PA152: Efficient Use of DB

7. Query Optimization

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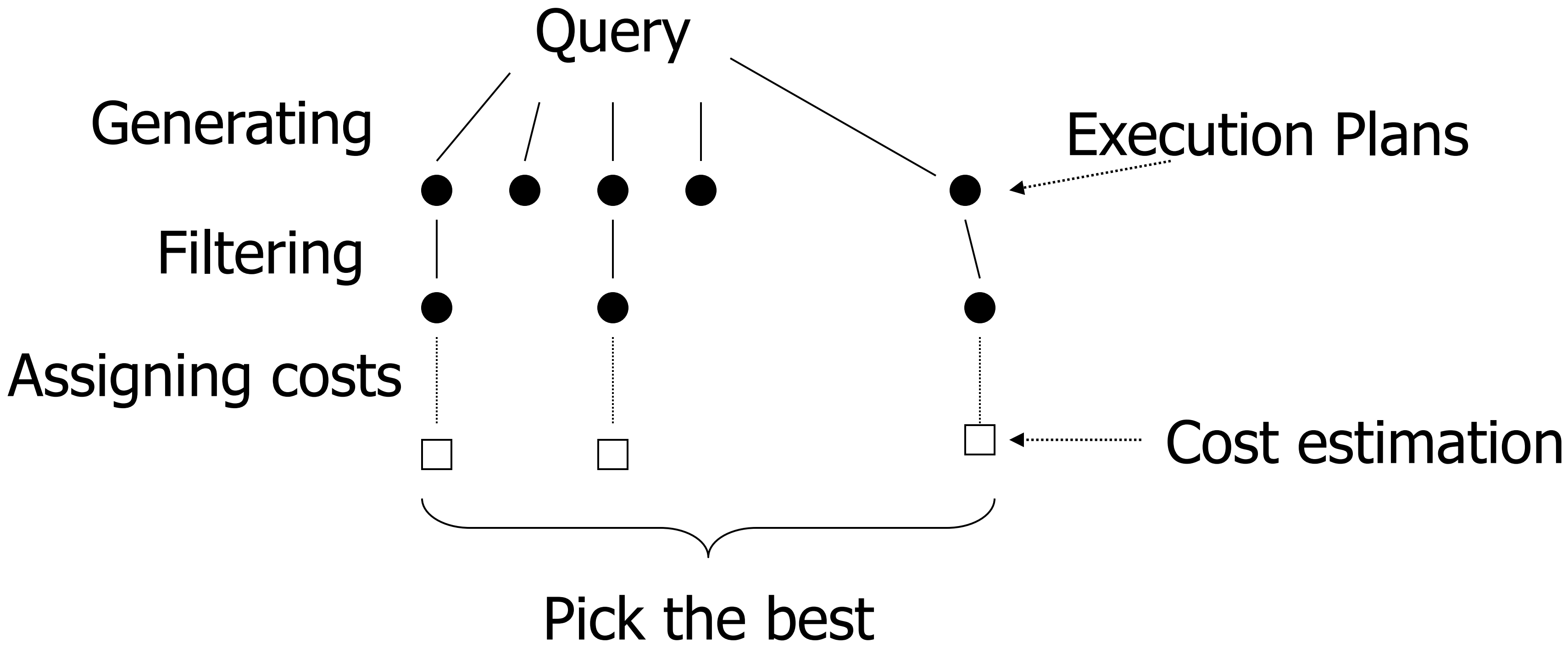
Query Optimization

- Generating and comparing query execution plans



Generating Execution Plans

- Consider using:
  - Rel. algebra transformation rules
  - Implementations of rel. alg. operations
  - Use of existing indexes
  - Building indexes and sorting on the fly

Plan Cost Estimation

- Depends on costs of each operation
  - i.e., its implementation
- Assumptions for operation costs:
  - Input is read from a disk
  - Output is kept in memory
  - Costs on CPU
    - Processing on CPU is faster than reading from disk
    - Can be neglected but often simplified (number of rows and ops)
  - Network communication costs
    - Issue in distributed databases
  - Ignoring contents of mem buffers/caches between queries
- Estimated costs of operation
  - = number of read and write accesses to disk

Operation Cost Estimation

- Example: settings in PostgreSQL
  https://www.postgresql.org/docs/15/runtime-config-query.html#RUNTIME-CONFIG-QUERY-CONSTANTS
  https://www.postgresql.org/docs/15/static/runtime-config-resource.html
  - seq_page_cost (1.0)
  - random_page_cost (4.0)
  - cpu_tuple_cost (0.01)
  - cpu_index_tuple_cost (0.005)
  - cpu_operator_cost (0.0025)

  - shared_buffers (32MB) – ¼ RAM
  - effective_cache_size (4GB) – ½ RAM
  - work_mem (8MB)
    - Memory available to an operation

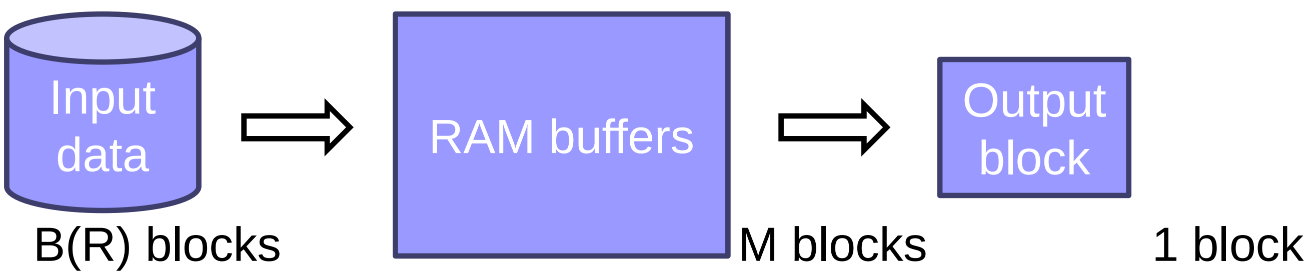
Operation Cost Estimation

- Parameters
  - B(R) – size of relation *R* in blocks
  - f(R) – max. record count to store in a block
  - M – max. RAM buffers available (in blocks)
    - i.e., work_mem in Pg

  - HT(i) – depth of index *i* (in levels)
  - LB(i) – sum of all leaf nodes of index *i*

Operation Implementation

- Based on concept of **iterator**
  - *Open* – initialization
    - preparations before returning any record of result
  - *GetNext* – return next record of result
  - *Close* – finalization
    - release temp buffers, …
- Result rows may be returned gradually
  - … and not all at once



Operation Implementation

- Advantages
  - Result does not occupy main memory
  - Intermediate results may not be materialized on a disk
  - Exploits *pipelining*
    - *i.e., passing result rows to another operation.*

Accessing Relation

- Table scan / Seq. scan
  - Always applicable
  - High costs if few records are returned
  - Used when a table is small

- Index scan
  - Available if an index exists
  - Selectivity of a query influences its costs
    - Index is an overhead if many records are returned
  - Rows themselves may not be accessed in some situations.

Accessing Relation: **table scan**

- Relation is not interlaced

R1 R2 R3 R4	R5 R6 R7 R8	...

  - Reading costs: B(R)
  - TwoPhase-MergeSort = 3B(R) reading/writing
    - Final writing is ignored
- Relation is interlaced

R1 R2 *S1 S2*	R3 R4 *S3 S4*	...

  - Reading costs are up to T(R) blocks!
  - TwoPhase-MergeSort
    - T(R) + 2B(R) reads and writes

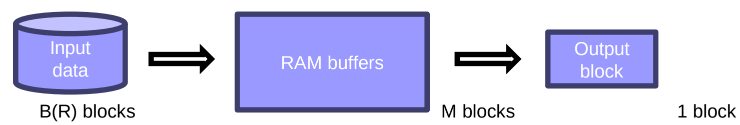
Accessing Relation: **index scan**

- Reading relation using an index
  - Scanning index → reading records
    - Read index blocks (<< B(R))
    - Read records of relation
  - Costs:
    - up to $(m^{HT+1} - 1)$ +
      - where *m* is an index arity ($\mathrm{LB} = m^{HT}$)
    - 1 to B(R) blocks of relation (depending on the selectivity)
  - If an index is a “covering” index for a query
    - no accesses to the relation.

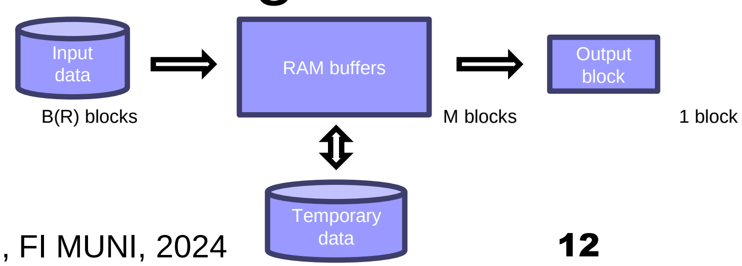
Max. number of nodes in an m-ary tree

Operation Implementation

- E.g., selection, projection, ordering (sorting), aggregation, distinct, join, …
- One-pass
  - Read the input data (relation) just once
  - All done in RAM



- Two-pass
  - Read the input data (relation) multiple times
  - Uses a temporary disk storage



One-Pass Algorithms

- Implementation:
  - Read relation → Processing in RAM → Output buffers
  - Processing records one by one
- Operations
  - Projection, Selection, Duplicate elimination (DISTINCT)
    - costs: B(R)
  - Aggregate functions (GROUP BY)
    - costs: B(R)
  - Set operations, cross product, joins
    - costs: B(R) + B(S)

Duplicate Elimination (DISTINCT)

- Procedure
  - Test whether the record has been sent to output
  - If not, output the record
- Test for existence in output
  - Store already-seen records in memory
    - Can use *M-2* blocks
  - No data structure: n^2 complexity (comparisons)
  - Use in-mem hashing
- Limitation: $B(R) < M-1$
- Can be implemented using iterators?

Distinct – example

- Relation company(company_key,company_name)

```
# explain analyze SELECT DISTINCT company_name FROM provider.company;
HashAggregate  (cost=438.68..554.67 rows=11600 width=20) (actual time=9.347..12.133 rows=11615 loops=1)
   Group Key: company_name
   ->  Seq Scan on company  (cost=0.00..407.94 rows=12294 width=20)
                                              (actual time=0.019..5.007 rows=12295 loops=1)
 Planning time: 0.063 ms
 Execution time: 12.799 ms

# explain analyze SELECT DISTINCT company_key FROM provider.company;
Unique  (cost=0.29..359.43 rows=12294 width=8) (actual time=0.041..8.857 rows=12295 loops=1)
   ->  Index Only Scan using company_pkey on company  (cost=0.29..328.69 rows=12294 width=8)
                                                      (actual time=0.039..5.686 rows=12295 loops=1)
         Heap Fetches: 4726
 Planning time: 0.063 ms
 Execution time: 9.645 ms

# explain analyze SELECT DISTINCT company_name FROM provider.company ORDER BY company_name;
Unique  (cost=1243.05..1304.52 rows=11600 width=20) (actual time=53.468..59.072 rows=11615 loops=1)
   ->  Sort  (cost=1243.05..1273.79 rows=12294 width=20) (actual time=53.467..55.482 rows=12295 loops=1)
         Sort Key: company_name
         Sort Method: quicksort  Memory: 1214kB
         ->  Seq Scan on company  (cost=0.00..407.94 rows=12294 width=20)
                                        (actual time=0.018..5.338 rows=12295 loops=1)
```

Aggregations / Grouping

- Procedure
  - Create groups for group-by attributes
  - Store accumulated values of aggregation functions
- Internal structure
  - Organize values of grouping attributes, e.g., hashing
  - Accumulated value of aggregations
    - MIN, MAX, COUNT, SUM – one value (number)
    - AVG – two numbers (SUM and COUNT)
  - Accumulated values are small: *M-1* blocks are enough

The output block is not needed.

- Iterators:
    - All prepared in *Open*
    - Advantage of pipelining is inapplicable

Set Operations

- Requirement: min(B(R), B(S)) ≤ M-2
  - Smaller relation read into memory
  - Larger relation is read gradually
  - Set union (possibly also Set difference):
    - Memory requirements: B(R)+B(S) ≤ M-2
- Assumption
  - R is larger relation, i.e., S is in memory
- Implementation
  - Create a temp search structure
    - E.g., in-mem hashing

Set union

- Notice: Not *multiset union*

i.e., without ALL in SQL

- Read S; construct search structure
  - Eliminate duplicates
  - Output unique records immediately
- Read R and check existence of the record in S
  - If present, skip it.
  - If not seen, output it and add to structure
- Limitations
  - $B(R)+B(S) \leq M-2$

Set intersection

- Notice: Not *multiset intersection*

i.e., without ALL in SQL

- Read S; construct search structure
  - Eliminate duplicates
- Read R and check existence of the record in S
  - If present, output the record and delete it from structure.
  - If not seen, skip it.
- Limitations
  - min(B(R), B(S)) ≤ M-2

Set Difference

- R–S
  - Read S; construct search structure
    - Eliminate duplicates
  - Read R and check existence of the record in S
    - If not present, output it
      - Also insert into internal structure
  - B(S) + B(R) ≤ M-2 (worse case, but with pipelining)
    - Or max(B(R),B(S)) ≤ M-2, when preprocessing R (no pipelining)
- S–R
  - Read S; construct search structure
    - Eliminate duplicates
  - Read R and check existence of the record in S
    - If present, delete it from internal structure
  - Output all remaining recs. in S (no pipelining)
  - B(S) ≤ M-1

Multiset (Bag) Operations

- Bag union $R \cup_B S$
  - Easy exercise…
- Bag intersection $R \cap_B S$
  - Read S; construct search structure
    - Eliminate duplicates by storing their count
  - Read R and check existence of the record in S
  - If record is present, output it
    - and decrement record count!
    - If counter is zero, delete it from internal structure
  - If record is not found, skip it
  - $\min(B(R), B(S)) \leq M\text{-}2$

Multiset (Bag) Operations

- Bag difference $S -_B R$
  - Same idea
  - If record of R is present in S, decrement its counter
  - Output internal structure (recs. of S)
    - with positive count (and output that many copies)
  - B(S) ≤ M-1
- Bag difference $R -_B S$
  - By analogy… (S is preprocessed)
  - If record of R is not present in S → output
  - If found,
    - → if counter is zero, output it
    - → decrement the counter and skip it
  - B(S) ≤ M-2

Join Operation – one pass version

- Cross product
  - Easy exercise…
- Natural join
  - Assume relations R(X,Y), S(Y,Z)
    - X – unique attributes is R, Z – unique attrs. in S
    - Y – common attributes in R and S
  - Read S; construct search structure on Y
  - For each record of R, find all matching recs. of S
    - Output concatenation of all combinations (eliminate repeating attributes Y)
- Outer join ?

Summary: One-Pass Algorithms

- Unary operation: *op*(R)
  - B(R) ≤ M-1, 1 block for output; some need 1 for input
- Binary operation: R *op* S
  - B(S) ≤ M-2, 1 block for R, 1 block for output
    - Some ops require: B(R)+B(S) ≤ M-2 or max(B(R),B(S))<M-1
- Cost = B(R) + B(S)

Summary: One-Pass Algorithms

- Choice is based on
  - available RAM buffers (M) and
  - input data size in blocks

  - Known → ok
  - Not known → estimate it
    - Wrong size → swapping (mem virtualization)

- Use a two-pass algo if input data exceeds the limits.

Join Algorithms (1½ Pass Algos)

- Relations do not fit in memory
  - So called "*one and a half*"-pass algorithms
- Basic variant: *Nested-loop join*
  - **for** each *s* in *S* **do**
    - **for** each *r* in *R* **do**
      - **if** *r* and *s* match in Y **then** output concatenation of *r* and *s*.
- Example
  - T(R) = 10 000 T(S) = 5 000 M=2
  - Costs = 5 000·(1+10 000) = 50 005 000 IOs

reading a record of S

Reading whole R

Join Algorithms

- Relations accessed by blocks
- *Block-based nested-loop join*
  - R – inner relation, S – outer relation
- Example:
  - B(R) = 1000 B(S) = 500 M=3
  - Costs = 500·(1+1000) = 500 500 IOs

Join Algorithms

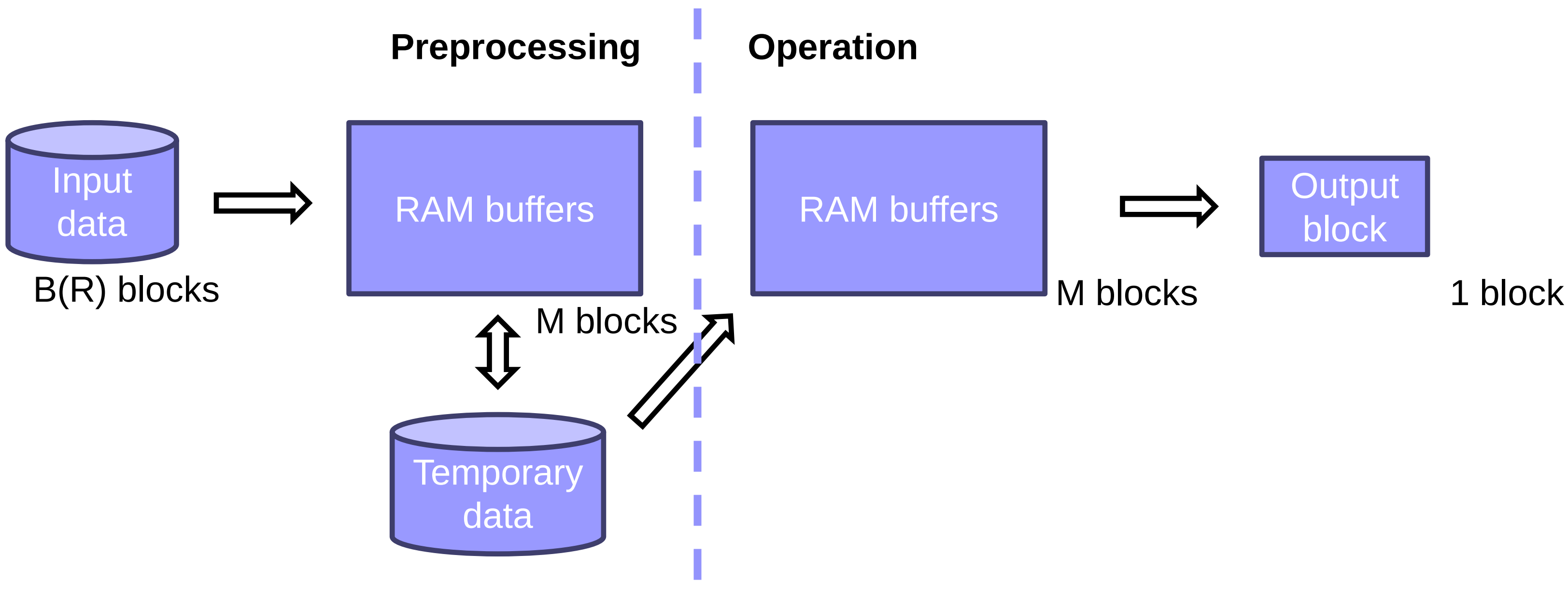
- Exploit all buffer blocks (M blocks)
  - Cached Block-based Nested-loop Join
  - Read M-2 blocks of relation S at once
    - Read relation R block by block
      - Join records
  - Costs in IOs: B(S)/(M-2) · (M-2 + B(R))
- Example $R \bowtie S$:
  - M=102
  - Costs: 5 · (100 + 1000) = 5 500 IOs
  - Swapping relations ($S \bowtie R$)
    - Costs: 10 · (100 + 500) = 6 000 IOs

Join Algorithms – Summary

- Nested-loops join
  - Use always blocked variant
  - Read the smaller relation into memory (if M>>3)
- Storage of relation
  - Important for final costs
    - Interlaced $\rightarrow$ each record needs one I/O
    - Non-interlaced $\rightarrow$ each record needs B(R)/T(R) I/Os only
- Applicable to any join condition
  - theta joins

Two-Pass Algorithms

- Procedure:
  - Preprocess input relation → store it
    - Sorting (Multi-way MergeSort)
    - Hashing
  - Processing

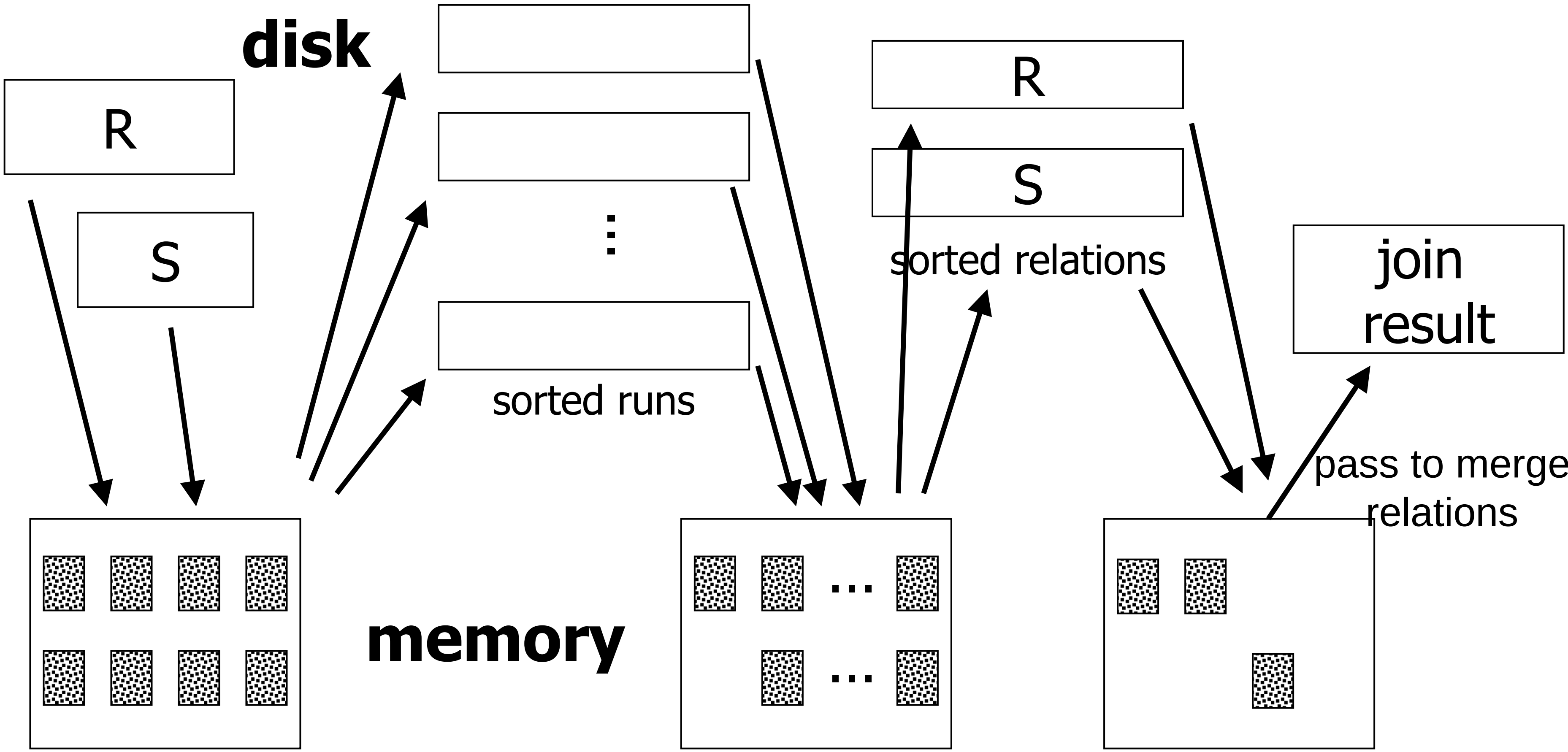


Two-Pass Algorithms

- Operations:
  - Joins
  - Duplicate elimination (DISTINCT)
  - Aggregations (GROUP BY)
  - Set operations

Join Algorithms – MergeJoin

- R⋈S   R(X,Y), S(Y,Z)



Join Algorithms – MergeJoin

- $R \bowtie S$ R(X,Y), S(Y,Z)
- Algorithm:
  - Sort R and S
  - i = 1; j = 1;
  - **while** (i ≤ T(R)) ∧ (j ≤ T(S)) **do**
    - **if** R[i].Y = S[j].Y **then** doJoin()
    - **else if** R[i].Y > S[j].Y **then** j = j+1
    - **else if** R[i].Y < S[j].Y **then** i = i+1

Join Algorithms – MergeJoin

- Function doJoin():
  - Proceed nested-loop join for records of same Y
    - We will keep all necessary block in mem
  - **while** (R[i].Y = S[j].Y) $\wedge$ (i $\leq$ T(R)) **do**
    - j2 = j
    - **while** (R[i].Y = S[j2].Y) $\wedge$ (j2 $\leq$ T(S)) **do**
      - Output joined R[i] and S[j2]
      - j2 = j2 + 1
    - i = i + 1
  - j = j2

Join Algorithms – MergeJoin

i	R[i].Y	S[j].Y	j
1	10	5	1
2	20	20	2
3	20	20	3
4	30	30	4
5	40	30	5
		50	6
		52	7

Join Algorithms – MergeJoin

- Costs
  - MergeSort of R and S $\rightarrow$ 4·(B(R) + B(S))
  - Join $\rightarrow$ B(R) + B(S)
- Example (M=102)
  - MergeJoin
    - Sorting: 4·(1000 + 500) = 6000 read/write IOs
    - Joining: 1000 + 500 = 1500 read IOs
    - Total: 7500 read/write IOs
  - Original cached block-based nested-loop join
    - 5500 read IOs

Join Algorithms – MergeJoin

10x larger relations!!!

- Another example
  - B(R) = 10 000 B(S) = 5 000
  - M = 102 blocks
  - Cached Block-based Nested-loop Join
    - (5 000/100) · (100 + 10 000) = 505 000 read IOs
  - MergeJoin
    - 5·(10 000 + 5 000) = 75 000 read/write IOs

Join Algorithms – MergeJoin

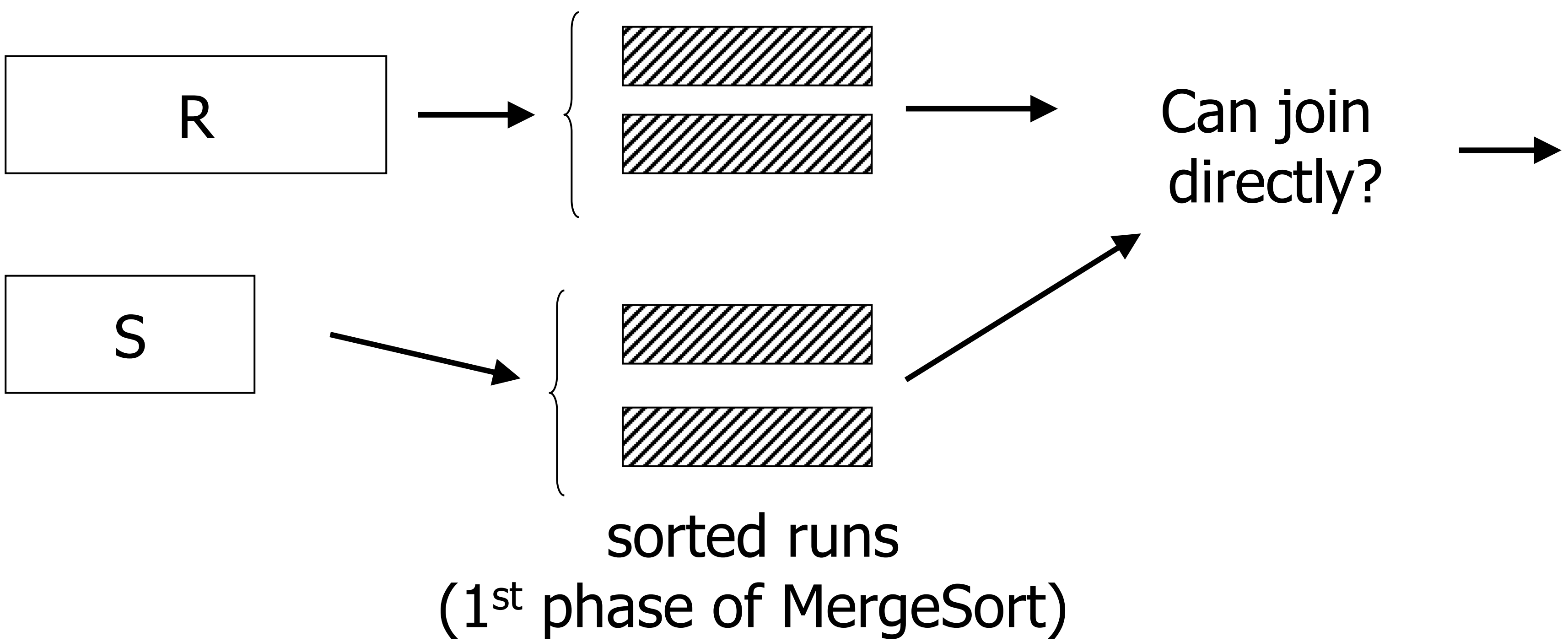
- MergeJoin
  - Preprocessing is expensive
    - If relations are sorted by Y, can be omitted.
- Analysis of IO costs
  - MergeJoin
    - linear complexity
  - Cached Block-based Nested-loop Join
    - quadratic complexity
  - → from a certain size of relations, MergeJoin is better

Join Algorithms – MergeJoin

- Memory requirements
  - Limitation to $\max\big(B(R), B(S)\big) < M^2$
- Optimal memory size
  - Using MergeSort on relation R
    - Number of runs = $B(R)/M$, Run length = M
    - Limitation: number of runs $\leq M - 1$
    - $B(R)/M < M \;\rightarrow\; B(R) < M^2 \;\rightarrow\; M > \left\lceil\sqrt{B(R)}\right\rceil$
- Example
  - B(R) = 1000 $\rightarrow\; M > \lceil 31.62 \rceil$
  - B(S) = 500 $\rightarrow M > \lceil 22.36 \rceil$

Join Algorithms – MergeJoin→SortJoin

- Improvement:
  - Not necessary to have the relations sorted completely



Join Algorithms – SortJoin

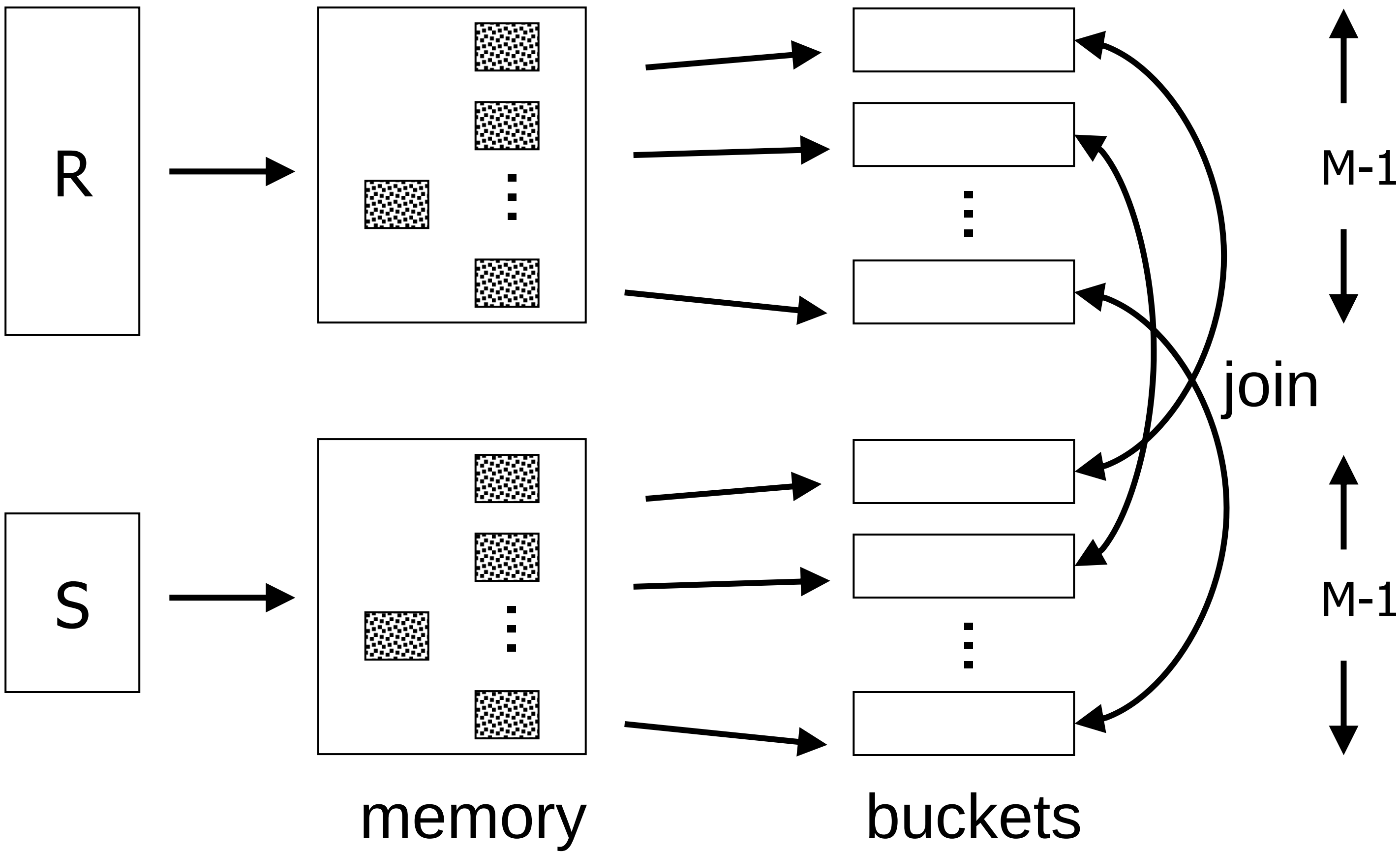
- Improvement
  - Prepare sorted runs of R and S
  - Read 1st block of all runs (R and S)
  - Get min value in Y
    - Find corresponding records in other runs
    - Join them
- In case too many records with the same Y
  - Apply block-nested-loop join in the remaining memory

Join Algorithms – SortJoin

- Costs
  - Sorted runs: 2·(B(R) + B(S))
  - Joining: B(R) + B(S)
- Limitations
  - Run length = M, number of runs < M
  - $\sqrt{B(R) + B(S)} < M$
- Example (M=102)
  - Sorting: 2·(1000 + 500)   Joining: 1000 + 500
  - Total: 4 500 read/write IOs
    - $\rightarrow$ better than cached block-based nested-loop join

Join Algorithms – HashJoin

- R⋈S R(X,Y), S(Y,Z)

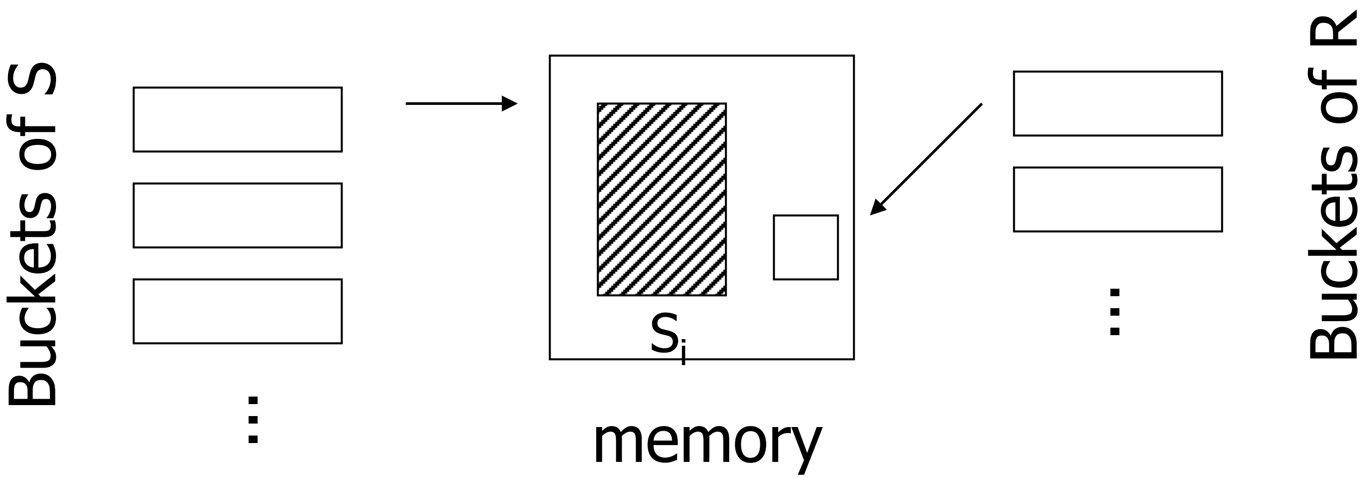


Join Algorithms – HashJoin

- $R \bowtie S$ R(X,Y), S(Y,Z)
  - Define a hash function for attributes Y
  - Create hashed index of R and S
    - Address space is M-1 buckets
  - For each i $\in$ [0,M-2]
    - Read bucket *i* of R and S
    - Find matching records and join them
      - add to the output block

Join Algorithms – HashJoin

- Joining buckets
  - Read whole bucket of S (≤ M-2)
    - Create an in-mem structure to speed up
  - Read bucket of R block by block



Join Algorithms – HashJoin

- Costs:
  - Create hashed index: 2·(B(R)+B(S))
  - Bucket joining: B(R)+B(S)
- Limitations:
  - Size of each bucket of S ≤ M-2
    - Estimate: $min\big(B(R), B(S)\big) < (M-1).(M-2)$
- Example:
  - Hashing: 2·(1000+500)
  - Joining: 1000+500
  - Total: 4 500 read/write IOs

Join Algorithms – HashJoin

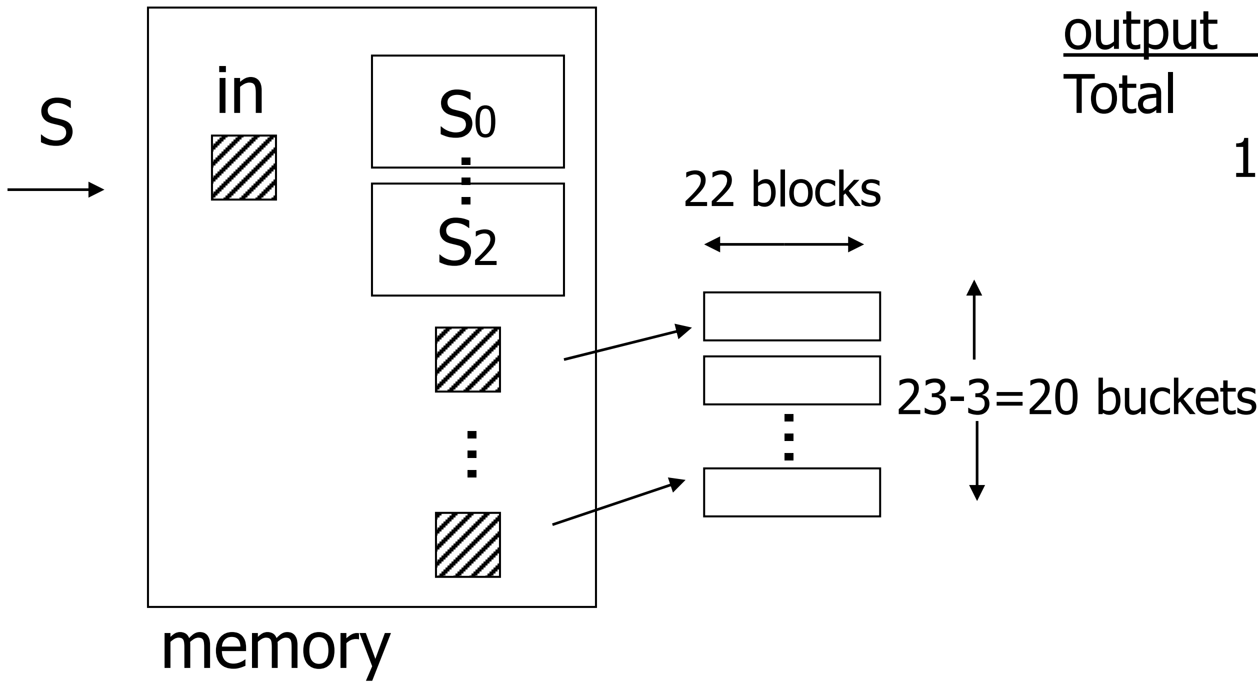
- Minimum memory requirements
  - Hashing S; optimal bucket occupation
    - Memory buffer: M blocks
    - Bucket size = B(S) / (M-1)
      - This must be smaller than M (due to joining)
      - → $\lceil B(S)/(M-1) \rceil \leq M-2$
    - $\approx M - 1 > \left\lceil \sqrt{B(S)} \right\rceil$

Join Algorithms – HashJoin

- Optimization
  - keep some buckets in memory
  - Hybrid HashJoin
- Bucketing of S – Optimal size
  - B(S)=500
  - $\sqrt{B(S)} \approx 23$
  - i.e., each bucket is of 22 blocks
  - M=102
    - $\rightarrow$ keep 3 buckets in memory (66 blocks)
    - $\rightarrow$ 36 blocks of memory to spare

Join Algorithm – Hybrid HashJoin

- Preprocessing S
  - Contents of memory buffer



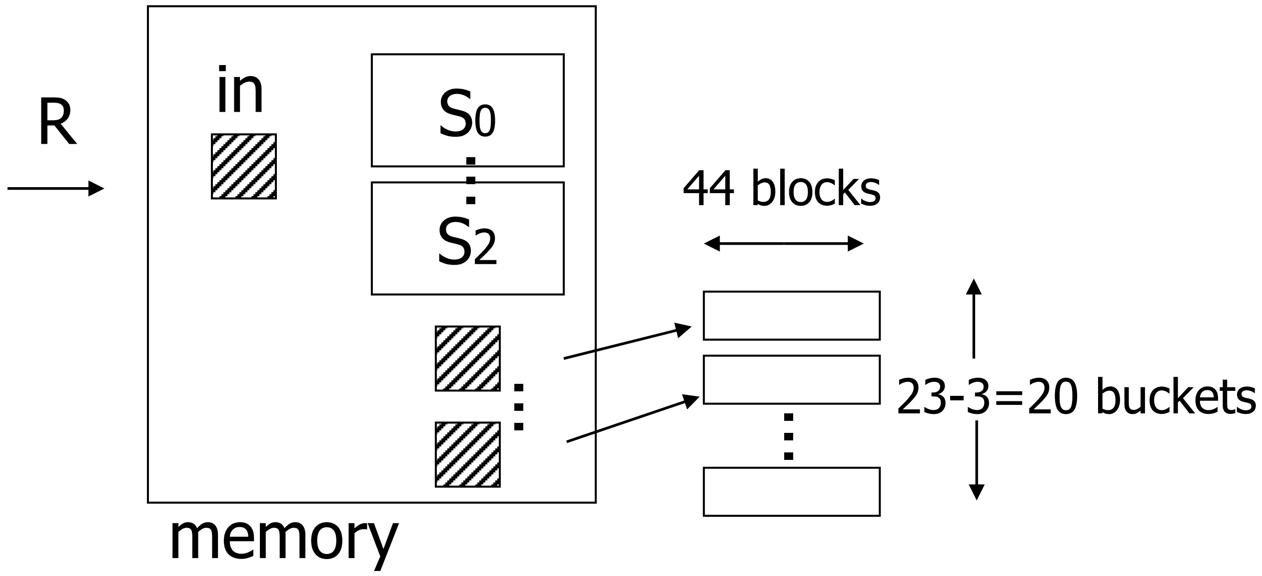
Memory usage (M=102):

S0-2	3*22 blocks
Other buckets	23-3 blocks
Reading S	1 block
output	1 block
Total	88 blocks

14 blocks are available!

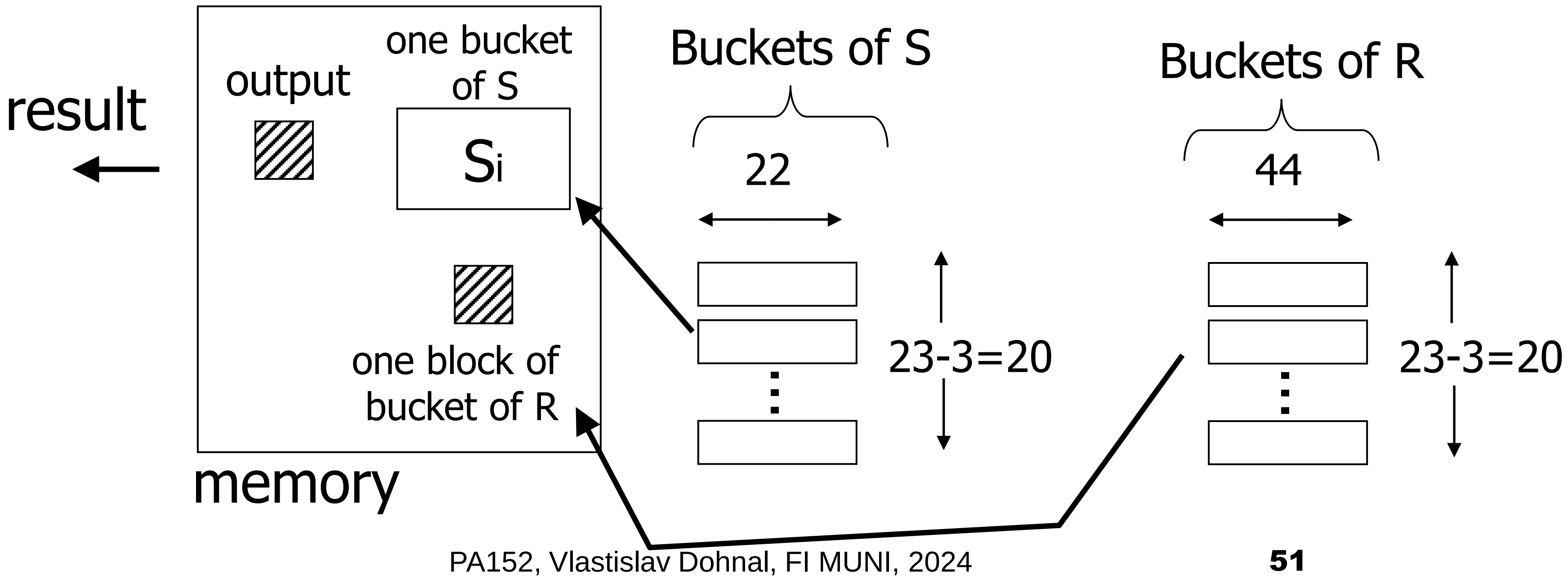
Join Algorithm – Hybrid HashJoin

- Structure of memory to hash R
  - 1000/23 = 44 blocks per bucket
  - Records hashed to bucket 0-2
    - Join immediately with S_{0-2} buckets (in memory) → output



Join Algorithm – Hybrid HashJoin

- Joining buckets
  - Do for buckets S_i and R_i with i = 3-22
  - Read one whole bucket in memory; read the other bucket block by block



Join Algorithm – Hybrid HashJoin

- Costs:
  - Bucketize S: 500 + 20·22 = 940 read/write IOs
  - Bucketize R: 1000 + 20·44 = 1880 read/write IOs
    - Only 20 buckets to write!
  - Joining: 20·44 + 20·22 = 1320 read IOs
    - Three buckets are already done (during bucketizing R)
  - In total: 4140 read/write IOs

Join Algorithms

- Hybrid HashJoin
  - How many buckets to keep in memory?
    - Empirically: 1 bucket

- Hashing record pointers
  - Organize pointers to records instead of records themselves
    - Store pairs [key value, rec. pointer] in buckets
  - Joining
    - If match, we must read the records

Join Algorithm – Hashing Pointers

- Example
  - 100 key-pointer pairs fit in one block
  - Estimate results size: 100 recs
  - Costs:
    - Bucketize S in memory (500 IOs)
      - 5000 records $\rightarrow$ 5000/100 blocks = 50 blocks in memory
    - Joining – read R gradually and join
      - If match, read full records of S $\rightarrow$ 100 read IOs
    - Total: 500 + 1000 + 100 = 1600 read IOs

Join Algorithms – IndexJoin

- $R \bowtie S \quad R(X,Y), S(Y,Z)$
- Assume:
  - Index on attributes Y of R
- Procedure:
  - For each record $s \in S$
  - Look up matches in index R.Y $\rightarrow$ records A
    - For each pointer $p_r \in A$, read r
    - Output concatenation of *r* and *s*

Join Algorithms – IndexJoin

- Example
  - Assume
    - Index on Y of R: HT=2, LB=200
- Scenario 1
  - Index R.Y fits in memory
  - Costs:
    - Pass of S: 500 read IOs (B(S)=500, T(S)=5000)
    - Searching in index: for free
      - If match, read record of R $\rightarrow$ 1 read IO

Join Algorithms – IndexJoin

- Costs
  - Depends on the number of matches
  - Variants:
    - A) Y in R is primary key; Y in S is foreign key
      $\rightarrow$ 1 record
      Costs: 500 + 5000·1·1 = 5500 read IOs
    - B) V(R,Y) = 5000 T(R) = 10 000
      uniform distribution $\rightarrow$ 2 records
      Costs: 500 + 5000·2·1 = 10500 read IOs
    - C) DOM(R,Y)=1 000 000 T(R) = 10 000
      $\rightarrow$ 10k/1m = 1/100 of record
      Costs: 500 + 5000·(1/100)·1 = 550 read IOs

Join Algorithms – IndexJoin

- Scenario 2
  - Index does not fit in memory
  - Index on R.Y is of 201 blocks
    - Keep root-node block and 99 leaf-node blocks in memory M=102
  - Costs for searching
    - 0·(99/200) + 1·(101/200) = 0.505 read IOs per search (query)

Join Algorithms – IndexJoin

- Scenario 2
  - Costs
    - $B(S) + T(S) \cdot$(searching index + reading records)
  - Variants:
    - A) $\rightarrow$ 1 record
      Costs: $500 + 5000 \cdot (0.5+1) = 8000$ read IOs
    - B) $\rightarrow$ 2 records
      Costs: $500 + 5000 \cdot (0.5+2) = 13000$ read IOs
    - C) $\rightarrow$ 1/100 of record
      Costs: $500 + 5000 \cdot (0.5+1/100)$
      $= 3050$ read IOs

Join Algorithms – Summary

$R \bowtie S$
$B(R) = 1000$
$B(S) = 500$

Algorithm	Costs
Cached Block-based Nested-loop Join	5500
Merge Join (w/o sorting)	1500
Merge Join (with sorting)	7500
Sort Join	4500
Index Join (R.Y index)	8000 $\rightarrow$ 550
Hash Join	4500
Hybrid	4140
Pointers	1600

Join Algorithms – Summary

R ⋈ S **Assume B(S) < B(R)**, Y are common attributes

Algorithm	Costs	Limits
Block-based Nested-loop	B(S) · (1+B(R))	M=3
Cached version	B(S)/(M-2) · (M-2 + B(R))	M≥3
Merge Join (w/o sorting)	B(R) + B(S)	M=3
Merge Join (with sorting)	5 · (B(R) + B(S))	$M = \sqrt{B(R)}$
Sort Join	3 · (B(R) + B(S))	$M > \sqrt{B(R) + B(S)}$
Index Join (R.Y index) (max costs)	B(S) + T(S) · (HT + θ) e.g. θ = T(R)/V(R,Y)	min. M=4
Hash Join	3 · (B(R) + B(S))	$M = 2 + \sqrt{B(S)}$ max. M-1 buckets
Hybrid	$3(B(R) + B(S)) - \frac{2(B(R) + B(S))}{\left\lceil\sqrt{B(R)}\right\rceil}$	$M = \frac{B(R)}{\left\lceil\sqrt{B(R)}\right\rceil} + \left(\left\lceil\sqrt{B(R)}\right\rceil\right) + 1$
Pointers	B(S)+B(R)+T(R) · θ e.g. θ = T(S)/V(S,Y)	M=B(hash index on S)+3

Join Algorithms – Recommendation

- Cached Block-based Nested-loop Join
  - Good for small relations (relative to memory size)
- HashJoin
  - For equi-joins (equality on attributes only)
  - Relations are not sorted or no indexes
- SortJoin
  - Good for *non-equi-joins*, but not all theta-joins
  - E.g., R.Y > S.Y
- MergeJoin
  - Best if relations are already sorted
- IndexJoin
  - If an index exists, it could be useful
  - Depends on expected result size

Two-Pass Algorithms

- Using sorting
  - Duplicate Elimination
  - Aggregations (GROUP BY)
  - Set operations

Duplicate Elimination

- Procedure
  - Do 1st phase of MergeSort
    - $\rightarrow$ sorted runs on disk
  - Read all runs block by block
    - Find smallest record and output it
    - Skip all duplicate records
- Properties
  - Costs: $3B(R)$
  - Limitations: $B(R) \leq M^*(M-1)$
    - Optimal $\mathrm{M} \geq \sqrt{B(R)} + 1$

Aggregations

- Procedure (analogous to previous)
  - Sort runs of R (by group-by attributes)
  - Read all runs block by block
    - Find smallest value → new group
      - Compute all aggregates over all records of this group
      - No more record in this group → output it
- Properties
  - Costs: $3B(R)$
  - Limitations: $B(R) \leq M*(M-1)$
    - Optimal $\mathrm{M} \geq \sqrt{B(R)} + 1$

Set union

- Notice: No two-pass algo for bag union

- Set union
  - Do 1st phase of MergeSort on *R* and *S*
    - $\rightarrow$ sorted runs on disk
  - Read all runs (both R and S) gradually
    - Find the first remaining record and output it
    - Skip all duplicates of this record (in R and S)
- Properties
  - Costs: 3(*B*(*R*) + *B*(*S*))
  - Limitations: $\sqrt{B(R) + B(S)} < M$
    - Need one block per all runs (of R and also S)

Set/bag intersection and difference

- $R \cap S$, $R - S$, $R \cap_B S$, $R -_B S$
- Procedure
  - Do 1st phase of MergeSort on *R* and *S*
  - Read all runs (both R and S) gradually
    - Find the first remaining record *t*
    - Count *t's* occurrences in R and S (separately)
      - $\#_R$, $\#_S$
    - Make a decision w.r.t. the specific operation
      - and copy selected records to output

Set/bag intersection and difference

- On *copy to output*:
  - $R \cap S$: output *t*,
    - if $\#_R > 0 \wedge \#_S > 0$
  - $R \cap_B S$: output *t* $\min(\#_R, \#_S)$-times
  - $R - S$: output *t*,
    - if $\#_R > 0 \wedge \#_S = 0$
  - $R -_B S$: output *t* $\max(\#_R - \#_S, 0)$-times
- Properties
  - Costs: $3(B(R) + B(S))$
  - Limitations: $\sqrt{B(R) + B(S)} < M$
    - Need one block per all runs (of R and also S) and 1 output block

Two-Pass Algorithms

- Using <u>hashing</u>
  - Duplicate Elimination
  - Aggregations (GROUP BY)
  - Set operations

Duplicate Elimination

- Procedure
  - Bucketize *R* into M-1 buckets
    - $\rightarrow$ store buckets on disk
  - For each bucket
    - Read it in memory and remove duplicates; output remaining records
      - bucket size is max. M-1 blocks
- Properties
  - Costs: $3B(R)$
  - Limitations: $B(R) \leq (M\text{-}1)^2$

Aggregations

- Procedure (analogous to previous)
  - Bucketize *R* into M-1 buckets by group-by attrs.
    - → store buckets on disk
  - For each bucket
    - Read block by block in memory and
    - Create groups for new values and compute aggregates
      - Limit on bucket size is not defined. But groups and partial aggregates must fit in max. M-1 blocks.
    - Output results
- Properties
  - Costs: $3B(R)$
  - Limitations: $B(R) \leq (M-1)^2$

It can be relaxed, since we store just the aggregates in RAM.

Set union, intersection, difference

- Procedure
  - Bucketize *R* and *S* (the same hash function)
    - into M-1 buckets
  - Process the pair of buckets R_i and S_i
    - Read one in memory (depends on operation)
      - bucket size: max. M-2
    - Read the other gradually
- Properties
  - Costs: $3(B(R) + B(S))$
  - Limitations on M depends on the operation

Set intersection, difference

- Intersection (smaller relation is S)
  - Load the bucket of S in mem
  - Restrictions: min($B(R)$, $B(S)$) ≤ $(M-2)*(M-1)$
- Difference R-S:
  - To eliminate duplicates in R, read bucket of R into mem
  - Restrictions: $B(R) \leq (M-2)*(M-1)$
- Difference S-R:
  - Load the bucket of S in mem
  - Restrictions: $B(S) \leq (M-2)*(M-1)$

Set Union

- Must eliminate duplicates in R and S
- for each *i* in hash addresses:
    - read Bkt^S_i , build in-mem hash table & eliminate dups
        - also output the unique records gradually
    - read Bkt^R_i gradually:
        - for each *r* in Bkt^R_i :
            - if *r* not in in-mem hash table
                - output *r* and <u>add to in-mem hash table</u>
- Restrictions: $\sqrt{B(R)} + \sqrt{B(S)} < M$
    - Need to load both the buckets (at worst) into M

Summary

- Operations
  - distinct, group by, set operations, joins
- Algorithm type
  - one-pass, one-and-a-half pass, two-pass
- Implementation
  - Sorting
  - Hashing
  - Exploiting indexes
- Costs
  - blocks to read/write
  - memory footprint

Lecture Takeaways

- Estimated sizes influence the choice of implementation
- Influence of algorithm implementation on costs
- If more mem is needed (estimation was wrong)
  - It is allocated, and the operation is *not* terminated.
- Also, tiny code changes count!