Systems Infrastructure for Data Science

Web Science Group
Uni Freiburg
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Lecture X:
Parallel Databases

Topics

– Motivation and Goals
– Architectures
– Data placement
– Query processing
– Load balancing

Motivation

- Large volume of data => Use disk and large main memory
- I/O bottleneck (or memory access bottleneck)
  - speed(disk) << speed(RAM) << speed(microprocessor)
- Predictions
  - (Micro-) processor speed growth: 50 % per year (Moore's Law)
  - DRAM capacity growth: 4 x every three years
  - Disk throughput: < 2 x in the last ten years
- Conclusion: the I/O bottleneck worsens

=> Increase the I/O bandwidth through parallelism

Motivation

- Also, Moore's Law doesn't quite apply any more because of the heat problem.
- Recent trend:
  - Instead of fitting more chips on a single board, increase the number of processors.

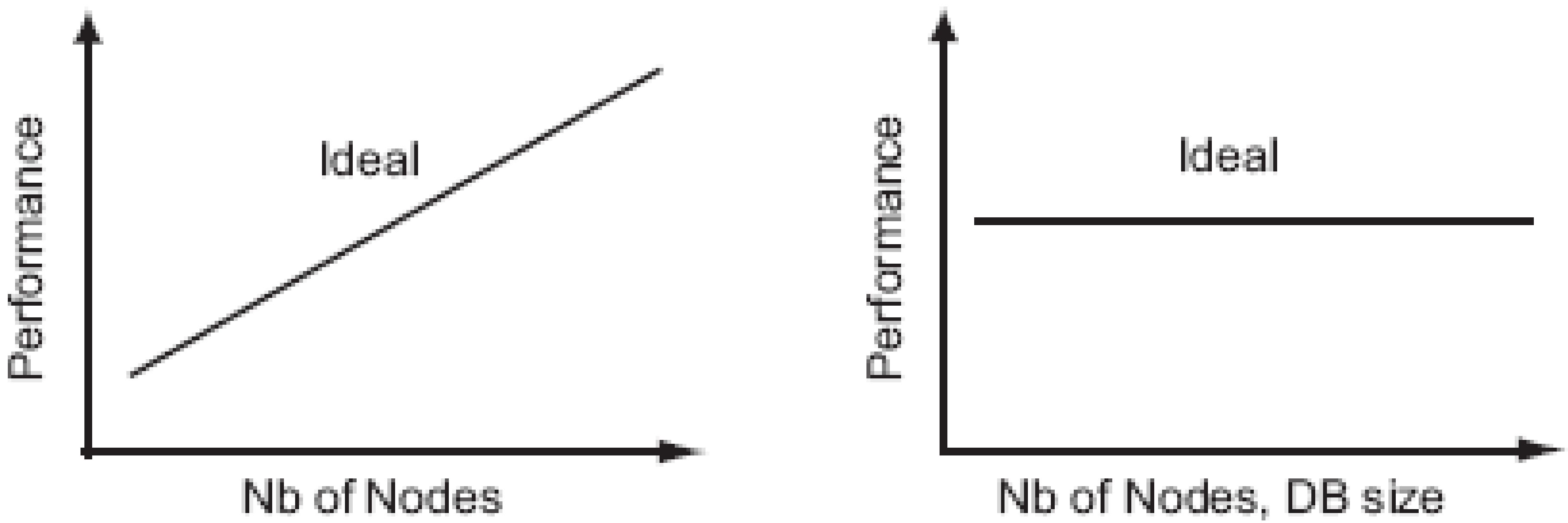
  => The need for parallel processing

N.B. Difference to distributed DDBMS – not necessary independent, not necessary via network

Goals

- I/O bottleneck
  - Increase the I/O bandwidth through parallelism
- Exploit multiple processors, multiple disks
  - Intra-query parallelism (for response time)
  - Inter-query parallelism (for throughput = # of transactions/second)
- High performance
  - Overhead
  - Load balancing
- High availability
  - Exploit the existing redundancy
  - Be careful about imbalance
- Extensibility
  - Speed-up and Scalability

Extensibility



(a) Linear speedup

(b) Linear scaleup

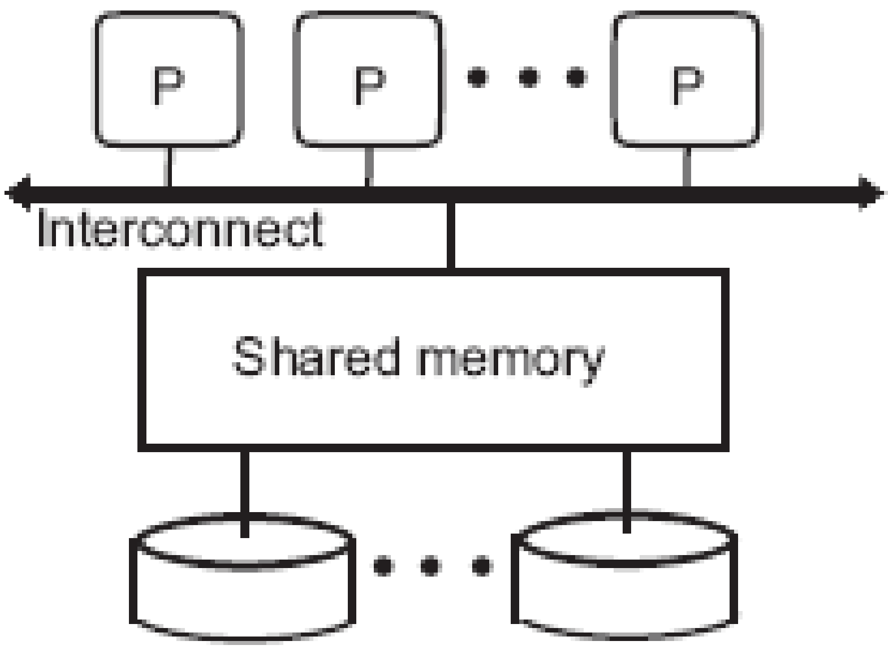
Today’s Topics

- Parallel Databases
  - Motivation and Goals
  - Architectures
  - Data placement
  - Query processing
  - Load balancing

Parallel System Architectures

- Shared-Memory
- Shared-Disk
- Shared-Nothing
- Hybrid
  - NUMA
  - Cluster

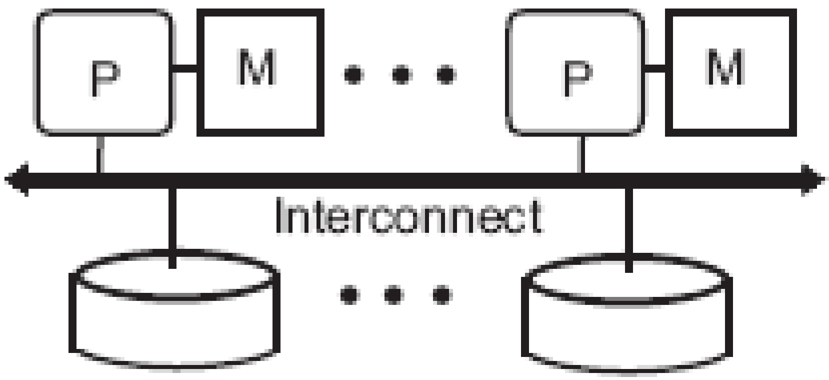
Shared-Memory



- Fast interconnect
- Single OS

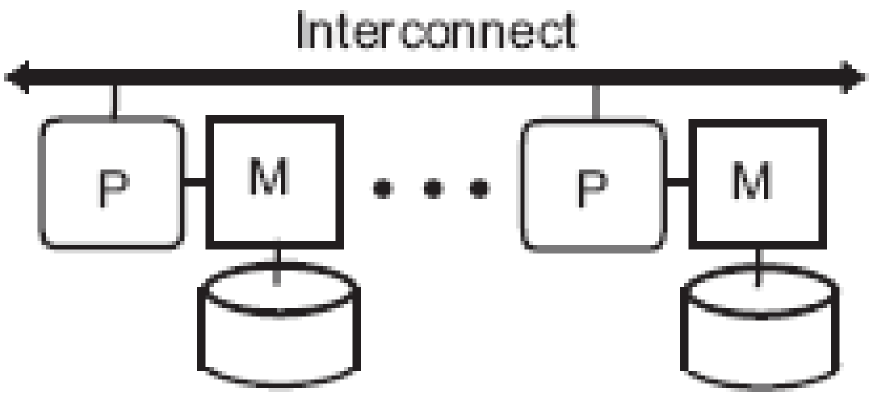
- Advantages:
  - Simplicity
  - Easy load balancing
- Problems:
  - High cost (the interconnect)
  - Limited extensibility (~ 10 P's)
  - Low availability

Shared-Disk



- Separate OS per P-M
- Advantages:
  - Lower cost
  - Higher extensibility (~ 100 P-M’s)
  - Load balancing
  - Availability
- Problems:
  - Complexity (cache consistency with lock-based protocols, 2PC, etc.)
  - Overhead
  - Disk bottleneck

Shared-Nothing

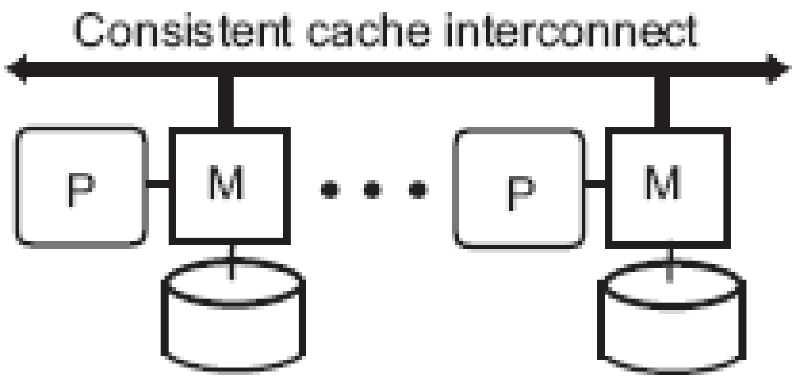


- Separate OS per P-M-D
- Each node ~ site

- Advantages:
  - Extensibility and scalability
  - Lower cost
  - High availability
- Problems:
  - Complexity
  - Difficult load balancing

Hybrid Architectures

Non Uniform Memory Architecture (NUMA)



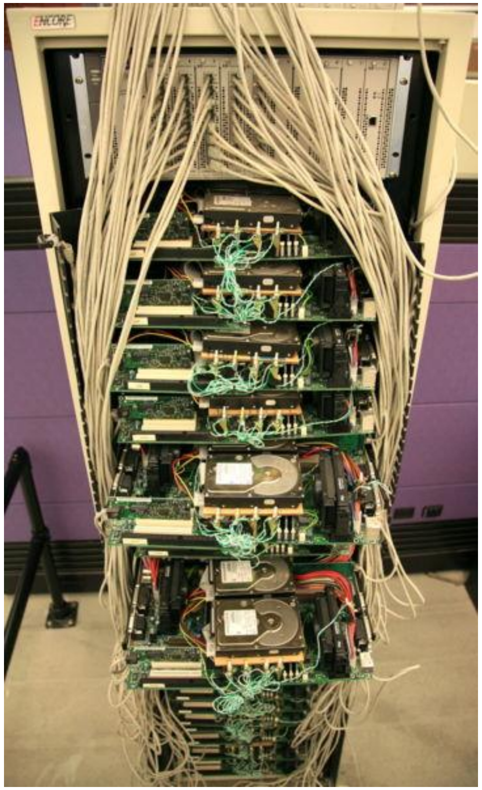
- Cache-coherent NUMA
- Any P can access to any M.
- More efficient cache consistency supported by interconnect hardware
- Memory access cost
  - Remote = 2-3 x Local

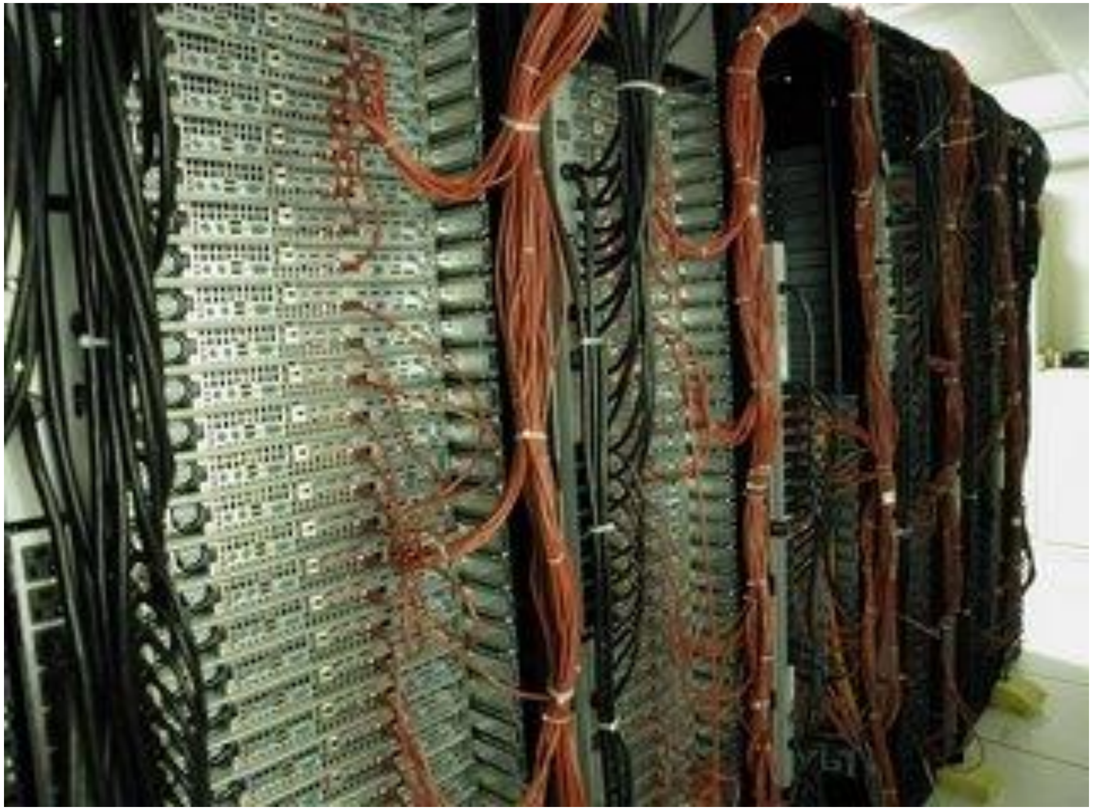
Hybrid Architectures
Cluster

- Independent homogeneous server nodes at a single site
- Interconnect options
  - LAN (cheap, slower)
  - Myrinet, Infiniband, etc. (faster, low-latency)
- Shared-disk alternatives:
  - NAS (Network-Attached Storage) -> low throughput
  - SAN (Storage-Area Network) -> high cost of ownership
- Advantages of cluster architecture:
  - Flexible and efficient as shared-memory
  - Extensible and available as shared-disk/shared-nothing

The Google Cluster

- ~ 15,000 nodes of homogeneous commodity PCs [BDH'03]
- Currently: over 5,000,000 servers world-wide





Parallel Architectures
Summary

- For small number of nodes:
  - Shared-memory -> load balancing
  - Shared-disk/Shared-nothing -> extensibility
  - SAN w/ Shared-disk -> simple administration
- For large number of nodes:
  - NUMA (~ 100 nodes)
  - Cluster (~ 1000 nodes)
  - Efficiency + Simplicity of Shared-memory
  - Extensibility + Cost of Shared-disk/Shared-nothing

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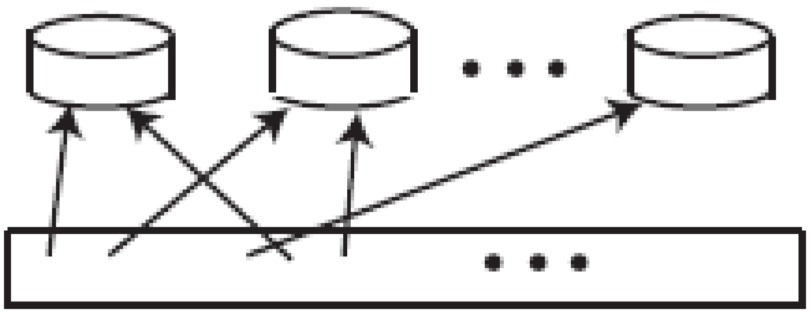
Parallel Data Placement

- Assume: shared-nothing (most general and common)
- To reduce communication costs, programs should be executed where the data reside.
- Similar to distributed DBMS's:
  - Fragmentation
- Differences:
  - Users are not associated with particular nodes.
  - Load balancing for large number of nodes is harder.
- How to place the data so that the system performance is maximized?
  - partitioning (min. response time) vs. clustering (min. total time)

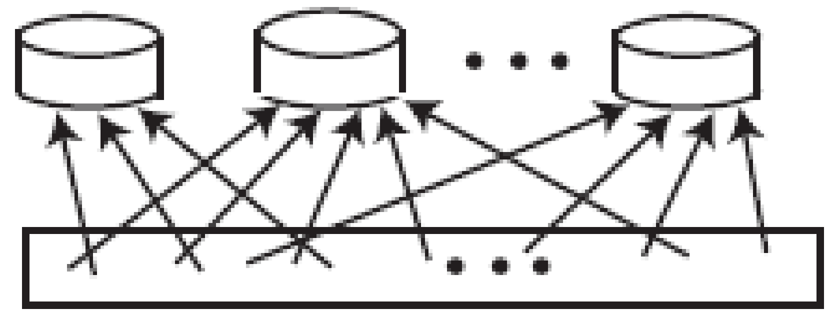
Data Partitioning

- Each relation is divided into *n* partitions that are mapped onto different disks.
- Implementation
  - Round-robin
    - Maps *i*-th element to node *i mod n*
    - Simple but only exact-match queries
  - Range
    - B-tree index
    - Supports range queries but large index
  - Hashing
    - Hash function
    - Only exact-match queries but small index

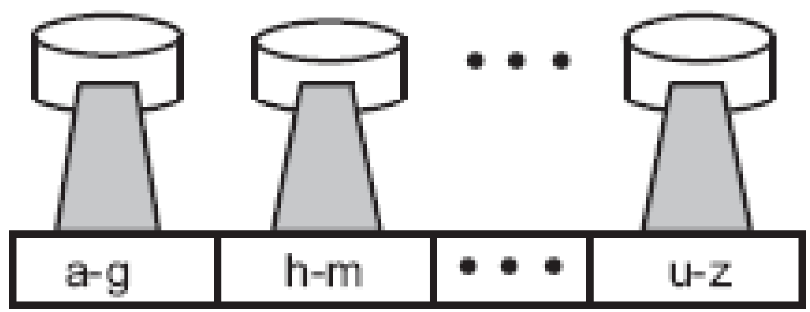
Full Partitioning Schemes



(a) Round-Robin



(b) Hashing

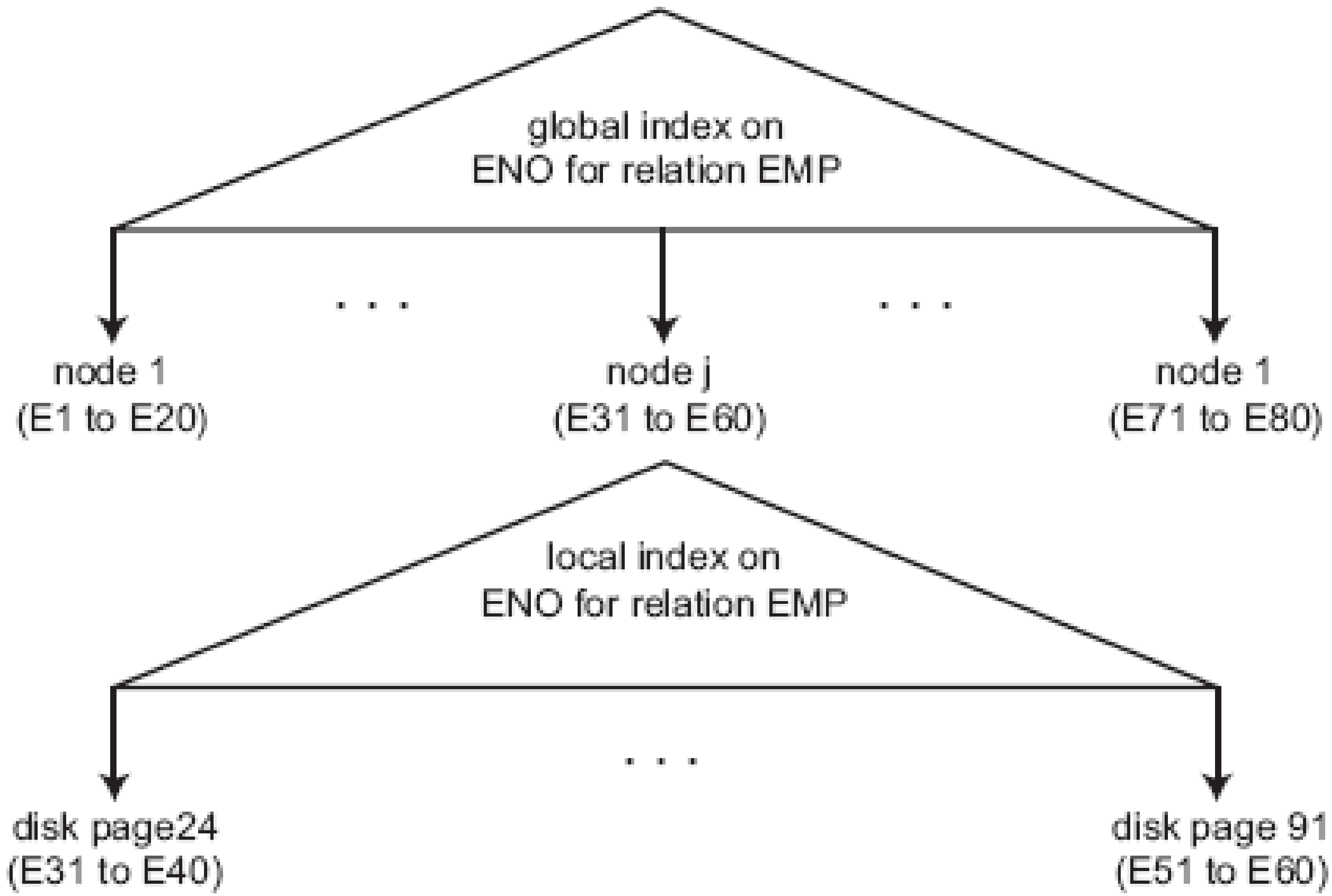


(c) Range

Variable Partitioning

- Each relation is partitioned across a certain number of nodes (instead of all), depending on its:
  - size
  - access frequency
- Periodic reorganization for load balancing
- Global index replicated on each node to provide associative access + Local indices

Global and Local Indices Example



Replicated Data Partitioning for H/A

- High-Availability requires data replication
  - simple solution is mirrored disks
    - hurts load balancing when one node fails
  - more elaborate solutions achieve load balancing
    - interleaved partitioning (Teradata)
    - chained partitioning (Gamma)

Replicated Data Partitioning for H/A

Interleaved Partitioning

Node	1	2	3	4
Primary copy	R1	R2	R3	R4
Backup copy	 r 2.3 r 3.2	r 1.1 r 3.3	r 1.2 r 2.1	r 1.3 r 2.2 r 3.1

Replicated Data Partitioning for H/A

Chained Partitioning

Node	1	2	3	4
Primary copy Backup copy	R1 r4	R2 r1	R3 r2	R4 r3

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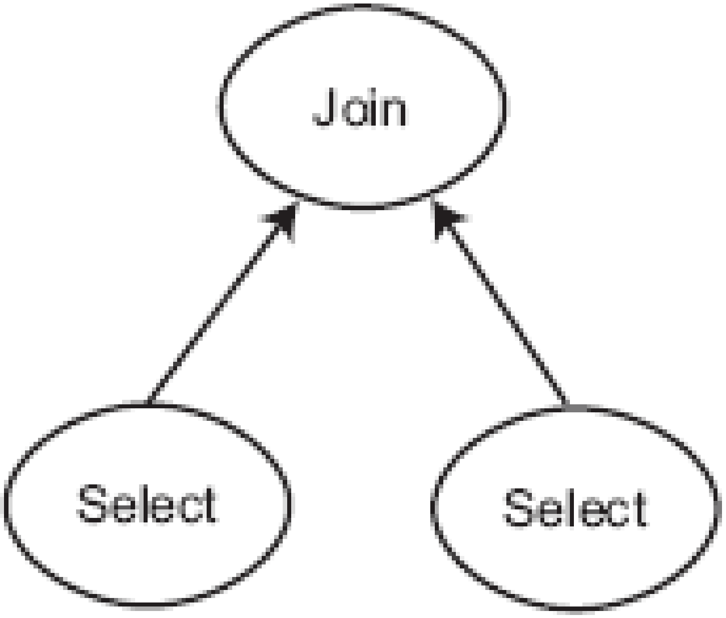
Parallel Query Processing

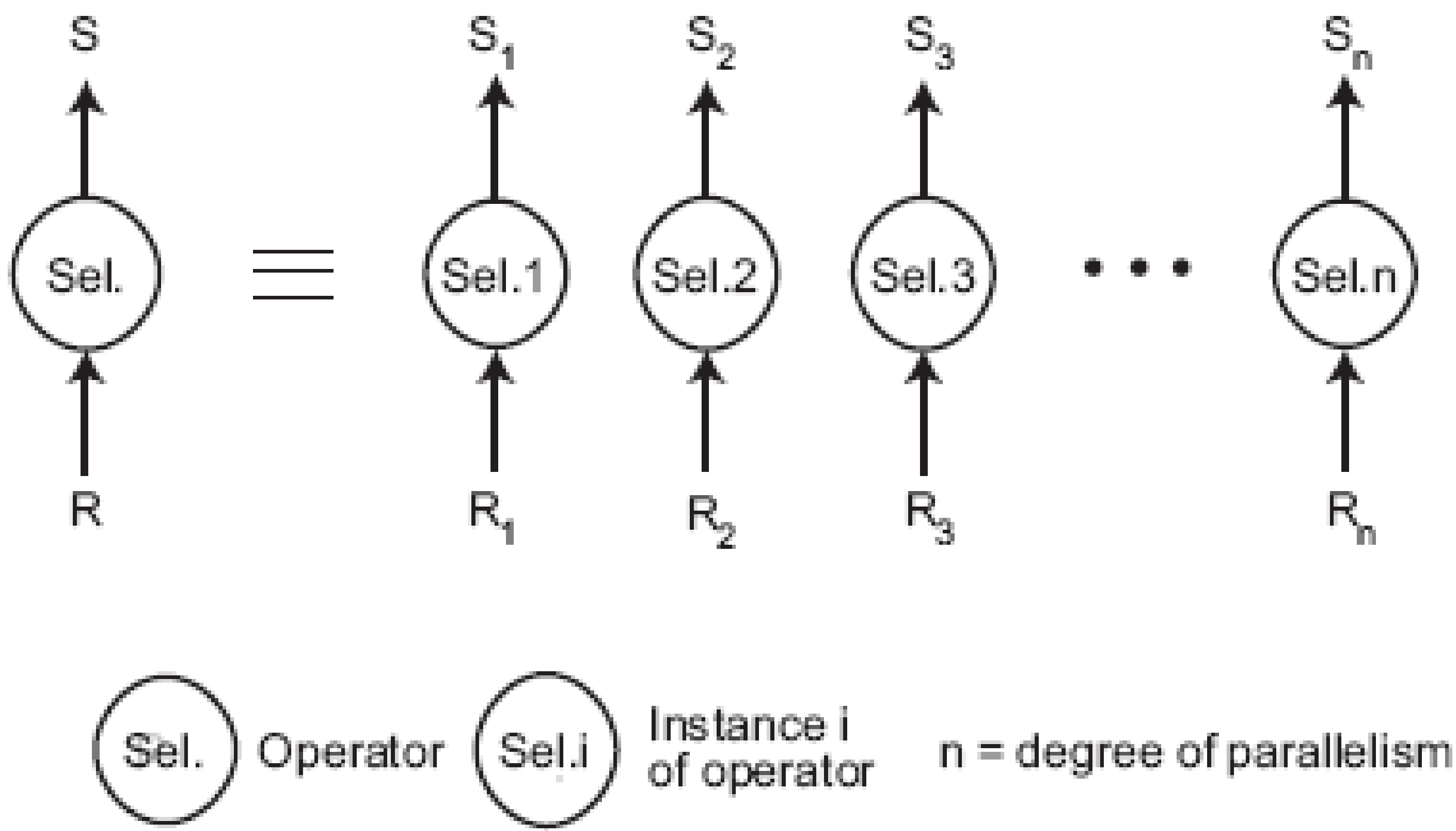
- Query parallelism
  - inter-query
  - intra-query
    - inter-operator
    - intra-operator

Inter-operator Parallelism
Example

- Pipeline parallelism
  - Join and Select execute in parallel.
- Independent parallelism
  - The two Select's execute in parallel.



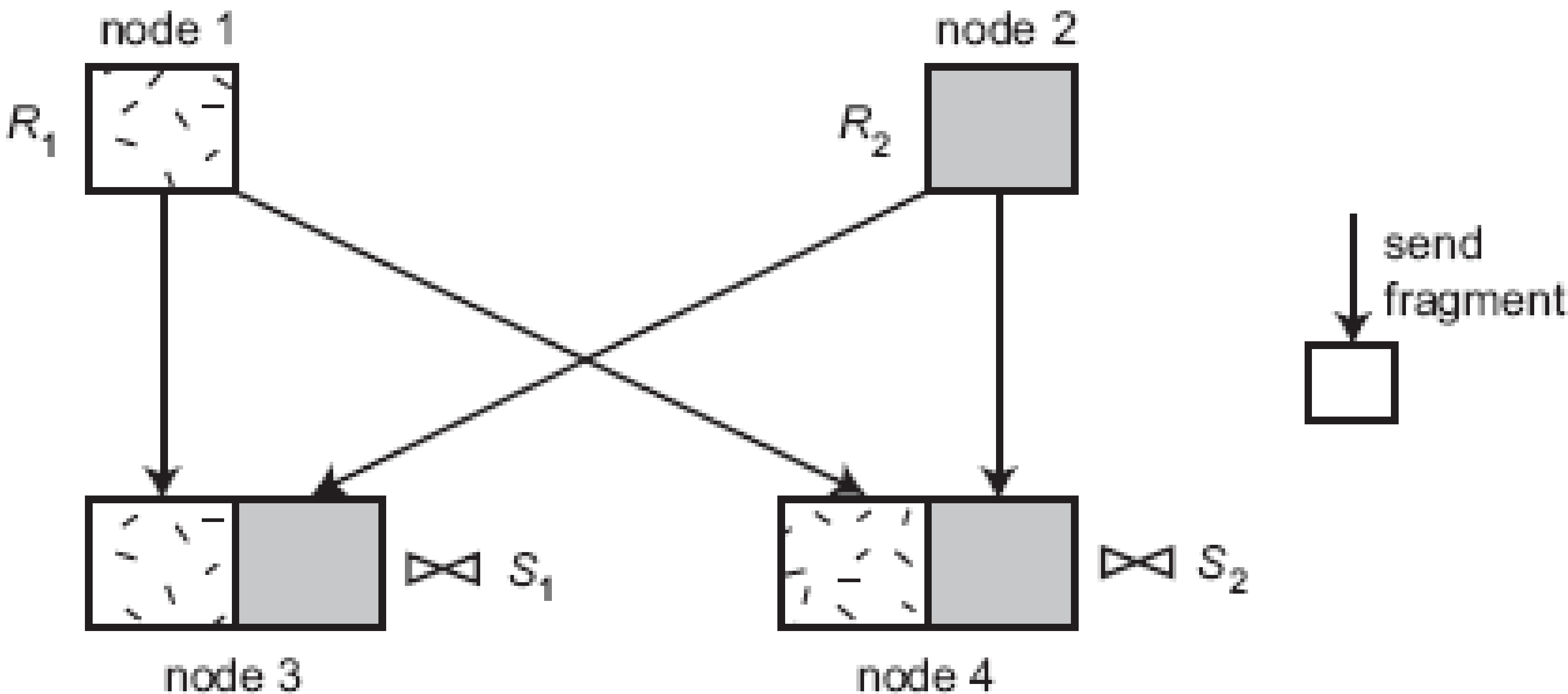
Intra-operator Parallelism
Example



Parallel Join Processing

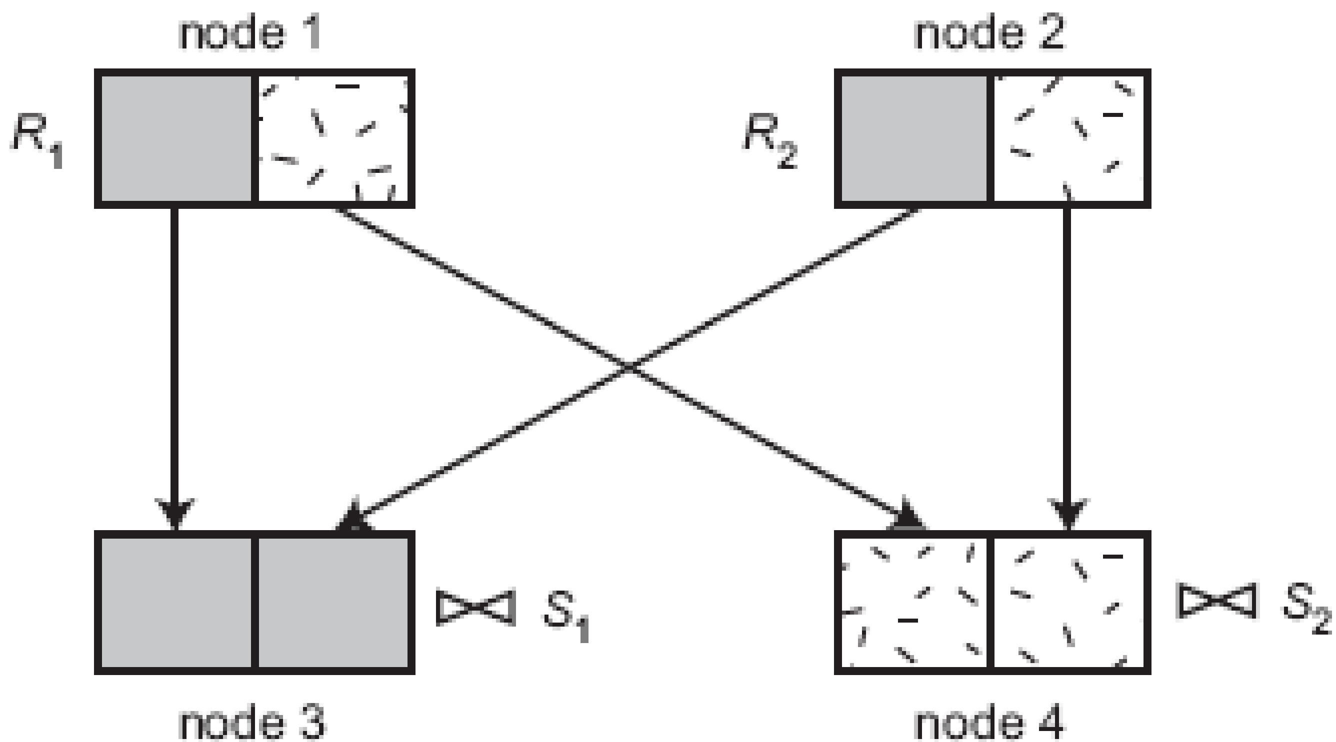
- Three basic algorithms for intra-operator parallelism:
  - Parallel Nested Loop Join:
    - no special assumptions
  - Parallel Associative Join:
    - assumption: one relation is declustered on join attribute + equi-join
  - Parallel Hash Join:
    - assumption: equi-join
- They also apply to other complex operators such as duplicate elimination, union, intersection, etc. with minor adaptation.

Parallel Nested Loop Join



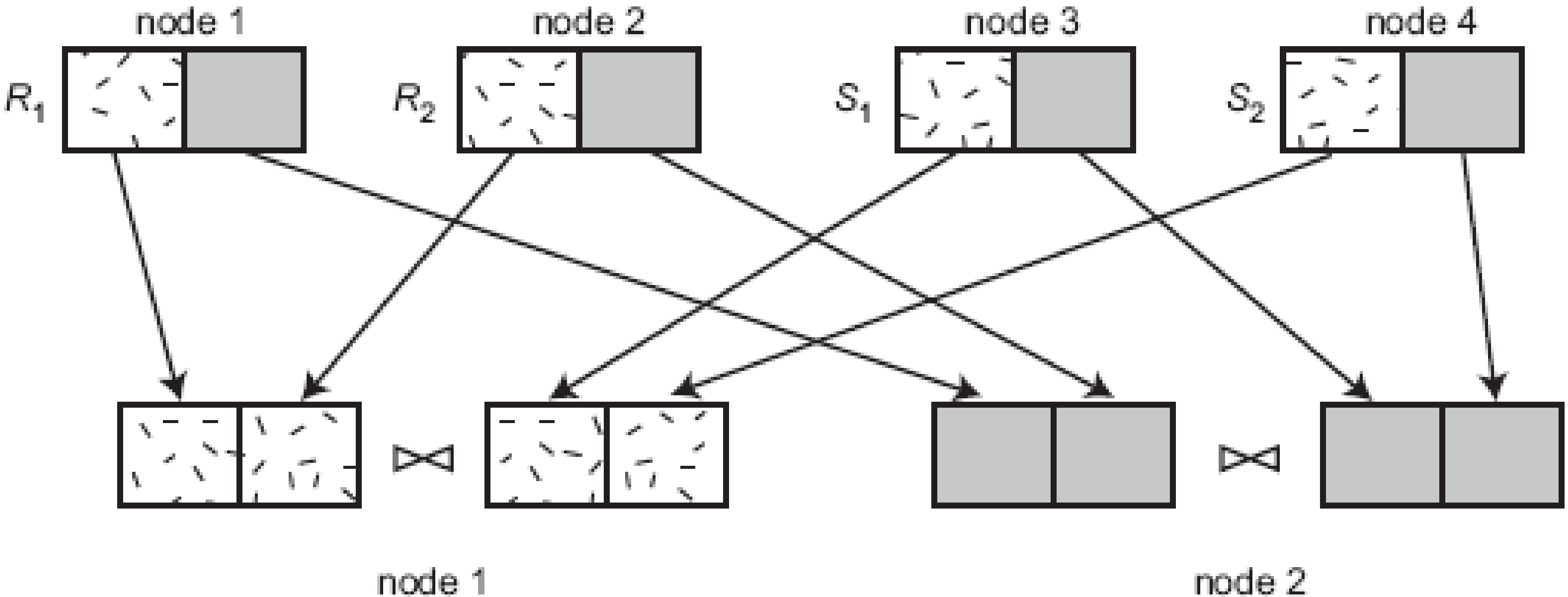
$$R \bowtie S \rightarrow \bigcup_{i=1}^{n} R \bowtie S_i$$

Parallel Associative Join



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

Parallel Hash Join



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

Which one to use?

- Use Parallel Associative Join where applicable (i.e., equi-join + partitioning based on the join attribute).

- Otherwise, compute total communication + processing cost for Parallel Nested Loop Join and Parallel Hash Join, and use the one with the smaller cost.

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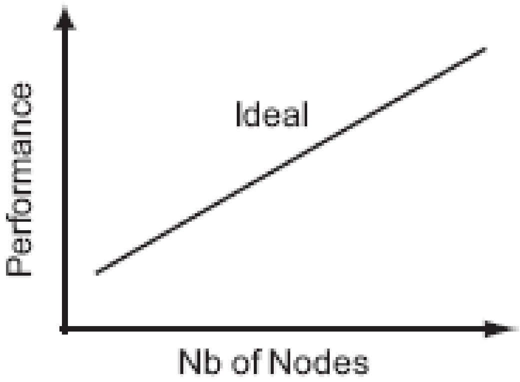
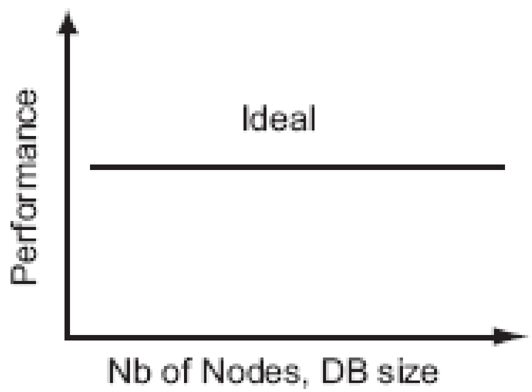
Three Barriers to Extensibility

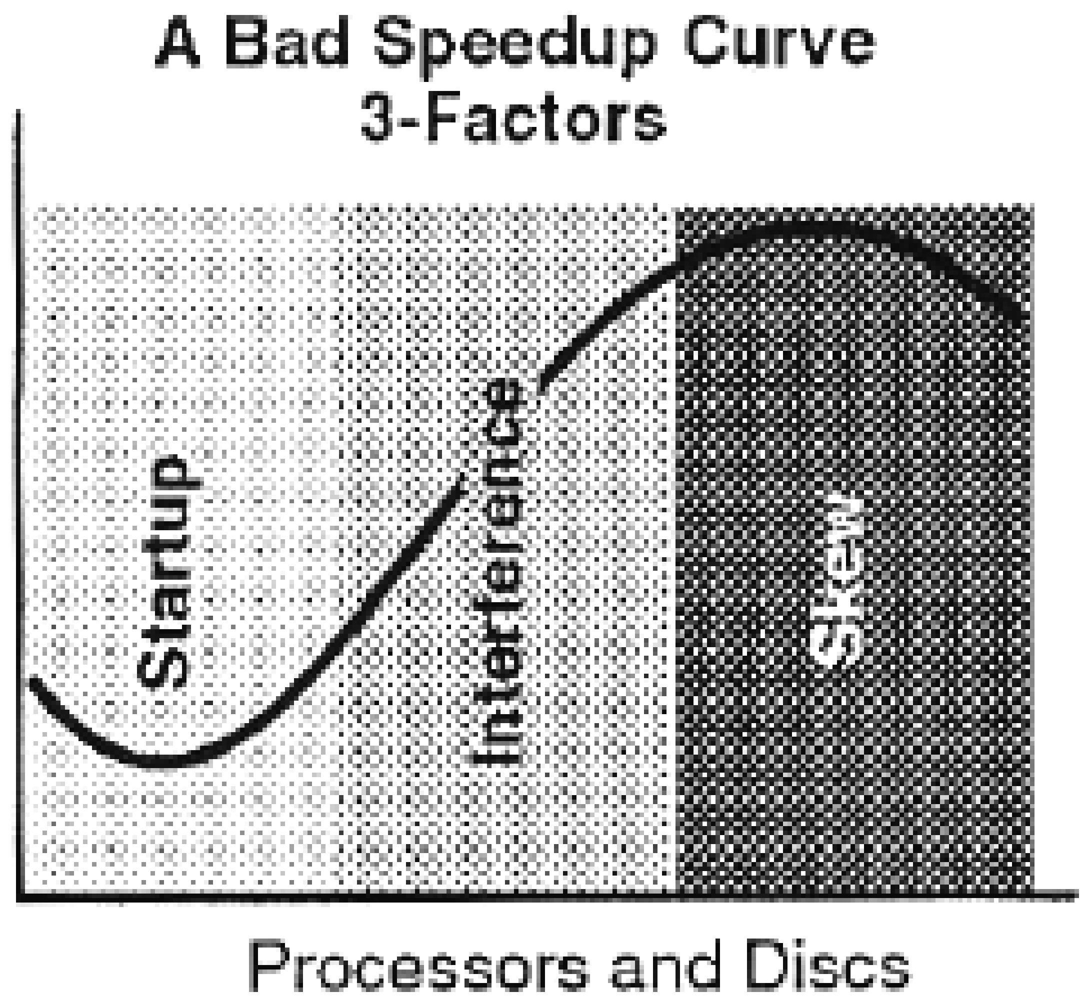
Ideal Curves



(a) Linear speedup



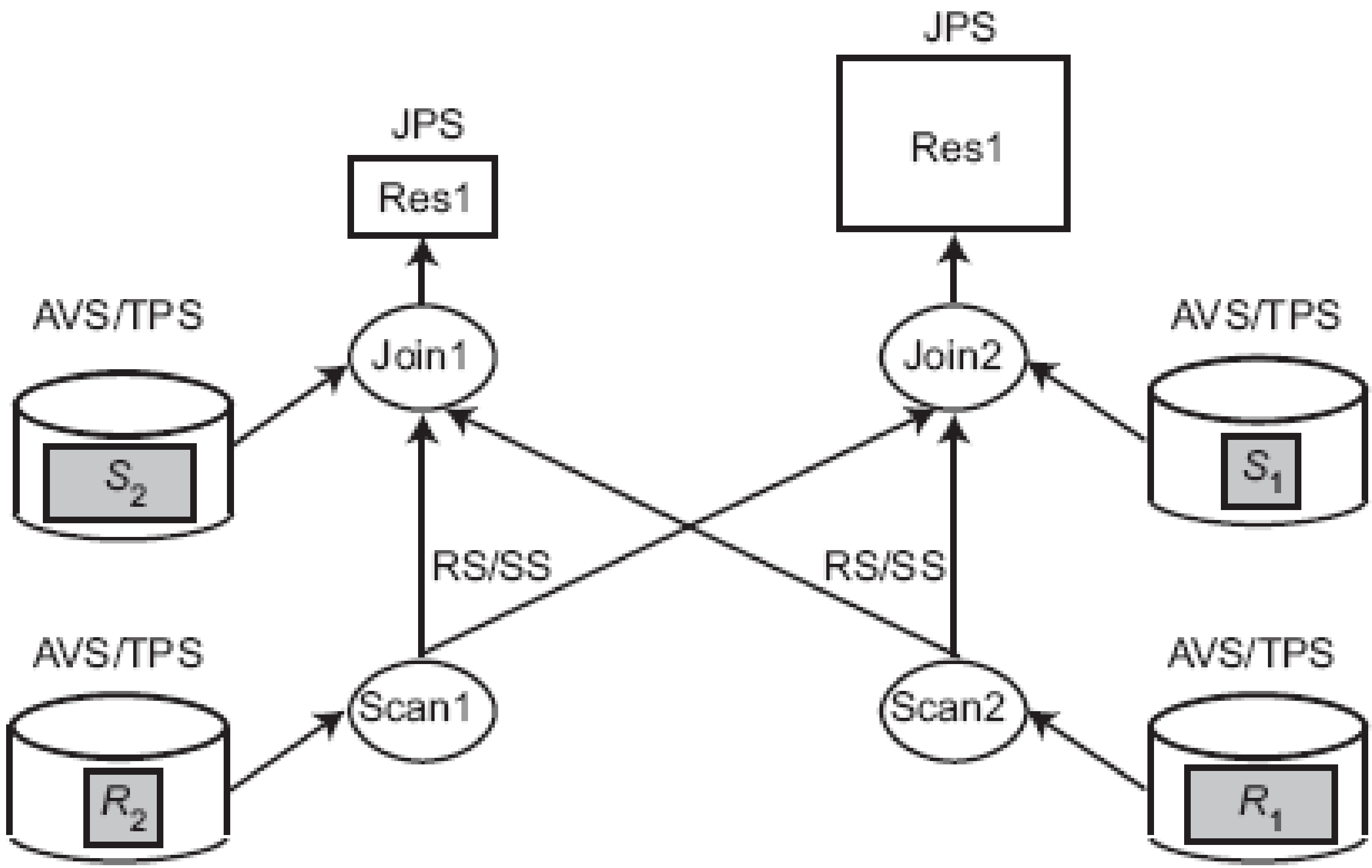
(b) Linear scaleup



Load Balancing

- Skewed data distributions in intra-operator parallelism make load balancing harder.
  - Attribute Value Skew (AVS)
  - Tuple Placement Skew (TPS)
  - Selectivity Skew (SS)
  - Redistribution Skew (RS)
  - Join Product Skew (JPS)

Data Skew Example



Load Balancing Techniques

- Intra-operator load balancing
  - Adaptive techniques (adapt to skew by dynamic load reallocation)
  - Specialized techniques (switch between specialized parallel join algorithms that can deal with skew)
- Inter-operator load balancing (increase pipeline parallelism)
- Intra-query load balancing (combine the two)