CompSci 516
Database Systems

Lecture 14
Query Evaluation
and
Join Algorithms

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Announcements (Tues, 3/15)

- Project midterm report due today noon
- HW3 to be released soon (in pairs)

Overview of Query Evaluation

- How queries are evaluated in a DBMS
  - How DBMS describes data (tables and indexes)

- Relational Algebra Tree/Plan = Logical Query Plan

- Now Algorithms will be attached to each operator = Physical Query Plan

- Plan = Tree of RA ops, with choice of algorithm for each op.
  - Each operator typically implemented using a "pull" interface
  - when an operator is "pulled" for the next output tuples, it "pulls" on its inputs and computes them

Overview of Query Evaluation

- Two main issues in query optimization:

1. For a given query, what plans are considered?
   – Algorithm to search plan space for cheapest (estimated) plan
2. How is the cost of a plan estimated?

- Ideally: Want to find best plan
- Practically: Avoid worst plans!

Some Common Techniques

- Algorithms for evaluating relational operators use some simple ideas extensively:
- Indexing:
  - Can use WHERE conditions to retrieve small set of tuples (selections, joins)
- Iteration:
  - Examine all tuples in an input tuple
  - Sometimes, faster to scan all tuples even if there is an index
- Partitioning:
  - By using sorting or hashing, we can partition the input tuples and replace an expensive operation by similar operations on smaller inputs

Watch for these techniques as we discuss query evaluation!

Relational Operations

- We will consider how to implement:
  - Join (⋈) Allows us to combine two relations (in detail)
- Also
  - Selection (σ) Selects a subset of rows from relation.
  - Projection (π) Deletes unwanted columns from relation.
  - Set-difference (-) Tuples in reln. 1, but not in reln. 2.
  - Union (∪) 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 each operation, we will discuss how to optimize queries formed by composing them (query optimization)

Assumption: ignore final write

- i.e. assume that your final results can be left in memory
  - and does not be written back to disk
  - unless mentioned otherwise

- Why such an assumption?

Algorithms for Joins

DO NOT MEMORIZE ”FORMULAS”!
Settings may change, they won’t hold then
Understand how we are deriving them!

Equality Joins With One Join Column

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

- In algebra: R $\bowtie$ S
  - Common! Must be carefully optimized
  - R X S is large; so, R X S followed by a selection is inefficient

- Cost metric: # of I/Os
  - Remember, we will ignore output costs (always)

    = the cost to write the final result tuples back to the disk

Common Join Algorithms

1. Nested Loops Joins (NLJ)
   – Simple nested loop join
   – Block nested loop join
   – index nested loop join

2. Sort Merge Join   Very similar to external sort

3. Hash Join

Algorithms for Joins

1. NESTED LOOP JOINS

Simple Nested Loops Join

$R \bowtie S$

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

M = 1000 pages in R
p_R = 100 tuples per page

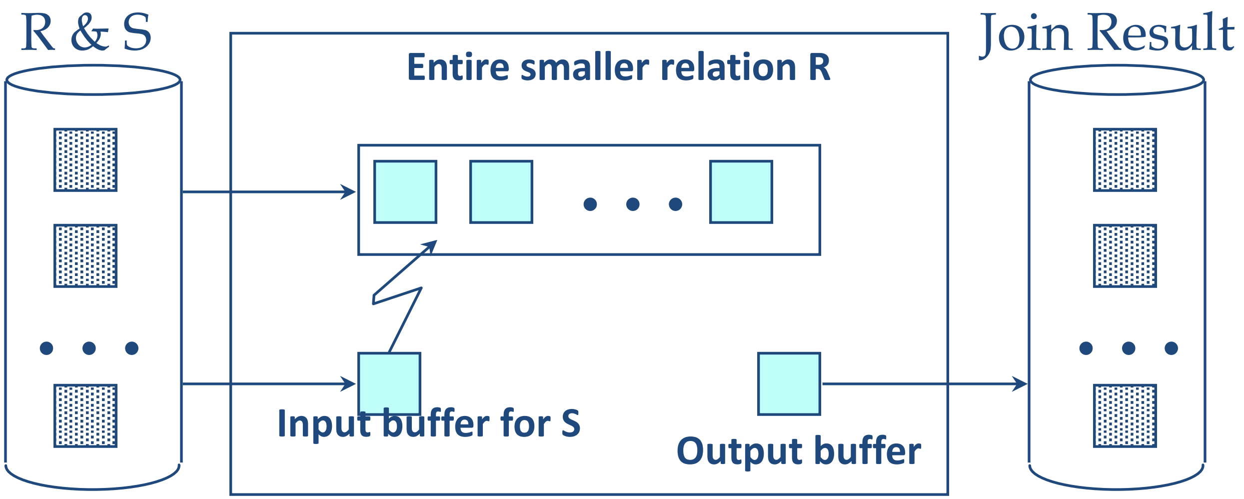
N = 500 pages in S
p_S = 80 tuples per page

- 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-oriented Nested Loops join:
  - 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: $M + M*N = 1000 + 1000*500$
- If smaller relation (S) is outer
  - Cost: $N + M*N = 500 + 500*1000$

How many buffer pages do you need?

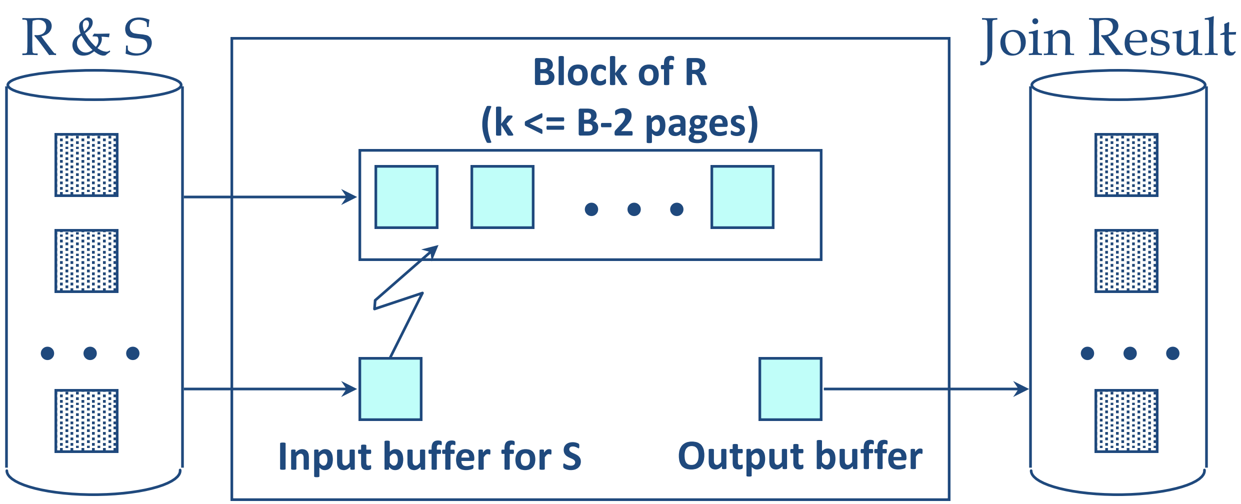
Block Nested Loops Join

- Simple-Nested does not properly utilize buffer pages (uses 3 pages)
- Suppose have enough memory to hold the smaller relation R + at least two other pages
  - e.g. in the example on previous slide (S is smaller), and we need 500 + 2 = 502 pages in the buffer
- Then use one page as an input buffer for scanning the inner
  - one page as the output buffer
  - For each matching tuple r in R-block, s in S-page, add <r, s> to result
- Total I/O = M+N



Block Nested Loops Join

- What if the entire smaller relation does not fit?
- If R does not fit in memory,
  - 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 ``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.



Cost of Block Nested Loops

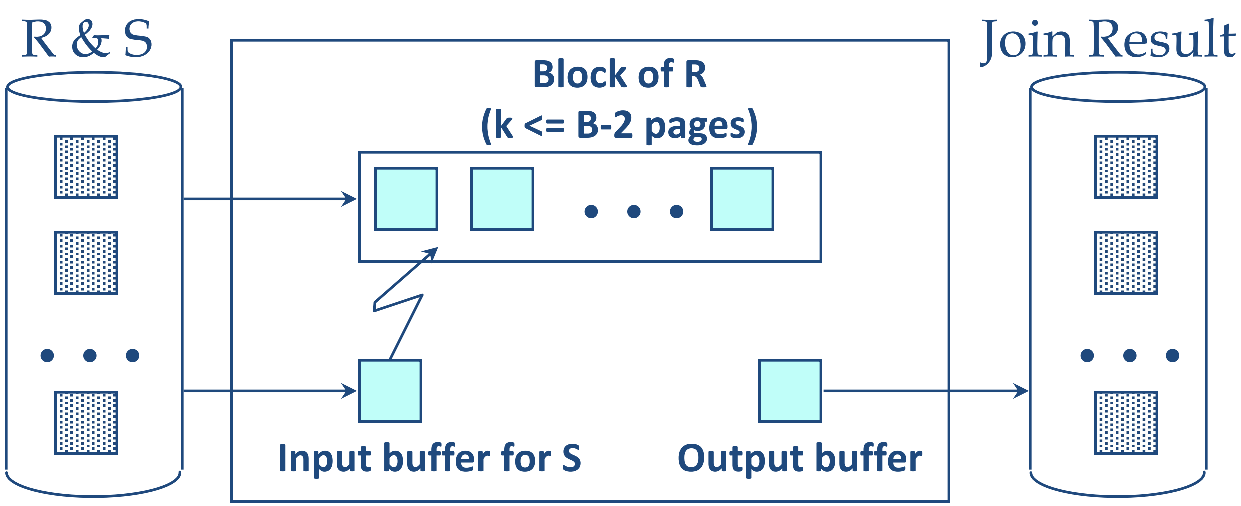
M = 1000 pages in R
p_R = 100 tuples per page

N = 500 pages in S
p_S = 80 tuples per page

in class

- R is outer
- B-2 = 100-page blocks
- How many blocks of R?
- Cost to scan R?
- Cost to scan S?
- Total Cost?

```
foreach block of B-2 pages of R do
        foreach page of S do {
                for all matching in-memory tuples r in R-
block and s in S-page
                add <r, s> to result
```



Cost of Block Nested Loops

M = 1000 pages in R
p_R = 100 tuples per page

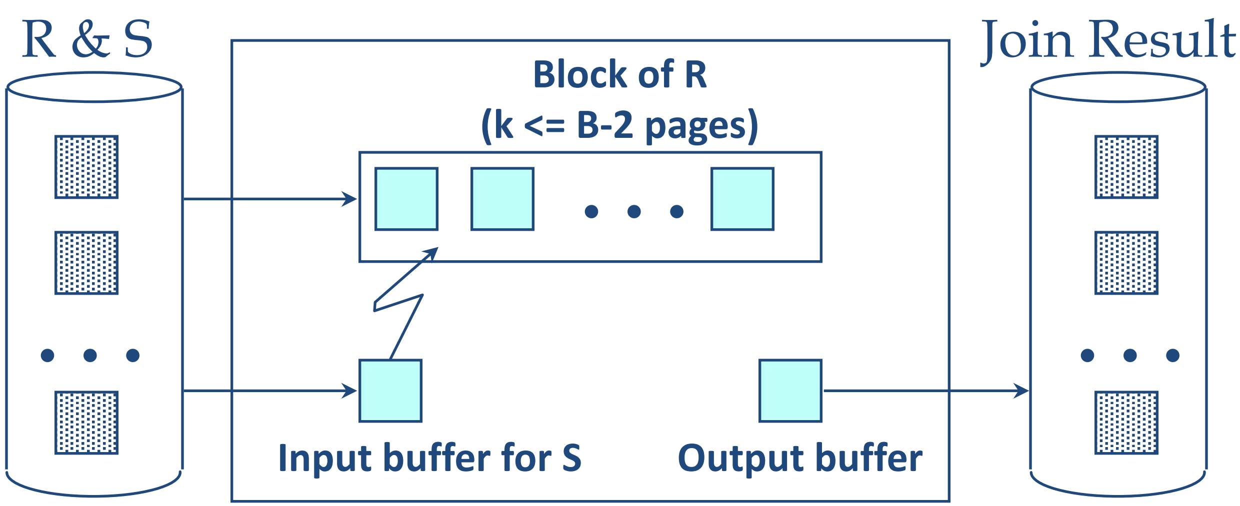
N = 500 pages in S
p_S = 80 tuples per page

- R is outer
- B-2 = 100-page blocks
- How many blocks of R? 10
- Cost to scan R? 1000
- Cost to scan S? 10 * 500
- Total Cost? 1000 + 5000 = 6000
- (check yourself)
  - If space for just 90 pages of R, we would scan S 12 times, cost = 7000

foreach block of B-2 pages of R do
foreach page of S do {
for all matching in-memory tuples r in R-block and s in S-page
add <r, s> to result

- Cost: Scan of outer + #outer blocks * scan of inner
  - #outer blocks = ⌈#pages of outer relation/blocksize⌉

for blocked access,
it might be good to equally divide buffer pages among R and S
("seek time" less)



Index Nested Loops Join

M = 1000 pages in R
p_R = 100 tuples per page

N = 500 pages in S
p_S = 80 tuples per page

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

- Suppose there is an index on the join column of one relation
  - say S
  - can make it the inner relation and exploit the index
  - Cost: $M + ((M*p_R) *$ cost of finding matching S tuples$)$
  - For each R tuple, cost of probing S index (get k*) is about
    - 1-2 for hash index
    - 2-4 for B+ tree.
  - Cost of then finding S tuples (assuming Alt. 2 or 3) depends on clustering!

Cost of Index Nested Loops

M = 1000 pages in R
p_R = 100 tuples per page

N = 500 pages in S
p_S = 80 tuples per page

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

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

- Hash-index (Alt. 2) on sid of Sailors (as inner), sid is a key
- Cost to scan Reserves?
  - 1000 page I/Os, 100*1000 tuples.
- Cost to find matching Sailors tuples?
  - For each Reserves tuple:
  - (suppose on avg) 1.2 I/Os to get data entry in index
  - + 1 I/O to get (the exactly one) matching Sailors tuple
- Total cost:
- 1000 + 100 * 1000 * 2.2 = 221,000 I/Os

Cost of Index Nested Loops

M = 1000 pages in R
p_R = 100 tuples per page

N = 500 pages in S
p_S = 80 tuples per page

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

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

- Hash-index (Alt. 2) on *sid* of Reserves (as inner), sid is NOT a key
- Cost to Scan Sailors:
  - 500 page I/Os, 80*500 tuples.
- For each Sailors tuple:
  - 1.2 I/Os to find index page with data entries
  - + 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 cost = 500 + 80 * 500 * 2.2 = 88, 500 if clustered
- up to ~ 500 + 80 * 500 * 3.7 = 148,500 if unclustered (approx)

even with unclustered index, index NLJ may be cheaper than simple NLJ

Algorithms for Joins

2. SORT-MERGE JOINS

Sort-Merge Join

- Sort R and S on the join column
- Then scan them to do a ``merge'' (on join col.)
- Output result tuples.

Sort-Merge Join: 1/3

- 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 as long as current R tuple = current S tuple

Sailors

S

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

Reserves

R

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

Sort-Merge Join: 2/3

- At this point, all R tuples with same value in R_i (*current R group*) and all S tuples with same value in S_j (*current S group*)
  - match
  - find all the equal tuples
  - output <r, s> for all pairs of such tuples

S

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

R

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

WRITE TWO OUTPUT TUPLES

Sort-Merge Join: 3/3

- Then resume scanning R and S

S

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

R

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

WRITE THREE OUTPUT TUPLES

Sort-Merge Join: 3/3

- … and proceed till end

S

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

R

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

NO MATCH, CONTINUE SCANNING S

Sort-Merge Join: 3/3

- … and proceed till end

S

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

WRITE ONE OUTPUT TUPLE

R

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

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

- Typical Cost: O(M log M) + O(N log N) + (M+N)
  - ignoring B (as the base of log)
  - cost of sorting R + sorting S + merging R, S
  - The cost of scanning in merge-sort, M+N, could be M*N!
    - assume the same single value of join attribute in both R and S
    - but it is extremely unlikely

Cost of Sort-Merge Join

M = 1000 pages in R
p_R = 100 tuples per page

N = 500 pages in S
p_S = 80 tuples per page

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

- 100 buffer pages
- Sort R:
  - (pass 0) 1000/100 = 10 sorted runs
  - (pass 1) merge 10 runs
  - read + write, 2 passes
  - 4 * 1000 = 4000 I/O
- Similarly, Sort S: 4 * 500 = 2000 I/O
- Second merge phase of sort-merge join
  - another 1000 + 500 = 1500 I/O
  - assume uniform ~2.5 matches per sid, so M+N is sufficient
- Total 7500 I/O

- Check yourself:
  - Consider #buffer pages 35, 100, 300
  - Cost of sort-merge = 7500 in all three
  - Cost of block nested 16500, 6000, 3000
  - (R outer, S inner)

Algorithms for Joins

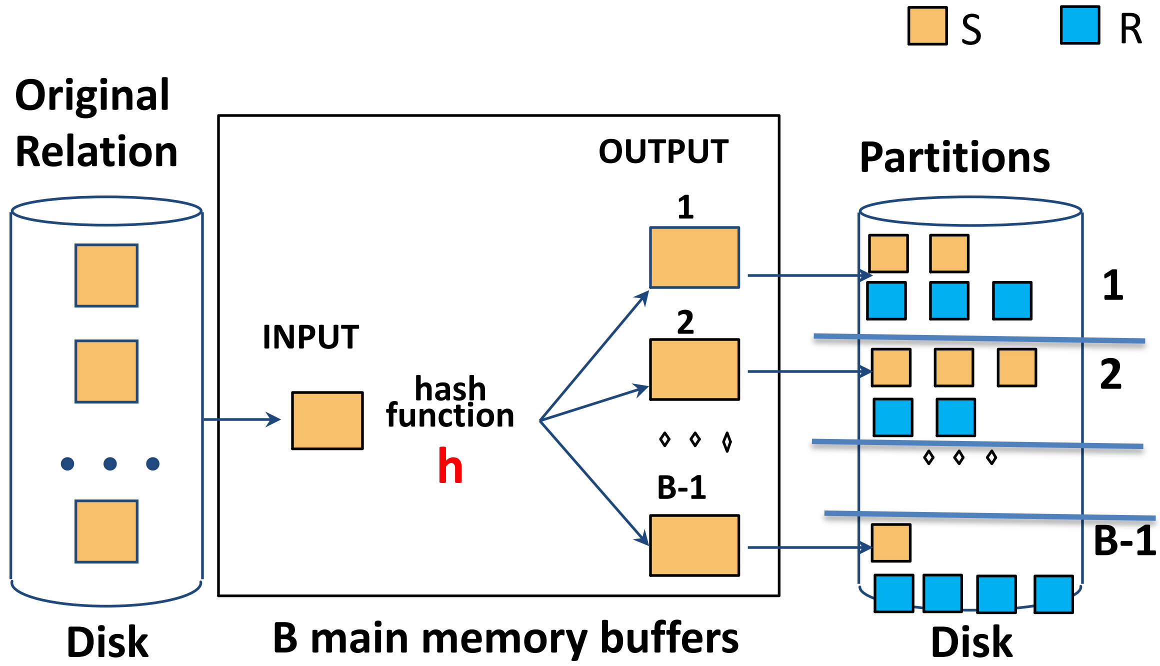
3. HASH JOINS

Two Phases

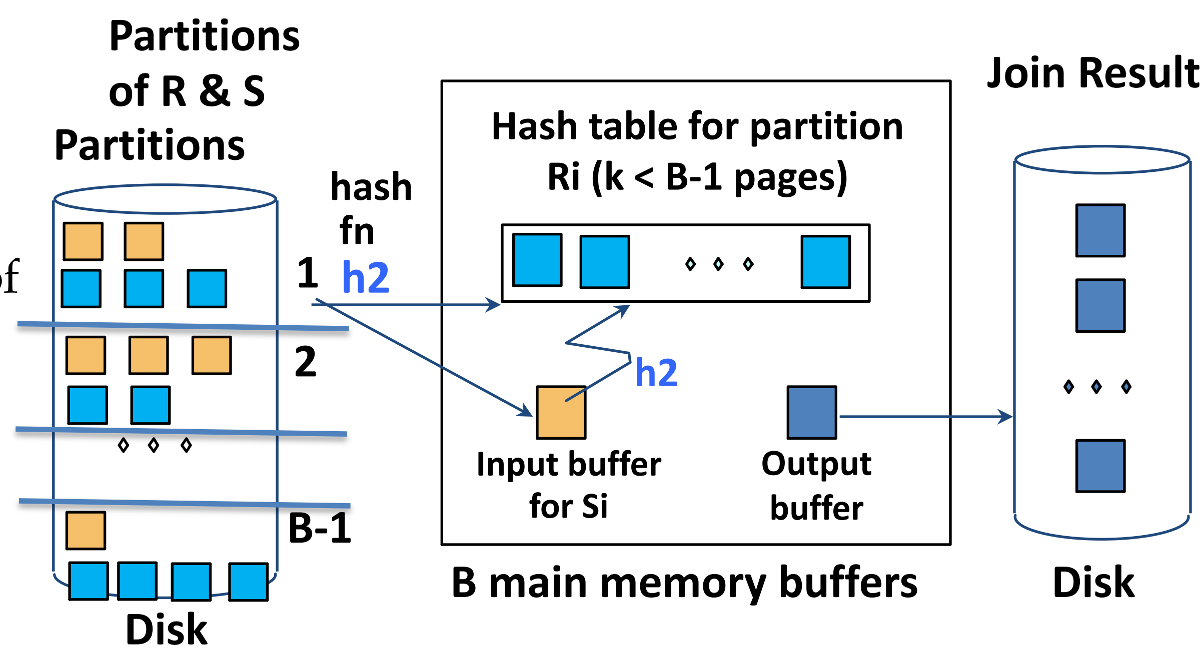
1. Partition Phase
   – partition R and S using the same hash function h
2. Probing Phase
   – join tuples from the same partition (same h(..) value) of R and S
   – tuples in different partition of h will never join
   – use a “different” hash function h2 for joining these tuples
     • (why different – see next slide first)

Hash-Join

- Partition both relations using 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.



Cost of Hash-Join

- In partitioning phase
  - read+write both relns; 2(M+N)
  - In matching phase, read both relns; M+N I/Os
  - remember – we are not counting final write

- In our running example, this is a total of 4500 I/Os
  - 3 * (1000 + 500)
  - Compare with the previous joins

Sort-Merge Join vs. Hash Join

- Both can have a cost of 3(M+N) I/Os
  - if sort-merge gets enough buffer (see 14.4.2)
- Hash join holds smaller relation in buffer- better if limited buffer
- Hash Join shown to be highly parallelizable
- Sort-Merge less sensitive to data skew
  - also result is sorted

Other operator algorithms

Check yourself the details!

Algorithms for Selection

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

- No index, unsorted data
  - Scan entire relation
  - May be expensive if not many `Joe's
- No index, sorted data (on 'rname')
  - locate the first tuple, scan all matching tuples
  - first binary search, then scan depends on matches
- B+-tree index, Hash index
  - Discussed earlier
  - Cost of accessing data entries + matching data records
  - Depends on clustered/unclustered
- More complex condition like day<8/9/94 AND bid=5 AND sid=3
  - Either use one index, then filter
  - Or use two indexes, then take intersection, then apply third condition
  - etc.

Algorithms for Projection

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

- Two parts
  - Remove fields: easy
  - Remove duplicates (if distinct is specified): expensive
- Sorting-based
  - Sort, then scan adjacent tuples to remove duplicates
  - Can eliminate unwanted attributes in the first pass of merge sort
- Hash-based
  - Exactly like hash join
  - Partition only one relation in the first pass
  - Remove duplicates in the second pass
- Sort vs Hash
  - Sorting handles skew better, returns results sorted
  - Hash table may not fit in memory – sorting is more standard
- Index-only scan may work too
  - If all required attributes are part of index

Algorithms for Set Operations

- Intersection, cross product are special cases of joins
- Union, Except
  - Sort-based
  - Hash-based
  - Very similar to joins and projection

Algorithms for Aggregate Operations

- SUM, AVG, MIN etc.
  - again similar to previous approaches

- 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
  - or, hash on group-by attributes
  - can combine sort/hash and aggregate
  - can do index-only scan here as well

Access Paths and Selectivity

Index "matching" a search condition

Recall

- A tree index *matches* (a conjunction of) terms that involve only attributes in a *prefix* of the search key.
  - E.g., Tree index on <*a, b, c*> matches the selection
  - *a=5 AND b=3,*
  - and *a=5 AND b>6,*
  - but not *b=3*

- A hash index *matches* (a conjunction of) terms that has a term *attribute* = *value* for every attribute in the search key of the index.
  - E.g., Hash index on <*a, b, c*> matches
  - *a=5 AND b=3 AND c=5*;
  - but it does not match *b=3,*
  - *or a=5 AND b=3,*
  - *or a>5 AND b=3 AND c=5*

Access Paths

- A way of retrieving tuples from a table
- Consists of
  - a file scan, or
  - an index + a matching condition
- The access method contributes significantly to the cost of the operator

Access Paths: Selectivity

- Selectivity:
  - the number of pages retrieved for an access path
  - includes data pages + index pages

- Options for access paths:
  - scan file
  - use matching index
  - scan index

- "Most selective" access paths == requires "fewest" page I/Os

Selectivity : Example 1

- Hash index on sailors <rname, bid, sid>
- Selection condition (rname = ‘Joe’ $\wedge$ bid = 5 $\wedge$ sid = 3)
- #of sailors pages = N
- #distinct keys = K
- Fraction of pages satisfying this condition = (approximately) N/K
- Assumes uniform distribution

Selectivity : Example 2

- Hash index on sailors <bid, sid>
- Selection condition (bid = 5 ∧ sid = 3)
- Suppose N_1 distinct values of bid, N_2 for sid
- Reduction factors
  - for (bid = 5) : $1/ N_1$
  - for (bid = 5 ∧ sid = 3): $1/ (N_1 \times N_2)$
- Assumes independence
- Fraction of pages retrieved or I/O:
  - for clustered index = $1/ (N_1 \times N_2)$
  - for unclustered index = 1

Selectivity : Example 3

- Tree index on sailors <bid>
- Selection condition (bid > 5)
- Lowest value of bid = 1, highest = 100
- Reduction factor
  - (100 - 5)/(100 - 1)
  - assumes uniform distribution
- In general:
  - key > value : (High – value) / (High – Low)
  - key < value : (value - Low) / (High – Low)

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 and the overall query
  - This is part of the broader task of optimizing a query composed of several ops