Parallel and Distributed Data Management

Parallel Databases

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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
  - large volumes of transaction data are collected and stored for later analysis
  - large objects like multimedia data 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

Databases naturally lend themselves to parallelism:

- Parallel I/O: data can be partitioned across multiple disks.
- Parallel execution: execute individual relational operations in parallel
  - e.g., sort, join, aggregation can be executed in parallel
  - each processor can work independently on its own data partition
- Queries are expressed at the logical level and in a high level language:
  - SQL is declarative and is translated to relational algebra
  - separation of logical and physical level makes parallelization easier
- Different queries can run in parallel:
  - concurrency control takes care of conflicts

Outline

Outline

I/O Parallelism

- 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.

Horizontal Partitioning

Let n be the number of disks.

- Round-robin:
  - send the i-th tuple inserted in the relation to disk i *mod* n.
- Hash partitioning:
  - choose one or more attributes A as the partitioning attributes
  - choose hash function h with range $0 \dots n-1$
  - send tuple t with hash value $i = h(t[A])$ to disk i
- Range partitioning:
  - choose one or more attributes A as the partitioning attributes
  - choose a partitioning vector $[v_0, v_1, \dots, v_{n-2}]$
    - tuples t with $t[A] < v_0$ got to disk 0
    - tuples with $v_i \leq t[A] < v_{i+1}$ to to disk $i+1$
    - tuples with $v_{n-2} \leq t[A]$ go to disk $n-1$
  - Example: with partitioning vector $[5, 11]$ on attribute A, a tuple t with partitioning attribute value of $t[A] = 2$ will go to disk 0, a tuple with $t[A] = 8$ will go to disk 1, while a tuple with $t[A] = 20$ will go to disk 2.

Comparison of Partitioning Techniques/1

- We distinguish three different types of data access:
  1. sequential scan: scan the entire relation
  2. point query: locate a specific tuple
     - predicate is equality, zero or one result tuple
     - e.g., tuple of relation r with $r.A = 25$ (A is a key)
     - multi point query: zero or more result tuples (A is not a key)
  3. range query: locate all tuples within a specified value range
     - e.g., all tuples of relation r with $10 \leq r.A < 25$.

Comparison of Partitioning Techniques/2

Round robin:

- Good for sequential scan:
  - all disks have almost an equal number of tuples
  - retrieval work is thus well balanced between disks
- Point queries and range queries are difficult to process
  - no clustering — relevant 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
  - 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:
  - lookup single disk, leaving others available for answering other queries
- Good for range queries on partitioning attribute:
  - lookup single or few disks
  - good if result tuples are from one to a few blocks of a disk
- Execution skew: affects range queries and multi point queries
  - if many blocks are to be fetched, they may still be fetched from one to a few disks: potential parallelism in disk access is wasted
  - e.g., partition by order date, then tuples with recent order dates will be accessed more frequently

Partitioning a Relation across Disks

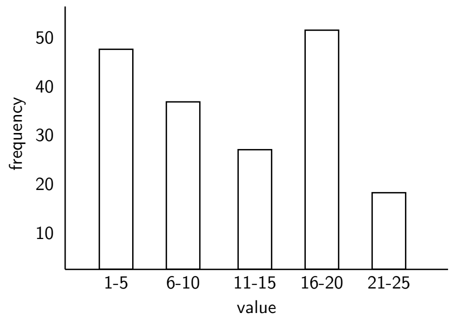
- If a relation contains only a few tuples which will fit into a single disk block, then assign the relation to a single disk.
- Large relations are preferably partitioned across all the available disks.
- If a relation consists of m disk blocks and there are n disks available, then the relation should be allocated to $min(m, n)$ 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 data 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$\times$ 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 on shared-disk or shared-nothing architectures:
  - locking and logging: coordinate 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.

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.

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.

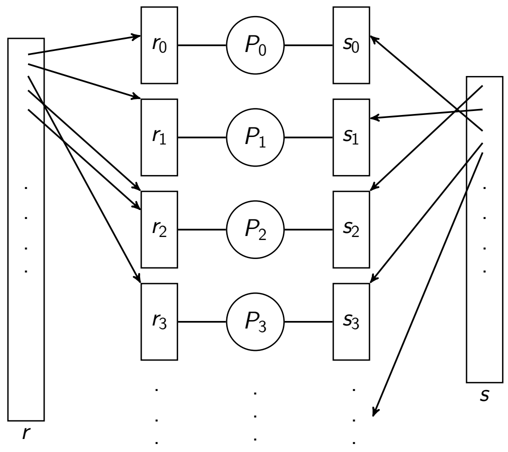
Parallel Join

- 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, then s is chosen as the build relation.
- A hash function h_1 takes the join attribute value x of each tuple in s and maps this tuple to one of the n processors.
- All tuples are sent to the appropriate processors: a tuple with hash value $h_1(x) = i$ is sent to processor P_i.
- 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 P_i, 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, probe relation r is redistributed across the n processors using hash function h_1.
- Let r_i denote the tuples of relation r that are sent to processor P_i.
- As tuples of relation r are received at the destination processors P_i, they are partitioned on P_i using hash function h_2.
- 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 to disk and reading them back in.

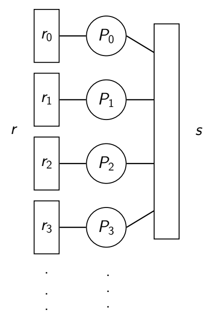
Fragment-and-Replicate Join/1

- 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.

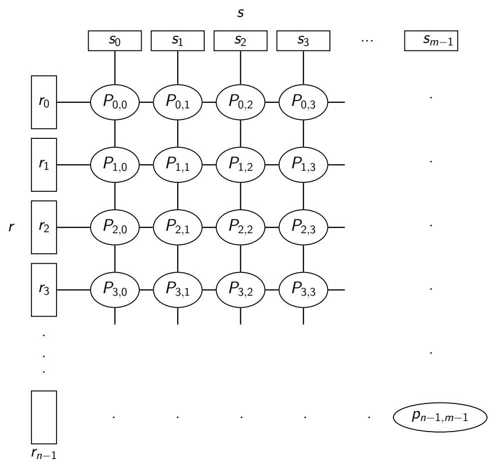
Parallel Nested-Loop Join

- 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) is replicated multiple times.
- Sometimes asymmetric fragment-and-replicate is preferable even though partitioning could be used.

Other Relational Operations/1

Selection $\sigma_\theta(r)$

- If θ 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 θ is of the form $l \leq a_i \leq u$ (i.e., θ 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.

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
- AsterixDB (2009), Java, open source, commodity hardware
- SAP Hana (2010), main memory, appliance