Algorithms for Query Processing and Optimization

Chapter Outline

0. Introduction to Query Processing
1. Translating SQL Queries into Relational Algebra
2. External Sorting
3. Algorithms for SELECT and JOIN Operations
4. Algorithms for PROJECT and SET Operations
5. Implementing Aggregate Operations and Outer Joins

Different File Organizations

We need to understand the importance of appropriate file organization and index

Search key = <age, sal>

Consider following options:

- Heap files
  - random order; insert at end-of-file
- Sorted files
  - sorted on *<age, sal>*
- Clustered B+ tree file
  - search key *<age, sal>*
- Heap file with unclustered B^{+}-tree index
  - on search key *<age, sal>*
- Heap file with unclustered hash index
  - on search key *<age, sal>*

Possible Operations

- Scan
  - Fetch all records from disk to buffer pool
- Equality search
  - Find all employees with age = 23 and sal = 50
  - Fetch page from disk, then locate qualifying record in page
- Range selection
  - Find all employees with age > 35
- Insert a record
  - identify the page, fetch that page from disk, inset record, write back to disk (possibly other pages as well)
- Delete a record
  - similar to insert

Understanding the Workload

- A workload is a mix of queries and updates

- For each query in the workload:
  - Which relations does it access?
  - Which attributes are retrieved?
  - Which attributes are involved in selection/join conditions? How selective are these conditions likely to be?

- For each update in the workload:
  - Which attributes are involved in selection/join conditions? How selective are these conditions likely to be?
  - The type of update (INSERT/DELETE/UPDATE), and the attributes that are affected

Choice of Indexes

- What indexes should we create?
  - Which relations should have indexes? What field(s) should be the search key? Should we build several indexes?
- For each index, what kind of an index should it be?
  - Clustered? Hash/tree?

More on Choice of Indexes

- One approach:
  - Consider the most important queries
  - Consider the best plan using the current indexes
  - See if a better plan is possible with an additional index.
  - If so, create it.
  - Obviously, this implies that we must understand how a DBMS evaluates queries and creates query evaluation plans
  - We will learn query execution and optimization later - For now, we discuss simple 1-table queries.
- Before creating an index, must also consider the impact on updates in the workload

Trade-offs for Indexes

- Indexes can make
  - queries go faster
  - updates slower

- Require disk space, too

Index Selection Guidelines

- Attributes in WHERE clause are candidates for index keys
  - Exact match condition suggests hash index
  - Range query suggests tree index
  - Clustering is especially useful for range queries
    - can also help on equality queries if there are many duplicates

- Try to choose indexes that benefit as many queries as possible
  - Since only one index can be clustered per relation, choose it based on important queries that would benefit the most from clustering

- Multi-attribute search keys should be considered when a WHERE clause contains several conditions
  - Order of attributes is important for range queries

- Note: clustered index should be used judiciously
  - expensive updates, although cheaper than sorted files

Examples of Clustered Indexes

- B+ tree index on E.age can be used to get qualifying tuples
- How selective is the condition?
  - everyone > 40, index not of much help, scan is as good
  - Suppose 10% > 40. Then?
- Depends on if the index is clustered
  - otherwise can be more expensive than a linear scan
  - if clustered, 10% I/O (+ index pages)

What is a good indexing strategy?

```
SELECT E.dno
FROM Emp E
WHERE  E.age>40
```

Which attribute(s)?
Clustered/Unclustered?
B+ tree/Hash?

Examples of Clustered Indexes

Group-By query

- Use E.age as search key?
  - Bad If many tuples have *E.age* > 10 or if not clustered....
  - ...using *E.age* index and sorting the retrieved tuples by E.dno may be costly
- Clustered *E.dno* index may be better
  - First group by, then count tuples with age > 10
  - good when age > 10 is not too selective
- Note: the first option is good when the WHERE condition is highly selective (few tuples have age > 10), the second is good when not highly selective

What is a good indexing strategy?

```
SELECT E.dno, COUNT (*)
FROM Emp E
WHERE E.age>10
GROUP BY E.dno
```

Which attribute(s)?
Clustered/Unclustered?
B+ tree/Hash?

Examples of Clustered Indexes

What is a good indexing strategy?

Equality queries and duplicates

- Clustering on *E.hobby* helps
  - hobby not a candidate key, several tuples possible

```
SELECT E.dno
FROM Emp E
WHERE E.hobby='Stamps'
```

Which attribute(s)?
Clustered/Unclustered?
B+ tree/Hash?

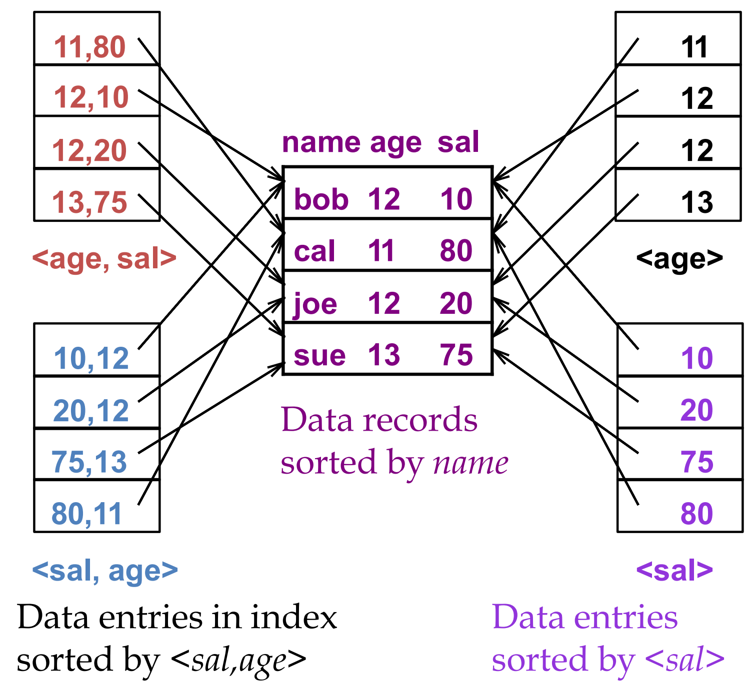
- Does clustering help now?
  - (eid = key)
  - Not much
  - at most one tuple satisfies the condition

```
SELECT E.dno
FROM Emp E
WHERE E.eid=50
```

Indexes with Composite Search Keys

- Composite Search Keys: Search on a combination of fields
- Equality query: Every field value is equal to a constant value. E.g. wrt <sal,age> index:
  - age=20 and sal =75
- Range query: Some field value is not a constant. E.g.:
  - sal > 10 – which combination(s) would help?
  - <age, sal> does not help
  - B+tree on <sal> or <sal, age> helps
  - has to be a prefix

Examples of composite key indexes using lexicographic order.



Composite Search Keys

- To retrieve Emp records with *age*=30 AND *sal*=4000, an index on <*age,sal*> would be better than an index on *age* or an index on sal
  - first find age = 30, among them search sal = 4000
- If condition is: 20<*age*<30 AND 3000<*sal*<5000:
  - Clustered tree index on <*age,sal*> or <*sal,age*> is best.
- If condition is: *age*=30 AND 3000<*sal*<5000:
  - Clustered <*age,sal*> index much better than <*sal,age*> index
  - more index entries are retrieved for the latter
- Composite indexes are larger, updated more often

Index-Only Plans

- A number of queries can be answered without retrieving any tuples from one or more of the relations involved if a suitable index is available

```
SELECT E.dno, COUNT(*)
FROM Emp E
GROUP BY  E.dno
```

<E.dno>

```
SELECT E.dno, MIN(E.sal)
FROM Emp E
GROUP BY  E.dno
```

<E.dno,E.sal>

Tree index!

<E. age,E.sal>

Tree index!

```
SELECT AVG(E.sal)
FROM Emp E
WHERE  E.age=25 AND
  E.sal BETWEEN 3000 AND 5000
```

- For index-only strategies, clustering is not important

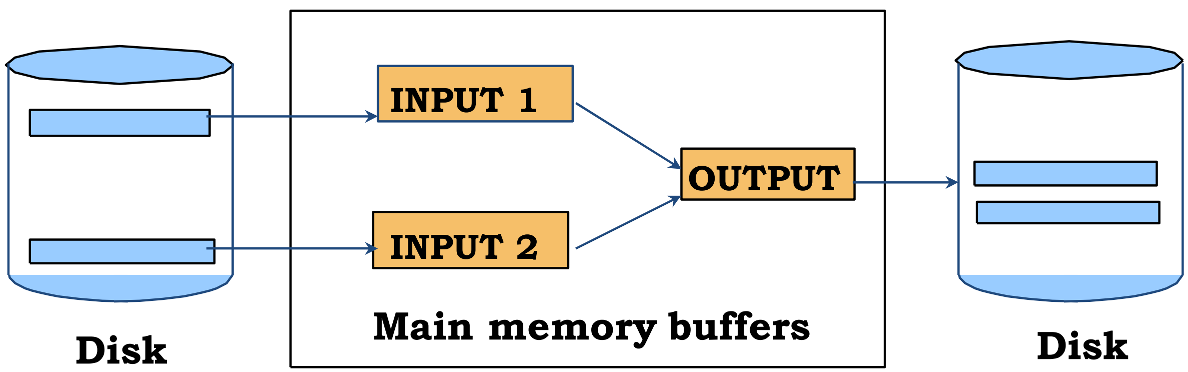
External Sorting

Why Sort?

- A classic problem in computer science
- Data requested in sorted order
  - e.g., find students in increasing gpa order
- Sorting is first step in bulk loading B+ tree index
- Sorting useful for eliminating duplicate copies in a collection of records
- Sort-merge join algorithm involves sorting
- Problem: sort 1Gb of data with 1Mb of RAM
  - need to minimize the cost of disk access

2-Way Sort: Requires 3 Buffers

- Suppose $N = 2^k$ pages in the file
- Pass 0: Read a page, sort it, write it.
  - repeat for all 2^k pages
  - only one buffer page is used
- Pass 1:
  - Read two pages, sort (merge) them using one output page, write them to disk
  - repeat 2^{k-1} times
  - three buffer pages used
- Pass 2, 3, 4, ….. continue



Two-Way External Merge Sort

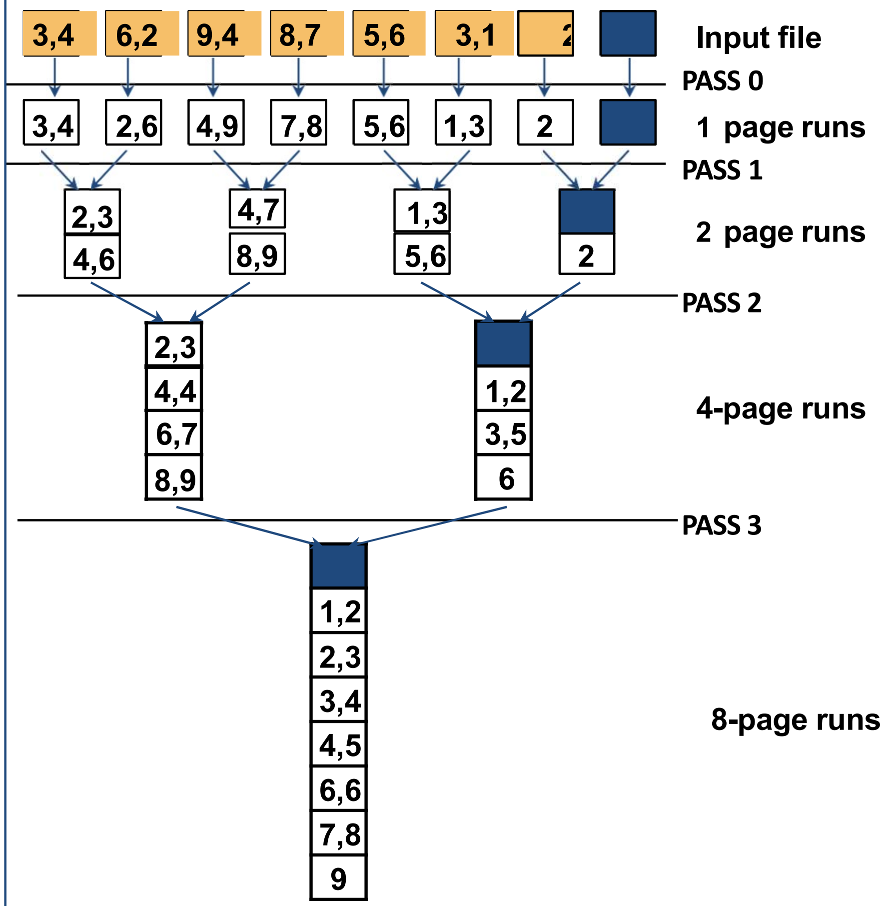
- Each sorted sub-file is called a run
  - each run can contain multiple pages
- Each pass we read + write each page in file.
- N pages in the file,
- => the number of passes

$$=\lceil \log_2 N \rceil + 1$$

- So toal cost is:

$$2N\left(\lceil \log_2 N \rceil + 1\right)$$

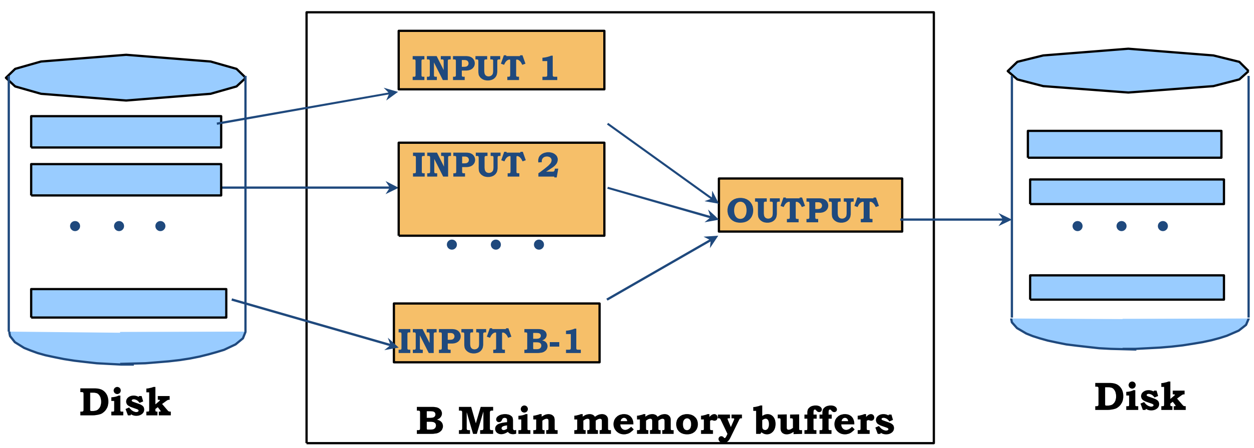
- Not too practical, but useful to learn basic concepts for external sorting



General External Merge Sort

- Suppose we have more than 3 buffer pages.
- How can we utilize them?

- To sort a file with N pages using B buffer pages:
  - Pass 0: use B buffer pages:
    - Produce ⌈N/B⌉ sorted runs of B pages each.
  - Pass 1, 2, …, etc.: merge B-1 runs to one output page
    - keep writing to disk once the output page is full



Cost of External Merge Sort

- Number of passes: $1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil$
- Cost = 2N * (# of passes) – why 2 times?
- E.g., with 5 buffer pages, to sort 108 page file:
- Pass 0: sorting 5 pages at a time
  - $\lceil 108/5 \rceil$ = 22 sorted runs of 5 pages each (last run is only 3 pages)
- Pass 1: 4-way merge
  - $\lceil 22/4 \rceil$ = 6 sorted runs of 20 pages each (last run is only 8 pages)
- Pass 2: 4-way merge
  - (but 2-way for the last two runs)
  - $\lceil 6/4 \rceil$ = 2 sorted runs, 80 pages and 28 pages
- Pass 3: 2-way merge (only 2 runs remaining)
  - Sorted file of 108 pages

Number of Passes of External Sort

High B is good, although CPU cost increases

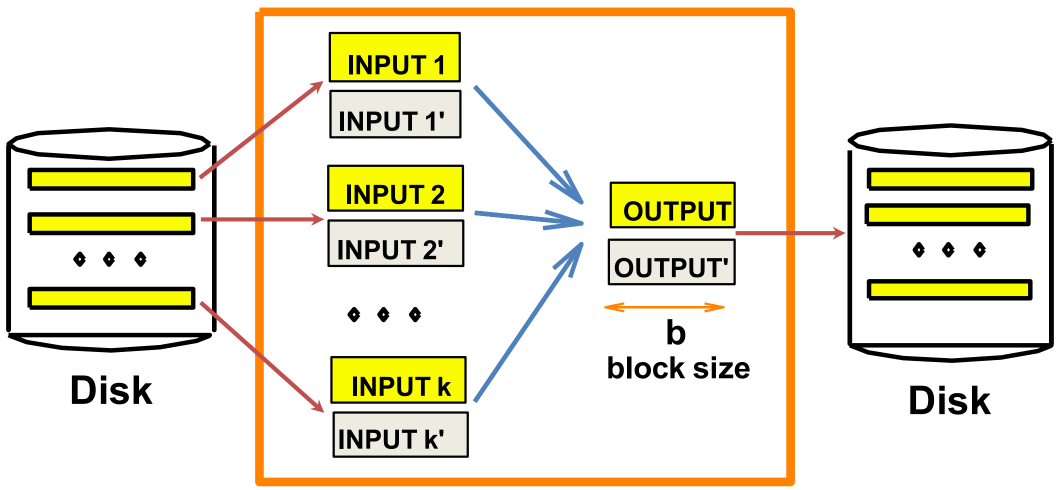
N	B=3	B=5	B=9	B=17	B=129	B=257
100	7	4	3	2	1	1
1,000	10	5	4	3	2	2
10,000	13	7	5	4	2	2
100,000	17	9	6	5	3	3
1,000,000	20	10	7	5	3	3
10,000,000	23	12	8	6	4	3
100,000,000	26	14	9	7	4	4
1,000,000,000	30	15	10	8	5	4

I/O for External Merge Sort

- If 10 buffer pages
  - either merge 9 runs at a time with one output buffer
  - or 8 runs with two output buffers
- If #page I/O is the metric
  - goal is minimize the #passes
  - each page is read and written in each pass
- If we decide to read a block of b pages sequentially
  - Suggests we should make each buffer (input/output) be a block of pages
  - But this will reduce fan-out during merge passes
    - i.e. not as many runs can be merged again any more
  - In practice, most files still sorted in 2-3 passes

Double Buffering

- To reduce CPU wait time for I/O request to complete, can prefetch into `shadow block'.



B main memory buffers, k-way merge

Overview of Query Evaluation

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!

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

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

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.

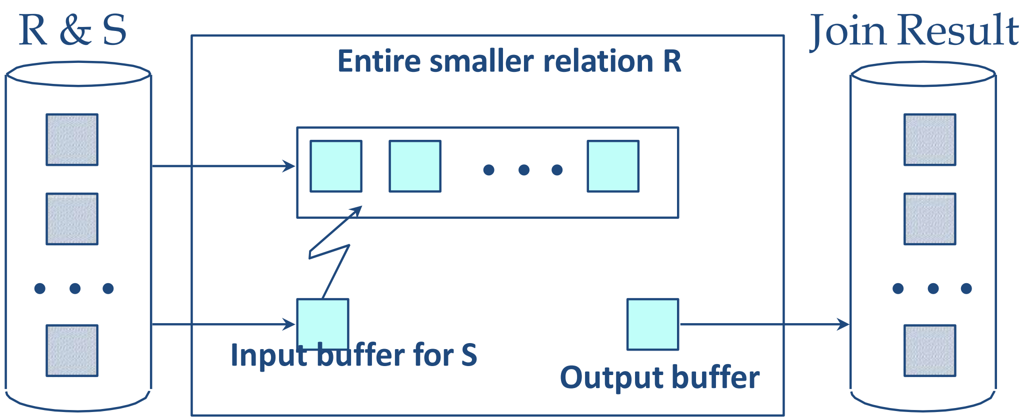
- Page-oriented Nested Loops join:
  - For each *page* of R, get each *page* of S
  - and write out matching pairs of tuples <r, s>
  - where r is in R-page and S is in S-page.
  - Cost: $M + M*N$ = 1000 + 1000*500

How many buffer pages do you need?

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

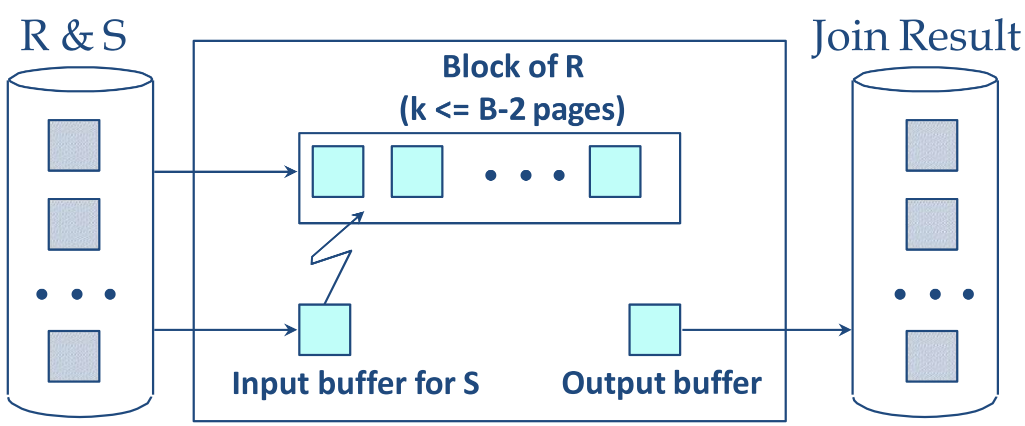
Block Nested Loops Join

- Simple-Nested does not properly utilize buffer pages (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
- 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

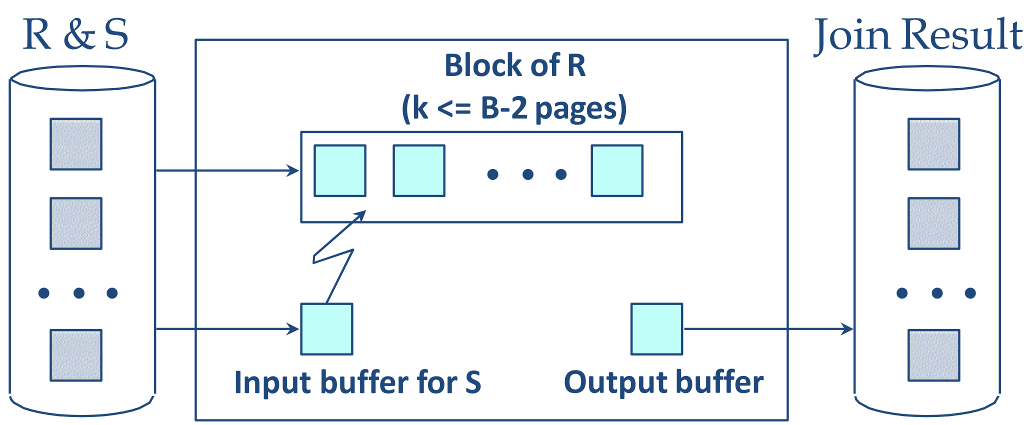
M = 1000 pages in R
p_R = 100 tuples per page

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

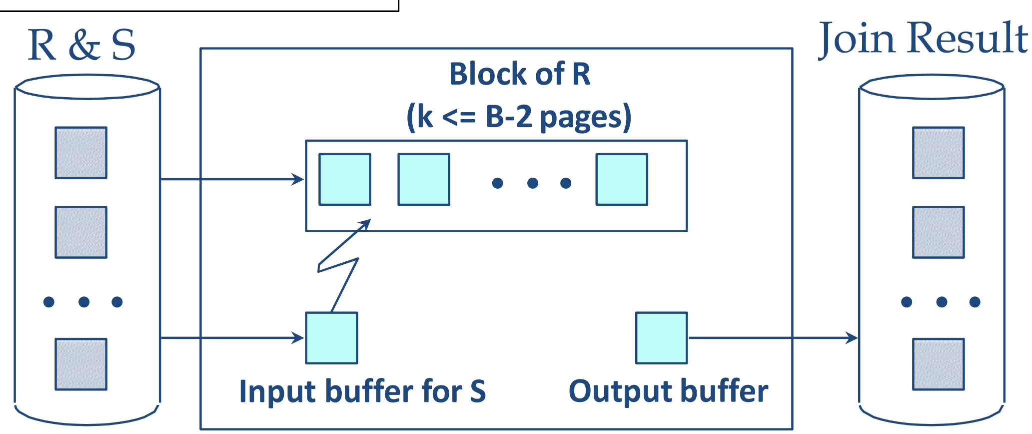
N = 500 pages in S
p_S = 80 tuples per page

- 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
("seek time" less)



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

WRITE THREE OUTPUT TUPLES

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: 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

NO MATCH, CONTINUE SCANNING S

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: 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, 2500

Algorithms for Joins

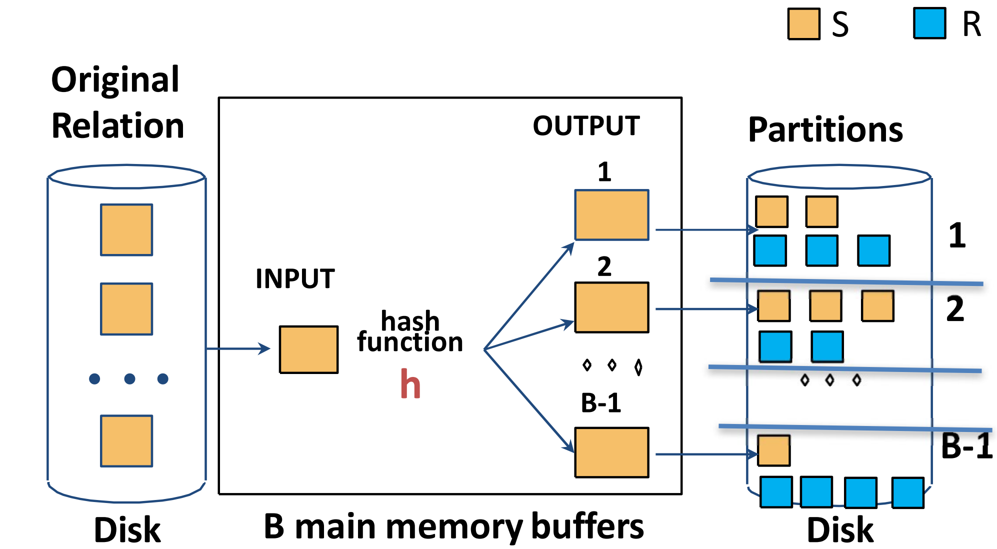
3. HASH JOINS

Two Phases

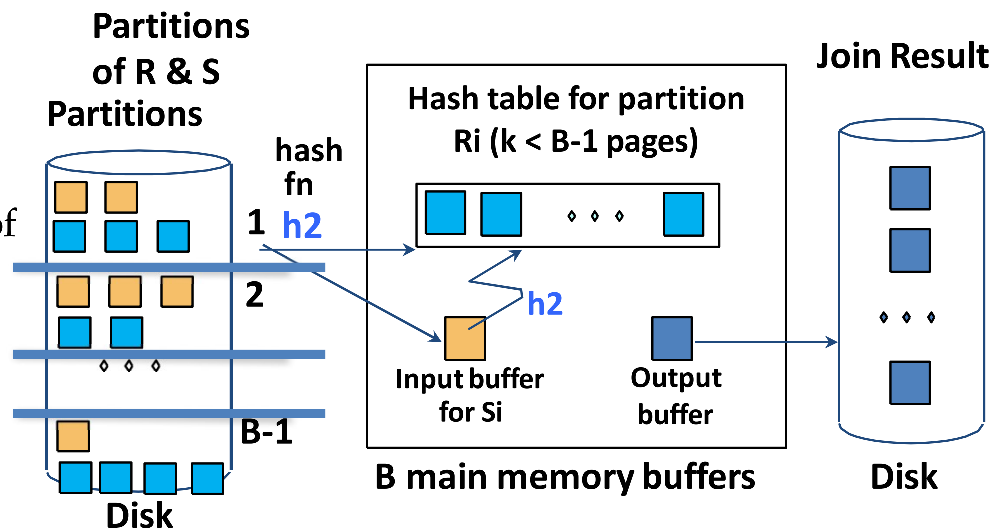
1. Partition Phase
   – partition R and S using the same hash function h
2. Probing Phase
   – join tuples from the same partition (same h(..) value) of R and S
   – tuples in different partition of h will never join
   – use a “different” hash function h2 for joining these tuples
     • (why different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



Visit in next lecture

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
- 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

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