Parallel and Distributed Data Management

Database System Architectures

Nikolaus Augsten
nikolaus.augsten@plus.ac.at
Department of Computer Science
University of Salzburg

database research group
https://dbresearch.uni-salzburg.at

Sommersemester 2026

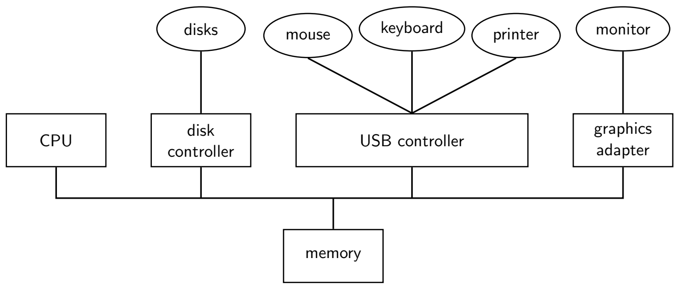
Version 19. Februar 2026

Outline

Outline

Centralized Database Systems

- Run on a single, centralized computer system that does not interact with other computer systems.
- A centralized computer system may run single-user or multi-user systems.



Single-User and Multi-User Systems

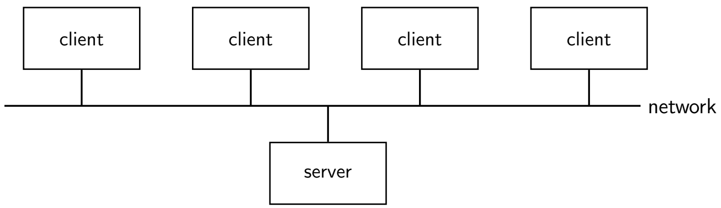
- Single-user system (e.g., smartphone or personal computer): single user, usually has only one CPU (with multiple cores) and one or two disks; the OS may support only one user.
- Multi-user system: more disks, more memory, multiple CPUs, and a multi-user OS. Serve a large number of users who are connected to the system remotely. Often called server systems.

Embedded Databases

- Databases on single-user systems may come with limited functionality:
  - simple concurrency control schemes
  - basic (e.g., copy before update) or no recovery mechanisms
  - provide API instead of declarative interface like SQL
- Such systems are called embedded databases and are typically linked to a single application.

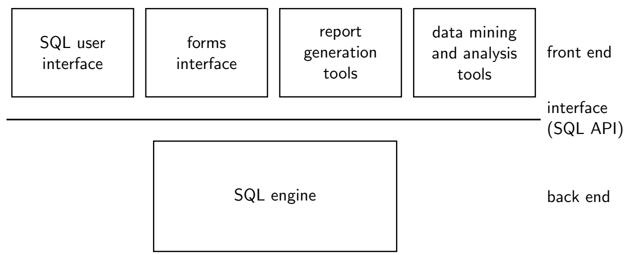
Client-Server Systems/1

- Server systems satisfy requests generated at client systems.



Client-Server Systems/2

- 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.



Outline

Server System Architecture

- Server systems can be broadly categorized into two kinds:
  - transaction servers which are widely used in relational database systems
  - data servers traditionally used in object-oriented database systems

Transaction Servers

- Also called query server or SQL server:
  - 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 (application program interface) standard from Microsoft for connecting to a server, sending SQL requests, and receiving results.
- JDBC standard is similar to ODBC, for Java.

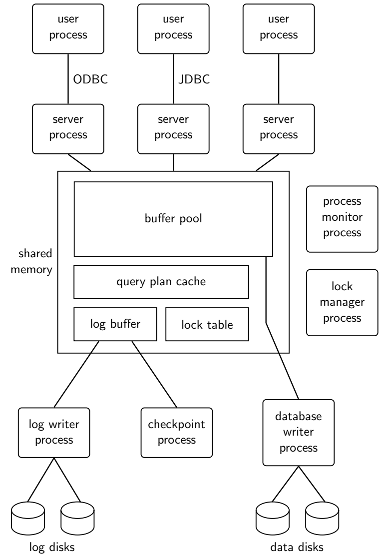
Transaction Server Process Structure/1

- A typical transaction 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
  - typically multiple multithreaded server processes run concurrently (e.g., one multithreaded process per user session)
- Lock manager process
  - grants and releases locks, detects deadlocks
- Database writer process
  - output modified buffer blocks to disks continually

Transaction Server Process Structure/2

- Log writer process
  - server processes simply add log records to a 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 them fails e.g., abort transaction of a failed server process and restart process

Transaction Server Process Structure/3



Transaction Server Process Structure/4

- All database processes can access shared data:
  - buffer pool
  - lock table
  - log buffer
  - cached query plans (reuse plan if same query is submitted again)
- To avoid two processes accessing the same data structure at the same time, databases systems implement mutual exclusion using either
  - operating system semaphores (wait and signal operations)
  - atomic instructions (test-and-set or compare-and-swap)
- To avoid overhead of message passing (sending requests to lock manager) for lock request/grant, database processes may operate directly on the lock table
- Lock manager process still used for deadlock detection

Data Servers

- Originally developed for object-oriented databases:
  - create, retrieve, and update persistent objects
  - persistent objects are accessed like main memory objects in programming languages
- All computations performed on client:
  - server ships required data items to client
  - client performs compute intensive tasks on data items
  - updated or new data items are shipped from client to server
- Server only needs to store and fetch data.
- Data servers are typically used when
  - the client performs extensive computations, e.g., a CAD system fetches a computer chip model and runs simulations
  - client and server are connected via high-speed network

Caching at Clients/1

- Client and server communicate via network:
  - network latency (also network round-trip time) is the time to send a message over a network and get response back
  - much slower than local memory references, e.g., milliseconds vs. 100 nanoseconds even in LAN (local are network)
- Optimization strategies to reduce the effect of network latency:
  - prefetching: send a data item before it is requested
  - data caching: client caches data received from server for future use
  - lock caching: client keeps the lock also after accessing the data
  - adaptive lock granularity: use coarse- and fine-grained locks to balance number of lock requests and lock contention

Caching at Clients/2

- Prefetching
  - network latency is per request: similar for large and small messages
  - sending one item at a time has a large overhead
  - prefetching sends also data items that are not requested, but are likely to be used in the near future
- 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 coherence)
  - check can be done when requesting lock on data item

Caching at Clients/3

- Lock caching
  - requesting and granting a lock requires a network round trip
  - 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
  - works well when data is partitioned among clients, i.e., two different clients rarely request lock on the same data item

Caching at Clients/4

- Adaptive lock granularity
  - multi-granularity locking: locks not only on individual data items (fine granularity), but also on pages, tables, etc. (coarse granularity)
  - avoid large number of locks, e.g., get a single page lock instead of multiple item locks on that page
  - coarse-granularity locks decrease number of locks but increase lock contention (i.e., transactions have to wait for a lock)
  - lock de-escalation adaptively decreases the lock granularity when there is lock contention:
    1. server sends de-escalation request to client
    2. client requests finer-granularity locks
    3. when finer-granularity locks are granted, coarse-granularity lock is released

Outline

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:

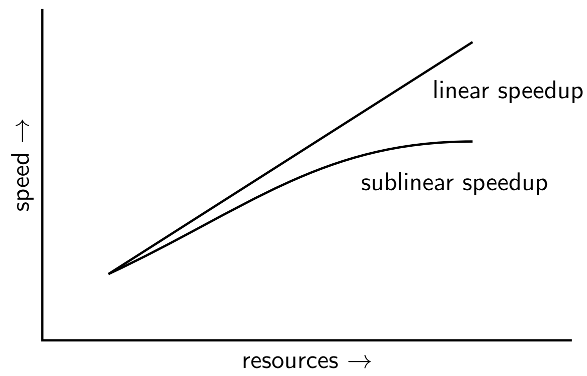
$$speedup = \frac{small\ system\ elapsed\ time}{large\ system\ elapsed\ time}$$

  - 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:

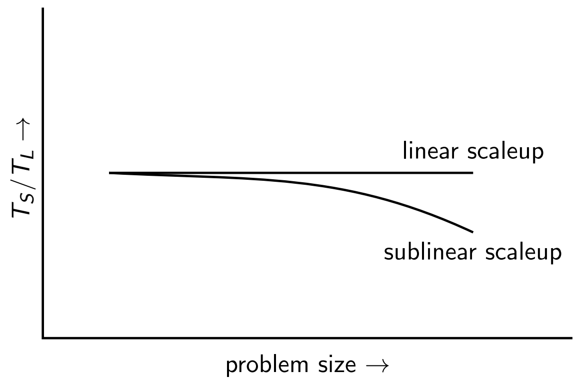
$$scaleup = \frac{small\ system\ small\ problem\ elapsed\ time}{big\ system\ big\ problem\ elapsed\ time}$$

  - Scaleup is linear if equation equals 1.

Speedup



Scaleup



Batch and Transaction Scaleup

- Batch scaleup: single large job.
  - typical for decision support queries and scientific simulations
  - 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 for 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

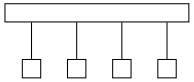
Speedup and scaleup are often sublinear due to:

- 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 tasks executing in parallel. Overall execution time determined by slowest of tasks executing in parallel.

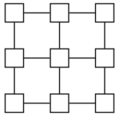
Interconnection Network Architectures

- 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:
  - number communication links grow with growing number of components, and so scales better
  - the number of hops to send message to a node is proportional to $\sqrt{n}$
- 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
  - can reach each other via at most $log(n)$ links
  - reduces communication delays

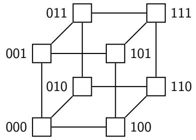
Interconnection Architectures



Bus



Mesh

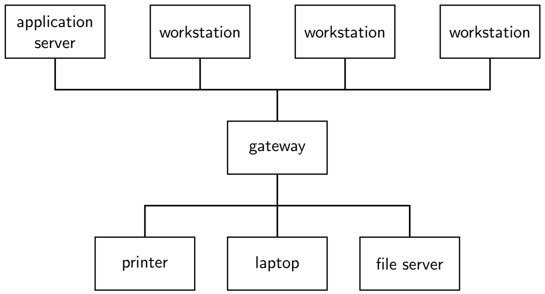


Hypercube

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.

Local-Area Network/1



Local-Area Network/2

- Link technology: twisted pair, coaxial cable, fiber optics, wireless connection
- Ethernet: Specification for computer networks
  - Software (e.g., protocols)
  - Hardware (e.g., cables, network cards, switches)
- Transfer rates
  - Fast Ethernet: 1, 10, 100 Mb/s (1 Mb/s = 10^6 bits / second)
  - Gigabit Ethernet: 1 Gb/s
  - Widely used: 10 Gb/s, highest transfer rate: 400 Gb/s
  - Higher transfer rates (1 Tb/s) require new technologies
- Distances:
  - usually single building or neighboring buildings
  - up to 70km with fiber optics

Wide-Area Network

- Fast wide-area links (fiber optics, satellite channel): hundreds of gigabits
- Last link typically slower (e.g., cable modem, wireless connection): some megabits
- Latency higher than in LAN
  - speed of light delay
  - queuing delay at routers
- WANs with continuous connection (e.g., the Internet) are needed for implementing distributed database systems.

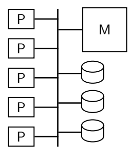
Example: Network Latency

- What are the number of routers and the network latency for
  - localhost (i.e., network connection to the local machine)
  - in the LAN (e.g., ssh.cosy.sbg.ac.at)
  - in the WAN (e.g., www.tum.de, unsw.edu.au)
- Use ping to measure latency and traceroute to learn how the network packets are routed

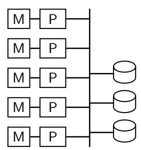
Parallel Database Architectures

- 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

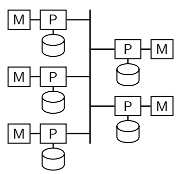
Parallel Database Architectures



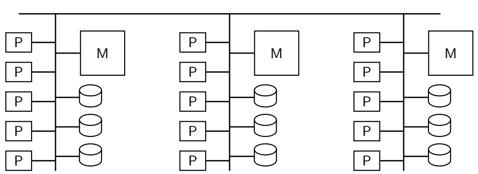
shared memory



shared disk



shared nothing



hierarchical

Shared Memory

- Processors have access to a common memory via bus or interprocessor communication network.
- Extremely efficient communication between processors ($< 1 \mu s$) — data in shared memory can be accessed by any processor.
- Memory bus becomes a bottleneck since only a single processor at a time can use the bus.
- NUMA (non-uniform memory access):
  - each processor has locally connected memory
  - processors can access memory of other processors through a high-speed interprocessor communication network
  - locally connected memory is faster
- Does not scalable beyond a few hundred cores:
  - limited by bus speed and number processors that can be interconnected
  - widely used for lower degrees of parallelism

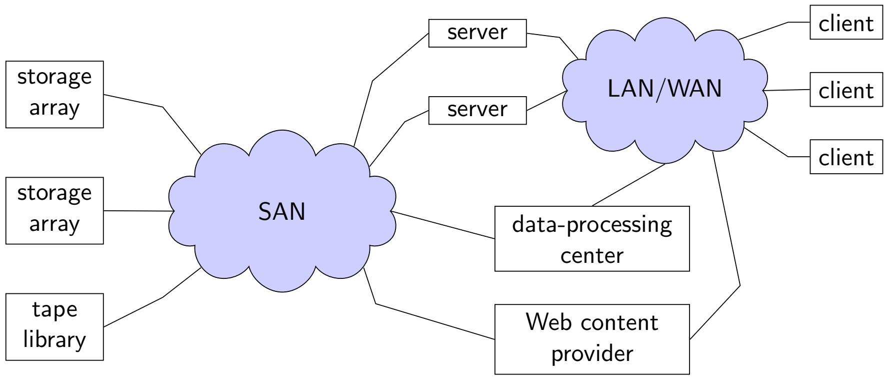
Shared Disk/1

- 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 scale to a larger number of processors, but communication between processors is slower (some *ms*).

Shared Disk/2

- File server / NAS (Network Attached Storage)
  - disks connected via RAID controller
  - mounted as directory in file system
    - Samba
    - NFS - Network File System
- SAN - Storage Array Network
  - block level access
  - appears to be locally attached block device
  - shared disk file system runs on top of SAN
    - IBM GPFS (General Parallel FS)
    - Oracle Cluster FS
    - Lustre (mainly super computing/Linux)

Storage Area Network



Shared Nothing

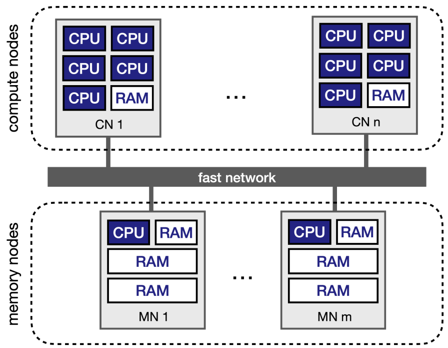
- Node consists of a processor, memory, and one or more disks.
- Nodes function as servers for the data on the disks they own.
- Communication between processors through interconnection network.
- Examples: Teradata, Tandem, Oracle-n CUBE
- Minimize interference of resource sharing: data accessed from local disks (and local memory accesses) do not pass through interconnection network
- Can be scaled up to thousands of processors without interference.
- Main drawbacks:
  - cost of communication
  - cost of 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

Disaggregated Memory Architecture

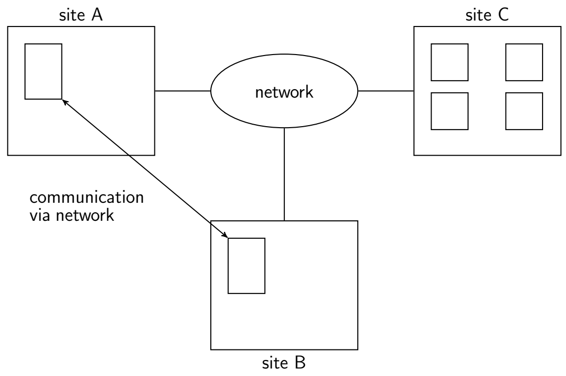
- compute nodes: strong CPUs, small memory (cache)
- memory nodes: large memory, wimpy CPU
- fast network: low latency and high bandwidth



Outline

Distributed Systems

- Data spread over multiple machines (called sites or nodes).
- Network interconnects the 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

Differences to Shared-Nothing Parallel Systems

- Sites geographically separated.
- Sites may be separately administrated.
- Slower and less reliable interconnection between sites.
  - higher latency, lower bandwidth
  - greater potential for network failure (network partitioning)
- 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 can access data residing at some other sites (heterogeneous distributed databases)
- Autonomy: each site retains a degree of control over data stored locally (heterogeneous distributed databases)
- Higher system availability through redundancy: data can be replicated at remote sites, and system can function even if a site fails.
- Disadvantage: proper coordination among sites adds complexity.
  - software development cost
  - greater potential for bugs
  - increased processing overhead

Implementation Issues for Distributed Databases

- Atomicity 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 coordinators 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

Conclusion

- Homogeneous vs. heterogeneous distributed database systems.
- Distributed database different from a shared nothing parallel systems.
- Geographical separation of sites comes with opportunities and challenges:
  - higher availability through geographically distributed redundancy
  - new implementation challenges