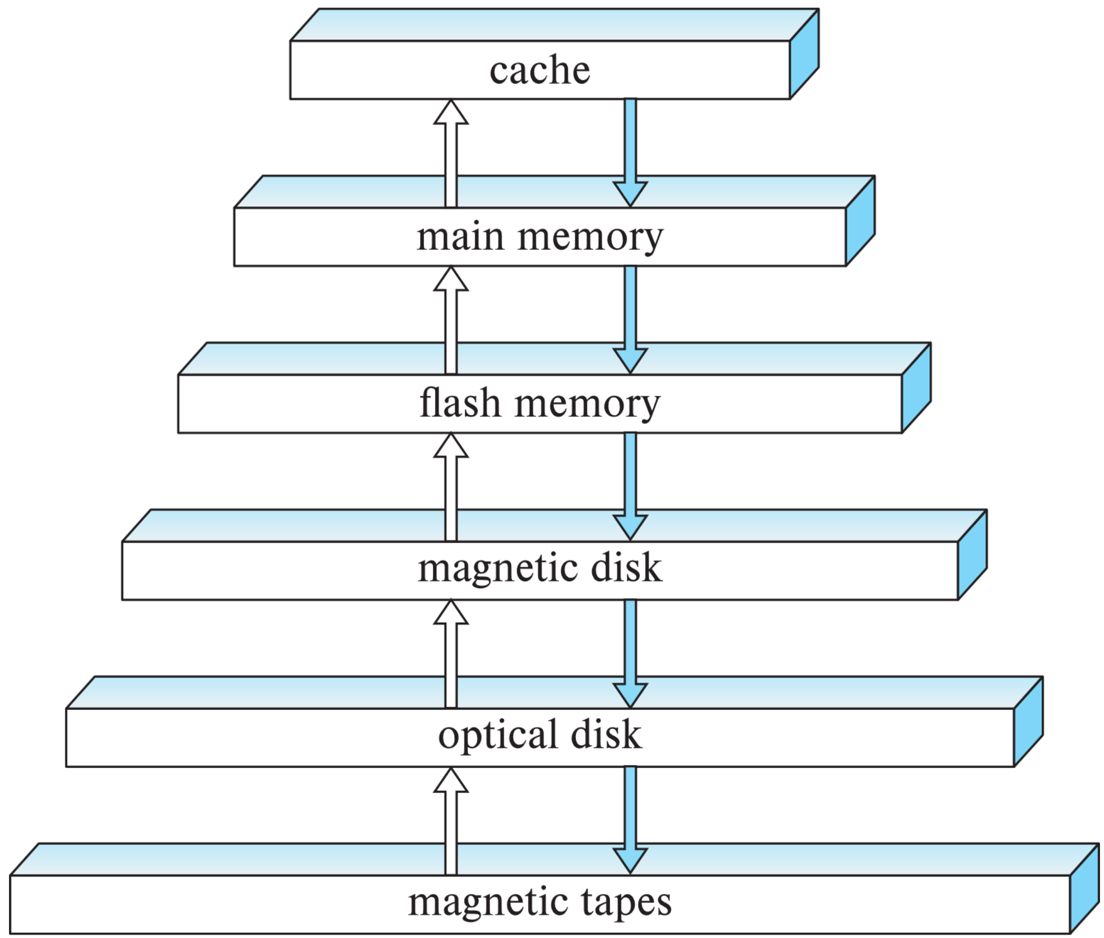
Chapter 8: Physical Storage and Data Structures

Database System Concepts, 7th Ed.

Classification of Physical Storage Media

- Can differentiate storage into:
  - **volatile storage:** loses contents when power is switched off
  - **non-volatile storage**:
    - Contents persist even when power is switched off.
    - Includes secondary and tertiary storage, as well as battery-backed-up main memory.
- Factors affecting the choice of storage media include
  - Speed with which data can be accessed
  - Cost per unit of data
  - Reliability

Storage Hierarchy



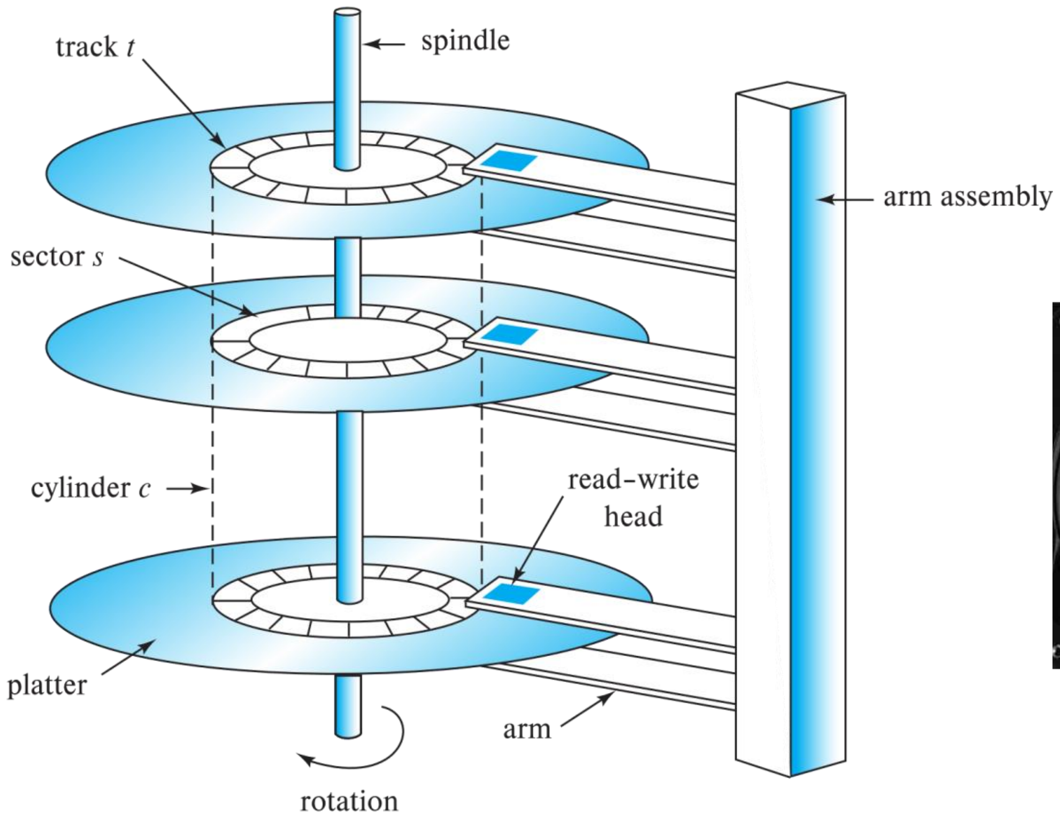
Storage Hierarchy (Cont.)

- **primary storage:** Fastest media but volatile (cache, main memory).
- **secondary storage:** next level in hierarchy, non-volatile, moderately fast access time
  - Also called **on-line storage**
  - E.g., flash memory, magnetic disks
- **tertiary storage:** lowest level in hierarchy, non-volatile, slow access time
  - also called **off-line storage** and used for **archival storage**
  - e.g., magnetic tape, optical storage
  - Magnetic tape
    - Sequential access, 1 to 12 TB capacity
    - A few drives with many tapes
    - Juke boxes with petabytes (1000's of TB) of storage

Storage Interfaces

- Disk interface standards families
  - SATA (Serial ATA - Advanced Technology Attachment)
    - SATA 3 supports data transfer speeds of up to 6 gigabits/sec
  - SAS (Serial Attached SCSI – Small Computer System Interface)
    - SAS Version 3 supports 12 gigabits/sec
  - NVMe (Non-Volatile Memory Express) interface
    - Works with PCIe (Peripheral Component Interconnect Express) connectors to support lower latency and higher transfer rates
    - Supports data transfer rates of up to 24 gigabits/sec
- Disks are usually connected directly to the computer system
- In **Storage Area Networks (SAN)**, a large number of disks are connected by a high-speed network to a number of servers
- In **Network Attached Storage (NAS)** networked storage provides a file system interface using networked file system protocol, instead of providing a disk system interface

Magnetic Hard Disk Mechanism



Schematic diagram of magnetic disk drive

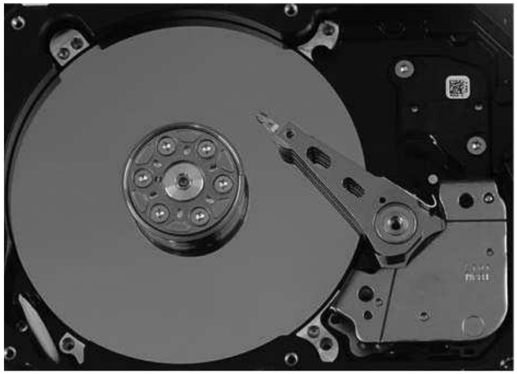


Photo of magnetic disk drive

Magnetic Disks

- **Read-write head**
- Surface of platter divided into circular **tracks**
  - Over 50K-100K tracks per platter on typical hard disks
- Each track is divided into **sectors.**
  - A sector is the smallest unit of data that can be read or written.
  - Sector size typically 512 bytes
  - Typical sectors per track: 500 to 1000 (on inner tracks) to 1000 to 2000 (on outer tracks)
- To read/write a sector
  - disk arm swings to position head on the right track
  - Platter spins continually; data is read/written as the sector passes under the head
- Head-disk assemblies
  - multiple disk platters on a single spindle (1 to 5 usually)
  - one head per platter, mounted on a common arm.
- **Cylinder** *i* consists of i^{th} track of all the platters

Magnetic Disks (Cont.)

- **Disk controller** – interfaces between the computer system and the disk drive hardware.
  - accepts high-level commands to read or write a sector
  - initiates actions such as moving the disk arm to the right track and actually reading or writing the data
  - Computes and attaches **checksums** to each sector to verify that data is read back correctly
    - If data is corrupted, with a very high probability stored checksum won't match the recomputed checksum
  - Ensures successful writing by reading back sector after writing it
  - Performs **remapping of bad sectors**

Performance Measures of Disks

- **Access time** – the time it takes from when a read or write request is issued to when data transfer begins. Consists of:
  - **Seek time** – the time it takes to reposition the arm over the correct track.
    - Average seek time is 1/2 the worst-case seek time.
      - Would be 1/3 if all tracks had the same number of sectors, and we ignore the time to start and stop the arm movement
    - 4 to 10 milliseconds on typical disks
  - **Rotational latency** – the time it takes for the sector to be accessed to appear under the head.
    - 4 to 11 milliseconds on typical disks (5400 to 15000 r.p.m.)
    - Average latency is 1/2 of the above latency.
  - Overall latency is 5 to 20 msec depending on the disk model
- **Data-transfer rate** – the rate at which data can be retrieved from or stored on the disk.
  - 25 to 200 MB per second max rate, lower for inner tracks

Performance Measures (Cont.)

- **Disk block** is a logical unit for storage allocation and retrieval
  - 4 to 16 kilobytes typically
    - Smaller blocks: more transfers from disk
    - Larger blocks: more space wasted due to partially filled blocks
- **Sequential access pattern**
  - Successive requests are for successive disk blocks
  - Disk seek required only for the first block
- **Random access pattern**
  - Successive requests are for blocks that can be anywhere on the disk
  - Each access requires a seek
  - Transfer rates are low since a lot of time is wasted on seeks
- **I/O operations per second (IOPS)**
  - Number of random block reads that a disk can support per second
  - 50 to 200 IOPS on current-generation magnetic disks

Performance Measures (Cont.)

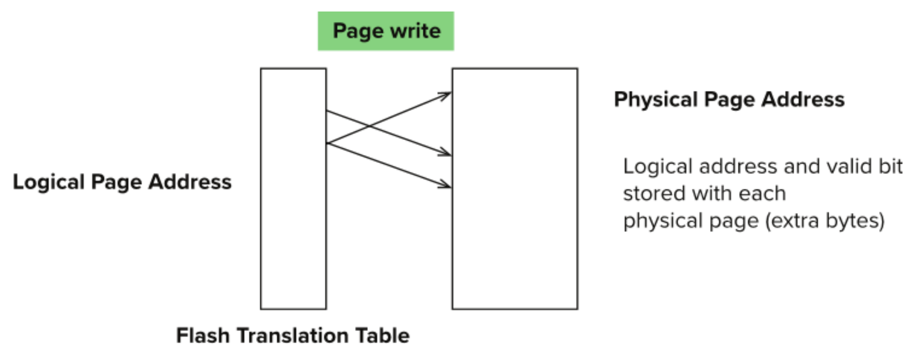
- **Mean time to failure (MTTF)** – the average time the disk is expected to run continuously without any failure.
  - Typically, 3 to 5 years
  - Probability of failure of new disks is quite low, corresponding to a "theoretical MTTF" of 500,000 to 1,200,000 hours for a new disk
    - E.g., an MTTF of 1,200,000 hours for a new disk means that given 1000 relatively new disks, on an average one will fail every 1200 hours
  - MTTF decreases as disk ages

Flash Storage

- NOR flash vs NAND flash
- NAND flash
  - used widely for storage, cheaper than NOR flash
  - requires page-at-a-time read (page: 512 bytes to 4 KB)
    - 20 to 100 microseconds for a page read
    - Not much difference between sequential and random read
  - Page can only be written once
    - Must be erased to allow rewrite
- **Solid-state disks**
  - Use standard block-oriented disk interfaces, but store data on multiple flash storage devices internally
  - Transfer rate of up to 500 MB/sec using SATA, and up to 3 GB/sec using NVMe PCIe

Flash Storage (Cont.)

- Erase happens in units of **erase block**
  - Takes 2 to 5 milliseconds
  - Erase block typically 256 KB to 1 MB (128 to 256 pages)
- **Remapping** of logical page addresses to physical page addresses avoids waiting for erase
- **Flash translation table** tracks mapping
  - also stored in a label field of the flash page
  - remapping carried out by **flash translation layer**



- After 100,000 to 1,000,000 erases, erase block becomes unreliable and cannot be used
  - **wear leveling**

SSD Performance Metrics

- Random reads/writes per second
  - Typical 4 KB reads: 10,000 reads per second (10,000 IOPS)
  - Typical 4KB writes: 40,000 IOPS
  - SSDs support parallel reads
    - Typical 4KB reads:
      - 100,000 IOPS with 32 requests in parallel (QD-32) on SATA
      - 350,000 IOPS with QD-32 on NVMe PCIe
    - Typical 4KB writes:
      - 100,000 IOPS with QD-32, even higher on some models
- Data transfer rate for sequential reads/writes
  - 400 MB/sec for SATA3, 2 to 3 GB/sec using NVMe PCIe
- **Hybrid disks**: combine a small amount of flash cache with a larger magnetic disk

RAID

- **RAID: Redundant Arrays of Independent Disks**
  - disk organization techniques that manage a large number of disks, providing a view of a single disk of
    - **High capacity** and **high speed** by using multiple disks in parallel,
    - **High reliability** by storing data redundantly, so that data can be recovered even if a disk fails
- The chance that some disk out of a set of *N* disks will fail is much higher than that of a specific single disk.
  - E.g., a system with 100 disks, each with an MTTF of 100,000 hours (approx. 11 years), will have a system MTTF of 1000 hours (approx. 41 days)
  - Techniques for using redundancy to avoid data loss are critical with large numbers of disks

Improvement of Reliability via Redundancy

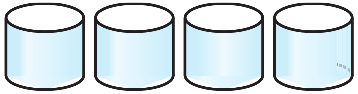
- **Redundancy** – store extra information that can be used to rebuild information lost in a disk failure
- E.g., **Mirroring** (or **shadowing**)
  - Duplicate every disk. A logical disk consists of two physical disks.
  - Every write is carried out on both disks
    - Reads can take place from either disk
  - If one disk in a pair fails, data is still available in the other
    - Data loss would occur only if a disk fails, and its mirror disk also fails before the system is repaired
      - Probability of a combined event is very small
        - Except for dependent failure modes such as fire or building collapse or electrical power surges
- **Mean time to data loss** depends on MTTF and **mean time to repair**
  - E.g., MTTF of 100,000 hours, mean time to repair of 10 hours gives mean time to data loss of $500*10^6$ hours (or 57,000 years) for a mirrored pair of disks (ignoring dependent failure modes)

Improvement in Performance via Parallelism

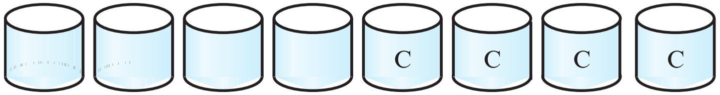
- Two main goals of parallelism in a disk system:
  1. Load balance multiple small accesses to increase throughput
  2. Parallelize large accesses to reduce response time.
- Improve transfer rate by striping data across multiple disks.
- **Bit-level striping** – split the bits of each byte across multiple disks
  - In an array of eight disks, write bit *i* of each byte to disk *i.*
  - Each access can read data at eight times the rate of a single disk.
  - But seek/access time worse than for a single disk
    - Bit level striping is not used much anymore
- **Block-level striping** – with *n* disks, block *i* of a file goes to disk (*i* mod *n*) + 1
  - Requests for different blocks can run in parallel if the blocks reside on different disks
  - A request for a long sequence of blocks can utilize all disks in parallel

RAID Levels

- Schemes to provide redundancy at lower cost by using disk striping combined with parity bits
  - Different RAID organizations, or RAID levels, have differing cost, performance and reliability characteristics
- **RAID Level 0**: Block striping; non-redundant.
  - Used in high-performance applications where data loss is not critical.
- **RAID Level 1**: Mirrored disks with block striping
  - Offers best write performance.
  - Popular for applications such as storing log files in a database system.



(a) RAID 0: nonredundant striping



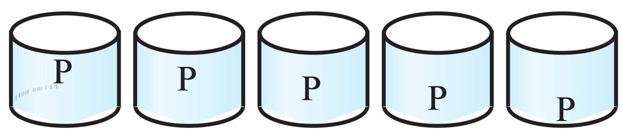
(b) RAID 1: mirrored disks

RAID Levels (Cont.)

- **Parity blocks**: Parity block *j* stores XOR of bits from block *j* of each disk
  - When writing data to a block *j*, parity block *j* must also be computed and written to disk
    - Can be done by using the old parity block, the old value of the current block, and the new value of the current block (2 block reads + 2 block writes)
    - Or by recomputing the parity value using the new values of blocks corresponding to the parity block
      - More efficient for writing large amounts of data sequentially
  - To recover data for a block, compute XOR of bits from all other blocks in the set including the parity block

RAID Levels (Cont.)

- **RAID Level 5:** Block-Interleaved Distributed Parity; partitions data and parity among all *N* + 1 disks, rather than storing data in *N* disks and parity in 1 disk.
  - E.g., with 5 disks, the parity block for the *n*th set of blocks is stored on disk (*n mod* 5) + 1, with the data blocks stored on the other 4 disks.

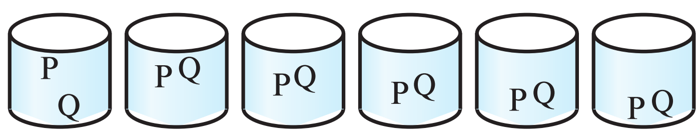


(c) RAID 5: block-interleaved distributed parity

P0	0	1	2	3
4	P1	5	6	7
8	9	P2	10	11
12	13	14	P3	15
16	17	18	19	P4

RAID Levels (Cont.)

- **RAID Level 5** (Cont.)
  - Block writes occur in parallel if the blocks and their parity blocks are on different disks.
- **RAID Level 6**: P+Q Redundancy scheme; similar to Level 5, but stores two error correction blocks (P, Q) instead of a single parity block to guard against multiple disk failures.
  - Better reliability than Level 5 at a higher cost
    - Becoming more important as storage sizes increase



(d) RAID 6: P + Q redundancy

RAID Levels (Cont.)

- **Other levels (not used in practice):**
  - **RAID Level 2**: Memory-Style Error-Correcting-Codes (ECC) with bit striping.
  - **RAID Level 3**: Bit-Interleaved Parity
  - **RAID Level 4:** Block-Interleaved Parity; uses block-level striping, and keeps a parity block on a separate ***parity disk*** for corresponding blocks from *N* other disks.
    - RAID 5 is better than RAID 4, since with RAID 4 with random writes, the parity disk gets a much higher write load than other disks and becomes a bottleneck

Choice of RAID Level

- Factors in choosing a RAID level
  - Monetary cost
  - Performance: Number of I/O operations per second, and bandwidth during normal operation
  - Performance during failure
  - Performance during the rebuild of a failed disk
    - Including time taken to rebuild failed disk
- RAID 0 is used only when data safety is not important
  - E.g., data can be recovered quickly from other sources

Choice of RAID Level (Cont.)

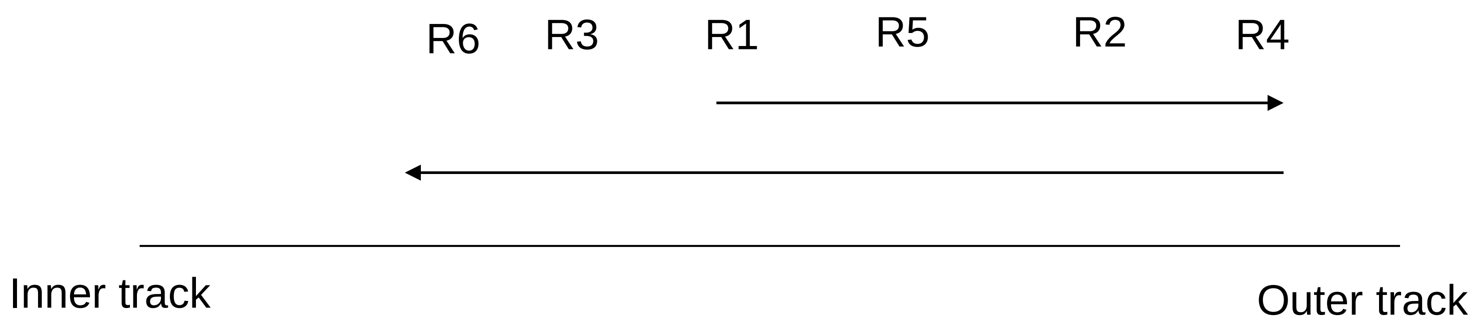
- Level 1 provides much better writing performance than Level 5
  - Level 5 requires at least 2 block reads and 2 block writes to write a single block, whereas Level 1 only requires 2 block writes
- Level 1 has a higher storage cost than Level 5
- Level 5 is preferred for applications where writes are sequential and large (many blocks), and need large amounts of data storage
- RAID 1 is preferred for applications with many random/small updates
- Level 6 gives better data protection than RAID 5 since it can tolerate two disk (or disk block) failures
  - Increasing in importance since latent block failures on one disk, coupled with a failure of another disk can result in data loss with RAID 1 and RAID 5.

Hardware Issues

- **Software RAID**: RAID implementations done entirely in software, with no special hardware support
- **Hardware RAID**: RAID implementations with special hardware
  - Use non-volatile RAM to record writes that are being executed
  - Beware: power failure during writing can result in a corrupted disk
    - E.g., failure after writing one block but before writing the second in a mirrored system
    - Such corrupted data must be detected when power is restored

Optimization of Disk-Block Access

- **Buffering:** in-memory buffer to cache disk blocks
- **Read-ahead:** Read extra blocks from a track in anticipation that they will be requested soon
- **Disk-arm-scheduling** algorithms re-order block requests so that disk arm movement is minimized
  - **elevator algorithm**



File Organization

- The database is stored as a collection of *files*. Each file is a sequence of *records.* A record is a sequence of fields.
- One approach
  - Assume record size is fixed
  - Each file has records of one particular type only
  - Different files are used for different relations

  This case is easiest to implement; will consider variable length records later
- We assume that records are smaller than a disk block

  .

Fixed-Length Records

- 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

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

Fixed-Length Records

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

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
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

Fixed-Length Records

- Deletion of record *i:* alternatives*:*
  - move records *i* + 1, . . ., *n* to *i*, . . . , *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
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
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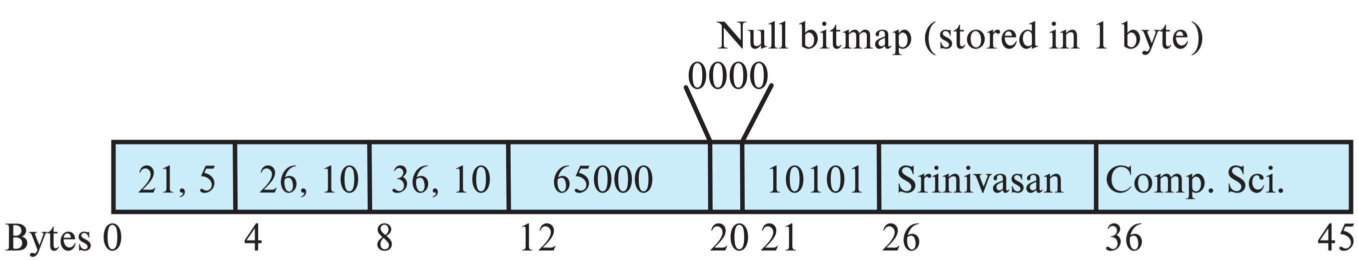
Fixed-Length Records

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

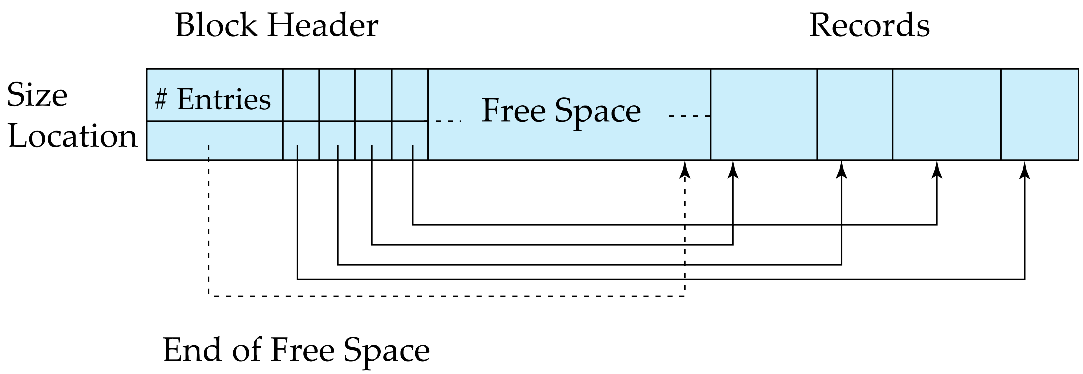
header				
record 0	10101	Srinivasan	Comp. Sci.	65000
record 1				
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4				
record 5	33456	Gold	Physics	87000
record 6				
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology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

Variable-Length Records

- 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 a null-value bitmap



Variable-Length Records: Slotted Page Structure



- **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 the record — instead they should point to the entry for the record in the header.

Storing Large Objects

- E.g., blob/clob types
- Records must be smaller than pages
- Alternatives:
  - Store as files in file systems
  - Store as files managed by a database
  - Break into pieces and store in multiple tuples in separate relation
    - PostgreSQL TOAST

Organization of Records in Files

- **Heap** – a 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 **multi-table 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
  - More in the following Chapter
  - **Hashing** – a hash function computed on the search key; the result specifies in which block of the file the record should be placed
  - More in the following Chapter

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

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	

32222	Verdi	Music	48000	

Multitable Clustering File Organization

Store several relations in one file using a **multi-table clustering** file organization

department

dept_name	*building*	*budget*
Comp. Sci.	Taylor	100000
Physics	Watson	70000

instructor

ID	*name*	*dept_name*	*salary*
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

Partitioning

- **Table partitioning**: Records in a relation can be partitioned into smaller relations that are stored separately
- E.g., *transaction* relation may be partitioned into *transaction_2018, transaction_2019, etc.*
- Queries written on *transaction* must access records in all partitions
  - Unless query has a selection such as *year*=2019, in which case only one partition in needed
- Partitioning
  - Reduces costs of some operations such as free space management
  - Allows different partitions to be stored on different storage devices
    - E.g., *transaction* partition for the current year on SSD, for older years on a magnetic disk

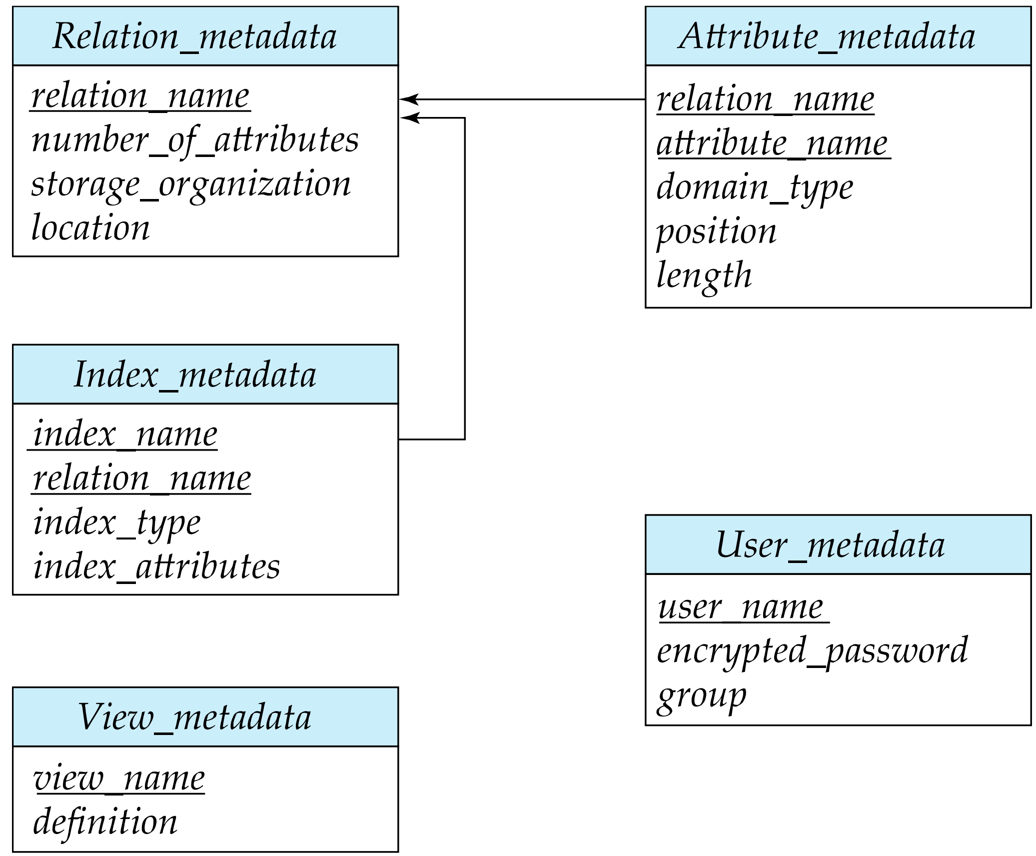
Data Dictionary Storage

The **Data dictionary** (also called **system catalog**) stores **metadata**; that is, data about data, such as

- Information about relations
  - names of relations
  - names, types, and lengths of attributes of each relation
  - names and definitions of views
  - integrity constraints
- User and accounting information, including passwords
- Statistical and descriptive data
  - number of tuples in each relation
- Physical file organization information
  - How relation is stored (sequential/hash/…)
  - Physical location of relation
- Information about indices

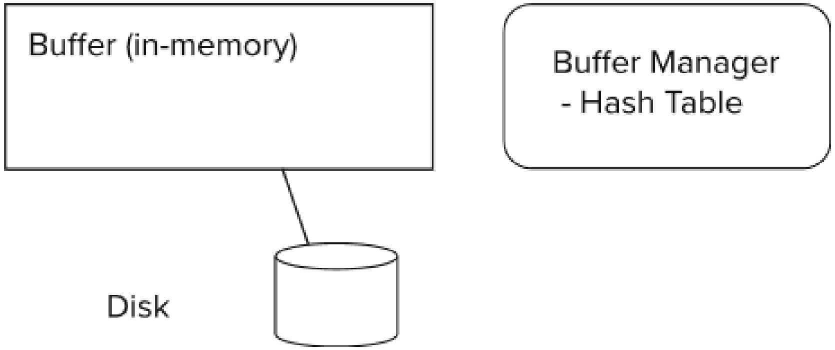
Relational Representation of System Metadata

- Relational representation on disk
- Specialized data structures designed for efficient access, in memory



Storage Access

- Blocks are units of both storage allocation and data transfer.
- Database system seeks to minimize the number of block transfers between the disk and memory. We can reduce the number of disk accesses by keeping as many blocks as possible in the main memory.
- **Buffer** – portion of main memory available to store copies of disk blocks.
- **Buffer manager** – subsystem responsible for allocating buffer space in main memory.



Buffer Manager

- Programs call on the buffer manager when they need a block from the disk.
  - If the block is already in the buffer, the buffer manager returns the address of the block in the main memory
  - If the block is not in the buffer, the buffer manager
    - Allocates space in the buffer for the block
      - Replacing (throwing out) some other block, if required, to make space for the new block.
      - Replaced block written back to disk only if it was modified since the most recent time that it was written to/fetched from the disk.
    - Reads the block from the disk to the buffer, and returns the address of the block in the main memory to the requester.

Buffer Manager

- **Buffer replacement strategy**
- **Pinned block:** memory block that is not allowed to be written back to disk
  - **Pin** done before reading/writing data from a block
  - **Unpin** done when read /write is complete
  - Multiple concurrent pin/unpin operations possible
    - Keep a pin count, buffer block can be evicted only if pin count = 0
- **Shared and exclusive locks on buffer**
  - Needed to prevent concurrent operations from reading page contents as they are moved/reorganized, and to ensure only one move/reorganize at a time
  - Readers get shared lock, updates to a block require an exclusive lock
  - **Locking rules:**
    - Only one process can get the exclusive lock at a time
    - Shared lock cannot be concurrent with the exclusive lock
    - Multiple processes may be given shared lock concurrently

Buffer-Replacement Policies

- Most operating systems replace the block **least recently used** (LRU strategy)
  - Idea behind LRU – use past pattern of block references as a predictor of future references
  - LRU can be bad for some queries
- Queries have well-defined access patterns (such as sequential scans), and a database system can use the information in a user's query to predict future references
- Mixed strategy with hints on replacement strategy provided by the query optimizer is preferable
- Example of bad access pattern for LRU: when computing the join of 2 relations r and s by the nested loops

```
for each tuple tr of r do
  for each tuple ts of s do
    if the tuples tr and ts match …
```

Buffer-Replacement Policies (Cont.)

- **Toss-immediate** strategy – frees the space occupied by a block as soon as the final tuple of that block has been processed
- **Most recently used (MRU) strategy** – the system must pin the block currently being processed. After the final tuple of that block has been processed, the block is unpinned, and it becomes the most recently used block.
- Buffer manager can use statistical information regarding the probability that a request will reference a particular relation
  - E.g., the data dictionary is frequently accessed. Heuristic: keep data-dictionary blocks in the main memory buffer
- Operating system or buffer manager may reorder writes
  - Can lead to corruption of data structures on disk
    - E.g., a linked list of blocks with a missing block on the disk
    - File systems perform consistency checks to detect such situations
  - Careful ordering of writes can avoid many such problems

Column-Oriented Storage

- Also known as **columnar representation**
- Store each attribute of a relation separately
- Example

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

Columnar Representation

- Benefits:
  - Reduced IO if only some attributes are accessed
  - Improved CPU cache performance
  - Improved compression
  - **Vector processing** on modern CPU architectures
- Drawbacks
  - Cost of tuple reconstruction from columnar representation
  - Cost of tuple deletion and update
  - Cost of decompression
- Columnar representation was found to be more efficient for decision support than row-oriented representation
- Traditional row-oriented representation preferable for transaction processing
- Some databases support both representations
  - Called **hybrid row/column stores**

End of Chapter 8