# CS143: Query processing and join algorithms

## 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?`

- <u>Joins can be very expensive (maybe $\approx |R| \times |S|$). How can we perform joins efficiently?</u>

## 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.

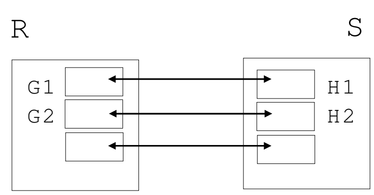
   (hash-join algorithm slide)

```
(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"?

## 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

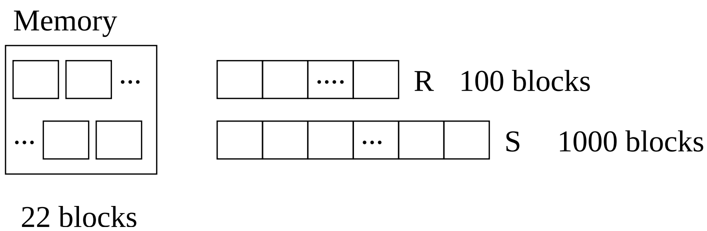
- Two tables $R$, $S$
- $|R| = 1,000$ tuples, $|S| = 10,000$ tuples, 10 tuples/block
- $b_R = 100$ blocks, $b_S =$ 1,000 blocks
- Memory buffer for 22 blocks

| | Cost | Formula (if $b_R < b_S$) |
|---|---|---|
| Nested Loop | | |
| Sort Merge | | |
| Hash | | |
| Index | | |

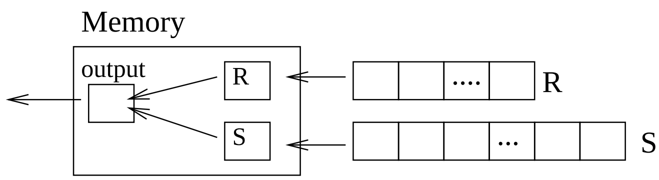
## Cost of join stage of sort-merge join

- Usage of main memory blocks for join

1. Available memory buffers. Disk blocks of each table



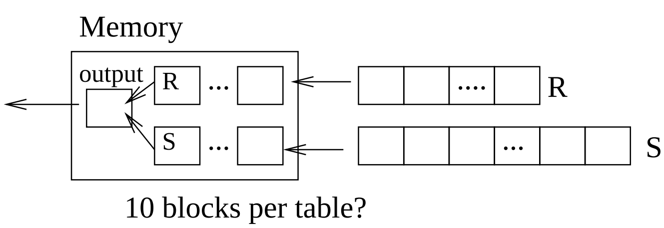

2. We need to read $R$ table, $S$ table and write the output.
   - Disk transfer unit is one block
   - → At least one memory buffer block to read $R$, read $S$ and write output.
   - → Three memory blocks used for these tasks.




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

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

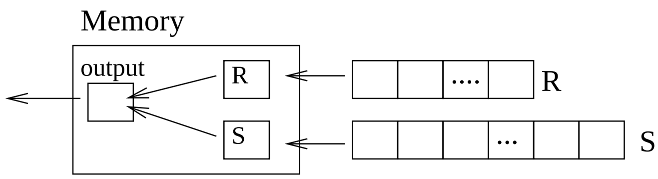
- **Q:** Under our cost metric, can we make it more efficient by allocating more buffers for reading $R$ and $S$? For example,




## Nested-Loop Join

(naive nested-loop join algorithm slide for reminder)

(join diagram)




- **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 $S$.
$\rightarrow$ 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 togeter in one scan of $S$
$\rightarrow$ 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?

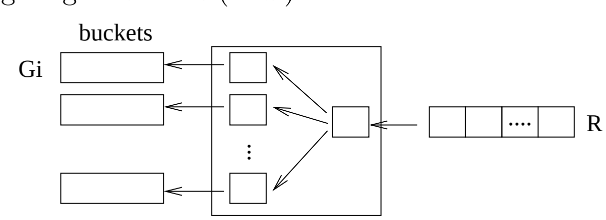
  $\rightarrow$ Use smaller table for the outer loop.

- **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.



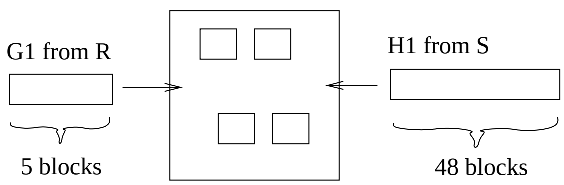

  - **Q:** One block for reading $R$, other blocks for bucketizing. How many buckets?

- **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: $\left\lceil \log_{M-1}\left(\frac{b_R}{M-2}\right)\right\rceil$
- * General hash join cost ($b_R < b_S$):

$$2(b_R + b_S)\left\lceil \log_{M-1}\left(\frac{b_R}{M-2}\right)\right\rceil + (b_R + b_S)$$

### 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 $S$.

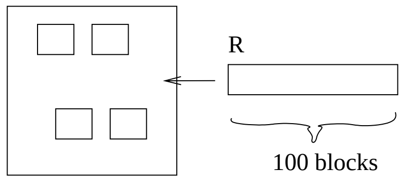
  **Q:** How many disk IOs? How should we use memory?

- 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:** $R \bowtie_{R.C=S.C} S$. $|S| = 10$, $V(C, R) = 1,000$. 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?

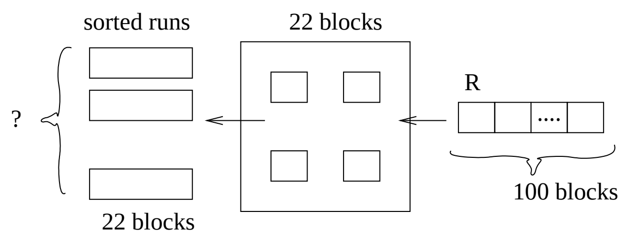
### Merge sort algorithm



- **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?




- **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 $M$: $(\lceil \log_{M-1}(b_R/M) \rceil + 1)$
  - Verify it at home on your own.
  - Total # of IOs for sorting: $2 \cdot b_R(\lceil \log_{M-1}(b_R/M) \rceil + 1)$

**Total sort-merge join cost**

- In total: 400 + 6,000 + 1,100 = 7,500
- In general: $2b_R(\lceil\log_{M-1}(b_R/M)\rceil + 1) + 2b_S(\lceil\log_{M-1}(b_S/M)\rceil + 1) + (b_R + b_S)$ 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?

  ```
  SELECT * FROM R, S, T
  WHERE R.B = S.B AND S.C = T.C AND R.A = 10 AND T.D < 30
  ```

  - 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 databse tuning and optimization
  - For 90% of the time, DBMS picks a good plan
  - To optimize the remaning 10%, companies pay big money to datbase 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 optimizer.