CSE 444: Database Internals

Lectures 8 and 9
Operator Algorithms

Why Learn About Op Algos?

- Good algorithms can greatly improve performance
  - Need to know operator algorithms to understand query plans
  - Need to understand query plans to tune a DBMS
- Implemented in commercial DBMSs
  - DBMSs implement different subsets of known algorithms
- Operator costs are first step toward query optimization
- Basic ideas to achieve high performance in operators go beyond relational operators

Operator Algorithms

- How to compare implementations/algorithms?
  - Using a cost model: IO, CPU, (and network bw)
  - Later, will see how this plays a role in optimization
- Some key design criteria
  - Cost: Different algorithms have different costs
    - Cost depends on input data and other parameters
  - Memory utilization
    - Operators only have access to limited amount of memory
  - Load balance (for parallel operators)

Cost Parameters

- In database systems the data is on disk
- **Cost = total number of I/Os**
  - This is a simplification
  - Normally, need to consider IO, CPU, and network
- Parameters:
  - **B(R) = # of blocks (i.e., pages) for relation R**
  - **T(R) = # of tuples in relation R**
  - **V(R, a) = # of distinct values of attribute a**
    - When a is a key, V(R,a) = T(R)
    - When a is not a key, V(R,a) can be anything < T(R)

Cost

- Cost of an operation = number of disk I/Os to
  - Read the operands
  - Compute the result
- Cost of writing the result to disk is *not included*
  - Need to count it separately when applicable

Cost of Scanning a Table

- Result may be unsorted: B(R)
- Result needs to be sorted: 3B(R)
  - We will discuss sorting later

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)

  - Note about readings:
    - In class, we will discuss only algorithms for join operator (because other operators are easier)
    - Read the book to get more details about these algos
    - Read the book to learn about algos for other operators

Basic Join Algorithms

- Logical operator:
  - Product(pname, cname) ⋈ Company(cname, city)

- Propose three physical operators for the join, assuming the tables are in main memory:
  - **Hash join**
  - **Nested loop join**
  - **Sort-merge join**

Hash Join

Hash join: R ⋈ S
- Scan R, build buckets in main memory
- Then scan S and join
- Cost: B(R) + B(S)

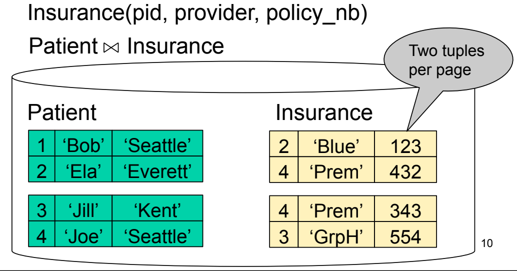
- One-pass algorithm when B(R) <= M
  - By "one pass", we mean that the operator reads its operands only once. It does not write intermediate results back to disk.

Hash Join Example

Patient(pid, name, address)

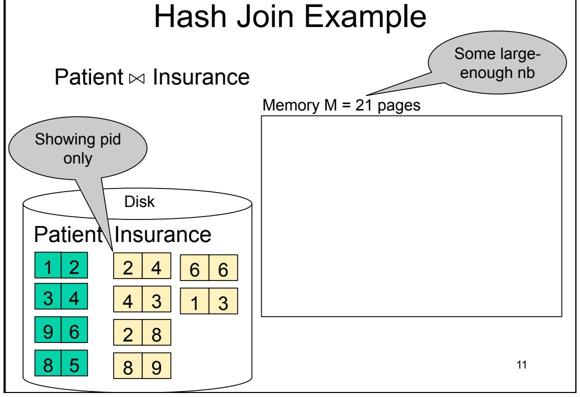
Insurance(pid, provider, policy_nb)

Patient ⋈ Insurance



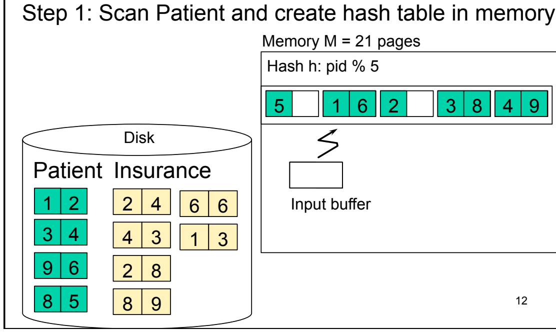
Hash Join Example

Patient ⋈ Insurance



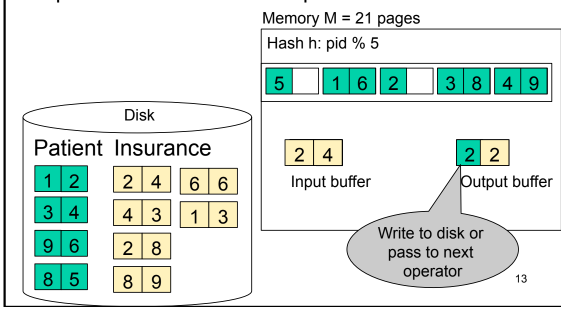
Hash Join Example

Step 1: Scan Patient and create hash table in memory



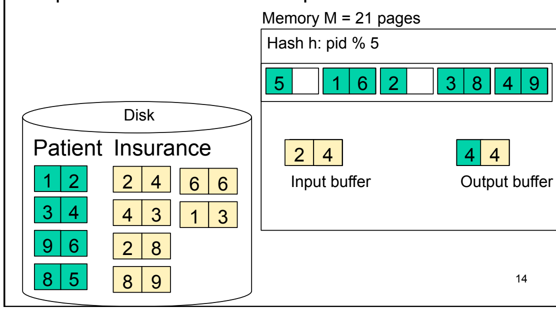
Hash Join Example

Step 2: Scan Insurance and probe into hash table



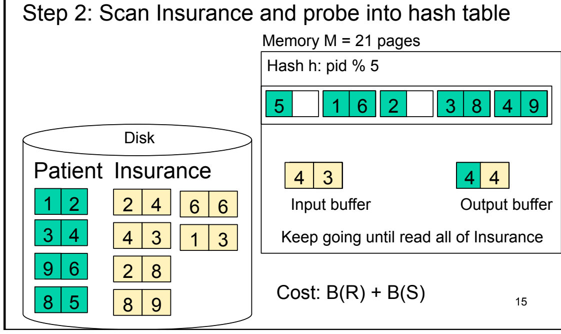
Hash Join Example

Step 2: Scan Insurance and probe into hash table



Hash Join Example

Step 2: Scan Insurance and probe into hash table



Cost: B(R) + B(S)

Hash Join Details

```
Open( ) {
  H = newHashTable( );
  S.Open( );
  x = S.GetNext( );
  while (x != null) {
      H.insert(x); x = S.GetNext( );
  }
  S.Close( );
  R.Open( );
  buffer = [ ];
}
```


Hash Join Details

```
GetNext( ) {
  while (buffer == [ ]) {
      x = R.GetNext( );
      if (x==Null) return NULL;
      buffer = H.find(x);
  }
  z = buffer.first( );
  buffer = buffer.reset( );
  return z;
}
```


Hash Join Details

```
Close( ) {
   release memory (H, buffer, etc.);
   R.Close( )
}
```

Nested Loop Joins

- Tuple-based nested loop R ⋈ S
- R is the outer relation, S is the inner relation

```
for each tuple r in R do
   for each tuple s in S do
      if r and s join then output (r,s)
```

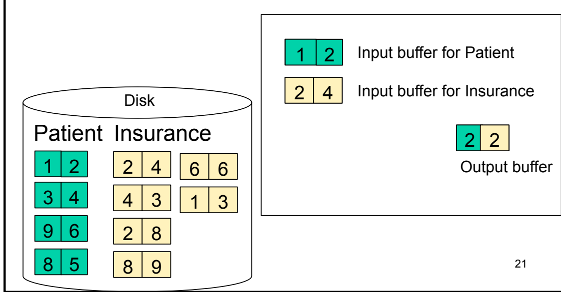
- Cost: B(R) + T(R) B(S)
- Not quite one-pass since S is read many times

Page-at-a-time Refinement

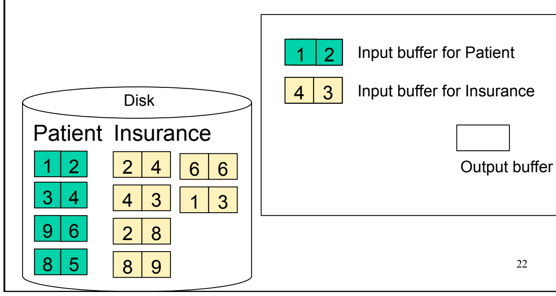
```
for each page of tuples r in R do
   for each page of tuples s in S do
         for all pairs of tuples
               if r and s join then output (r,s)
```

- Cost: B(R) + B(R)B(S)

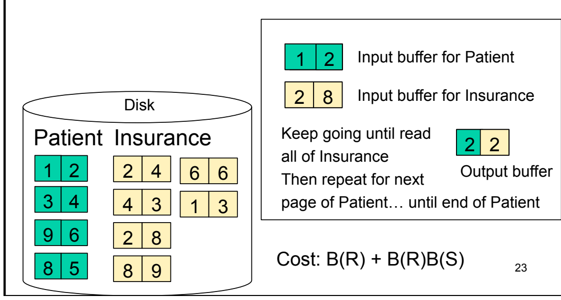
Nested Loop Example



Nested Loop Example



Nested Loop Example



Cost: B(R) + B(R)B(S)

Sort-Merge Join

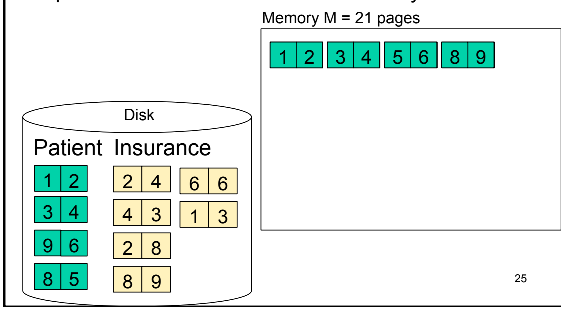
Sort-merge join: R ⋈ S

- Scan R and sort in main memory
- Scan S and sort in main memory
- Merge R and S

- Cost: B(R) + B(S)
- One pass algorithm when B(S) + B(R) <= M
- Typically, this is NOT a one pass algorithm

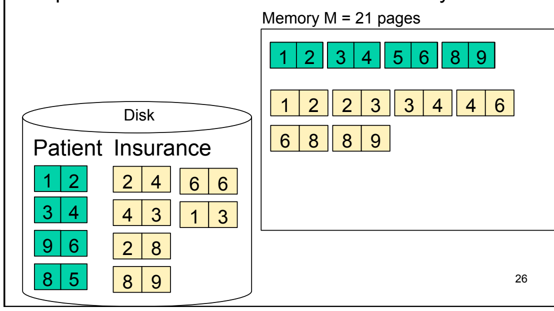
Sort-Merge Join Example

Step 1: Scan Patient and sort in memory



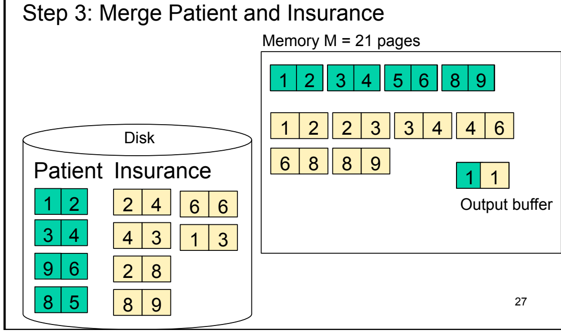
Sort-Merge Join Example

Step 2: Scan Insurance and sort in memory



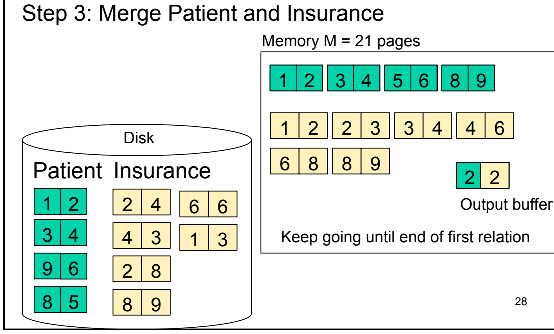
Sort-Merge Join Example

Step 3: Merge Patient and Insurance



Sort-Merge Join Example

Step 3: Merge Patient and Insurance



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)

Review: Access Methods

- **Heap file**
  - Scan tuples one at the time
- **Hash-based index**
  - Efficient selection on equality predicates
  - Can also scan data entries in index
- **Tree-based index**
  - Efficient selection on equality or range predicates
  - Can also scan data entries in index

Index Based Selection

- Selection on equality: $\sigma_{a=v}(R)$
- V(R, a) = # of distinct values of attribute a
- Clustered index on a: cost B(R)/V(R,a)
- Unclustered index on a: cost T(R)/V(R,a)
- Note: we ignored 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: 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

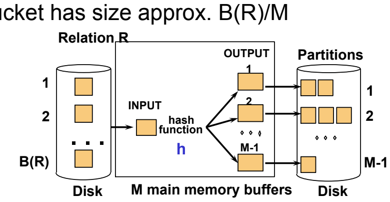
- **Join operator algorithms**
  - One-pass algorithms (Sec. 15.2 and 15.3)
  - Index-based algorithms (Sec 15.6)
  - Two-pass algorithms (Sec 15.4 and 15.5)

Two-Pass Algorithms

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

Two Pass Algorithms Based on Hashing

- Idea: partition a relation R into buckets, on disk
- Each bucket has size approx. B(R)/M



- Does each bucket fit in main memory ?
  - Yes if B(R)/M <= M, i.e. $B(R) <= M^2$

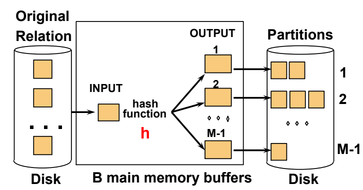
Partitioned (Grace) Hash Join

R ⋈ S

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

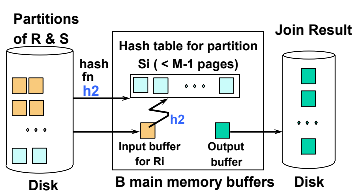
Partitioned Hash Join

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



Partitioned Hash Join

- Read in partition of R, hash it using h2 (≠ h)
  - Build phase
- Scan matching partition of S, search for matches
  - Probe phase



Partitioned Hash Join

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

Partitioned Hash Join

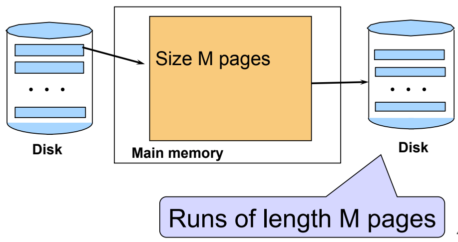
- See detailed example on the board

External Sorting

- Problem: Sort a file of size B with memory M
- Where we need this:
  - ORDER BY in SQL queries
  - Several physical operators
  - Bulk loading of B+-tree indexes.
- Sorting is two-pass when B < M^2

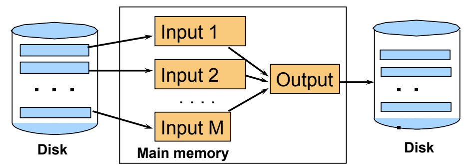
External Merge-Sort: Step 1

- Phase one: load M pages in memory, sort



External Merge-Sort: Step 2

- Merge M – 1 runs into a new run
- Result: runs of length M (M – 1)≈ M2



If B <= M^2 then we are done

External Merge-Sort

- Cost:
  - Read+write+read = 3B(R)
  - Assumption: B(R) <= M^2
- Other considerations
  - In general, a lot of optimizations are possible

External Merge-Sort

- See detailed example on the board

Two-Pass Join Algorithm Based on Sorting

Join R ⋈ S

- Step 1: sort both R and S on the join attribute:
  - Cost: 4B(R)+4B(S) (because need to write to disk)
- Step 2: Read both relations in sorted order, match tuples
  - Cost: B(R)+B(S)
- Total cost: 5B(R)+5B(S)
- Assumption: B(R) <= M^2, B(S) <= M^2

Two-Pass Join Algorithm Based on Sorting

Join R ⋈ S

- If B(R) + B(S) <= M^2
  - Or if use a priority queue to create runs of length 2|M|
- If the number of tuples in R matching those in S is small (or vice versa)
- We can compute the join during the merge phase
- Total cost: 3B(R)+3B(S)

Two-Pass Join Algorithm Based on Sorting

- See detailed example on the board

Summary of Join Algorithms

- Nested Loop Join: B(R) + B(R)B(S)
  - Assuming page-at-a-time refinement
- Hash Join: 3B(R) + 3B(S)
  - Assuming: min(B(R), B(S)) <= M2
- Sort-Merge Join: 3B(R)+3B(S)
  - Assuming B(R)+B(S) <= M2
- Index Nested Loop Join: B(R) + T(R)B(S)/V(S,a)
  - Assuming S has clustered index on a

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?