Query Processing 1: Joins and Sorting

R&G, Chapters 12, 13, 14
Lecture 8

One of the advantages of being disorderly is that one is constantly making exciting discoveries.
A. A. Milne

Administrivia

- **Homework 1 Due Tonight**
- **You must be in groups of 3 to submit**
  (11 without groups Wednesday PM, if you're the last two you're allowed to be a group of two)
- **Homework 2 Available over the Weekend**

Review

- **Data Modelling**
  - Relational
  - E-R
- **Storing Data**
  - File Indexes
  - Buffer Pool Management
- **Query Languages**
  - SQL
  - Relational Algebra
  - Relational Calculus

Review – SQL Queries

- **Data Definition Language (DDL)**
- **Data Manipulation Language (DML)**
  - Range variables in Select clause
  - Expressions in Select, Where clauses
  - Set operators between queries:
    - Union, Intersect, Except/Minus
  - Set operators in nested queries:
    - In, Exists, Unique, <op> Any, <op> All
  - Aggregates: Count, Sum, Avg, Min, Max
  - Group By
  - Group By/Having

Questions

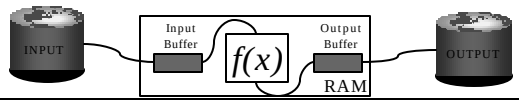
- **We learned that the same query can be written many ways.**
  - How does DBMS decide which is best?
- **We learned about tree & hash indexes.**
  - How does DBMS know when to use them?
- **Sometimes we need to sort data.**
  - How to sort more data than will fit in memory?

Why Sort?

- **A classic problem in computer science!**
- **Database needs it in order**
  - e.g., find students in increasing *gpa* order
  - first step in *bulk loading* B+ tree index.
  - eliminating *duplicates*
  - aggregating related groups of tuples
  - *Sort-merge* join algorithm involves sorting.
- **Problem: sort 1Gb of data with 1Mb of RAM.**
  - why not virtual memory?

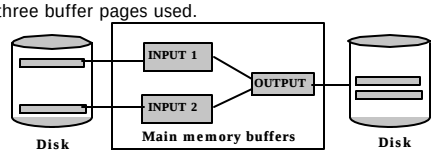
Streaming Data Through RAM

- **An important detail for sorting & other DB operations**
- **Simple case:**
  - Compute *f(x)* for each record, write out the result
  - Read a page from INPUT to Input Buffer
  - Write *f(x)* for each item to Output Buffer
  - When Input Buffer is consumed, read another page
  - When Output Buffer fills, write it to OUTPUT
- **Reads and Writes are *not* coordinated**
  - E.g., if f() is Compress(), you read many pages per write.
  - E.g., if f() is DeCompress(), you write many pages per read.



2-Way Sort

- **Pass 0: Read a page, sort it, write it.**
  - only one buffer page is used (as in previous slide)
- **Pass 1, 2, …, etc.:**
  - requires 3 buffer pages
  - merge pairs of runs into runs twice as long
  - three buffer pages used.



Two-Way External Merge Sort

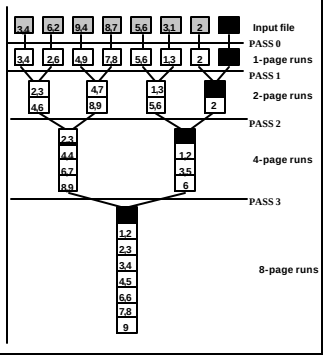
- **Each pass we read + write each page in file.**
- **N pages in the file => the number of passes**

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

- **So total cost is:**

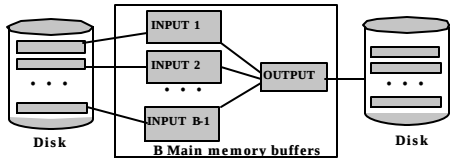
$$2N\left(\lceil \log_2 N \rceil + 1\right)$$

- ***Idea:*** *Divide and conquer:* **sort subfiles and merge**



General External Merge Sort

- ***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 $\lceil N / B \rceil$ sorted runs of *B* pages each.
  - Pass 1, 2, …, etc.: merge *B-1* runs.



Cost of External Merge Sort

- **Number of passes:** $1 + \lceil \log_{B-1} \lceil N / B \rceil \rceil$
- **Cost = 2N * (# of passes)**
- **E.g., with 5 buffer pages, to sort 108 page file:**
  - Pass 0: $\lceil 108 / 5 \rceil$ = 22 sorted runs of 5 pages each (last run is only 3 pages)
- **Now, do four-way (B-1) merges**
  - Pass 1: $\lceil 22 / 4 \rceil$ = 6 sorted runs of 20 pages each (last run is only 8 pages)
  - Pass 2: 2 sorted runs, 80 pages and 28 pages
  - Pass 3: Sorted file of 108 pages

Number of Passes of External Sort

(I/O cost is 2N times number of passes)

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

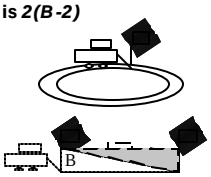
Internal Sort Algorithm

- **Quicksort is a fast way to sort in memory.**
- **Alternative: "tournament sort" (a.k.a. "heapsort", "replacement selection")**
- **Keep two heaps in memory, H1 and H2**

```
read B-2 pages of records, inserting into H1;
while (records left) {
    m = H1.removemin();  put m in output buffer;
    if (H1 is empty)
        H1 = H2;  H2.reset();  start new output run;
    else
        read in a new record r (use 1 buffer for
          input pages);
        if (r < m)  H2.insert(r);
        else        H1.insert(r);
}
H1.output();  start new run;  H2.output();
```

More on Heapsort

- **Fact: average length of a run is *2(B-2)***
  - The "snowplow" analogy
- **Worst-Case:**
  - What is min length of a run?
  - How does this arise?
- **Best-Case:**
  - What is max length of a run?
  - How does this arise?
- **Quicksort is faster, but ... longer runs often means fewer passes!**



I/O for External Merge Sort

- **Actually, doing I/O a page at a time**
  - Not an I/O per record
- **In fact, read a *block (chunk)* of pages sequentially!**
- **Suggests we should make each buffer (input/output) be a *chunk* of pages.**
  - But this will reduce fan-out during merge passes!
  - In practice, most files still sorted in 2-3 passes.

Number of Passes of Optimized Sort

N	B=1,000	B=5,000	B=10,000
100	1	1	1
1,000	1	1	1
10,000	2	2	1
100,000	3	2	2
1,000,000	3	2	2
10,000,000	4	3	3
100,000,000	5	3	3
1,000,000,000	5	4	3

✉ *Block size = 32, initial pass produces runs of size 2B.*

Sorting Records!

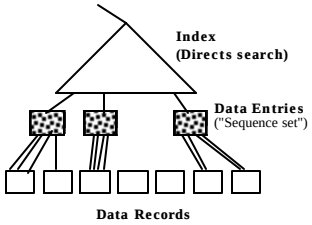
- **Sorting has become a blood sport!**
  - Parallel sorting is the name of the game ...
- **Minute Sort: how many 100-byte records can you sort in a minute?**
  - Typical DBMS: 10MB (~100,000 records)
  - Current World record: 21.8 ***GB***
    - 64 dual-processor Pentium-III PCs (1999)
- **Penny Sort: how many can you sort for a penny?**
  - Current world record: 12GB
    - 1380 seconds on a $672 Linux/Intel system (2001)
    - $672 spread over 3 years = 1404 seconds/penny
- **See http://research.microsoft.com/barc/SortBenchmark/**

Using B+ Trees for Sorting

- **Scenario: Table to be sorted has B+ tree index on sorting column(s).**
- **Idea: Can retrieve records in order by traversing leaf pages.**
- *Is this a good idea?*
- **Cases to consider:**
  - B+ tree is clustered — ***Good idea!***
  - B+ tree is not clustered — ***Could be a very bad idea!***

Clustered B+ Tree Used for Sorting

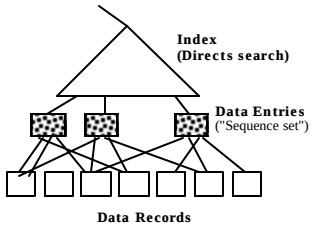
- **Cost: root to the left-most leaf, then retrieve all leaf pages (Alternative 1)**
- **If Alternative 2 is used? Additional cost of retrieving data records: each page fetched just once.**



✉ ***Better than external sorting!***

Unclustered B+ Tree Used for Sorting

- **Alternative (2) for data entries; each data entry contains *rid* of a data record. In general, one I/O per data record!**



External Sorting vs. Unclustered Index

N	Sorting	p=1	p=10	p=100
100	200	100	1,000	10,000
1,000	2,000	1,000	10,000	100,000
10,000	40,000	10,000	100,000	1,000,000
100,000	600,000	100,000	1,000,000	10,000,000
1,000,000	8,000,000	1,000,000	10,000,000	100,000,000
10,000,000	80,000,000	10,000,000	100,000,000	1,000,000,000

✉ ***p*: # of records per page**
✉ ***B=1,000 and block size=32 for sorting***
✉ ***p=100 is the more realistic value.***

Sorting - Review

- **External sorting is important; DBMS may dedicate part of buffer pool for sorting!**
- **External merge sort minimizes disk I/O cost:**
  - Pass 0: Produces sorted ***runs*** of size ***B*** (# buffer pages). Later passes: ***merge*** runs.
  - # of runs merged at a time depends on ***B***, and ***block size***.
  - Larger block size means less I/O cost per page.
  - Larger block size means smaller # runs merged.
  - In practice, # of passes rarely more than 2 or 3.

Sorting – Review (cont)

- **Choice of internal sort algorithm may matter:**
  - Quicksort: Quick!
  - Heap/tournament sort: slower (2x), longer runs
- **The best sorts are wildly fast:**
  - Despite 40+ years of research, we're still improving!
- **Clustered B+ tree is good for sorting; unclustered tree is usually very bad.**

A Related Topic: Joins

- **How does DBMS join two tables?**
- **Sorting is one way…**
- **Database must choose best way for each query**

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 total.
- **Sailors:**
  - Each tuple is 50 bytes long,
  - 80 tuples per page,
  - 500 pages total.

Equality Joins With One Join Column

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

- **In algebra: R⋈S. Common! Must be carefully optimized. R × S is large; so, R × S followed by a selection is inefficient.**
- **Assume: M tuples in R, p_R tuples per page, N tuples in S, p_S tuples per page.**
  - In our examples, R is Reserves and S is Sailors.
- **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 do
    foreach tuple s in S do
        if r_i == s_j then 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 = 500 + 500*1000

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
```

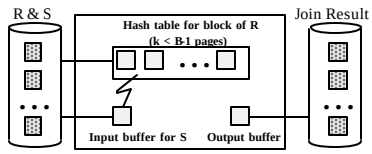
- **If there is an index on the join column of one relation (say S), can make it the inner and exploit the index.**
  - Cost: $M + ((M*p_R)$ * cost of finding matching S tuples)
- **For each R tuple, cost of probing S index is about 1.2 for hash index, 2 -4 for B+ tree. Cost of then finding S tuples (assuming Alt. (2) or (3) for data entries) 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

- **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.



Examples of Block Nested Loops

- **Cost: Scan of outer + #outer blocks * scan of inner**
  - #outer blocks = $\lceil \#\ of\ pages\ of\ outer\ /\ blocksize \rceil$
- **With Reserves (R) as outer, and 100 pages of R:**
  - 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.
  - If space for just 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.
- **With *sequential reads* considered, analysis changes: may be best to divide buffers evenly between R and S.**

Sort-Merge Join ($R \underset{i=j}{\times} S$)

- **Sort R and S on the join column, then scan them to do a ``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, all R tuples with same value in Ri (*current R group*) and all S tuples with same value in Sj (*current S group*) *match*; output <r, s> for all pairs of such tuples.
  - Then resume scanning R and S.
- **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.)**

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: M log M + N log N + (M+N)**
  - The cost of scanning, M+N, could be M*N (very unlikely!)
- **With 35, 100 or 300 buffer pages, both Reserves and Sailors can be sorted in 2 passes; total join cost: 7500.**

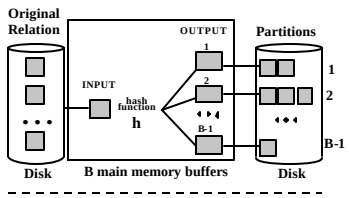
(*BNL cost: 2500 to 15000 I/Os*)

Refinement of Sort-Merge Join

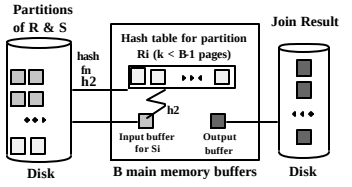
- **We can combine the merging phases in the *sorting* of R and S with the merging required for the join.**
  - With B > $\sqrt{L}$, where *L* is the size of the larger relation, using the sorting refinement that produces runs of length 2B in Pass 0, #runs of each relation is < B/2.
  - Allocate 1 page per run of each relation, and `merge' while checking the join condition.
  - Cost: read+write each relation in Pass 0 + read each relation in (only) merging pass (+ writing of result tuples).
  - In example, cost goes down from 7500 to 4500 I/Os.
- **In practice, cost of sort-merge join, like the cost of external sorting, is *linear*.**

Hash-Join

- **Partition both relations using hash fn 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

- **#partitions k < B-1 (why?), and B-2 > size of largest partition to be held in memory. Assuming uniformly sized partitions, and maximizing k, we get:**
  - k= B-1, and M/(B-1) < B-2, i.e., B must be > $\sqrt{M}$
- **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 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:**
  - Given a minimum amount of memory (*what is this, for each?*) both have a cost of 3(M+N) I/Os. Hash Join superior on this count if relation sizes differ greatly. Also, Hash Join shown to be highly parallelizable.
  - Sort-Merge less sensitive to data skew; 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.
    - 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.

Conclusions

- **Database needs to run queries fast**
- **Sorting efficiently is one factor**
- **Choosing the right join another factor**
- **Next time: optimizing all parts of a query**