VirginiaTech

CS 4604: Introduction to Database Management Systems

B. Aditya Prakash

Lecture #10: Query Processing

Outline

- introduction
- selection
- projection
- join
- set & aggregate operations

Introduction

- Today's topic: QUERY PROCESSING
- Some database operations are EXPENSIVE
- Can greatly improve performance by being "smart"
  - e.g., can speed up 1,000,000x over naïve approach

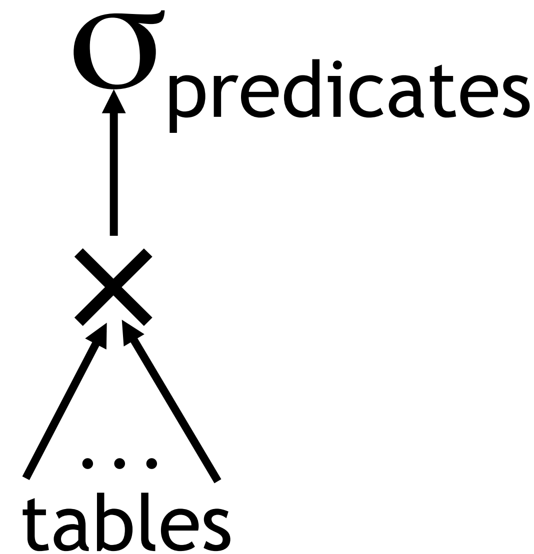
Introduction (cnt' d)

- Main weapons are:
  - clever implementation techniques for operators
  - exploiting "equivalencies" of relational operators
  - using statistics and cost models to choose among these.

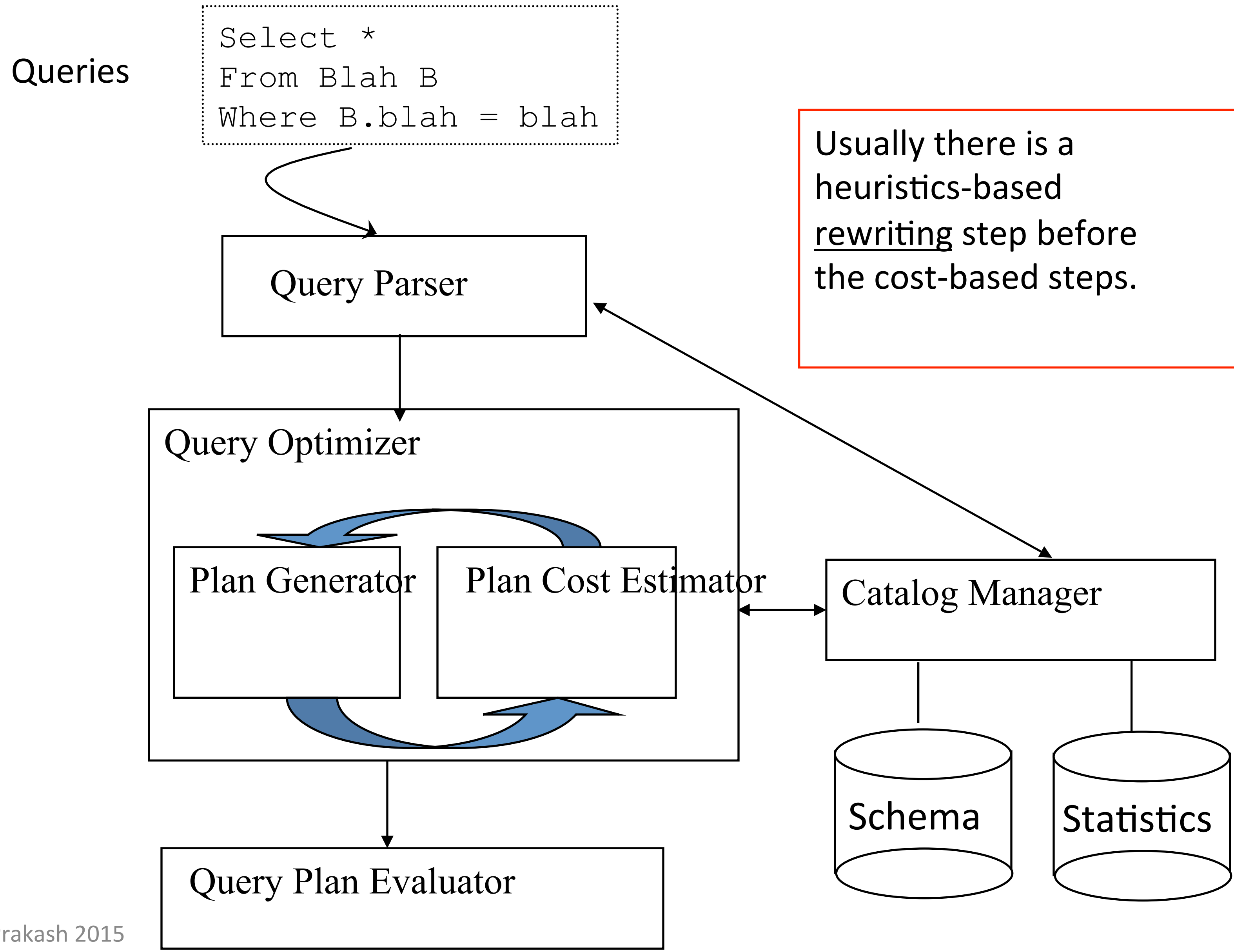
VirginiaTech

A Really Bad Query Optimizer

- For each Select-From-Where query block
  - do cartesian products first
  - then do selections
  - etc, ie.:
    - GROUP BY; HAVING
    - projections
    - ORDER BY
- Incredibly inefficient
  - Huge intermediate results!



Cost-based Query Sub-System



Usually there is a heuristics-based rewriting step before the cost-based steps.

The Query Optimization Game

- "Optimizer" is a bit of a misnomer…
- Goal is to pick a "good" (i.e., low expected cost) plan.
  - Involves choosing access methods, physical operators, operator orders, …
  - Notion of cost is based on an abstract "cost model"

Relational Operations

- We will consider how to implement:
  - *Selection* (σ) Selects a subset of rows from relation.
  - *Projection* (π) Deletes unwanted columns from relation.
  - *Join* ($\bowtie$) Allows us to combine two relations.
  - *Set-difference* (-) Tuples in reln. 1, but not in reln. 2.
  - *Union* ($\cup$) Tuples in reln. 1 and in reln. 2.
  - *Aggregation* (SUM, MIN, etc.) and GROUP BY
- Recall: ops can be *composed* !
- Later (after spring break), we'll see how to *optimize* queries with many ops

Schema for Examples

Sailors (<u>*sid*: integer</u>, *sname*: string, *rating*: integer, *age*: real)
Reserves (<u>*sid*: integer, *bid*: integer, *day*: dates</u>, *rname*: string)

- Similar to old schema; *rname* added for variations.
- Sailors:
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages.
  - $N=500$, $p_S=80$.
- Reserves:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.
  - $M=1000$, $p_R=100$.

VirginiaTech

Simple Selections

- Of the form $\sigma_{R.attr\ op\ value}(R)$
- Question: how best to perform?

```
SELECT  *
FROM    Reserves R
WHERE   R.rname < 'C%'
```

Simple Selections

- A: Depends on:
  - what indexes/access paths are available
  - what is the expected size of the result (in terms of number of tuples and/or number of pages)

Simple Selections

- Size of result approximated as

  *size of R * reduction factor*

  – "reduction factor" is also called *selectivity.*

  – estimate of reduction factors is based on statistics – we will discuss shortly.

Alternatives for Simple Selections

- With no index, unsorted:
  - Must essentially scan the whole relation
  - cost is M (#pages in R). For "reserves" = 1000 I/Os.

Simple Selections (cnt’d)

- With no index, sorted:
  – cost of binary search + number of pages containing results.
  – For reserves = 10 I/Os + $\lceil$selectivity*#pages$\rceil$

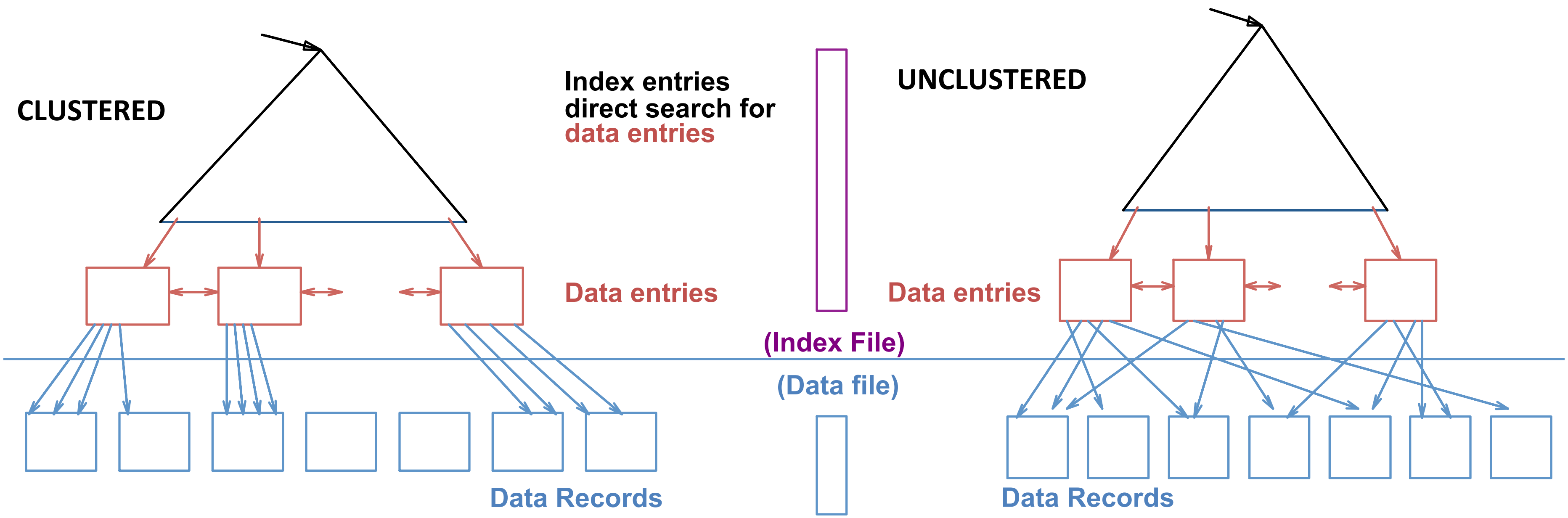
Simple Selections (cnt' d)

- With an index on selection attribute:
  - Use index to find qualifying data entries,
  - then retrieve corresponding data records.
  - (Hash index useful only for equality selections.)

Using an Index for Selections

- Cost depends on #qualifying tuples, and clustering.
  - Cost:
    - finding qualifying data entries (typically small)
    - plus cost of retrieving records (could be large w/o clustering).

Selections using Index (cnt'd)



Selections using Index (cnt' d)

– In example "reserves" relation, if 10% of tuples qualify (100 pages, 10,000 tuples).
  - With a *clustered* index, cost is little more than 100 I/Os;
  - if *unclustered*, could be up to 10,000 I/Os! unless…

Selections using Index (cnt' d)

- *Important refinement for unclustered indexes*:
  1. Find qualifying data entries.
  2. Sort the rid' s of the data records to be retrieved.
  3. Fetch rids in order. This ensures that each data page is looked at just once (though # of such pages likely to be higher than with clustering).

General Selection Conditions

SKIP

(day<8/9/94 AND rname= 'Paul') OR bid=5 OR sid=3

- Q: What would you do?

General Selection Conditions

SKIP

(day<8/9/94 AND rname= 'Paul') OR bid=5 OR sid=3

- Q: What would you do?
- A: try to find a selective (clustering) index. Specifically:

VirginiaTech

General Selection Conditions

SKIP

(day<8/9/94 AND rname= 'Paul') OR bid=5 OR sid=3

- Convert to *conjunctive normal form* (CNF):
  - *(day<8/9/94* OR *bid=5* OR *sid=3)* AND
    (rname= 'Paul' OR *bid=5* OR *sid=3)*
- We only discuss the case with no ORs (a conjunction of *terms* of the form *attr* ***op*** *value*).

General Selection Conditions

SKIP

(day<8/9/94 AND rname= 'Paul') OR bid=5 OR sid=3

- A B-tree index ***matches*** (a conjunction of) terms that involve only attributes in a *prefix* of the search key.
  - Index on *<a, b, c>* matches *a=5 AND b= 3*, but not *b=3*.
- For Hash index, must have all attributes in search key

Two Approaches to General Selections

SKIP

- First approach: Find the *cheapest access path*, retrieve tuples using it, and apply any remaining terms that don't match the index
- Second approach:get rids from first index; rids from second index; intersect and fetch.

Two Approaches to General Selections

SKIP

- <u>First approach:</u> Find the *cheapest access path*, retrieve tuples using it, and apply any remaining terms that don't match the index:
  - *Cheapest access path:* An index or file scan with fewest I/Os.
  - Terms that match this index reduce the number of tuples *retrieved*; other terms help discard some retrieved tuples, but do not affect number of tuples/pages fetched.

VirginiaTech

Cheapest Access Path - Example

SKIP

- Consider *day < 8/9/94 AND bid=5 AND sid=3*.
- A B+ tree index on *day* can be used;
  - then, *bid=5* and *sid=3* must be checked for each retrieved tuple.
- Similarly, a hash index on <*bid, sid*> could be used;
  - *Then, day<8/9/94* must be checked.

VirginiaTech

Cheapest Access Path - cnt' d

SKIP

- Consider *day < 8/9/94 AND bid=5 AND s*

- *How about a B+tree on <rname,day>?*
- *How about a B+tree on <day, rname>?*
- *How about a Hash index on <day, rname>?*

Intersection of RIDs

SKIP

- Second approach: if we have 2 or more matching indexes (w/Alternatives (2) or (3) for data entries):
  - Get sets of rids of data records using each matching index.
  - Then *intersect* these sets of rids.
  - Retrieve the records and apply any remaining terms.

Intersection of RIDs (cnt' d)

SKIP

- EXAMPLE: Consider *day<8/9/94 AND bid=5 AND sid=3*.
- With a B+ tree index on *day* and an index on *sid*,
- we can retrieve rids of records satisfying *day<8/9/94* using the first,
- rids of recs satisfying *sid=3* using the second,
- intersect,
- retrieve records and check *bid=5.*

The Projection Operation

```
SELECT  DISTINCT
        R.sid, R.bid
FROM    Reserves R
```

- Issue is removing duplicates.
- Basic approach: sorting
  - 1. Scan R, extract only the needed attrs (why?)
  - 2. Sort the resulting set
  - 3. Remove adjacent duplicates

Cost: Reserves with size ratio 0.25 = 250 pages. With 20 buffer pages can sort in 2 passes, so
1000 +250 + 2 * 2 * 250 + 250 = 2500 I/Os

Projection

SKIP

- Can improve by modifying external sort algorithm (see chapter 13):
  - Modify Pass 0 of external sort to eliminate unwanted fields.
  - Modify merging passes to eliminate duplicates.

  Cost: for above case: read 1000 pages, write out 250 in runs of 40 pages, merge runs = 1000 + 250 +250 = 1500.

Discussion of Projection

- If an index on the relation contains all wanted attributes in its search key, can do *index-only* scan.
  - Apply projection techniques to data entries (much smaller!)

Discussion of Projection

- If an ordered (i.e., tree) index contains all wanted attributes as *prefix* of search key, can do even better:
  - Retrieve data entries in order (index-only scan), discard unwanted fields, compare adjacent tuples to check for duplicates.

A B-tree index *matches* (a conjunction of) terms that involve only attributes in a *prefix* of the search key.

- Index on *<a, b, c>* matches *a=5* AND *b= 3*, but not *b=3*.

For Hash index, must have all attributes in search key

Joins

- Joins are very common.
- Joins can be very expensive (cross product in worst case).
- Many approaches to reduce join cost.

Joins

- Join techniques we will cover:
  - Nested-loops join
  - Index-nested loops join
  - Sort-merge join
  - Hash join

Equality Joins With One Join Column

```
SELECT  *
FROM    Reserves R1, Sailors S1
WHERE   R1.sid=S1.sid
```

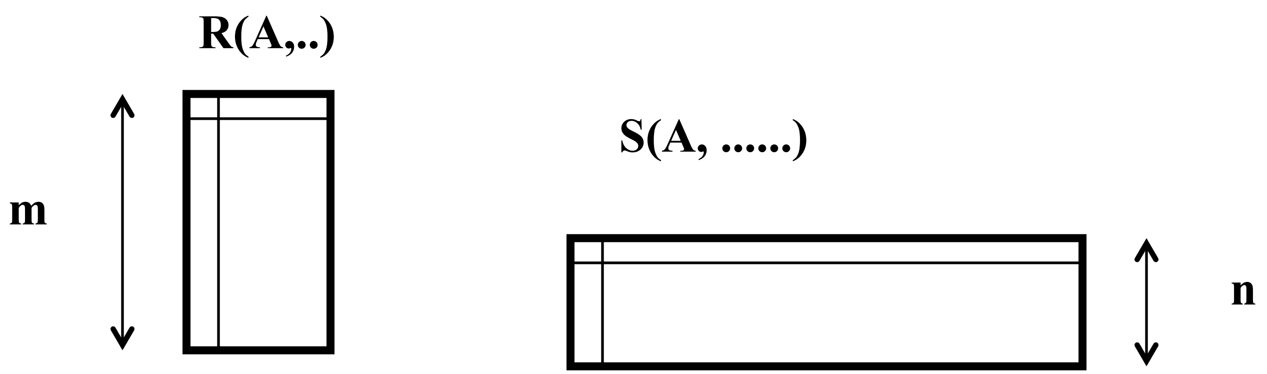
- In algebra: R $\bowtie$ S. Common! Must be carefully optimized. R $\times$ S is large; so, R $\times$ S followed by a selection is inefficient.
- Remember, join is associative and commutative.

Equality Joins

- Assume:
  - M pages in R, p_R tuples per page, *m* tuples total
  - N pages in S, p_S tuples per page, *n* tuples total
  - In our examples, R is Reserves and S is Sailors.
- We will consider more complex join conditions later.
- *Cost metric*: # of I/Os. We will ignore output costs.

Nested loops

- Algorithm #0: (naive) nested loop (**SLOW**!)



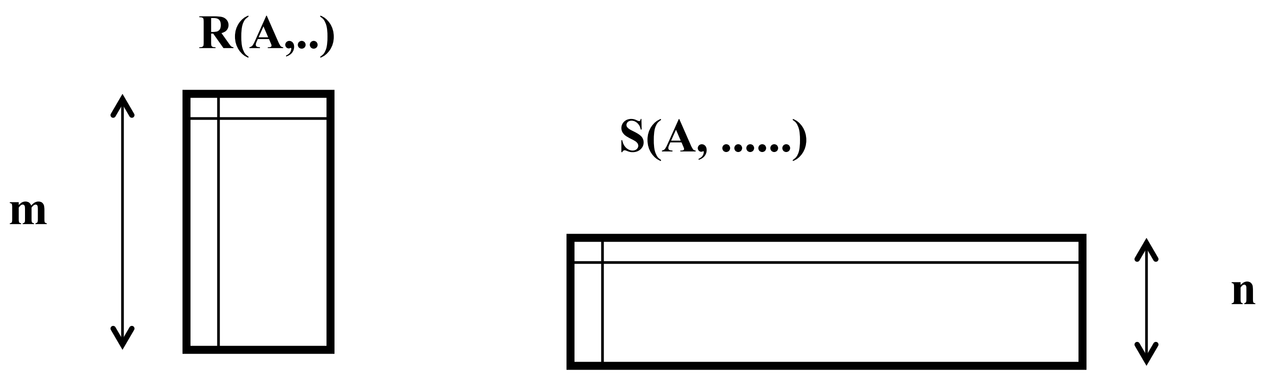
Nested loops

- Algorithm #0: (naive) nested loop (**SLOW**!)

  for each tuple r of R

      for each tuple s of S

          print, if they match



Nested loops

- Algorithm #0: (naive) nested loop (<u>**SLOW**</u>!)

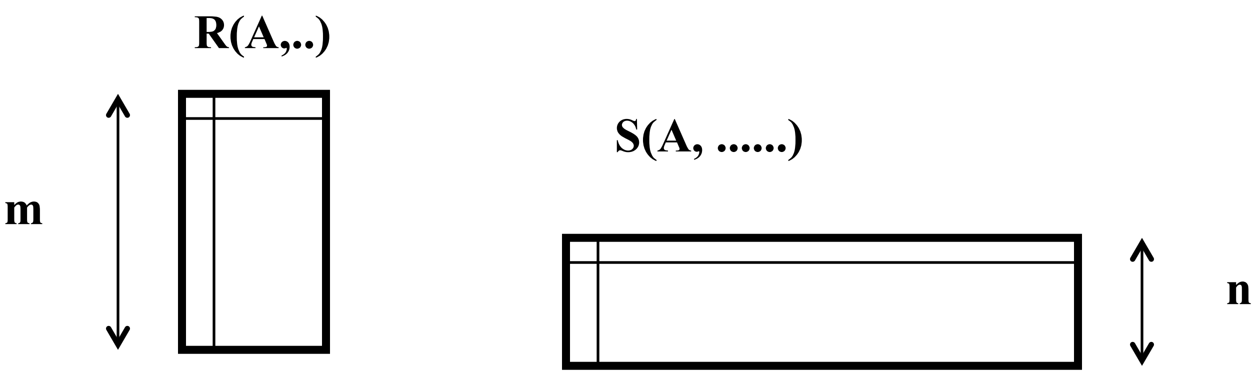
  for each tuple r of R

      for each tuple s of S

          print, if they match

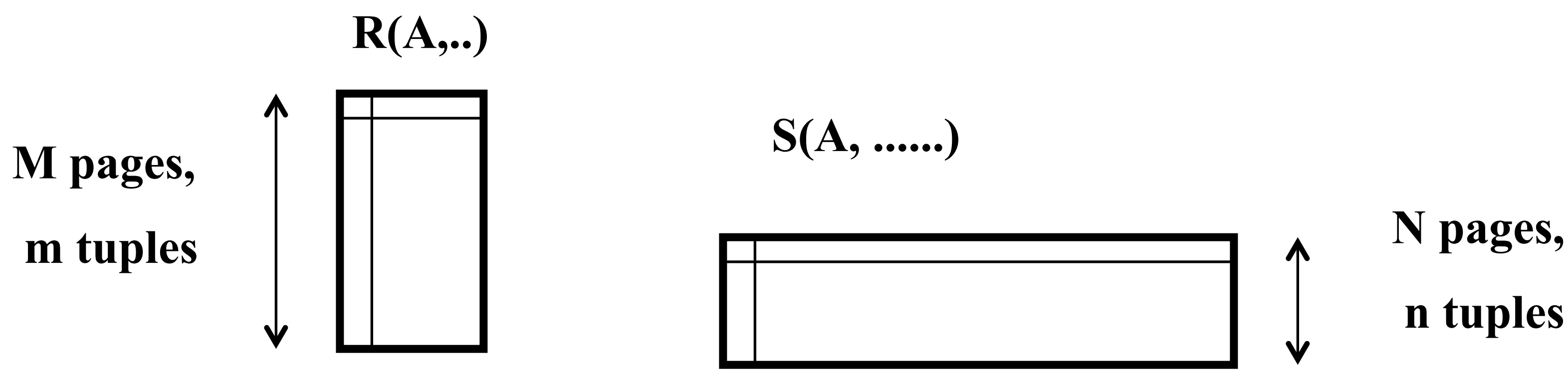
outer relation

inner relation



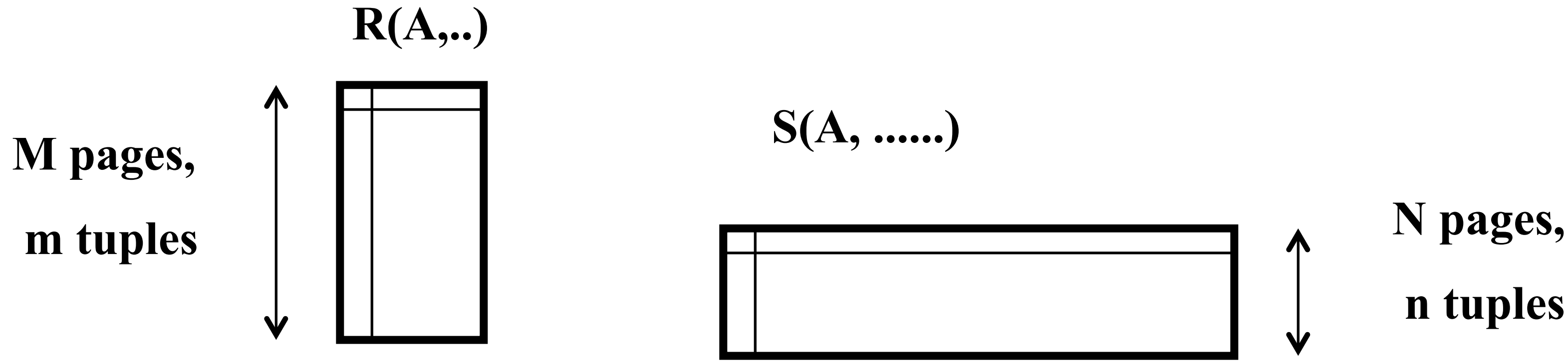
Nested loops

- Algorithm #0: why is it bad?
- how many disk accesses ('M' and 'N' are the number of blocks for 'R' and 'S')?



Nested loops

- Algorithm #0: why is it bad?
- how many disk accesses ('M' and 'N' are the number of blocks for 'R' and 'S')? M +m*N



Simple Nested Loops Join

- Actual number

$(p_R * M) * N + M = 100*1000*500 + 1000$ I/Os.

  - At 10ms/IO, Total: ???

- What if smaller relation (S) was outer?

- What assumptions are being made here?

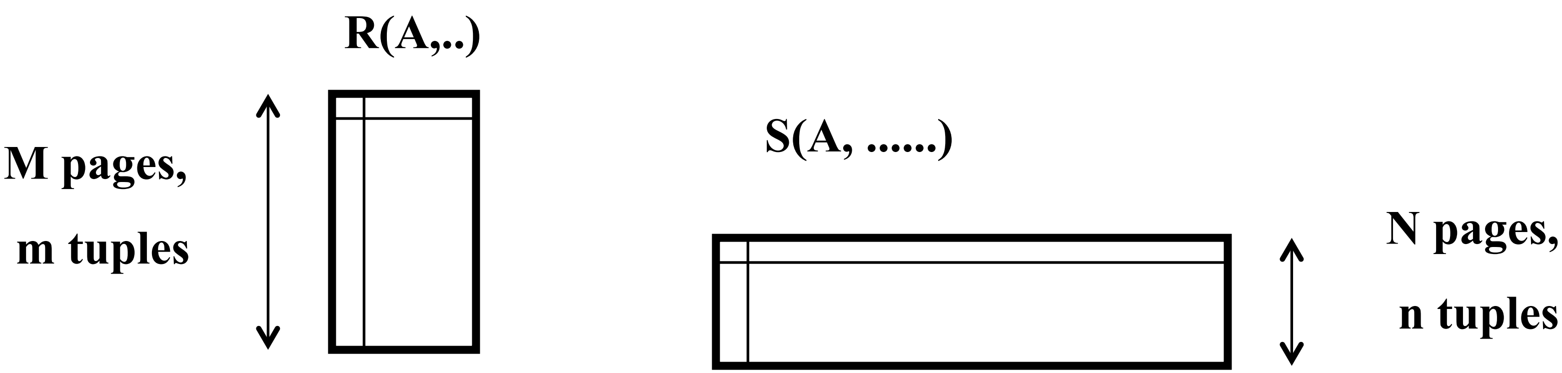
Simple Nested Loops Join

- Actual number
- $(p_R * M) * N + M = 100*1000*500 + 1000$ I/Os.
  - At 10ms/IO, Total: ~6days (!)
- What if smaller relation (S) was outer?
  - slightly better
- What assumptions are being made here?
  - 1 buffer for each table (and 1 for output)

Nested loops

- Algorithm #1: Blocked nested-loop join
  - read in a block of R
    - read in a block of S
      - print matching tuples

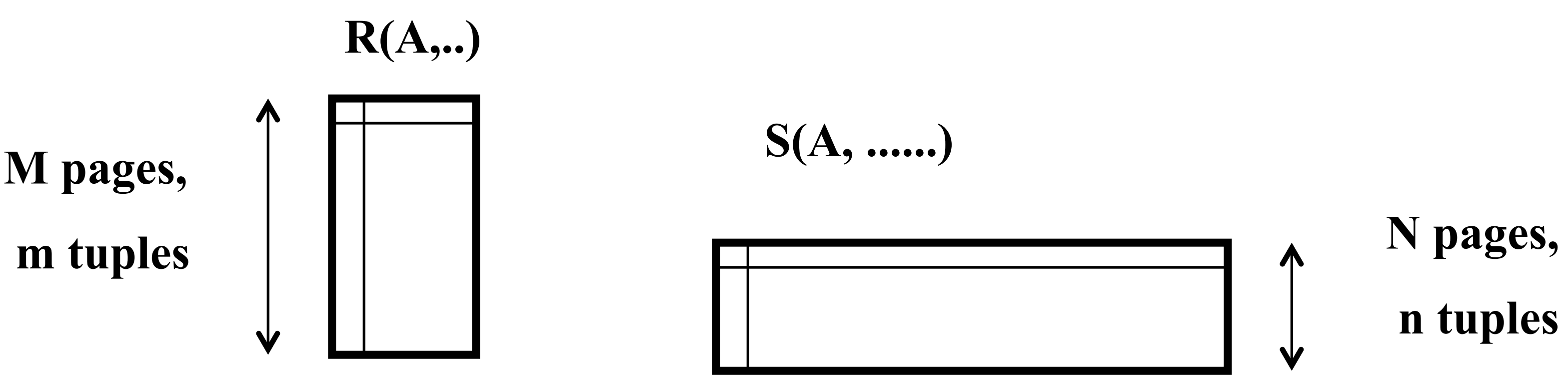
COST?



Nested loops

- Algorithm #1: Blocked nested-loop join
  - read in a block of R
    - read in a block of S
      - print matching tuples

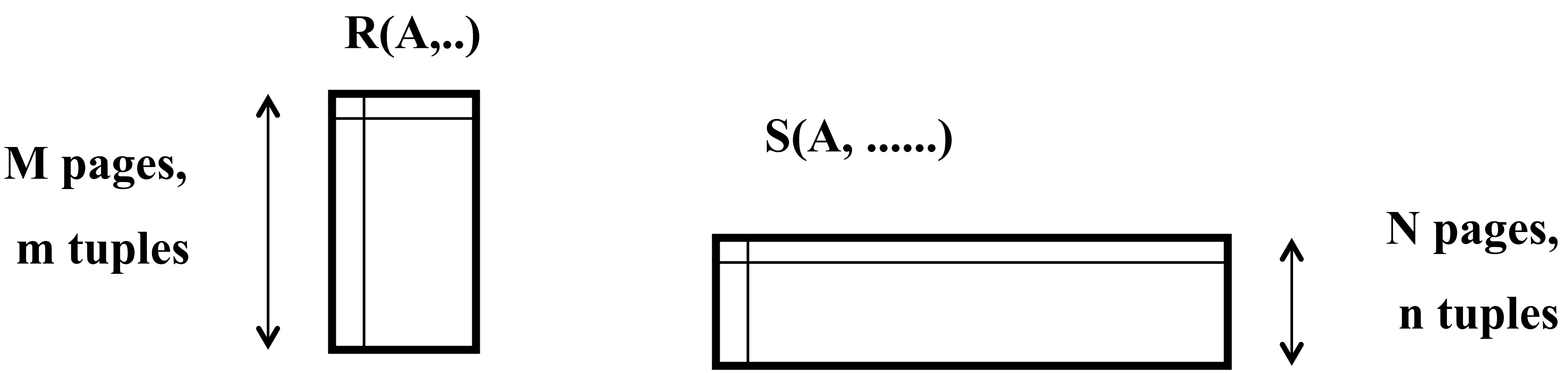
COST= M+M*N



Nested loops

- Which one should be the outer relation?

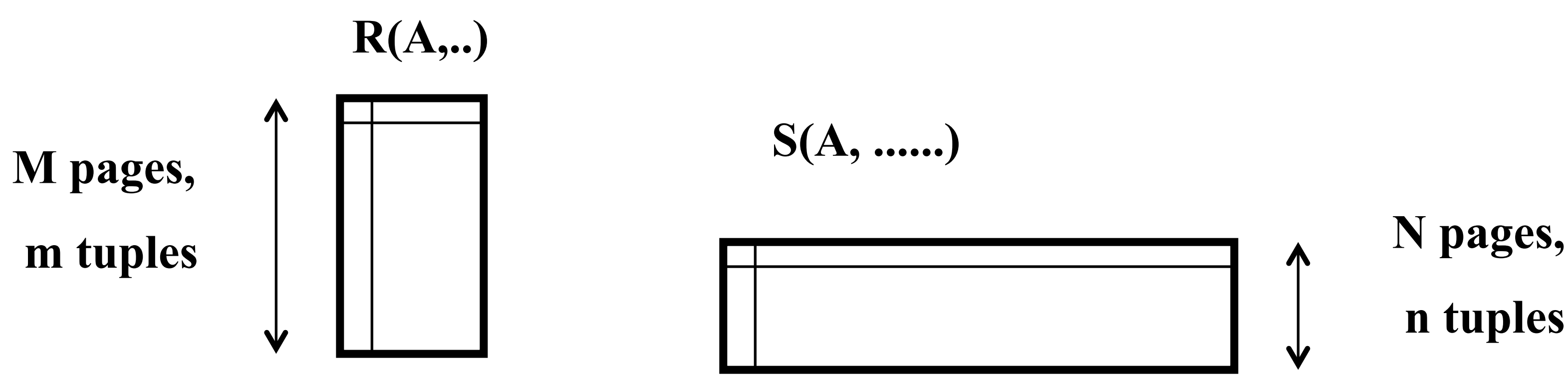
COST= M+M*N



Nested loops

- Which one should be the outer relation?
- A: the smallest (page-wise)

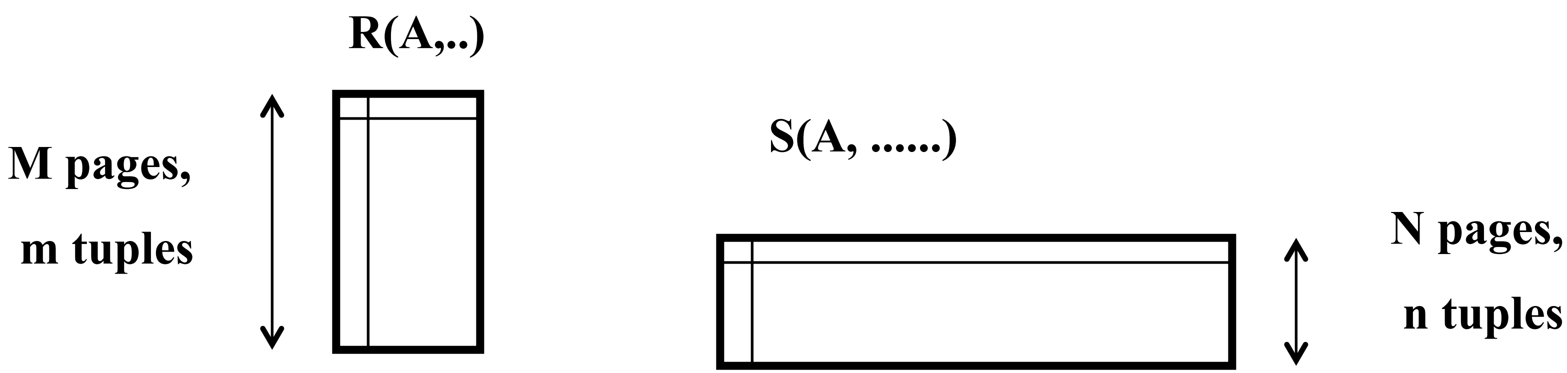
COST= M+M*N



Nested loops

- M=1000, N=500
- Cost = 1000 + 1000*500 = 501,000
- = 5010 sec ~ 1.4h

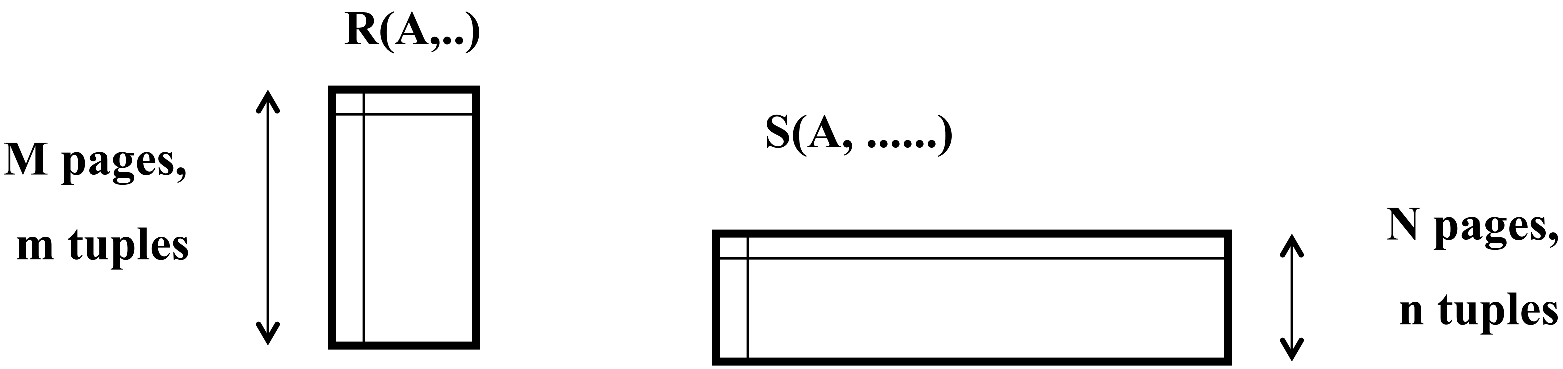
COST= M+M*N



Nested loops

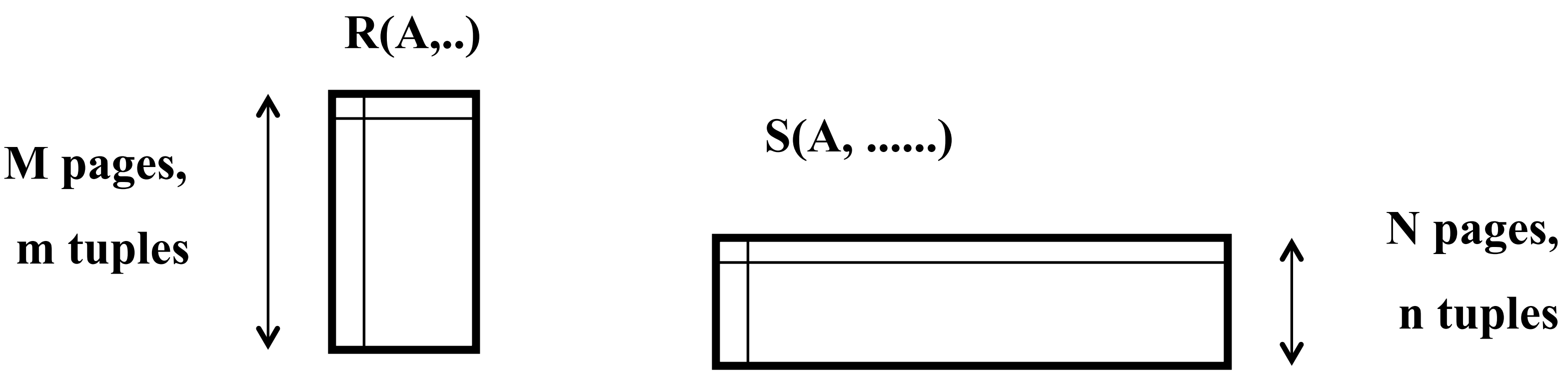
- M=1000, N=500 - if smaller is outer:
- Cost = 500 + 1000*500 = 500,500
- = 5005 sec ~ 1.4h

COST= N+M*N



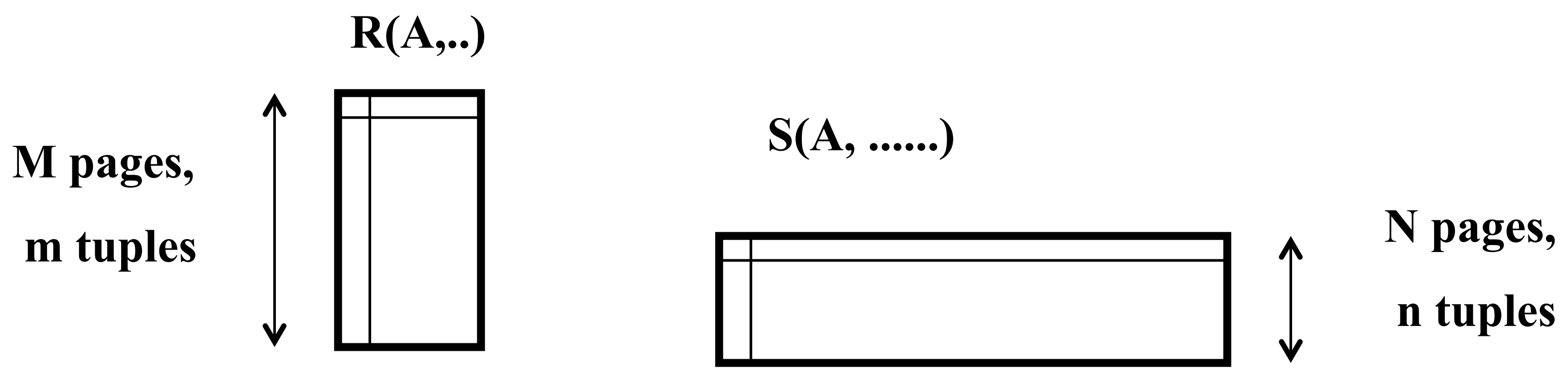
Nested loops

- What if we have B buffers available?



Nested loops

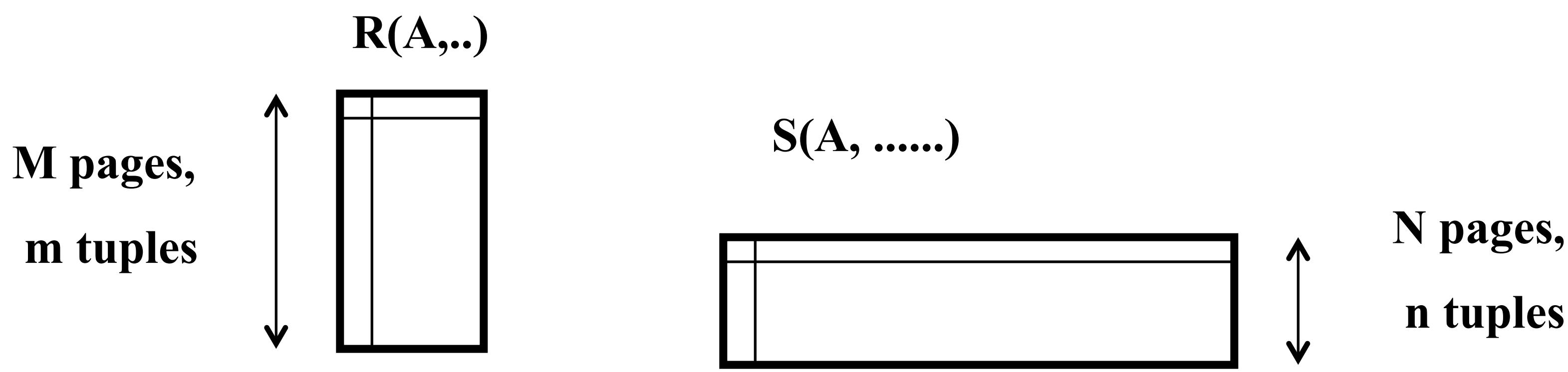
- What if we have B buffers available?
- A: give *B-2* buffers to outer, 1 to inner, 1 for output



Nested loops

- Algorithm #1: Blocked nested-loop join
  - read in *B-2* blocks of R
    - read in a block of S
      - print matching tuples

COST= ?



Nested loops

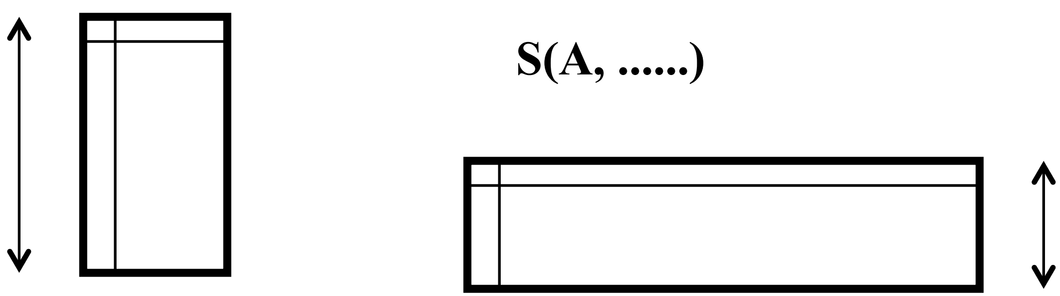
- Algorithm #1: Blocked nested-loop join
  - read in *B-2* blocks of R
    - read in a block of S
      - print matching tuples

COST= M+M/(B-2)*N

R(A,..)

M pages,

m tuples



S(A, ……)

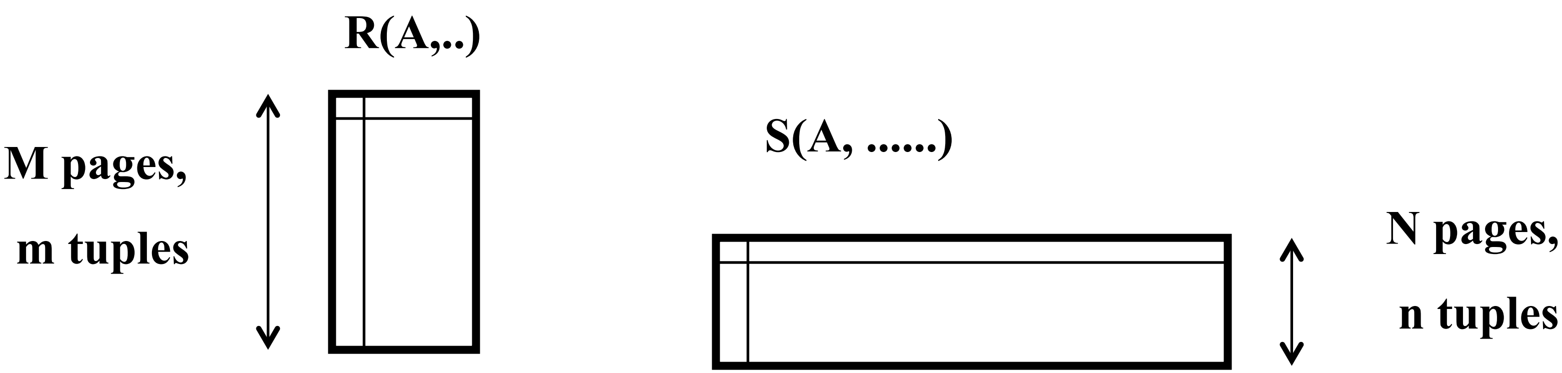
N pages,

n tuples

Nested loops

- and, actually:
- Cost = M + ceiling(M/(B-2)) * N

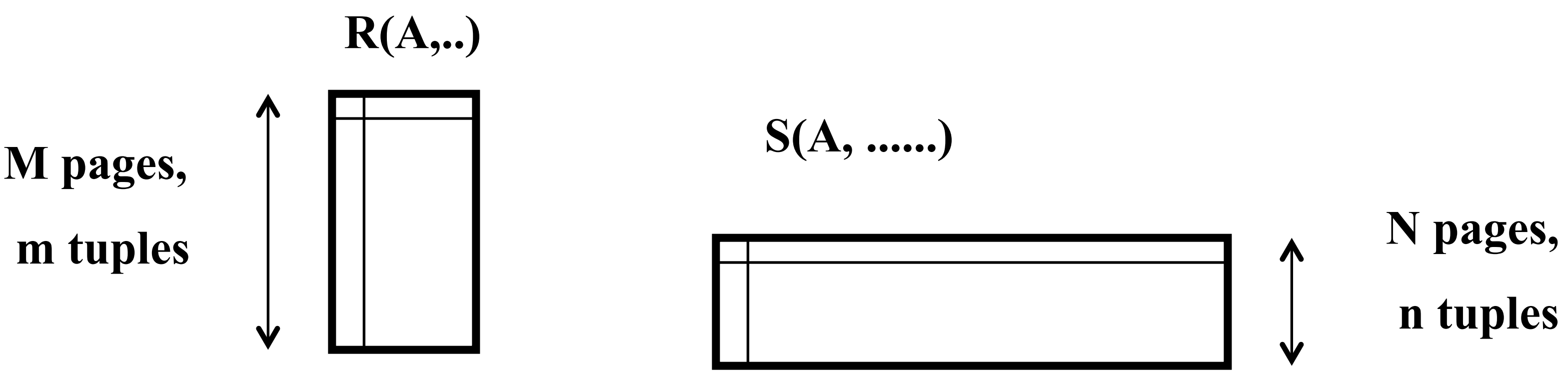
COST= M+M/(B-2)*N



Nested loops

- If smallest (outer) fits in memory
- (ie., B= N+2),
- Cost =?

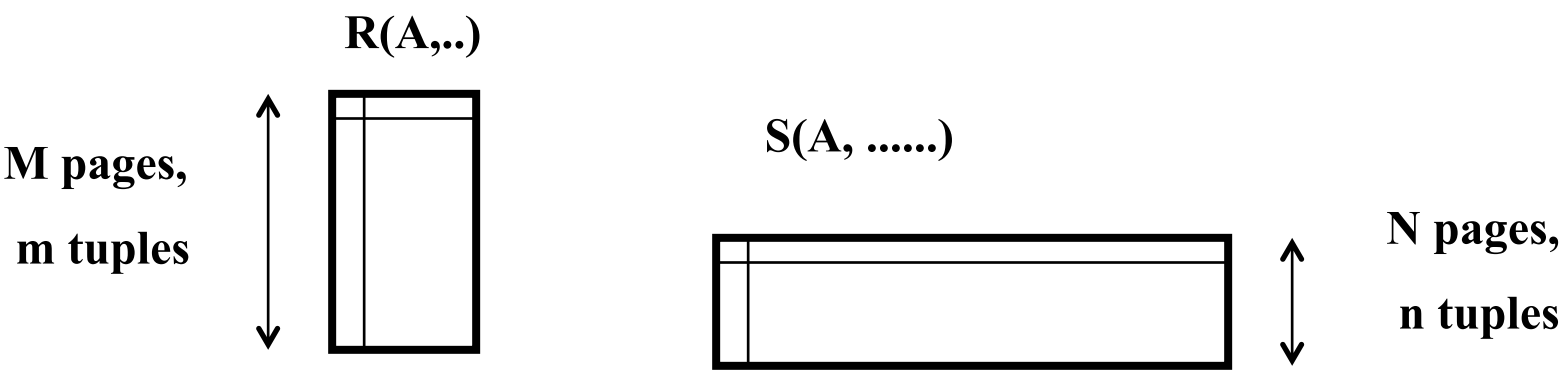
COST= N+N/(B-2)*M



Nested loops

- If smallest (outer) fits in memory
- (ie., B= N+2),
- Cost =N+M (minimum!)

COST= N+N/(B-2)*M

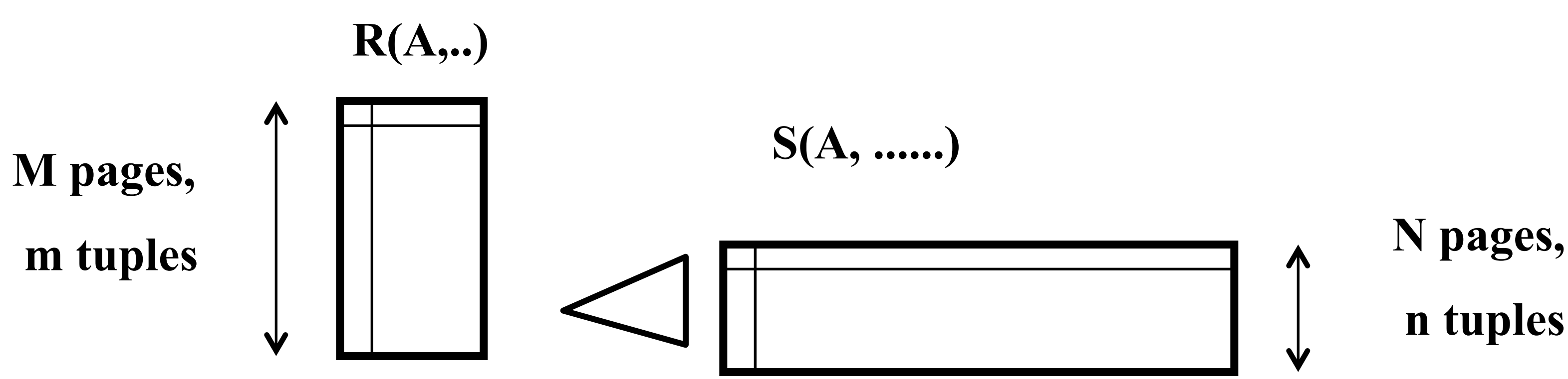


Nested loops - guidelines

- pick as outer the smallest table (= fewest pages)
- fit as much of it in memory as possible
- loop over the inner

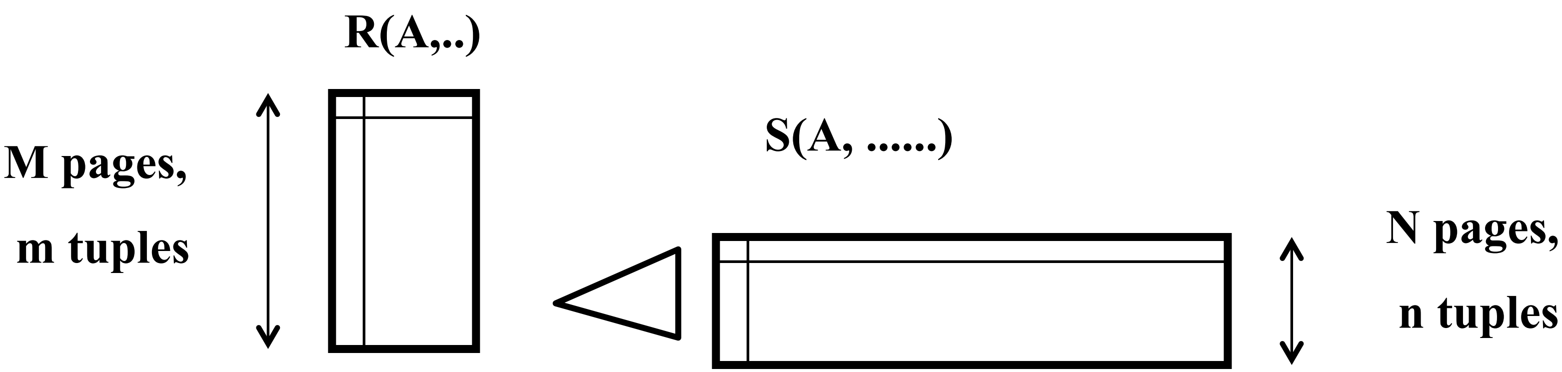
Index NL join

- use an existing **index**, or even build one on the fly
- cost: M + m * c   (c: look-up cost)



Index NL join

- cost: M + m * c   (c: look-up cost)
- ‘c’ depends whether the index is clustered or not.

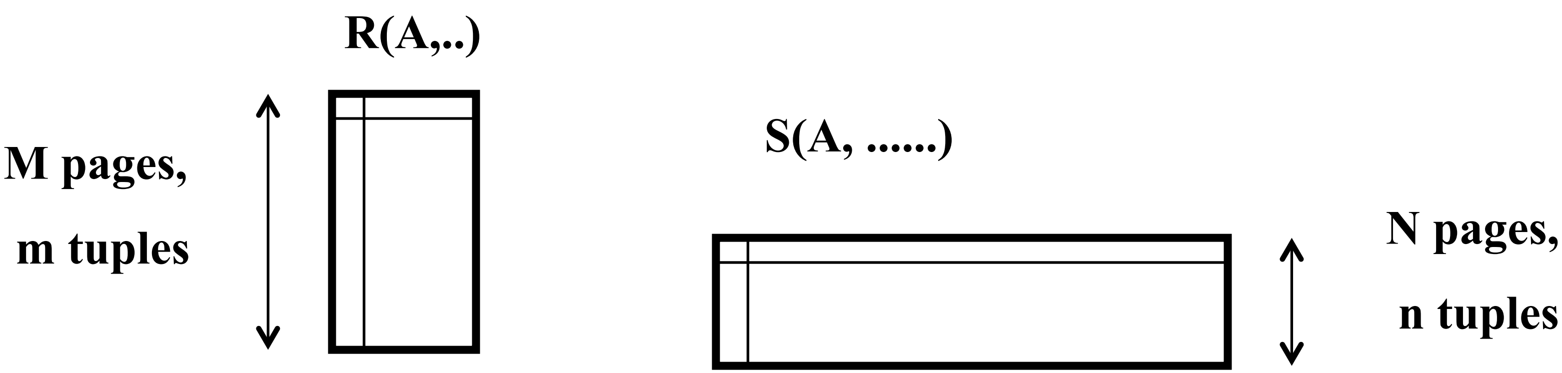


Joins

- Join techniques we will cover:
  - Nested-loops join
  - Index-nested loops join
  - Sort-merge join
  - Hash join

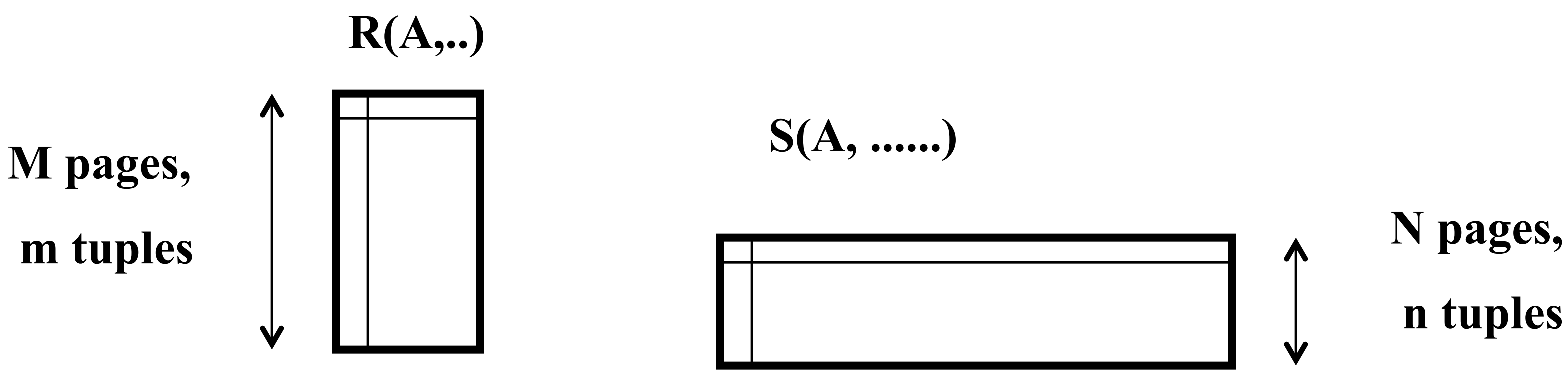
Sort-merge join

- sort both on joining attributed
- scan each and merge
- Cost, given B buffers?



Sort-merge join

- Cost, given B buffers?
- ~ 2*M*logM/logB + 2*N* logN/logB + M + N



Sort-Merge Join

- Useful if

Sort-Merge Join

- Useful if
  - one or both inputs are already sorted on join attribute(s)
  - output is required to be sorted on join attributes(s)
- "Merge" phase can require some back tracking if duplicate values appear in join column

Example of Sort-Merge Join

sid	sname	rating	age
22	dustin	7	45.0
28	yuppy	9	35.0
31	lubber	8	55.5
44	guppy	5	35.0
58	rusty	10	35.0

sid	bid	day	rname
28	103	12/4/96	guppy
28	103	11/3/96	yuppy
31	101	10/10/96	dustin
31	102	10/12/96	lubber
31	101	10/11/96	lubber
58	103	11/12/96	dustin

Example of Sort-Merge Join

- With 35, 100 or 300 buffer pages, both Reserves and Sailors can be sorted in 2 passes; total join cost: 7500.
- (while *Block Nested Loop (BNL) cost: 2,500 to 15,000 I/Os*)

Sort-merge join

- Worst case for merging phase?
- Cost?

Refinements

- All the refinements of external sorting
- plus overlapping of the merging of sorting with the merging of joining.

Joins

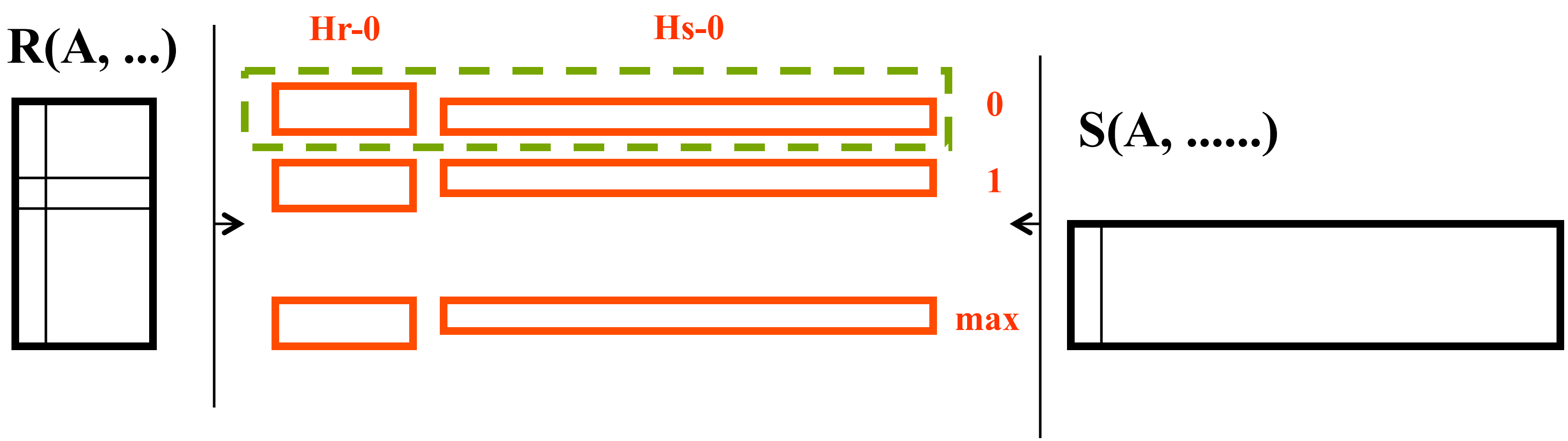
- Join techniques we will cover:
  – Nested-loops join
  – Index-nested loops join
  – Sort-merge join
  – Hash join

Hash joins

- hash join: use hashing function h()
  - hash ‘R’ into (0, 1, ..., ‘max’) buckets
  - hash ‘S’ into buckets (same hash function)
  - join each pair of matching buckets

Hash join - details

– how to join each pair of partitions Hr-i, Hs-i ?
– A: build another hash table for Hs-i, and probe it with each tuple of Hr-i



Hash join - details

- In more detail:
- Choose the (page-wise) smallest - if it fits in memory, do ~NL
  - and, actually, build a hash table (with h2() != h())
  - and probe it, with each tuple of the other

Hash join details

- what if Hs-i is too large to fit in main-memory?
- A: recursive partitioning
- more details (overflows, hybrid hash joins): in book
- cost of hash join? (if we have enough buffers:)

    3(M + N) (why? See next slide)

Cost of Hash-Join

- In partitioning phase, read+write both relns; 2(M+N). In matching phase, read both relns; M+N I/Os.
- In our running example, this is a total of 4500 I/Os.

Hash join details

- [cost of hash join? (if we have enough buffers:)

  3(M + N)

  ]
- What is 'enough'? sqrt(N), or sqrt(M)?

Hash join details

- [cost of hash join? (if we have enough buffers:)

  3(M + N)

  ]
- What is 'enough'? sqrt(N), or sqrt(M)?
- A: sqrt(smallest) (why?)
  - Because you only need enough memory to hold the hash table partitions of the smaller table in memory so B > size of smaller/B -1 → B ~ sqrt(size-of-smaller)

Sort-Merge Join vs. Hash Join

- Given a minimum amount of memory both have a cost of 3(M+N) I/Os.

(min. memory for sort-merge = sqrt(larger table) using aggressive refinements---in textbook)

(min. memory for hash = sqrt(smaller table)---see previous slides)

Sort-Merge vs Hash join

- Hash Join Pros:
  - ??
  - ??
  - ??
- Sort-Merge Join Pros:
  - ??

Sort-Merge vs Hash join

- Hash Join Pros:
  - Superior if relation sizes differ greatly
  - Shown to be highly parallelizable *(beyond scope of class)*
- Sort-Merge Join Pros:
  - ??

Sort-Merge vs Hash join

- Hash Join Pros:
  - Superior if relation sizes differ greatly
  - Shown to be highly parallelizable *(beyond scope of class)*
- Sort-Merge Join Pros:
  - Less sensitive to data skew
  - Result is sorted (may help "upstream" operators)
  - goes faster if one or both inputs already sorted

General Join Conditions

- Equalities over several attributes (e.g., *R.sid=S.sid* AND *R.rname=S.sname*):
  - all previous methods apply, using the composite key

VirginiaTech

General Join Conditions

- Inequality conditions (e.g., *R.rname < S.sname*):
- which methods still apply?
  - NL
  - index NL
  - Sort merge
  - Hash join

General Join Conditions

- Inequality conditions (e.g., *R.rname < S.sname*):
- which methods still apply?
  - NL (probably, the best!)
  - index NL (only if clustered index)
  - Sort merge (does not apply!) (why?)
  - Hash join (does not apply!) (why?)

Set Operations

SKIP

- Intersection and cross-product: special cases of join
- Union (Distinct) and Except: similar; we'll do union:
- Effectively: concatenate; use sorting or hashing
- Sorting based approach to union:
  - Sort both relations (on combination of all attributes).
  - Scan sorted relations and merge them.
  - *Alternative*: Merge runs from Pass 0 for *both* relations.

Set Operations, cont'd

SKIP

- Hash based approach to union:
  - Partition R and S using hash function *h*.
  - For each S-partition, build in-memory hash table (using *h2*), scan corresponding R-partition and add tuples to table while discarding duplicates.

Aggregate Operations (AVG, MIN, etc.)

SKIP

- Without grouping:
  - In general, requires scanning the relation.
  - Given index whose search key includes all attributes in the SELECT or WHERE clauses, can do index-only scan.

VirginiaTech

Summary

- A virtue of relational DBMSs:
  - queries are composed of **a few basic operators**
  - The implementation of these operators can be **carefully tuned**
  - **Important** to do this!
- Many alternative implementation techniques for each operator
  - No universally superior technique for most operators.

"it depends" [Guy Lohman (IBM)]

Summary cont’d

- Must consider available alternatives for each operation in a query and choose best one based on system statistics, etc.
  – Part of the broader task of optimizing a query composed of several ops.