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DBMS Architectures

Fundamentals of Databases

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Acknowledgements

- These slides are adaptations (mostly minor, but some major) of material authored and made available to instructors by **A. Silberschatz, H. F. Korth, and S. Sudarshan** to accompany their textbook **Database System Concepts, 6th Edition, McGraw-Hill, 2006, 978-0-07-352332-3**.

- Copyright remains with them, whom I thank.

- Any errors are my responsibility.

In Previous Handouts

- We learned that data is an enterprise asset of such importance that specialized software systems, called DBMSs, are crucial to manage it well and that using files alone won't do.

- We learned the importance of separating concerns and of adopting different levels of abstraction in designing and implementing databases.

- We learned how data models lead to schemas and instances that enable a logical view of the data.

- We learned how to capture data requirements in the form of an (E)ER conceptual model.

- We learned how to derived from this conceptual model a logical one in the relational case, which is directly implementable in a DBMS.

- We learned how SQL has been extended to Turing-completeness and how views and trigger enrich our capability to capture and enforce domain semantics.

- We learned how DBMSs use the notion of transactions to manage concurrency and recovery.

- We learned how file organizations and indexed enable a logical-to-physical abstraction level at the storage layer too.

In This Handout

- What is the internal architecture of a classical DBMS like?

  ▸ What are the main subsystems?

  ▸ What are the main classes of users of DBMSs?

- What are the main kinds of database architecture in use today?

▸ How are client-server designs realized in DBMS architecture?

▸ What kinds of server are there?

▸ What parallelization and distribution approaches are there for DBMSs?

▸ How do DBMSs scale?

What is the internal architecture of a classical DBMS like? What are the main subsystems? What are the main classes of users?
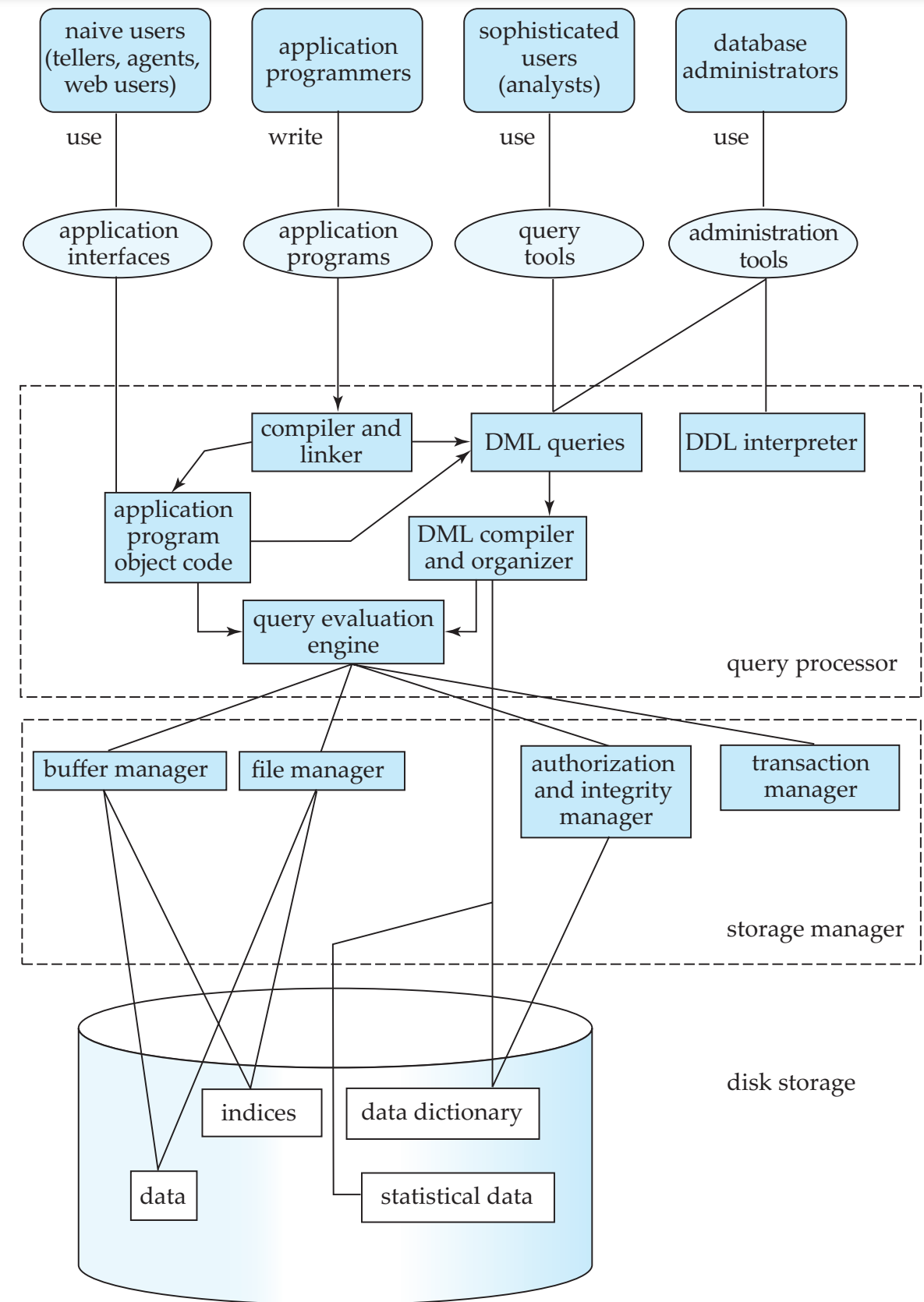
- Storage manager is a program module that provides the interface between the low-level data stored in the database and the application programs and queries submitted to the system.

- The storage manager is responsible to the following tasks:

  ‣ Interaction with the file manager

  ‣ Efficient storing, retrieving and updating of data

- Design/implementation issues:

  ‣ Storage access

 ‣ File organization

  ‣ Indexing and hashing
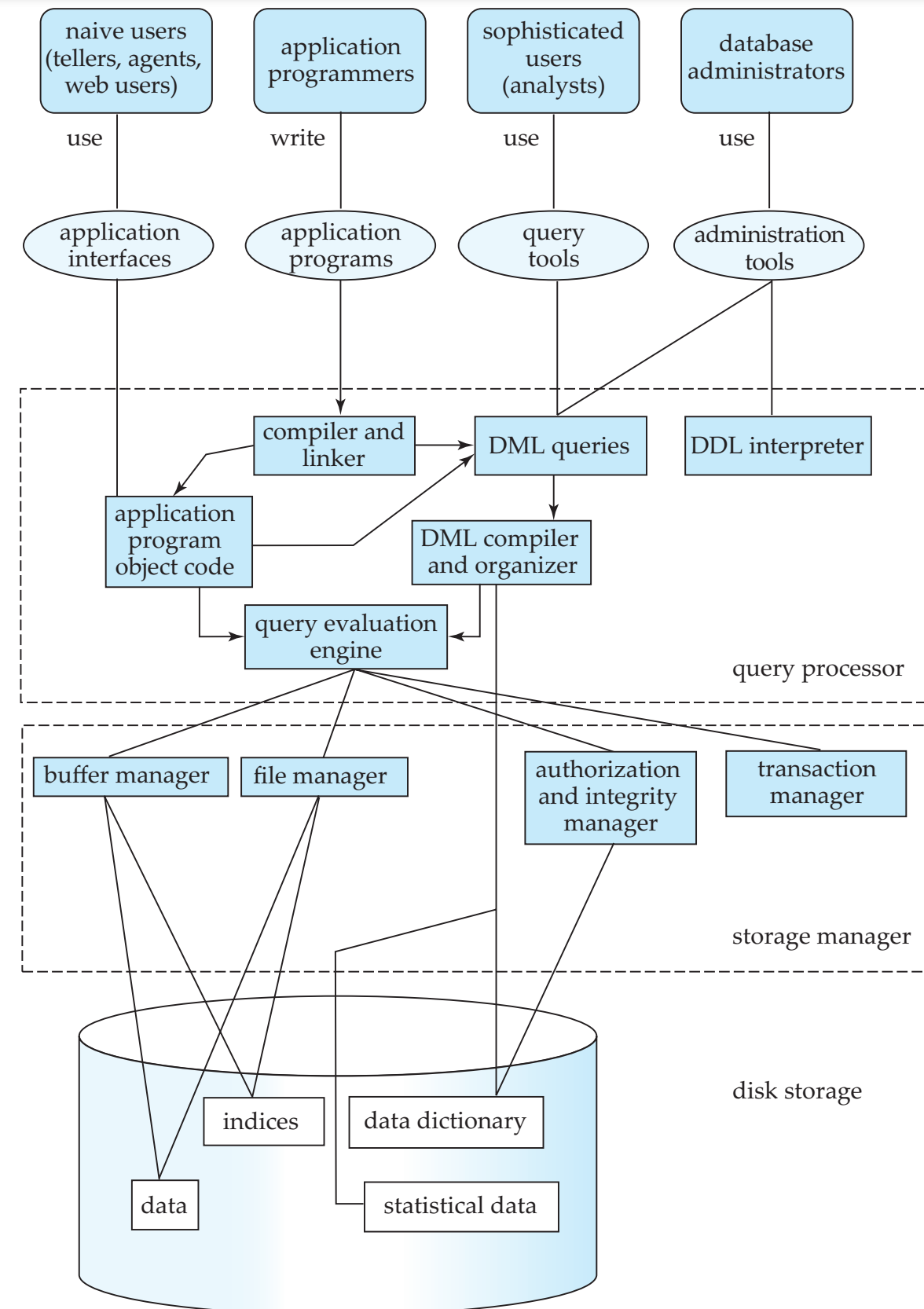
- What if the system fails?

- A transaction is a collection of operations that performs a single logical function in a database application

- Transaction-management component ensures that the database remains in a consistent (correct) state despite system failures (e.g., power failures and operating system crashes) and transaction failures.
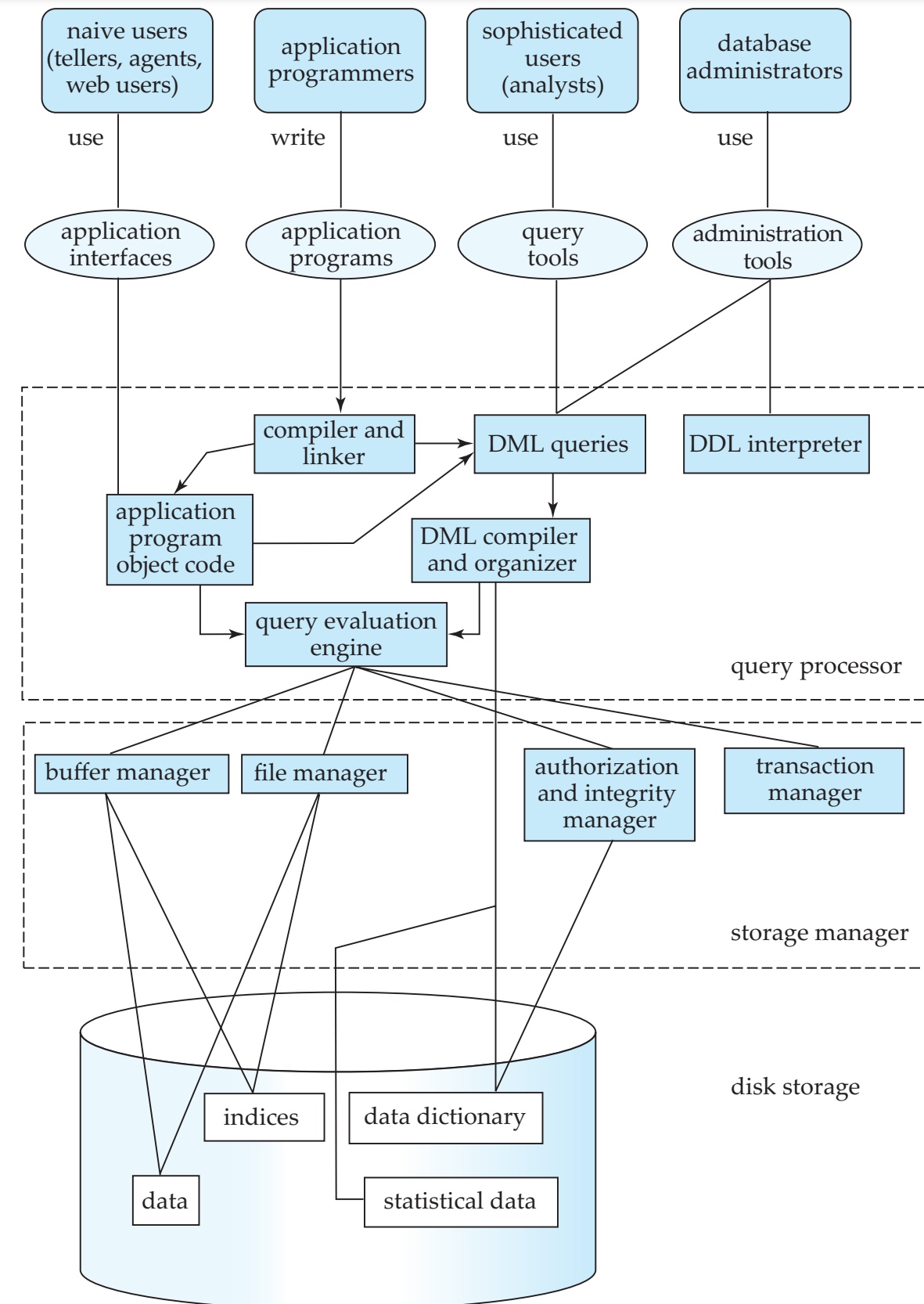
- What if more than one user is concurrently updating the same data?

- Concurrency controller ensures that the interaction among the concurrent transactions do not compromise the consistency of the database.
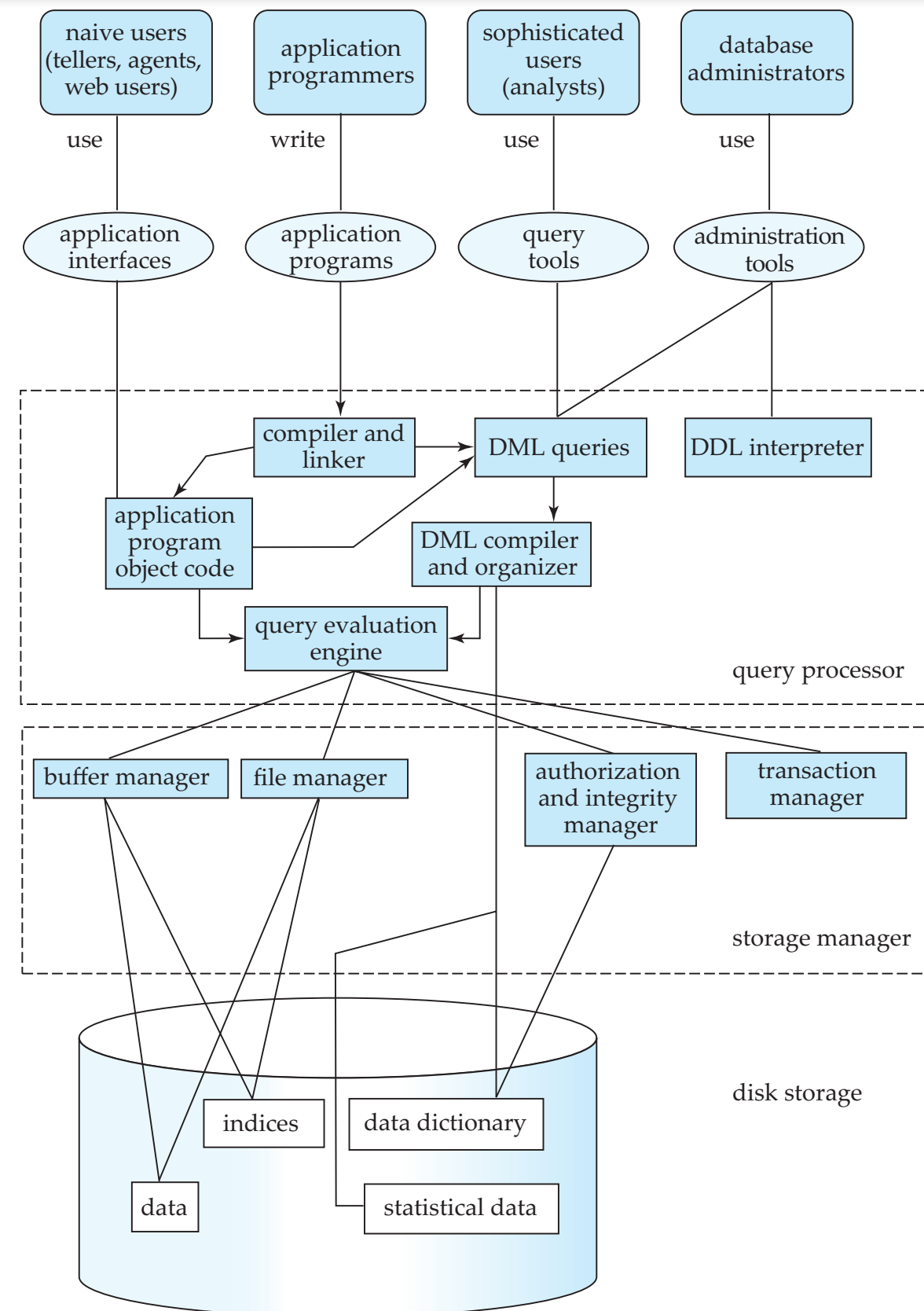
- Here, by query is meant DDL, QL and DML expressions

- Code in the database languages is compiled and installed in the DBMS.

- Application programs in general-purpose languages can invoke compiled queries or pass queries for evaluation using the libraries and APIs exposed by the DBMS

- The HCI interfaces invoke bits of application that interact with the DBMS.
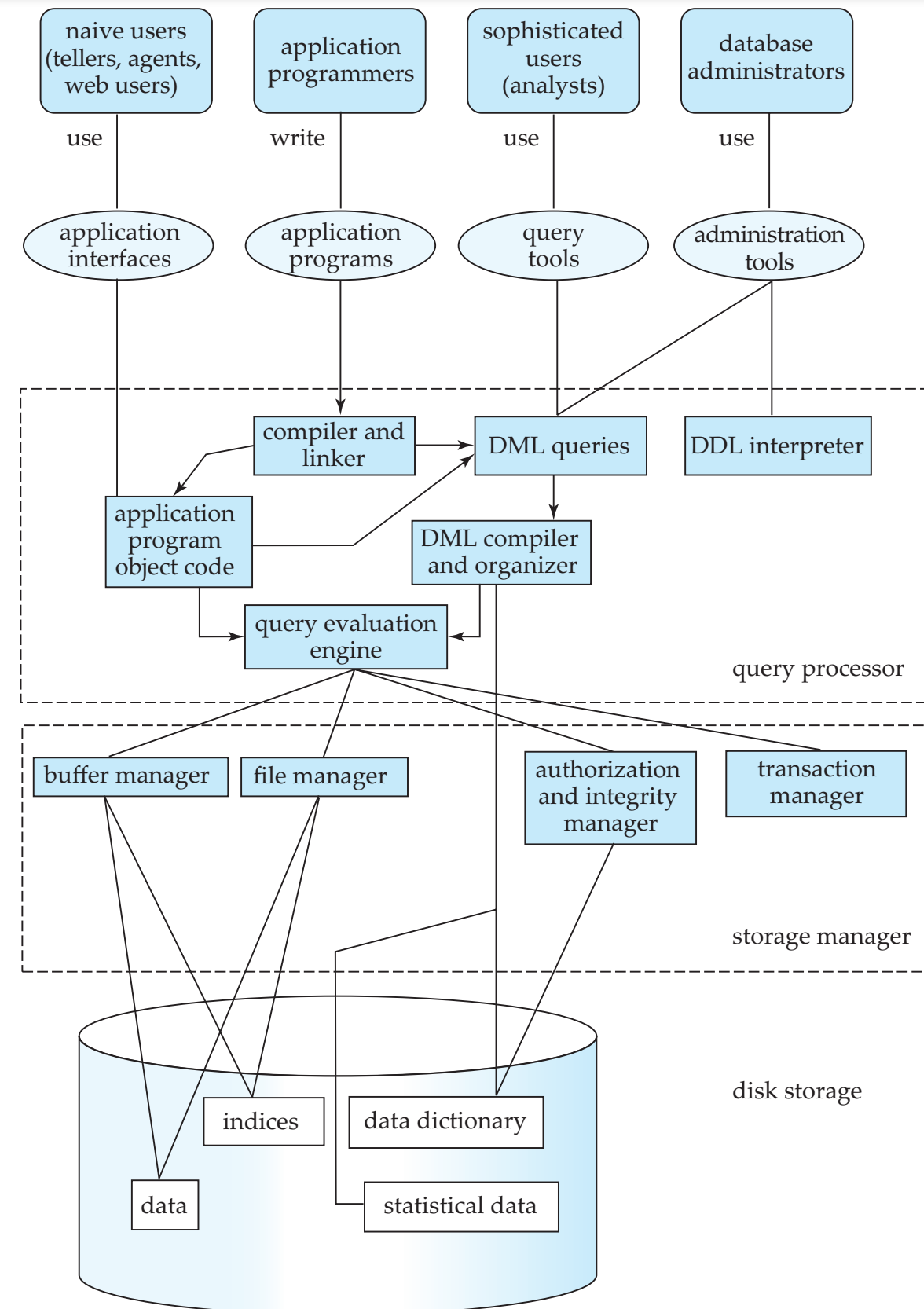
Main Phases of Query Processing

- Parsing and translation

- Optimization

- Evaluation
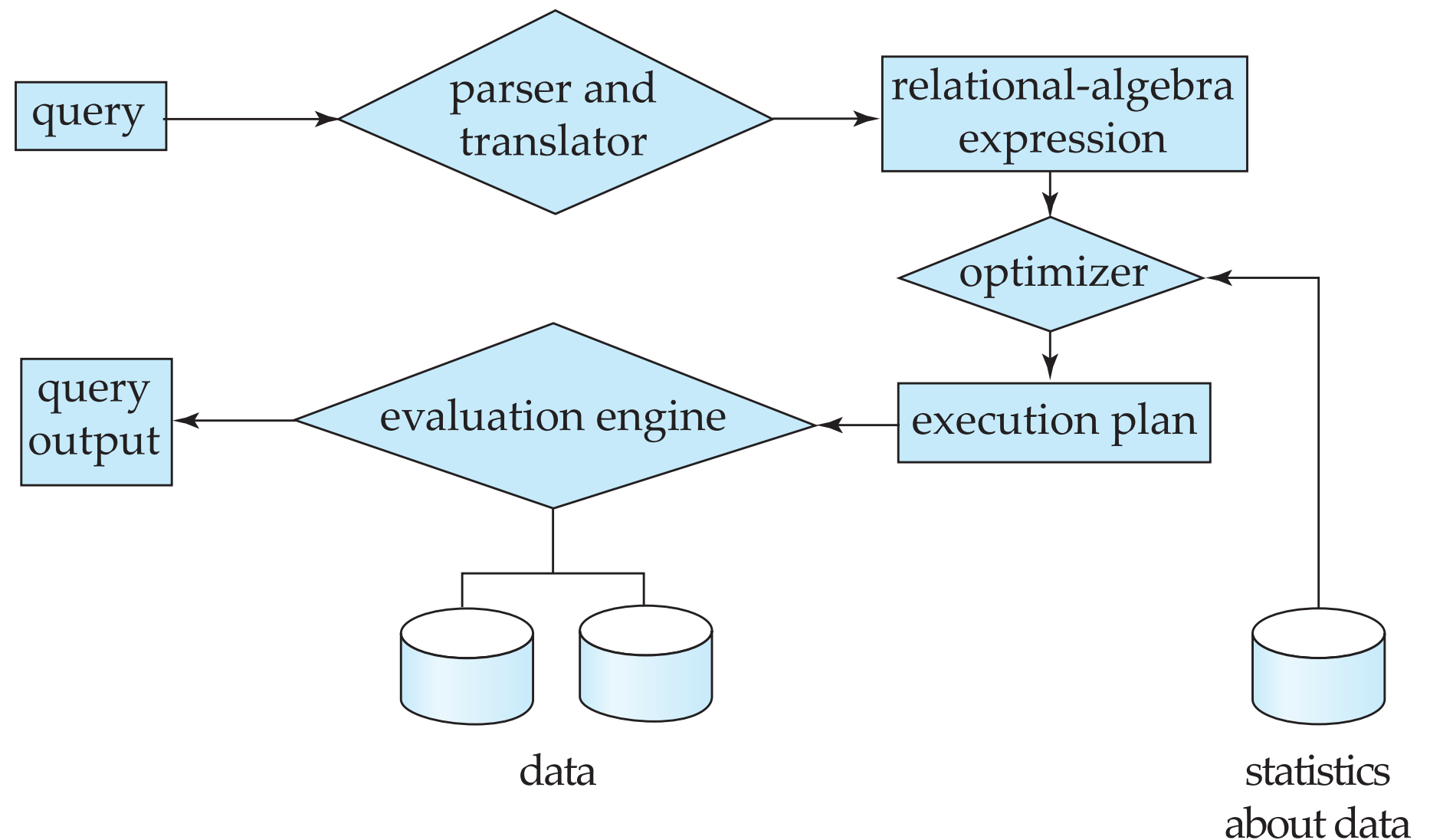
- There are alternative ways of evaluating a given query

  ▸ Many equivalent logical expressions

  ▸ Many algorithms for each logical operation with different associated costs

- Cost difference between a good and a bad way of evaluating a query can be enormous

- Need to estimate the cost of operations

  ▸ Depends critically on statistical information about relations which the database must maintain

  ▸ Need to estimate statistics for intermediate results to compute cost of complex expressions
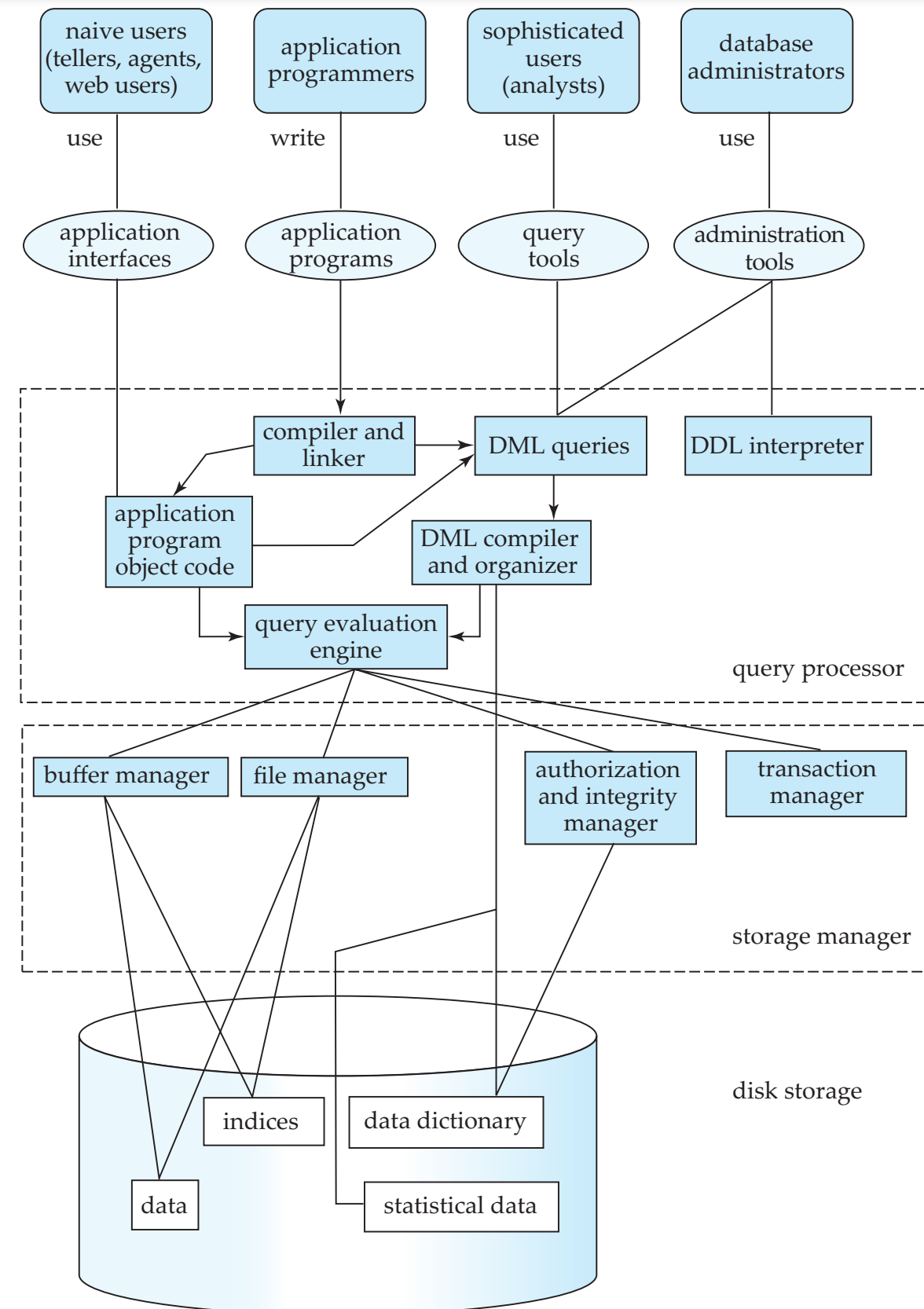
- Database administrators assign privileges to users and monitor performance.

- They continually study the statistics and revise configuration parameters to fine-tune performance.

- Sophisticated users (e.g., database designers) use CLI to implement and maintain logical models.

- Application programmers write software that uses APIs over the database, including HCI interfaces for naïve users.

- Naïve users rely on HCI interfaces for both back-room and customer-facing tasks.
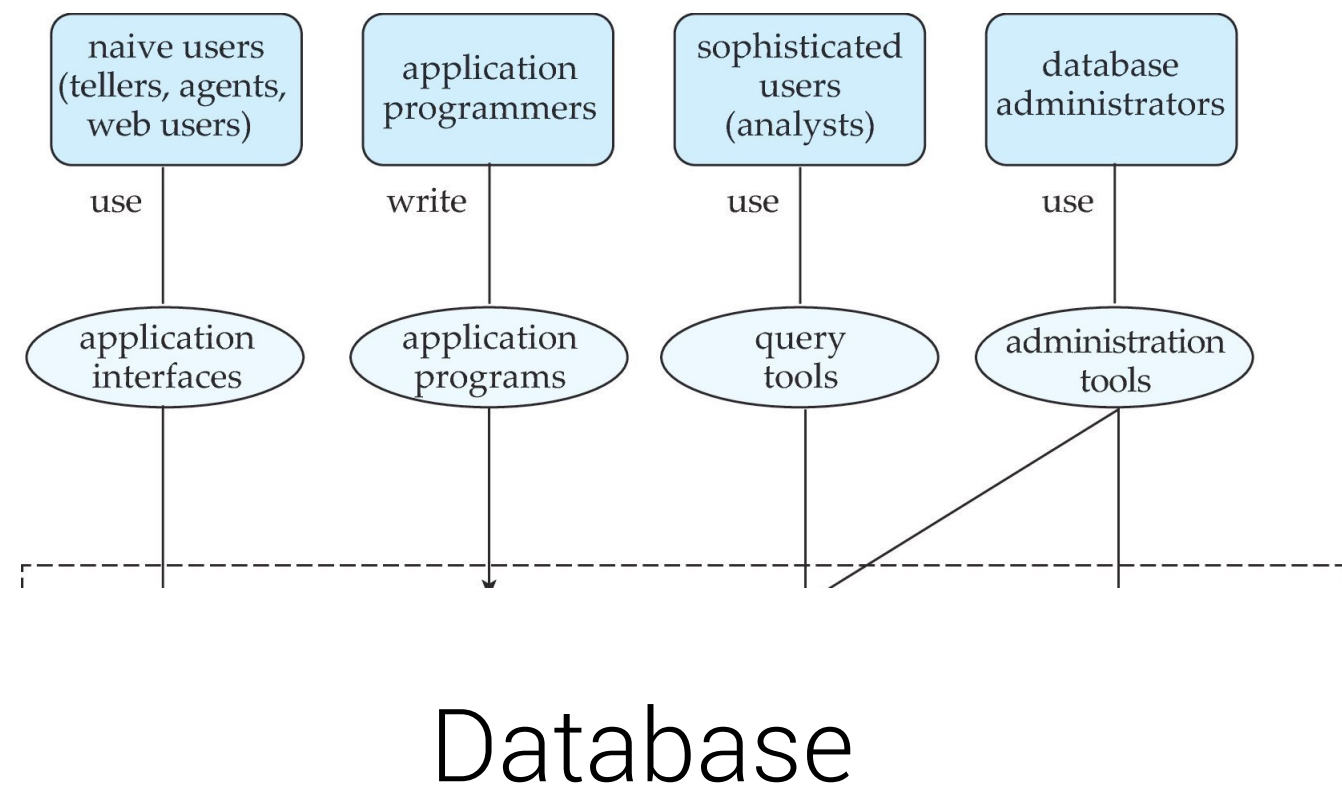
naive users (tellers, agents, web users)	application programmers	sophisticated users (analysts)	database administrators
use	write	use	use
application interfaces	application programs	query tools	administration tools

Database

What are the main kinds of database architecture in use today?

- The architecture of a database systems is greatly influenced by the underlying computer system on which the database is running:

    ▸ Centralized

    ▸ Client-server

    ▸ Parallel (multi-processor)

    ▸ Distributed

Centralized Systems

- Run on a single computer system and do not need to interact with other computer systems.

- General-purpose computer systems: one to a few CPUs and a number of device controllers that are connected through a common bus that provides access to shared memory

- Single-user systems (e.g., personal computer or workstation): desk-top unit, logically for single user, logically one CPU and one secondary mass storage unit; the OS need not usually worry about more than one user at a time

- Multi-user systems: logically and physically many disks, much more memory, multiple CPUs, and a multi-user OS to serve a large number of users who are connected via terminals, workstations, PCs
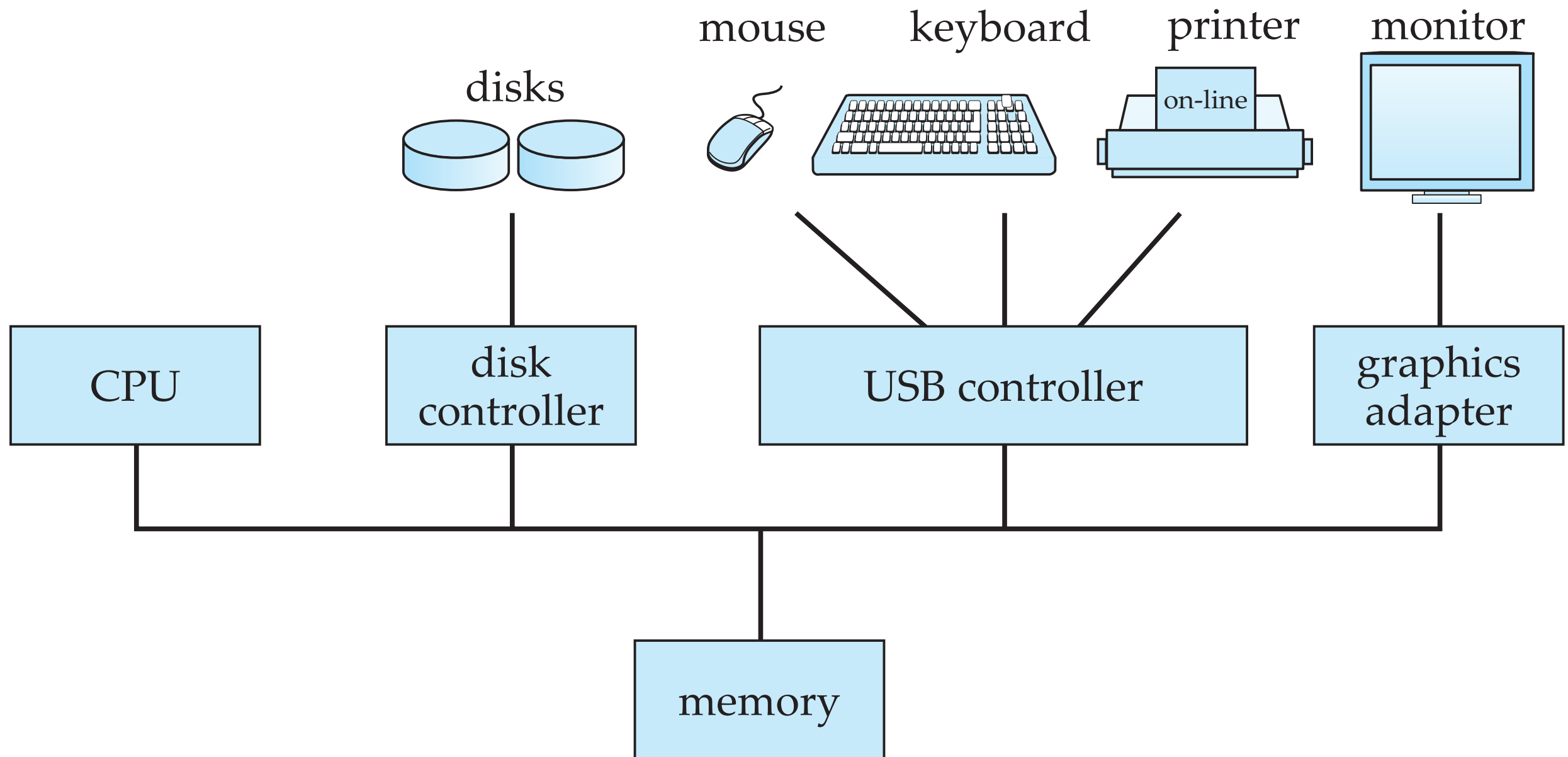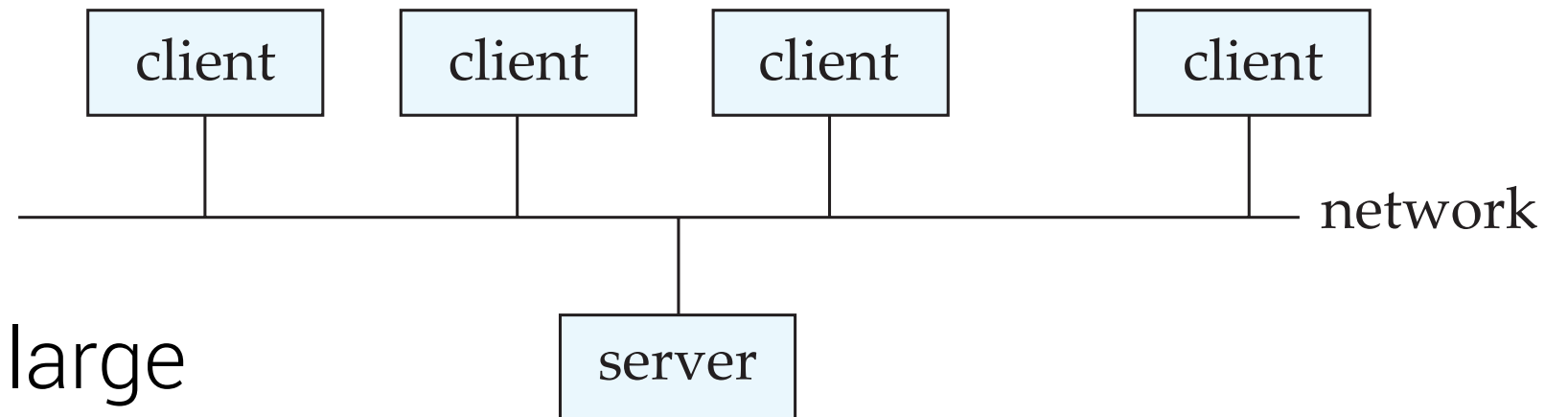
Client-Server Systems
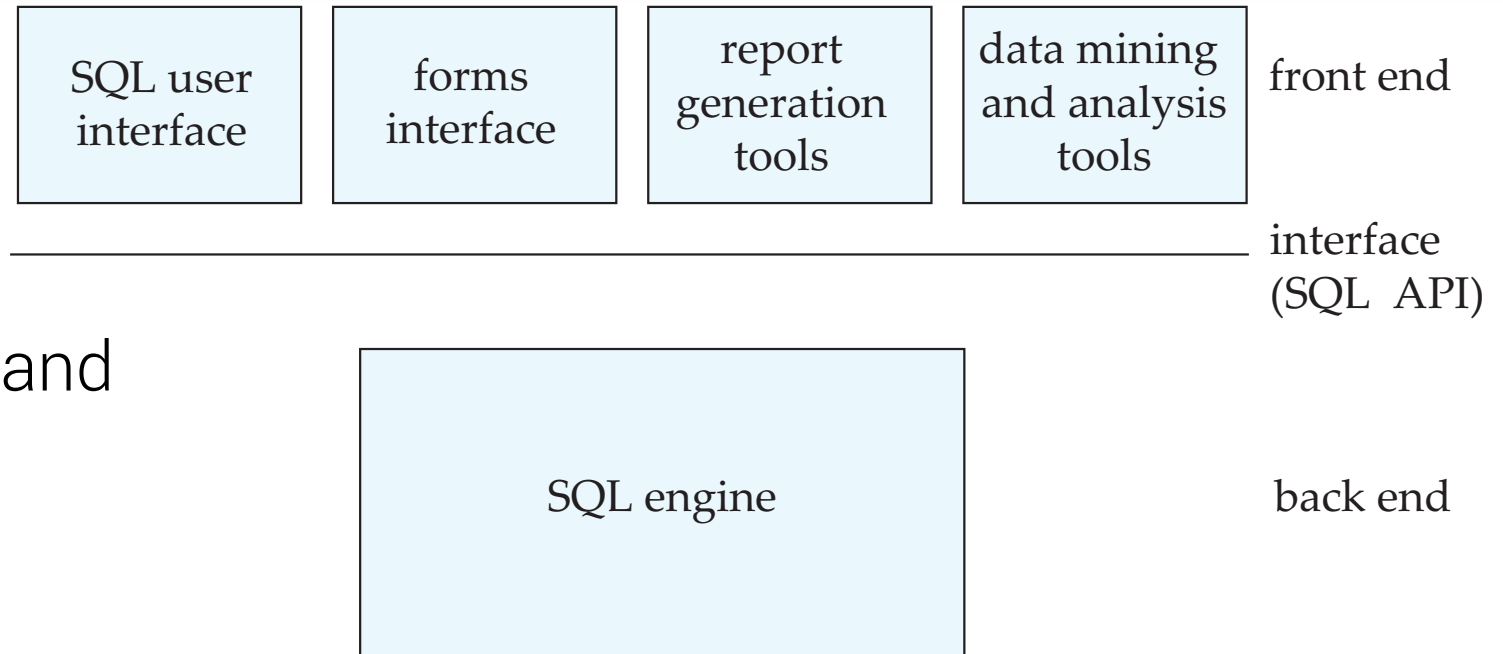
Client-Server Systems

- Server systems are large multi-user systems that aim to satisfy requests generated at many client systems, each (logically) a single-user system.

- There is an asymmetry assumption that the server is many times better resourced than any client.

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.

- The interface between the front-end and the back-end is

  - ▸ directly through a SQL engine (i.e., a query processor)

  - ▸ indirectly through an API.

SQL user interface	forms interface	report generation tools	data mining and analysis tools	front end

interface
(SQL API)

SQL engine

back end

Client-Server Systems

- Some advantages of replacing mainframes (i.e., very large centralized computer systems) with networks of workstations or personal computers (i.e., single-user systems) acting as clients by way of a connection to back-end server machines (i.e., multi-user systems) are:

  ▸ more functionality for the same cost,

  ▸ flexibility in locating resources and expanding facilities,
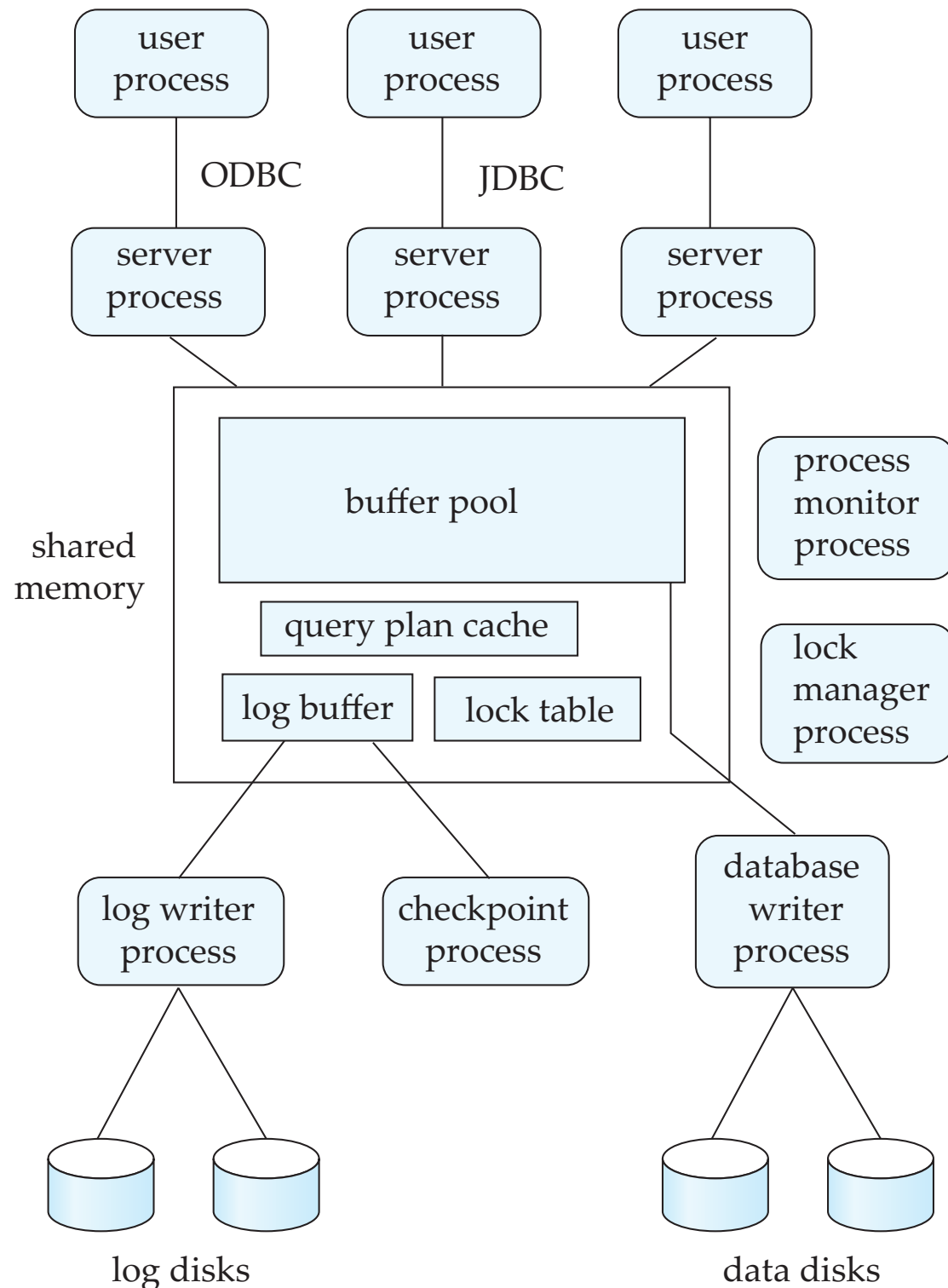
  ▸ better user interfaces,

  ▸ easier maintenance.

Types of Server

- Server systems can be broadly categorized into two kinds:

  ▸ transaction servers, which are widely used in relational database systems

  ▸ data servers, which are often used in object-based stores

Transaction Servers
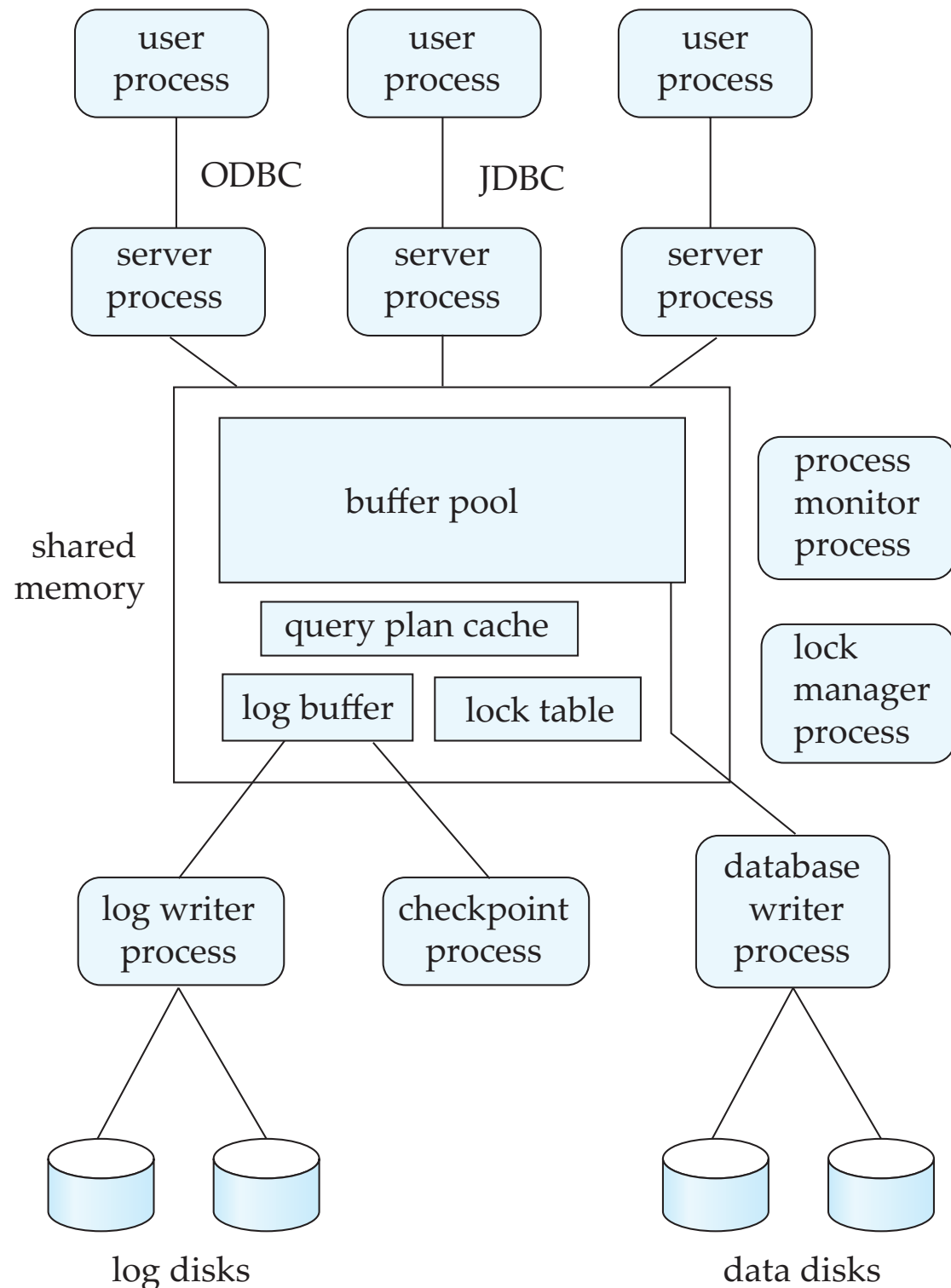
- Also called query server or SQL server systems

  ‣ Clients send requests to the server

  ‣ Transactions are executed at the server
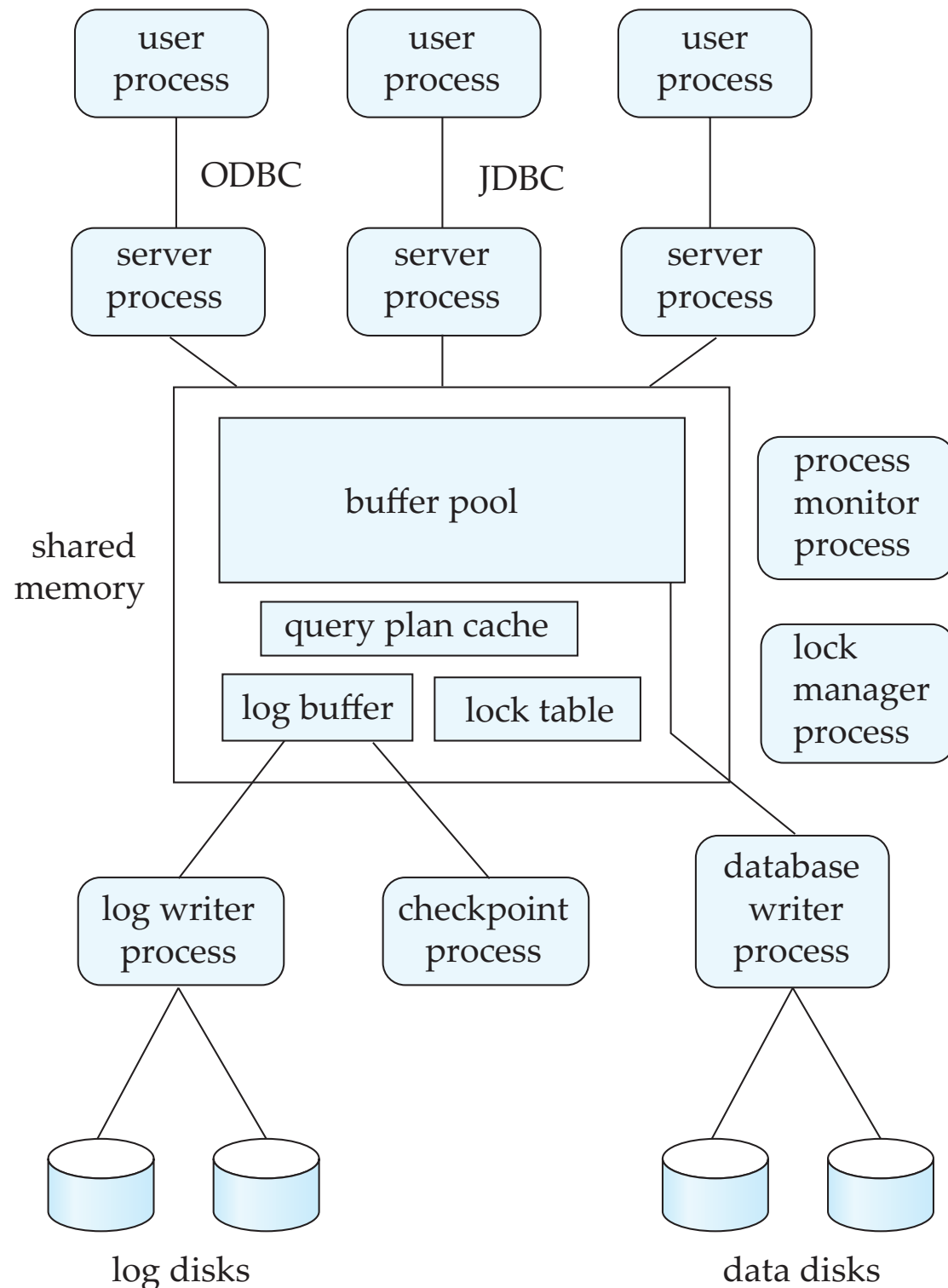
  ‣ Results are shipped back to the client.

- Requests are specified in SQL, and communicated to the server through a remote procedure call (RPC) mechanism.

- Transactional RPC allows many RPC calls to form a transaction.

- Open Database Connectivity (ODBC) is a C-language API for connecting to a server, sending SQL requests, and receiving results.
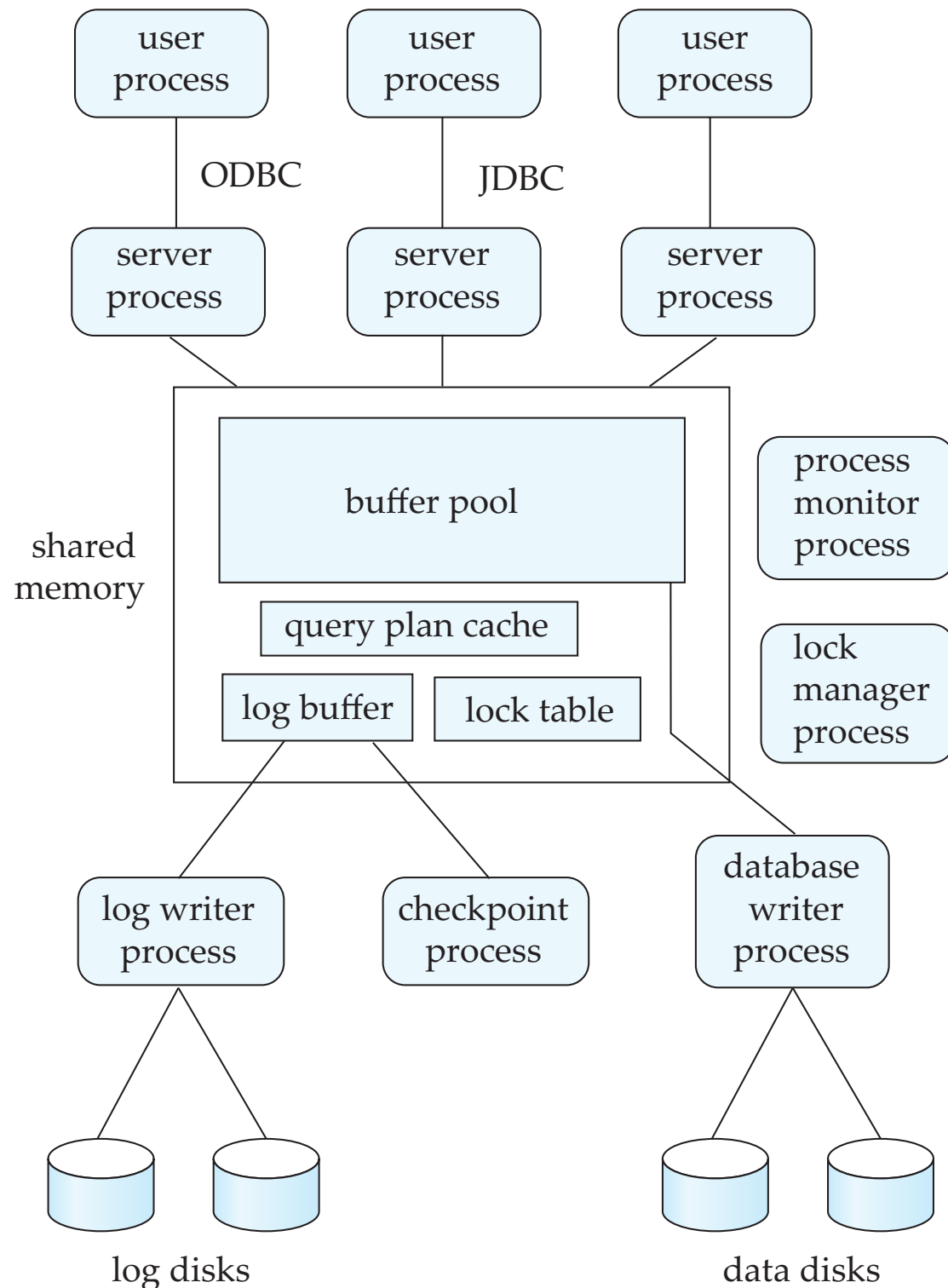
- JDBC is Java-based ODBC.

- In a transaction server, many processes cooperate to implement the database architecture we saw earlier.

- Queries are handled by server processes (i.e., these instantiate query processing functionality)

- These are typically multithreaded, typically massively so

- Other processes control access to shared memory:

  ▸ lock manager for concurrent access

  ▸ database writer for traffic between volatile and persistent storage

  ▸ process monitor, checkpoint and log-writer for transactional semantics (e.g., commits and aborts/roll-backs, recovery, etc.)

- There are many trade-offs at play here: all the helper processes (i.e., lock manager, buffer writers/off-loaders, etc.) ensure semantic correctness but risk being performance drains
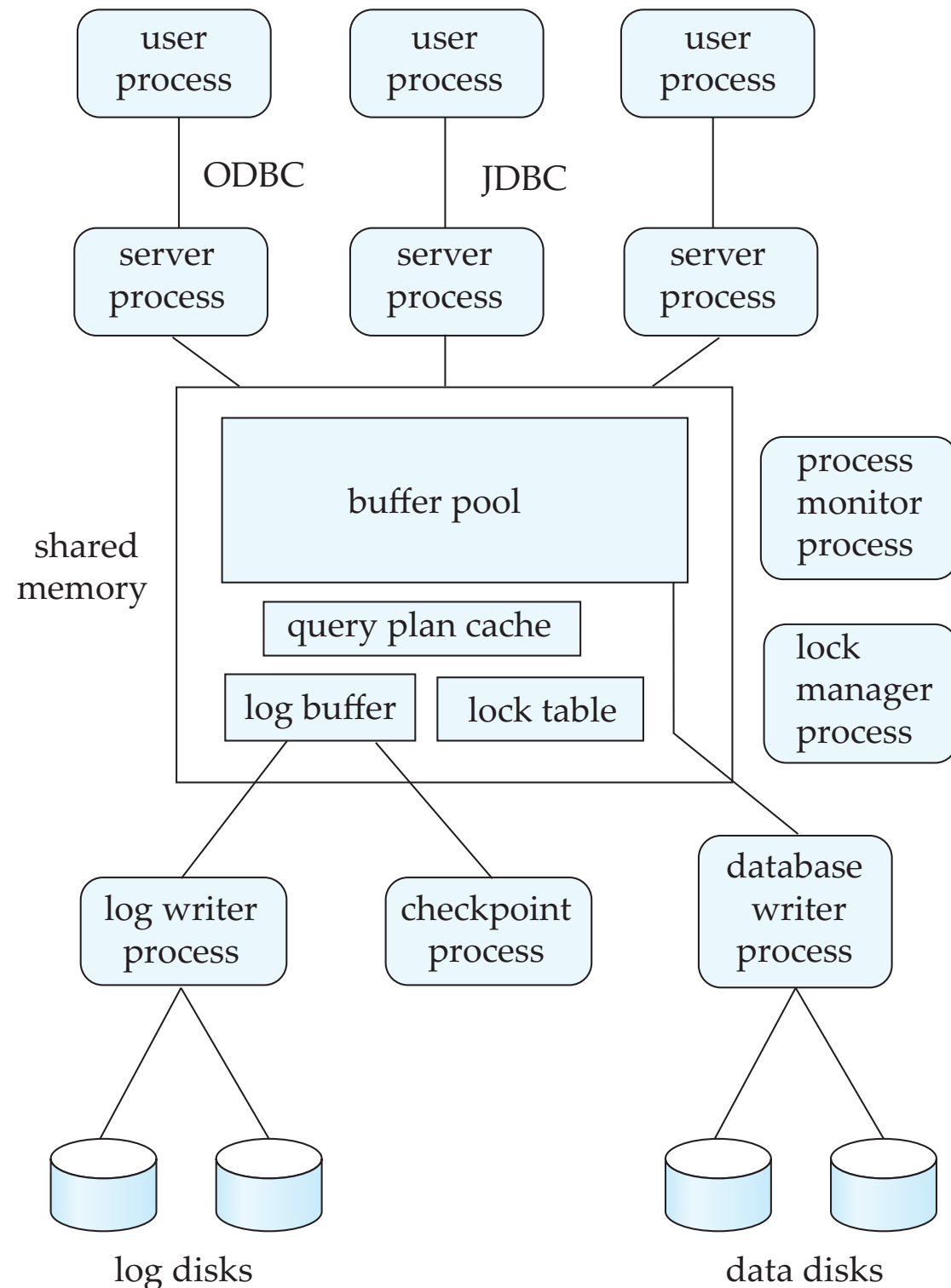
- Shared memory contains shared data, i.e.:

  ‣ Buffer pool

  ‣ Lock table

  ‣ Log buffer

  ‣ Cached query plans (reused if same query submitted again)

- All database processes can access shared memory

- To ensure that no two processes are accessing the same data structure at the same time, databases systems implement some form of mutual exclusion

Data Servers

Data Servers, Classically

- Used in high-speed LANs, in cases where

    ▸ The clients are comparable in processing power to the server

    ▸ The tasks to be executed are compute-intensive.

- Data is shipped to clients for processing, and then shipped results back to the server.

- This architecture requires full back-end functionality at the clients.

- Often used in object-based systems

Data Servers, Recently

- More recently, so-called NoSQL systems focus on massive replication of essentially equipotent systems

- Specialization leads to data servers for, say, images or sound, to be separate from classical retrieval

- Note that in the NoSQL world, there no queries in the sense we understand them here.

Parallel Systems

Parallel 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

- The goal is to improve performance as we increase the degree of parallelism (i.e., the number of resources deployed in parallel)

- Assume a problem of a given size $|P| = p$ that is executing on a small system of size $|S|$ is given to a larger system $|L| = n.|S|$

|P| = p |P| = p
|S| = 3 |L| = 4.|S|

- The speed-up goal is to then solve P in time inversely proportional to n, i.e., the growth in resources

- The problem size remains constant

linear speedup

sublinear speedup

speed ⟶

resources ⟶
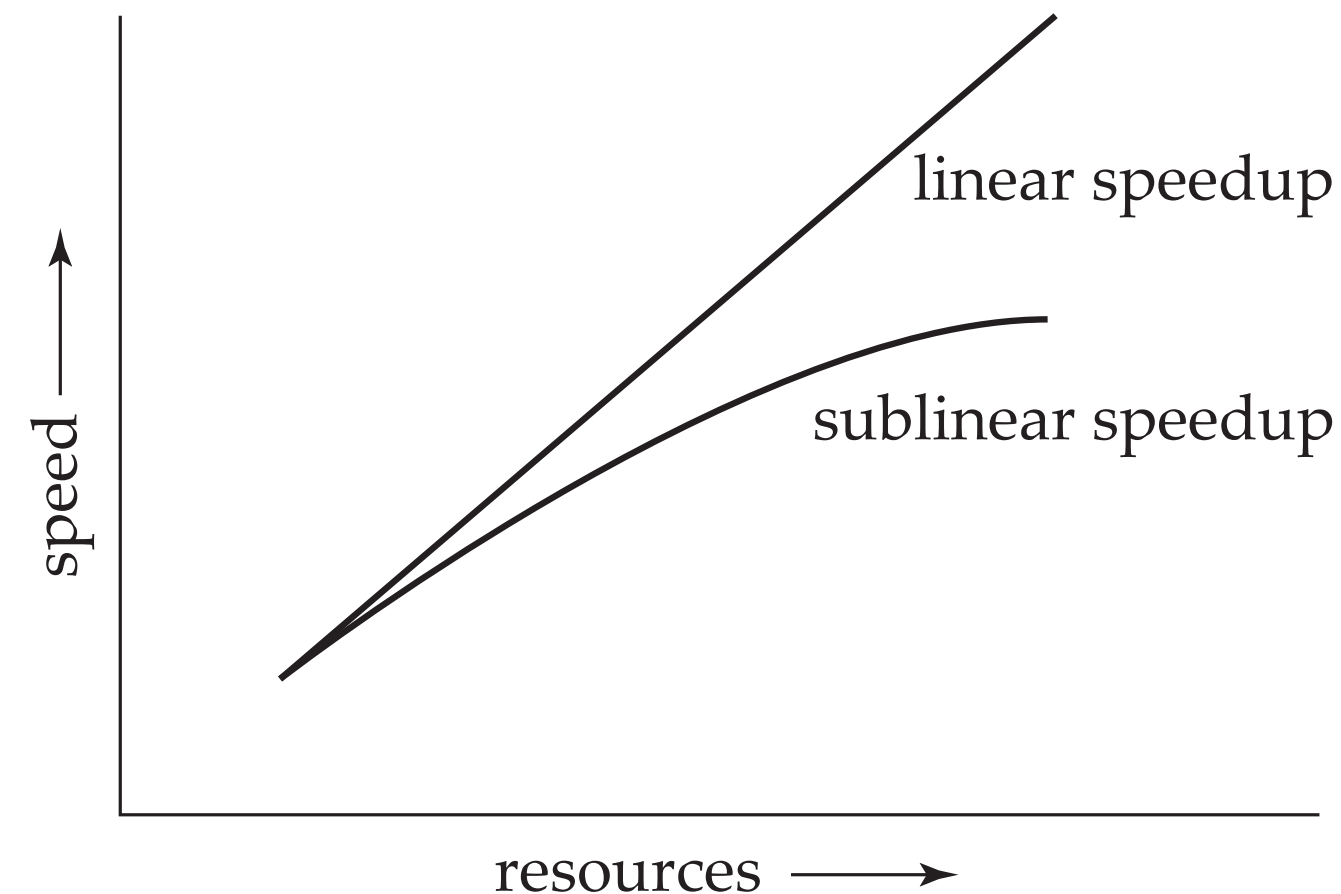
$|P| = p$ $|P| = p$
$|S| = 3$ $|L| = 4.|S|$
$T_S = 1$ $T_L = 0.25$
$T_S/T_L = 4 \rightarrow$ linear

- Speed-up is defined as

$$SpUP = T_S/T_L$$

i.e., the elapsed-time T_S to solve P in S divided by the elapsed-time T_L to solve P in L where $|L| = n.|S|$, $n>1$

- Speed-up is linear if SpUP = n

- Sub-linear speed-up means that the full investment on more resources is not fully recouped in elapsed-time reduction

- Assume a problem of a given size |P| that is executing on a small system of size |S|.

- Now, assume that faced with an increase of k, $k>1$ in the size of the problem, we increase the system k-times

- The goal here is to solve the larger problem in the same time as before.

- Both the problem size and the system size grow.

|P| = p |P'| = 4.p
|S| = 3 |L| = 4.|S|

Scale-Up

- Scale-up is defined as

$$ScUP = T_S/T_L$$

i. e., the elapsed-time T_S to solve P in S divided by the elapsed-time T_L to solve P' in L where $|P'| = k.|P|$ and $|L| = k.|S|$, $k>1$

linear scaleup

sublinear scaleup

problem size →

$\frac{T_S}{T_L}$

- Scale-up is linear if ScUP = 1

- Sub-linear scale-up means that the full investment on more resources is not fully recouped in elapsed-time stability

$|P| = p$ $|P'| = 4.p$
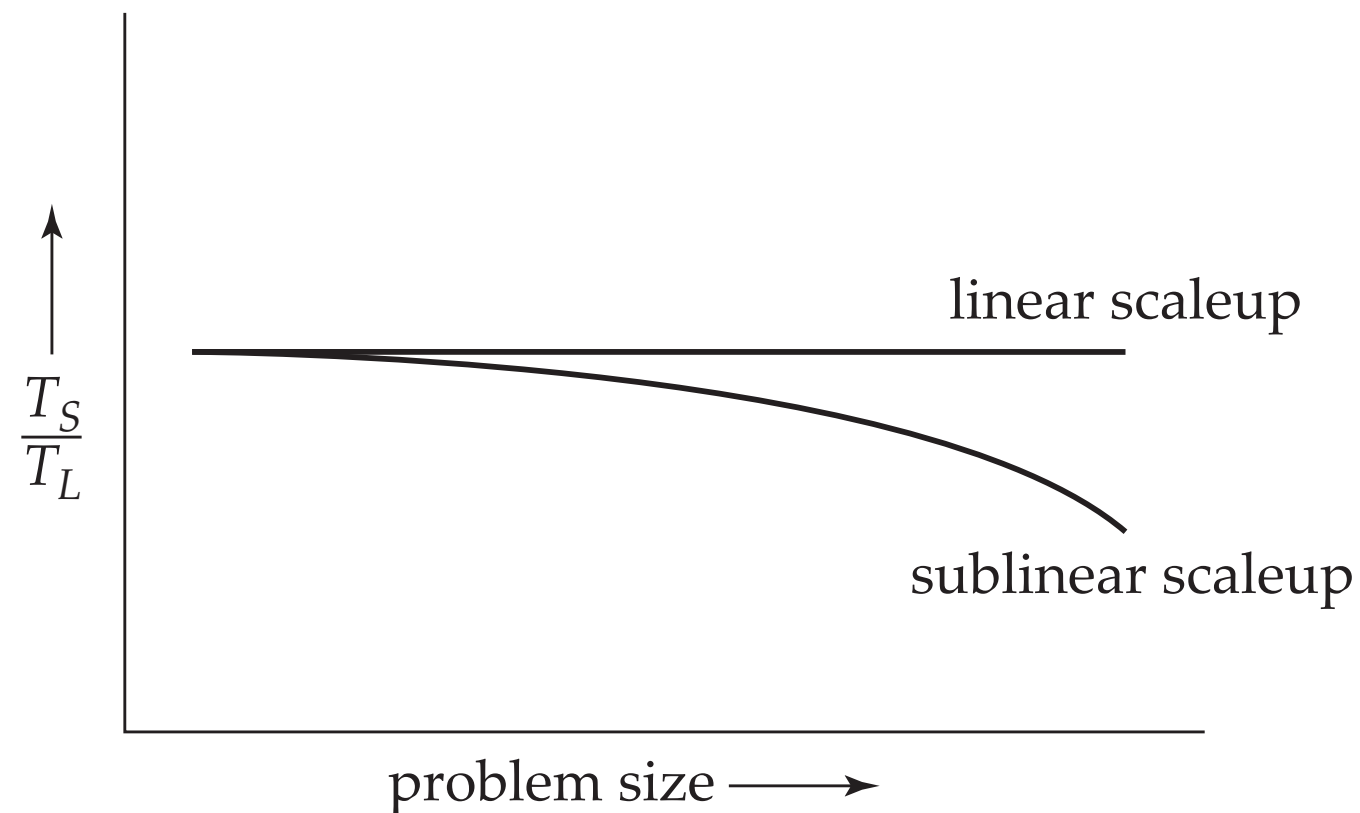$|S| = 3$ $|L| = 4.|S|$
$T_S = 2$ $T_L = 2$
$T_S/T_L = 1$ → linear

Batch Scale-UP

- A single large job; typical of most decision support queries and scientific simulation.

- Use an N-times larger computer on N-times larger problem.

Transaction Scale-Up

- Numerous small queries submitted by independent users to a shared database; typical transaction processing and timesharing systems.

- N-times as many users submitting requests (hence, N-times as many requests) to an N-times larger database, on an N-times larger computer.

- Well-suited to parallel execution.

Speed-Up and Scale-Up Limiting Factors

- Speed-up and scale-up are often sublinear due to:

  ‣ Start-up costs: Cost of starting up multiple processes may dominate computation time, if the degree of parallelism is high.

  ‣ Interference: Processes accessing shared resources (e.g., system bus, disks, or locks) compete with each other, 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 parallel-executing tasks. Overall execution time determined by slowest of parallel-executing tasks.
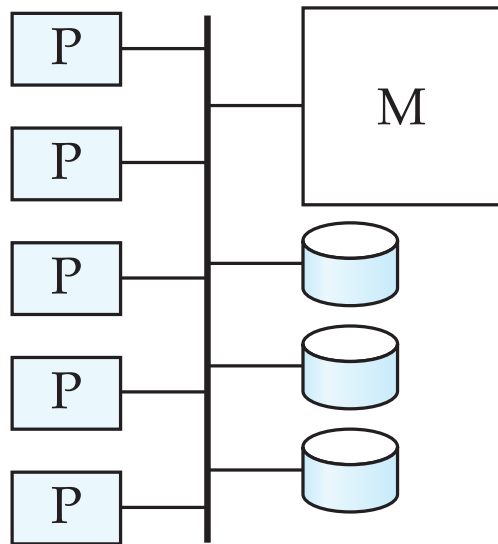
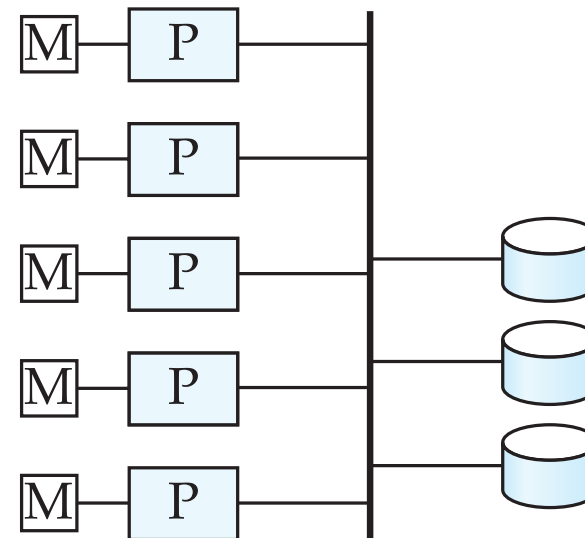# Parallel Database Architectures

- Shared memory -- processors share a common memory

- Shared disk -- processors share a common disk (array)

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

- Hierarchical -- hybrid of the above architectures
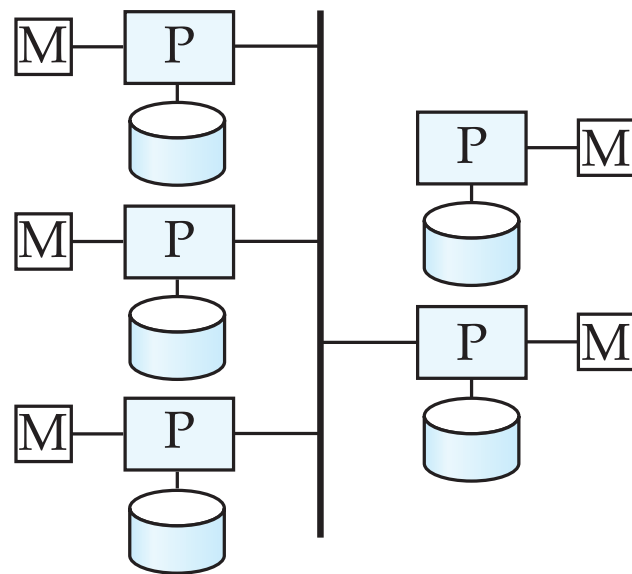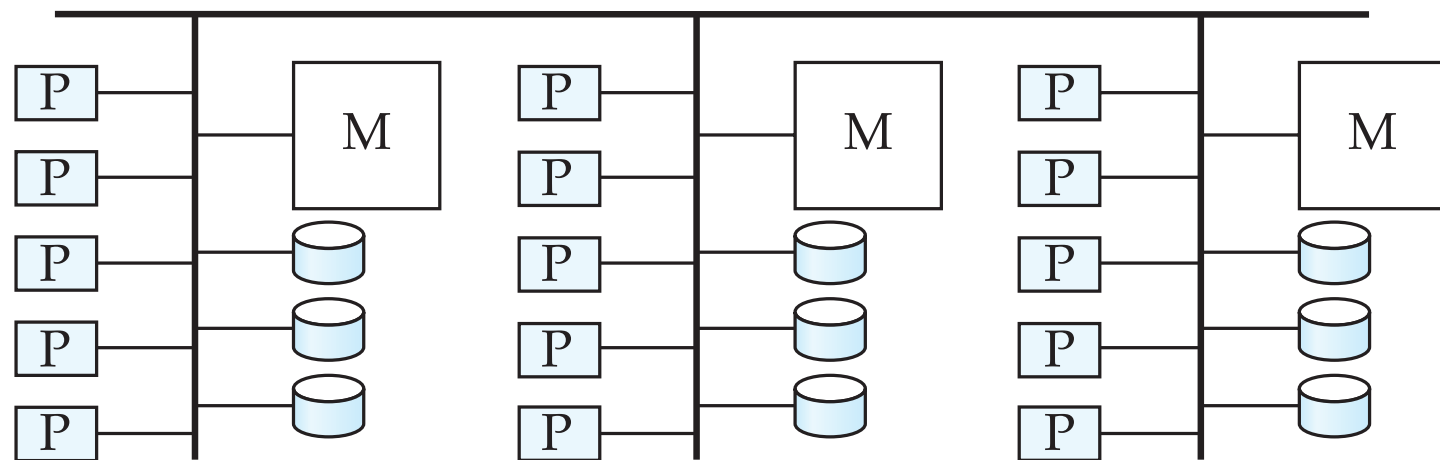
(a) shared memory

(b) shared disk

(c) shared nothing

(d) hierarchical

Shared-Memory Architectures

- 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.

Shared-Memory Architectures

- Downside – architecture is not scalable beyond 32 or 64 processors since the bus or the interconnection network becomes a bottleneck

- Widely used for lower degrees of parallelism (4 to 8).

Shared-Disk Architectures

- All processors can directly access all disks via an interconnection network, but the processors have private memories.

- The memory bus is not a bottleneck

- Architecture provides a degree of fault-tolerance — if a processor fails, the other processors can take over its tasks since the database is resident on disks that are accessible from all processors.

Shared-Disk Architectures

- 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.

- Examples: IBM Sysplex and DEC clusters (now part of Compaq) running Rdb (now Oracle Rdb) were early commercial users

Shared-Nothing Architectures

- Node consists of a processor, memory, and one or more disks. Processors at one node communicate with another processor at another node using an interconnection network. A node functions as the server for the data on the disk or disks the node 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 Architectures

- 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.

- Examples: Teradata, Tandem, Oracle-n CUBE

Hierarchical Architectures

- Combines characteristics of shared-memory, shared-disk, and shared-nothing architectures.

- Top level is a shared-nothing architecture – nodes connected by an interconnection network, and do not share disks or memory with each other.

- Each node of the system could be a shared-memory system with a few processors.

Hierarchical Architectures

- Alternatively, each node could be a shared-disk system, and each of the systems sharing a set of disks could be a shared-memory system.

- Reduce the complexity of programming such systems by distributed virtual-memory architectures

- Also called non-uniform memory architecture (NUMA)

Distributed Systems

Distributed Systems

- Data spread over multiple machines (also referred to as sites or nodes).

- Network interconnects the machines

- Data shared by users on multiple machines
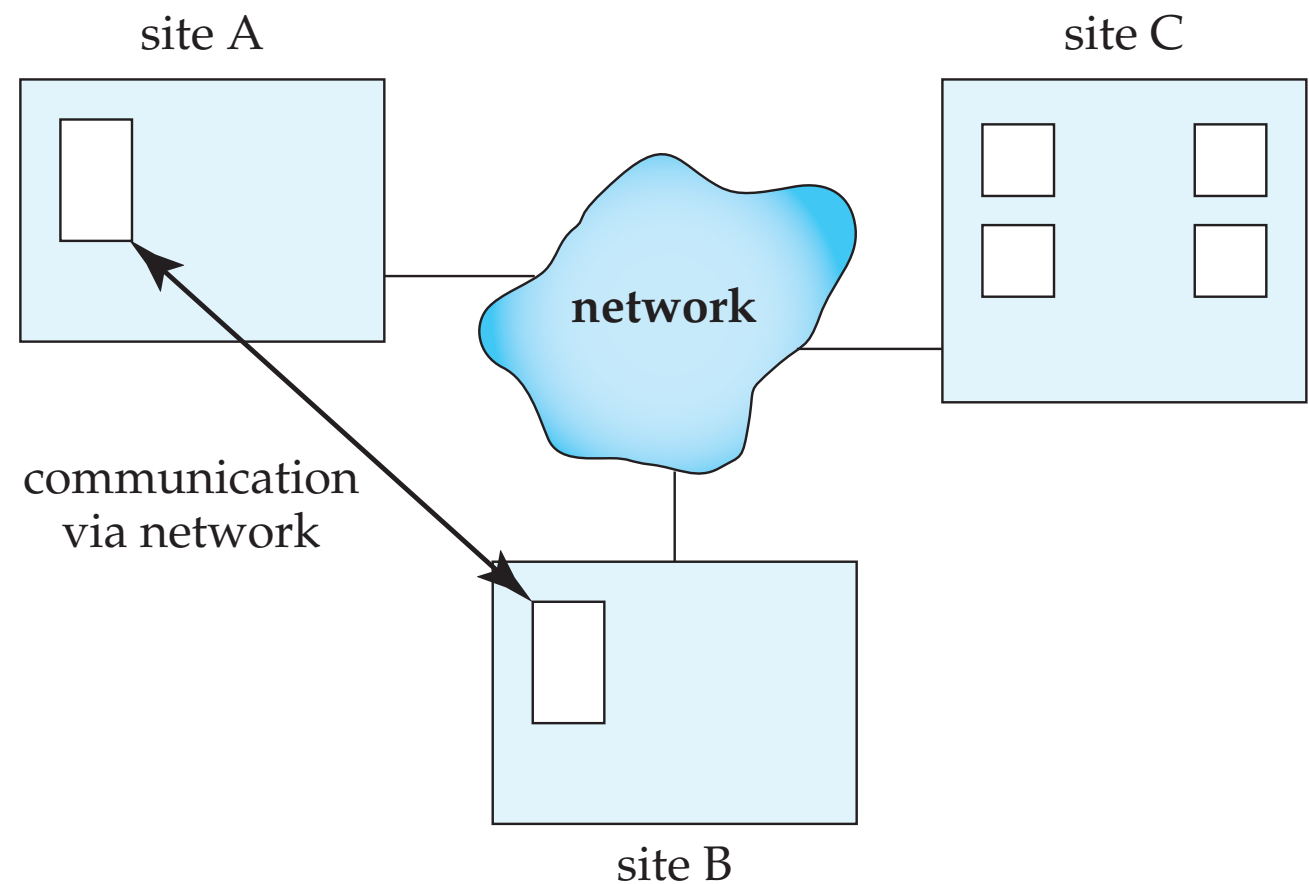
Distributed Databases :: Homogeneous

- Same software/schema on all sites, data may be partitioned among sites

- Goal: provide a view of a single database, hiding details of distribution

- Different software/schema on different sites

- Goal: integrate existing databases to provide useful functionality

- 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 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.

Trade-Offs in Distributed Systems

- Disadvantage: added complexity required to ensure proper coordination among sites.

  ‣ Software development cost.

  ‣ Greater potential for bugs.

  ‣ Increased processing overhead.

- 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 the 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

Implementation Issues in Distributed Databases
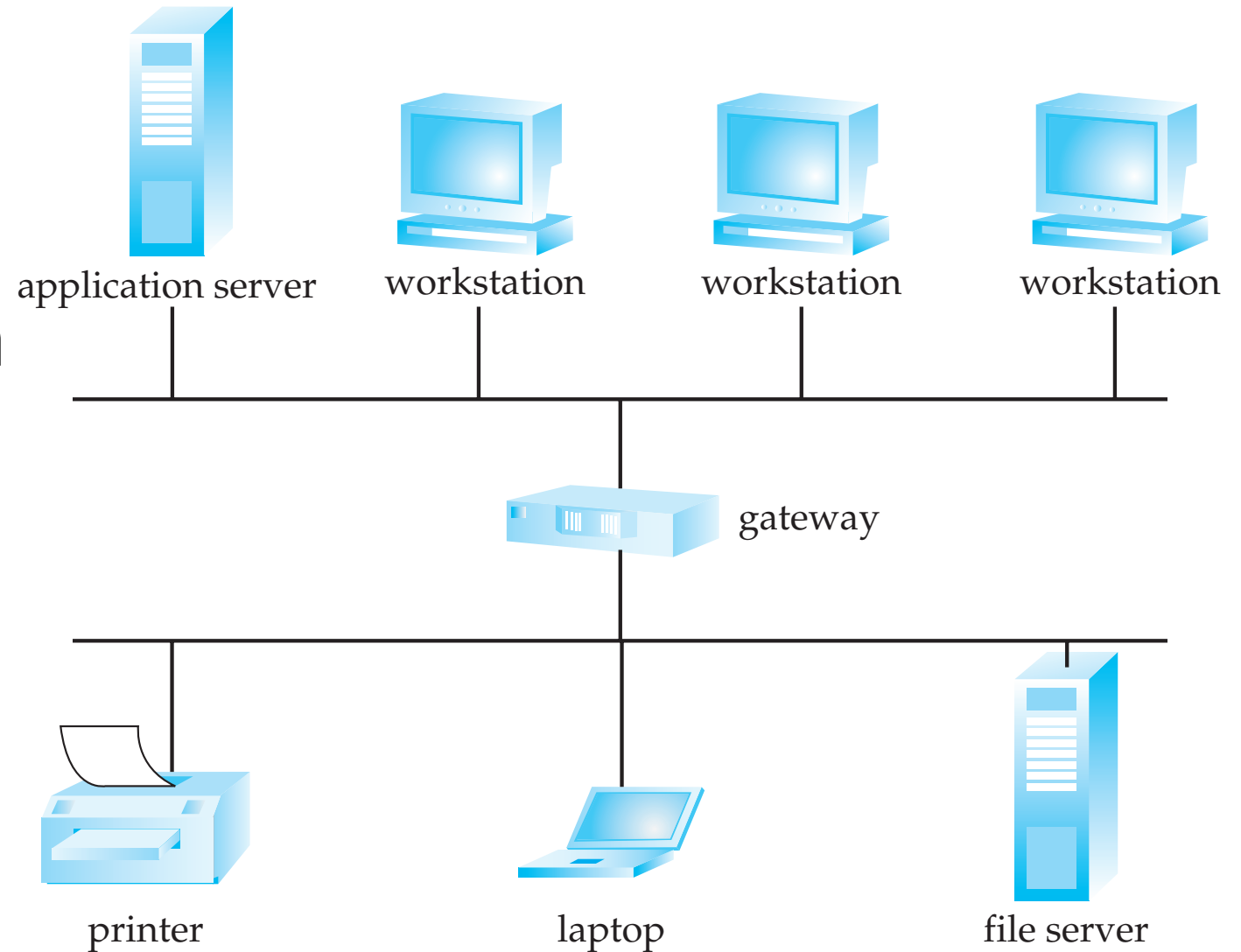
- 2PC is not always appropriate: other transaction models based on persistent messaging, and workflows, are also used

- Distributed concurrency control (and deadlock detection) required

- Data items may be replicated to improve data availability

Types of Network

- Local-area networks (LANs) – composed of processors that are distributed over small geographical areas, such as a single building or a few adjacent buildings.

- Wide-area networks (WANs) – composed of processors distributed over a large geographical area.

application server   workstation   workstation   workstation

gateway

printer   laptop   file server

Types of Network

- WANs with continuous connection (e.g., the Internet) are needed for implementing distributed database systems

- Groupware applications such as Lotus notes can work on WANs with discontinuous connection:

  ‣ Data is replicated.

  ‣ Updates are propagated to replicas periodically.

  ‣ Copies of data may be updated independently.

  ‣ Non-serializable executions can thus result. Resolution is application dependent.
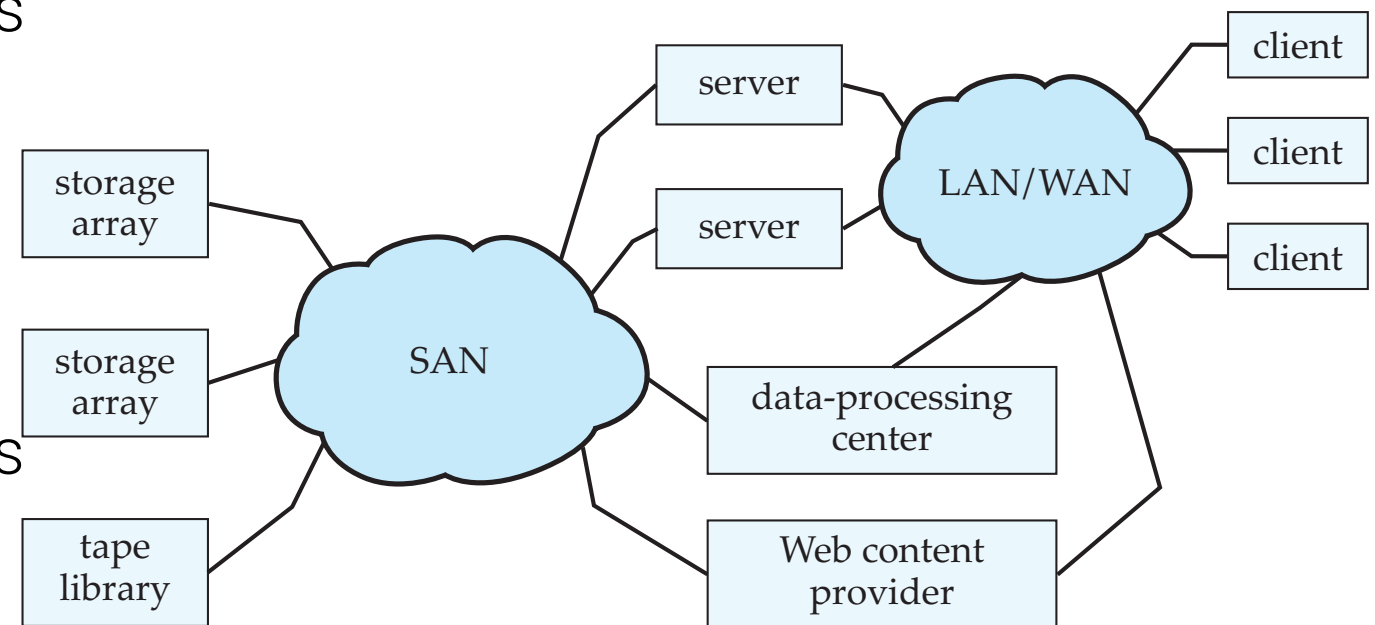
Summary

- The main components of DBMSs are the query processor and the storage manager.

- The query processor (QP) parses, translates and optimizes a query to generate an evaluation plan, which when executed by the query evaluation engine, produces the query results.

- In so doing the QP relies on the storage manager to regulate access to buffers in primary memory and to manage its movement from and to secondary memory.

- Important subsystems also include the concurrency and the transaction managers.

- The main classes of users of DBMSs are causal/occasional users, sophisticated users, application programmers and administrators.

- They rely on tools and APIs provided/exposed by the DBMS.

- The main kinds of database architectures used today are client-server, parallel and distributed.

- Each of these have variants (e.g., finely- or coarsely-grained parallel, WAN- or LAN-distributed).

The End

- Thanks for studying these handouts.

- I hope you have enjoyed the course.