



Parallel Databases

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- Interoperation Parallelism
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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
 - data can be partitioned and each processor can work independently on its own 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

- 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 $i \bmod n$.

Hash partitioning:

- Choose one or more attributes as the partitioning attributes.
- Choose hash function h with range $0 \dots n - 1$
- 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 (Cont.)

- Partitioning techniques (cont.):
- **Range partitioning:**
 - Choose an attribute as the partitioning attribute.
 - A partitioning vector $[v_0, v_1, \dots, v_{n-2}]$ is chosen.
 - 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 $n-1$.

E.g., 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

- 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 (Cont.)

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 (Cont.)

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



Comparison of Partitioning Techniques (Cont.)

- 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 are still fetched from one to a few disks, and potential parallelism in disk access is wasted
- 4 Example of 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 Skew

- The distribution of tuples to disks may be **skewed** — that is, some disks have many tuples, while others may have fewer tuples.
- **Types of skew:**
 - **Attribute-value skew.**
 - 4 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.
 - 4 Can occur with range-partitioning and hash-partitioning.
 - **Partition skew.**
 - 4 With range-partitioning, badly chosen partition vector may assign too many tuples to some partitions and too few to others.
 - 4 Less likely with hash-partitioning if a good hash-function is chosen.



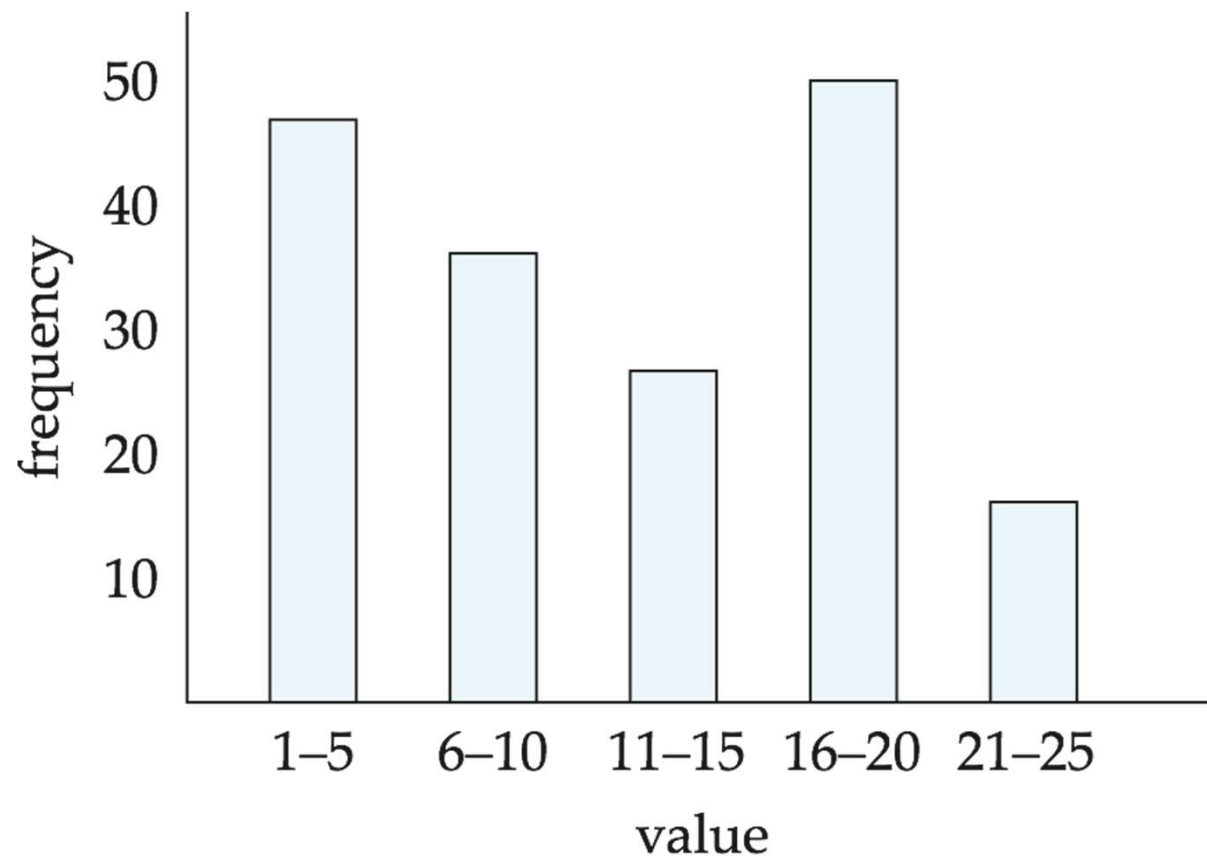
Handling Skew in Range-Partitioning

- To create a **balanced partitioning vector** (assuming partitioning attribute forms a key of the relation):
 - Sort the relation on the partitioning attribute.
 - Construct the partition vector by scanning the relation in sorted order as follows.
 - 4 After every $1/n^{th}$ of the relation has been read, the value of the partitioning attribute of the next tuple is added to the partition vector.
 - n denotes the number of partitions to be constructed.
 - Duplicate entries or imbalances can result if duplicates are present in partitioning attributes.
- Alternative technique based on **histograms** used in practice



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!



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.



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.

the first form 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, \dots, P_{n-1} , and n disks D_0, \dots, 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 .
- 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

Range-Partitioning Sort

- Choose processors P_0, \dots, P_m , where $m \leq n - 1$ to do sorting.
- Create range-partition vector with m entries, 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 $1 \leq j \leq m$, the key values in processor P_i are all less than the key values in P_j .



Parallel Sort (Cont.)

Parallel External Sort-Merge

- Assume the relation has already been partitioned among disks D_0, \dots, D_{n-1} (in whatever manner).
- Each processor P_i locally sorts the data on disk D_i .
- The sorted runs on each processor are then 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, \dots, 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, \dots, 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.

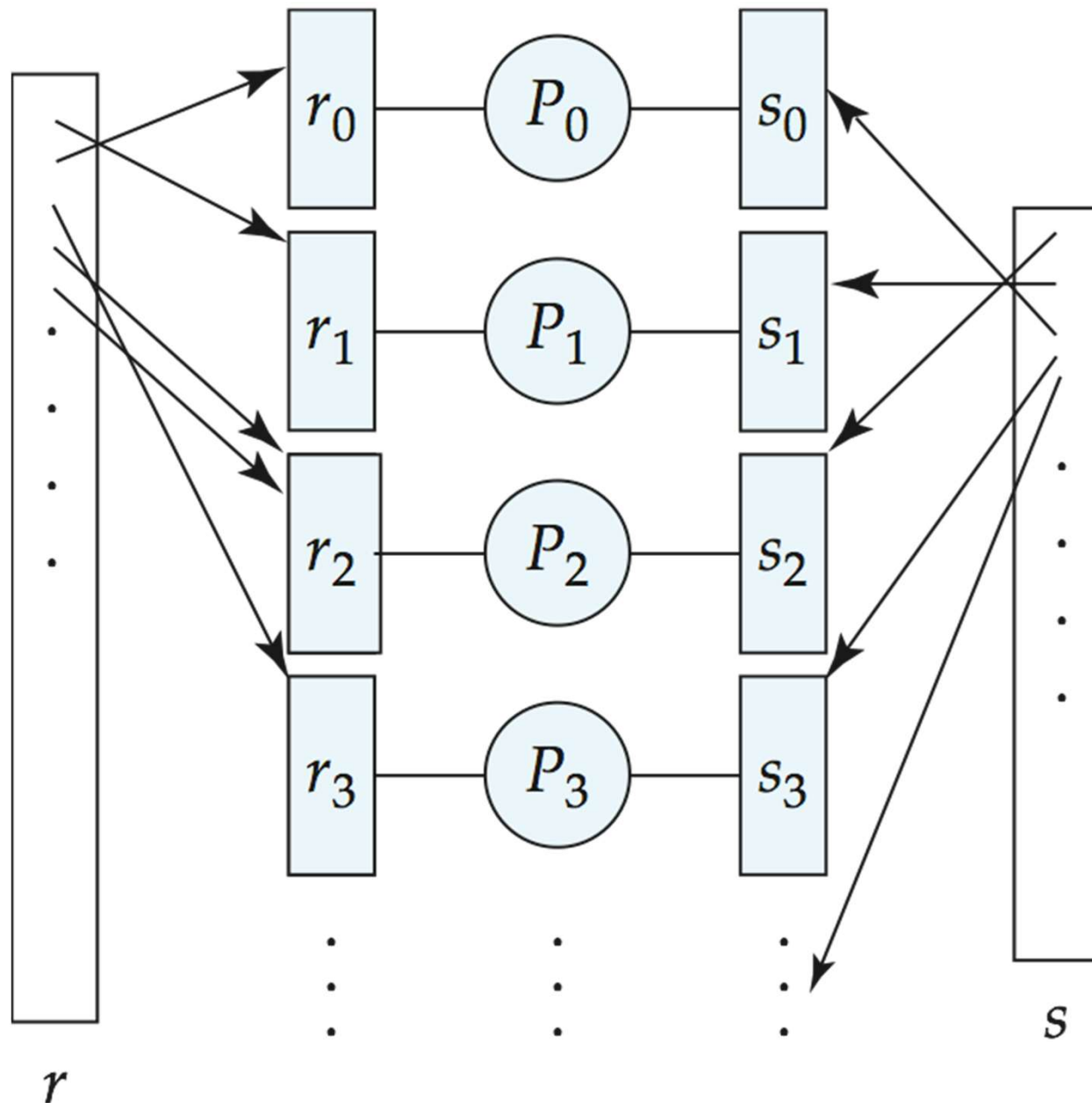


Partitioned Join

- 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, \dots, r_{n-1} and s_0, s_1, \dots, 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 (Cont.)



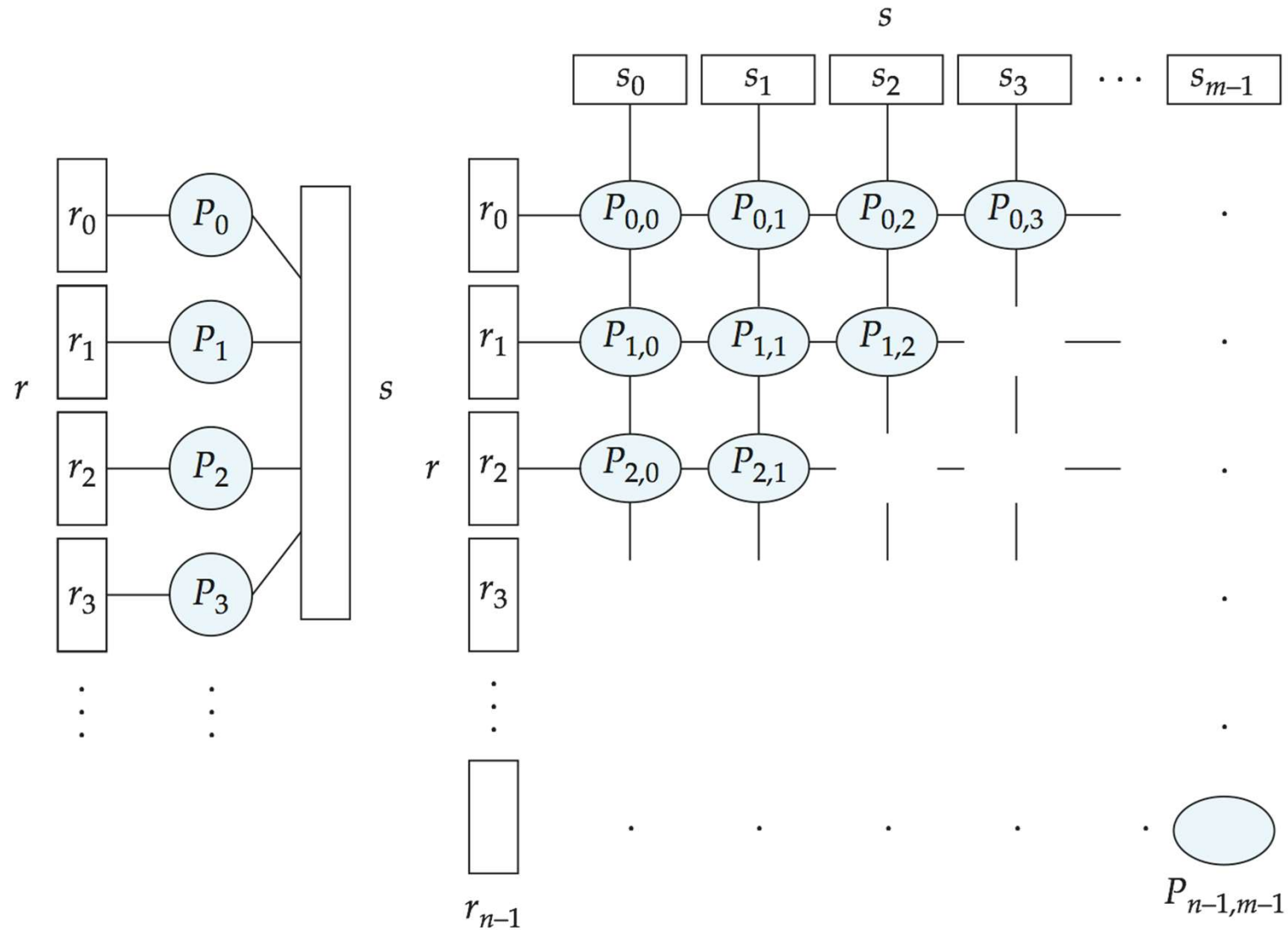


Fragment-and-Replicate Join

- Partitioning not possible for some join conditions
 - E.g., non-equi-join conditions, such as $r.A > s.B$.
- For joins where partitioning is not applicable, parallelization can be accomplished by **fragment and replicate** technique
 - Depicted on next slide
- 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.



Depiction of Fragment-and-Replicate Joins





Fragment-and-Replicate Join (Cont.)

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



Fragment-and-Replicate Join (Cont.)

- 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.
 - E.g., say s is small and r is large, and already partitioned. It may be cheaper to replicate s across all processors, rather than repartition r and s on the join attributes.



Partitioned Parallel Hash-Join

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. (*Cont.*)



Partitioned Parallel Hash-Join (Cont.)

- 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 of r and s 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.



Parallel Nested-Loop Join

- Assume that
 - relation s is much smaller than relation r and that r is stored by partitioning.
 - 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 .



Other Relational Operations

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 (Cont.)

- Duplicate elimination
 - Perform by using either of the parallel sort techniques
 - 4 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
 - 4 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 speed-up will be $1/n$
- If skew and overheads are also to be taken into account, the time taken by a parallel operation can be estimated as

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

- 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
 - 4 this needs to be estimated taking into account the skew, and the time wasted in contentions.



Interoperator Parallelism

- **Pipelined parallelism**

- Consider a join of four relations

4 $r_1 \bowtie r_2 \bowtie r_3 \bowtie r_4$

- Set up a pipeline that computes the three joins in parallel

- 4 Let P1 be assigned the computation of

$$\text{temp1} = r_1 \bowtie r_2$$

- 4 And P2 be assigned the computation of $\text{temp2} = \text{temp1} \bowtie r_3$

- 4 And P3 be assigned the computation of $\text{temp2} \bowtie r_4$

- Each of these operations can execute in parallel, sending result tuples it computes to the next operation even as it is computing further results
 - 4 Provided a pipelineable join evaluation algorithm (e.g., indexed nested loops join) is used



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 skew in which one operator's execution cost is much higher than the others.



Independent Parallelism

- **Independent parallelism**

- Consider a join of four relations

$$r_1 \bowtie r_2 \bowtie r_3 \bowtie r_4$$

- 4 Let P_1 be assigned the computation of

$$\text{temp1} = r_1 \bowtie r_2$$

- 4 And P_2 be assigned the computation of $\text{temp2} = r_3 \bowtie r_4$

- 4 And P_3 be assigned the computation of $\text{temp1} \bowtie \text{temp2}$

- 4 P_1 and P_2 can work **independently in parallel**

- 4 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

- 4 useful with a lower degree of parallelism.

- 4 less useful in a highly parallel system.



Query Optimization

- 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 (Cont.)

- The number of parallel evaluation plans from which to choose from is much larger than the number of sequential evaluation plans.
 - Therefore heuristics are needed while optimization
- Two alternative heuristics for choosing parallel plans:
 - No pipelining and inter-operation pipelining; just parallelize every operation across all processors.
 - 4 Finding best plan is now much easier --- use standard optimization technique, but with new cost model
 - 4 Volcano parallel database popularize 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
 - First choose most efficient sequential plan and then choose how best to parallelize the operations in that plan.
 - 4 Can explore pipelined parallelism as an option
- Choosing a good physical organization (partitioning technique) is important to speed up queries.



Design of Parallel Systems

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 (Cont.)

- 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.
 - 4 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).