CSE 544
Principles of Database Management Systems

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Lecture 7 - Query execution and operator algorithms

References

- Join processing in database systems with large main memories. Leonard Shapiro. ACM Transactions on Database Systems 11(3), 1986. Also in Red Book (3rd and 4th ed)
- The Anatomy of a Database System. J. Hellerstein and M. Stonebraker. **Section 4**. Red Book. 4th Ed.
- Database management systems.

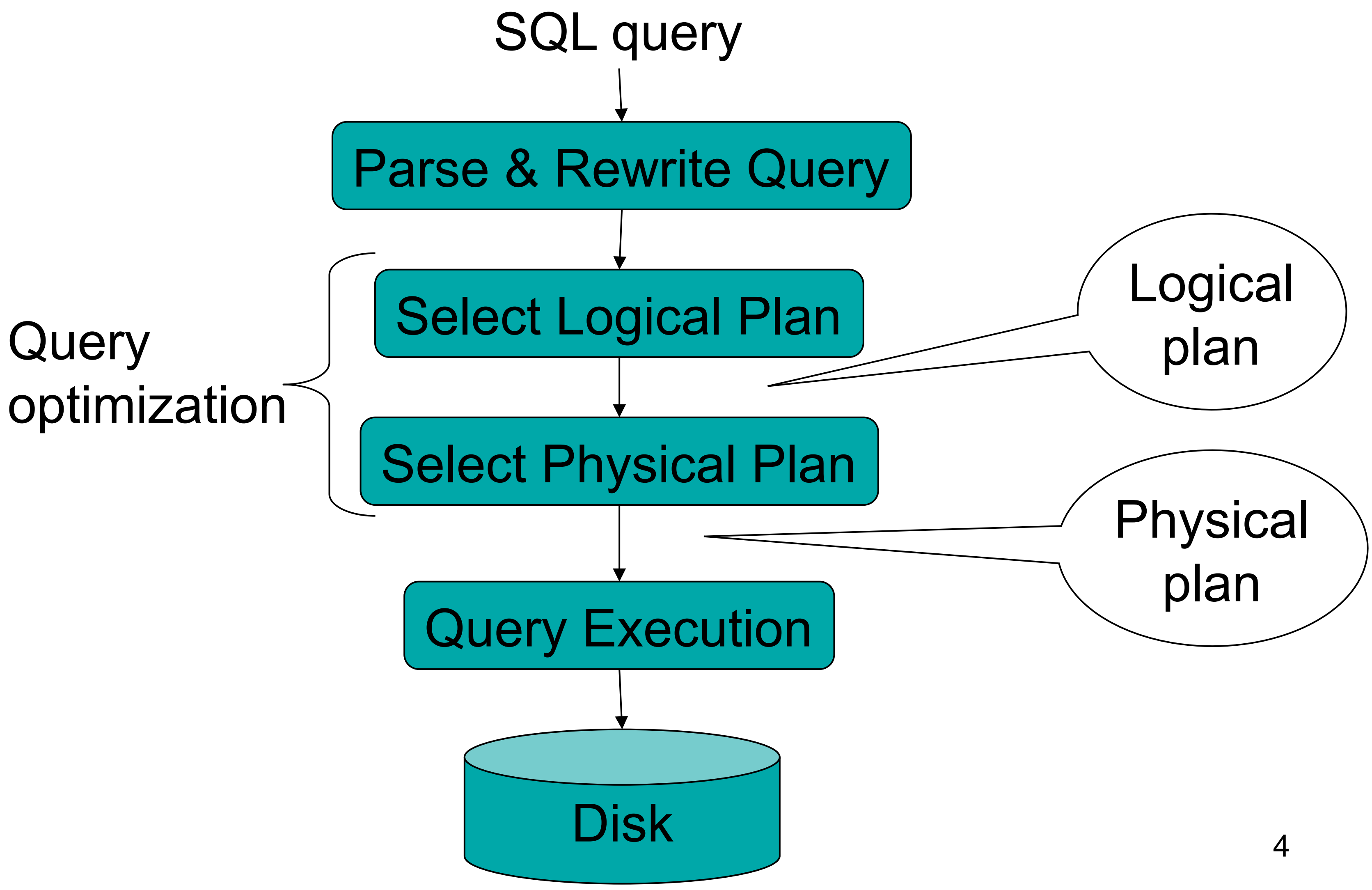
  Ramakrishnan and Gehrke.

  Third Ed. **Chapters 12, 13 and 14.**

Outline

- **Steps involved in processing a query**
  - Logical query plan
  - Physical query plan
  - Query execution overview
- **Operator implementations**
  - One pass algorithms
  - Two-pass algorithms
  - Index-based algorithms

Query Evaluation Steps



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

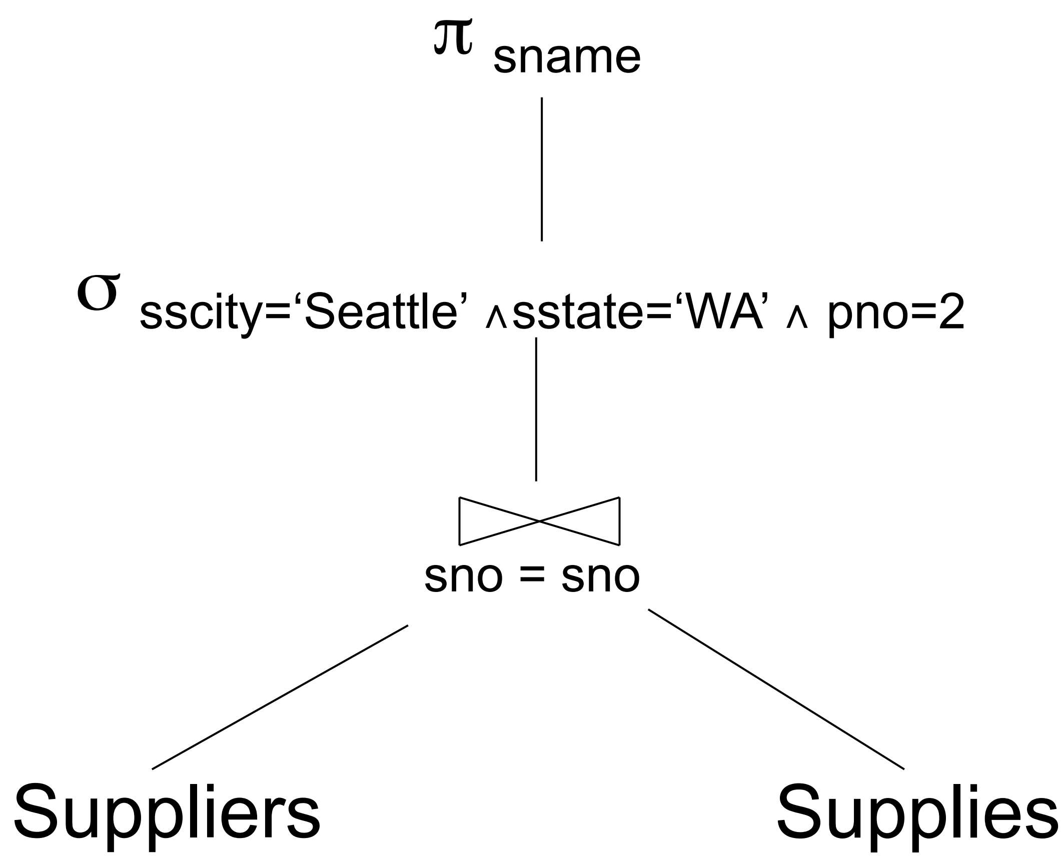
- **Step 3: Query optimization**
  - Find an efficient query plan for executing the query
  - We will spend a whole lecture on this topic

- 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

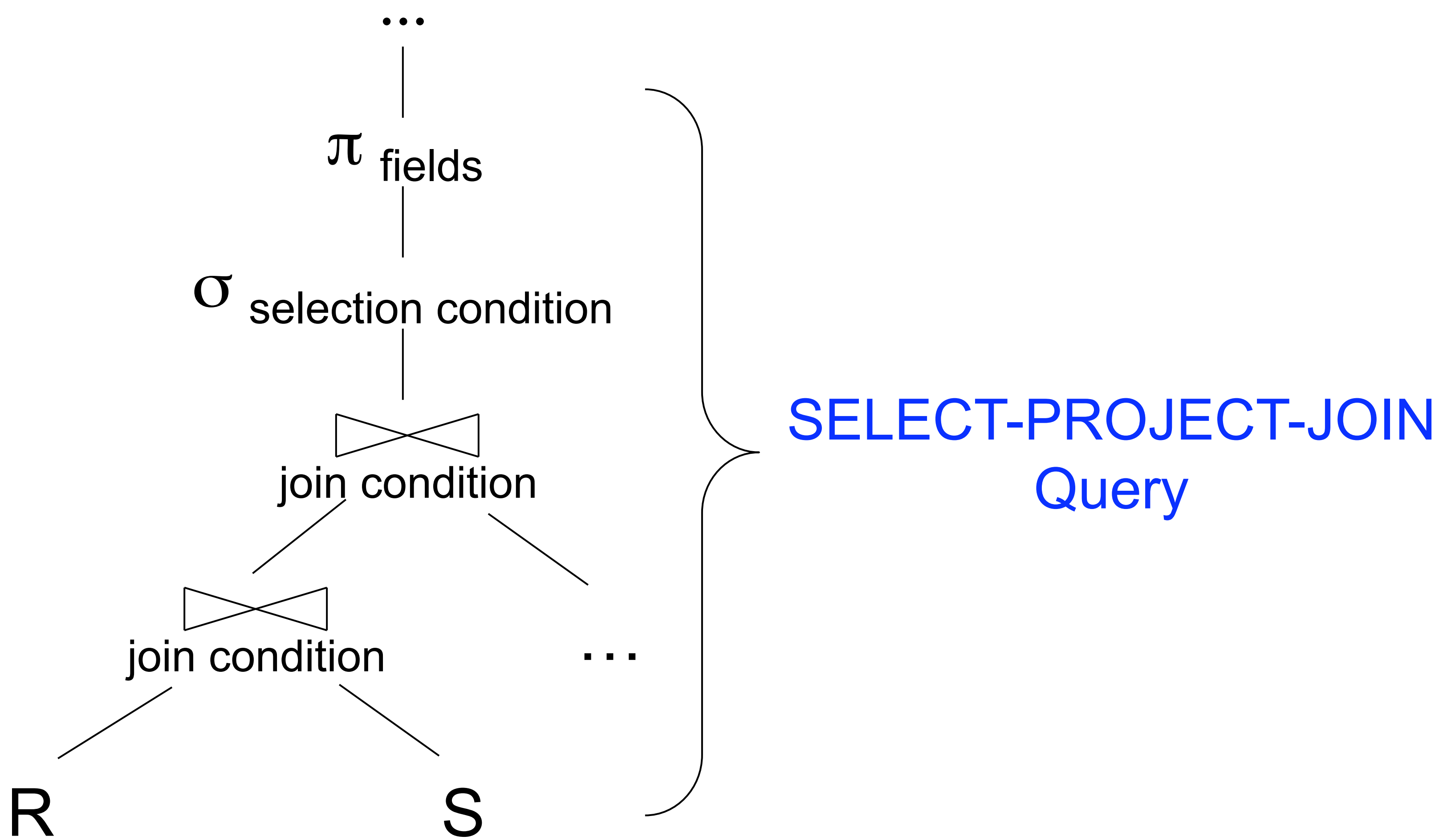


Query Block

- 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)



Typical Plan For Block (2/2)

$\text{having}_{\text{condition}}$

|

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

|

π $_{\text{fields}}$

|

σ $_{\text{selection condition}}$

|

$\bowtie$ join condition

/ \

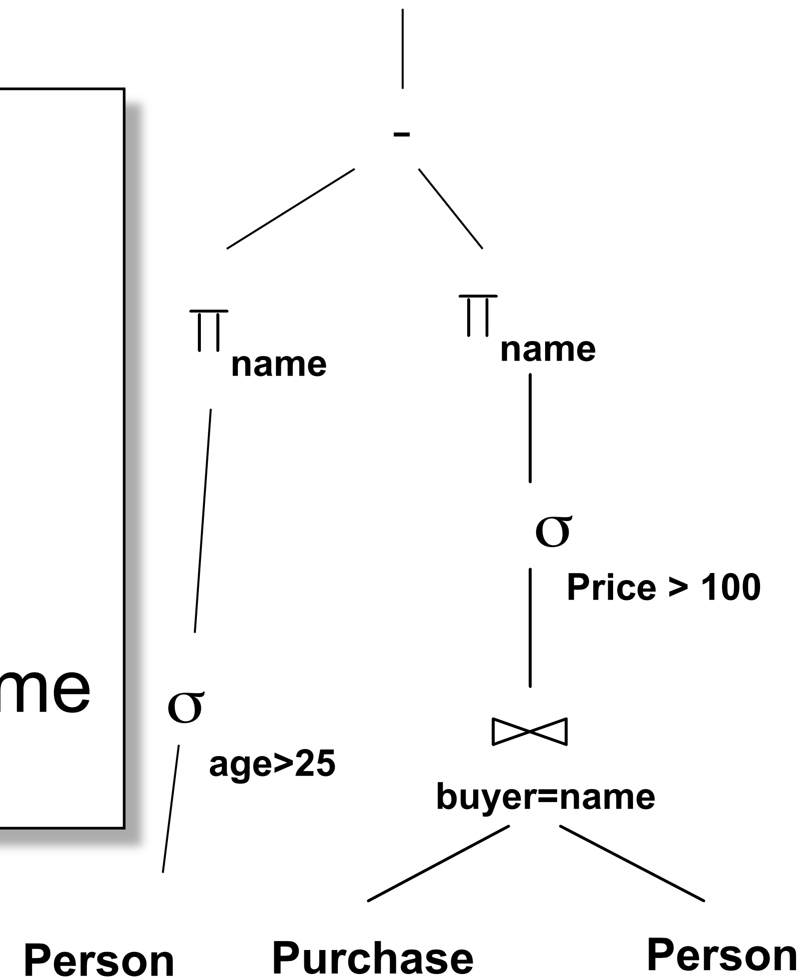
… …

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?

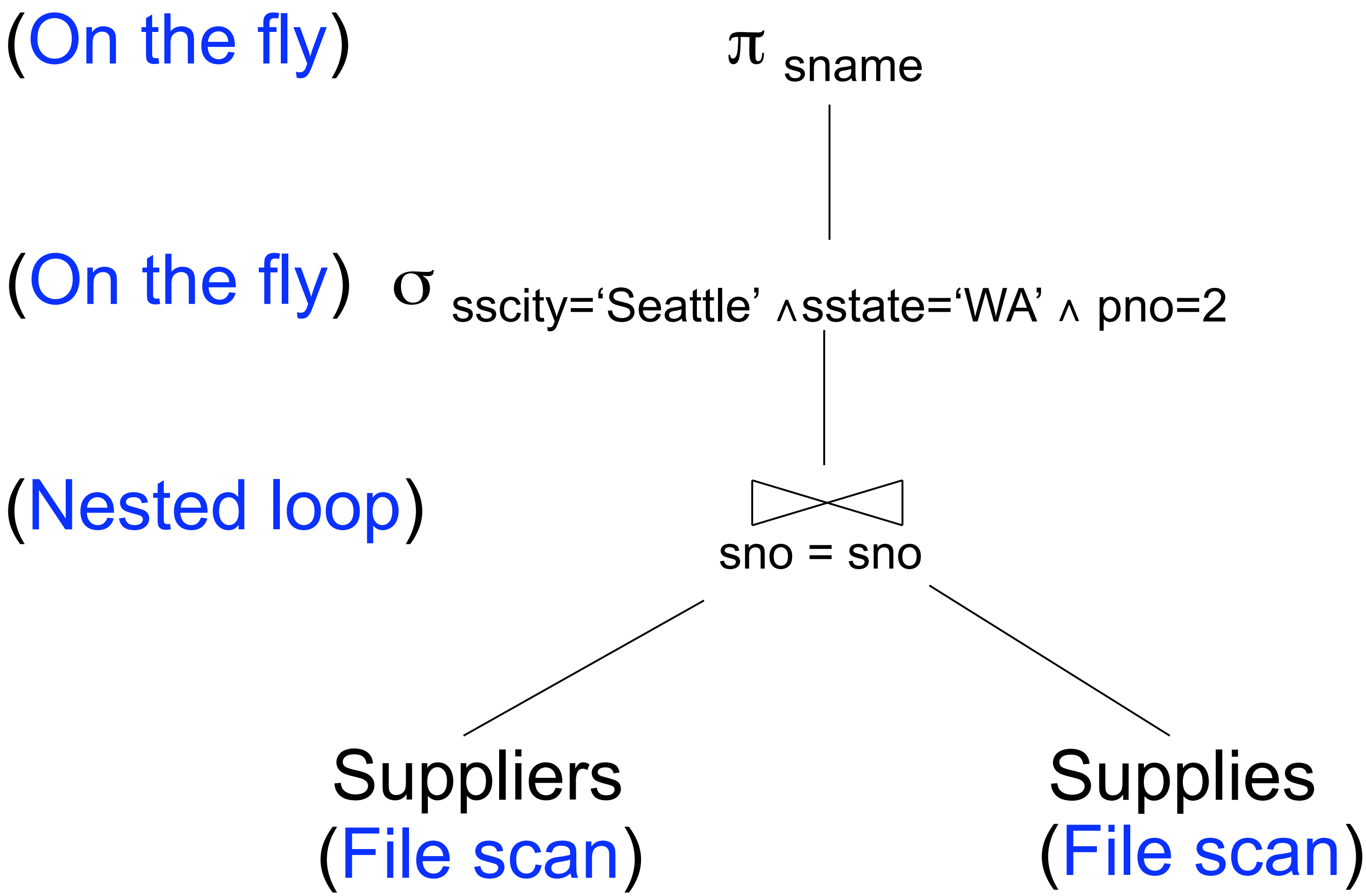
```
SELECT  Q.name
FROM Person Q
WHERE  Q.age > 25
    and not exists
      SELECT *
      FROM Purchase P
      WHERE P.buyer = Q.name
              and P.price > 100
```



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



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()**: clean-up state

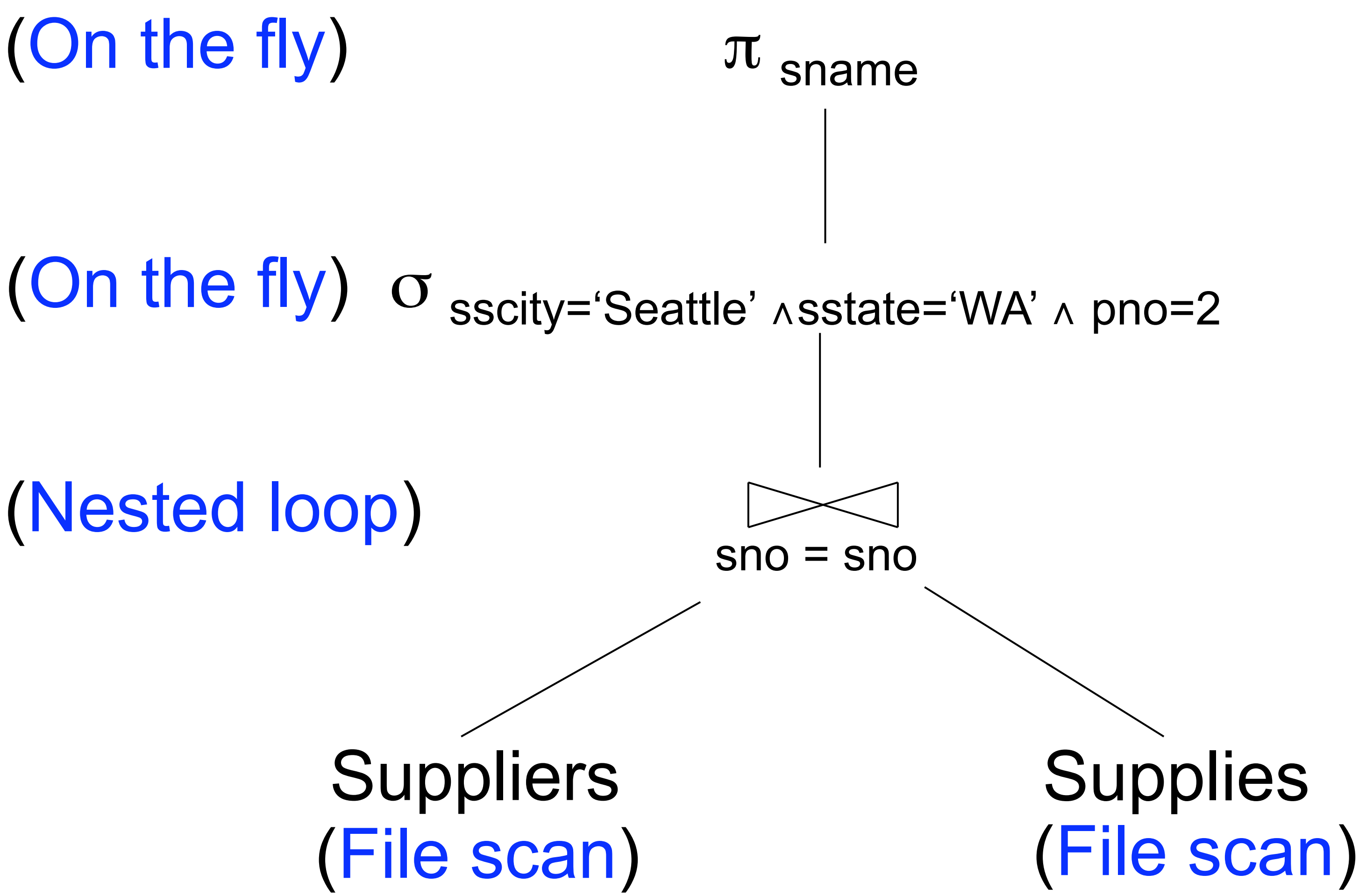
Pipelined Execution

- 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

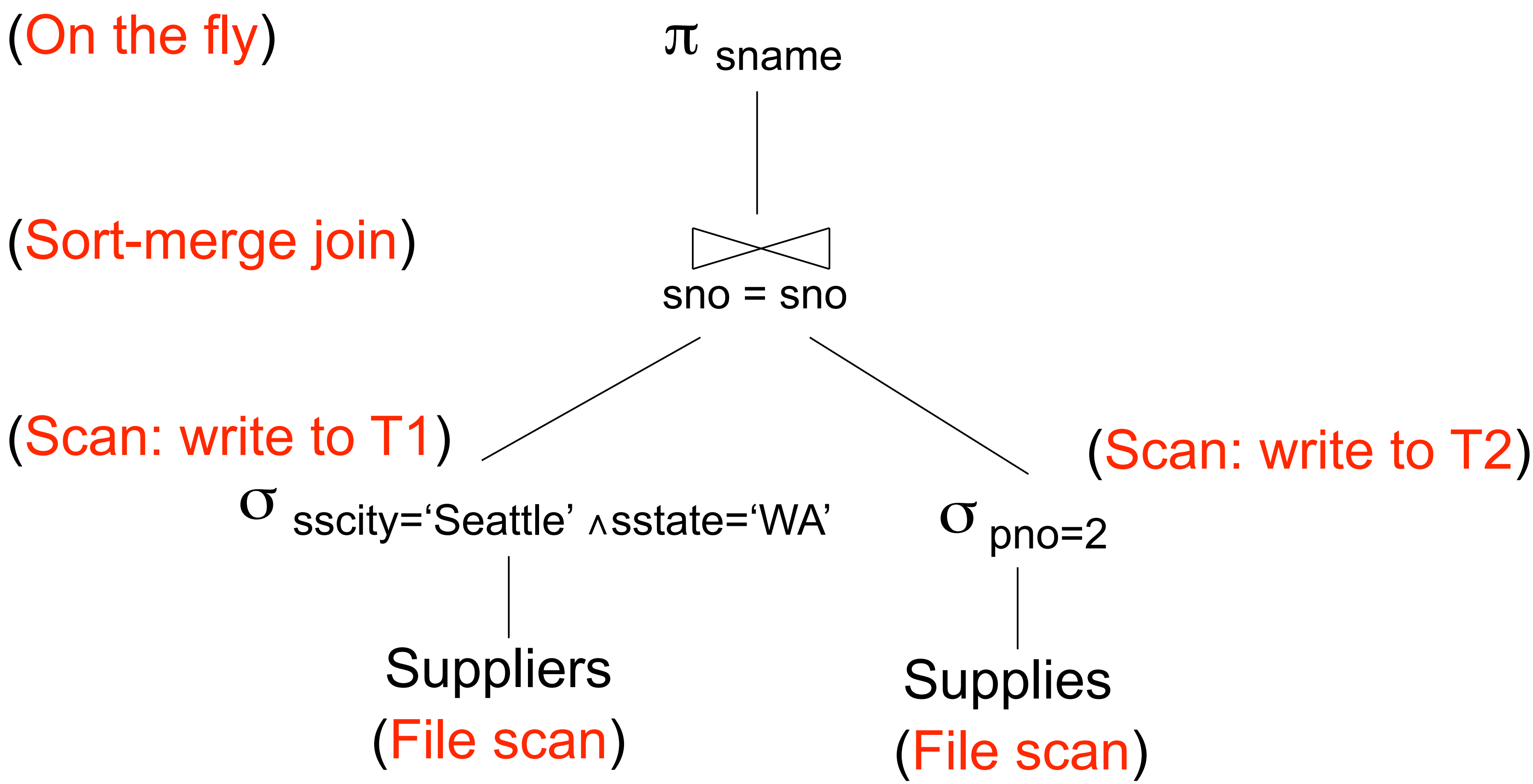


Intermediate Tuple Materialization

- 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



Outline

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  - One pass algorithms
  - Two-pass algorithms
  - Index-based algorithms

Why Learn About Op Algos?

- Implemented in commercial DBMSs
- Different DBMSs implement different subsets of these algorithms
- Good algorithms can greatly improve performance
- Need to know about physical operators to understand query optimization

Cost Parameters

- In database systems the data is on disk
- **Cost = total number of I/Os**

- Parameters:
  - **B(R) = # of blocks (i.e., pages) for relation R**
  - **T(R) = # of tuples in relation R**
  - **V(R, a) = # of distinct values of attribute a**

Cost

- Cost of an operation = number of disk I/Os to
  - read the operands
  - compute the result
- Cost of writing the result to disk is *not included*
  - Need to count it separately when applicable

Notions of Clustering

- **Clustered-file organization** (aka co-clustering)
  - Tuples of one relation R are placed with a tuple of another relation S with a common value
- **Clustered relation**
  - Tuples of relation are stored on blocks predominantly devoted to storing that relation
  - Sometimes also called “clustered file organization”
- **Clustered index (aka clustering index)**
  - When ordering of data records is close to the ordering of data entries in the index

Cost Parameters

- Clustered relation R:
  - Blocks consists mostly of records from this table
  - B(R) ≈ T(R) / blockSize

- Unclustered relation R:
  - Its records are placed on blocks with other tables
  - When R is unclustered: B(R) ≈ T(R)

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

Cost of Scanning a Table

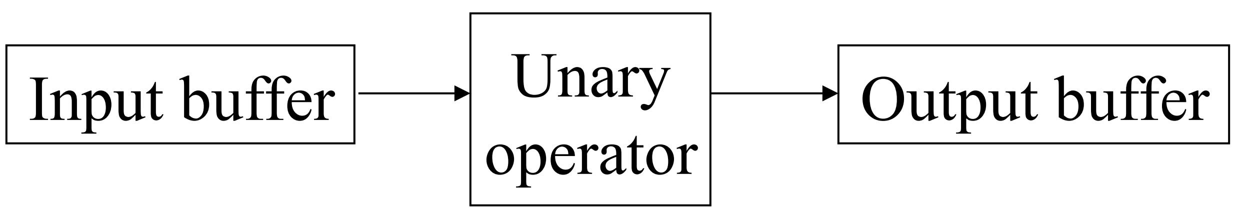
- Clustered relation:
  - Result may be unsorted: B(R)
  - Result needs to be sorted: 3B(R)

- Unclustered relation
  - Unsorted: T(R)
  - Sorted: T(R) + 2B(R)

One-pass Algorithms

Selection $\sigma(R)$, projection $\Pi(R)$

- Both are ***tuple-at-a-time*** algorithms
- Cost: B(R), the cost of scanning the relation



Join Algorithms

- Logical operator:
  - Product(pname, cname) $\bowtie$ Company(cname, city)

- Propose three physical operators for the join, assuming the tables are in main memory:
  - **Hash join**
  - **Nested loop join**
  - **Sort-merge join**

Hash Join

Hash join: R $\bowtie$ S

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

- Cost: B(R) + B(S)

- One pass algorithm when B(R) <= M

Nested Loop Joins

- Tuple-based nested loop R ⋈ S
- R is the outer relation, S is the inner relation

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

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

Page-at-a-time Refinement

```
for each page of tuples r in R do
   for each page of tuples s in S do
      for all pairs of tuples
         if r and s join then output (r,s)
```

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

Nested Loop Joins

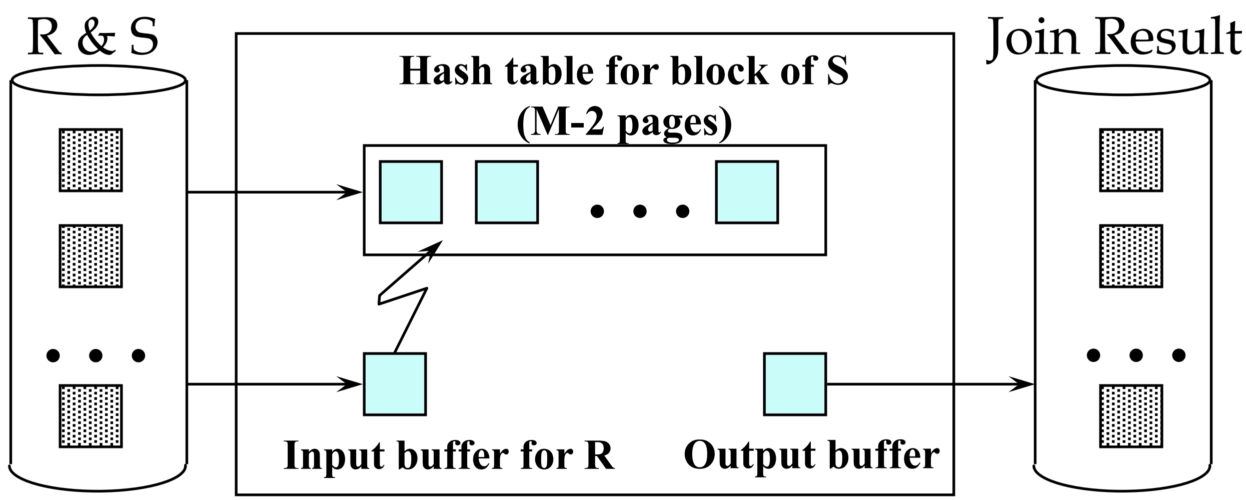
- We can be much more clever
- How would you compute the join in the following cases ? What is the cost ?
  - B(R) = 1000, B(S) = 2, M = 4
  - B(R) = 1000, B(S) = 3, M = 4
  - B(R) = 1000, B(S) = 6, M = 4

Nested Loop Joins

- Block Nested Loop Join
- Group of (M-2) pages of S is called a "block"

```
for each (M-2) pages ps of S do
  for each page pr of R do
      for each tuple s in ps
          for each tuple r in pr do
              if "r and s join" then output(r,s)
```

Nested Loop Joins



Nested Loop Joins

- Cost of block-based nested loop join
  - 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

Sort-Merge Join

Sort-merge join: R $\bowtie$ S

- Scan R and sort in main memory
- Scan S and sort in main memory
- Merge R and S

- Cost: B(R) + B(S)
- One pass algorithm when B(S) + B(R) <= M
- Typically, this is NOT a one pass algorithm

One-pass Algorithms

Duplicate elimination $\delta(R)$

- Need to keep tuples in memory
- When new tuple arrives, need to compare it with previously seen tuples
- Balanced search tree or hash table
- Cost: B(R)
- Assumption: $B(\delta(R)) <= M$

One-pass Algorithms

Grouping:

Product(name, department, quantity)

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

How can we compute this in main memory ?

One-pass Algorithms

- Grouping: $\gamma_{\text{department, sum(quantity)}}$ (R)

- Need to store all departments in memory
- Also store the sum(quantity) for each department
- Balanced search tree or hash table
- Cost: B(R)
- Assumption: number of depts fits in memory

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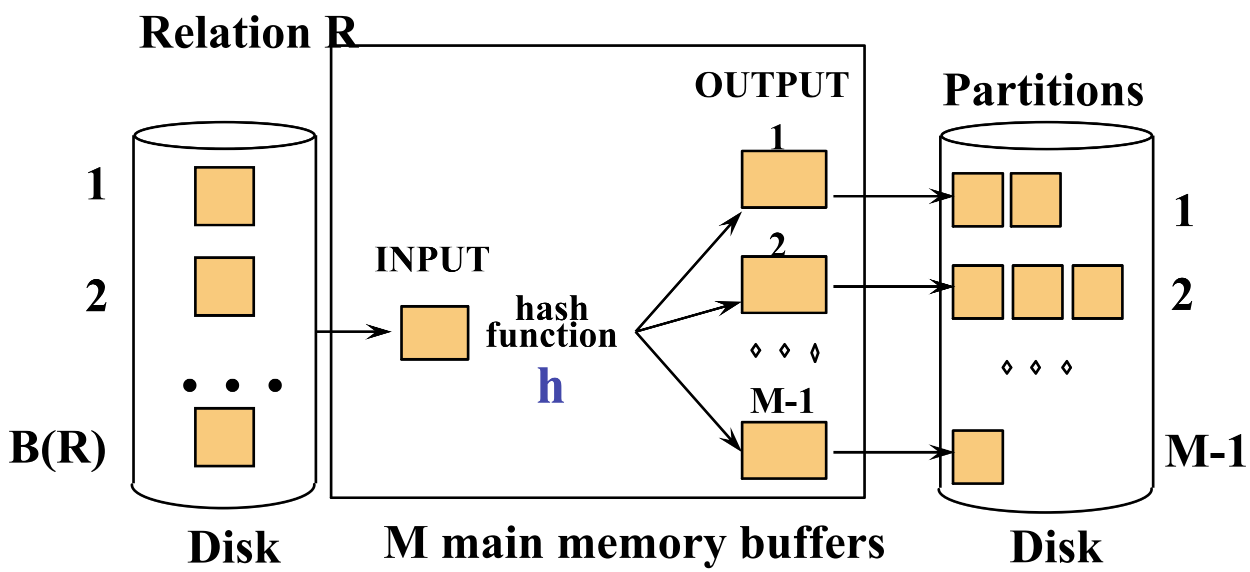
Two-Pass Algorithms

- What if data does not fit in memory?
- Need to process it in multiple passes

- Two key techniques
  - Hashing
  - Sorting

Two Pass Algorithms Based on Hashing

- 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 $B(R)/M \le M$, i.e. $B(R) \le M^2$

Hash Based Algorithms for δ

- Recall: δ(R) = duplicate elimination

- Step 1. Partition R into buckets
- Step 2. Apply δ to each bucket

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

Hash Based Algorithms for γ

- Recall: γ(R) = grouping and aggregation

- Step 1. Partition R into buckets
- Step 2. Apply γ to each bucket

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

Simple Hash Join

$R \bowtie S$

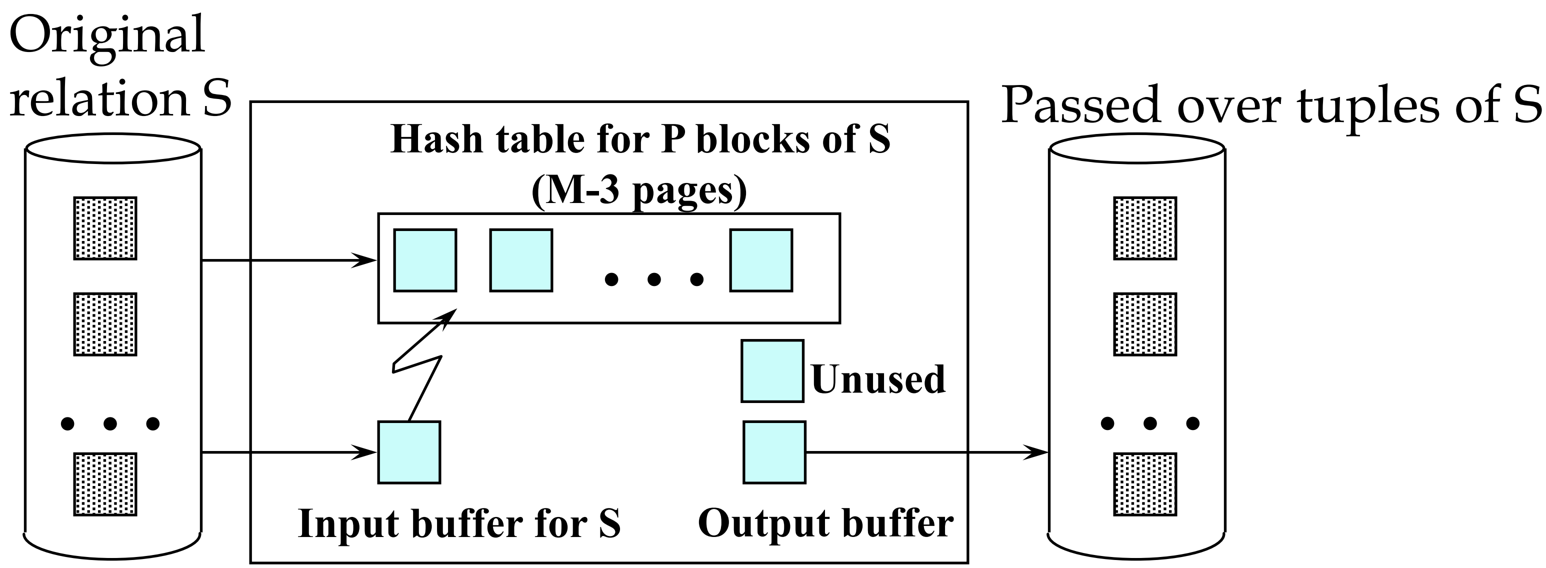
- Step 1:
  - P = min(M-3, B(S))
  - Choose hash function h and set of hash values s.t. P blocks of S tuples will hash into that set
  - Hash S and either insert tuple into hash table or write to disk

- Step 2
  - Hash R and either probe the hash table for S or write to disk

- Step 3
  - Repeat steps 1 and 2 until all tuples are processed

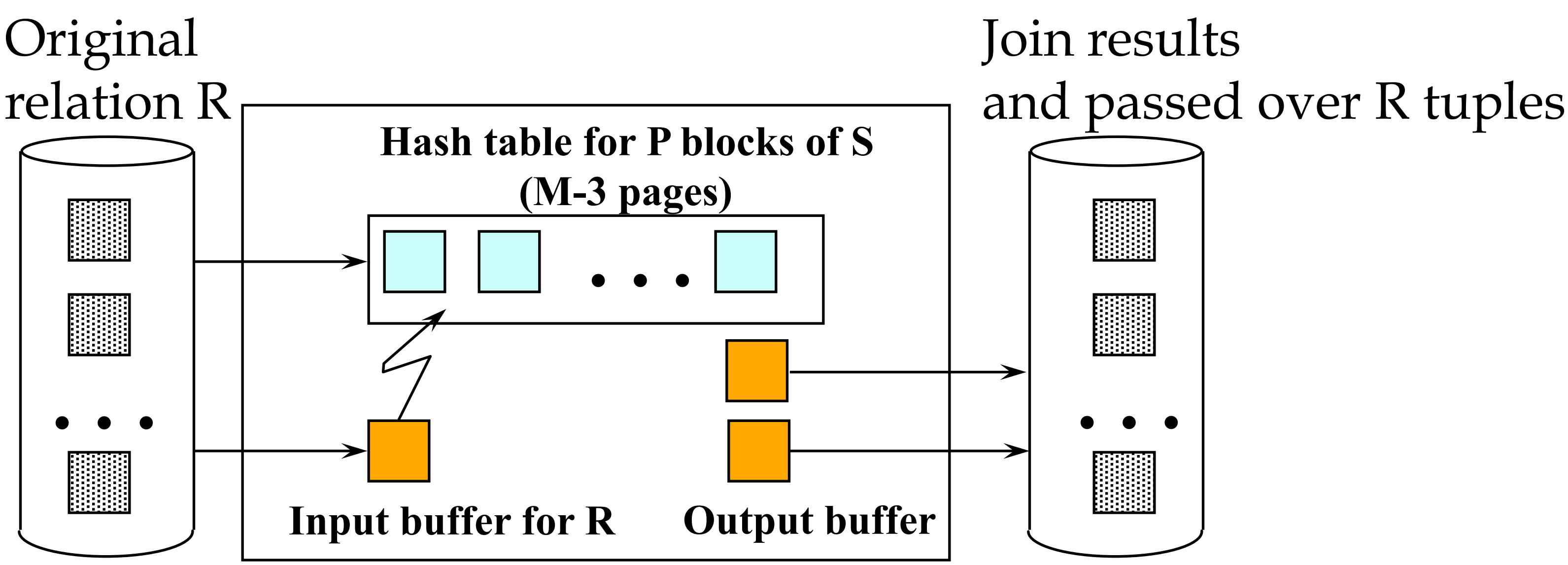
Simple Hash Join

- Build a hash-table for M-3 pages of S
- Write remaining pages of S back to disk



Simple Hash Join

- Hash R using the same hash function
- Probe hash table for S or write tuples of R back to disk



- Repeat these two steps until all tuples are processed
- Requires many passes

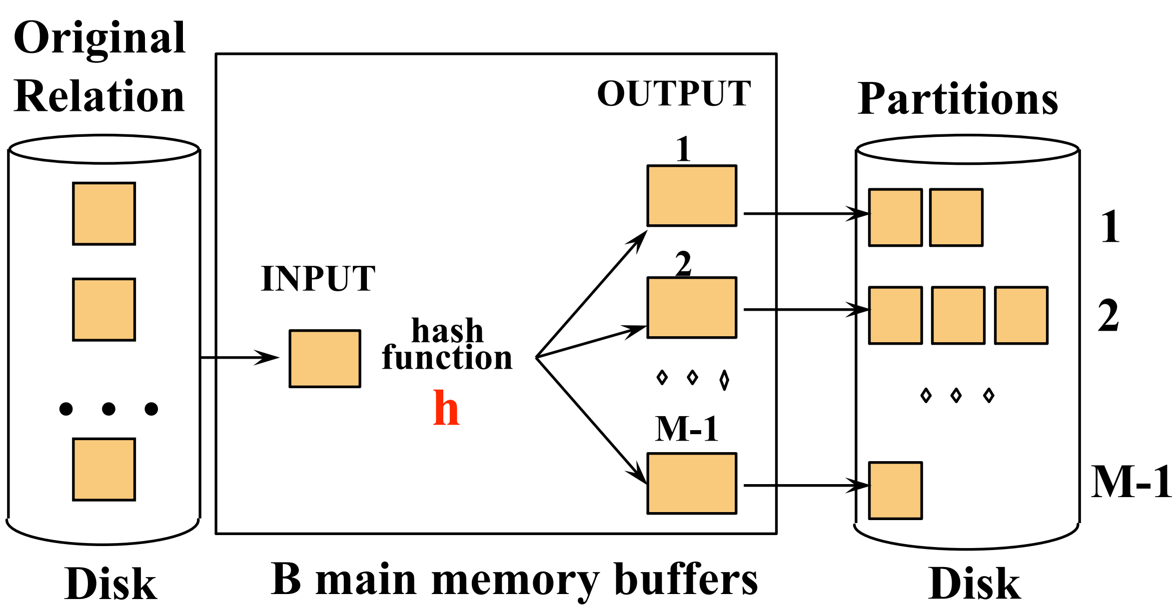
Partitioned (Grace) Hash Join

R $\bowtie$ S

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

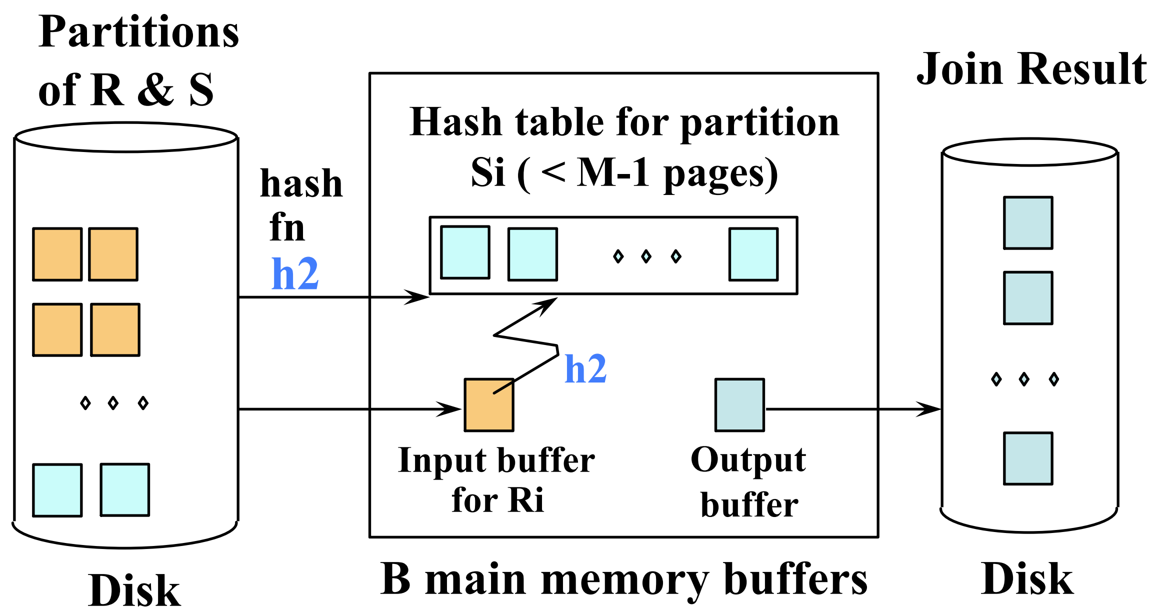
Partitioned Hash Join

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



Partitioned Hash Join

- Read in partition of R, hash it using h2 (≠ h)
  - Build phase
- Scan matching partition of S, search for matches
  - Probe phase



Partitioned Hash Join

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

Hybrid Hash Join Algorithm

- Assume we have extra memory available
- Partition S into k buckets
  t buckets S_1 , …, S_t stay in memory
  k-t buckets S_{t+1}, …, S_k to disk
- Partition R into k buckets
  - First t buckets join immediately with S
  - Rest k-t buckets go to disk
- Finally, join k-t pairs of buckets:
  (R_{t+1},S_{t+1}), (R_{t+2},S_{t+2}), …, (R_k,S_k)

Hybrid Hash Join Algorithm

- How to choose k and t ?
  - Choose k large but s.t. $k <= M$
  - Choose t/k large but s.t. $t/k * B(S) <= M$
  - Moreover: $t/k * B(S) + k-t <= M$

- Assuming $t/k * B(S) >> k-t$: $t/k = M/B(S)$

Hybrid Hash Join Algorithm

- How many I/Os ?

- Cost of partitioned hash join: 3B(R) + 3B(S)

- Hybrid join saves 2 I/Os for a t/k fraction of buckets
- Hybrid join saves 2t/k(B(R) + B(S)) I/Os

- Cost: (3-2t/k)(B(R) + B(S)) = (3-2M/B(S))(B(R) + B(S))

External Sorting

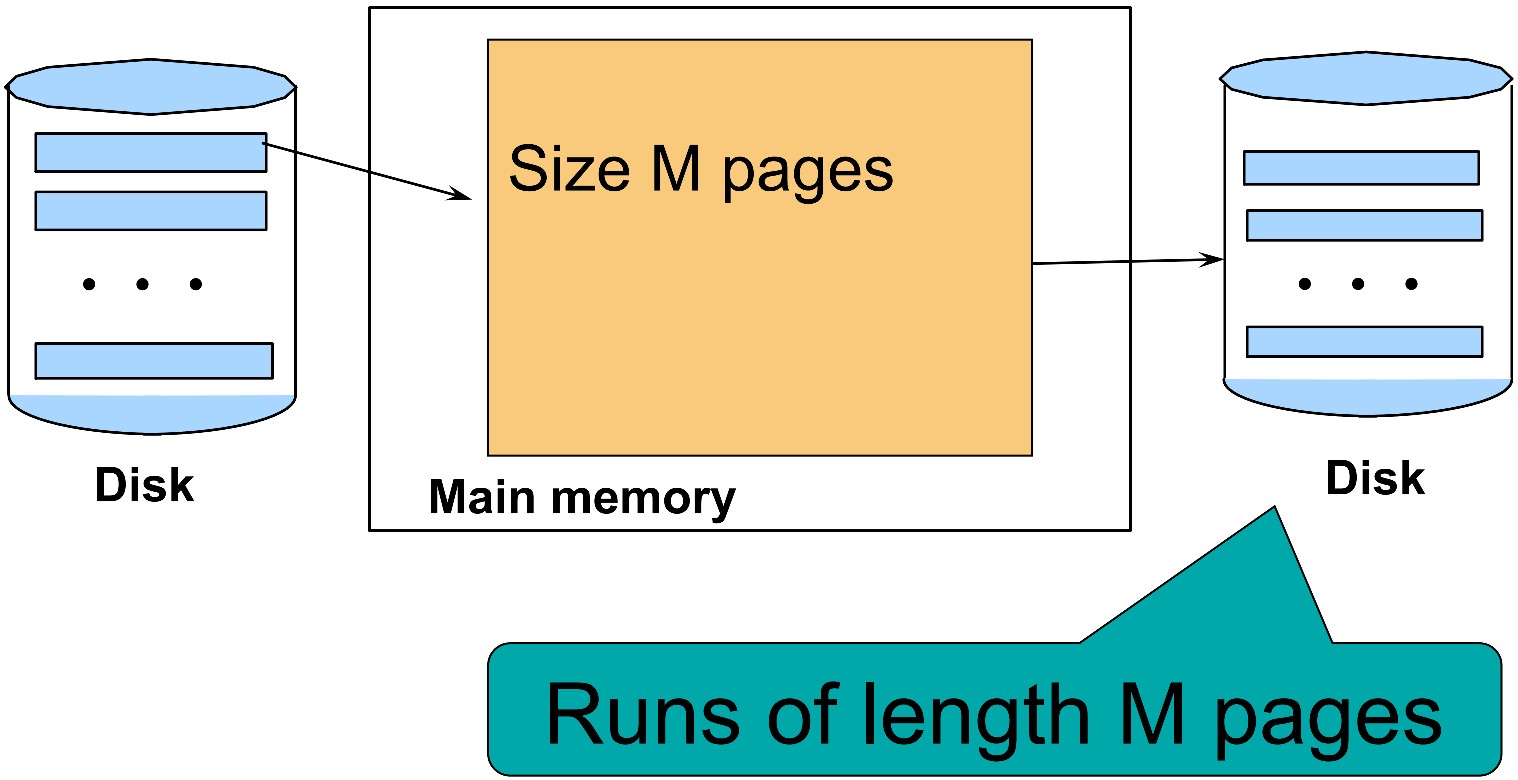
- Problem: Sort a file of size B with memory M

- 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 $B < M^2$

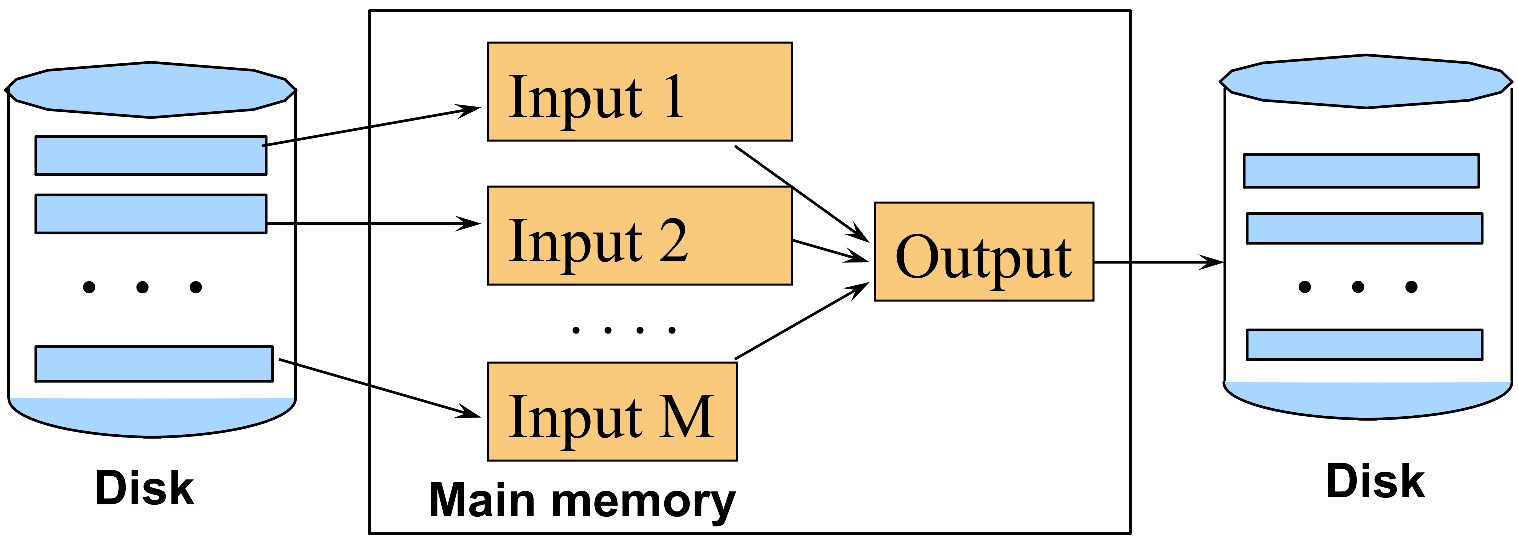
External Merge-Sort: Step 1

- Phase one: load M pages in memory, sort



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

External Merge-Sort

- Cost:
  - Read+write+read = 3B(R)
  - Assumption: B(R) <= M^2

- Other considerations
  - In general, a lot of optimizations are possible

Two-Pass Algorithms Based on Sorting

Duplicate elimination $\delta(R)$

- Trivial idea: sort first, then eliminate duplicates
- Step 1: sort chunks of size M, write
  - cost 2B(R)
- Step 2: merge M-1 runs, but include each tuple only once
  - cost B(R)
- Total cost: 3B(R), Assumption: $B(R) <= M^2$

Two-Pass Algorithms Based on Sorting

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

Two-Pass Algorithms Based on Sorting

Join R $\bowtie$ S

- Start by sorting both R and S on the join attribute:
  - Cost: 4B(R)+4B(S) (because need to write to disk)
- Read both relations in sorted order, match tuples
  - Cost: B(R)+B(S)
- Total cost: 5B(R)+5B(S)
- Assumption: $B(R) <= M^2$, $B(S) <= M^2$

Two-Pass Algorithms Based on Sorting

Join R ⋈ S

- If $B(R) + B(S) <= M^2$

  Or if we use a priority queue to create runs of length 2|M|

  (see paper)
- 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)

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Review: Access Methods

- **Heap file**
  - Scan tuples one at the time
- **Hash-based index**
  - Efficient selection on equality predicates
  - Can also scan data entries in index
- **Tree-based index**
  - Efficient selection on equality or range predicates
  - Can also scan data entries in index

Index Based Selection

- Selection on equality: $\sigma_{a=v}(R)$
- V(R, a) = # of distinct values of attribute a
- Clustered index on a: cost B(R)/V(R,a)
- Unclustered index on a: cost T(R)/V(R,a)
- Note: we ignored the I/O cost for the index pages

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 Nested Loop Join

R ⋈ S

- Assume S has an index on the join attribute
- Iterate over R, for each tuple fetch corresponding tuple(s) from S

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

Summary of External Join Algorithms

- Block Nested Loop Join: B(R) + B(R)*B(S)/M
- Hybrid Hash Join: (3-2M/B(S))(B(R) + B(S))
  Assuming t/k * B(S) >> k-t
- Sort-Merge Join: 3B(R)+3B(S)
  Assuming B(R)+B(S) <= M^2
- Index Nested Loop Join: B(R) + T(R)B(S)/V(S,a)
  Assuming R is clustered and S has clustered index on a

Summary of Query Execution

- For each logical query plan
  - There exist many physical query plans
  - Each plan has a different cost
  - Cost depends on the data
- Additionally, for each query
  - There exist several logical plans
- Next lecture: query optimization
  - How to compute the cost of a complete plan?
  - How to pick a good query plan for a query?