

# CS 4604: Introduction to Database Management Systems

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Lecture #11: Query Processing and  
Midterm Review

# 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.

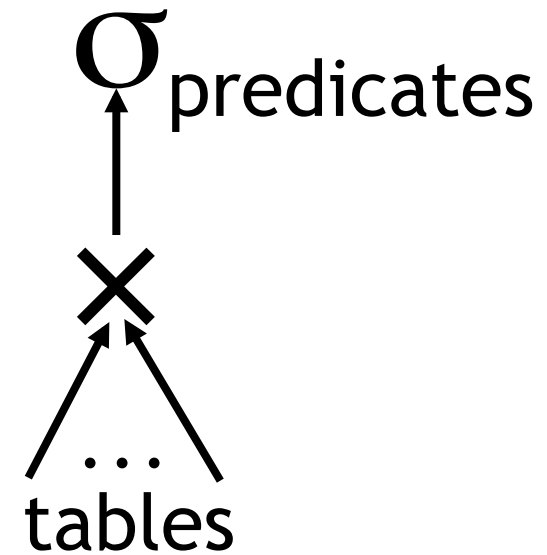
# A Really Bad Query Optimizer

- For each Select-From-Where query block

- do cartesian products first
- then do selections
- etc, ie.:
  - GROUP BY; HAVING
  - projections
  - ORDER BY

- Incredibly inefficient

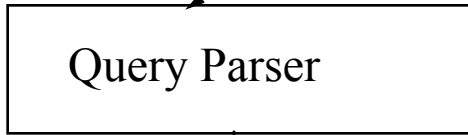
- Huge intermediate results!



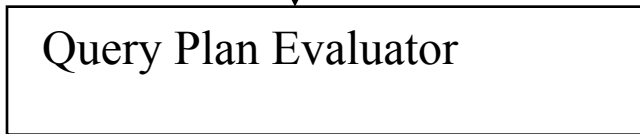
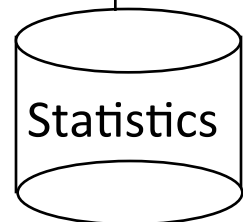
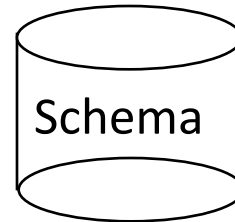
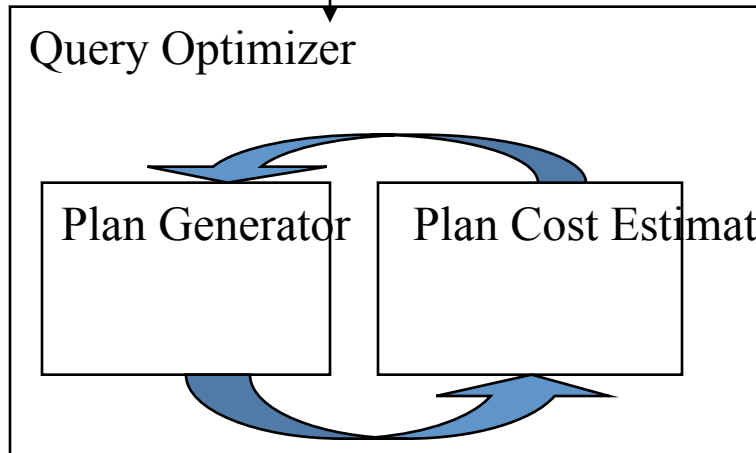
# Cost-based Query Sub-System

Queries

```
Select *
From Blah B
Where B.blah = blah
```



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 (  $\sigma$  ) Selects a subset of rows from relation.
  - Projection (  $\pi$  ) 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 (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)

Reserves (*sid*: integer, *bid*: integer, *day*: dates, *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.
  - $M=1000$ ,  $p_R=100$ .

# Simple Selections

- Of the form  $\sigma_{R.attr \text{ op } value} (R)$
- 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 =  $10 \text{ I/Os} + [\text{selectivity} * \# \text{pages}]$

# Simple Selections (cont'd)

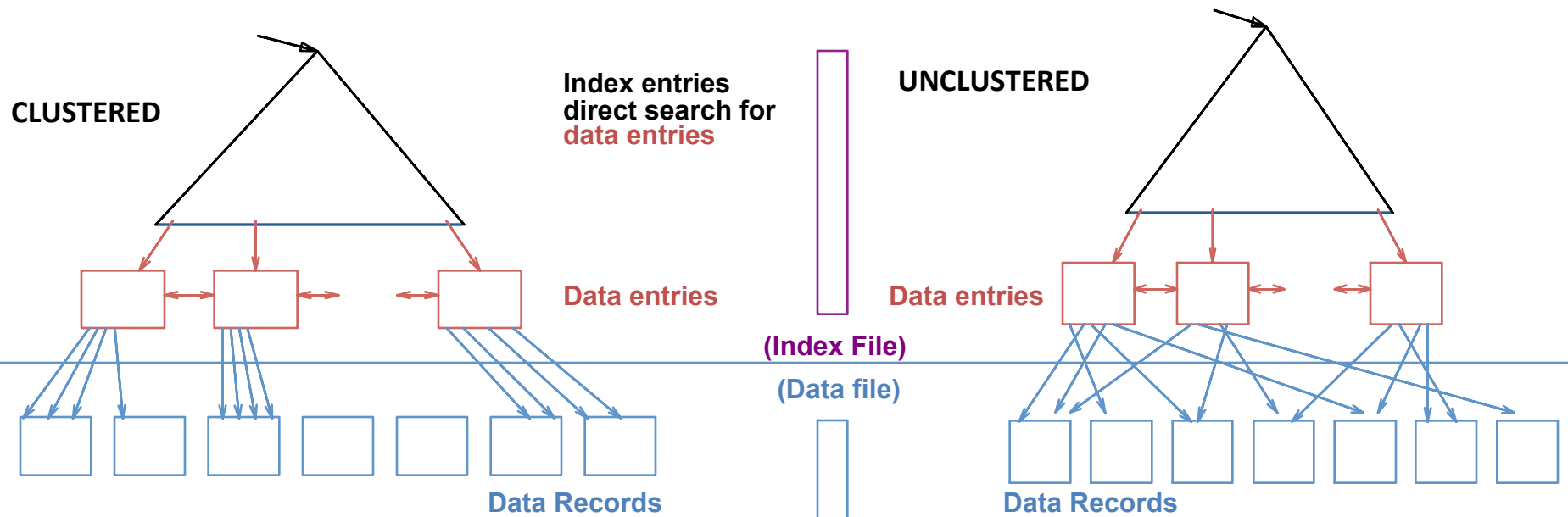
- With an index on selection attribute:
  - Use index to find qualifying data entries,
  - then retrieve corresponding data records.
  - (Hash index useful only for equality selections.)

# 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 (cont'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

*(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:

# General Selection Conditions



*(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



*(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  $\langle a, b, c \rangle$  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



- 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



- First approach: 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.

# Cheapest Access Path - Example

- 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  $\langle bid, sid \rangle$  could be used;
  - Then, *day < 8/9/94* must be checked.



# Cheapest Access Path - cnt'd

- 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>?*



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# Intersection of RIDs



- 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)

- 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.



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# 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

$$1000 + 250 + 2 * 2 * 250 + 250 = 2500 \text{ I/Os}$$

# Projection



- 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  $\langle a, b, c \rangle$  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
```

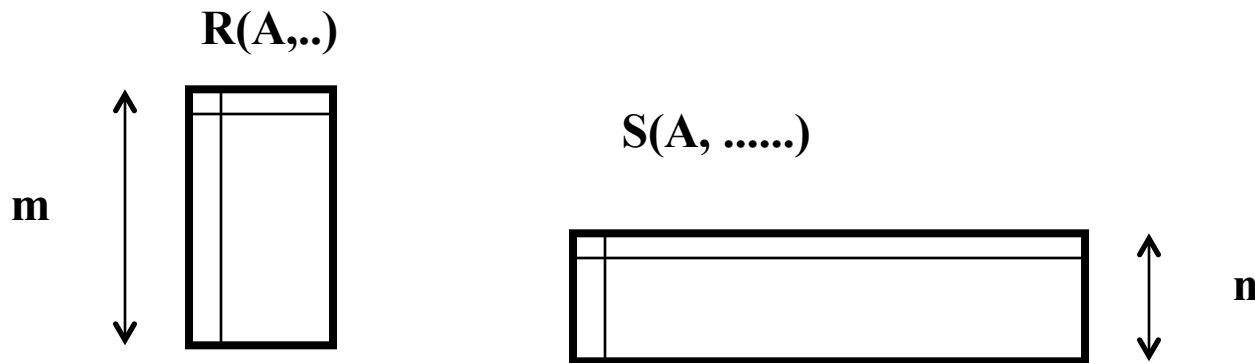
- In algebra:  $R \bowtie S$ . Common! Must be carefully optimized.  $R \times S$  is large; so,  $R \times S$  followed by a selection is inefficient.
- Remember, join is associative and commutative.

# 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.

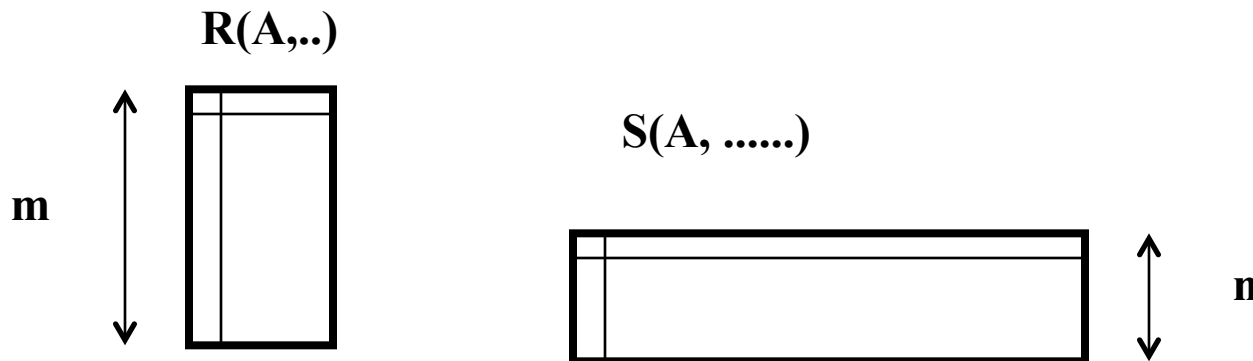
# Nested loops

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



# Nested loops

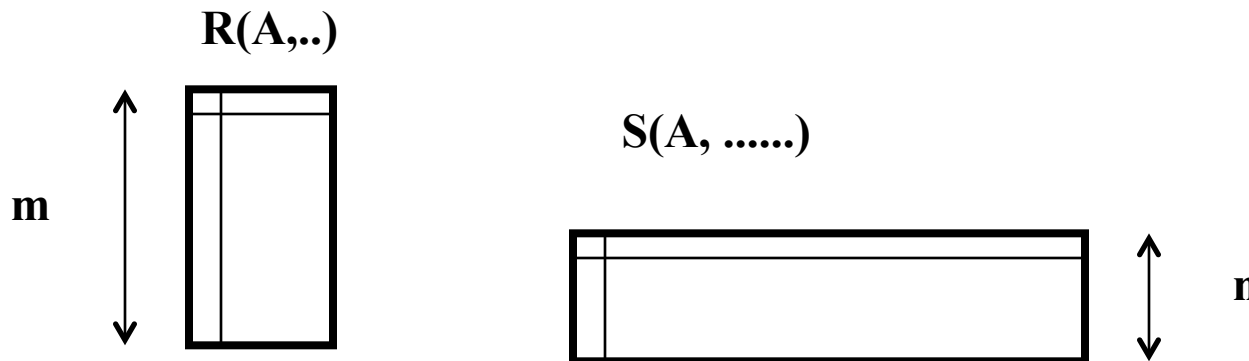
- Algorithm #0: (naive) nested loop (**SLOW!**)  
 for each tuple  $r$  of  $R$   
   for each tuple  $s$  of  $S$   
     print, if they match



# Nested loops

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

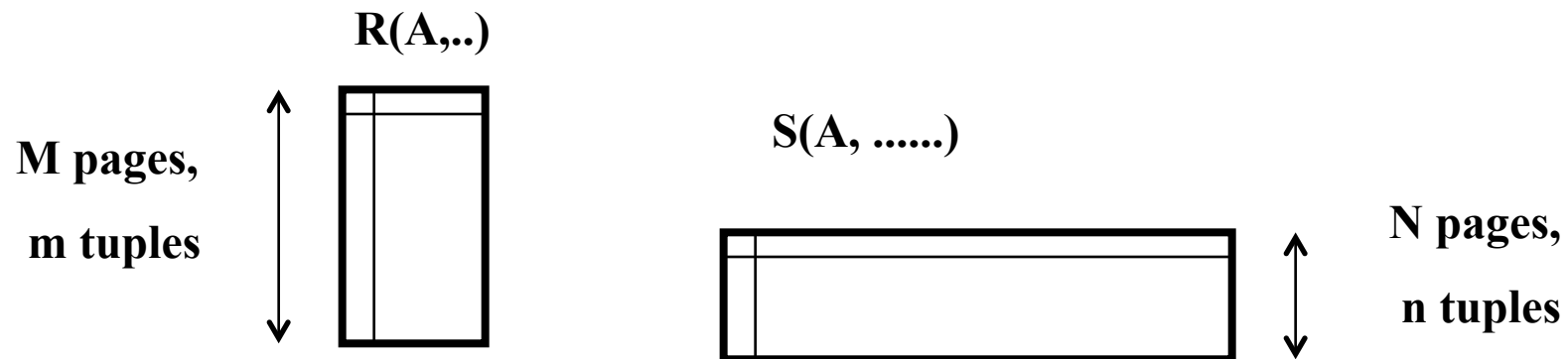
for each tuple  $r$  of  $R$  ← outer relation  
 for each tuple  $s$  of  $S$  ← inner relation  
 print, if they match





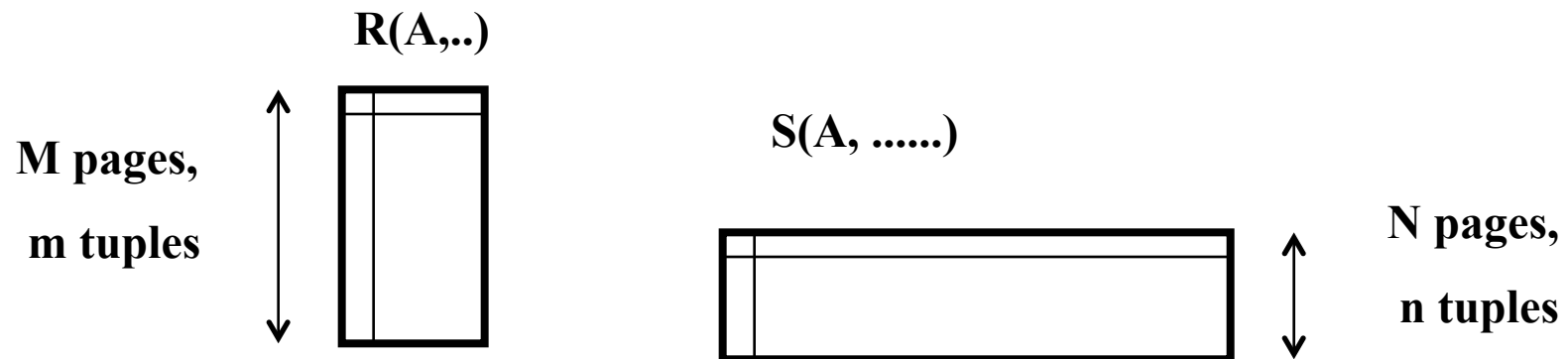
# Nested loops

- 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

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

– At 10ms/IO, Total: ???

- What if smaller relation (S) was outer?
- What assumptions are being made here?

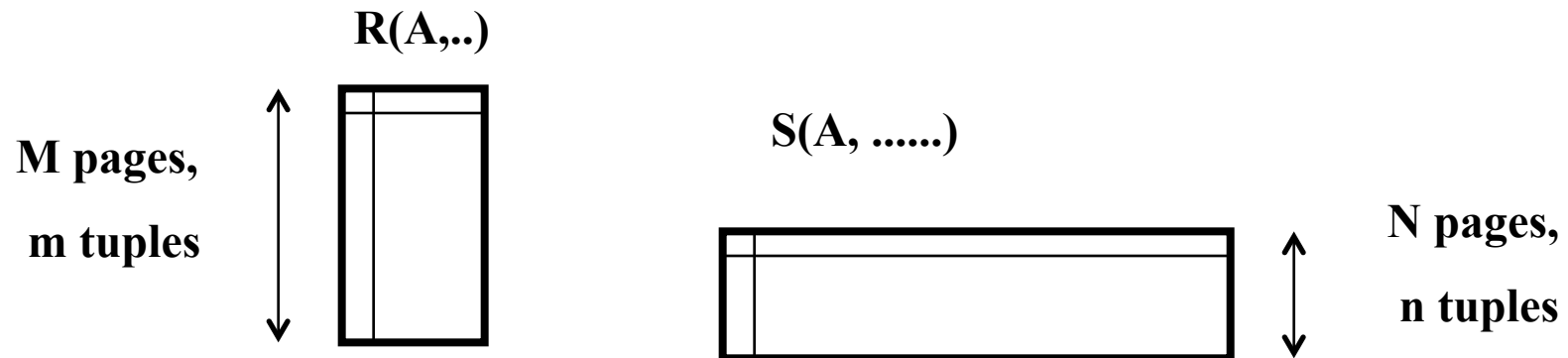
# Simple Nested Loops Join

- 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

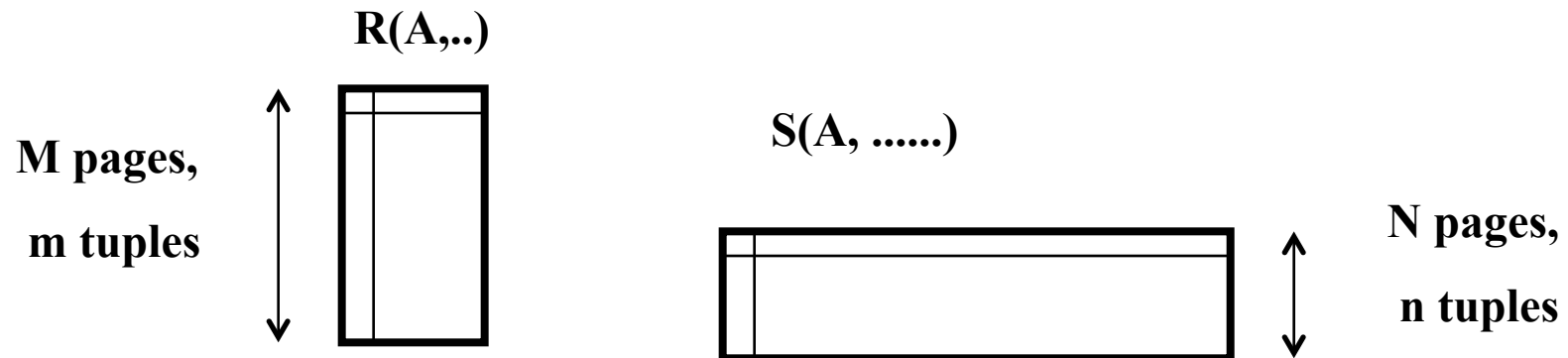
COST?



# Nested loops

- Algorithm #1: Blocked nested-loop join
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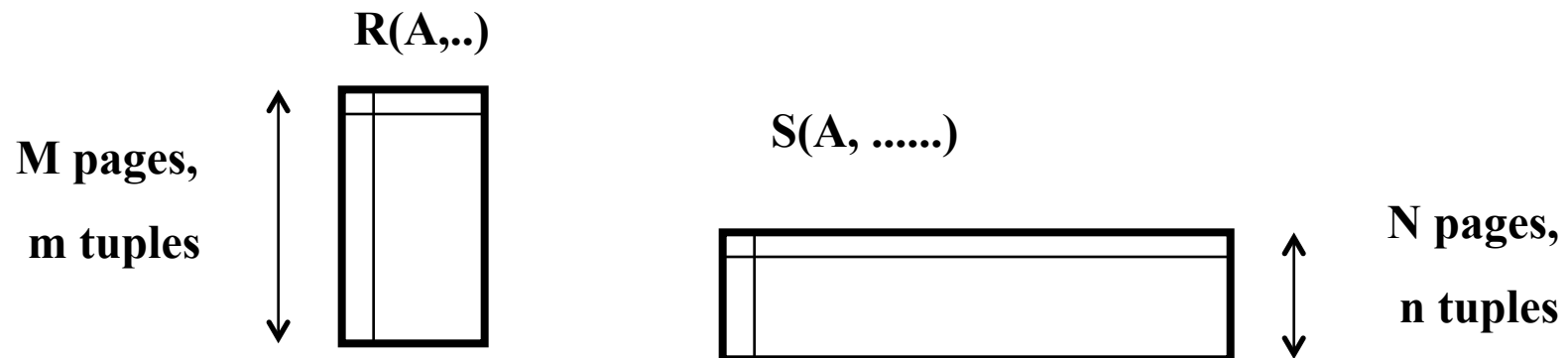
$$\text{COST} = M + M * N$$



# Nested loops

- Which one should be the outer relation?

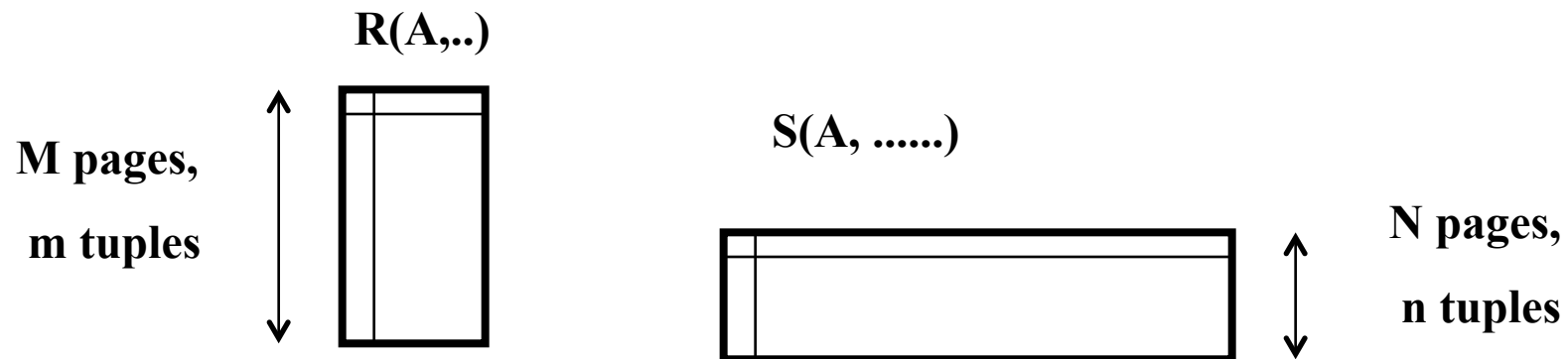
$$\text{COST} = M + M * N$$



# Nested loops

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

$$\text{COST} = M + M * N$$

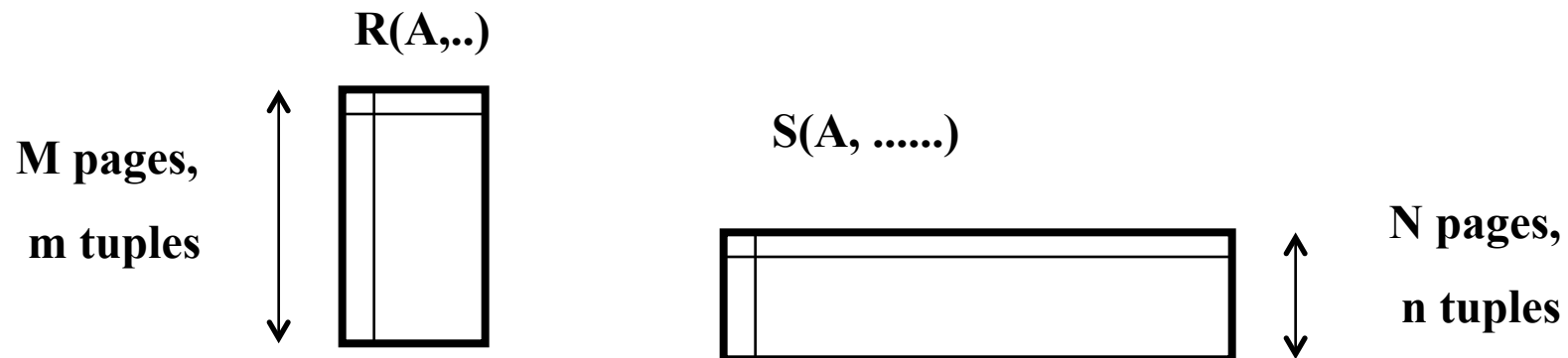




# Nested loops

- $M=1000, N=500$
- $\text{Cost} = 1000 + 1000*500 = 501,000$
- $= 5010 \text{ sec} \sim 1.4\text{h}$

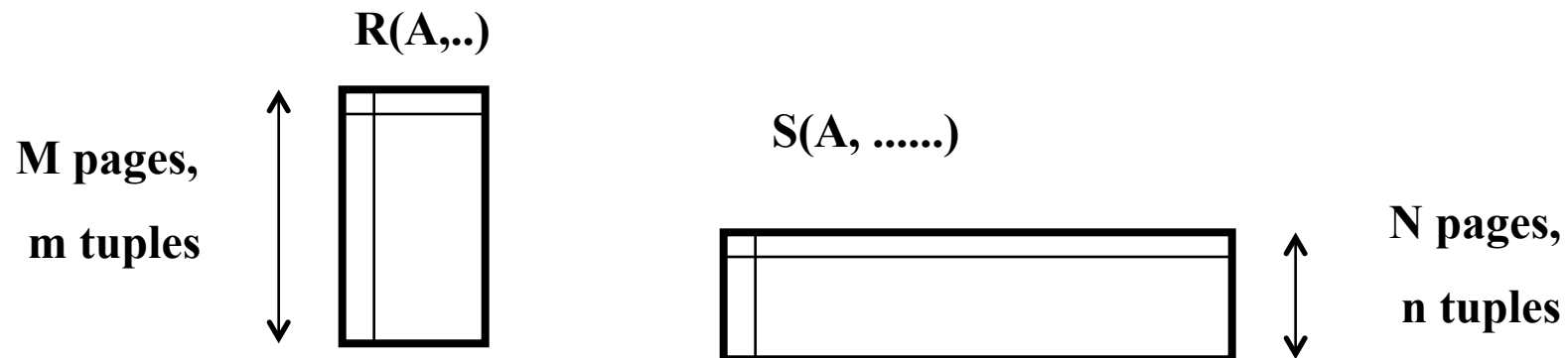
$$\text{COST} = M + M * N$$



# Nested loops

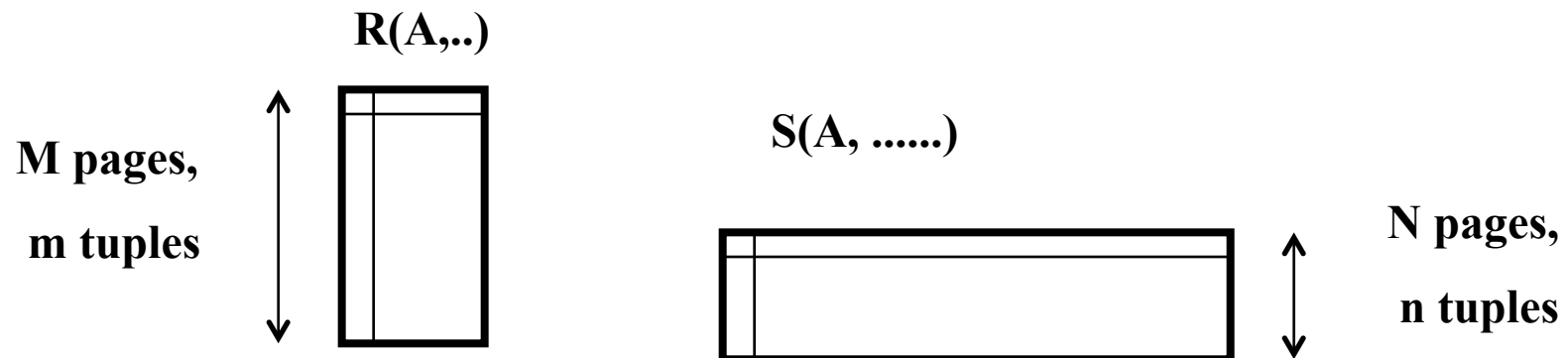
- $M=1000$ ,  $N=500$  - if smaller is outer:
- $\text{Cost} = 500 + 1000 * 500 = 500,500$
- $= 5005 \text{ sec} \sim 1.4\text{h}$

$$\text{COST} = N + M * N$$



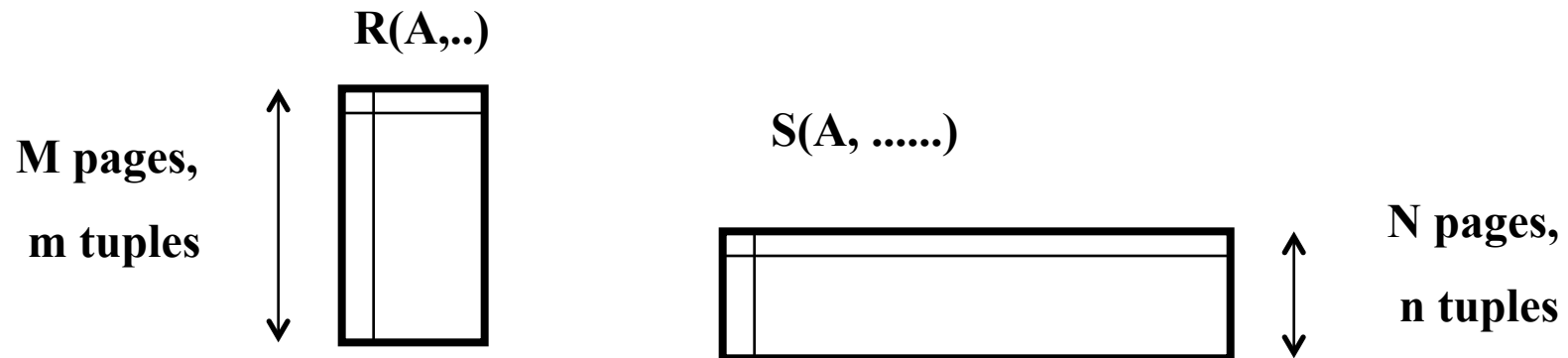
# Nested loops

- What if we have  $B$  buffers available?



# Nested loops

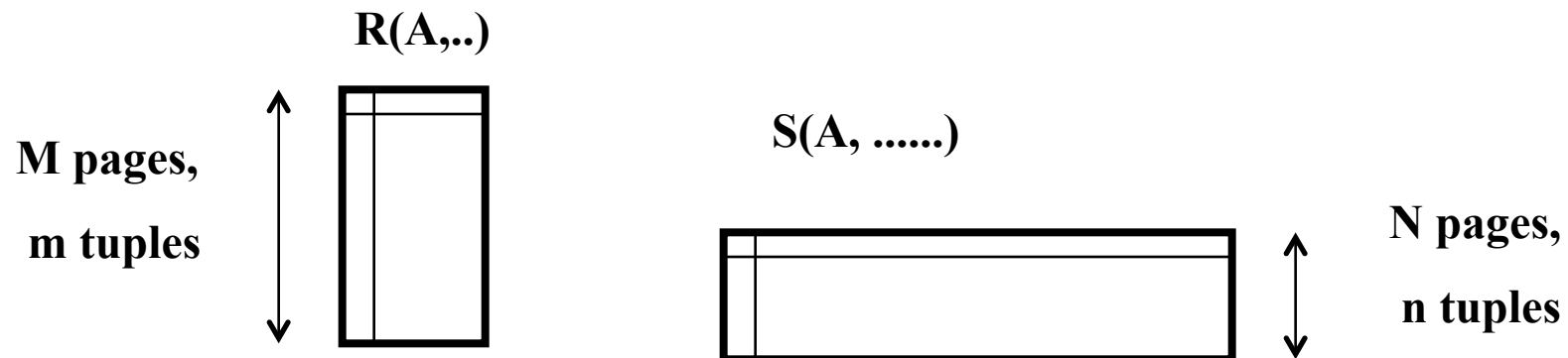
- What if we have  $B$  buffers available?
- A: give  $B-2$  buffers to outer, 1 to inner, 1 for output



# Nested loops

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

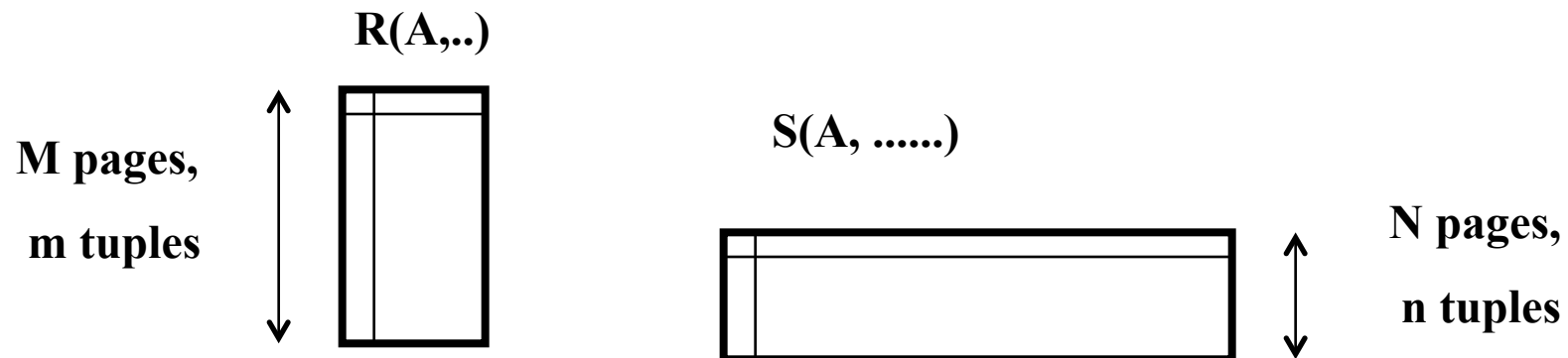
COST= ?



# Nested loops

- Algorithm #1: Blocked nested-loop join
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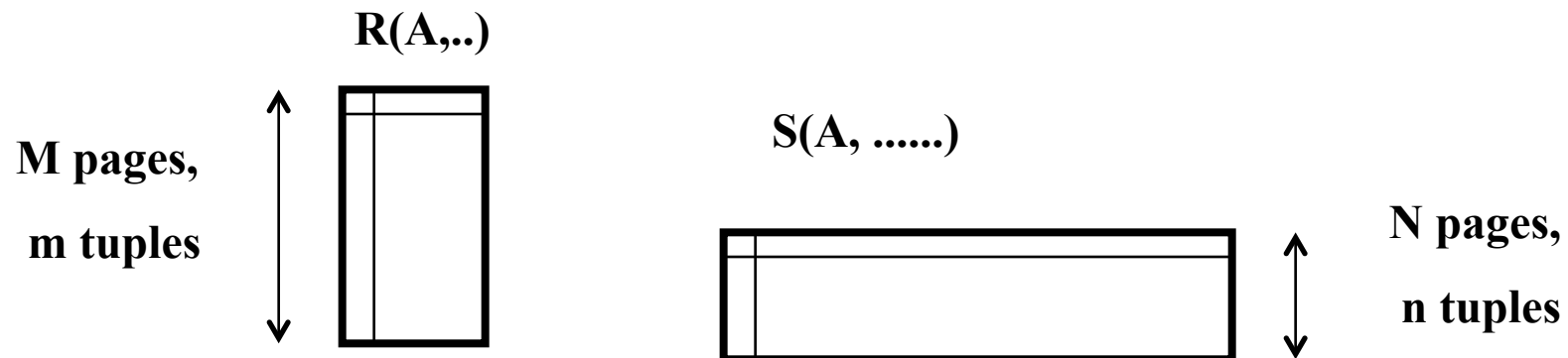
$$\text{COST} = M + M/(B-2) * N$$



# Nested loops

- and, actually:
- $\text{Cost} = M + \text{ceiling}(M/(B-2)) * N$

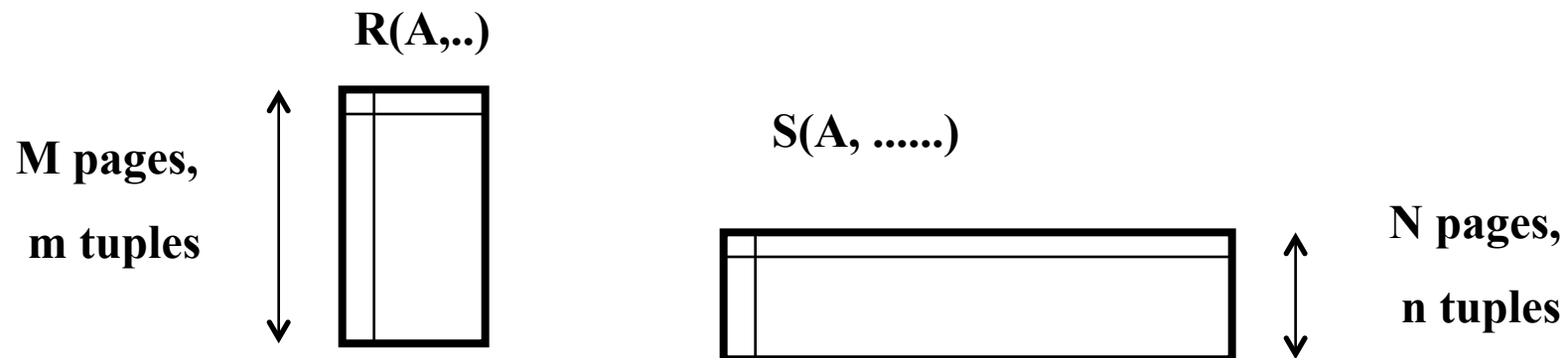
$$\text{COST} = M + M/(B-2) * N$$



# Nested loops

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

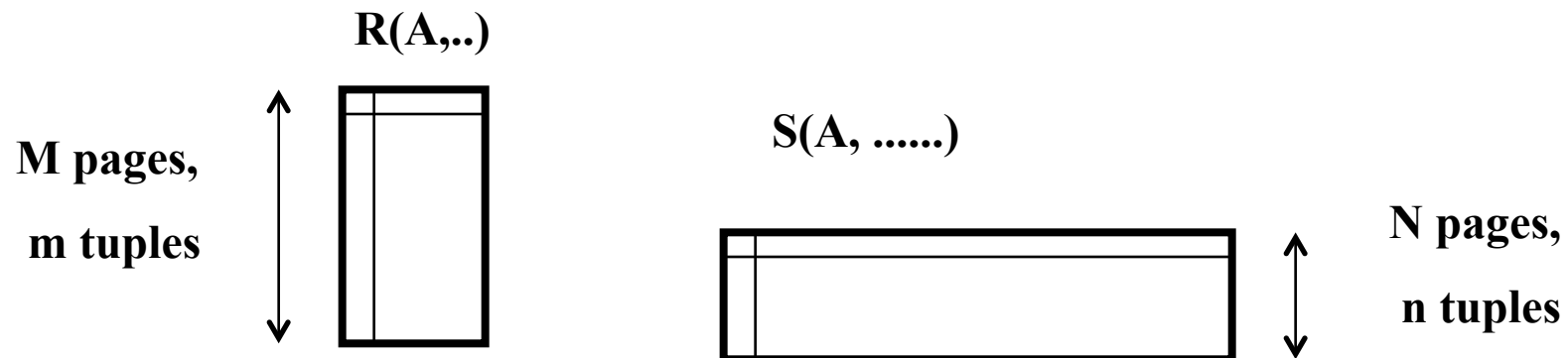
$$\text{COST} = N + N / (B - 2) * M$$





# Nested loops

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

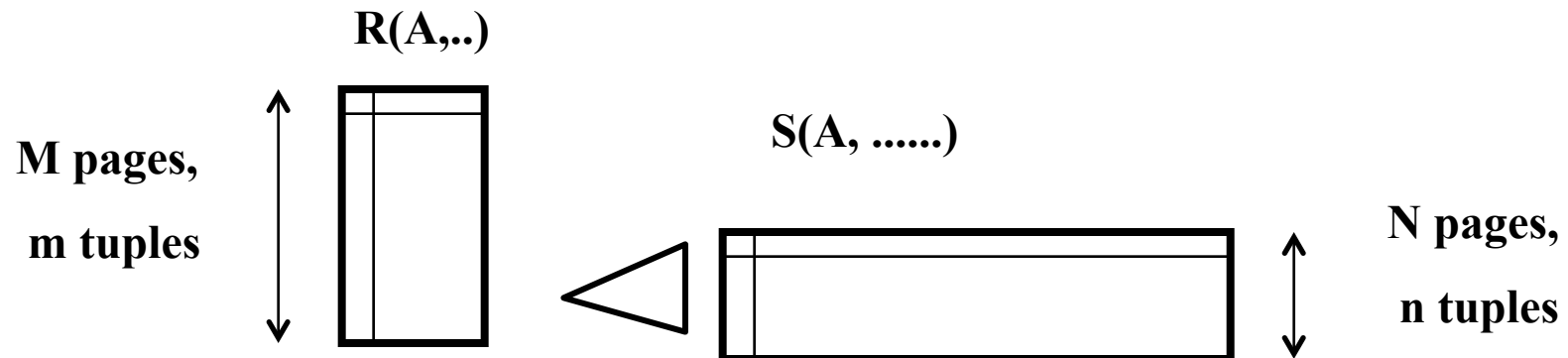


# Nested loops - guidelines

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

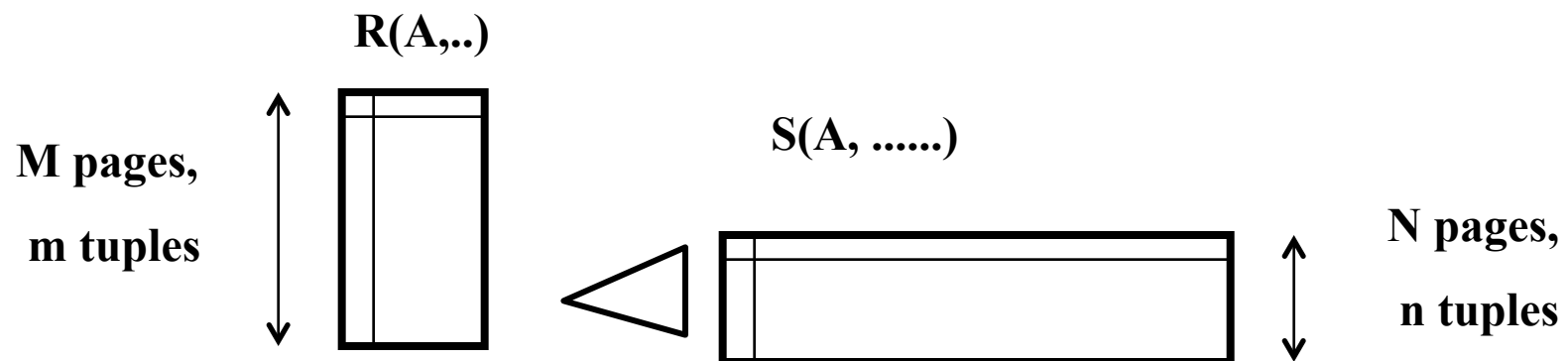
# Index NL join

- 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

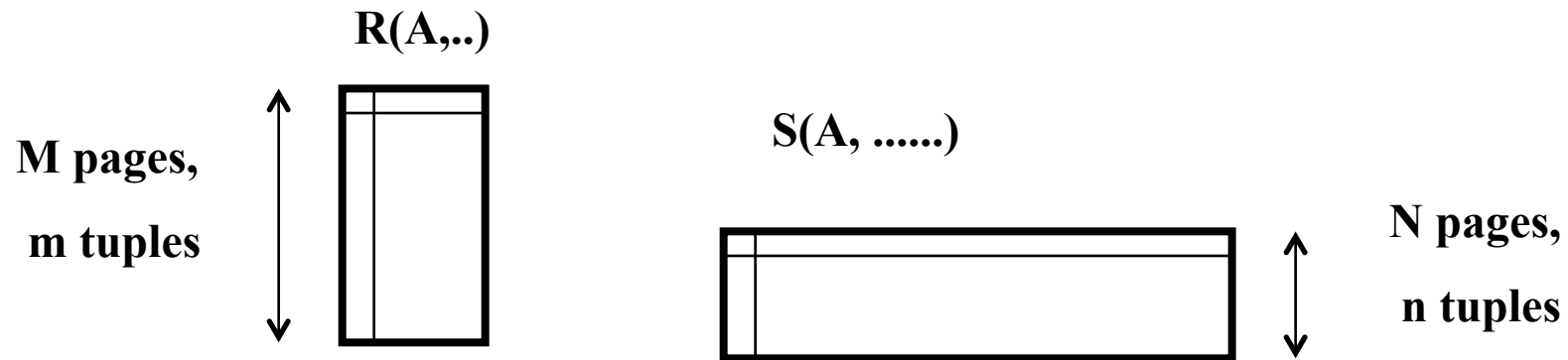
# Sort-merge join

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



# Sort-merge join

- Cost, given  $B$  buffers?
- $\sim 2 * M * \log M / \log B + 2 * N * \log N / \log B + M + N$



# 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

<u>sid</u>	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

<u>sid</u>	<u>bid</u>	<u>day</u>	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

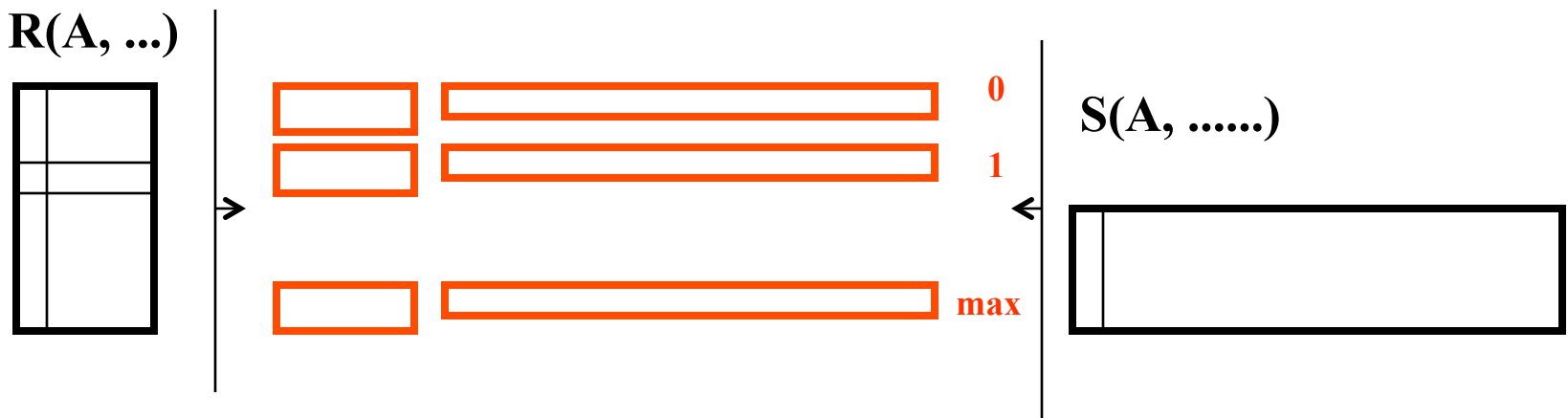
- All the refinements of external sorting
- plus overlapping of the merging of sorting with the merging of joining.

# Joins

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

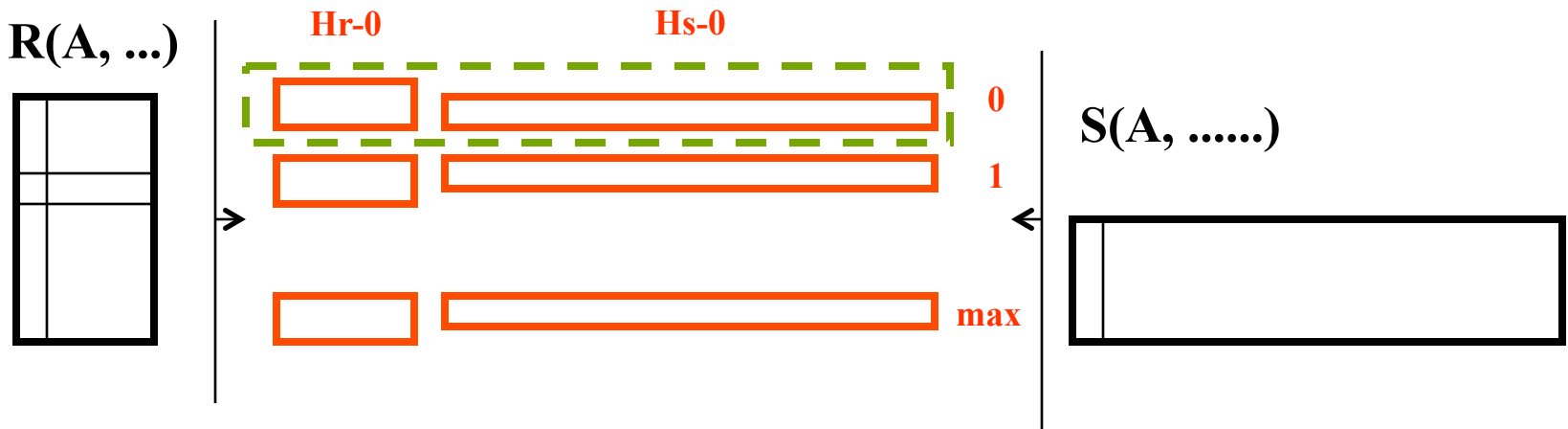
# Hash joins

- hash join: use hashing function  $h()$ 
  - hash ‘R’ into  $(0, 1, \dots, \text{‘max’})$  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  $\sim NL$ 
  - and, actually, build a hash table (with  $h_2() \neq h()$ )
  - and probe it, with each tuple of the other

# Hash join details

- what if  $H_{s-i}$  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:  $\sqrt{\text{smallest}}$  (why?)
  - Because you only need enough memory to hold the hash table partitions of the smaller table in memory so  $B > \text{size of smaller} / B - 1 \rightarrow B \sim \sqrt{\text{size-of-smaller}}$

# 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 =  $\sqrt{\text{larger table}}$ )  
using aggressive refinements---in textbook)

(min. memory for hash =  $\sqrt{\text{smaller table}}$ )---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

# 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



- 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



- Hash based approach to union:
  - Partition R and S using hash function  $h$ .
  - For each S-partition, build in-memory hash table (using  $h_2$ ), scan corresponding R-partition and add tuples to table while discarding duplicates.

# Aggregate Operations (AVG, MIN, etc.)



- 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.

# 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.

# MIDTERM REVIEW

# Course Outline

- Weeks 1–4: Query/ Manipulation Languages and Data Modeling
  - Relational Algebra
  - Data definition
  - Programming with SQL
  - Entity-Relationship (E/R) approach
  - Specifying Constraints
  - Good E/R design
- Weeks 5–8: Indexes, Processing and Optimization
  - Storing
  - Hashing/Sorting
  - Query Optimization
  - NoSQL and Hadoop
- Week 9-10: Relational Design
  - Functional Dependencies
  - Normalization to avoid redundancy
- Week 11-12: Concurrency Control
  - Transactions
  - Logging and Recovery
- Week 13–14: Students' choice
  - Practice Problems
  - XML
  - Data mining and warehousing

# Course Outline: For Midterm Exam

- Weeks 1–4: Query/ Manipulation Languages and Data Modeling
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  - Data mining and warehousing

No Query Processing/ Optimization

# FUNDAMENTAL

## Relational operators

- selection

$$\sigma_{condition} (R)$$

- projection

$$\pi_{att-list} (R)$$

- cartesian product

$$R \times S$$

- set union

$$R \cup S$$

- set difference

$$R - S$$

# Relational ops

- Surprisingly, they are enough!
- Derived/convenience operators:
  - set intersection  $\cap$
  - **join** (theta join, natural join)  $\bowtie$
  - ‘rename’ operator  $\rho_{R'}(R)$
  - division  $R \div S$

# Extended Operators

- Powerful operators based on basic relational operators and bag semantics.
- **Sorting**: convert a relation into a list of tuples.
- **Duplicate elimination**: turn a bag into a set by eliminating duplicate tuples.
- **Grouping**: partition the tuples of a relation into groups, based on their values among specified attributes.
- **Aggregation**: used by the grouping operator and to manipulate/combine attributes.
- **Extended projections**: projection on **steroids**.
- **Outerjoin**: extension of joins that make sure every tuple is in the output.

# Basic SQL Query

```
SELECT [DISTINCT] target-list  
FROM relation-list  
WHERE qualification;
```

- **Relation-list:** A list of relation names (possibly with **range-variable** after each name).
- **Target-list:** A list of attributes of relations in relation-list
- **Qualification:** conditions on attributes
- **DISTINCT:** optional keyword for duplicate removal.
  - Default = no duplicate removal!



# SQL

- Handling Sub-queries
- SQL Data Definition Commands
- Constraints
- Triggers
- ...

# E/R Diagrams

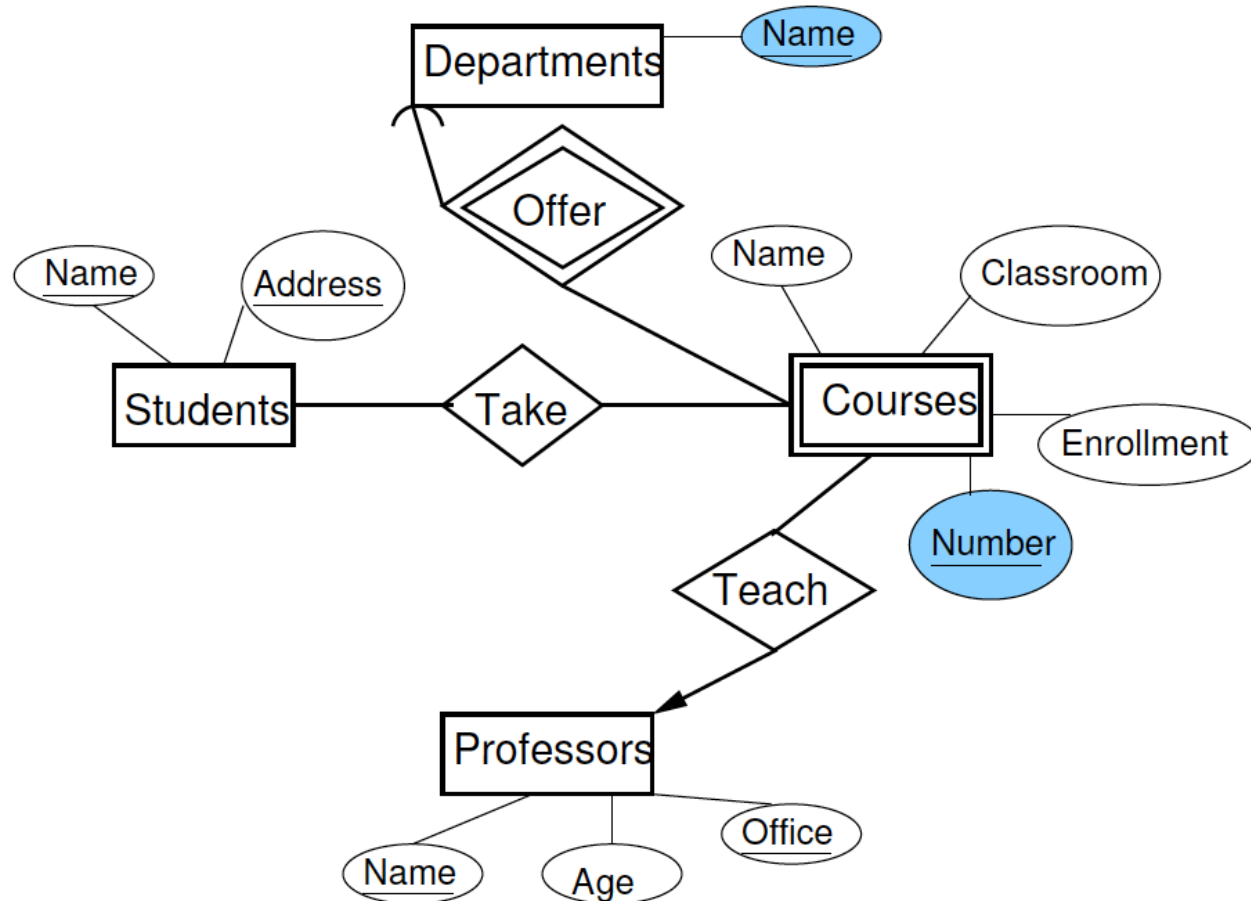
- **IMPORTANT:**
  - **Follow only lecture slides for this topic!**
  - Differences from the book:
    - More details
    - Slightly different notation

# Relationships

- Show a many-one relationship by **an arrow entering the “one” side.**      Many  $\longrightarrow$  One
- Show a one-one relationship by **arrows entering both entity sets.**      One  $\longleftrightarrow$  One
- In some situations, we can also assert **“exactly one,”** i.e., each entity of one set must be related to exactly one entity of the other set. To do so, we use a **rounded arrow.**       $\longrightarrow$  Exactly One

# E/R Example (does not contain ISA)

- Each department teaches multiple courses. Each course has a number. What is the key for the entity set Courses?



# Converting E/R Diagrams to Relational Designs

- Entity Set  $\rightarrow$  Relation
  - Attribute of Entity Set  $\rightarrow$  Attribute of a Relation
- Relationship  $\rightarrow$  relation whose attributes are
  - Attribute of the relationship itself
  - Key attributes of the connected entity sets
- Several special cases:
  - Weak entity sets.
  - Combining relations (especially for many-one relationships)
  - *ISA* relationships and subclasses

# Tree Indexes

- B+-Trees
  - **Carefully internalize the Definition!**
  - Searching
  - Inserting
  - Deleting

# Hashing/Sorting

- Extendible Hashing
  - Linear Hashing
  - External Sorting
- 
- Again, how to search and build, internalize the structure
  - Sorting: understand the process, how to cost it, how many passes it takes etc.

# Exam

- **No** aids allowed EXCEPT:
  - **Only written (not typed)** 1 letter-size page (you may use **both** sides)
  - A calculator (NOT your smartphone)
- Duration: 75 mins, during class March 6, Thursday
- More or less equal weightage to all the topics
  - Questions will be similar to the HWs, Handouts