# Non-Standard Database Systems

## Parallel Databases

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# Outline







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# Introduction

- Parallel machines are becoming quite common and affordable
  - Prices of microprocessors, memory, and disks have dropped sharply
  - Recent desktop computers feature multiple processors and this trend is projected to accelerate
- Databases are growing increasingly large
  - large volumes of transaction data are collected and stored for later analysis.
  - multimedia objects like images are increasingly stored in databases
- Large-scale parallel database systems increasingly used for:
  - storing large volumes of data
  - processing time-consuming decision-support queries
  - providing high throughput for transaction processing

## Parallelism in Databases

- Data can be partitioned across multiple disks for parallel I/O.
- Individual relational operations (e.g., sort, join, aggregation) can be executed in parallel
  - each processor can work independently on its own data partition
- Queries are expressed in high level language (SQL, translated to relational algebra)
  - makes parallelization easier
- Different queries can be run in parallel with each other. Concurrency control takes care of conflicts.
- Thus, databases naturally lend themselves to parallelism.





## I/O Parallelism/1

- Reduce the time required to retrieve relations from disk by partitioning the relations on multiple disks.
- Horizontal partitioning — tuples of a relation are divided among many disks such that each tuple resides on one disk.
- Partitioning techniques (number of disks $= n$):
  - Round-robin:
    - Send the $I^{th}$ tuple inserted in the relation to disk $i$ *modn*.
  - Hash partitioning:
    - Choose one or more attributes as the partitioning attributes.
    - Choose hash function h with range $0 \ldots n-1$
    - Let $i$ denote result of hash function $h$ applied to the partitioning attribute value of a tuple. Send tuple to *disk* $i$.





## I/O Parallelism/2

- Range partitioning
  - Choose an attribute as the partitioning attribute.
  - A partitioning vector $[v_0, v_1, \ldots, v_{n-2}]$ is chosen.
  - Partitioning: Let $v$ be the partitioning attribute value of a tuple. Tuples such that $v_i \leq v_{i+1}$ go to *disk* $i+1$. Tuples with $v < v_0$ go to *disk* 0 and tuples with $v \geq v_{n-2}$ go to *disk* $n-1$.
  - Example: with a partitioning vector $[5, 11]$, a tuple with partitioning attribute value of 2 will go to disk 0, a tuple with value 8 will go to *disk* 1, while a tuple with value 20 will go to *disk* 2.





## Comparison of Partitioning Techniques/1

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

## Comparison of Partitioning Techniques/2

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.
- Range queries are difficult to process
  - No clustering — tuples are scattered across all disks





## Comparison of Partitioning Techniques/3

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.
- No clustering, so difficult to answer range queries





## Comparison of Partitioning Techniques/4

Range partitioning:

- Provides data clustering by partitioning attribute value.
- Good for sequential access
- 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.
  - If many blocks are to be fetched, they may still fetched from one to a few disks: potential parallelism in disk access is wasted.
    Example: partition by order date, then tuples with recent order dates will be accessed more frequently, leading to so-called execution skew





## Partitioning a Relation across Disks

- If a relation contains only a few tuples which will fit into a single disk block, then assign the relation to a single disk.
- Large relations are preferably partitioned across all the available disks.
- If a relation consists of $m$ disk blocks and there are $n$ disks available in the system, then the relation should be allocated $min(m, n)$ disks.

## Handling of Data Skew

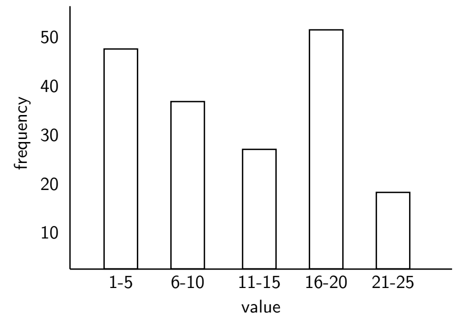
- Distribution of tuples to disks may be skewed: some disks have many tuples, while others have fewer tuples.
- Skew limits speedup. Example:
  - relation with 1000 tuples is partitioned to 100 disks (10 tuples/disk)
  - expected speedup for scan: $\times 100$
  - skew: one disk has 40 tuples $\Rightarrow$ max. speedup is $\times 25$
- Types of skew:
  - Attribute-value skew:
    - Some values appear in the partitioning attributes of many tuples; all the tuples with the same value for the partitioning attribute end up in the same partition.
    - Can occur with range-partitioning and hash-partitioning.
  - Partition skew:
    - With range-partitioning, badly chosen partition vector may assign too many tuples to some partitions and too few to others.
    - Less likely with hash-partitioning if a good hash-function is chosen.





## Handling Skew using Histograms

- Balanced partitioning vector can be constructed from histogram in a relatively straightforward fashion
  - Assume uniform distribution within each range of the histogram
- Histogram can be constructed by scanning relation, or sampling (blocks containing) tuples of the relation








## Handling Skew Using Virtual Processor Partitioning

- Skew in range partitioning can be handled elegantly using virtual processor partitioning:
  - create a large number of partitions (say 10 to 20 times the number of processors)
  - Assign virtual processors to partitions either in round-robin fashion or based on estimated cost of processing each virtual partition
- Basic idea:
  - If any normal partition would have been skewed, it is very likely the skew is spread over a number of virtual partitions
  - Skewed virtual partitions get spread across a number of processors, so work gets distributed evenly!





## Outline

## Interquery Parallelism

- Queries/transactions execute in parallel with one another.
- Increases transaction 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, because even sequential database systems support concurrent processing.
- More complicated to implement on shared-disk or shared-nothing architectures
  - 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.





## Cache Coherency Protocol

- Example of a cache coherency protocol for shared-disk systems:
  - Before reading/writing to a page, the page must be locked in shared/exclusive mode.
  - On locking a page, the page must be read from disk
  - Before unlocking a page, the page must be written to disk if it was modified.
- More complex protocols with fewer disk reads/writes exist.
- Cache coherency protocols for shared-nothing systems are similar. Each database page is assigned a home processor. Requests to fetch the page or write it to disk are sent to the home processor.





## Outline







## Intraquery Parallelism

- Execution of a single query in parallel on multiple processors/disks; important for speeding up long-running queries.
- Two complementary forms of intraquery parallelism:
  - Intraoperation Parallelism — parallelize the execution of each individual operation in the query.
  - Interoperation Parallelism — execute the different operations in a query expression in parallel.
- Intraoperation parallelism 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.

## Parallel Processing of Relational Operations

- Our discussion of parallel algorithms assumes:
  - read-only queries
  - shared-nothing architecture
  - $n$ processors, $P_0, \ldots, P_{n-1}$, and $n$ disks $D_0, \ldots, D_{n-1}$, where disk $D_i$ is associated with processor $P_i$.
- If processor has multiple disks: simulate a single disk $D_i$.
- Shared-nothing architectures can be efficiently simulated on shared-memory and shared-disk systems.
  - Algorithms for shared-nothing systems can thus be run on shared-memory and shared-disk systems.
  - However, some optimizations may be possible.





## Parallel Sort/1

### Range-Partitioning Sort

- Choose processors $P_0, \ldots, P_{m-1}$, where $m \leq n$ to do sorting.
- Create range-partition vector with $m$ ranges, on the sorting attributes
- Redistribute the relation using range partitioning
  - all tuples that lie in the $i^{th}$ range are sent to processor $P_i$
  - $P_i$ stores the tuples it received temporarily on disk $D_i$
  - this step requires I/O and communication overhead
- Each processor $P_i$ sorts its partition of the relation locally.
- Each processors executes same operation (sort) in parallel with other processors, without any interaction with the others (data parallelism).
- Final merge operation is trivial: range-partitioning ensures that, for $0 \leq i < j < m$, the key values in processor $P_i$ are all less than the key values in $P_j$.





## Parallel Sort/2

### Parallel External Sort-Merge

- Assume the relation has already been partitioned among disks $D_0, \ldots, D_{n-1}$ (in whatever manner).
- Each processor $P_i$ locally sorts the data on disk $D_i$.
- Sorted runs of processors are merged to get the final sorted output.
- Parallelize the merging of sorted runs as follows:
  - The sorted partitions at each processor $P_i$ are range-partitioned across the processors $P_0, \ldots, P_{m-1}$.
  - Each processor $P_i$ performs a merge on the streams as they are received, to get a single sorted run.
  - The sorted runs on processors $P_0, \ldots, P_{m-1}$ are concatenated to get the final result.





## Parallel Join

- The join operation requires pairs of tuples to be tested to see if they satisfy the join condition, and if they do, the pair is added to the join output.
- Parallel join algorithms attempt to split the pairs to be tested over several processors. Each processor then computes part of the join locally.
- In a final step, the results from each processor can be collected together to produce the final result.

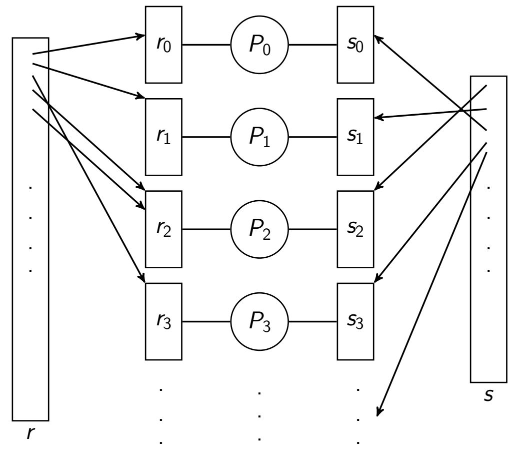
# Partitioned Join/1

- For equi-joins and natural joins, it is possible to partition the two input relations across the processors, and compute the join locally at each processor.
- Let $r$ and $s$ be the input relations, and we want to compute $r \bowtie_{r.A=s.B} s$.
- $r$ and $s$ each are partitioned into $n$ partitions, denoted $r_0, r_1, \ldots, r_{n-1}$ and $s_0, s_1, \ldots, s_{n-1}$.
- Can use either range partitioning or hash partitioning.
- $r$ and $s$ must be partitioned on their join attributes ($r.A$ and $s.B$), using the same range-partitioning vector or hash function.
- Partitions $r_i$ and $s_i$ are sent to processor $P_i$,
- Each processor $P_i$ locally computes $r_i \bowtie_{r_i.A=s_i.B} s_i$. Any of the standard join methods can be used.





# Partitioned Join/2








# Partitioned Parallel Hash-Join/1

Parallelizing partitioned hash join:

- Assume $s$ is smaller than $r$ and therefore $s$ is chosen as the build relation.
- A hash function $h_1$ takes the join attribute value of each tuple in $s$ and maps this tuple to one of the $n$ processors.
- Each processor $P_i$ reads the tuples of $s$ that are on its disk $D_i$, and sends each tuple to the appropriate processor based on hash function $h_1$. Let $s_i$ denote the tuples of relation $s$ that are sent to processor $P_i$.
- As tuples of relation $s$ are received at the destination processors, they are partitioned further using another hash function, $h_2$, which is used to compute the hash-join locally.





# Partitioned Parallel Hash-Join/2

- Once the tuples of $s$ have been distributed, the larger relation $r$ is redistributed across the m processors using the hash function $h_1$
  - Let $r_i$ denote the tuples of relation $r$ that are sent to processor $P_i$.
- As the $r$ tuples are received at the destination processors, they are repartitioned using the function $h_2$
  - (just as the probe relation is partitioned in the sequential hash-join algorithm).
- Each processor $P_i$ executes the build and probe phases of the hash-join algorithm on the local partitions $r_i$ and $s_i$ to produce a partition of the final result of the hash-join.
- Note: Hash-join optimizations can be applied to the parallel case
  - e.g., the hybrid hash-join algorithm can be used to cache some of the incoming tuples in memory and avoid the cost of writing them and reading them back in.

# Fragment-and-Replicate Join/1

- Partitioning not possible for some join conditions
  - E.g., non-equijoin conditions, such as $r.A > s.B$.
- For joins were partitioning is not applicable, parallelization can be accomplished by fragment and replicate technique
- Special case – asymmetric fragment-and-replicate:
  - One of the relations, say $r$, is partitioned; any partitioning technique can be used.
  - The other relation, $s$, is replicated across all the processors.
  - Processor $P_i$ then locally computes the join of $r_i$ with all of s using any join technique.





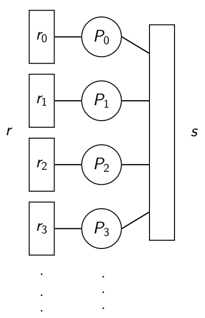
# Parallel Nested-Loop Join

- Assume that
  - relation $s$ is much smaller than relation $r$
  - $r$ is stored by partitioning (partitioning technique irrelevant)
  - there is an index on a join attribute of relation $r$ at each of the partitions of relation $r$.
- Use asymmetric fragment-and-replicate, with relation $s$ being replicated, and using the existing partitioning of relation $r$.
- Each processor $P_j$ where a partition of relation $s$ is stored reads the tuples of relation $s$ stored in $D_j$, and replicates the tuples to every other processor $P_i$.
  - At the end of this phase, relation $s$ is replicated at all sites that store tuples of relation $r$.
- Each processor $P_i$ performs an indexed nested-loop join of relation $s$ with the $i^{th}$ partition of relation $r$.

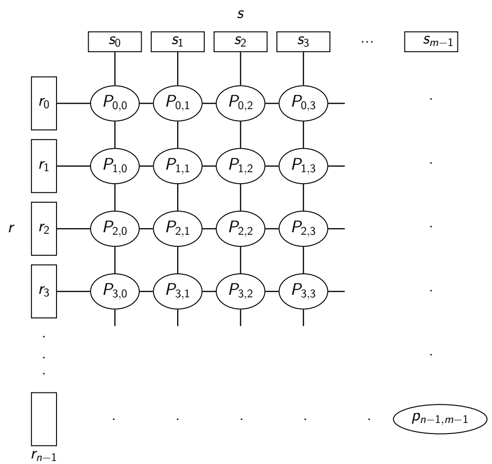




# Fragment-and-Replicate Join/2




Asymmetric fragment and replicate




Fragment and replicate





# Fragment-and-Replicate Join/3

- General case: reduces the sizes of the relations at each processor.
  - $r$ is partitioned into $n$ partitions, $r_0, r_1, \ldots, r_{n-1}$; $s$ is partitioned into $m$ partitions, $s_0, s_1, \ldots, s_{m-1}$.
  - Any partitioning technique may be used.
  - There must be at least $m * n$ processors.
  - Label the processors as
  - $P_{0,0}, P_{0,1}, \ldots, P_{0,m-1}, P_{1,0}, \ldots, P_{n-1,m-1}$.
  - $P_{i,j}$ computes the join of $r_i$ with $s_j$. In order to do so, $r_i$ is replicated to $P_{i,0}, P_{i,1}, \ldots, P_{i,m-1}$, while $s_i$ is replicated to $P_{0,i}, P_{1,i}, \ldots, P_{n-1,i}$
  - Any join technique can be used at each processor $P_{i,j}$.

## Fragment-and-Replicate Join/4

- Both versions of fragment-and-replicate work with any join condition, since every tuple in $r$ can be tested with every tuple in $s$.
- Usually has a higher cost than partitioning, since one of the relations (for asymmetric fragment-and-replicate) or both relations (for general fragment-and-replicate) have to be replicated.
- Sometimes asymmetric fragment-and-replicate is preferable even though partitioning could be used.





## Other Relational Operations/1

Selection $\sigma_\theta(r)$

- If $\theta$ is of the form $a_i = v$, where $a_i$ is an attribute and $v$ a value.
  - If $r$ is partitioned on $a_i$ the selection is performed at a single processor.
- If $\theta$ is of the form $l \leq a_i \leq u$ (i.e., $\theta$ is a range selection) and the relation has been range-partitioned on $a_i$
  - Selection is performed at each processor whose partition overlaps with the specified range of values.
- In all other cases: the selection is performed in parallel at all the processors.





## Other Relational Operations/2

- Duplicate elimination
  - Perform by using either of the parallel sort techniques
    - eliminate duplicates as soon as they are found during sorting.
  - Can also partition the tuples (using either range- or hash-partitioning) and perform duplicate elimination locally at each processor.
- Projection
  - Projection without duplicate elimination can be performed as tuples are read in from disk in parallel.
  - If duplicate elimination is required, any of the above duplicate elimination techniques can be used.





## Grouping/Aggregation

- Partition the relation on the grouping attributes and then compute the aggregate values locally at each processor.
- Can reduce cost of transferring tuples during partitioning by partly computing aggregate values before partitioning.
- Consider the sum aggregation operation:
  - Perform aggregation operation at each processor $P_i$ on those tuples stored on disk $D_i$
    - results in tuples with partial sums at each processor.
  - Result of the local aggregation is partitioned on the grouping attributes, and the aggregation performed again at each processor $P_i$ to get the final result.
- Fewer tuples need to be sent to other processors during partitioning.

## Cost of Parallel Evaluation of Operations

- If there is no skew in the partitioning, and there is no overhead due to the parallel evaluation, expected speedup will be $n$
- If skew and overheads are also to be taken into account, the time taken by a parallel operation can be estimated as

$$T_{part} + T_{asm} + max(T_0,\ T_1,\ \ldots,\ T_{n-1})$$

  - $T_{part}$ is the time for partitioning the relations
  - $T_{asm}$ is the time for assembling the results
  - $T_i$ is the 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.





## Interoperator Parallelism

- Two types of interoperation parallelism:
  - pipelined parallelism
  - independent parallelism





## Pipelined Parallelism

- Example: Consider a join of four relations

  $r_1 \bowtie r_2 \bowtie r_3 \bowtie r_4$
- Set up a pipeline that computes the three joins in parallel
  - Let $P_1$ be assigned the computation of $temp_1 = r_1 \bowtie r_2$
  - And $P_2$ be assigned the computation of $temp_2 = temp_1 \bowtie r_3$
  - And $P_3$ be assigned the computation of $temp_2 \bowtie r_4$
- Each operation can execute in parallel sending result tuples to the next operation even while it is computing further results
- Requires pipelineable (non-blocking) join evaluation algorithm (e.g., indexed nested loops join)





## Factors Limiting Utility of Pipeline Parallelism

- Pipeline parallelism is useful since it avoids writing intermediate results to disk
- Useful with small number of processors, but does not scale up well with more processors. One reason is that pipeline chains do not attain sufficient length.
- Cannot pipeline operators which do not produce output until all inputs have been accessed (e.g., aggregate and sort)
- Little speedup is obtained for the frequent cases of execution skew in which one operator's execution cost is much higher than the others.
- Advantage: avoids writing intermediate results to disk

# Independent Parallelism

- Example: Consider a join of four relations

  $r_1 \bowtie r_2 \bowtie r_3 \bowtie r_4$
- Independent parallelism:
  - Let $P_1$ be assigned the computation of $temp_1 = r_1 \bowtie r_2$
  - And $P_2$ be assigned the computation of $temp_2 = r_3 \bowtie r_4$
  - And $P_3$ be assigned the computation of $temp_1 \bowtie temp_2$
  - $P_1$ and $P_2$ can work independently in parallel
  - $P_3$ has to wait for input from $P_1$ and $P_2$
    - Can pipeline output of $P_1$ and $P_2$ to $P_3$, combining independent parallelism and pipelined parallelism
- Does not provide a high degree of parallelism
  - useful with a lower degree of parallelism.
  - less useful in a highly parallel system.





# Outline







# Query Optimization/1

- Query optimization in parallel databases is significantly more complex than query optimization in sequential databases.
- Cost models are more complicated, since we must take into account partitioning costs and issues such as skew and resource contention.
- When scheduling execution tree in parallel system, must decide:
  - How to parallelize each operation and how many processors to use for it.
  - What operations to pipeline, what operations to execute independently in parallel, and what operations to execute sequentially, one after the other.
- Determining the amount of resources to allocate for each operation is a problem.
  - E.g., allocating more processors than optimal can result in high communication overhead.
- Long pipelines should be avoided as the final operation may wait a lot for inputs, while holding precious resources





# Query Optimization/2

- Use heuristics: Number of parallel evaluation plans much larger than number of sequential evaluation plans.
- Heuristic 1: No pipelining, only intra-operation parallelism:
  - Parallelize every operation on all processors
  - Use standard optimization technique, but with new cost model
- Heuristic 2: First choose most efficient sequential plan and then choose how best to parallelize the operations in that plan.
  - Volcano parallel database popularized the exchange-operator model
  - exchange operator is introduced into query plans to partition and distribute tuples
  - each operation works independently on local data on each processor, in parallel with other copies of the operation
- Choosing a good physical storage organization (partitioning technique) is important to speed up queries.

## Design of Parallel Systems/1

Some issues in the design of parallel systems:

- Parallel loading of data from external sources is needed in order to handle large volumes of incoming data.
- Resilience to failure of some processors or disks.
  - Probability of some disk or processor failing is higher in a parallel system.
  - Operation (perhaps with degraded performance) should be possible in spite of failure.
  - Redundancy achieved by storing extra copy of every data item at another processor.





## Design of Parallel Systems/2

- On-line reorganization of data and schema changes must be supported.
  - For example, index construction on terabyte databases can take hours or days even on a parallel system.
    - Need to allow other processing (insertions/deletions/updates) to be performed on relation even as index is being constructed.
  - Basic idea: index construction tracks changes and "catches up" on changes at the end.
- Also need support for on-line repartitioning and schema changes (executed concurrently with other processing).





## Examples of Parallel Database Systems

- Teradata (1979), appliance, still large market share
- IBM Netezza (1999), appliance
- Microsoft DATAllegro / Parallel Data Warehouse (2003), appliance
- Greenplum (2005), Pivotal, open source
- Vertica Analytic Database (2005) commodity hardware
- Oracle Exadata (2008), appliance
- SAP Hana (2010), main memory, appliance