Algorithms for Relational Algebra Operations (Join Algorithms)

Overview of Join Algorithms

- Nested-loop and block nested-loop join $R \bowtie_{\theta} S$
- Sort-merge join $R \bowtie S$
- Hash-based join strategies $R \bowtie S$
- Index join $R \bowtie S$

Join Operator

- JOIN: Most important relational operator
  - Potentially very expensive
  - Required in all practical queries and applications
  - Often appears in groups of joins

- Example: Relations R (A, B) and S (B, C)

  SELECT *
  FROM R JOIN S ON (R.B θ S.B)
  with θ: $=, \neq, <, \leq, >, \geq$

Unary versus Binary Operations

- Relational operators working on one table
  - Selection, projection
- On two tables
  - Product, Join, Semi-join, Intersection, Union, Difference
- Binary operators are usually more expensive
  - Unary: Look at table (scanning, index, hash, …)
  - Binary: Look at each tuple of first table for each tuple of second table
  - "Potentially" quadratic complexity

Nested-loop Join

```
Nested-loop join
FOR EACH r IN R DO
    FOR EACH s IN S DO
        IF (r.B θ s.B) THEN OUTPUT (r ⋈θ s)

Some improvement (block-based)
FOR EACH block x IN R DO
    FOR EACH block y IN S DO
      FOR EACH r in x DO
         FOR EACH s in y DO
            IF (r.B θ s.B) THEN OUTPUT (r ⋈θ s)
```

- Cost estimations
  - b(R), b(S) number of blocks in R and in S, respectively
  - Each block of outer relation is read once
  - Inner relation is read once for each block of outer relation
  - Inner two loops are free (only main memory operations)
  - Altogether: b(R)+b(R)*b(S)

Example

- Assume b(R)=10,000, b(S)=2,000
- R as outer relation
  - IO = 10,000 + 10,000*2,000 = 20,010,000
- S as outer relation
  - IO = 2,000 + 2,000*10,000 = 20,002,000
- Use smaller relation as outer relation
  - For large relations, choice doesn't really matter

- Can we do better?

Block nested-loop join

- M – Size of main memory in blocks (or number of buffers)
- Rule of thumb: Use all memory you can get
  - Use all memory the buffer manager allocates to the process

- Blocked-nested-loop

```
FOR i=1 TO b(R)/M DO
  READ NEXT R-chunk of M blocks of R into Memory buffer
  FOR EACH block y IN S DO
   FOR EACH r in R-chunk DO
     FOR EACH s in y do
       IF ( r.B θ s.B) THEN OUTPUT (r ⋈θ s)
```

- Cost estimation
  - Outer relation is read once
  - Inner relation is read once for every chunk of R
  - There are ~b(R)/M chunks
  - IO = $b(R) + b(R)*b(S)/M$

- Example
  - Assume b(R)=10,000, b(S)=2,000, M =500
  - R as outer relation
    - IO = 10,000 + 10,000*2,000/500 = 50,000
  - S as outer relation
    - IO = 2,000 + 2,000*10,000/500 = 42,000
  - Compare to one-block NL: 20,002,000 IO
- Use smaller relation as outer relation
- But sizes of relations do matter:
  - If one relation fits into memory (min(b(R),b(S)) < M)
  - Total cost: b(R) + b(S)

Sort-Merge Join

- How does it work?
- Only works for Natural Join $R \bowtie S$
- What does it cost?
- Does it matter which is outer/inner relation?
- When is it better then block-nested loop?
- Be concerned about skew on join attribute

Sort-Merge Join

- How does it work?
  - Sort both relations on join attribute(s)
  - Merge both sorted relations
- Caution if duplicates (skew) exist
  - The result size still is |R|*|S| in worst case
  - If there are r/s tuples with value x in the join attribute in R / S, we need to output r*s tuples for x
  - More importantly, all these r/s must simultaneously fit in main memory (not always true if there is skew)

Example

R

A	B
A1	0
A2	1
A4	1
A3	2

S

B	C
1	C1
1	C3
1	C5
2	C2
3	C4

Partial join

$\{\langle A1,0\rangle,\langle A2,1\rangle\} \bowtie S$

A	B	C
A2	1	C1
A2	1	C3
A2	1	C5

R

A	B
A1	0
A2	1
A4	1
A3	2

S

B	C
1	C1
1	C3
1	C5
2	C2
3	C4

Partial join

$\{\langle A1,0\rangle,\langle A2,1\rangle,$
$\langle A4,1\rangle\} \bowtie S$

A	B	C
A2	1	C1
A2	1	C3
A2	1	C5
A4	1	C1
A4	1	C3
A4	1	C5

new

Cost estimation (without skew)

- Sorting R costs 2*b(R) * ceil($\log_M$(b(R)))
- Sorting S costs 2*b(S) * ceil($\log_M$(b(S)))
- Merge phase reads each relation once
- Total IO
  - b(R) + b(S) + 2*b(R)*ceil($\log_M$(b(R))) + 2*b(S)*ceil($\log_M$(b(S)))

This is only the case when, for each join-value b, the R and S blocks with that value b fit together in the buffer.
If this is not the case for value b, then the sort-merge algorithm needs to do a local block-nested join loop on the R and S blocks with value b.

Better than Block-Nested-Loop?

- Assume b(R)=10,000, b(S)=2,000, M=500
  - BNL costs 42,000
    - With S as outer relation
  - SM: 10,000+2,000+4*10,000+4*2,000 = 60,000 since
    $\text{ceil}(\log_{500}(10{,}000) = \text{ceil}(\log_{500}(2{,}000)) = 2$

- Assume b(R)=1,000.000, b(S)=1,000, M=500
  - BNL costs 1,000 + 1,000,000*1000/500 = 2,001,000
  - SM: 1.000.000+1.000+6*1.000.000+4*1.000 = 7,005,000

Comparison

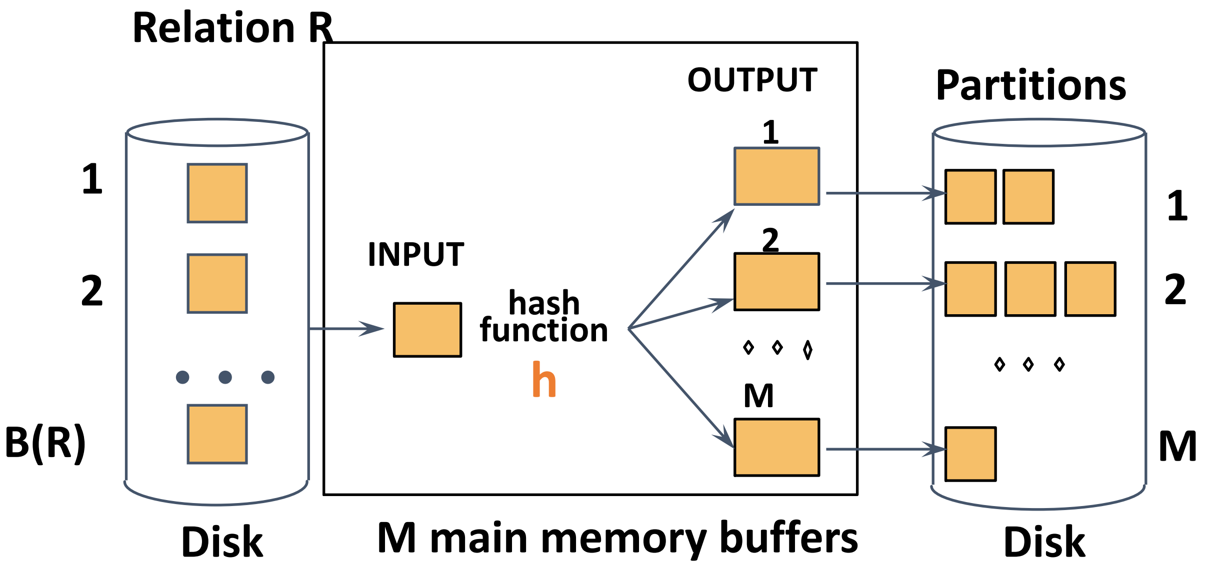
- Assume relations of equal size: B blocks
- SM: $2*B + 4*B*\log_M(B)$
- BNL: $B+B^2/M$
- BNL > SM
  - $B+B^2/M > 2*B + 4*B*\log_M(B)$
  - $B/M > 1+ 4*\log_M(B)$
  - $B > M + 4*M*\log_M(B)$

Hash Join

- As always, we may save sorting if good hash function available
- Assume a very good hash function
  - Distributes hash values almost uniformly over hash table
  - If we have good histograms (later), a simple interval- based hash function will usually work
- How can we apply hashing to joins?

Hashing a file on join attribute(s)

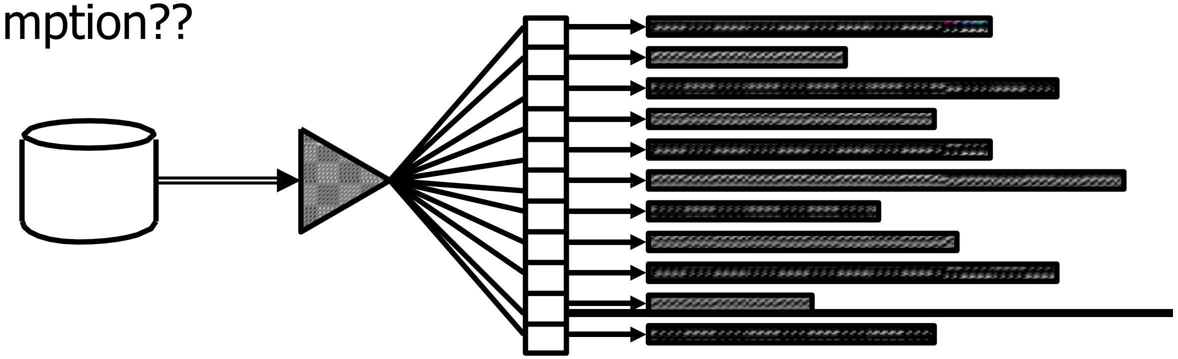
- Idea: partition a relation R into buckets, on disk
- Each bucket has size approx. B(R)/M



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

Hash Join Idea

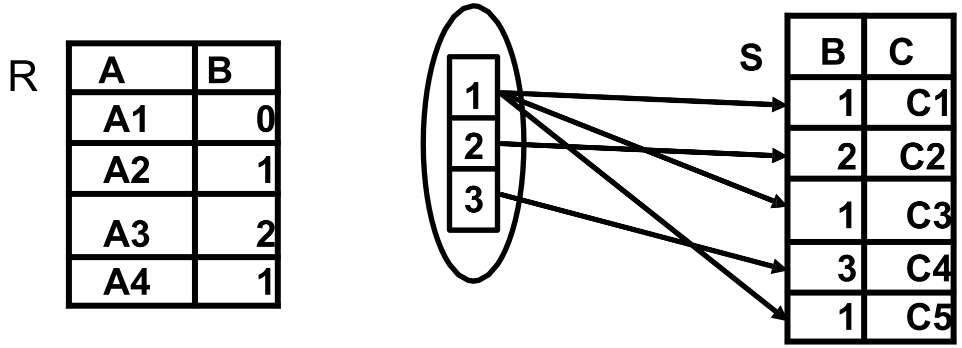
- Use join attributes as hash keys in both R and S
- Choose hash function for hash table of size M
  - Each bucket has size b(R)/M, b(S)/M
- Hash phase
  - Scan R, compute hash table, writing full blocks to disk immediately
  - Scan S, compute hash table, writing full blocks to disk immediately
- Merge phase
  - Iteratively, load same bucket of R and of S in memory
  - Compute join
- Total cost
  - Hash phase costs 2*b(R)+2*b(S)
  - Merge phase costs b(R) + b(S)
  - Total: 3*(b(R)+b(S))
  - Under what assumption??



Index Join

- Assume we have an index “B_Index” on one join attribute
- Choose indexed relation as inner relation
- Index join

```
FOR EACH r IN R DO
     X = { SEARCH (S.B_Index, <r.B>) }
     FOR EACH TID i in X DO
         s = READ (S, i) ; output (r ⋈ s).
```



S.B_Index auf S

- Actually, this is a one block-nested loop with index access
  - Using BNL possible (and better)

Semi Join

- Consider queries such as
  - SELECT DISTINCT R.* FROM S,R WHERE R.B=S.B
  - SELECT R.* FROM R WHERE R.B IN (SELECT S.B FROM S)
- What's special?
  - No values from S are requested in result
  - S (or inner query) acts as filter on R
- Semi-Join R $\ltimes$ S

Implementing Semi-Join

- Using blocked-nested-loop join
  - Choose relation R as outer relation
  - Perform BNL
  - Whenever partner for R.B is found, exit inner loop
- Using sort-merge join
  - Sort R
  - Sort join attribute values from S, remove duplicates on the way
  - Perform merge phase as usual
- Using hash join
  - Hash R
  - Hash join values from S, remove duplicates on the way
  - Perform hash phase as usual

Implementing Intersection, Union, Difference

- Analogous with semi-join
- Using sort-merge join
  - Sort R, remove duplicates on the way
  - Sort S, remove duplicates on the way
  - Perform merge phase as usual (checking for and, or, not)
- Using hash join
  - Hash R, remove duplicates on the way
  - Hash S, remove duplicates on the way
  - Perform hash phase as usual (checking for and, or, not)

Observe that the performance is never O(R*S)