Overview of Query Evaluation

Chapter 12

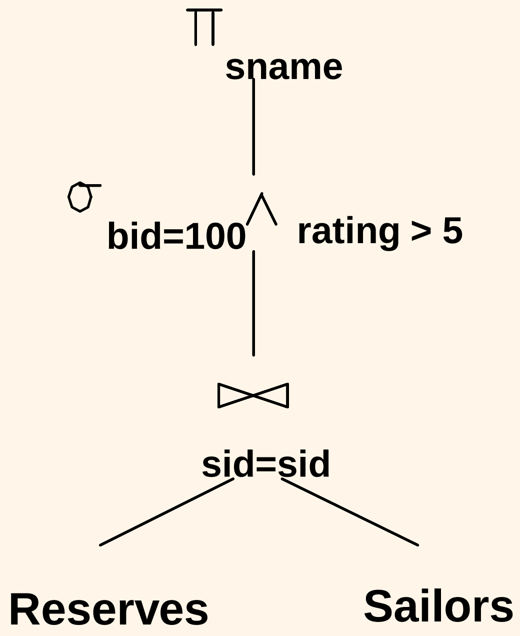
Outline

- Query Optimization Overview
- Algorithm for Relational Operations

Overview of Query Evaluation

- DBMS keeps descriptive data in system catalogs.
- SQL queries are translated into an extended form of relational algebra:
  - *Query Plan Reasoning*:
    - Tree of operators
    - with choice of one among several algorithms for each operator

Query Plan Evaluation



- *Query Plan Execution:*
  - Each operator typically implemented using a \`pull' interface
  - when an operator is \`pulled' for next output tuples, it \`pulls' on its inputs and computes them.

Overview of Query Evaluation

- Query Plan Optimization :
  - Ideally: Want to find best plan.
    Practically: Avoid worst plans!

- Two main issues in query optimization:
  - For a given query, what plans are considered?
    - Algorithm to search plan space for cheapest (estimated) plan.
  - How is the cost of a plan estimated?
    - Cost models based on I/O estimates

Query Processing

- Common Techniques for Query Processing Algorithms:
  - Indexing: Can use WHERE conditions to retrieve small set of tuples from large relation
  - Iteration: Examine all tuples in an input table, one after the other (like in sorting algorithm).
  - Partitioning: By using sorting or hashing, we partition input tuples and replace expensive operation by similar operations on smaller inputs.

** Watch for these techniques as we discuss query evaluation!*

Access Paths

- An <u>access path</u>
  - A method of retrieving tuples from a table
- Method:
  - File scan,
  - Index that matches a selection (in the query)
- Note :
  - Contributes significantly to cost of relational operator.

Matching an Access Path

- A tree index ***matches*** (a conjunction of) terms that involve only attributes in a *prefix* of search key.

- Example : Given tree index on <*a, b, c*>
  - selection *a=5 AND b=3 ?*
  - selection *a=5 AND b>6* ?
  - selection *b=3* ?

Matching an Access Path

- A hash index *matches* (a conjunction of) terms that has a term *attribute = value* for every attribute in search key of index.

- Example : Given hash index on <*a, b, c*>
  - selection *a=5 AND b=3 and c =5 ?*
  - selection *c = 5 AND b = 6* ?
  - selection *a = 5* ?
  - selection *a* > *5 AND b=3 and c =5 ?*

Query Evaluation of Selection

Selection

- Example : $\sigma_{\text{R.attr OP value}}$ (R)

- Case 1: No Index, NOT sorted on R.attr

- Must scan the entire relation.
  Most selective access path = file scan
  Cost: M

Selection

- Case 2: No Index, Sorted Data on R.attr

- Binary search for first tuple.
  Scan R for all satisfied tuples.
  Cost: O($\log_2 M$)

Selection Using B+ tree index

- Case 3: B+ tree Index
  - Cost I (finding qualifying data entries) + cost II (retrieving records) :
    - Cost I: 2-3 I/Os. (depth of B+ tree)
    - Cost II:
      - clustered index 1 I/O,
      - unclustered index upto one I/O per qualifying tuple.

Example : Using B+ Index for Selections

```
SELECT  *
FROM    Reserves R
WHERE   R.rname < 'C%'
```

- Example :
  - Assume uniform distribution of names, about 10% of tuples qualify (100 pages, 10,000 tuples).
  - Clustered index:
    - little more than 100 I/Os;
  - Unclustered index :
    - up to 10,000 I/Os!

Selection --- B+ Index

- ***Refinement for unclustered indexes*:**
  1. Find qualifying data entries.
  2. Sort rid's of data records to be retrieved.
  3. Fetch rids in order.
     Avoid retrieving the same page multiple times.

  However, # of such pages likely to be still higher than with clustering.

- Use of unclustered index for a range selection could be expensive. Simpler if just scan data file.

Selection – Hash Index

- Hash index is good for equality selection.

- Cost:
  Cost I (retrieve index bucket page)
  + Cost II (retrieving qualifying tuples from R)
    - Cost I is one I/O
    - Cost II could up to one I/O per satisfying tuple.

General Condition : Conjunction

- A condition with several predicates combined by conjunction (AND):

- Example : *day<8/9/94 AND bid=5 AND sid=3*.

General Selections (Conjunction)

First approach: (utilizing single index)

- Find the *most selective access path*, retrieve tuples using it.
  - To reduce the number of tuples *retrieved*
- Apply any remaining terms that don't match the index:
  - To discard some retrieved tuples
  - This does not affect number of tuples/pages fetched.

- Example : Consider *day*<*8/9/94 AND bid*=*5 AND sid*=*3*.
  - A B+ tree index on *day* can be used;
  - then *bid*=*5* and *sid*=*3* must be checked for each retrieved tuple.
  - Hash index on <*bid, sid*> could be used
  - *day*<*8/9/94* must then be checked on fly.

General Selections

Second approach (utilizing multiple index)

- Assuming 2 or more matching indexes that use Alternatives (2) or (3) for data entries.
  - Get sets of rids of data records using each matching index.
  - Then *intersect* these sets of rids
  - Retrieve records and apply any remaining terms.

- Example : Consider *day<8/9/94 AND bid=5 AND sid=3*.
  - A B+ tree index I on *day* and an index II on *sid*, both Alternative (2).
  - - Retrieve rids of records satisfying *day<8/9/94* using index I,
  - - Retrieve rids of recs satisfying *sid=3* using Index II
  - - Intersect rids
  - - Retrieve records and check *bid=5.*

General Condition : Disjunction

- Disjunction condition: one or more terms (R.attr op value) connected by OR ($\vee$).

- Example : (*day<8/9/94) OR (bid=5 AND sid=3)*

General Selection (Disjunction)

- Case 1: Index is not available for one of terms. Need a file scan. Check other conditions in this file scan.

- E.g., Consider *day<8/9/94 OR rname ='Joe'*
  - No index on day. Need a File scan.
  - Even index is available in rname, does not help.

General Selection (Disjunction)

- Case 2: Every term has a matching index.
  - Retrieve candidate tuples using index.
  - Then Union the results

- Example : consider *day<8/9/94 OR rname ='Joe'*
  - *Assume two B+ tree indexes on day and rname.*
  - *Retrieve tuples satisfying day < 8/9/94*
  - *Retrieve tuples satisfying rname = 'Joe'*
  - *Union the retrieved tuples.*

Query Evaluation of Projection

Algorithms for Projection

```
SELECT   DISTINCT
         R.sid, R.bid
FROM     Reserves R
```

- The expensive part is removing duplicates.
  - SQL systems don't remove duplicates unless keyword DISTINCT is specified in query.
- Sorting Approach:
  - Sort on <sid, bid> and remove duplicates.
    (Can optimize this by dropping unwanted information while sorting.)
- Hashing Approach:
  - Hash on <sid, bid> to create partitions.
    Load partitions into memory one at a time, build in-memory hash structure, and eliminate duplicates.
- Indexing Approach :
  - If there is an index with both R.sid and R.bid in the search key, may be cheaper to sort data entries!

Query Evaluation of Joins

Schema for Examples

Sailors (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)
Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

- Similar to old schema; *rname* added for variations.
- Reserves:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.
- Sailors:
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages.

Equality Joins With One Join Column

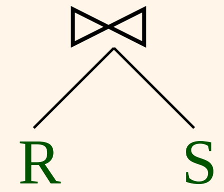
```
SELECT *
FROM    Reserves R1, Sailors S1
WHERE  R1.sid=S1.sid
```

- In algebra: $R \bowtie S$. Common! Must be carefully optimized.
- $R \times S$ is large; so $R \times S$ followed by a selection is inefficient.
- Assume:
  - M pages of R, p_R tuples per page (i.e., number of tuples of R = M * p_R), N pages of S, p_S tuples per page (i.e., number of tuples of S = N * p_S),
  - In our examples, R is Reserves and S is Sailors.
- *Cost metric*: # of I/Os. We will ignore output costs.

Typical Choices for Joins

- Nested Loops Join
  - Simple Nested Loops Join: Tuple-oriented
  - Simple Nested Loops Join: Page-oriented
  - Block Nested Loops Join
  - Index Nested Loops Join
- Sort Merge Join
- Hash Join

Simple Nested Loops Join



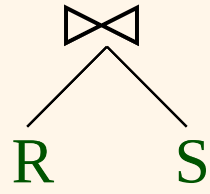
foreach ***tuple*** r in R do
    foreach ***tuple*** s in S do
        if $r_i == s_j$ then add <r, s> to result

- Algorithm :

  For each tuple in outer relation R, we scan inner relation S.

- Cost :
  - Scan of outer + for each tuple of outer, scan of inner relation.
  - Cost = $M + p_R * M * N$
  - Cost = 1000 + 100*1000*500 I/Os.

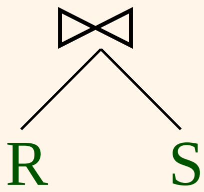
Simple Nested Loops Join



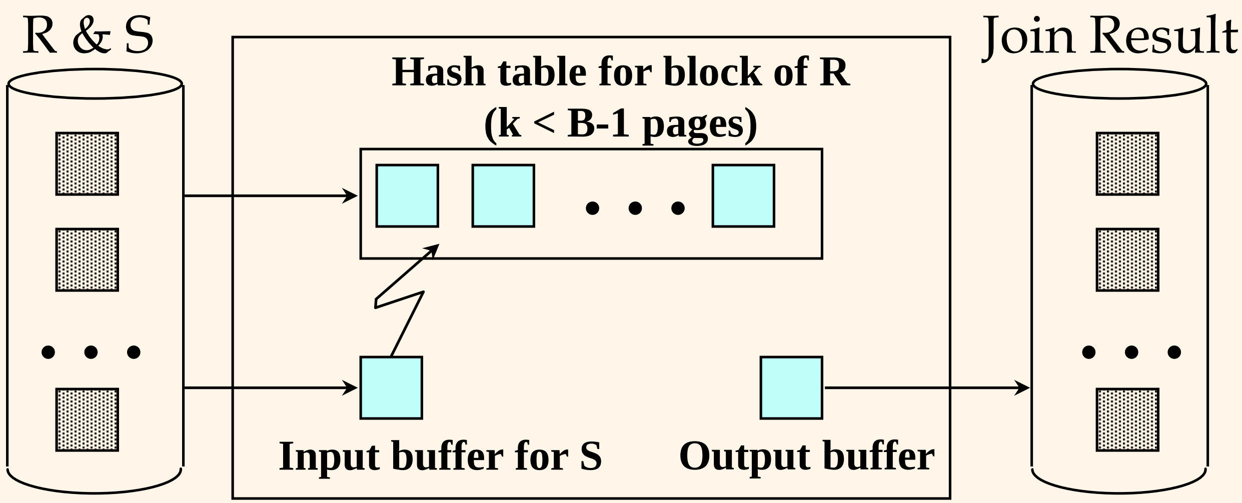
foreach ***tuple*** r in R do
    foreach ***tuple*** s in S do
        if $r_i == s_j$ then add <r, s> to result

- Tuple-oriented:
  For each tuple in *outer* relation R, we scan *inner* relation S.
  - Cost: $M + p_R * M * N = 1000 + 100*1000*500$ I/Os.
- Page-oriented:
  For each *page* of R, get each *page* of S, and write out matching pairs of tuples <r, s>, where r is in R-page and S is in S-page.
- Cost :
  - Scan of outer pages + for each page of outer, scan of inner relation.
  - Cost = M + M * N
  - Cost = 1000 + 1000*500 IOs.
  - smaller relation (S) is outer, cost = 500 + 500*1000 IOs.

Block Nested Loops Join



- One page as input buffer for scanning inner S,
- One page as the output buffer,
- Remaining pages to hold ``block'' of outer R.
  - For each matching tuple r in R-block, s in S-page, add <r, s> to result.
  - Then read next R-block, scan S again. Etc.
  - Find matching tuple ? → Use in-memory hashing.



Cost of Block Nested Loops

- Cost: Scan of outer + #outer blocks * scan of inner
  - #outer blocks =

$$\left\lceil \textit{\# of pages of outer / blocksize} \right\rceil$$

Examples of Block Nested Loops

- Cost: Scan of outer + #outer blocks * scan of inner

- With Reserves (R) as outer, & 100 pages of R as block:
  - Cost of scanning R is 1000 I/Os; a total of 10 *blocks*.
  - Per block of R, we scan Sailors (S); 10*500 I/Os.
  - E.g., If a block is 90 pages of R, we would scan S 12 times.

- With 100-page block of Sailors as outer:
  - Cost of scanning S is 500 I/Os; a total of 5 blocks.
  - Per block of S, we scan Reserves; 5*1000 I/Os.

Examples of Block Nested Loops

- Optimizations?
  - With ***sequential reads*** considered, analysis changes: may be best to divide buffers evenly between R and S.
  - Double buffering would also be suitable.

Index Nested Loops Join

```
foreach tuple r in R do
        foreach tuple s in S where r_i == s_j do
                add <r, s> to result
```

- An index on join column of one relation (say S), use S as inner and exploit the index.
- Cost:
  - Scan the outer relation R
  - For each R tuple, sum cost of finding matching S tuples
  - Cost: M + (($M*p_R$) * cost of finding matching S tuples)

Index Nested Loops Join

- For each R tuple, cost of probing S index is :
  - about 1.2 for hash index,
  - 2-4 for B+ tree.
- Cost of retrieving S tuples (assuming Alt. (2) or (3) for data entries) depends on clustering:
  - Clustered : 1 I/O (typical),
  - Unclustered: up to 1 I/O per matching S tuple.

Examples of Index Nested Loops

- Hash-index (Alt. 2) on *sid* of Sailors (as inner):
  - Scan Reserves:
    - 1000 page I/Os,
    - 100*1000 tuples.
  - For each Reserves tuple:
    - 1.2 I/Os to get data entry in index,
    - plus 1 I/O to get (the exactly one) matching Sailors tuple.
    - Total: 100,000 * (1.2 + 1) = 220,000 I/Os.
  - In total, we have:
    - 1000 I/Os plus
    - 220,000 I/Os.
    - Equals 221,000 I/Os

Examples of Index Nested Loops

- Hash-index (Alt. 2) on *sid* of Reserves (as inner):
  - Scan Sailors:
    - 500 page I/Os,
    - 80*500 tuples.
  - For each Sailors tuple:
    - 1.2 I/Os to find index page with data entries,
    - plus cost of retrieving matching Reserves tuples.

    - Assuming uniform distribution:
      2.5 reservations per sailor (100,000 / 40,000).
    - Cost of retrieving them is 1 or 2.5 I/Os
      depending on whether the index is clustered.

    Total : 500 + 40,000 * (1.2 + 2.5).

Simple vs. Index Nested Loops Join

- Assume: M Pages in R, p_R tuples per page,
  N Pages in S, p_S tuples per page,
  B Buffer Pages.
- Nested Loops Join
  - Simple Nested Loops Join
    - Tuple-oriented: $M + p_R * M * N$
    - Page-oriented: $M + M * N$
    - Smaller as outer helps.
  - Block Nested Loops Join
    - $M + N * \lceil M/(B-2) \rceil$
    - Dividing buffer evenly between R and S helps.
  - Index Nested Loops Join
    - M + (($M*p_R$) * cost of finding matching S tuples)
    - cost of finding matching S tuples = cost of Probe + cost of retrieving
- With unclustered index, if number of matching inner tuples for each outer tuple is small, cost of INLJ is much smaller than SNLJ.

Join: Sort-Merge $(R \bowtie_{i=j} S)$

(1). Sort R and S on the join column.
(2). Scan R and S to do a ``merge'' on join column
(3). Output result tuples.

Example of Sort-Merge Join

sid	sname	rating	age
22	dustin	7	45.0
28	yuppy	9	35.0
31	lubber	8	55.5
44	guppy	5	35.0
58	rusty	10	35.0

sid	bid	day	rname
28	103	12/4/96	guppy
28	103	11/3/96	yuppy
31	101	10/10/96	dustin
31	102	10/12/96	lubber
31	101	10/11/96	lubber
58	103	11/12/96	dustin

Join: Sort-Merge $(R \bowtie_{i=j} S)$

(1). Sort R and S on the join column.
(2). Scan R and S to do a ``merge'' on join col.
(3). Output result tuples.

- Merge on Join Column:
  - Advance scan of R until current R-tuple >= current S tuple,
  - then advance scan of S until current S-tuple >= current R tuple;
  - do this until current R tuple = current S tuple.

  - At this point, all R tuples with same value in Ri (*current R group*) and all S tuples with same value in Sj (*current S group*) *match*;
  - So output <r, s> for all pairs of such tuples.

  - Then resume scanning R and S (as above)

Join: Sort-Merge $(R \bowtie_{i=j} S)$

- Note :
  - R is scanned once; each S group is scanned once per matching R tuple.
  - Multiple scans of an S group are likely to find needed pages in buffer.

Cost of Sort-Merge Join

sid	sname	rating	age
22	dustin	7	45.0
28	yuppy	9	35.0
31	lubber	8	55.5
44	guppy	5	35.0
58	rusty	10	35.0

sid	bid	day	rname
28	103	12/4/96	guppy
28	103	11/3/96	yuppy
31	101	10/10/96	dustin
31	102	10/12/96	lubber
31	101	10/11/96	lubber
58	103	11/12/96	dustin

Cost of sort-merge :

- Sort R
- Sort S
- Merge R and S

Example of Sort-Merge Join

sid	sname	rating	age
22	dustin	7	45.0
28	yuppy	9	35.0
31	lubber	8	55.5
44	guppy	5	35.0
58	rusty	10	35.0

sid	bid	day	rname
28	103	12/4/96	guppy
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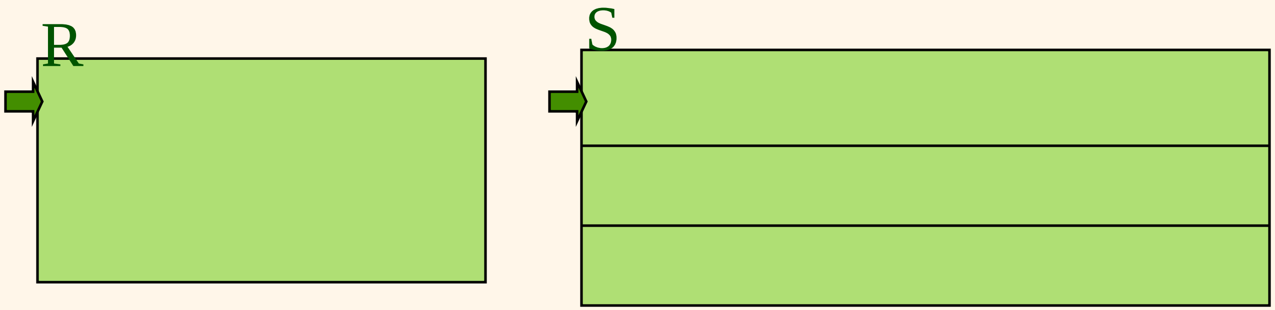
31	101	10/10/96	dustin
31	102	10/12/96	lubber
31	101	10/11/96	lubber
58	103	11/12/96	dustin

- Best case: ?
- Worst case: ?
- Average case ?

Cost of Sort-Merge Join

- Best Case Cost: (M+N)
  - Already sorted.
  - The cost of scanning, M+N

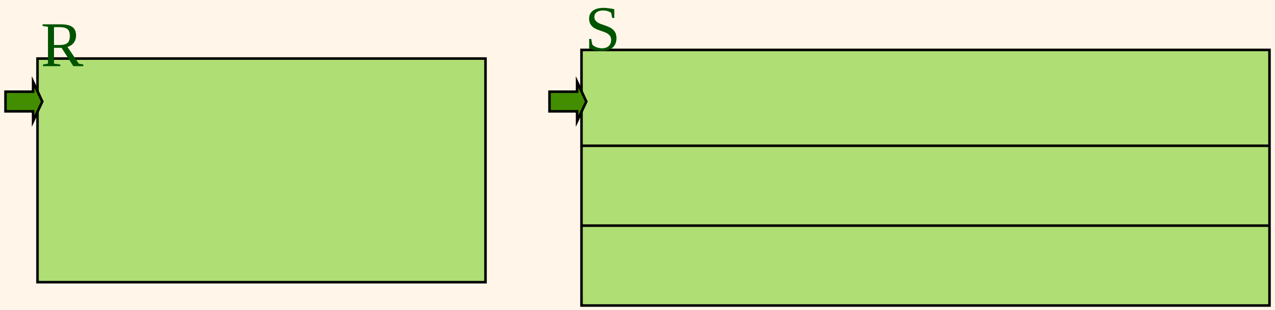


- Worst Case Cost: M log M + N log N + (M+N)
- Many pages in R in same partition. (Worst, all of them). The pages for this partition in S don't fit into RAM. Re-scan S is needed. Multiple scan S is expensive!

- Note: Guarantee M+N if key-FK join, or no duplicates.

Cost of Sort-Merge Join

- Average Cost:
  - ~ In practice, roughly linear in M and N
  - So O (M log M + N log N + (M+N))



Comparison with Sort-Merge Join

- Average Cost: $O(M \log M + N \log N + (M+N))$
- Assume B = {35, 100, 300}; and
  R = 1000 pages, S = 500 pages

- <u>Sort-Merge Join</u>
- both R and S can be sorted in 2 passes,
- logM = log N = 2
- total join cost: 2*2*1000 + 2*2*500 + (1000 + 500)
  = 7500.

- <u>Block Nested Loops Join:</u> 2500 ~ 15000

Refinement of Sort-Merge Join

- IDEA :
  - Combine the merging phases when *sorting* R (or S) with the merging in join algorithm.

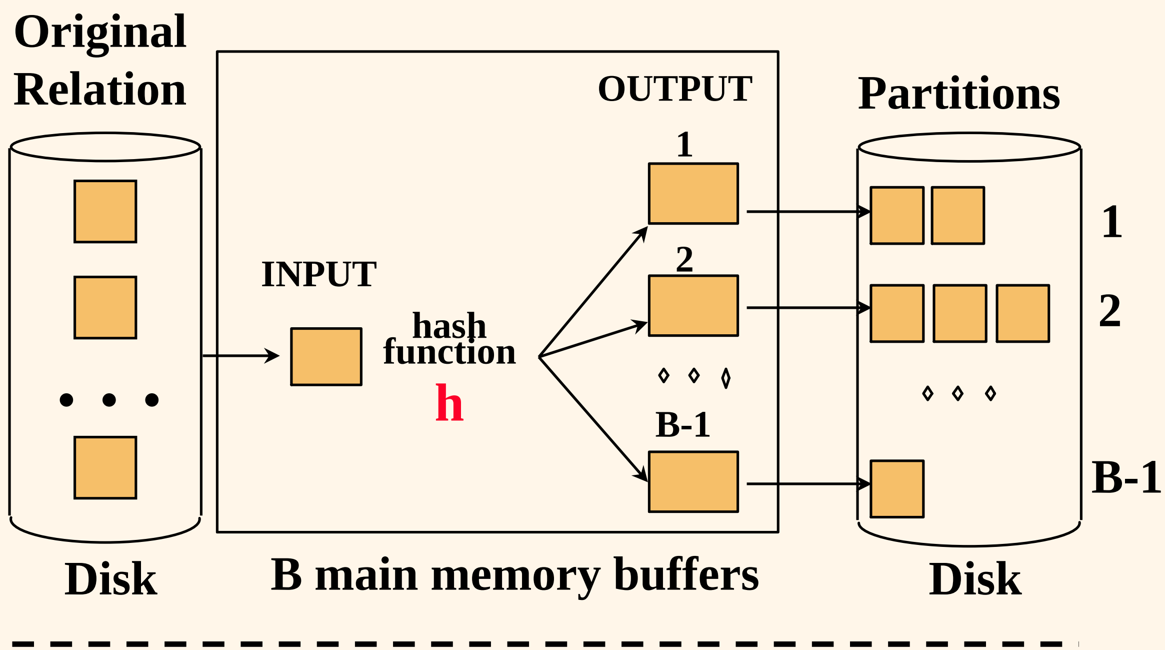
Refinement of Sort-Merge Join

- IDEA : Combine the merging phases when *sorting* R (or S) with the merging in join algorithm.
  - If we do the following: perform Pass 0 of sort on R; perform Pass 0 of sort on S; merge and join on the fly – the total IO cost for join is 3 (M + N)
  - When is the above possible? When M/B + N/B + 1 <= B; In other words when B (B – 1) >= (M + N)

    (The above expression is modified from that in the book)
  - Cost: 3 (M + N) as follows
    - (read+write R and S in Pass 0)
    - + (read R and S in merging pass and join on fly)
    - + (writing of result tuples).
  - In example, cost goes down from 7500 to 4500 I/Os.

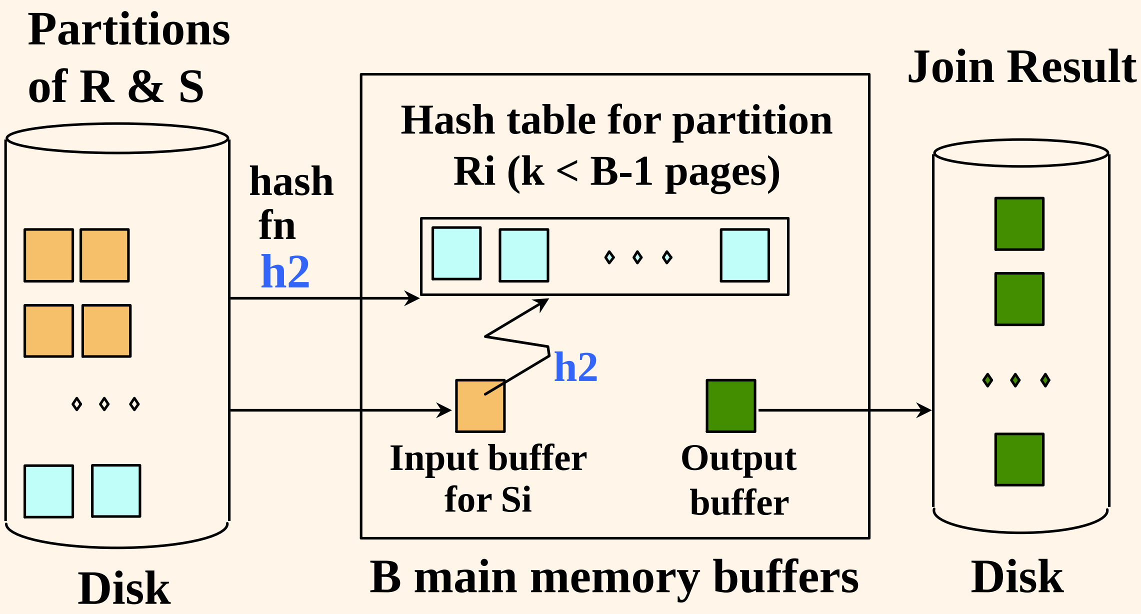
Hash-Join

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



Hash-Join

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



Cost of Hash-Join

- In partitioning phase, read+write both relations:
  - 2(M+N).
- In matching phase, read both relations:
  - M+N.
- Total : 3(M+N)
- E.g., total of 4500 I/Os in our running example.

Observation on Hash-Join

- Memory Requirement: When is total cost 3 (M + N)?
  - Partition fit into available memory?
  - Assuming B buffer pages. #partitions k <= B-1 (why?), (to min size of each partition, we choose #partitions = B – 1)
  - Assuming uniformly sized partitions, and maximizing k, we get:
    - k= B-1, and size of partition = M/(B-1) (*M is the number of pages of R*)
    - in-memory hash table to speed up the matching of tuples, a little more memory is needed: f * M/(B-1) (You can assume f = 1, unless explicitly specified)
    - f is fudge factor used to capture the small increase in size between the partition and a hash table for partition.
  - Probing phase, one for S, one for output, B>= f*M/(B-1)+2 for hash join to perform well (i.e., cost of hash join = 3 (M + N)). In other words, (B – 1) (B – 2) >= f * M

Observation on Hash Join

- Overflow
  - If the hash function does not partition uniformly, one or more R partitions may not fit in memory.
  - Significantly degrade the performance.
  - Can apply hash-join technique recursively to do the join of this overflow R-partition with corresponding S-partition.

Hybrid Hash-Join

- Idea: Do not write one of the partitions of R and S to disk.
- When is it possible? We can keep one of the partitions of the smaller relation always in memory.
- B >= f * M/k (buffers for keeping a partition)

  + (k – 1) (keep 1 page in buffer for each of the remaining partitions)

  + 1 (1 page in buffer for reading in S (or later R))

  + 1 (1 output page when reading in R)

  Remember: k = number of partitions

  i.e., (B – (k + 1)) >= f * M/k
- Choose such an appropriate k (or number of partitions)

Hybrid Hash-Join (contd)

- How to perform Hybrid Hash-Join?
  - Partitioning S is done as:
    - Build an in-memory hash table for the first partition of S during the partitioning phase.
    - Other partitions keep 1 page in buffer and write to disk when needed.
    - 1 buffer page for reading in S
  - Partitioning R is done as:
    - If a tuple hashes to the partition corresponding to the in-memory partition of S, then join and output tuples
    - If a tuple hashes to any of the remaining (k – 1) partitions, write it to the buffer page (and write this buffer page to disk as needed)
    - 1 buffer page for reading in R; 1 buffer page for output
  - Remaining partitions of R and S are done as usual
- Saving: avoid writing the first partitions of R and S to disk.
    - E.g. R = 500 pages, S=1000 pages B = 300 (We make 2 partitions)
      partition phase: scan R and write one partition out. 500 + 250
      scan S and write out one partition. 1000 + 500
      probing phase: only second partition is scaned: 250+500
    - Total = 3000 (Hash Join will take 4500)

Hash-Join vs. Sort-Merge Join

- Sort-Merge Join vs. Hash Join:
  - Given a certain amount of memory: B (B – 1) >= (M + N) both have a cost of 3(M+N) I/Os.
  - If partition is not uniformly sized (data skew); Hash-Join less sensitive.
  - Hash Join superior if relation sizes differ greatly;

  B is between $\sqrt{N}$ and $\sqrt{L}$ (roughly), where L = (M + N)

General Join Conditions

- Equalities over several attributes
  - (e.g., *R.sid*=*S.sid* AND *R.rname*=*S.sname*):
  - INL-Join : build index on <*sid, sname*> (if S is inner); or use existing indexes on *sid* or *sname*.
  - SM-Join and H-Join : sort/partition on combination of the two join columns.

- Inequality conditions
  - (e.g., *R.rname* < *S.sname*):
  - INL-Join: need (clustered!) B+ tree index.
    - Range probes on inner; # matches likely to be much higher than for equality joins.
  - Hash Join, Sort Merge Join not applicable.
  - Block NL quite likely to be the best join method here.

Summary

- There are several alternative evaluation algorithms for each relational operator.

Conclusion

Not one method wins !

Optimizer must assess situation to select best possible candidate