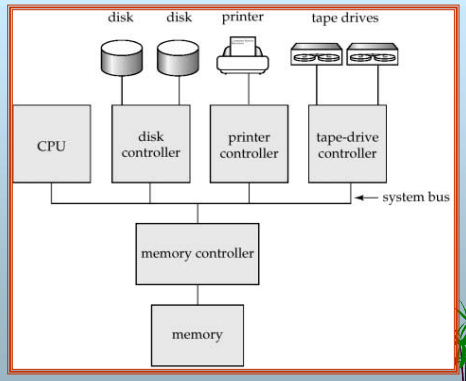
Chapter 18: Database System Architectures

- Centralized Systems
- Client--Server Systems
- Parallel Systems
- Distributed Systems
- Network Types

Centralized Systems

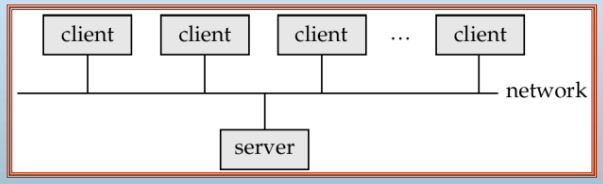
- Run on a single computer system and do not interact with other computer systems.
- General-purpose computer system: one to a few CPUs and a number of device controllers that are connected through a common bus that provides access to shared memory.
- Single-user system (e.g., personal computer or workstation): desk-top unit, single user, usually has only one CPU and one or two hard disks; the OS may support only one user.
- Multi-user system: more disks, more memory, multiple CPUs, and a multi-user OS. Serve a large number of users who are connected to the system vie terminals. Often called *server* systems.

A Centralized Computer System



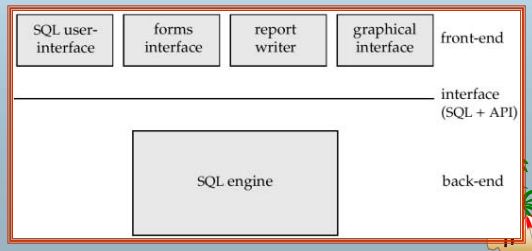
Client-Server Systems

- Server systems satisfy requests generated at *m* client systems, whose general structure is shown below:



Client-Server Systems (Cont.)

- 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 through SQL or through an application program interface.



Client-Server Systems (Cont.)

- Advantages of replacing mainframes with networks of workstations or personal computers connected to back-end server machines:
  - 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** which are widely used in relational database systems, and
  - **data servers**, used in object-oriented database systems

Transaction Servers

- Also called **query server** systems or SQL *server* systems; clients send requests to the server system where the transactions are executed, and results are shipped back to the client.
- Requests specified in SQL, and communicated to the server through a *remote procedure call (RPC)* mechanism.
- Transactional RPC allows many RPC calls to collectively form a transaction.
- *Open Database Connectivity (ODBC)* is a C language application program interface standard from Microsoft for connecting to a server, sending SQL requests, and receiving results.
- JDBC standard similar to ODBC, for Java

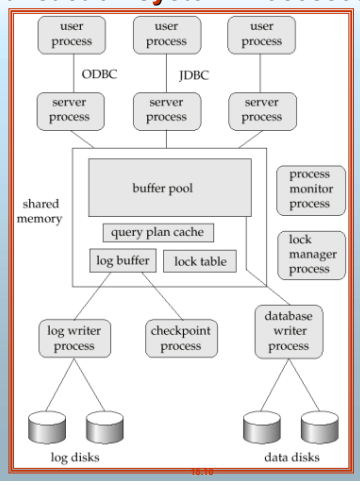
Transaction Server Process Structure

- A typical transaction server consists of multiple processes accessing data in shared memory.
- Server processes
  - These receive user queries (transactions), execute them and send results back
  - Processes may be **multithreaded**, allowing a single process to execute several user queries concurrently
  - Typically multiple multithreaded server processes
- Lock manager process
  - More on this later
- Database writer process
  - Output modified buffer blocks to disks continually

Transaction Server Processes (Cont.)

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

Transaction System Processes (Cont.)



Transaction System Processes (Cont.)

- 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 ensure that no two processes are accessing the same data structure at the same time, databases systems implement **mutual exclusion** using either
  - Operating system semaphores
  - Atomic instructions such as test-and-set

Transaction System Processes (Cont.)

- To avoid overhead of interprocess communication for lock request/grant, each database process operates directly on the lock table data structure (Section 16.1.4) instead of sending requests to lock manager process
  - Mutual exclusion ensured on the lock table using semaphores, or more commonly, atomic instructions
  - If a lock can be obtained, the lock table is updated directly in shared memory
  - If a lock cannot be immediately obtained, a lock request is noted in the lock table and the process (or thread) then waits for lock to be granted
  - When a lock is released, releasing process updates lock table to record release of lock, as well as grant of lock to waiting requests (if any)
  - Process/thread waiting for lock may either:
    - Continually scan lock table to check for lock grant, or
    - Use operating system semaphore mechanism to wait on a semaphore.
      - Semaphore identifier is recorded in the lock table
      - When a lock is granted, the releasing process signals the semaphore to tell the waiting process/thread to proceed
- Lock manager process still used for deadlock detection

Data Servers

- Used in LANs, where there is a very high speed connection between the clients and the server, the client machines are comparable in processing power to the server machine, and the tasks to be executed are compute intensive.
- Ship data to client machines where processing is performed, and then ship results back to the server machine.
- This architecture requires full back-end functionality at the clients.
- Used in many object-oriented database systems
- Issues:
  - Page-Shipping versus Item-Shipping
  - Locking
  - Data Caching
  - Lock Caching

Data Servers (Cont.)

- **Page-Shipping** versus **Item-Shipping**
  - Smaller unit of shipping ⇒ more messages
  - Worth **prefetching** related items along with requested item
  - Page shipping can be thought of as a form of prefetching
- Locking
  - Overhead of requesting and getting locks from server is high due to message delays
  - Can grant locks on requested and prefetched items; with page shipping, transaction is granted lock on whole page.
  - Locks on a prefetched item can be P{called back} by the server, and returned by client transaction if the prefetched item has not been used.
  - Locks on the page can be **deescalated** to locks on items in the page when there are lock conflicts. Locks on unused items can then be returned to server.

Data Servers (Cont.)

- **Data Caching**
  - Data can be cached at client even in between transactions
  - But check that data is up-to-date before it is used (**cache coherency**)
  - Check can be done when requesting lock on data item
- **Lock Caching**
  - Locks can be retained by client system even in between transactions
  - Transactions can acquire cached locks locally, without contacting server
  - Server **calls back** locks from clients when it receives conflicting lock request. Client returns lock once no local transaction is using it.
  - Similar to deescalation, but across transactions.

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

Speed-Up and Scale-Up

- **Speedup**: a fixed-sized problem executing on a small system is given to a system which is *N*-times larger.
  - Measured by:

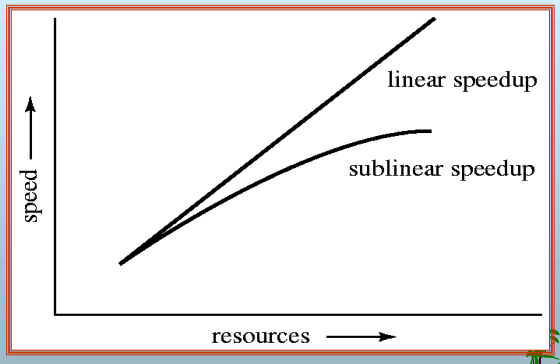
  $$speedup = \frac{small\ system\ elapsed\ time}{large\ system\ elapsed\ time}$$

  - Speedup is **linear** if equation equals N.
- **Scaleup**: increase the size of both the problem and the system
  - *N*-times larger system used to perform *N*-times larger job
  - Measured by:

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

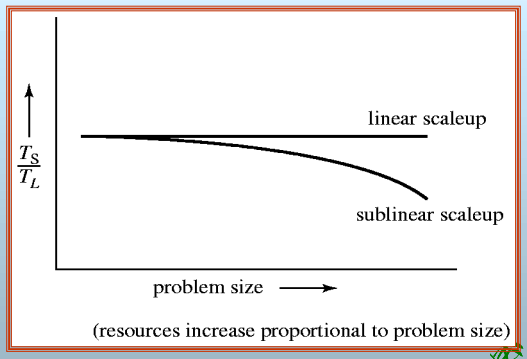
  - Scale up is **linear** if equation equals 1.

Speedup



Speedup

Scaleup



Scaleup

Batch and Transaction Scaleup

- **Batch scaleup**:
  - A single large job; typical of most database queries and scientific simulation.
  - Use an *N*-times larger computer on *N*-times larger problem.
- **Transaction scaleup**:
  - 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.

Factors Limiting Speedup and Scaleup

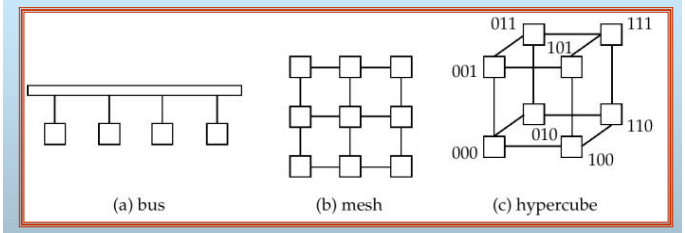
Speedup and scaleup are often sublinear due to:

- **Startup 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 parallely executing tasks. Overall execution time determined by **slowest** of parallely executing tasks.

Interconnection Network Architectures

- **Bus**. System components send data on and receive data from a single communication bus;
  - Does not scale well with increasing parallelism.
- **Mesh**. Components are arranged as nodes in a grid, and each component is connected to all adjacent components
  - Communication links grow with growing number of components, and so scales better.
  - But may require $2\sqrt{n}$ hops to send message to a node (or $\sqrt{n}$ with wraparound connections at edge of grid).
- **Hypercube**. Components are numbered in binary; components are connected to one another if their binary representations differ in exactly one bit.
  - *n* components are connected to *log(n)* other components and can reach each other via at most *log(n)* links; reduces communication delays.

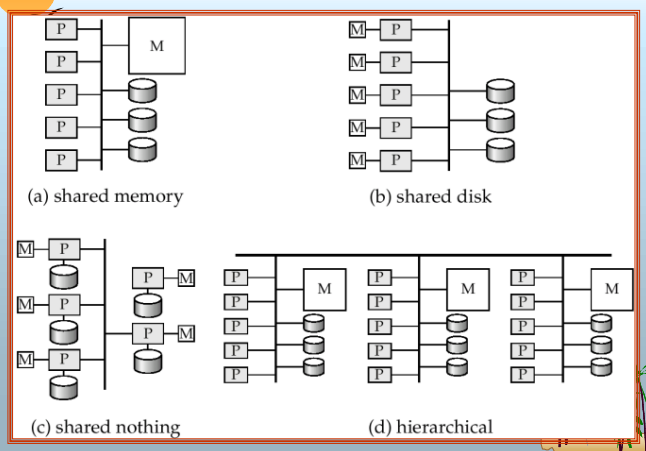
Interconnection Architectures



Parallel Database Architectures

- **Shared memory** -- processors share a common memory
- **Shared disk** -- processors share a common disk
- **Shared nothing** -- processors share neither a common memory nor common disk
- **Hierarchical** -- hybrid of the above architectures

Parallel Database 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.
- 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

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

Shared Nothing

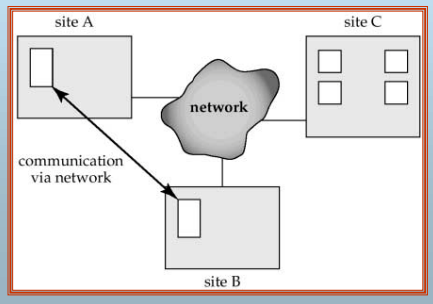
- Node consists of a processor, memory, and one or more disks. Processors at one node communicate with another processor at another node using an interconnection network. A node functions as the server for the data on the disk or disks the node owns.
- Examples: Teradata, Tandem, Oracle-n CUBE
- Data 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.

Hierarchical

- 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.
- 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

- 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 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 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 for Distributed Databases

- Atomicity needed even for transactions that update data at multiple site
  - Transaction cannot be committed at one site and aborted at another
- The two-phase commit protocol (2PC) used to ensure atomicity
  - Basic idea: each site executes transaction till 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 coordinators decision
    - To do so, updates of transaction are logged to stable storage and transaction is recorded as "waiting"
  - More details in Sectin 19.4.1
- 2PC is not always appropriate: other transaction models based on persistent messaging, and workflows, are also used
- Distributed concurrency control (and deadlock detection) required
- Replication of data items required for improving data availability
- Details of above in Chapter 19

Network Types

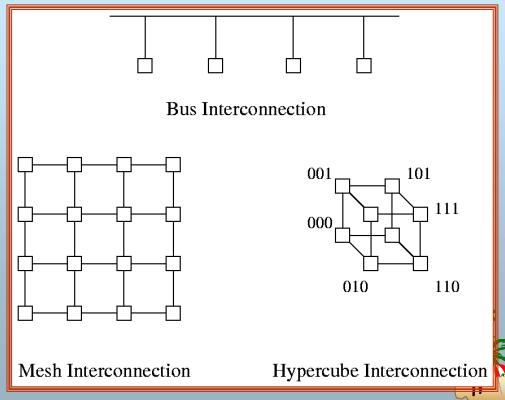
- **Local-area networks** (LANs) – composed of processors that are distributed over small geographical areas, such as a single building or a few adjacent buildings.
- **Wide-area networks** (WANs) – composed of processors distributed over a large geographical area.
- *Discontinuous connection* – WANs, such as those based on periodic dial-up (using, e.g., UUCP), that are connected only for part of the time.
- *Continuous connection* – WANs, such as the Internet, where hosts are connected to the network at all times.

Networks Types (Cont.)

- WANs with continuous connection 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.
  - No global locking is possible, and copies of data may be independently updated.
  - Non-serializable executions can thus result. Conflicting updates may have to be detected, and resolved in an application dependent manner.

End of Chapter

Interconnection Networks



A Distributed System

Local-Area Network