

Spatial storage and access methods

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Storage and File Structure

- Overview of Physical Storage Media
- Magnetic Disks
- Tertiary Storage
- Storage Access
- File Organization
- Organization of Records in Files
- Data-Dictionary Storage

Classification of Physical Storage Media

- Speed with which data can be accessed
- Cost per unit of data
- Reliability
 - data loss on power failure or system crash
 - physical failure of the storage device
- 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 batter-backed up main-memory.

Physical Storage Media

- **Cache** – fastest and most costly form of storage; volatile; managed by the computer system hardware.
- **Main memory:**
 - fast access (10s to 100s of nanoseconds; 1 nanosecond = 10^{-9} seconds)
 - generally too small (or too expensive) to store the entire database
 - capacities of up to a few Gigabytes widely used currently
 - Capacities have gone up and per-byte costs have decreased steadily and rapidly (roughly factor of 2 every 2 to 3 years)
- **Volatile** — contents of main memory are usually lost if a power failure or system crash occurs.

➤ Flash memory

- Data survives power failure
- Data can be written at a location only once, but location can be erased and written to again
 - Can support only a limited number (10K – 1M) of write/erase cycles.
 - Erasing of memory has to be done to an entire bank of memory
- Reads are roughly as fast as main memory
- But writes are slow (few microseconds), erase is slower
- Widely used in embedded devices such as digital cameras, phones, and USB keys

➤ Magnetic-disk

- Data is stored on spinning disk, and read/written magnetically
- Primary medium for the long-term storage of data; typically stores entire database.
- Data must be moved from disk to main memory for access, and written back for storage
 - Much slower access than main memory (more on this later)
- **direct-access** – possible to read data on disk in any order, unlike magnetic tape
- Capacities range up to roughly 1.5 TB as of 2009
 - Much larger capacity and cost/byte than main memory/flash memory
 - Growing constantly and rapidly with technology improvements (factor of 2 to 3 every 2 years)
- Survives power failures and system crashes
 - disk failure can destroy data, but is rare

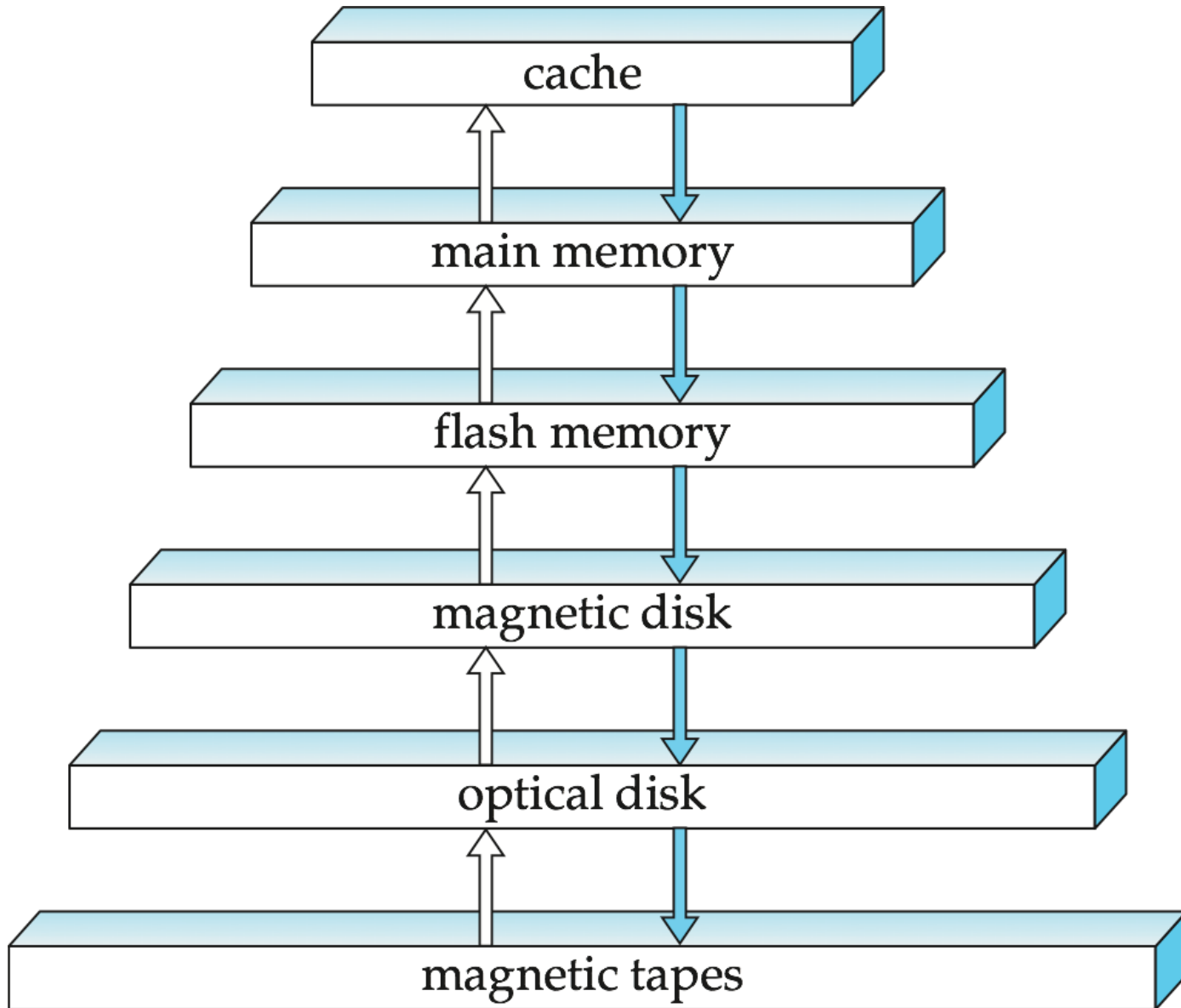
➤ Optical storage

- non-volatile, data is read optically from a spinning disk using a laser
- CD-ROM (640 MB) and DVD (4.7 to 17 GB) most popular forms
- Blu-ray disks: 27 GB to 54 GB
- Write-one, read-many (WORM) optical disks used for archival storage (CD-R, DVD-R, DVD+R)
- Multiple write versions also available (CD-RW, DVD-RW, DVD+RW, and DVD-RAM)
- Reads and writes are slower than with magnetic disk
- **Juke-box** systems, with large numbers of removable disks, a few drives, and a mechanism for automatic loading/unloading of disks available for storing large volumes of data

➤ Tape storage

- non-volatile, used primarily for backup (to recover from disk failure), and for archival data
- **sequential-access** – much slower than disk
- very high capacity (40 to 300 GB tapes available)
- tape can be removed from drive \Rightarrow storage costs much cheaper than disk, but drives are expensive
- Tape jukeboxes available for storing massive amounts of data
 - hundreds of terabytes (1 terabyte = 10^9 bytes) to even multiple **petabytes** (1 petabyte = 10^{12} bytes)

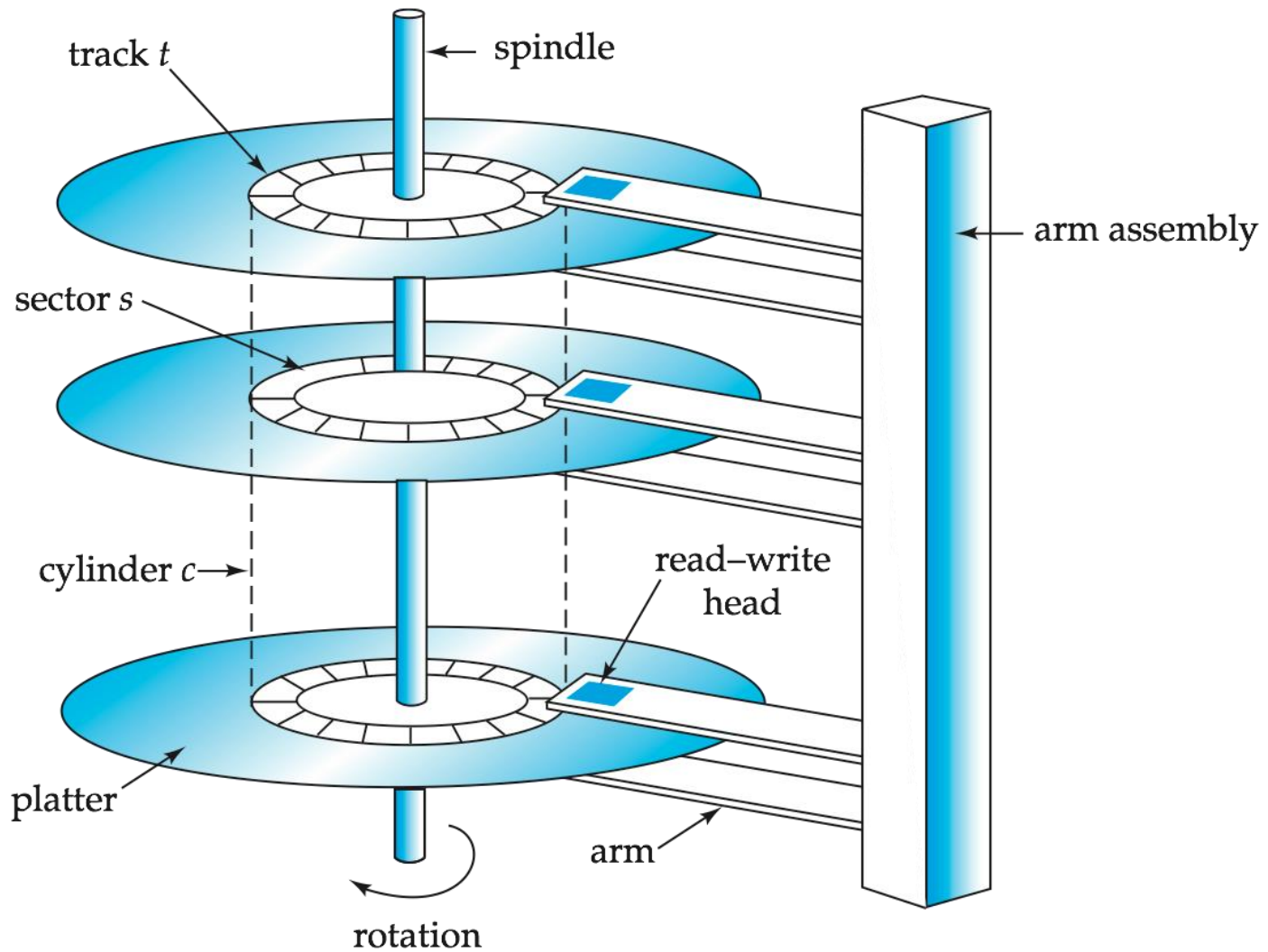
Storage Hierarchy



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**
 - E.g. magnetic tape, optical storage

Magnetic Hard Disk Mechanism



NOTE: Diagram is schematic, and simplifies the structure of actual disk drives

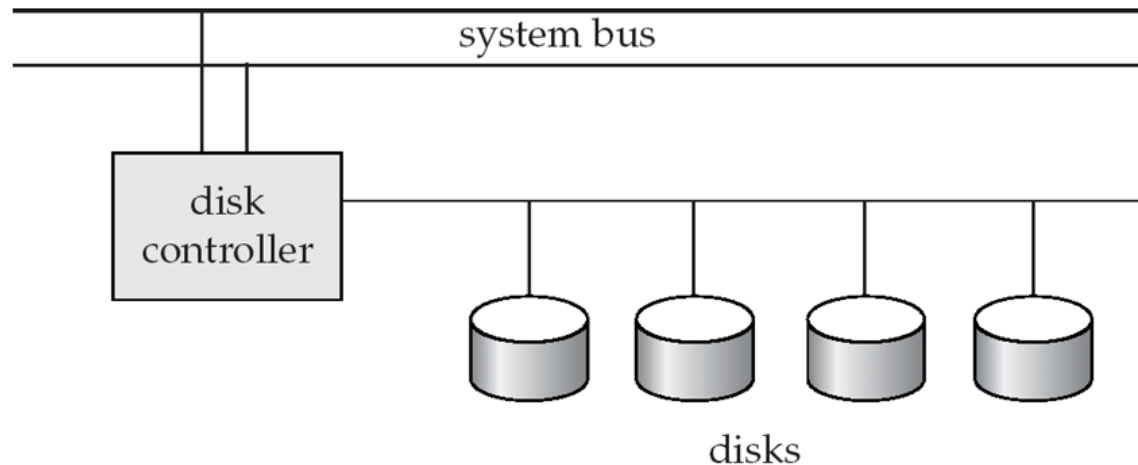
Magnetic Disks

- Read-write head
 - Positioned very close to the platter surface (almost touching it)
 - Reads or writes magnetically encoded information.
- 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 right track
 - platter spins continually; data is read/written as sector passes under 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.)

- Earlier generation disks were susceptible to head-crashes
 - Surface of earlier generation disks had metal-oxide coatings which would disintegrate on head crash and damage all data on disk
 - Current generation disks are less susceptible to such disastrous failures, although individual sectors may get corrupted
- **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 very high probability stored checksum won't match recomputed checksum
- Ensures successful writing by reading back sector after writing it
- Performs **remapping of bad sectors**

Disk Subsystem



- Multiple disks connected to a computer system through a controller
 - Controllers functionality (checksum, bad sector remapping) often carried out by individual disks; reduces load on controller
- Disk interface standards families:
 - **ATA** (AT adaptor) range of standards
 - **SATA** (Serial ATA)
 - **SCSI** (Small Computer System Interconnect) range of standards
 - **SAS** (Serial Attached SCSI)
 - Several variants of each standard (different speeds and capabilities)

Disk Subsystem

- Disks usually connected directly to 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

Performance Measures of Disks

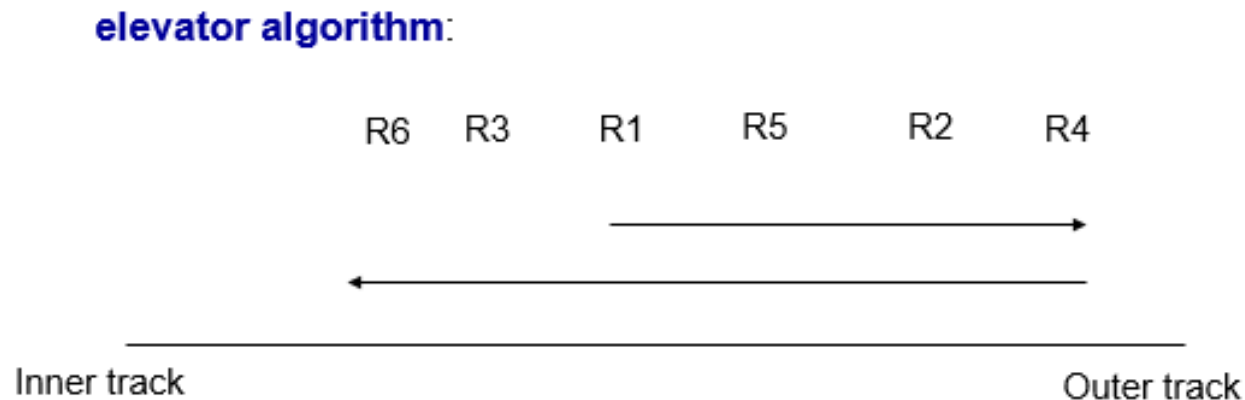
- **Access time** – the time it takes from when a read or write request is issued to when data transfer begins. Consists of:
 - **Seek time** – time it takes to reposition the arm over the correct track.
 - Average seek time is 1/2 the worst case seek time.
 - Would be 1/3 if all tracks had the same number of sectors, and we ignore the time to start and stop arm movement
 - 4 to 10 milliseconds on typical disks
 - **Rotational latency** – time it takes for the sector to be accessed to appear under the head.
 - Average latency is 1/2 of the worst case latency.
 - 4 to 11 milliseconds on typical disks (5400 to 15000 r.p.m.)
- **Data-transfer rate** – the rate at which data can be retrieved from or stored to the disk.
 - 25 to 100 MB per second max rate, lower for inner tracks
 - Multiple disks may share a controller, so rate that controller can handle is also important
 - E.g. SATA: 150 MB/sec, SATA-II 3Gb (300 MB/sec)
 - Ultra 320 SCSI: 320 MB/s, SAS (3 to 6 Gb/sec)
 - Fiber Channel (FC2Gb or 4Gb): 256 to 512 MB/s

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

Optimization of Disk-Block Access

- **Block** – a contiguous sequence of sectors from a single track
 - data is transferred between disk and main memory in blocks
 - sizes range from 512 bytes to several kilobytes
 - Smaller blocks: more transfers from disk
 - Larger blocks: more space wasted due to partially filled blocks
 - Typical block sizes today range from 4 to 16 kilobytes
- **Disk-arm-scheduling** algorithms order pending accesses to tracks so that disk arm movement is minimized.



Optimization of Disk Block Access (Cont.)

- **File organization** – optimize block access time by organizing the blocks to correspond to how data will be accessed
 - E.g. Store related information on the same or nearby cylinders.
 - Files may get **fragmented** over time
 - E.g. if data is inserted to/deleted from the file
 - Or free blocks on disk are scattered, and newly created file has its blocks scattered over the disk
 - Sequential access to a fragmented file results in increased disk arm movement
- Some systems have utilities to **defragment** the file system, in order to speed up file access

Optimization of Disk Block Access (Cont.)

- **Nonvolatile write buffers** speed up disk writes by writing blocks to a non-volatile RAM buffer immediately
 - Non-volatile RAM: battery backed up RAM or flash memory
 - Even if power fails, the data is safe and will be written to disk when power returns
 - Controller then writes to disk whenever the disk has no other requests or request has been pending for some time
 - Database operations that require data to be safely stored before continuing can continue without waiting for data to be written to disk
 - *Writes can be reordered to minimize disk arm movement*
- **Log disk** – a disk devoted to writing a sequential log of block updates
 - Used exactly like nonvolatile RAM
 - Write to log disk is very fast since no seeks are required
 - No need for special hardware (NV-RAM)
 - File systems typically reorder writes to disk to improve performance
 - **Journaling file systems** write data in safe order to NV-RAM or log disk
 - Reordering without journaling: risk of corruption of file system data

Flash Storage

➤ NOR flash vs NAND flash

➤ NAND flash

- used widely for storage, since it is much cheaper than NOR flash
- requires page-at-a-time read (page: 512 bytes to 4 KB)
- transfer rate around 20 MB/sec
- **solid state disks**: use multiple flash storage devices to provide higher transfer rate of 100 to 200 MB/sec
- erase is very slow (1 to 2 millisecs)
 - erase block contains multiple pages
 - **remapping** of logical page addresses to physical page addresses avoids waiting for erase
 - **translation table** tracks mapping
 - » also stored in a label field of 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**

Optical Disks

- Compact disk-read only memory (CD-ROM)
 - Removable disks, 640 MB per disk
 - Seek time about 100 msec (optical read head is heavier and slower)
 - Higher latency (3000 RPM) and lower data-transfer rates (3-6 MB/s) compared to magnetic disks
- Digital Video Disk (DVD)
 - DVD-5 holds 4.7 GB , and DVD-9 holds 8.5 GB
 - DVD-10 and DVD-18 are double sided formats with capacities of 9.4 GB and 17 GB
 - Blu-ray DVD: 27 GB (54 GB for double sided disk)
 - Slow seek time, for same reasons as CD-ROM
- Record once versions (CD-R and DVD-R) are popular
 - data can only be written once, and cannot be erased.
 - high capacity and long lifetime; used for archival storage
 - Multi-write versions (CD-RW, DVD-RW, DVD+RW and DVD-RAM) also available

Magnetic Tapes

- Hold large volumes of data and provide high transfer rates
 - Few GB for DAT (Digital Audio Tape) format, 10-40 GB with DLT (Digital Linear Tape) format, 100 GB+ with Ultrium format, and 330 GB with Ampex helical scan format
 - Transfer rates from few to 10s of MB/s
- Tapes are cheap, but cost of drives is very high
- Very slow access time in comparison to magnetic and optical disks
 - limited to sequential access.
 - Some formats (Accelis) provide faster seek (10s of seconds) at cost of lower capacity
- Used mainly for backup, for storage of infrequently used information, and as an off-line medium for transferring information from one system to another.
- Tape jukeboxes used for very large capacity storage
 - Multiple petabytes (10^{15} bytes)

File Organization, Record Organization and Storage Access

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.

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

- 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 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

Deleting record 3 and compacting

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

Deleting record 3 and moving last record

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
record 9	76766	Crick	Biology	72000
record 10	83821	Brandt	Comp. Sci.	92000

Free Lists

- Store the address of the first deleted record in the file header.
- Use this first record to store the address of the second deleted record, and so on
- Can think of these stored addresses as **pointers** since they “point” to the location of a record.
- More space efficient representation: reuse space for normal attributes of free records to store pointers. (No pointers stored in in-use records.)

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

The diagram illustrates a linked list of free records. Arrows show the sequence: record 0 points to record 1, record 1 points to record 4, record 4 points to record 6, and record 6 points to a ground symbol, indicating the end of the list.

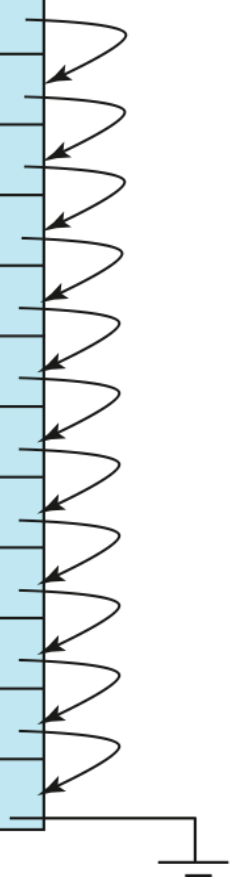
Organization of Records in Files

- **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
- **Hashing** – a hash function computed on some attribute of each record; the result specifies in which block of the file the record should be placed
- Records of each relation may be stored in a separate file. 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

Sequential File Organization

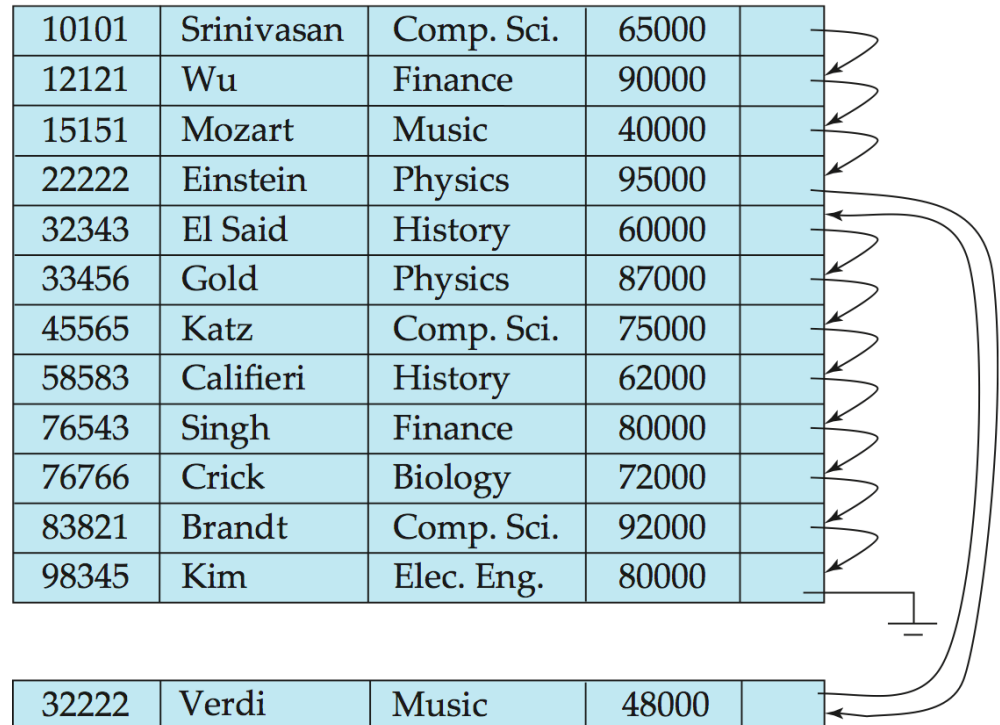
- Suitable for applications that require sequential processing of the entire file
- The records in the file are ordered by a **search-key**

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

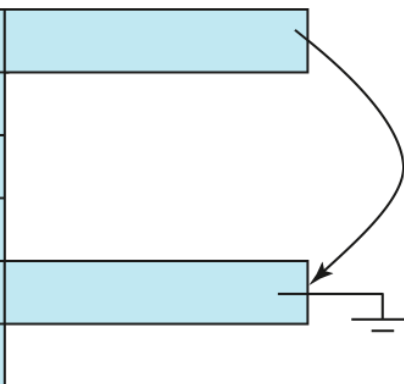
multitable clustering
of *department* and
instructor

Comp. Sci.	Taylor	100000
45564	Katz	75000
10101	Srinivasan	65000
83821	Brandt	92000
Physics	Watson	70000
33456	Gold	87000

Multitable Clustering File Organization (cont.)

- good for queries involving *department* ⋈ *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

Comp. Sci.	Taylor	100000	
45564	Katz	75000	
10101	Srinivasan	65000	
83821	Brandt	92000	
Physics	Watson	70000	
33456	Gold	87000	



The diagram illustrates a pointer chain between records of different departments. A curved arrow originates from the empty fourth column of the 'Comp. Sci.' record (Taylor) and points to the empty fourth column of the 'Physics' record (Watson). A small ground symbol is located at the end of the arrow pointing to the 'Physics' record.

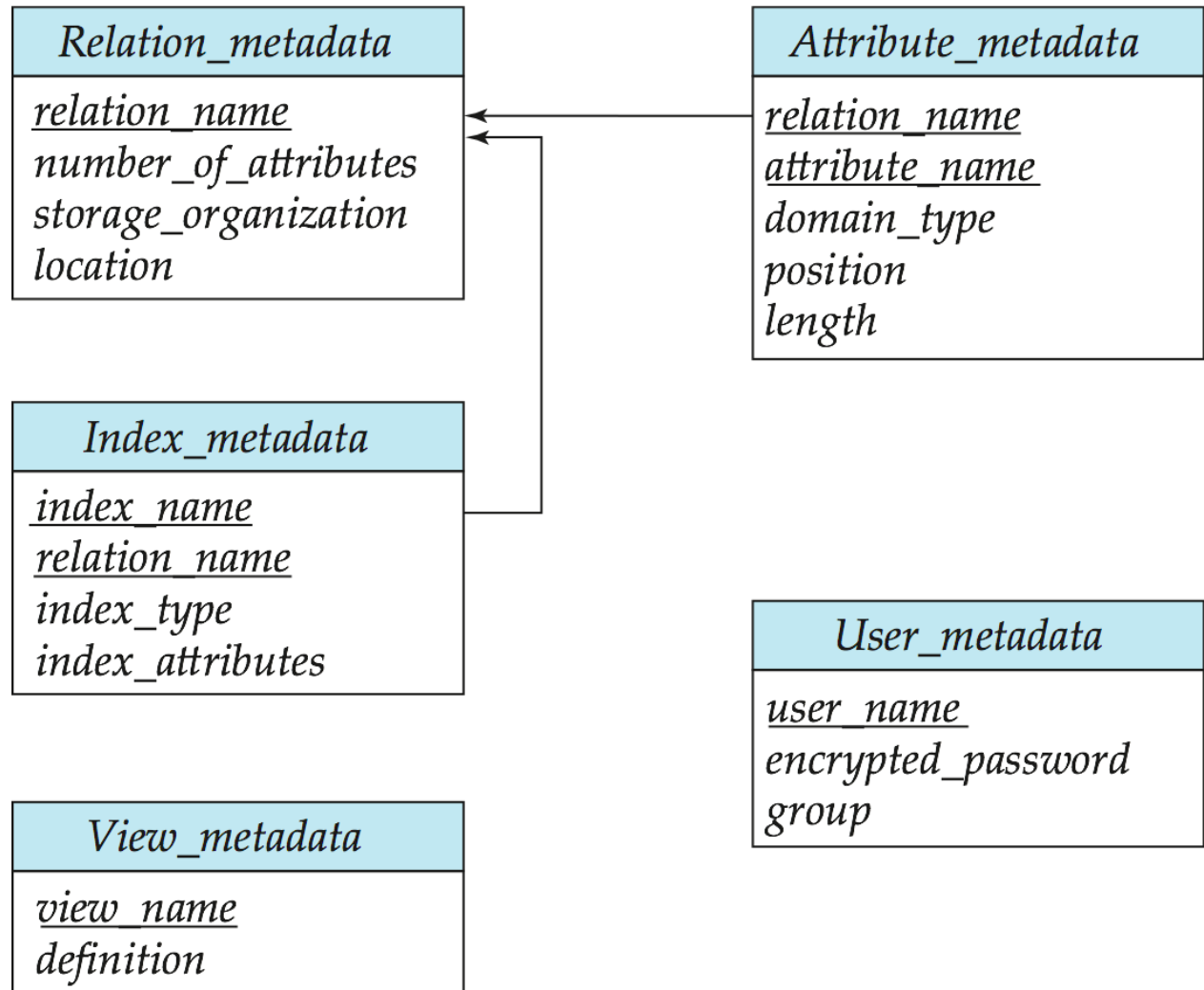
Data Dictionary Storage

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

- A database file is partitioned into fixed-length storage units called **blocks**. 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 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 disk.
 - If the block is already in the buffer, buffer manager returns the address of the block in main memory
 - If the block is not in the buffer, the buffer manager
 - ❖ Allocates space in the buffer for the block
 1. Replacing (throwing out) some other block, if required, to make space for the new block.
 2. 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.
 - 1. Reads the block from the disk to the buffer, and returns the address of the block in main memory to requester.

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
- 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
 - LRU can be a bad strategy for certain access patterns involving repeated scans of data
 - For example: when computing the join of 2 relations r and s by a nested loops
for each tuple tr of r do
for each tuple ts of s do
if the tuples tr and ts match ...
 - Mixed strategy with hints on replacement strategy provided by the query optimizer is preferable

Buffer-Replacement Policies (Cont.)

- **Pinned block** – memory block that is not allowed to be written back to disk.
- **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** – 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 main memory buffer
- Buffer managers also support **forced output** of blocks for the purpose of recovery.

Assignment 7

1. What do you understand by Spatial Storage and access method? Describe classification of physical storage media in detail.
2. Describe components of Storage Hierarchy in detail with suitable diagram.
3. Describe the mechanism of magnetic hard disk in detail with suitable diagram.
4. What do you understand by disk subsystem? Mention disk interface standards families.
5. How disk performance measures? Mention optimization of Disk-Block Access in detail.
6. Describe File Organization, Record Organization and Storage Access in detail with suitable example.
7. How records are organize in a files? Mention buffer replacement policies.
8. Write Short note:
 - a) Flash storage
 - b) Optical Disk
 - c) Magnetic Tapes
 - d) Free Lists
 - e) Sequential file organization
 - f) Buffer Manager
 - g) Data Dictionary storage