Database Applications (15-415)

DBMS Internals- Part VII
Lecture 18, March 29, 2015

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Carnegie Mellon University Qatar

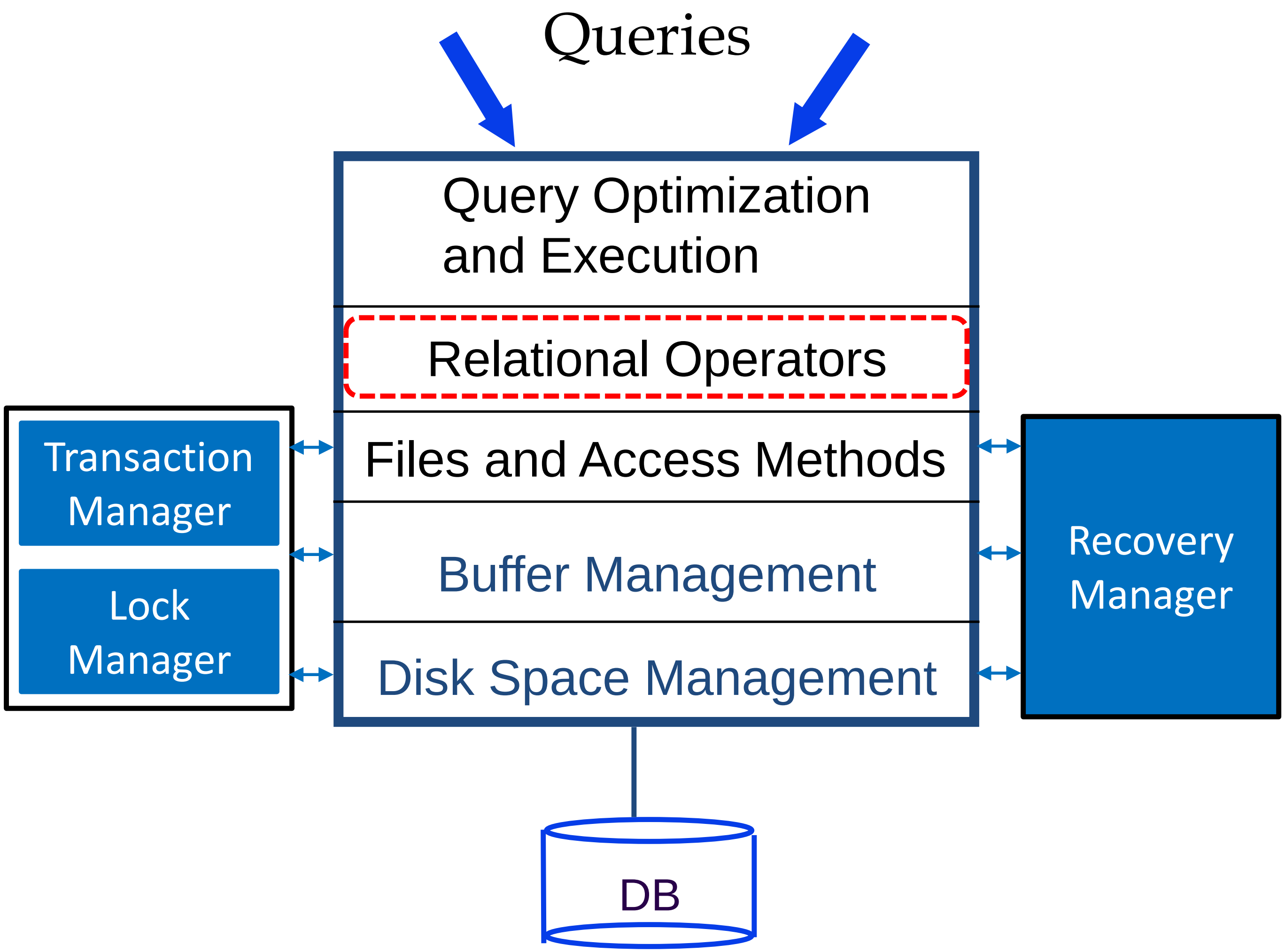
Today…

- Last Session:
  - DBMS Internals- Part VI
    - Algorithms for Relational Operations

- Today's Session:
  - DBMS Internals- Part VII
    - Algorithms for Relational Operations (*Cont'd*)

- Announcements:
  - Project 3 is due on Thursday, April 2nd by midnight
  - Quiz II will be held on Thursday, April 9th (all concepts covered after the midterm are included)

DBMS Layers



Queries
Query Optimization
and Execution
Relational Operators
Files and Access Methods
Buffer Management
Disk Space Management
Transaction
Manager
Lock
Manager
Recovery
Manager
DB

Relational Operations

- We will consider how to implement:
  - *Selection* (σ)
  - *Projection* (π)
  - *Join* ($\bowtie$)
  - *Set-difference* ($-$)
  - *Union* ($\cup$)
  - *Aggregation* (SUM, MIN, etc.) and GROUP BY
- Since each operation returns a relation, ops can be *composed*!
- After we cover how to implement operations, we will discuss how to *optimize* queries (formed by composing operators)

Outline

- Introduction
- The Selection Operation
- The Projection Operation
- The Join Operation ✓

Last Class

The Join Operation

- Consider the following query, Q, which implies a join:

```
SELECT *
FROM Reserves R, Sailors S
WHERE R.sid = S.sid
```

- How can we evaluate Q?
  - Compute R × S
  - Select (and project) as required

- But, the result of a cross-product is typically much larger than the result of a join

- Hence, it is very important to implement joins *without* materializing the underlying cross-product

The Join Operation

- We will study *five* join algorithms, *two* which enumerate the cross-product and *three* which do not

- Join algorithms which enumerate the cross-product:
  - Simple Nested Loops Join
  - Block Nested Loops Join

- Join algorithms which do not enumerate the cross-product:
  - Index Nested Loops Join
  - Sort-Merge Join
  - Hash Join

Assumptions

- We assume the following two relations:

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

- For Reserves, we assume:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages
- For Sailors, we assume:
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages
- Our cost metric is the number of I/Os

Assumptions (*Cont'd*)

- We assume *equality* joins with:
  - ***R*** representing Reserves and ***S*** representing Sailors
  - ***M*** pages in ***R***, p_R tuples per page, ***m*** tuples total
  - ***N*** pages in ***S***, p_S tuples per page, ***n*** tuples total

- We ignore the output and computational costs

The Join Operation

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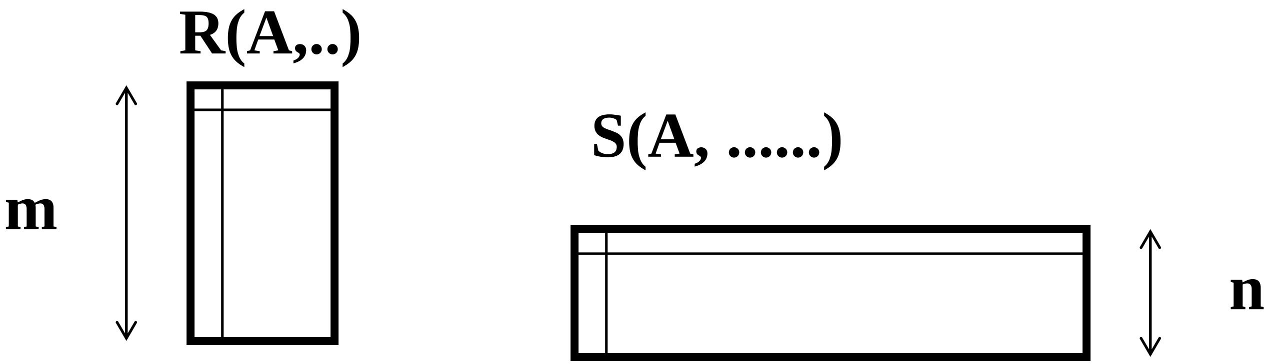
Simple Nested Loops Join

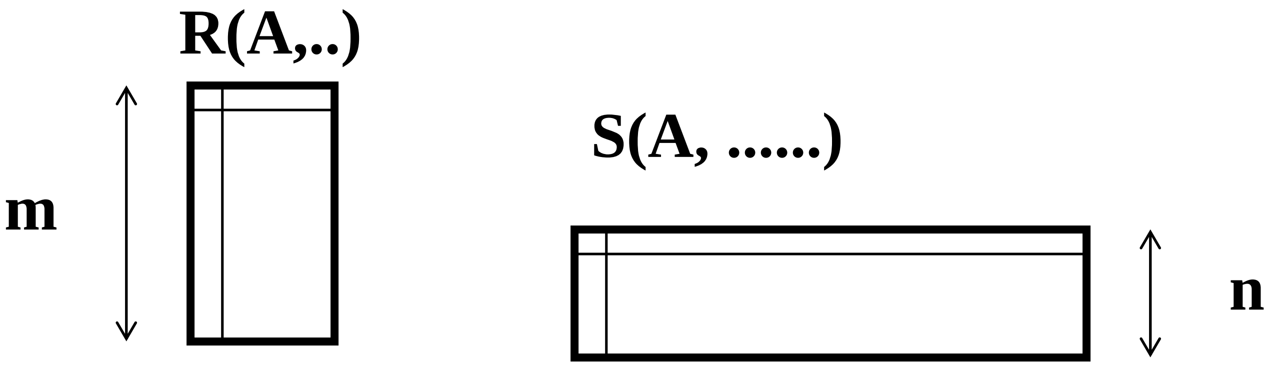
- Algorithm #0: (*naive*) nested loop (**SLOW**!)



Simple Nested Loops Join

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

```
for each tuple r of R
    for each tuple s of S
        print, if they match
```



Simple Nested Loops Join

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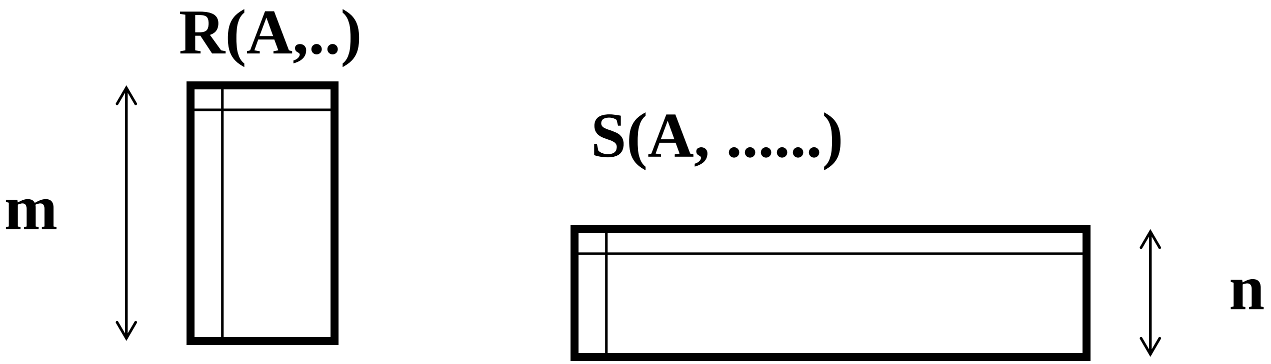
Outer Relation

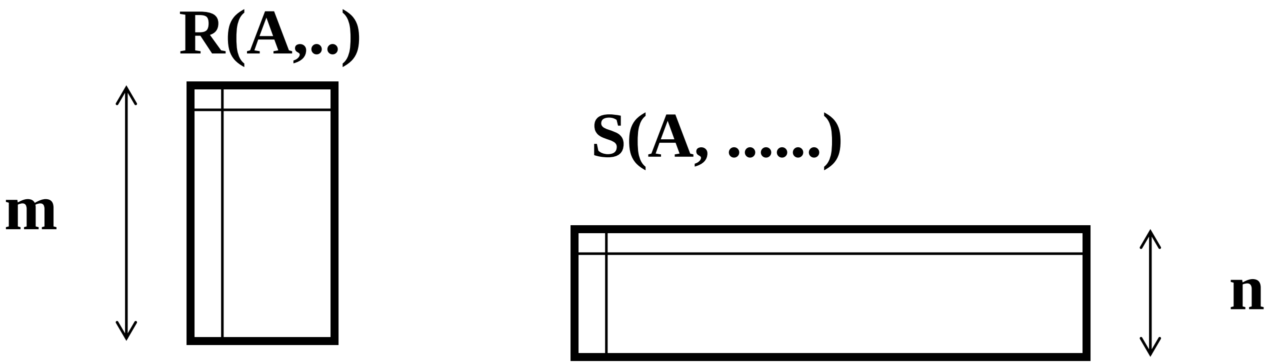
Inner Relation



Simple Nested Loops Join

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

How many disk accesses ('M' and 'N' are the numbers of pages for 'R' and 'S')?



Simple Nested Loops Join

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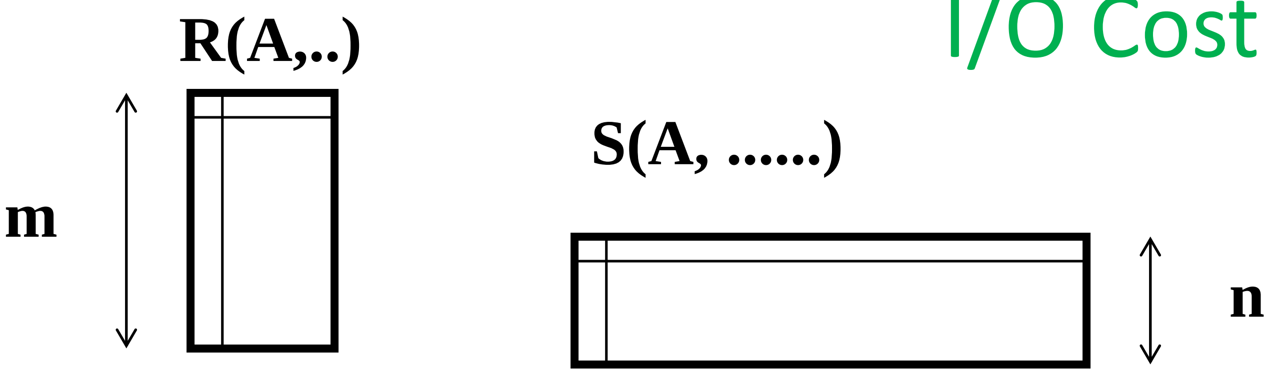
How many disk accesses ('M' and 'N' are the numbers of pages for 'R' and 'S')?

I/O Cost = M+m*N

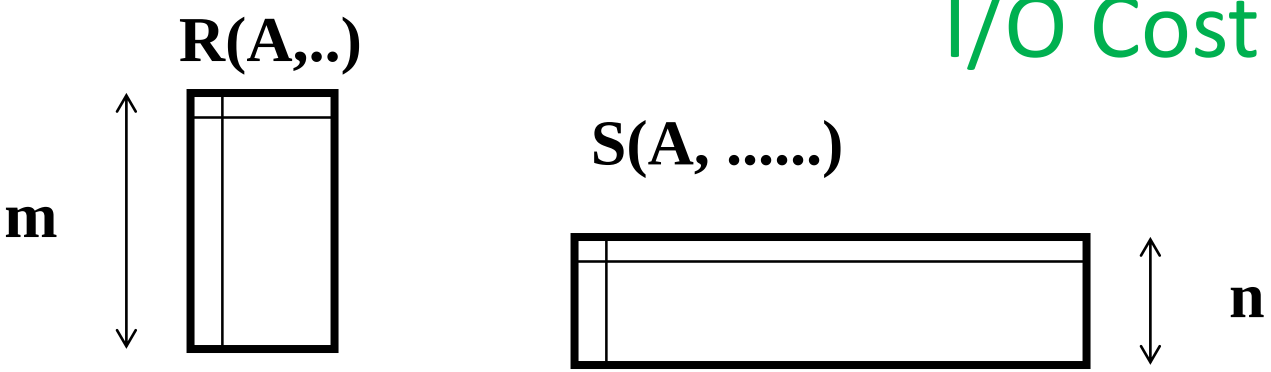


Simple Nested Loops Join

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

- Cost = M + (p_R * M) * N = 1000 + 100*1000*500 I/Os
- At 10ms/IO, total = ~6 days (!)

I/O Cost = M+m*N



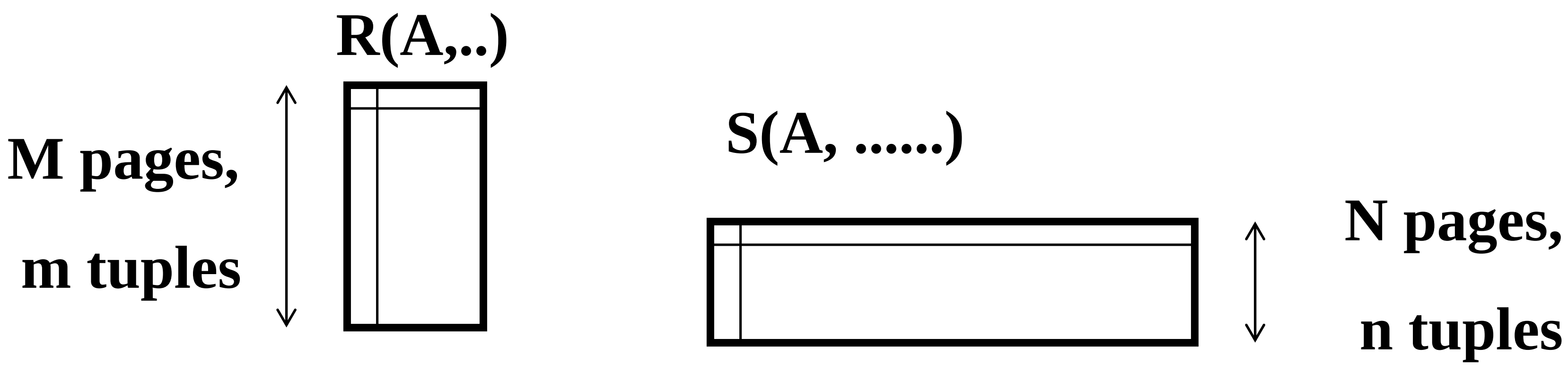
Can we do better?

Nested Loops Join: A Simple Refinement

- Algorithm:

> **Read in a *page* of R**
>
> **Read in a *page* of S**
>
> **Print matching tuples**

COST= ?

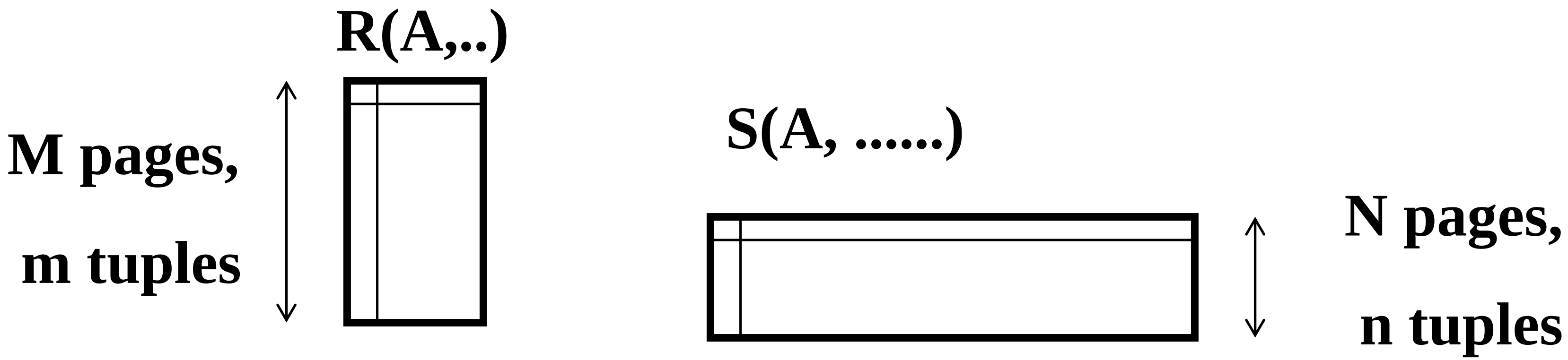


Nested Loops Join: A Simple Refinement

- Algorithm:

> **Read in a *page* of R**
>
>   **Read in a *page* of S**
>
>   **Print matching tuples**

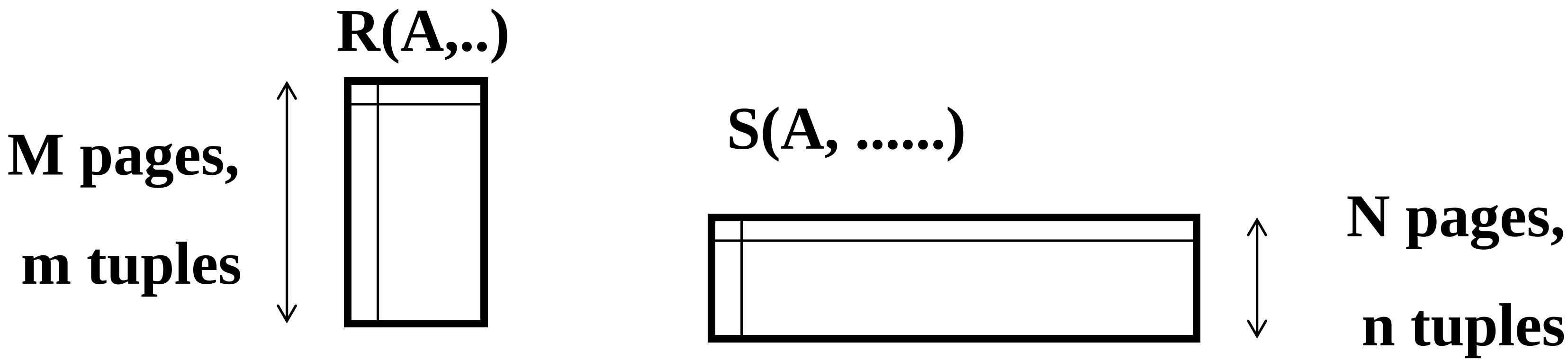
COST= M+M*N



Nested Loops Join

- Which relation should be the *outer*?

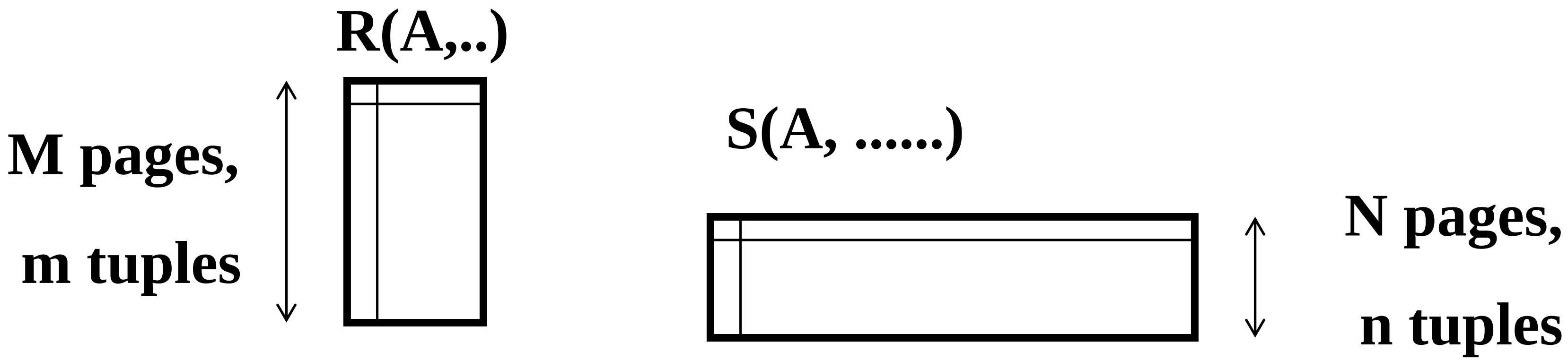
COST= M+M*N



Nested Loops Join

- Which relation should be the *outer*?
- A: The smaller (page-wise)

COST= M+M*N

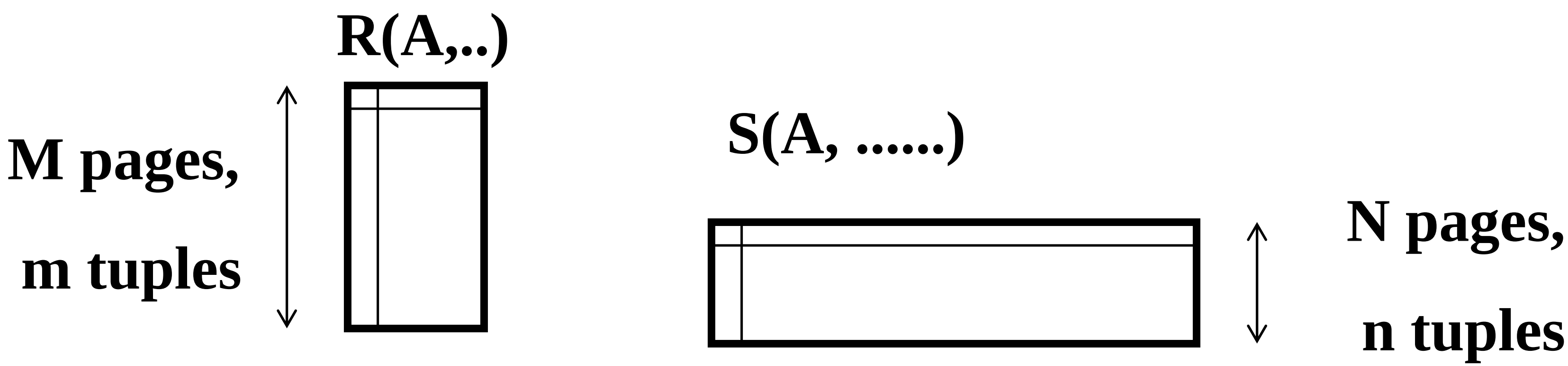


Nested Loops Join

- M=1000, N=500 - *if larger is the outer*:
- Cost = 1000 + 1000*500 = 501,000

  = 5010 sec (~ 1.4h)

COST= M+M*N

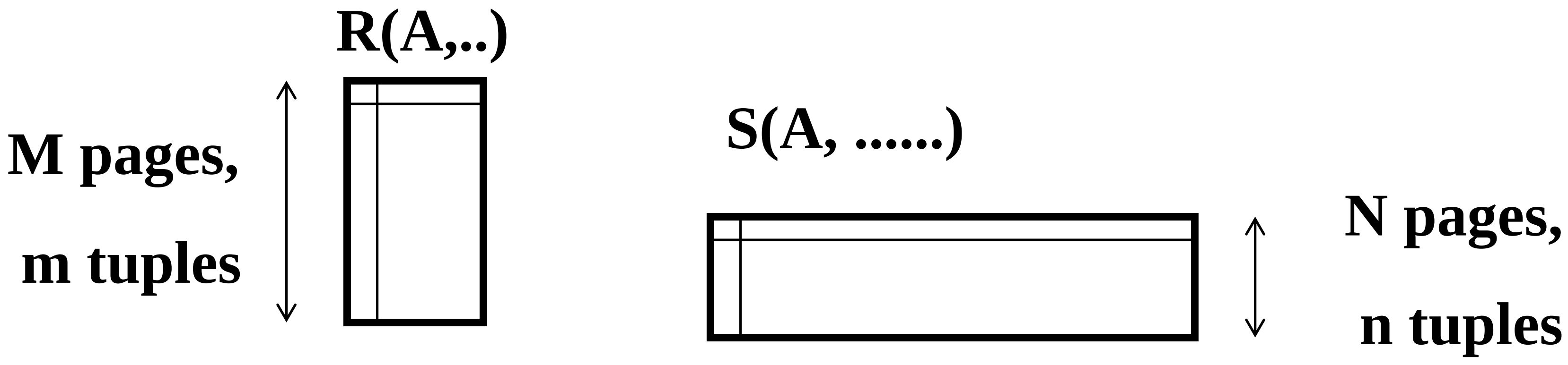


Nested Loops Join

- M=1000, N=500 - *if smaller is the outer*:
- Cost = 500 + 1000*500 = 500,500

  = 5005 sec (~ 1.4h)

COST= N+M*N



Summary: Simple Nested Loops Join

- What if we do not apply the page-oriented refinement?
  - Cost = M+ (p_R * M) * N = 1000 + 100*1000*500 I/Os
  - At 10ms/IO, total = ~6 days (!)
- What if we apply the page-oriented refinement?
  - Cost = M * N + M = 1000*500+1000 I/Os
  - At 10ms/IO, total = 1.4 hours (!)
- What if the *smaller* relation is the outer?
  - Slightly better

The Join Operation

- We will study *five* join algorithms, *two* which enumerate the cross-product and *three* which do not

- Join algorithms which enumerate the cross-product:
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  - Block Nested Loops Join ✓

- Join algorithms which do not enumerate the cross-product:
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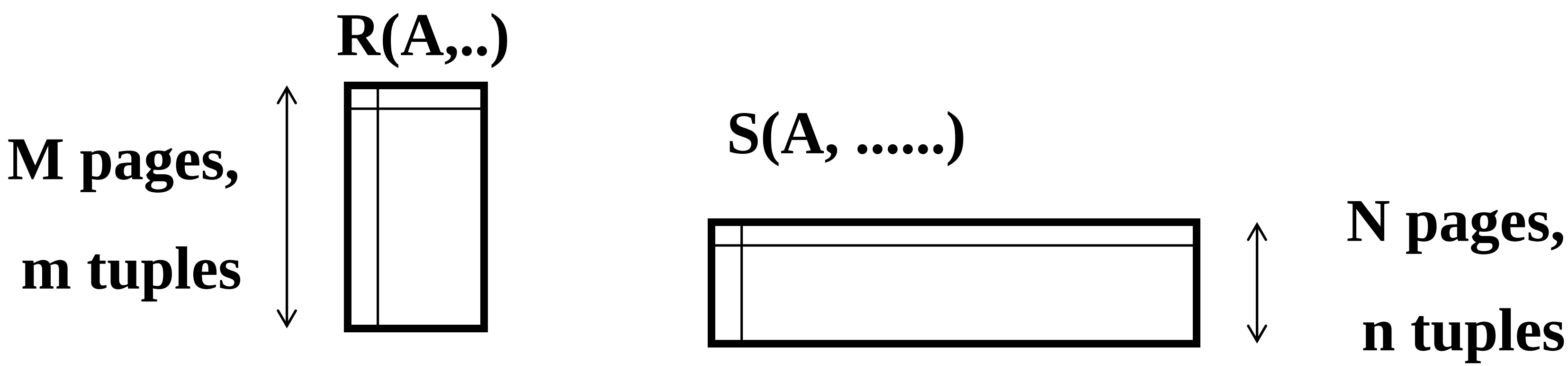
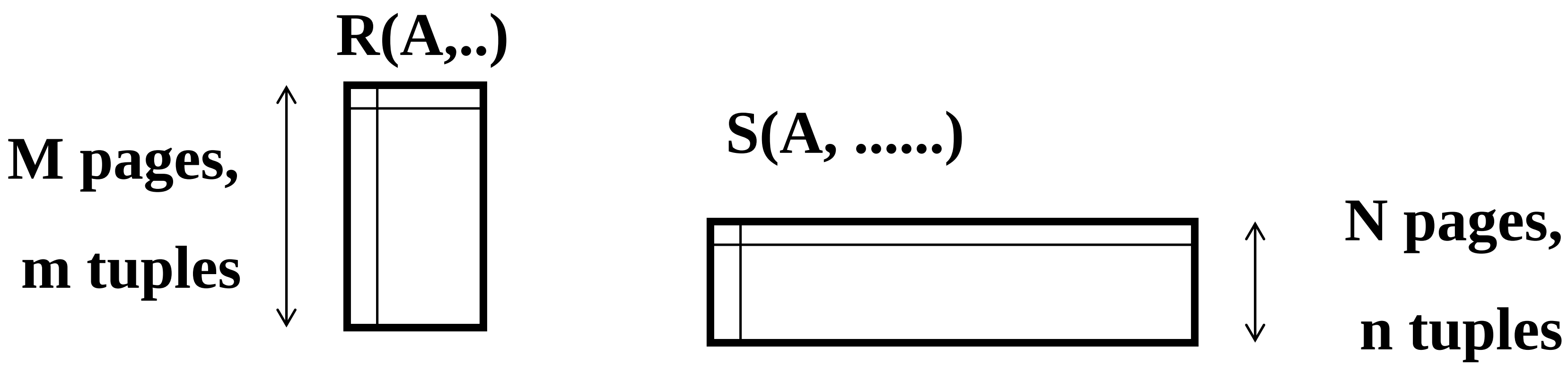
Block Nested Loops

- What if we have ***B*** buffer pages available?



Block Nested Loops

- What if we have ***B*** buffer pages available?
- A: Give ***B***-*2* buffer pages to outer, 1 to inner, 1 for output



Block Nested Loops

- Algorithm:

Read in *B-2* pages of R

    Read in a page of S

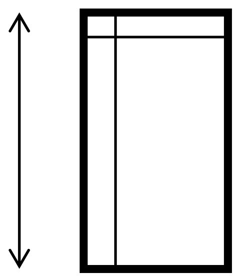
        Print matching tuples

COST= ?

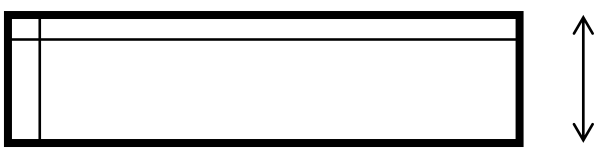
R(A,..)

M pages,

m tuples



S(A, ...)



N pages,

n tuples

Block Nested Loops

- Algorithm:

Read in *B-2* pages of R

Read in a page of S

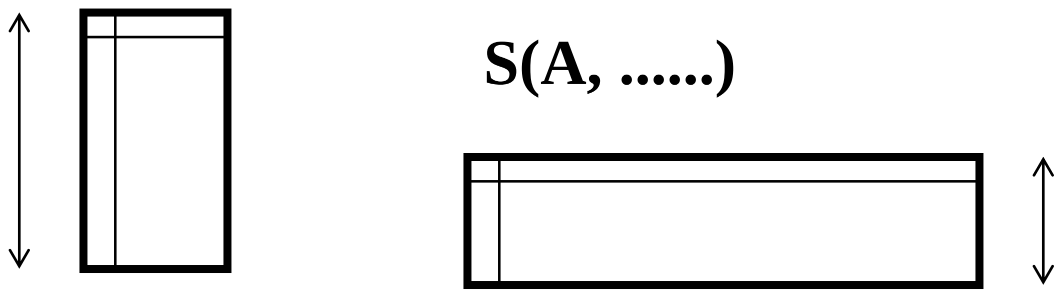
Print matching tuples

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

R(A,..)

S(A, ...)

M pages, m tuples

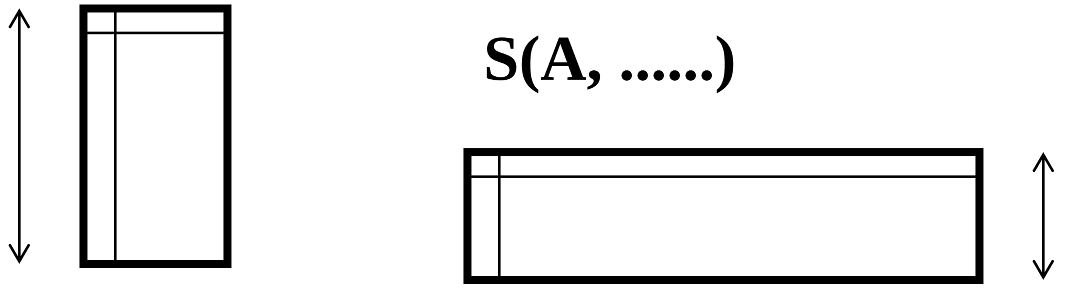


N pages, n tuples

Block Nested Loops

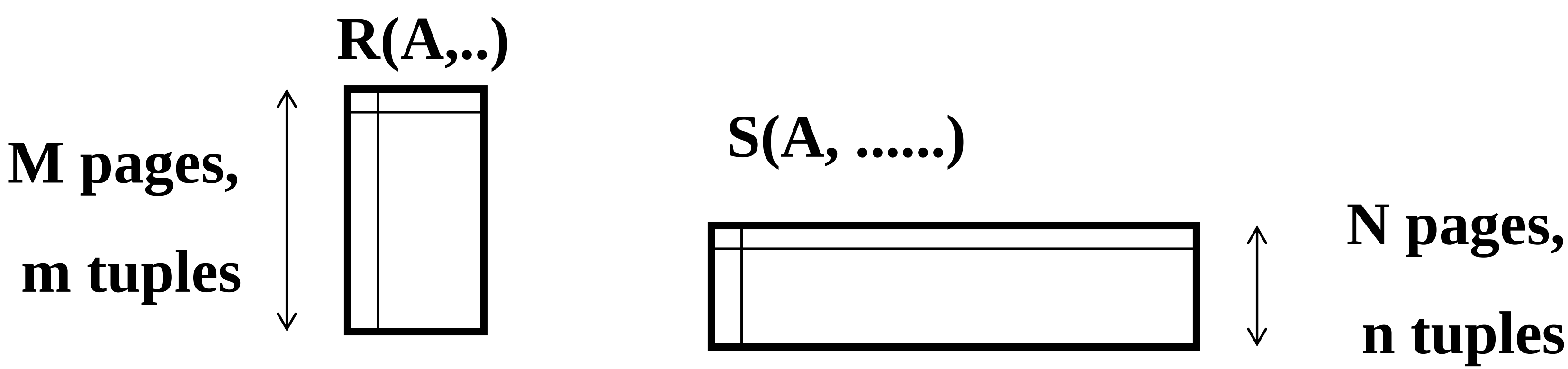
- And, actually:
- Cost = M + ceiling(M/(B-2)) * N

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



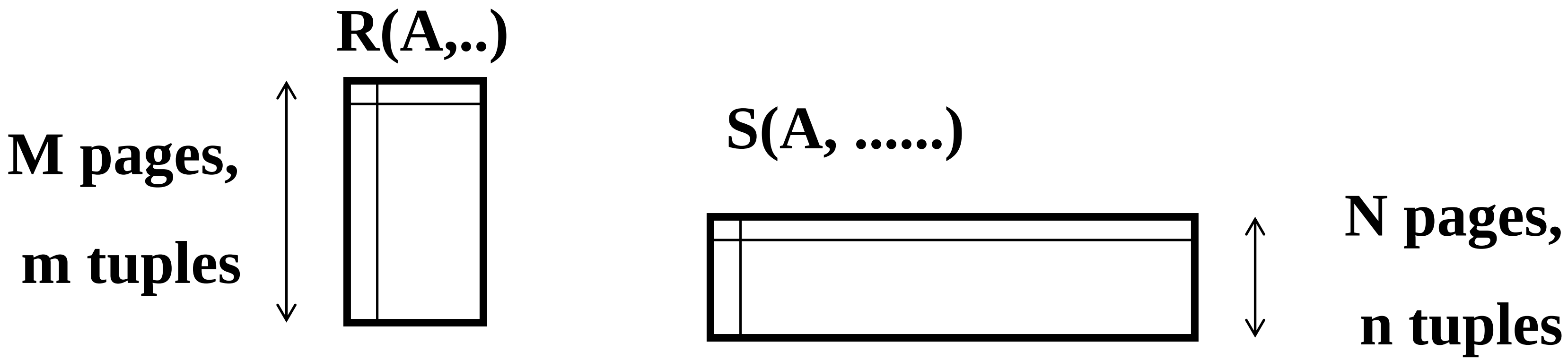
Block Nested Loops

- If the smallest (outer) relation fits in memory?
- That is, ***B*** = N+2
- Cost =?



Block Nested Loops

- If the smallest (outer) relation fits in memory?
- That is, ***B*** = N+2
- Cost =N+M (minimum!)



Nested Loops - Guidelines

- Pick as outer the smallest table
(= fewest pages)

- Fit as much of it in memory as possible

- Loop over the inner

The Join Operation

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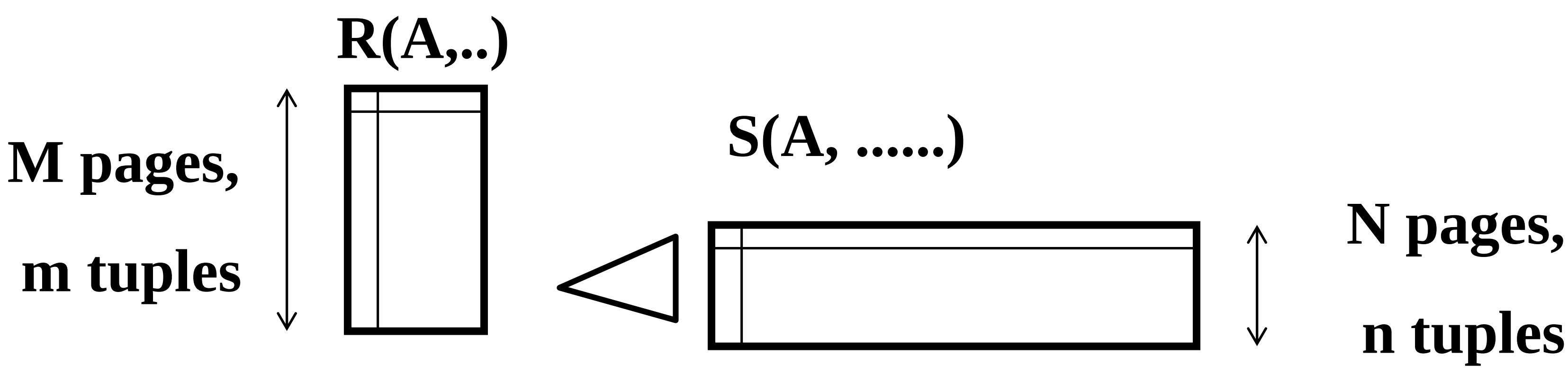
- Join algorithms which <u>do not</u> enumerate the cross-product:
  - Index Nested Loops Join ✓
  - Sort-Merge Join
  - Hash Join

Index Nested Loops Join

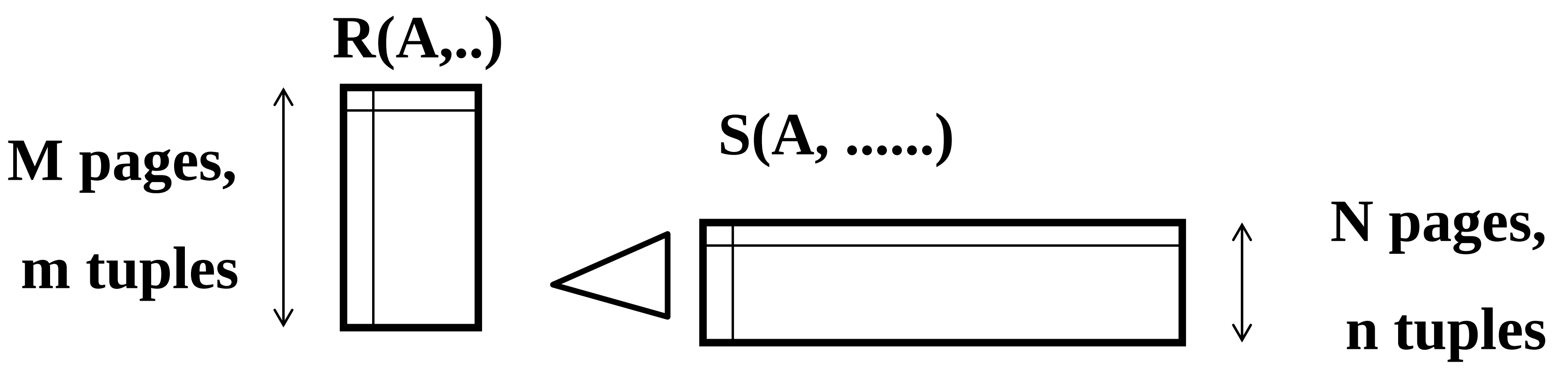
- What if there is an index on one of the relations on the join attribute(s)?
- A: Leverage the index by making the indexed relation *inner*



Index Nested Loops Join

- Assuming an index on S:

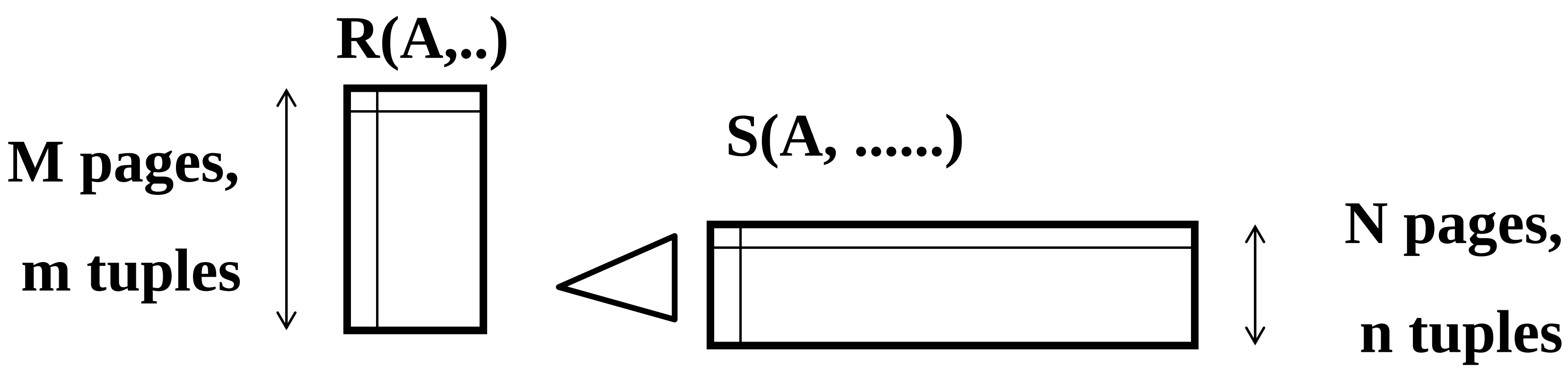
for each tuple r of R
for each tuple s of S where r_i == s_j
Add (r, s) to result



Index Nested Loops Join

- What will be the cost?
- Cost: M + m * c   (c: look-up cost)

'c' depends on the type of index, the adopted alternative and whether the index is clustered or un-clustered!



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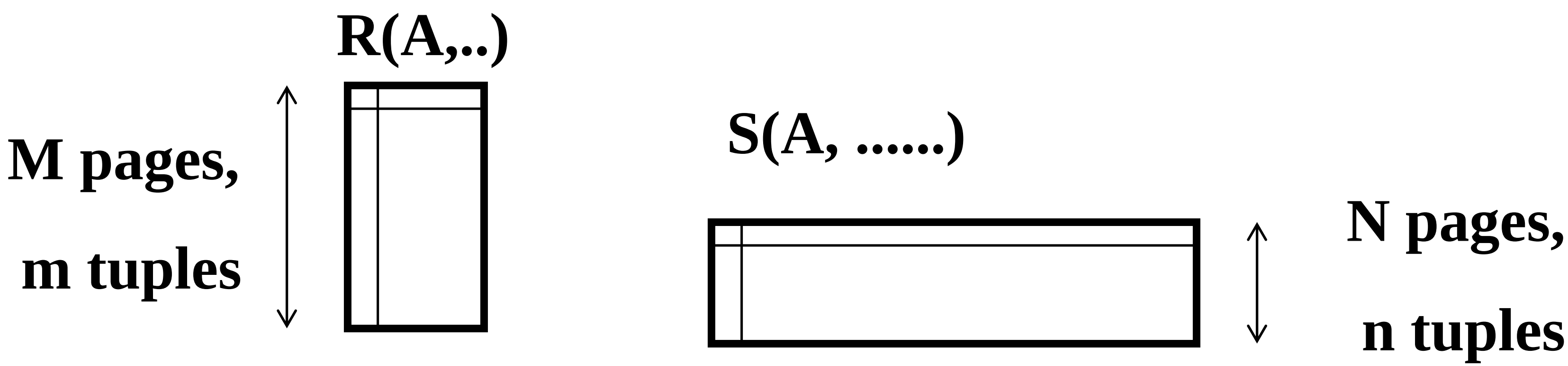
Sort-Merge Join

- Sort both relations on join attribute(s)
- Scan each relation and merge
- This works only for equality join conditions!



Sort-Merge Join: An Example

= ?

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

Sort-Merge Join: An Example

= NO

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Output the two tuples

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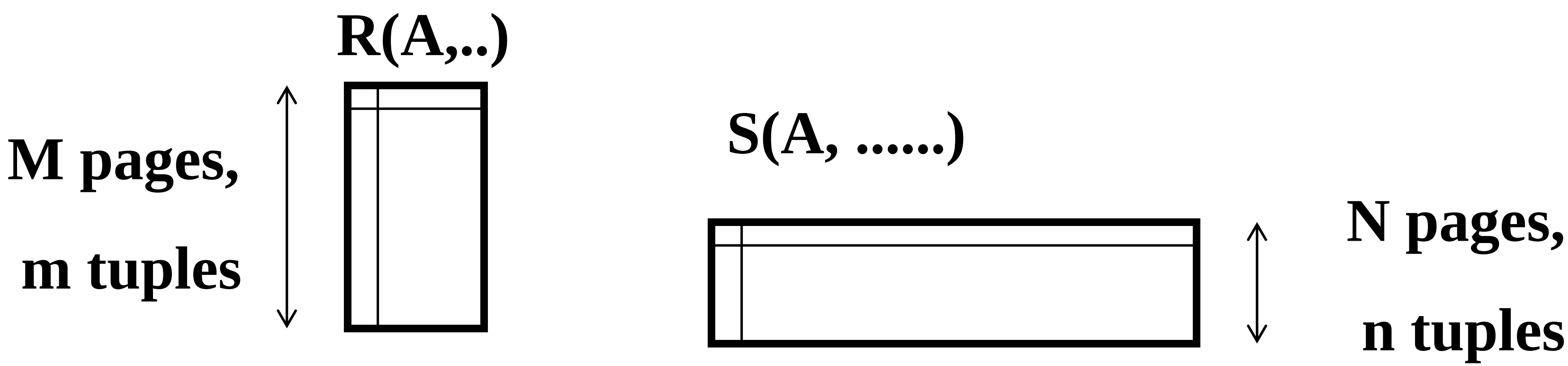
Output the two tuples

Continue the same way!

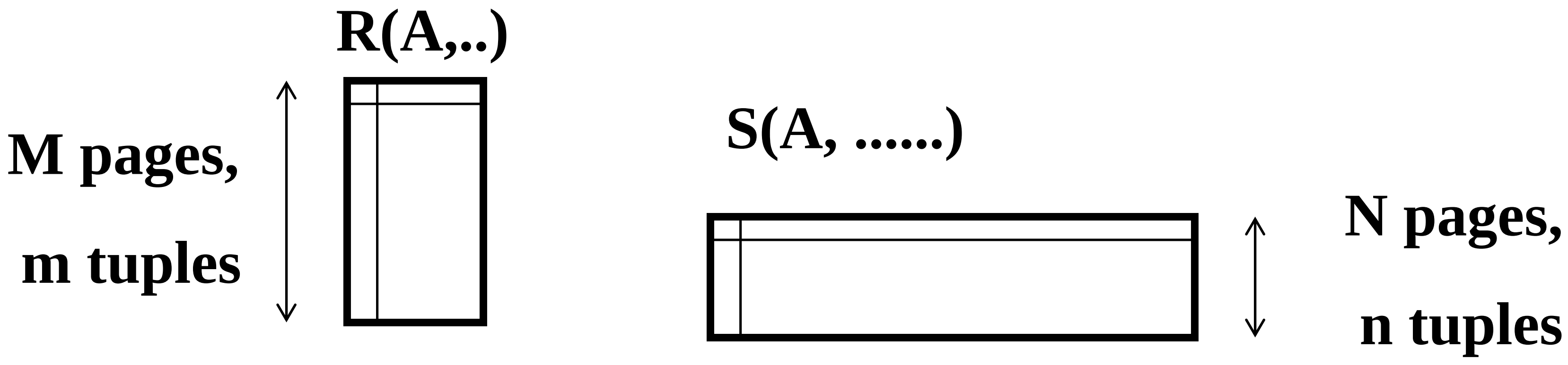
Sort-Merge Join

- What is the cost?
- ~ 2*M*logM/logB + 2*N* logN/logB + M + N



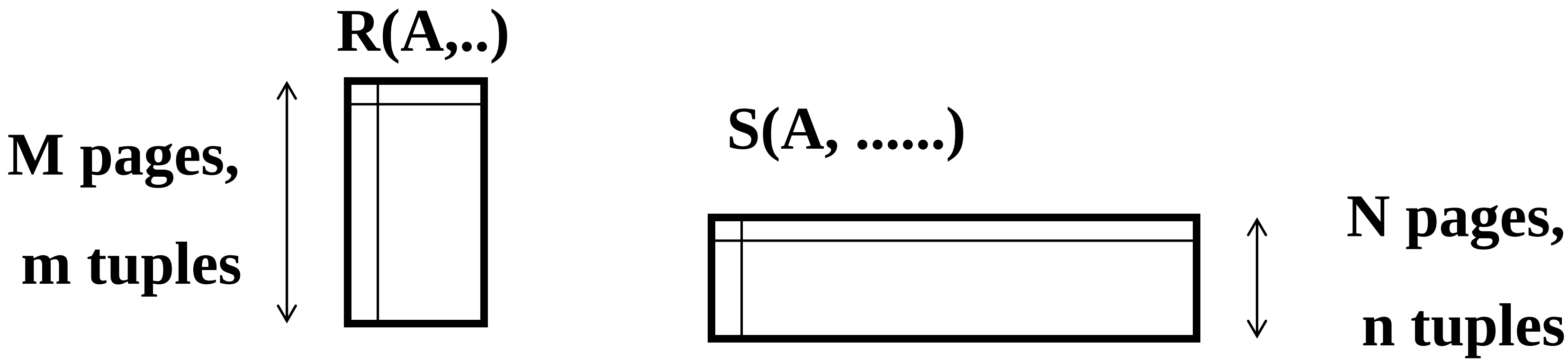
Sort-Merge Join

- Assuming 100 buffer pages, Reserves and Sailors can be sorted in 2 passes
- Total cost = 7500 I/Os
- Cost of Block Nested Loops Join = 7500 I/Os



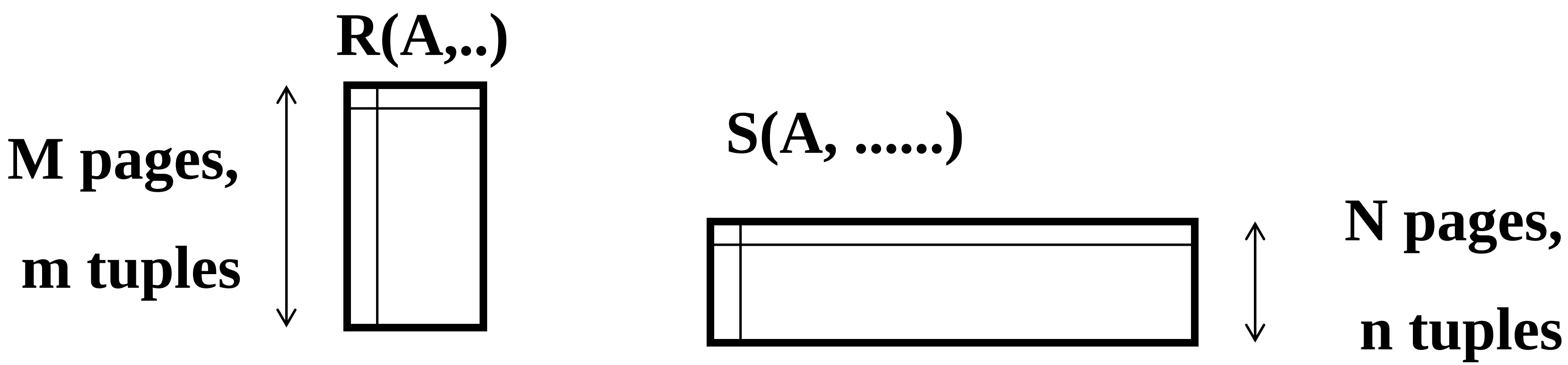
Sort-Merge Join

- Assuming 35 buffer pages, Reserves and Sailors can be sorted in 2 passes
- Total cost = 7500 I/Os
- Cost of Block Nested Loops Join = 15000 I/Os



Sort-Merge Join

- Assuming 300 buffer pages, Reserves and Sailors can be sorted in 2 passes
- Total cost = 7500 I/Os
- Cost of Block Nested Loops Join = 2500 I/Os



The Block Nested Loops Join is more sensitive to the buffer size!

The Join Operation

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- Join algorithms which enumerate the cross-product:
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- Join algorithms which do not enumerate the cross-product:
  - Index Nested Loops Join
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  - Hash Join ✓

Hash Join

- The join algorithm based on hashing has two phases:
  - Partitioning (also called *Building*) Phase
  - Probing (also called *Matching*) Phase

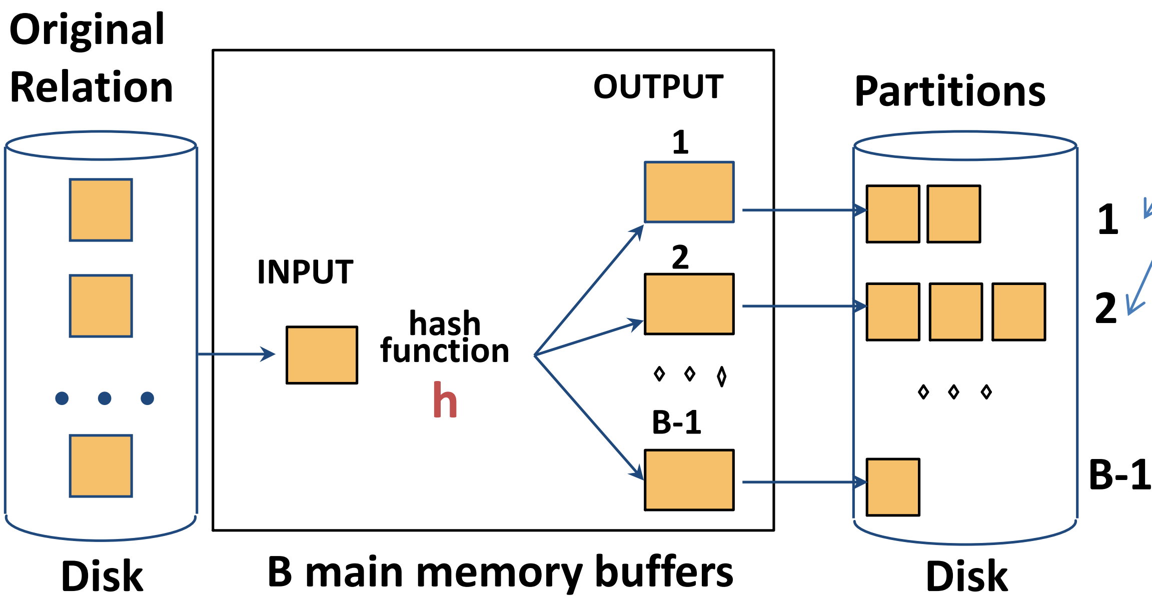
- Idea: Hash both relations on the join attribute into ***k*** partitions, using the same hash function ***h***

- Premise: R tuples in partition ***i*** can join only with S tuples in the same partition ***i***

Hash Join: Partitioning Phase

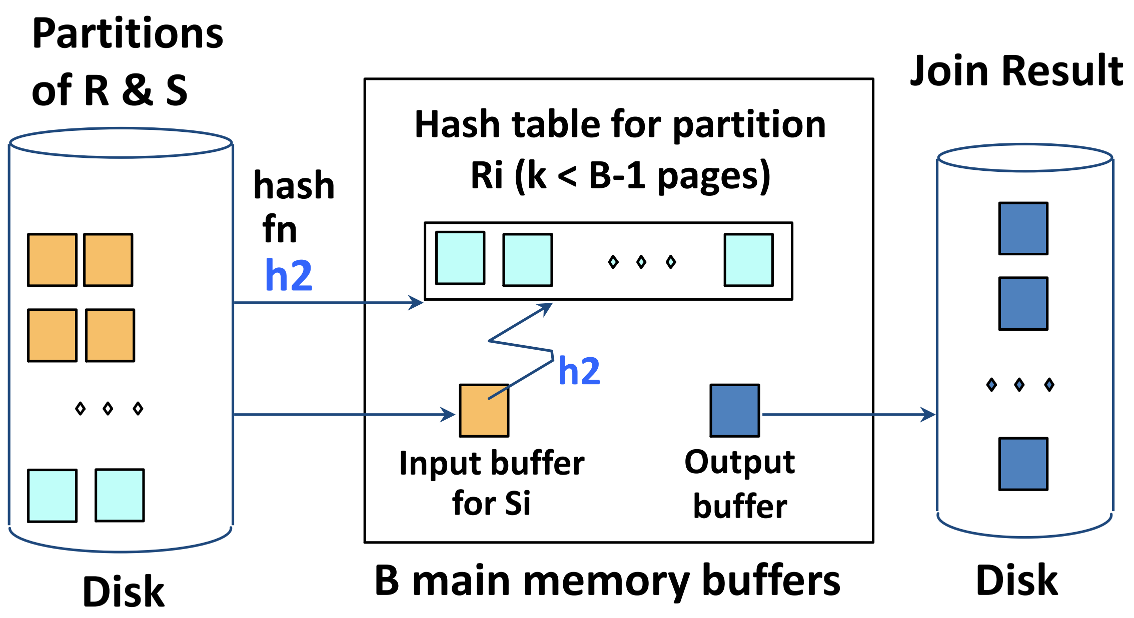
- Partition both relations using hash function ***h***

Two tuples that belong to different partitions are guaranteed not to match



Hash Join: Probing Phase

- Read in a partition of R, hash it using ***h2*** **(<> *h*)**
- Scan the corresponding partition of S and search for matches



Hash Join: Cost

- What is the cost of the partitioning phase?
  - We need to scan R and S, and write them out once
  - Hence, cost is 2(M+N) I/Os

- What is the cost of the probing phase?
  - We need to scan each partition once (*assuming no partition overflows*) of R and S
  - Hence, cost is M + N I/Os

- Total Cost = 3 (M + N)

Hash Join: Cost (*Cont'd*)

- Total Cost = 3 (M + N)

- Joining Reserves and Sailors would cost 3 (500 + 1000) = 4500 I/Os

- Assuming 10ms per I/O, hash join takes less than 1 minute!

- This underscores the importance of using a good join algorithm (e.g., *Simple NL Join takes ~140 hours!*)

But, so far we have been assuming that partitions fit in memory!

Memory Requirements and Overflow Handling

- How can we increase the chances for a given partition in the probing phase to fit in memory?
  - Maximize the number of partitions in the building phase

- If we partition R (or S) into ***k*** partitions, what would be the size of each partition (in terms of B)?
  - At least ***k*** output buffer pages and 1 input buffer page
  - Given B buffer pages, ***k*** = B – 1
  - Hence, the size of an R (or S) partition = M/B-1

- What is the number of pages in the (in-memory) hash table built during the probing phase per a partition?
  - ***f***.M/B-1, where ***f*** is a *fudge factor*

Memory Requirements and Overflow Handling

- What do we need else in the probing phase?
  - A buffer page for scanning the S partition
  - An output buffer page

- What is a good value of B as such?
  - B > f.M/B-1 + 2
  - Therefore, we need ~$B > \sqrt{f.M}$

- What if a partition overflows?
  - Apply the hash join technique *recursively* (as is the case with the projection operation)

Hash Join vs. Sort-Merge Join

- If $B > \sqrt{M}$ (M is the # of pages in the *smaller* relation) and we assume uniform partitioning, the cost of hash join is 3(M+N) I/Os

- If $B > \sqrt{N}$ (N is the # of pages in the *larger* relation), the cost of sort-merge join is 3(M+N) I/Os

Which algorithm to use, hash join or sort-merge join?

Hash Join vs. Sort-Merge Join

- If the available number of buffer pages falls between $\sqrt{M}$ and $\sqrt{N}$, hash join is preferred (why?)
- Hash Join shown to be highly parallelizable (*beyond the scope of the class*)
- Hash join is sensitive to data skew while sort-merge join is not
- Results are sorted after applying sort-merge join (may help "upstream" operators)
- Sort-merge join goes fast if one of the input relations is already sorted

The Join Operation

- We will study *five* join algorithms, *two* which enumerate the cross-product and *three* which do not

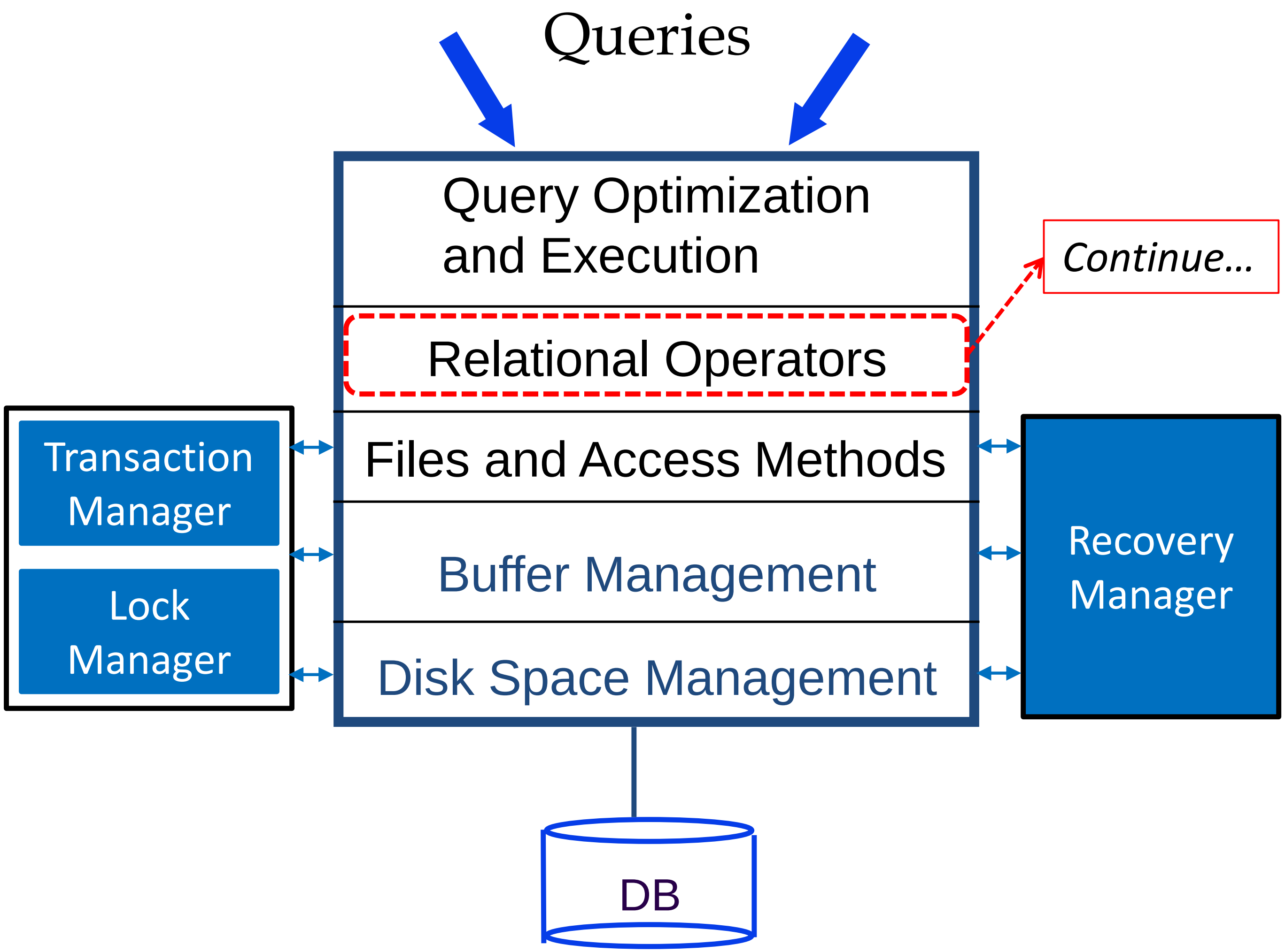
- Join algorithms which enumerate the cross-product:
  - Simple Nested Loops Join
  - Block Nested Loops Join

  ✓

- Join algorithms which do not enumerate the cross-product:
  - Index Nested Loops Join
  - Sort-Merge Join
  - Hash Join

  ✓

Next Class


Queries
Query Optimization and Execution
Relational Operators
Continue…
Files and Access Methods
Buffer Management
Disk Space Management
Transaction Manager
Lock Manager
Recovery Manager
DB