File Systems

COMS W4118
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References: Operating Systems Concepts (9e), Linux Kernel Development, previous W4118s

Outline

- File system concepts
  - What is a file?
  - What operations can be performed on files?
  - What is a directory and how is it organized?

- File implementation
  - How to allocate disk space to files?

What is a file

- User view
  - Named byte array
    - Types defined by user
  - Persistent across reboots and power failures

- OS view
  - Map bytes as collection of blocks on physical storage
  - Stored on nonvolatile storage device
    - Magnetic Disks

Role of file system

- Naming
  - How to “name” files
  - Translate “name” + offset ➔ logical block #
- Reliability
  - Must not lose file data
- Protection
  - Must mediate file access from different users
- Disk management
  - Fair, efficient use of disk space
  - Fast access to files

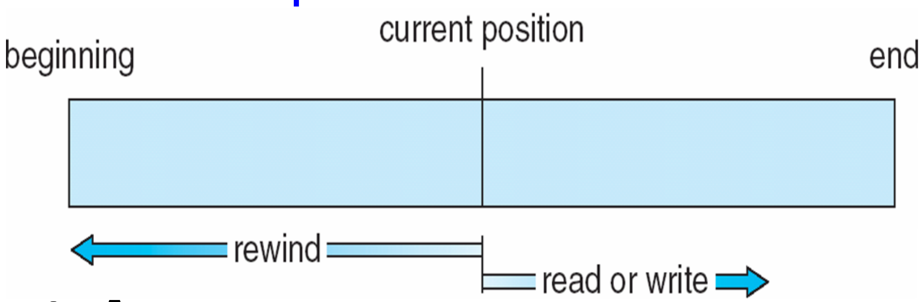
File metadata

- Name – only information kept in human-readable form
- Identifier – unique tag (number) identifies file within file system (inode number in UNIX)
- Location – pointer to file location on device
- Size – current file size
- Protection – controls who can do reading, writing, executing
- Time, date, and user identification – data for protection, security, and usage monitoring

- How is metadata stored? (inode in UNIX)

File Access Methods

- Sequential Access
  - Maintain file pointer



- Direct Access
  - Relative block number
  - Relative block numbers: allow OS to decide where file should be placed (like paging virtual memory addresses)
- Indexed Access (e.g., ISAM)
  - File records kept sorted on a specified index-key
  - Index block tracks beginning record in each data block

UNIX File operations

- int creat(const char* pathname, mode_t mode)
- int unlink(const char* pathname)
- int rename(const char* oldpath, const char* newpath)
- int open(const char* pathname, int flags, mode_t mode)
- int read(int fd, void* buf, size_t count);
- int write(int fd, const void* buf, size_t count)
- int lseek(int fd, offset_t offset, int whence)
- int truncate(const char* pathname, offset_t len)
- ...

Everything as a file

- A core UNIX tenet from the early days
  - Block devices (disks, graphics cards in /dev)
  - Character devices (USB devices, network cards in /dev)
  - IPC: Pipes, Network sockets
  - Accessing kernel data structures (/proc, /sys)
  - Setting kernel configuration
  - Volatile filesystems in RAM (e.g., tmpfs)
  - Shared memory (based on tmpfs/shmfs)
  - Remote files (NFS, SMB, AFP, …)
  - Even normal local files
- Implications
  - Everything accessed using common API (open, read, write)
  - Implementation may be totally different
  - OS must support some measure of object orientedness

Open files

- Problem: expensive to resolve name to identifier on each access
- Solution: open file before access
  - Name resolution: search directories for file name and check permission
  - Read relevant file metadata into open file table in memory
  - Return index in open file table (file descriptor)
  - Application pass index to OS for subsequent access

- System-wide open file table shared across processes
- Per-process open file table stores current pointer position and index to system-wide open file table

Directories

- Organization technique
  - Map file name to location on disk
  - Also stored on disk
- Single-Level directory
  - Single directory for entire disk
    - Each file must have unique name
  - Not very usable
- Two-level directory
  - Directory for each user
  - Still not very usable

Tree-structured directory

- Directory stored on disk just like files
  - Data consists of <name, index> pairs
    - Index points to file identifier (inode)
    - Name can be another directory
  - Designated by special bit in meta-data
  - Reference by separating names with slashes
  - Operations
    - User programs can read (readdir())
    - Only special system calls can write
- Special directories
  - Root (/): fixed index for metadata
  - . : this directory
  - .. : parent directory

Acyclic-graph directories

- Directories can share files
- Create links from one file
- Two types of links
  - Symbolic link
    - Special file, designated by bit in meta-data
    - File data is name to another file
  - Hard link
    - Multiple directory entries point to same file
    - All hard-links are equal: no primary
    - Store reference count in file metadata
    - Cannot refer to directories; why?

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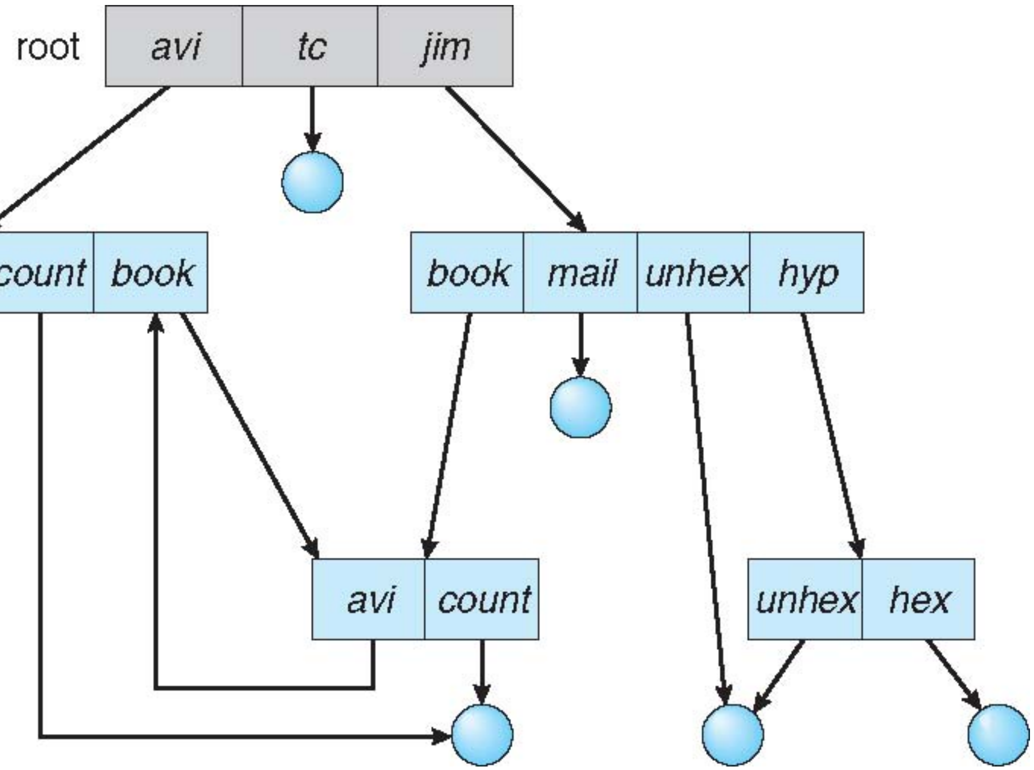
General Graph Directory and Cycles



- Cycles cause problems with reference counts
- E.g., a cycle that isn't accessible through root
- Need garbage collection

Path names

- Absolute path name (full path name)
  - Start at root directory
    - E.g. /home/html
- Relative path name
  - Full path is lengthy and inflexible
  - Give each process current working directory
  - Assume file in current directory

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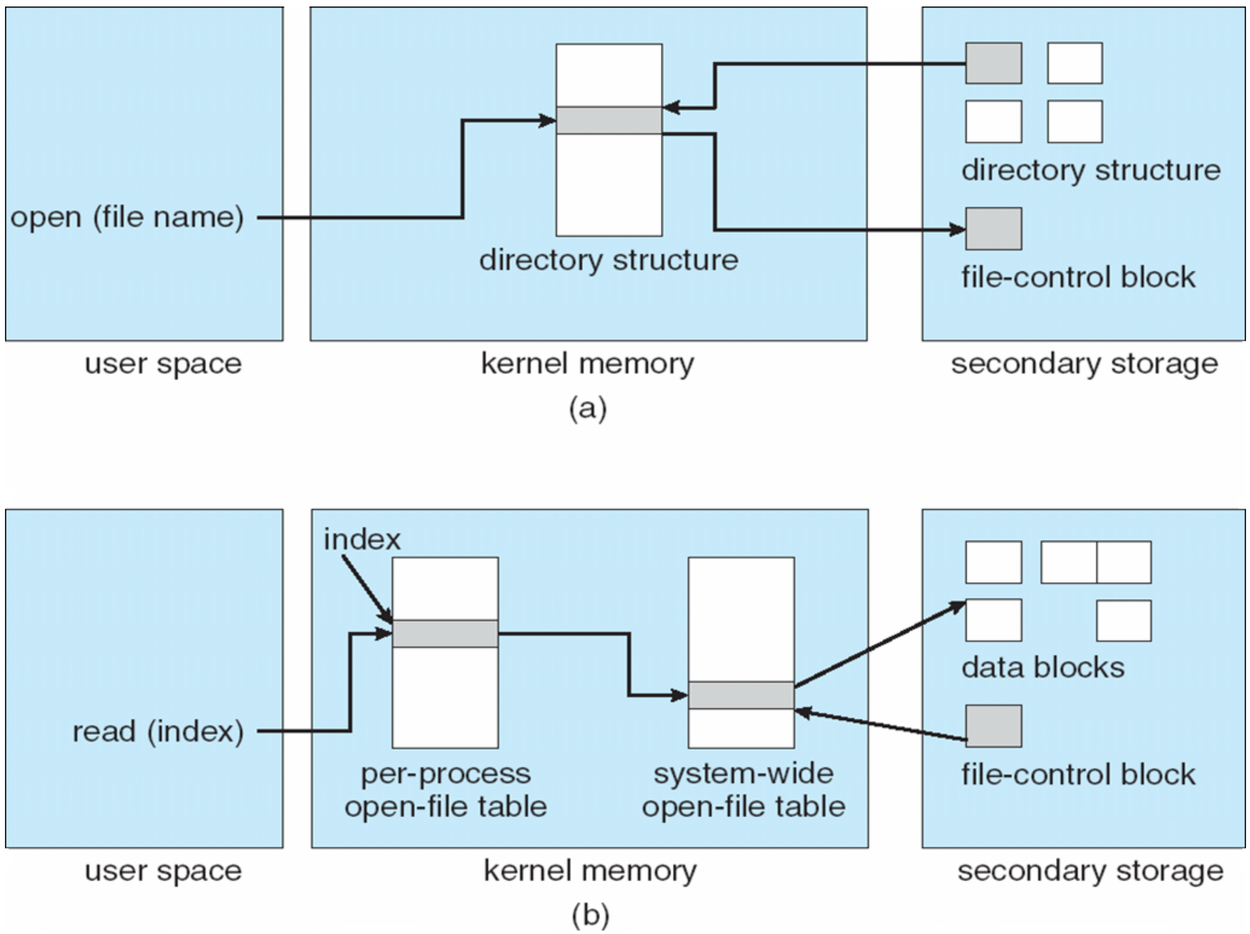
Directories as files

- Direction as special files that store pointers to the contained files
  - File data is interpreted by FS code
- Separate functionality in two levels
  - Lowest: storage management
  - Highest: naming, directory
- Advantage: simplifies design and implementation

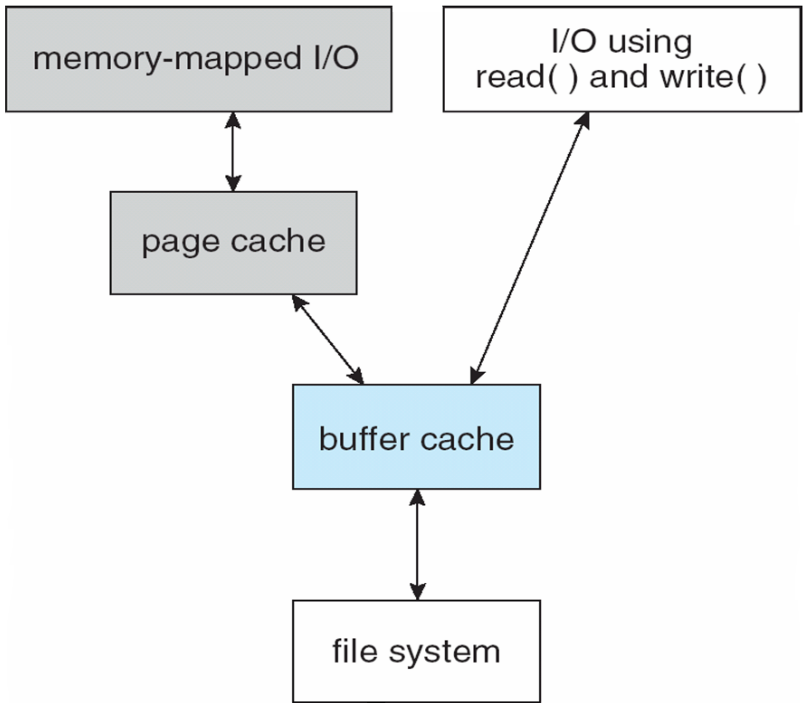
In-Memory File System Structures

Principle: heavy caching to reduce impact of slow disk I/O

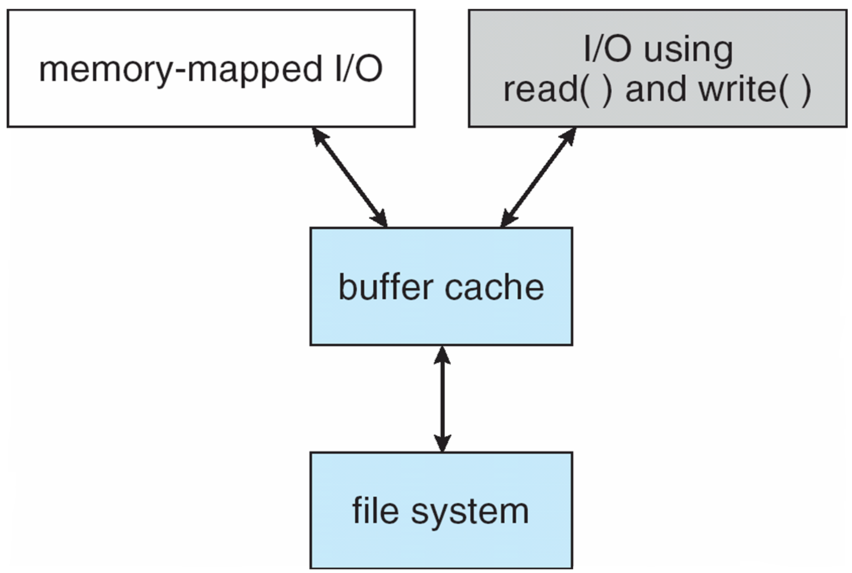


Unified Buffer Cache

- We've seen the Linux page cache
  - Example of unified memory-disk subsystems



Separate I/O and paging systems
(double caching)



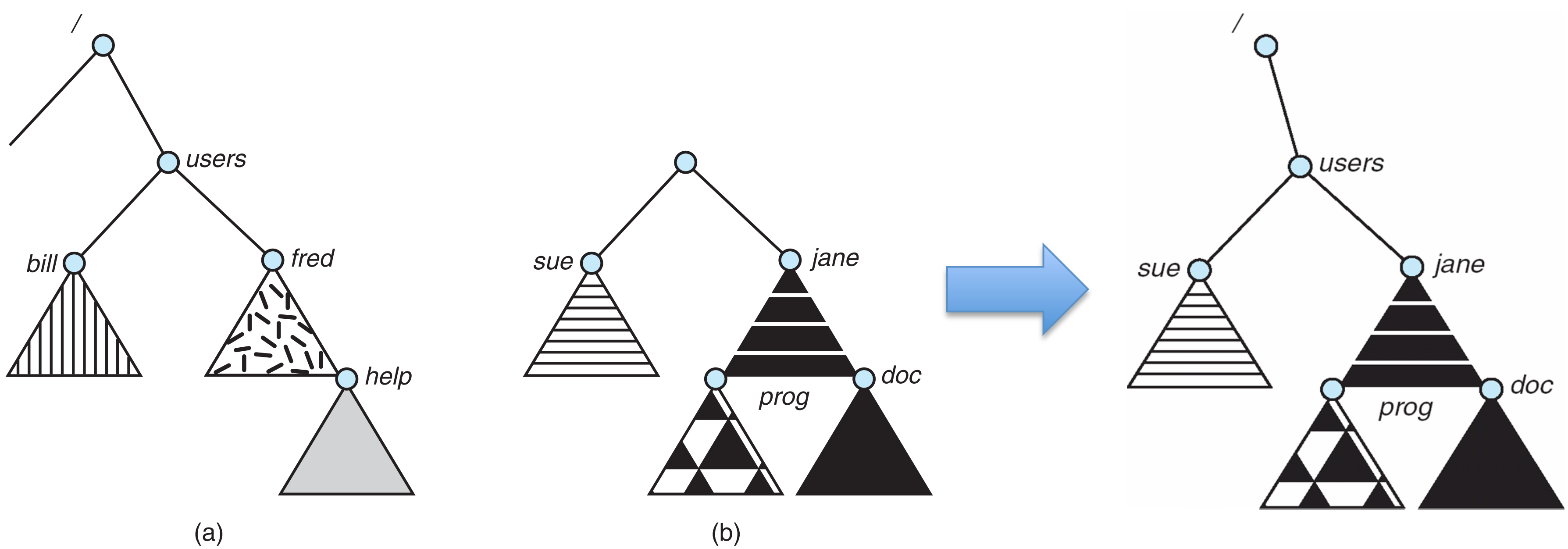
Unified disk and paging cache

Example: Linux In-memory Data Structures

- struct super_block
  - Contains FS type, size, free space, pointer to root dir
- struct inode
  - One per physical file
  - Unique inode number
  - Contains file size, permissions, attributes, timestamps
- struct dentry
  - A directory entry (to file or another directory)
  - Contains name used to access file, inode number
- struct file
  - File opened by process
  - Contains file pointer, mode user opened the file in

File System Mounting

- Start off with root filesystem
- New file systems can be mounted into an existing directory (mount point)
- E.g., mount –o opts –t ext2 /dev/hda3 /users



Protection

- Type of access
  - Read, write, execute, append, delete, list …
- Access control list
  - Associate lists of users with access rights for every file
  - Advantage: complete control
  - Disadvantage
    - Tedious to construct list (may not know in advance for all users)
    - Require variable-size information
- Classify users
  - Assign a owner and group to each file
  - Different permissions based on who is accessing: owner, group, other
  - Advantage: easier to implement
  - Disadvantage: no fine grained control

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Typical file access patterns

- Sequential Access
  - Data read or written in order
    - Most common access pattern
      - E.g., copy files, compiler read and write files,
  - Can be made very fast (peak transfer rate from disk)
- Random Access
  - Randomly address any block
    - E.g., update records in a database file
  - Difficult to make fast (seek time and rotational delay)

Disk management

- Need to track where file data is on disk
  - How should we map logical sector # to surface #, track #, and sector #?
    - Order disk sectors to minimize seek time for sequential access
- Need to track where file metadata is on disk
- Need to track free versus allocated areas of disk
  - E.g., block allocation bitmap (Unix)
    - Array of bits, one per block
    - Usually keep entire bitmap in memory

Allocation strategies

- Various approaches (similar to memory allocation)
  - Contiguous
  - Extent-based
  - Linked
  - FAT tables
  - Indexed
  - Multi-Level Indexed

- Key metrics
  - Fragmentation (internal & external)?
  - Grow file over time after initial creation?
  - Fast to find data for sequential and random access?
  - Easy to implement?
  - Storage overhead?

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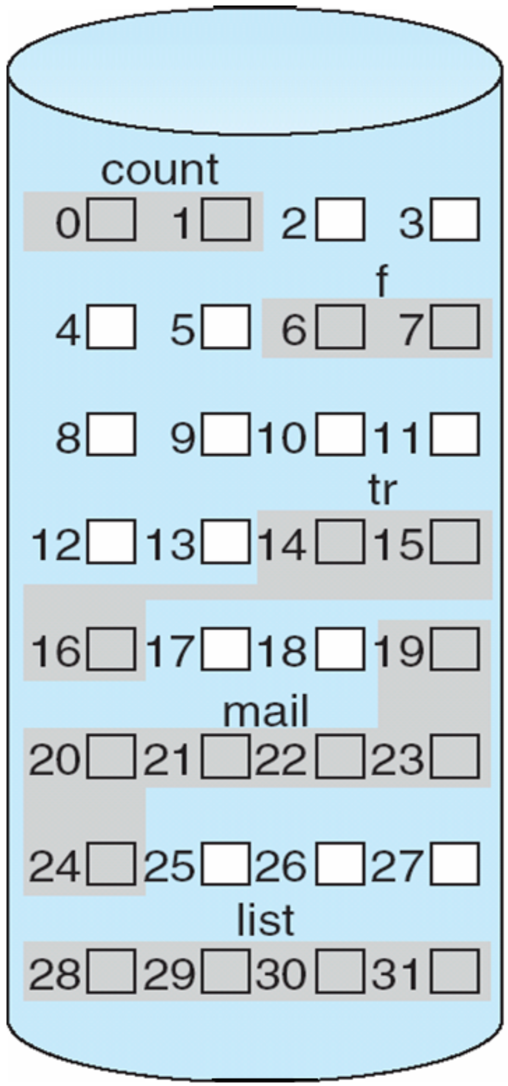
Contiguous allocation

- Allocate files like continuous memory allocation (base & limit)
  - User specifies length, file system allocates space all at once
  - Can find disk space by examining bitmap
  - Metadata: contains starting location and size of file

Contiguous allocation example



directory

file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

Pros and cons

- Pros
  - Easy to implement
  - Low storage overhead (two variables to specify disk area for file)
  - Fast sequential access since data stored in continuous blocks
  - Fast to compute data location for random addresses. Just an array index

- Cons
  - Large external fragmentation
  - Difficult to grow file

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Extent-based allocation

- Multiple contiguous regions per file (like segmentation)
  - Each region is an extent
  - Metadata: contains small array of entries designating extents
    - Each entry: start and size of extent

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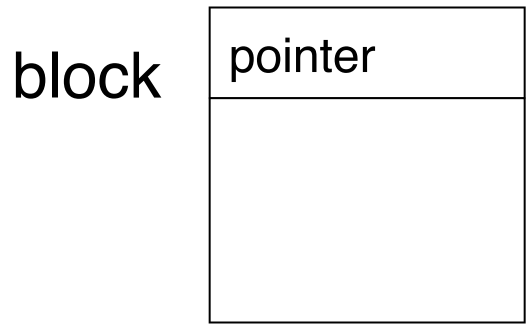
Pros and cons

- Pros
  - Easy to implement
  - Low storage overhead (a few entries to specify file blocks)
  - File can grow overtime (until run out of extents)
  - Fast sequential access
  - Simple to calculate random addresses

- Cons
  - Help with external fragmentation, but still a problem

Linked allocation

- All blocks (fixed-size) of a file on linked list
  - Each block has a pointer to next
  - Metadata: pointer to the first block



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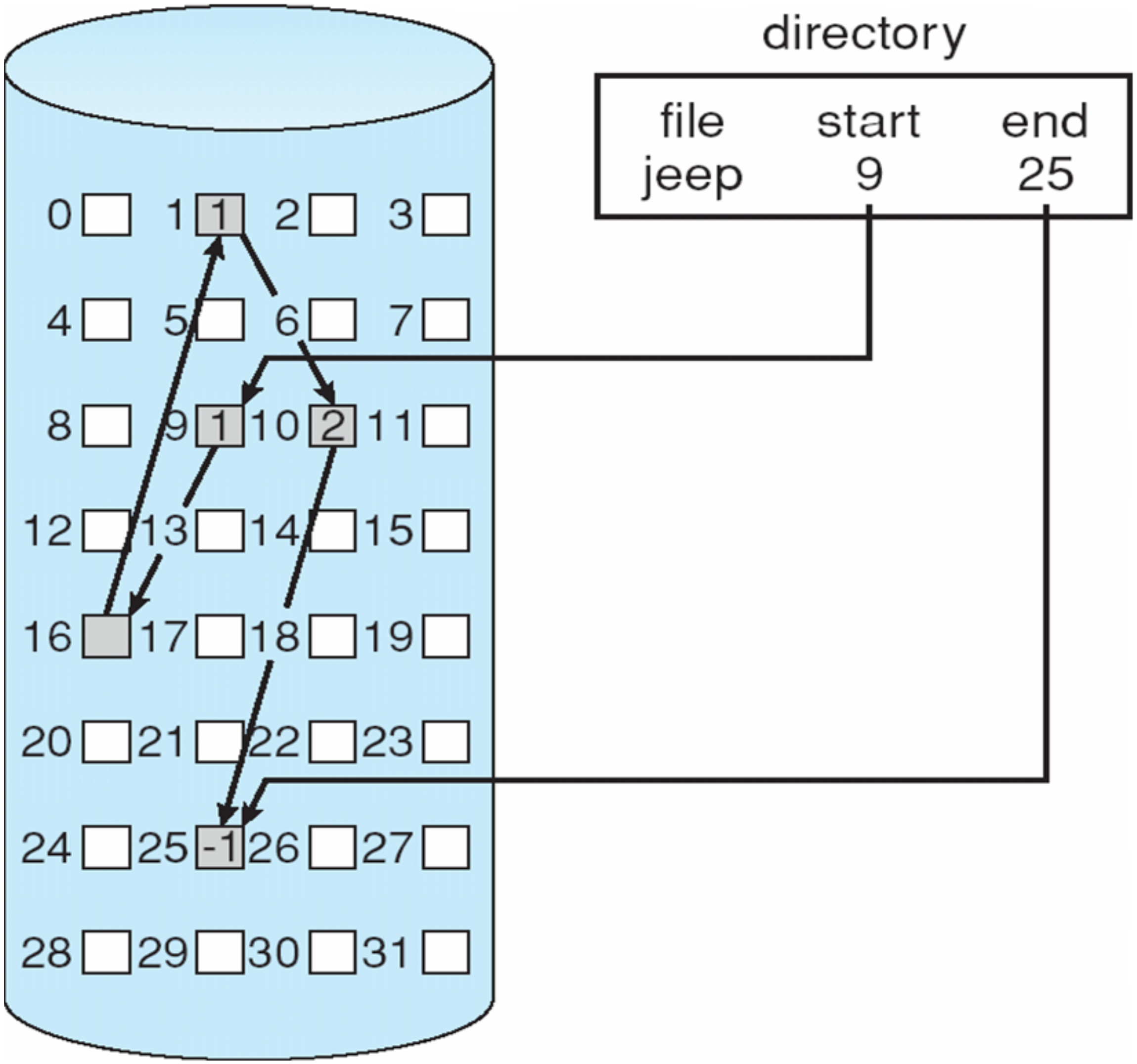
Linked allocation example



Pros and cons

- Pros
  - No external fragmentation
  - Files can be easily grown with no limit
  - Also easy to implement, though awkward to spare space for disk pointer per block
- Cons
  - Large storage overhead (one pointer per block)
  - Potentially slow sequential access
  - Difficult to compute random addresses

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Variation: FAT table

- Store linked-list pointers outside block in File-Allocation Table
  - One entry for each block
  - Linked-list of entries for each file
- Used in MSDOS and Windows operating systems

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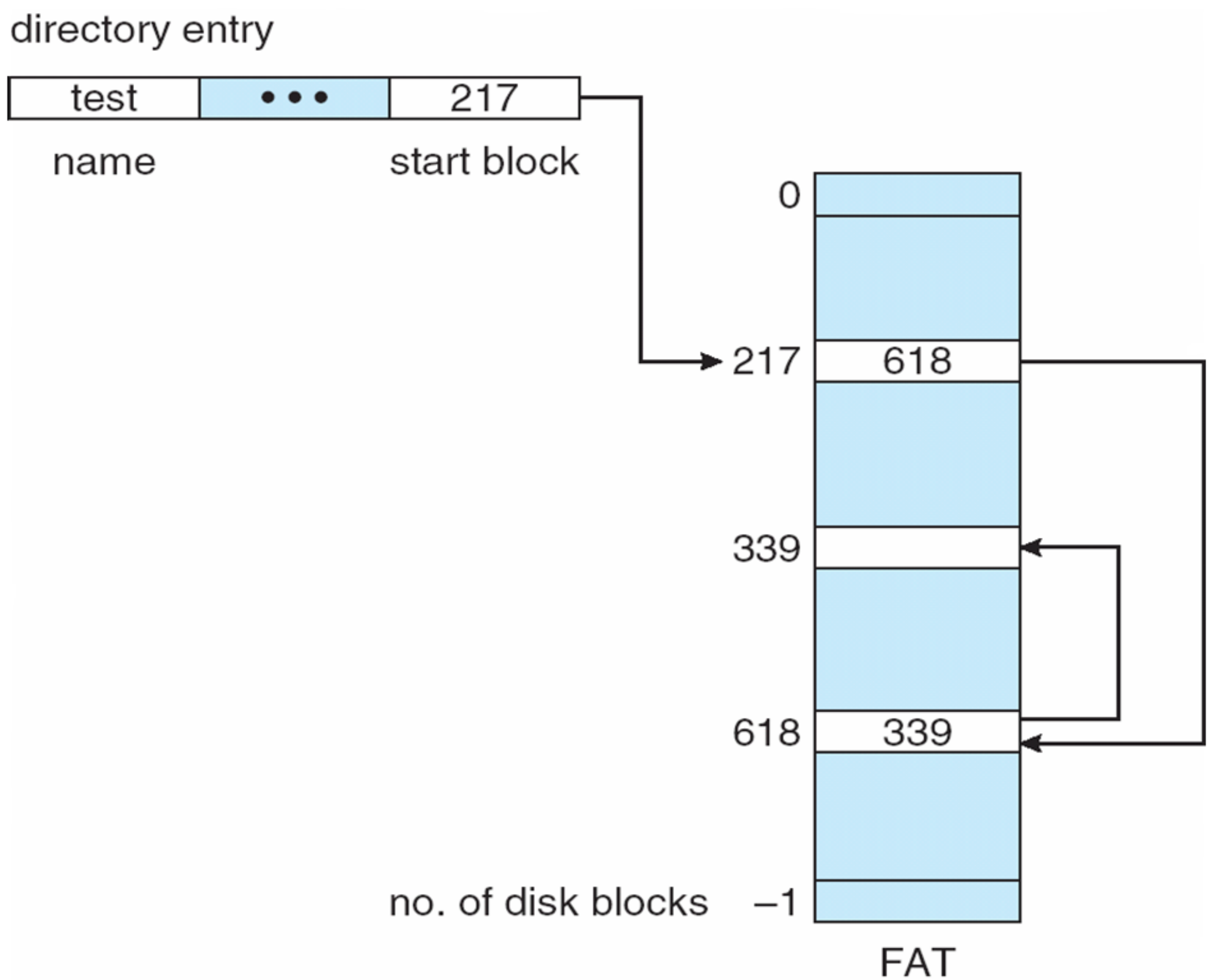
FAT example


directory entry
test
• • •
217
name
start block
0
217
618
339
618
339
no. of disk blocks
–1
FAT

Pros and cons

- Pros
  - Fast random access. Only search cached FAT
- Cons
  - Large storage overhead for FAT table
  - Potentially slow sequential access

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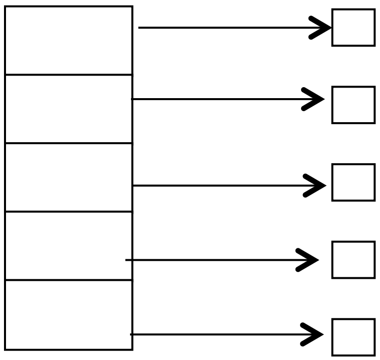
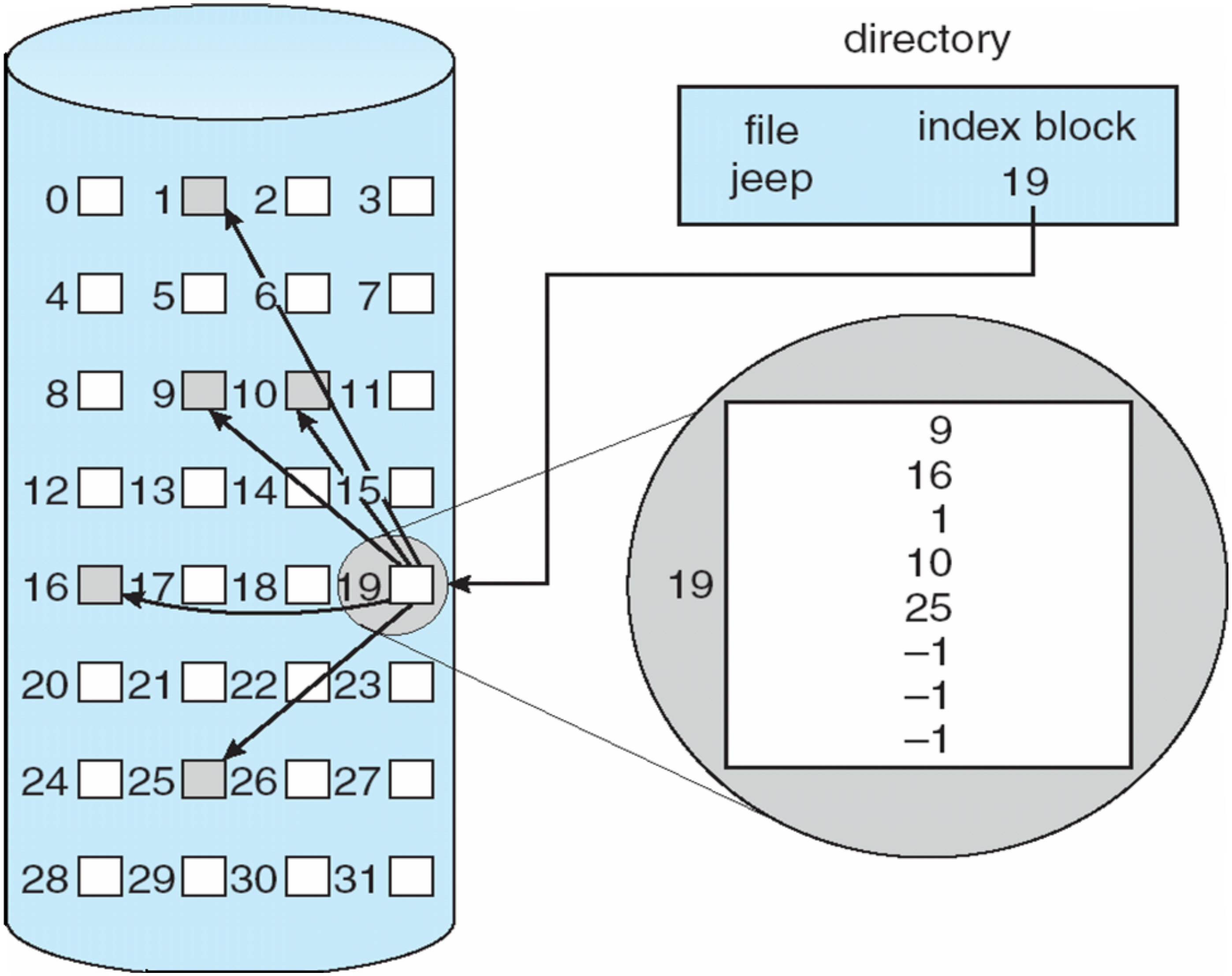
Indexed allocation

- File has array of pointers (index) to block
  - Allocate block pointers contiguously in metadata
    - Must set max length when file created
    - Allocate pointers at creation, allocate blocks on demand
    - Cons: fixed size, same overhead as linked allocation
  - Maintain multiple lists of block pointers
    - Last entry points to next block of pointers
    - Cons: may need to access a large number of pointer blocks

block pointers



Indexed allocation example



Pros and cons

- Pros
  - Easy to implement
  - No external fragmentation
  - Files can be easily grown with the limit of the array size
  - Fast random access. Use index

- Cons
  - Large storage overhead for the index
  - Sequential access may be slow.
    - Must allocate contiguous block for fast access

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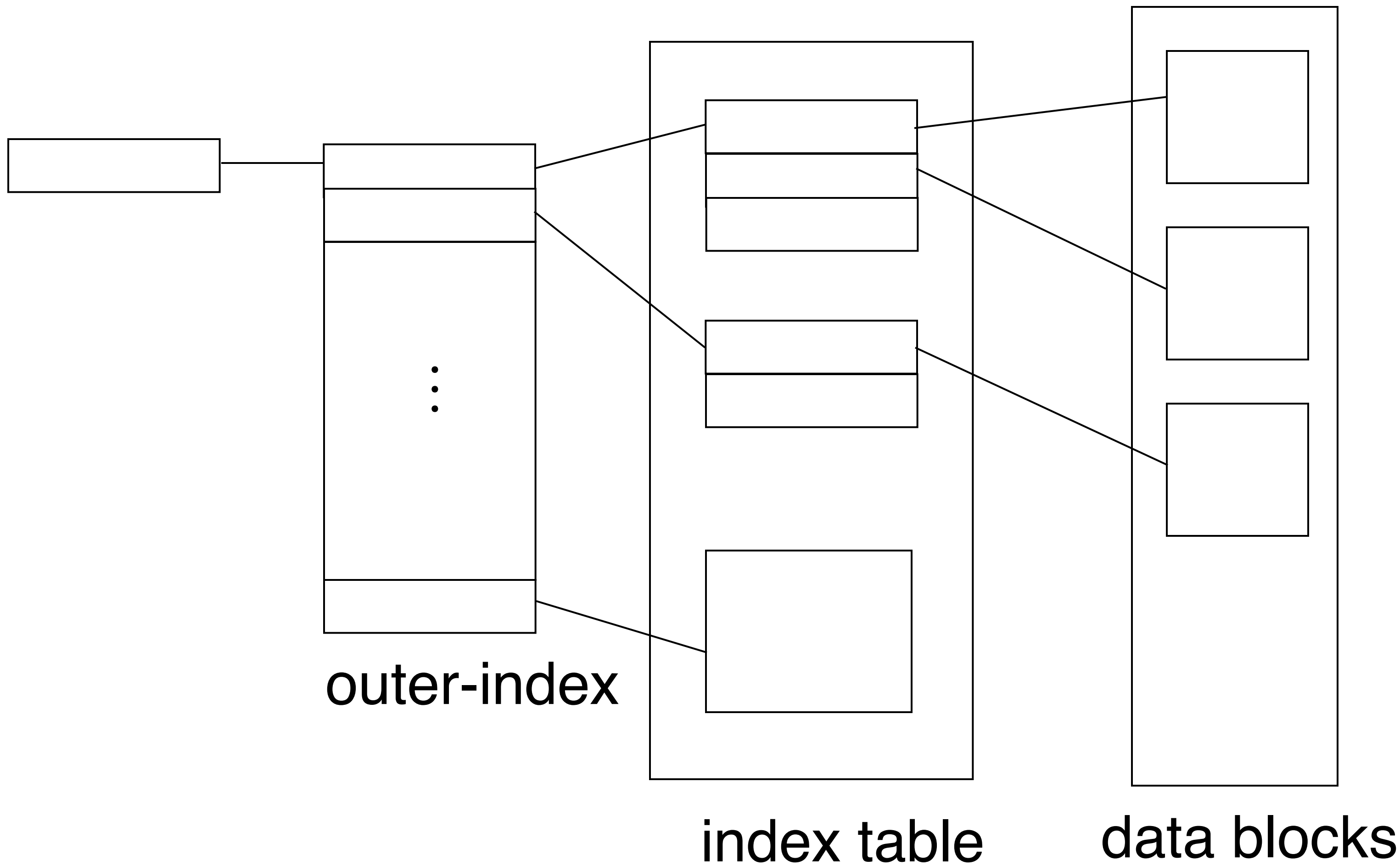
Multi-level indexed files

- Block index has multiple levels



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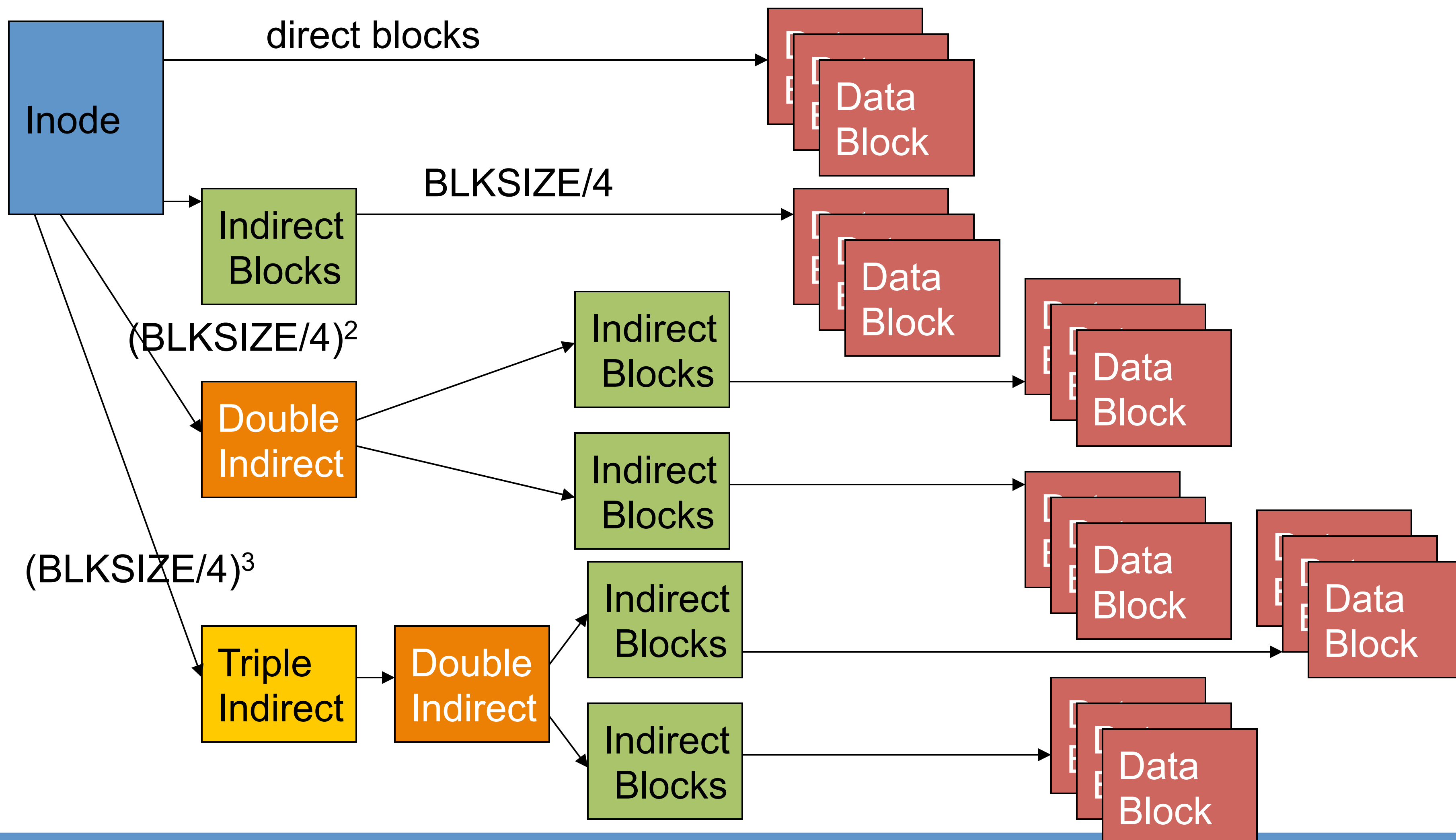
Multi-level indexed allocation (UNIX FFS, and Linux ext2/ext3)



Pros and cons

- Pros
  - No external fragmentation
  - Files can be easily grown with much larger limit compared to one-level index
  - Fast random access. Use index

- Cons
  - Large space overhead (index)
  - Sequential access may be slow.
    - Must allocate contiguous block for fast access
  - Implementation can be complex

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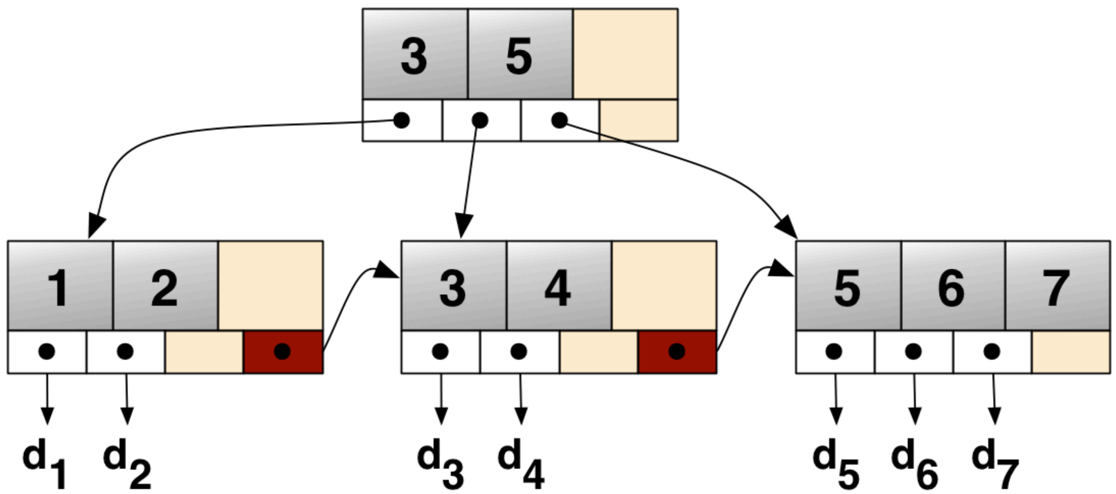
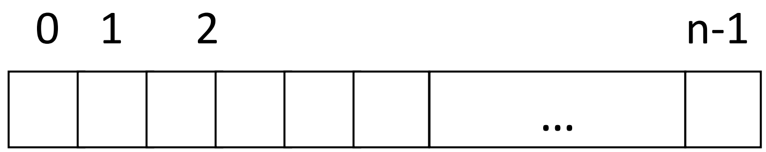
Advanced Data Structures

- Combine Indexes with extents/multiple cluster sizes
- More sophisticated data stuctures
- B+ Trees
  - Used by many high perf filesystems for directories and/or data
  - E.g., XFS, ReiserFS, ext4, MSFT NTFS and ReFS, IBM JFS, brtfs
  - Can support very large files (including sparse files)
  - Can give very good performance (minimize disk seeks to find block)

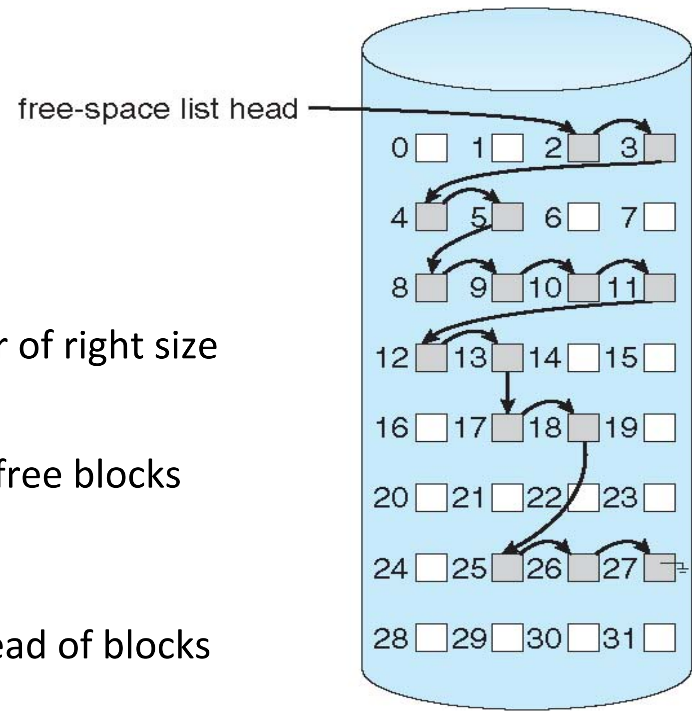


Free Space Management

- File system maintains **free-space list** to track available blocks/clusters
- **Free bitmap** stored in the superblock



$$\text{bit}[i] = \begin{cases} 1 \Rightarrow \text{block}[i] \text{ free} \\ 0 \Rightarrow \text{block}[i] \text{ occupied} \end{cases}$$



- Linked free list in free blocks
  - Pros: space efficient
  - Cons: requires many disk reads to find free cluster of right size
- Grouping
  - Use a free index-block containing n-1 pointers to free blocks and a pointer to the next free index-block
- Counting
  - Free list of variable sized contiguous clusters instead of blocks
  - Reduces number of free list entries