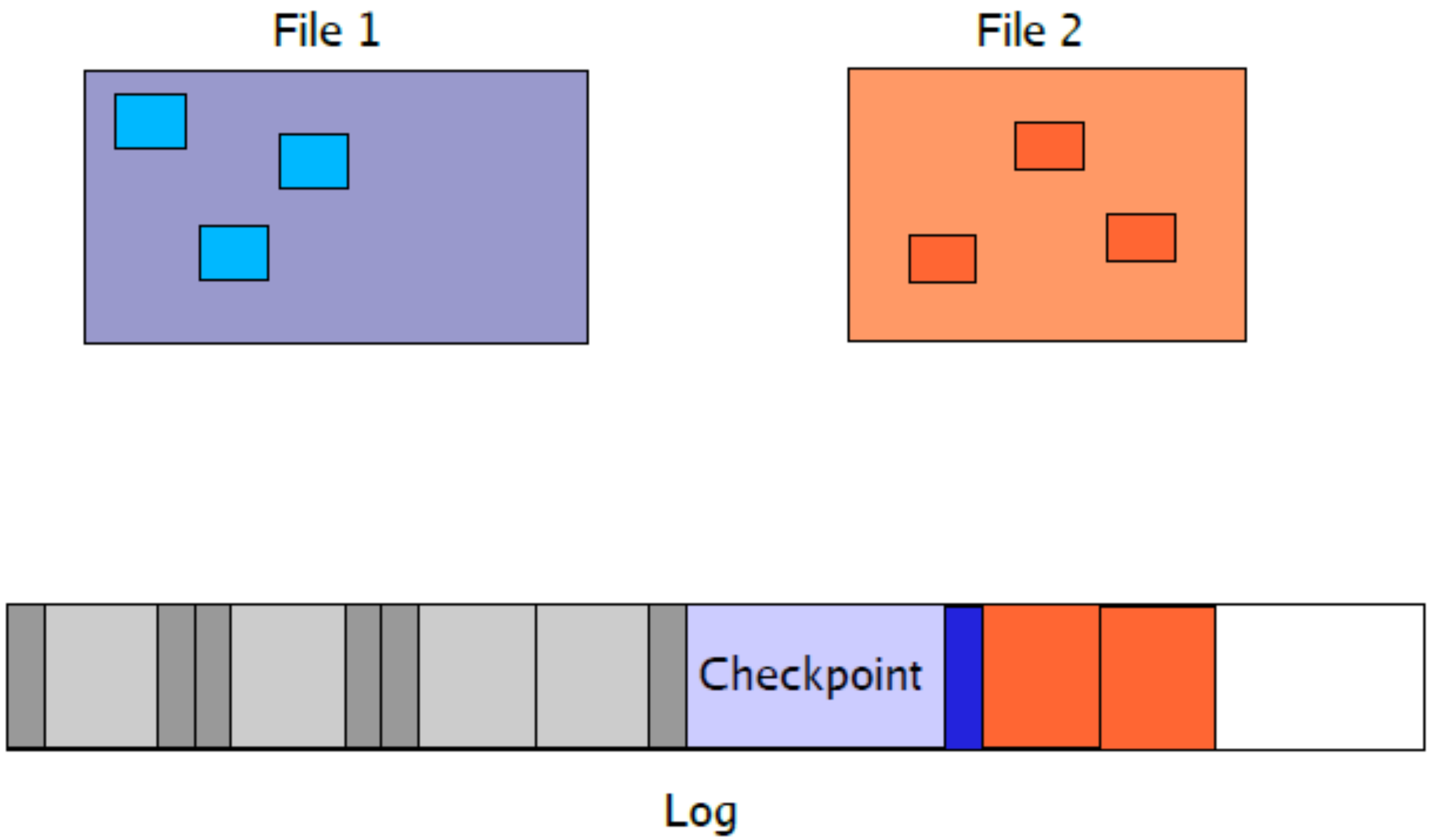
Journaling FS Example



Journaling FS Example



Journaling FS Example



- Filesystem reflects changes up to last checkpoint
- Fsck scans changelog from last checkpoint forward
- Doesn't find a commit record ... changes are simply ignored

Bonus: NFS

More recent filesystems

- How can we share filesystems over a network?
  - NFS, SAN, NAS, Hadoop
- How can we make a filesystem resilient to failures?
  - RAID (covered in earlier slides)

Networked File System (NFS)

- NFS allows a system to access files over a network
  - One of many distributed file systems
  - Extremely successful and widely used
    - You use NFS on all your shared files in the lab machines

Networked File System (NFS)

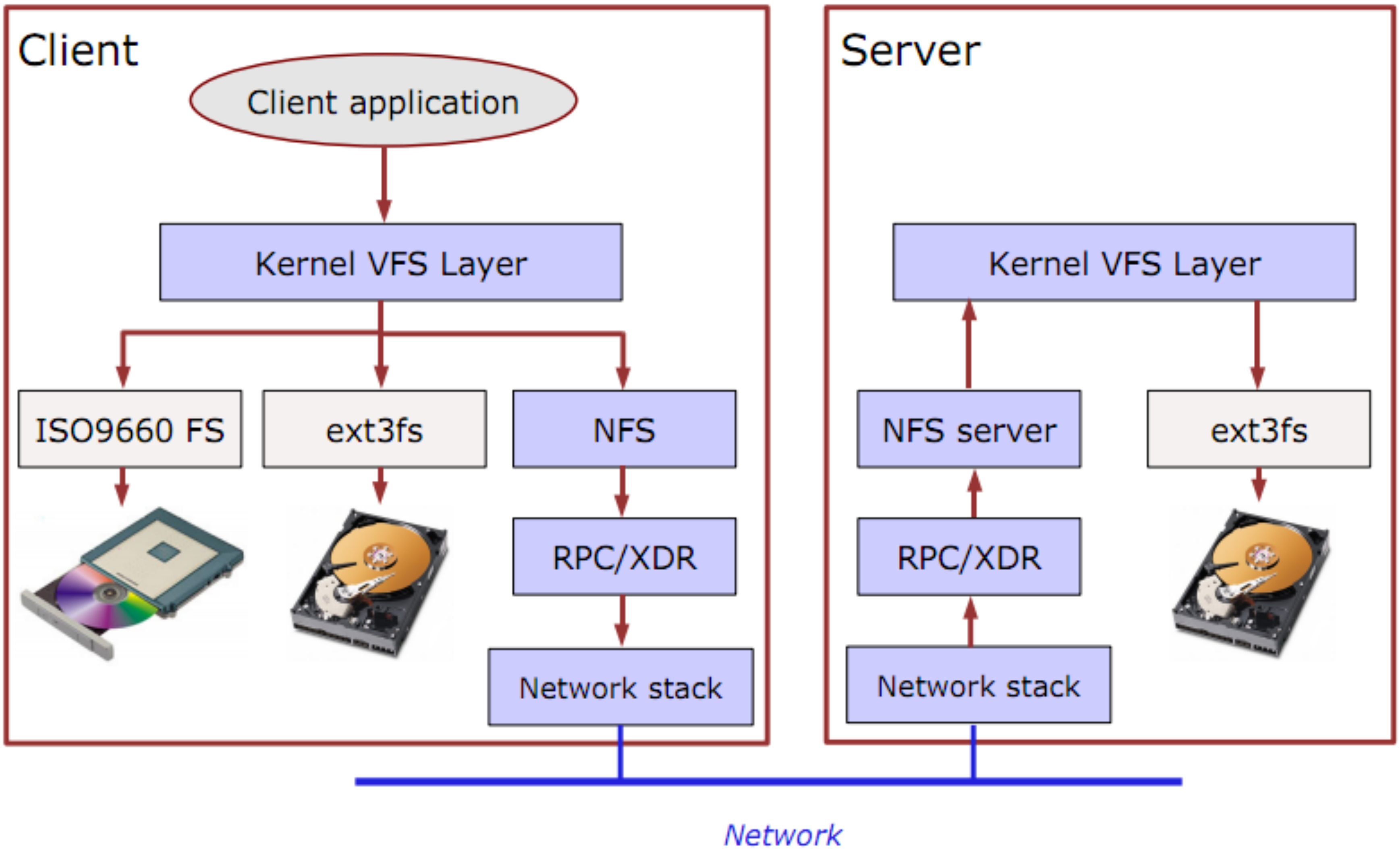
- Development of LANs made it really attractive to provide shared file systems to all machines on a network
  - Login to any machine and see the same set of files
  - Install software on a single server that all machines can run
  - Let users collaborate on shared set of files (before CVS)

- Why might this be hard to do?
  - Clients and servers might be running different OS
  - Clients and servers might be using different CPU architecture with differing byte ordering (endianess)
  - Client or server might crash independently of each other
    - Must be easy to recover from crashes
  - Potentially very large number of client machines on a network
  - Different users might be trying to modify a shared file at the same time
  - Transparency: Allow user programs to access remote files just like local files
    - No special libraries, recompilation, etc.

NFS Overview

- NFS was developed by Sun Microsystems in the mid-80s
  - Networked machines at the time were predominantly UNIX-based workstations
  - Various vendors: Sun, DEC, IBM, etc.
  - Different CPU architectures and OS implementations
    - But, all used UNIX filesystem structure and semantics
- NFS is based on Remote Procedure Call (RPC)
  - Allows a client machine to invoke a function on a server machine, over a network
  - Client sends a message with the function arguments
  - Server replies with a message with the return value.
- External Data Representation (XDR) to represent data types
  - Canonical network representation for ints, longs, byte arrays, etc.
  - Clients and servers must translate parameters and return values of RPC calls into XDR before shipping on the network
  - Otherwise, a little-endian machine and a big-endian machine would disagree on what is meant by the stream of bytes "fe 07 89 da" interpreted as an "int"

NFS Design



Client
Client application
Kernel VFS Layer
ISO9660 FS
ext3fs
NFS
RPC/XDR
Network stack
Server
Kernel VFS Layer
NFS server
ext3fs
RPC/XDR
Network stack
Network

Stateless Protocol

- The NFS protocol is *stateless*
  - The server maintains no information about individual clients!
  - This means that NFS does not support any notion of "opening" or "closing" files
  - Each client simply issues read and write requests specifying the file, offset in the file, and the requested size
- Advantages:
  - Server doesn't need to keep track of open/close status of files
  - Server doesn't need to keep track of "file offset" for each client's open files
    - Clients do this themselves
  - Server doesn't have to do anything to recover from a crash!
    - Clients simply retry NFS operations until the server comes back up
- Disadvantages:
  - Server doesn't keep track of concurrent access to same file
  - Multiple clients might be modifying a file at the same time
    - NFS does not provide any consistency guarantees!!!
  - However, there is a separate locking protocol – discussed later

NFS Protocol Overview

- mount() returns filehandle for root of filesystem
  - Actually a separate protocol from NFS...
- lookup(dir-handle, filename) returns filehandle, attribs
  - Returns unique file handle for a given file
  - File handle used in subsequent read/write/etc. calls
- create(dir-handle, filename, attributes) returns filehandle
- remove(dir-handle, filename) returns status
- getattr(filehandle) returns attribs
  - Returns attributes of the file, e.g., permissions, owner, group ID, size, access time, last-modified time
- setattr(filehandle, attribs) returns attribs
- read(filehandle, offset, size) returns attribs, data
- write(filehandle, offset, count, data) returns attribs

NFS Caching

- NFS clients are responsible for caching recently-accessed data
  - Remember: the server is stateless!
- The NFS protocol does not *require* that clients cache data ...
  - But, it provides support allowing a range of client-side caching techniques
- This is accomplished through the getattr() call
  - Returns size, permissions, and last-modified time of file
  - This can tell a client whether a file has changed since it last read it
  - Read/write calls also return attributes so client can tell if object was modified since the last getattr() call
- How often should the client use getattr()?
  - Whenever the file is accessed?
    - Could lead to a lot of getattr calls!
  - Only if the file has not been accessed for some time?
    - e.g., If the file has not been accessed in 30 sec?
  - Different OSs implement this differently!

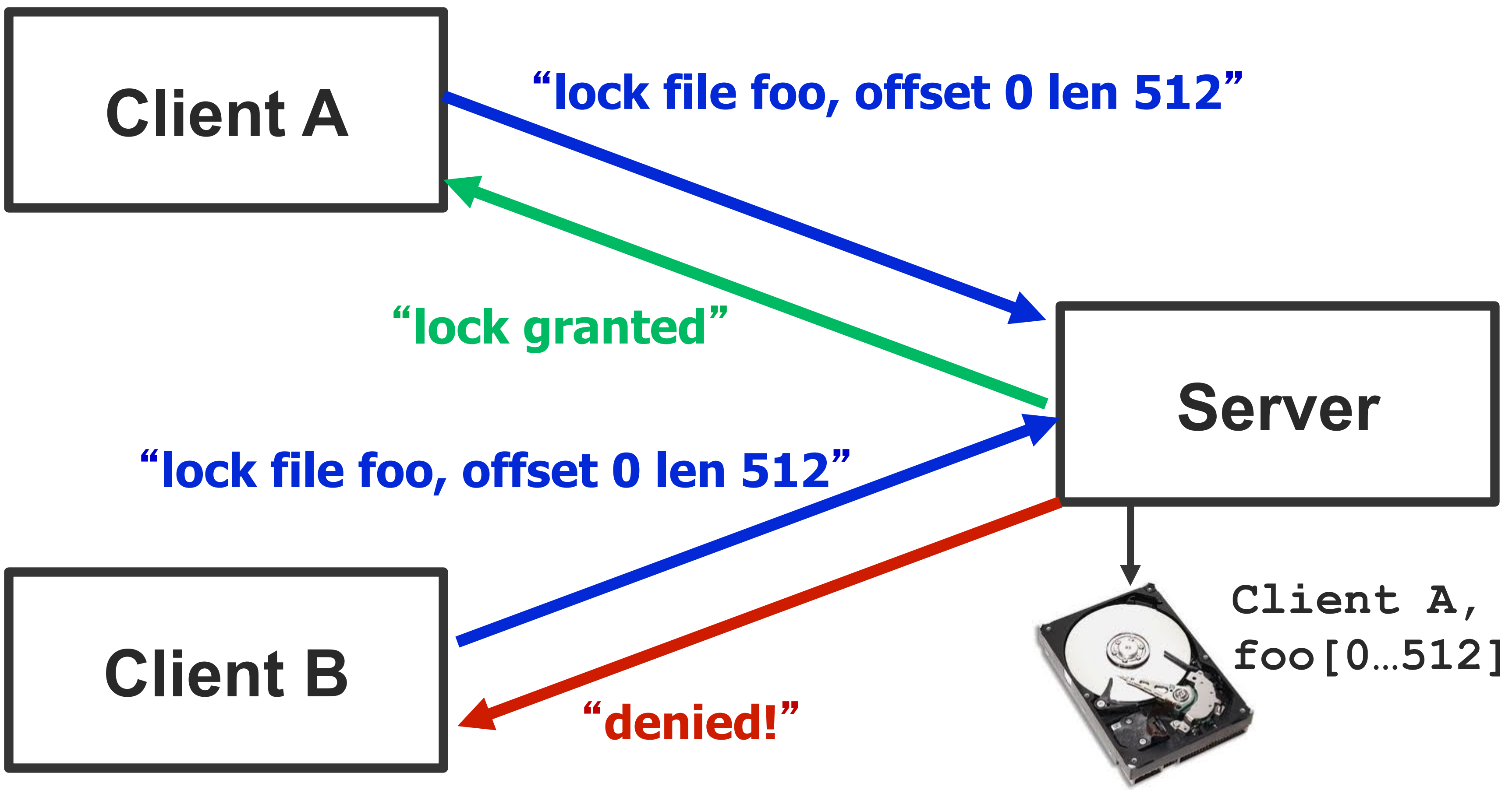
NFS Locking

- NFS does not prevent multiple clients from modifying a file simultaneously
  - Clearly, this can be a Bad Thing for some applications...
- Solution: Network Lock Manager (NLM) protocol
  - Works alongside NFS to provide file locking
  - NFS itself does not know anything about locks
    - Clients have to use NLM "voluntarily" to avoid stomping on each other
  - NLM has to be stateful
    - Why?

NLM Protocol

- NLM server has to keep track of locks held by clients
- If the NLM server crashes...
  - All locks are released!
  - BUT ... clients can reestablish locks during a "grace period" after the server recovers
    - No new locks are granted during the grace period
    - Server has to remember which locks were previously held by clients
- If an NLM client crashes...
  - The server is notified when the client recovers and releases all of its locks
    - What happens if a client crashes and does not come back up for a while?
- Servers and clients must be notified when they crash and recover
  - This is done with the simple "Network Status Monitor" (NSM) protocol
  - Essentially, send a notification to the other host when you reboot

NLM Example

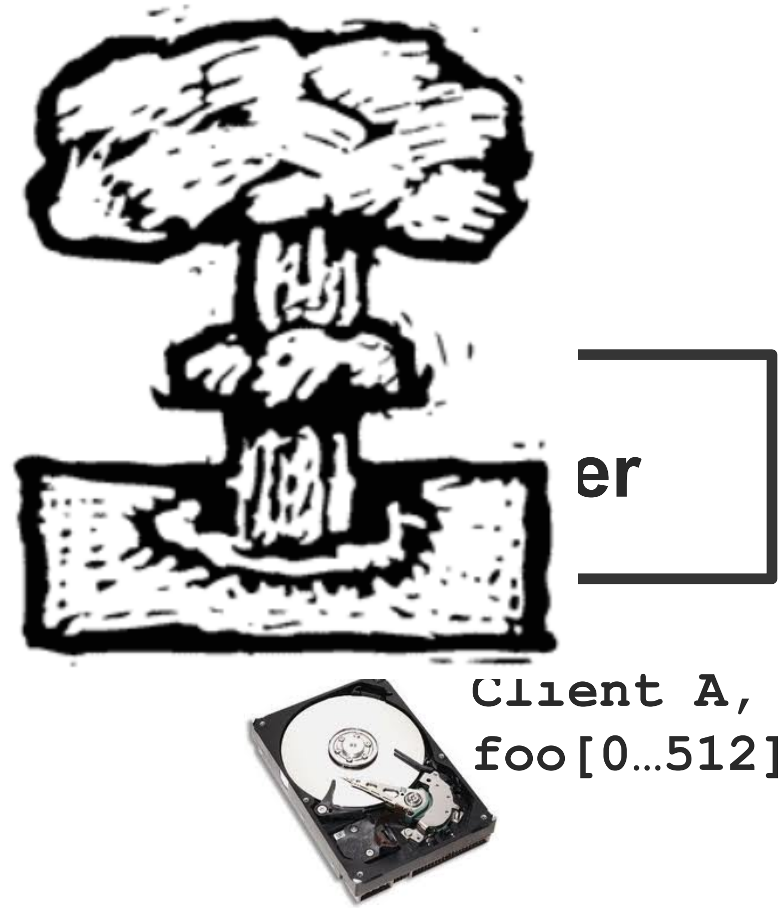


Client A
"lock file foo, offset 0 len 512"
"lock granted"
Server
"lock file foo, offset 0 len 512"
Client B
"denied!"
Client A,
foo[0…512]

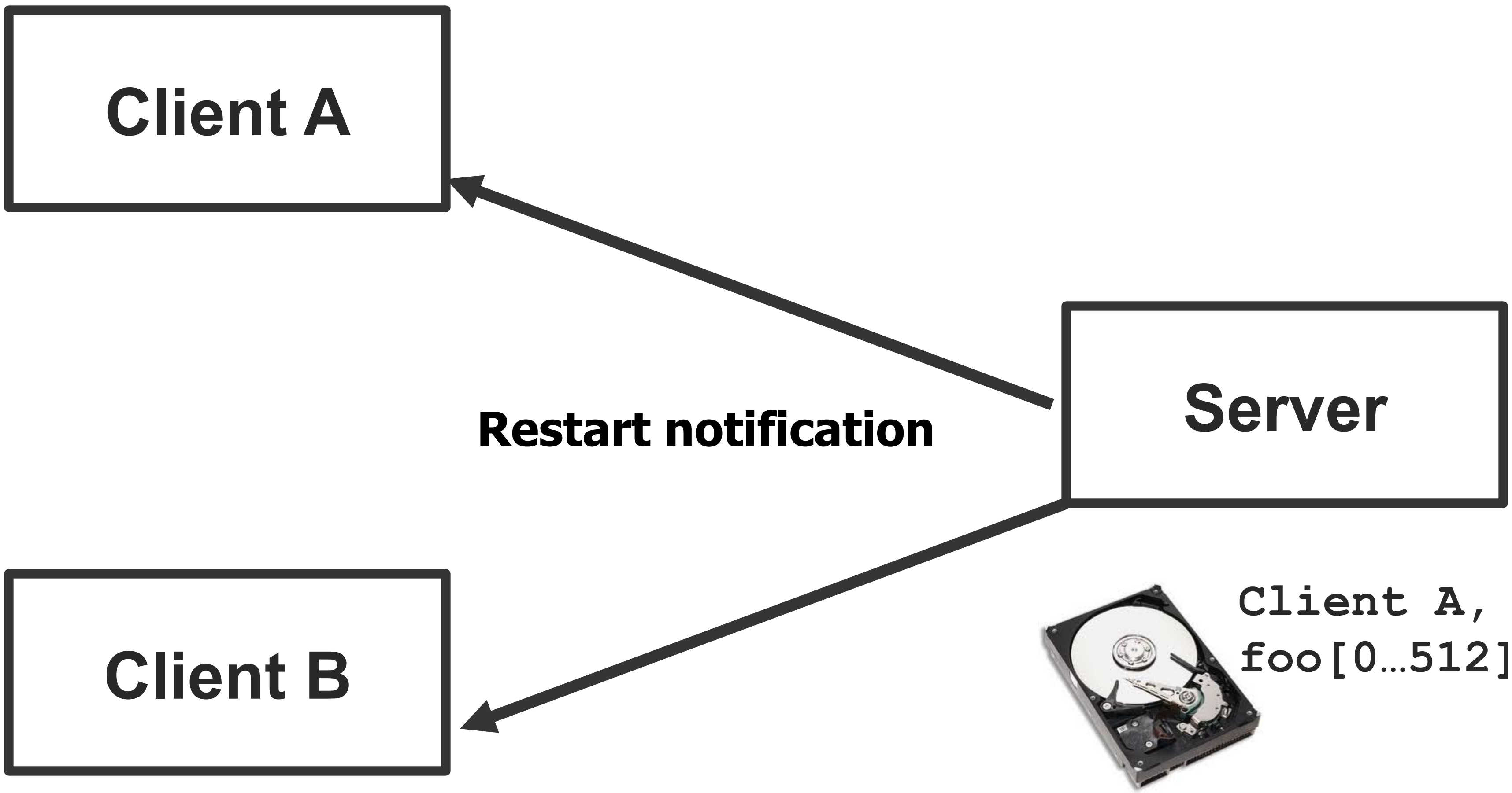
NLM Example

Client A

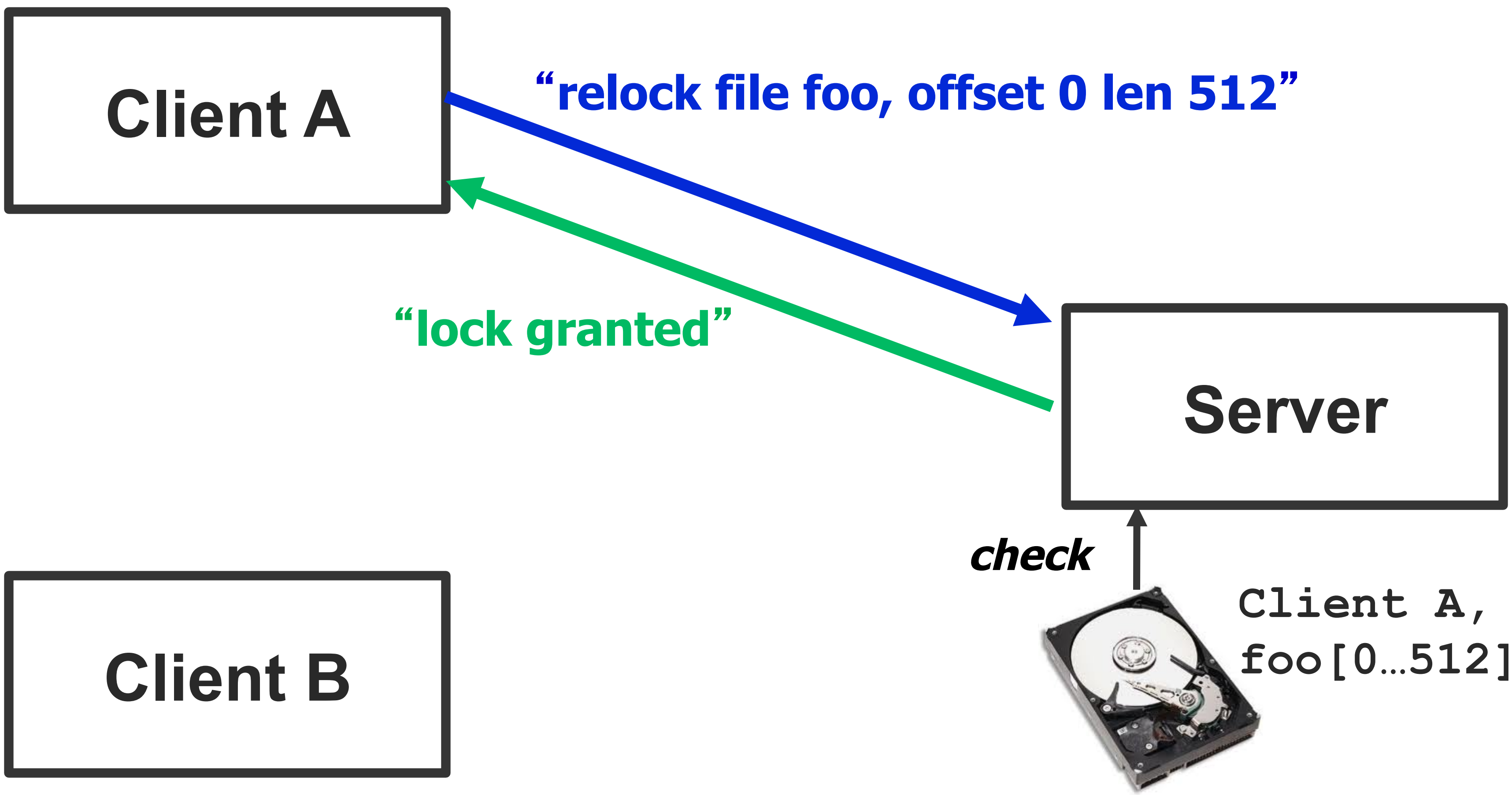
Client B



NLM Example


Client A
Restart notification
Server
Client B
Client A,
foo[0…512]

NLM Example


Client A
"relock file foo, offset 0 len 512"
"lock granted"
Server
check
Client A,
foo[0…512]
Client B