Bucknell UNIVERSITY

File Systems: Interface and Implementation

CSCI 315 Operating Systems Design

Department of Computer Science

Notice: The slides for this lecture have been largely based on those from an earlier edition of the course text *Operating Systems Concepts, 9th ed.*, by Silberschatz, Galvin, and Gagne. Many, if not all, the illustrations contained in this presentation come from this source.

File System Topics

- File Concept
- Access Methods
- Directory Structure
- File System Mounting
- File Sharing
- Protection

File Concept

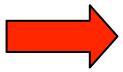
- A file is a named collection of related information recorded on secondary storage.
- **“Contiguous” logical** address space.
- File types:
  - Data:
    - numeric.
    - character.
    - binary.
  - Program (executable).

File Structure

- None: just a sequence of words or bytes.
- Simple **record** structure:
  - Lines,
  - Fixed length,
  - Variable length.
- Complex Structures:
  - Formatted document,
  - Relocatable load file.
- Can simulate last two with first method by inserting appropriate control characters.
- Who decides:
  - Operating system,
  - Program.

File Attributes

- **Name** – only information kept in human-readable form.
- **Type** – needed for systems that support different types.
- **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.



Information about files is kept in the directory structure, which **resides on the disk**.

File Types: Name and Extension

file type	usual extension	function
executable	exe, com, bin or none	ready-to-run machine-language program
object	obj, o	compiled, machine language, not linked
source code	c, cc, java, pas, asm, a	source code in various languages
batch	bat, sh	commands to the command interpreter
text	txt, doc	textual data, documents
word processor	wp, tex, rtf, doc	various word-processor formats
library	lib, a, so, dll	libraries of routines for programmers
print or view	ps, pdf, jpg	ASCII or binary file in a format for printing or viewing
archive	arc, zip, tar	related files grouped into one file, sometimes compressed, for archiving or storage
multimedia	mpeg, mov, rm, mp3, avi	binary file containing audio or A/V information

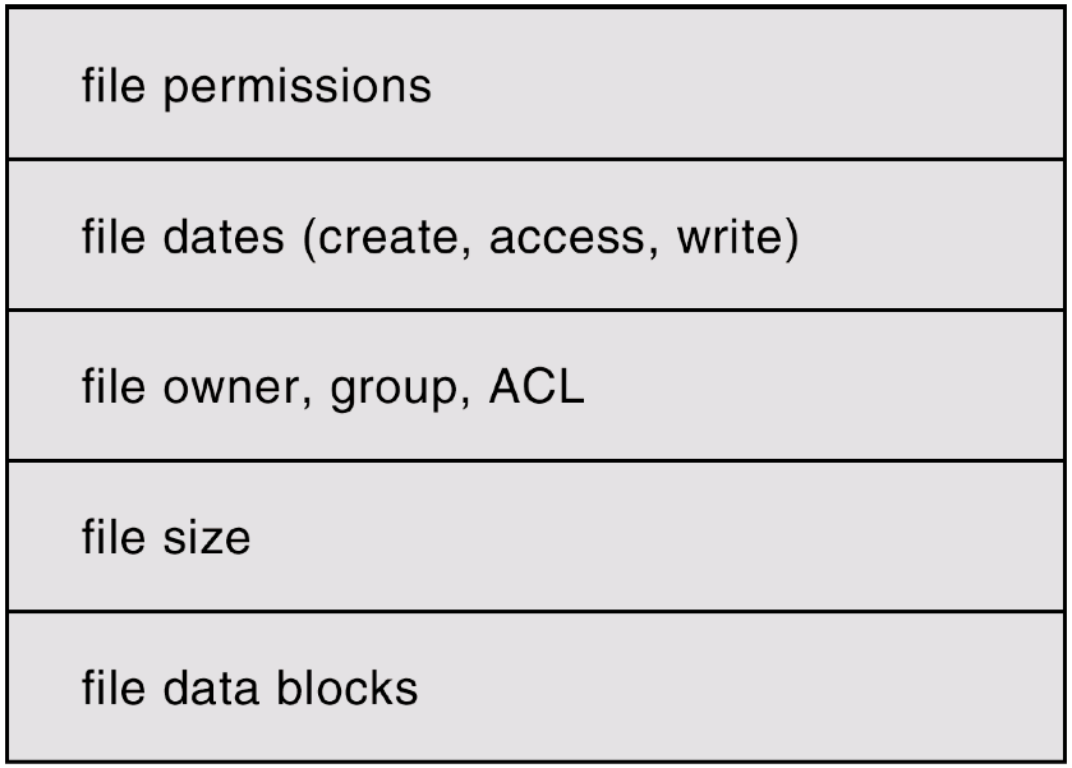
File Types in Unix

- In Unix, file names do not have extensions.
- The *type* of each file is determined by the contents of the file.
- Well known file types are associated *magic numbers* (byte sequences) contained inside the file. See file `/usr/share/file/magic`.
- You can inspect the binary content of any file with command `xxd(1)`. and look at the first few bytes. You are better off using the command `file(1)` to determine the type of a file, though. Read its manual page.

File Types in Unix

- Well known file types are associated *magic numbers* (byte sequences) contained inside the file. Here are a few examples:
  - `JPG: ffd8`
  - `PNG: 8950 4e47 0d0a 1a0a`
  - `PDF: 2550 4446`
  - `ELF: 7F45 4C46` (binary executable)
  - …

File Control Block



File Sharing

- Sharing of files on multi-user systems is desirable.
- Sharing may be done through a *protection* scheme.
- On distributed systems, files may be shared across a network.
- Network File System (NFS) is a common distributed file-sharing method.

Users and Passwords

- In Unix, globally readable file `/etc/passwd` maps each user's name to an integer number, to a home directory, and to a shell.

- `/etc/shadow` maps each user to a an encrypted (actually, *hashed*) password. Not readable to prevent "password guessing" attacks.

Groups

- In Unix, `/etc/group` maps each group's name to an integer number and to a collection of users

```
chgrp game mine
```

group

file

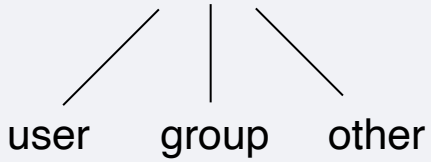
Access Control: Protection Bits

- Mode of access: **read (`r`), write (`w`), execute (`x`)**
- Three classes of access

		`rwx`	
a) **owner access** user	7 ⇒	1 1 1	(octal ⇒ binary)
		`rwx`	
b) **group access**	6 ⇒	1 1 0	
		`rwx`	
c) **public access** other	1 ⇒	0 0 1	

- For a particular file (say *game*) or subdirectory, define an appropriate access.

`chmod 761 mine`



`chmod u+rwx mine`

Access Control (Protection)

- **File owner/creator should be able to control:**
  - what can be done,
  - by whom.

Discretionary Access Control (DAC)

- **Types of access:**
  - Read,
  - Write,
  - Execute,
  - Append,
  - Delete,
  - List.

Users decide **what** to share and **with whom** to share (no policy): flexible.

Users can make bad decisions and share **with the wrong people what they shouldn't be sharing.**

Access Control (Protection)

- **Mandatory Access Control (MAC):**
  - **System policy:** files tied to access levels = (public, restricted, confidential, classified, top-secret).
  - Process also has access level: can read from and write to all files at same level, can only read from files below, can only write to files above.

A policy that guarantees information access rights **for each user** based on their needs is determined in advance and strictly enforced by the system.

Users are locked into the policy and changes in access rights requires a revision of the policy and the action of an administrator.

Access Control (Protection)

- **Role-Based Access Control (RBAC):**
  - **System policy:** defines **"roles"** (generalization of the Unix idea of groups).
  - Roles are associated with access rules to sets of files and devices.
  - A process can change roles (in a pre-defined set of possibilities) during execution.

A policy determines information access rights **for each role** based on needs is determined in advance and is strictly enforced by the system. Users can be granted access to multiple roles. The assignment of users to roles can be changed more easily.

The a change in the rights for each roles requires a change in the policy and actions carried out by an administrator

File Operations

- **Create**.
- **Write**.
- **Read**.
- **Random access**. `[lseek(2)]`
- **Delete**.
- **Append**.
- **Truncate** (reset size to 0, keep current attributes).
- **Open(F_i)** – search the directory structure on disk for entry F_i, and move the content of entry to memory.
- **Close (F_i)** – move the content of entry F_i in memory to directory structure on disk.

Open Files

Several pieces of data are needed to manage open files:

- **Open-file table**: tracks open files
- **File pointer:** pointer to last read/write location, per process that has the file open
- **File-open count:** counter of number of times a file is open – to allow removal of data from open-file table when last processes closes it
- **Disk location of the file:** cache of data access information
- **Access rights:** per-process access mode information

Open File Locking

- Provided by some operating systems and file systems
  - Similar to reader-writer locks
  - **Shared lock** similar to reader lock – several processes can acquire concurrently
  - **Exclusive lock** similar to writer lock
- Mediates access to a file
- Mandatory or advisory:
  - **Mandatory** – access is denied depending on locks held and requested
  - **Advisory** – processes can find status of locks and decide what to do

Access Methods

- **Sequential Access**

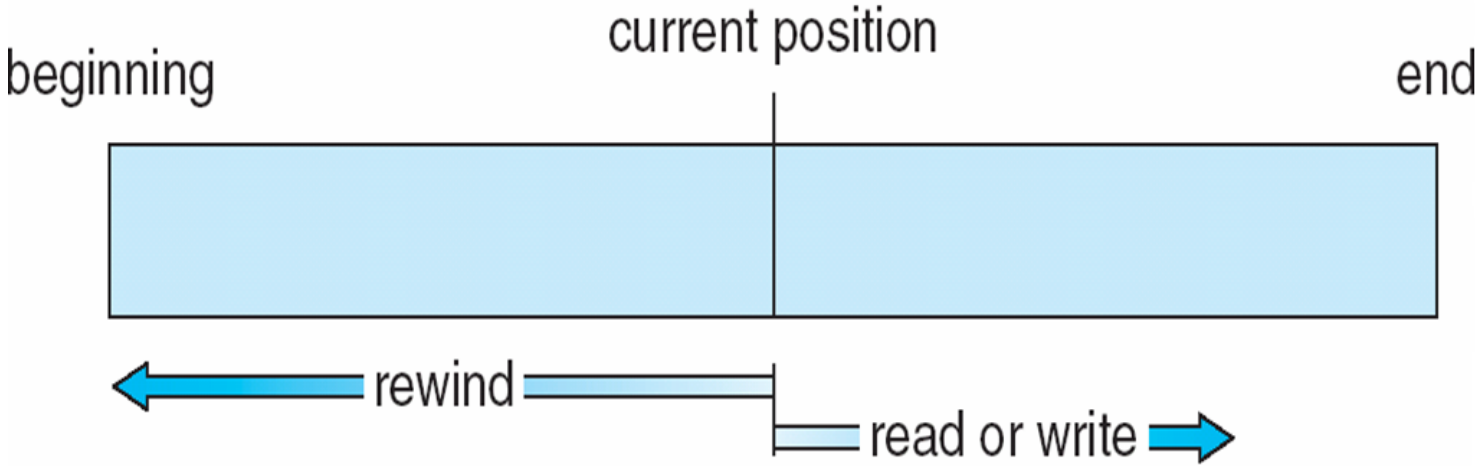
  read next
  write next
  reset
  no *read after last write*
  (rewrite)

- **Direct Access**

  read n
  write n
  position to n
  read next
  write next
  rewrite n

n = relative block number

Sequential-access File



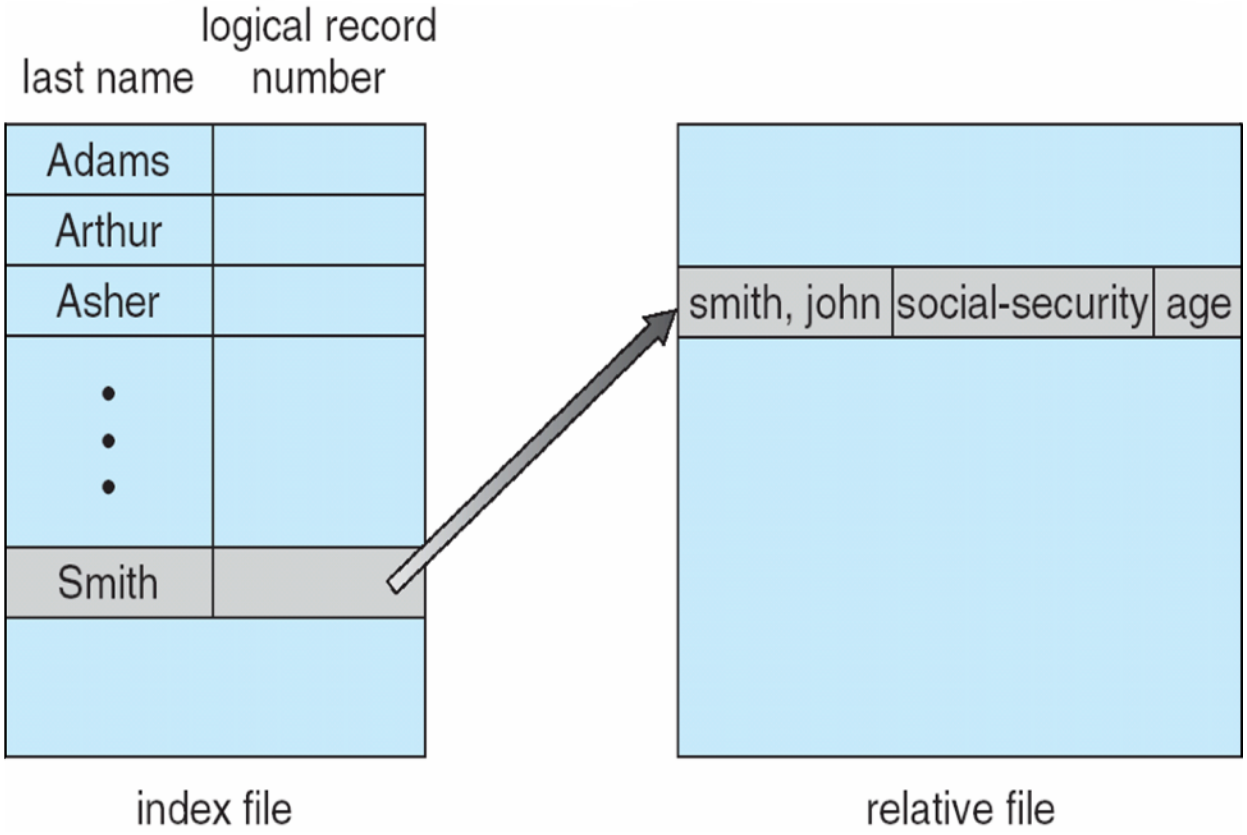
Simulation of Sequential Access on a Direct-access File

sequential access	implementation for direct access
reset	*cp* = 0;
read next	*read cp*; *cp* = *cp* + 1;
write next	*write cp*; *cp* = *cp* + 1;

Other Access Methods

- Can be built on top of base methods
- Generally involve creation of an index for the file
- Keep index in memory for fast determination of location of data to be operated on (consider UPC code plus record of data about that item)
- If too large, index (in memory) of the index (on disk)
- IBM indexed sequential-access method (ISAM)
- Small master index, points to disk blocks of secondary index
- File kept sorted on a defined key
- All done by the OS
- VMS operating system provides index and relative files as another example (see next slide)

Index and Relative Files



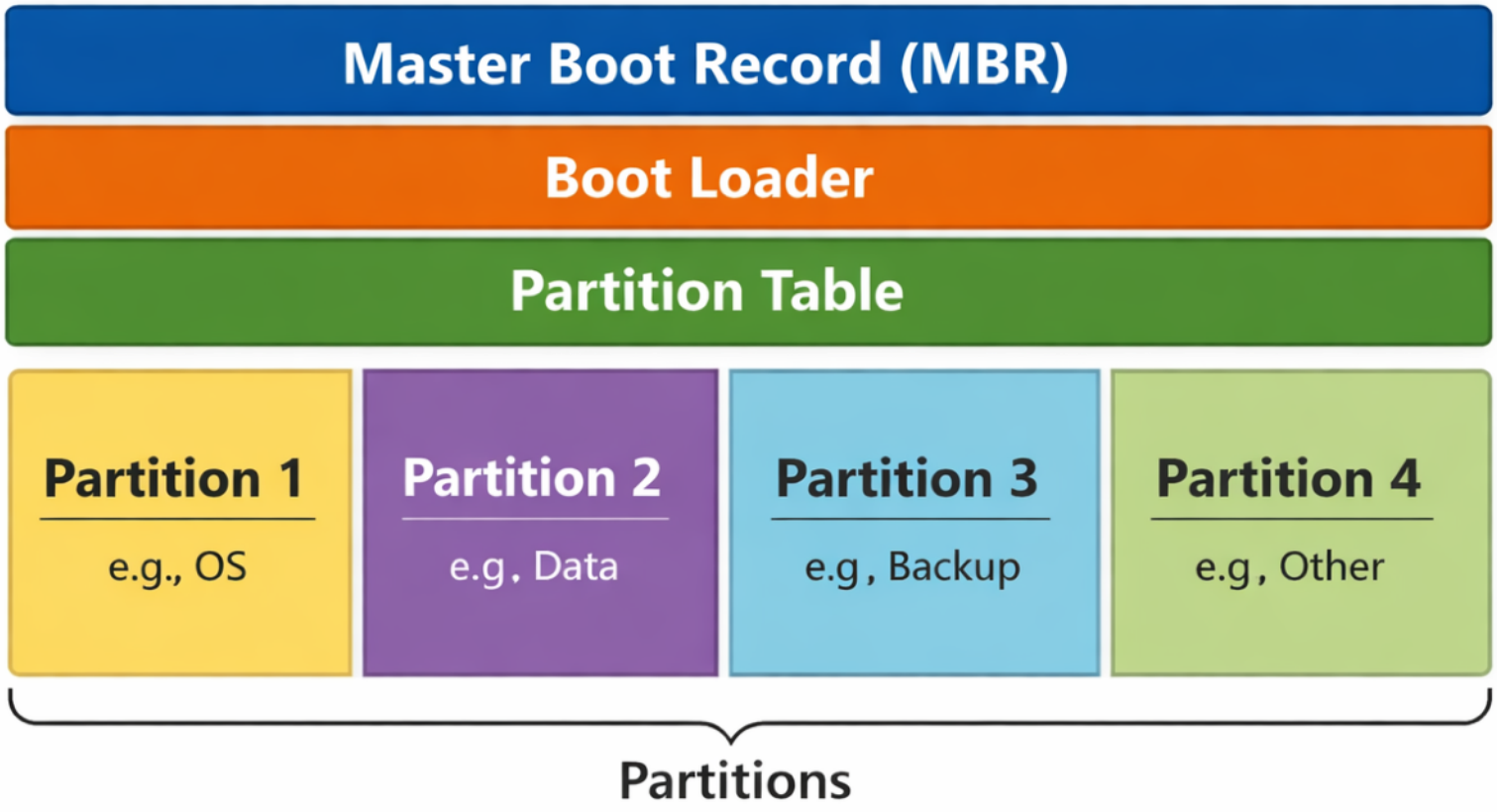
Disk Structure

- Disk can be subdivided into ***partitions*** which are logical divisions inside a physical drive
- Partitions are also known as minidisks or slices
- A disk or partition can be used *raw* (without a file system) or *formatted with a file system*
- Once a partition is formatted with a file system, it is seen a *volume*
- As well as *general-purpose file systems* there are many *special-purpose file systems*, frequently all within the same operating system or computer
- Disks or partitions can be protected against failure by *Redundant Array of Independent Disks* (RAID)

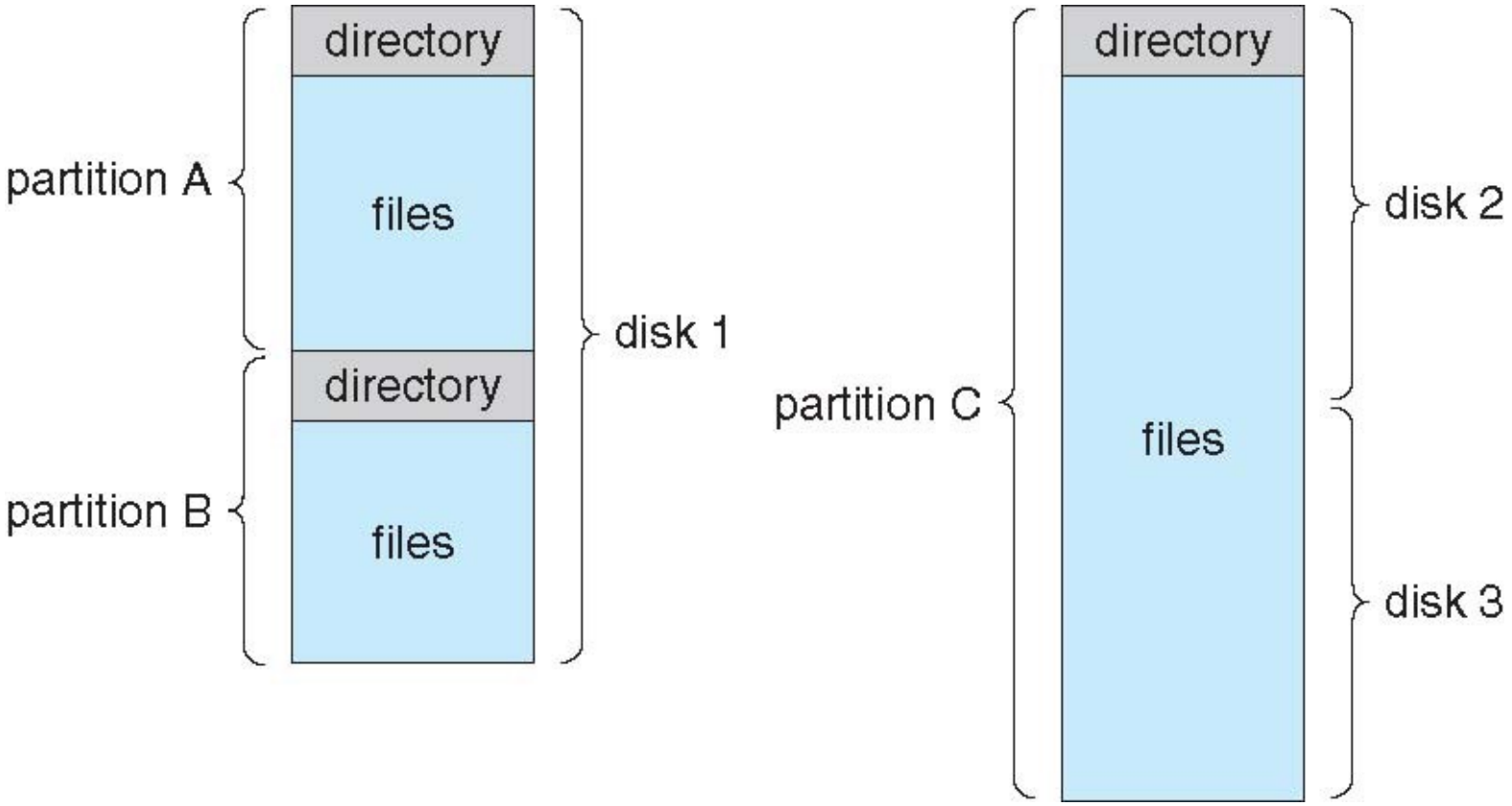
Why should one partition a drive?

- To keep a disk organized systematically
- To create **different compartments** for multiple operating systems
- To create **different compartments** for *data* of different kinds
- To create **different compartments** for *data* that needs to be backed up
- To create **different compartments** for the sake of reliability: if one gets corrupted, others may stay intact

Partitioning a Disk



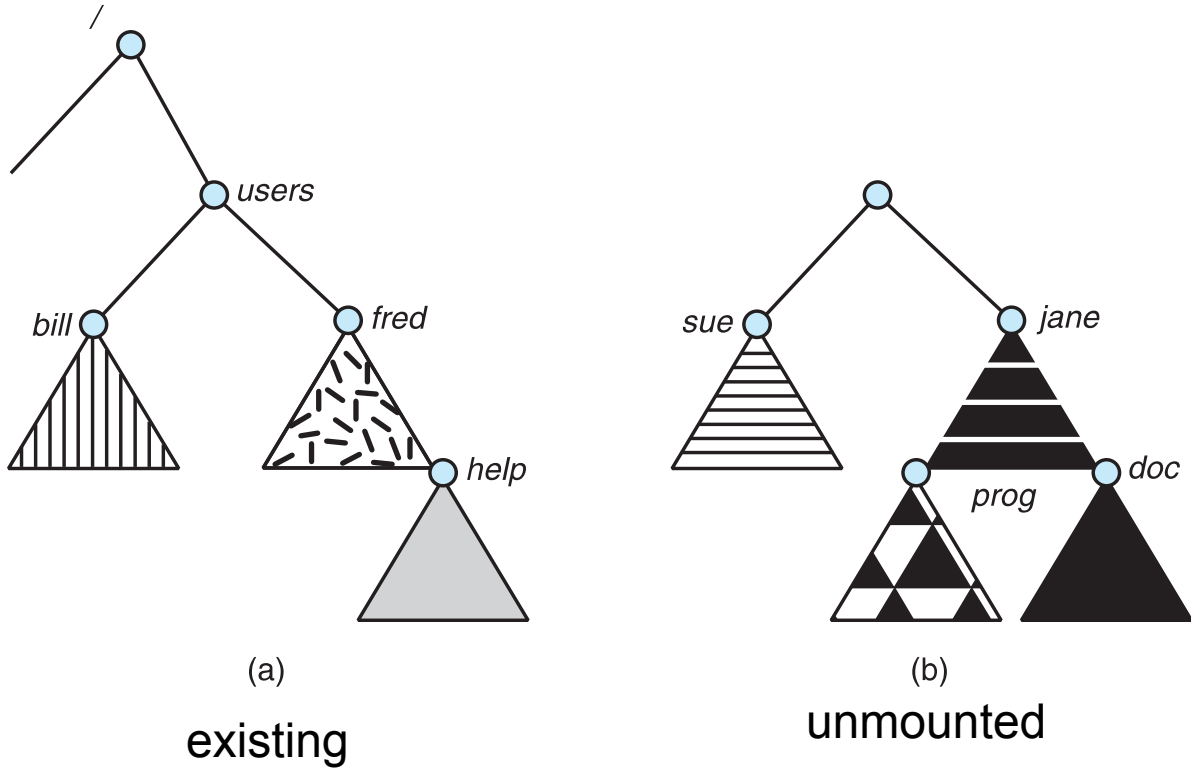
Partitions and Directories
(File system organization)



Practical information for those interested in Linux: Partitioning Recommendations

File System Mounting

- A file system (partition) must be `mounted` before it can be accessed. Mounting allows one to attach the file system on one device to the file system on another device.
- A unmounted file system needs to be attached to a mount point before it can be accessed.



Operations on Directories

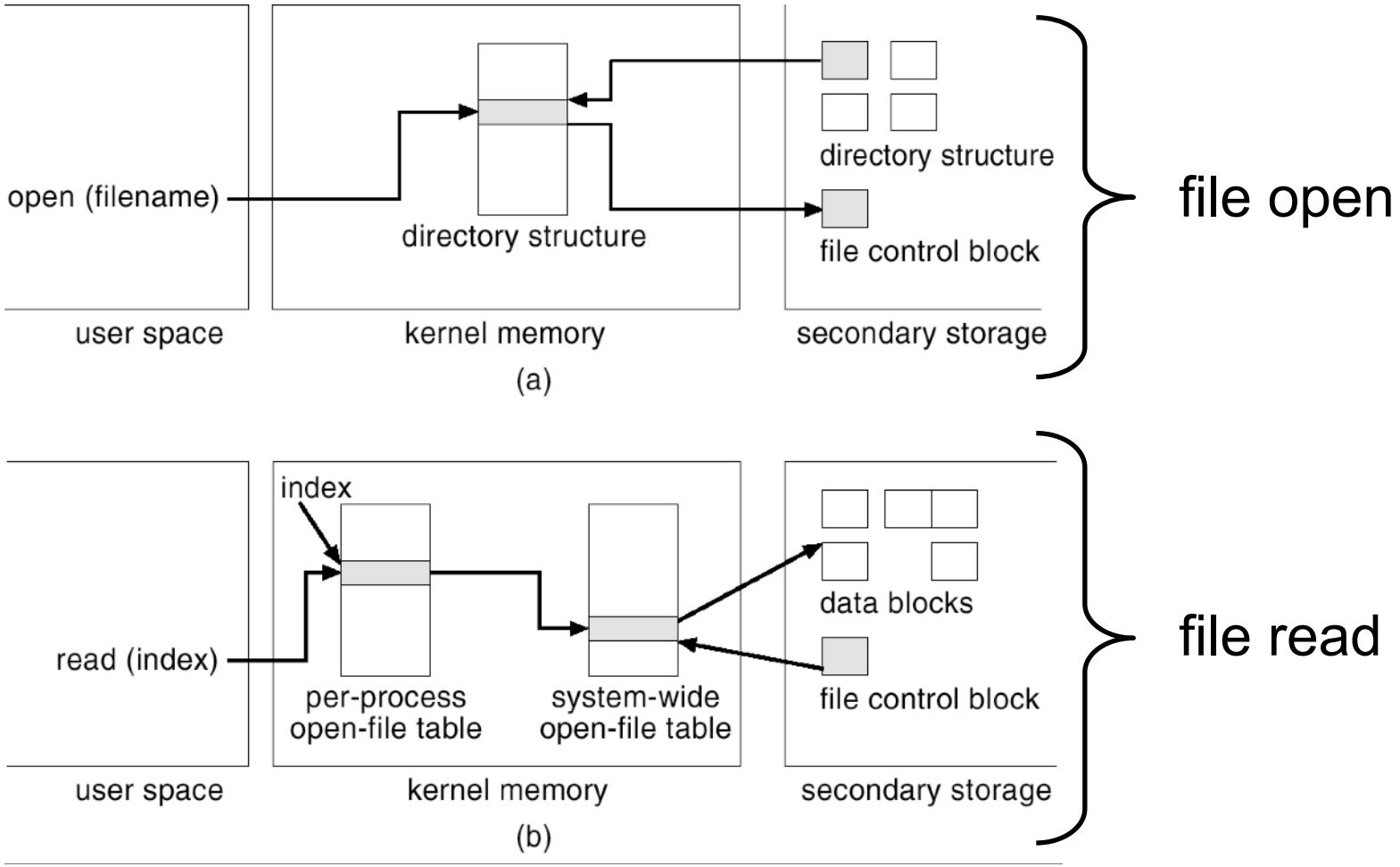
- Create a directory [**mkdir(1), mkdir(2)**]
- Rename a directory [**mv(1), rename(2)**]
- Delete a directory [**rmdir(1), remove(3)**]
- List the contents of a directory [**ls(1)**]
- Create a link to a directory [**ln(1), symlink(2)**]
- Remove a link to a directory or file [**unlink(2)**]
- …

Directory Implementation

The directory is a **symbol table** that maps file names to pointers that lead to an FCB or to the blocks comprising a file (of course, this depends on implementation)

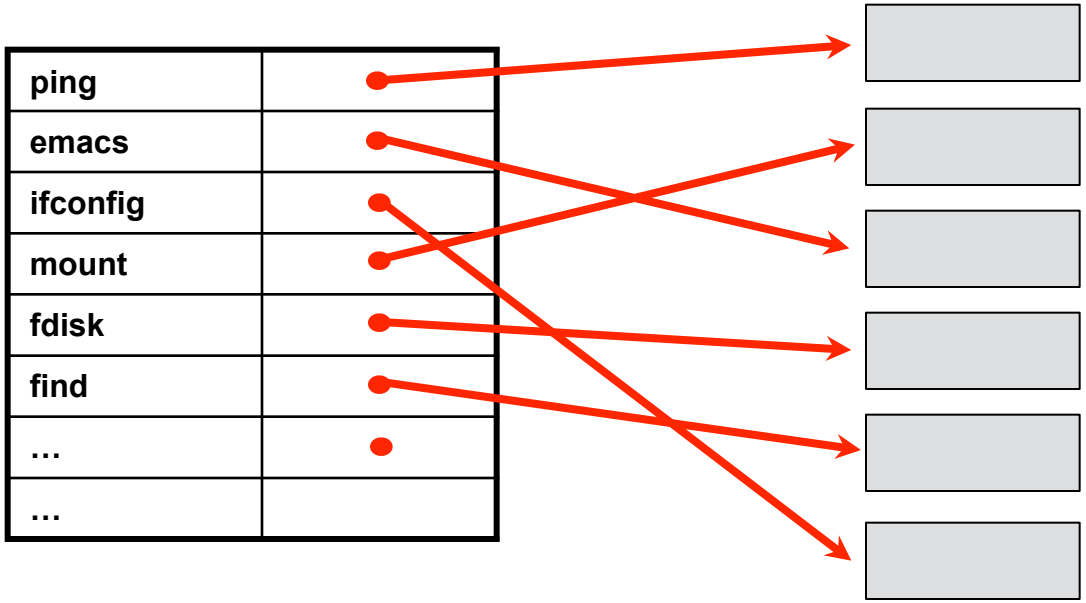
- **Linear list** of file names with pointer to the data blocks:
  - simple to program, but…
  - time-consuming to execute.
- **Hash Table:**
  - decreases directory search time,
  - *collisions* – situations where two file names hash to the same location,
  - fixed size.

In-Memory File System Structures



Directory Structure

Directory: a symbol table that translates file names into directory entries.



Both the directory structure and the files reside on disk.
Backups of these two structures are kept on tapes.

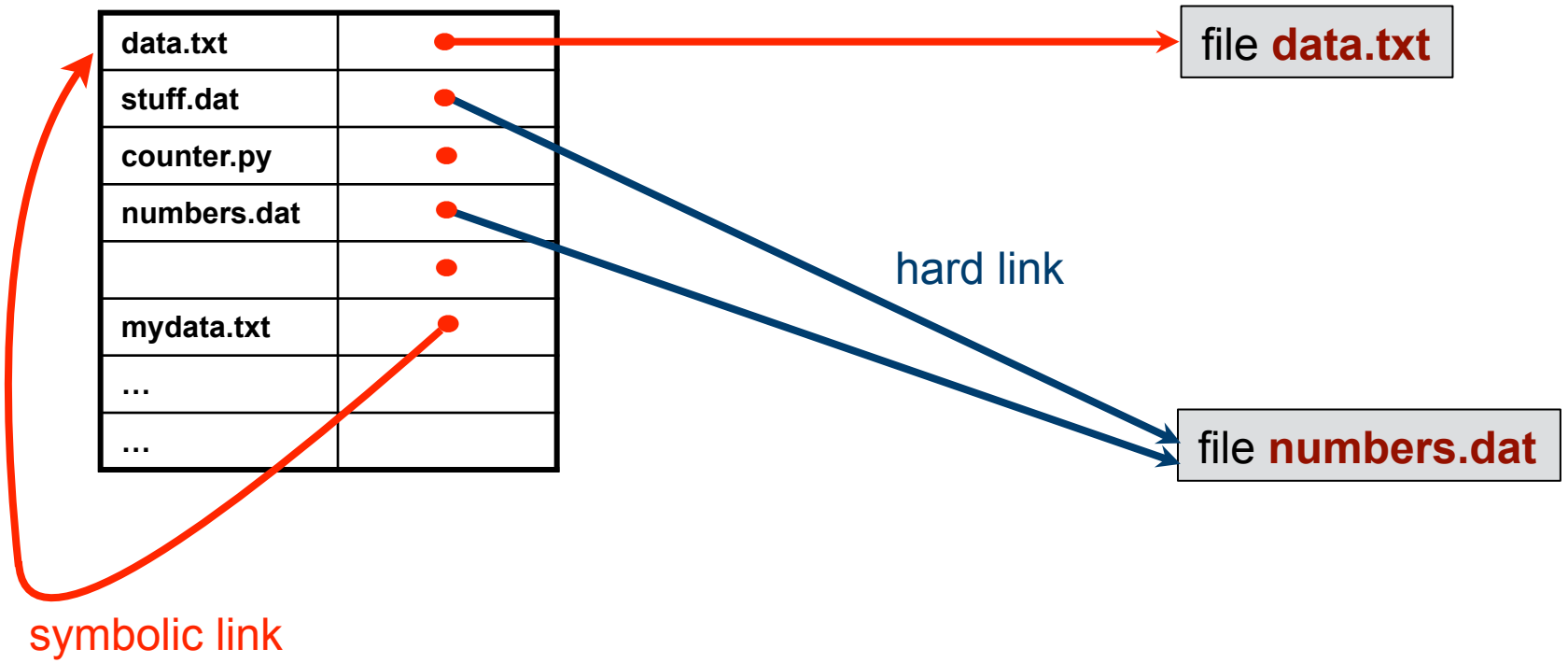
Links

In Unix, the command `ln` allows the user to create symbolic and hard links.

- `symbolic link` - a directory entry that points to another directory entry.

- `hard link` - “another” directory entry that points to a file object that already appeared in the directory.

Links


data.txt
stuff.dat
counter.py
numbers.dat
mydata.txt
...
...
file data.txt
hard link
file numbers.dat
symbolic link

RTFMP Interlude

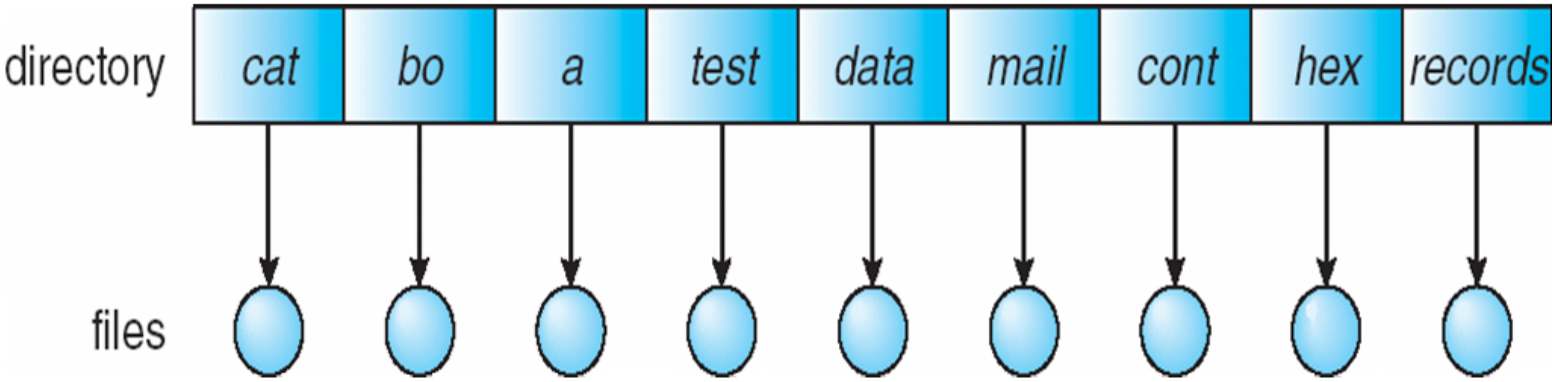
```
LN(1) User Commands

NAME
       ln - make links between files

SYNOPSIS
       ln [OPTION]... [-T] TARGET LINK_NAME   (1st form)

…

       -s, --symbolic
              make symbolic links instead of hard links
```

Goals of Directory Logical Organization

- **Efficiency** – locating a file quickly
- **Naming** – convenient to users
  - Two users can have same name for different files
  - The same file can have several different names
- **Grouping** – logical grouping of files by properties, (e.g., all Java programs, all games, …)

Single-Level Directory

A single directory for all users

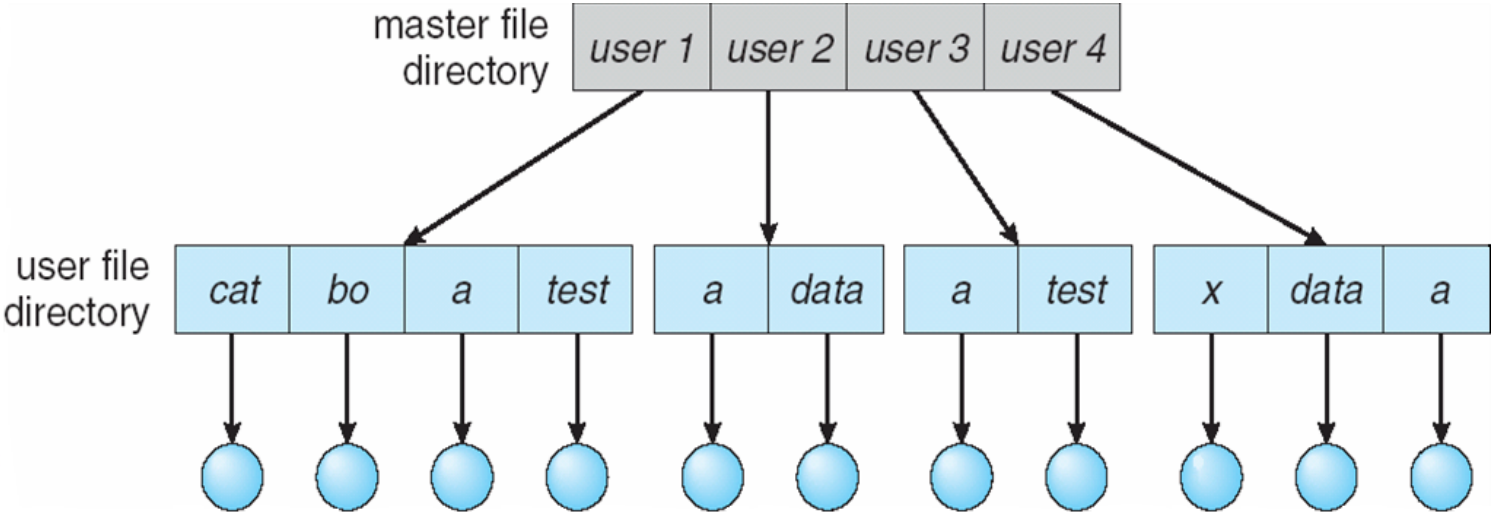


Major drawbacks:

- Naming problem
- Grouping problem

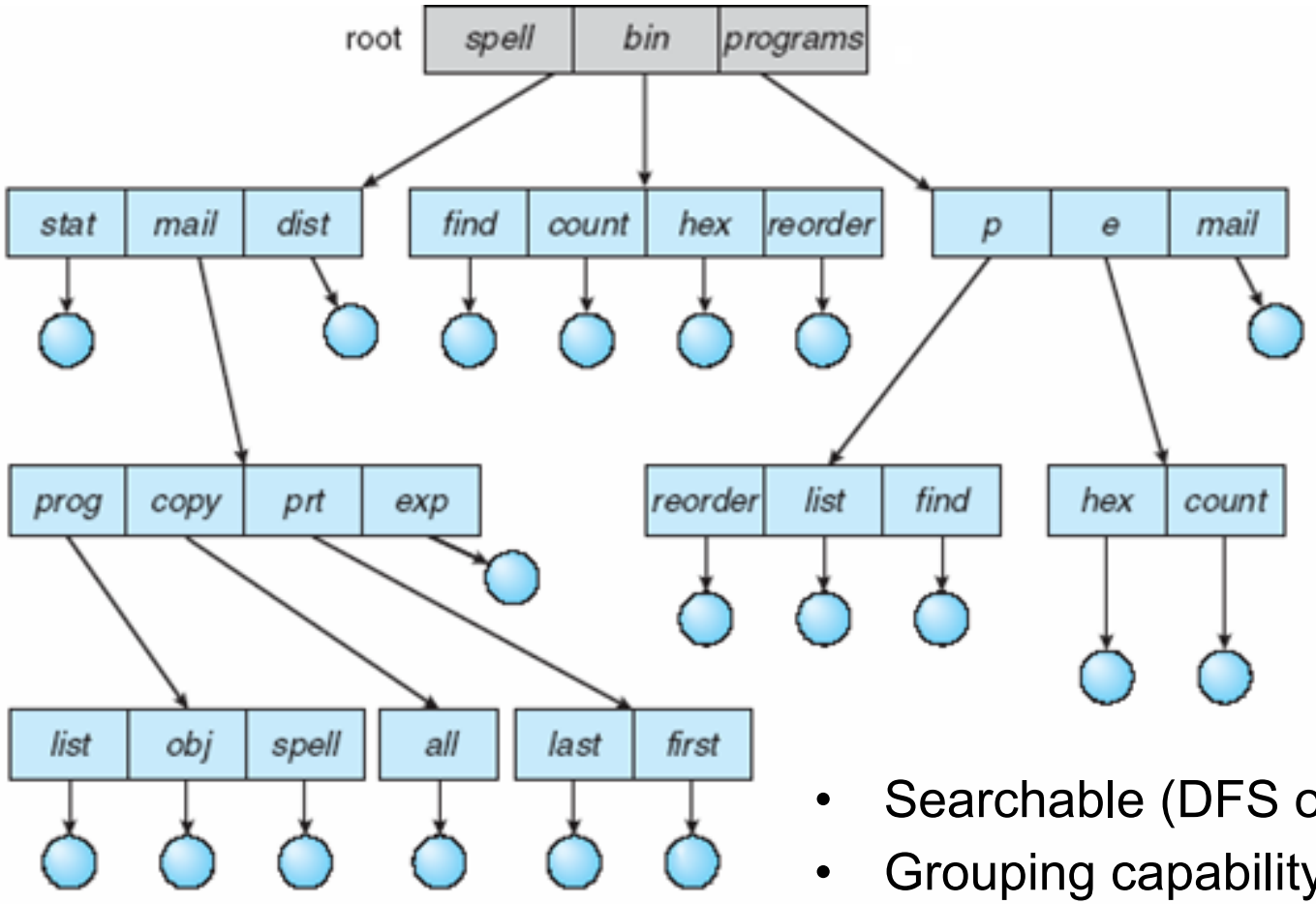
Two-Level Directory

A separate directory for each user



- Path name
- Allows same file name for different users
- Efficient searching
- No grouping capability

Tree-Structured Directories



- Searchable (DFS or BFS)
- Grouping capability
- Must remember current directory

Tree-Structured Directories

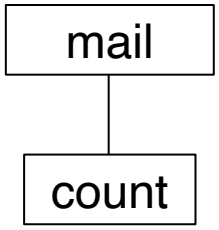
- Introduces the concepts of **absolute** and **relative** path
- Creating a new file is done in current directory by default
- Delete a file

  rm <file-name>
- Creating a new subdirectory is done in current directory

  mkdir <dir-name>

  Example: if in current directory **../mail**

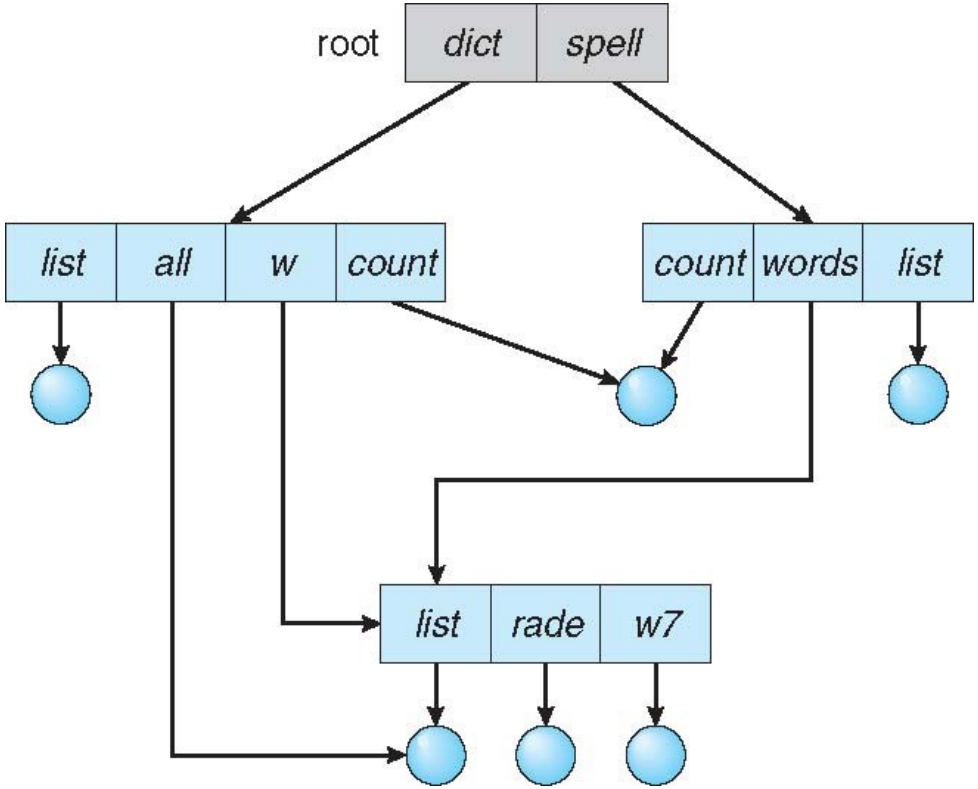
  mkdir count



rm -rf * ⇒ doesn't mean "read all mail really fast"

Acyclic-Graph Directories

Have shared subdirectories and files



link types { soft (symbolic); hard

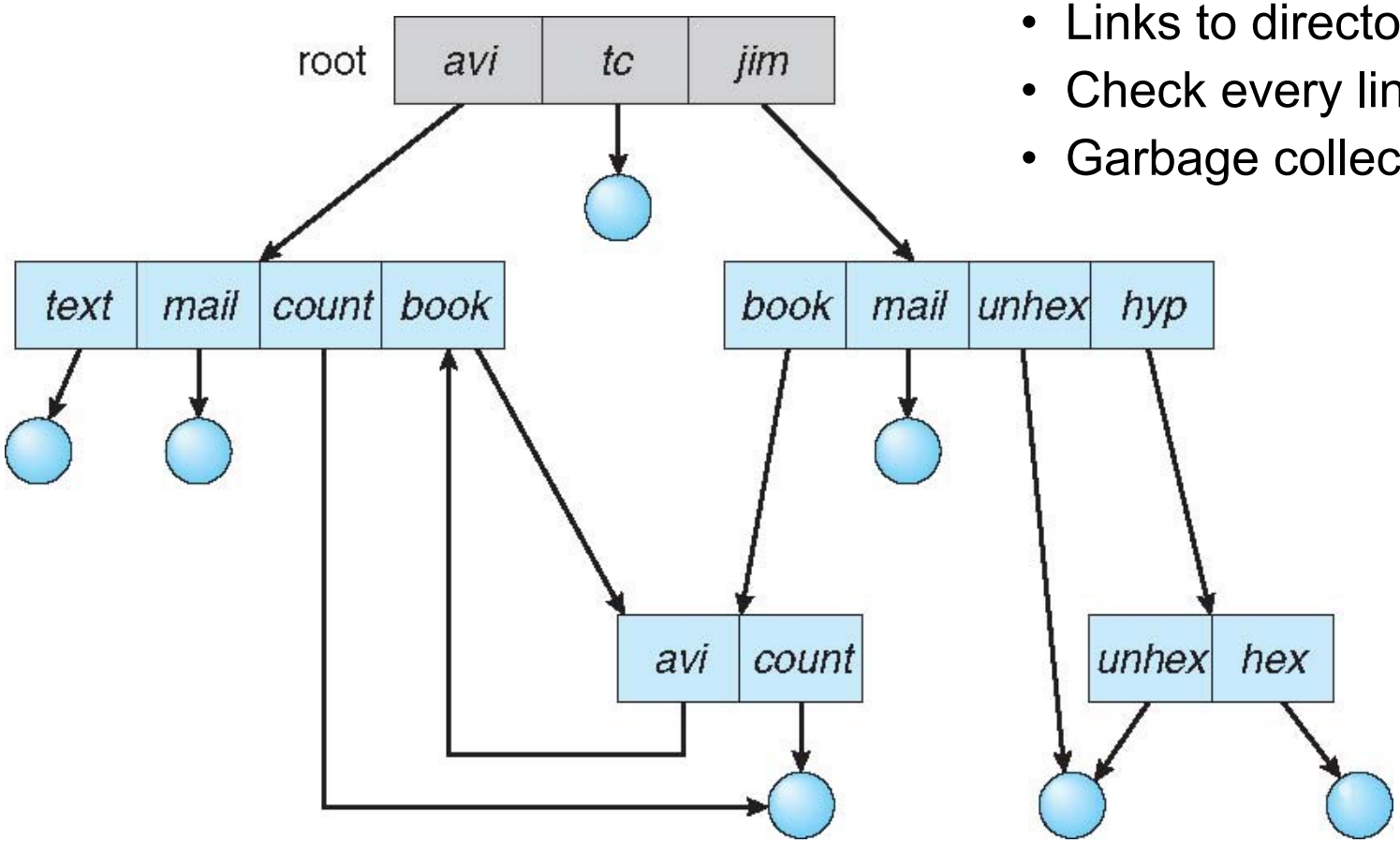
Unix: `ln(1)` (read man page); keep a reference count on each file or directory.

Acyclic-Graph Directories

- Different names (aliasing) for the same file or directory (solution or problem?)
- Must be careful with removals to avoid dangling pointers

  Solutions:
  - Use *backpointers*, so we can delete all pointers when the target is removed
  - Use reference counters

General Graph Directory



How do we avoid cycles?

- Links to files ok
- Links to directories not ok
- Check every link at creation
- Garbage collection

File-System Structure

- File structure:
  - Logical storage unit,
  - Collection of related information
- File system resides on secondary storage (disks)
- File system is organized into layers
- **File control block** – storage structure consisting of information about a file

Disk Allocation Methods

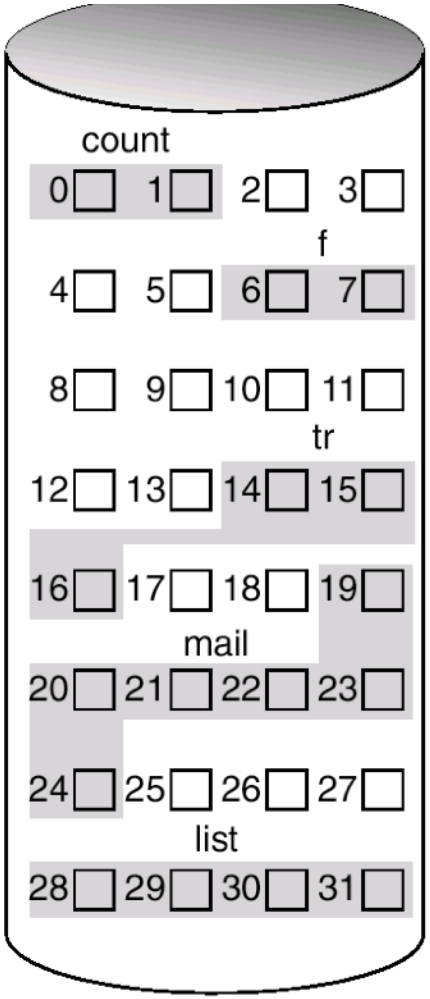
An **allocation method** refers to how disk blocks are allocated for files. We'll discuss three options:

- Contiguous allocation,
- Linked allocation,
- Indexed allocation

Contiguous Allocation

- Each file occupies a set of **contiguous blocks** on the disk
- Simple: only starting location (block #) and length (number of blocks) are required
- Suitable for **sequential** and **random** access
- Wasteful of space: dynamic storage-allocation problem
- Files cannot grow unless more space than necessary is allocated when file is created (clearly this strategy can lead to **internal fragmentation**)

Contiguous Allocation of Disk Space



directory

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

To deal with the dynamic allocation problem (external fragmentation), the system should periodically **compact** the disk.

Compaction may take a long time, during which the system is effectively **down**.

To deal with possibly growing files, one needs to pre-allocate space larger than required at the initial time which leads to **internal fragmentation**.

Does this disk allocation, **in general**, suffer from **internal fragmentation**?
Does this method suffer from **external fragmentation**?

Indexed Allocation

Brings all pointers together into an *index block.*

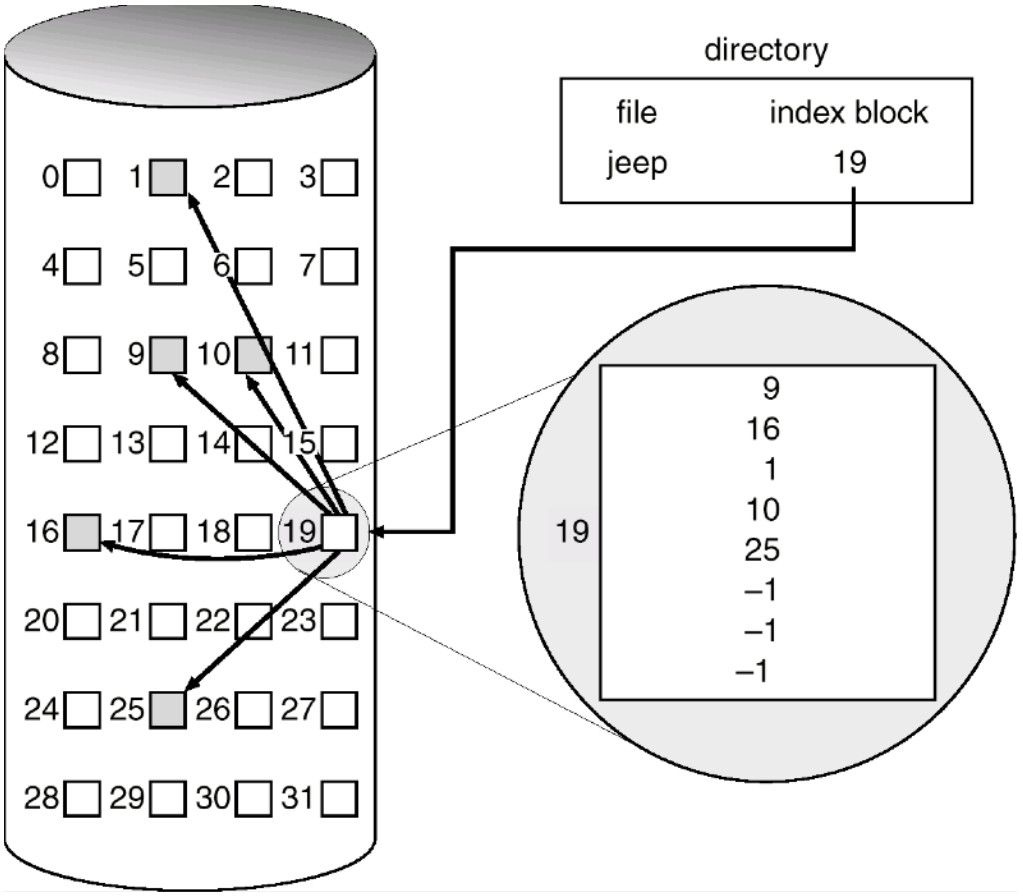
One index block ***per file***.

Random access comes easy.

Dynamic access without external fragmentation, but have overhead of index block.

Wasted space: how large should an index block be to minimize the overhead?

- linked index blocks
- multilevel index
- combined scheme



Linked Allocation

Each file is a linked list of disk blocks.

Simple: need only starting address.

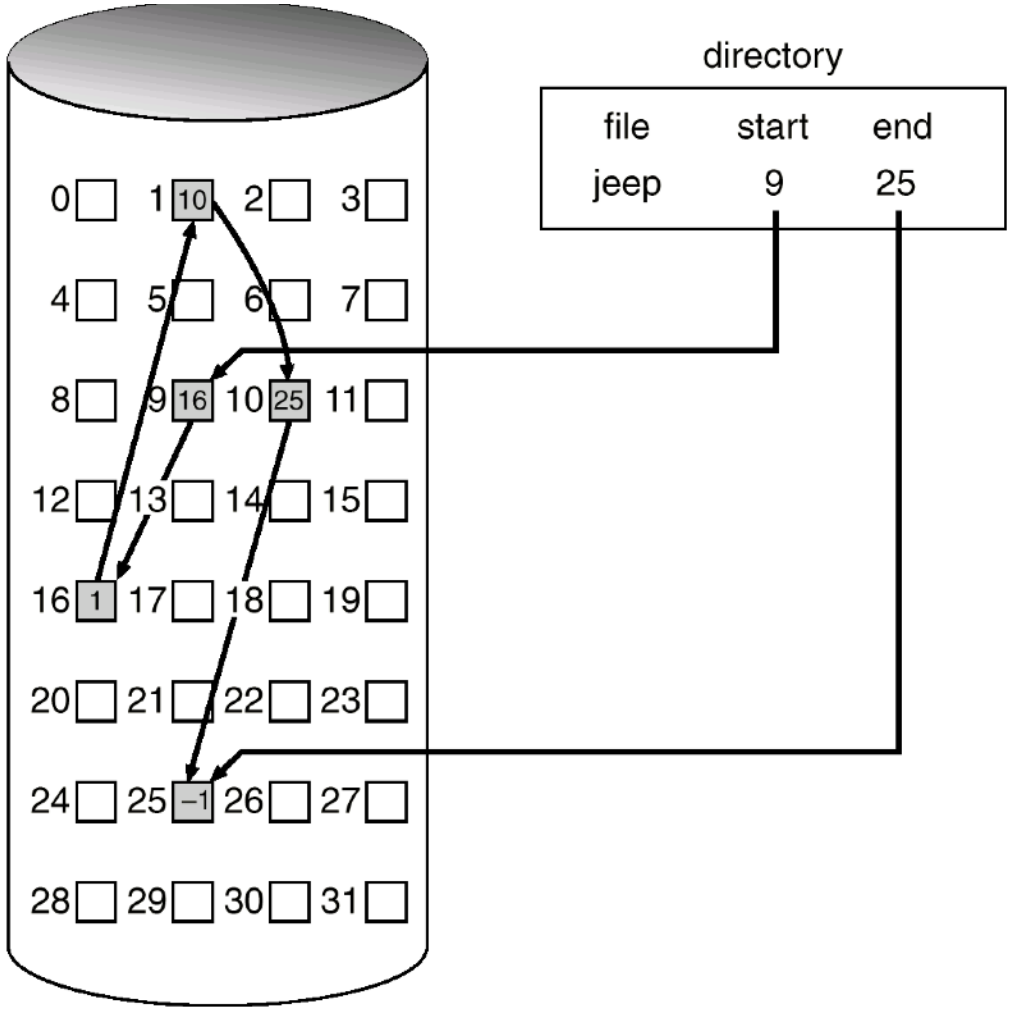
Overhead: each block links to the next.

Space cost to store pointer.

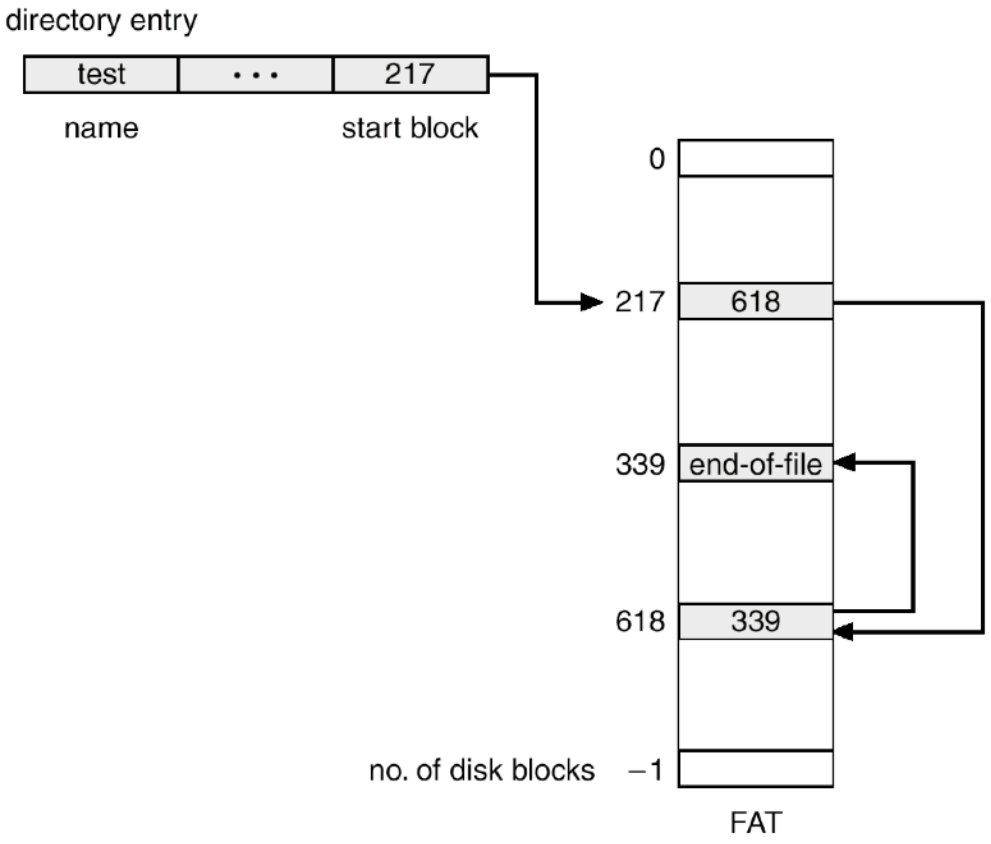
Time cost to read one block to find the next.

Internal fragmentation, but not external.

Sequential access comes naturally, random does not.



File-Allocation Table (FAT)



Simple and efficient: One entry for each block; indexed by block number. The table is implements the list linking the blocks in a file.

Growing a file is easy: find a free block and link it in.

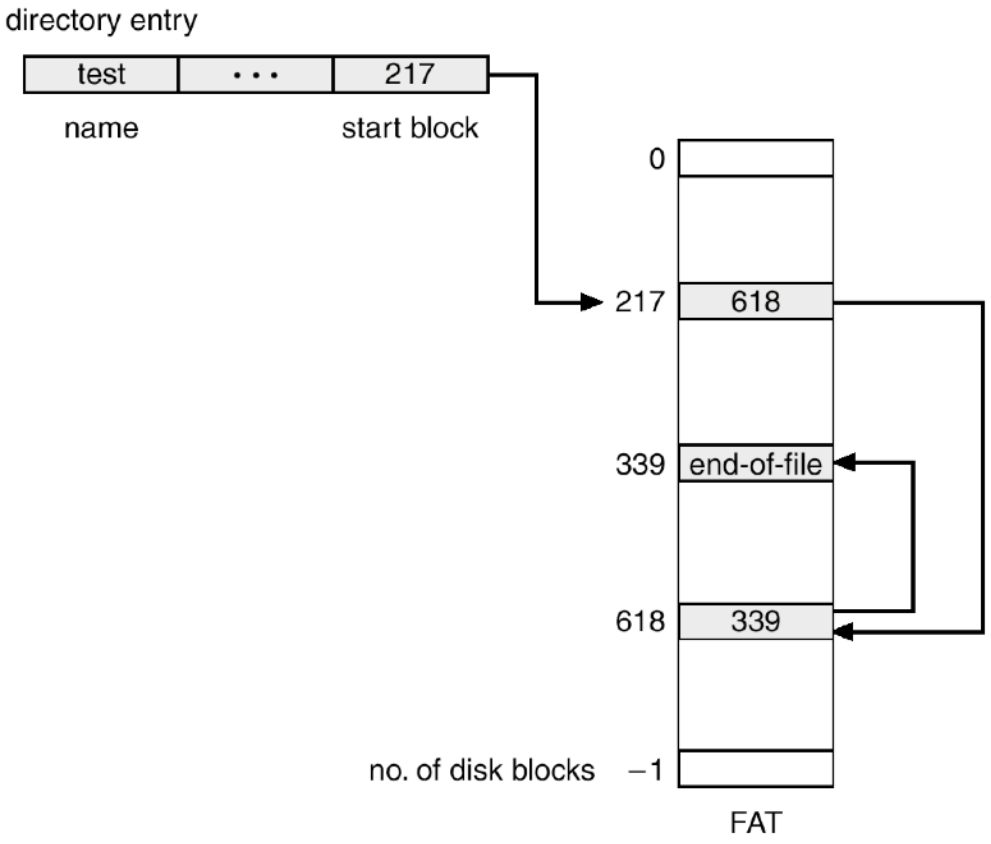
Random access is easy.

The FAT should be cached in memory.

If the FAT is not cached in memory, a considerable number of disk seeks happens.

Used by MS-DOS and OS/2.

File-Allocation Table (FAT)



Performance

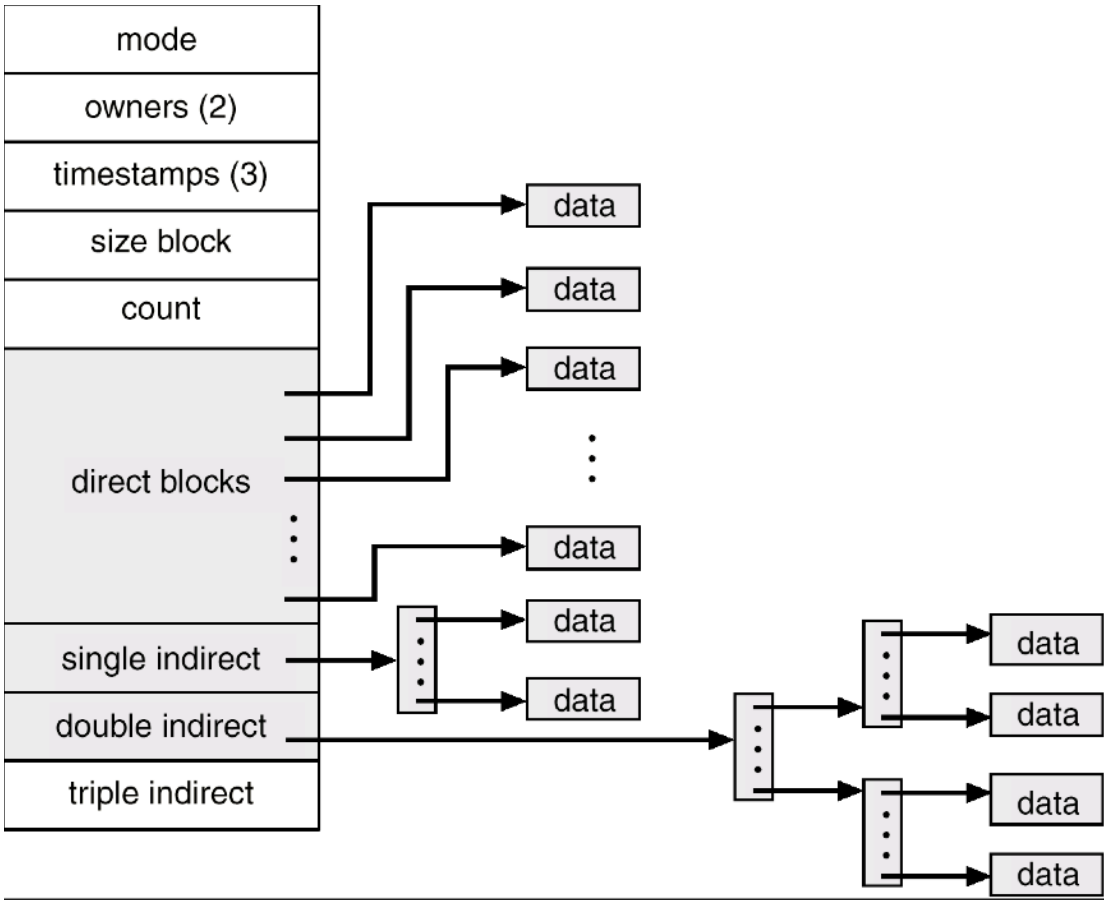
If the FAT is not cached in memory, a considerable number of disk seeks happens.

Reliability

Should you periodically save the FAT to disk? How often?

If the system crashes and the last state of the FAT in memory was not saved, will your file system be corrupted?

Combined Scheme: Unix `inode`



If file is small enough, use only **direct blocks** pointers.

If number of blocks in file is greater than the number of direct block pointers, use **single**, **double**, or **triple indirect**.

Additional levels of indirection increase the number of blocks that can be associated with a file.

Index blocks can be cached in memory, like FAT. **Access to data blocks, however, may require many disk seeks**.

Overhead

Take some time to reason out how much disk space is used to keep track of the allocation in each of the strategies we studied.

Ask yourself:

- Where is the control information stored?
- Does the control information use space that would otherwise have been used to store data?
- How much space does the control information use?

Contiguous allocation: nothing stored in data blocks.

Linked allocation: each data block must store a “link" to the next allocated block.

FAT scheme: nothing stored in data blocks, but it requires a table in mass storage and in RAM.

Indexed allocation: at least one data block is used to store an index block; if you chain index blocks to have unlimitedly large files, each index block is overhead.

Unix inode: the overhead grows with the size of the file. Small files: no overhead. Bigger files require more levels of indirection and more index blocks.

Resilience

Ask yourself:

- What happens to a file when some of the control information gets corrupted?
- How easy is it to recover the file in its entirety or partially?
- What could be done differently in each method so that it becomes more resilient to media failures?
- What is the cost of each possible solution? (More disk space? Memory space? Run time?)

Contiguous allocation: information on the file's contents is in the directory or in the FCB.

Linked allocation: if/when links are corrupted, there may be information in the directory to help locate blocks that get disconnected.

FAT scheme: this replicates outside the file's space the links that connect one block to another. The FAT has to be periodically saved to disk.

Indexed allocation: individual links may be corrupted; the entire disk block that contains links may be lost.

Unix inode: consider if this is the best possible solution for resilience and overhead.

Extent-Based Systems

- Many newer file systems use a modified contiguous allocation scheme.
- Extent-based file systems allocate disk blocks in **extents**.
- An **extent** is a contiguous set of blocks. Extents are allocated for each file. A file consists of one or more extents.
- Extents can be added to an existing file that needs space to grow. A block can be found given by the location of the first block in the file and the block count, plus a link to the first extent.

Free-Space Management

We have to think differently about *overhead* in free-space management.

In the various strategies that we will see, be sure to ask yourself *where* the control information is stored.

Whenever the control information is stored in a disk block that is unallocated (free), the control information is not taking away any space that would have been used for data!

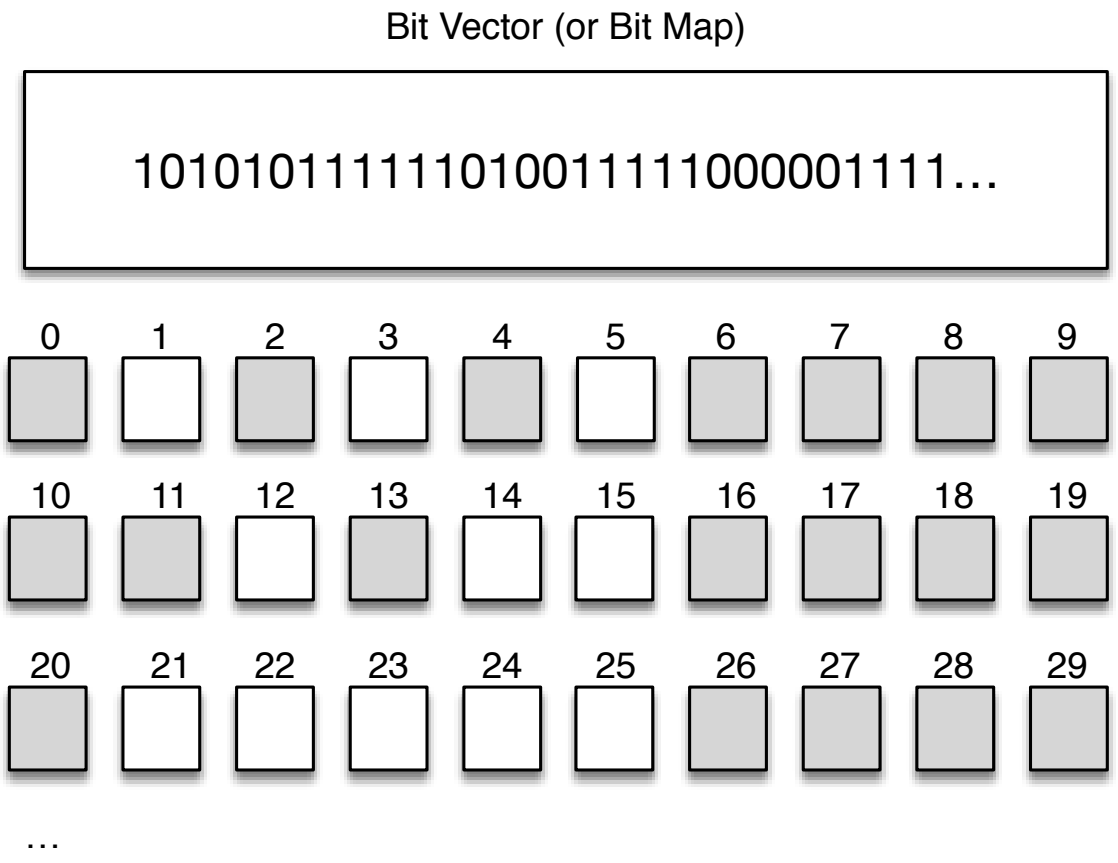
If a strategy calls for information to be stored elsewhere (not in unallocated blocks), it will take away space that could have been used for data.

Free-Space Management

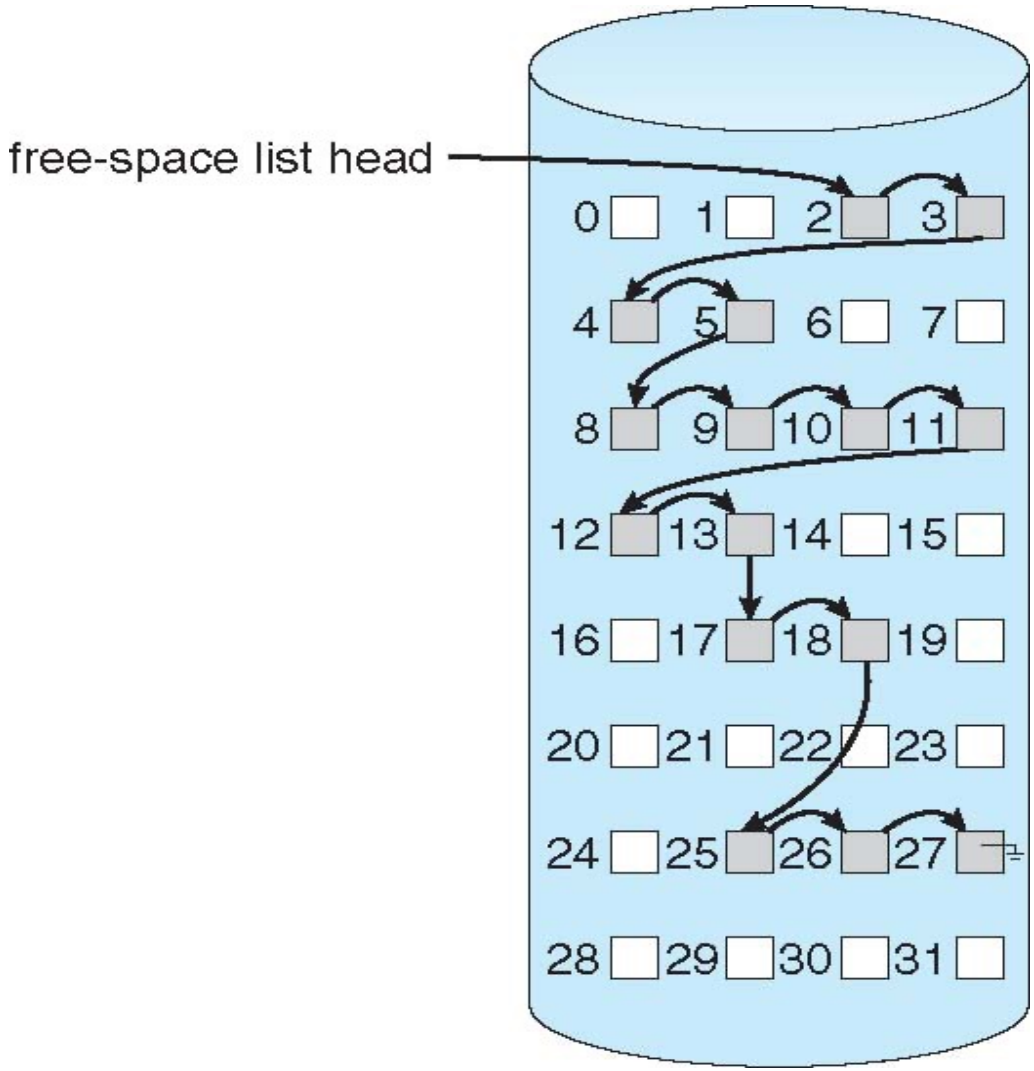
- **Bit vector** (1 bit per disk block)
- **Linked list** (free list)
- **Grouping**
  - like linked list: first free block has n block addresses (the n-1 addresses are free blocks, the nth is the address of a block with the next bundle of addresses)
- **Counting**
  - like linked list, but each node points to a cluster of contiguous, free blocks

The OS can cache in memory the free-space management structures for increased performance. Depending on disk size, this may not be easy.

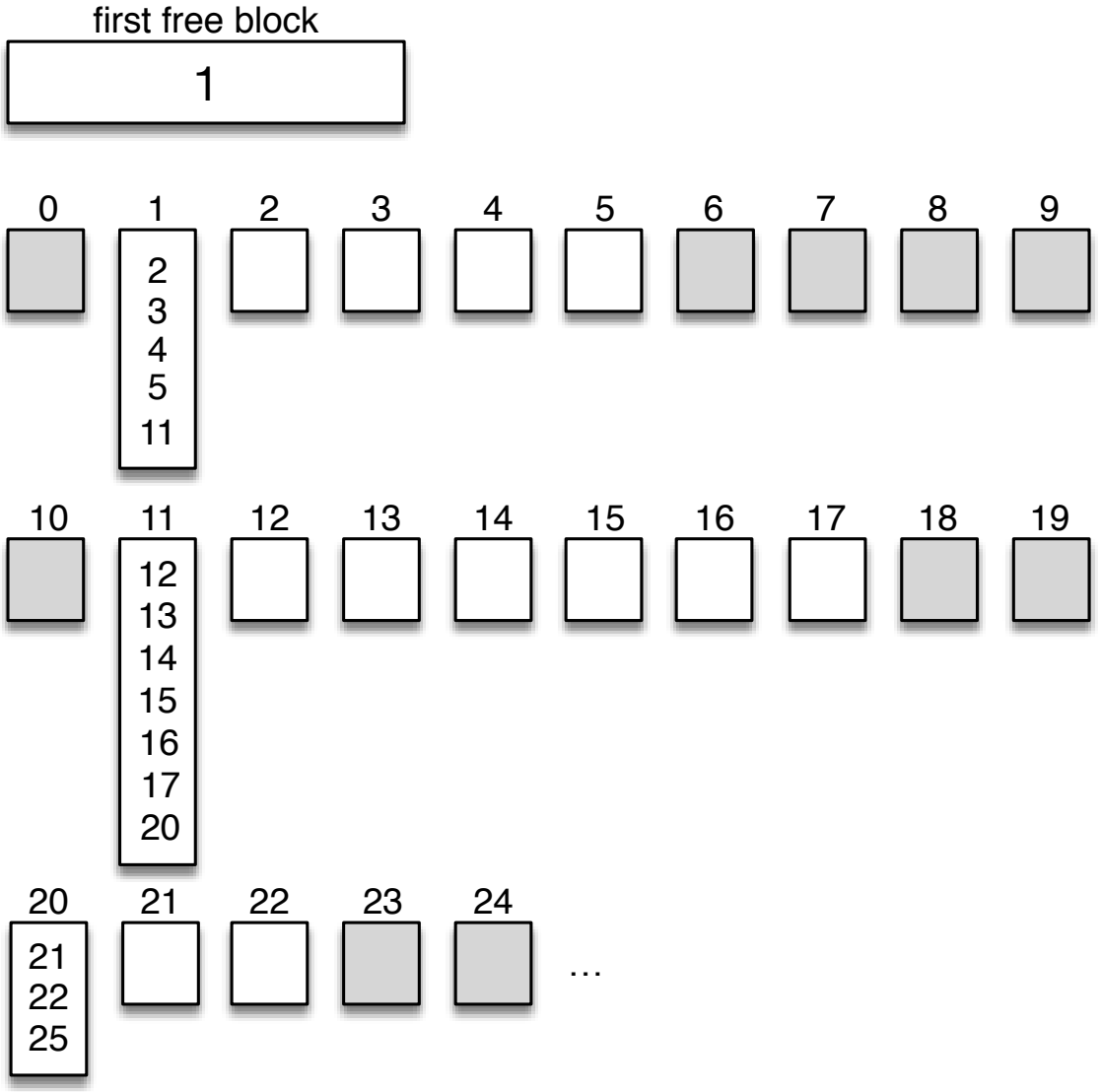
Bit Vector


Bit Vector (or Bit Map)
10101011111101001111100000111 1…
0 1 2 3 4 5 6 7 8 9
10 11 12 13 14 15 16 17 18 19
20 21 22 23 24 25 26 27 28 29
…

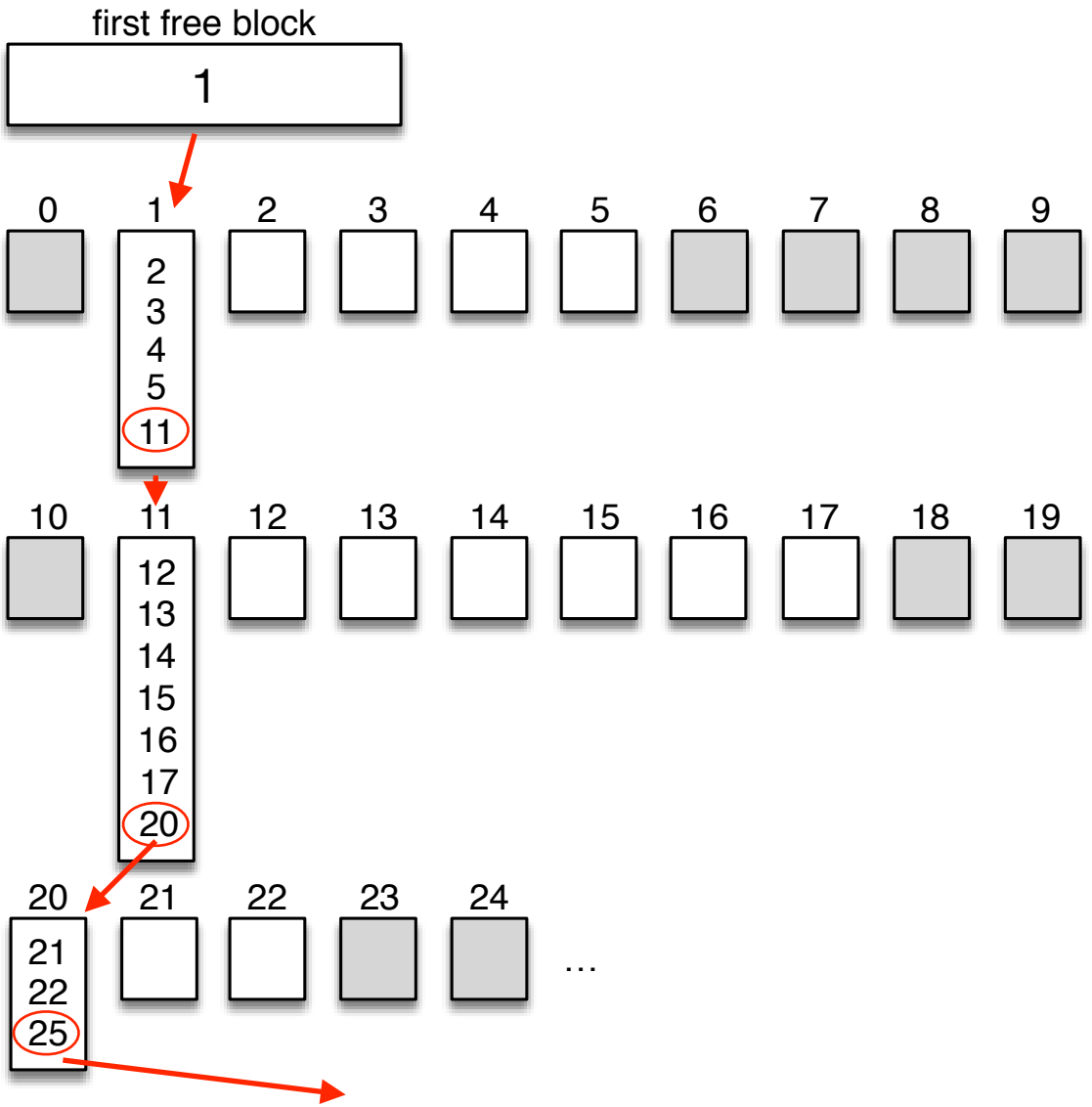
Linked List


free-space list head
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

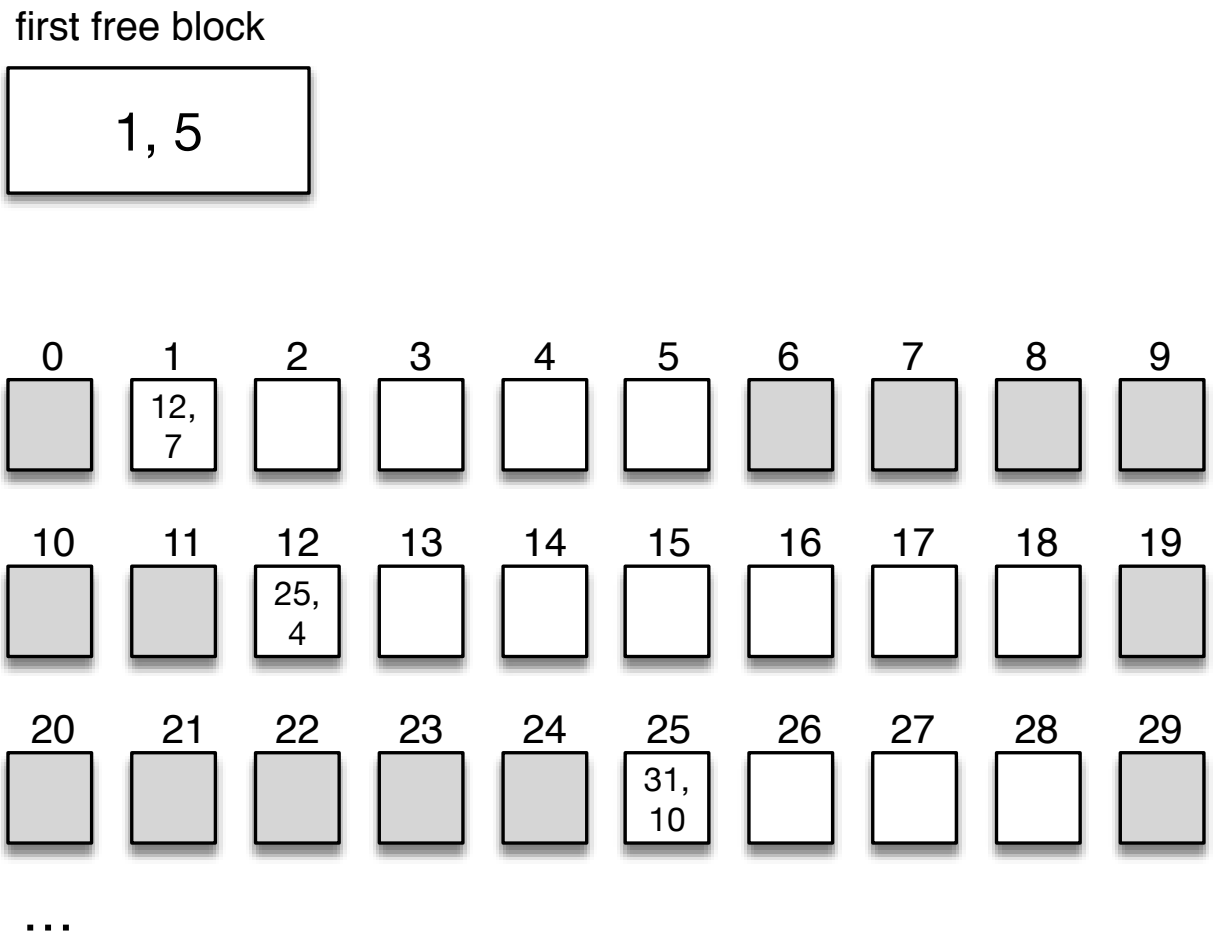
Grouping


first free block
1
0
1
2
3
4
5
11
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
20
12
13
14
15
16
17
18
19
20
21
22
25
21
22
23
24
…

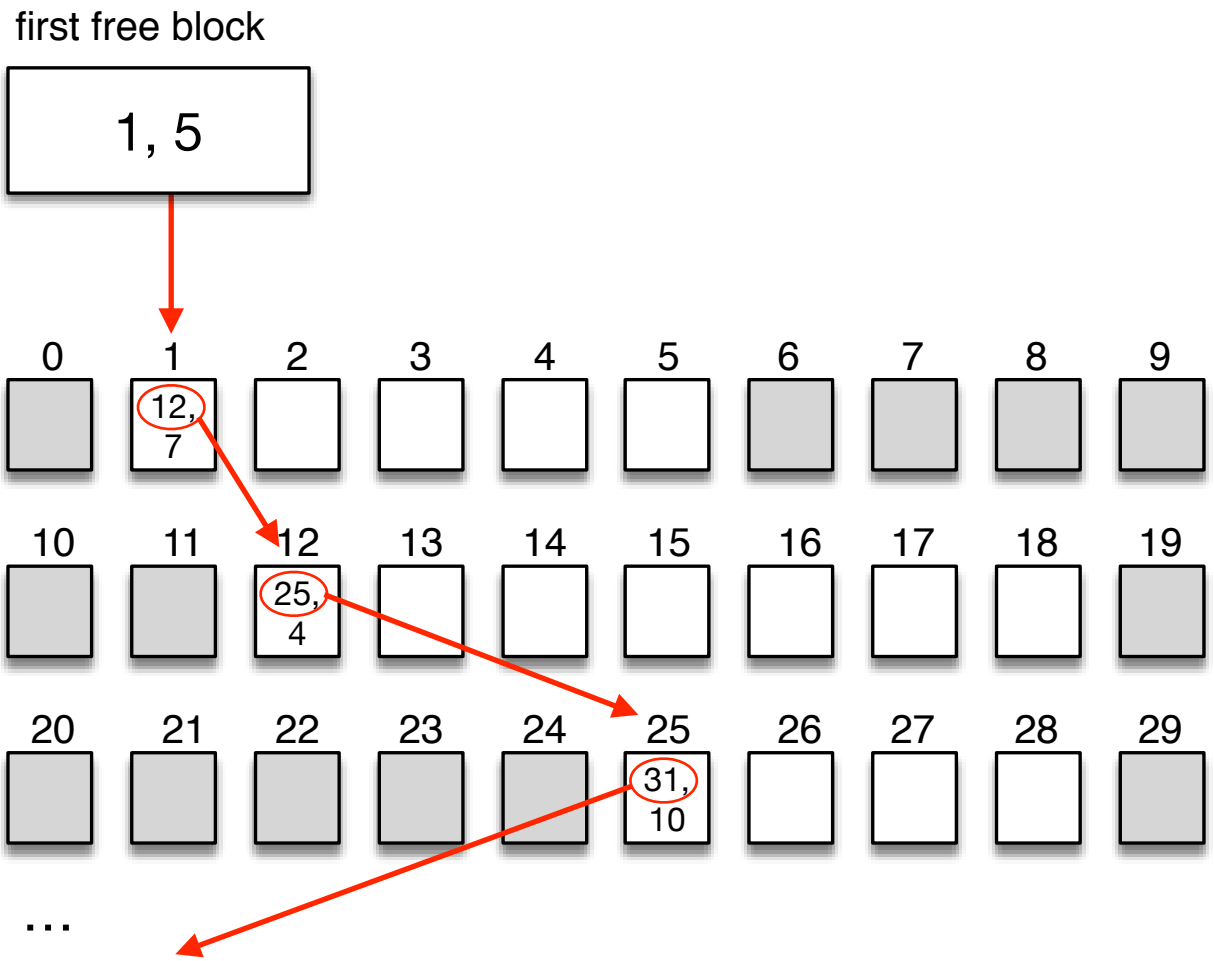
Grouping


first free block
1
0
1
2
3
4
5
6
7
8
9
2
3
4
5
11
10
11
12
13
14
15
16
17
18
19
12
13
14
15
16
17
20
20
21
22
23
24
21
22
25
...

Counting


first free block
1, 5
0
1
12, 7
2
3
4
5
6
7
8
9
10
11
12
25, 4
13
14
15
16
17
18
19
20
21
22
23
24
25
31, 10
26
27
28
29
…

Counting


first free block
1, 5
0
1
2
3
4
5
6
7
8
9
12, 7
10
11
12
13
14
15
16
17
18
19
25, 4
20
21
22
23
24
25
26
27
28
29
31, 10
...

Recovery

- **Consistency checking** – compares data in directory structure with data blocks on disk, and tries to fix inconsistencies. (Takes time!)

- **What events or failures can cause file system inconsistency?**

- **Philosophy:** Allow structures to break and provide ways to repair them.
- Use system programs to *back up* data from disk to another storage device (floppy disk, magnetic tape).
- Recover lost file or disk by *restoring* data from backup.

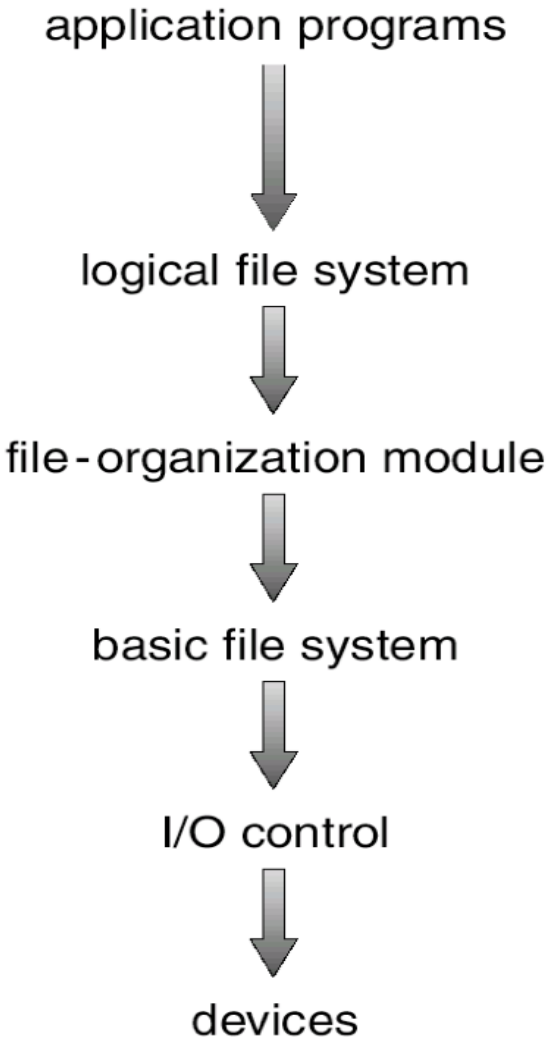
Log-Structured File Systems

- **Log-structured** (or journaling) file systems record each update to the file system as a **transaction**.
- All transactions are written to a **log**. A transaction is considered **committed** once it is written to the log (the file system may not yet be updated).
- The transactions in the log are asynchronously written to the file system. When the file system is modified, the transaction is removed from the log.
- After a system crash, all transactions that remained in the file system log are performed.

Virtual File Systems

- **Virtual File Systems (VFS)** provide an object-oriented way of implementing file systems.
- VFS allows the same system call interface (the API) to be used for different types of file systems.
- The API is to the VFS interface, rather than any specific type of file system.

Layered File System



Schematic View of a Virtual File System