

Module 4

Physical Database Design and Query

File Organization - Indexing: Single level indexing, multi-level indexing, dynamic multilevel Indexing - B+ Tree Indexing – Hashing Techniques: Static and Dynamic Hashing – Relational Algebra - Translating SQL Queries into Relational Algebra – Query Processing – Query Optimization: Algebraic Query Optimization, Heuristic query optimization Rules, Join Query Optimization using Indexing and Hashing - Tuple Relational Calculus.

Reference :

R. Elmasri & S. B. Navathe, Fundamentals of Database Systems, Addison Wesley, 7th Edition, 2016

A. Silberschatz, H. F. Korth & S. Sudarshan, Database System Concepts, McGraw Hill, 7th Edition 2019.

Indexing and Hashing

- Basic Concepts
- Ordered Indices
- B+-Tree Index Files
- B-Tree Index Files
- Static Hashing
- Dynamic Hashing
- Comparison of Ordered Indexing and Hashing
- Index Definition in SQL
- Multiple-Key Access

Introduction

- Database data must be stored physically on storage media.
- DBMS retrieves, updates, and processes stored data.
- Storage hierarchy consists of **primary, secondary, and tertiary storage**.

Primary Storage

- Operated directly by CPU (e.g., **main memory, cache memory**).
- Provides **fast access** to data.
- **Limited storage capacity** compared to enterprise database needs.
- **Expensive** relative to disks.
- **Volatile** – data lost during power failure or system crash.

Secondary Storage

- Primary medium for online storage of enterprise databases.
- Traditionally **magnetic disks** used.
- **Flash memory** (SSDs) increasingly popular.
- **Non-volatile** and permanent storage.
- Suitable for large databases.

Tertiary Storage

- **Optical disks** (CD-ROM, DVD) and **tapes** used for archiving.
- **Removable, offline** storage.
- Provides **large capacity** at **lower cost**.
- **Slower access** compared to primary/secondary.
- Data must be copied to **primary storage** before CPU can process.

Memory Hierarchies and Storage Devices

Memory Hierarchy Concept

- Data resides in multiple storage levels → **speed vs. cost trade-off**.
- **High-speed memory** = expensive, low capacity (e.g., cache).
- **Low-speed memory** = cheaper, very high capacity (e.g., tapes).

Primary Storage

- **Cache Memory (SRAM)**
 - ✓ Fastest, most expensive.
 - ✓ Used by CPU for **prefetching & pipelining**.
- **DRAM (Main Memory)**
 - ✓ Cheaper, larger than cache.
 - ✓ Volatile & slower than SRAM.
 - ✓ Holds program instructions & data.
 - ✓ Now available in **GB to hundreds of GB** range.
 - ✓ **Main-memory databases** possible → useful for **real-time applications** (e.g., telephone switching).

Memory Hierarchies and Storage Devices

Secondary & Tertiary Storage

- **Magnetic Disks (HDDs)**
 - Traditional medium for databases.
- **Flash Memory (SSD, USB, NAND/NOR flash)**
 - ✓ Non-volatile, high performance.
 - ✓ Used in **cameras, mobiles, laptops, USB drives**.
 - ✓ NAND → higher storage capacity per cost.
- **Optical Drives (CD/DVD/Blu-ray)**
 - ✓ CD: ~700 MB, DVD: 4.5–15 GB, Blu-ray: 27–54 GB.
 - ✓ Types: **CD-ROM (read-only), CD-R/DVD-R (WORM – write once, read many)**.
 - ✓ Declining usage due to cheap, high-capacity disks.
- **Magnetic Tapes**
 - ✓ Used for **backup & archiving**.
 - ✓ Very large capacity (terabytes to petabytes with jukeboxes).
 - ✓ Example: **NASA EOS satellite data archives**.

Memory Hierarchies and Storage Devices

Storage Measurement Units

KB = 1,000 bytes

MB = 1 million bytes

GB = 1 billion bytes

TB = 1,000 GB

PB = 1,000 TB (10^{15} bytes) – now relevant for big science & enterprise databases.

Memory Hierarchies and Storage Devices

Comparison of Storage Devices (2014 Commodity Prices)

Type	Capacity	Access Time	Max Bandwidth	Cost
Main Memory (RAM)	4 GB – 1 TB	30 ns	35 GB/s	\$100 – \$20K
Flash SSD	64 GB – 1 TB	50 µs	750 MB/s	\$50 – \$600
Flash USB	4 GB – 512 GB	100 µs	50 MB/s	\$2 – \$200
Magnetic Disk (HDD)	400 GB – 8 TB	10 ms	200 MB/s	\$70 – \$500
Optical Storage	50 – 100 GB	180 ms	72 MB/s	~\$100
Magnetic Tape	2.5 – 8.5 TB	10–80 sec	40–250 MB/s	\$2.5K – \$30K
Tape Library	25 TB – 2.4M TB	10–80 sec	250 MB/s – 1.2 PB/s	\$3K – \$1M+

Storage Organization of Databases

Persistent Data

- Stored for long periods, accessed repeatedly.
- Contrast: **Transient data** exists only during program execution.

Why stored on magnetic disks (secondary storage):

- Databases are **too large** for main memory.
- Disk storage is **non-volatile**, unlike volatile main memory.
- **Cheaper cost per unit** compared to primary storage.

Emerging Technologies:

- **SSDs** may replace magnetic disks in some cases.
- Future DBs may use **different hierarchy levels** (main memory → SSD → tape jukebox).
- But **magnetic disks** expected to remain dominant for large DBs.

Other Storage Media:

- **Magnetic tapes** – cheap, used for **backup/archiving**.
- Require operator/auto-loader; **offline access** (slower).
- **Disks** – online, **direct access** anytime.

Storage Organization of Databases

Physical Database Design:

- DB designers/DBA must know **advantages/disadvantages** of storage methods.
- DBMS offers **multiple organization techniques**.
- Choice depends on **application requirements**.

Data Access:

- Applications usually need only a **small portion** of DB at a time.
- Process: **Disk → Main Memory → CPU → (back to Disk if modified)**.
- Data organized as **files of records** (entities, attributes, relationships).

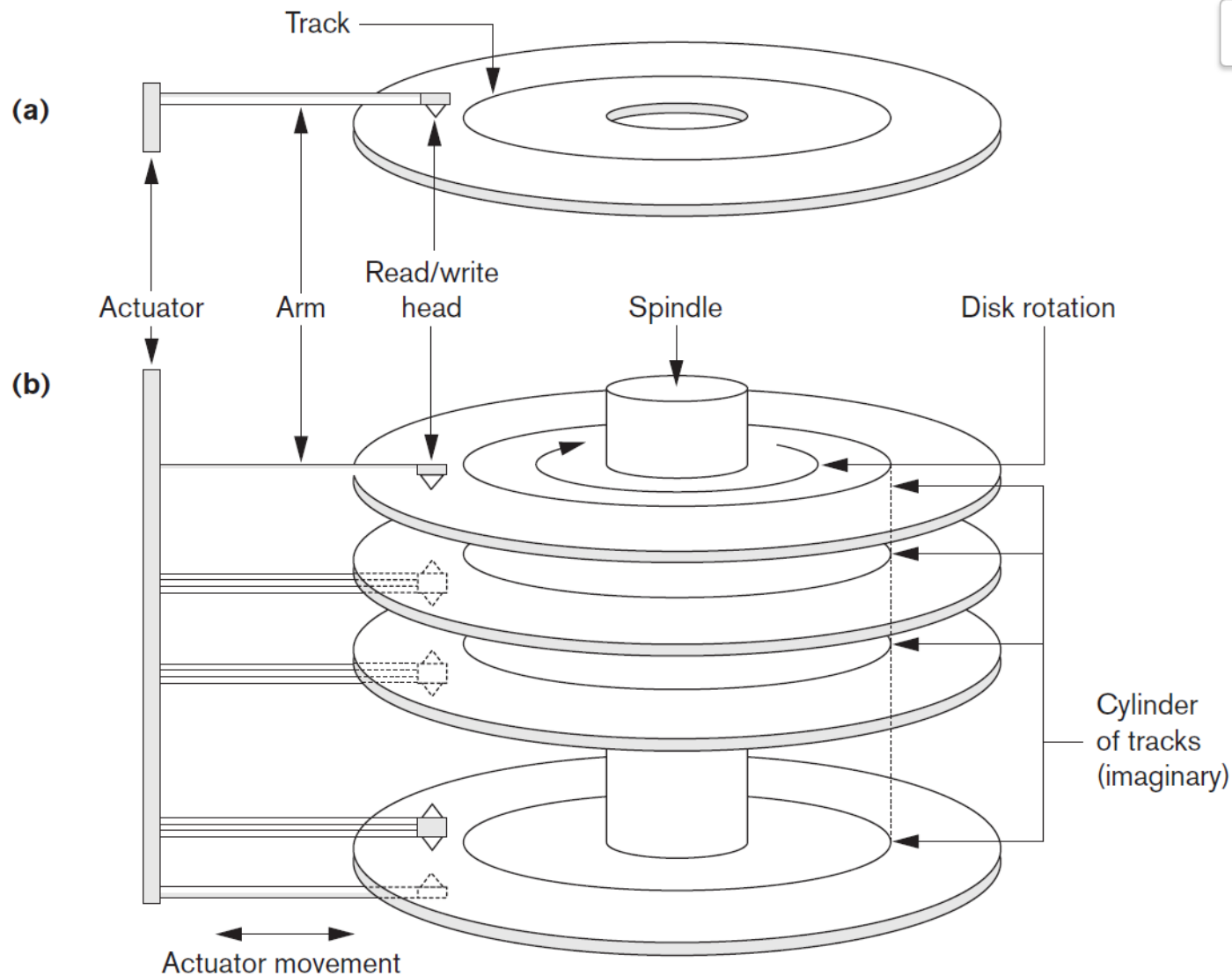
File Organization Techniques:

- **Heap (Unordered file)**: Records appended without order.
- **Sorted (Sequential file)**: Ordered by a field (**sort key**).
- **Hashed file**: Uses **hash function** on a **hash key**.
- **B-trees (and variants)**: Tree-based structure for efficient access.

Secondary (Auxiliary) Organization:

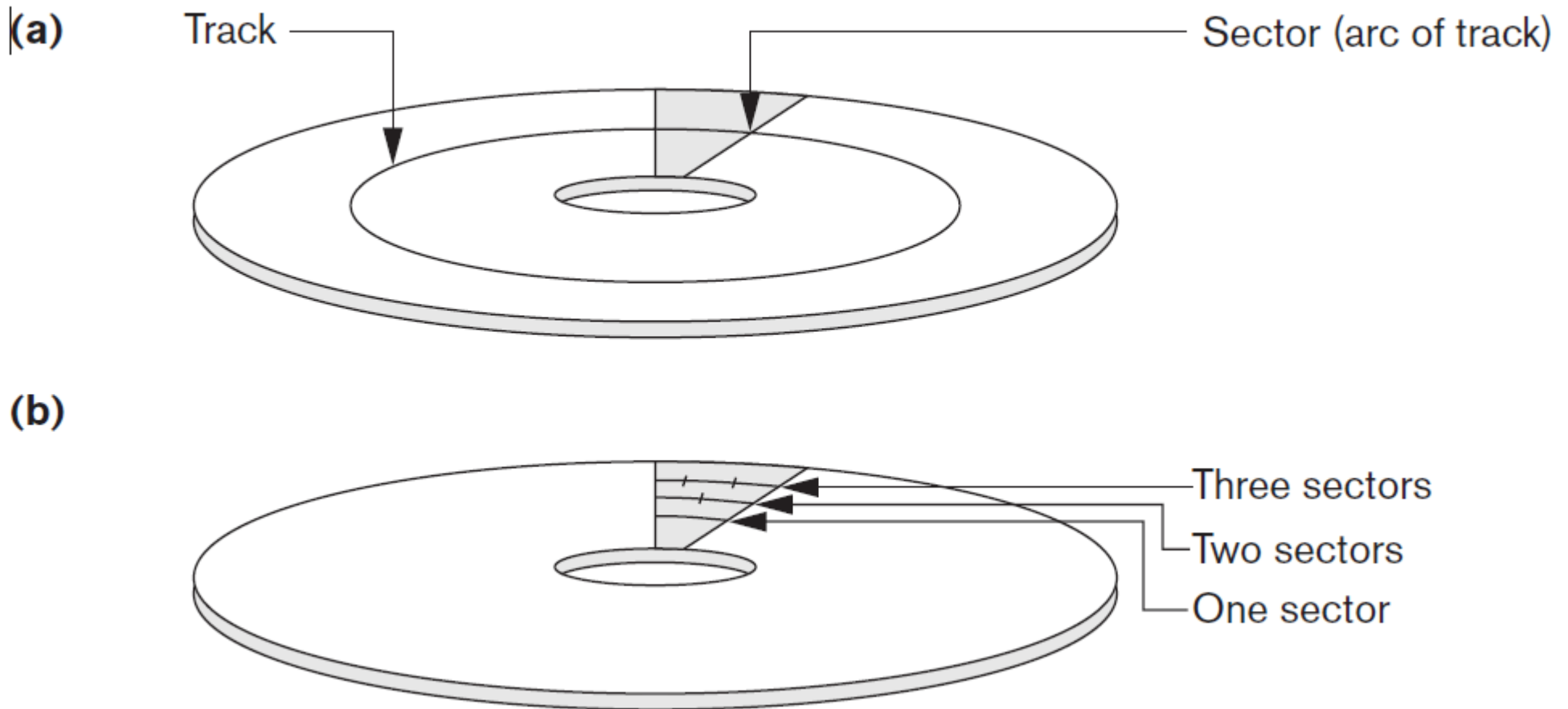
- Provides **efficient access via alternate fields**.
- Implemented mostly as **indexes**

Secondary Storage Devices



(a) A single-sided disk with read/write hardware. (b) A disk pack with read/write hardware.

Secondary Storage Devices



Different sector organizations on disk.

(a) Sectors subtending a fixed angle. (b) Sectors maintaining a uniform recording density

Techniques to Make Disk Data Access More Efficient

1. Buffering of Data

- Balances speed mismatch between CPU and slow HDD.
- Uses memory buffers to hold data temporarily.
- Double buffering improves throughput.

2. Proper Organization of Data on Disk

- Store related data in **contiguous blocks/cylinders**.
- Reduces arm movement and seek time.

3. Reading Data Ahead of Request (Prefetching)

- Reads additional consecutive blocks even if not requested.
- Works well for sequential access. Not effective for random access.

4. Proper Scheduling of I/O Requests

- Organizes block access to minimize arm movement.
- **Elevator algorithm (SCAN)** → services requests in one direction, then reverse

5. Use of Log Disks for Writes

- Dedicated disk (or area) used to store writes sequentially.
- Eliminates seek time.
- Improves write performance but adds cost.

6. Use of SSDs/Flash for Recovery

- SSD/flash used as fast **non-volatile buffer** for updates.
- Prevents update loss in case of system crash.
- Data is then written to HDD, reducing the time taken to write data to disk.

Secondary Storage Devices

Hardware Description of Disk Devices

Magnetic Disks (HDDs):

- ✓ Store large amounts of data.
- ✓ Basic unit: **bit** (0 or 1 via magnetization).
- ✓ Bits grouped into **bytes** (8 bits = 1 character, most common).
- ✓ Capacity = number of bytes it can store (modern disks → **hundreds of GBs to TBs**).

Disk Structure:

- ✓ Made of thin **circular magnetic material**, protected by cover.
- ✓ **Single-sided** (one surface used) or **double-sided** (both surfaces).
- ✓ Disks assembled into **disk packs** (multiple disks/surfaces).
- ✓ Common form factors: **3.5 inch, 2.5 inch**.
- ✓ Data stored in **tracks** (concentric circles).
- ✓ Tracks of same diameter across surfaces = **cylinder** → faster retrieval if data stored in one cylinder.

Secondary Storage Devices

Tracks, Sectors, and Blocks:

- ✓ Disk has **thousands of tracks** (up to ~152,000).
- ✓ Each track divided into **sectors** (fixed, hard-coded).
- ✓ Sector sizes: commonly **512 bytes**.
- ✓ Tracks also divided into **blocks/pages** (set during formatting).
- ✓ Typical block sizes: **512 bytes – several KB**.
- ✓ Several blocks = **cluster** (transferred as a unit).

Read/Write Mechanism:

- ✓ Performed by **disk head** attached to mechanical arm.
- ✓ Multiple surfaces → multiple heads, controlled together by **actuator motor**.
- ✓ Disk rotates continuously (speed: **5,400 – 15,000 rpm**).
- ✓ **Fixed-head disks**: one head per track → faster, but costly.
- ✓ **Movable-head disks**: common, cheaper.

Secondary Storage Devices

Disk Interfaces:

- ✓ **Older:** SCSI (Small Computer System Interface).
- ✓ **Modern:** SATA (Serial ATA) and SAS (Serial Attached SCSI).
- ✓ SATA: common in PCs (1.5 – 6 Gbps).
- ✓ SAS: used in servers, better **IOPS (Input/Output per second)**.
- ✓ Drive sizes:
- ✓ **3.5-inch:** up to 8 TB, 7,200–10,000 rpm.
- ✓ **2.5-inch:** up to 1.2 TB, up to 15,000 rpm.

Disk Access Times:

- ✓ **Seek Time:** Time to move head to correct track (3–10 ms).
- ✓ **Rotational Delay (Latency):** Time for block to rotate under head (depends on rpm; e.g., ~2 ms at 15,000 rpm).
- ✓ **Block Transfer Time:** Time to actually transfer data (smaller).
- ✓ Total = Seek Time + Rotational Delay + Transfer Time.
- ✓ Access time: ~**9 – 60 ms**.
- ✓ Contiguous block transfer much faster (saves seek/latency).

Secondary Storage Devices

Performance Bottleneck:

- ✓ Disk I/O is **slower** compared to CPU/main memory speeds.
- ✓ Hence, **file organization techniques** try to minimize block transfers.
- ✓ Goal: store **related info in contiguous blocks** to reduce delays.

Secondary Storage Devices

Performance Bottleneck:

- ✓ Disk I/O is **slower** compared to CPU/main memory speeds.
- ✓ Hence, **file organization techniques** try to minimize block transfers.
- ✓ Goal: store **related info in contiguous blocks** to reduce delays.

Placing File Records on Disk

- Data in a database is stored as **records** organized into **files**.
- A **record**: a collection of related data values (fields) representing an entity.
- A **record type**: defines the fields and their data types.
- Files contain sequences of records; placement affects performance
Each record describes an **entity** (e.g., EMPLOYEE).
- Fields have **data types**:
 - ✓ Numeric: integer, long, floating point
 - ✓ String: fixed-length or variable-length
 - ✓ Boolean: 0/1 or TRUE/FALSE
 - ✓ Date/Time: fixed-size format

Example in C:

```
struct employee {  
    char name[30];  
    char ssn[9];  
    int salary;  
    int job_code;  
    char department[20];  
};
```

File Types

Large Data Items

- ✓ **BLOB (Binary Large Object):** stores images, audio, video, or free text.
- ✓ Usually stored **separately** from the main record.
- ✓ Example: CLOB (Character Large Object) for free text.
- ✓ Alternatives:
 - Store as files in file systems
 - Store as files managed by database
 - Break into pieces and store in multiple tuples in separate relation
 - PostgreSQL TOAST
- **Fixed-length records:** all records same size.
- **Variable-length records:** record sizes differ due to:
 1. Variable-length fields (e.g., Name field)
 2. Repeating fields (multi-valued)
 3. Optional fields
 4. Mixed record types

File Types- Fixed-Length Records

- ✓ All fields have **fixed sizes** → predictable record length.
- ✓ Example: EMPLOYEE record = 71 bytes
- ✓ Easy to locate field values by byte offset.
- ✓ Limitation: wasted space for optional or repeating fields.
- ✓ Simple approach:
 - Store record i starting from byte $n * (i - 1)$, where n is the size of each record.
 - Record access is simple but records may cross blocks
 - Modification: do not allow records to cross block boundaries

File Types- Fixed-Length Records

record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4	32343	El Said	History	60000
record 5	33456	Gold	Physics	87000
record 6	45565	Katz	Comp. Sci.	75000
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology	72000
record 10	83821	Brandt	Comp. Sci.	92000
record 11	98345	Kim	Elec. Eng.	80000

Record 3 deleted

record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 4	32343	El Said	History	60000
record 5	33456	Gold	Physics	87000
record 6	45565	Katz	Comp. Sci.	75000
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record 9	76766	Crick	Biology	72000
record 10	83821	Brandt	Comp. Sci.	92000
record 11	98345	Kim	Elec. Eng.	80000

■ Deletion of record i : alternatives:

- move records $i + 1, \dots, n$ to $i, \dots, n - 1$
- move record n to i
- do not move records, but link all free records on a *free list*

File Types- Fixed-Length Records

- Deletion of record i : alternatives:
 - move records $i + 1, \dots, n$ to $i, \dots, n - 1$
 - **move record n to i**
 - do not move records, but link all free records on a *free list*

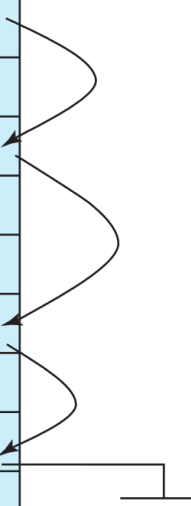
Record 3 deleted and replaced by record 11

record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 11	98345	Kim	Elec. Eng.	80000
record 4	32343	El Said	History	60000
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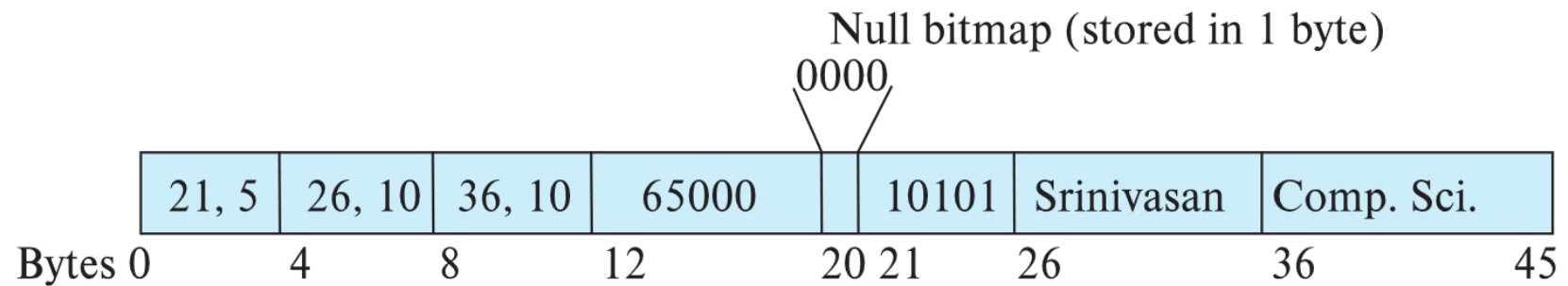
header				
record 0	10101	Srinivasan	Comp. Sci.	65000
record 1				
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4				
record 5	33456	Gold	Physics	87000
record 6				
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record 10	83821	Brandt	Comp. Sci.	92000
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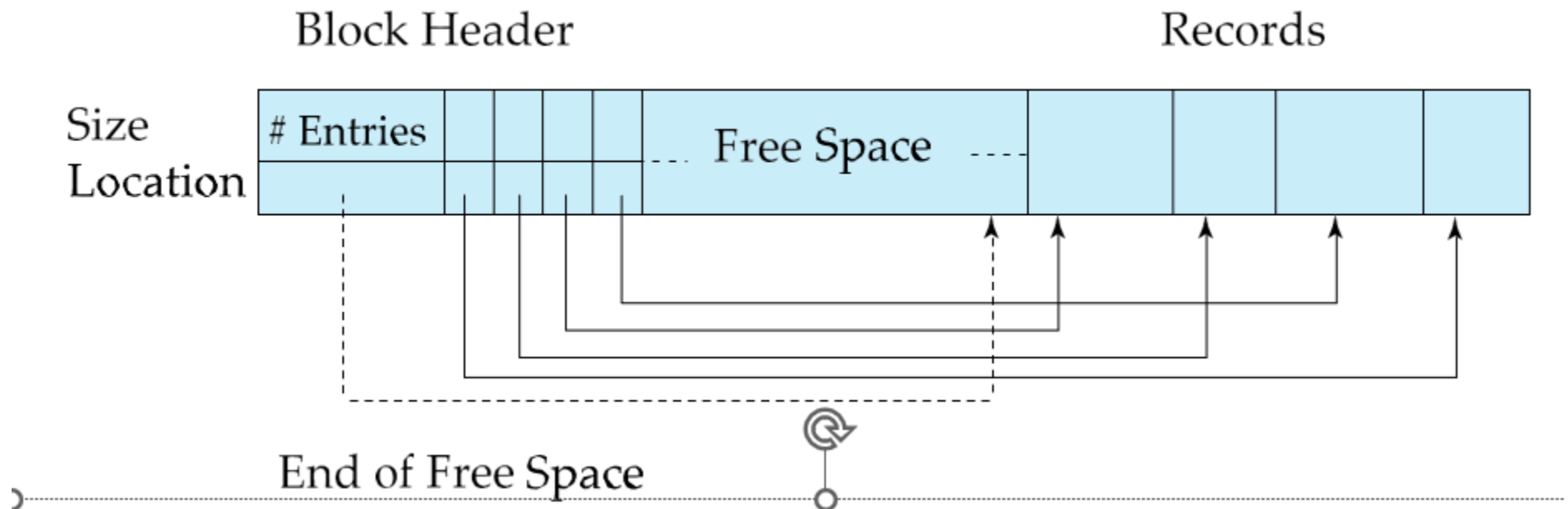
File Types- Variable-Length Records

- ✓ Field lengths can vary; require **special handling**:
 - **Separator characters** (e.g., ?, %, \$) between fields
 - **Field-name/value pairs** for optional fields
 - **Field-type/value pairs** for efficiency
 - Repeating fields: separators between values, terminator at end
- ✓ Variable-length records arise in database systems in several ways:
 - Storage of multiple record types in a file.
 - Record types that allow variable lengths for one or more fields such as strings (**varchar**)
 - Record types that allow repeating fields (used in some older data models).
- ✓ Attributes are stored in order
- ✓ Variable length attributes represented by fixed size (offset, length), with actual data stored after all fixed length attributes
- ✓ Null values represented by null-value bitmap

File Types- Variable-Length Records



Null values represented by null-value bitmap



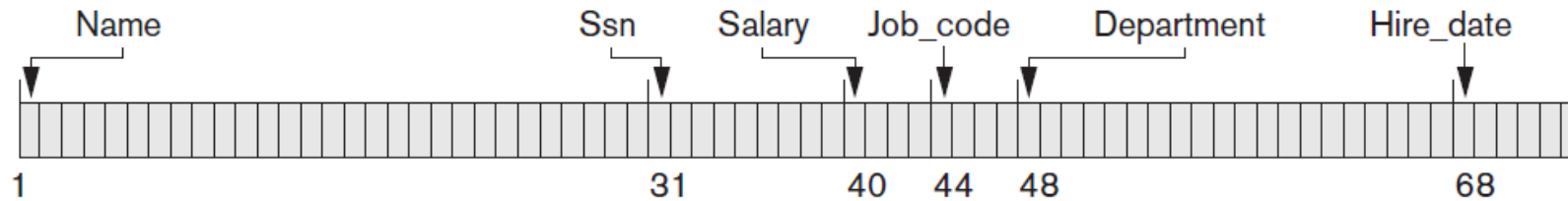
Slotted Page Structure

File Types- Variable-Length Records

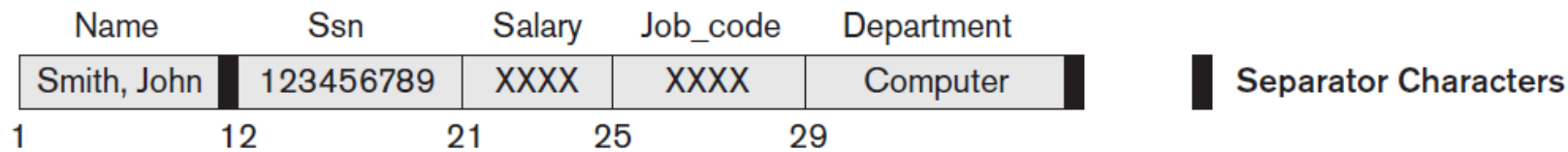
- **Slotted page** header contains:
 - number of record entries
 - end of free space in the block
 - location and size of each record
- Records can be moved around within a page to keep them contiguous with no empty space between them; entry in the header must be updated.
- Pointers should not point directly to record — instead they should point to the entry for the record in header.

File Types- Three record storage formats.

(a)



(b)



(c)



Separator Characters	
=	Separates field name from field value
█	Separates fields
⊠	Terminates record

Three record storage formats. (a) A fixed-length record with six fields and size of 71 bytes. (b) A record with two variable-length fields and three fixed-length fields. (c) A variable-field record with three types of separator characters.

Record Blocking and Spanned vs Unspanned Records

Disk Storage and File Organization

- ✓ Disk blocks are the **unit of data transfer** between disk and memory.
- ✓ Each block can store multiple records if the **block size (B) > record size (R)**.
- ✓ **Blocking factor (bfr)**: number of records per block

$$bfr = \lfloor B/R \rfloor$$

- ✓ Unused space per block:

$$B - (bfr \times R) \text{ bytes}$$

Record Blocking and Spanned vs Unspanned Records

Spanned Records :

- ✓ Part of a record can be stored on one block and the rest on another.
- ✓ Requires a **pointer** to the next block containing the remainder.
- ✓ **Advantages:**
 - Utilizes unused space efficiently
 - Useful for **records larger than a block**
- ✓ **Applicable to:** Fixed-length or variable-length records when record size $>$ block size

Record Blocking and Spanned vs Unspanned Records

UnSpanned Records :

- ✓ Records cannot cross block boundaries..
- ✓ Requires a **pointer** to the next block containing the remainder.
- ✓ **Advantages:**
 - Each record starts at a **known position** within a block
 - Simplifies **record processing**
- ✓ **Applicable to:** Fixed-length records where block size $>$ record size

Record Blocking and Spanned vs Unspanned Records

Choosing Between Spanned and Unspanned

Organization Type	Pros	Cons	Use Case
Spanned	Efficient space usage	More complex processing	Large or variable-length records
Unspanned	Simple processing	Wasted space in partially filled blocks	Fixed-length small records

File Block Allocation Techniques

Efficiently store file blocks on disk for fast access and expansion.

Common techniques:

1. Contiguous Allocation

- ✓ Blocks stored in consecutive disk locations
- ✓ Pros: Fast sequential read (double buffering)
- ✓ Cons: Difficult to expand file

2. Linked Allocation

- ✓ Each block contains a pointer to the next block
- ✓ Pros: Easy to expand file
- ✓ Cons: Slow sequential read

File Block Allocation Techniques

3. Combined/Clustered Allocation

- Groups of consecutive blocks (clusters) are linked
- Clusters also called file segments or extents

4. Indexed Allocation

- One or more index blocks store pointers to file blocks
- Often combined with other techniques

File Headers

- Metadata about the file needed for access.
- **Contents of a file header:**
 - Disk addresses of file blocks
 - Record format description
 - **Fixed-length unspanned records:** field lengths & field order
 - **Variable-length records:** field-type codes, separator characters, record type codes
- Programs use header information to locate and read records efficiently.

Searching Records Using File Headers

- When searching for a record:
 - Copy one or more blocks into **main memory buffers**
 - Use **file header info** to identify record location
- Without block address info: **linear search** through all blocks is needed
 - Time-consuming for large files
- **Goal of file organization:** Avoid linear search and minimize full file scans

Operations on Files

Two main categories:

- 1. Retrieval operations:** Locate records without changing data.
- 2. Update operations:** Change data by inserting, deleting, or modifying records.
 - Selection condition (filtering) used to locate records:
 - Example: (Ssn = '123456789')_{or} (Salary >= 30000 AND Department = 'Research')
 - Complex conditions are **decomposed** into simple conditions for locating records.

Record-at-a-Time Operations

Operations applied to a single record rather than multiple records simultaneously.

- **Open:** Prepare file for access, allocate buffers, read file header.
- **Reset:** Move file pointer to beginning.
- **Find / Locate:** Search for first record satisfying condition, load block into buffer.
- **Read / Get:** Copy current record into program variable, may advance pointer.
- **FindNext:** Locate next record satisfying condition.
- **Delete:** Remove current record from file.
- **Modify:** Change fields of current record.
- **Insert:** Add new record into file block and update disk.
- **Close:** Release buffers and complete file access.

Scan Operation and Set-at-a-Time Operations

Scan Operation

- Combines **Find**, **FindNext**, and **Read** into a single operation.
- Returns first or next record satisfying a condition.
- Simplifies sequential access for retrieval operations.

Set-at-a-Time Operations

Operate on multiple records at once:

- **FindAll**: Retrieve all records satisfying a condition.
- **Find n**: Retrieve first n records satisfying a condition.
- **FindOrdered**: Retrieve records in a specified order.
- **Reorganize**: Reorder records (e.g., by sorting) for efficiency.

File Organization vs Access Method and Considerations for File Organization

- ✓ **File organization:** How data is physically stored in records, blocks, and structures.
 - ✓ **Access method:** Set of operations applied to a file (e.g., Find, Scan).
 - ✓ Multiple access methods can operate on a single file organization.
 - ✓ Indexed access requires an index; not all methods are universally applicable
-
- Expected usage patterns influence organization:
 - **Static files:** mostly read-only, few updates
 - **Dynamic files:** frequent insert, delete, modify operations
 - Optimizing for common search conditions improves efficiency

Organization of Records in Files

- **Heap** – record can be placed anywhere in the file where there is space
- **Sequential** – store records in sequential order, based on the value of the search key of each record
- In a **multitable clustering file organization** records of several different relations can be stored in the same file
 - Motivation: store related records on the same block to minimize I/O
- **B⁺-tree file organization**
 - Ordered storage even with inserts/deletes
- **Hashing** – a hash function computed on search key; the result specifies in which block of the file the record should be placed

Heap File Organization

- Heap file = simplest and most basic file organization.
- Records are stored in the order they are inserted (**no sorting**).
- **New records are appended to the end of the file.**
- Commonly used for:
 - Collecting and storing records for future use.
 - Supporting secondary indexes for faster access.
 - Easy insertion, but searching and deletion are less efficient.

Insertion

Very efficient operation:

- Copy the last disk block into buffer.
- Add new record into buffer.
- Write block back to disk.
- File header keeps address of the last block.
- Minimal overhead compared to other organizations.

Heap File Organization

Searching

- No ordering of records → requires **linear search**.
- Must scan block by block until condition is met.
- Average cost:
 - If one record satisfies condition → $\sim b/2$ blocks must be checked (where b = number of blocks).
 - If no records (or multiple records) match → all b blocks must be scanned.
- Searching is expensive for large files.

Deletion

Two main methods:

1. Physical Deletion

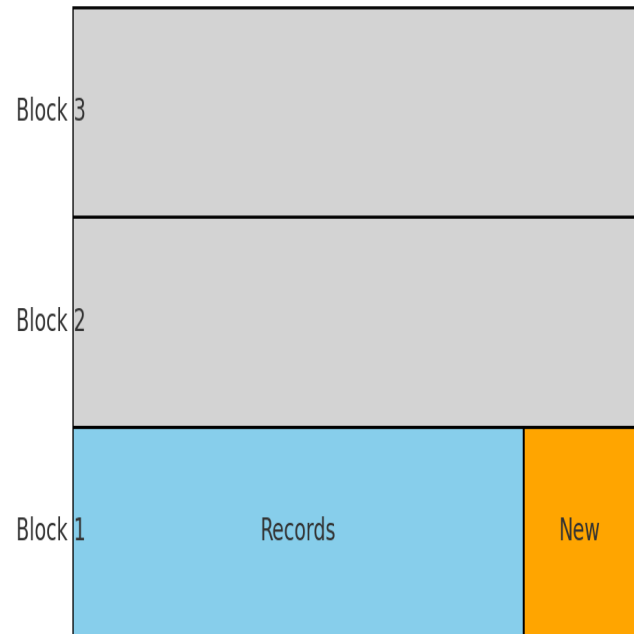
- Find the block, load into buffer, delete record, write back.
- Leaves unused space in the block.
- Deleting many records wastes storage space.

2. Logical Deletion (Deletion Marker)

- Add an extra bit/byte to mark record as deleted.
- Valid records are those without deletion marker.
- Both methods require **periodic reorganization** to reclaim unused space.

Heap File Organization

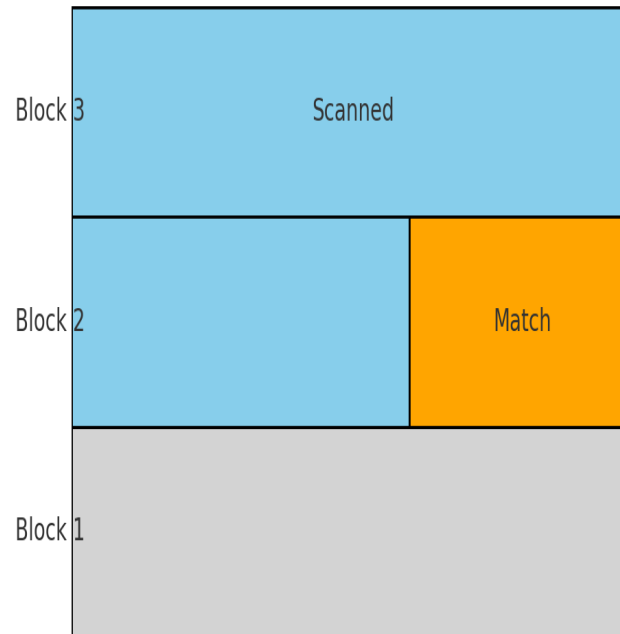
Heap File: Insertion



Insertion

- New records are always added at the **end of the file (last block)**.
- Example: Orange block = newly inserted record.

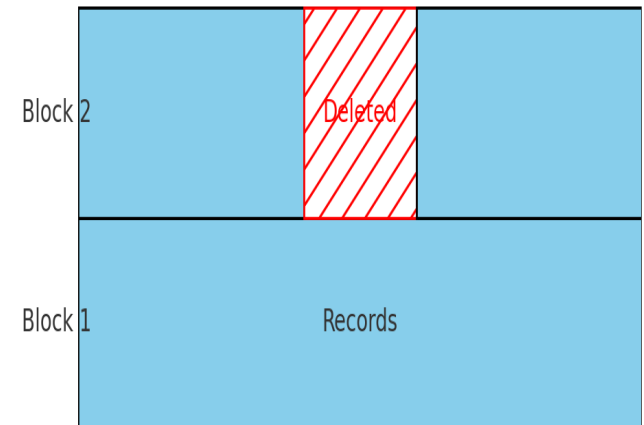
Heap File: Searching



Searching

- Searching requires a **linear scan**.
- Blocks are checked one by one until the match is found.
- Example: Blue = scanned, Orange = matching record found.

Heap File: Deletion



Deletion

- To delete, the record is located and removed.
- This leaves **unused space** (shown with red hatched area).
- Over time, too many deletions waste space → requires **reorganization**.

Heap File Organization

Reorganization

- Required when many deletions have occurred.
- Process:
 - Sequentially access all blocks.
 - Pack valid records together, remove deleted ones.
 - Fill blocks to full capacity again.
- Alternative approach:
 - Reuse deleted record space during new insertions.
 - Requires bookkeeping to track free space.

Heap - Record Organization Options

Spanned vs. Unspanned Organization:

- Spanned: Records can span across multiple blocks.
- Unspanned: Each record fits entirely within a single block.

Fixed-Length vs. Variable-Length Records:

Fixed: Easier to manage and access.

Variable: More flexible, but modification may require deletion + reinsertion.

Sorting records:

To read in sorted order, file must be copied and sorted.

Sorting is expensive for large files → **external sorting** is used.

Heap File Organization

Relative (Direct) Files

- Special type of unordered file with **fixed-length records + unspanned blocks**.
- Allows **direct access to records by position**:
 - If file has r records numbered $0 \dots r-1$, and block has bfr (blocking factor) records:
 - Record i is located in block $\lfloor i / bfr \rfloor$
 - Position = $(i \bmod bfr)$ in that block.
- Provides **direct positional access** (efficient).
- Still does not help with conditional searches.
- Useful for building access paths like indexes.

Heap File Organization

Need for Free-Space Tracking

- Since records can go into **any available free space**, the system must be able to **quickly find blocks with enough empty space**.
- If we scan every block to find free space, it becomes **very expensive**.
- Solution: use a **Free-Space Map**.

Free-Space Map

- A **free-space map** is an **array** with one entry per block in the file
- Each entry is only a few **bits or a byte**, recording the **fraction of the block that is free**.

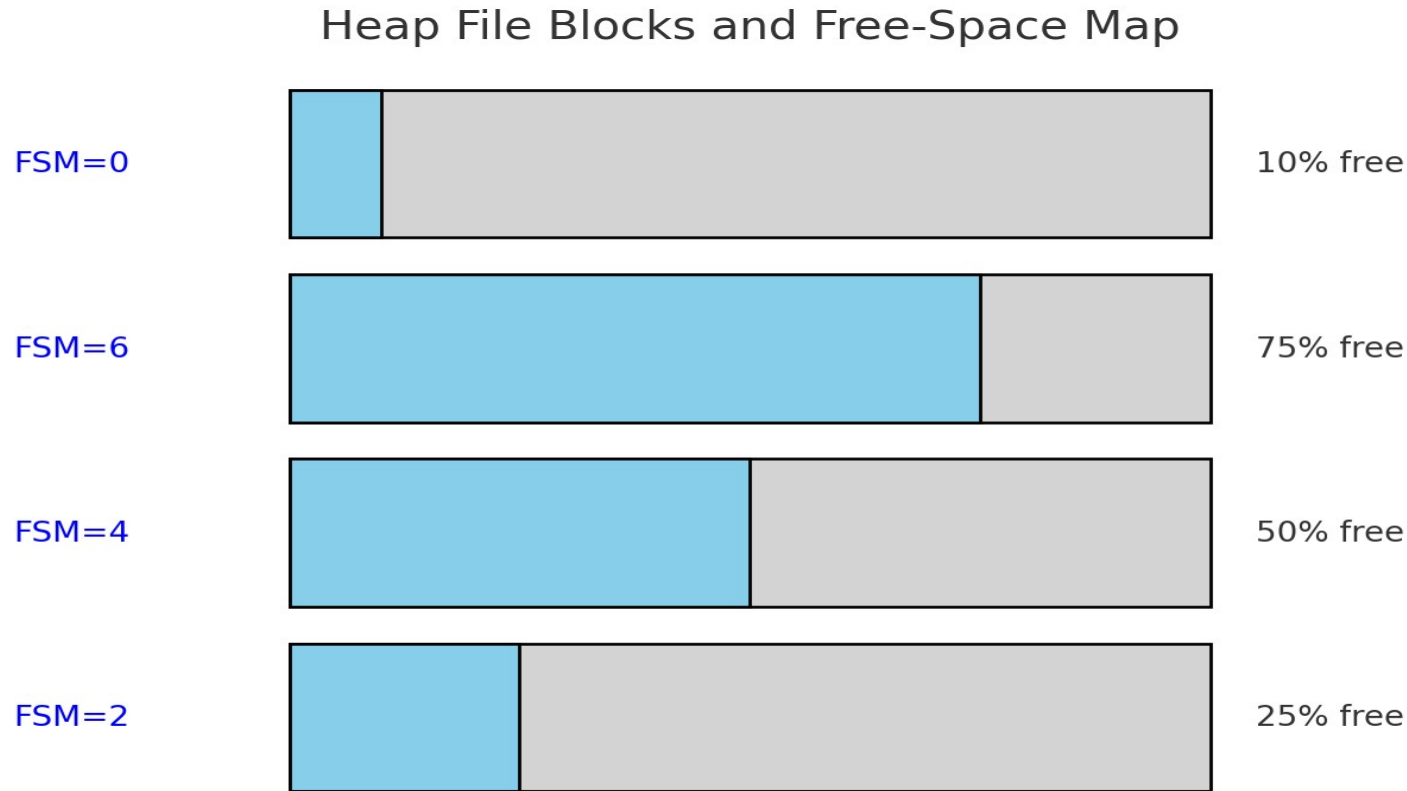
Example:

Using 3 bits per block.

Value $\div 8$ gives the fraction of free space.

If value = 4, it means half ($4/8 = 0.5$) of the block is free.

Heap File Organization- Free space map



- Each horizontal bar = one disk block.
- **Blue portion** = free space in the block.
- **Grey portion** = occupied records.
- **FSM value** (on the left) shows what is stored in the free-space map (scaled using few bits).
- **% free** (on the right) indicates the actual free space available.

Heap File Organization- Free space map

Suppose each disk block has a fixed size, say **8 KB (8192 bytes)**
Free-Space Map (FSM) does **not store exact bytes free**.

Example:

if FSM uses **3 bits per block**, it can represent values from 0 to 7 .

$$\text{Fraction Free} = \text{FSM Value} / 8$$

If FSM = 2

$$\text{Fraction Free} = 2 \div 8 = 0.25$$

So **25% of block is free**.

$$\text{If block size} = 8 \text{ KB} \rightarrow \text{Free space} = 0.25 \times 8192 = \mathbf{2048 \text{ bytes}}.$$

Similarly,

- FSM = 0 \rightarrow 0% free \rightarrow Block is full.
- FSM = 4 \rightarrow 50% free \rightarrow 4 KB free in an 8 KB block.
- FSM = 6 \rightarrow 75% free \rightarrow 6 KB free in an 8 KB block.
- FSM = 7 \rightarrow 100% free \rightarrow Entire block is empty.

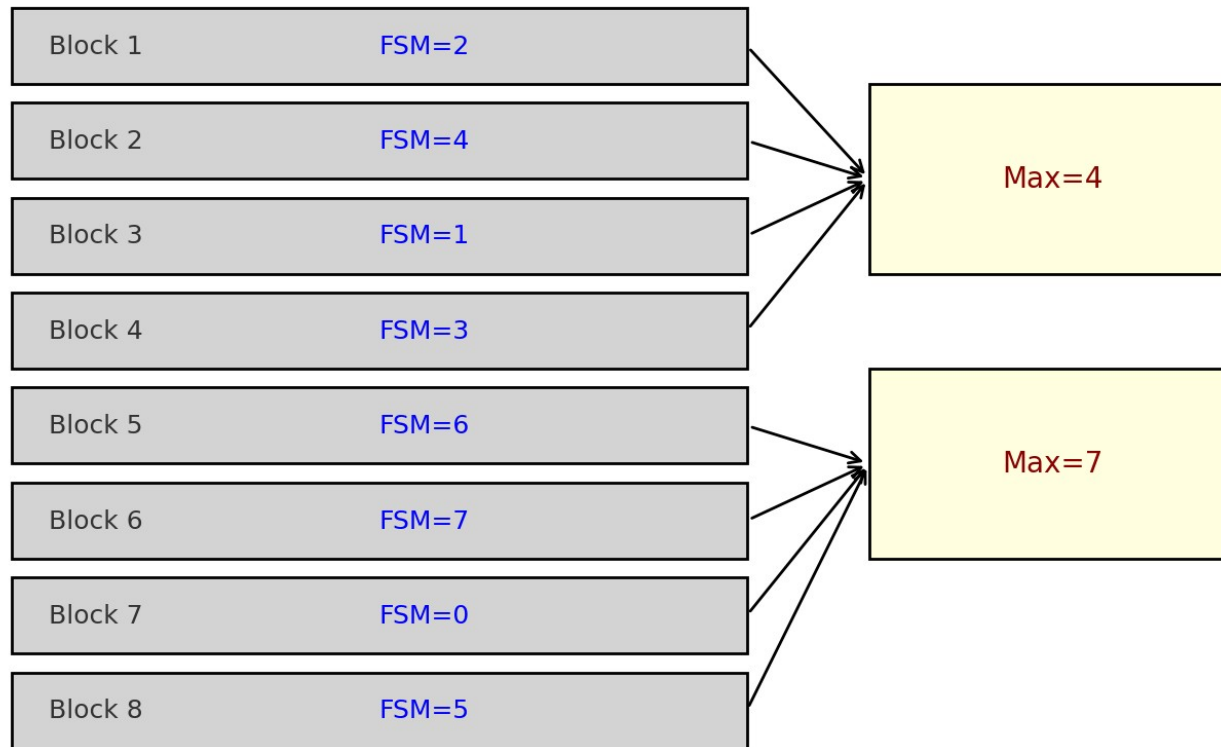
Heap File Organization

Second-Level Free-Space Map

- For **very large files**, scanning the entire first-level map is still expensive.
- A **second-level map** is created, where each entry stores the **maximum free space value** of a group of first-level entries.
- Example:
 - Each second-level entry summarizes 4 first-level entries.
 - This allows the system to **quickly locate a region** where enough free space exists, and then check only a few blocks in detail.

Heap File Organization

Second-Level Free-Space Map



- **Left side:** First-level FSM values (one entry per block, 0–7 scale).
- **Right side:** Second-level FSM entries. Each summarizes **4 blocks** by storing the **maximum free space value** among them.
- Arrows show how groups of 4 blocks are linked to one second-level entry. This hierarchy lets the system quickly skip over groups of blocks and find a region with enough space for insertion, instead of scanning every block's entry.

Heap File Organization

- **Block size** = 8 KB (8192 bytes)
- **FSM uses 3 bits per block** → values 0–7 (bucketed free space)
 - We'll store **$\text{floor}(8 \times \text{free_fraction})$** in FSM, so an FSM value of k means **at least $k/8$ of the block is free** (may be more).
- **Record to insert = 3 KB**

Required fraction = $3/8 = 0.375$ → **required FSM bucket = 3**
(since $\text{floor}(8 \times 0.375) = 3$).

Maps (same numbers as the diagram)

First-level FSM (8 blocks):

[2, 4, 1, 3, 6, 7, 0, 5]

(so Block1=2, Block2=4, ..., Block8=5)

Second-level FSM (groups of 4 blocks):

- Group A (Blocks 1–4) → $\text{max} = 4$
- Group B (Blocks 5–8) → $\text{max} = 7$

Heap File Organization

Insertion using the maps (step-by-step)

1. Use second-level to choose a group needing at least bucket 3.

1. Group A has $\text{max}=4$ (≥ 3) \rightarrow **eligible**

2. Group B has $\text{max}=7$ (≥ 3) \rightarrow also eligible

Pick the first eligible group to minimize seek (say **Group A**, Blocks 1-4).

2. Scan first-level entries within Group A for the first block with value ≥ 3 :

1. Block1 = 2

2. Block2 = 4 (means $\geq 4/8 = 50\%$ free $\rightarrow \geq 4$ KB free)

Choose **Block2**.

3. Validate actual free bytes in Block2 (quick header check).

1. Suppose Block2 actually has **4.2 KB free** (FSM rounded down to bucket 4).

2. 4.2 KB \geq 3 KB, so the record **fits**.

4. Insert record into Block2.

1. New free space in Block2 $\approx 4.2 - 3.0 = 1.2$

Heap File Organization

Update maps

1. First-level: Block2 value goes **4** → **1**.
2. Second-level Group A becomes $\max(2, 1, 1, 3) = 3$ (was 4 before).

(We write the updated entries eventually; it's OK if the persisted map lags a bit.)

What if a value was stale?

Say we had picked **Block8** (FSM=5) but it actually had only **2.5 KB free** (because the FSM entry wasn't updated yet).

- On validation, we detect **2.5 KB < 3 KB**, so we **fail the placement, downgrade Block8's FSM** to the correct bucket (2), and **retry**:
 - Group B's max might still be ≥ 3 (because of other blocks), so we try the next eligible block in that group; otherwise we fall back to Group A.

Heap File Organization

- Required bucket for a record of size S in a block of size B :

$$k_{\text{req}} = \left\lceil 8 \times \frac{S}{B} \right\rceil$$

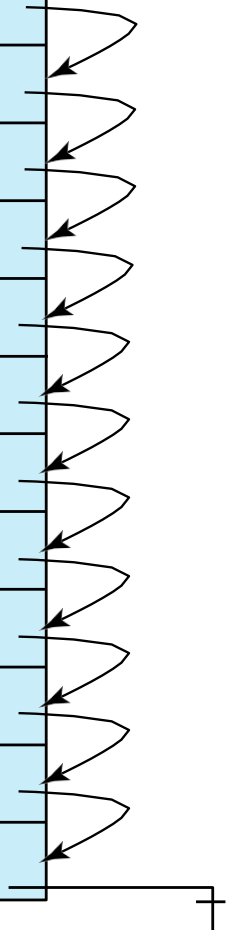
- FSM bucket for a block with F bytes free:

$$k = \left\lceil 8 \times \frac{F}{B} \right\rceil$$

Sequential File Organization

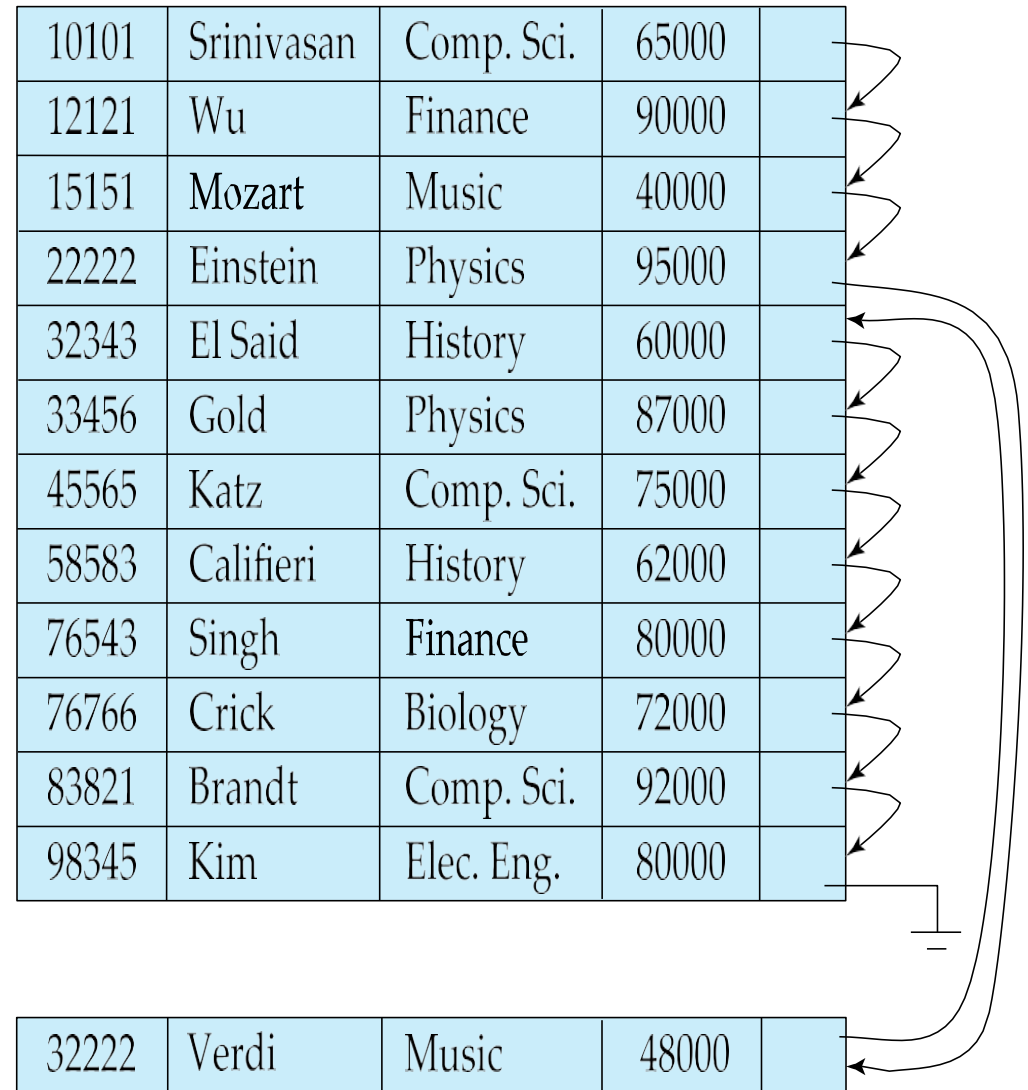
- Suitable for applications that require sequential processing of the entire file
- The records in the file are ordered by a **search-key**

10101	Srinivasan	Comp. Sci.	65000	
12121	Wu	Finance	90000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
32343	El Said	History	60000	
33456	Gold	Physics	87000	
45565	Katz	Comp. Sci.	75000	
58583	Califieri	History	62000	
76543	Singh	Finance	80000	
76766	Crick	Biology	72000	
83821	Brandt	Comp. Sci.	92000	
98345	Kim	Elec. Eng.	80000	



Sequential File Organization (Cont.)

- Deletion – use pointer chains
- Insertion – locate the position where the record is to be inserted
 - if there is free space insert there
 - if no free space, insert the record in an **overflow block**
 - In either case, pointer chain must be updated
 - Need to reorganize the file from time to time to restore sequential order



Multitable Clustering File Organization

Store several relations in one file using a **multitable clustering** file organization

department

<i>dept_name</i>	<i>building</i>	<i>budget</i>
Comp. Sci.	Taylor	100000
Physics	Watson	70000

instructor

<i>ID</i>	<i>name</i>	<i>dept_name</i>	<i>salary</i>
10101	Srinivasan	Comp. Sci.	65000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
83821	Brandt	Comp. Sci.	92000

multitable clustering
of *department* and
instructor

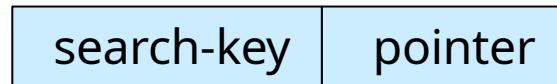
Comp. Sci.	Taylor	100000	
10101	Srinivasan	Comp. Sci.	65000
45565	Katz	Comp. Sci.	75000
83821	Brandt	Comp. Sci.	92000
Physics	Watson	70000	
33456	Gold	Physics	87000

Multitable Clustering File Organization (cont.)

- good for queries involving *department* \bowtie *instructor*, and for queries involving one single department and its instructors
- bad for queries involving only *department*
- results in variable size records
- Can add pointer chains to link records of a particular relation

Indexing- Basic Concepts

- Indexing mechanisms used to speed up access to desired data.
 - E.g., author catalog in library
- **Search Key** - attribute to set of attributes used to look up records in a file.



- An **index file** consists of records (called **index entries**) of the form
 - Index files are typically much smaller than the original file
 - Two basic kinds of indices:
 - **Ordered indices:** search keys are stored in sorted order
 - Hash indices: search keys are distributed uniformly across “buckets” using a “hash function”.

Index Evaluation Metrics

- Access types supported efficiently.
 - records with a specified value in the attribute
 - or records with an attribute value falling in a specified range of values.
- Access time
- Insertion time
- Deletion time
- Space overhead

Ordered Indices

Indexing techniques evaluated on basis of:

- In an **ordered index**, index entries are stored sorted on the search key value. E.g., author catalog in library.
- **Primary index**: in a sequentially ordered file, the index whose search key specifies the sequential order of the file.
 - Also called **clustering index**- defined on non-key ordering field (multiple records can share value).
 - The search key of a primary index is usually but not necessarily the primary key.
- **Secondary index**: an index whose search key specifies an order **different from the sequential order of the file**. Also called **non-clustering index**.
- **Index-sequential file**: ordered sequential file with a primary index.

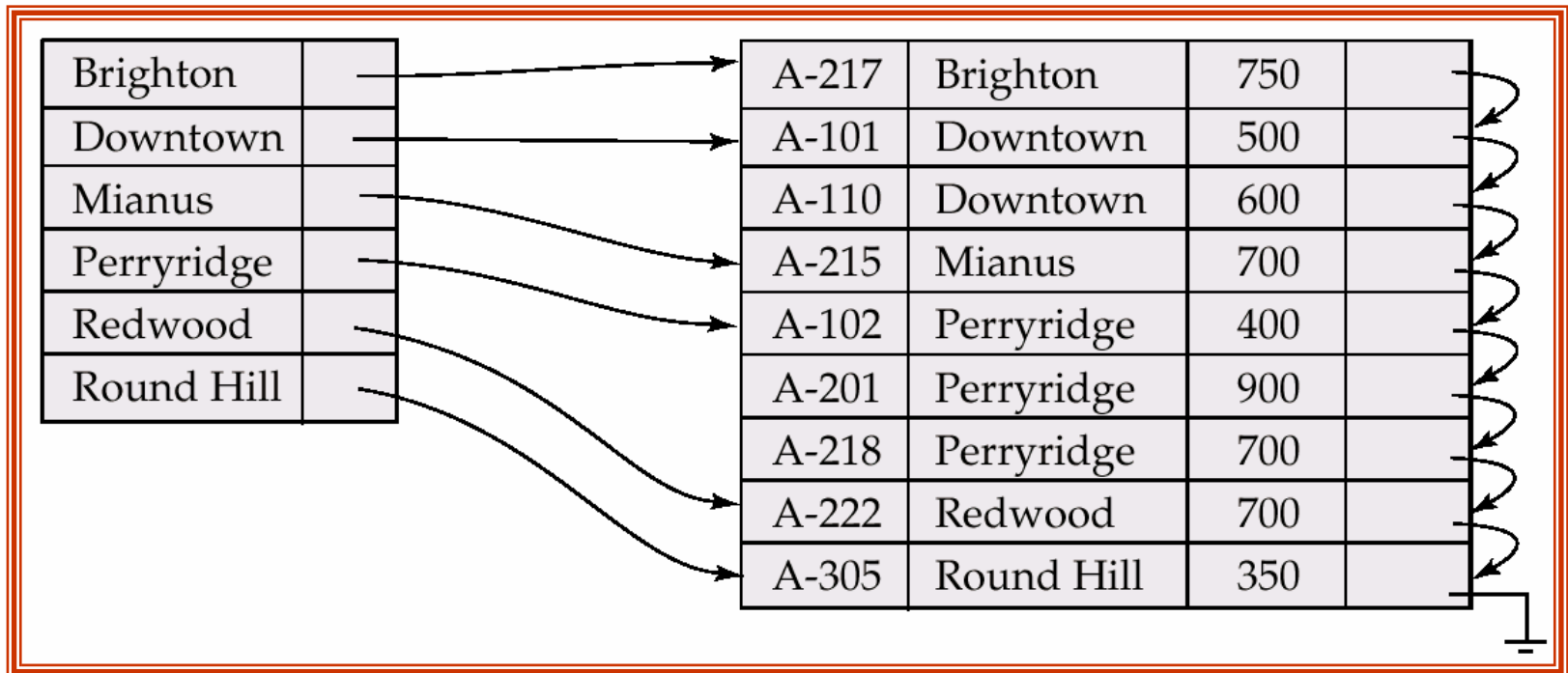
Ordered Indices

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 - The search key of a primary index is usually but not necessarily the primary key.
- **Secondary index**: an index whose search key specifies an order different from the sequential order of the file. Also called **non-clustering index**.
- **Index-sequential file**: ordered sequential file with a primary index.

Dense Index Files

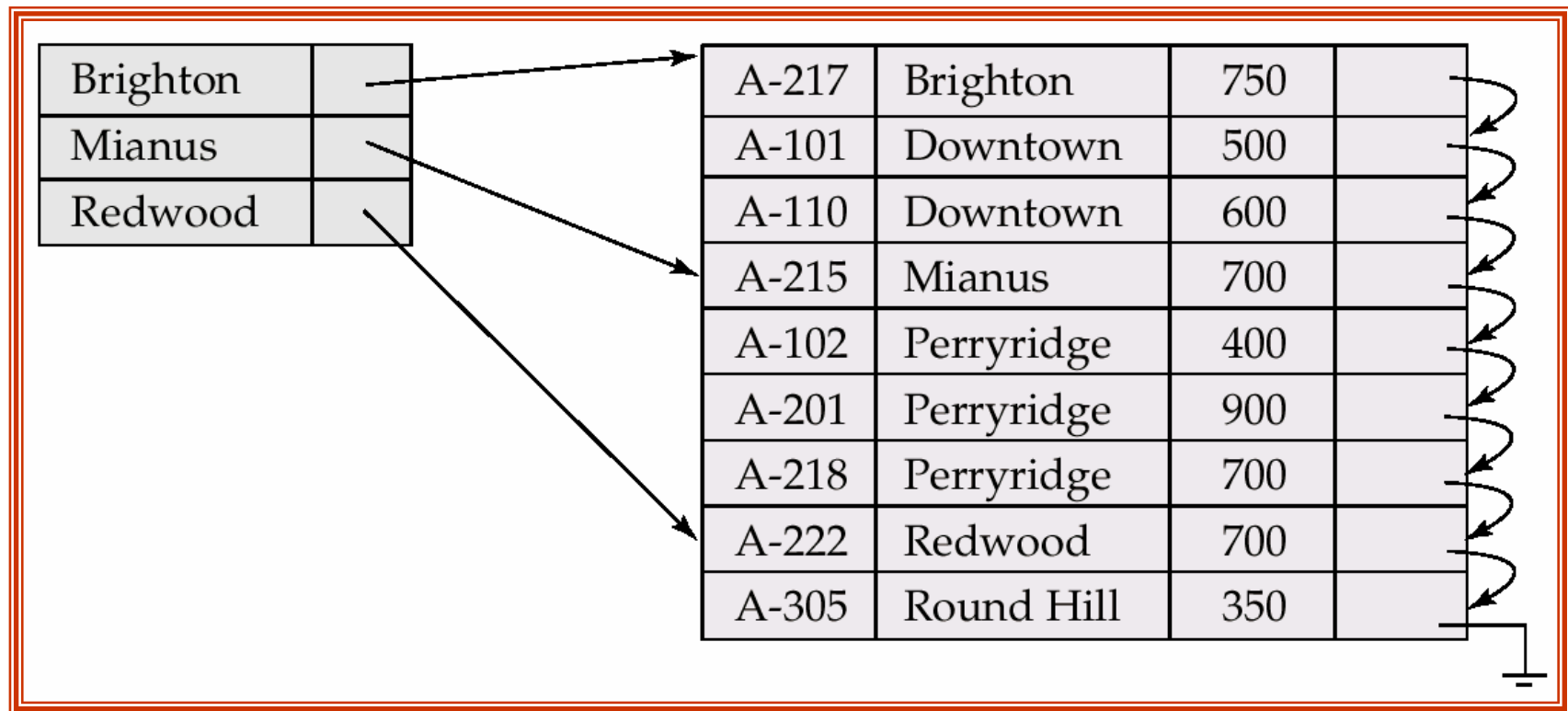
- **Dense index** — Index record appears for every search-key value in the file.



Sparse Index Files

- **Sparse Index:** contains index records for only some search-key values.
 - Applicable when records are sequentially ordered on search-key
- To locate a record with search-key value K we:
 - Find index record with largest search-key value $< K$
 - Search file sequentially starting at the record to which the index record points
- Less space and less maintenance overhead for insertions and deletions.
- Generally slower than dense index for locating records.
- Good tradeoff: sparse index with an index entry for every block in file, corresponding to least search-key value in the block.

Example of Sparse Index Files



Dense vs Sparse Index

- **Dense Index:** One entry per record.
- **Sparse Index:** One entry per block (Primary Index).
 - Primary Index = **Sparse**.
 - Advantage:
 - Index file much smaller than data file.
 - Faster binary search.

Searching with Primary Index

- Binary search performed on index file (with b_i blocks).
- Total accesses = $\log_2(b_i) + 1$
 - $\log_2(b_i) \rightarrow$ binary search on index file.
 - $+1 \rightarrow$ access data block.
- Example:
 - Data file = 1,000 blocks.
 - Index file = 100 blocks.
 - Binary search index = $\log_2(100) \approx 7$.
 - Access data block = 1.
 - Total \approx **8 accesses vs 10 on data file.**

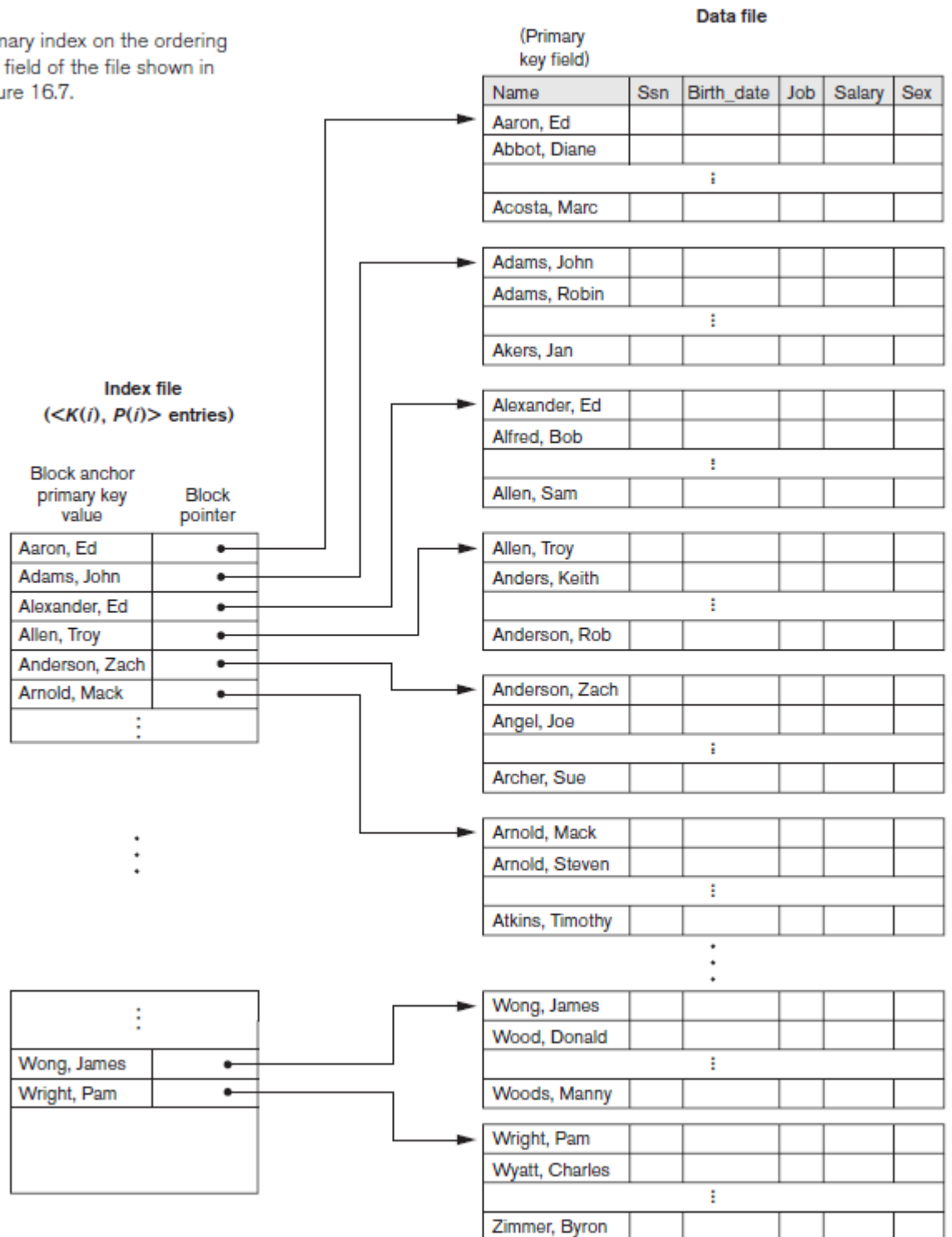
Clustering Index

- Defined on a **non-key ordering field**.
- File = **clustered file**.
- Example: Records ordered by *Department*, but many employees may share same department.
- Index entry contains:
 - Value of clustering field.
 - Pointer to block containing first occurrence.

Primary Index

- Built on **ordering key field** of an ordered file.
- One entry per block.
- Each entry $\langle K(i), P(i) \rangle$ contains:
 - $K(i)$** : first key (anchor record) in block i .
 - $P(i)$** : pointer to block i .
- Example:
 - $\langle (\text{Aaron, Ed}), P(1) \rangle \rightarrow \text{Block 1}$
 - $\langle (\text{Adams, John}), P(2) \rangle \rightarrow \text{Block 2}$

Primary index on the ordering key field of the file shown in Figure 16.7.



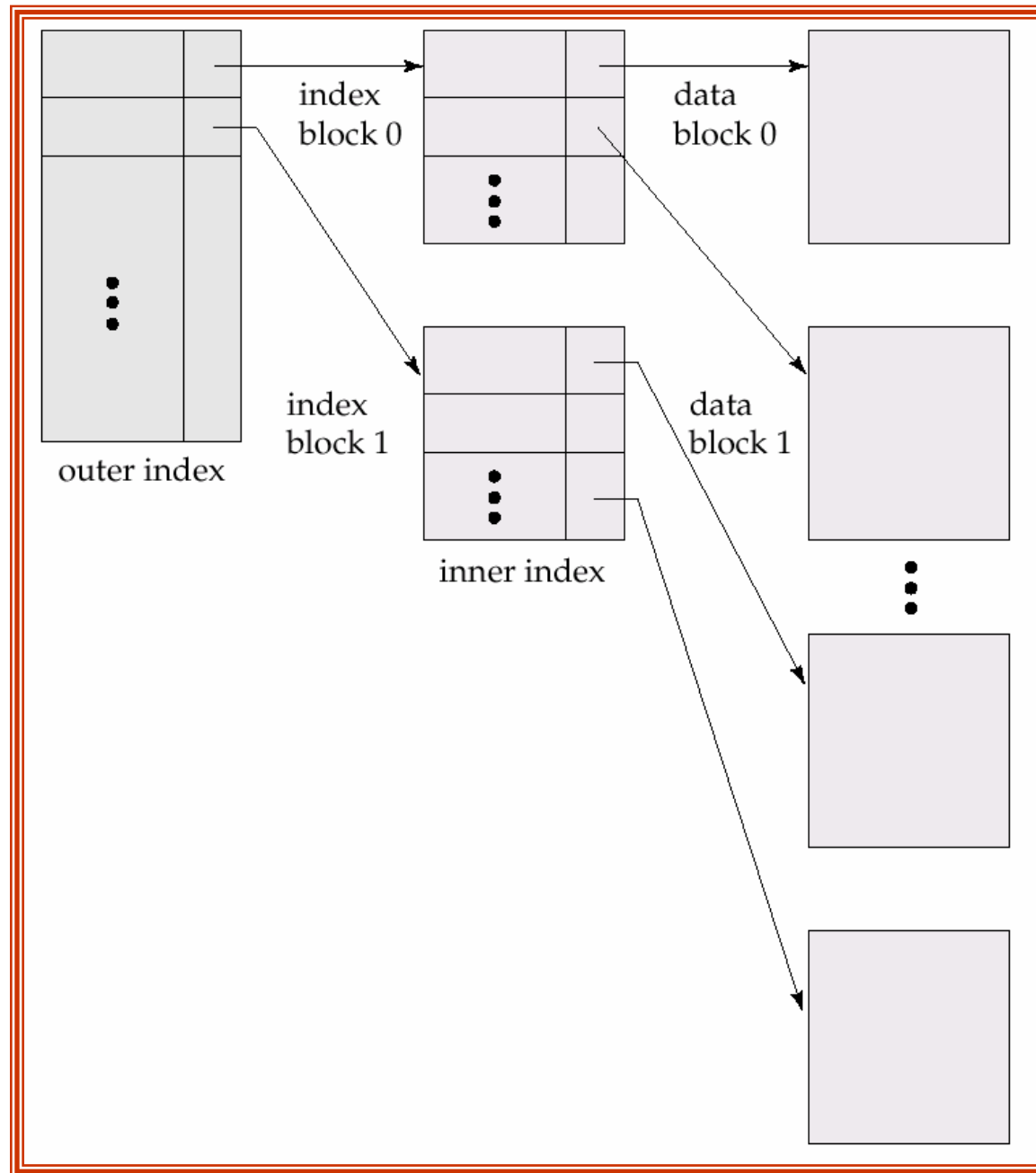
Secondary Index

- Built on a **nonordering field** (not sorted in file).
- Separate access path.
- Can be **dense** (usually 1 entry per record).
- More expensive in terms of storage.

Multilevel Index

- If primary index does not fit in memory, access becomes expensive.
- To reduce number of disk accesses to index records, treat primary index kept on disk as a sequential file and construct a sparse index on it.
 - outer index – a sparse index of primary index
 - inner index – the primary index file
- If even outer index is too large to fit in main memory, yet another level of index can be created, and so on.
- Indices at all levels must be updated on insertion or deletion from the file.

Multilevel Index (Cont.)



Index Update: Deletion

- If deleted record was the only record in the file with its particular search-key value, the search-key is deleted from the index also.
- Single-level index deletion:
 - Dense indices – deletion of search-key is similar to file record deletion.
 - Sparse indices – if an entry for the search key exists in the index, it is deleted by replacing the entry in the index with the next search- key value in the file (in search-key order). If the next search-key value already has an index entry, the entry is deleted instead of being replaced.

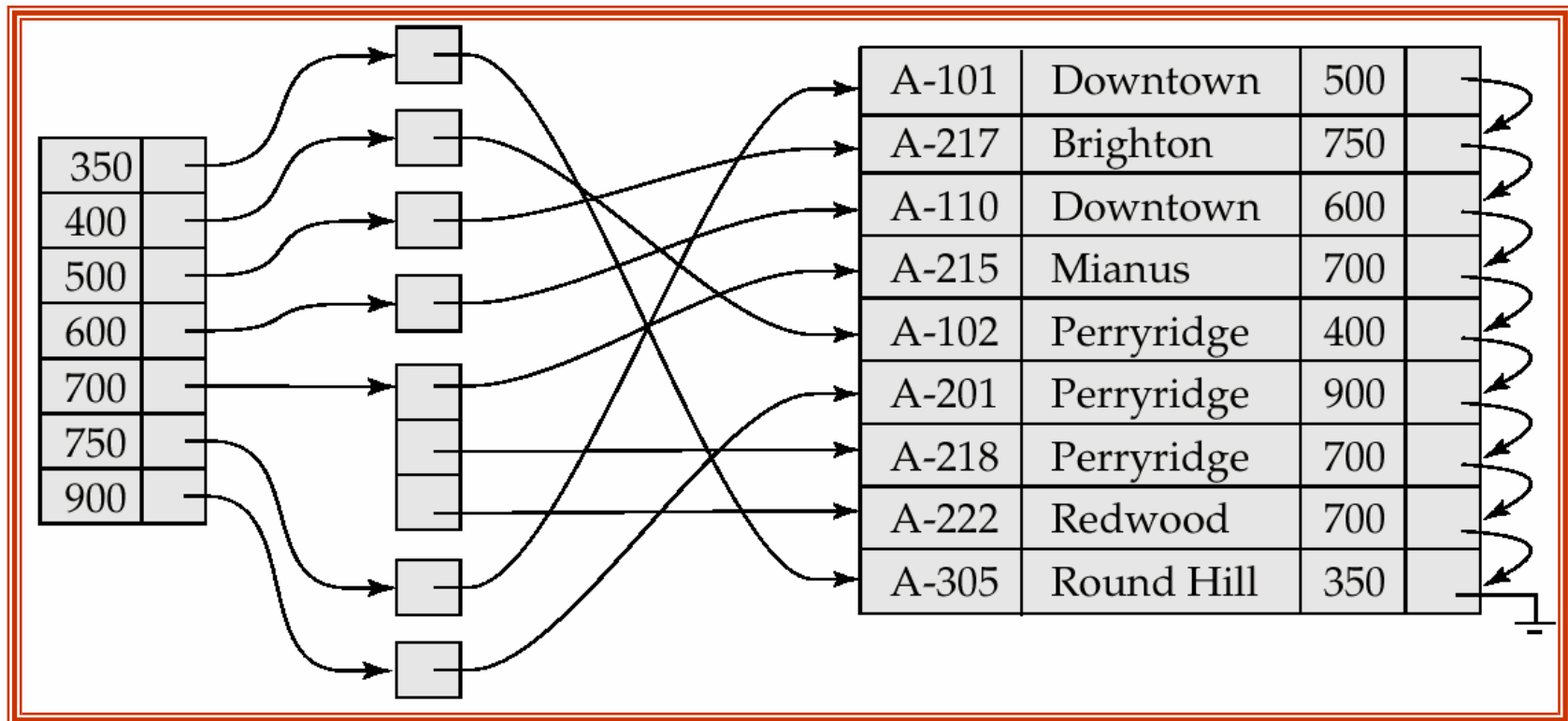
Index Update: Insertion

- Single-level index insertion:
 - Perform a lookup using the search-key value appearing in the record to be inserted.
 - Dense indices – if the search-key value does not appear in the index, insert it.
 - Sparse indices – if index stores an entry for each block of the file, no change needs to be made to the index unless a new block is created. In this case, the first search-key value appearing in the new block is inserted into the index.
- Multilevel insertion (as well as deletion) algorithms are simple extensions of the single-level algorithms

Secondary Indices

- Frequently, one wants to find all the records whose values in a certain field (which is not the search-key of the primary index satisfy some condition.
 - Example 1: In the *account* database stored sequentially by account number, we may want to find all accounts in a particular branch
 - Example 2: as above, but where we want to find all accounts with a specified balance or range of balances
- We can have a secondary index with an index record for each search-key value; index record points to a bucket that contains pointers to all the actual records with that particular search-key value.

Secondary Index on *balance* field of *account*



Primary and Secondary Indices

- Secondary indices have to be dense.
- Indices offer substantial benefits when searching for records.
- When a file is modified, every index on the file must be updated, Updating indices imposes overhead on database modification.
- Sequential scan using primary index is efficient, but a sequential scan using a secondary index is expensive
 - each record access may fetch a new block from disk

Binary Search for Disk Files

- Records in a file are stored across **b blocks** (numbered 1, 2, ..., b).
- Records are sorted by their **ordering key field**.
- Goal: efficiently search for a record with key **K**.
- Disk block addresses are stored in the **file header**

Uses **divide and conquer** principle:

- Check middle block.
- If K is smaller, search left half.
- If K is larger, search right half.
- Repeat until found or search space is empty.

Linear Search (Traditional Method)

- Sequentially checks blocks one by one.
- **Average Case:** $\sim b/2$ block accesses if record is found.
- **Worst Case:** b block accesses if record is not found.
- Inefficient for large files.

Binary Search Approach

- Works on **blocks**, not individual records.
- Uses **divide and conquer** principle:
- Check middle block.
- If K is smaller, search left half.
- If K is larger, search right half.
- Repeat until found or search space is empty

Algorithm (Binary Search on Blocks)

1. Set $low = 1$, $high = b$.
2. While $low \leq high$:
 1. $mid = (low + high)/2$.
 2. Read $block[mid]$.
 3. If K is in $block[mid] \rightarrow$ **record found**.
 4. Else if $K < \text{first key of } block[mid] \rightarrow$ set $high = mid - 1$.
 5. Else \rightarrow set $low = mid + 1$.
3. If no match \rightarrow **record not found**.

Binary Search Approach

Suppose a file has **b = 8 blocks**, each containing sorted records by **Roll No.**

Block No	First Record Key	Last Record Key
1	1	100
2	101	200
3	201	300
4	301	400
5	401	500
6	501	600
7	601	700
8	701	800

We want to **search for Roll No = 630**.

Step 1: Initialization

- Low = 1, High = 8

Step 2: Midpoint Block

- Mid = $(1+8)/2 = 4.5 \approx 4$
- Block 4 range = 301–400
- Since **630 > 400**, search right half
→ Low = 5, High = 8

Step 3: Next Midpoint

- Mid = $(5+8)/2 = 6.5 \approx 6$
- Block 6 range = 501–600
- Since **630 > 600**, search right half
→ Low = 7, High = 8

Step 4: Next Midpoint

- Mid = $(7+8)/2 = 7.5 \approx 7$
- Block 7 range = 601–700
- Since **630 lies in 601–700**, target block = 7

Step 5: Search Inside Block

- Binary search now continues **inside block 7**.
- Records in Block 7 are scanned (either sequentially or with binary search, if block itself is indexed).
- Record 630 is **found in Block 7**.

Analysis of Accesses

- Blocks checked: **Block 4** → **Block 6** → **Block 7**
- Total = **$\log_2(8) = 3$ block accesses**
- Much better than Linear Search:
 - Average = $8/2 = 4$ accesses
 - Worst case = 8 accesses

Performance Comparison

- **Binary Search:**
 - Accesses $\approx \log_2(\mathbf{b})$ blocks.
 - Independent of whether record is found or not.
- **Linear Search:**
 - Average: $\mathbf{b}/2$ blocks.
 - Worst: \mathbf{b} blocks.
- Binary search is much faster for large files.

Example

- Suppose file has $\mathbf{b} = 1024$ blocks.
- **Linear search:** ~ 512 accesses (avg).
- **Binary search:** $\log_2(1024) = 10$ accesses only.

Table 16.3 Average Access Times for a File of b Blocks under Basic File Organizations

Type of Organization	Access/Search Method	Average Blocks to Access a Specific Record
Heap (unordered)	Sequential scan (linear search)	$b/2$
Ordered	Sequential scan	$b/2$
Ordered	Binary search	$\log_2 b$
