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OPERATING SYSTEM CONCEPTS

Chapter 12. File-System Implementation

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Warm-up

File System Measurement Summary

Most files are small	Roughly 2K is the most common size
Average file size is growing	Almost 200K is the average
Most bytes are stored in large files	A few big files use most of the space
File systems contains lots of files	Almost 100K on average
File systems are roughly half full	Even as disks grow, file systems remain ~50% full
Directories are typically small	Many have few entries; most have 20 or fewer

Warm-up

Size of A File

- Why the files are of these sizes and use these spaces.

Filename	Content	Description	**Size**	**Space**
test1	-	-	0	0
test2	“This is a test file.\r\n"	×1 (line)	22 bytes	0
test3	“This is a test file.\r\n"	×40 (lines)	878 bytes	4 KB
test4	“This is a test file.\r\n"	×(40 — 39) (lines)	22 bytes	4 KB

Objectives

- To describe the details of implementing local file systems and directory structures.
- To describe the implementation of remote file systems.
- To discuss block allocation and free-block algorithms and trade-offs.

Contents

Contents

Typical File System

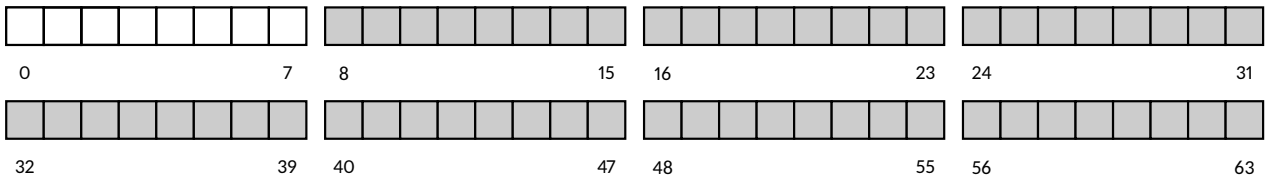
Very Simple File System

- We are now discussing a simple file system implementation, known as VSFS (the Very Simple File System)
  - A simplified version of a typical UNIX file system.
- You should understand
  - **Data structures**: what types of on-disk structures are utilized by the file system to organize its data and metadata?
  - **Access methods**: How does it map the calls made by a process onto its structures?

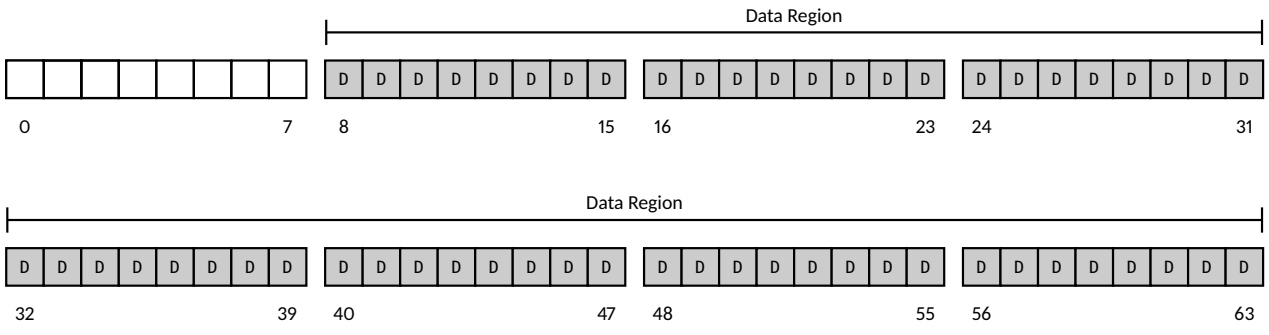
Typical File System

Overall Organization

- Divide the disk into blocks (with a commonly-used block size of 4 KB).
  - Assume a really small disk, with just 64 blocks.



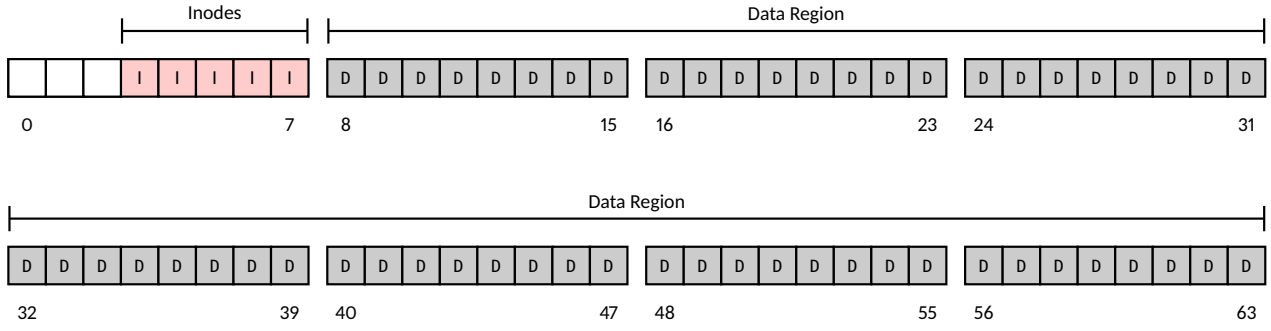
- Reserve a fixed portion of the disk for the data region
  - Say the last 56 of 64 blocks on the disk:



Typical File System

Overall Organization (contd.)

- To track information about each file, the **inodes** are stored in the **inode table**.
  - Assume 5 of 64 blocks for inodes.

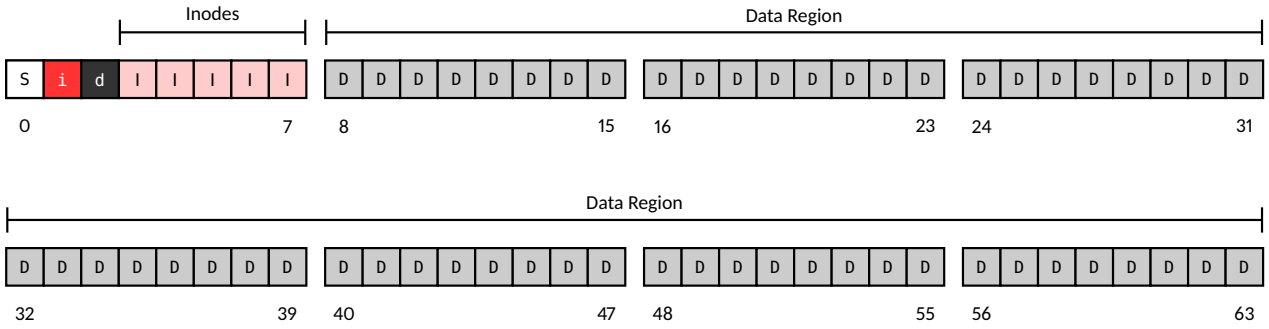


  - Assuming 256 bytes per inode, our file system contains ? total inodes.
  - This number represents the maximum number of files we can have in our file system.
  - How could the file system know which inode /data block is free?

Typical File System

Overall Organization (contd.)

- To track whether inodes or data blocks are free or allocated, an inode bitmap and a data bitmap are required.



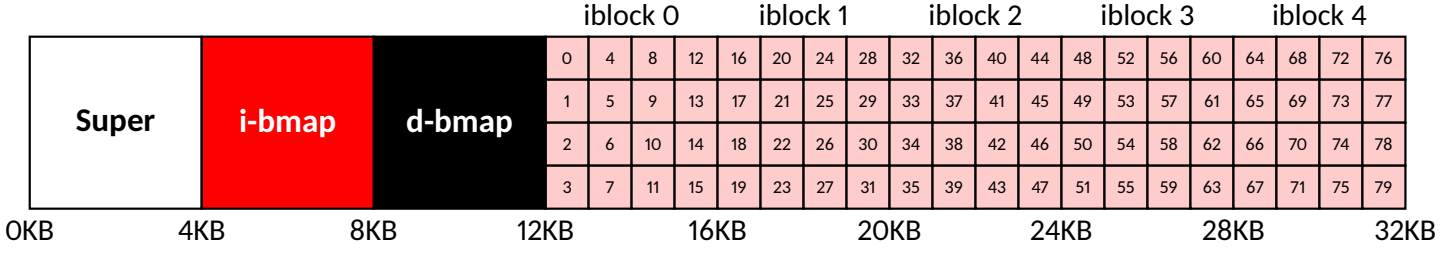
  - Optional data structures include a free list.

- The remaining block is the Superblock.
  - It contains information about this particular file system, including, for example, how many inodes and data blocks are in the file system, where the inode table begins, and so forth.
  - When mounting a file system, the operating system will read the superblock first.

Typical File System

File Organization: the Inode

- An inode in UNIX FS is a **File Control Block** (FCB).
- The name **inode** is short for **index node**.
- Each inode is implicitly referred to by a number, called the **inumber**.



  - How to read a given inode number *X*?
  - By calculating the offset into the inode region ($X \cdot sizeof(inode)$), add it to the start address of the inode table on disk.

Typical File System

File Organization: the Inode (contd.)

Size	Name	What is this inode field for?
2	mode	can this file be read/written/executed?
2	uid	who owns this file?
4	size	how many bytes are in this file?
4	time	what time was this file last accessed?
4	ctime	what time was this file created?
4	mtime	what time was this file last modified?
4	dtime	what time was this inode deleted?
2	gid	which group does this file belong to?
2	links_count	how many hard links are there to this file?
4	blocks	how many blocks have been allocated to this file?
4	flags	how should ext2 use this inode?
4	osd1	an OS-dependent field
60	block	a set of disk pointers (15 total)
4	generation	file version (used by NFS)
4	file_acl	a new permissions model beyond mode bits
4	dir_acl	called access control lists

Simplified Ext2 Inode

Typical File System

File Organization: the Inode (contd.)

- How an inode refers to where data blocks are.
- Suppose a simple approach:
  - To have one or more **direct pointers** (disk addresses) inside the inode; each pointer refers to one disk block that belongs to the file.
- Such an approach is limited:
  - For example, if you want to have a file that is really big (e.g., bigger than the size of a block multiplied by the number of direct pointers).
- Solution: To make use of **indirect pointers**.
  - Instead of pointing to a block that contains user data, it points to a block that contains more pointers, each of which point to user data.
    - » What is the maximum size, with 12 direct pointers and 1 indirect pointer

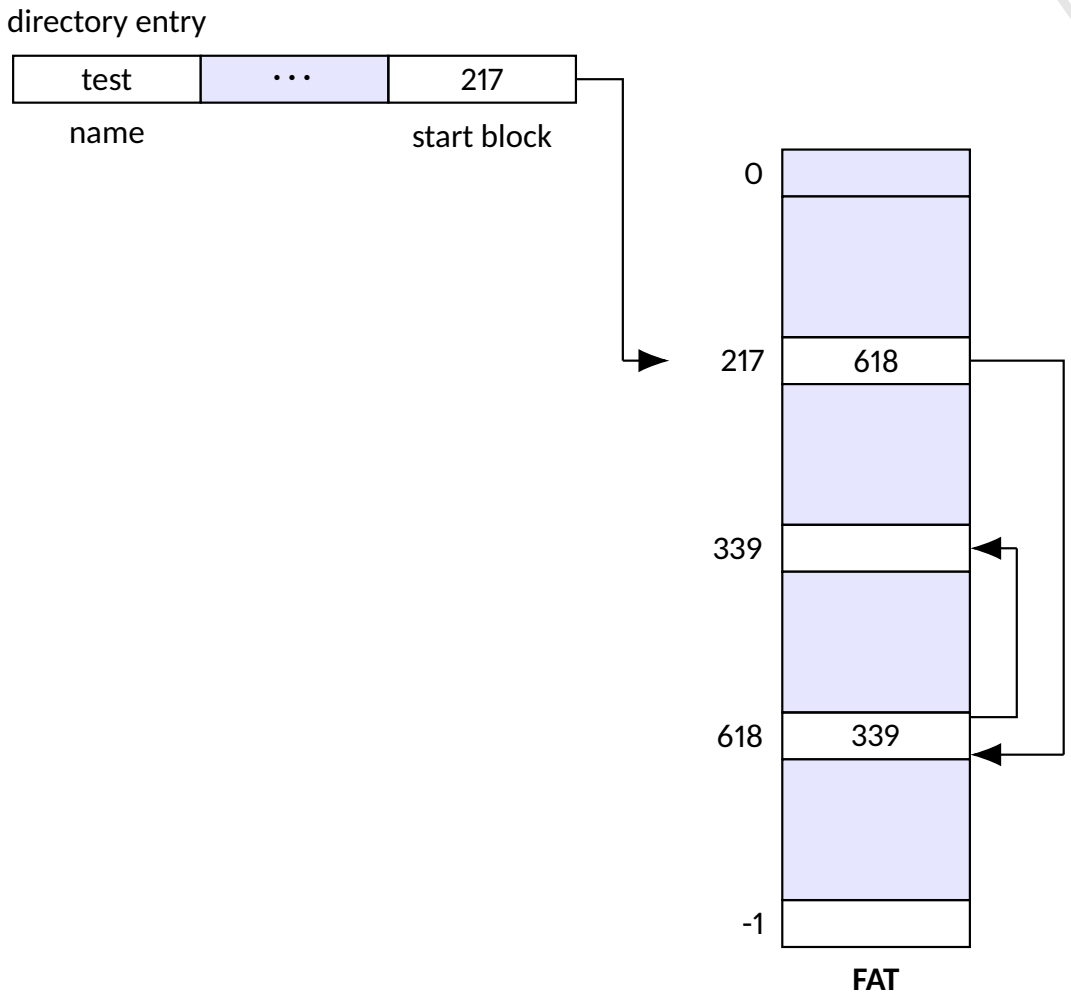
Typical File System

The Multi-Level Index

- To support even larger files, by adding a
  - **double indirect pointer**
    - » What is the maximum size, with 12 direct pointers, 1 indirect pointer, 1 double indirect pointer
  - **triple indirect pointer**
    - » What is the maximum size, with 12 direct pointers, 1 indirect pointer, 1 double indirect pointer, 1 triple indirect pointer
- Or, by using extents instead of pointers. (ext4)
  - An extent is simply a disk pointer plus a length (in blocks) to specify the on-disk location of a file.
  - Extent-based file systems often allow for more than one extent.
  - Less flexible but more compact.

Typical File System

FAT (File-Allocation Table)



Typical File System

NTFS

- NTFS (new technology file system) with MFT (master file table)
- A record in MFT (each is 1*KB* in size):
  - Body contains attr. data, or a pointer to an extent

<table>
<tr><td colspan="4">Head (ASCII FILE + · · ·)</td></tr>
<tr><td rowspan="8">Attr.</td><td rowspan="2">Attr. 1</td><td>Head</td><td>0x10</td></tr>
<tr><td>Body</td><td>Standard Information</td></tr>
<tr><td rowspan="2">Attr. 2</td><td>Head</td><td>0x30</td></tr>
<tr><td>Body</td><td>File Name</td></tr>
<tr><td colspan="2">· · ·</td></tr>
<tr><td rowspan="2">Attr. 8</td><td>Head</td><td>0x80</td></tr>
<tr><td>Body</td><td>Data</td></tr>
<tr><td colspan="2">· · ·</td></tr>
<tr><td colspan="4">FF FF FF FF</td></tr>
</table>

Typical File System

Allocation Method

- **Contiguous allocation**
  - Each file occupies a set of contiguous blocks on the disk.
  - ext4, ntfs
- **Linked allocation**
  - Each file is a linked list of disk blocks
  - fat
- **Indexed allocation**
  - Brings all pointers together into the index block
  - ext2, ext3

Typical File System

In Class Exercise

- Imagine a file system which uses inodes to manage files on disk. Each inode consists of a file name (4 bytes), user id (2 bytes), three timestamps (4 bytes each), protection bits (2 bytes), a reference count (2 bytes), a file type (2 bytes), and the file size (4 bytes). Additionally, the inode contains 13 direct indices, 1 index to a single indirect block, 1 index to a double indirect block, and one index to a triple indirect block. Each of these indices (block pointer) is 4 bytes. The file system also stores the first 356 bytes of each file in the inode.

    1. Three major methods of allocating disk space are introduced in our textbook. What are these three allocation methods? Which one is used in the previous file system?
    2. Assume a disk sector is 512 bytes and that each indirect block fills a single sector. What is the maximum file size for this file system? Show your work clearly. You need not do the arithmetic to get full credit.
    3. Is there any benefit to including the first 356 bytes of the file in the inode? If so, what is the reason? If not, why not?

Typical File System

Key

- indexed allocation
- $(512/4)^3 * 512 + (512/4)^2 * 512 + (512/4)^1 * 512 + 13 * 512 + 356$
- Yes, Efficiency in both spatial and temporal. Most files are small. For small files (<356 bytes), do not need to access disk twice. save disk space (internal fragmentation within blocks).

Typical File System

Directory Organization

- A directory basically contains a list of (entry name, inode number) pairs.

inum	reclen	strlen	name
5	4	2	.
2	4	3	..
12	4	4	foo
13	4	4	bar
24	8	7	foobar

  - Deleting a file (e.g., calling *unlink*()) can leave an empty space in the middle of the directory, and hence there should be some way to mark that as well (e.g., with a reserved inode number such as zero).
  - Such a delete is one reason the record length (reclen) is used: a new entry may reuse an old, bigger entry and thus have extra space within.
  - A directory has an inode, somewhere in the inode table (with the type field of the inode marked as “directory” instead of “regular file”).

Typical File System

Access Paths: Reading and Writing

- Suppose we want to open a file, e.g., /foo/bar, read it, then close it.
- Opening a file from disk

$$open(\text{"/foo/bar"}, O\_RDONLY)$$

- The file system must traverse the pathname and thus locate the desired inode.

1. Read the inode of the root directory which is simply called /.
2. Look inside the inode to find pointers to data blocks, which contain the contents of the root directory.
3. Find the entry for foo, and the inode number.
4. ...

Typical File System

Access Paths: Reading and Writing (contd.)

- Reading a file from disk

read()

1. The first read (at offset 0 unless *lseek*() has been called) will thus read in the first block of the file, consulting the inode to find the location of such a block.
2. ...

Typical File System

Access Paths: Reading and Writing (contd.)

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
open(*bar*)			read			read				
				read						
							read			
					read					
read()					read					
								read		
					write					
read()					read					
									read	
					write					
read()					read					
										read
					write					

Typical File System

Access Paths: Reading and Writing (contd.)

- Writing to disk is a similar process

write()

- Unlike reading, writing to the file may also allocate a block.
- Each write to a file logically generates five I/Os:
  - one to read the data bitmap (which is then updated to mark the newly-allocated block as used),
  - one to write the bitmap (to reflect its new state to disk),
  - two more to read and then write the inode (which is updated with the new block's location), and
  - finally one to write the actual block itself.

Typical File System

Access Paths: Reading and Writing (contd.)

- Writing to disk

  write()

- Considering file creation, the total amount of I/O traffic to do so is quite high:
  - one read to the inode bitmap (to find a free inode),
  - one write to the inode bitmap (to mark it allocated),
  - one write to the new inode itself (to initialize it),
  - one write to the data of the directory (to link the high-level name of the file to its inode number), and
  - one read and write to the directory inode to update it.
  - if the directory needs to grow to accommodate the new entry, additional I/Os (i.e., to the data bitmap, and the new directory block) will be needed too.

Typical File System

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
create (*/foo/bar*)		read write	read	read	read write	read	read write			
write()	read write				read write			write		
write()	read write				read write				write	
write()	read write				read write					write

Contents

Fast File System

- Performance problems
  - Expensive positioning costs, if data was spread all over the place
    - The data blocks of a file were often very far away from its inode, thus inducing an expensive seek whenever one first read the inode and then the data blocks.
  - Fragmented file system, if the free space was not carefully managed.
  - The original block size was too small (512bytes).
- Fast File System (FFS): disk awareness
  - Design the file system structures and allocation policies to be “disk aware” and thus improve performance.
  - It keeps the same interface to the FS, but changes the internal implementation.

Fast File System

- Modern drives do not export enough information for the file system to truly understand whether a particular cylinder is in use.
- Modern file systems (such as Linux ext2, ext3, and ext4) instead organize the drive into block groups.
- Whether you call them cylinder groups or block groups, these groups are the central mechanism that FFS uses to improve performance.
  - By placing two files within the same group, FFS can ensure that accessing one after the other will not result in long seeks across the disk.

Fast File System

- FFS keeps within a single cylinder group all the structures you might expect a file system to have.

  - FFS keeps a copy of the super block (S) in each group for reliability reasons.
  - A per-group inode bitmap (ib) and data bitmap (db) to track whether the inodes and data blocks of the group are allocated.
  - The inode and data block regions are just like those in the previous very-simple file system.

Fast File System

- Policies: how to allocate files and directories
- The basic principle is: keep related stuff together (and its corollary, keep unrelated stuff far apart).
- Placement heuristics: e.g.,
  - For directories
    - » Place a directory in the cylinder group with a low number of allocated directories and a high number of free inodes.
  - For files
    - » First, it makes sure (in the general case) to allocate the data blocks of a file in the same group as its inode.
    - » Second, it places all files that are in the same directory in the cylinder group of the directory they are in.

Fast File System

- Assume three directories (/, /a, and /b), and four files (/a/c, /a/d, /a/e, and /b/f).
- In general FS

group	inodes	data
0	/---------	/---------
1	a---------	a---------
2	b---------	b---------
3	c---------	c---------
4	d---------	d---------
5	e---------	e---------
6	f---------	f---------
7	----------	----------
	...	

- In FFS

group	inodes	data
0	/---------	/---------
1	acde------	accddee---
2	bf--------	bff-------
3	----------	----------

Fast File System

- The Large-File Exception
  - Without a different rule, a large file would entirely fill the block group it is first placed within (and maybe others).
  - Filling a block group in this manner is undesirable, as it prevents subsequent “related” files from being placed within this block group, and thus may hurt file-access locality.
  - After some number of blocks are allocated into the first block group, FFS places the next “large” chunk of the file in another block group.
  - A tradeoff here, since spreading blocks of a file across the disk will hurt performance.

Fast File System

- If a user creates one big file, /a
- In general FS-- not enough room for new files in the group in the root directory (/).

group	inodes	data			
0	/a--------	/aaaaaaaaa	aaaaaaaaaa	aaaaaaaaaa	a---------
1	----------	----------	----------	----------	----------
			...		

- In FFS

group	inodes	data			
0	/a--------	/aaaaa----	----------	----------	----------
1	----------	aaaaa-----	----------	----------	----------
2	----------	aaaaa-----	----------	----------	----------
3	----------	aaaaa-----	----------	----------	----------
4	----------	aaaaa-----	----------	----------	----------
5	----------	aaaaa-----	----------	----------	----------
6	----------	----------	----------	----------	----------
			...		

Contents

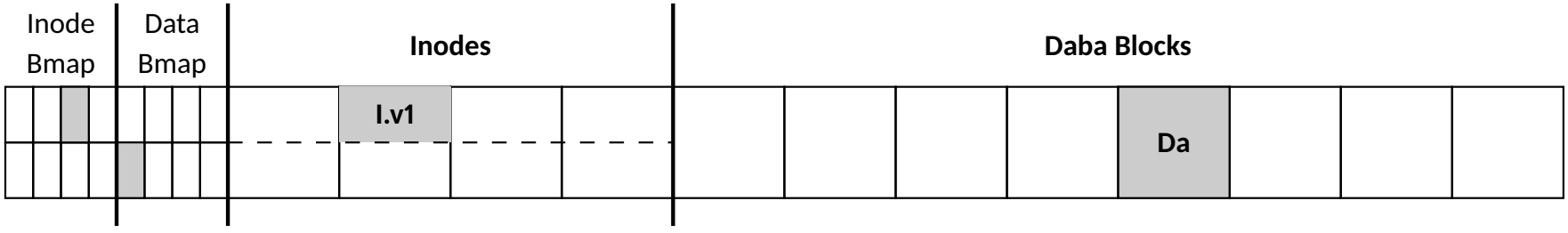
FSCK and Journaling

- Considering consistency
  - How to update persistent data structures despite the presence of a power loss or system crash?
- Crash-consistency problem
  - Imagine you have to update two on-disk structures, A and B, in order to complete a particular operation. Because the disk only services a single request at a time, one of these requests will reach the disk first (either A or B). If the system crashes or loses power after one write completes, the on-disk structure will be left in an inconsistent state.
- How to update the disk despite crashes?
- Two approaches
  - A file system checker (fsck)
  - Journaling (also known as write-ahead logging)

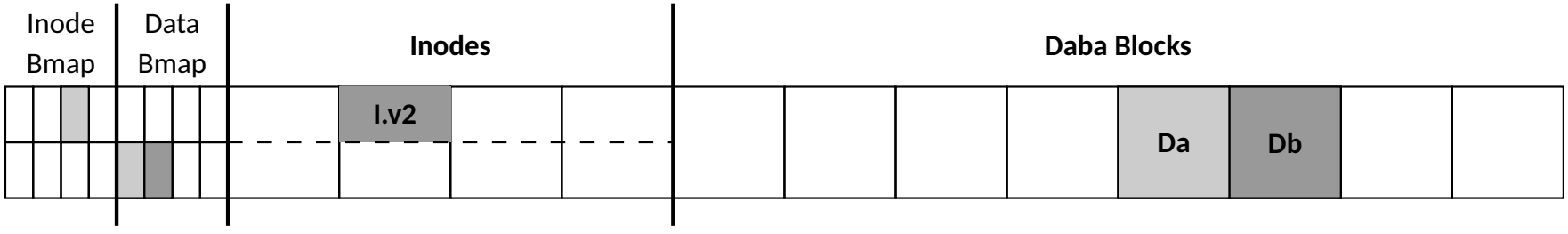
FSCK and Journaling

A Detailed Example

From



To



Three separate writes to the disk are required

FSCK and Journaling

A Detailed Example (contd.)

- Crash Scenarios: Imagine only a single write succeeds.
  - Just the data block (Db) is written to disk.
    - » This case is not a problem at all, from the perspective of file-system crash consistency.
  - Just the updated inode (I[v2]) is written to disk.
    - » If we trust the inode pointer, we will read garbage data from the disk.
    - » File-system inconsistency: The on-disk bitmap is telling us that data block 5 has not been allocated, but the inode is saying that it has.
  - Just the updated bitmap (B[v2]) is written to disk.
    - » File-system inconsistency: The bitmap indicates that block 5 is allocated, but there is no inode that points to it.
    - » Space leak: block 5 would never be used by the file system.

FSCK and Journaling

A Detailed Example (contd.)

- Crash Scenarios (contd.): Two writes succeeds.
  - The inode (I[v2]) and bitmap (B[v2]) are written to disk, but not data (Db).
    - » The file system metadata is completely consistent.
    - » But block 5 has garbage in it.
  - The inode (I[v2]) and the data block (Db) are written, but not the bitmap (B[v2]).
    - » File-system inconsistency.
  - The bitmap (B[v2]) and data block (Db) are written, but not the inode (I[v2]).
    - » File-system inconsistency.
    - » We have no idea which file block 5 belongs to.

FSCK and Journaling

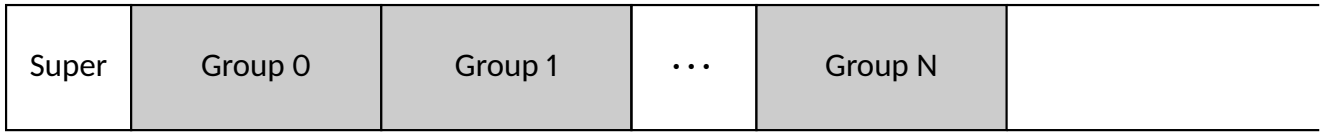
Solution #1: FSCK

- Superblock: If fsck finds a suspect (corrupt) superblock; in this case, the system (or administrator) may decide to use an alternate copy of the superblock.
- Free blocks: Fsck scans the inodes, indirect blocks, double indirect blocks, etc., to build an understanding of which blocks are currently allocated within the file system. It uses this knowledge to produce a correct version of the allocation bitmaps; thus, if there is any inconsistency between bitmaps and inodes, it is resolved by trusting the information within the inodes.
- Inode state: Each inode is checked for corruption or other problems. Suspect inode is cleared by fsck.
- Inode links: Fsck scans through the entire directory tree to verify the link count of each allocated inode.
- Duplicates: Fsck checks for duplicate pointers. If one inode is obviously bad, it may be cleared. Alternately, the pointed-to block could be copied, thus giving each inode its own copy as desired.
- Bad blocks: A pointer is considered “bad” if it obviously points to something outside its valid range.
- Directory checks: Fsck performs additional integrity checks on the contents of each directory, e.g., making sure that each inode referred to in a directory entry is allocated and no directory is linked to more than once.

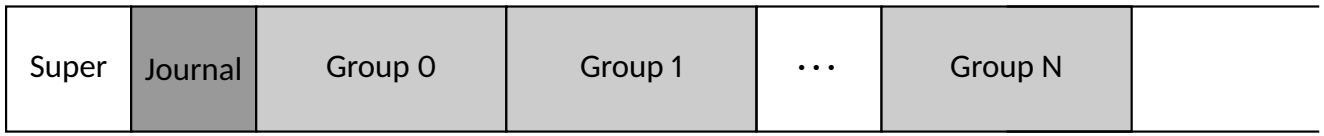
FSCK and Journaling

Solution #2: Journaling

- Fsck is too slow and it allows inconsistencies happen and then find and fix them later when rebooting.
- An alternate solution is journaling (a.k.a. write-ahead logging).
  - When updating the disk, before overwriting the structures in place, first write down a little note (somewhere else on the disk, in a well-known location) describing what you are about to do.
  - If a crash takes places, the note tells exactly what to fix (and how to fix it) after a crash, instead of having to scan the entire disk.
- Linux ext2 without journaling



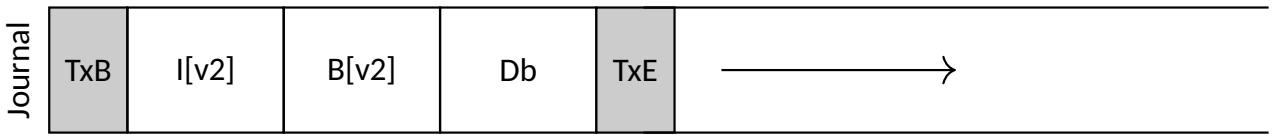
- Linux ext3 with journaling



FSCK and Journaling

Solution #2: Journaling (contd.)

- Recall our update example, where we wish to write the inode (I[v2]), bitmap (B[v2]), and data block (Db) to disk.
- Before any writing, we are now first going to write them to the log (a.k.a. journal).



  - The transaction begin (TxB) tells us about this update, and contains a transaction identifier (TID).
  - The middle three blocks just contain the exact contents of the blocks themselves. (physical logging vs. logical logging).
  - The final block (TxE) is a marker of the end of this transaction, and also contains the TID.

FSCK and Journaling

Solution #2: Journaling (contd.)

- Once this transaction is safely on disk, we are ready to overwrite the old structures in the file system; this process is called checkpointing.
- To checkpoint the file system (i.e., bring it up to date with the pending update in the journal), we issue the writes I[v2], B[v2], and Db to their disk locations.
- If these writes complete successfully, we have successfully checkpointed the file system and are basically done.

FSCK and Journaling

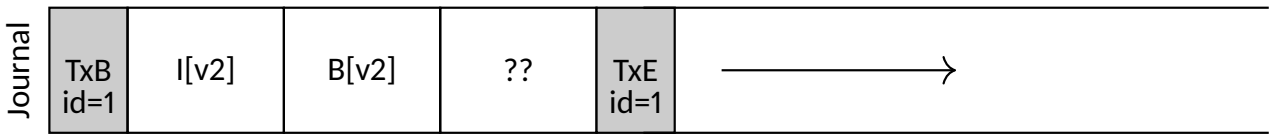
Solution #2: Journaling (contd.)

- Protocol to update the file system
  1. Journal write: Write the transaction, including a transaction-begin block, all pending data and metadata updates, and a transaction-end block, to the log; wait for these writes to complete.
  2. Checkpoint: Write the pending metadata and data updates to their final locations in the file system.

FSCK and Journaling

Solution #2: Journaling (contd.)

- When a crash occurs during the writes to the journal.
  - Issue each write at a time, waiting for each to complete, and then issuing the next. But this is slow.
  - Issue all five block writes at once, as this would turn five writes into a single sequential write and thus be faster. However this is unsafe.



  - Thus the file system issues the transactional write in two steps.

FSCK and Journaling

Solution #2: Journaling (contd.)

- Protocol to update the file system
  1. Journal write: Write the contents of the transaction (including TxB, metadata, and data) to the log; wait for these writes to complete.
  2. Journal commit: Write the transaction commit block (containing TxE) to the log; wait for write to complete; transaction is said to be committed.
  3. Checkpoint: Write the pending metadata and data updates to their final locations in the file system.

FSCK and Journaling

Solution #2: Journaling (contd.)

- A crash may happen at any time during this sequence of updates.
  - If the crash happens before the transaction is written safely to the log (i.e., before Step 2 above completes), then our job is easy: the pending update is simply skipped.
  - If the crash happens after the transaction has committed to the log, but before the checkpoint is complete, the file system can recover the update.

FSCK and Journaling

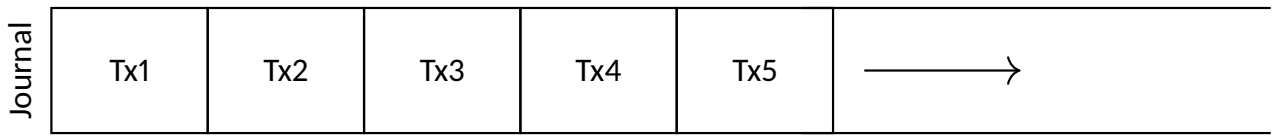
Solution #2: Journaling (contd.)

- Batching Log Updates
- Now suppose we create multiple files in a row in the same directory.
  - To create one file, one has to update a number of on-disk structures, minimally including:
    - » the inode bitmap,
    - » the newly-created inode of the file,
    - » the data block of the parent directory containing the new directory entry,
    - » the parent directory inode,
    - » etc.
  - We are writing these same blocks over and over.
- Solution: buffer all updates into a global transaction.

FSCK and Journaling

Solution #2: Journaling (contd.)

- Making The Log Finite
  - The log is of a finite size. If we keep adding transactions to it (as in this figure), it will soon fill.



  - Use a journal superblock to record enough information to know which transactions have not yet been checkpointed, and thus reduces recovery time as well as enables re-use of the log in a circular fashion.

FSCK and Journaling

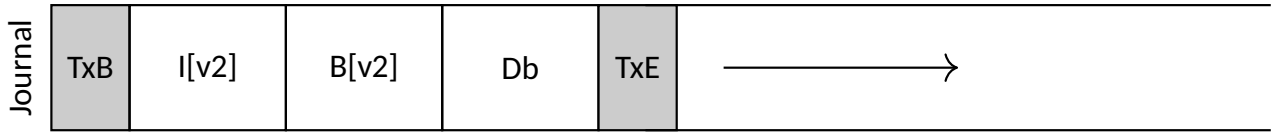
Solution #2: Journaling (contd.)

- Protocol to update the file system
  1. Journal write: Write the contents of the transaction (including TxB, metadata, and data) to the log; wait for these writes to complete.
  2. Journal commit: Write the transaction commit block (containing TxE) to the log; wait for write to complete; transaction is said to be committed.
  3. Checkpoint: Write the pending metadata and data updates to their final locations in the file system.
  4. Free: Some time later, mark the transaction free in the journal by updating the journal superblock.

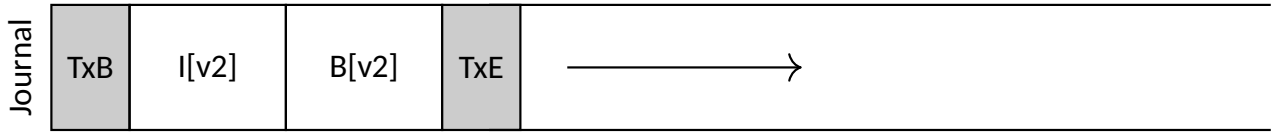
FSCK and Journaling

Solution #2: Journaling (contd.)

- Journaling Mode: Data / Ordered / Unordered.
  - Data journaling (as in Linux ext3) requires writing data twice to the disk.



  - Metadata journaling, does not write data to the journal.



    - When should we write Db?
    - Ordered / Unordered

FSCK and Journaling

Solution #2: Journaling (contd.)

- Protocol to update the file system
  1. Data write: Write data to final location; wait for completion (the wait is optional).
  2. Journal metadata write: Write the begin block and metadata to the log; wait for writes to complete.
  3. Journal commit: Write the transaction commit block (containing TxE) to the log; wait for write to complete; transaction is said to be committed.
  4. Checkpoint: Write the pending metadata and data updates to their final locations in the file system.
  5. Free: Some time later, mark the transaction free in the journal by updating the journal superblock.

FSCK and Journaling

Solution #2: Journaling (contd.)

- Block Reuse
  - User adds an entry to the directory *foo*, assume the location of the *foo* directory data is block 1000.
  - User deletes everything in the directory as well as the directory itself, freeing up block 1000 for reuse.
  - User creates a new file *foobar*, which ends up reusing the same block 1000.

  - Now assume a crash occurs and all of this information is still in the log. What will happen?

FSCK and Journaling

Solution #2: Journaling (contd.)

- Solutions:
  - Never reuse blocks until the delete of said blocks is checkpointed out of the journal
  - Linux ext3: add a new type of record (revoke) between two transactions. Such revoked data is never replayed.

FSCK and Journaling

Solution #3: Copy-on-Write

- Other Approaches include copy-on-write (in storage not memory management).
  - Never overwrites files or directories in place; rather, it places new updates to previously unused locations on disk.
  - Doing so makes keeping the file system consistent straightforward.
  - We will discuss the log-structured file system (LFS), which is an early example of a COW.

Contents

Log-Structured File System

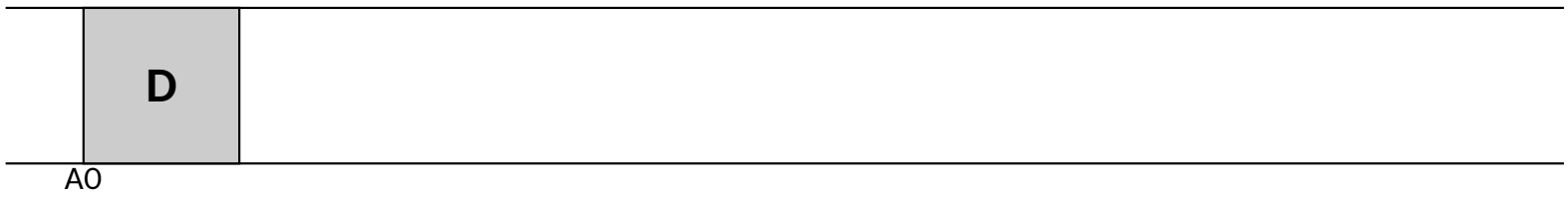
- Observations:
  - System memories are growing
    - » As more data is cached in memory, disk traffic increasingly consists of writes, as reads are serviced by the cache
  - There is a large gap between random I/O performance and sequential I/O performance
    - » Hard-drive transfer bandwidth has increased a great deal over the years, however seek and rotational delay costs have decreased slowly
  - Existing file systems perform poorly on many common workloads
    - » Even FFS incurs many short seeks and subsequent rotational delays
  - File systems are not RAID-aware
    - » Small writes problem in RAID-4 and RAID-5

Log-Structured File System

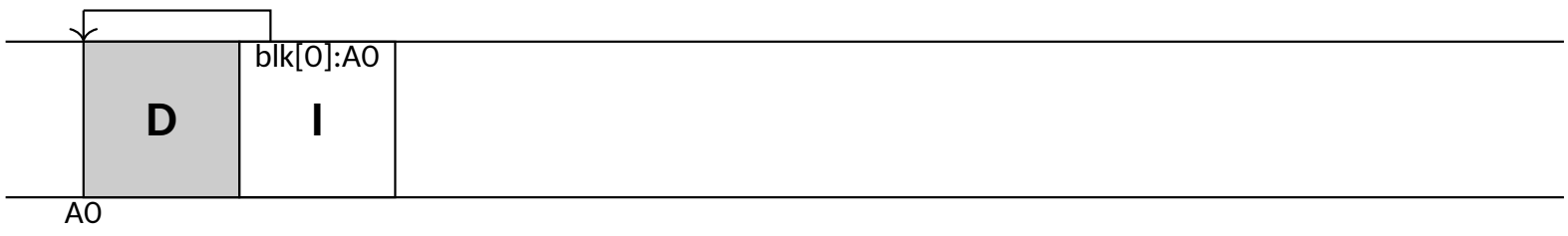
- Log-structured File System (LFS)
  - When writing to disk, LFS first buffers all updates (including metadata!) in an in-memory segment;
  - when the segment is full, it is written to disk in one long, sequential transfer to an unused part of the disk.
  - LFS never overwrites existing data, but rather always writes segments to free locations.
  - Because segments are large, the disk is used efficiently, and performance of the file system approaches its zenith.
  - How can a file system transform all writes into sequential writes?

Log-Structured File System

- Writing To Disk Sequentially
  - Imagine we are writing a data block D to a file, at disk address A0.

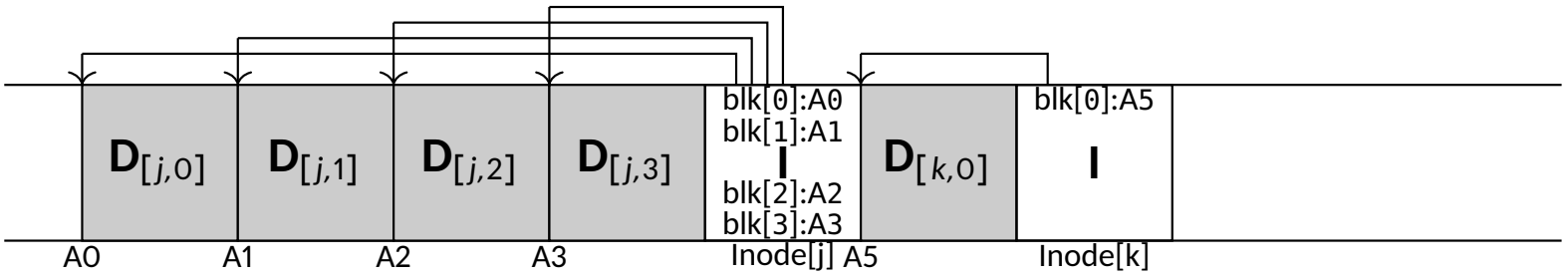


  - When a user writes a data block, it is not only data that gets written to disk; there is also other metadata that needs to be updated.



Log-Structured File System

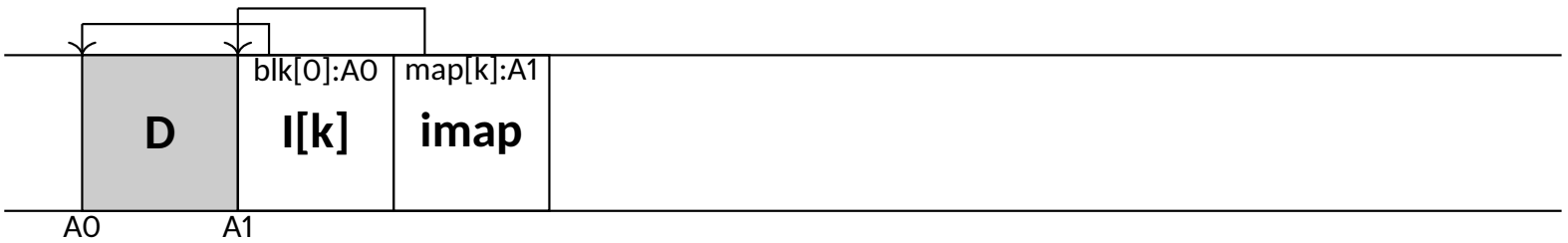
- With write buffering



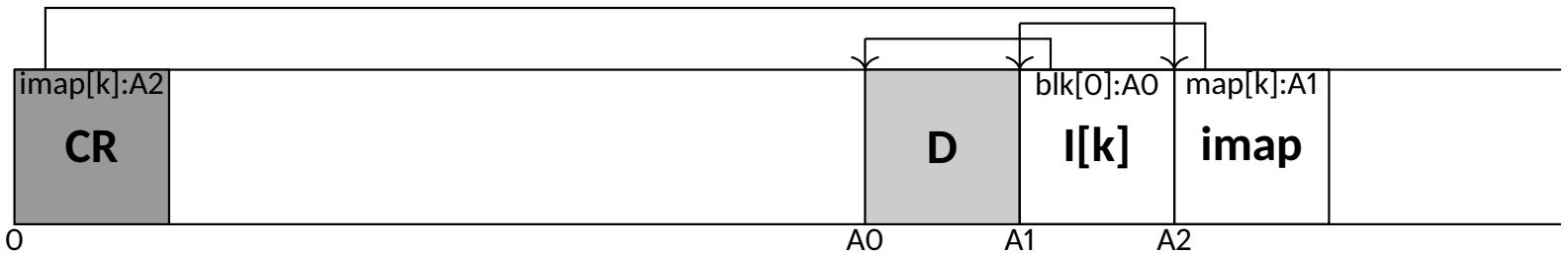
- How much to buffer?
- Some calculation:
  - With a disk with a positioning time of 10*milliseconds* and peak transfer rate of 100*MB/s*; assume we want an effective bandwidth of 90% of peak.
  - In this case, $D = 9MB$.

Log-Structured File System

- How to find inodes?
  - LFS uses a level of indirection between inode numbers and the inodes through a data structure called the inode map (imap).

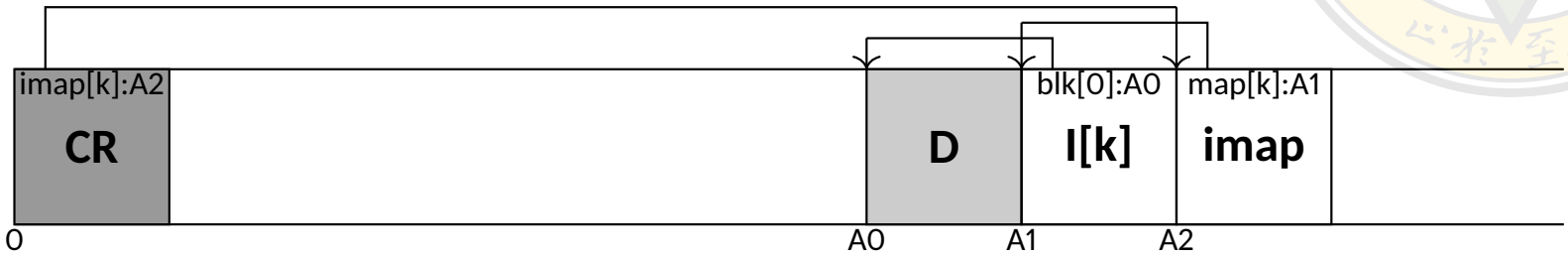


- How to find imaps?
  - The file system must have some fixed and known location to begin a file lookup. Such location is the checkpoint region (CR).



  - Note the checkpoint region is only updated periodically (say every 30 seconds or so), and thus performance is not ill-affected.

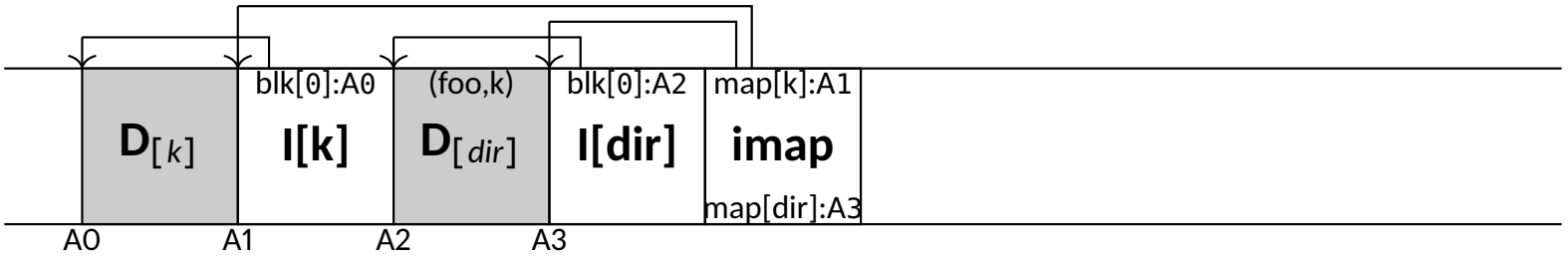
Log-Structured File System



- Reading a file
  1. Read the checkpoint region, which contains pointers to the entire inode map.
  2. Read the inode map, and caches it in memory.
  3. Looks up the inode-number to inode-disk-address mapping in the imap.
  4. Reads in the most recent version of the inode.
  5. ··· (Similar as typical UNIX file system).

Log-Structured File System

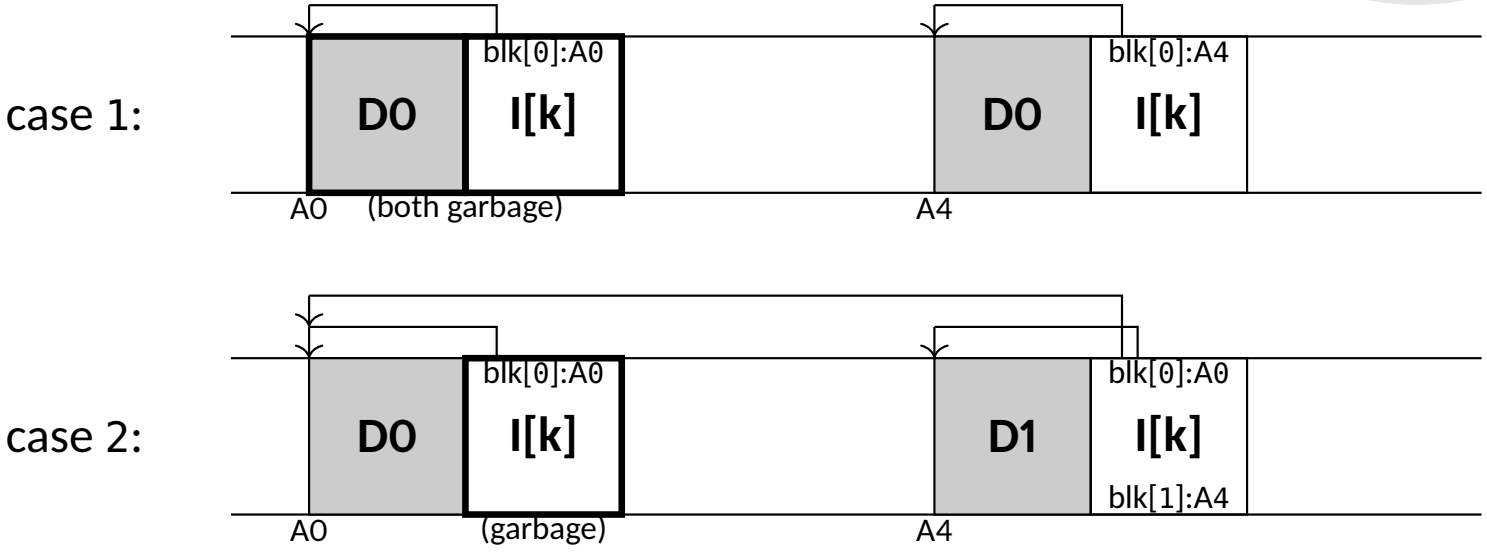
- Considering directories
  - When creating a file on disk, LFS must both write a new inode, some data, as well as the directory data and its inode that refer to this file.



  - Recursive update problem (when updating an inode)
  - Solution is simple: Even though the location of an inode may change, the change is never reflected in the directory itself. (This is because imap instead of directory, now record the location of inode.)

Log-Structured File System

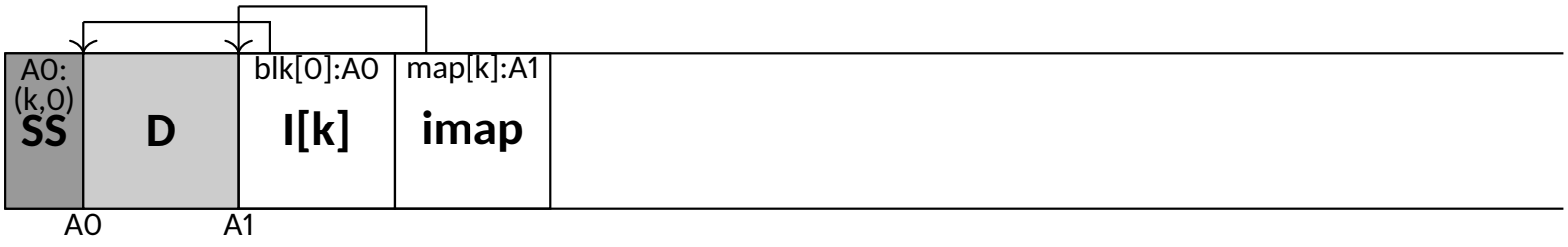
- Garbage Collection



  - Versioning file system keeps track of the different versions.
  - Using compaction, to get rid of free holes.

Log-Structured File System

- Determining Block Liveness
  - LFS includes, for each data block D, its inode number (which file it belongs to) and its offset (which block of the file this is). This information is recorded in a structure at the head of the segment known as the segment summary block.



Log-Structured File System

- Crash Recovery And The Log
  - What happens if the system crashes while LFS is writing to disk?
    - » LFS organizes the writes in a log pointed by the checkpoint region. (the checkpoint region points to a head and tail segment, and each segment points to the next segment to be written.)
    - » To ensure that the CR update happens atomically, LFS actually keeps two CRs.
    - » Suppose a crash happens during writing to a segment. Roll forward.

Contents

Solid-state Storage Device

Advantages

- Solid-state Storage Device (SSD)
  - Fast
    - » unlike hard drives, since no mechanical or moving parts;
    - » built out of transistors, much like memory and processor.
  - Non-volatile
    - » unlike typical random-access memory (e.g., DRAM);
    - » retains information despite power loss.
- We are now describing one technique: NAND-based flash.

Solid-state Storage Device

Challenges

- Challenge #1:
  - to write to a given chunk of SSD (i.e., a flash page), one first has to erase a bigger chunk (i.e., a flash block), which can be quite expensive.
- Challenge #2:
  - writing too often to a page will cause it to wear out.

Solid-state Storage Device

Storing a Single Bit

- One or more bits can be stored in a single transistor.
  - Single-level cell (SLC) flash: 0 or 1.
  - Multi-level cell (MLC) flash: 00, 01, 10, and 11, are encoded into different levels of charge.
  - Triple-level cell (TLC) flash: 3 bits.

Solid-state Storage Device

From Bits to Banks/Planes

- Flash chips are organized into banks or planes which consist of a large number of cells.
- A **bank** is accessed in two different sized units:
  - **blocks** (sometimes called erase blocks), which are typically of size 128 KB or 256 KB;
  - **pages** which are a few KB in size (e.g., 4KB).
- Within each **plane** there are a large number of banks; within each bank there are a large number of blocks; within each block, there are a large number of pages.

Solid-state Storage Device

Basic Flash Operations

- SSD supports three low-level operations:
  - **Read** (a page)
    - » Random access
  - **Erase** (a block)
    - » Before writing to a page within a flash, the nature of the device requires that you first erase the entire block the page lies within.
  - **Program** (a page)
    - » Change some of the 1's within a page to 0's

Solid-state Storage Device

Basic Flash Operations: A Detailed Example

- About to write:

Page 0	Page 1	Page 2	Page 3
00011000	11001110	00000001	00111111
VALID	VALID	VALID	VALID

- After erase:

Page 0	Page 1	Page 2	Page 3
11111111	11111111	11111111	11111111
ERASED	ERASED	ERASED	ERASED

- After write:

Page 0	Page 1	Page 2	Page 3
00000011	11111111	11111111	11111111
VALID	ERASED	ERASED	ERASED

- The previous contents of pages 1, 2, and 3 are all gone!

Solid-state Storage Device

Flash Performance And Reliability

- Performance:
  - Reading a random page is fast;
  - Writing a page is trickier.

Device	Read (μs)	Erase (μs)	Program (μs)
SLC	25	200-300	1500-2000
MLC	50	600-900	3000
TLC	75	900-1350	4500

Solid-state Storage Device

Flash Performance And Reliability

- Reliability: Unlike mechanical disks, flash chips are pure silicon and in that sense have fewer reliability issues to worry about.
  - The primary concern is wear out.
    - When a flash block is erased and programmed, it slowly accrues a little bit of extra charge. Over time, as that extra charge builds up, it becomes increasingly difficult to differentiate between a 0 and a 1.
    - Typically, 10,000 P/E (Program/Erase) cycle lifetime form MLC and 100,000 P/E cycles for SLC, or more.
  - One other problem is disturbance.
    - When accessing a particular page within a flash, it is possible that some bits get flipped in neighboring pages, known as read disturbs or program disturbs.

Solid-state Storage Device

From Raw Flash to Flash-Based SSDs

- Flash translation layer (FTL)
  - It satisfies client reads and writes, turning them into internal flash operations as need be.
  - A bad organization: direct mapping.
    - A read to logical page N is mapped di-rectly to a read of physical page N.
    - What are the limitations?
  - Log-Structured FTL.
    - Log structured in both storage devices (as we'll see now) and file systems above them (will be detailed in the next chapter).

Solid-state Storage Device

Log-Structured FTL

- Assume the following operations:
  - Write(100) with contents a1
  - Write(101) with contents a2
  - Write(2000) with contents b1
  - Write(2001) with contents b2

Table: 100 → 0, 101 → 1, 2000 → 2, 2001 → 3 Memory

Block:	0				1				2			
Page:	00	01	02	03	04	05	06	07	08	09	10	11
Content:	a1	a2	b1	b2								
State:	V	V	V	V	I	I	I	I	I	I	I	I

Flash Chip

Solid-state Storage Device

Log-Structured FTL (Contd.)

- Now, let's assume that blocks 100 and 101 are written to again, with contents c1 and c2.

Table: 100 → 4, 101 → 5, 2000 → 2, 2001 → 3 — Memory

Block:	0				1				2				
Page:	00	01	02	03	04	05	06	07	08	09	10	11	
Content:	a1	a2	b1	b2	c1	c2							Flash Chip
State:	V	V	V	V	V	V	E	E	I	I	I	I	

Solid-state Storage Device

Log-Structured FTL (Contd.)

- Garbage collection:
  - find a block that contains one or more garbage pages,
  - read in the live (non-garbage) pages from that block,
  - write out those live pages to the log,
  - reclaim the entire block for use in writing.

Table: 100 → 4, 101 → 5, 2000 → 6, 2001 → 7 Memory

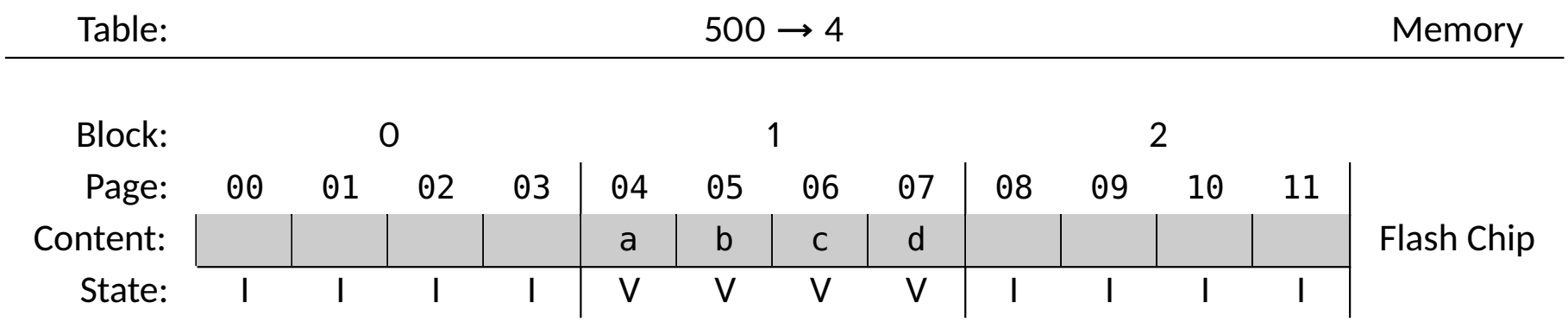
Block:	0				1				2			
Page:	00	01	02	03	04	05	06	07	08	09	10	11
Content:					c1	c2	b1	b2				
State:	E	E	E	E	V	V	V	V	I	I	I	I

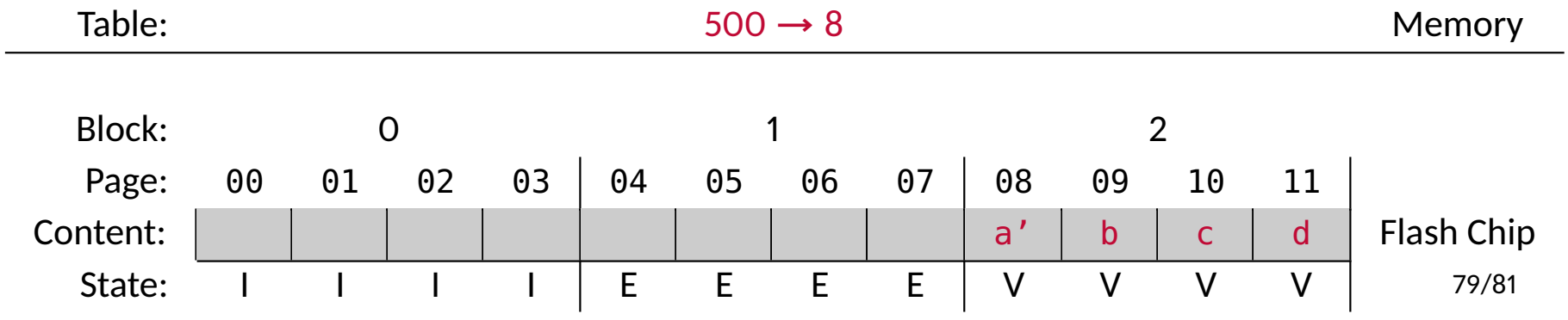
Flash Chip

Solid-state Storage Device

Log-Structured FTL (Contd.)

- Mapping table size:
  - Block-level FTL intead of page-level - small updates requires updating the whole block (e.g., updating a to a').

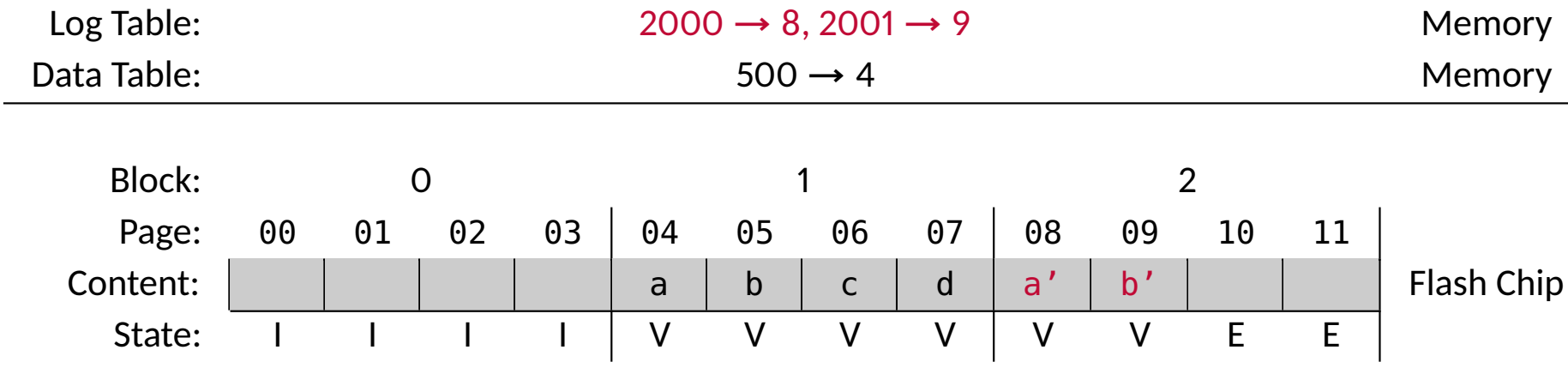




Solid-state Storage Device

Log-Structured FTL (Contd.)

- Hybrid mapping:
  - Block-level FTL intead of page-level - small updates requires updating the whole block (e.g., updating c to c').



Solid-state Storage Device

Log-Structured FTL (Contd.)

- Hybrid mapping:
  - Block-level FTL intead of page-level - small updates requires updating the whole block (e.g., updating c to c').

Devices	**Performance**				**Cost**
	Random		Sequential		
	Reads (MB/s)	Writes (MB/s)	Reads (MB/s)	Writes (MB/s)	(CNY/1TB)
Western Digital SN550 SSD	1640	1620	2400	1950	899
Samsung 980 SSD	2000	1920	3500	3000	1399
Seagate FireCuda 520 SSD	3040	2800	5000	4400	1599
Seagate IronWolf HDD	0.28	0.28	180	180	499