CompSci 516
Data Intensive Computing Systems

Lecture 9
Join Algorithms
and
Query Optimizations

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Announcements

Takeaway from Homework 1

- You learnt
  - SQL + Postgres
  - Basic data analysis (from data acquisition, cleaning*, querying, to visualizing results – did you find some interesting/expected results? do people collaborate more now?)
- Start early
- But don’t hesitate to ask last minute questions on Piazza!
  - avg response time = 40 min for 66 posts/250 contributions including questions posted at night
- If you have an important reason (health, interview, paper deadline, computer crash, but NOT another exam or hw), you **might** get a short extension
  - at the discretion of the course staff
  - may depend on your effort in the two weeks
  - strongly encourage to finish early
  - must have the permission prior to the deadline

Announcements

- Homework 2
  - To be posted soon, due after 2 weeks
  - No coding, Q/A on all topics so far

- Homework 3
  - Part 1 will be posted soon too
  - Due 2 weeks **after** the due date of HW2 (in ~4 weeks)
  - You will learn Spark/Scala
  - Which will be useful when you do an assignment on AWS using Spark/Scala in HW4

What will we learn?

- Last lecture:
  - External sorting (limited buffer pages)
  - Operator Algorithms for Selection and Projection
- Next:
  - Join Algorithms
  - Other operators (set, aggregate)
  - Query Optimization

to be continued in the next lecture
with Cost-based optimization
and Selinger's algorithm

Reading Material

- [RG]
  - – Join Algorithm: Chapter 14.4
  - – Set/Aggregate: Chapter 14.5, 14.6
  - – Query optimization: Chapter 15 (overview only)

Acknowledgement:
The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.

Algorithms for Joins

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
  - 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
    - Simple nested loop join
    - Block nested loop join
    - index nested loop join

2. Sort Merge Join   Very similar to external sort

3. Hash Join   Very similar to duplicate elimination in projection

Algorithms for Joins

1. NESTED LOOP JOINS

Simple 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

$R \bowtie S$

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

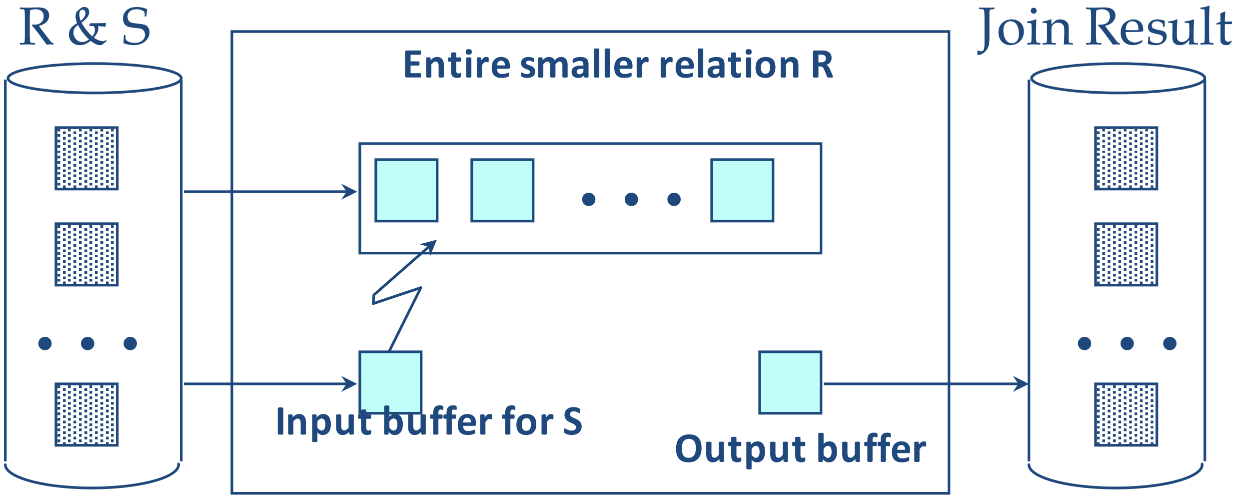
- For each tuple in the outer relation R, we scan the entire inner relation S.
  - Cost: $M + (p_R * M) * N = 1000 + 100*1000*500$ I/Os.

- 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: $N + M*N = 500 + 500*1000$

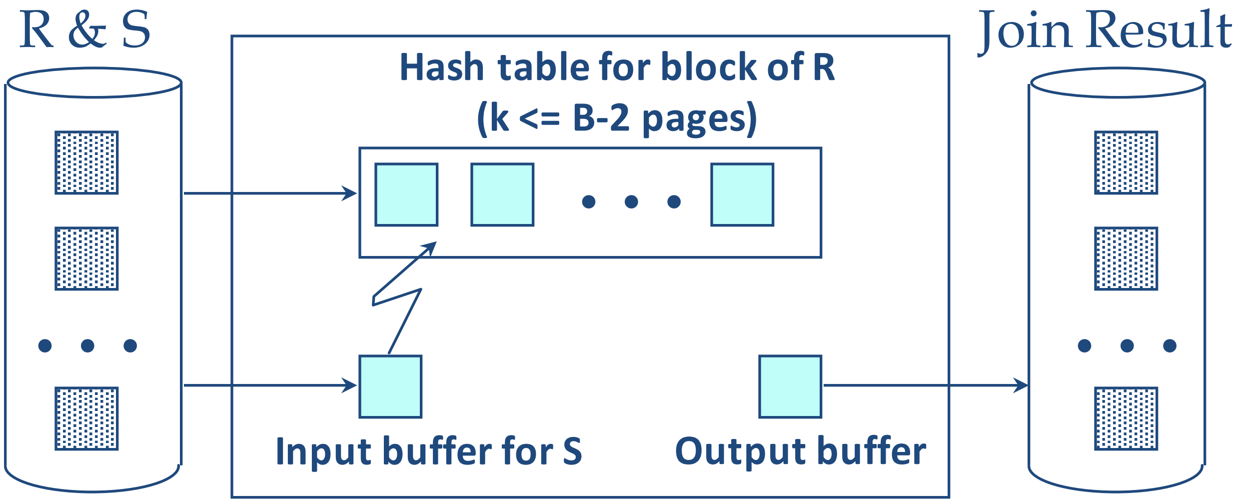
Block Nested Loops Join

- Simple-Nested does not properly utilize buffer 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
- What if the entire smaller relation does not fit?



Block Nested Loops Join

- 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

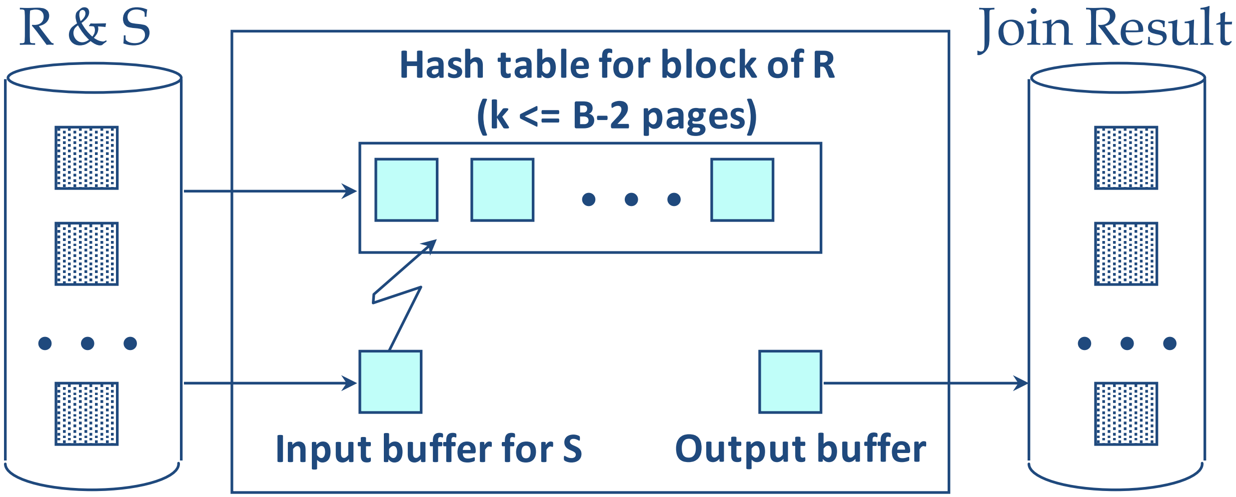
N = 500 pages in S

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

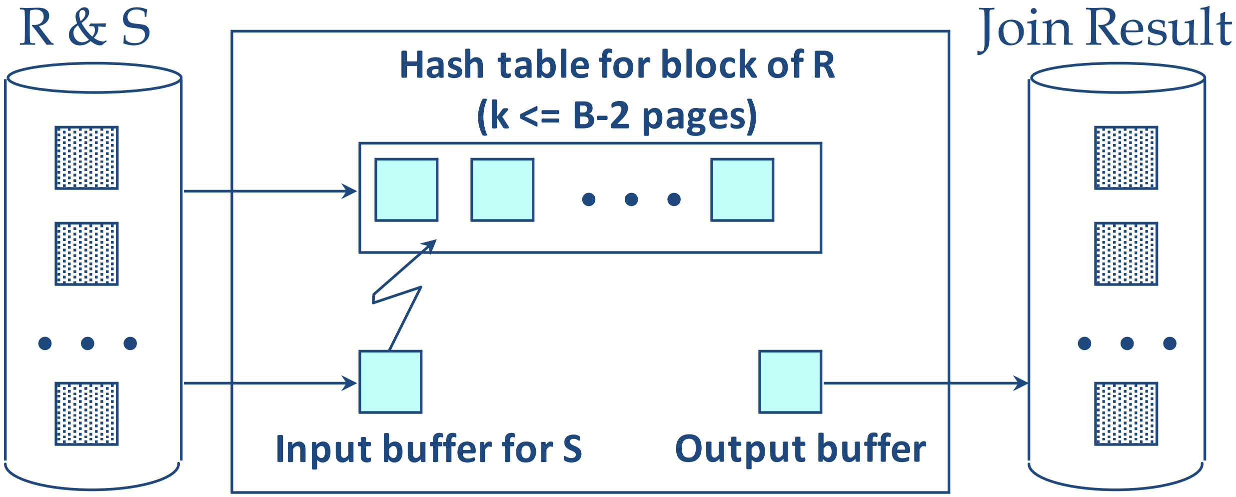
p_S = 80 tuples per page

- 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



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
    - (see previous lecture)

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:
  - 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 if clustered
- up to ~ 500 + 80 * 500 * 3.7 if unclustered (approx)

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

- 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

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

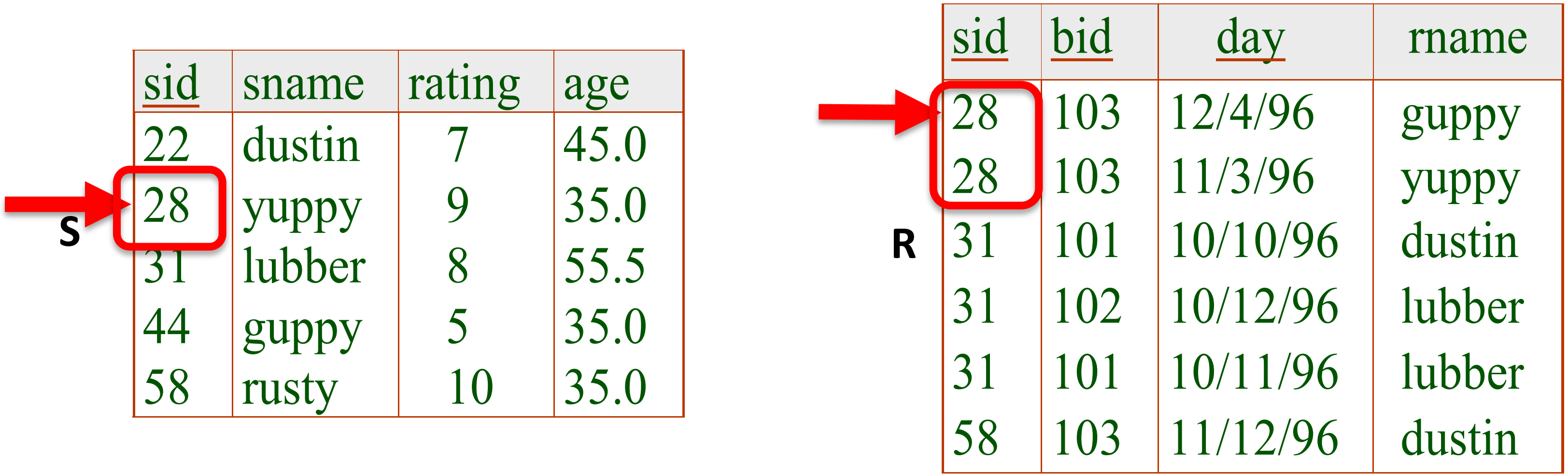
R

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

- 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*
  - 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

- 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*
  - find all the equal tuples
  - output <r, s> for all pairs of such tuples

- 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

Sort-Merge Join

- 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*
  - find all the equal tuples
  - output <r, s> for all pairs of such tuples
- 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

- 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*
  - find all the equal tuples
  - output <r, s> for all pairs of such tuples

- 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

NO MATCH, CONTINUE SCANNING R

Sort-Merge Join

- 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*
  - find all the equal tuples
  - output <r, s> for all pairs of such tuples

- 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

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

- Cost: O(M log M) + O(N log N) + (M+N)
  - cost of sorting R + sorting S + merging R, S
  - The cost of scanning, M+N, could be M*N (suppose single value of join attribute in both R and S)

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
- Total 7500 I/O

- Check yourself:
  - Consider #buffer pages 35, 100, 300
  - Cost of sort-merge = 7500 in all three
  - Cost of block nested 15000, 6000, 2500

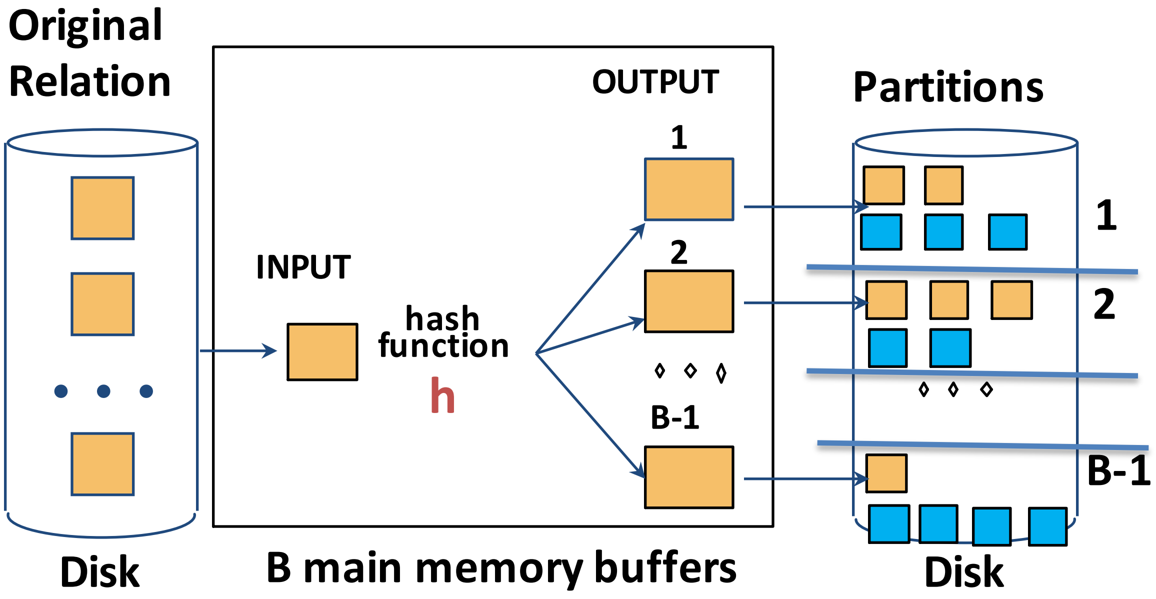
Algorithms for Joins

3. HASH JOINS

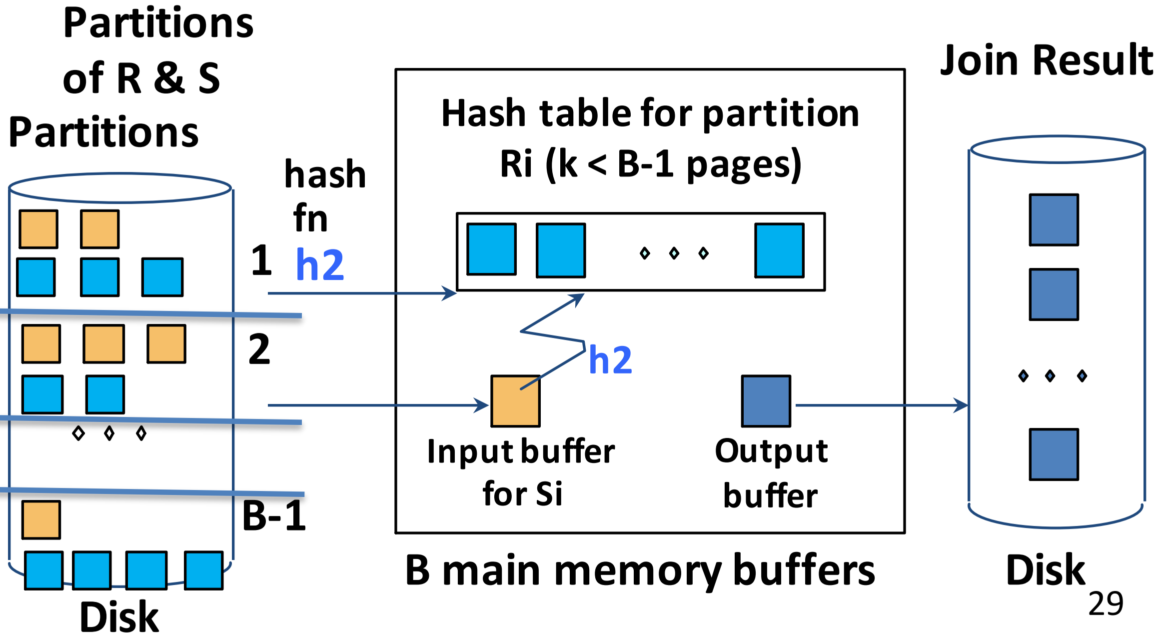
🟧 S 🟦 R

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.

General Join Conditions

- Equalities over several attributes
  - e.g., *R.sid=S.sid* AND *R.rname=S.sname*
  - For Index Nested Loop, 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.
  - Hash Join, Sort Merge Join not applicable

Review: Join Algorithms

- Nested loop join:
  - for all tuples in R.. for all tuples in S....
  - variations: block-nested, index-nested
- Sort-merge join
  - like external merge sort
- Hash join

- Make sure you understand how the I/O varies
- No one join algorithm is uniformly superior to others
  - depends on relation size, buffer pool size, access methods, skew

Algorithms for Set Operations

Set Operations

- Intersection and cross-product special cases of join.
- Union (Distinct) and Except similar; we'll do union
  - very similar to external sort and join algorithms

- Sorting based approach to union:
  - Sort both relations (on combination of all attributes)
  - Scan sorted relations and merge them.
  - *Alternative*: Merge runs from Pass 0 for *both* relations

- Hash based approach to union:
  - Partition R and S using hash function *h*.
  - For each S-partition, build in-memory hash table (using *h2*), scan corr. R-partition and add tuples to table while discarding duplicates

Algorithms for Aggregate Operations

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

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
  - recall sequential flooding (lecture 6 and piazza post)
  - 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

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.

Query Optimization

Old Running Example

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.

Query Blocks: Units of Optimization

- Query Block
    - No nesting
    - One SELECT., one FROM
    - At most one WHERE, GROUP BY, HAVING

```
SELECT  S.sname
FROM  Sailors S
WHERE  S.age IN
     (SELECT  MAX (S2.age)
       FROM  Sailors S2
       GROUP BY  S2.rating)
```

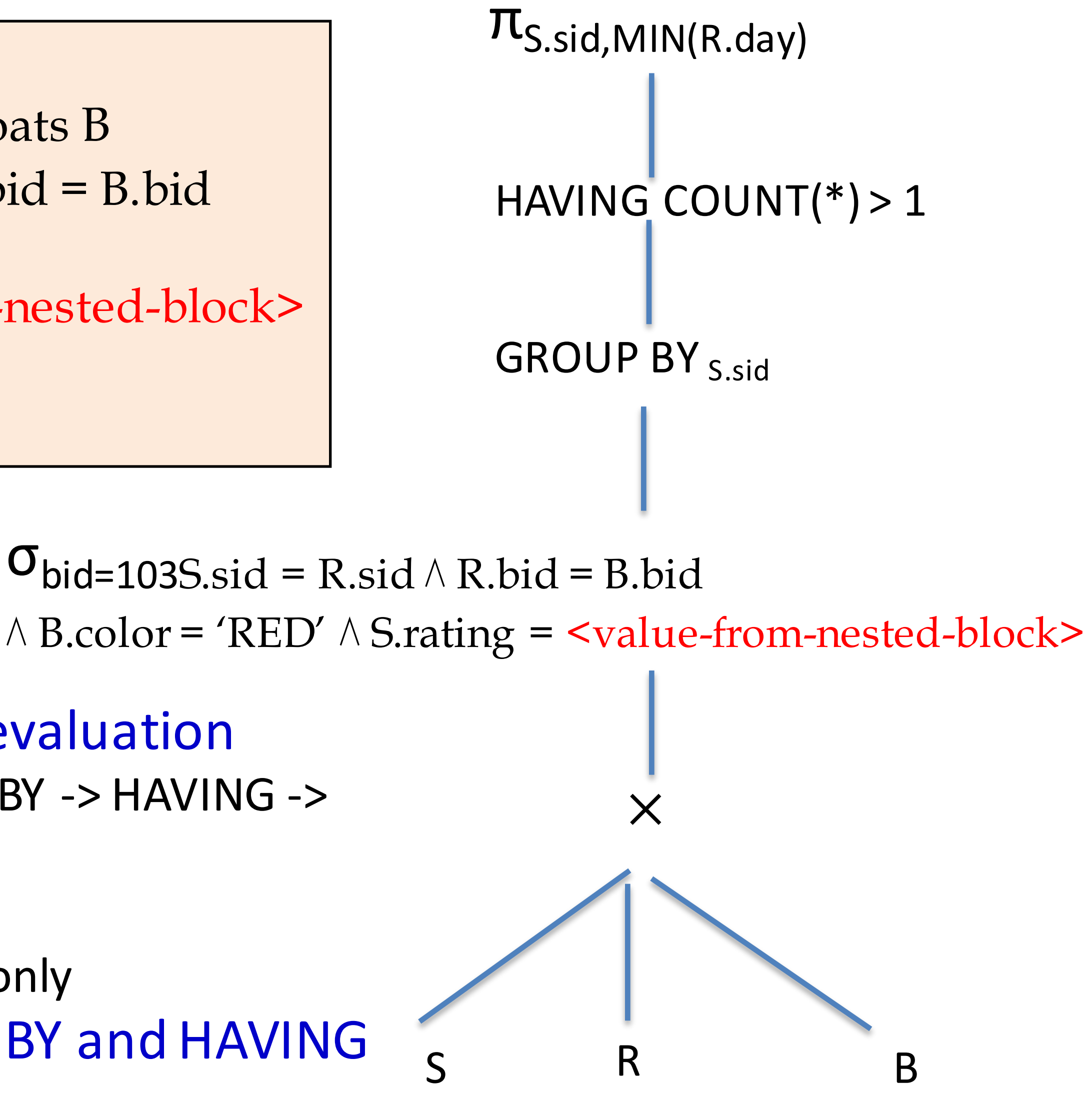
Outer block   *Nested block*

- SQL query
- => parsed into a collection of query blocks
- => the blocks are optimized one block at a time

- First we discuss single query block
- Express it as a relational algebra (RA) expression

Query Block as an RA expression

```
SELECT  S.sid, MIN (R.day)
FROM  Sailors S, Reserves R, Boats B
WHERE  S.sid = R.sid AND R.bid = B.bid
     AND B.color = ‘RED’
    AND S.rating = <reference-to-nested-block>
GROUP BY S.sid
HAVING COUNT(*) > 1
```



$\pi_{S.sid, MIN(R.day)}$

HAVING COUNT(*) > 1

GROUP BY $_{S.sid}$

$\sigma_{bid=103}$S.sid = R.sid ∧ R.bid = B.bid ∧ B.color = ‘RED’ ∧ S.rating = <value-from-nested-block>

×

S R B

- Recall the semantic of SQL evaluation
  - FROM -> WHERE -> GROUP BY -> HAVING -> SELECT
- This is not quite an RA plan
  - e.g. × can have two inputs only
- Also we considered GROUP BY and HAVING as RA operators

Cost Estimation

- For each plan considered, must estimate cost:

- Must estimate cost of each operation in plan tree.
  - Depends on input cardinalities.
  - We’ve already discussed how to estimate the cost of operations (sequential scan, index scan, joins, etc.)

- Must also estimate size of result for each operation in tree
  - Use information about the input relations.
  - For selections and joins, assume independence of predicates.

- also consider whether the output is sorted

Estimating Result Sizes

```
SELECT  <attr>
FROM    R1, R2, R3, ….
WHERE   <condn1> AND
           <condn2>..
```

- Max #tuples =
  - |R1|× |R2| × |R3| × ….

- But we can model the effect of WHERE clause by associating a reduction factor for each <condn>

Estimating Result Sizes: for different <condn>

```
SELECT  <attr>
FROM     R1, R2, R3, ….
WHERE  <condn1> AND
              <condn2>..
```

- column = value
  - if an index I on column, then 1/Nkeys(I)
  - assumes uniform distribution
  - some DBMS assumes a constant reduction factor like 1/10
- column1 = column2
  - 1/max(Nkeys(I1), Nkeys(I2))
    - I1, I2 are indexes
  - again assumes each value in column2 is equally likely for a match
- column1 > value
  - High(I) – value / High(I) - low(I)
- Advanced methods use histograms (see book)

Relational Algebra Equivalences

- Allow us to choose different join orders and to `push' selections and projections ahead of joins.
- Selections: $\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\ldots \sigma_{cn}(R))$ (Cascade)

  $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R))$ (Commute)
- Projections: $\pi_{a1}(R) \equiv \pi_{a1}(\ldots(\pi_{an}(R)))$ (Cascade)
- Joins: $R \bowtie (S \bowtie T) \equiv (R \bowtie S) \bowtie T$ (Associative)

  $(R \bowtie S) \equiv (S \bowtie R)$ (Commute)

There are many more intuitive equivalences, see 15.3.4 for details

Next lecture: cost-based optimization and Selinger's algorithm