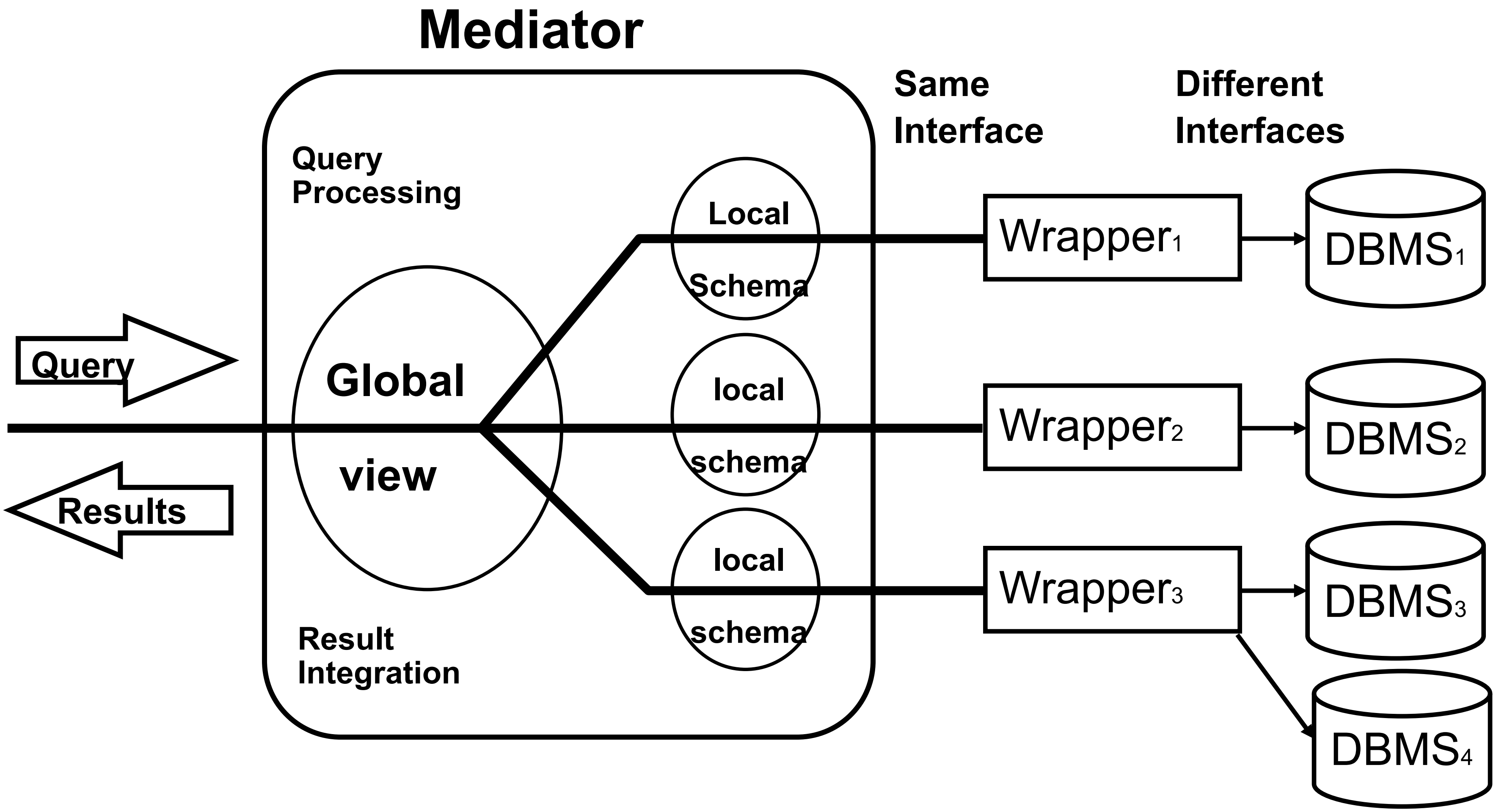
Outline

- Introduction & architectural issues
- Data distribution
- Distributed query processing
- Distributed query optimization
- Distributed transactions & concurrency control
- Distributed reliability
- Data replication
- Parallel database systems
- ❑ Database integration & querying
  - ❑ Query rewriting
  - ❑ Optimization issues
- ❑ Peer-to-Peer data management
- ❑ Stream data management
- ❑ MapReduce-based distributed data management

Multidatabase Query Processing

- Mediator/wrapper architecture
- MDB query processing architecture
- Query rewriting using views
- Query optimization and execution
- Query translation and execution

Mediator/Wrapper Architecture



Advantages of M/W Architecture

- Wrappers encapsulate the details of component DBMS
  - Export schema and cost information
  - Manage communication with Mediator
- Mediator provides a global view to applications and users
  - Single point of access
    - May be itself distributed
  - Can specialize in some application domain
  - Perform query optimization using global knowledge
  - Perform result integration in a single format

Issues in MDB Query Processing

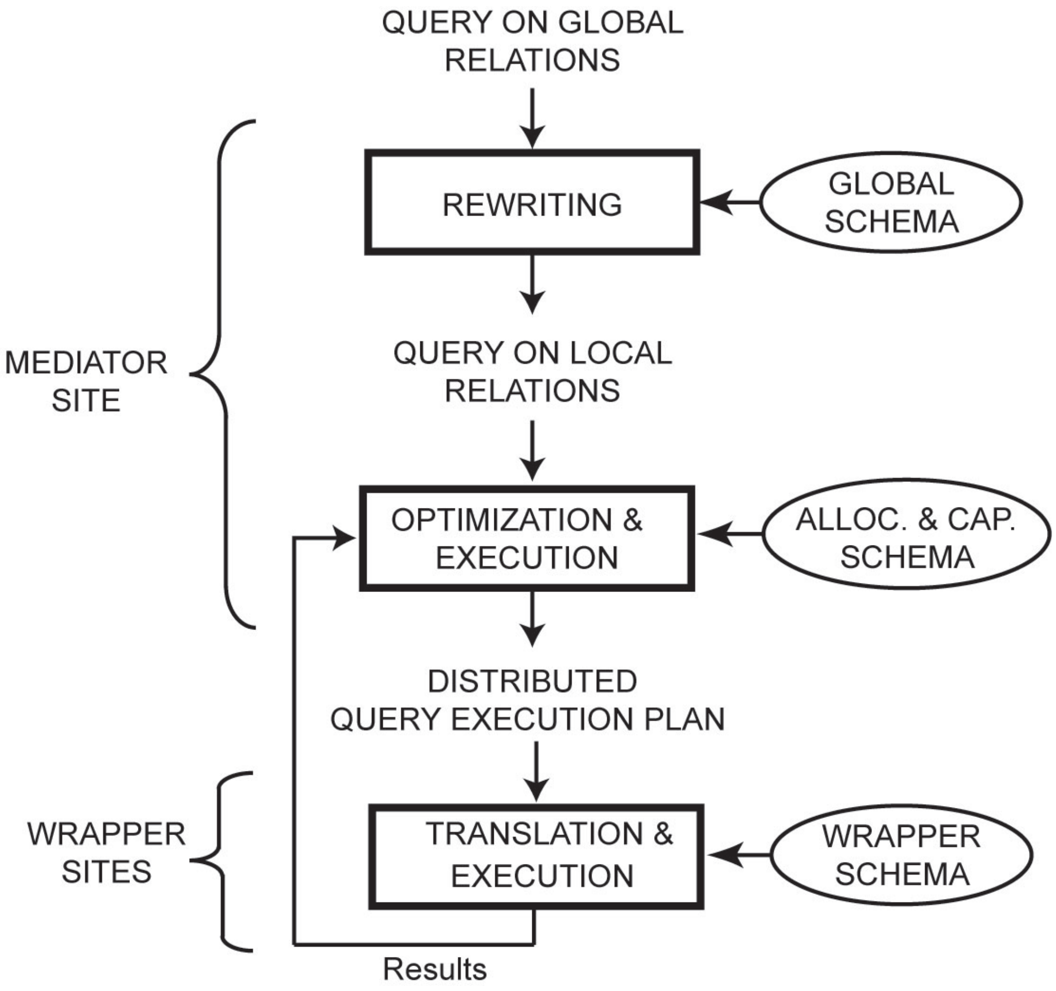
- Component DBMSs are autonomous and may range from full-fledge relational DBMS to flat file systems
  - Different computing capabilities
    - Prevents uniform treatment of queries across DBMSs
  - Different processing cost and optimization capabilities
    - Makes cost modeling difficult
  - Different data models and query languages
    - Makes query translation and result integration difficult
  - Different runtime performance and unpredictable behavior
    - Makes query execution difficult

Mediator Data Model

- Relational model
  - Simple and regular data structures
  - Mandatory schema
- Object model
  - Complex (graphs) and regular data structures
  - Mandatory schema
- Semi-structured (XML) model
  - Complex (trees) and irregular data structures
  - Optional schema (DTD or XSchema)

In this chapter, we use the relational model which is sufficient to explain MDB query processing

MDB Query Processing Architecture



Global/local correspondences

Allocation and capabilities

Local/DBMS mappings

Query Rewriting Using Views

- Views used to describe the correspondences between global and local relations
  - **Global As View**: the global schema is integrated from the local databases and each global relation is a view over the local relations
  - **Local As View**: the global schema is defined independently of the local databases and each local relation is a view over the global relations
- Query rewriting best done with Datalog, a logic-based language
  - More expressive power than relational calculus
  - Inline version of relational domain calculus

Datalog Terminology

- Conjunctive (SPJ) query: a rule of the form
  - $Q(T) :- R_1(T_1), \ldots R_n(T_n)$
  - $Q(T)$: head of the query denoting the result relation
  - $R_1(T_1), \ldots R_n(T_n)$: subgoals in the body of the query
  - $R_1, \ldots R_n$: predicate names corresponding to relation names
  - $T_1, \ldots T_n$: refer to tuples with variables and constants
  - Variables correspond to attributes (as in domain calculus)
  - "-" means unnamed variable
- Disjunctive query = n conjunctive queries with same head predicate

Datalog Example

With EMP(ENAME,TITLE,CITY) and
ASG(ENAME,PNAME,DUR)

```
SELECT   ENAME,TITLE, PNAME
FROM     EMP, ASG
WHERE    EMP.ENAME = ASG.ENAME
AND      TITLE = "Programmer" OR DUR=24
```

Q(ename,title,pname) :- Emp(ename,title,-)
Asg(ename,pname,-),
title = "Programmer".

Q(ename,title,pname) :- Emp(ename,title,-)
Asg(ename,pname,24).

Rewriting in GAV

- Global schema similar to that of homogeneous DDBMS
  - Local relations can be fragments
  - But no completeness: a tuple in the global relation may not exist in local relations
    - Yields incomplete answers
  - And no disjointness: the same tuple may exist in different local databases
    - Yields duplicate answers
- Rewriting (*unfolding*)
  - Similar to query modification
    - Apply view definition rules to the query and produce a union of conjunctive queries, one per rule application
    - Eliminate redundant queries

GAV Example Schema

Global relations

EMP(ENAME,CITY)

ASG(ENAME,PNAME,TITLE, DUR)

Local relations

EMP1(ENAME,TITLE,CITY)

EMP2(ENAME,TITLE,CITY)

ASG1(ENAME,PNAME,DUR)

Emp(ename,city) :-	*Emp1(ename,title,city).*	(r_1)
Emp(ename,city) :-	*Emp2(ename,title,city).*	(r_2)
Asg(ename,pname,title,dur) :-	*Emp1(ename,title,city),* *Asg1(ename,pname,dur).*	(r_3)
Asg(ename,pname,title,dur) :-	*Emp2(ename,title,city),* *Asg1(ename,pname,dur).*	(r_4)

GAV Example Query

Let *Q*: name and project for employees in Paris

Q(e,p) :- Emp(e,"Paris"), Asg(e,p,-,-).

Unfolding produces Q'

Q'(e,p) :- Emp1(e,-,"Paris"), Asg1(e,p,-,). (q_1)

Q'(e,p) :- Emp2(e,-,"Paris"), Asg1(e,p,-,). (q_2)

where

q_1 is obtained by applying r_3 only or both r_1 and r_3

In the latter case, there are redundant queries

same for q_2 with r_2 only or both r_2 and r_4

Rewriting in LAV

- More difficult than in GAV
  - No direct correspondence between the terms in GS (emp, ename) and those in the views (emp1, emp2, ename)
  - There may be many more views than global relations
  - Views may contain complex predicates to reflect the content of the local relations
    - e.g. a view Emp3 for only programmers
- Often not possible to find an equivalent rewriting
  - Best is to find a *maximally-contained query* which produces a maximum subset of the answer
    - e.g. Emp3 can only return a subset of the employees

Rewriting Algorithms

- The problem to find an equivalent query is NP-complete in the number of views and number of subgoals of the query
- Thus, algorithms try to reduce the numbers of rewritings to be considered
- Three main algorithms
  - **Bucket**
  - Inverse rule
  - MiniCon

LAV Example Schema

Local relations	Global relations
EMP1(ENAME,TITLE,CITY)	EMP(ENAME,CITY)
EMP2(ENAME,TITLE,CITY)	ASG(ENAME,PNAME,TITLE, DUR)
ASG1(ENAME,PNAME,DUR)	

Emp1(ename,title,city) :- Emp(ename,city), (r_1)
Asg(ename,-,title,-).

Emp2(ename,title,city) :- Emp(ename,city), (r_2)
Asg(ename,-,title,-).

Asg1(ename,pname,dur) :-
Asg(ename,pname,-,dur) (r_3)

Bucket Algorithm

- Considers each predicate of the query Q independently to select only the relevant views

Step 1

- Build a bucket b for each subgoal q of Q that is not a comparison predicate
- Insert in b the heads of the views which are relevant to answer q

Step 2

- For each view V of the Cartesian product of the buckets, produce a conjunctive query
  - If it is contained in Q, keep it

- The rewritten query is a union of conjunctive queries

LAV Example Query

Let Q be *Q(e,p) :- Emp(e, "Paris"), Asg(e,p,-,-).*

Step1: we obtain 2 buckets (one for each subgoal of Q)

b_1 = *Emp1(ename,title',city), Emp2(ename,title',city)*

b_2 = *Asg1(ename,pname,dur')*

(the prime variables (title' and dur') are not useful)

Step2: produces

Q'(e,p) :- Emp1(e,-, "Paris"), Asg1(e,p,-,). (q_1)

Q'(e,p) :- Emp2(e,-, "Paris"), Asg1(e,p,-,). (q_2)

Query Optimization and Execution

- Takes a query expressed on local relations and produces a distributed QEP to be executed by the wrappers and mediator
- Three main problems
  - Heterogeneous cost modeling
    - To produce a global cost model from component DBMS
  - Heterogeneous query optimization
    - To deal with different query computing capabilities
  - Adaptive query processing
    - To deal with strong variations in the execution environment

Heterogeneous Cost Modeling

- Goal: determine the cost of executing the subqueries at component DBMS
- Three approaches
  - Black-box: treats each component DBMS as a black-box and determines costs by running test queries
  - Customized: customizes an initial cost model
  - Dynamic: monitors the run-time behavior of the component DBMS and dynamically collect cost information

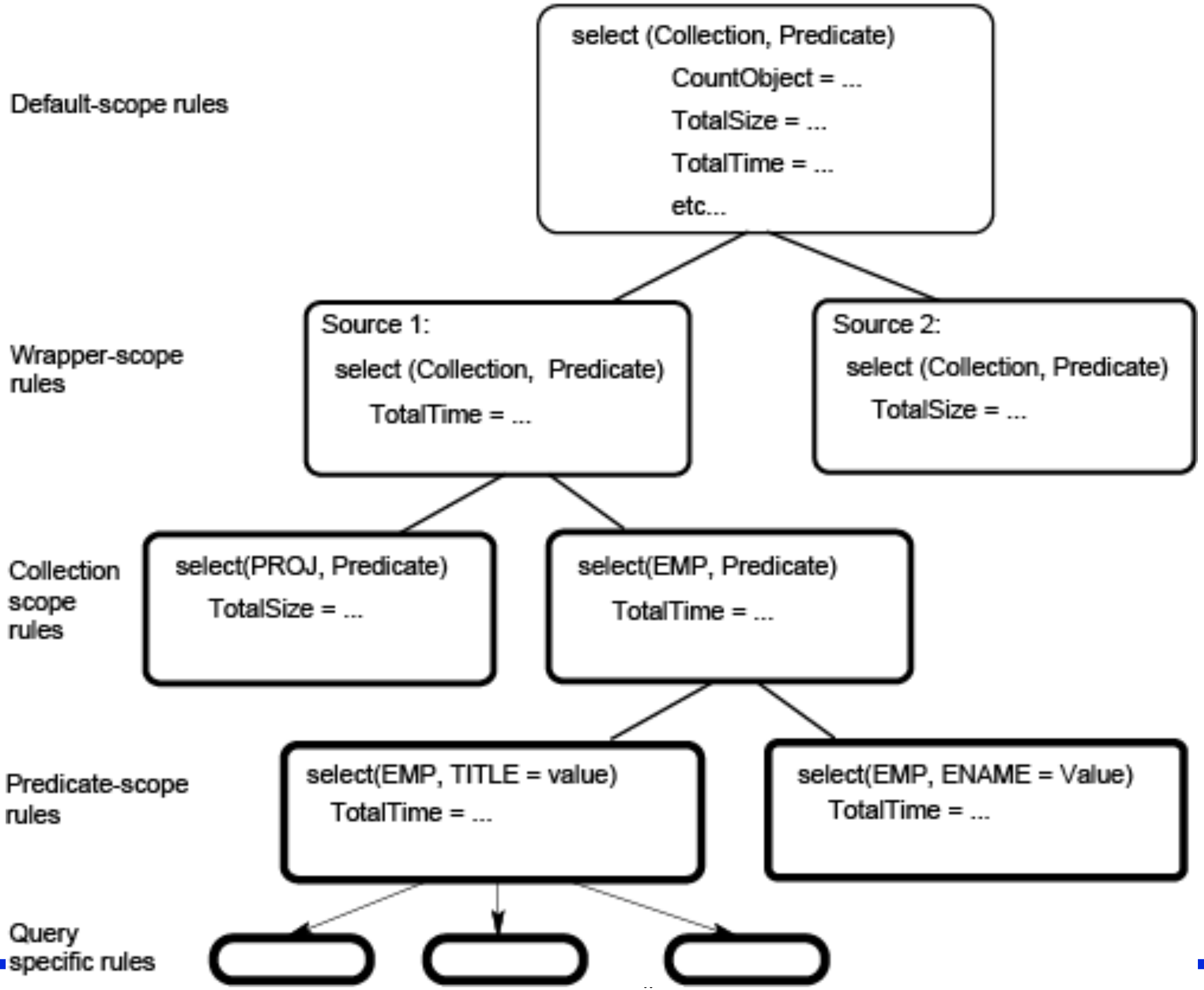
Black-box Approach

- Define a logical cost expression
    - *Cost* = *init cost* + *cost to find qualifying tuples* + *cost to process selected tuples*
        - The terms will differ much with different DBMS
- Run probing queries on component DBMS to compute cost coefficients
    - Count the numbers of tuples, measure cost, etc.
    - Special case: sample queries for each class of important queries
        - Use of classification to identify the classes
- Problems
    - The instantiated cost model (by probing or sampling) may change over time
    - The logical cost function may not capture important details of component DBMS

Customized Approach

- Relies on the wrapper (i.e. developer) to provide cost information to the mediator
- Two solutions
  - Wrapper provides the logic to compute cost estimates
    - Access_cost = reset + (card-1)*advance
      - reset = time to initiate the query and receive a first tuple
      - advance = time to get the next tuple (advance)
      - card = result cardinality
  - Hierarchical cost model
    - Each node associates a query pattern with a cost function
    - The wrapper developer can give cost information at various levels of details, depending on knowledge of the component DBMS

Hierarchical Cost Model



Default-scope rules

select (Collection, Predicate)
CountObject = ...
TotalSize = ...
TotalTime = ...
etc...

Wrapper-scope rules

Source 1:
select (Collection, Predicate)
TotalTime = ...

Source 2:
select (Collection, Predicate)
TotalSize = ...

Collection scope rules

select(PROJ, Predicate)
TotalSize = ...

select(EMP, Predicate)
TotalTime = ...

Predicate-scope rules

select(EMP, TITLE = value)
TotalTime = ...

select(EMP, ENAME = Value)
TotalTime = ...

Query specific rules

Dynamic Approach

- Deals with execution environment factors which may change
  - Frequently: load, throughput, network contention, etc.
  - Slowly: physical data organization, DB schemas, etc.
- Two main solutions
  - Extend the sampling method to consider some new queries as samples and correct the cost model on a regular basis
  - Use adaptive query processing which computes cost during query execution to make optimization decisions

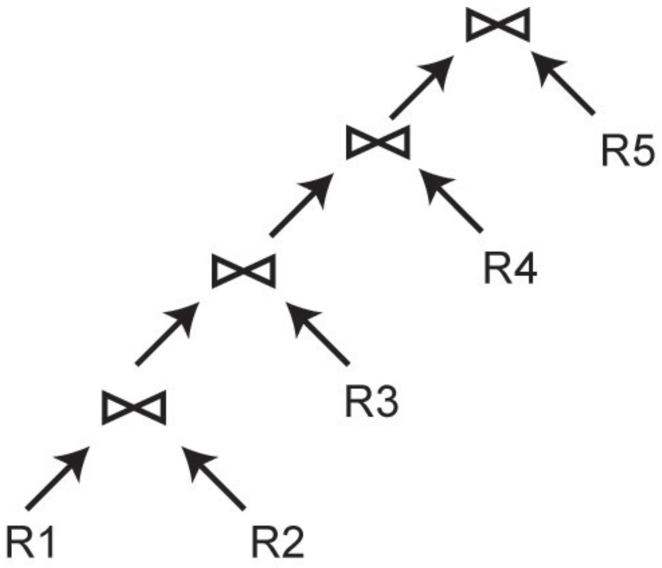
Heterogeneous Query Optimization

- Deals with heterogeneous capabilities of component DBMS
  - One DBMS may support complex SQL queries while another only simple select on one fixed attribute
- Two approaches, depending on the M/W interface level
  - Query-based
    - All wrappers support the same query-based interface (e.g. ODBC or SQL/MED) so they appear homogeneous to the mediator
    - Capabilities not provided by the DBMS must be supported by the wrappers
  - Operator-based
    - Wrappers export capabilities as compositions of operators
    - Specific capabilities are available to mediator

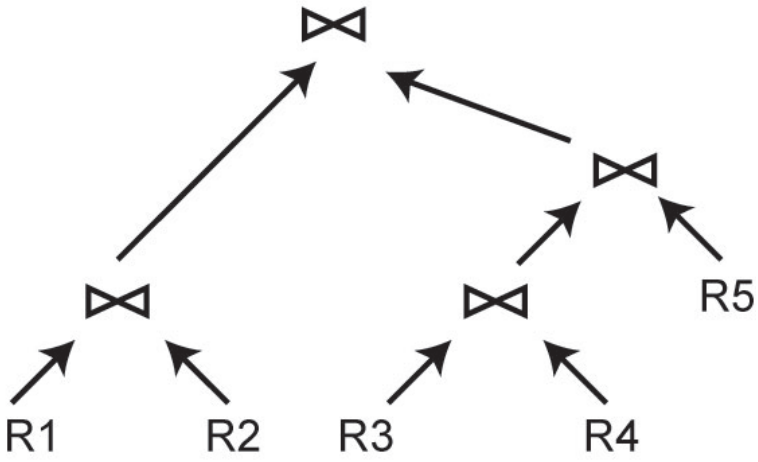
Query-based Approach

- We can use 2-step query optimization with a heterogeneous cost model
  - But centralized query optimizers produce left-linear join trees whereas in MDB, we want to push as much processing in the wrappers, i.e. exploit bushy trees
- Solution: convert a left-linear join tree into a bushy tree such that
  - The initial total cost of the QEP is maintained
  - The response time is improved
- Algorithm
  - Iterative improvement of the initial left-linear tree by moving down subtrees while response time is improved

Left Linear vs Bushy Join Tree



(a) Left Linear Join Tree



(b) Bushy Join Tree

Operator-based Approach

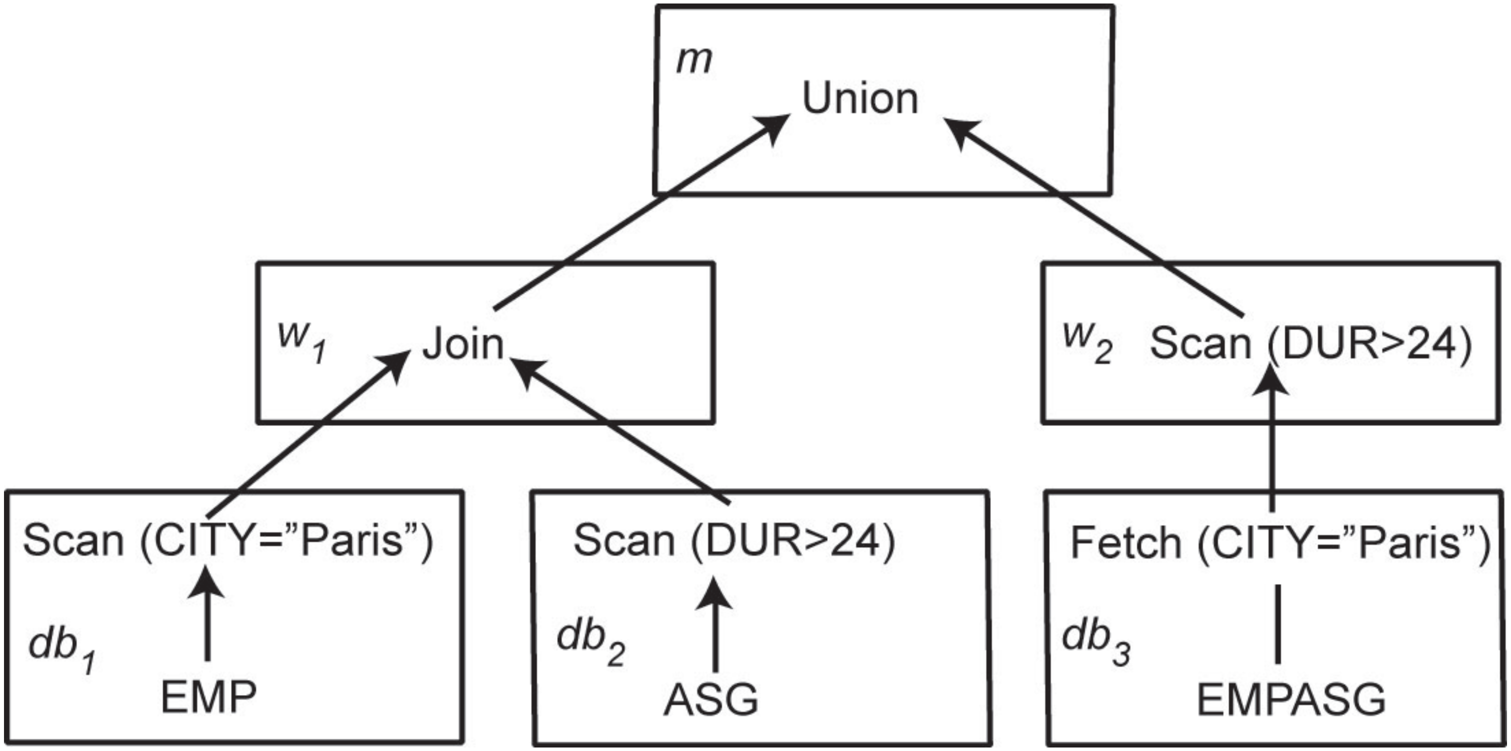
- M/W communication in terms of subplans
- Use of planning functions (Garlic)
  - Extension of cost-based centralized optimizer with new operators
    - Create temporary relations
    - Retrieve locally stored data
    - Push down operators in wrappers
    - accessPlan and joinPlan rules
  - Operator nodes annotated with
    - Location of operands, materialization, etc.

Planning Functions Example

- Consider 3 component databases with 2 wrappers:
  - $w_1 .db_1$: EMP(ENO,ENAME,CITY)
  - $w_1 .db_2$: ASG(ENO,PNAME,DUR)
  - $w_2 . db_3$: EMPASG(ENAME,CITY,PNAME,DUR)
- Planning functions of w_1
  - AccessPlan (R: rel, A: attlist, P: pred) = scan(R, A, P, db(R))
  - JoinPlan (R_1, R_2: rel, A: attlist, P: joinpred) = join(R_1, R_2, A, P)
    - condition: db(R_1) $\neq$ db(R_2)
    - implemented by w_1
- Planning functions of w_2
  - AccessPlan (R: rel, A: attlist, P: pred) = fetch(city=c)
    - condition: (city=c) included in P
  - AccessPlan (R: rel, A: attlist, P: pred) = scan(R, A, P, db(R))
    - implemented by w_2

Heterogenous QEP

```
SELECT    ENAME,PNAME,DUR
FROM      EMPASG
WHERE     CITY = "Paris" AND DUR>24
```

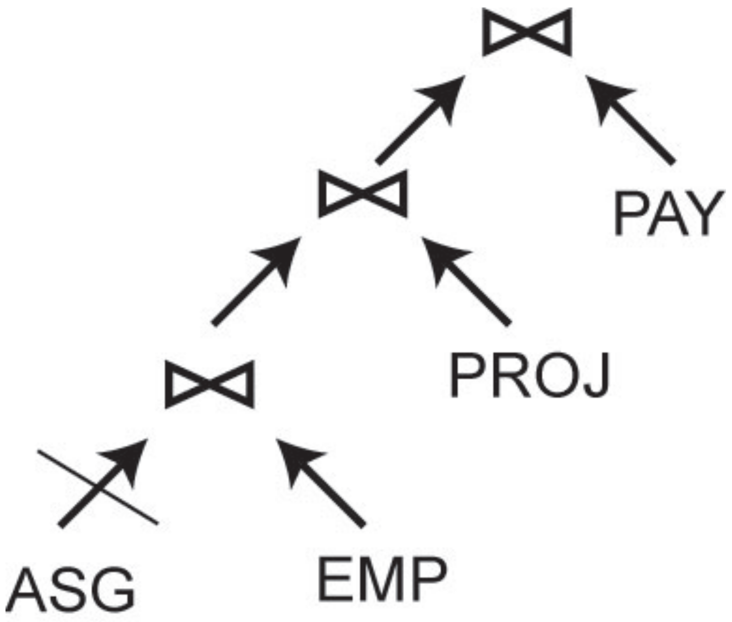


Adaptive Query Processing - Motivations

- Assumptions underlying heterogeneous query optimization
  - The optimizer has sufficient knowledge about runtime
    - Cost information
  - Runtime conditions remain stable during query execution
- Appropriate for MDB systems with few data sources in a controlled environment
- Inappropriate for changing environments with large numbers of data sources and unpredictable runtime conditions

Example: QEP with Blocked Operator

- Assume ASG, EMP, PROJ and PAY each at a different site
- If ASG site is down, the entire pipeline is blocked
- However, with some reorganization, the join of EMP and PAY could be done while waiting for ASG



Adaptive Query Processing – Definition

- A query processing is adaptive if it receives information from the execution environment and determines its behavior accordingly
  - Feed-back loop between optimizer and runtime environment
  - Communication of runtime information between mediator, wrappers and component DBMS
    - Hard to obtain with legacy databases
- Additional components
  - Monitoring, assessment, reaction
  - Embedded in control operators of QEP
- Tradeoff between reactiveness and overhead of adaptation

Adaptive Components

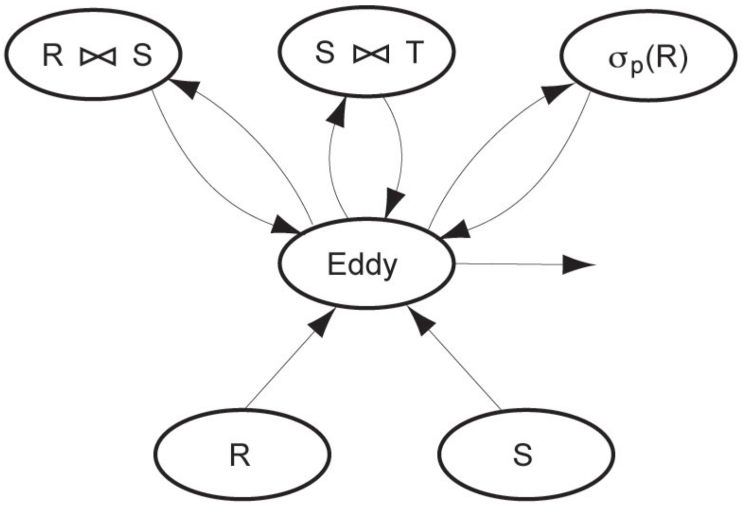
- Monitoring parameters (collected by sensors in QEP)
  - Memory size
  - Data arrival rates
  - Actual statistics
  - Operator execution cost
  - Network throughput
- Adaptive reactions
  - Change schedule
  - Replace an operator by an equivalent one
  - Modify the behavior of an operator
  - Data repartitioning

Eddy Approach

- Query compilation: produces a tuple $\langle D, P, C, \text{Eddy}\rangle$
  - *D*: set of data sources (e.g. relations)
  - *P*: set of predicates
  - *C*: ordering constraints to be followed at runtime
  - Eddy: *n*-ary operator between D and P
- Query execution: operator ordering on a tuple basis using Eddy
  - On-the-fly tuple routing to operators based on cost and selectivity
  - Change of join ordering during execution
    - Requires symmetric join algorithms such Ripple joins

QEP with Eddy

- $D = \{R, S, T\}$
- $P = \{\sigma_P(R), R \text{ JN}_1 S, S \text{ JN}_2 T)$
- $C = \{S < T\}$ where < imposes S tuples to probe T tuples using an index on join attribute
  - Access to T is wrapped by JN



Result tuples

Query Translation and Execution

- Performed by wrappers using the component DBMS
  - Conversion between common interface of mediator and DBMS-dependent interface
    - Query translation from wrapper to DBMS
    - Result format translation from DBMS to wrapper
  - Wrapper has the local schema exported to the mediator (in common interface) and the mapping to the DBMS schema
  - Common interface can be query-based (e.g. ODBC or SQL/MED) or operator-based
- In addition, wrappers can implement operators not supported by the component DBMS, e.g. join

Wrapper Placement

- Depends on the level of autonomy of component DB
- Cooperative DB
  - May place wrapper at component DBMS site
  - Efficient wrapper-DBMS com.
- Uncooperative DB
  - May place wrapper at mediator
  - Efficient mediator-wrapper com.
- Impact on cost functions