Department of Computer Science
University of Cyprus

EPL446 – Advanced Database Systems

Lecture 11

Evaluation of Relational Operators

(Joins)

Chapter 14.4: Ramakrishnan & Gehrke

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Lecture Outline
Evaluation of Relational Operators

- 14.4) Algorithms for Evaluating **Joins** (Συνενώσεις)
  - **Simple Nested** Loops Join (SNLJ)
  - **Block-Nested** Loop Join (BNLJ)

Enumerate Cross Product

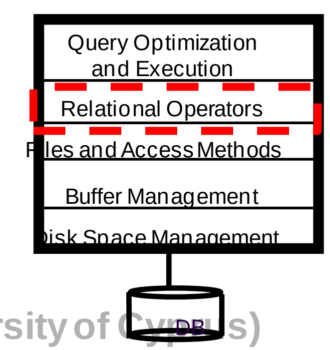
  - **Index-Nested** Loops Join (INLJ)

Use Existing Index

  - **Sort-Merge** Join (SNLJ)
  - **Hash-Join** (Grace, Hybrid Hash)
  - **Comparisons:**
    - Hash-Join vs. Block-Nested Loops Join
    - Hash-Join vs. Sort-Merge Join

Omitted

Partition the Data to avoid Enumerating the Cross Product



Introduction to Join Evaluation
(Εισαγωγή στην Αποτίμηση του Τελεστή Συνένωσης)

- The **JOIN operator (⊗)** combines records from **two tables** in a database, creating a set that can be **materialized** (saved as an intermediate table) or used **on-the-fly** (we shall only consider the latter case)
- It is among the most **common operators**, thus must be optimized carefully.
- We know that **R⊗S** ⇔ $\boldsymbol{\sigma_c(R \times S)}$**,** yet **R** and **S** might be large so **R×S** followed by a selection is inefficient!
- Our objective is to implement the join without enumerating the underlying cross-product.

Cartesian Product vs. Join Example
(Παράδειγμα Καρτεσιανού Γινομένου vs. Συνένωσης)

Reserves

sid	bid	day	rname
28	103	12/4/06	guppy
28	103	11/3/06	yuppy
31	101	10/10/06	dustin
31	102	10/12/06	lubber
31	101	10/11/06	lubber
58	103	11/12/06	dustin

$\times$ **vs.** $\bowtie$

Sailors

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**

Cartesian Product

```
foreach tuple r in R do
    foreach tuple s in S do
        add <r, s> to result
```

```
SELECT *
FROM   Reserves R1, Sailors S1
```

28,103,12/4/06, guppy, 22, dustin,7, 45.0
28,103,11/3/06, yuppy, 22, dustin,7, 45.0
….
58,103,11/12/06, dustin, 22, dustin,7, 45.0
28,103,12/4/06, guppy, 28, yuppy,9 ,35.0
….
103, 11/12/06, dustin, 58, rusty, 10, 35.0

Tuples Returned: M*N (i.e., 30 tuples with the above example)

Join

```
foreach tuple r in R do
    foreach tuple s in S do
        if R1.sid=S1.sid then  add <r, s> to result
```

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

28, 103, 12/4/06, guppy, yuppy, 9, 35.0,
28, 103, 11/3/06, yuppy, yuppy, 9, 35.0,
31, 101, 10/10/06, dustin, lubber, 8, 55.5,
31, 102, 10/12/06, lubber, lubber, 8, 55.5,
31, 101, 10/11/06, lubber, lubber, 8, 55.5,
58, 103, 11/12/06, dustin, rusty, 10, 35.0,

Tuples Returned: Depends on selectivity (only 6 tuples in example)

Schema for Examples
(Σχήμα για Παραδείγματα)

- **Notation:**
  - M tuples in **R (Reserves)**, p_R tuples per page,
    - **M=1000 pages, p_R=100 tuples/page**
  - N tuples in **S (Sailors)**, p_S tuples per page.
    - **N=500 pages, p_s=80 tuples/page**

  Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

  Sailors (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)

- **Query: SELECT * FROM Reserves R1, Sailors S1**
  WHERE R1.sid=S1.sid
- ***Cost metric*****:** # of I/Os.
- We will **ignore output costs** (as always) as the results are sent to the user **on-the-fly**

SNLJ
BNLJ
INLJ
SMJ

Simple Nested Loops Join
(Απλή Συνένωση Εμφωλευμένων Βρόγχων)

```
foreach tuple r in R do                   // Outer relation
      foreach tuple s in S do             // Inner relation
            if r_i == s_j then add <r, s> to result
```

- **A) Tuple-at-a-time Nested Loops join:** Scan *outer* relation R, and for each **tuple r ∈ R**, we scan the entire *inner* relation S a **tuple-at-a-time.**

  Times scanning R
  Times scanning S

  Cost: $M + p_R*M*N$

  - Cost: $M + p_R * M * N$ = 1000 + 100*1000*500 =**50,001,000 ~50M I/Os**

- **B) Page-at-a-time Nested Loops join:** Scan *outer* relation R, and for each **page ∈ R**, scan the entire *inner* relation S a **page-at-a-time**

  Cost: $M + M*N$

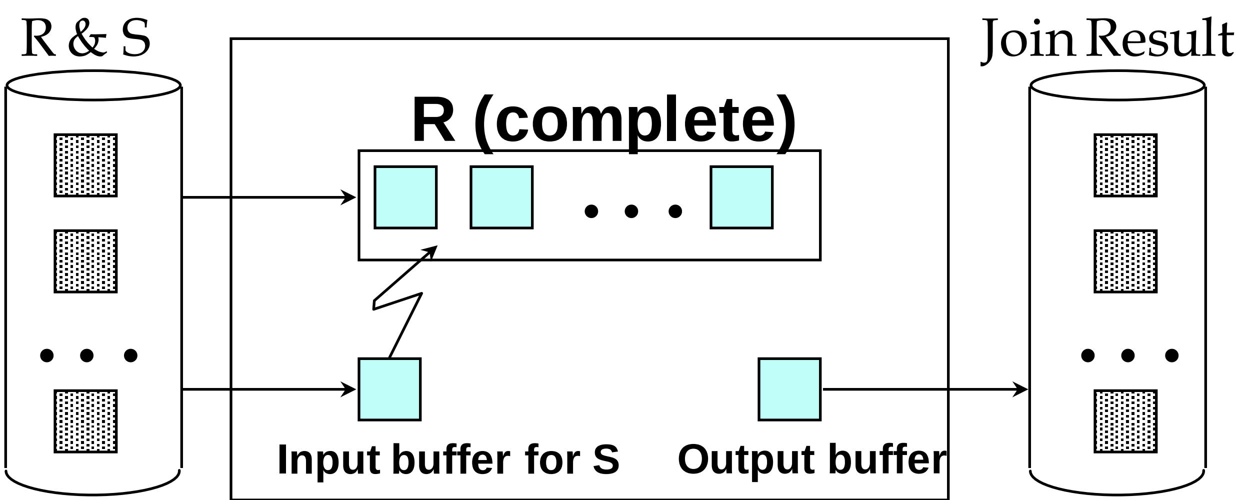
  - Cost: $M + M*N$ = 1000 + 1000*500 =**501,000 I/Os**
  - If smaller relation (S) is outer, cost = 500 + 500*1000 = **500,500 I/Os**

Rule: *The **outer relation** should be the **smaller** of the two relations*
(recall than **R⊗S ⇔ S⊗R, i.e., Commutative (Αντιμεταθετική))**

Block Nested Loops Join

(Συνένωση Εμφωλευμένων Βρόγχων με χρήση Μπλόκ)

- **Problem:** SNLJ algorithm does **not** effectively **utilize buffer pages** (i.e., it uses **3** Buffer pages B_R, B_S and B_{out}).
- **Idea:** Load the smaller relation in memory (if it fits, its ideal!)
- **C) Block-Nested Loops Join (Case I)**
  - Load the complete **smaller R** relation to memory (assuming it fits)
  - Use one page as an **output buffer**
  - Use **remaining pages** (even 1 page is adequate) to load the larger S in memory and perform the join.

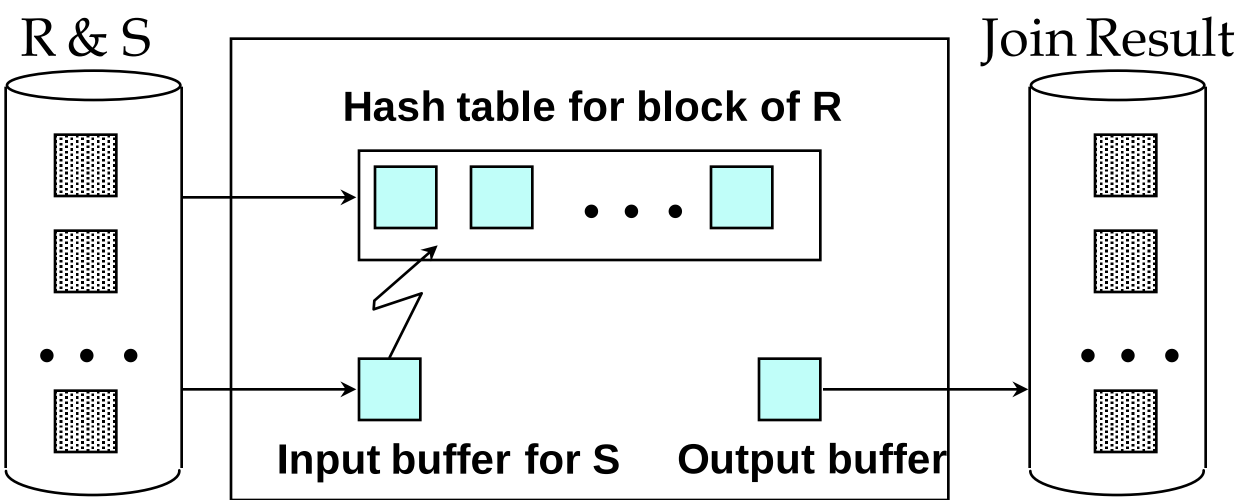


Cost: M+N

SNLJ
BNLJ
INLJ
SMJ

Block Nested Loops Join
(Συνένωση Εμφωλευμένων Βρόγχων με χρήση Μπλόκ)

- **Problem: BNLJ spends time to join the results in memory**
- **Idea:** Build an In-Memory Hash Table for R (such that the in-memory matching is conducted in O(1) time)
- **C) Block-Nested Loops Join (Case II)**
  - Load the complete smaller **R** relation to memory and Build a Hashtable
  - Use one page as an **output buffer**
  - Use **remaining pages** (even 1 page is adequate) to load the larger S in memory and perform the join (by using the in-memory Hashtable).



Like previously,

Cost: M+N

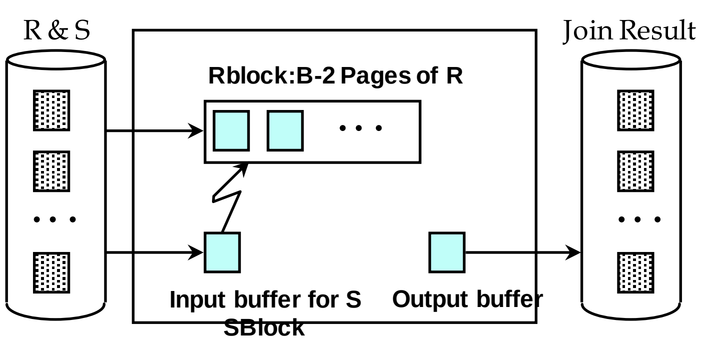
(But CPU cost is lower)

SNLJ
BNLJ
INLJ
SMJ

Block Nested Loops Join

(Συνένωση Εμφωλευμένων Βρόγχων με χρήση Μπλόκ)

- **Problem: What if smaller relation can't fit in buffer?**
- **Idea:** Use the previous idea but **break the relation R** into **blocks** (of size B-2) that can fit into the buffer.
- **C) Block-Nested Loops Join (Case III)**
  - Scan **B-2** pages of smaller **R** to memory (named **R-block**) (additionally, could build a hash table for this in-memory table)
  - Use 1 page as an **output buffer** and **1 page to scan S** relation to memory a page-at-a-time (named **S-page**) and perform the join.
  - Need to repeat the above [M/(B-2)] times (i.e., Number of Rblocks)



foreach block of $B-2$ pages of R **do**
  foreach page of S **do** {
    for all matching in-memory tuples $r \in R\text{-}block$ and $s \in S\text{-}page$,
    add $\langle r, s \rangle$ to result
  }

Cost: M + N * [M/(B-2)]

Examples of Block Nested Loops (Παράδειγμα Εμφωλευμένων Βρόγχων με χρήση Μπλόκ)

- **Let us consider an Example with BNLJ (case III), which has a cost of: M + N * ⌈M/(B-2)⌉**
- Let us consider various scenarios:
  - **Reserves (R) as outer** and **B=102**
    - **Cost =** 1000 + 500 * ⌈1000/100 ⌉ = 1000 + 500*10 = **6000 I/Os**
  - **Reserves (R) as outer** and **B=92**
    - **Cost =**1000 + 500 * ⌈1000/90 ⌉ = 1000 + 500*12 = **7000 I/Os**
  - **Sailors (S) as outer** and **B=102**
    - **Cost =**500 + 1000 * ⌈500/100 ⌉ = 500 + 1000*5 = **5500 I/Os**
  - **Sailors (S) as outer** and **B=92**
    - **Cost =**500 + 1000 * ⌈500/90 ⌉ = 500 + 1000*6 = **6500 I/Os**

Less Buffers => More I/O

Larger Outer => More IO

- It might be best to **divide buffers evenly** between R and S (instead of allocating B-2 to one of the two relations)
  - **Seek time** can be **reduced** (data can be transferred sequentially to memory instead of **1 page-at-a-time for the S-page**)

Index Nested Loops Join

(Συνένωση Εμφωλευμένων Βρόγχων μέσω Ευρετηρίου)

- **Problem:** Previous approaches essentially enumerate the R×S set and do not exploit any existing indexes.
- **Idea:** If there is **an index** on the join column of one relation (say S), why not make it the **inner** and exploit the index.
- **d) Index-Nested Loops Join**
  - Scan *outer* relation R (page-at-a-time), for each **tuple r ∈ R**, we use the available index to retrieve the matching tuples of **S.**
  - **Cost: M + (p_R* M* Index_Cost)**
- **Index_Cost = Probing_Cost + Retrieval_Cost**
  - **Probing_Cost:** Depends on Index Type
    - **Hash Index:** ~1.2 I/Os **B+Tree Index:** 2-3 I/Os
  - **Retrieval_Cost:** Depends on Clustering
    - **Clustered (Altern. 2)**: 1 I/O (typical) **Clustered (Altern. 1)**: 0 I/Os
    - **Unclustered (Altern. 2):** upto 1I/O per matching S tuple.

Examples of Index Nested Loops

(Παράδειγμα Εμφωλευμένων Βρόγχων με χρήση Ευρετηρίου)

```
foreach tuple r in R do
        foreach tuple s in S where r_i == s_j do
                add <r, s> to result
```

Use Index on S

- Let us consider an Example with INLJ which has a cost:

  M + (p_R* M* Index_Cost)

- **Hash-index (Alt. 2)** on *sid* of **Sailors** (as **inner**):
  - **Cost =** 1000 + 100 * 1000 * (**1.2 + 1.0**) = **220,000 I/Os**
  - **Retrieval_Cost: 1.2 I/Os** to get data entry in index, plus **1.0 I/O** to get (**the exactly one, as sid is sailor's key**) matching Sailors tuple.
  - **Note:** Better than Simple (Page-at-a-time) Nested Loops join: M + M* N, which was **500,500 I/Os!**
  - Not comparing with **BNLJ** as the performance of the latter depends on the buffer size (shall compare BNLJ with SMJ later).
- **Hash-index (Alt. 1)** on *sid* of **Sailors** (as **inner**):
  - **Cost =** 1000 + 100 * 1000 * (**1.2 + 0.0**) = **120,000 I/Os**

Sort-Merge Join
(Σύζευξη με Ταξινόμηση και Συγχώνευση)

- Another method, like Index-Nested Loop Join, that avoids enumerating the **R×S** set.
- **Sort-Merge Join** utilizes a **partition-based approach** to join two relations (works only for equality joins)

e) Sort Merge Join Algorithm:

- **Sort Phase: Sort** both relations **R** and **S** on the **join attribute** using an **external sort** algorithm.
- **Merge Phase:** Look for **qualifying tuples** r ∈ R and s ∈ S by **merging** the two relations.

- Sounds similar to **external sorting**. In fact the Sorting phase of the sort alg. can be combined with the sorting phase of SMJ (we will see this next)

Sort-Merge Join

(Σύζευξη με Ταξινόμηση και Συγχώνευση)

- **Sort-Merge Join I/O Cost**

$$= \text{ExternalSort(R)} + \text{ExternalSort(S)} + \underbrace{M + N}_{\text{merge}}$$

=2M*#passes + 2N*#passes + M + N

$$= 2M\left(1+\left\lceil \log_{B-1}\left\lceil M/B \right\rceil\right\rceil\right) + 2N\left(1+\left\lceil \log_{B-1}\left\lceil N/B \right\rceil\right\rceil\right) + M + N$$

- Asymptotically, the I/O cost for SMJ is :

$$= O(M \log M) + O(N \log N) + O(M+N) \in O(M \log M + N \log N)$$

(however we will utilize the real cost in our equations)

- See next slide for examples…

Sort-Merge Join
(Σύζευξη με Ταξινόμηση και Συγχώνευση)

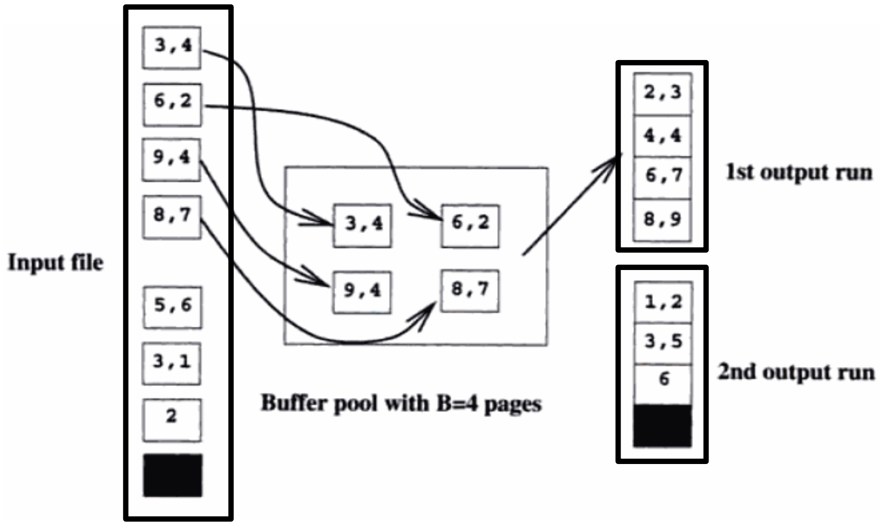
- **Let us consider an Example with SMJ, which has a cost of:** $2M(1+\lceil \log_{B-1}\lceil M/B\rceil\rceil)+2N(1+\lceil \log_{B-1}\lceil N/B\rceil\rceil)+M+N$
- Let us consider various scenarios:
  - **Buffer B=35, M=1000, N=500**
    - **Cost =** 2*1000***2** + **2***500***2** + 1000 + 500 = **7500 I/Os**
      - **Note:** $1+\lceil \log_{B-1}\lceil M/B\rceil\rceil = 1+\lceil \log_{34}\lceil 1000/35\rceil\rceil = 1+\lceil 0.73\rceil = 2$
    - Block-Nested Loops Join: **N + M*⌈N/(B-2)⌉ =500+1000*⌈500/33⌉ =16,500 I/Os**
  - **Buffer B=100, M=1000, N=500**
    - **Cost =** 2*1000***2** + **2***500***2** + 1000 + 500 = **7500 I/Os**
    - Similar to the Block-Nested Loops Join: **N + M*⌈N/(B-2)⌉= 6500 I/Os**
  - **Buffer B=300, M=1000, N=500**
    - **Cost =** 2*1000***2** + **2***500***2** + 1000 + 500 = **7500 I/Os**
    - Block-Nested Loops Join: **M + N*⌈M/(B-2)⌉=500+1000*⌈500/300⌉ = 2,500 I/Os**

SMJ not better with larger buffer (i.e., Number of passes won't drop below 2)

* The number of passes during sorting remains at 2 in the above examples

Refinement of Sort-Merge Join (Βελτιστοποίηση Σύζευξης με Ταξινόμηση και Συγχώνευση)

- We can combine the **merging phases of sorting** with the **merging phase of the join**.
  - **Step 1 (Sort):** Generate runs of size **B** for both R and S (using Phase 1 of the External Sort Algorithm)



    - Each Relation is read/written once, thus the **Cost = 2(M+N)**

Refinement of Sort-Merge Join

(Βελτιστοποίηση Σύζευξης με Ταξινόμηση και Συγχώνευση)

- **Step 2 (Merge/Join):** Load ALL runs of R and S and join merge/join them.
  - **How big should the Buffer B be to accomplish this task?**
  - **Answer: B > 2√M. i.e.,**
    - We need to fit all Runs in memory (i.e., #R_runs + #S_runs)
    - **B > #R_runs + #S_runs**

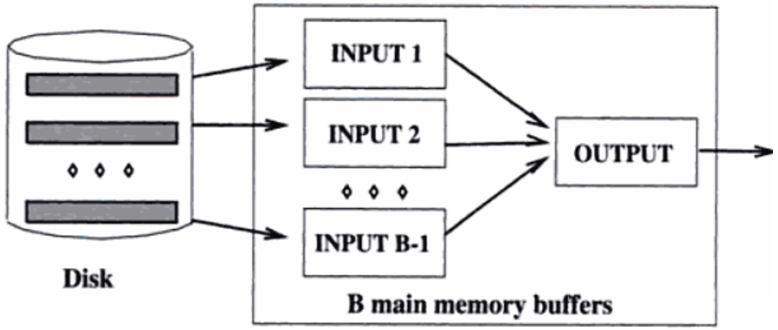
      #R_runs: B > ⌈M/(B-1)⌉ => B(B-1) > ⌈M⌉, approximately B>√M

      #S_runs: B > ⌈N/(B-1)⌉ => B(B-1) > ⌈N⌉, approximately B>√N => B>√M

      » To simplify the notation let is assume that a larger buffer is available, i.e., B>√M>√N (where R is the larger relation).
    - **Consequently, B > 2√M**
  - Each Relation is read once (results outputted on-the-fly), consequently the cost of this phase is **Cost = M+N)**

- **Total Cost = 3 (M+N) (Refined SMJ)**

In example, cost goes down from 7500 to 4500 I/Os.



Join Alg. in Commercial DBMS (Αλγόριθμοι Συνένωσης σε Εμπορικές Β.Δ.)

- **Oracle 8** supports page-oriented nested loop, sort-merge join and a variant of hybrid hash join.
- **IBM DB2** supports block-nested loop ,sort-merge and hybrid hash join.
- **Microsoft SQL Server** supports block nested loops, index nested loops, sort merge, hash join.
- **Informix:** supports block-nested loops, index-nested loops and hybrid hash join
- **Sybase ASE:** support index nested loop and Sort-Merge Join.
- **Sybase ASIQ:** page-oriented nested loop , index-nested loop, simple hash join and sort-merge join.