CSE 444: Database Internals

Lecture 8
Operator Algorithms (part 2)

Announcements

- Lab 2 / part 1 due on Friday
- Paper review for master's due on Wednesday
- Homework 2 due next week on Monday

Outline

- **Join operator algorithms**
  - One-pass algorithms (Sec. 15.2 and 15.3)
  - Index-based algorithms (Sec 15.6)
  - Two-pass algorithms (Sec 15.4 and 15.5)

Index Based Selection

Selection on equality: $\sigma_{a=v}(R)$
- B(R)= size of R in blocks
- T(R) = number of tuples in R
- V(R, a) = # of distinct values of attribute a

Index Based Selection

Selection on equality: $\sigma_{a=v}(R)$
- B(R)= size of R in blocks
- T(R) = number of tuples in R
- V(R, a) = # of distinct values of attribute a

What is the cost in each case?
- Clustered index on a:
- Unclustered index on a:

Index Based Selection

Selection on equality: $\sigma_{a=v}(R)$
- B(R)= size of R in blocks
- T(R) = number of tuples in R
- V(R, a) = # of distinct values of attribute a

What is the cost in each case?
- Clustered index on a: B(R)/V(R,a)
- Unclustered index on a: T(R)/V(R,a)

Index Based Selection

Selection on equality: $\sigma_{a=v}(R)$
- B(R)= size of R in blocks
- T(R) = number of tuples in R
- V(R, a) = # of distinct values of attribute a

What is the cost in each case?
- Clustered index on a: B(R)/V(R,a)
- Unclustered index on a: T(R)/V(R,a)

Note: we ignore I/O cost for index pages

Index Based Selection

- Example: B(R) = 2000, T(R) = 100,000, V(R, a) = 20 — cost of $\sigma_{a=v}(R)$ = ?
- Table scan:
- Index based selection:

Index Based Selection

- Example: B(R) = 2000, T(R) = 100,000, V(R, a) = 20 — cost of $\sigma_{a=v}(R)$ = ?
- Table scan: B(R) = 2,000 I/Os
- Index based selection:

Index Based Selection

- Example: B(R) = 2000, T(R) = 100,000, V(R, a) = 20 — cost of $\sigma_{a=v}(R)$ = ?
- Table scan: B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered:
  - If index is unclustered:

Index Based Selection

- Example: B(R) = 2000, T(R) = 100,000, V(R, a) = 20 — cost of $\sigma_{a=v}(R)$ = ?
- Table scan: B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered: B(R)/V(R,a) = 100 I/Os
  - If index is unclustered:

Index Based Selection

- Example: B(R) = 2000, T(R) = 100,000, V(R, a) = 20 — cost of $\sigma_{a=v}(R)$ = ?
- Table scan: B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered: B(R)/V(R,a) = 100 I/Os
  - If index is unclustered: T(R)/V(R,a) = 5,000 I/Os

Index Based Selection

- Example:

B(R) = 2000
T(R) = 100,000
V(R, a) = 20

cost of $\sigma_{a=v}(R)$ = ?

- Table scan: B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered: B(R)/V(R,a) = 100 I/Os
  - If index is unclustered: T(R)/V(R,a) = 5,000 I/Os

Lesson: Don't build unclustered indexes when V(R,a) is small !

Index Nested Loop Join

R ⋈ S

- Assume S has an index on the join attribute
- Iterate over R, for each tuple fetch corresponding tuple(s) from S
- Cost:
  - If index on S is clustered: B(R) + T(R)B(S)/V(S,a)
  - If index on S is unclustered: B(R) + T(R)T(S)/V(S,a)

Outline

- **Join operator algorithms**
  - One-pass algorithms (Sec. 15.2 and 15.3)
  - Index-based algorithms (Sec 15.6)
  - Two-pass algorithms (Sec 15.4 and 15.5)

Two-Pass Algorithms

- What if data does not fit in memory?
- Need to process it in multiple passes
- Two key techniques
  - Sorting
  - Hashing

Basic Terminology

- A run in a sequence is an increasing subsequence
- What are the runs?

2, 4, 99, 103, 88, 77, 3, 79, 100, 2, 50

Basic Terminology

- A run in a sequence is an increasing subsequence
- What are the runs?

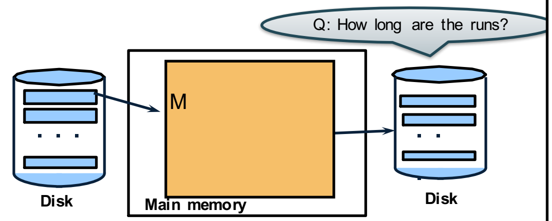
2, 4, 99, 103 | 88 | 77 | 3, 79, 100 |, 2, 50

External Merge-Sort: Step 1

Phase one: load M blocks in memory, sort, sent to disk, repeat

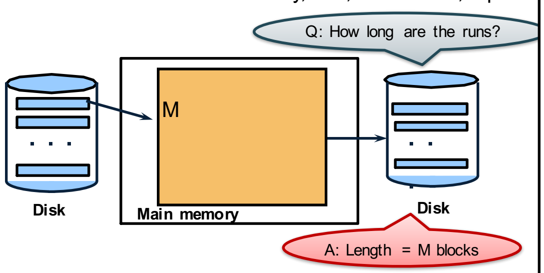
External Merge-Sort: Step 1

Phase one: load M blocks in memory, sort, sent to disk, repeat



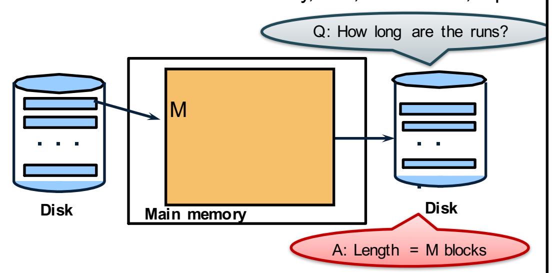
External Merge-Sort: Step 1

Phase one: load M blocks in memory, sort, sent to disk, repeat



External Merge-Sort: Step 1

Phase one: load M blocks in memory, sort, sent to disk, repeat

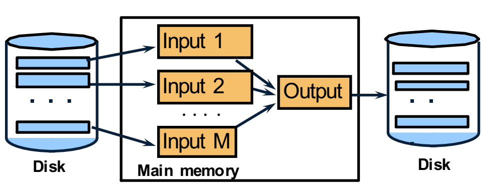


Can increase to length 2M using "replacement selection"

External Merge-Sort: Step 2

Phase two: merge M runs into a bigger run

- Merge M – 1 runs into a new run
- Result: runs of length M (M – 1) ≈ M^2



If B <= M^2 then we are done

Example

- Merging three runs to produce a longer run:

0, 14, 33, 88, 92, 192, 322
2, 4, 7, 43, 78, 103, 523
1, 6, 9, 12, 33, 52, 88, 320

Output:
0

Example

- Merging three runs to produce a longer run:

0, **14, 33, 88, 92, 192, 322**
2, 4, 7, 43, 78, 103, 523
1, 6, 9, 12, 33, 52, 88, 320

Output:
0, ?

Example

- Merging three runs to produce a longer run:

0, **14, 33, 88, 92, 192, 322**
2, 4, 7, 43, 78, 103, 523
1, **6, 9, 12, 33, 52, 88, 320**

Output:
0, 1, ?

Example

- Merging three runs to produce a longer run:

0, **14, 33, 88, 92, 192, 322**
2, 4, 7, **43, 78, 103, 523**
1, 6, **9, 12, 33, 52, 88, 320**

Output:
0, 1, 2, 4, 6, 7, ?

Cost of External Merge Sort

- Read+write+read = 3B(R)
- Assumption: B(R) <= M^2

Discussion

- What does B(R) <= M^2 mean?
- How large can R be?

Discussion

- What does B(R) <= M^2 mean?
- How large can R be?
- Example:
  - Page size = 32KB
  - Memory size 32GB: M = 10^6-pages

Discussion

- What does $B(R) <= M^2$ mean?
- How large can R be?

- Example:
  – Page size = 32KB
  – Memory size 32GB: $M = 10^6$-pages

- R can be as large as 10^{12}-pages
  – 32×10^{15} Bytes = 32 PB

Merge-Join

Join R ⋈ S

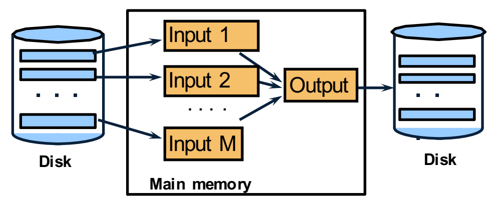
- How?....

Merge-Join

Join R ⋈ S

- Step 1a: initial runs for R
- Step 1b: initial runs for S
- Step 2: merge and join

Merge-Join



$M_1 = B(R)/M$ runs for R
$M_2 = B(S)/M$ runs for S
Merge-join $M_1 + M_2$ runs;
need $M_1 + M_2 <= M$

Partitioned Hash Algorithms

- Partition R it into k buckets:
  $R_1, R_2, R_3, \ldots, R_k$

Partitioned Hash Algorithms

- Partition R it into k buckets:
  $R_1, R_2, R_3, \ldots, R_k$

- Assuming $B(R_1)=B(R_2)=\ldots= B(R_k)$, we have
  $B(R_i) = B(R)/k$, for all i

Partitioned Hash Algorithms

- Partition R it into k buckets:
  $R_1, R_2, R_3, \ldots, R_k$
- Assuming $B(R_1)=B(R_2)=\ldots= B(R_k)$, we have
  $B(R_i) = B(R)/k$, for all i
- Goal: each R_i should fit in main memory:
  $B(R_i) \leq M$

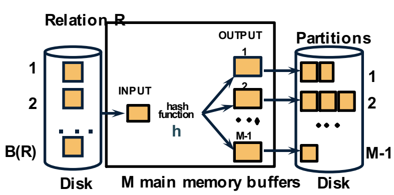
Partitioned Hash Algorithms

- Partition R it into k buckets:
  $R_1, R_2, R_3, \ldots, R_k$
- Assuming $B(R_1)=B(R_2)=\ldots= B(R_k)$, we have
  $B(R_i) = B(R)/k$, for all i
- Goal: each R_i should fit in main memory:
  $B(R_i) \leq M$

How do we choose k?

Partitioned Hash Algorithms

- We choose k = M-1 Each bucket has size approx. $B(R)/(M-1) \approx B(R)/M$



Assumption: $B(R)/M \leq M$, i.e. $B(R) \leq M^2$

Grace-Join

$R \bowtie S$

Note: grace-join is also called *partitioned hash-join*

Grace-Join

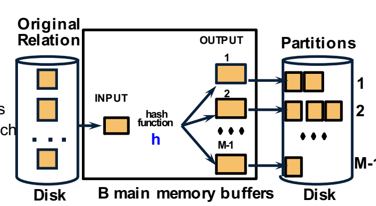
$R \bowtie S$

Note: grace-join is also called *partitioned hash-join*

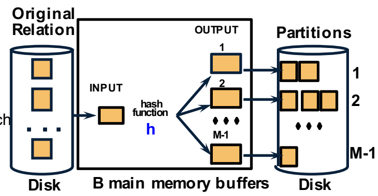
- Step 1:
  - Hash S into M buckets
  - Send all buckets to disk
- Step 2
  - Hash R into M buckets
  - Send all buckets to disk
- Step 3
  - Join every pair of buckets

Grace-Join

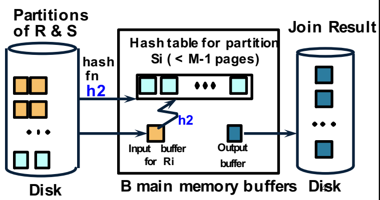
- Partition both relations using hash fn **h**: R tuples in partition i will only match S tuples in partition i.



Grace-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.

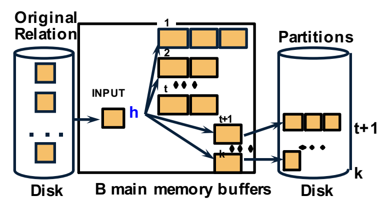
Grace Join

- Cost: 3B(R) + 3B(S)
- Assumption: min(B(R), B(S)) <= M^2

Hybrid Hash Join Algorithm

- Partition S into k buckets
  t buckets S_1 , …, S_t stay in memory
  k-t buckets S_{t+1}, …, S_k to disk
- Partition R into k buckets
  - First t buckets join immediately with S
  - Rest k-t buckets go to disk
- Finally, join k-t pairs of buckets:
  (R_{t+1},S_{t+1}), (R_{t+2},S_{t+2}), …, (R_k,S_k)

Hybrid Hash Join Algorithm



Hybrid Join Algorithm

- How to choose k and t?

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. k <= M

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. $k <= M$ (One block/bucket in memory)

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. $k <= M$ (One block/bucket in memory)
  - Choose t/k large but s.t. $t/k * B(S) <= M$

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. $k <= M$ (One block/bucket in memory)
  - Choose t/k large but s.t. $t/k * B(S) <= M$ (First t buckets in memory)

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. $k <= M$ (One block/bucket in memory)
  - Choose t/k large but s.t. $t/k * B(S) <= M$ (First t buckets in memory)
  - Together: $t/k * B(S) + k-t <= M$

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. $k <= M$ (One block/bucket in memory)
  - Choose t/k large but s.t. $t/k * B(S) <= M$ (First t buckets in memory)
  - Together: $t/k * B(S) + k-t <= M$
- Assuming $t/k * B(S) >> k-t$: $t/k = M/B(S)$

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. $k <= M$ (One block/bucket in memory)
  - Choose t/k large but s.t. $t/k * B(S) <= M$ (First t buckets in memory)
  - Together: $t/k * B(S) + k-t <= M$
- Assuming $t/k * B(S) >> k-t$: $t/k = M/B(S)$ (Total size of first t buckets)

Hybrid Join Algorithm

- How to choose k and t?
  - Choose k large but s.t. k <= M (One block/bucket in memory)
  - Choose t/k large but s.t. t/k * B(S) <= M (First t buckets in memory)
  - Together: t/k * B(S) + k-t <= M
- Assuming t/k * B(S) >> k-t: t/k = M/B(S)

(t/k * B(S): Total size of first t buckets; k-t: Number of remaining buckets)

Hybrid Join Algorithm

Even better: adjust t dynamically

- Start with t = k: all buckets are in main memory
- Read blocks from S, insert tuples into buckets
- When out of memory:
  - Send one bucket to disk
  - t := t-1
- Worst case:
  - All buckets are sent to disk (t=0)
  - Hybrid join becomes grace join

Hybrid Join Algorithm

Cost of Hybrid Join:

- Grace join: 3B(R) + 3B(S)
- Hybrid join:
  - Saves 2 I/Os for t/k fraction of buckets
  - Saves 2t/k(B(R) + B(S)) I/Os
  - Cost:
    (3-2t/k)(B(R) + B(S)) = (3-2M/B(S))(B(R) + B(S))

Hybrid Join Algorithm

- What is the advantage of the hybrid algorithm?

Hybrid Join Algorithm

- What is the advantage of the hybrid algorithm?

It degrades gracefully when S larger than M:

- When B(S) <= M
  - Main memory hash-join has cost B(R) + B(S)
- When B(S) > M
  - Grace-join has cost 3B(R) + 3B(S)
  - Hybrid join has cost (3-2t/k)(B(R) + B(S))

Summary of External Join Algorithms

- Block Nested Loop: B(S) + B(R)*B(S)/M
- Index Join: B(R) + T(R)B(S)/V(S,a)
- Partitioned Hash: 3B(R)+3B(S);
  - min(B(R),B(S)) <= M^2
- Merge Join: 3B(R)+3B(S)
  - B(R)+B(S) <= M^2

Summary of Query Execution

- For each logical query plan
  - There exist many physical query plans
  - Each plan has a different cost
  - Cost depends on the data
- Additionally, for each query
  - There exist several logical plans
- Next lecture: query optimization
  - How to compute the cost of a complete plan?
  - How to pick a good query plan for a query?