



## Chapter 20: Parallel Databases

- Introduction
- I/O Parallelism
- Interquery Parallelism
- Intraquery Parallelism
- Intraoperation Parallelism
- Interoperation Parallelism
- Design of Parallel Systems



## Introduction

- Parallel machines are becoming quite common and affordable
  - ★ Prices of microprocessors, memory and disks have dropped sharply
- 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  $i^{\text{th}}$  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

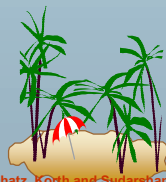
- Evaluate how well partitioning techniques support the following types of data access:
  1. Scanning the entire relation.
  2. Locating a tuple associatively – **point queries**.
    - ★ E.g.,  $r.A = 25$ .
  3. Locating all tuples such that the value of a given attribute lies within a specified range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



## Comparison of Partitioning Techniques (Cont.)

Round robin:

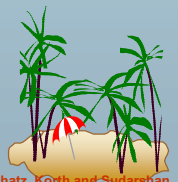
- Advantages
  - ★ Best suited for sequential scan of entire relation on each query.
  - ★ All disks have almost an equal number of tuples; retrieval work is thus well balanced between disks.
- Range queries are difficult to process
  - ★ No clustering -- tuples are scattered across all disks



## 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
- ★ 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.**
    - 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 in Range-Partitioning

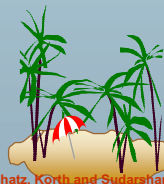
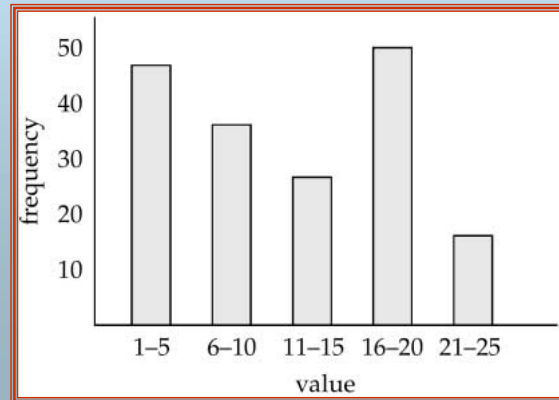
- To create a **balanced partitioning vector** (assuming partitioning attribute forms a key of the relation):
  - ★ Sort the relation on the partitioning attribute.
  - ★ Construct the partition vector by scanning the relation in sorted order as follows.
    - After every  $1/n^{\text{th}}$  of the relation 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



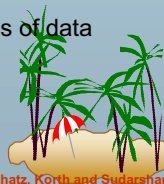
## Handling Skew using Virtual Processor Partitioning

- 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

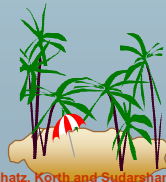
- Example of a cache coherency protocol for shared disk systems:
  - ★ Before reading/writing to a page, the page must be locked in shared/exclusive mode.
  - ★ On locking a page, the page must be read from disk
  - ★ Before unlocking a page, the page must be written to disk if it was modified.
- More 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  $i^{\text{th}}$  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  $P^j$  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.

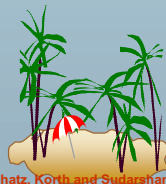
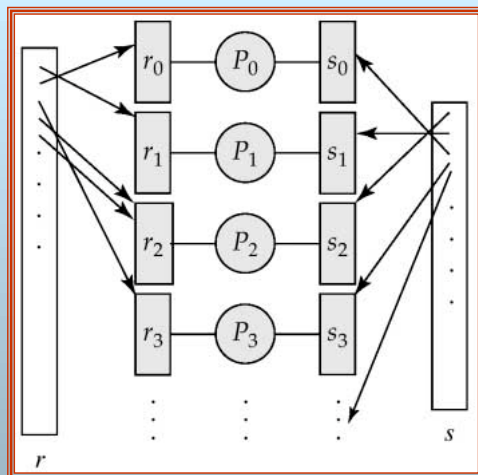


## Partitioned Join

- 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.)

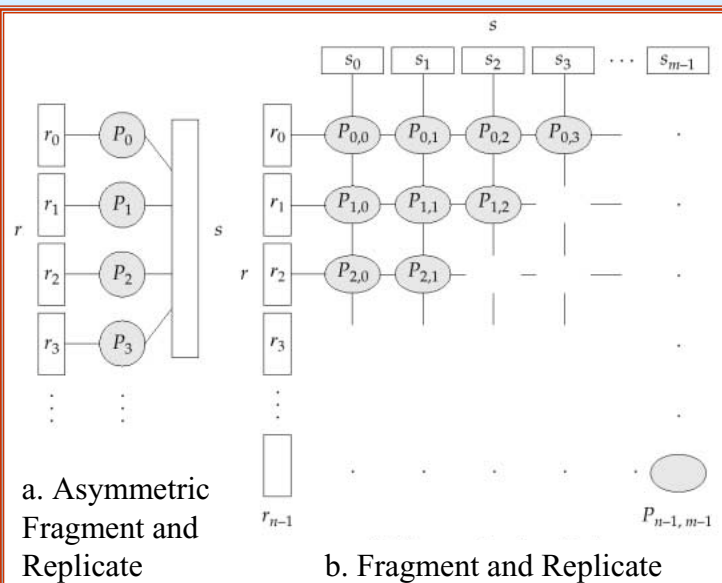


## Fragment-and-Replicate Join

- Partitioning not possible for some join conditions
  - ★ e.g., non-equijoin 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.)



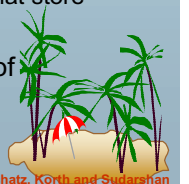
## Partitioned Parallel Hash-Join (Cont.)

- 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.



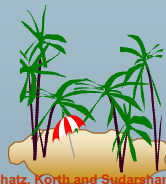
## Parallel Nested-Loop Join

- 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  $i^{\text{th}}$  partition of relation  $r$ .



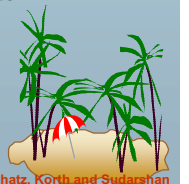
## Other Relational Operations

- 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 (Cont.)

- 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.



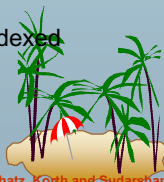
## Cost of Parallel Evaluation of Operations

- If there is no skew in the partitioning, and there is no overhead due to the parallel evaluation, expected 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
 
$$T_{\text{part}} + T_{\text{asm}} + \max(T_0, T_1, \dots, T_{n-1})$$
  - ★  $T_{\text{part}}$  is the time for partitioning the relations
  - ★  $T_{\text{asm}}$  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

- **Pipelined parallelism**
  - ★ 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  $\text{temp1} = r_1 \bowtie r_2$
    - And  $P_2$  be assigned the computation of  $\text{temp2} = \text{temp1} \bowtie r_3$
    - And  $P_3$  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
    - 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

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

- Let P1 be assigned the computation of  $\text{temp1} = r_1 \bowtie r_2$
- And P2 be assigned the computation of  $\text{temp2} = r_3 \bowtie r_4$
- And P3 be assigned the computation of  $\text{temp1} \bowtie \text{temp2}$
- P1 and P2 can work **independently in parallel**
- P3 has to wait for input from P1 and P2
  - Can pipeline output of P1 and P2 to P3, 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,



## 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.
    - Finding best plan is now much easier --- use standard optimization technique, but with new cost model
    - 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.
    - 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.
    - 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).



**End of Chapter**