File System Implementation

Chapter 12

Adapted from the slides given by Silberschatz, Galvin, and Gagne
In "Operating System Concepts", 10th edition
John Wiley and Sons, Inc 2018.

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Outline of this lecture

In this lecture, we will discuss the following:

- File-System Implementation
- Directory Implementation
- Allocation Methods
- Free-Space Management

Objectives

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

File System Implementation

- The implementation must
  - Keep track of the files and directories stored in the file system, i.e. which disk blocks/sectors store the file data.
  - Keep track of the free blocks/sectors in the disk.
- Structures used for implementing FS:

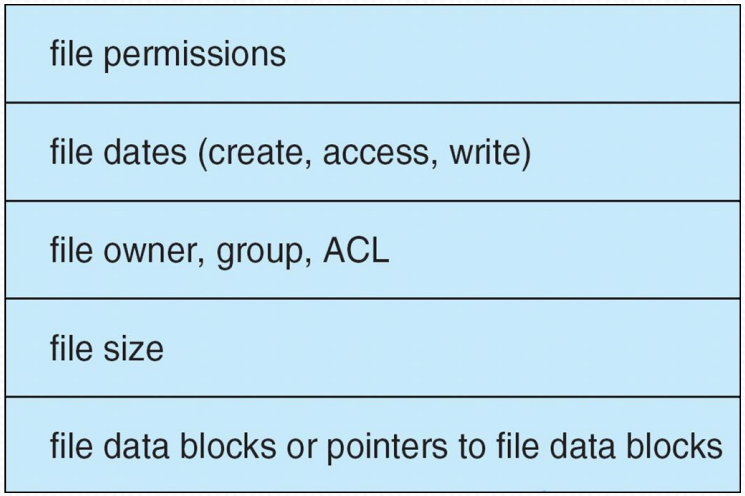
1. on-disk structure – fast,
2. in-memory structure

on-disk File-System Implementation

- There are various **on disk data structures** that are used to implement a file system. This structure may vary depending upon the OS. The *FS may contain info* about
- **Boot control block (Boot Sector)** contains info needed by system to boot OS from that volume
  - Needed if volume contains OS, usually **first block** of volume
- **Volume control block** (**superblock, master file table**) contains volume (partitions) details
  - Total # of blocks, # of free blocks, block size, free block pointers or array
- **Directory structure** is used to organize **all** the files - starting with the root directory
  - In UNIX, it includes inode numbers associated to file names.

On-disk File-System Implementation (Cont.)

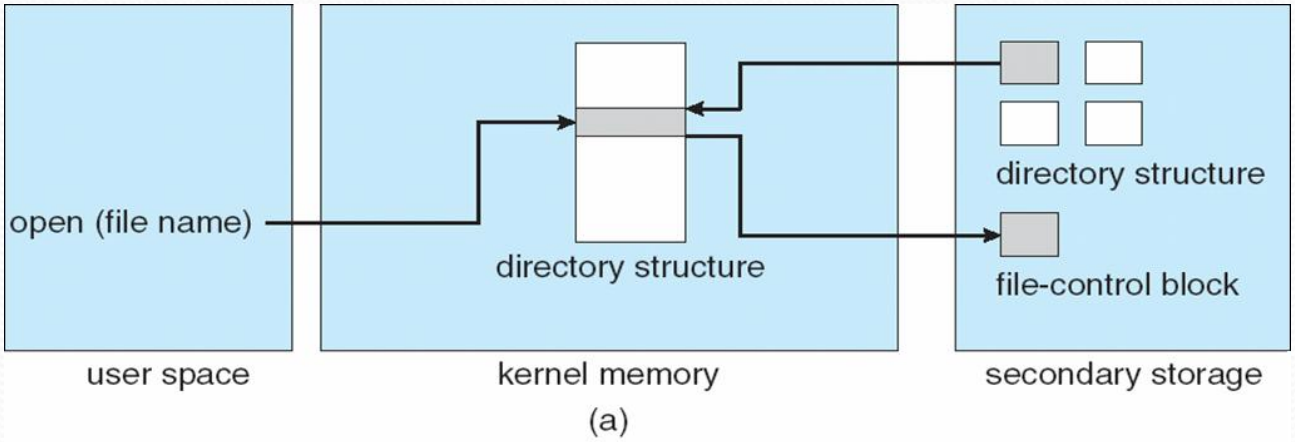
- Per-file **File Control Block** (**FCB/inodes in most unix systems**) contains many details about the file (i.e. name, attributes associated with the file, size, location, owner…)
  - A typical FCB is shown below:

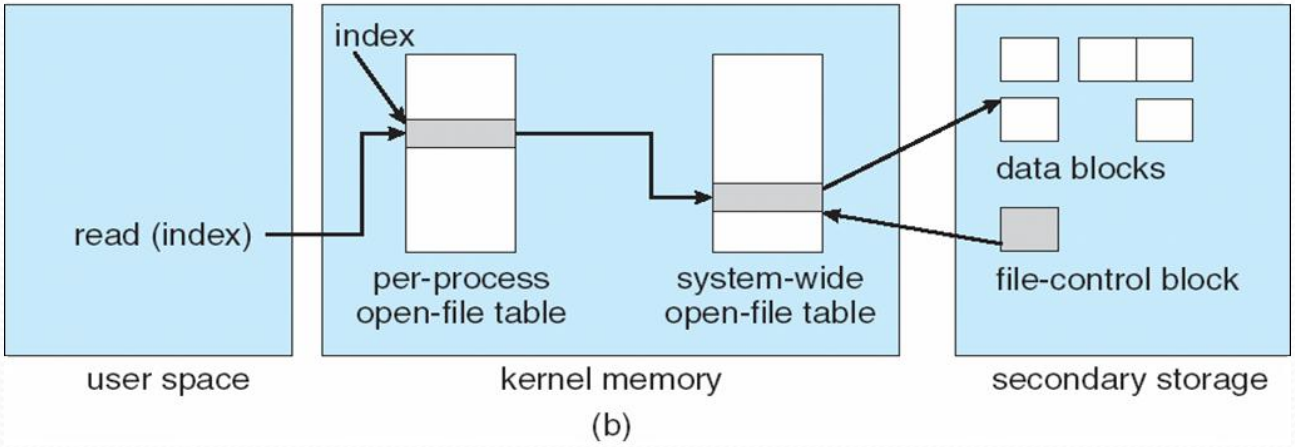


In-Memory File System Structures

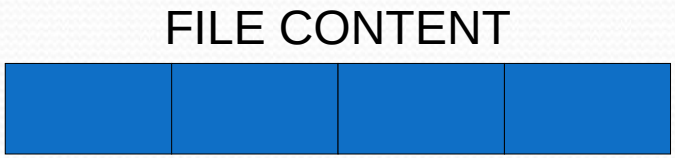
- A **mount table** – contains information about each mounted volume- list of all the devices which are being mounted to the system.
- A **directory structure cache** – info about **recently** accessed directories by the CPU.
- A **system-wide open file table** contains a copy of the FCB of **all open file** in the system and other info.
- A **per-process open-file table** (1 process file info) contains a pointer to the appropriate entry in the system-wide open-file table and other info.
- Buffers that hold file-system blocks as they are being read and written to the disk.

In-Memory File System Structures





Allocation Methods



A file is viewed as a sequence of **logical** blocks (data blocks)

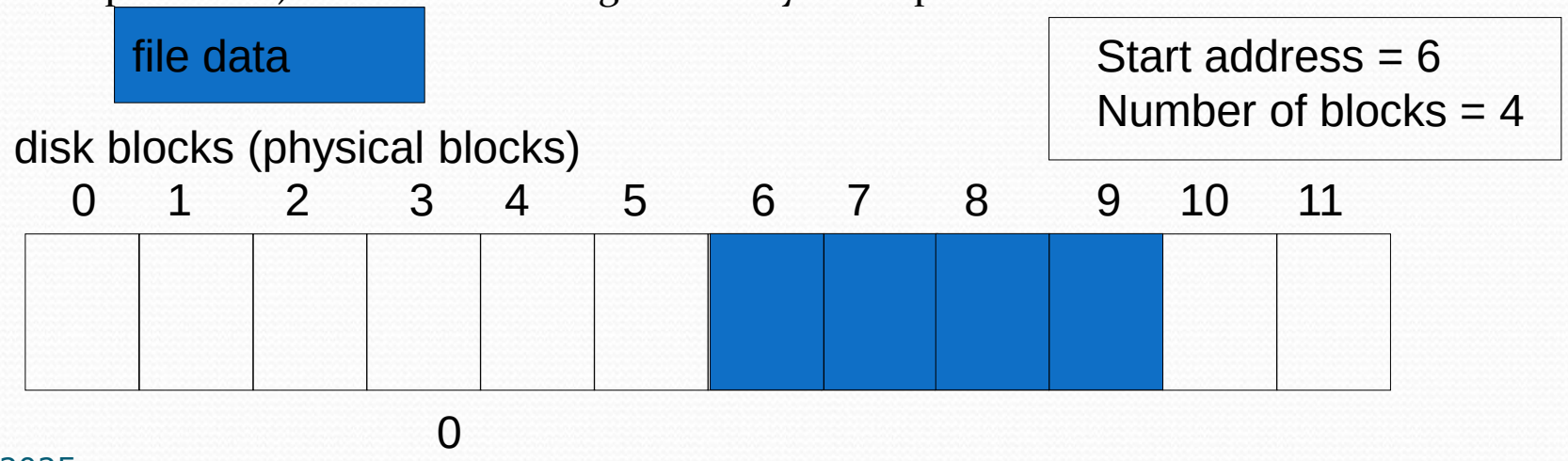
Mapping

A disk is viewed as a sequence of **physical** blocks

Allocation Methods - Contiguous

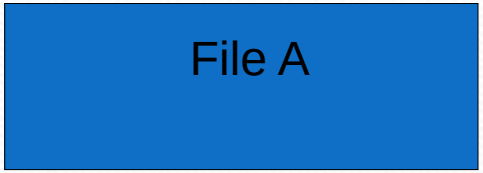
- An allocation method refers to how to allocate space to files so that the disk is utilized effectively and files can be accessed quickly:

1. **Contiguous allocation** – each file occupies set of contiguous blocks
   - Simple – only starting location (block #) and length (number of blocks) are required to find out the *disk data blocks of file*
   - Problems - Files cannot grow
   - finding space for new file, knowing file size (the size of an output file may be difficult to estimate), external fragmentation, need for
     - **compaction off-line** (**downtime,** normal system operation cannot be permitted) or **on-line** during normal system operation



Example

offset 0

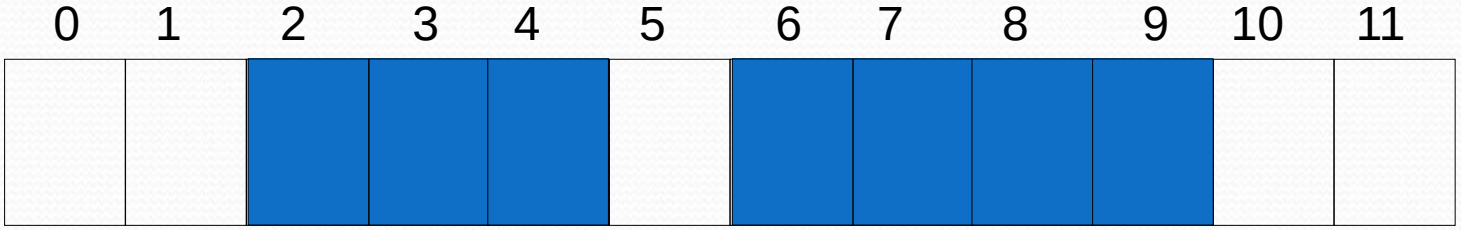


offset 0

File A: start=6, size_in_disk_blocks=4

File B: start=2, size_in_disk_blocks=3

disk blocks (physical blocks)



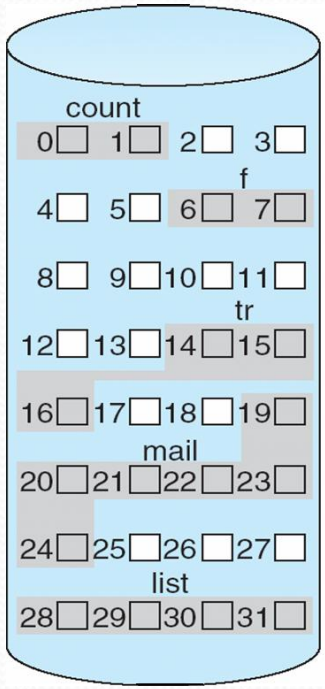
Contiguous Allocation

- LA: logical address into a file: file offset (i.e. address of a byte in file) (first byte has address 0)
- Mapping from logical (file) address to physical (disk) address

LA/DiskBlockSize

Q = LA / DiskBlockSize

R=LA Mod DiskBlockSize



directory

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

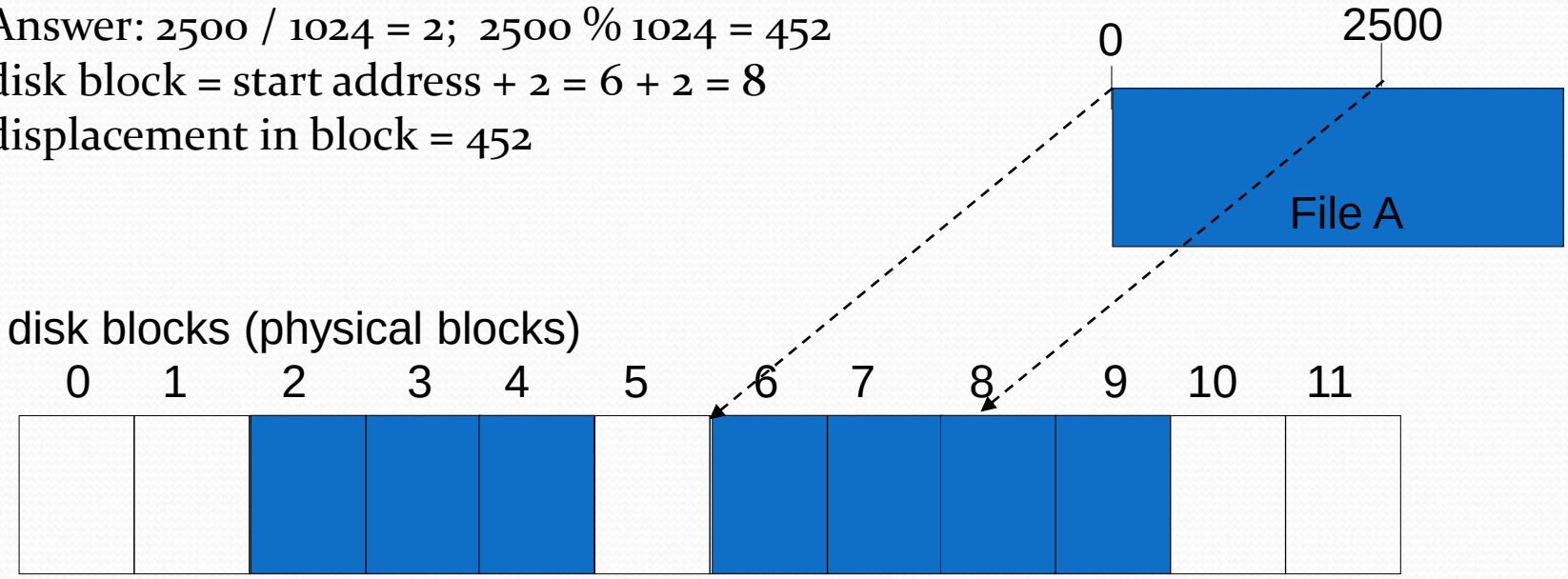
Block to be accessed = Q + starting disk block number (address)

Displacement into block = R

Example

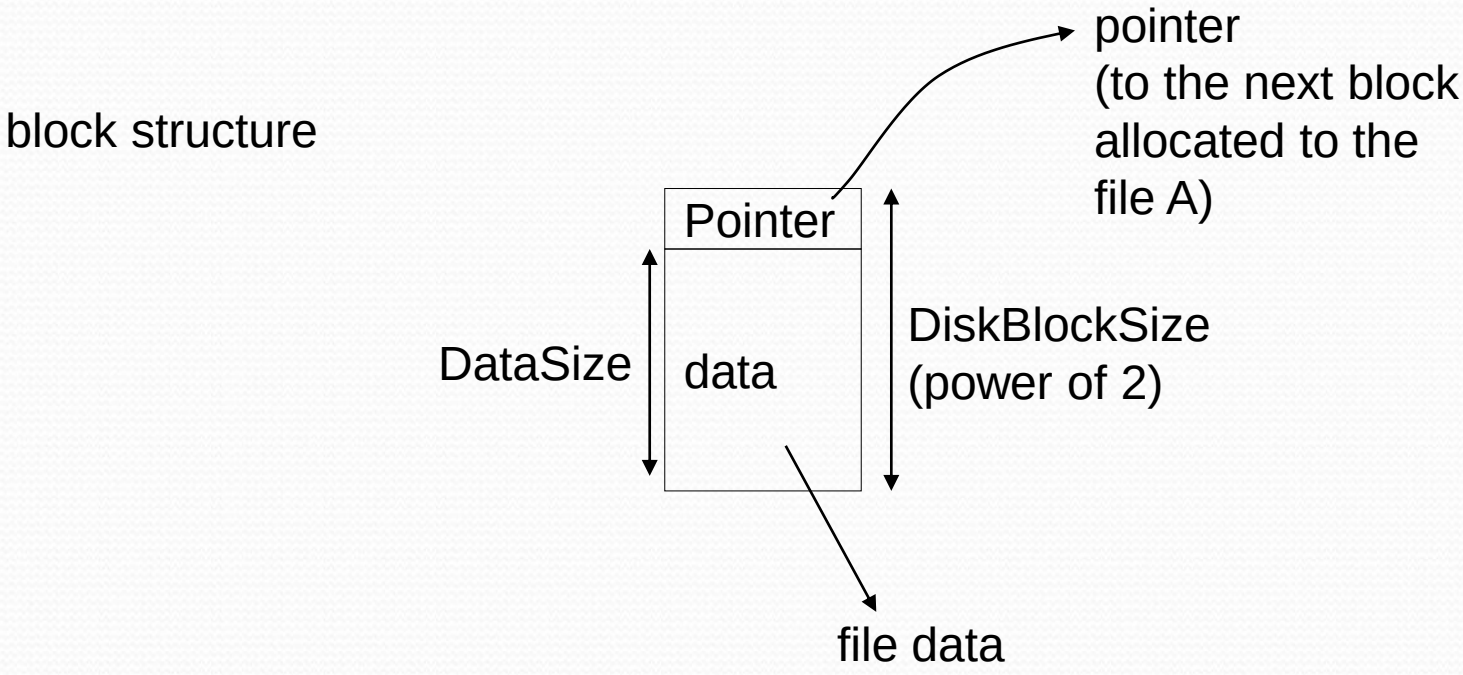
- Assume block size = 1024 bytes
- Which disk block contains the byte 0 of file A (LA = 0)? What is the displacement inside that block?
  - Answer : disk block = 6, displacement (disk block offset) = 0
- Which disk block contains the byte at LA (at file offset) 2500? In other words, where is LA 2500 mapped in disk?

Answer: 2500 / 1024 = 2; 2500 % 1024 = 452
disk block = start address + 2 = 6 + 2 = 8
displacement in block = 452



Allocation Methods – Linked

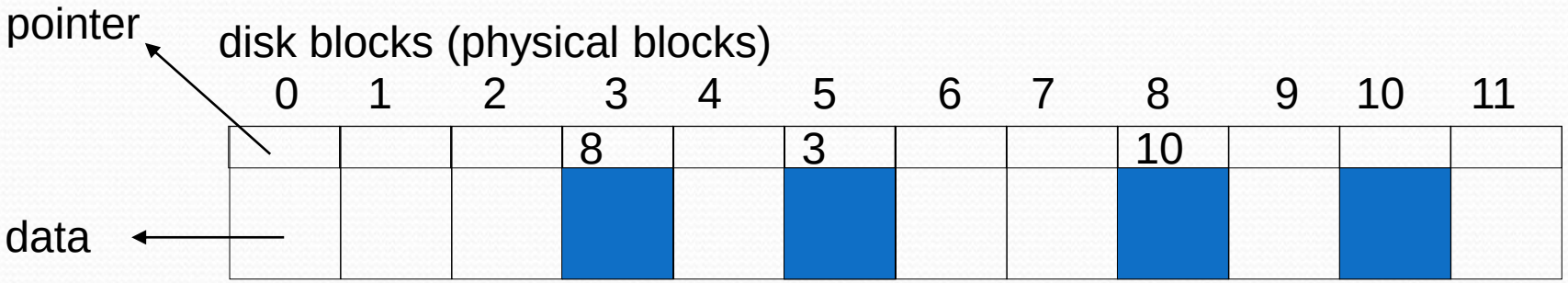
- Each file is a linked list of disk blocks: blocks may be scattered anywhere on the disk.



File data size in a disk block is no longer a power of 2

Linked Allocation

File A



Linked Allocation

2. Linked allocation – solves all problems of contiguous allocation.

- No external fragmentation
- No compaction, external fragmentation
- Each block contains pointer to next block
- File ends at nil pointer (the end-of-list pointer value)
- Free space management system called when new block needed
- Locating a block can take many I/Os and disk seeks
- can be used only for sequential access file (to find the ith block of a file, we must start at the begining of that file & follow the pointers until we get to the ith block).
- The space required for the pointers. i.e. Each file requires more space that it would otherwise

- Improve efficiency by clustering blocks into groups but **increases internal fragmentation** (More space is wasted when a cluster is partially full than when the block is partially full.)
- Reliability can be a problem

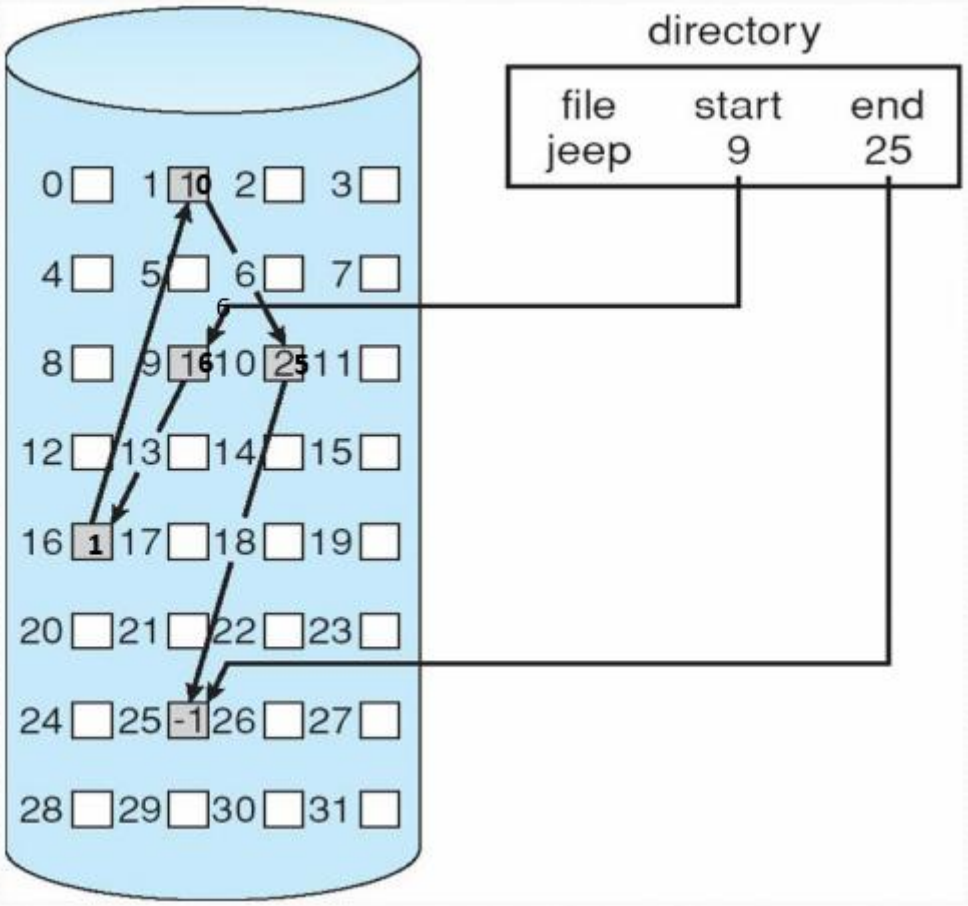
Linked Allocation (Cont.)

Mapping Algorithm

Logical Address (LA) / (BlockSize-**PointerSize**) → Q, R

Block to be accessed = the Qth disk block in the linked chain of disk blocks representing the file.
Displacement into disk block = R **+ PointerSize**

Linked Allocation



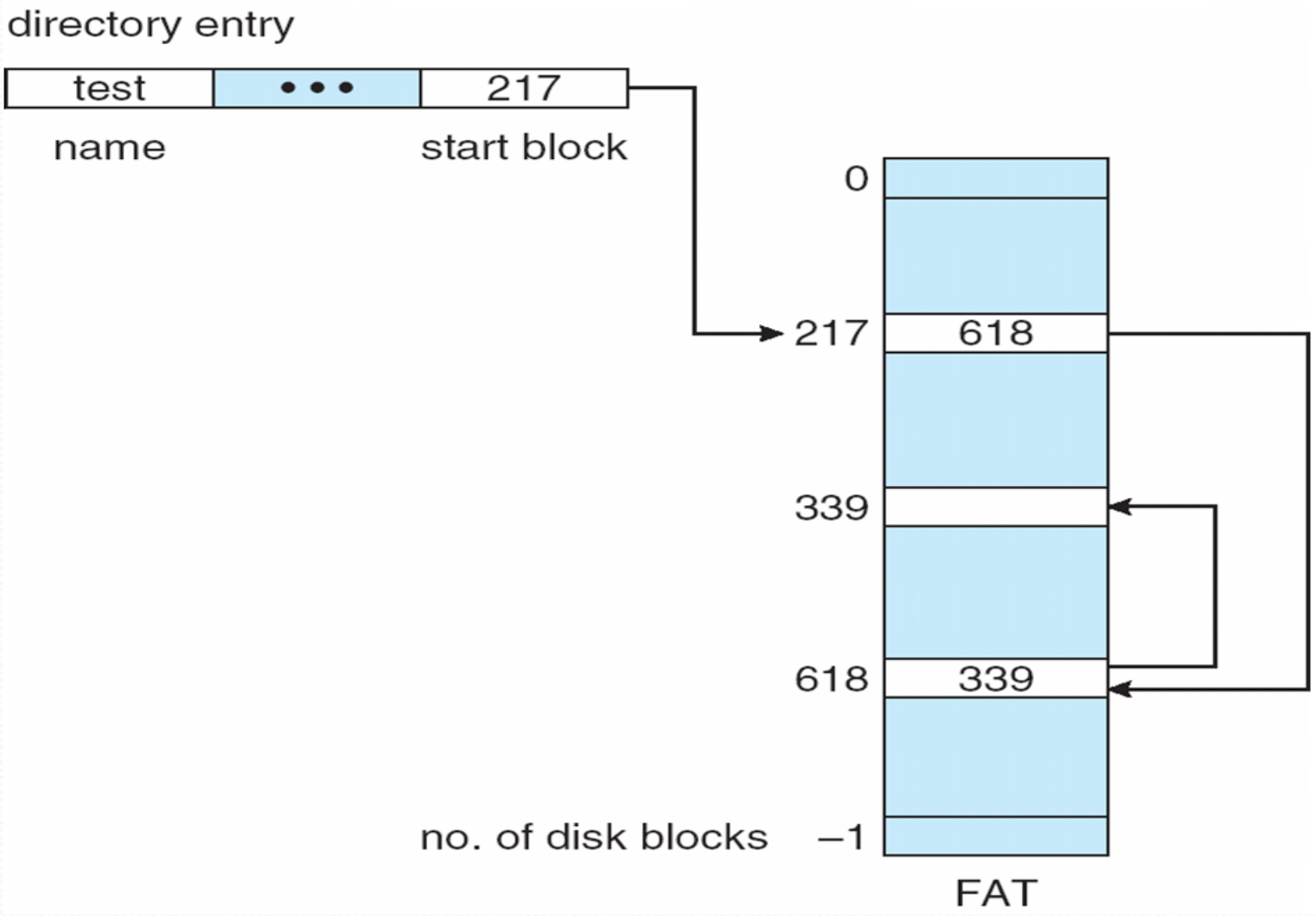
Allocation Methods – Linked (Cont.)

- FAT (File Allocation Table) variation on linked allocation – disk-space allocation used by MS-DOS and OS/2.
  - Simple but efficient method of disk space allocation
  - A section of disk at the Beginning of volume has table, which has 1 entry for each disk block & indexed by block no
  - Much like a linked list, but faster on disk and cacheable
  - Pointers (i.e. disk data blocks numbers) are kept in a table (FAT)
  - Data Block does not hold a pointer; hence data size in a disk block is a power of 2.

Disadvantages:

- Linked allocation cannot support efficient direct access since the pointers to the blocks are scattered with the block themselves all over the disk.
- **Solution:** bringing all the pointers together into 1 location: **the index block**

File-Allocation Table

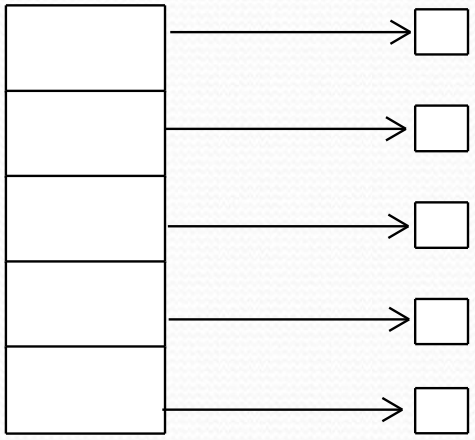


Allocation Methods - Indexed

3. Indexed allocation

- Solve the problem of linked allocation (No Random access)
- Each file has its own **index block**(s) of pointers to its data blocks, , which is an array of disk-block addresses.

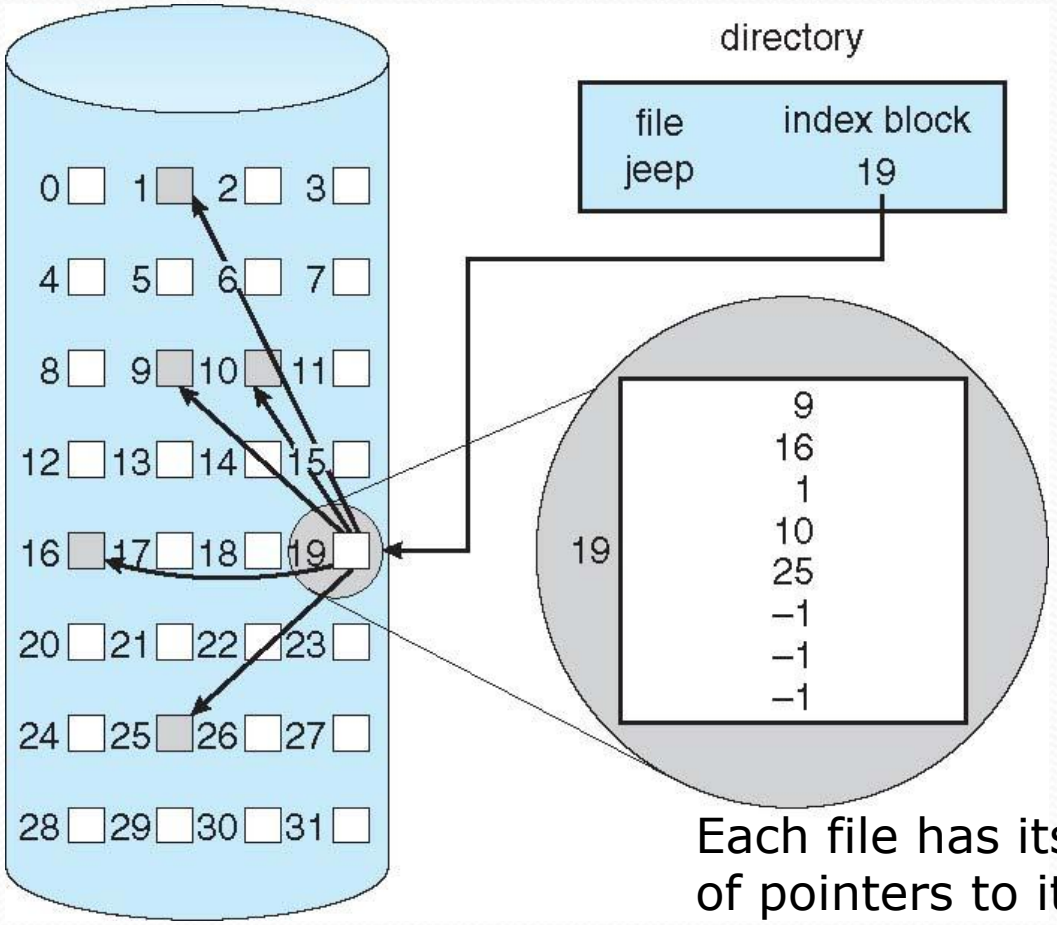
- Logical view



index table

- When the **file is created**, all pointers in the index block are set to null (-1). When the *ith block is first written, a block is obtained from the free-space* manager, and its address is put in the *ith index-block entry.*

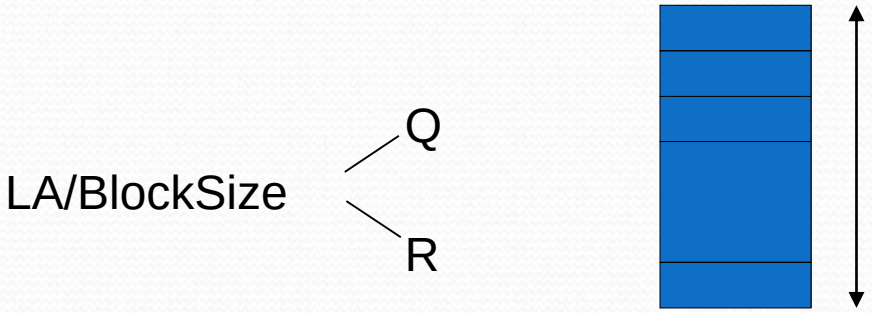
Example of Indexed Allocation



Each file has its own **index block** of pointers to its own data blocks

Indexed Allocation (Cont.)

- Need index table
- Random access
- Dynamic access without external fragmentation, but have overhead of index block
- Mapping from logical to physical in a file of maximum size of 256K bytes and block size of 512 bytes. We need only 1 block for index table

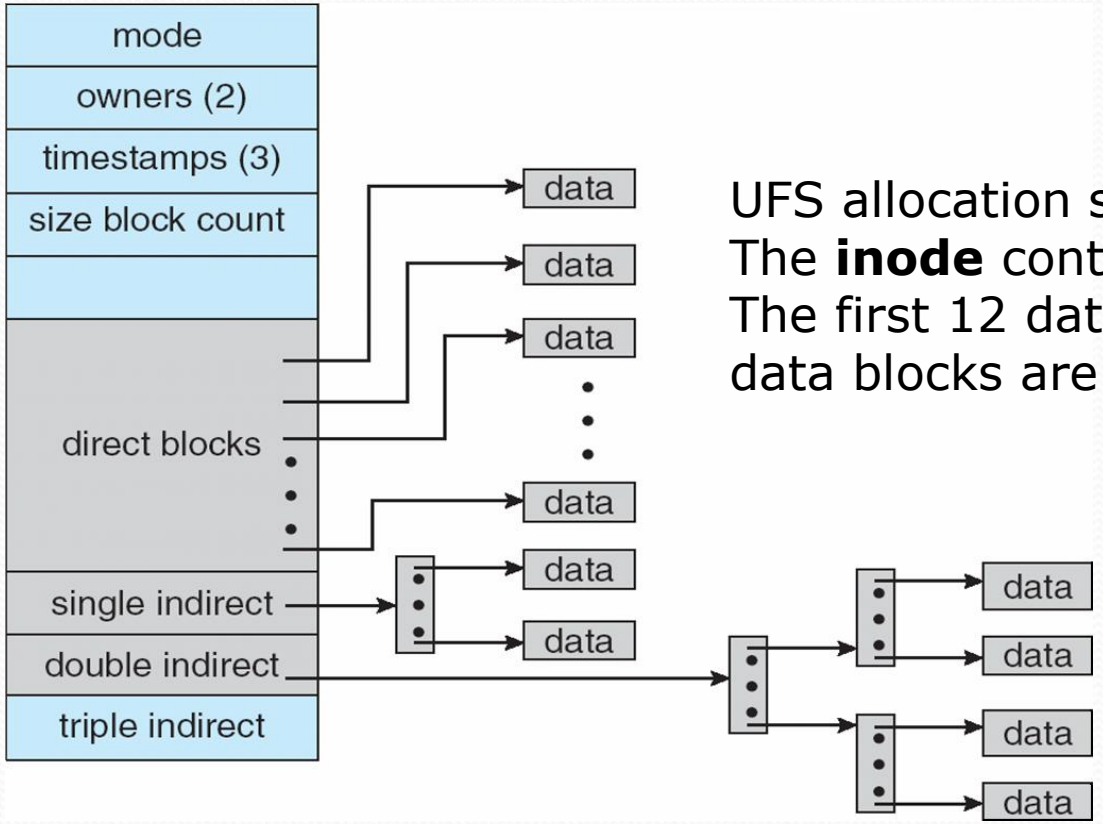


Q = displacement into index table (logical block number)

R = displacement into block (offset)

Combined Scheme: UNIX UFS

4K bytes per block, 32-bit addresses



UFS allocation scheme is index. The **inode** contains the addresses of The first 12 data blocks. Remaining data blocks are addressed indirectly

More index blocks than can be addressed with 32-bit file pointer

Free Space Management

- File system maintains **free-space list** to track available blocks/clusters
  - (Using term "block" for simplicity)
- How can we keep track of free blocks of the disk?
  - Which blocks are free?

- We need this info when we want to allocate a new block to a file.
  - Allocate a block that is free.

- There are several methods to keep track of free blocks:

  - Bit vector (bitmap) method
  - Linked list method
  - Grouping
  - Counting

Free-Space Management: 1) Bit Vector

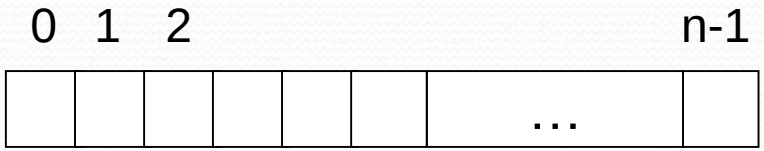
- The free-space list is implemented as a bit map or bit vector.
- Each block is represented by 1 bit.
  - If the block is free, the bit is 1;
  - If the block is allocated, the bit is 0.

- For example, consider a disk where blocks 2, 3, 4, 5, 8, 9, 10, 11, 12, 13, 17, 18,25,26, and 27 are free and the rest of the blocks are allocated.

- The free-space bit map would be 00111100111111000110000001110000
- The main advantage of this approach is its relative simplicity and its efficiency in finding the first free block or n consecutive free blocks on the disk.

Free-Space Management: 1) Bit Vector (Cont.)

- Implementation: Bit vector (n blocks)



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

Block number calculation

(number of bits per word) *(number of 0-value words) + offset of first 1 bit

0-value words has all bits 0

Where:

- A **bit vector** tracks free/allocated blocks.
- A **word** = group of bits (e.g., 8, 16, or 32 bits depending on system architecture)
- A **0-value word** means all bits in that word are zero (i.e., all blocks in that word are allocated)

Example:

Suppose that we have:

Each word = **8 bits**
Bit vector =
Word 0: 00000000 → All bits 0 → 1st word = 0-value
Word 1: 00000000 → All bits 0 → 2nd word = 0-value
Word 2: 00010000 → Not all 0s → this word has a free block

Step-by-step calculation:

- **Bits per word** = 8
- **Number of 0-value words** before we find a free block = 2
- **Offset of first 1 bit** in Word 2 = 3 (since it's the 3rd bit, counting from the **left**, index 3) -> Offset = 3

Block number = 8*2 + 3 = 19

The **first free block** is block **19**.

Free-Space Management: 1) Bit Vector (Cont.)

- Easy to get contiguous files

- Inefficient unless the entire vector is kept in memory (possible for smaller disks but not for larger ones)
- Bit map requires extra space
  - Example:

Given the following:

- **Block Size:** 4 KB=4096 bytes
- **Disk Size:** 1 TB=1024^4=1,099,511,627,776 bytes

Calculation:

To manage a disk with a bitmap:

1. Calculate the number of blocks on the disk:

Number of Blocks=Block Size/Disk Size

=1,099,511,627,776 / 4096

= 268,435,456 blocks

2. Each block requires **1 bit** in the bitmap to indicate whether it is free or used.

3. Convert the number of bits required for the bitmap into bytes:

Bitmap Size (in bytes)= Number of Blocks / 8 =268,435,456 / 8

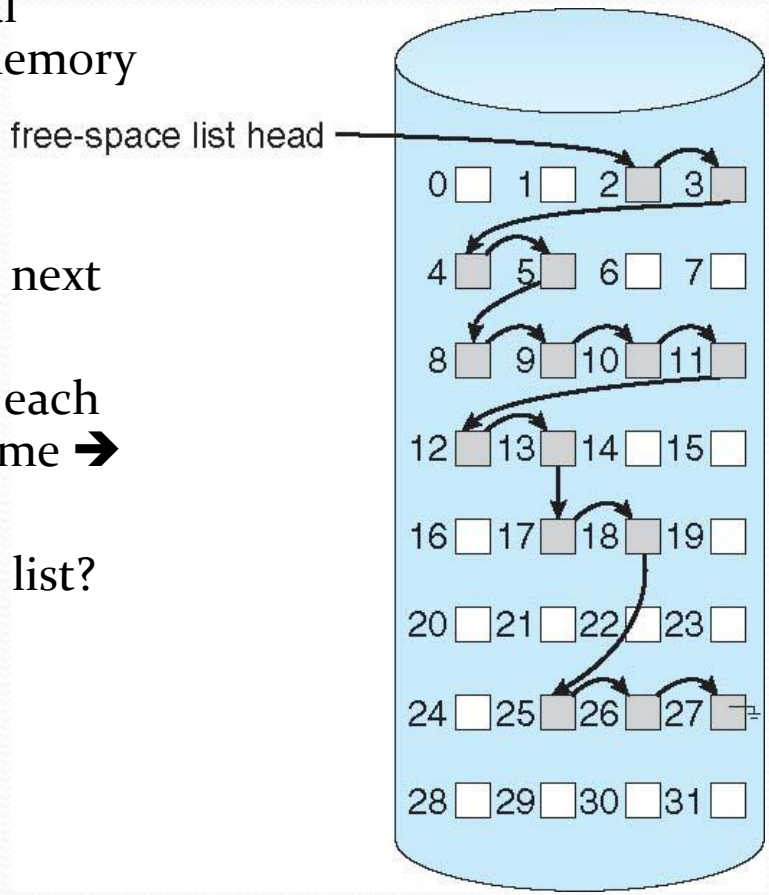
= 33,554,432bytes = 32MB

The space required for the bitmap to manage a 1 TB disk with a 4 KB block size is 32 MB.

Free-Space Management: 2) Linked List

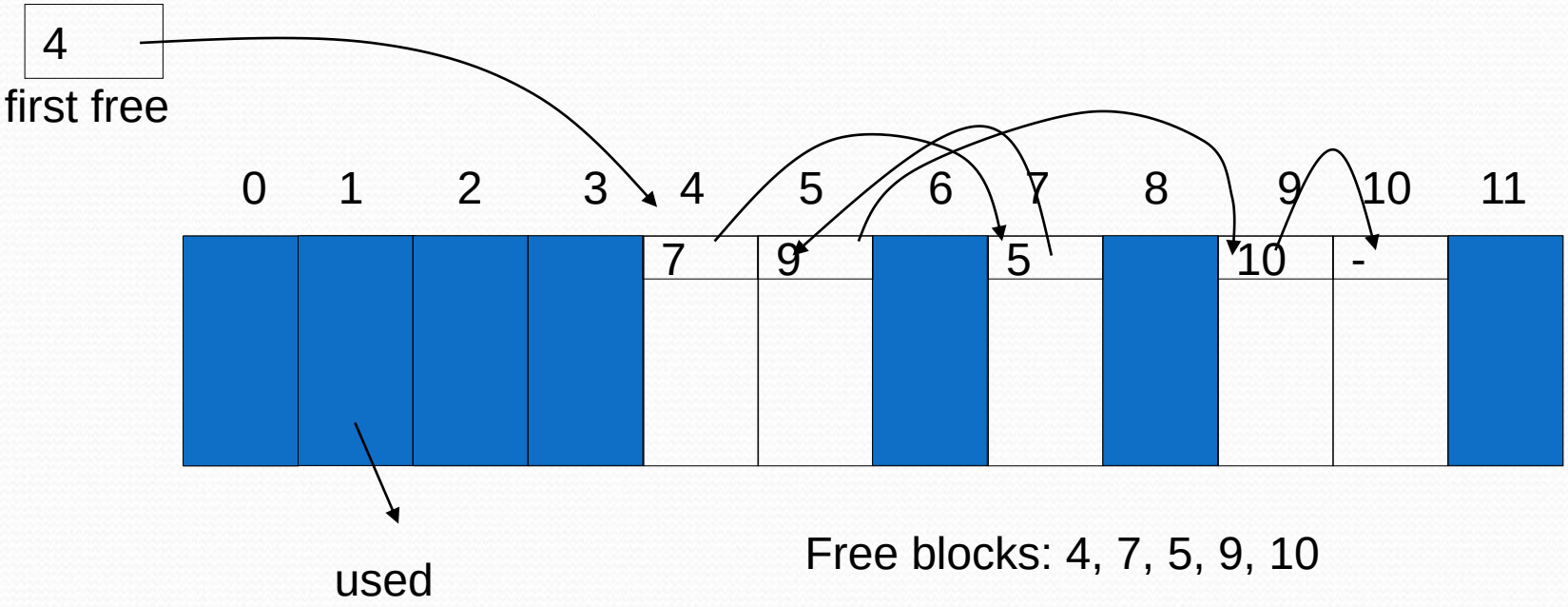
2. Linked list (free list)

- link together all the free disk blocks, keeping a pointer to the first free block in a special location on the disk and caching it in memory
- No waste of space
- Cannot get contiguous space easily
- The first block contains a pointer to the next free disk block, and so on.
- To traverse the entire list, we must read each block, which requires substantial I/O time ➔ not efficient scheme.
- How many free blocks are in this linked list?
  - 15



Free-Space Management: 2) Linked List(cont.)

- Each free block has pointer to the next free block
- We keep a pointer to the first free block somewhere (like superblock)
- Features:

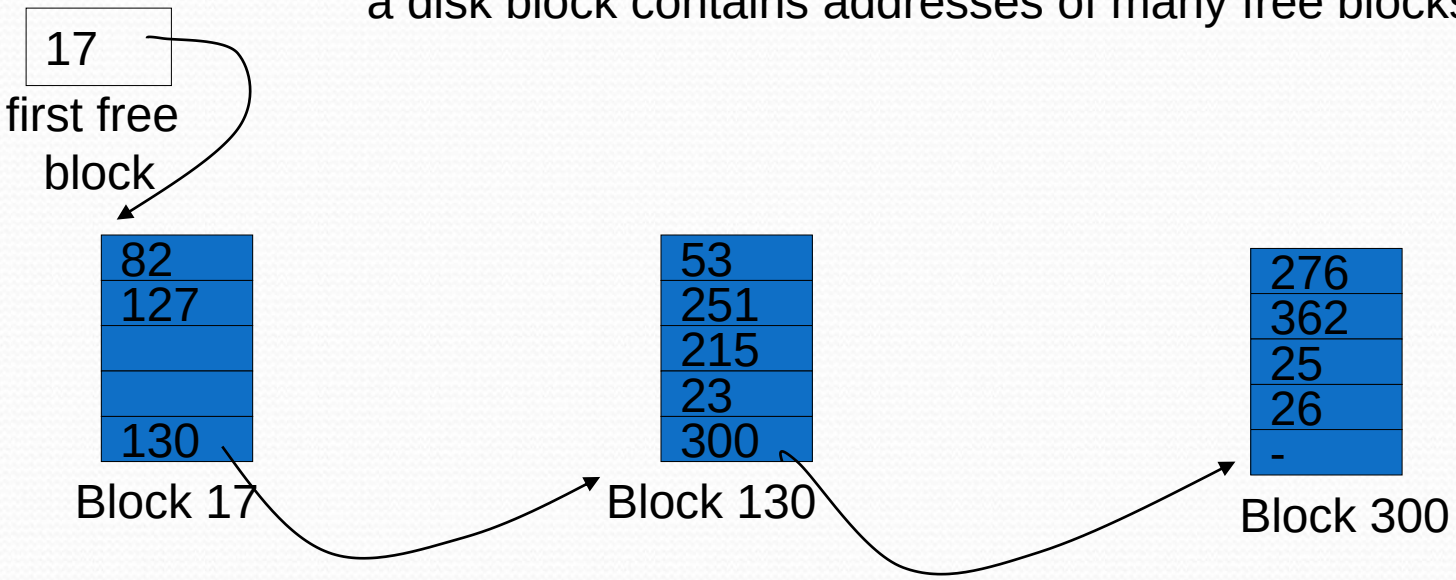


Free-Space Management: 3) Grouping

- A modification of the free-list approach is to store the addresses of n free blocks in the first free block.
- The first n-1 of these blocks are actually free. The last block contains the addresses of another n free blocks, and so on.
- The addresses of a large number of free blocks can now be found quickly, unlike the situation when the standard linked-list approach is used.

Free-Space Management: 3) Grouping

a disk block contains addresses of many free blocks



Free blocks are:
82 127 53 251 215 23 276 362 25 26

The last block contains the addresses of another n free blocks, and so on

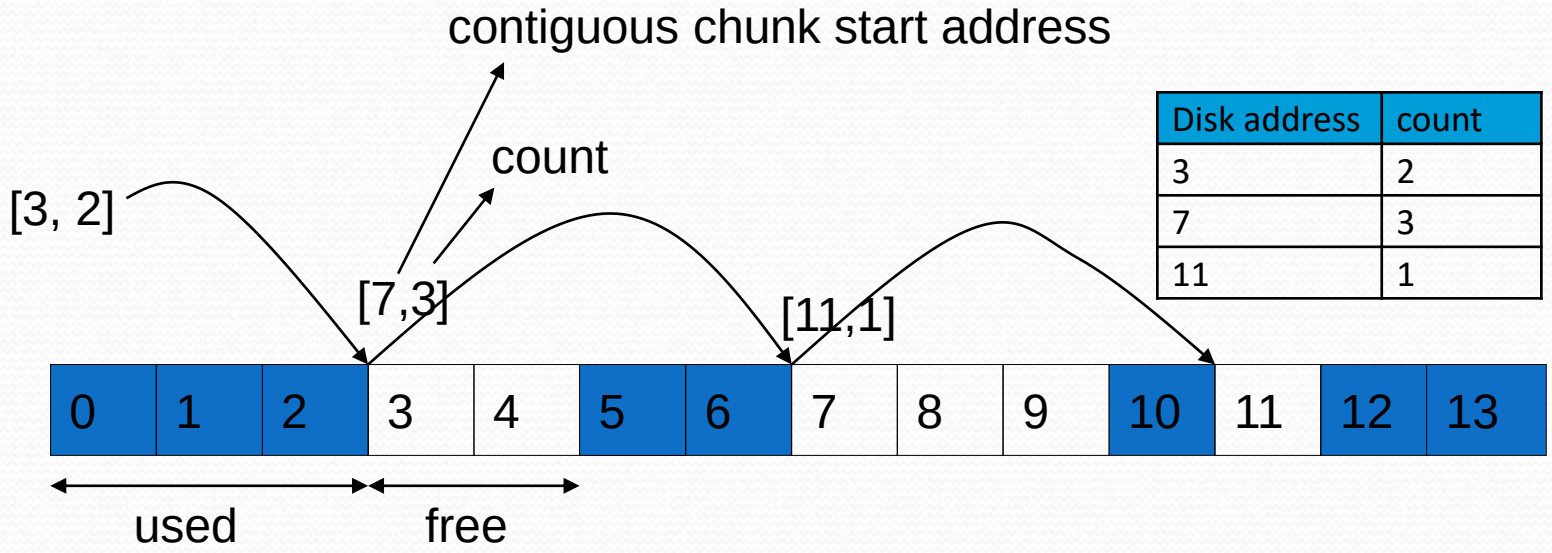
a block containing free block pointers will be free when those blocks are used.

Free-Space Management: 4) Counting

- rather than keeping a list of n free disk addresses, we can keep the address of the first free block and the number (n) of free contiguous blocks that follow the first block.
- Each entry in the free-space list then consists of a disk address and a count.
- Although each entry requires more space than would a simple disk address, the overall list will be shorter, as long as the count is generally greater than 1.

Free-Space Management: 4) Counting

- Besides the free block pointer, keep a counter saying how many block are free contiguously after that free block



Disk address	count
3	2
7	3
11	1

End of Chapter 11