

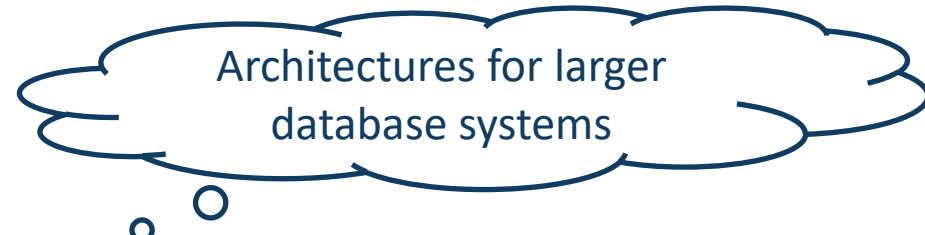
Database Architectures

CS460 Databases for Data Scientists



Outline

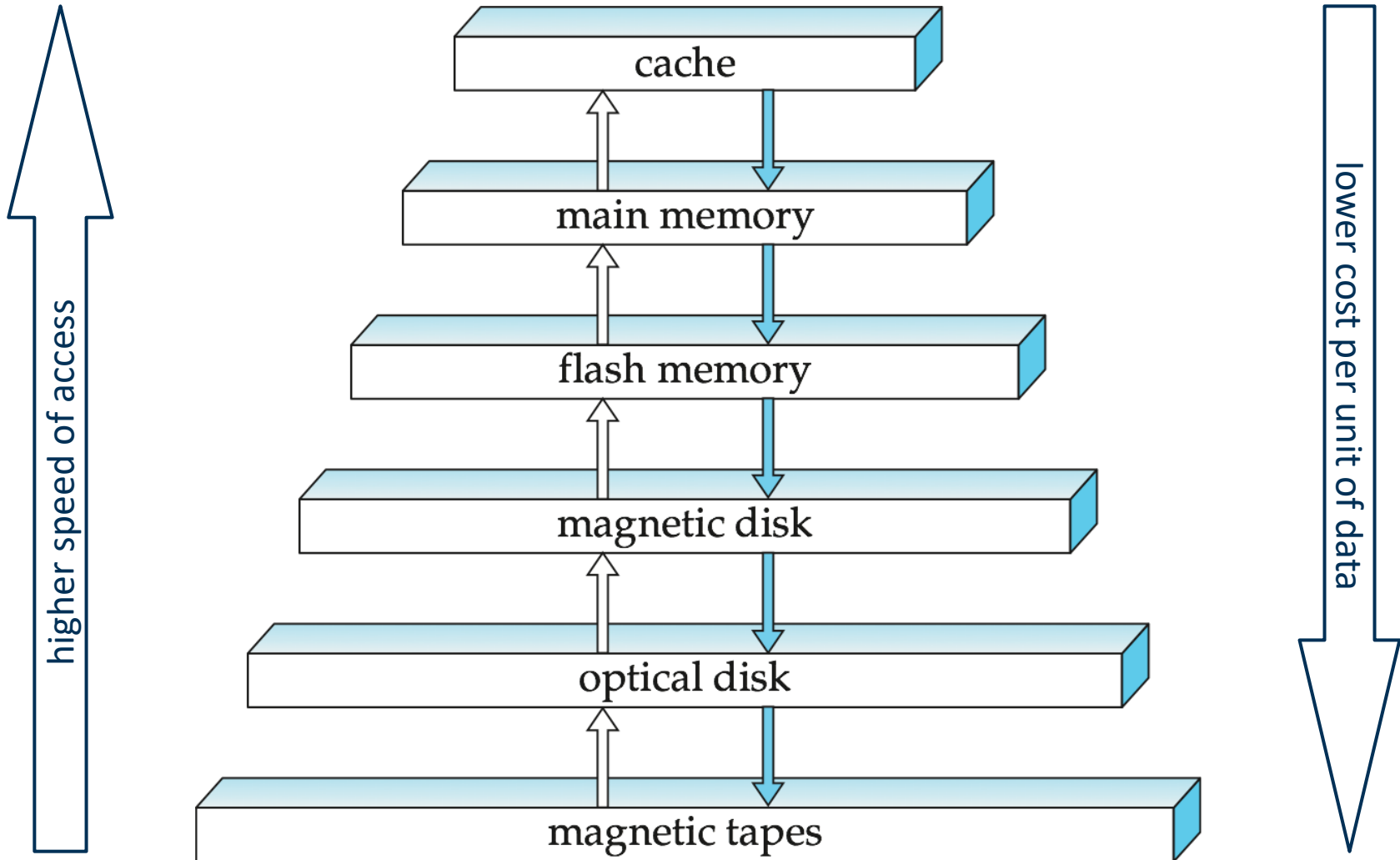
- Physical Data Storage
- File Organization
- Storage Access
- Database System Architectures
 - Centralized and Client-Server Systems
 - Server System Architectures
 - Parallel Systems
 - Distributed Systems



Physical Data Storage

- A manifold of options
 - Hard disks, flash memory, magnetic tape, CDs, DVDs, BluRays, ...
- Considerations
 - 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
 - secondary & tertiary storage, battery backed up main-memory

Storage Hierarchy

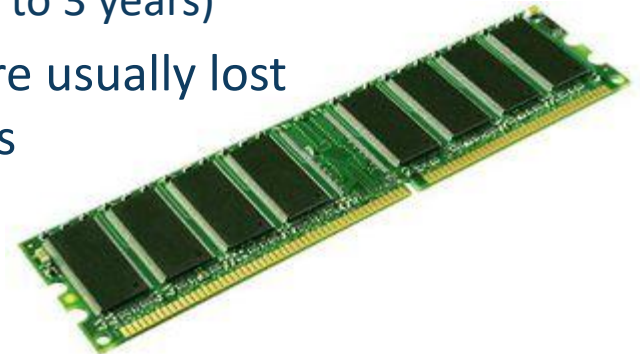


Storage Hierarchy

- **Primary storage:** Fastest media but volatile (cache, main memory)
 - data on which the processor operates
- **Secondary storage:** next level in hierarchy, non-volatile, moderately fast access time
 - also called **on-line storage**
 - e.g., flash memory, magnetic disks
 - needs to be loaded in memory for processing
- **Tertiary storage:** lowest level in hierarchy, non-volatile, slow access time
 - also called **off-line storage**
 - e.g., magnetic tape, optical storage
 - typically used for backup

Physical Storage

- **Cache**
 - fastest and most costly form of storage; volatile; managed by the computer system hardware
- **Main memory**
 - fast access (10s to 100s of nanoseconds ($1 \text{ ns} = 10^{-9}$ seconds))
 - generally too small (or too expensive) to store the entire database
 - typically: gigabyte capacity
 - 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



Physical Storage

- **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
- Also used in modern SSD drives



Physical Storage

- **Magnetic disk (hard 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
 - **Direct-access** – possible to read data on disk in any order, unlike magnetic tape
 - Terabyte sized
 - Much larger capacity and lower cost/byte than (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



Physical Storage

- **Optical storage**

- non-volatile, data is read optically from a spinning disk using a laser
- CD-ROM (640 MB), DVD (4.7 to 17 GB), Blu-ray (27 to 54 GB)
- Write-once, read-many (WORM) optical disks for archival storage

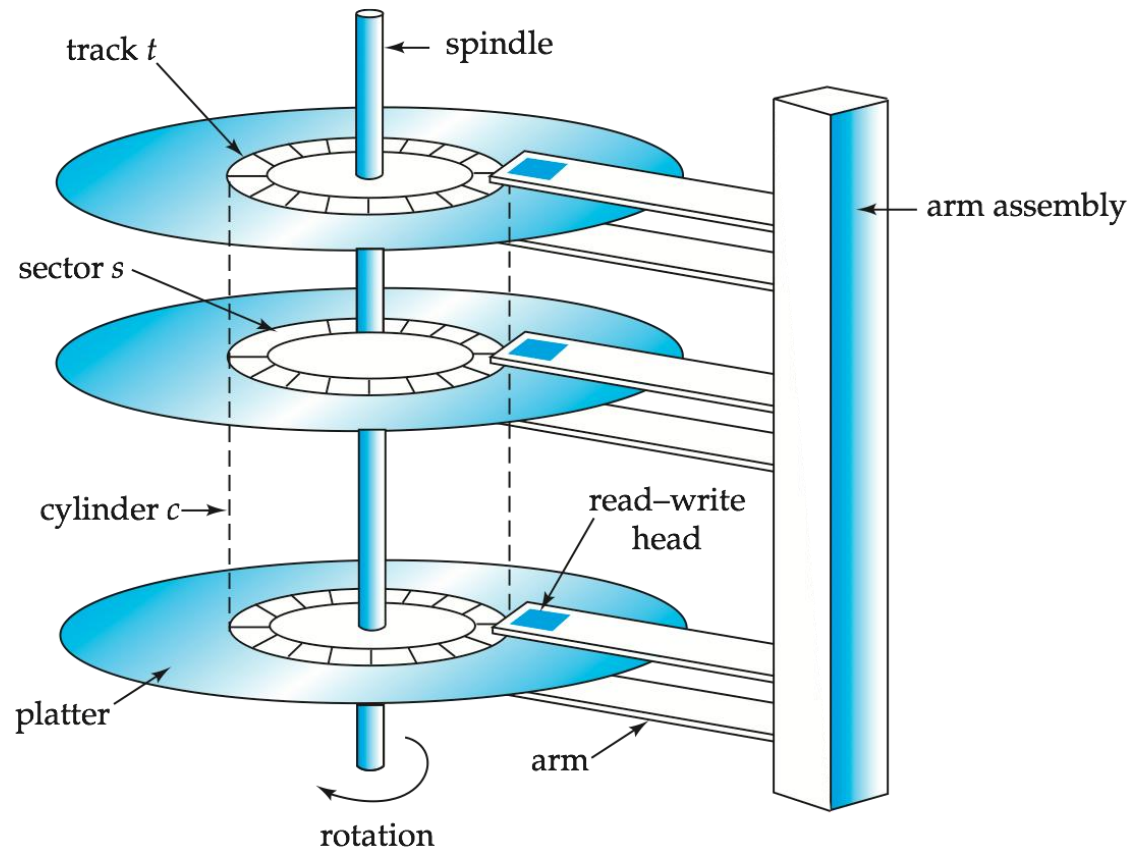
- **Tape storage**

- non-volatile, used primarily for backup (to recover from disk failure), and for archival data
- **sequential access** – much slower than disk
- very high capacity (terabyte scale)
- Tape library/jukeboxes available
- Still used in e.g.
 - [heiARCHIVE \(Uni Heidelberg\)](#)
 - [Goethe Uni Frankfurt](#)



Anatomy of a Hard Disk Drive

- Schematic view
 - sectors are the smallest unit to be read or written
 - also called *blocks*
- Goal for storage
 - minimize number of blocks transferred



File Organization

- The database is stored as a collection of *files*
 - each file is a sequence of *records*
 - each record is a sequence of *fields*
- Simple approach:
 - assume record size is fixed
 - each file has records of one particular type only
 - different files are used for different relations

 - 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 disk blocks
 - Modification: do not allow records to cross block boundaries


File Organization

- Alternatives for the deletion of record i (in the example $i=3$)

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

1) Compacting


move records $i + 1, \dots, n$
to $i, \dots, n - 1$



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
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record 11	98345	Kim	Elec. Eng.	80000

2) Moving last record

move record n to i

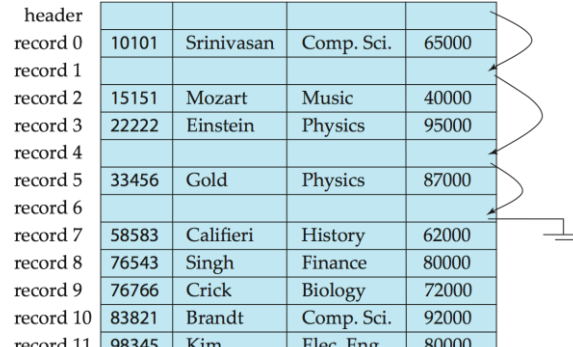


record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 11	98345	Kim	Elec. Eng.	80000
record 4	32343	El Said	History	60000
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record 8	76543	Singh	Finance	80000
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3) Free Lists

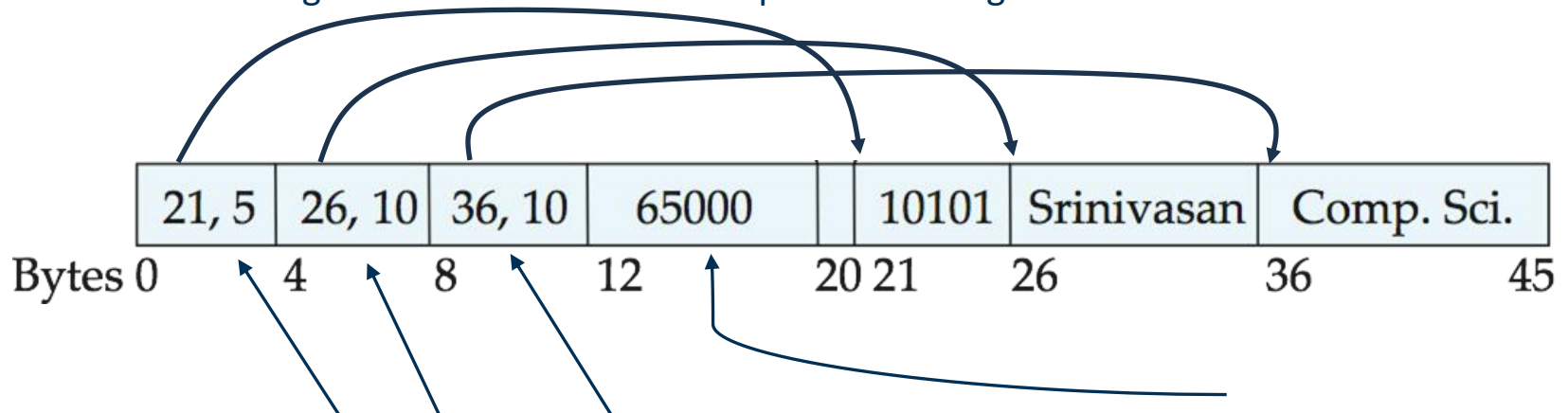
do not move records,
but link all free records
on a free list

header				
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				
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
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Storing Variable Length Records

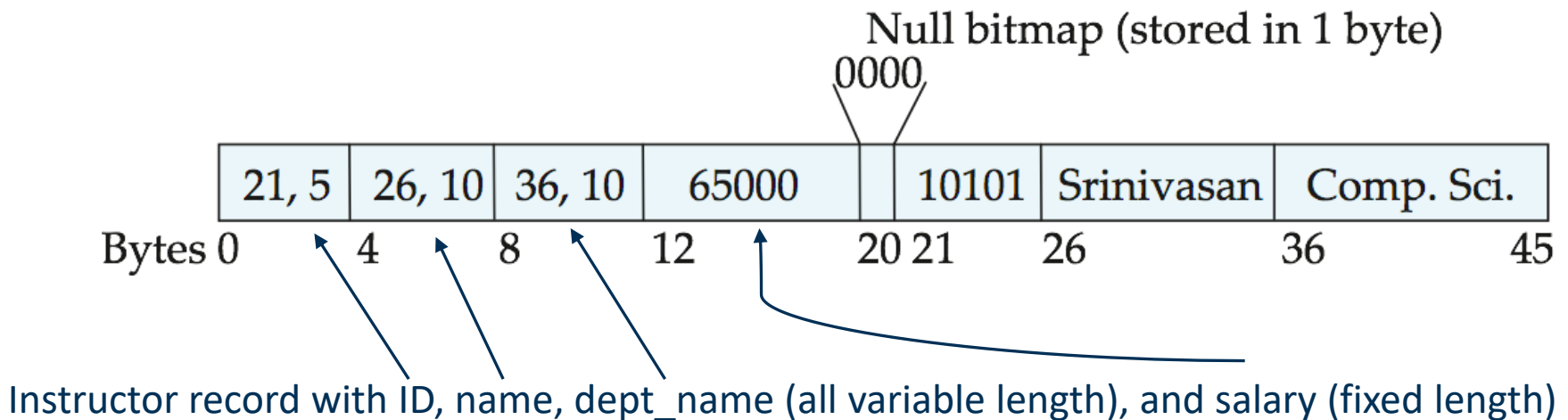
- Variable-length records arise in database systems in several ways:
 - e.g., storage of multiple record types or record types record types that allow variable lengths for one or more fields (such as strings)
- Attributes are stored in order
 - Variable length attributes are represented by fixed size (offset, length), with actual data stored after all fixed length attributes
 - Fixed length attributes do not need special handling



Instructor record with ID, name, dept_name (all variable length), and salary (fixed length)

Storing Variable Length Records

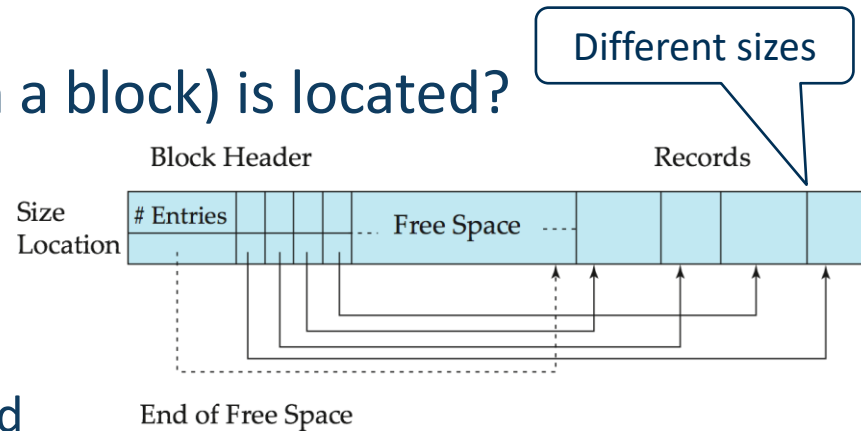
- Null bitmap stores information which attributes of the record have null values
 - E.g. if salary (fourth attribute) would be null then the fourth bit in Null bitmap is set to one (0001)



Storing Variable Length Records

- How to know where a record (in a block) is located?

- **Slotted page** header contains:
 - number of record entries
 - end of free space in the block
 - location and size of each record



- Records are allocated contiguously in the block, starting from the end of the block
 - If record is added, space is allocated at the end of free space
 - Records can also be moved to keep them contiguous with no empty space between them
 - Pointers (e.g., foreign keys) should not point directly to record, but to entry for the record in header


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
 - requires re-organizations
- Hashing
 - a hash function computed on some attribute(s) of each record
 - the result specifies in which block of the file the record should be placed
- Records of different relations
 - stored either in separate files
 - or: store related relations in one file
(called: **Multitable Clustering File Organization**)
 - Motivation: store related records on the same block to minimize I/O

Sequential File Organization

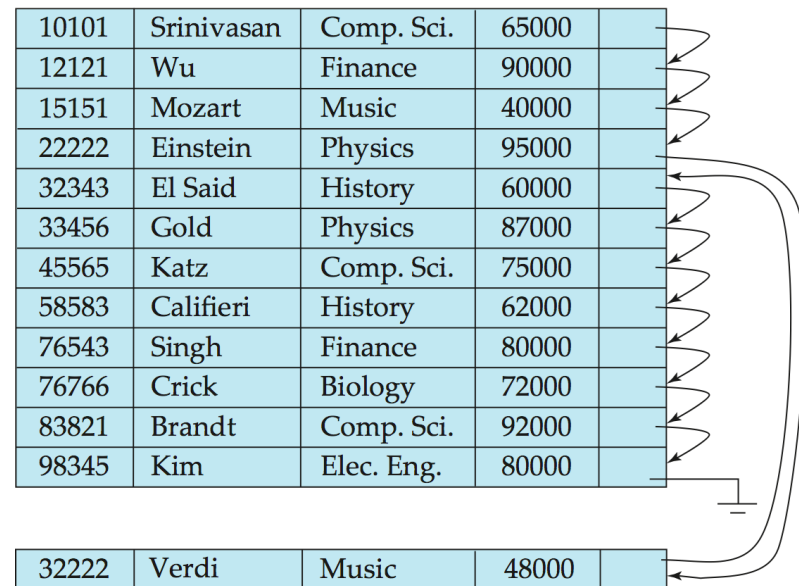
- Suitable for applications that require sequential processing of the entire file
- The records in the file are ordered by a search-key

10101	Srinivasan	Comp. Sci.	65000	
12121	Wu	Finance	90000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
32343	El Said	History	60000	
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76766	Crick	Biology	72000	
83821	Brandt	Comp. Sci.	92000	
98345	Kim	Elec. Eng.	80000	



Sequential File Organization

- Deletion – use pointer chains
- Insertion – locate the position where the record needs 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

Multitable clustering of
department and *instructor*

department

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

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

instructor

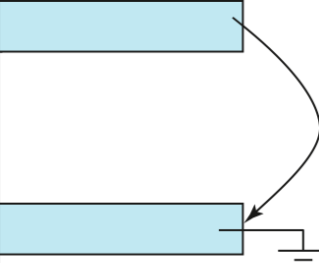
<i>ID</i>	<i>name</i>	<i>dept_name</i>	<i>salary</i>
10101	Srinivasan	Comp. Sci.	65000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
83821	Brandt	Comp. Sci.	92000

- Good for queries
 - Involving *department* ⋈ *instructor*
 - Involving one single department (and its instructors)
 - Involving only the *instructor* relation
- Bad for queries involving only the *department* relation
- Results in variable size records

Multitable Clustering File Organization

- 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	

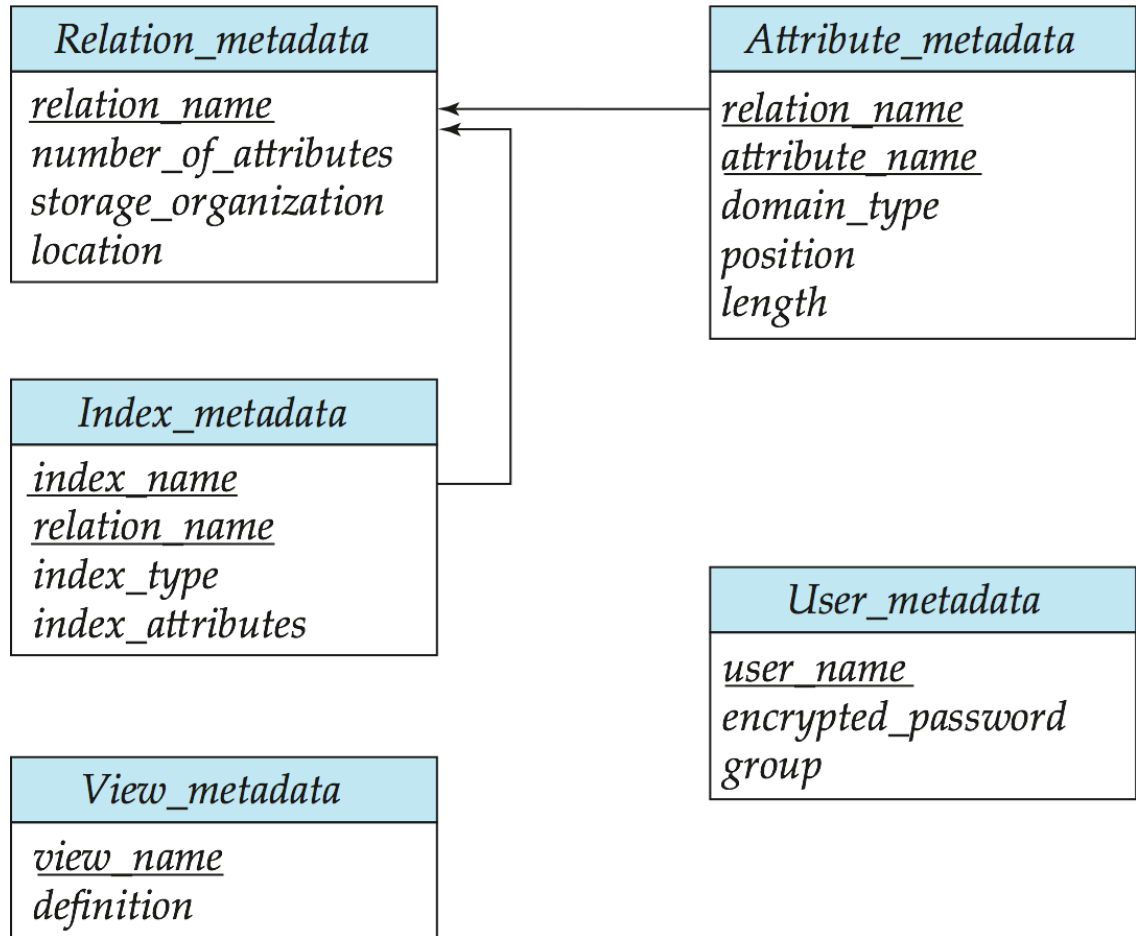


Data Dictionary Storage

- 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

Data Dictionary Storage

- Many RDBMS use relations also for the data dictionary
- Those relations are typically held in memory for fast access
- Details may vary

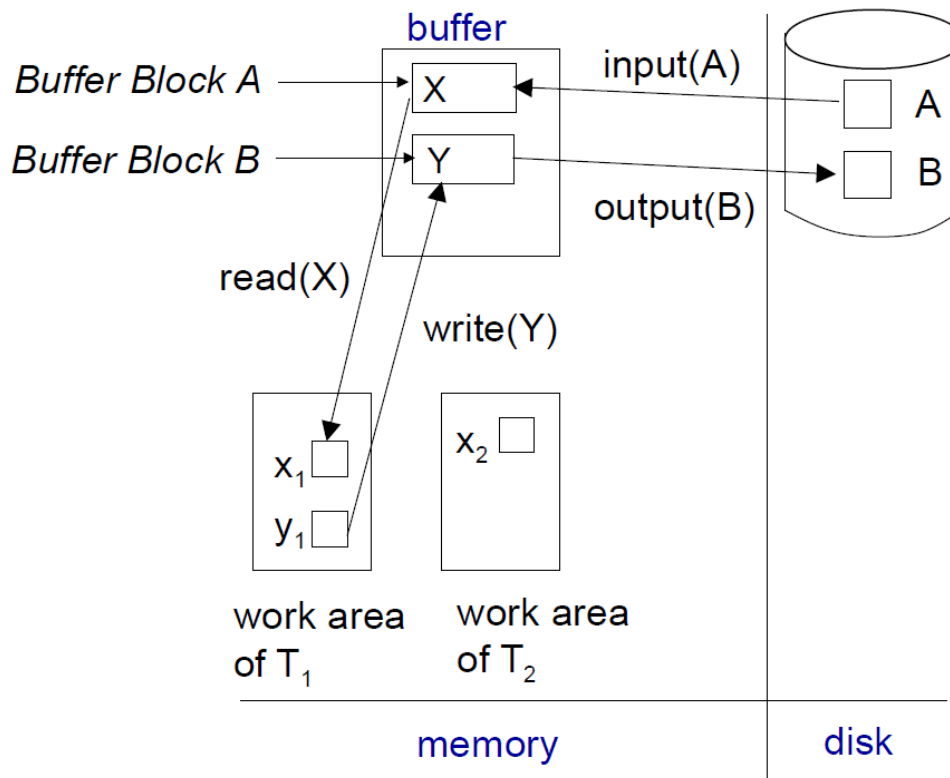


Storage Access

- A database file is partitioned into fixed-length storage units called **blocks**
 - Blocks are units of both storage allocation and data transfer
 - Multiple tuples/rows can be stored in one block
- Database system seeks to minimize the number of block transfers between the disk and memory
 - Simple: by keeping as many blocks as possible in main memory
 - Advanced: planning which blocks to keep in 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

- Not every change is directly written on disk
 - What happens in case of a power outage -> see recovery lecture



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
 - Replaces (i.e., removes) **some other block**, if required, to make space for the new block
 - If replaced block was changed: write back to disk
 - Read the block from the disk to the buffer
 - return the address of the block in main memory to requester



Potential for optimization

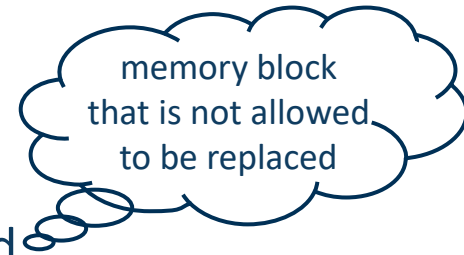
Buffer Replacement Strategies

- Most operating systems replace the block that is **least recently used (LRU strategy)**:
 - 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
 - LRU can be a bad strategy for certain access patterns involving repeated scans of data
 - Example: when computing the join of 2 relations r and s by a nested loop

```
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 Strategies

- Other strategy:
Replace the **most recently used (MRU)** block
 - System must pin the block currently being processed
 - After processing the final tuple, 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

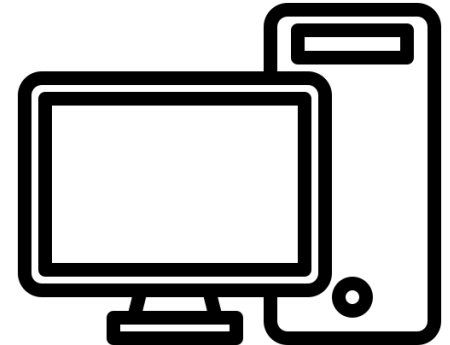


Database System Architectures

- Variants for creating a database system
 - Centralized and Client-Server Systems
 - Server System Architectures
 - Parallel Systems
 - Distributed Systems

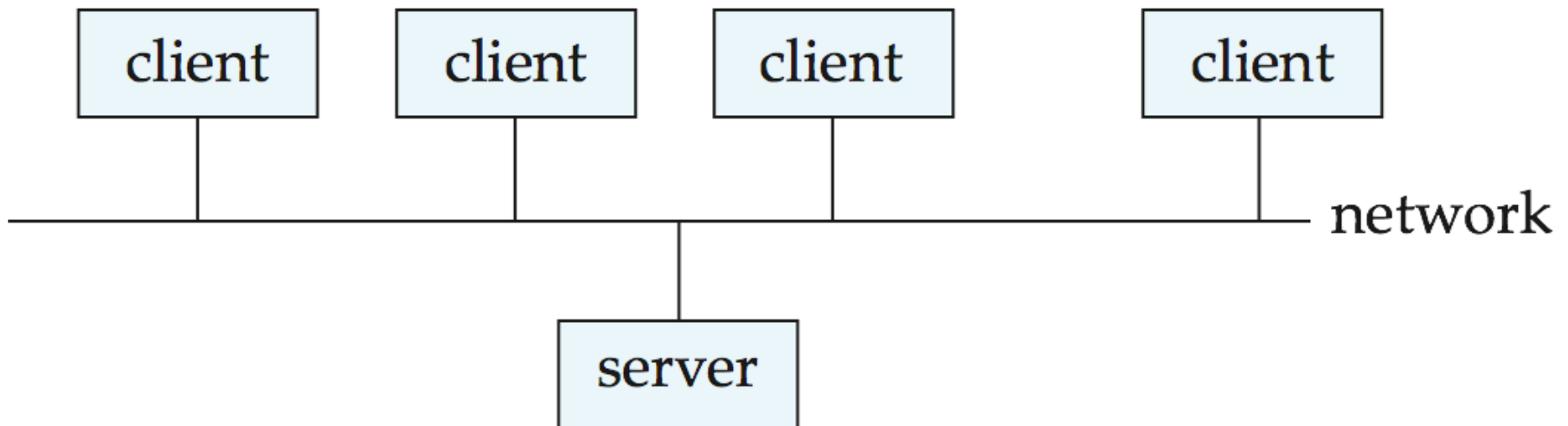
Centralized Systems

- Run on a single computer system
 - and do not interact with other computer systems
- General-purpose computer system
 - one to a few CPUs and a number of device controllers
 - shared memory
- Single-user system
 - e.g., personal computer or workstation
 - desk-top unit, single user, usually one CPU and one or two hard disks
- Multi-user system
 - more disks, more memory, multiple CPUs
 - serve a large number of users, usually connected to the system via terminals
 - also called *server systems*



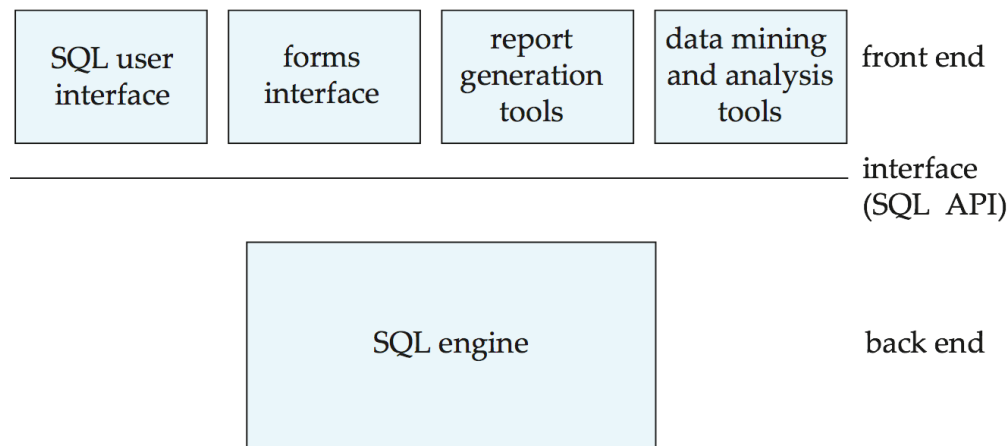
Client-Server Systems

- Server systems satisfy requests generated at m client systems
- They are connected to the server via a network
 - local or internet
 - LAN or WIFI
 - ...



Client-Server Systems

- Database functionality can be divided into:
 - **Back-end:** manages access structures, query evaluation and optimization, concurrency control and recovery
 - **Front-end:** consists of tools such as *forms*, *report-writers*, and graphical user interface facilities
- Interface between the front-end and the back-end:
 - SQL or proprietary application program interface (API)



Client-Server Systems

- Advantages of client-server systems over single machine systems:
 - better functionality for the cost
 - flexibility in locating resources and expanding facilities
 - better user interfaces
 - easier maintenance
- Server systems can be broadly categorized into two kinds:
 - **transaction servers** (used for RDBMS, aka SQL servers)
 - **data servers** (used for object-oriented databases)

SQL Servers

- Also called **query server** systems or transaction servers
 - Clients send requests to the server
 - Transactions are executed at the server
 - Results are shipped back to the client
- Requests are specified in SQL, and communicated to the server through a *remote procedure call* (RPC) mechanism
- Different APIs exist for programming languages
 - C: *Open Database Connectivity* (ODBC) is an API standard from Microsoft for connecting to a server, sending SQL requests, and receiving results
 - Java: JDBC standard
 - Python: [PEP 249](#) introduced DB-API (sqlite3 is compliant) but there are libraries for many DBMS: mysql-connector-python, psycopg2 (PostgreSQL), etc

SQL Server Processes

- A typical SQL server consists of multiple processes accessing data in shared memory

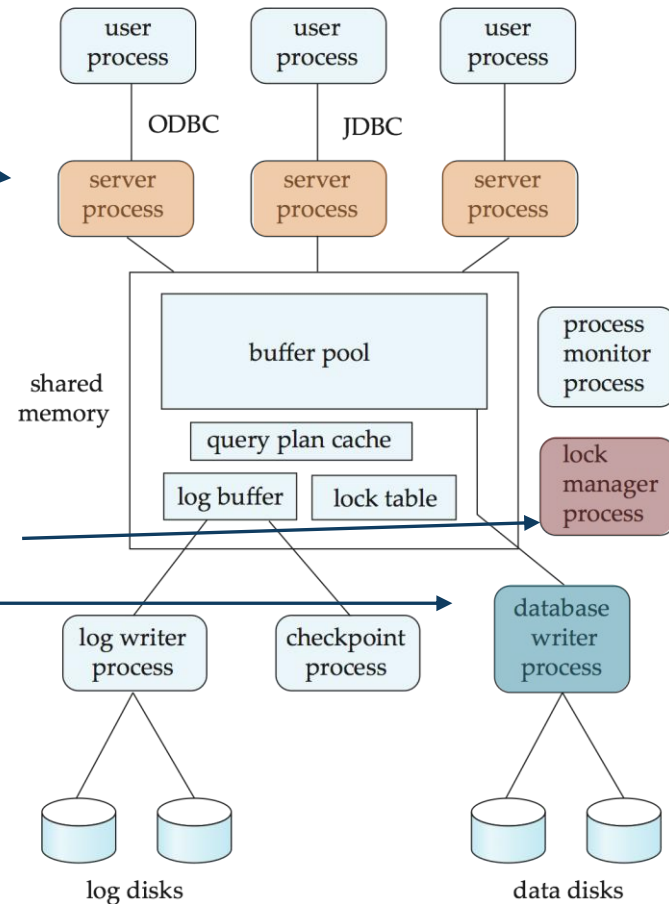
- **Server processes**

- Receive user queries (transactions), execute them and send results back
- Processes may be **multithreaded**, allowing a single process to execute several user queries concurrently

- **Lock manager process** (see future lectures)

- **Database writer process**

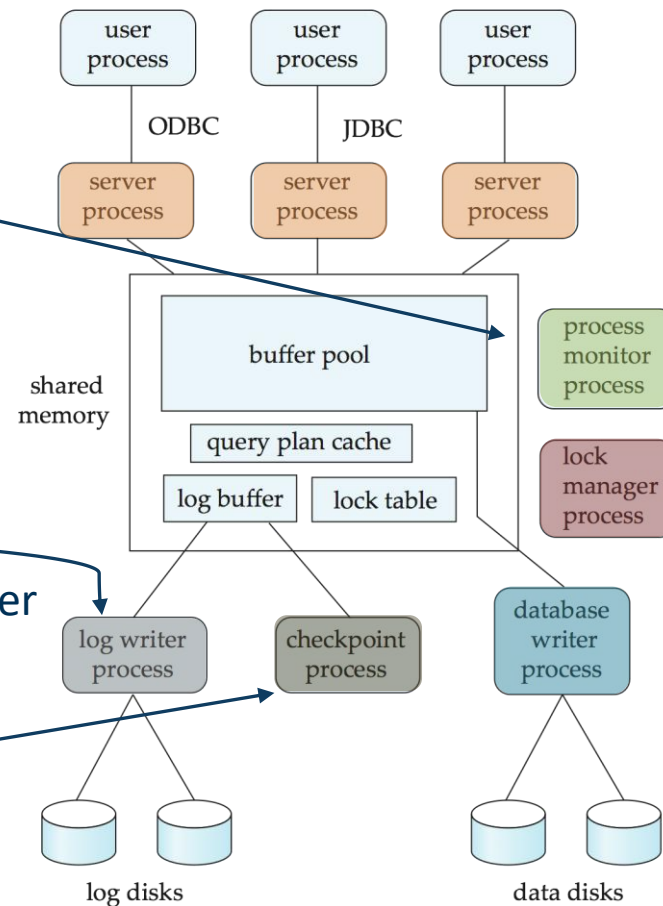
- Output modified buffer blocks to disks continually



SQL Server Processes

- A typical SQL server consists of multiple processes accessing data in shared memory

- **Process monitor process**
 - Monitors other processes, and takes recovery actions if other processes fail
 - e.g., aborting any transactions being executed by a server process and restarting it
- **Log writer process**
 - Server processes add log records to log buffer
 - Log writer process outputs log records to stable storage
- **Checkpoint process**
 - Performs periodic checkpoints



SQL Server Processes: Overview

- Shared memory contains shared data
 - Buffer pool
 - Lock table
 - Log buffer
 - Cached query plans (reused if same query submitted again)
- All database processes can access shared memory
- To avoid concurrency, DBMS implement *mutual exclusion* using either
 - Operating system semaphores
 - Atomic instructions such as test-and-set
- To avoid overhead of interprocess communication for lock request/grant
 - each database process operates directly on the lock table
 - instead of sending requests to lock manager process
- Lock manager process still used for deadlock detection

Parallel Database Systems

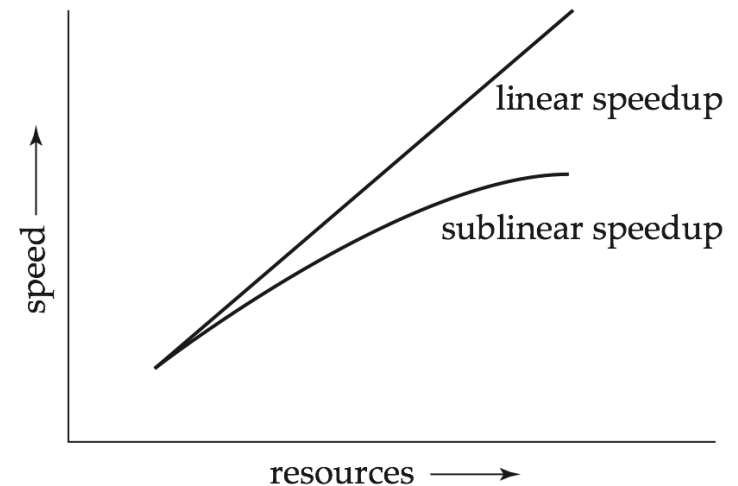
- Parallel database systems consist of multiple processors and multiple disks connected by a fast interconnection network
- A **coarse-grain parallel** machine consists of a small number of powerful processors
- A **massively parallel** or **fine grain parallel** machine utilizes thousands of smaller processors
- Two main performance measures:
 - **Throughput** – the number of tasks that can be completed in a given time interval
 - **Response time** – the amount of time it takes to complete a single task from the time it is submitted

Speedup and Scaleup

- Question: how much performance do we gain by enlarging the system?
 - Optimum: linear scalability: doubling the system doubles the performance
- **Speedup**: a fixed-sized problem executing on a small system is given to a system which is N -times larger
- Measured by:

$$\text{speedup} = \frac{\text{small system elapsed time}}{\text{large system elapsed time}}$$

- Speedup is **linear** if equation equals N

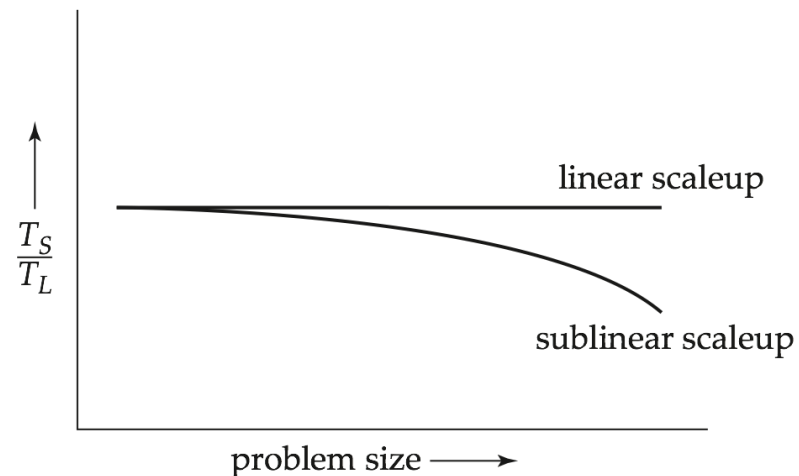


Speedup and Scaleup

- Question: how much performance do we gain by enlarging the system?
 - Optimum: linear scalability: doubling the system doubles the performance
- **Scaleup**: increase the size of both the problem and the system
 - N -times larger system used to perform N -times larger job
- Measured by:

$$scaleup = \frac{\text{small system small problem elapsed time}}{\text{big system big problem elapsed time}}$$

- Scale up is **linear** if equation equals 1.

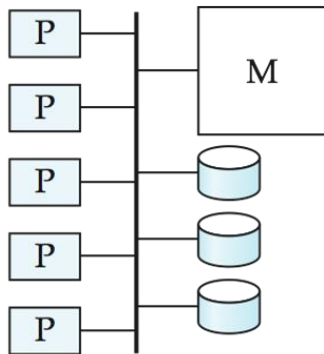


Limitation of Speedup and Scaleup

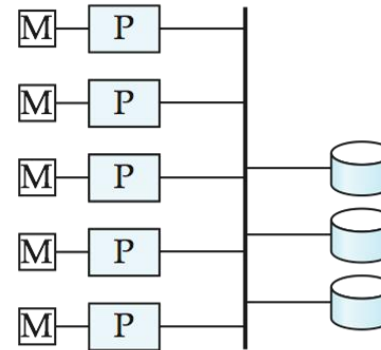
Speedup and scaleup are often sublinear due to:

- **Startup costs**
 - cost of starting up multiple processes may dominate computation time
 - esp. if the degree of parallelism is high
- **Interference**
 - processes accessing shared resources (e.g., system bus, disks, or locks) compete with each other → bottlenecks
 - thus spending time waiting on other processes, rather than performing useful work
- **Skew**
 - Increasing the degree of parallelism increases the variance in service times of parallelly executing tasks
 - Overall execution time determined by **slowest** of parallelly executing task

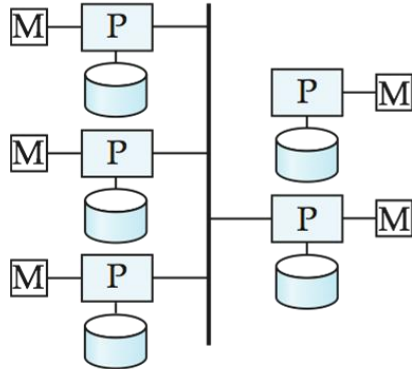
Parallel Database Architectures



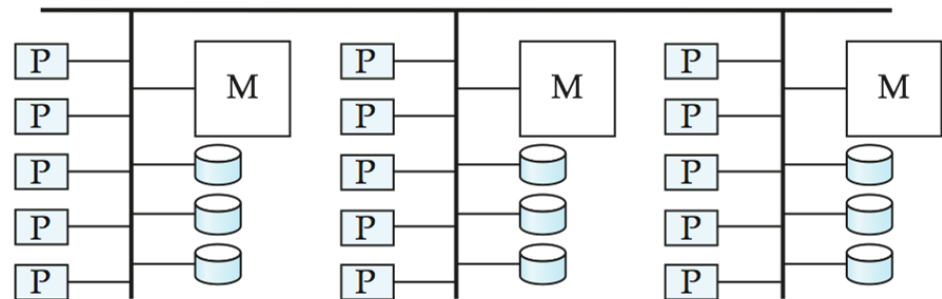
(a) Shared memory
processors share a common memory



(b) Shared disk
processors share a common disk



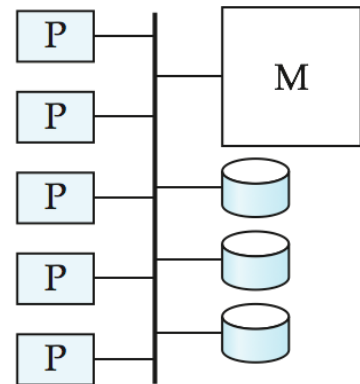
(c) Shared nothing
processors share neither
a common memory nor
common disk



(d) Hierarchical
hybrid of the other architectures

Shared Memory

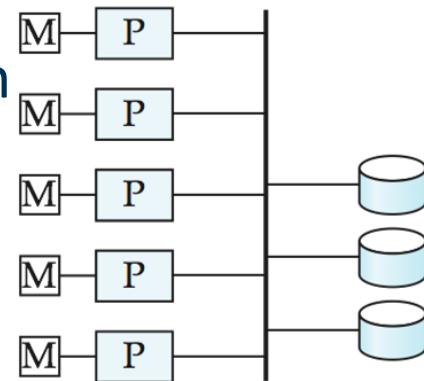
- Processors and disks have access to a common memory
 - typically via a bus or through an interconnection network
- Extremely efficient communication between processors
 - data in shared memory can be accessed by any processor
 - without having to move it using software
- Architecture is not scalable beyond 32 or 64 processors
 - interconnection network becomes a bottleneck
- Widely used for lower degrees of parallelism (4 to 8)



(a) shared memory

Shared Disk

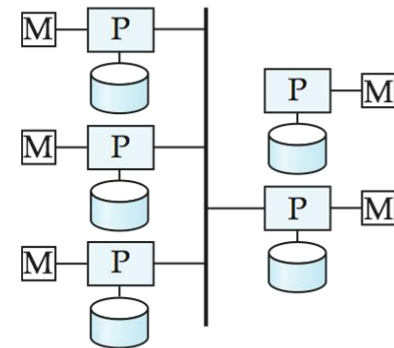
- All processors can directly access all disks via an interconnection network, but the processors have private memories
 - i.e., the memory bus is not a bottleneck
- Downside
 - bottleneck now occurs at interconnection to the disk subsystem
- Shared-disk systems can scale to a somewhat larger number of processors, but communication between processors is slower



(b) shared disk

Shared Nothing

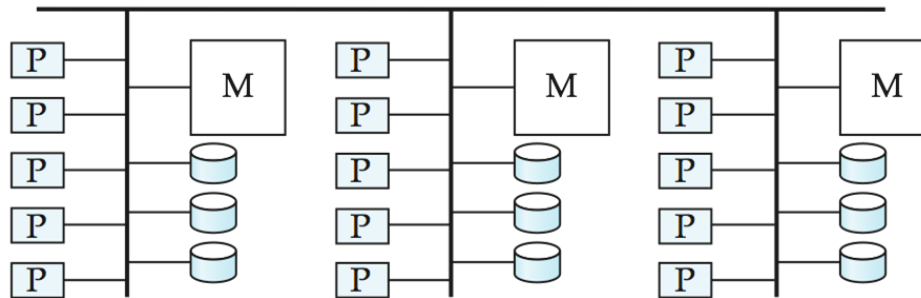
- Each node consists of a processor, memory, and one or more disks
- Node functions as the server for the data on the disk(s) it owns
- Data accessed from local disks (and local memory accesses) do not pass through interconnection network, thereby minimizing the interference of resource sharing
- Shared-nothing multiprocessors can be scaled up to thousands of processors without interference
- Main drawback:
 - cost of communication and non-local disk access;
 - sending data involves software interaction at both ends



(c) shared nothing

Hierarchical

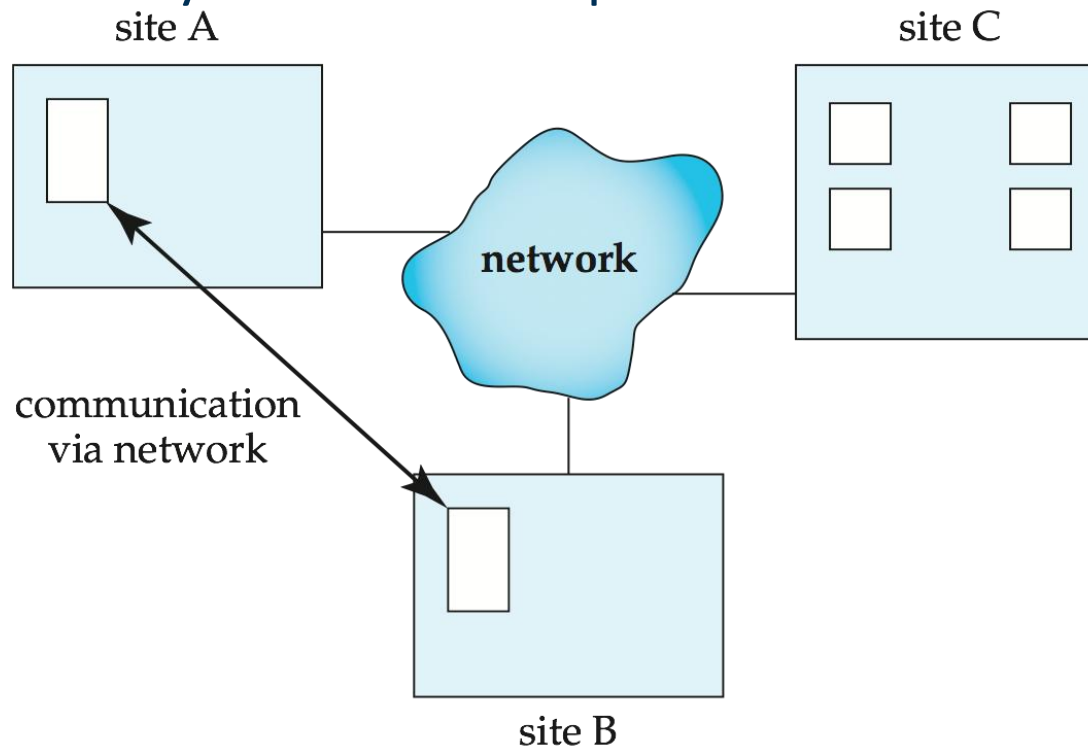
- Combines characteristics of all three architectures
- Top level is a shared-nothing architecture
 - Each node of the system could be a shared-memory system or a shared-disk system
- Reduce the complexity of programming such systems by **distributed virtual-memory** architectures
- Also called **non-uniform memory architecture (NUMA)**



(d) hierarchical

Distributed Database Systems

- Data spread over multiple machines (also: *sites*)
- Network interconnects the machines
- Data shared by users on multiple machines



Distributed Database Systems

- **Homogeneous** distributed databases
 - Same software/schema on all sites, data may be partitioned among sites
 - Goal: provide a view of a single database, hiding details of distribution
- **Heterogeneous** distributed databases
 - Different software/schema on different sites
 - Goal: integrate existing databases to provide useful functionality
- Differentiate between *local* and *global* transactions
 - A **local transaction** accesses data in the *single* site at which the transaction was initiated
 - A **global transaction** either accesses data in a site different from the one at which the transaction was initiated or accesses data in several different sites

Trade Offs in Distributed Database Systems

- Sharing data
 - users at one site able to access the data residing at some other sites
- Autonomy
 - each site is able to retain a degree of control over data stored locally
- Higher system availability through redundancy
 - data can be replicated at remote sites,
and system can function even if a site fails
- Disadvantage: added complexity required to ensure proper coordination among sites
 - Software development cost
 - Greater potential for bugs
 - Increased processing overhead

Implementation Issues

- Atomicity needed even for transactions that update data at multiple sites
- The two-phase commit protocol (2PC) is used to ensure atomicity
 - Basic idea: each site executes transaction until just before commit, and then leaves final decision to a coordinator
 - Each site must follow decision of coordinator, even if there is a failure while waiting for coordinator's decision
- 2PC is not always appropriate: other transaction models based on persistent messaging, and workflows, are also used
- Distributed concurrency control (and deadlock detection) required
- Data items may be replicated to improve data availability

Summary

- Data storage is layered
 - trading off cost/byte vs. access speed
- Data organization in files
 - trading off disk usage vs. reorganization cost
 - minimize block transfer
- Database architectures
 - single machine vs. distributed
 - scalability of distributed databases (speedup/scaleup)
 - design issues of distributed databases

Questions?

