# *Evaluation of Relational Operations*

## Chapter 14

# *Relational Operations*

- We will consider in more detail how to implement:
    - *Selection* ($\sigma$) Selects a subset of rows from relation.
    - *Projection* ($\pi$) Deletes unwanted columns from relation.
    - *Join* ($\bowtie$) Allows us to combine two relations.
    - *Set-difference* ($-$) Tuples in left but not right relation.
    - *Union* ($\cup$) Tuples in reln. 1 and in reln. 2.
    - *Aggregation* (SUM, MIN, etc.) and GROUP BY
- Since each op returns a relation, ops can be *composed*! After we cover the operations, we will discuss how to *optimize* queries formed by composing them.

# *Running Database Example*

- Schema

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

- ~100, 000 Reserves:
  - Each tuple is 40 bytes, 100 tuples per page, 1000 pages.
- ~40,000 Sailors:
  - Each tuple is 50 bytes, 80 tuples per page, 500 pages.

# Selection (from Chapter 12)

(Note: we ignore "output costs")

SELECT *
FROM Reserves R
WHERE R.rname='Joe'

- No Index, Unsorted Data
  - Scan the entire relation, for Reserves → 1000 I/Os
- No Index, Sorted Data
  - Binary search, for Reserves → $\log_2 1000 \sim 10$ I/Os
- $B^+$-Tree Index, Clustered on selection attribute
  - Use index to find smallest tuple satisfying selection, scan forward from there, for Reserves → 3 I/Os to find starting point + K Blocks containing 'Joe' (K ~ 1-2 if op is '=' << 1000)
- $B^+$-Tree Index, Unclustered
  - Discussion follows

# *Using an Index for Selections*

- Cost depends on #qualifying tuples, and clustering.
  - Cost of finding qualifying data entries is typically small, but the cost of retrieving records could be large w/o clustering.
  - Example, assuming uniform distribution of ratings (1-10), about 10% of tuples qualify (100 pages, 10000 tuples). With a clustered index, cost is little more than 100 I/Os; if unclustered, upto 10000 I/Os!
- *Important refinement for unclustered indexes*:

1. Find qualifying data entries in index.
2. Find ***distinct*** *rids* of the pages to be retrieved. (2 ways)
   A. Sort by *rid* while removing replicates
   B. Build Hash of *rids* while eliminating replicates
3. Scan surviving *rids* while applying selection (result set will be unordered).

- Ensures each page is considered just once (though # of pages is still likely higher than with clustering).

# *General Selections*

- Selections typically involve more than one attribute with logical conjuncts (and, or)
- Recall we transform to CNF (product-of-sum) form
- Can be sorted or clustered by only one attribute
- Only a subset of attributes might have indices
- What order to process selection terms?
- How *selective* is a selection term?

| | |
|---|---|
| rname = “Joe” | < 4% of Sailors |
| age < 20 | ~ 10% of Sailors |
| Rating > 7 | ~ 30 % Sailors |

- Conjunctions vs disjunctions

# *Two Approaches to General Selections*

- First approach: Find the *most selective access path*, retrieve tuples using it, and apply any remaining selection terms during scan:
  - *Most selective access path:* An index or file scan that we estimate will require the *fewest page I/Os*.
  - Terms that match this index reduce the number of tuples *retrieved*; other terms are used further discard retrieved tuples, but do not affect number of pages fetched.
  - 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. Similarly, a hash index on <*bid, sid*> could be used; *day*<8/9/94 must then be checked.

# *Set Operation on Rids*

- Second approach (if we have 2 or more matching indexes):
  - Get sets of *rids* of data records using each matching index.
  - *Intersect* and/or *union* these sets of rids (we'll see how shortly)
  - Retrieve the records and apply any remaining terms.
  - Consider *day<8/9/94 AND bid=5 AND sid=3*. If we have a B+ tree index on *day* and an index on *sid*, both unclustered, we can retrieve *distinct rids* satisfying *day<8/9/94* using the first, *rids* of recs satisfying *sid=3* using the second, intersect the *rid sets*, then retrieve records and check *bid=5*.

# *The Projection Operation*

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

- Modified external sorting:
  - Modify Pass 0 of external sort to eliminate repeated fields. Thus, extending the run-size produced. Tuples in later runs are smaller than input tuples. (Size ratio depends on # and size of fields that are dropped.)
  - Modify merging passes to eliminate duplicates. Thus, number of result tuples smaller than input. (Difference depends on # of duplicates.)
  - Cost: In Pass 0, read original pages, but write out fewer pages (same number of smaller tuples). In merge passes, fewer tuples are written out due to duplicates.

# *Projection Based on Hashing*

- Modified hashing:
  - *Partitioning phase*: Read R using one input buffer. For each tuple, discard unwanted fields, apply hash function $h_1$ to direct output to one of B-1 output buffers.
    - Result is B-1 partitions (of tuples with no unwanted fields). Tuples from different partitions are guaranteed to be distinct.
  - *Duplicate elimination phase*: Foreach partition either:
    - Build another "in-memory" hash table, using hash function $h_2$ ($\neq h_1$), while discarding duplicates (handled on collisions).
    - Sort while eliminating duplicates
  - Cost: For partitioning, read R, write out each tuple, but with fewer fields. This is read in next phase.

# *Discussion of Projection*

- Sort-based approach is the standard; better handling of skewed attribute distributions and result is sorted.
- If an index on the relation contains the wanted projection attributes as its search key, then we use an *index-only* scan (no fetching of the data pages).
- If an ordered (i.e., tree) index contains all wanted attributes in the search key's *prefix* we can
    - Retrieve data entries in order (index-only scan), discard unwanted fields, compare adjacent tuples to check for duplicates.

# *Equijoins w/one common column*

```
SELECT   *
FROM     Reserves R, Sailors S
WHERE    R.sid=S.sid
```

- In algebra: $R \bowtie S$. Very common! Must be carefully optimized. $R \times S$ is large; so, $R \times S$ followed by a selection is inefficient.
- Assume: M tuples in R, $p_R$ tuples/page, N tuples in S, $p_S$ tuples/page.
- We will consider more complex join conditions later.
- *Cost metric*: # of I/Os. We will ignore output costs.

# *Simple Nested Loops Join*

```
foreach tuple r in R:
    foreach tuple s in S:
        if $r_i == s_j$ :
            add <r, s> to result
```

- Naïve Approach: For each tuple in the *outer* relation R, we scan the entire *inner* relation S.
  - Cost: $M + (p_R * M) * N = 1000 + 100*1000*500$ I/Os.
- *Page-at-a-time* Nested Loops join: For each *page* of R, get each *page* of S, and handle all matching pairs of tuples <r, s>, where r is in R-page and S is in S-page.
  - Cost: $M + M*N = 1000 + 1000*500$
  - If smaller relation (S) is outer, cost = $500 + 500*1000$

# *Index Nested Loops Join*

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

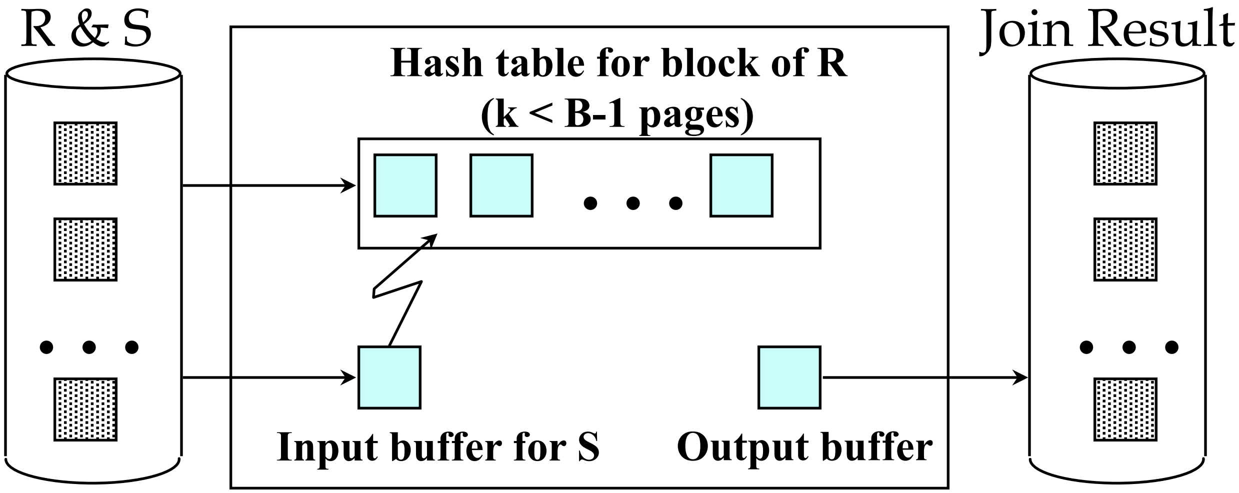
- If there is an index on the join column of one relation (say S), make it the inner loop, and exploit the index.
  - Cost: M + ( ($M*p_R$) * cost of finding matching S tuples)
- For each R tuple, cost of probing S index is about 1.2 for hash index, 2-4 for B+ tree. Cost of then finding S tuples depends on clustering.
  - Clustered index: 1 I/O (typical), unclustered: upto 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: 220,000 I/Os.
- 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.

# *Block Nested Loops Join*

- Small twist on Simple Nested Loops
- Use one page as an input buffer for scanning the inner S, one page as the output buffer, and use all remaining pages to hold a "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, etc.



# *Examples of Block Nested Loops*

- Cost: $M + \lceil M/(B-2) \rceil N$
- With Reserves (R) as outer and 100 buffer pages:
  - Cost of scanning R is 1000 I/Os over 10 *passes*.
  - Per pass of R, we scan Sailors (S); 10*500 I/Os.
  - With space for 90 pages of R, we 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.
- Better yet, double buffer with a pass size of (B-3). Fetch next block while joining current one

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

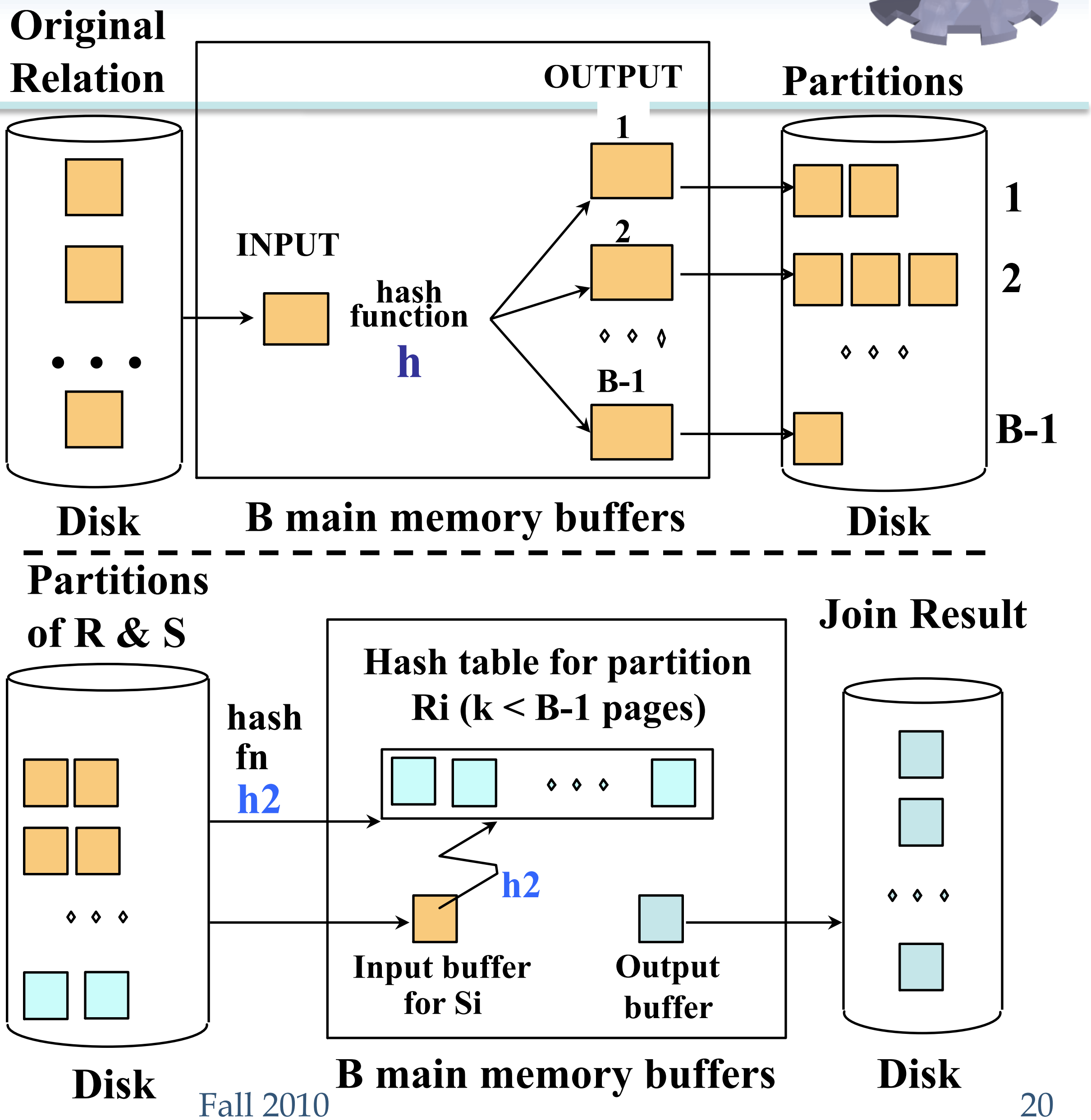
- Sort R and S on the join column, then scan them to "merge" (on join col.), and output result tuples.
  - Advance scan of R until current R-tuple >= current S tuple, then advance scan of S until current S-tuple >= current R tuple; do this until current R tuple = current S tuple.
  - At this point, one-or-more, $\rho$ , R tuples match one-or-more, $\sigma$ , S tuples; output <r, s> for all pairs of such tuples ( $\rho \times \sigma$ ).
  - Then resume scanning R and S.
- Cost: M log M + N log N + (M+N)

# *Refinements of Sort-Merge Join*

- Combine the merging phases of *external sorting* of R and S with the merging required for the join.
  - Using the sorting refinement that merges multiple runs each pass, we sort R and S up to their last merge pass.
  - Allocate 1 page per run of each relation, and “merge” while checking the join condition.
  - Cost: read+writes in (Pass 0.. Pass N-1) + read each relation in (only) merging pass (+ writing of result tuples).
  - Typically reduces I/O cost by a factor of ½.
- In practice, cost of sort-merge join, like the cost of external sorting, is nearly *linear*.

# *Hash-Join*

- Partition both relations using a common hash function, 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.



# *Observations on Hash-Join*

- We want each partition of R to fit in B-2 buffer pages, so #partitions, k = M / (B – 2), if we assume no skew
- If we build an in-memory hash table to speed up the matching of tuples, a little more memory is needed.
- If the hash function does not partition uniformly, one or more R partitions may not fit in memory. Can apply hash-join technique recursively to this partition and do the join of this R-partition with corresponding S-partition.

# *Cost of Hash-Join*

- In partitioning phase, read+write both relns; 2(M+N). In matching phase, read both relns; M+N I/Os.
- In our running example, this is a total of 4500 I/Os.
- Sort-Merge Join vs. Hash Join:
  - Both have a cost of 3(M+N) I/Os. Hash-Join is superior if relation sizes differ greatly. Also, Hash-Join shown to be highly parallelizable.
  - Sort-Merge insensitive to data skew; and result is sorted.

# *General Join Conditions*

- Equalities over several attributes (e.g., *R.sid=S.sid* AND *R.rname=S.sname*):
  - For Index NL, build index on <*sid, sname*> (if S is inner); or use existing indexes on *sid* or *sname*.
  - For Sort-Merge and Hash Join, sort/partition on combination of the two join columns.
- Inequality conditions (e.g., *R.rname < S.sname*):
  - For Index NL, need (clustered!) B+ tree index.
    - Perform 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.

# *Set Operations*

- Intersection and cross-product special cases of join.
- Union (Distinct) and Except similar; we'll do union.
- Sorting based approach to union:
  - Sort both relations (on combination of all attributes).
  - Scan sorted relations and merge them.
  - *Alternative*: Merge runs from final pass of *both* relations.
- Hash based approach to union:
  - Partition R and S using hash function *h*.
- Set Subtraction, Intersection (modified merge passes)
  - R- S Subtract – write to output if key appears in R but not S
  - R ∩ S Intersection – write to output if keys match

# *Aggregate Operations (AVG, MIN, etc.)*

- Without grouping:
  - In general, requires scanning the relation.
  - Given index whose search key includes all attributes in the SELECT or WHERE clauses, can do index-only scan.
- With grouping:
  - Sort on group-by attributes, then scan relation and compute aggregate for each group. (Can improve upon this by combining sorting and aggregate computation.)
  - Similar approach based on hashing on group-by attributes.
  - Given tree index whose search key includes all attributes in SELECT, WHERE and GROUP BY clauses, can do index-only scan; if group-by attributes form prefix of search key, can retrieve data entries/tuples in group-by order.

# *Impact of Buffering*

- If several operations are executing concurrently, estimating the number of available buffer pages is guesswork.
- Repeated access patterns interact with buffer replacement policy.
    - e.g., Inner relation is scanned repeatedly in Simple Nested Loop Join. With enough buffer pages to hold inner, replacement policy does not matter. Otherwise, MRU is best, LRU is worst (*sequential flooding*).
    - Does replacement policy matter for Block Nested Loops?
    - What about Index Nested Loops? Sort-Merge Join?

# Summary

- A virtue of relational DBMSs: *queries are composed of a few basic operators*; the implementation of these operators can be carefully tuned (and it is important to do this!).
- Many alternative implementation techniques for each operator; no universally superior technique for most operators.
- Must consider available alternatives for each operation in a query and choose best one based on system statistics, etc. This is part of the broader task of optimizing a query composed of several ops.