Lecture 7:
Query Execution and Optimization

Tuesday, February 20, 2007

Outline

- Relational Algebra: Chapter 4
- Query evaluation: Chapters 12, 13, 14

The WHAT and the HOW

- In SQL we write WHAT we want to get form the data
- The database system needs to figure out HOW to get the data we want
- The passage from WHAT to HOW goes through the Relational Algebra

SQL = WHAT

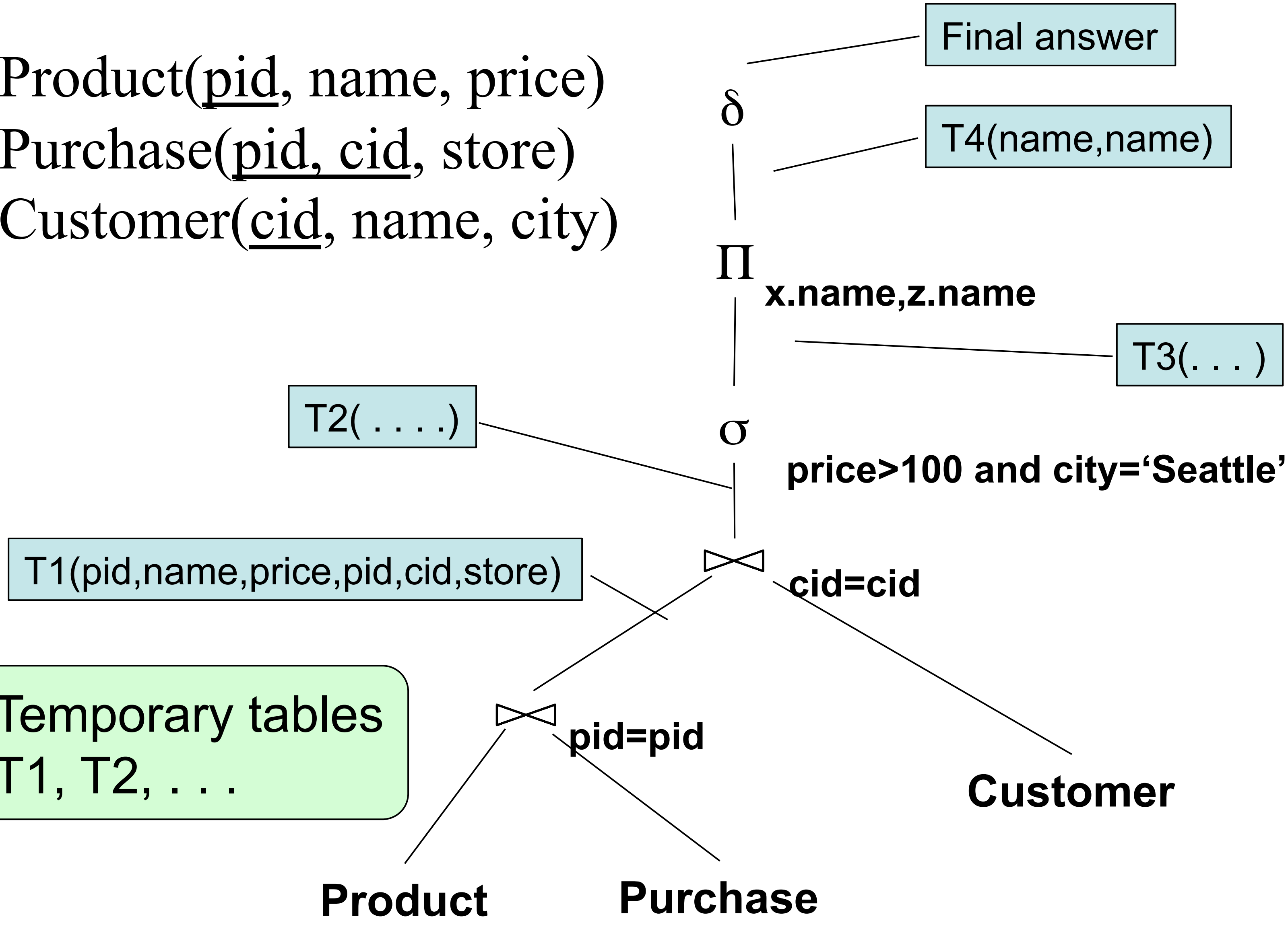
Product(pid, name, price)
Purchase(pid, cid, store)
Customer(cid, name, city)

```
SELECT DISTINCT x.name, z.name
FROM Product x, Purchase y, Customer z
WHERE x.pid = y.pid and y.cid = y.cid and
         x.price > 100 and z.city = ‘Seattle’
```

It’s clear WHAT we want, unclear HOW to get it

Relational Algebra = HOW

Product(pid, name, price)
Purchase(pid, cid, store)
Customer(cid, name, city)



Final answer

δ

T4(name,name)

$\Pi_{\text{x.name,z.name}}$

T3(. . .)

T2(. . . .)

$\sigma_{\text{price>100 and city='Seattle'}}$

T1(pid,name,price,pid,cid,store)

$\bowtie_{\text{cid=cid}}$

$\bowtie_{\text{pid=pid}}$

Customer

Product

Purchase

Temporary tables
T1, T2, . . .

Relational Algebra = HOW

The order is now clearly specified:

Iterate over PRODUCT…
…join with PURCHASE…
…join with CUSTOMER…
…select tuples with Price>100 and City=‘Seattle’…
…eliminate duplicates…
…and that’s the final answer !

Plan for Today

- Relational Algebra
- Implementation of physical operators

Next lecture:

- Optimizations

Sets v.s. Bags

- Sets: {a,b,c}, {a,d,e,f}, { }, . . .
- Bags: {a, a, b, c}, {b, b, b, b, b}, . . .

Relational Algebra has two flavors:

- Over sets: theoretically elegant but limited
- Over bags: needed to expresses SQL queries

We discuss set semantics, and mention bag semantics only where needed

Relational Algebra (1/3)

The Basic Five operators:

- Union: $\cup$
- Difference: -
- Selection: σ
- Projection: Π
- Join: $\bowtie$

Relational Algebra (2/3)

Derived or auxiliary operators:

- Intersection, complement
- Variations of joins
  - natural, equi-join, theta join, semi-join, cartesian product
- Renaming: ρ

Relational Algebra (3/3)

Extensions for bags:

- Duplicate elimination: δ
- Group by: γ
- Sorting: τ

Union and Difference

$R1 \cup R2$

$R1 - R2$

What do they mean over bags ?

What about Intersection ?

- It is a derived operator

$$\boxed{R1 \cap R2 = R1 - (R1 - R2)}$$

- Also expressed as a join (will see later)

Selection

- Returns all tuples which satisfy a condition

$$\boxed{\sigma_c(R)}$$

- Examples
  - $\sigma_{\text{Salary > 40000}}$ (Employee)
  - $\sigma_{\text{name = “Smith”}}$ (Employee)
- The condition c can be =, <, ≤, >, ≥, <>

SSN	Name	Salary
1234545	John	200000
5423341	Smith	600000
4352342	Fred	500000

$\sigma_{\text{Salary > 40000}}$ (Employee)

SSN	Name	Salary
5423341	Smith	600000
4352342	Fred	500000

Projection

- Eliminates columns

$$\boxed{\Pi_{A1,\ldots,An}(R)}$$

- Example: project social-security number and names:
  - $\Pi_{\text{SSN, Name}}$ (Employee)
  - Output schema: Answer(SSN, Name)

Semantics differs over set or over bags

SSN	Name	Salary
1234545	John	200000
5423341	John	600000
4352342	John	200000

$\Pi_{\text{Name,Salary}}$ (Employee)

Name	Salary
John	20000
John	60000

Set semantics: duplicate elimination automatic

SSN	Name	Salary
1234545	John	200000
5423341	John	600000
4352342	John	200000

$\Pi_{\text{Name,Salary}}$ (Employee)

Name	Salary
John	20000
John	60000
John	20000

Bag semantics: no duplicate elimination; need explicit δ

Cartesian Product

- Each tuple in R1 with each tuple in R2

$$\boxed{R1 \times R2}$$

- Very rare in practice; mainly used to express joins

Employee

Name	SSN
John	999999999
Tony	777777777

Dependent

EmpSSN	DepName
999999999	Emily
777777777	Joe

Employee × Dependent

Name	SSN	EmpSSN	DepName
John	999999999	999999999	Emily
Tony	777777777	777777777	Joe
John	999999999	777777777	Joe
Tony	777777777	999999999	Emily

Renaming

- Changes the schema, not the instance

$$\boxed{\rho_{B1,\ldots,Bn}(R)}$$

- Example:
  - $\rho_{N,\ S}$(Employee) → Answer(N, S)

Natural Join

$$\boxed{R1 \bowtie R2}$$

- Meaning: $R1 \bowtie R2 = \Pi_A(\sigma(R1 \times R2))$

- Where:
  - The selection σ checks equality of all common attributes
  - The projection eliminates the duplicate common attributes

Natural Join

R

A	B
X	Y
X	Z
Y	Z
Z	V

S

B	C
Z	U
V	W
Z	V

R ⋈ **S** =

A	B	C
X	Z	U
X	Z	V
Y	Z	U
Y	Z	V
Z	V	W

Natural Join

- Given the schemas R(A, B, C, D), S(A, C, E), what is the schema of $R \bowtie S$?
- Given R(A, B, C), S(D, E), what is $R \bowtie S$?
- Given R(A, B), S(A, B), what is $R \bowtie S$?

Theta Join

- A join that involves a predicate

$$\boxed{R1 \bowtie_{\theta} R2 \;=\; \sigma_{\theta}\,(R1 \times R2)}$$

- Here θ can be any condition

Eq-join

- A theta join where θ is an equality

$$R1 \bowtie_{A=B} R2 = \sigma_{A=B} (R1 \times R2)$$

- This is by far the most used variant of join in practice

So Which Join Is It ?

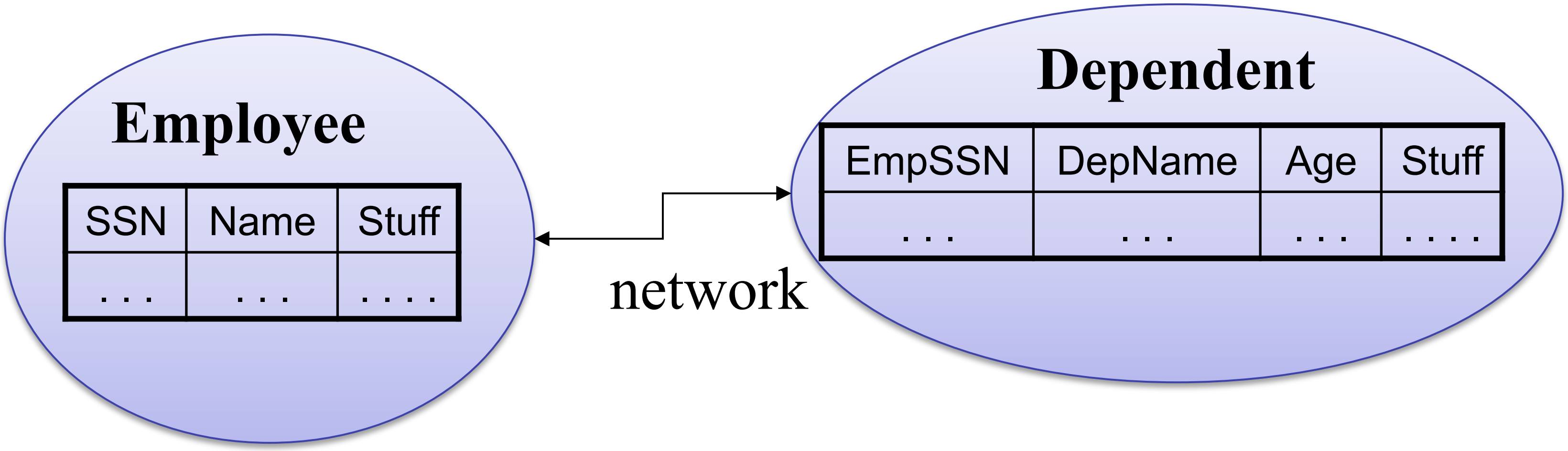
- When we write R ⋈ S we usually mean an eq-join, but we often omit the equality predicate when it is clear from the context

Semijoin

$$\boxed{R \ltimes_C S = \Pi_{A1,\ldots,An} (R \bowtie_C S)}$$

- Where $A_1, \ldots, A_n$ are the attributes in R

Semijoins in Distributed Databases



Employee

SSN	Name	Stuff
. . .	. . .	. . . .

Dependent

EmpSSN	DepName	Age	Stuff
. . .	. . .	. . .	. . . .

$$\text{Employee} \bowtie_{\text{SSN=EmpSSN}} (\sigma_{\text{age}>71}(\text{Dependent}))$$

$$T = \Pi_{\text{SSN}}\, \sigma_{\text{age}>71}(\text{Dependents})$$

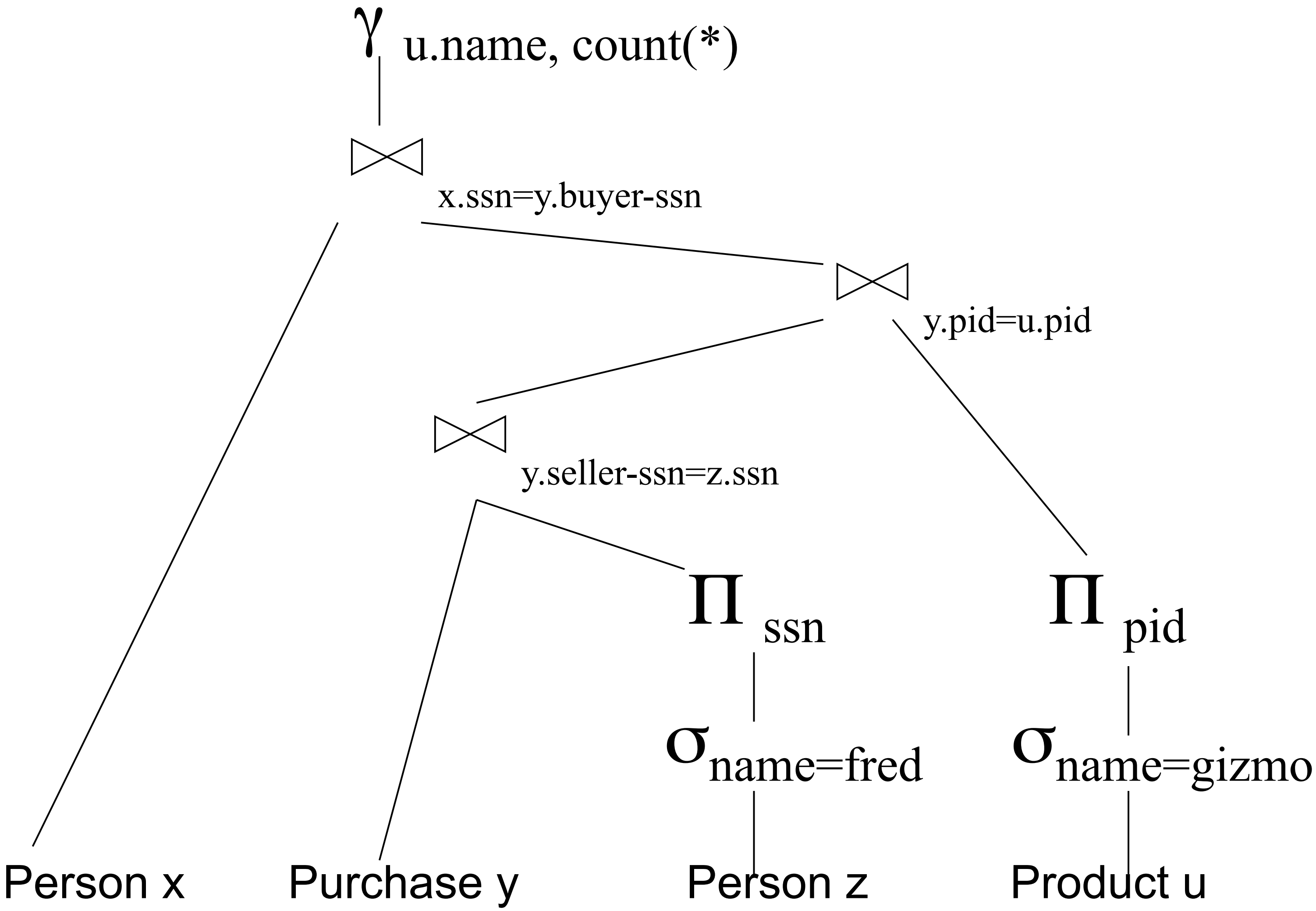
$$R = \text{Employee} \ltimes_{\text{SSN=EmpSSN}} T$$

$$\text{Answer} = R \bowtie_{\text{SSN=EmpSSN}} \text{Dependents}$$

Operators on Bags

- Duplicate elimination δ
- Grouping γ
- Sorting τ

Complex RA Expressions



$\gamma_{\text{u.name, count(*)}}$

$\bowtie_{\text{x.ssn=y.buyer-ssn}}$

$\bowtie_{\text{y.pid=u.pid}}$

$\bowtie_{\text{y.seller-ssn=z.ssn}}$

Π_{ssn}

Π_{pid}

$\sigma_{\text{name=fred}}$

$\sigma_{\text{name=gizmo}}$

Person x

Purchase y

Person z

Product u

RA Expressions v.s. Programs

- An Algebra Expression is like a program
  - Several operations
  - Strictly specified order

- But Algebra expressions have limitations

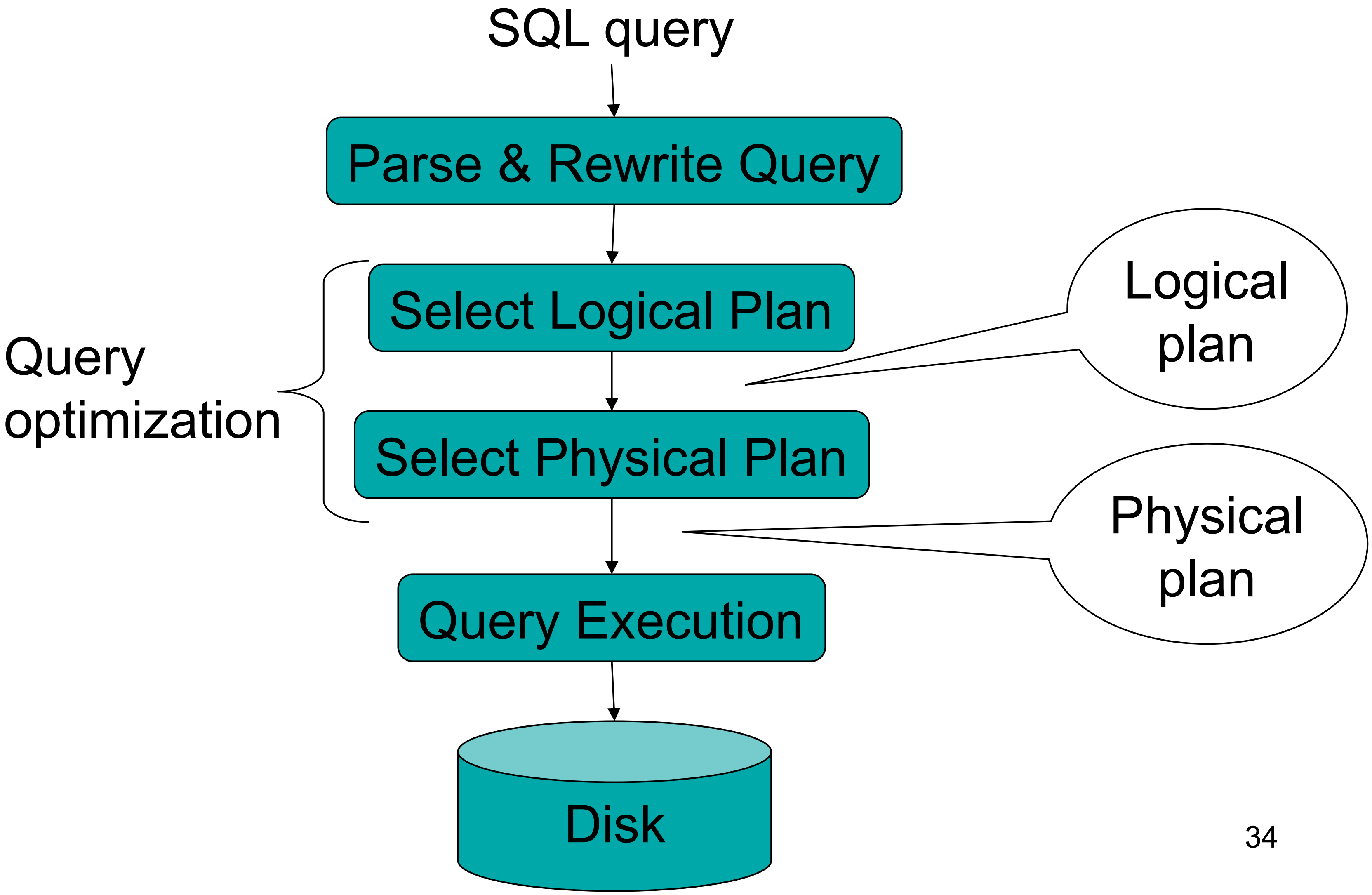
RA and Transitive Closure

- Cannot compute “transitive closure”

Name1	**Name2**	**Relationship**
Fred	Mary	Father
Mary	Joe	Cousin
Mary	Bill	Spouse
Nancy	Lou	Sister

- Find all direct and indirect relatives of Fred
- Cannot express in RA !!! Need to write Java program
- Remember *the Bacon number* ? Needs TC too !

Query Evaluation Steps



SQL query

Parse & Rewrite Query

Select Logical Plan

Select Physical Plan

Query Execution

Disk

Query optimization

Logical plan

Physical plan

Example Database Schema

```
Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)
```

View: Suppliers in Seattle

```
CREATE VIEW NearbySupp AS
SELECT sno, sname
FROM Supplier
WHERE scity='Seattle' AND sstate='WA'
```

Example Query

Find the names of all suppliers in Seattle who supply part number 2

```
SELECT sname FROM NearbySupp
WHERE sno IN ( SELECT sno
               FROM Supplies
               WHERE pno = 2 )
```

Steps in Query Evaluation

- **Step 0: Admission control**
  - User connects to the db with username, password
  - User sends query in text format
- **Step 1: Query parsing**
  - Parses query into an internal format
  - Performs various checks using catalog
    - Correctness, authorization, integrity constraints
- **Step 2: Query rewrite**
  - View rewriting, flattening, etc.

Rewritten Version of Our Query

Original query:

```
SELECT sname
FROM NearbySupp
WHERE sno IN ( SELECT sno
               FROM Supplies
               WHERE pno = 2 )
```

Rewritten query:

```
SELECT S.sname
FROM Supplier S, Supplies U
WHERE S.scity='Seattle' AND S.sstate='WA’
AND S.sno = U.sno
AND U.pno = 2;
```

Continue with Query Evaluation

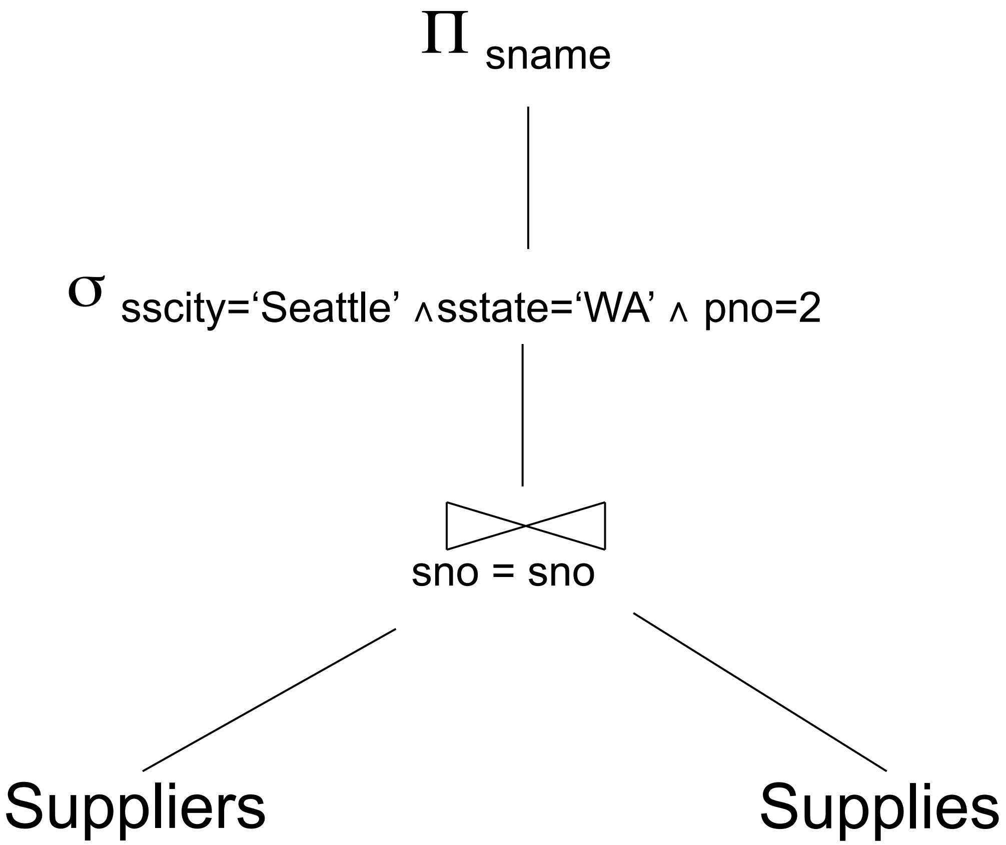
- **Step 3: Query optimization**
  - Find an efficient query plan for executing the query

- A **query plan** is
  - **Logical query plan**: an extended relational algebra tree
  - **Physical query plan**: with additional annotations at each node
    - Access method to use for each relation
    - Implementation to use for each relational operator

Extended Algebra Operators

- Union $\cup$, intersection $\cap$, difference $-$
- Selection σ
- Projection π
- Join $\bowtie$
- Duplicate elimination δ
- Grouping and aggregation γ
- Sorting τ
- Rename ρ

Logical Query Plan



Π_{sname}

$\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'} \wedge \text{pno=2}}$

$\bowtie_{\text{sno = sno}}$

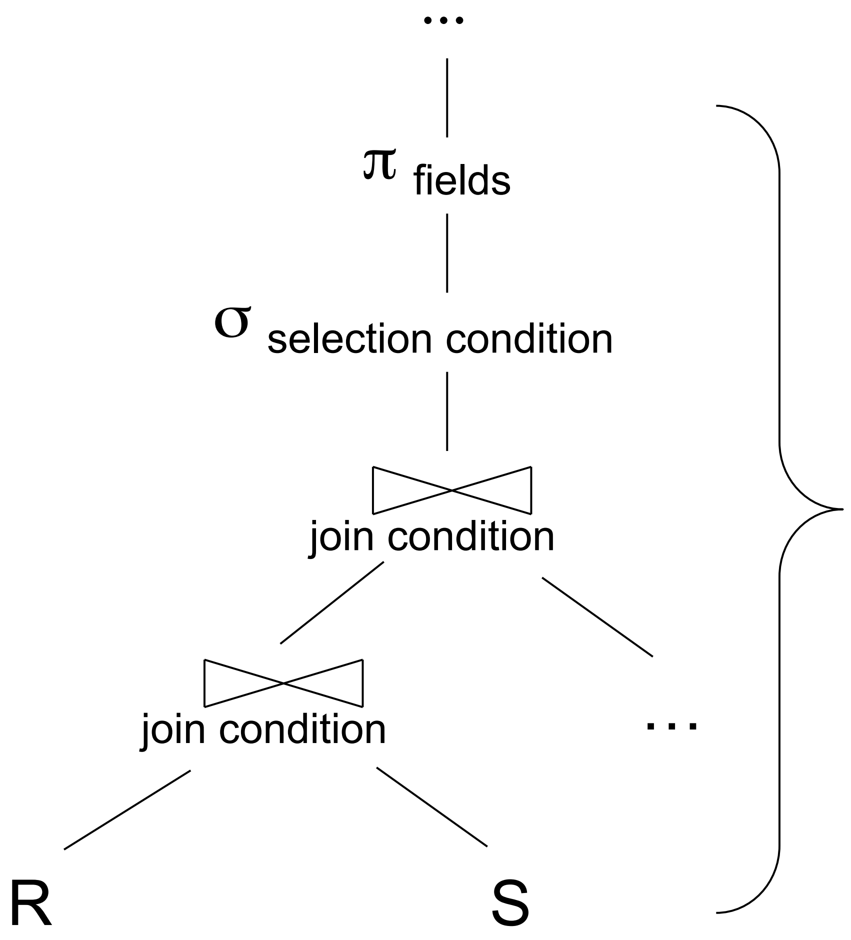
Suppliers

Supplies

Query Block

- Most optimizers operate on individual query blocks
- A query block is an SQL query with **no nesting**
  - **Exactly one**
    - SELECT clause
    - FROM clause
  - **At most one**
    - WHERE clause
    - GROUP BY clause
    - HAVING clause

Typical Plan for Block (1/2)



…

π fields

σ selection condition

$\bowtie$ join condition

$\bowtie$ join condition

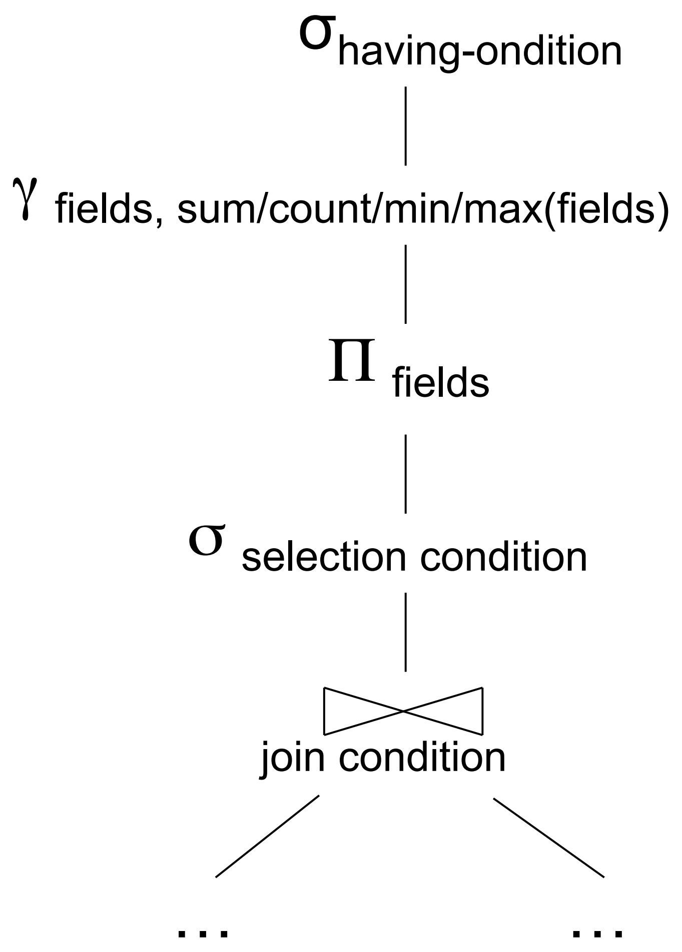
…

R

S

SELECT-PROJECT-JOIN Query

Typical Plan For Block (2/2)



$\sigma_{\text{having-ondition}}$

$\gamma_{\text{fields, sum/count/min/max(fields)}}$

Π_{fields}

$\sigma_{\text{selection condition}}$

$\bowtie_{\text{join condition}}$

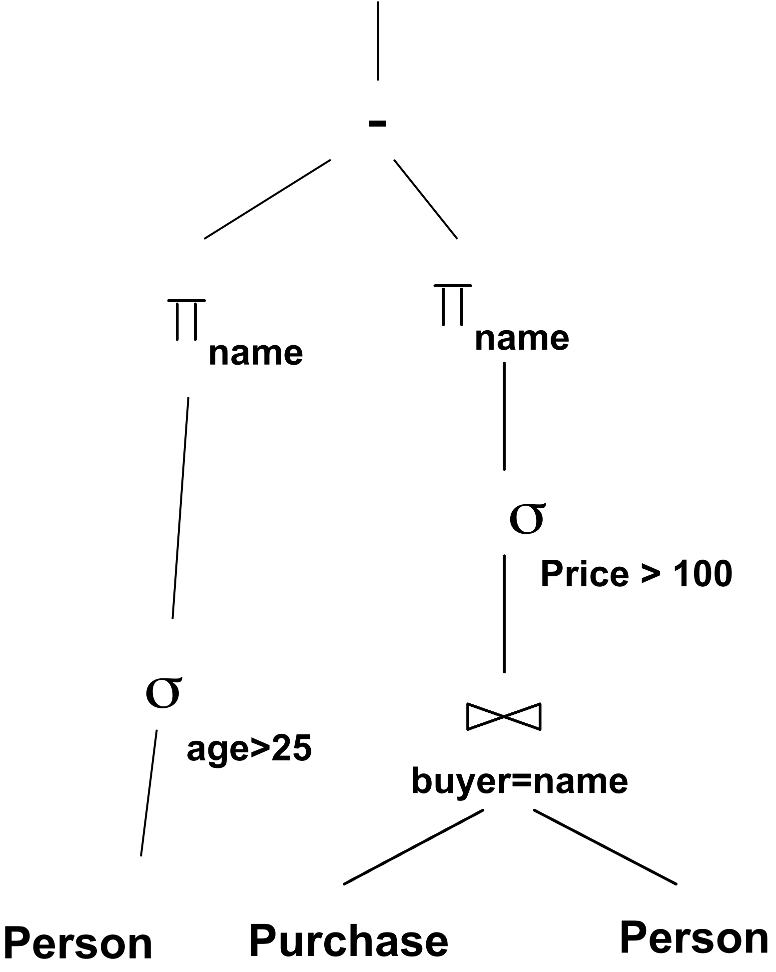
… …

How about Subqueries?

```
SELECT  Q.name
FROM Person Q
WHERE  Q.age > 25
    and not exists
       SELECT *
       FROM Purchase P
       WHERE P.buyer = Q.name
               and P.price > 100
```

How about Subqueries?

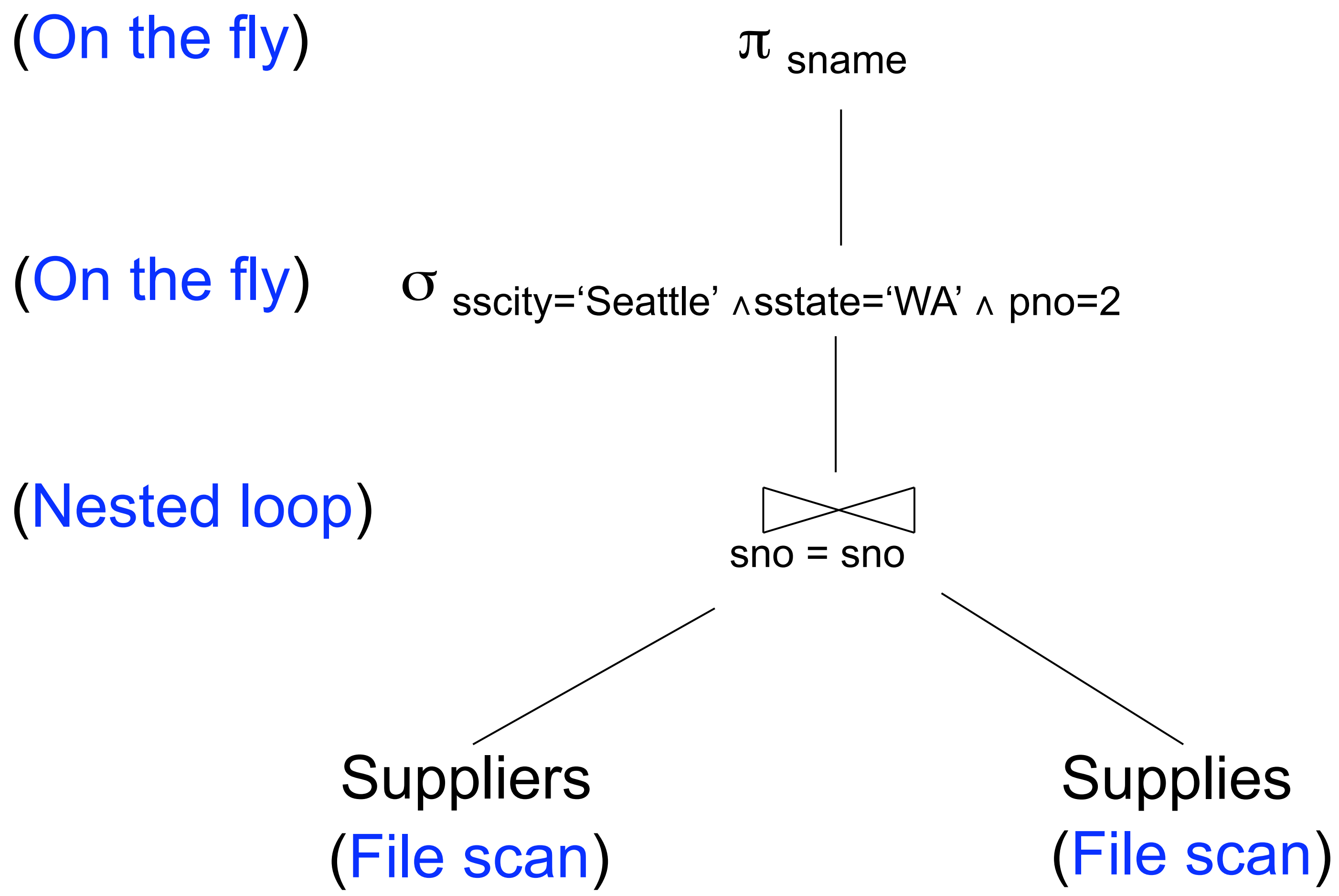
```
SELECT  Q.name
FROM Person Q
WHERE  Q.age > 25
    and not exists
       SELECT *
       FROM Purchase P
       WHERE P.buyer = Q.name
               and P.price > 100
```



Physical Query Plan

- Logical query plan with extra annotations
- **Access path selection** for each relation
  - Use a file scan or use an index
- **Implementation choice** for each operator
- **Scheduling decisions** for operators

Physical Query Plan



(On the fly) π_{sname}

(On the fly) $\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'} \wedge \text{pno=2}}$

(Nested loop) $\bowtie_{\text{sno = sno}}$

Suppliers (File scan)

Supplies (File scan)

Final Step in Query Processing

- **Step 4: Query execution**
  - How to synchronize operators?
  - How to pass data between operators?

- What techniques are possible?
  - One thread per process
  - Iterator interface
  - Pipelined execution
  - Intermediate result materialization

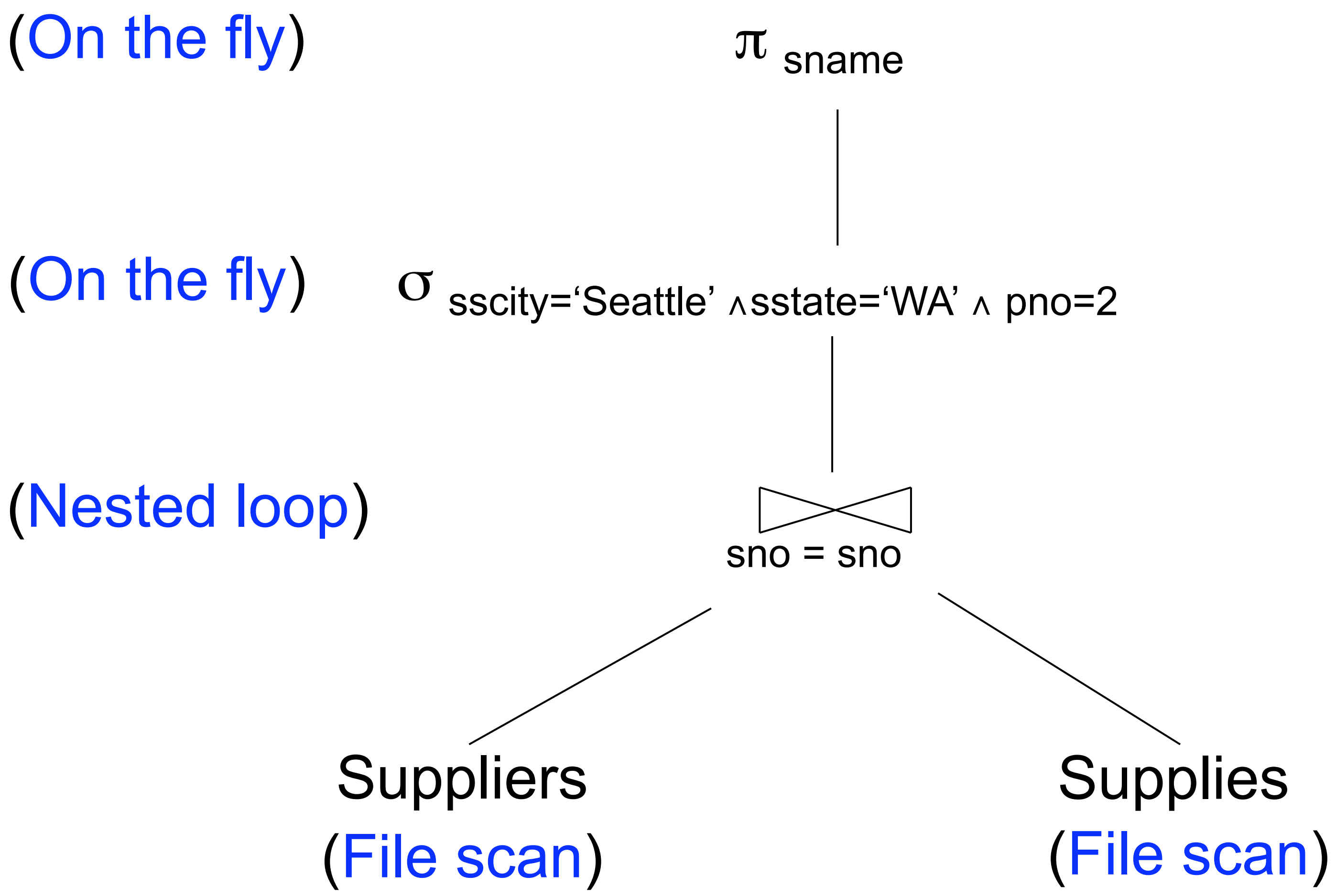
Iterator Interface

- Each **operator implements this interface**
- Interface has only three methods
- **open()**
  - Initializes operator state
  - Sets parameters such as selection condition
- **get_next()**
  - Operator invokes get_next() recursively on its inputs
  - Performs processing and produces an output tuple
- **close()**: cleans-up state

Pipelined Execution

- Applies parent operator to tuples directly as they are produced by child operators
- Benefits
  - No operator synchronization issues
  - Saves cost of writing intermediate data to disk
  - Saves cost of reading intermediate data from disk
  - Good resource utilizations on single processor
- This approach is used whenever possible

Pipelined Execution



(On the fly) π_{sname}

(On the fly) $\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'} \wedge \text{pno=2}}$

(Nested loop) $\bowtie_{\text{sno = sno}}$

Suppliers (File scan)

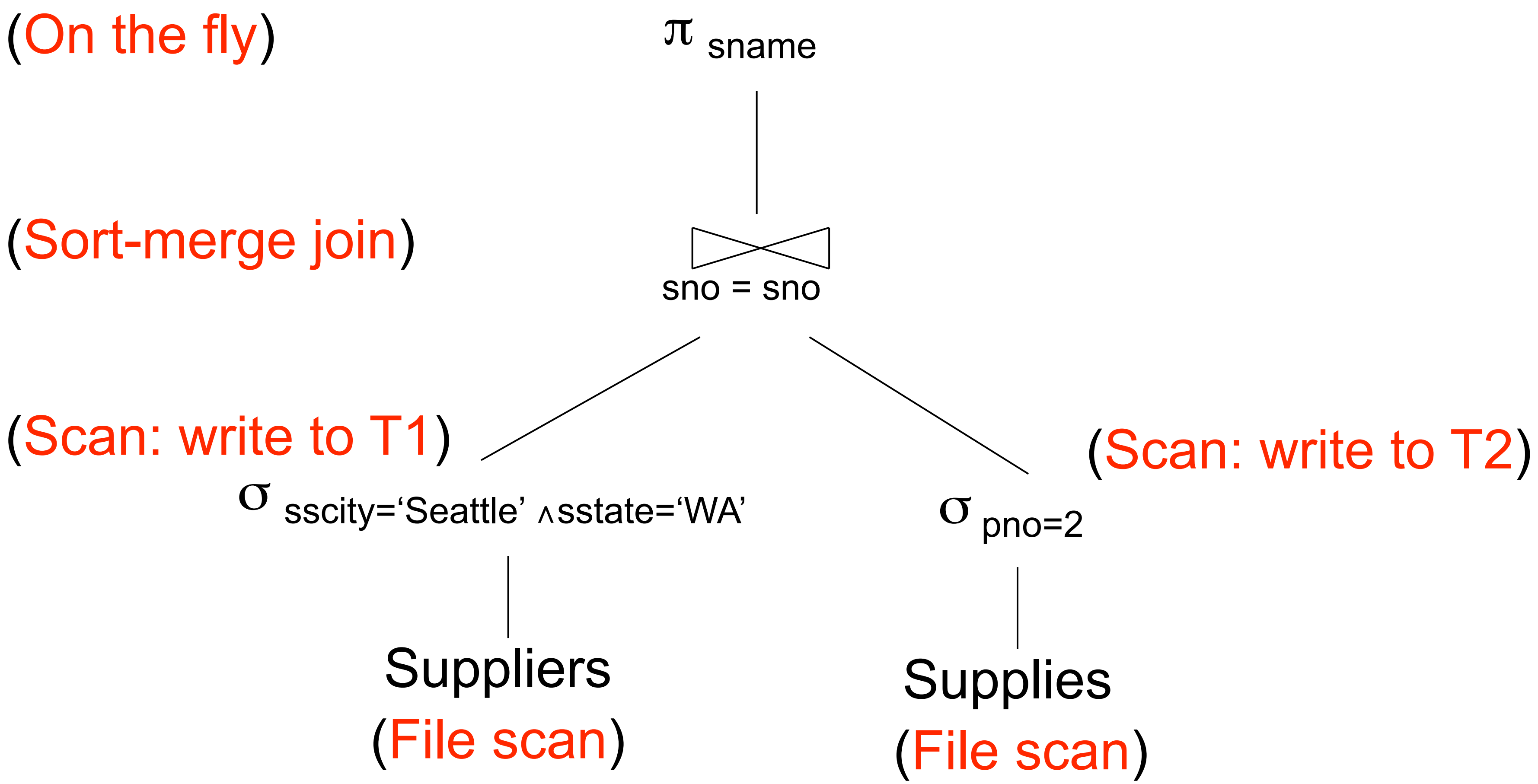
Supplies (File scan)

Intermediate Tuple Materialization

- Writes the results of an operator to an intermediate table on disk

- No direct benefit but
- Necessary for some operator implementations
- When operator needs to examine the same tuples multiple times

Intermediate Tuple Materialization



(On the fly)

π_{sname}

(Sort-merge join)

$\bowtie_{\text{sno = sno}}$

(Scan: write to T1)

$\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'}}$

(Scan: write to T2)

$\sigma_{\text{pno=2}}$

Suppliers

(File scan)

Supplies

(File scan)

Physical Operators

Each of the logical operators may have one or more implementations = physical operators

Will discuss several basic physical operators, with a focus on join

Question in Class

Logical operator:

Product(pname, cname) ⋈ Company(cname, city)

Propose three physical operators for the join, assuming the tables are in main memory:

1.
2.
3.

Question in Class

Product(pname, cname) $\bowtie$ Company(cname, city)

- 1000000 products
- 1000 companies

How much time do the following physical operators take if the data is **<u>in main memory</u>** ?

• Nested loop join	time =
• Sort and merge (="merge-join")	time =
• Hash join	time =

The Iterator Model of Execution

Each operator implements three methods:

- Open( )
- GetNext( )
- Close( )

Cost Parameters

The *cost* of an operation = total number of I/Os

result assumed to be delivered in main memory

Cost parameters:

- B(R) = number of blocks for relation R
- T(R) = number of tuples in relation R
- V(R, a) = number of distinct values of attribute a
- M = size of main memory buffer pool, in blocks

Cost Parameters

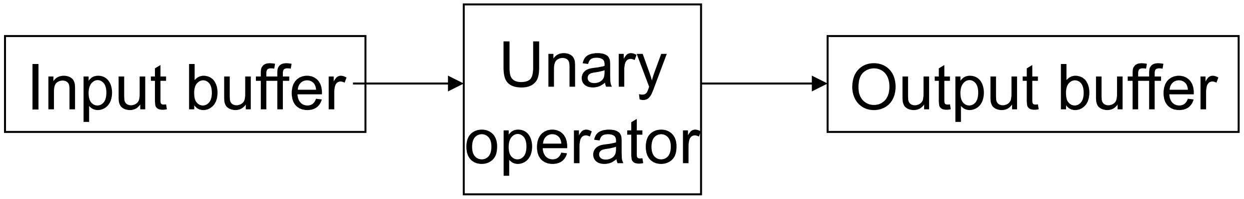
- *Clustered* table R:
  - Blocks consists only of records from this table
  - B(R) << T(R)
- *Unclustered* table R:
  - Its records are placed on blocks with other tables
  - B(R) ≈ T(R)

- When a is a key, V(R,a) = T(R)
- When a is not a key, V(R,a) << T(R)

Selection and Projection

Selection σ(R), projection Π(R)

- Both are *tuple-at-a-time* algorithms
- Cost: B(R)



Input buffer

Unary operator

Output buffer

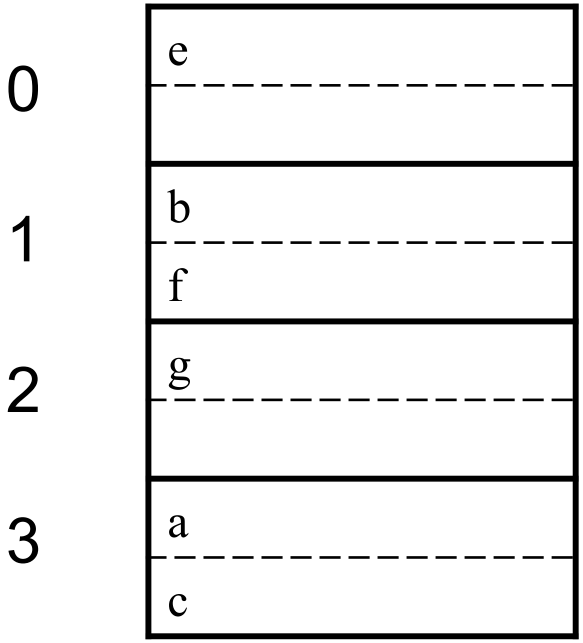
What are Open( ), GetNext( ), Close( ) here ?

Hash Tables

- Key data structure used in many operators
- May also be used for indexes, as alternative to B +trees
- Recall basics:
  - There are n *buckets*
  - A hash function f(k) maps a key k to {0, 1, …, n-1}
  - Store in bucket f(k) a pointer to record with key k
- Secondary storage: bucket = block, use overflow blocks when needed

Hash Table Example

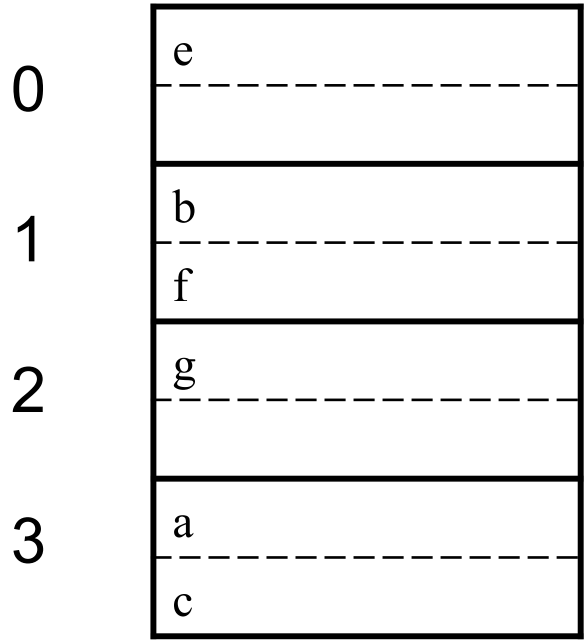
- Assume 1 bucket (block) stores 2 keys + pointers
- h(e)=0
- h(b)=h(f)=1
- h(g)=2
- h(a)=h(c)=3



Here: h(x) = x mod 4

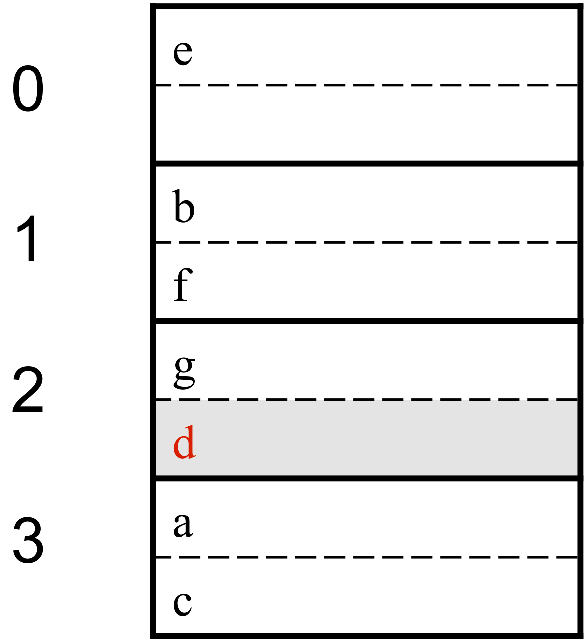
Searching in a Hash Table

- Search for a:
- Compute h(a)=3
- Read bucket 3
- 1 disk access



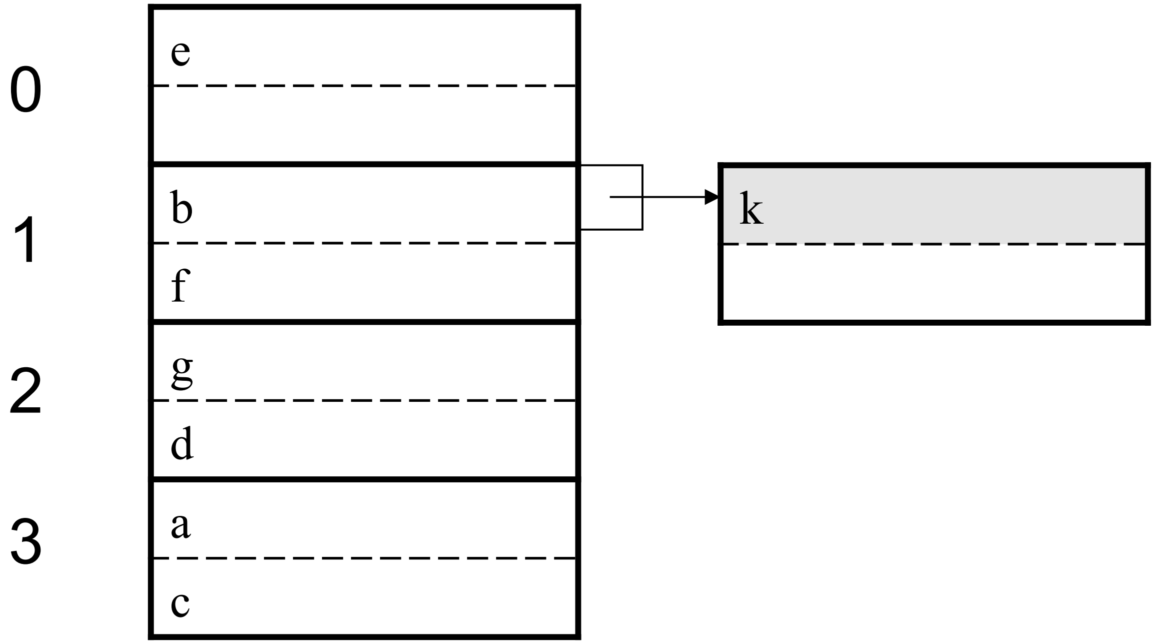
Insertion in Hash Table

- Place in right bucket, if space
- E.g. h(d)=2



Insertion in Hash Table

- Create overflow block, if no space
- E.g. h(k)=1



- More overflow blocks may be needed

Hash Table Performance

- Excellent, if no overflow blocks
- Degrades considerably when number of keys exceeds the number of buckets (I.e. many overflow blocks).

Main Memory Hash Join

Hash join: R $\bowtie$ S

- Scan S, build buckets in main memory
- Then scan R and join

- Cost: B(R) + B(S)
- Assumption: B(S) <= M

Main Memory Hash Join

- What are Open( ), GetNext( ), Close( ) ?

Main Memory Hash Join

```
Open( ) {
   H = newHashTable( );
   S.Open( );
   x = S.GetNext( );
   while (x != null) { H.insert(x); x = S.GetNext( );}
   S.Close( );
   R.Open( );
   buffer = [ ];
  }
```

Main Memory Hash Join

```
GetNext( ) {
    while (buffer == [ ]) {
        x = R.GetNext( );
        if (x==Null) return NULL;
        buffer = H.find(x);
    }
    z = buffer.first( );
    buffer = buffer.rest( );
    return z;
}
```

Main Memory Hash Join

```
Close( ) {
    release memory (H, buffer, etc.);
   R.Close( )
   }
```

Duplicate Elimination

Duplicate elimination $\delta(R)$

- Hash table in main memory

- Cost: B(R)
- Assumption: $B(\delta(R)) <= M$

Grouping

Grouping:

Product(name, department, quantity)

$\gamma_{\text{department, sum(quantity)}}$ (Product) → Answer(department, sum)

Main memory hash table

Question: How ?

Nested Loop Joins

- Tuple-based nested loop R ⋈ S

```
for each tuple r in R do
   for each tuple s in S do
      if r and s join then output (r,s)
```

- Cost: T(R) B(S) when S is clustered
- Cost: T(R) T(S) when S is unclustered

What are Open( ), GetNext( ), Close( ) here ?

Nested Loop Joins

- We can be much more clever

- *Question*: how would you compute the join in the following cases ? What is the cost ?

  – B(R) = 1000, B(S) = 2, M = 4

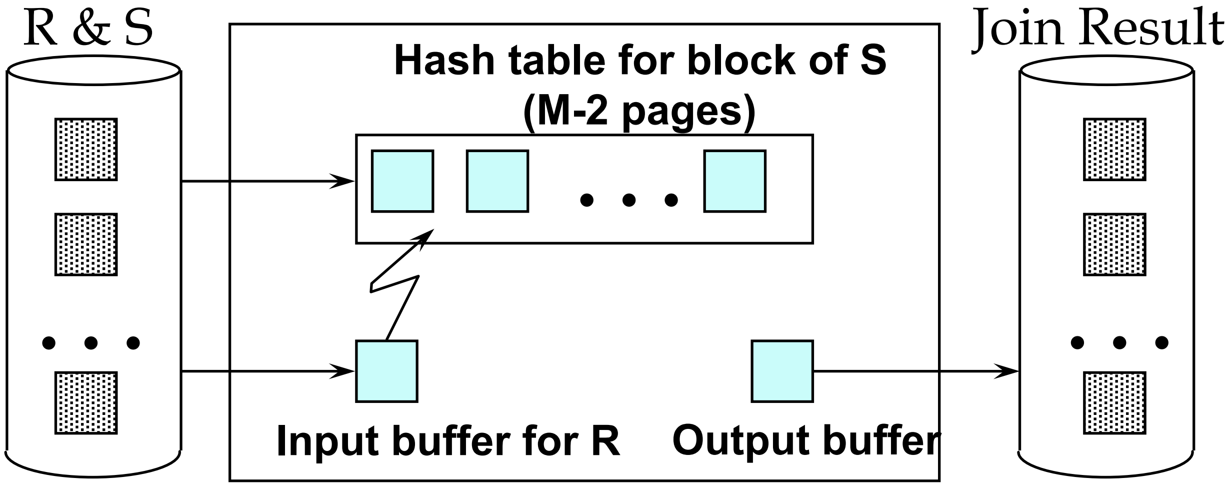
  – B(R) = 1000, B(S) = 3, M = 4

  – B(R) = 1000, B(S) = 6, M = 4

Block-Based Nested-loop Join

```
for each (M-2) blocks bs of S do
  for each block br of R do
      for each tuple s in bs
          for each tuple r in br do
              if "r and s join" then output(r,s)
```

Block-Based Nested-loop Join



Block-Based Nested-loop Join

- Cost:
  - Read S once: cost B(S)
  - Outer loop runs B(S)/(M-2) times, and each time need to read R: costs B(S)B(R)/(M-2)
  - Total cost: B(S) + B(S)B(R)/(M-2)
- Notice: it is better to iterate over the smaller relation first
- R ⋈ S: R=outer relation, S=inner relation

Index Based Selection

Selection on equality: $\sigma_{a=v}(R)$

- Clustered index on a: cost B(R)/V(R,a)
- Unclustered index : cost T(R)/V(R,a)

Index Based Selection

- Example:

B(R) = 2000
T(R) = 100,000
V(R, a) = 20

cost of $\sigma_{a=v}(R)$ = ?

- Table scan (assuming R is clustered):
  - B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered: B(R)/V(R,a) = 100 I/Os
  - If index is unclustered: T(R)/V(R,a) = 5,000 I/Os

- Lesson: don’t build unclustered indexes when V(R,a) is small !

Index Based Join

- $R \bowtie S$
- Assume S has an index on the join attribute

```
for each tuple r in R do
    lookup the tuple(s) s in S using the index
    output (r,s)
```

Index Based Join

Cost (Assuming R is clustered):

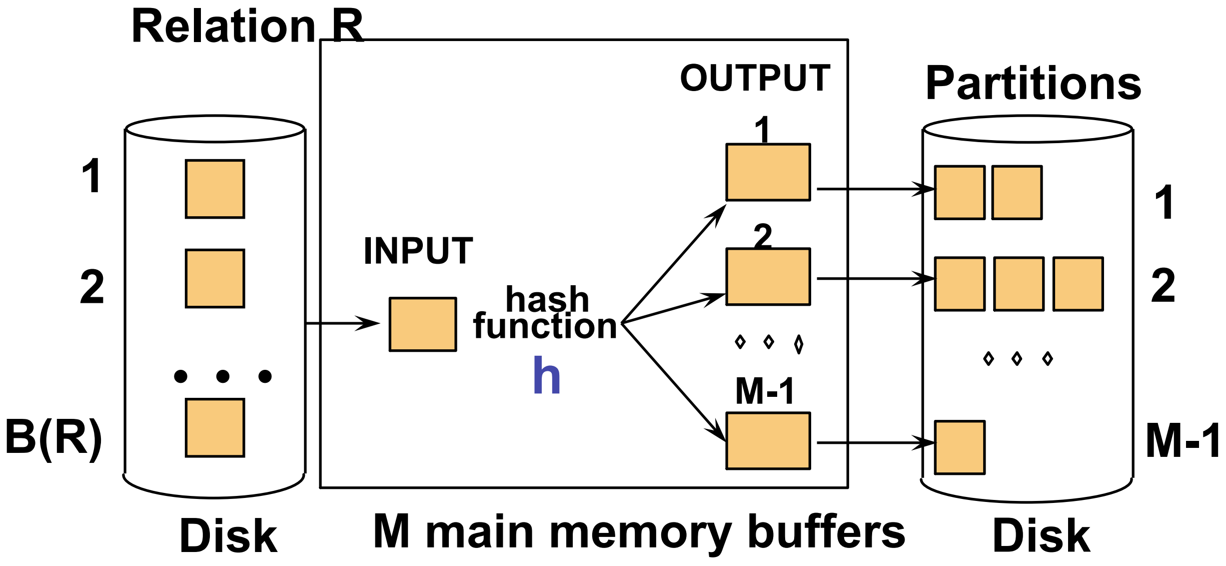
- If index is clustered: B(R) + T(R)B(S)/V(S,a)
- If unclustered: B(R) + T(R)T(S)/V(S,a)

Operations on Very Large Tables

- Partitioned hash algorithms
- Merge-sort algorithms

Partitioned Hash Algorithms

- Idea: partition a relation R into buckets, on disk
- Each bucket has size approx. B(R)/M



- Does each bucket fit in main memory ?
  - Yes if B(R)/M <= M, i.e. $B(R) \le M^2$

Duplicate Elimination

- Recall: $\delta(R)$ = duplicate elimination
- Step 1. Partition R into buckets
- Step 2. Apply δ to each bucket (may read in main memory)

- Cost: 3B(R)
- Assumption:B(R) <= M^2

Grouping

- Recall: $\gamma(R)$ = grouping and aggregation
- Step 1. Partition R into buckets
- Step 2. Apply γ to each bucket (may read in main memory)

- Cost: 3B(R)
- Assumption:$B(R) <= M^2$

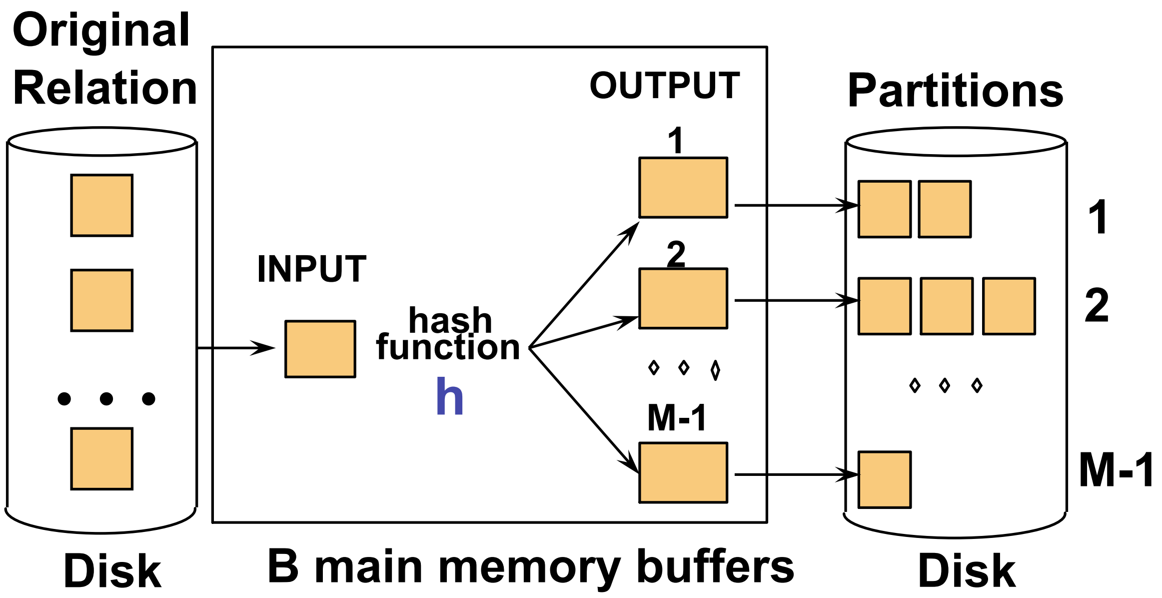
Partitioned Hash Join

$R \bowtie S$

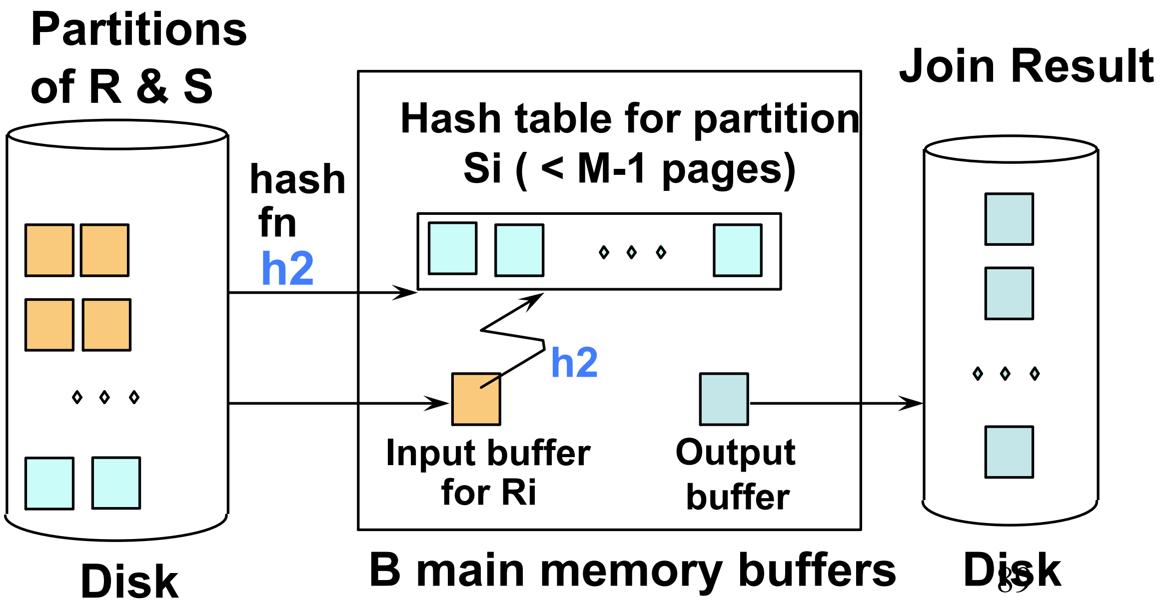
- Step 1:
  - Hash S into M buckets
  - send all buckets to disk
- Step 2
  - Hash R into M buckets
  - Send all buckets to disk
- Step 3
  - Join every pair of buckets

Hash-Join

- Partition both relations using hash fn **h**: R tuples in partition i will only match S tuples in partition i.



- Read in a partition of R, hash it using **h2 (<> h!)**. Scan matching partition of S, search for matches.



Partitioned Hash Join

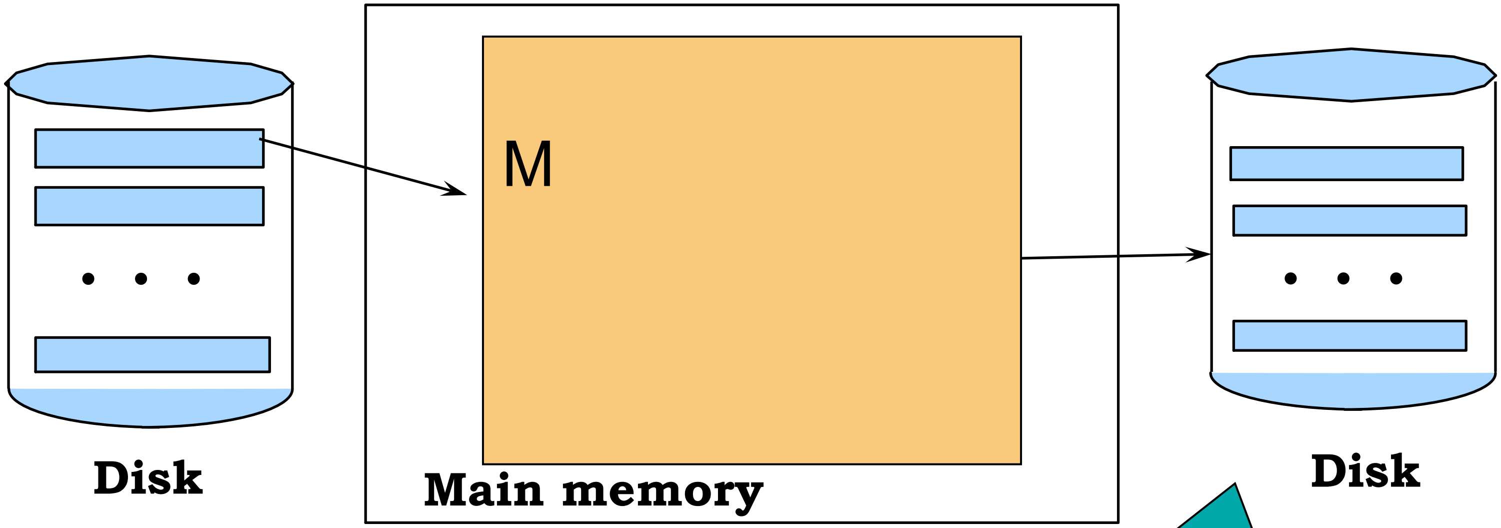
- Cost: 3B(R) + 3B(S)
- Assumption: min(B(R), B(S)) <= M^2

External Sorting

- Problem:
- Sort a file of size B with memory M
- Where we need this:
  - ORDER BY in SQL queries
  - Several physical operators
  - Bulk loading of B+-tree indexes.
- Will discuss only 2-pass sorting, for when $B < M^2$

External Merge-Sort: Step 1

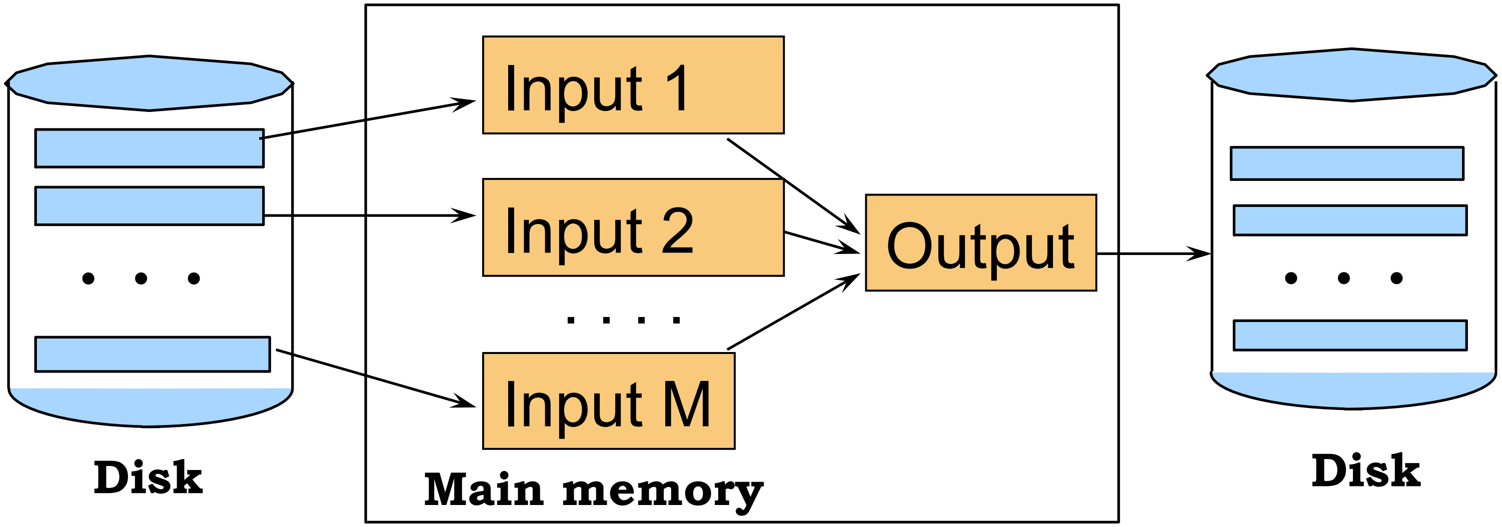
- Phase one: load M bytes in memory, sort



Runs of length M bytes

External Merge-Sort: Step 2

- Merge M – 1 runs into a new run
- Result: runs of length M (M – 1)≈ M^2



If B <= M^2 then we are done

Cost of External Merge Sort

- Read+write+read = 3B(R)

- Assumption: $B(R) <= M^2$

Duplicate Elimination

Duplicate elimination $\delta(R)$

- Idea: do a two step merge sort, but change one of the steps

- Question in class: which step needs to be changed and how ?

- Cost = 3B(R)
- Assumption: $B(\delta(R)) <= M^2$

Grouping

Grouping: $\gamma_{a,\ sum(b)}$ (R)

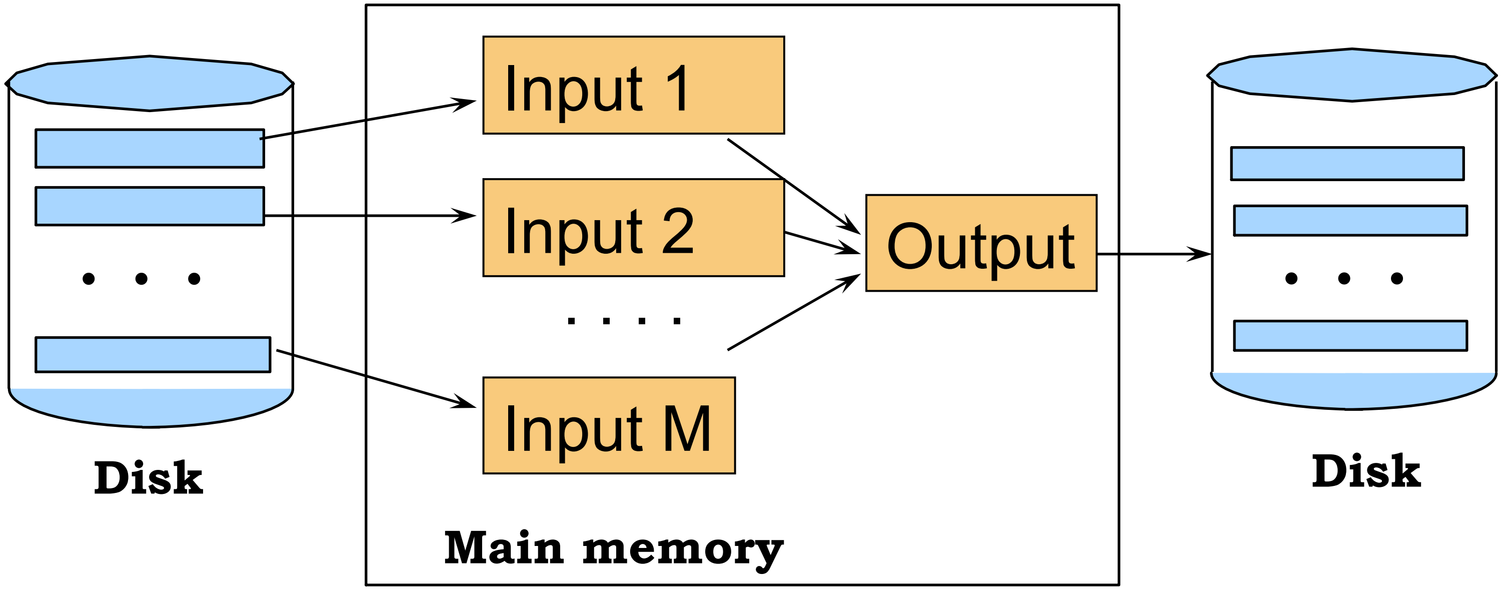
- Same as before: sort, then compute the sum(b) for each group of a's
- Total cost: 3B(R)
- Assumption: B(R) <= M^2

Merge-Join

Join R ⋈ S

- Step 1a: initial runs for R
- Step 1b: initial runs for S
- Step 2: merge and join

Merge-Join



$M_1 = B(R)/M$ runs for R

$M_2 = B(S)/M$ runs for S

If $B <= M^2$ then we are done

Two-Pass Algorithms Based on Sorting

Join R ⋈ S

- If the number of tuples in R matching those in S is small (or vice versa) we can compute the join during the merge phase
- Total cost: 3B(R)+3B(S)
- Assumption: B(R) + B(S) <= M^2

Summary of External Join Algorithms

- Block Nested Loop: $B(S) + B(R)*B(S)/M$
- Index Join: $B(R) + T(R)B(S)/V(S,a)$
- Partitioned Hash: $3B(R)+3B(S)$;
  - $\min(B(R),B(S)) <= M^2$
- Merge Join: $3B(R)+3B(S$
  - $B(R)+B(S) <= M^2$