Parallel and Distributed Databases

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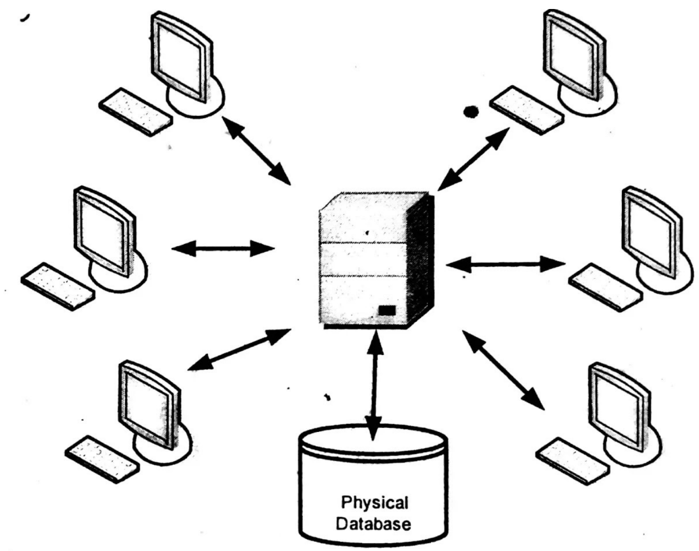
Centralized DBMS

- **Centralized** database (DBMS)
  - Data is located in one place (e.g. server)
  - All DBMS functionalities are done by the server
    - Enforcing ACID properties of transactions
    - Concurrency control, recovery mechanisms
    - Answering queries



Biggest Database Problem

- Large volume of data $\Rightarrow$ use disk and large memory
- **Bottlenecks**
  - Speed(disk) << speed(RAM) << speed(microprocessor)
- Evolution
  - Processor speed growth (with multicore): 50 % per year
  - DRAM capacity growth: 4 × every three years
  - Disk throughput: 2 × in the last ten years
- **Biggest bottleneck: I/O**
- Solution to increase the I/O bandwidth
  - parallel data access
  - data partitioning

Parallel and Distributed DBMS

- **Parallel** database (Parallel DBMS)
  - A "Centralized" DBMS with multiple resources such as CPUs and disks working in parallel.
    - It supports parallel operations such as query processing and data loading.

- **Distributed** databases (DDBMS)
  - Data is stored in multiple places (each is running a DBMS)
  - New notion of distributed transactions
  - DBMS functionalities are now distributed over many machines

Why Parallel Databases?

- Processing 1 Terabyte?
  - at 10MB/s => ~1.2 days to scan
  - 1000 x parallel => 1.5 minute to scan
- **Divide a big problem** into many smaller ones to be solved in parallel
- Data may be stored in a distributed fashion
  - But the distribution is governed solely by **performance** considerations.
- **Large-scale parallel database** systems increasingly used for:
  - Insert/store large volumes of data
  - processing time-consuming decision-support queries
  - providing high throughput for transaction processing

Why Distributed Databases?

- **Scalability**
  - If data volume, read load or write load grows bigger than a single machine can handle, you can potentially **spread the load across multiple machines**.
- **Fault tolerance / High availability**
  - Multiple machines can provide **redundancy**. When one fails, another one can take over.
- **Latency**
  - Applications are by nature distributed. With users around the world, and DB servers at various locations worldwide, **users can be served from a closer datacenter**.

Parallel Databases

- Parallel databases improve processing and I/O speeds by using **multiple CPUs and disks in parallel**
  - data can be partitioned across multiple disks
  - each processor can work independently on its own partition
- Exploit the parallelism in data management to deliver **high-performance**, **high-availability** and **extensibility**
  - support very large databases with very high loads
- Different **queries** can be **run** in **parallel.**

Parallel Databases (cont.)

- **Critical issues**
  - data placement
  - parallel query processing
  - load balancing

- **Research** done in the **context** of the **relational model** provides a good basis for data-based parallelism
  - individual relational operations (e.g., sort, join, aggregation) can be executed in parallel

Parallel vs Distributed Databases

Although the **basic principles** of **parallel DBMS** are the **same** as in **distributed DBMS**, the **techniques are** fairly **different**

typically...

Parallel DB

- Fast interconnect
- Homogeneous software
- High performance is goal
- Transparency is goal

Distributed DB

- Geographically distributed
- Data sharing is goal
- Disconnected operation possible

Parallel vs Distributed Databases

- **Distributed processing can use parallel processing**
  - Parallel processing on a single machine (not the opposite)
- **Parallel** Databases
  - Machines are physically close (e.g. same server room)
  - .. and connects with dedicated high-speed LANs
  - Communication cost is assumed to be small
  - Architecture: can be **shared-memory, shared-disk or shared-nothing**
- **Distributed** Databases
  - Machines can be in distinct geographic locations
  - .. and connected using public-purpose network, e.g., Internet
  - Communication cost and problems cannot be ignored
  - Architecture: usually **shared-nothing**

Parallel DBMS – Main Goals

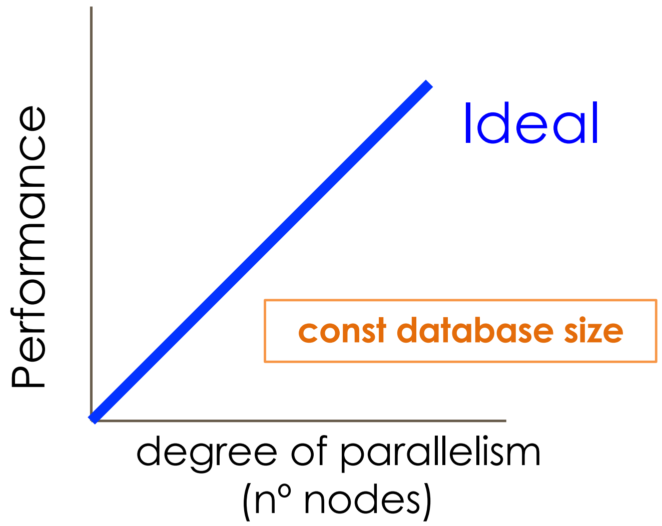
- **High-performance** through parallelization of various operations
  - **High throughput** with inter-query parallelism
  - **Low response time** with intra-operation parallelism
  - **Load balancing** is the ability of the system to divide a given workload equally among all processors

- **High availability** by exploiting data replication

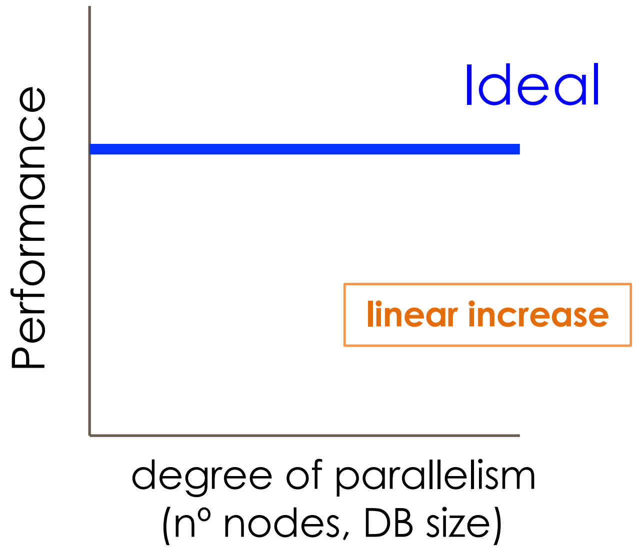
- **Extensibility** with the ideal goals
  - Linear speed-up
  - Linear scale-up

Ideal Extensibility Scenario

- **Speed-Up**
  - refers to a **linear increase** in **performance** for a **constant database size** while the **number of nodes** (i.e. processing and storage power) are **increased linearly**
  - more resources means proportionally less time for given amount of data



- **Scale-Up**
  - refers to a **sustained performance** for a **linear increase** in both **database size** and **number** of **nodes**
  - if resources increased in proportion to increase in data size, time is constant



Barriers to Parallelism

- **Startup**
  - The time needed to start a parallel operation may dominate the actual computation time
- **Interference**
  - When accessing shared resources, each new process slows down the others (hot spot problem)
- **Skew**
  - The response time of a set of parallel processes is the time of the slowest one

➢ Parallel data management techniques intend to overcome these barriers

Database Architectures

… to scale to higher loads:

- **Multiprocessor architecture**
  - Shared memory (SM)
  - Shared disk (SD)
  - Shared nothing (SN)

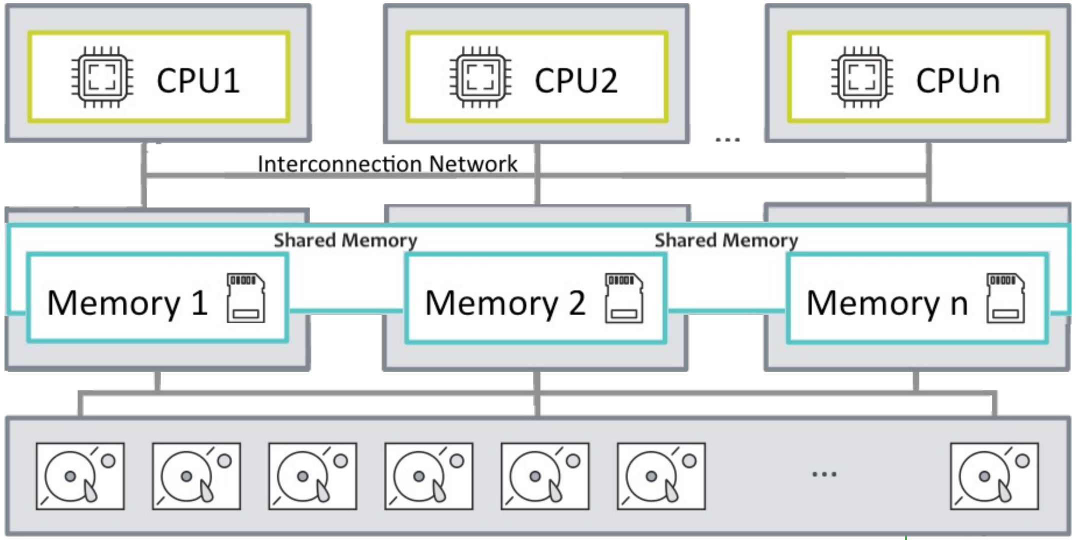
Also called vertical scaling (or scaling up)
Simplest approach - buy a more powerful machine

Aka horizontal scaling (or scaling out)

- **Hybrid architectures**
  - Non-Uniform Memory Architecture (NUMA)
  - Cluster (or hierarchical)

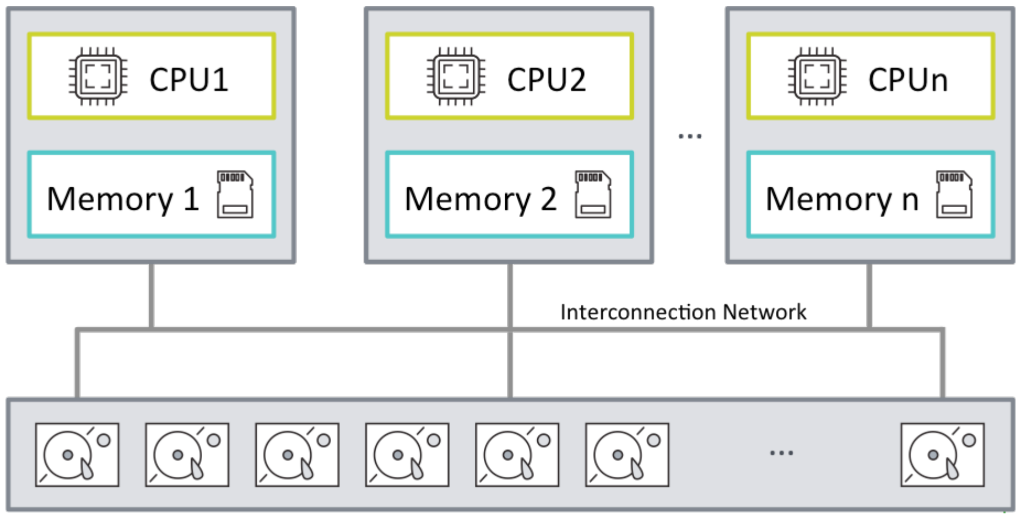
Shared Memory

- Multiple processors share the main memory (RAM) space, but each processor has its own disk (HDD)
  - provide communications among them and avoid redundant copies
- **Bottlenecks**
  - cost is super-linear: a machine with twice resources (CPU, RAM, disk) typically costs significantly more than twice
  - a machine twice the size cannot necessarily handle twice the load
  - limited fault tolerance



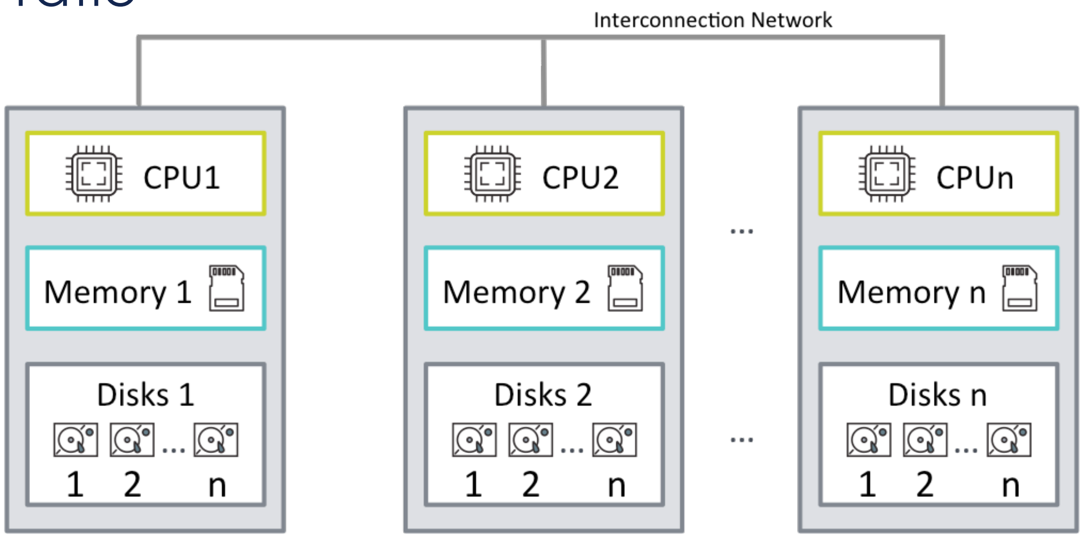
Shared Disk

- Uses several machines with independent CPUs and RAM, but **stores data on an array of disks** that is shared between the machines, connected via a fast network
- Used for some data warehousing workloads
- **Advantages** over shared memory
  - each processor has its own memory - is not a bottleneck
  - a simple way to provide a degree of fault tolerance.
- **Disadvantages**
  - I/O contention
  - limited scalability



Shared Nothing

- Each machine running the database software (**node**) uses its CPUs, RAM and disks independently
- Any coordination between nodes is done at the software level, using a conventional network
- Most common architecture nowadays
- **Advantages**:
  - best price/performance ratio
  - extensibility
  - availability
  - reduce latency
- **Disadvantages**:
  - complexity
  - difficult load balancing



Hybrid Architectures

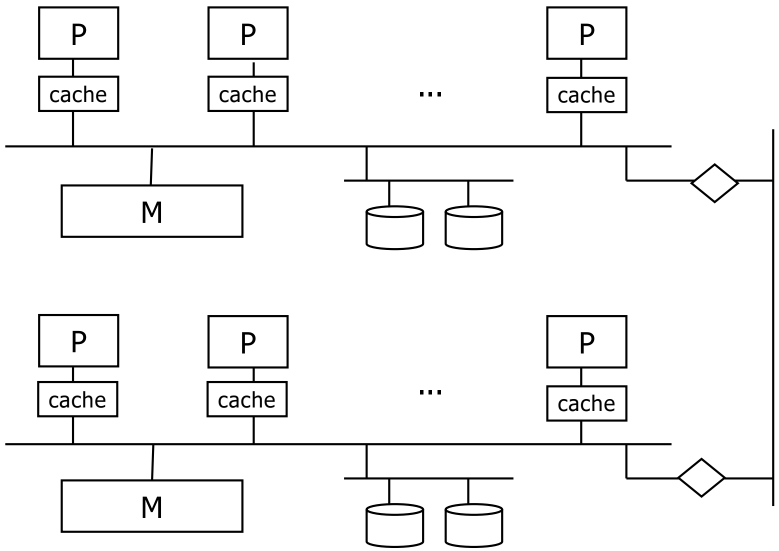
- Various possible **combinations** of the three basic architectures are possible
  - to obtain different **trade-offs** between **cost**, **performance**, **extensibility**, **availability**, etc.
- Hybrid architectures try to obtain the **advantages of different architectures**:
  - **efficiency** and **simplicity** of **shared-memory**
  - **extensibility** and **cost** of either **shared disk** or **shared nothing**
- Two main types:
  - NUMA (*non-uniform memory access*)
  - Cluster

NUMA (non-uniform memory access)

- Shared Memory vs. Distributed Memory
  - mixes two different aspects:
    - addressing: single address space *and* multiple address spaces
    - physical memory: central *and* distributed
- NUMA uses **single address space on distributed physical memory**
  - eases application portability
  - extensibility
- Cache Coherent NUMA (CC-NUMA)
  - the most successful

CC-NUMA

- Principle: main **memory distributed** as with shared-nothing. However, any **processor has access to all other processors**' memories
  - remote memory access very efficient, only a few times (typically between 2 and 3 times) the cost of local access
- Different processors can access the same data in a conflicting update mode
  - a global cache consistency protocols are needed



Parallel & Distributed DBMS Techniques

- **Data placement**
  - Physical placement of the DB into multiple nodes
  - Static vs. Dynamic
- **Parallel data processing algorithms**
  - Select is easy
  - Join (and all other non-select operations) is more difficult
- **Parallel query optimization**
  - Choice of the best parallel execution plans
  - Automatic parallelization of the queries and load balancing
- **Distributed Transaction management**

Distributed Data Storage

Two common ways of distribute data across nodes:

- **Partitioning**
  - splitting a big database into smaller subsets called partitions
  - different partitions can be assigned to different nodes
- **Replication**
  - keeping a copy of the same data on several different nodes; potentially in different locations
  - provides redundancy; if some nodes are unavailable, the data can still be served from the remaining nodes
  - can also help improve performance
- Replication and Partitioning can be combined

Data Transparency

- Transparency means that the DBMS hides all the added complexities of distribution
  - allowing users to think that they are working with a single centralised system.

- Consider transparency issues in relation to:
  - Replication mechanism
  - Partitioning mechanism
  - Location

I/O Parallelism

- In horizontal partitioning, tuples of a relation are divided among many disks

Partitioning techniques (number of disks = n):

- **Round-robin**
  - send the i^{th} tuple inserted in the relation to the disk: i mod n.
- **Hash partitioning**
  - apply a hash function to one or more attributes that range 0…n - 1
- **Range partitioning**
  - associates a range of key attribute(s) to every partition

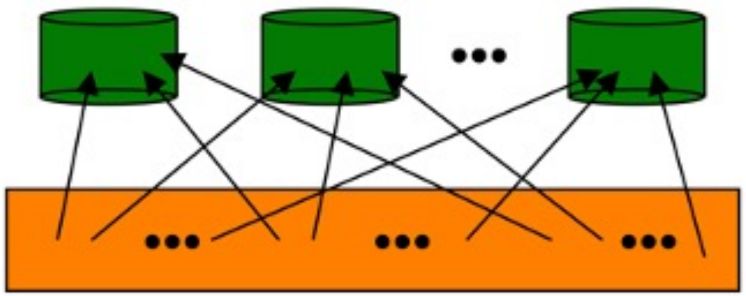
Comparison of Partitioning Techniques

- Evaluate how well partitioning techniques support the following types of data access:
  - Scanning the entire relation.
  - Locating a tuple associatively – point queries.
    - E.g., r.A = 25.
  - Locating all tuples such that the value of a given attribute lies within a specified range – range queries.
    - E.g., $10 \leq r.A < 25$.

	Round Robin	Hashing	Range
Sequential Scan	Best/good parallelism	Good	Good
Point Query	Difficult	Good for hash key	Good for range vector
Range Query	Difficult	Difficult	Good for range vector

Round robin

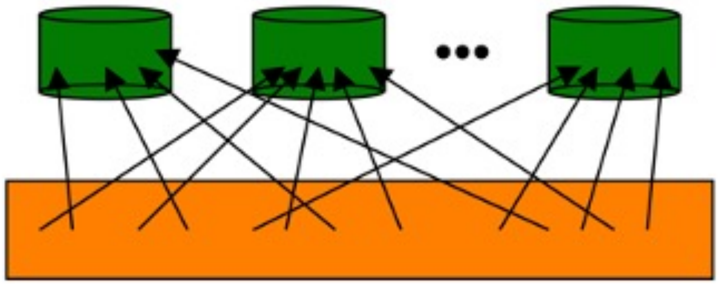
- Advantages
  - Best suited for sequential scan of entire relation on each query.
  - All disks have almost an equal number of tuples; retrieval work is thus well balanced between disks.
- Location and Range queries are difficult to process
  - No clustering – tuples are scattered across all disks



Round-Robin

Hash partitioning

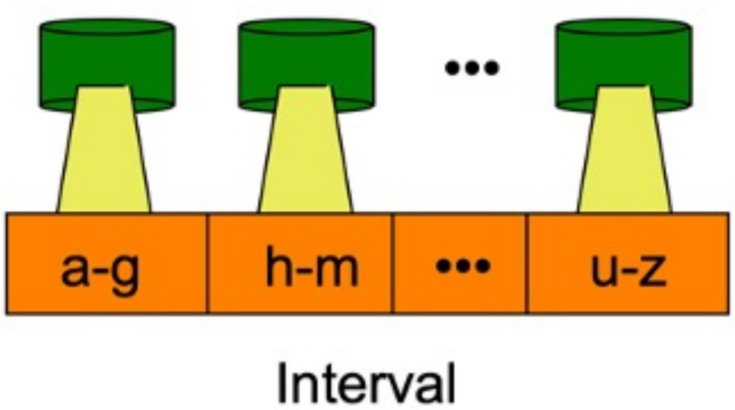
- Good for sequential access
  - Assuming hash function is good, and partitioning attributes form a key, tuples will be equally distributed between disks
  - Retrieval work is then well balanced between disks.
- Good for point queries on partitioning attribute
  - Can lookup single disk, leaving others available for answering other queries.
  - Index on partitioning attribute can be local to disk, making lookup and update more efficient
- No clustering, so difficult to answer range queries



Hashing

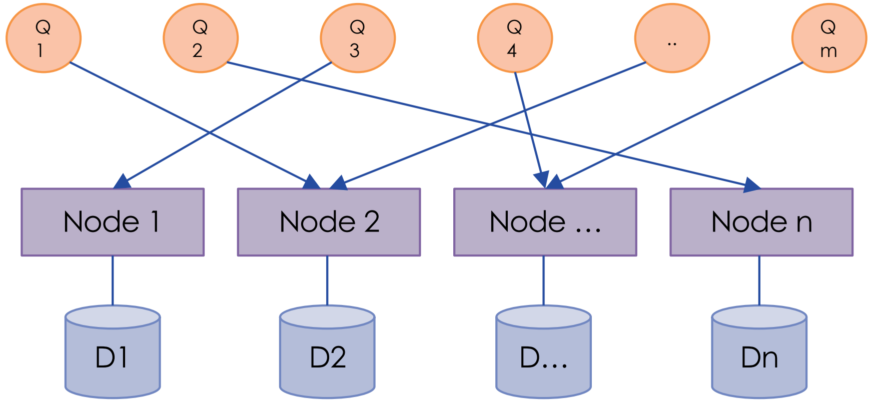
Range partitioning

- Good for sequential access
- Provides data clustering by partitioning attribute value.
- Good for point queries on partitioning attribute: only one disk needs to be accessed.
- For range queries on partitioning attribute, one to a few disks may need to be accessed
  - Remaining disks are available for other queries.
  - Good if result tuples are from one to a few blocks.

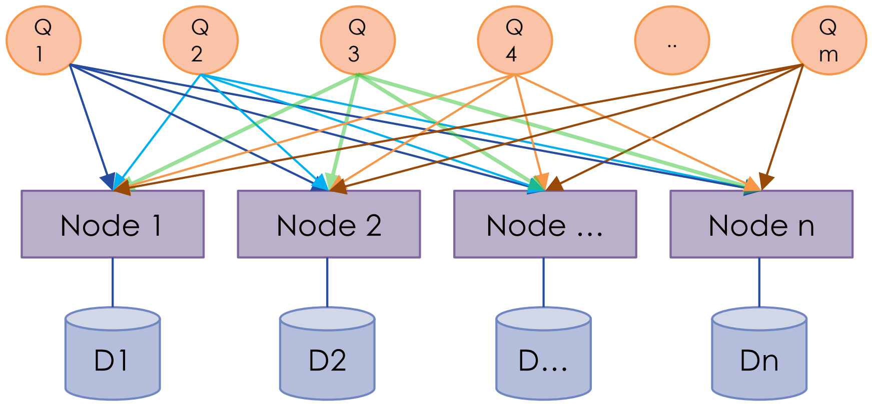


Query Parallelism

- **Interquery** Parallelism
  - Parallel execution of multiple queries generated by concurrent transactions



- **Intraquery** Parallelism
  - Split the execution of a single query in parallel on multiple nodes



Interquery Parallelism

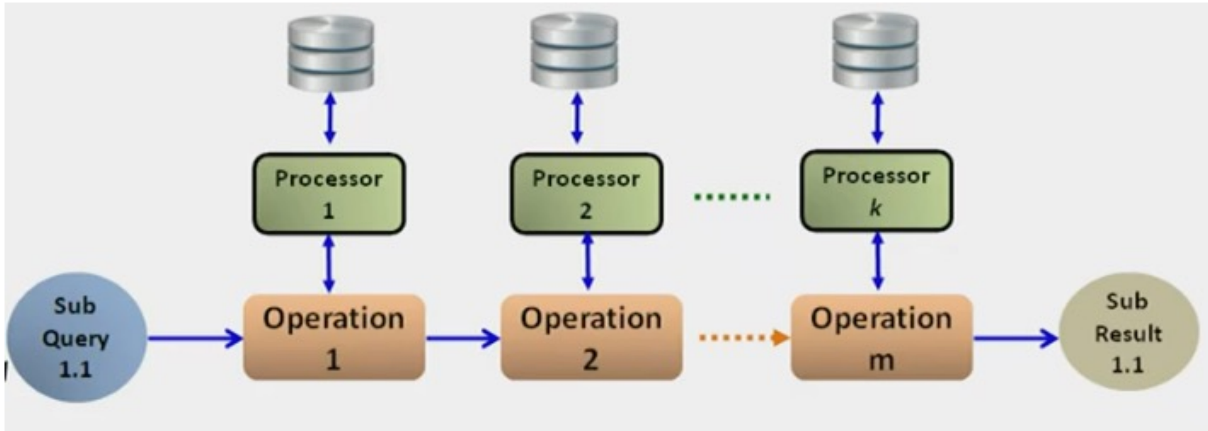
- To **increase** the **transactional throughput**
  - used primarily to scale up a transaction processing system to support a **larger number of transactions per second**
- **Easiest** form of parallelism to support
  - particularly in a **shared-memory** parallel database
- More **complicated** on **shared-disk** or **shared-nothing**
  - locking and logging must be coordinated by passing messages between processors
  - data in a local buffer may have been updated at another processor
  - cache-coherency has to be maintained: reads and writes of data in buffer must find latest version of data

Intraquery Parallelism

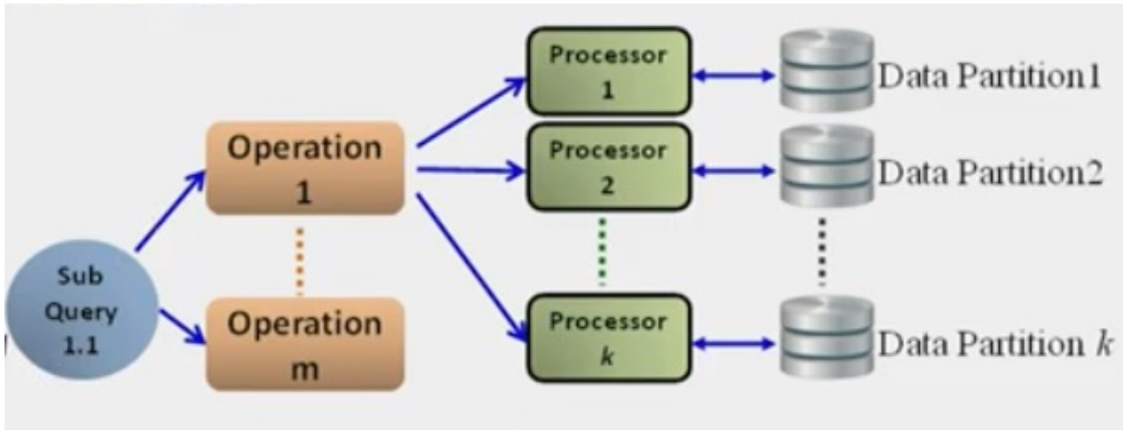
- The **same query** is **executed** by **many processors**, **each** one **working** on a **subset** of the **data**
  - for speeding up long-running queries
- Two complementary forms of intraquery parallelism:
  - **Intra-operation**:
    - break up a query into multiple parts within a single database partition and execute these parts at the same time.
  - **Inter-operation**:
    - break up a query into multiple parts across multiple partitions of a partitioned database on a single server or between multiple servers
- Intra-operation scales better with increasing parallelism because the number of tuples processed by each operation is typically more than the number of operations in a query

Intraquery Operator Parallelism

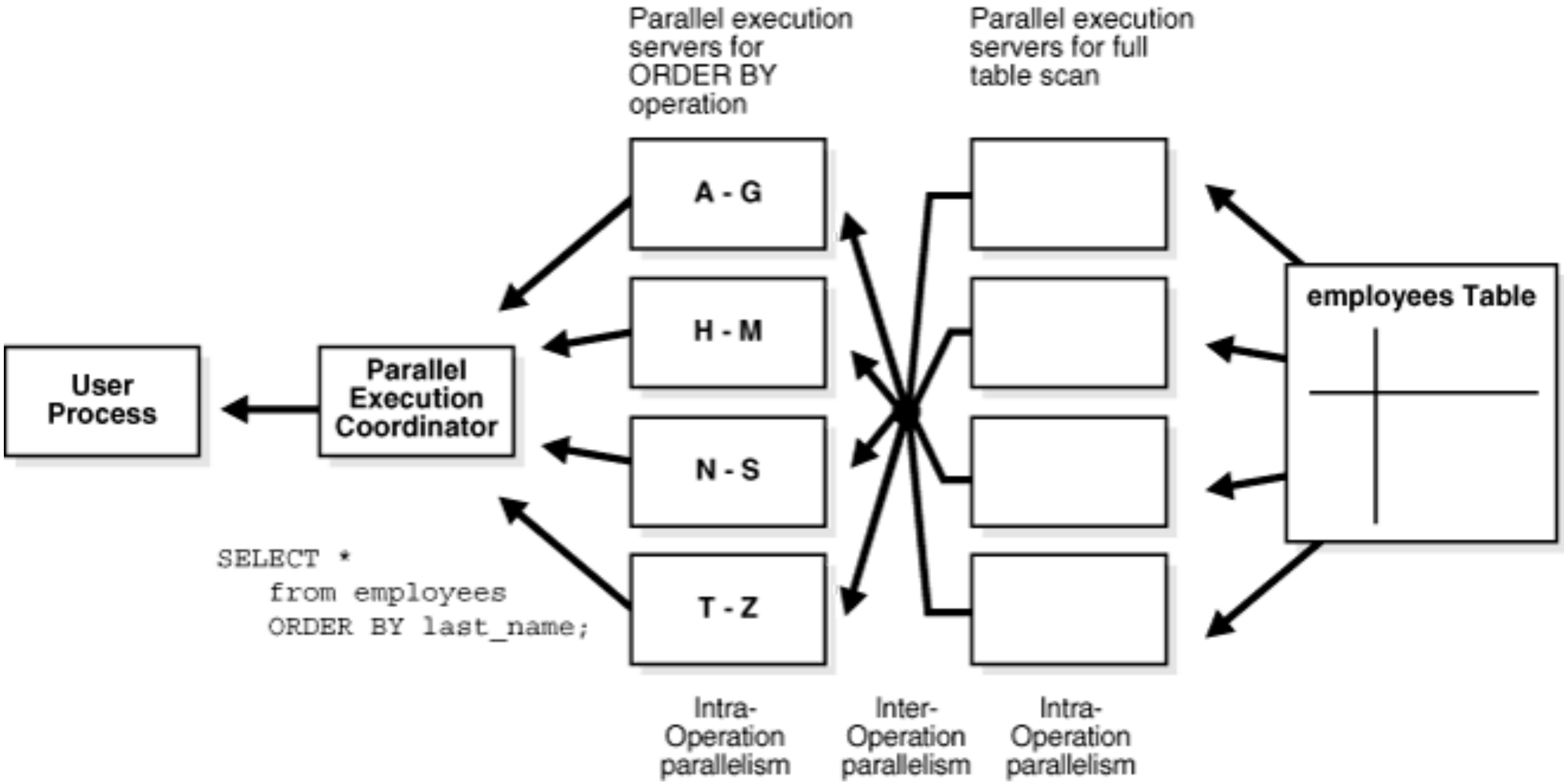
- **Inter-operator** (Pipeline): ordered (or partially ordered) tasks and **different machines** are **performing different tasks**



- **Intra-operator** (Partitioned): a **task divided** over all machines to **run in parallel**



Intraquery Parallelism



Parallel Data Processing

The following discussion assumes:

- **Read-only** queries
- **Shared-nothing** architecture
  - shared-nothing architectures can be efficiently simulated on shared-memory and shared-disk systems
- ***n* processors** (P_0, ..., P_{n-1}) and n disks (D_0, ..., D_{n-1}) where disk D_i is associated with processor P_i
  - if a processor has multiple disks they can simply simulate a single disk D_i

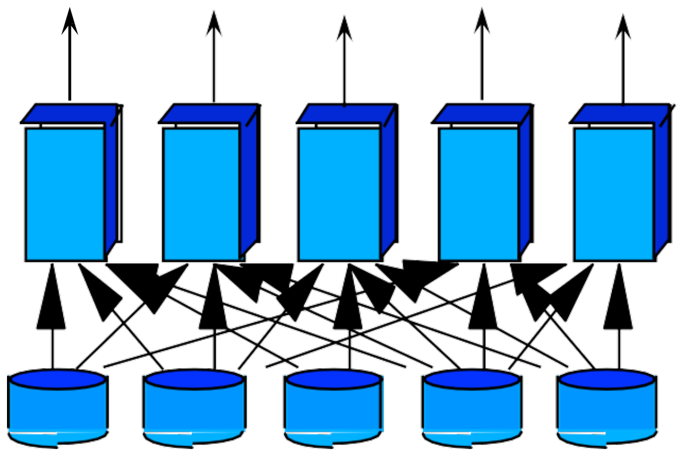
- We will focus on **select, sort** and **join** operators
  - other binary operators (such as union) can be handled in similar way to join

Parallel Selection - $\sigma_c(R)$

- Relation **R** is **partitioned** over **m machines**
  – each partition of R is around |R|/m tuples
- **Each machine scans** its own **partition** and applies the **Selection** condition **c**
- Data Partitioning impact:
  – **round robin** or a **hash function** (over the entire tuple)
    • relation is expected to be well distributed over all nodes
    ➢ **all partitions will be scanned**
  – **range** or hash-based (on the selection column)
    • relation can be clustered on few nodes
    ➢ **few partitions need to be touched**

Parallel Sorting

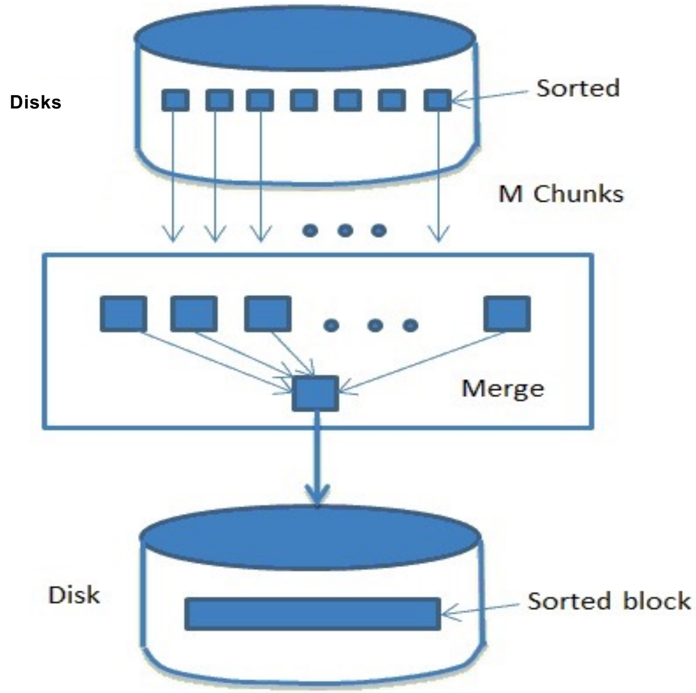
1. **Range-Partitioning Sort**
   - **Choose processors** $P_0, \ldots, P_m$, where $m \leq n - 1$ **to do sorting**
   - **Re-partition R based on ranges (on the sorting attributes) into m partitions**
     - this step **requires I/O** and **communication overhead**
   - Machine *i* receives all *i*^th^ partitions from all machines and sort that partition, without any interaction with the others
     - P_i stores the tuples it received temporarily on disk D_i
   - **Final merge** operation is trivial
     - range-partitioning ensures that, for $i < j < m$, the key values in processor P_i are all less than the key values in P_j
   - Skewed data is an issue
     - ranges can be of different width
     - apply sampling phase first



Parallel Sorting (Cont.)

2. Parallel External Sort-Merge

- Assume the relation has already been partitioned among disks D_0, ..., D_{n-1} (in whatever manner).
- **Each node sorts its own data**
- **All nodes** start **sending** their **sorted data** (one block at a time) to a **single machine**
- This **machine** applies **merge-sort** technique as data come



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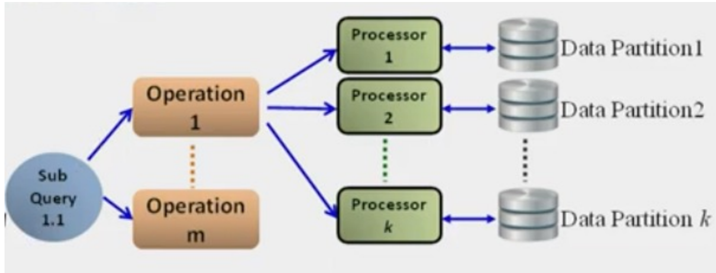
Parallel Join

- The join operation **requires pairs** of **tuples** to be **tested** to see if they satisfy the join condition
  - If tuples satisfy the join condition, the pair is added to the join output
- Steps…

1. **Parallel join algorithms** attempt to **split the pairs-testing** over **several processors**
2. **Each processor** then **computes part** of the **join** locally
3. **Results** from each processor are **collected** together to **produce** the **final result**

Join Algorithms

- Three basic parallel join algorithms for partitioned databases
  - **Parallel Nested Loop** (PNL)
  - **Parallel Associative Join** (PAJ)
  - **Parallel Hash Join** (PHJ)

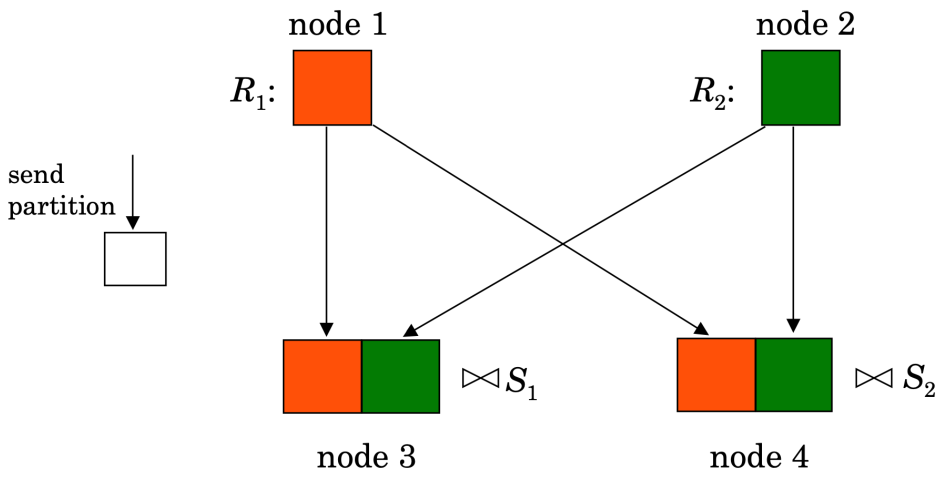


- All previous **algorithms** are **intra-operator parallelism**
- They also apply to other complex operators such as duplicate elimination, union, intersection, etc. with minor adaptation

- Next Examples:
  - join of two **relations *R*** and ***S*** that are partitioned over ***m*** and ***n* nodes**, respectively.

Parallel Nested Loop Join

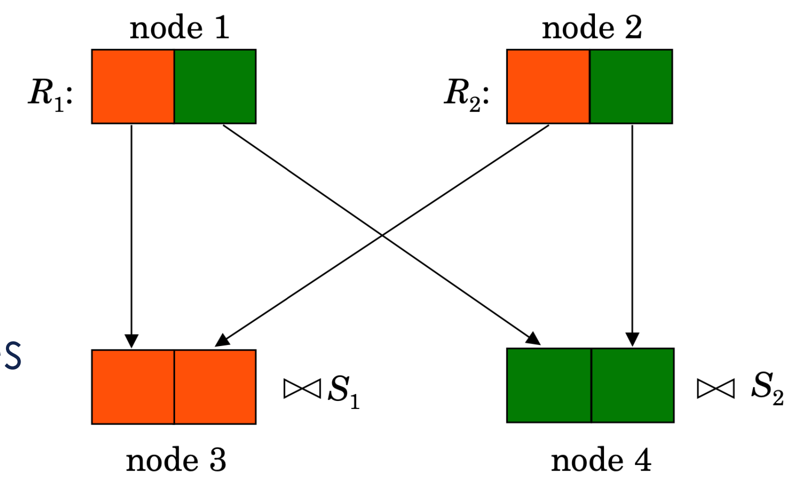
- **Cartesian product** *R* x *S* of relations ***R*** and ***S,*** in parallel.
  - **Simplest** and most **general** method
- **Algorithm phases**:
  1. each fragment of *R* (outer relation) is send and compared to each fragment of *S* (inner relation)
     - this phase is done in parallel by *m* nodes
  2. each *S*-node *j* receives relation *R* entirely, and locally joins *R* with fragment *Sj*.
     - join processing may start as soon as data are received
- **Optimization**:
  - R **<<** S
  - If S has **index** on the **join attribute** at each partition, this is fast



$$R \bowtie S \rightarrow \cup_{i=1,n}(R \bowtie S_i)$$

Parallel Associative Join

- Applies **only** to **equijoin** with **one** of the **operand relations partitioned** according to the **join attribute**
- Assume
  - **equijoin** predicate is on **attribute *A*** from ***R***, and ***B*** from ***S***
  - ***S*** *is* **partitioned** according to **hash function applied** to attribute ***B***
    - tuples of *S* that have the same *h*(*B*) value are placed at the same node
  - **no knowledge** of how ***R*** is **partitioned**
- Algorithm phases:
  1. relation ***R*** is **sent** associatively to the ***S*-nodes based** on the **hash function** *h* applied to **attribute *A***
  2. **each *S*-node *j* receives** in parallel from the different *R*-nodes the relevant subset of *R* (i.e., *Rj*) and **joins** it **locally** with the fragments *Sj*

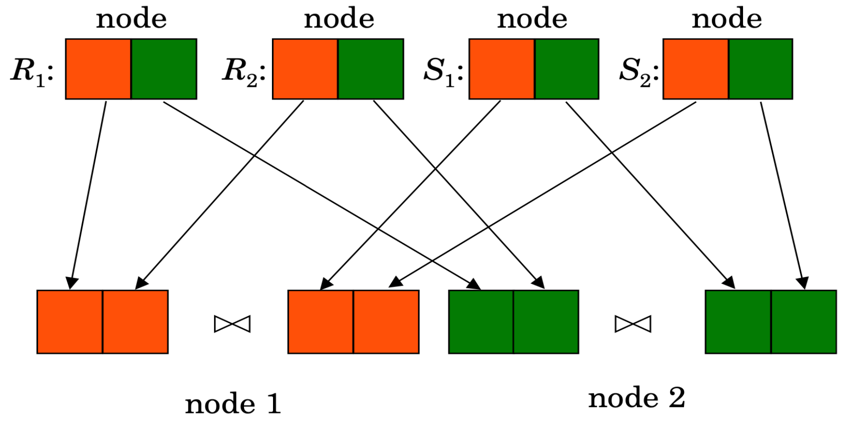


$$R \bowtie S \rightarrow \cup_{i=1,n}(R_i \bowtie S_i)$$

Parallel Hash Join

- Generalization of parallel associative join algorithm
  - Does not require any specific partitioning of the operand relations
- **Basic idea**:
  - **partition** of ***R*** and ***S*** into the same number distinct ***p* fragments**
    - *R1,R2,...,Rp*, and *S1,S2,...,Sp*,
  - The ***p* nodes** may be **selected** at **run time** based on the load of the system
- **Algorithm phases**:
  1. *build*: **hashes *R*** on the **join attribute**, **sends** it to the **target *p* nodes** that build a hash table for the incoming tuples
  2. probe: **sends *S* associatively** to the **target *p* nodes** that probe the hash table for each incoming tuple
  3. join each p node and merge all

$$R \bowtie S = \bigcup_{i=1}^{p} (R_i \bowtie S_i)$$



Parallel Processing - Costs

- **Join processing** is achieved with a degree of parallelism of **n processors**/nodes
  - each algorithm **requires moving** at least **one** of the operand **relations** (R or S)
- **Ideal scenario**: no skew in the Pi, and no overhead due to the parallel evaluation
  - **expected speed-up: 1/n**
- But considering skew and overheads, the time taken by a parallel operation can be estimated as:
  - $T_{cost} = T_{part} + T_{asm} + \max(T_0, T_1, \ldots, T_{n-1})$
    - T_{part} - time for partitioning the relations (including communications costs)
    - T_{asm} - time for assembling the results
    - T_i - time taken for the operation at processor P_i. This needs to be estimated taking into account the skew, and the time wasted in contentions

Parallel Query Optimization

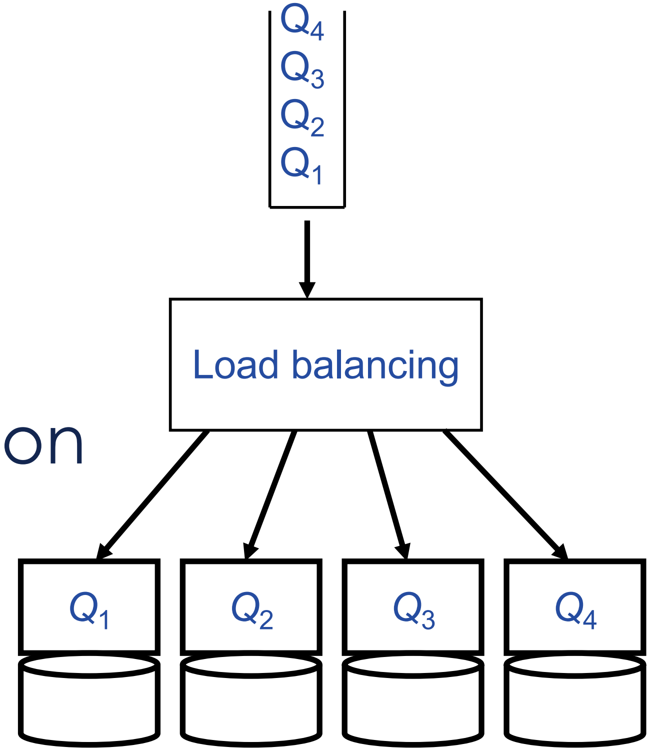
- The **objective** is to **select the "best" parallel execution plan** for a query using the following components:
  - Search space
    - Alternative model execution plans as operator trees
    - Left-deep vs. Right-deep vs. Bushy trees
  - Search strategy
    - Dynamic programming for small search space
    - Randomized for large search space
  - Cost model (abstraction of execution system)
    - Physical schema info. (partitioning, indexes, etc.)
    - Statistics and cost functions
- **Target**: **minimize** the **movement of data** among machines

Load Balancing

- **Balancing** the **load** of **different transactions** and **queries among different nodes** is essential to **maximize throughput**
- **Problems** arise for **intra-operator parallelism** with ***skewed* data distributions**
  - attribute data skew (AVS)
    - inherent to dataset (e.g., there are more citizens in Paris than in Aveiro).
  - tuple placement skew (TPS)
    - introduced when the data are initially partitioned (e.g., with range partitioning)
  - selectivity skew (SS)
    - introduced when there is variation in the selectivity of select predicates on each node
  - redistribution skew (RS)
    - occurs in the redistribution step between two operators (similar to TPS)
  - join product skew (JPS)
    - occurs because the join selectivity may vary between nodes
- **Solutions**
  - sophisticated parallel algorithms that deal with skew
  - dynamic processor allocation (at execution time)

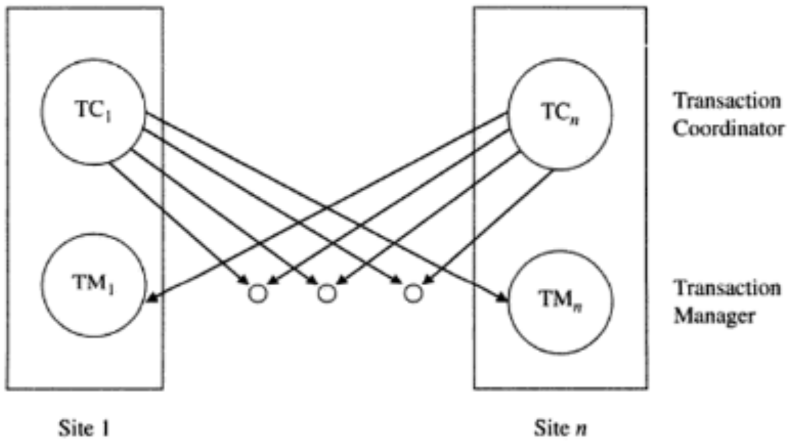
Load Balancing in a DB Cluster

- Choose the node to execute Q_i
  - round robin
  - the least loaded
    - need to get load information
- Failover
  - If the N node fails, N's queries are assumed by other node
- In case of interference/contention
  - data of an overloaded node are replicated to another node



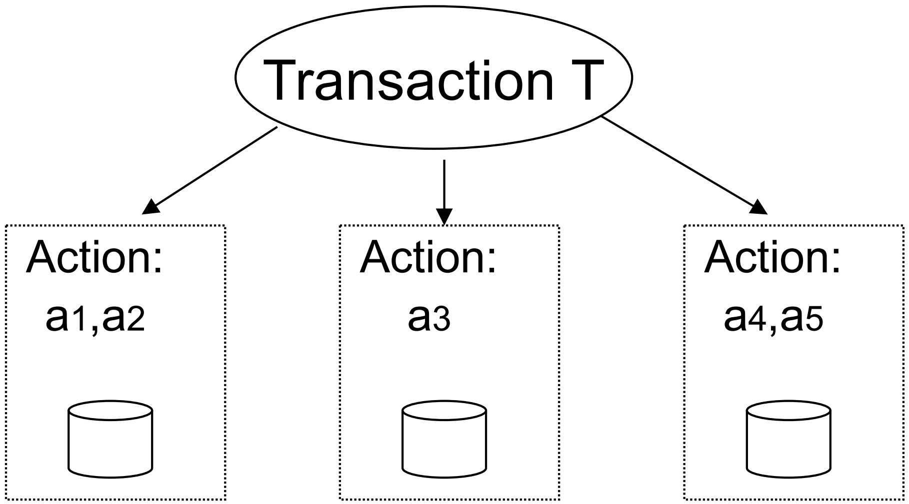
Distributed Transactions

- Transaction may access data at several sites
- Each site has a **transaction coordinator** for:
  - **starting** the execution of every transactions at that site
  - **Breaking transaction and distributing** sub-transactions
  - coordinating the **termination** of each transaction
    - may result in the transaction being committed or aborted at all sites
- Each site has a **transaction manager** responsible for:
  - maintaining a log for recovery purposes
  - coordinating the concurrent execution of the transactions executing at that site



Distributed commit problem

- **Commit** must be **atomic**…
- How a distributed transaction that has components at several sites can execute atomically?

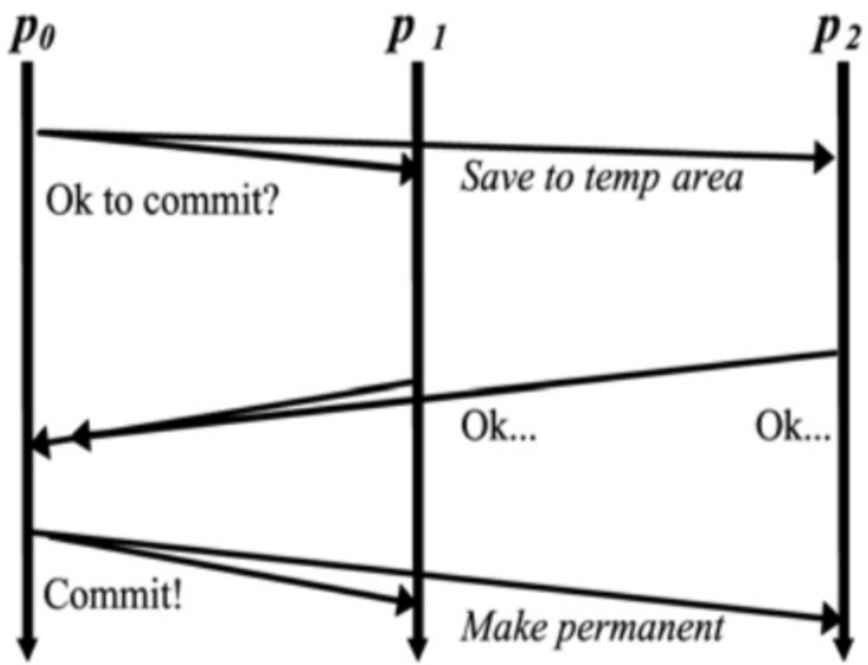


- **Solution**: Two-phase commit (2PC), Centralized 2PC, Distributed 2PC, Linear 2PC, etc.

Example: Two-phase commit protocol

- **First phase** - **coordinator collecting a vote** (commit or abort) **from each participant**
  - Participant stores partial results in permanent storage before voting
- **Second phase** - **coordinator** makes a **decision**
  - **if** all participants want to commit and no one has crashed, coordinator multicasts "commit" message
    - everyone commits
    - if participant fails, then on recovery, can get commit msg from coordinator
  - **else** if any participant has crashed or aborted, coordinator multicasts "abort" message to all participants
    - everyone aborts

Two-phase commit protocol



Coordinator :
- multicast: *ok to commit?*
- collect replies
  - all *ok* => *send commit*
  - else => *send abort*

Participant:
- *ok to commit* =>
  - save to temp area, reply *ok*
- *commit* =>
  - make change permanent
- *abort* =>
  - delete temp area

Summary

- Centralized vs Distributed vs Parallelized Systems

- Parallel Databases
  - Concept / Objectives
  - Architectures
  - Types of Parallelism
  - DBMS Techniques
    - Data Placement
    - Processing Algorithms
    - Query Optimization
    - Transaction Management

Resources

- Martin Kleppmann, ***Designing Data-Intensive Applications***, O'Reilly Media, Inc., 2017.

- M. Tamer Ozsu, Patrick Valduriez, **Principles Of Distributed Database Systems** – 3rd ed, Springer, 2011.

- Abraham Silberschatz, Henry F. Korth, S. Sudarshan, **Database System Concepts –** 6th ed**,** McGraw-Hill, 2010.