File System Implementation

2023/24 COMP3230B

Contents

- File system metadata
- What is inode?
- Free space management
- Access control and protection
- Crash Consistency

Related Learning Outcome

- ILO 2d - describe the principles and techniques used by OS to support persistent data storage

Readings & References

- Required Readings
  - Chapter 40 – **File System Implementation**
    - http://pages.cs.wisc.edu/~remzi/OSTEP/file-implementation.pdf

- Reference
  - Chapter 42 – **Crash Consistency: FSCK and Journaling**
    - http://pages.cs.wisc.edu/~remzi/OSTEP/file-journaling.pdf

Management of Files and Storages

- A file needs space to store its contents
- The file system needs space to store its management data related to files and storage space – metadata
  - Where are these metadata being stored? Of course, on the disk

- What kinds of on-disk structures are used by the file system to organize files' data and its metadata?
  - **Superblock** (for Windows, similar set of info can be located via **Master File Table**)
  - Inode table (for Windows – Master File Table)
  - Data block bitmap (for Windows – Cluster Bitmap)
  - Inode bitmap

Superblock

- Superblock is a data structure contains information about the **file system as a whole**
- A superblock might contain
  - The file system identifier
  - Tell us the number of inodes (file control blocks) and data blocks available in this file system
  - Where is the inode tables? Inode bitmap? Data block bitmap?
  - Information of the inode of the root directory
- When mounting a file system, OS reads the superblock to locate others on-disk data structures
  - Usually the superblock is found at the first disk block of this file system
- To reduce the risk of data loss, most file systems distribute redundant copies of the superblock throughout the storage device

Inodes Table & Inode Bitmap

- Each file has an inode (**file control block**) that stores the metadata of a file
- Where is the inodes being stored?
  - Some disk blocks are reserved for holding these file control blocks – in the form of an array of inodes (**inode table**)
  - We can view the inode number (low-level id) is an index to the inode table

- Inode bitmap
  - When a file is created, one inode will be allocated from the inode table for this new file
  - When a file is deleted, the inode will be released back to the inode table
  - Thus, the system needs a mechanism to easily check which inodes in the inode table are free or in used
  - A **inode bitmap** is a simple structure with each bit is used to indicate whether the corresponding inode is free or in-use in the inode table

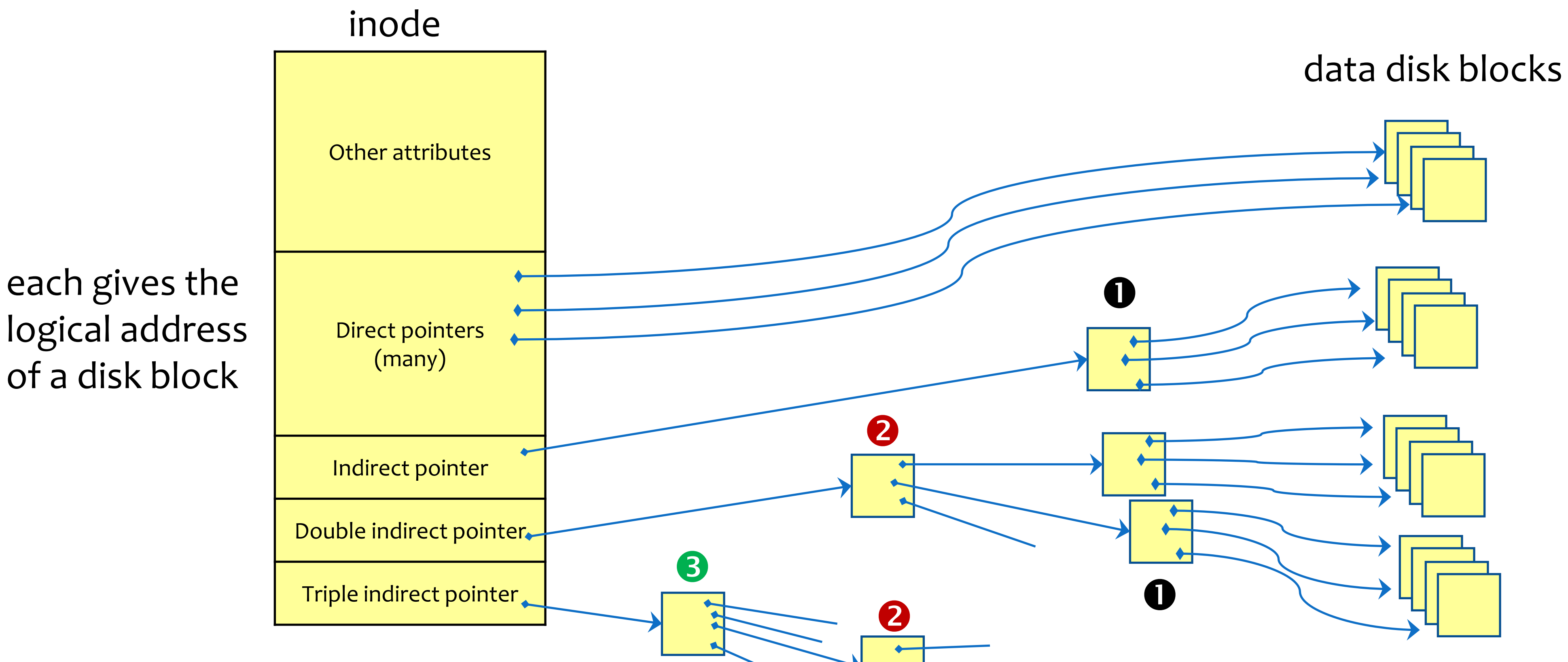
Inode (File Control Block)

- The most important on-disk structure of a file system
  - In Unix, this is called inode
  - In NTFS, this is called file record

- It stores virtually all of the information about a file, including its type, its size, ownerships, permissions, . . ., and location of file contents

- One important design decision of the inode is that how can the inode keep track on the data blocks of a file
  - The data content of the file is stored in data disk block(s)
  - Thus, inode needs to have some way to **tell us** which **data blocks** are associated to this file in the disk
  - The adopt mechanism may limit the max size a single file can have in such file system

Inode – Multi-level Index



❶ Indirect block - a disk block full of direct pointers

❷ Double indirect block - a disk block full of indirect pointers

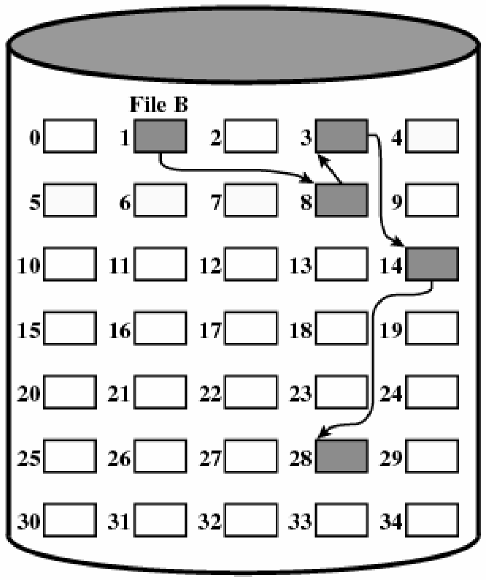
❸ Triple indirect block - a disk block full of double indirect pointers

Inode – Multi-level Index

- Disadvantage
  - Used up some space in the inode to store the pointers
  - Disk blocks used by a file may be scattered all over the disk
- Advantages
  - Can support a very large file size
  - Brings all pointers together (centralized) to the inode; facilitate searching for a particular data block
    - Most files are small; with a small number of direct pointers (typically 12), all data blocks can be located by the direct pointers
- Examples: ext2fs, ext3fs, ext4fs, and NTFS

Other Approaches

- Linked-list approach
  - Inside the inode, instead of having multiple direct pointers, just only one pointer which points to the first data block of the file in the disk
  - For a larger file, each data block contains a pointer to the next block in the chain
  - Disadvantages
    - To locate a data item in the file
      - The chain must be searched from the beginning to locate the data; search process can be slow as block-to-block seeks occur
    - Reliability issue – if the linked list is broken
    - Disk blocks used by a file may be scattered all over the disk



Other Approaches

- Tabular approach
  - Uses a table to keep track of the allocation of data blocks in the file system
  - Directory entry or inode records the block number of the first data block of a file
    - This block number is used as an index into the **block allocation table** to find the location of the next block.
    - If current block is the file's last block, then its entry is set to null
  - Advantage
    - Pointers that locate file data blocks are centralized
      - The table can be cached so that searching can be traversed quickly; this improves access times
  - Disadvantage
    - For large disks, the block allocation table can become quite large
  - Example: Microsoft's FAT file system

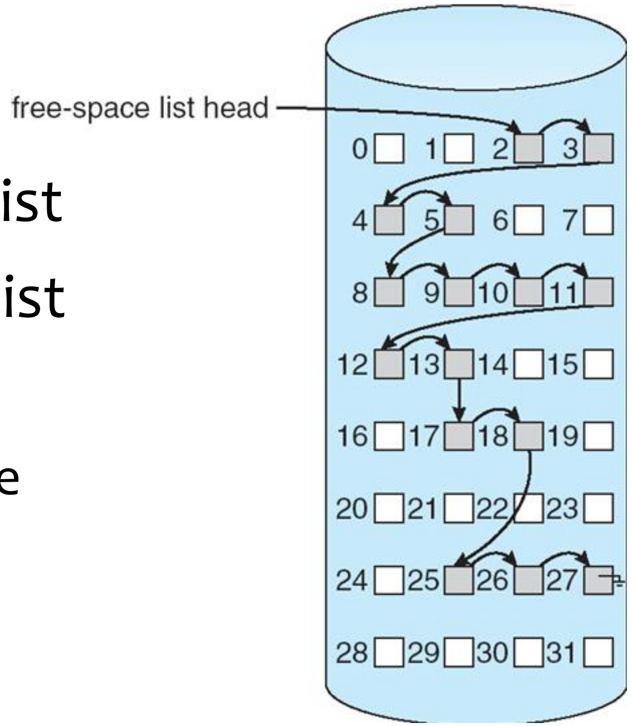
0	22
1	NULL
2	5
3	26
4	9
5	20
6	10
7	FREE
8	17
9	1
10	14
11	FREE
12	3
13	4
14	0
15	FREE
16	FREE
17	12
18	13
19	NULL
20	23
21	FREE
22	18
23	19

Free Space Management

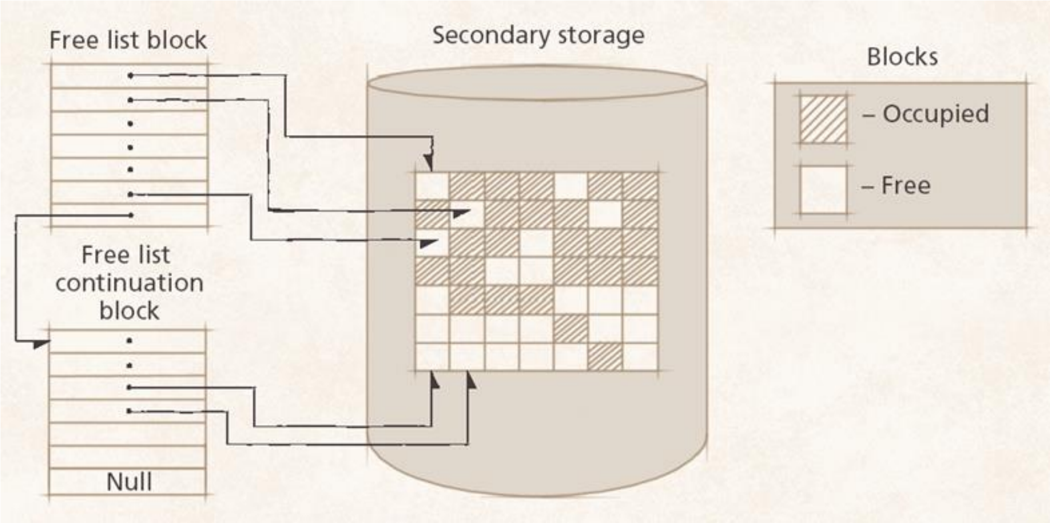
- Data Block Bitmap is
  - A bitmap that tells us which data disk blocks are free or in-use
  - Each bit represents a data block in disk
    - If the file system has *x* data blocks, it needs at least *x* bits = *x*/8 bytes
      - Example: block size = 2^{12} bytes and disk size = 2^{30} bytes (1 GiB); $x = 2^{18}$ bits (or 32 KiB)
  - Advantage
    - Can determine if contiguous blocks are available at certain locations on disk
  - Disadvantage
    - May need to search the entire bitmap to find a free block

Free Space Management

- Free linked-list
  - Keep a pointer points to the first free block
  - Each block contains a pointer to the next free block, and so on
  - Blocks are allocated from the beginning of the free list
  - Newly freed blocks are appended to the end of the list
  - Disadvantage
    - Every disk block allocation results in a disk read to locate the next free block for updating the pointer



Free Space Management



- Free block-list
  - A disk block has n entries which stores addresses of n-1 free disk blocks; the last entry stores a pointer to the next block in the free block-list
  - Faster to find a large number of free blocks
  - Advantage
    - Both free block list and free linked list have low overhead to perform free list maintenance operations
  - Disadvantage
    - Files are likely to be allocated in noncontiguous blocks

Caching and Buffering

- Imagine a file open operation to open an existing file:

  /home/c3230a/overview.txt,

  without touching on the data content
  - Assume the file system has been mounted with the superblock being loaded in only; everything else is still on the disk

- Every file open would require **at least two** reads (disk I/O) for every level in the directory hierarchy
  - One to read the inode of the directory in question, and at least one to read the data of the directory
    - 2 reads for "/"
    - 2 reads for "home"
    - 2 reads for "c3230a"
    - 1 read for the inode of "overview.txt"

Caching and Buffering

- Most file systems use physical memory to cache important blocks
  - If caching is in-used, the first open may generate a lot of I/O traffic
  - subsequent file opens of files in the directories along the path will mostly result in a cache hit, thus no I/O is needed
    - Both inode and data block of the directory are in cache

Access Control and Protection

- Through the user access control procedure, user is assigned a unique user ID (and group ID)

- The most common approach to file protection is to make access dependent on the identity of the user
  - Each file has an associated **access (-control) list**
    - Mode of access: Read, Write, Execute
  - Many systems recognize three classes of users: Owner, Group, Public
  - For a particular file or subdirectory, define an appropriate access control
    - e.g.,

		RWX
owner access	7	1 1 1
group access	6	1 1 0
public access	1	0 0 1

  - Can be stored in the inode

Access Control and Protection

- Upon receiving a request from a process to open the file, access permission is checked and all associated actions are performed
- If no access right, operation will be denied
- All information is recorded in a new entry in the open file table; returns the index (indirectly via the file descriptor) of this file in the open file table to user
- The process could only access the file via this index
  - The right to access must still **be checked** on every access
  - The open-file-table entry has a capability only for the allowed operations
    - For example, if the file is opened for read only, an attempt to have write operation on the file will be denied even the user has the write access right

Integrity Protection

- System crash can result in data inconsistencies (files and file system)
  - A typical file creation may involve following actions
    - Update the directory's inode and data block, inode bitmap, data block bitmap, free counts, new inode, new data block, and other control structures
      - If a system failure occurs during the file creation operation, file data (and metadata) may be left in an inconsistent state
- Routinely backup is the most effective protection scheme
  - e.g. superblocks are duplicated and stored as backup
  - e.g. physical backup of the whole disk, using dd
  - e.g., logical backups
    - Store file system data and its logical structure
    - Inspect the directory structure to determine which files need to be backed up, then write these files to a backup device in a common, often compressed, archival format
    - Example: Unix command - tar
    - Incremental backups are logical backups that store only file system data that has changed since the previous backup

Integrity Protection

- Consistency checking
  - Compares data in directory structure with data blocks on disk, and tries to fix inconsistencies
  - Example: Unix command: fsck or DOS command: chkdsk
    - FSCK
      - checking superblock to find suspect corruption
      - scan all inodes' state
      - scan all inodes' direct and indirect block pointers to build a correct Free block bitmap
      - scan all inodes to build the Free inode bitmap

Journaling File Systems

- Examples: NTFS and ext3fs (and ext4fs)
- Perform all file system operations as logged transactions to ensure that they do not leave the system in an inconsistent state
  - Each update to the file system is considered as a transaction and is labeled by a sequence #
  - All transactions are first written to a log – a pre-allocated space in the disk
    - **Physical logging** - putting the exact physical contents of the update in the log
  - A transaction is **considered committed** once it is written to the log
  - However, the file system may not yet be updated
  - Only when the update has been written to disk, we called this transaction has completed, and record that in the log so that the space can be reused

Journaling File Systems

- If an error occurs, when the system reboots, the file system recovery process will scan the log and look for not completed transactions; these transactions are thus replayed (in order).
- Two modes of operation
  - Log all updates, including data blocks are recorded
  - Only metadata updates are logged

Summary

- Explain what is metadata of the file system
- Discuss and compare various file storage allocation schemes
  - Linked-list allocation
  - Tabular allocation
  - Indexed allocation
- Discuss and compare various free space management schemes
  - Free linked list
  - Free block list
  - Bitmap
- Describe how modern OSs provide access control and data integrity