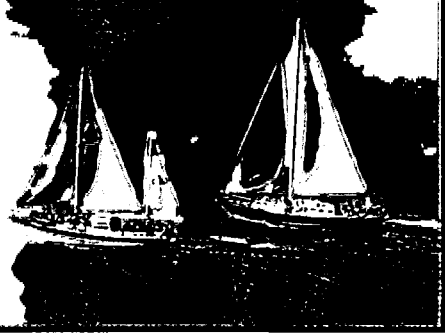
CHAPTER 17



Database-System Architectures

The architecture of a database system is greatly influenced by the underlying computer system on which it runs, in particular by such aspects of computer architecture as networking, parallelism, and distribution:

- Networking of computers allows some tasks to be executed on a server system and some tasks to be executed on client systems. This division of work has led to *client–server database systems*.
- Parallel processing within a computer system allows database-system activities to be speeded up, allowing faster response to transactions, as well as more transactions per second. Queries can be processed in a way that exploits the parallelism offered by the underlying computer system. The need for parallel query processing has led to *parallel database systems*.
- Distributing data across sites in an organization allows those data to reside where they are generated or most needed, but still to be accessible from other sites and from other departments. Keeping multiple copies of the database across different sites also allows large organizations to continue their database operations even when one site is affected by a natural disaster, such as flood, fire, or earthquake. *Distributed database systems* handle geographically or administratively distributed data spread across multiple database systems.

We study the architecture of database systems in this chapter, starting with the traditional centralized systems, and covering client–server, parallel, and distributed database systems.

17.1 Centralized and Client–Server Architectures

Centralized database systems are those that run on a single computer system and do not interact with other computer systems. Such database systems span a range from single-user database systems running on personal computers to high-performance database systems running on high-end server systems. Client

–server systems, on the other hand, have functionality split between a server system and multiple client systems.

17.1.1 Centralized Systems

A modern, general-purpose computer system consists of one to a few processors and a number of device controllers that are connected through a common bus that provides access to shared memory (Figure 17.1). The processors have local cache memories that store local copies of parts of the memory, to speed up access to data. Each processor may have several independent **cores**, each of which can execute a separate instruction stream. Each device controller is in charge of a specific type of device (for example, a disk drive, an audio device, or a video display). The processors and the device controllers can execute concurrently, competing for memory access. Cache memory reduces the contention for memory access, since it reduces the number of times that the processor needs to access the shared memory.

We distinguish two ways in which computers are used: as single-user systems and as multiuser systems. Personal computers and workstations fall into the first category. A typical **single-user system** is a desktop unit used by a single person, usually with only one processor and one or two hard disks, and usually only one person using the machine at a time. A typical **multiuser system**, on the other hand, has more disks and more memory and may have multiple processors. It serves a large number of users who are connected to the system remotely.

Database systems designed for use by single users usually do not provide many of the facilities that a multiuser database provides. In particular, they may not support concurrency control, which is not required when only a single user can generate updates. Provisions for crash recovery in such systems are either absent or primitive—for example, they may consist of simply making a backup of the database before any update. Some such systems do not support SQL, and they provide a simpler query language, such as a variant of QBE. In contrast,

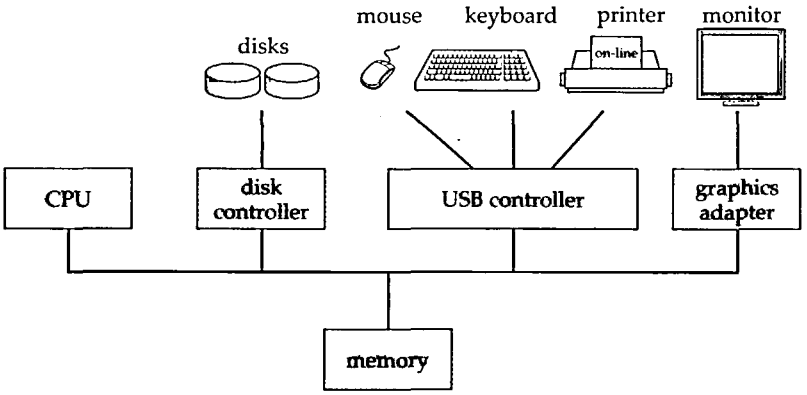


Figure 17.1 A centralized computer system.

database systems designed for multiuser systems support the full transactional features that we have studied earlier.

Although most general-purpose computer systems in use today have multiple processors, they have **coarse-granularity parallelism**, with only a few processors (about two to four, typically), all sharing the main memory. Databases running on such machines usually do not attempt to partition a single query among the processors; instead, they run each query on a single processor, allowing multiple queries to run concurrently. Thus, such systems support a higher throughput; that is, they allow a greater number of transactions to run per second, although individual transactions do not run any faster.

Databases designed for single-processor machines already provide multitasking, allowing multiple processes to run on the same processor in a time-shared manner, giving a view to the user of multiple processes running in parallel. Thus, coarse-granularity parallel machines logically appear to be identical to single-processor machines, and database systems designed for time-shared machines can be easily adapted to run on them.

In contrast, machines with **fine-granularity parallelism** have a large number of processors, and database systems running on such machines attempt to parallelize single tasks (queries, for example) submitted by users. We study the architecture of parallel database systems in Section 17.3.

Parallelism is emerging as a critical issue in the future design of database systems. Whereas today those computer systems with multicore processors have only a few cores, future processors will have large numbers of cores.[1] As a result, parallel database systems, which once were specialized systems running on specially designed hardware, will become the norm.

17.1.2 Client–Server Systems

As personal computers became faster, more powerful, and cheaper, there was a shift away from the centralized system architecture. Personal computers supplanted terminals connected to centralized systems. Correspondingly, personal computers assumed the user-interface functionality that used to be handled directly by the centralized systems. As a result, centralized systems today act as **server systems** that satisfy requests generated by *client systems*. Figure 17.2 shows the general structure of a client–server system.

Functionality provided by database systems can be broadly divided into two parts—the front end and the back end. The back end manages access structures, query evaluation and optimization, concurrency control, and recovery. The front end of a database system consists of tools such as the SQL user interface, forms interfaces, report generation tools, and data mining and analysis tools (see Figure 17.3). The interface between the front end and the back end is through SQL, or through an application program.

[1]The reasons for this pertain to issues in computer architecture related to heat generation and power consumption. Rather than make processors significantly faster, computer architects are using advances in chip design to put more cores on a single chip, a trend likely to continue for some time.

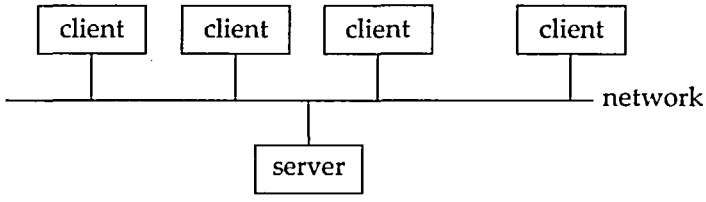


Figure 17.2 General structure of a client–server system.

Standards such as *ODBC* and *JDBC*, which we saw in Chapter 3, were developed to interface clients with servers. Any client that uses the ODBC or JDBC interface can connect to any server that provides the interface.

Certain application programs, such as spreadsheets and statistical-analysis packages, use the client–server interface directly to access data from a back-end server. In effect, they provide front ends specialized for particular tasks.

Systems that deal with large numbers of users adopt a three-tier architecture, which we saw earlier in Figure 1.6 (Chapter 1), where the front end is a Web browser that talks to an application server. The application server, in effect, acts as a client to the database server.

Some transaction-processing systems provide a **transactional remote procedure call** interface to connect clients with a server. These calls appear like ordinary procedure calls to the programmer, but all the remote procedure calls from a client are enclosed in a single transaction at the server end. Thus, if the transaction aborts, the server can undo the effects of the individual remote procedure calls.

17.2 Server System Architectures

Server systems can be broadly categorized as transaction servers and data servers.

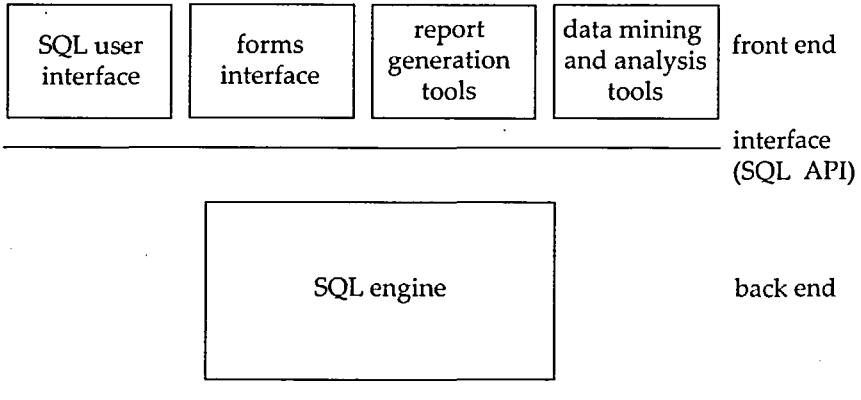


Figure 17.3 Front-end and back-end functionality.

- **Transaction-server** systems, also called **query-server** systems, provide an interface to which clients can send requests to perform an action, in response to which they execute the action and send back results to the client. Usually, client machines ship transactions to the server systems, where those transactions are executed, and results are shipped back to clients that are in charge of displaying the data. Requests may be specified by using SQL, or through a specialized application program interface.
- **Data-server systems** allow clients to interact with the servers by making requests to read or update data, in units such as files or pages. For example, file servers provide a file-system interface where clients can create, update, read, and delete files. Data servers for database systems offer much more functionality; they support units of data—such as pages, tuples, or objects —that are smaller than a file. They provide indexing facilities for data, and provide transaction facilities so that the data are never left in an inconsistent state if a client machine or process fails.

Of these, the transaction-server architecture is by far the more widely used architecture. We shall elaborate on the transaction-server and data-server architectures in Sections 17.2.1 and 17.2.2.

17.2.1 Transaction Servers

A typical transaction-server system today consists of multiple processes accessing data in shared memory, as in Figure 17.4. The processes that form part of the database system include:

- **Server processes**: These are processes that receive user queries (transactions), execute them, and send the results back. The queries may be submitted to the server processes from a user interface, or from a user process running embedded SQL, or via JDBC, ODBC, or similar protocols. Some database systems use a separate process for each user session, and a few use a single database process for all user sessions, but with multiple threads so that multiple queries can execute concurrently. (A **thread** is like a process, but multiple threads execute as part of the same process, and all threads within a process run in the same virtual-memory space. Multiple threads within a process can execute concurrently.) Many database systems use a hybrid architecture, with multiple processes, each one running multiple threads.
- **Lock manager process**: This process implements lock manager functionality, which includes lock grant, lock release, and deadlock detection.
- **Database writer process**: There are one or more processes that output modified buffer blocks back to disk on a continuous basis.
- **Log writer process**: This process outputs log records from the log record buffer to stable storage. Server processes simply add log records to the log

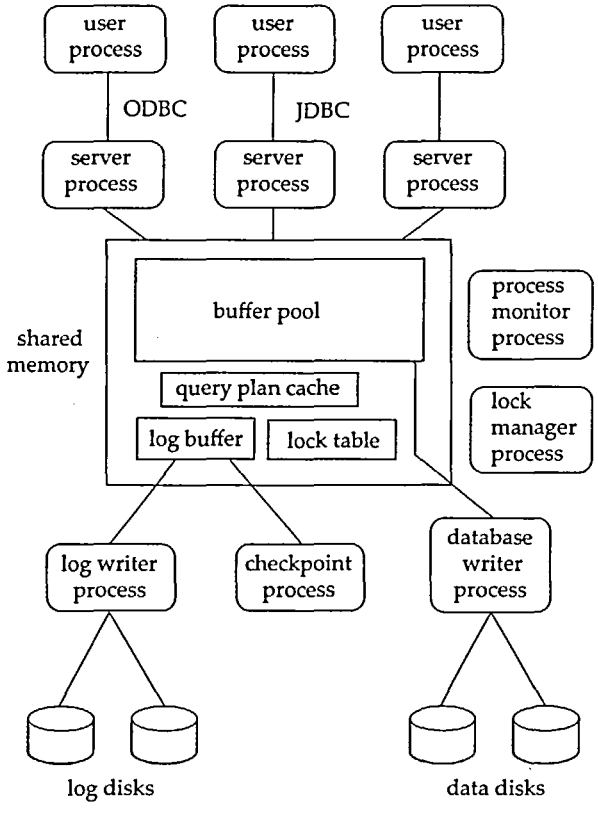


Figure 17.4 Shared memory and process structure.

record buffer in shared memory, and if a log force is required, they request the log writer process to output log records.

- **Checkpoint process:** This process performs periodic checkpoints.
- **Process monitor process:** This process monitors other processes, and if any of them fails, it takes recovery actions for the process, such as aborting any transaction being executed by the failed process, and then restarting the process.

The shared memory contains all shared data, such as:

- Buffer pool.
- Lock table.
- Log buffer, containing log records waiting to be output to the log on stable storage.

- Cached query plans, which can be reused if the same query is submitted again.

All database processes can access the data in shared memory. Since multiple processes may read or perform updates on data structures in shared memory, there must be a mechanism to ensure that a data structure is modified by at most one process at a time, and no process is reading a data structure while it is being written by others. Such **mutual exclusion** can be implemented by means of operating system functions called semaphores. Alternative implementations, with less overhead, use special **atomic instructions** supported by the computer hardware; one type of atomic instruction tests a memory location and sets it to 1 atomically. Further implementation details of mutual exclusion can be found in any standard operating system textbook. The mutual exclusion mechanisms are also used to implement latches.

To avoid the overhead of message passing, in many database systems, server processes implement locking by directly updating the lock table (which is in shared memory), instead of sending lock request messages to a lock manager process. The lock request procedure executes the actions that the lock manager process would take on getting a lock request. The actions on lock request and release are like those in Section 15.1.4, but with two significant differences:

- Since multiple server processes may access shared memory, mutual exclusion must be ensured on the lock table.
- If a lock cannot be obtained immediately because of a lock conflict, the lock request code may monitor the lock table to check when the lock has been granted. The lock release code updates the lock table to note which process has been granted the lock.

  To avoid repeated checks on the lock table, operating system semaphores can be used by the lock request code to wait for a lock grant notification. The lock release code must then use the semaphore mechanism to notify waiting transactions that their locks have been granted.

Even if the system handles lock requests through shared memory, it still uses the lock manager process for deadlock detection.

17.2.2 Data Servers

Data-server systems are used in local-area networks, where there is a 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 computation intensive. In such an environment, it makes sense to ship data to client machines, to perform all processing at the client machine (which may take a while), and then to ship the data back to the server machine. Note that this architecture requires full back-end functionality at the clients. Data-server architectures have been particularly popular in object-oriented database systems (Chapter 22).

Interesting issues arise in such an architecture, since the time cost of communication between the client and the server is high compared to that of a local memory reference (milliseconds, versus less than 100 nanoseconds):

- **Page shipping versus item shipping.** The unit of communication for data can be of coarse granularity, such as a page, or fine granularity, such as a tuple (or an object, in the context of object-oriented database systems). We use the term **item** to refer to both tuples and objects.

  If the unit of communication is a single item, the overhead of message passing is high compared to the amount of data transmitted. Instead, when an item is requested, it makes sense also to send back other items that are likely to be used in the near future. Fetching items even before they are requested is called **prefetching**. Page shipping can be considered a form of prefetching if multiple items reside on a page, since all the items in the page are shipped when a process desires to access a single item in the page.

- **Adaptive lock granularity.** Locks are usually granted by the server for the data items that it ships to the client machines. A disadvantage of page shipping is that client machines may be granted locks of too coarse a granularity —a lock on a page implicitly locks all items contained in the page. Even if the client is not accessing some items in the page, it has implicitly acquired locks on all prefetched items. Other client machines that require locks on those items may be blocked unnecessarily. Techniques for lock **de-escalation** have been proposed where the server can request its clients to transfer back locks on prefetched items. If the client machine does not need a prefetched item, it can transfer locks on the item back to the server, and the locks can then be allocated to other clients.

- **Data caching.** Data that are shipped to a client on behalf of a transaction can be cached at the client, even after the transaction completes, if sufficient storage space is available. Successive transactions at the same client may be able to make use of the cached data. However, **cache coherency** is an issue: Even if a transaction finds cached data, it must make sure that those data are up to date, since they may have been updated by a different client after they were cached. Thus, a message must still be exchanged with the server to check validity of the data, and to acquire a lock on the data.

- **Lock caching.** If the use of data is mostly partitioned among the clients, with clients rarely requesting data that are also requested by other clients, locks can also be cached at the client machine. Suppose that a client finds a data item in the cache, and that it also finds the lock required for an access to the data item in the cache. Then, the access can proceed without any communication with the server. However, the server must keep track of cached locks; if a client requests a lock from the server, the server must **call back** all conflicting locks on the data item from any other client machines that have cached the locks. The task becomes more complicated when machine failures are taken into account. This technique differs from lock de-escalation in that lock caching takes place across transactions; otherwise, the two techniques are similar.

The bibliographical references provide more information about client–server database systems.

17.2.3 Cloud-Based Servers

Servers are usually owned by the enterprise providing the service, but there is an increasing trend for service providers to rely at least in part upon servers that are owned by a "third party" that is neither the client nor the service provider.

One model for using third-party servers is to outsource the entire service to another company that hosts the service on its own computers using its own software. This allows the service provider to ignore most details of technology and focus on the marketing of the service.

Another model for using third-party servers is **cloud computing**, in which the service provider runs its own software, but runs it on computers provided by another company. Under this model, the third party does not provide any of the application software; it provides only a collection of machines. These machines are not "real" machines, but rather simulated by software that allows a single real computer to simulate several independent computers. Such simulated machines are called **virtual machines**. The service provider runs its software (possibly including a database system) on these virtual machines. A major advantage of cloud computing is that the service provider can add machines as needed to meet demand and release them at times of light load. This can prove to be highly cost-effective in terms of both money and energy.

A third model uses a cloud computing service as a data server; such *cloud-based data storage* systems are covered in detail in Section 19.9. Database applications using cloud-based storage may run on the same cloud (that is, the same set of machines), or on another cloud. The bibliographical references provide more information about cloud-computing systems.

17.3 Parallel Systems

Parallel systems improve processing and I/O speeds by using multiple processors and disks in parallel. Parallel machines are becoming increasingly common, making the study of parallel database systems correspondingly more important. The driving force behind parallel database systems is the demands of applications that have to query extremely large databases (of the order of terabytes—that is, 10^{12} bytes) or that have to process an extremely large number of transactions per second (of the order of thousands of transactions per second). Centralized and client–server database systems are not powerful enough to handle such applications.

In parallel processing, many operations are performed simultaneously, as opposed to serial processing, in which the computational steps are performed sequentially. A **coarse-grain** parallel machine consists of a small number of powerful processors; a **massively parallel** or **fine-grain parallel** machine uses thousands of smaller processors. Virtually all high-end machines today offer some degree of coarse-grain parallelism: at least two or four processors. Massively parallel com-

puters can be distinguished from the coarse-grain parallel machines by the much larger degree of parallelism that they support. Parallel computers with hundreds of processors and disks are available commercially.

There are two main measures of performance of a database system: (1) **throughput**, the number of tasks that can be completed in a given time interval, and (2) **response time**, the amount of time it takes to complete a single task from the time it is submitted. A system that processes a large number of small transactions can improve throughput by processing many transactions in parallel. A system that processes large transactions can improve response time as well as throughput by performing subtasks of each transaction in parallel.

17.3.1 Speedup and Scaleup

Two important issues in studying parallelism are speedup and scaleup. Running a given task in less time by increasing the degree of parallelism is called **speedup**. Handling larger tasks by increasing the degree of parallelism is called **scaleup**.

Consider a database application running on a parallel system with a certain number of processors and disks. Now suppose that we increase the size of the system by increasing the number of processors, disks, and other components of the system. The goal is to process the task in time inversely proportional to the number of processors and disks allocated. Suppose that the execution time of a task on the larger machine is T_L, and that the execution time of the same task on the smaller machine is T_S. The speedup due to parallelism is defined as T_S/T_L. The parallel system is said to demonstrate **linear speedup** if the speedup is N when the larger system has N times the resources (processors, disk, and so on) of the smaller system. If the speedup is less than N, the system is said to demonstrate **sublinear speedup**. Figure 17.5 illustrates linear and sublinear speedup.

Scaleup relates to the ability to process larger tasks in the same amount of time by providing more resources. Let Q be a task, and let Q_N be a task that is N times bigger than Q. Suppose that the execution time of task Q on a given machine

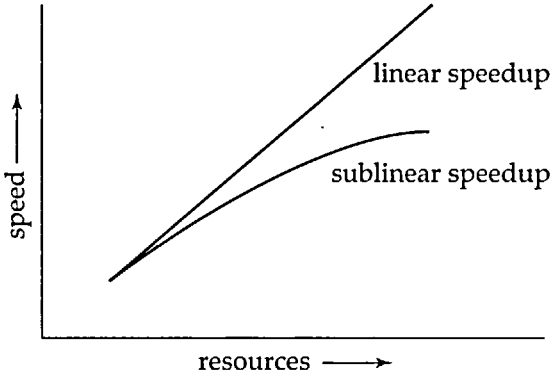


Figure 17.5 Speedup with increasing resources.

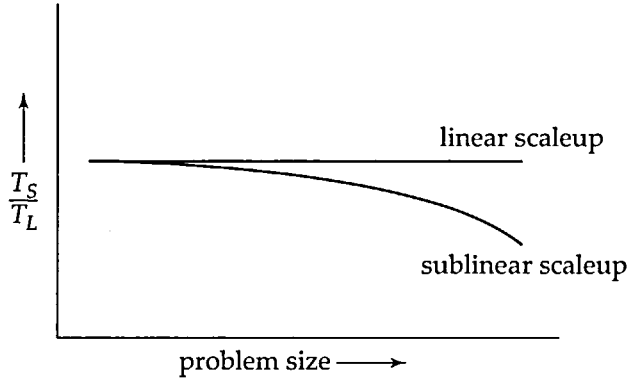


Figure 17.6 Scaleup with increasing problem size and resources.

M_S is T_S, and the execution time of task Q_N on a parallel machine M_L, which is N times larger than M_S, is T_L. The scaleup is then defined as T_S/T_L. The parallel system M_L is said to demonstrate **linear scaleup** on task Q if $T_L = T_S$. If $T_L > T_S$, the system is said to demonstrate **sublinear scaleup**. Figure 17.6 illustrates linear and sublinear scaleups (where the resources increase in proportion to problem size). There are two kinds of scaleup that are relevant in parallel database systems, depending on how the size of the task is measured:

- In **batch scaleup**, the size of the database increases, and the tasks are large jobs whose runtime depends on the size of the database. An example of such a task is a scan of a relation whose size is proportional to the size of the database. Thus, the size of the database is the measure of the size of the problem. Batch scaleup also applies in scientific applications, such as executing a query at an N-times finer resolution or performing an N-times longer simulation.
- In **transaction scaleup**, the rate at which transactions are submitted to the database increases and the size of the database increases proportionally to the transaction rate. This kind of scaleup is what is relevant in transaction-processing systems where the transactions are small updates—for example, a deposit or withdrawal from an account—and transaction rates grow as more accounts are created. Such transaction processing is especially well adapted for parallel execution, since transactions can run concurrently and independently on separate processors, and each transaction takes roughly the same amount of time, even if the database grows.

Scaleup is usually the more important metric for measuring efficiency of parallel database systems. The goal of parallelism in database systems is usually to make sure that the database system can continue to perform at an acceptable speed, even as the size of the database and the number of transactions increases. Increasing the capacity of the system by increasing the parallelism provides a smoother path for growth for an enterprise than does replacing a centralized

system with a faster machine (even assuming that such a machine exists). However, we must also look at absolute performance numbers when using scaleup measures; a machine that scales up linearly may perform worse than a machine that scales less than linearly, simply because the latter machine is much faster to start off with.

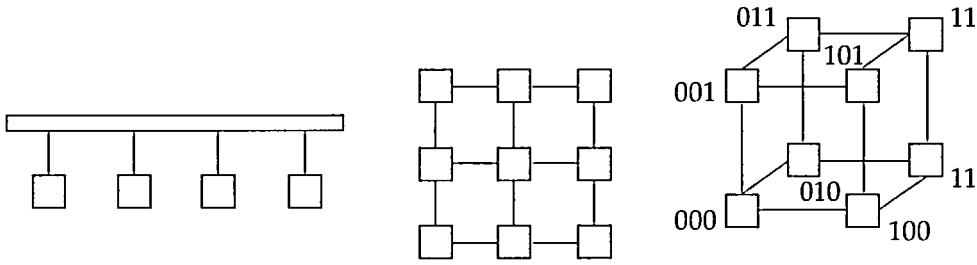
A number of factors work against efficient parallel operation and can diminish both speedup and scaleup.

- **Start-up costs.** There is a start-up cost associated with initiating a single process. In a parallel operation consisting of thousands of processes, the *start-up time* may overshadow the actual processing time, affecting speedup adversely.
- **Interference.** Since processes executing in a parallel system often access shared resources, a slowdown may result from the *interference* of each new process as it competes with existing processes for commonly held resources, such as a system bus, or shared disks, or even locks. Both speedup and scaleup are affected by this phenomenon.
- **Skew.** By breaking down a single task into a number of parallel steps, we reduce the size of the average step. Nonetheless, the service time for the single slowest step will determine the service time for the task as a whole. It is often difficult to divide a task into exactly equal-sized parts, and the way that the sizes are distributed is therefore *skewed*. For example, if a task of size 100 is divided into 10 parts, and the division is skewed, there may be some tasks of size less than 10 and some tasks of size more than 10; if even one task happens to be of size 20, the speedup obtained by running the tasks in parallel is only five, instead of ten as we would have hoped.

17.3.2 Interconnection Networks

Parallel systems consist of a set of components (processors, memory, and disks) that can communicate with each other via an **interconnection network**. Figure 17.7 shows three commonly used types of interconnection networks:

- **Bus.** All the system components can send data on and receive data from a single communication bus. This type of interconnection is shown in Figure 17.7a. The bus could be an Ethernet or a parallel interconnect. Bus architectures work well for small numbers of processors. However, they do not scale well with increasing parallelism, since the bus can handle communication from only one component at a time.
- **Mesh.** The components are nodes in a grid, and each component connects to all its adjacent components in the grid. In a two-dimensional mesh each node connects to four adjacent nodes, while in a three-dimensional mesh each node connects to six adjacent nodes. Figure 17.7b shows a two-dimensional mesh.



(a) bus (b) mesh (c) hypercube

Figure 17.7 Interconnection networks.

Nodes that are not directly connected can communicate with one another by routing messages via a sequence of intermediate nodes that are directly connected to one another. The number of communication links grows as the number of components grows, and the communication capacity of a mesh therefore scales better with increasing parallelism.

- **Hypercube.** The components are numbered in binary, and a component is connected to another if the binary representations of their numbers differ in exactly one bit. Thus, each of the n components is connected to $\log(n)$ other components. Figure 17.7c shows a hypercube with eight nodes. In a hypercube interconnection, a message from a component can reach any other component by going through at most $\log(n)$ links. In contrast, in a mesh architecture a component may be $2(\sqrt{n} - 1)$ links away from some of the other components (or $\sqrt{n}$ links away, if the mesh interconnection wraps around at the edges of the grid). Thus communication delays in a hypercube are significantly lower than in a mesh.

17.3.3 Parallel Database Architectures

There are several architectural models for parallel machines. Among the most prominent ones are those in Figure 17.8 (in the figure, M denotes memory, P denotes a processor, and disks are shown as cylinders):

- **Shared memory.** All the processors share a common memory (Figure 17.8a).
- **Shared disk.** All the processors share a common set of disks (Figure 17.8b). Shared-disk systems are sometimes called **clusters**.
- **Shared nothing.** The processors share neither a common memory nor common disk (Figure 17.8c).
- **Hierarchical.** This model is a hybrid of the preceding three architectures (Figure 17.8d).

In Sections 17.3.3.1 through 17.3.3.4, we elaborate on each of these models.

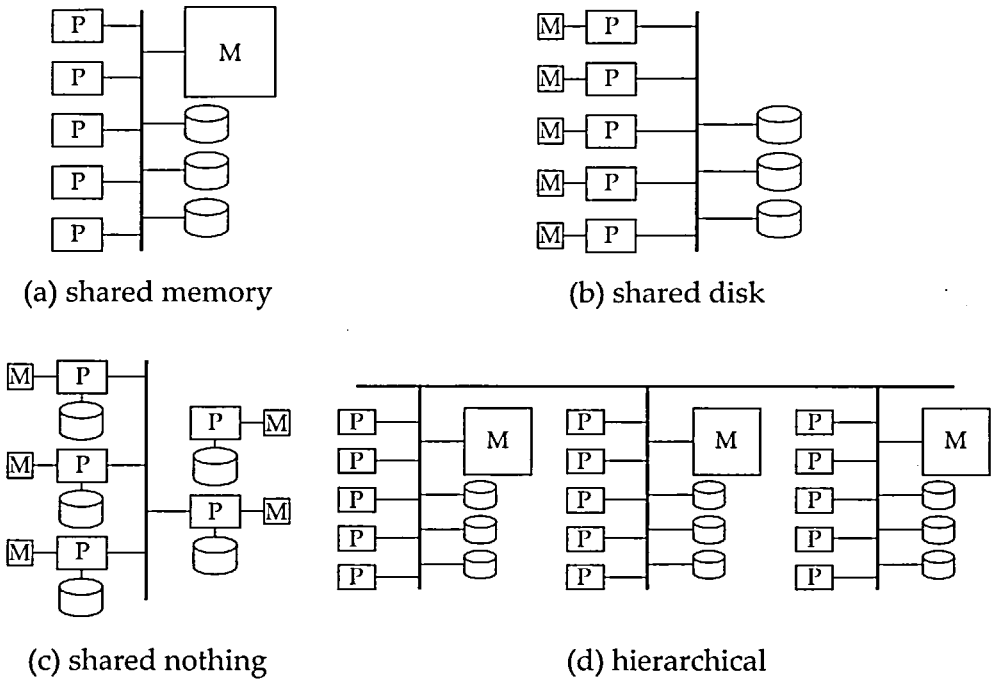


Figure 17.8 Parallel database architectures.

Techniques used to speed up transaction processing on data-server systems, such as data and lock caching and lock de-escalation, outlined in Section 17.2.2, can also be used in shared-disk parallel databases as well as in shared-nothing parallel databases. In fact, they are very important for efficient transaction processing in such systems.

17.3.3.1 Shared Memory

In a **shared-memory** architecture, the processors and disks have access to a common memory, typically via a bus or through an interconnection network. The benefit of shared memory is extremely efficient communication between processors—data in shared memory can be accessed by any processor without being moved with software. A processor can send messages to other processors much faster by using memory writes (which usually take less than a microsecond) than by sending a message through a communication mechanism. The downside of shared-memory machines is that the architecture is not scalable beyond 32 or 64 processors because the bus or the interconnection network becomes a bottleneck (since it is shared by all processors). Adding more processors does not help after a point, since the processors will spend most of their time waiting for their turn on the bus to access memory.

Shared-memory architectures usually have large memory caches at each processor, so that referencing of the shared memory is avoided whenever possible.

However, at least some of the data will not be in the cache, and accesses will have to go to the shared memory. Moreover, the caches need to be kept coherent; that is, if a processor performs a write to a memory location, the data in that memory location should be either updated at or removed from any processor where the data are cached. Maintaining cache coherency becomes an increasing overhead with increasing numbers of processors. Consequently, shared-memory machines are not capable of scaling up beyond a point; current shared-memory machines cannot support more than 64 processors.

17.3.3.2 Shared Disk

In the **shared-disk** model, all processors can access all disks directly via an interconnection network, but the processors have private memories. There are two advantages of this architecture over a shared-memory architecture. First, since each processor has its own memory, the memory bus is not a bottleneck. Second, it offers a cheap way to provide a degree of **fault tolerance**: If a processor (or its memory) fails, the other processors can take over its tasks, since the database is resident on disks that are accessible from all processors. We can make the disk subsystem itself fault tolerant by using a RAID architecture, as described in Chapter 10. The shared-disk architecture has found acceptance in many applications.

The main problem with a shared-disk system is again scalability. Although the memory bus is no longer a bottleneck, the interconnection to the disk subsystem is now a bottleneck; it is particularly so in a situation where the database makes a large number of accesses to disks. Compared to shared-memory systems, shared-disk systems can scale to a somewhat larger number of processors, but communication across processors is slower (up to a few milliseconds in the absence of special-purpose hardware for communication), since it has to go through a communication network.

17.3.3.3 Shared Nothing

In a **shared-nothing** system, each node of the machine consists of a processor, memory, and one or more disks. The processors at one node may communicate with another processor at another node by a high-speed interconnection network. A node functions as the server for the data on the disk or disks that the node owns. Since local disk references are serviced by local disks at each processor, the shared-nothing model overcomes the disadvantage of requiring all I/O to go through a single interconnection network; only queries, accesses to nonlocal disks, and result relations pass through the network. Moreover, the interconnection networks for shared-nothing systems are usually designed to be scalable, so that their transmission capacity increases as more nodes are added. Consequently, shared-nothing architectures are more scalable and can easily support a large number of processors. The main drawbacks of shared-nothing systems are the costs of communication and of nonlocal disk access, which are higher than in a shared-memory or shared-disk architecture since sending data involves software interaction at both ends.

17.3.3.4 Hierarchical

The **hierarchical architecture** combines the characteristics of shared-memory, shared-disk, and shared-nothing architectures. At the top level, the system consists of nodes that are connected by an interconnection network and do not share disks or memory with one another. Thus, the top level is a shared-nothing architecture. Each node of the system could actually 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. Thus, a system could be built as a hierarchy, with shared-memory architecture with a few processors at the base, and a shared-nothing architecture at the top, with possibly a shared-disk architecture in the middle. Figure 17.8d illustrates a hierarchical architecture with shared-memory nodes connected together in a shared-nothing architecture. Commercial parallel database systems today run on several of these architectures.

Attempts to reduce the complexity of programming such systems have yielded **distributed virtual-memory** architectures, where logically there is a single shared memory, but physically there are multiple disjoint memory systems; the virtual-memory-mapping hardware, coupled with system software, allows each processor to view the disjoint memories as a single virtual memory. Since access speeds differ, depending on whether the page is available locally or not, such an architecture is also referred to as a **nonuniform memory architecture** (NUMA).

7.4 Distributed Systems

In a **distributed database system**, the database is stored on several computers. The computers in a distributed system communicate with one another through various communication media, such as high-speed private networks or the Internet. They do not share main memory or disks. The computers in a distributed system may vary in size and function, ranging from workstations up to mainframe systems.

The computers in a distributed system are referred to by a number of different names, such as **sites** or **nodes**, depending on the context in which they are mentioned. We mainly use the term **site**, to emphasize the physical distribution of these systems. The general structure of a distributed system appears in Figure 17.9.

The main differences between shared-nothing parallel databases and distributed databases are that distributed databases are typically geographically separated, are separately administered, and have a slower interconnection. Another major difference is that, in a distributed database system, we differentiate between local and global transactions. A **local transaction** is one that accesses data only from sites where the transaction was initiated. A **global transaction**, on the other hand, is one that either accesses data in a site different from the one at which the transaction was initiated, or accesses data in several different sites.

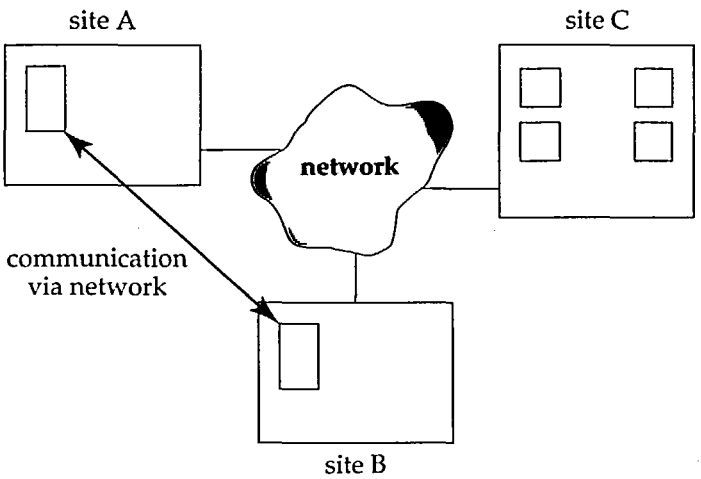


Figure 17.9 A distributed system.

There are several reasons for building distributed database systems, including sharing of data, autonomy, and availability.

- **Sharing data.** The major advantage in building a distributed database system is the provision of an environment where users at one site may be able to access the data residing at other sites. For instance, in a distributed university system, where each campus stores data related to that campus, it is possible for a user in one campus to access data in another campus. Without this capability, the transfer of student records from one campus to another campus would have to resort to some external mechanism that would couple existing systems.
- **Autonomy.** The primary advantage of sharing data by means of data distribution is that each site is able to retain a degree of control over data that are stored locally. In a centralized system, the database administrator of the central site controls the database. In a distributed system, there is a global database administrator responsible for the entire system. A part of these responsibilities is delegated to the local database administrator for each site. Depending on the design of the distributed database system, each administrator may have a different degree of **local autonomy**. The possibility of local autonomy is often a major advantage of distributed databases.
- **Availability.** If one site fails in a distributed system, the remaining sites may be able to continue operating. In particular, if data items are **replicated** in several sites, a transaction needing a particular data item may find that item in any of several sites. Thus, the failure of a site does not necessarily imply the shutdown of the system.

The failure of one site must be detected by the system, and appropriate action may be needed to recover from the failure. The system must no longer use the services of the failed site. Finally, when the failed site recovers or is repaired, mechanisms must be available to integrate it smoothly back into the system.

Although recovery from failure is more complex in distributed systems than in centralized systems, the ability of most of the system to continue to operate despite the failure of one site results in increased availability. Availability is crucial for database systems used for real-time applications. Loss of access to data by, for example, an airline may result in the loss of potential ticket buyers to competitors.

17.4.1 An Example of a Distributed Database

Consider a banking system consisting of four branches in four different cities. Each branch has its own computer, with a database of all the accounts maintained at that branch. Each such installation is thus a site. There also exists one single site that maintains information about all the branches of the bank.

To illustrate the difference between the two types of transactions—local and global—at the sites, consider a transaction to add $50 to account number A-177 located at the Valleyview branch. If the transaction was initiated at the Valleyview branch, then it is considered local; otherwise, it is considered global. A transaction to transfer $50 from account A-177 to account A-305, which is located at the Hillside branch, is a global transaction, since accounts in two different sites are accessed as a result of its execution.

In an ideal distributed database system, the sites would share a common global schema (although some relations may be stored only at some sites), all sites would run the same distributed database-management software, and the sites would be aware of each other's existence. If a distributed database is built from scratch, it would indeed be possible to achieve the above goals. However, in reality a distributed database has to be constructed by linking together multiple already-existing database systems, each with its own schema and possibly running different database-management software. Such systems are sometimes called **multidatabase systems** or **heterogeneous distributed database systems**. We discuss these systems in Section 19.8, where we show how to achieve a degree of global control despite the heterogeneity of the component systems.

17.4.2 Implementation Issues

Atomicity of transactions is an important issue in building a distributed database system. If a transaction runs across two sites, unless the system designers are careful, it may commit at one site and abort at another, leading to an inconsistent state. Transaction commit protocols ensure such a situation cannot arise. The *two-phase commit protocol* (2PC) is the most widely used of these protocols.

The basic idea behind 2PC is for each site to execute the transaction until it enters the partially committed state, and then leave the commit decision to a single coordinator site; the transaction is said to be in the *ready* state at a site at this point. The coordinator decides to commit the transaction only if the transaction reaches the ready state at every site where it executed; otherwise (for example, if the transaction aborts at any site), the coordinator decides to abort the transaction. Every site where the transaction executed must follow the decision of the coordinator. If a site fails when a transaction is in ready state, when the site recovers from failure it should be in a position to either commit or abort the transaction, depending on the decision of the coordinator. The 2PC protocol is described in detail in Section 19.4.1.

Concurrency control is another issue in a distributed database. Since a transaction may access data items at several sites, transaction managers at several sites may need to coordinate to implement concurrency control. If locking is used, locking can be performed locally at the sites containing accessed data items, but there is also a possibility of deadlock involving transactions originating at multiple sites. Therefore deadlock detection needs to be carried out across multiple sites. Failures are more common in distributed systems since not only may computers fail, but communication links may also fail. Replication of data items, which is the key to the continued functioning of distributed databases when failures occur, further complicates concurrency control. Section 19.5 provides detailed coverage of concurrency control in distributed databases.

The standard transaction models, based on multiple actions carried out by a single program unit, are often inappropriate for carrying out tasks that cross the boundaries of databases that cannot or will not cooperate to implement protocols such as 2PC. Alternative approaches, based on *persistent messaging* for communication, are generally used for such tasks; persistent messaging is discussed in Section 19.4.3.

When the tasks to be carried out are complex, involving multiple databases and/or multiple interactions with humans, coordination of the tasks and ensuring transaction properties for the tasks become more complicated. *Workflow management systems* are systems designed to help with carrying out such tasks, and are described in Section 26.2.

In case an organization has to choose between a distributed architecture and a centralized architecture for implementing an application, the system architect must balance the advantages against the disadvantages of distribution of data. We have already seen the advantages of using distributed databases. The primary disadvantage of distributed database systems is the added complexity required to ensure proper coordination among the sites. This increased complexity takes various forms:

- **Software-development cost.** It is more difficult to implement a distributed database system; thus, it is more costly.
- **Greater potential for bugs.** Since the sites that constitute the distributed system operate in parallel, it is harder to ensure the correctness of algorithms,

especially operation during failures of part of the system, and recovery from failures. The potential exists for extremely subtle bugs.

- **Increased processing overhead.** The exchange of messages and the additional computation required to achieve intersite coordination are a form of overhead that does not arise in centralized systems.

There are several approaches to distributed database design, ranging from fully distributed designs to ones that include a large degree of centralization. We study them in Chapter 19.

17.5 Network Types

Distributed databases and client–server systems are built around communication networks. There are basically two types of networks: **local-area networks** and **wide-area networks**. The main difference between the two is the way in which they are distributed geographically. In local-area networks, processors are distributed over small geographical areas, such as a single building or a number of adjacent buildings. In wide-area networks, on the other hand, a number of autonomous processors are distributed over a large geographical area (such as the United States or the entire world). These differences imply major variations in the speed and reliability of the communication network, and are reflected in the distributed operating-system design.

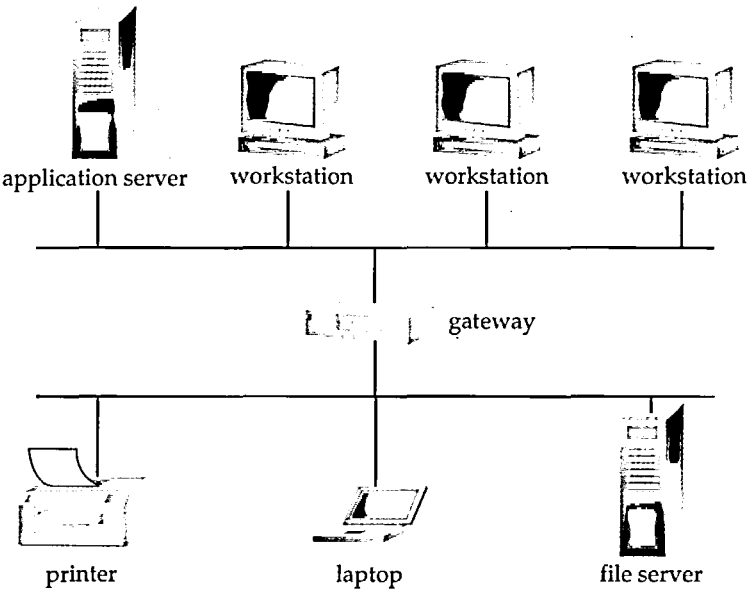


Figure 17.10 Local-area network.

17.5.1 Local-Area Networks

Local-area networks (LANs) (Figure 17.10) emerged in the early 1970s as a way for computers to communicate and to share data with one another. People recognized that, for many enterprises, numerous small computers, each with its own self-contained applications, are more economical than a single large system. Because each small computer is likely to need access to a full complement of peripheral devices (such as disks and printers), and because some form of data sharing is likely to occur in a single enterprise, it was a natural step to connect these small systems into a network.

LANs are generally used in an office environment. All the sites in such systems are close to one another, so the communication links tend to have a higher speed and lower error rate than do their counterparts in wide-area networks. The most common links in a local-area network are twisted pair, coaxial cable, fiber optics, and wireless connections. Communication speeds range from tens of megabits per second (for wireless local-area networks), to 1 gigabit per second for Gigabit Ethernet. The most recent Ethernet standard is 10-gigabit Ethernet.

A **storage-area network** (SAN) is a special type of high-speed local-area network designed to connect large banks of storage devices (disks) to computers that use the data (see Figure 17.11).

Thus storage-area networks help build large-scale *shared-disk systems*. The motivation for using storage-area networks to connect multiple computers to large banks of storage devices is essentially the same as that for shared-disk databases, namely:

- Scalability by adding more computers.
- High availability, since data are still accessible even if a computer fails.

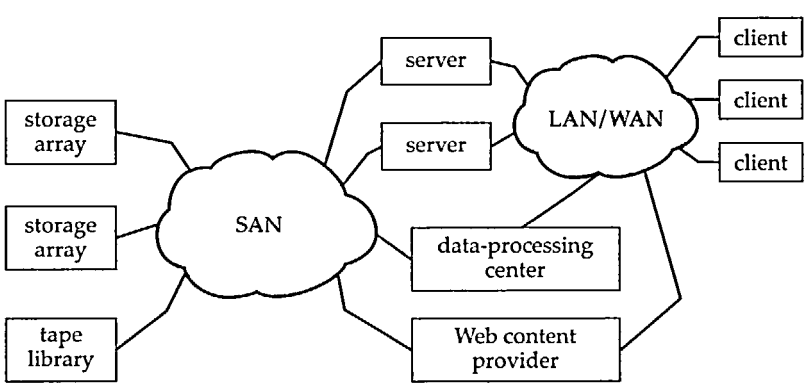


Figure 17.11 Storage-area network.

RAID organizations are used in the storage devices to ensure high availability of the data, permitting processing to continue even if individual disks fail. Storage-area networks are usually built with redundancy, such as multiple paths between nodes, so if a component such as a link or a connection to the network fails, the network continues to function.

17.5.2 Wide-Area Networks

Wide-area networks (WANs) emerged in the late 1960s, mainly as an academic research project to provide efficient communication among sites, allowing hardware and software to be shared conveniently and economically by a wide community of users. Systems that allowed remote terminals to be connected to a central computer via telephone lines were developed in the early 1960s, but they were not true WANs. The first WAN to be designed and developed was the *Arpanet*. Work on the Arpanet began in 1968. The Arpanet has grown from a four-site experimental network to a worldwide network of networks, the **Internet**, comprising hundreds of millions of computer systems. Typical links on the Internet are fiber-optic lines and, sometimes, satellite channels. Data rates for wide-area links typically range from a few megabits per second to hundreds of gigabits per second. The last link, to end user sites, has traditionally been the slowest link, using such technologies as *digital subscriber line* (DSL) technology (supporting a few megabits per second) or dial-up modem connections over land-based telephone lines (supporting up to 56 kilobits per second). Today, the last link is typically a cable modem or fiber optic connection (each supporting tens of megabits per second), or a wireless connection supporting several megabits per second.

In addition to limits on data rates, communication in a WAN must also contend with significant **latency**: a message may take up to a few hundred milliseconds to be delivered across the world, both due to speed of light delays, and due to queuing delays at a number of routers in the path of the message. Applications whose data and computing resources are distributed geographically have to be carefully designed to ensure latency does not affect system performance excessively.

WANs can be classified into two types:

- In **discontinuous connection** WANs, such as those based on mobile wireless connections, hosts are connected to the network only part of the time.
- In **continuous connection** WANs, such as the wired Internet, hosts are connected to the network at all times.

Networks that are not continuously connected typically do not allow transactions across sites, but may keep local copies of remote data, and refresh the copies periodically (every night, for instance). For applications where consistency is not critical, such as sharing of documents, groupware systems such as Lotus Notes allow updates of remote data to be made locally, and the updates are then propagated back to the remote site periodically. There is a potential for conflicting updates at different sites, conflicts that have to be detected and resolved. A mech-

anism for detecting conflicting updates is described later, in Section 25.5.4; the resolution mechanism for conflicting updates is, however, application dependent.

17.6 Summary

- Centralized database systems run entirely on a single computer. With the growth of personal computers and local-area networking, the database front-end functionality has moved increasingly to clients, with server systems providing the back-end functionality. Client–server interface protocols have helped the growth of client–server database systems.
- Servers can be either transaction servers or data servers, although the use of transaction servers greatly exceeds the use of data servers for providing database services.
  - Transaction servers have multiple processes, possibly running on multiple processors. So that these processes have access to common data, such as the database buffer, systems store such data in shared memory. In addition to processes that handle queries, there are system processes that carry out tasks such as lock and log management and checkpointing.
  - Data-server systems supply raw data to clients. Such systems strive to minimize communication between clients and servers by caching data and locks at the clients. Parallel database systems use similar optimizations.
- Parallel database systems consist of multiple processors and multiple disks connected by a fast interconnection network. Speedup measures how much we can increase processing speed by increasing parallelism for a single transaction. Scaleup measures how well we can handle an increased number of transactions by increasing parallelism. Interference, skew, and start-up costs act as barriers to getting ideal speedup and scaleup.
- Parallel database architectures include the shared-memory, shared-disk, shared-nothing, and hierarchical architectures. These architectures have different trade-offs of scalability versus communication speed.
- A distributed database system is a collection of partially independent database systems that (ideally) share a common schema, and coordinate processing of transactions that access nonlocal data. The systems communicate with one another through a communication network.
- Local-area networks connect nodes that are distributed over small geographical areas, such as a single building or a few adjacent buildings. Wide-area networks connect nodes spread over a large geographical area. The Internet is the most extensively used wide-area network today.
- Storage-area networks are a special type of local-area network designed to provide fast interconnection between large banks of storage devices and multiple computers.

Review Terms

- Centralized systems
- Server systems
- Coarse-granularity parallelism
- Fine-granularity parallelism
- Database process structure
- Mutual exclusion
- Thread
- Server processes
  - Lock manager process
  - Database writer process
  - Log writer process
  - Checkpoint process
  - Process monitor process
- Client–server systems
- Transaction server
- Query server
- Data server
  - Prefetching
  - De-escalation
  - Data caching
  - Cache coherency
  - Lock caching
  - Call back
- Parallel systems
- Throughput
- Response time
- Speedup
  - Linear speedup
  - Sublinear speedup
- Scaleup
  - Linear scaleup
  - Sublinear scaleup
  - Batch scaleup
  - Transaction scaleup
- Start-up costs
- Interference
- Skew
- Interconnection networks
  - Bus
  - Mesh
  - Hypercube
- Parallel database architectures
  - Shared memory
  - Shared disk (clusters)
  - Shared nothing
  - Hierarchical
- Fault tolerance
- Distributed virtual memory
- Nonuniform memory architecture (NUMA)
- Distributed systems
- Distributed database
  - Sites (nodes)
  - Local transaction
  - Global transaction
  - Local autonomy
- Multidatabase systems
- Network types
  - Local-area networks (LAN)
  - Wide-area networks (WAN)
  - Storage-area network (SAN)

Practice Exercises

17.1 Instead of storing shared structures in shared memory, an alternative architecture would be to store them in the local memory of a special process, and access the shared data by interprocess communication with the process. What would be the drawback of such an architecture?

17.2 In typical client–server systems the server machine is much more powerful than the clients; that is, its processor is faster, it may have multiple processors, and it has more memory and disk capacity. Consider instead a scenario where client and server machines have exactly the same power. Would it make sense to build a client–server system in such a scenario? Why? Which scenario would be better suited to a data-server architecture?

17.3 Consider a database system based on a client–server architecture, with the server acting as a data server.

a. What is the effect of the speed of the interconnection between the client and the server on the choice between tuple and page shipping?

b. If page shipping is used, the cache of data at the client can be organized either as a tuple cache or a page cache. The page cache stores data in units of a page, while the tuple cache stores data in units of tuples. Assume tuples are smaller than pages. Describe one benefit of a tuple cache over a page cache.

17.4 Suppose a transaction is written in C with embedded SQL, and about 80 percent of the time is spent in the SQL code, with the remaining 20 percent spent in C code. How much speedup can one hope to attain if parallelism is used only for the SQL code? Explain.

17.5 Some database operations such as joins can see a significant difference in speed when data (for example, one of the relations involved in a join) fits in memory as compared to the situation where the data does not fit in memory. Show how this fact can explain the phenomenon of **superlinear speedup**, where an application sees a speedup greater than the amount of resources allocated to it.

17.6 Parallel systems often have a network structure where sets of n processors connect to a single Ethernet switch, and the Ethernet switches themselves connect to another Ethernet switch. Does this architecture correspond to a bus, mesh or hypercube architecture? If not, how would you describe this interconnection architecture?

Exercises

17.7 Why is it relatively easy to port a database from a single processor machine to a multiprocessor machine if individual queries need not be parallelized?

17.8 Transaction-server architectures are popular for client–server relational databases, where transactions are short. On the other hand, data-server architectures are popular for client–server object-oriented database systems, where transactions are expected to be relatively long. Give two reasons why data servers may be popular for object-oriented databases but not for relational databases.

17.9 What is lock de-escalation, and under what conditions is it required? Why is it not required if the unit of data shipping is an item?

17.10 Suppose you were in charge of the database operations of a company whose main job is to process transactions. Suppose the company is growing rapidly each year, and has outgrown its current computer system. When you are choosing a new parallel computer, what measure is most relevant—speedup, batch scaleup, or transaction scaleup? Why?

17.11 Database systems are typically implemented as a set of processes (or threads) sharing a shared memory area.

a. How is access to the shared memory area controlled?

b. Is two-phase locking appropriate for serializing access to the data structures in shared memory? Explain your answer.

17.12 Is it wise to allow a user process to access the shared memory area of a database system? Explain your answer.

17.13 What are the factors that can work against linear scaleup in a transaction processing system? Which of the factors are likely to be the most important in each of the following architectures: shared memory, shared disk, and shared nothing?

17.14 Memory systems can be divided into multiple modules, each of which can be serving a separate request at a given time. What impact would such a memory architecture have on the number of processors that can be supported in a shared-memory system?

17.15 Consider a bank that has a collection of sites, each running a database system. Suppose the only way the databases interact is by electronic transfer of money between themselves, using persistent messaging. Would such a system qualify as a distributed database? Why?

Bibliographical Notes

Hennessy et al. [2006] provides an excellent introduction to the area of computer architecture. Abadi [2009] provides an excellent introduction to cloud computing and the challenges of running database transactions in such an environment.

Gray and Reuter [1993] provides a textbook description of transaction processing, including the architecture of client–server and distributed systems. The

bibliographical notes of Chapter 5 provide references to more information on ODBC, JDBC, and other database access APIs.

DeWitt and Gray [1992] surveys parallel database systems, including their architecture and performance measures. A survey of parallel computer architectures is presented by Duncan [1990]. Dubois and Thakkar [1992] is a collection of papers on scalable shared-memory architectures. DEC clusters running Rdb were among the early commercial users of the shared-disk database architecture. Rdb is now owned by Oracle, and is called Oracle Rdb. The Teradata database machine was among the earliest commercial systems to use the shared-nothing database architecture. The Grace and the Gamma research prototypes also used shared-nothing architectures.

Ozsu and Valduriez [1999] provides textbook coverage of distributed database systems. Further references pertaining to parallel and distributed database systems appear in the bibliographical notes of Chapters 18 and 19, respectively.

Comer [2009], Halsall [2006], and Thomas [1996] describe computer networking and the Internet. Tanenbaum [2002], Kurose and Ross [2005], and Peterson and Davie [2007] provide general overviews of computer networks.