Chapter 17: Database System Architectures

Database System Concepts, 6th Ed.

Chapter 17: Database System Architectures

- 17.1 Centralized and Client-Server Systems
- 17.2 Server System Architectures
- 17.3 Parallel Systems
- 17.4 Distributed Systems
- 17.5 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.

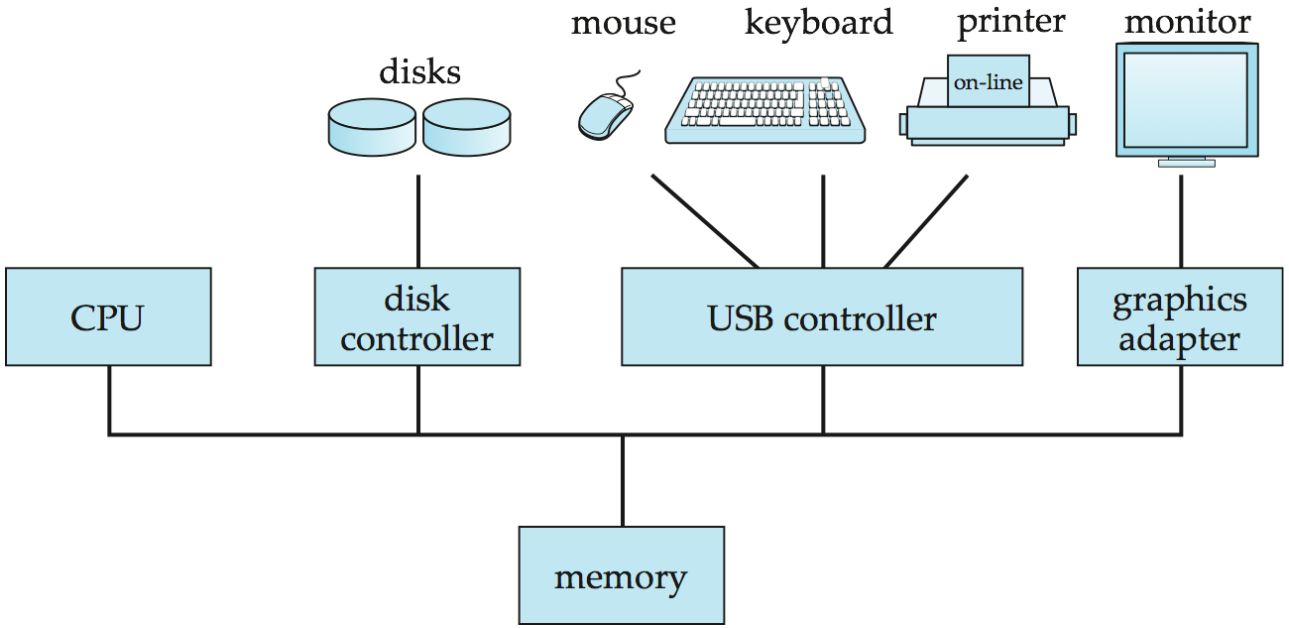
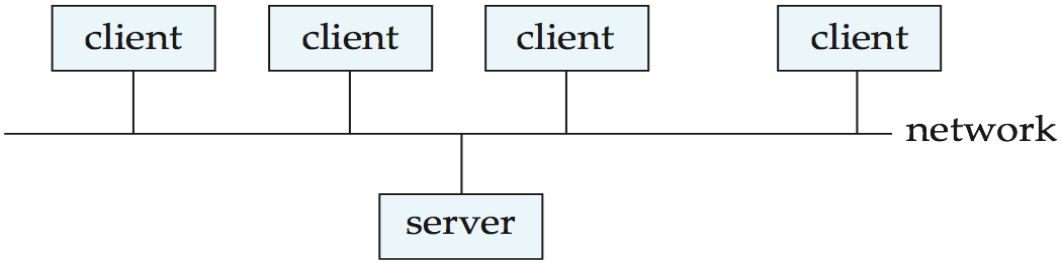


Fig 17.01

Client-Server Systems [1/2]

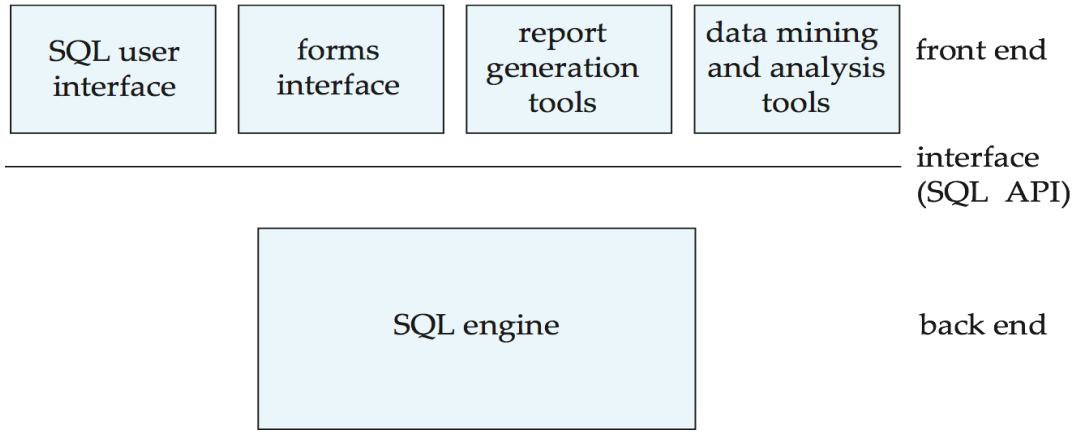
- Server systems satisfy requests generated at *m* client systems, whose general structure is shown below:

Fig 17.02



- Database functionality can be divided into:
  - **Back-end**: manages access structures, query evaluation & optimization, CC and recovery.
  - **Front-end**: consists of tools such as *forms*, *report-writers*, and graphical UI facilities.
- The interface between the front-end and the back-end is through SQL or through an application program interface (ex. CLI)

Fig 17.03



Client-Server Systems [2/2]

- Client-Server System의 시작동기: Down Sizing

- 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
  - **data servers**, used in object-oriented database systems

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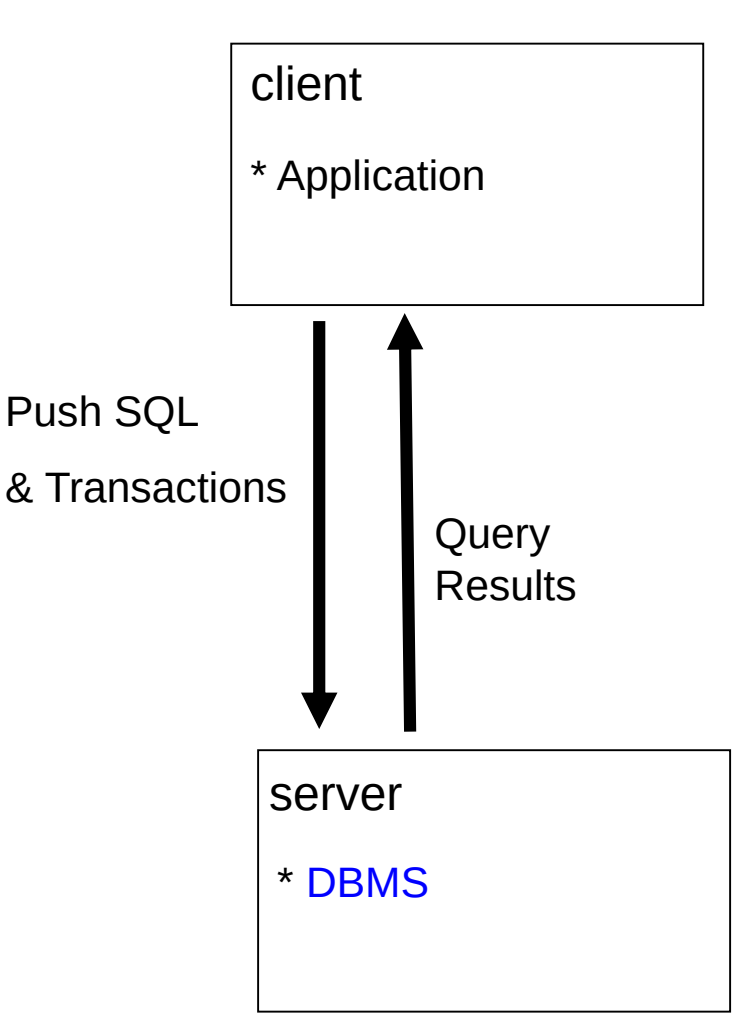
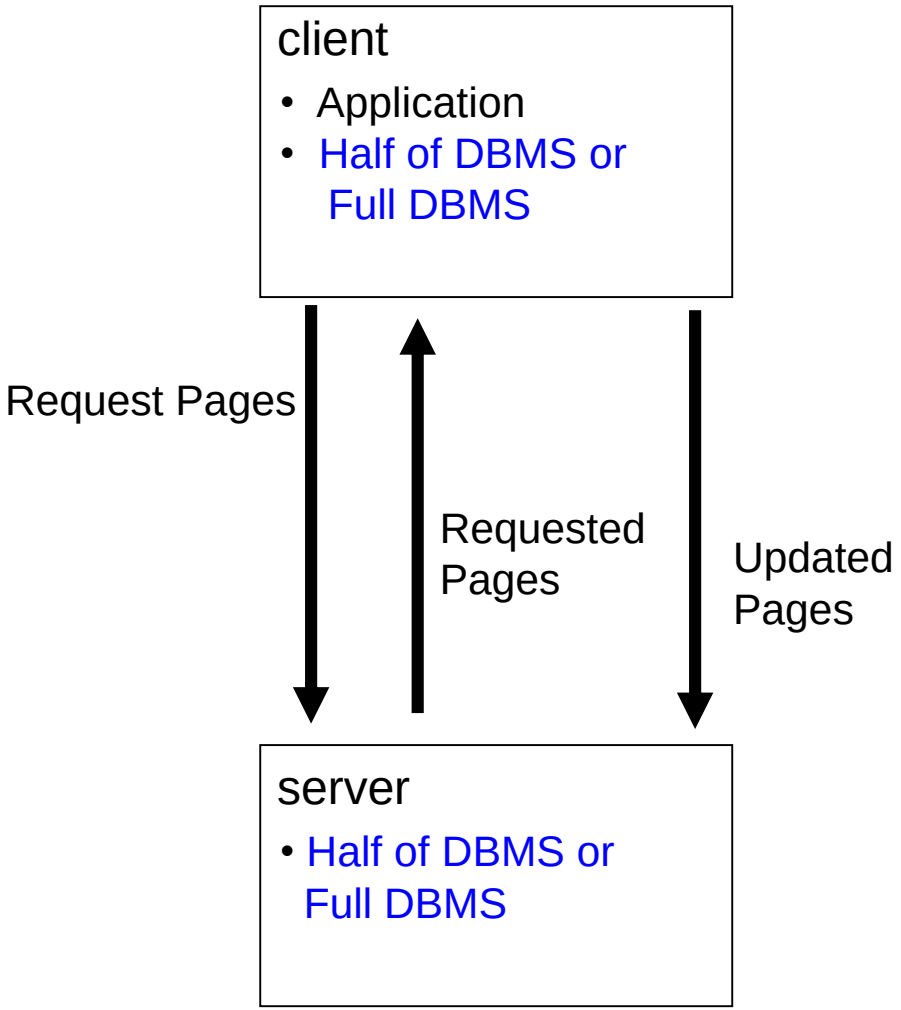
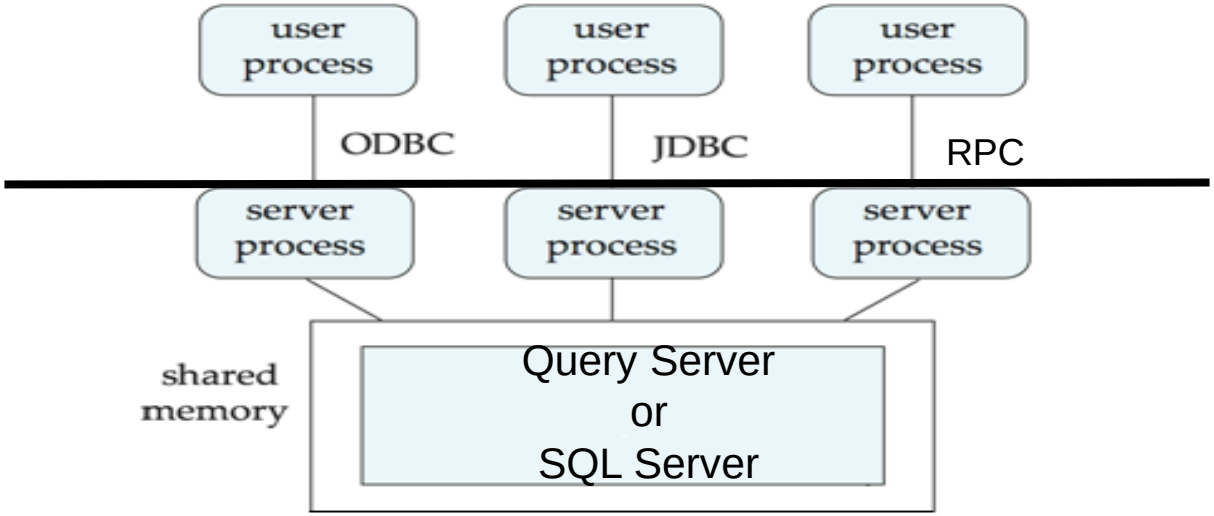
Transaction Server vs Data Server





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 API standard from Microsoft for connecting to a server, sending SQL requests, and receiving results
  - JDBC standard similar to ODBC, for Java

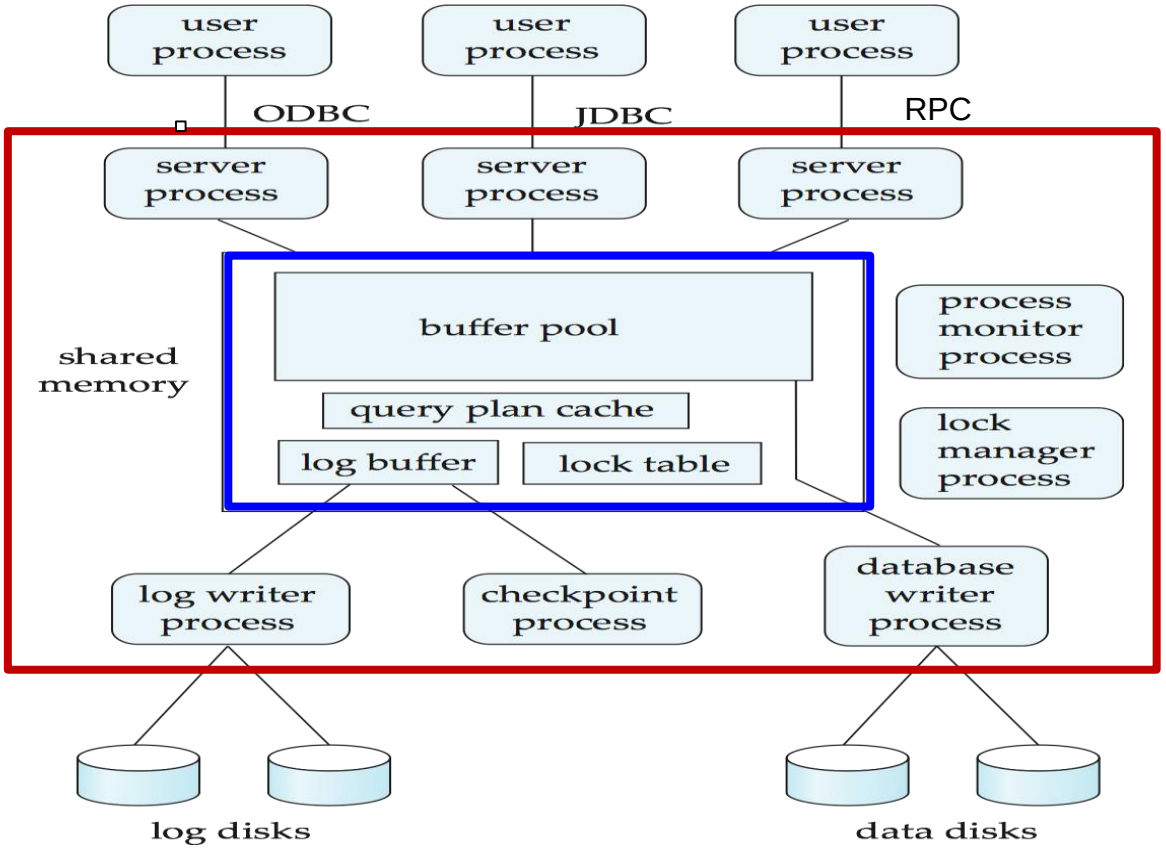


Transaction Server Processes [1/3]

- A typical transaction server consists of multiple processes accessing data in shared memory
- Server processes
  - Receive user queries (transactions), execute them & send results back
  - Typically multiple multithreaded server processes allowing a single process to execute several user queries concurrently
- Lock manager process: More on this later
- Database writer process: Output modified buffer blocks to disks continually
- 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 Server Processes [2/3]

Fig 17.04



Process Control?

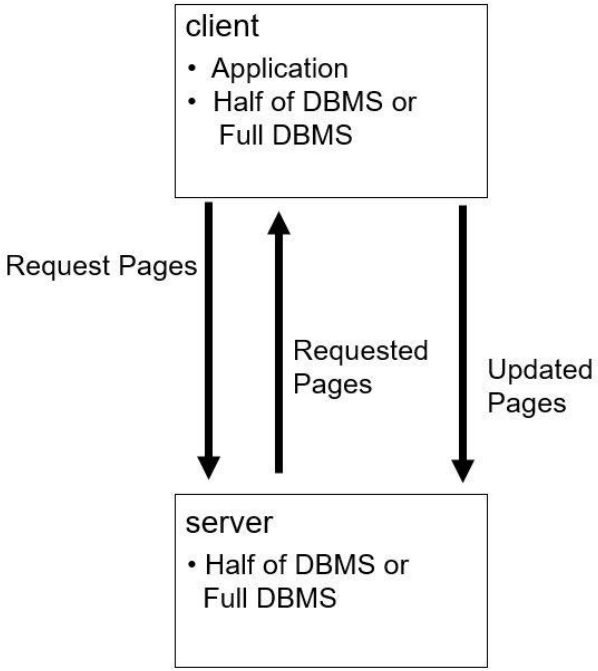
- Shared memory contains shared data
  - Buffer pool // Lock table // Log buffer // Cached query plans
  - All database processes can access shared memory
- To ensure that no two processes are accessing the same data structure at the same time, databases systems implement **mutual exclusion**
  - OS semaphores or Atomic instructions such as test-and-set

Transaction Server Processes [3/3]

- Lock Manager의 역할: Lock의 허가, Deadlock의 해결
- Sending requests to lock manager process creates severe overhead of interprocess communication for lock request/grant (Lock manager에 message passing는 큰부담)
- Instead each DB server process operates directly on the lock table (Section 15.1)
  - 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 OS 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 [1/3]

- Used in high-speed LANs, in cases where
  - The client machines are comparable in processing power to the server machine
  - The tasks to be executed in the client machines are compute intensive
- Data are shipped to client machines where processing is performed, and then shipped 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 [2/3]

- **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
    - With item shipping, locks are granted on requested and prefetched items
    - With page shipping, locks are granted on whole page
  - Locks on a prefetched item can be 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

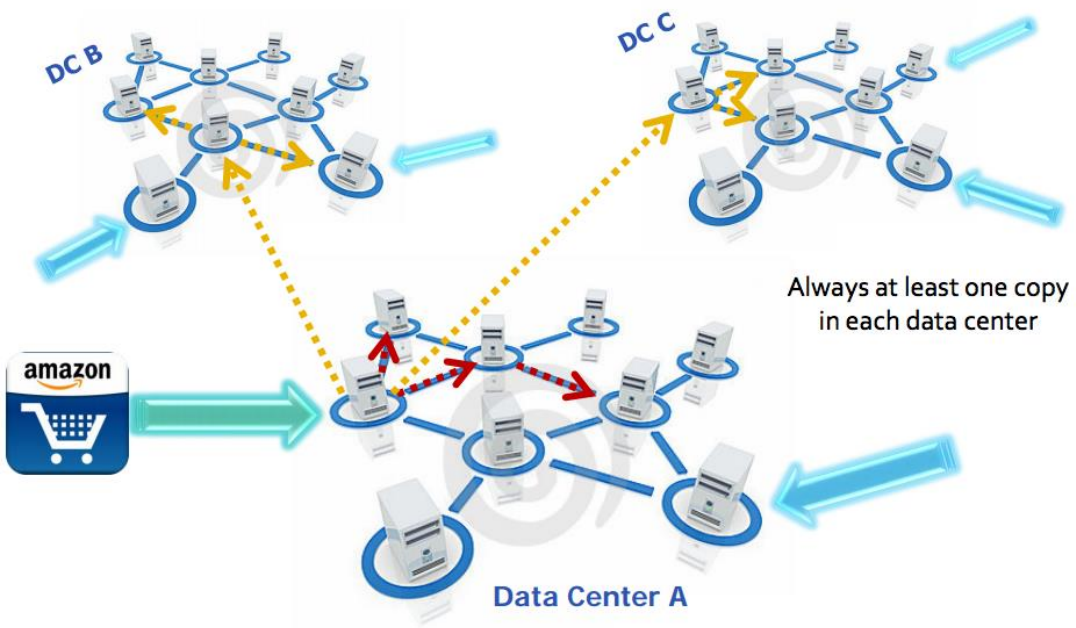
Data Servers [3/3]

- **Data Caching**
  - Data can be cached at client even in between transactions
  - But need to 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
    - Reduce communication overhead
  - 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

Cloud-based Servers

- Third party cloud vendors provide a collection of machines
- Not real machines, but software simulated machines (called virtual machines)
  - Add/Release machines as needed
  - Software define architecture (SDA)
  - Software defined storage (SDS)
- Various degree of cloud services
  - Providing Just raw storage and virtual machines
  - Providing varying degree of control over data placement and replication
  - Providing even DBMS service



Game Venture Company

Internet Shopping Company

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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 **fine grain parallel** or **massively 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 *N*-times larger system

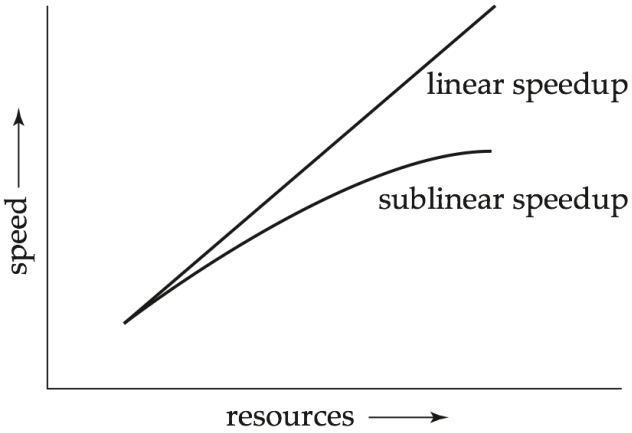
  speedup = small system elapsed time / large system elapsed time

  - 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

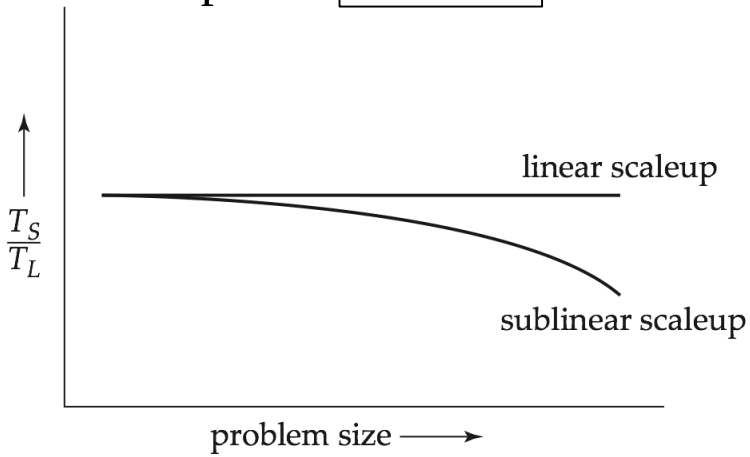
  scaleup = small system small problem elapsed time (T_S) / big system big problem elapsed time (T_L)

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

Speedup Fig 17.05



Scaleup Fig 17.06



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 of parallel processing 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 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

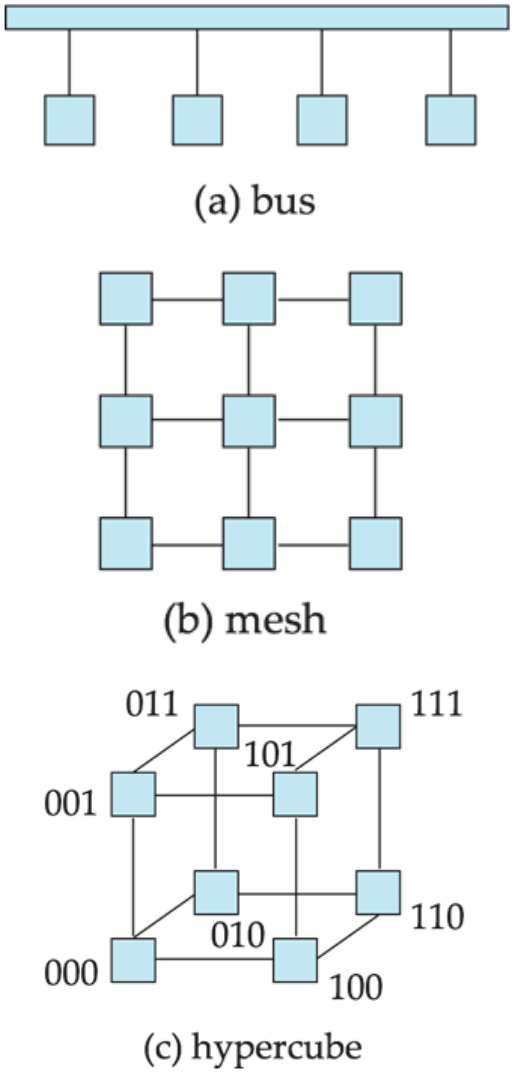
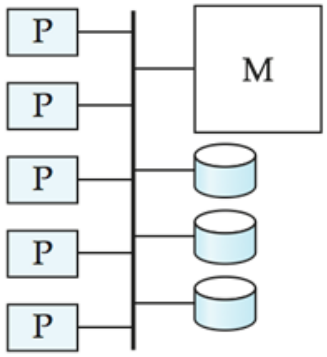


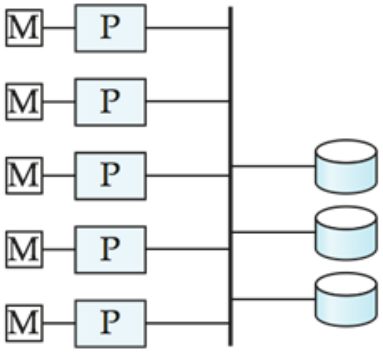
Fig 17.07

Parallel Database Architectures

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

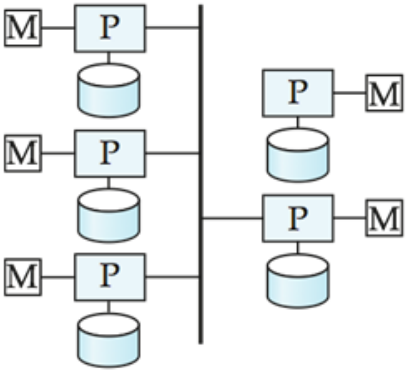


(a) shared memory

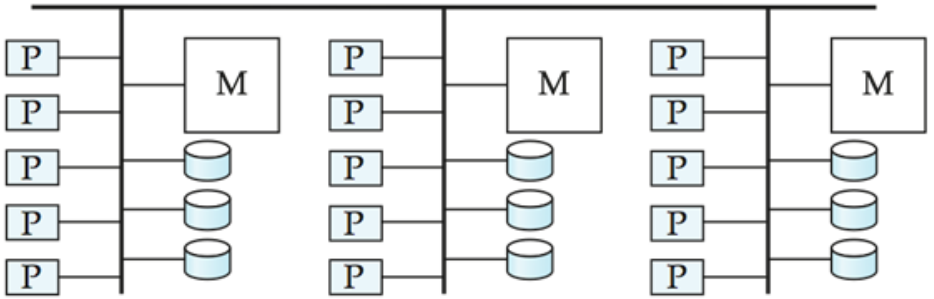


(b) shared disk

Fig 17.08



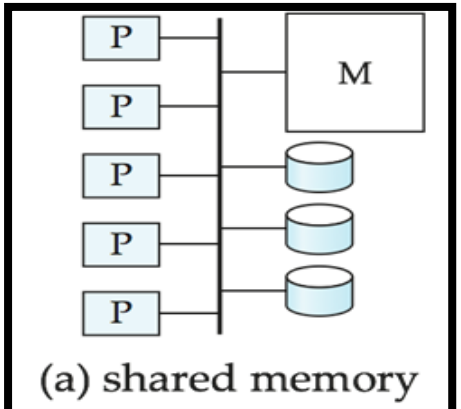
(c) shared nothing



(d) hierarchical

Shared-Memory Parallel DB

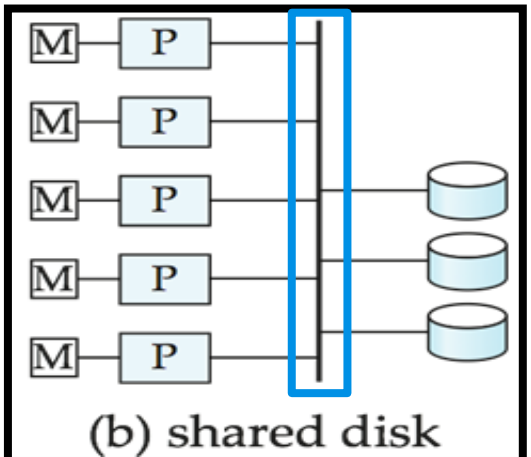
- Processors and disks have access to a common memory, typically via a bus or through an interconnection network
  - SMP (Symmetric Multi Processing) 방식
  - Each processor has its own cache ➔ cache coherence problem
  - Widely used for lower degrees of parallelism (4 to 8)
- Advantage
  - Extremely efficient 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



(a) shared memory

Shared-Disk Parallel DB

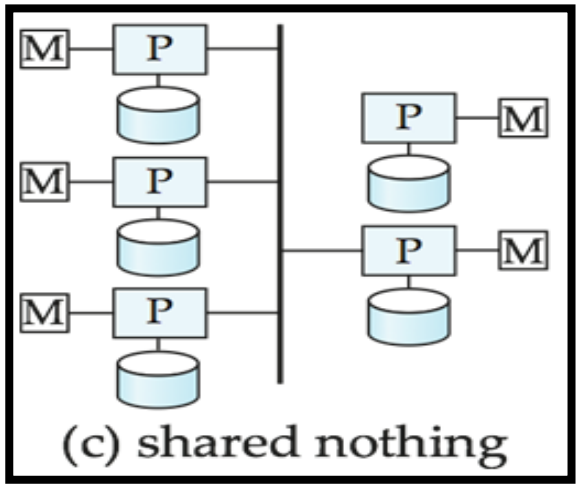
- All processors with private memories can directly access all disks via an interconnection network
  - The memory bus is not a bottleneck
  - Architecture provides a degree of **fault-tolerance** — if a processor fails, the other processors can take over its tasks since the database is resident on disks that are accessible from all processors
  - Mainframe 기반 parallel processor
    - IBM Sysplex with IBM DB2 and IMS
    - DEC clusters (now part of Compaq) running Oracle RDBMS
- Downside: bottleneck now occurs at interconnection to the disk subsystem
- Shared-disk systems can scale to a somewhat larger number of processors, but communication between processors is slower



(b) shared disk

Shared-Nothing Parallel DB

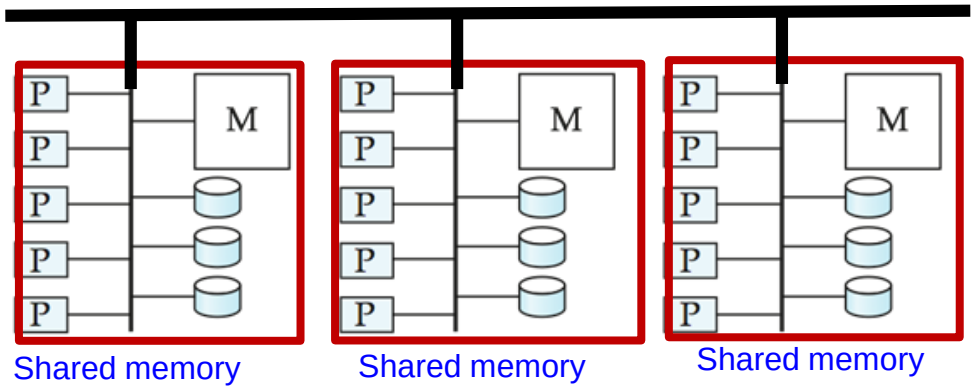
- Node consists of a processor, memory, and one or more disks
  - Processors at one node communicate with another processor at another node using an interconnection network
  - A node functions as the server for the data on the disk the node owns
- Examples: Teradata, Tandem, Oracle n-CUBE
- Data in local disks (and local memory) cannot be accessed through interconnection network, thereby minimizing the interference of resource sharing
- Shared-nothing multiprocessors can be scaled up to thousands of processors without interference
  - MPP (Massively Parallel Processing) 방식
- Main drawback: cost of communication and non-local disk access
  - Sending data involves software interaction at both ends

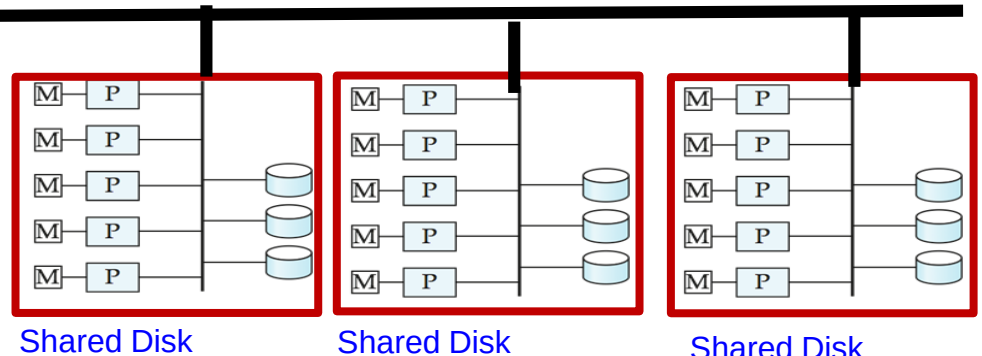


nCUBE 2 circuit board with 64 processors and memory

Hierarchical Parallel DB

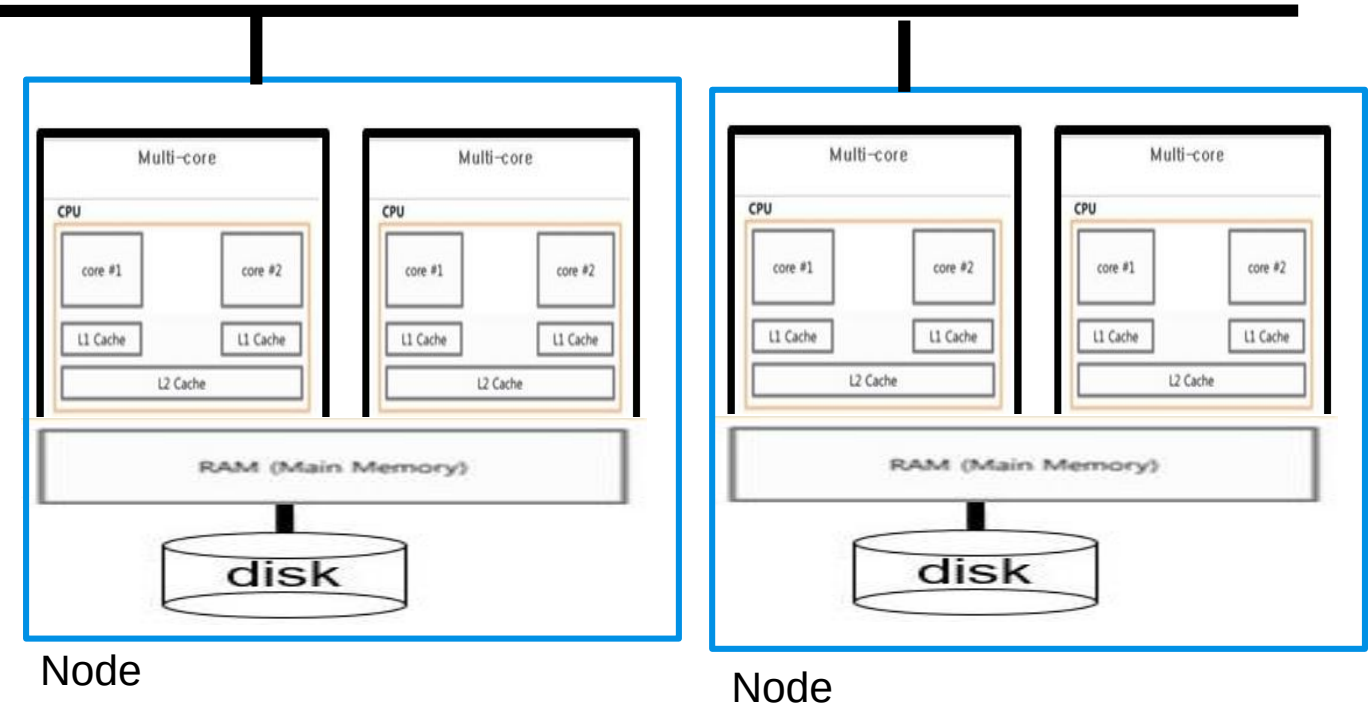
- Combines characteristics of shared-memory, shared-disk, and shared-nothing
  - Top level is a shared-nothing architecture – nodes connected by an interconnection network, and do not share disks or memory with each other
  - Each node could be a shared-memory system with a few processors
  - Alternatively, each node could be a shared-disk system, and each of the systems sharing a set of disks could be a shared-memory system





대세! PC Cluster and Server Cluster (기본적으로 Shared Nothing 방식)

- Multiprocessors vs. Multicores
  - Multiprocessors have private cache hierarchy (on chip)
  - Multicores have shared L2 (on chip)



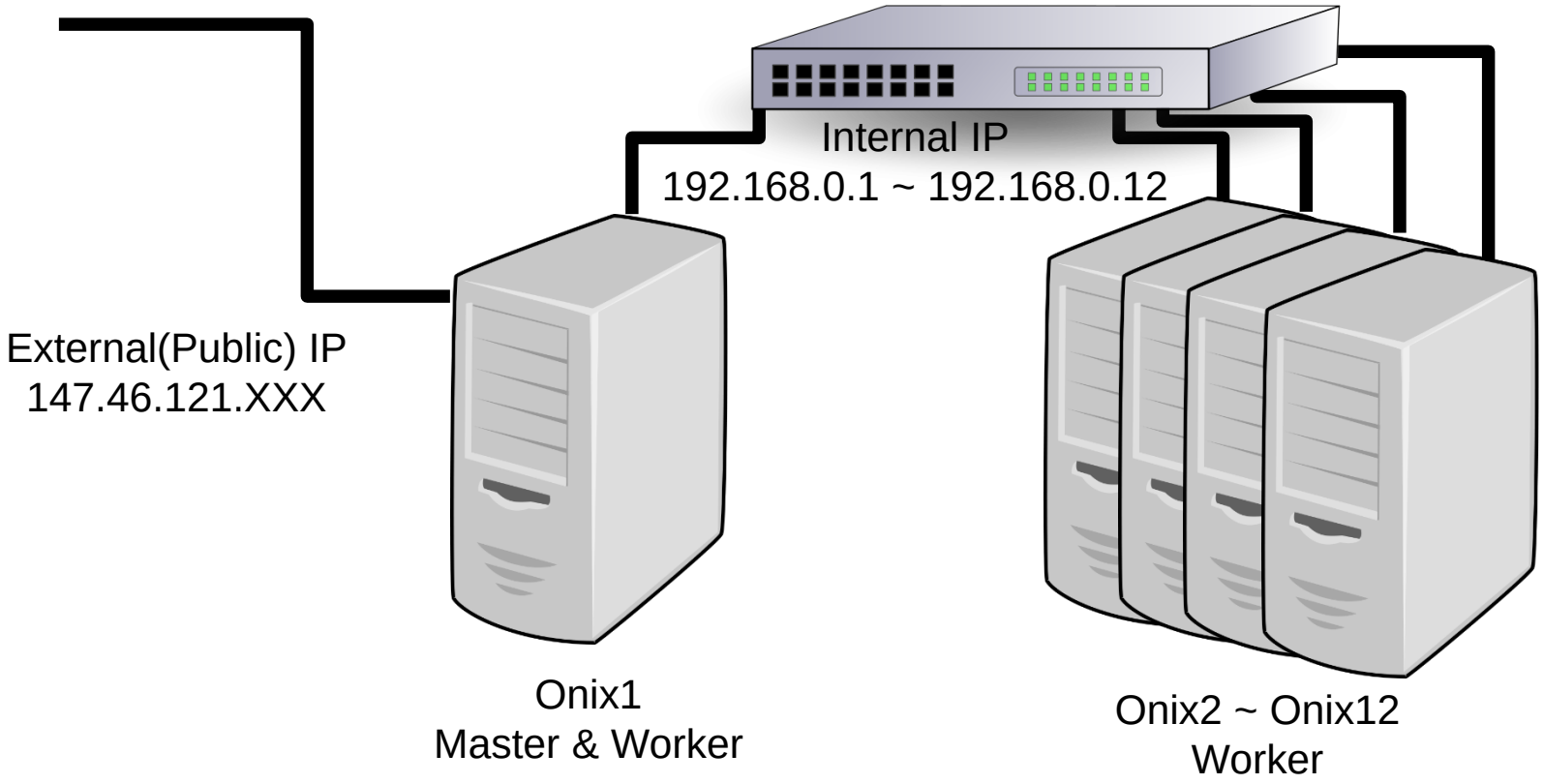
Node

Node

- Total 12 node cluster
- Each node
  - Intel Core i5-2400 SandyBridge (3.1GHz, quad-core)
  - 4GB memory / 4TB HDD

Sample Cluster Environment

- 12 Clusters
  - 1 Master & 12 Workers
    - Master node works as a worker node (slave node)



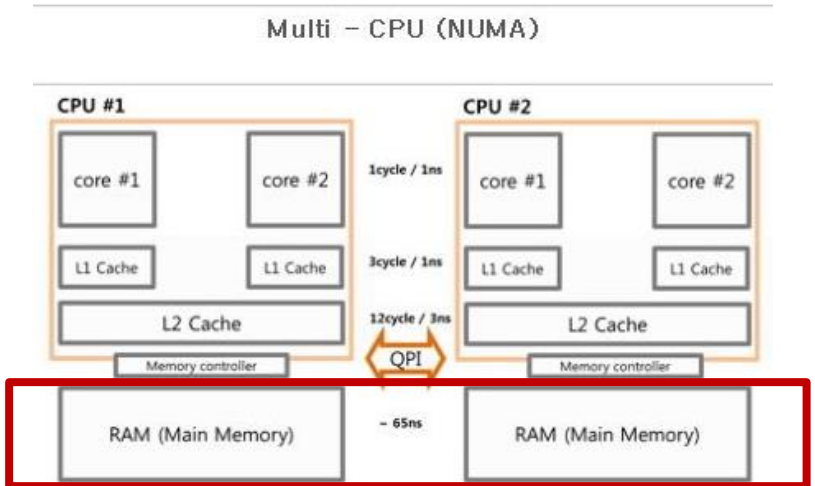
Modern Day Parallel Programming

참고자료

- **Thread기반 Parallel Programming**
- **SMP 방식: openMP library or pthread library를 사용**
  - **OpenMP** (**Open Multi-Processing**) is an application programming interface (API) that supports multi-platform shared memory multiprocessing programming in C, C++, and Fortran, on most platforms, architectures and operating systems, including Solaris, Linux, OS X, Windows
  - **POSIX Threads**, usually referred to as **Pthreads**, is an execution model that exists independently from a language, as well as a parallel execution model. For creating and controlling over threads.
- **Shared Nothing방식: MPI library**
  - **Message Passing Interface** (**MPI**) is a standardized and portable message-passing system on a wide variety of parallel computing architectures. The standard defines the syntax and semantics of a core of library routines for writing portable message-passing programs in C, C++, and Fortran.

Difficult Parallel Programming!

- Shared Memory Parallel Architecture의 문제점 ➔ Memory bottleneck
- Shared Nothing Parallel Architecture의 문제점 ➔ Difficult Parallel Programming
- Parallel Programming with **distributed virtual-memory on NUMA (Non-Uniform Memory Access) Capable Architecture**
  - **To view multiple disjoint memories as a single virtual memory**
  - 성능향상 (동등한 **SMP**환경보다 **10-20%** 향상), 시스템확장성증대
  - **SMP**의 **memory bottleneck**을 극복하지만 다른 **CPU**에 속한 **Memory**를 접근할때는 **access time**이 느린 문제가 있음
    - 가급적 다른 **CPU**에 할당된 **memory**의 접근을 피하도록 **coding**
    - **NUMA-aware SW**를 만드는것이 **issue**

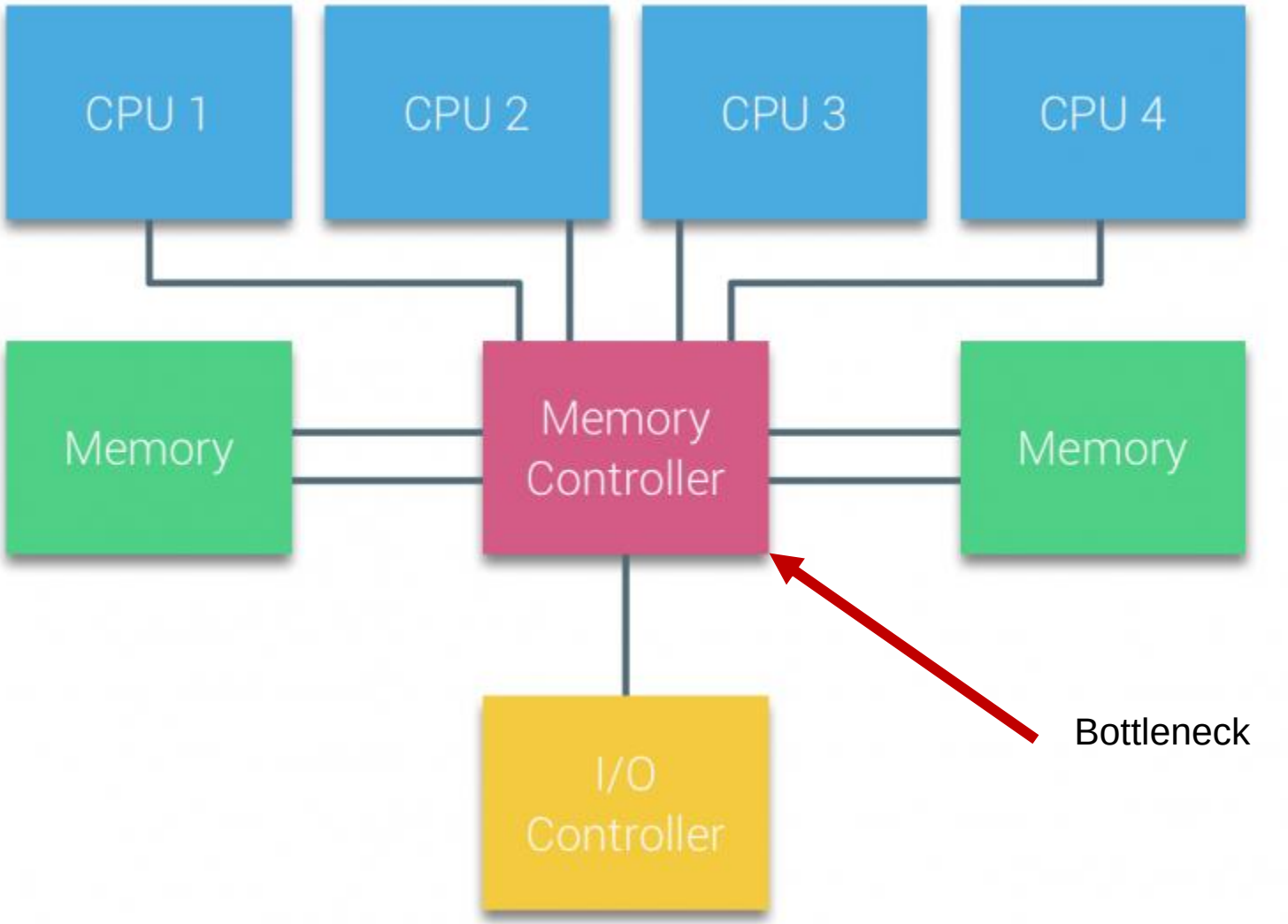


현재의 상황은 NUMA.

현재의 상황에서 RAM을 CPU1에만 몰아서 장착하면 UMA: CPU1에서는 Memory access가 빠르고 CPU2에서는 Memory access가 느리지만 uniform 하므로

참고자료

Typical UMA Structure (Uniform Memory Access)

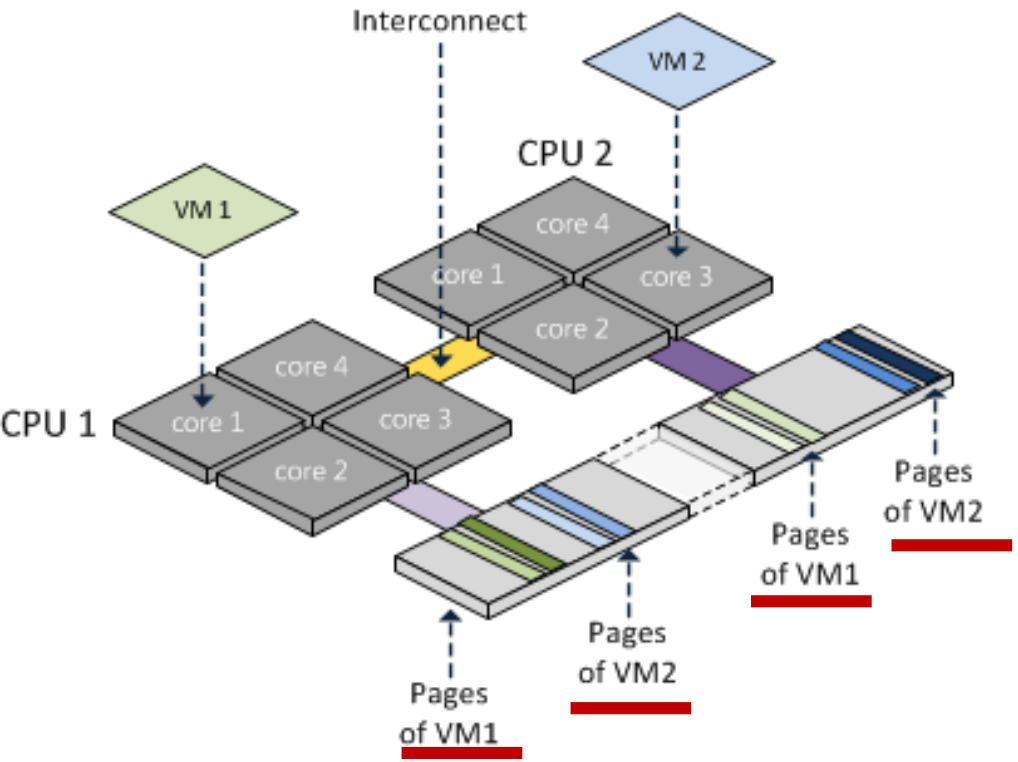


http://frankdenneman.nl/2016/07/07/numa-deep-dive-part-1-uma-numa/

참고자료

UMA

- Virtual machine usage



2 VM on UMA Structure

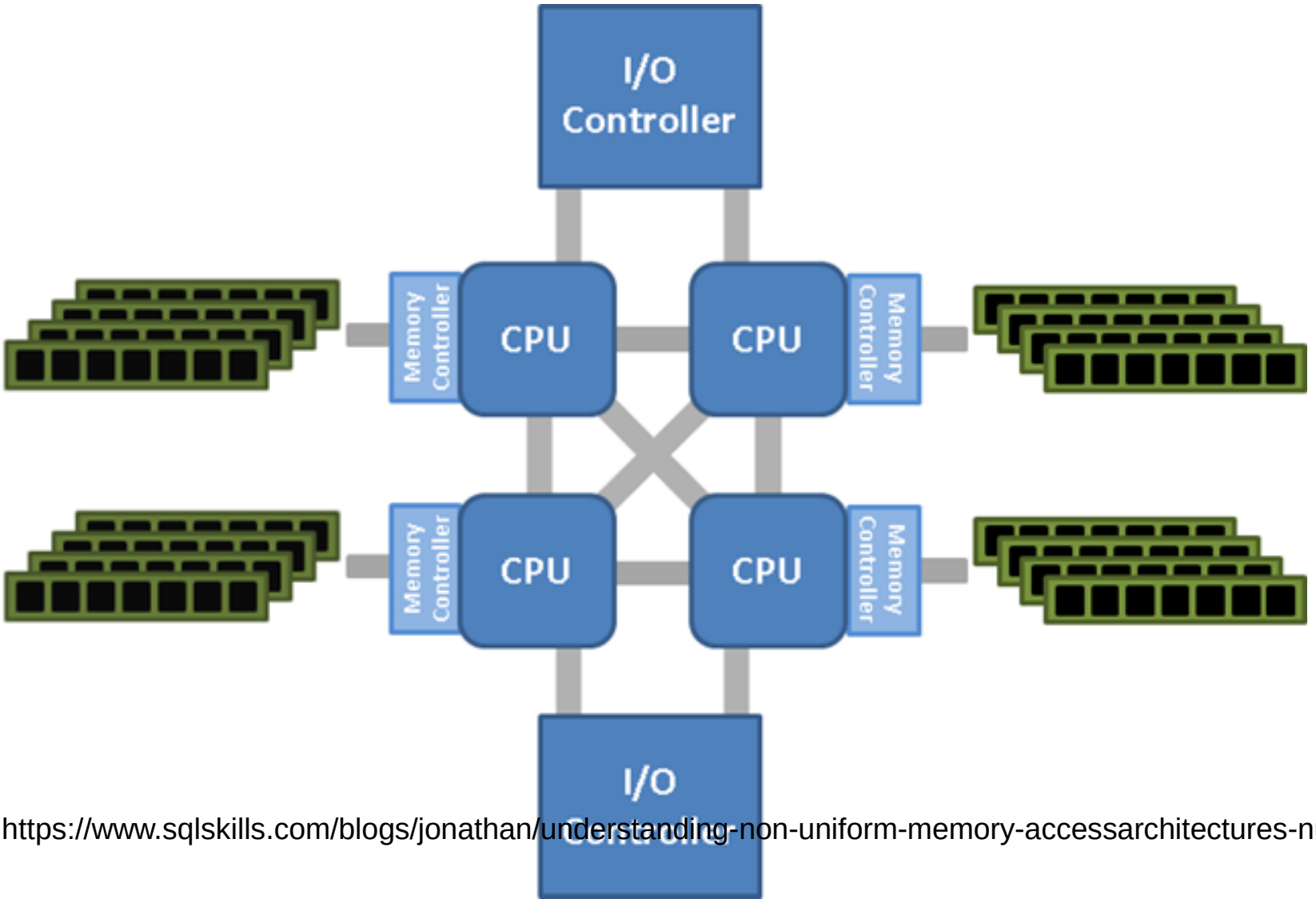
Vm1과 VM2가 각각 다른 CPU에 존재하나 메모리는 하나를 사용하므로 두 VM이 동시에 메모리를 접근하려면 한쪽이 기다려야 함

http://frankdenneman.nl/2015/02/27/memory-deep-dive-numa-data-locality/

참고자료

NUMA Structure (Non Uniform Memory Access)

- Each CPU reserves its' own Memory & Controller

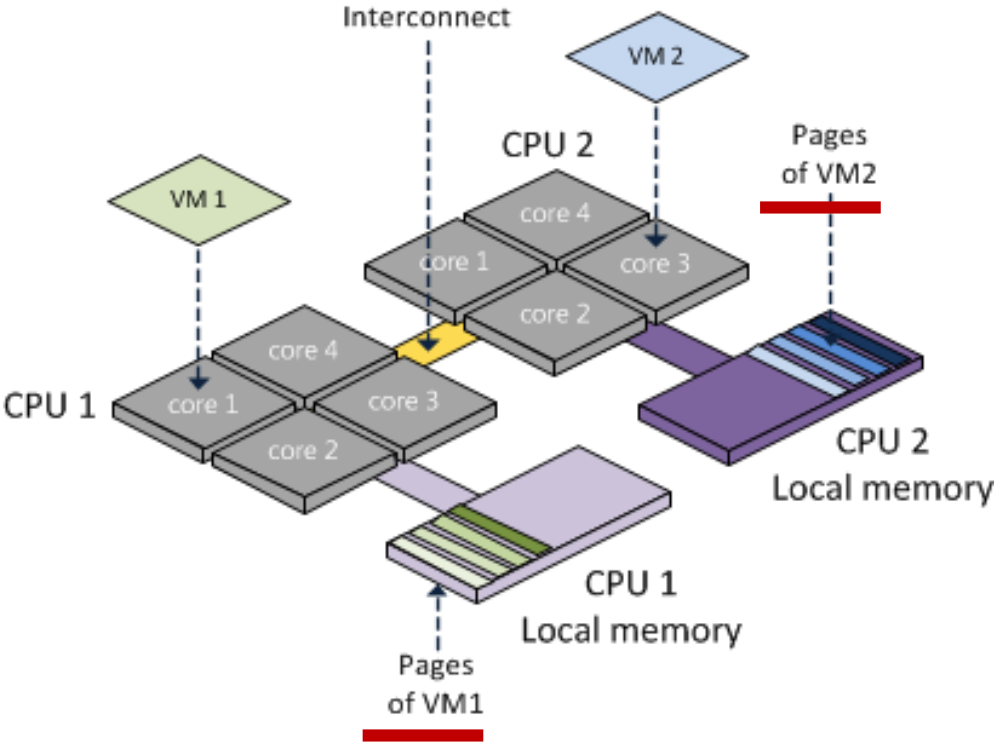


https://www.sqlskills.com/blogs/jonathan/understanding-non-uniform-memory-accessarchitectures-numa/

참고자료

NUMA

- Virtual machine usage



2 VM on NUMA Structure

각각의 CPU가 각각의 메모리를 가지기 때문에 동시에 서로 메모리를 접근하더라도 동시에 처리가 가능하다.

http://frankdenneman.nl/2015/02/27/memory-deep-dive-numa-data-locality/

Numa C code

참고자료

- Check if NUMA is available
- Bind thread to specific core
- Not always NUMA is better
  - If remote memory access is often

```
#define _GNU_SOURCE
#include <numa.h>
#include <sched.h>
#include <stdio.h>
#include <pthread.h>

int main(int argc, const char **argv)
{
   int num_cpus = numa_num_task_cpus();
   printf("num cpus: %d\n", num_cpus);

   printf("numa available: %d\n", numa_available());
   numa_set_localalloc();

   struct bitmask *bm = numa_bitmask_alloc(num_cpus);
   for (int i=0; i<=numa_max_node(); ++i)
   {
      numa_node_to_cpus(i, bm);
      printf("numa node %d ", i);
      print_bitmask(bm);
      printf(" - %g GiB\n", numa_node_size(i, 0) / (1024.*1024*1024.));
   }
   numa_bitmask_free(bm);

#pragma omp parallel
   {
      assert(omp_get_num_threads() == num_cpus);
      int tid = omp_get_thread_num();

      pin_to_core(tid);
      if(tid == 0)
         x = (char *) numa_alloc_local(array_size);

   }
```

https://github.com/hpc12/lec8-demo/blob/87660fc/numa_test.c

참고자료

NUMA Coding

- UMA coding과 NUMA coding이 특별히 달라지기 보다는 thread를 어느 core에 binding하느냐에 따라 해당 thread는 release 되기 전까지 계속 동일한 core에서 수행

- NUMA를 disable시키는 것이 좋은 경우 (즉 UMA방식이 더 좋은 경우)
- 예를 들어 cpu0에서 main thread를 실행시켜 3개의 thread를 추가로 생성해 각각 cpu 1, cpu 2, cpu 3에 bind했다면, 이 때 3개의 생성된 thread가 main thread의 메모리를 참조할 경우 계속해서 cpu0의 메모리를 참조하게 되어 오버헤드가 발생

- 결론 적으로 CPU Intense작업을 주로 할 경우에는 NUMA가 성능을 더 낼 수 있으나 Application에 따라 memory intensive할 경우 UMA가 더 좋을 수도 있습니다.

Chapter 17: Database System Architectures

- 17.1 Centralized and Client-Server Systems
- 17.2 Server System Architectures
- 17.3 Parallel Systems
- 17.4 Distributed Systems
- 17.5 Network Types

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

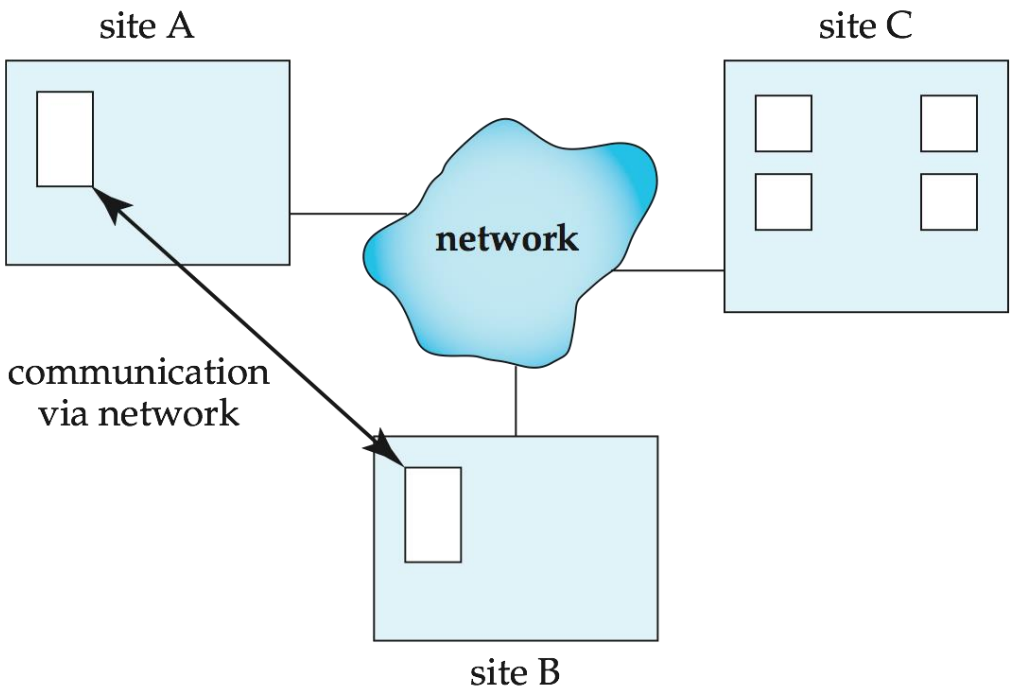


Fig 17.09

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

- Advantages
  - 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
    - Primary site vs Back-up site
- Disadvantages: added complexity for 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 sites
- The two-phase commit protocol (2PC) used to ensure atomicity (Section 19.4.1)
  - 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
  - 2PC is not always appropriate
    - Other transaction models (persistent messaging, workflows), may be used
- Distributed concurrency control (and deadlock detection) required
- Distributed query processing: reducing communication overhead
- Replication of data items required for improving data availability
- Details of above in Chapter 19

Chapter 17: Database System Architectures

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Local-Area Network

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

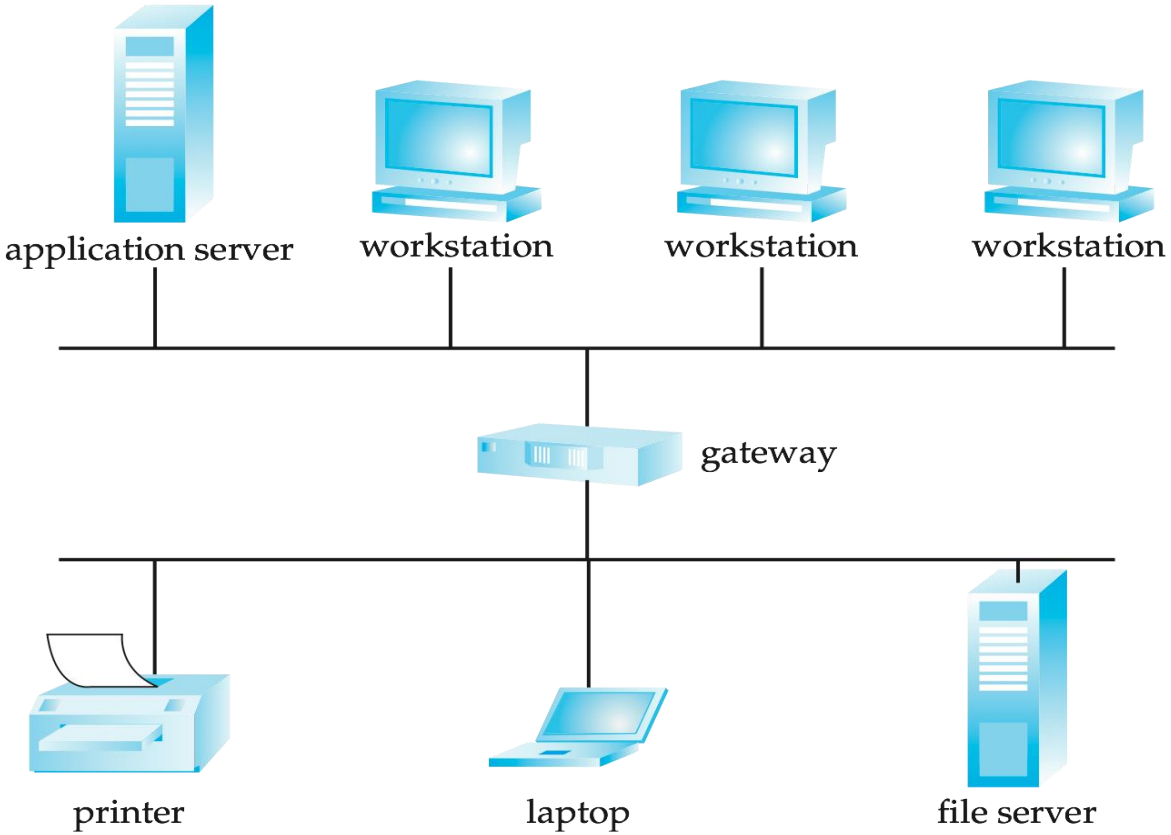
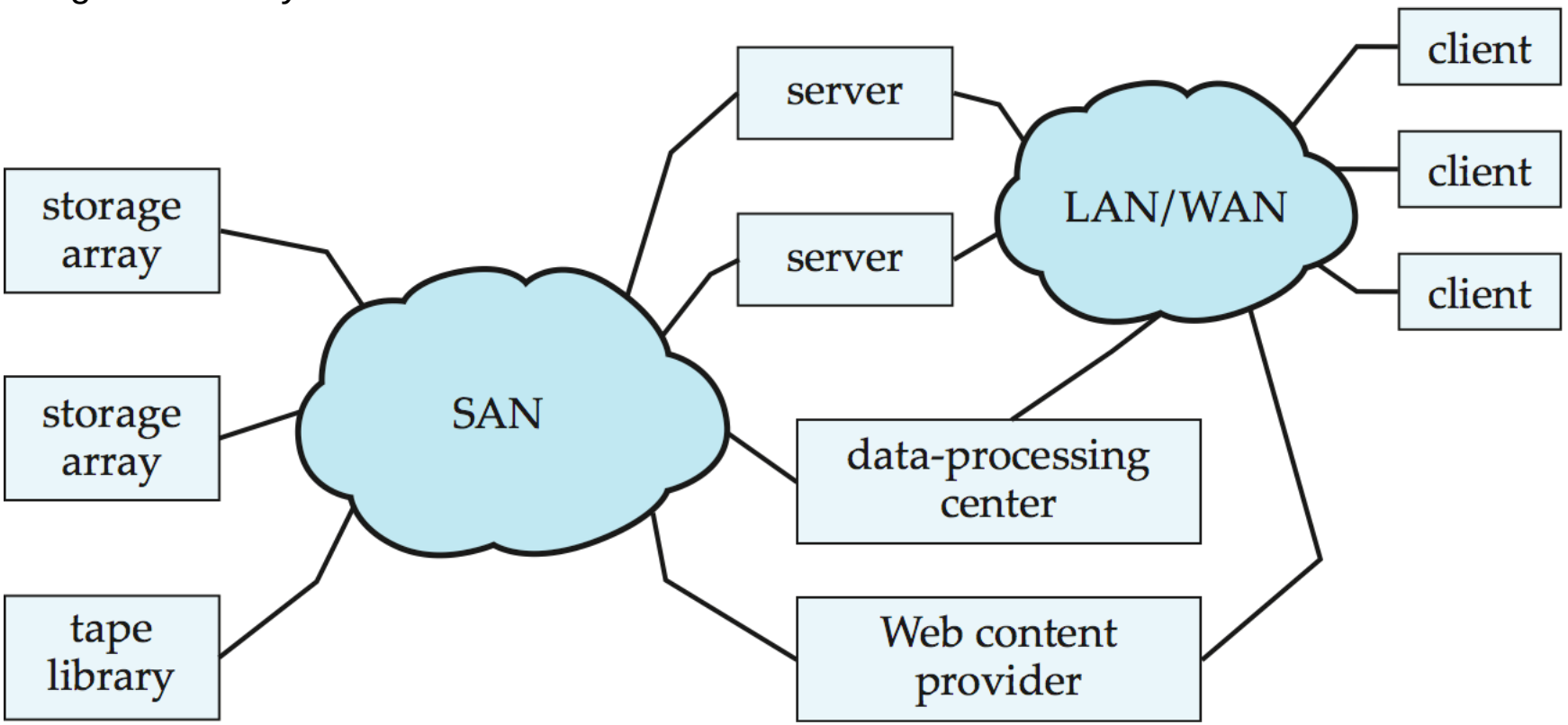


Fig 17.10

Storage-Area Network

- To build large-scale shared-disk systems
  - Scalability by adding more computer
  - High availability

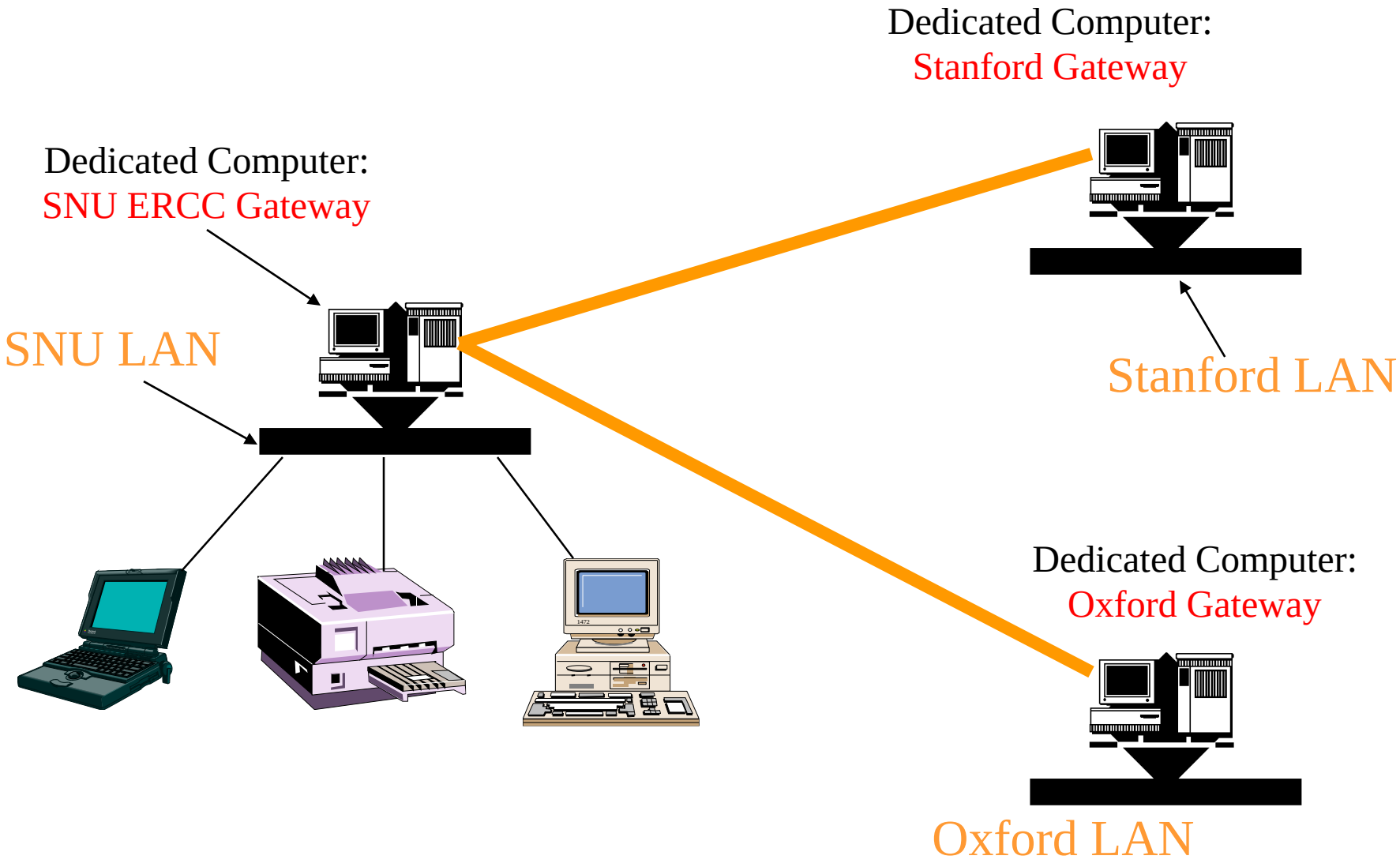


Wide Area Networks

- **Wide-area networks (**WANs) – composed of processors distributed over a large geographical area
  - *Discontinuous Connection* WANs, such as those based on periodic dial-up (e.g. using 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

- WANs with continuous connection are needed for distributed database systems
- WANs with discontinuous connection
  - Mobile wireless connection
  - Earlier groupware applications such as Lotus Notes can work on this
  - Data is replicated, so 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

WAN (Wide Area Network): Example



So What?

- Client-Server System 특징
- Transactional Server, Data Server, Cloud Server의 특징
- Parallel HW의 성질, Distributed Computing 환경의 성질

- Parallel HW의 성질의 이용해서 DBMS 내부에서 어떻게 이용할것인가?
  - Chapter 18

- Distributed Computing 환경을 고려하여 DBMS는 무었을 지원해야 하나?
  - Chapter 19

- Bonus Project (Optional Team Project: 3%)
  - NUMA를 직관적으로 설명하는 PPT
  - 기술현황, 제품현황, Application 개발 현황
  - NUMA위에서 Programming할때의 핵심 issue
  - NUMA위에서 작동하는 DBMS를 만들때의 주요 issue