

Datenbanksysteme II: Implementation of Database Systems

Implementing Joins



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Content of this Lecture

- Nested loop and blocked nested loop
- Sort-merge join
- Hash-based join strategies
- Index join
- (Star – Join later)

Join Operator

- JOIN: Most important relational operator
 - Potentially very expensive
 - Required in all practical queries and applications
 - Often appears in groups of joins
 - Many variations with different characteristics, suited for different situations
- Example: Relations R (A, B) and S (B, C)
SELECT * FROM R, S WHERE R.B = S.B

R

A	B
A1	0
A2	1
A3	2
A4	1

S

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

$R \bowtie S$

A	B	C
A2	1	C1
A2	1	C3
A2	1	C5
A3	2	C2
A4	1	C1
A4	1	C3
A4	1	C5

Unary versus Binary Operations

- Relational operators working on one table
 - Selection, projection
- On two tables
 - Product, Join, Intersection, Union, Minus
- **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

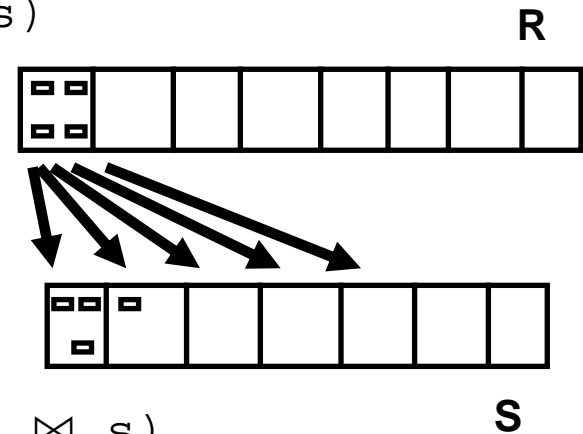
Nested-loop Join

- Super-naïve

```
FOR EACH r IN R DO
  FOR EACH s IN S DO
    IF ( r.B=s.B) THEN OUTPUT (r ⋈ s)
```

- Slight improvement

```
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=s.B) THEN OUTPUT (r ⋈ s)
```



- Cost estimations

- $b(R)$, $b(S)$ number of blocks in R and in S
- 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: $b(R) + b(R) * b(S)$ IO

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 relation, choice doesn't really matter

- Can't we do better??

...

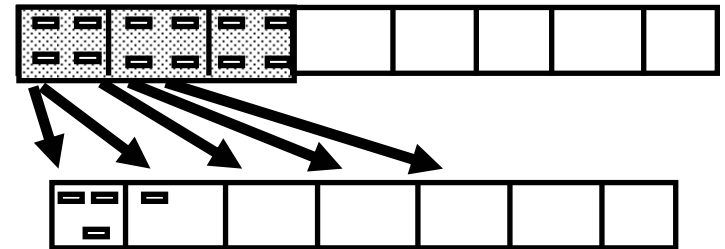
- There is no “m” in the formula
 - m: Size of main memory in blocks
- This should make you suspicious
- We are not using our available main memory

Blocked nested-loop join

- Rule of thumb: **Use all memory you can get**
 - Use all memory the buffer manager allocates to your process
 - This might be a difficult decision even for a single query – which operations get how much memory?

- Blocked-nested-loop

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



- Cost estimation

- Outer relation is read once
- Inner relation is read once for **every chunk** of R
- There are $\sim b(R)/m$ chunks
- $IO = b(R) + b(R)*b(S)/m$
- Further advantage: Outer relation is read in chunks – **sequential IO**

Example

- 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: $20.000 * 2.000$ IO
- Use **smaller relation as outer relation**
 - Again, difference irrelevant as tables get larger
- **But sizes of relations do matter**
 - If one relation fits into memory ($b < m$)
 - Total cost: $b(R) + b(S)$
 - **One pass** blocked-nested-loop
- We can do a little better with blocked-nested loop??

Zig-Zag Join

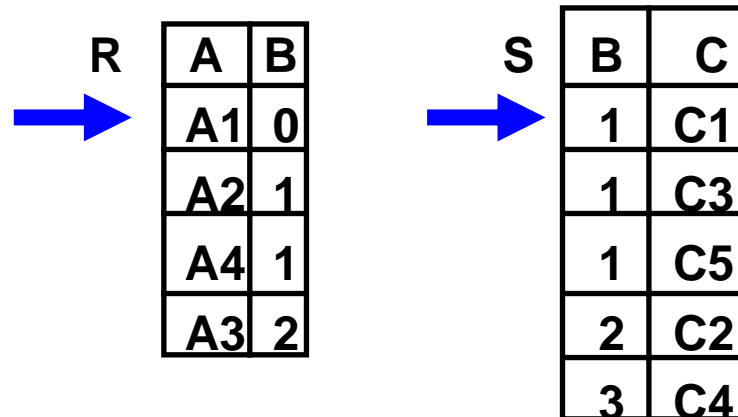
- When finishing a chunk of outer relation, hold last block of inner relation in memory
- Load next chunk of outer relation and compare with the still available last block of inner relation
- For each chunk, we need to read one block less
- Thus: Saves $b(R)/m$ IO
 - If R is outer relation

Sort-Merge Join

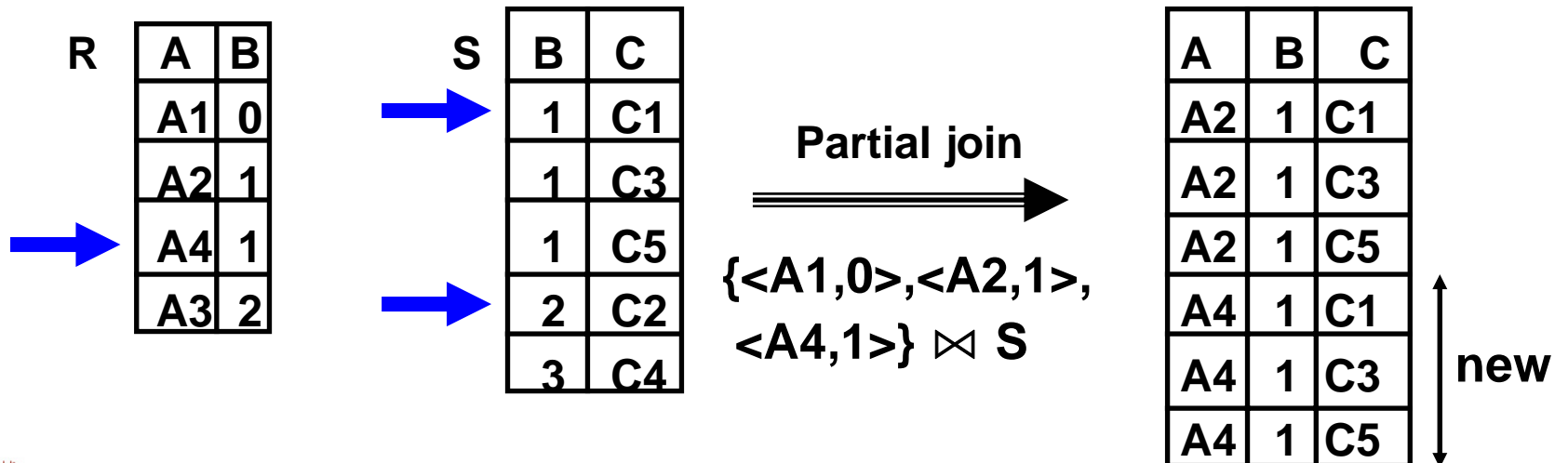
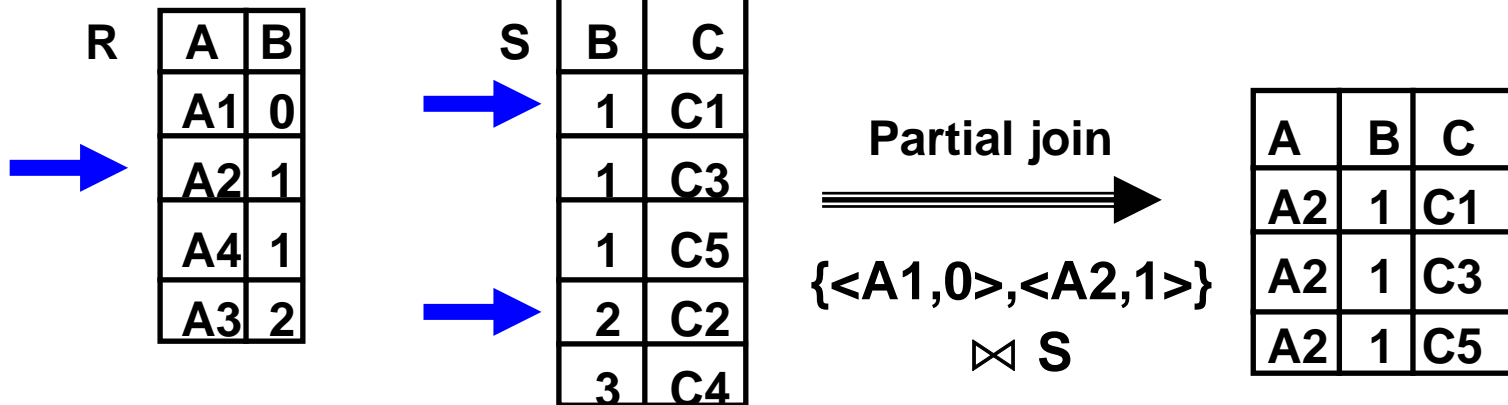
- How does it work??
- What does it cost??
- Does it matter which is outer/inner relation??
- When is it better than blocked-nested loop??

Sort-Merge Join

- How does it work?
 - Sort both relations on join attribute(s)
 - Merge both sorted relations
- Caution if duplicates 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
 - So what is the worst case??
- Example



Example Continued



Merge Phase

```
r := first (R);  s := first (S);
WHILE NOT EOR (R) and NOT EOR (S) DO
  IF r[B] < s[B] THEN r := next (R)
  ELSEIF r[B] > s[B] THEN s := next (S)
  ELSE
    /* r[B] = s[B]*/
    b := r[B];  B := ∅;
    WHILE NOT EOR(S) and s[B] = b DO
      B := B ∪ {s};
      s = next (S);
    END DO;
    WHILE NOT EOR(R) and r[B] = b DO
      FOR EACH e in B DO
        OUTPUT (r,e);
      r := next (R);
    END DO;
  END DO;
```

- Can we improve pipeline behavior??

Cost estimation

- Sorting R costs $2 * b(R) * \text{ceil}(\log_m(b(R)))$
- Sorting S costs $2 * b(S) * \text{ceil}(\log_m(b(S)))$
- Merge phase reads each relation once
- Total IO
 - $b(R) + b(S) + 2 * b(R) * \text{ceil}(\log_m(b(R))) + 2 * b(S) * \text{ceil}(\log_m(b(S)))$
- Improvement
 - While sorting, do not perform last read/write phase
 - Open all sorted runs in parallel for merging
 - Saves $2 * b(R) + 2 * b(S)$ IO
- Sometimes, we are able to **save the sorting phase**
 - If sort is performed somewhere down in the tree
 - Needs to be a sort on the same attribute(s)
- Merge-sort join: No inner/outer relation

Better than Blocked-Nested-Loop?

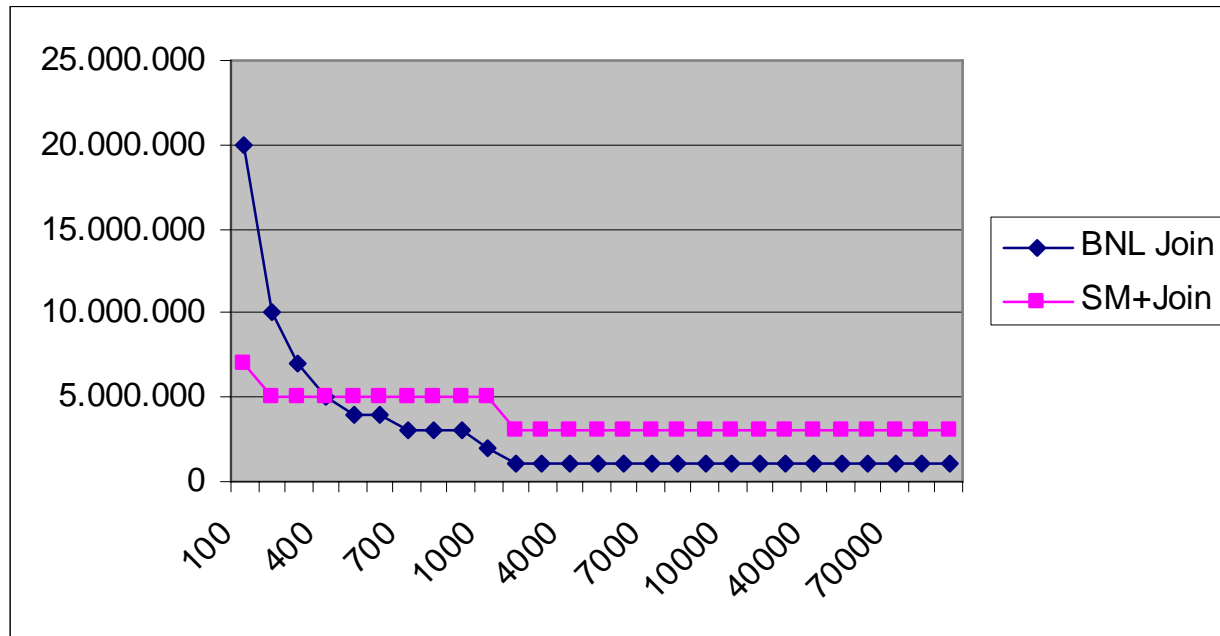
- Assume $b(R)=10.000$, $b(S)=2.000$, $m=500$
 - BNL costs 42.000
 - With S as outer relation
 - SM: $10.000+2.000+4*10.000+4*2.000 = 60.000$
 - Improved SM: 36.000
- Assume $b(R)=1.000.000$, $b(S)=1.000$, $m=500$
 - BNL costs $1000 + 1.000.000*1000/500 = 2.001.000$
 - SM: $1.000.000+1.000+6*1.000.000+4*1.000 = 7.005.000$
 - Improved SM: 5.003.000
- When is SM better than BNL??
 - Consider improved version with
 - $2*b(R)*\text{ceil}(\log_m(b(R))) + 2*b(S)*\text{ceil}(\log_m(b(S))) - b(R) - b(S) \sim$
 - $2*b(R)*(\log_m(b)+1) + 2*b(S)*(\log_m(S)+1) - b(R) - b(S) \sim$
 - $2*b(R)*\log_m(b) + 2*b(S)*\log_m(S) - b(R) - b(S) \sim$
 - $b(R)*(2*\log_m(b)-1) + b(S)*(2*\log_m(S)-1)$
 - In most cases, this means $3*(b(S)+b(R))$

Comparison

- Assume relations of equal size b
- SM: $2 * b * (2 * \log_m(b) - 1)$
- BNL: $b + b^2/m$
- BNL > SM
 - $b + b^2/m > 2 * b * (2 * \log_m(b) - 1)$
 - $1 + b/m > 4 * \log_m(b) - 2$
 - $b > 4m * \log_m(b) - 3m$
- Example
 - $b = 10.000, m = 100$ ($10.000 > 500$)
 - BNL: $10.000 + 1.000.000$, SM: $6 * 10.000 = 60.000$
 - $b = 10.000, m = 5000$ ($10.000 < 25.000$)
 - BNL: $10.000 + 20.000$, SM: $6 * 10.000 = 60.000$

Comparison 2

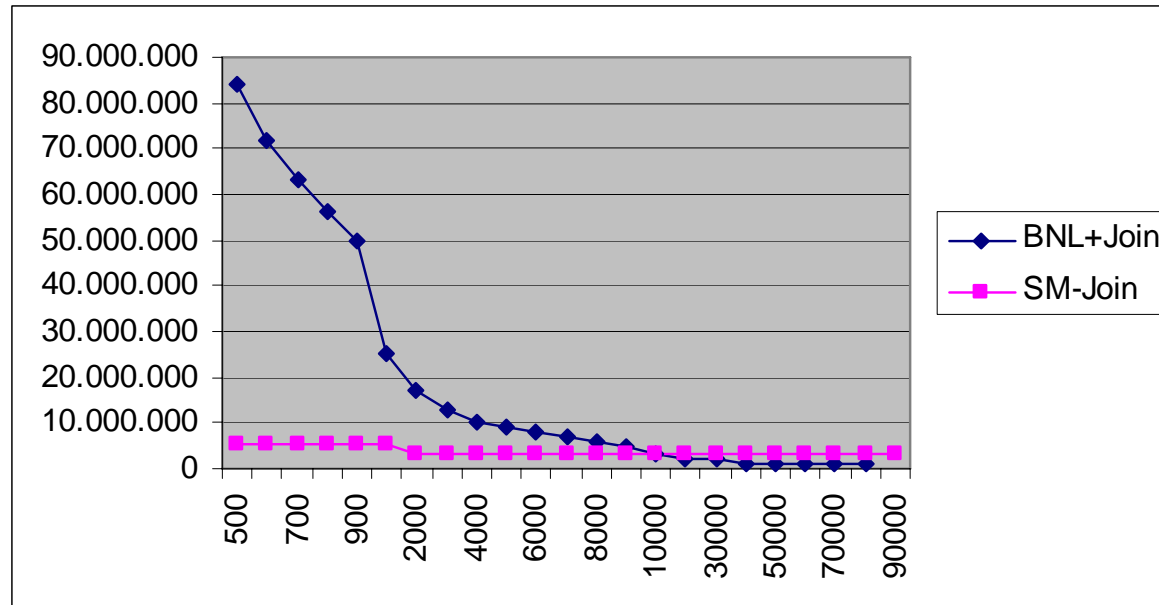
- $b(R)=1.000.000$, $b(S)=2.000$, m between 100 and 90.000



- BNL very good is one relation is much smaller than other and sufficient memory available
- SM can better cope with limited memory
- SM profit from more memory has jumps (= number of runs)

Comparison 3

- $b(R)=1.000.000$, $b(S)=50.000$, m between 500 and 90.000



- BNL very sensible to small memory sizes

Merge-Join and Main Memory

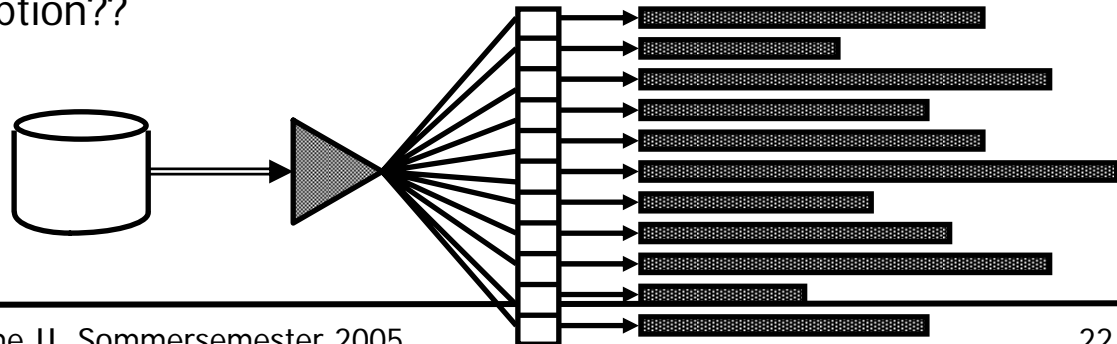
- We have no „m“ in the formula of the merge phase
 - Implicitly, it is in the number of runs required
- More memory doesn't decrease number of blocks to read, but can be used for sequential reads
 - Always fill memory with $m/2$ blocks from R and $m/2$ blocks from S
 - Use **asynchronous IO**
 1. Schedule request for $m/4$ blocks from R and $m/4$ blocks from S
 2. Wait until loaded
 3. Schedule request for next $m/4$ blocks from R and next $m/4$ blocks from S
 4. **Do not wait – perform merge on first 2 chunks of $m/4$ blocks**
 5. Wait until previous request finished
 1. We used this waiting time very well
 6. Jump to 3, using $m/4$ chunks of M in turn

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??

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**
 - Notice: Probably better to use some $n < b(R)/m$ to allow for sequential writes
- 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??



Hash Join with Large Tables

- Merge phase assumes that 2 buckets can be hold in memory
 - Thus, we roughly assume that $2 \cdot b(R)/m < m$ (if $b(R) \sim b(S)$)
 - Note: Merge phase of sorting only requires 2 blocks (or more for more runs), hashing requires 2 buckets to be loaded
- What if $b(R) > m^2/2$??
 - We need to create smaller buckets
 - Partition R/S such that each partition is smaller than $m^2/2$
 - Compute buckets for all partitions in both relations
 - Merge in cross-product manner
 - $P_{R,1}$ with $P_{S,1}, P_{S,2}, \dots, P_{S,n}$
 - $P_{R,2}$ with $P_{S,1}, P_{S,2}, \dots, P_{S,n}$
 - ...
 - $P_{R,m}$ with $P_{S,1}, P_{S,2}, \dots, P_{S,n}$
- Actually, it suffices if either $b(R)$ or $b(S)$ is small enough
 - Chose the smaller relation as driver (outer relation)
 - Load one bucket into main memory
 - Load same bucket in other relation block by block and filter tuples

Hybrid Hash Join

- Assume that $\min(b(R), b(S)) < m^2/2$
- Notice: During merge phase, we used only $(b(R) + b(S))/m$ (size of two buckets) memory blocks
 - Although there are much more
- Improvement
 - Chose smaller relation (assume S)
 - Chose a **number k of buckets** to build (with $k < m$)
 - Again, assuming perfect hash functions, each bucket has size $b(S)/k$
 - When hashing S, **keep first x buckets completely in memory**, but only one block for each of the $(k-x)$ other buckets
 - These x buckets are **never written to disk**
 - When hashing R
 - If hash value maps into buckets 1..x, **perform join immediately**
 - Otherwise, map to the $k-x$ other buckets/blocks and write buckets to disk
 - After first round, we have performed the join on x buckets and have $k-x$ buckets of both relations on disk
 - Perform “normal” merge phase on $k-x$ buckets

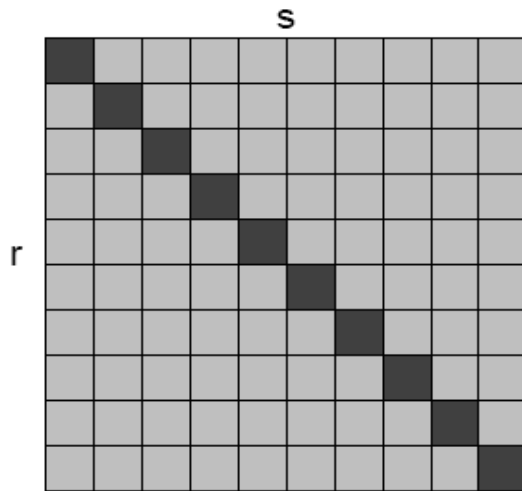
Hybrid Hash Join - Complexity

- Total saving (compared to normal hash join)
 - We save 2 IO (writing) for every block that is never written to disk
 - We keep x buckets in memory, each having $b(S)/k$ and $b(R)/k$ blocks, respectively
 - Together, we save $2 * x/k * (b(S) + b(R))$ IO operations
- Question: How should we choose k and x ?
- **Optimal solution**
 - $x=1$ and k as small as possible
 - Build as large partitions as possible, such that still one entire partition and one block for all other partitions fits into memory
 - Thus, we use as much memory as possible for savings
 - Optimum reached at approximately $k=b(S)/m$
 - k must be smaller, so that M can accommodate 1 block for each other bucket
- Together, we save $2m/b(S) * (b(S) + b(R))$
- Total cost: $(3 - 2m/b(S)) * (b(S) + b(R))$

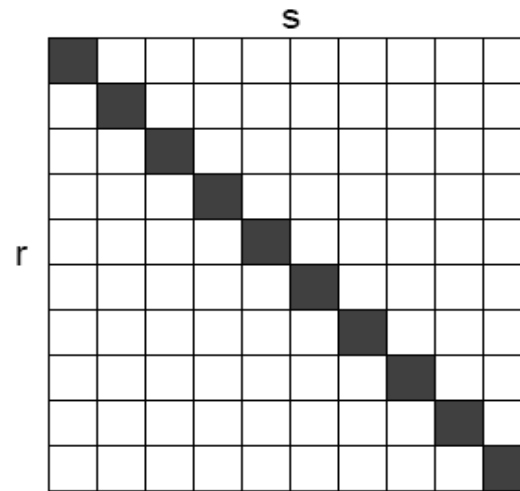
Comparing Hash Join and Sort-Merge Join

- If enough memory provided, both require approximately the same number of IOs
 - $3 \cdot (b(R) + b(S))$
 - Hybrid-hash join improves slightly
- SM generates **sorted results** – sort phase of other joins in query plan can be dropped
 - **Advantage propagates up the tree**
- HJ does not need to perform $O(n \cdot \log(n))$ sorting in main memory
- HJ requires that **only one relation is “small enough”**, SM needs two small relations
 - Because both are sorted independently
- HJ depends on roughly **equally sized buckets**
 - Otherwise, performance might degrade due to unexpected paging
 - To prevent, estimate k more conservative and do not fill m completely
 - Some memory remains unused
- Both can be tuned to generate mostly sequential IO

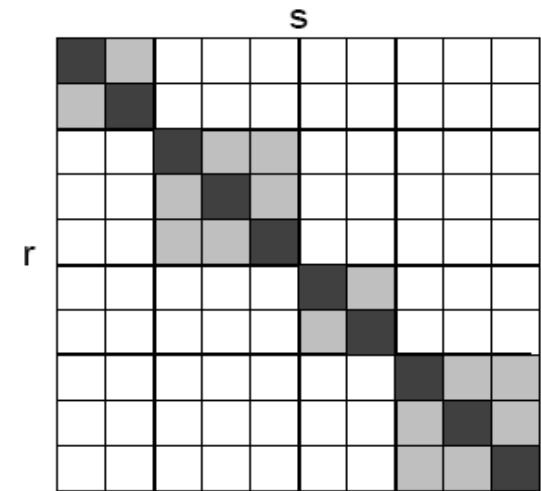
Comparing Join Methods



Nested-Loops-Join



Merge-Join



Hash-Join

Index Join

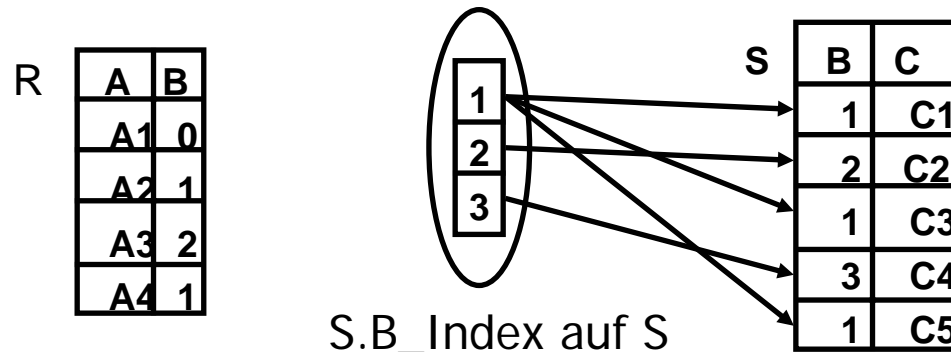
- Assume we have an index "B_Index" on one join attribute
- Choose indexed relation as inner relation
- **Index join**

```
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).
```



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

Index Join Cost

- Assumptions
 - R.B is foreign key referencing S.B
 - Every tuple from R has one or more join tuples in S
- Let $v(X,B)$ be the number of different values of attribute B in X
 - Each value in S.B appears $v \sim b(S)/v(S,B)$ times
- For each $r \in R$, we read all tuples with given value in S
- Total cost: $b(R) + |R| * (\log_k(S/b) + v/k + v)$
 - Outer relation read once
 - Find value in B^* , read all matching TIDs, access S for each TID
- Other way round: Assume that S.B is foreign key for R.B
 - Some tuples of R will have no join partner in S
 - Assume only r R tuples have partner
- Total cost: $b(R) + r * (\log_k(S/b) + v/k + v)$
 - No real change

Index Join Cost

- Comparison to sort-merge join
 - Neglect $\log_k(S/b) + v/k$
 - First term is only ~ 2 , second ~ 1 in many cases
 - SM > IJ roughly requires
 - Assuming that 2 passes suffice for sorting
 - $3 \cdot (b(R) + b(S)) > b(R) + |R| \cdot b(S) / v(S, B)$
- Example
 - $b(R) = 10.000$, $b(S) = 2.000$, $m = 500$, $v(S, B) = 10$, $k = 50$
 - SM: 36.000
 - IJ: $10.000 + 10.000 \cdot 50 \cdot 2.000 / 10 \sim 1.000.000.000$
- When is an index join a good idea??

Index Join: Advantageous Situations

- When r is very small
 - If join is combined with selection on R
 - Most tuples are filtered, only very few accesses to S
 - Index pays off
- When R is very small, $R.B$ is foreign key, $S.B$ is primary key
 - Similar to previous case
 - If S is primary key, then $v(S,B) = |S|$, and hence $v=1$
 - R can be read fast and “probes” into S
 - We get total cost of $\sim b(R) + |R|$ (plus index access etc.)

Index Join with Sorting

- Problem with last approach: Blocks of S are read many times
 - Caching will reduce the overhead – difficult to predict
- Alternative
 - First compute all necessary TID's from S
 - Sort and read in sorted order
 - Advantage: blocks of S will mostly be in cache when accessed
 - Requires enough memory for keeping TID list and tuples of R
- Further improvement
 - Perform Sort-Merge join on B values only
 - B values from S are already sorted (if B*-index) is used
 - Hence: Sort R on B, merge lists, probe into S for required values
 - Can be combined with previous improvement

Index Join with 2 Indexes

- Assume we have an index on both join attributes
- What are we doing??

Index Join with 2 Indexes

- TID list join
 - Read both indexes sequentially (order does not matter)
 - Join (value, TID) lists
 - Probe into R and S
 - Large advantage, if intersection is small
 - Otherwise, we need sorted tables (index-organized)
 - But then sort-merge is probably faster

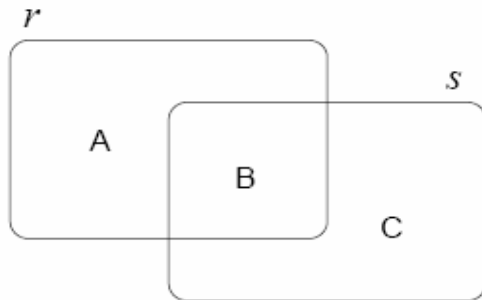
Semi Join

- 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)`
 - `SELECT R.* FROM R WHERE R.B IN (...)`
- What's special?
 - No values from S are requested in result
 - S (or inner query) acts as filter on R
- Semi-Join $R \bowtie S$
 - Very important for distributed databases
 - Accessing data becomes even more expensive
 - Idea: First ship only join attribute values, compute Semi-Join, then retrieve rest of matching tuples
 - Technique also can be used for very large tuples and small result sizes
 - First project on attribute values
 - Intersect lists, probe into tables and load data
 - Question: How do we know the sizes of intermediate result?

Implementing Semi-Join

- Using blocked-nested-loop join
 - Chose filter relation 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
 - Very effective if $v(S,B)$ is small

Union, Difference, Intersection



Ergebnis- extensionen	Übereinstimmung auf allen Attributen	Übereinstimmung auf einigen Attri- buten
A	Differenz $r - s$	Anti-Semi-Verbund
B	Schnitt $r \cap s$	Verbund, Semi- Verbund
C	Differenz $s - r$	Anti-Semi-Verbund
$A \cup B$		Left Outer Join
$A \cup C$	symmetrische Diffe- renz $(r - s) \cup (s - r)$	Anti-Verbund
$B \cup C$		Right Outer Join
$A \cup B \cup C$	Vereinigung $r \cup s$	Full Outer Join

- Other binary operations use methods similar as those for joins
 - Sorting, hashing, index, ...
- See Garcia-Molina et al. for detailed discussion