Book Chapters
(4th) Chapter 13.1-6
(5th) Chapter 13.1-6
(6th) Chapter 12.1-6

Things to Learn
• Join algorithms

Motivation
Student(sid, name, addr, age, GPA)
Enroll(sid, dept, cnum, sec)
B+tree index on sid, age of Student table

• Q: How do we process SELECT * FROM Student WHERE sid > 30?

• Q: How do we process SELECT * FROM Student WHERE sid > 30 AND age > 19?

• Q: How do we process SELECT * FROM Student S, Enroll E WHERE S.sid = E.sid?

• Joins can be very expensive (maybe $\approx |R| \times |S|$). How can we perform joins efficiently?
Join algorithms

(R and S example slide)

- Q: How to join R and S? What is the simplest algorithm? What if we have an index? Any other ideas that we can use?
  - Four join algorithms
    * Nested-loop join
    * Index join
    * Sort-merge join
    * Hash join
  - We now learn how they work

1. Nested-Loop Join:

(nested-loop-join slide)

For each r in R do
  For each s in S do
    if r.C = s.C then output r,s pair

- Q: If R has 100,000 tuples, how many times the entire S table is scanned?
- The simplest algorithm. It works, but may not be efficient.

2. Index Join:

(index-join slide)

For each r in R do
  X <- index-lookup(S.C, r.C)
  For each s in X do
    output (r,s)

- Look up index to find matching tuples from S.
- Q: Benefit of index join compared to nested-loop join?

3. Sort-Merge Join:

(Sort-merge-join slide)

- Main idea: If tables have been sorted by the join attribute, we need to scan each table only once.
  - Maintain one cursor per table and move the cursor forward.
- Sort tables and join them.

(sort-merge algorithm slide)
(1) if R and S not sorted, sort them
(2) i <- 1; j <- 1;
   While (i <= |R|) AND (j <= |S|) do
       if R[i].C = S[j].C then outputTuples
       else if R[i].C > S[j].C then j <- j+1
       else if R[i].C < S[j].C then i <- i+1

Procedure outputTuples
   While (R[i].C = S[j].C) AND (i <= |R|) do
       k <- j;
       While (R[i].C = S[k].C) AND (k <= |S|) do
         output R[i], S[k] pair;
         k <- k + 1;
       i <- i + 1;

4. Hash Join:
   • Main idea: If hash values are different, the tuples will never join, i.e., if \( h(R.C) \neq h(S.C) \), then \( R.C \neq S.C \).
   • Join two tuples only if their hash values are the same.

(hash-join algorithm slide)

(1) Hashing stage (bucketizing)

   Hash R tuples into G1,...,Gk buckets
   Hash S tuples into H1,...,Hk buckets

(2) Join stage

   For i = 1 to k do
      match tuples in Gi, Hi buckets

Comparison of Join Algorithms

   • Q: Which algorithm is better?

   • Q: What do we mean by “better”? 

3
Cost model

- The ultimate bottom-line:
  - How long does it take for each algorithm to finish for a particular data?
- Need of cost model
  - We need a “cost model” to estimate the performance of different algorithms
- Our cost model: Total number of disk blocks that have been read/written
  - Not very realistic
    - Ignore random, sequential IO issues, CPU cost, etc.
  - Yet simple to analyze and doable in class
    - More sophisticated models are too complex to analyze in class
  - Good approximation given that disk IOs dominate the cost
  - Most algorithms that we will study do mostly sequential scan
  - A better algorithm = smaller number of disk block access
  - Ignore the last IOs for result writing (the same for every algorithm)

Example to use

- Two tables \( R, S \)
- \( |R| = 1,000 \) tuples, \( |S| = 10,000 \) tuples, 10 tuples/block
- \( b_R = 100 \) blocks, \( b_S = 1,000 \) blocks
- Memory buffer for 22 blocks

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Formula (if ( b_R &lt; b_S ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nested Loop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sort Merge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hash</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cost of join stage of sort-merge join

- Usage of main memory blocks for join

  1. Available memory buffers. Disk blocks of each table
22 blocks

2. We need to read $R$ table, $S$ table and write the output.
   - Disk transfer unit is one block
   - At least one memory buffer block to read $R$, read $S$ and write output.
   - Three memory blocks used for these tasks.

3. We sequentially read $R$ and $S$ blocks one block at a time, and join them (using the join algorithm)

- **Q:** How many disk IOs (block reads/writes) for $R$ and $S$ during join stage?

- **Q:** Under our cost metric, can we make it more efficient by allocating more buffers for reading $R$ and $S$? For example,

**Nested-Loop Join**

(naive nested-loop join algorithm slide for reminder)
- **Q:** How many disk blocks are read?

- **Q:** Can we do any better?

### Optimization 1: Block-nested loop join

Once we read a block from $R$, join everything in the block in one scan of $S$.
→ reduces the number of scans of $S$ table

- **Q:** What is the cost?

- **Q:** Can we do any better?

### Optimization 2

Read as many blocks of $R$ and join them together in one scan of $S$.
→ reduces the number of scans of $S$ table

- **Q:** What is the maximum # of blocks that we can read in one batch from $R$?
• Q: What is the cost?

• Q: What is general cost for $b_R$, $b_S$ and $M$?

• Q: What if we read $S$ first? Would it be any different?

→ Use smaller table for the outer loop.

• Summary
  – Always use block nested loop (not the naive algorithm)
  – Read as many blocks as we can for the left table in one iteration
  – Use the smaller table on the left (or outer loop)

Hash Join
(hash join slide for reminder. two stages: hashing stage and join stage)

• Hashing stage: Read $R$ (or $S$) table and hash them into different buckets.

  – Q: One block for reading $R$, other blocks for bucketizing. How many buckets?
- **Q:** Assuming random hashing, how many blocks per bucket?

- **Q:** During bucketizing, $R$ table is read once and written once. How many disk IOs (read or write)?

- Repeat the same for $S$

- **Join stage:** Join $H_1$ with $G_1$

- **Q:** 5 blocks for $G_1$, 48 blocks for $H_1$. How should we join $G_1$ and $H_1$?

- **Q:** How many disk IOs?

- **Q:** Total disk IOs?

- **Q:** What if $R$ is large and $G_1 > 20$?

**Recursive partitioning**
* # of bucketizing steps: \(\lceil \log_{M-1} \left( \frac{b_R}{M-2} \right) \rceil\)
* General hash join cost \((b_R < b_S)\):
  \[
  \frac{2(b_R + b_S)}{2} \left[ \log_{M-1} \left( \frac{b_R}{M-2} \right) \right] + (b_R + b_S)
  \]

**Index join**
(index-join slide for reminder)

- **Q:** How many disk IOs?

- **Q:** What should the system do to perform index join?

Index join cost:
- IO for \(R\) scanning
- IO for index look up
- IO for tuple read from \(S\).

- **Example 1**
  - 15 blocks for index
    - 1 root, 14 leaf
  - On average, 1 matching \(S\) tuples per an \(R\) tuple.

**Q:** How many disk IOs? How should we use memory?

**Q:** Any better way?
• Example 2
  – 40 blocks for index
    * 1 root, 39 leaf
  – On average, 10 matching tuples in $S$.

**Q:** How many disk IOs? How should we use memory?

• General cost: $b_R + |R| \cdot (C + J)$
  – $C$ average index look up cost
  – $J$ matching tuples in $S$ for every $R$ tuple
  – $|R|$ tuples in $R$

**Q:** How can we compute $J$?

– **Example:** $R \bowtie_{C=S.C} S$. $|S| = 10$, $V(C, R) = 1,000$. Uniform distribution for $C$ values. How many tuples in $S$ with $C = c$?

**Sort-Merge Join**

• Two stage algorithm:
  1. Sort stage: Sort $R$ and $S$
  2. Merge stage: Merge sorted $R$ and $S$

• # of disk IOs during merge stage: $b_R + b_S = 100 + 1,000 = 1,100$.

**Q:** How many disk IOs during sort stage?

**Merge sort algorithm**

![Diagram](//)
• **Q:** How many blocks can we sort in main memory?

  – **Q:** Do we need to allocate one block for output?

• **Q:** How many sorted runs after sorting $R$ in chunk of 22 blocks?

<table>
<thead>
<tr>
<th>sorted runs</th>
<th>22 blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>100 blocks</td>
</tr>
</tbody>
</table>

• **Q:** What should we do with 5 sorted-runs?

• **Q:** How many disk IOs?

  – **Q:** During first-stage sorting?

  – **Q:** During second-stage merging?

Repeat it for $S$ table of 1,000 blocks. Show that now we need three stages.

• In general, the number of passes for $b_R$ and $M$: $ ([\log_{M-1}(b_R/M)] + 1)$

  – Verify it at home on your own.

  – Total # of IOs for sorting: $2 \cdot b_R([\log_{M-1}(b_R/M)] + 1)$
Total sort-merge join cost

- In total: $400 + 6,000 + 1,100 = 7,500$

- In general: $2b_R([\log_{M-1}(b_R/M)] + 1) + 2b_S([\log_{M-1}(b_S/M)] + 1) + (b_R + b_S)$ IOs

Summary of join algorithms

- Nested-loop join ok for “small” relations (relative to memory size)
- Hash join usually best for equi-join
  - if relations not sorted and no index
- Merge join for sorted relations
  - Sort merge join good for non-equi-join
- Consider index join if index exists
- To pick the best, DBMS maintains statistics on data

High-level query optimization

Tables: $R(A, B)$, $S(B, C)$, $T(C, D)$

- Q: How can we process the following query?
  
  ```sql
  SELECT * FROM R, S, T
  ```
  
  - Many different ways. (Show a couple of logical query trees)

- Q: For now, focus on $R \bowtie S \bowtie T$. How many different ways to execute it?
• In general, for $n$ way joins, $\frac{(2(n-1))!}{(n-1)!}$ ways.
  
  – Study why this is the case at home.
  – For $n = 3$, $4!/2! = 12$
  – For $n = 5$, $8!/4! = 1680$
  – For $n = 10$, $18!/9! = 17 \times 10^9$

• DBMS tries to pick the best based on statistics
  
  – In reality, picking the best is too difficult
    * For $n = 10$, it is clearly impossible to examine all 17 billion plans
  – DBMS tries to avoid “obvious mistakes” using a number of heuristics to examine only
    the ones that are likely to be reasonable

• Read the PDF file on database tuning and optimization
  
  – For 90% of the time, DBMS picks a good plan
  – To optimize the remaining 10%, companies pay big money to database consultants

Statistics collection commands on DBMS
• DBMS has to collect statistics on tables/indexes for optimal performance
  
  – Without stats, DBMS does stupid things

• DB2
  
  – RUNSTATS ON TABLE <userid>.<table> AND INDEXES ALL

• Oracle
  
  – ANALYZE TABLE <table> COMPUTE STATISTICS
  – ANALYZE TABLE <table> ESTIMATE STATISTICS (cheaper than COMPUTE)

• Run the command after major update/index construction

• Does not matter for MySQL. No optimization based on actual data. Only rule-based opti-
  mizer.