Database Management Systems

Lecture 8

Evaluating Relational Operators

Query Optimization

Sabina S. CS

- running example - schema
  - Students (<u>SID: integer</u>, SName: string, Age: integer)
  - Courses (<u>CID: integer</u>, CName: string, Description: string)
  - Exams (<u>SID: integer, CID: integer</u>, EDate: date, Grade: integer, FacultyMember: string)

  - Students
    - every record has 50 bytes
    - there are 80 records / page
    - 500 pages of Students tuples
  - Courses
    - every record has 50 bytes
    - there are 80 records / page
    - 100 pages of Courses tuples
  - Exams
    - every record has 40 bytes
    - there are 100 records / page
    - 1000 pages of Exams tuples

Sort-Merge Join

- equality join, one join column: $\mathrm{E} \otimes_{i=j} S$ (i^{th} column's value in E = j^{th} column's value in S)
- sort E and S on the join column (if not already sorted):
  - for instance, by using External Merge Sort

  => *partitions* = groups of tuples with the same value in the join column
- merge E and S; look for tuples *e* in E, *s* in S such that $e_i = s_j$:
  - while *current* $e_i <$ *current* s_j
    - advance the scan of E
  - while *current* $e_i >$ *current* s_j
    - advance the scan of S
  - if *current* $e_i =$ *current* s_j
    - output joined tuples <*e, s*>, where *e* and *s* are in the current partition (i.e., they have the same value in the i^{th} and j^{th} column, respectively)
    - there could be multiple tuples in E with the same value in the i^{th} column as the current tuple *e* (same is true for S)

Sort-Merge Join

- partitions are illustrated on tables Students and Exams below (join column SID in both tables):

SID	SName	Age
20	Ana	20
30	Dana	20
40	Dan	20
45	Daniel	20
50	Ina	20

SID	CID	EDate	Grade	FacultyMember
30	2	20/1/2018	10	Ionescu
30	1	21/1/2018	9.99	Pop
45	2	20/1/2018	9.98	Ionescu
45	1	21/1/2018	9.98	Pop
45	3	22/1/2018	10	Stan
50	2	20/1/2018	10	Ionescu

Sort-Merge Join

- during the merging phase, E is scanned once; every partition in S is scanned as many times as there are matching tuples in the corresponding partition in E

E

…	i^{th} column	…
	1	
	3	
	3	
	3	
	8	
	…	

S

…	j^{th} column	…
	2	
	3	
	3	
	4	
	…	
	…	

partition P

  - for instance, partition P in the above table S is scanned 3 times, once per matching tuple in the corresponding partition in E
  - there are 6 output joined tuples <*e, s*> for partition P
- this algorithm avoids the enumeration of the cross-product: tuples in a partition in E are compared only with the S tuples in the same partition!

Sort-Merge Join

- cost:
  - sorting E
    - cost: O(MlogM)
  - sorting S
    - cost: O(NlogN)
  - cost of merging: M + N I/Os, assuming partitions in S are scanned only once
    - worst-case scenario: O(M * N) I/Os (when all records in E and S have the same value in the join column)

* E - M pages; S - N pages*

Sort-Merge Join (Exams$\otimes_{Exams.SID=Students.SID}$ Students)

- 100 buffer pages
  - sort Exams
    - 2 passes => cost: 2 * 2 * 1000 = 4000 I/Os
  - sort Students
    - 2 passes => cost: 2 * 2 * 500 = 2000 I/Os
  - merging phase
    - cost: 1000 + 500 = 1500 I/Os
  - total cost: 4000 + 2000 + 1500 = 7500 I/Os
    - similar to the cost of Block Nested Loops Join
- 35 buffer pages, 300 buffer pages – cost remains unchanged (need 2 passes to sort Exams, 2 passes to sort Students)
    - ex: compute cost of BNLJ and compare

* E - M pages, p_E records / page * * 1000 pages * * 100 records / page*

* S - N pages, p_S records / page * * 500 pages * * 80 records / page *

Hash Join - equality join, one join column: $\mathrm{E} \otimes_{i=j} \mathrm{S}$

- phases: partitioning (building phase) & probing (matching phase)

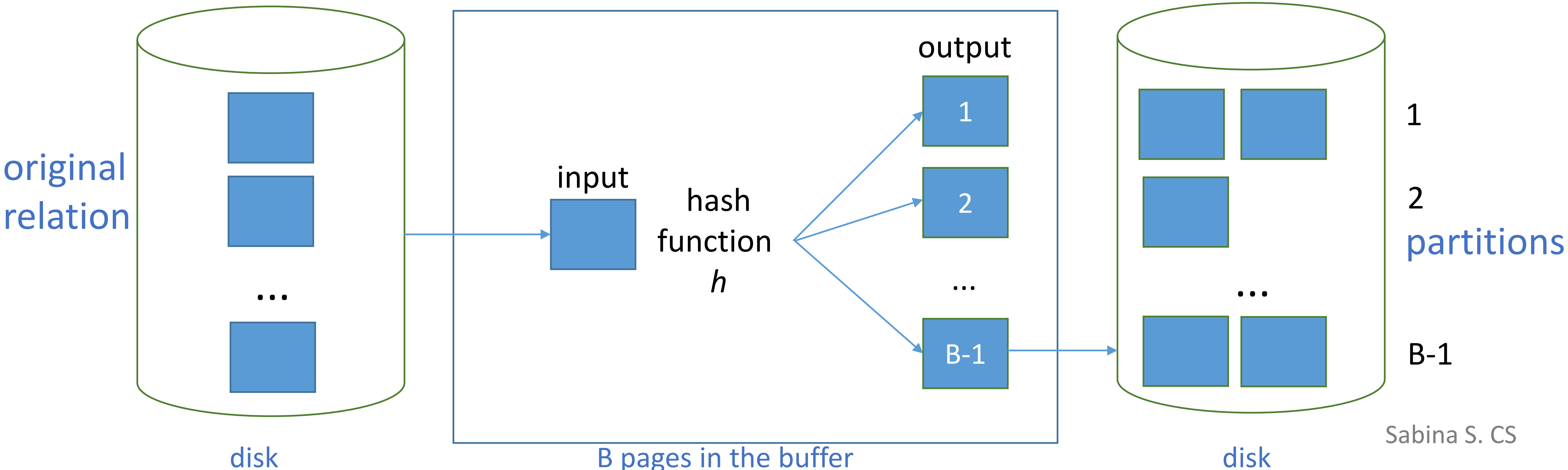
- partitioning phase:
  - there are B pages available in the buffer:
    - use one page as the input buffer page
    - and the remaining B-1 pages as output buffer pages

  - choose a hash function *h* that distributes tuples uniformly to one of B-1 partitions

  - hash E and S on the join column (the i^{th} column of E, the j^{th} column of S) with the same hash function *h*

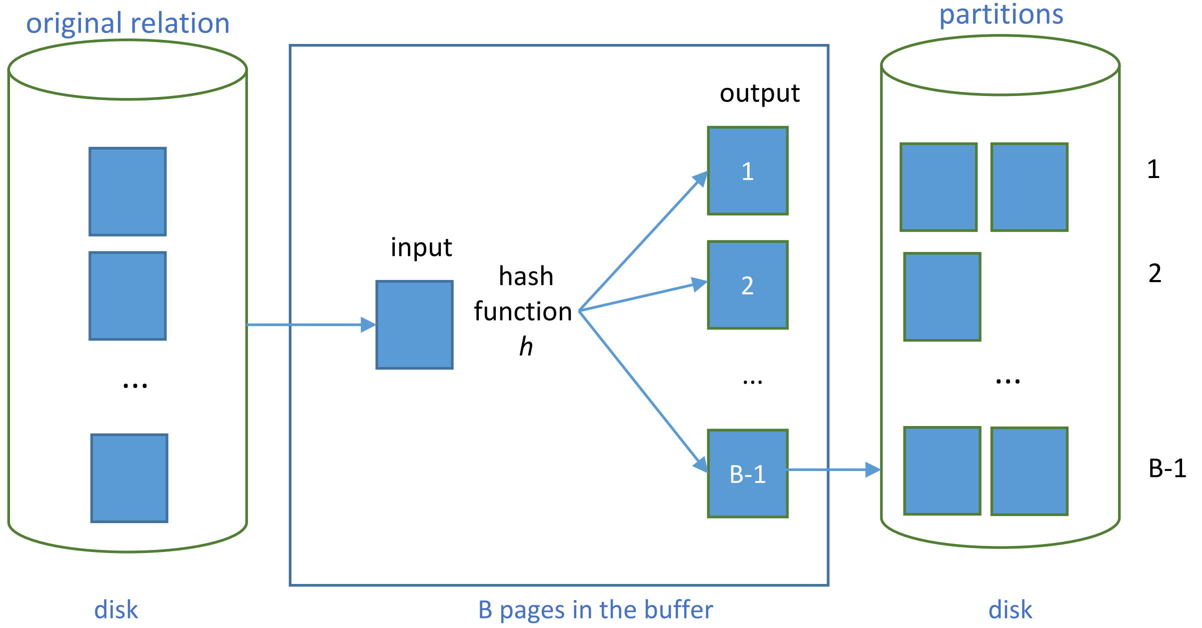
Hash Join

- hash E on the join column with hash function *h* (similarly for S):
  - for each tuple *e* in E, compute $h(e_i)$
    (e_i: the value of the i^{th} column in tuple *e*)
  - add tuple *e* to the output buffer page that it is hashed to by *h* (buffer page $h(e_i)$)
  - when an output buffer page fills up, flush the page to disk



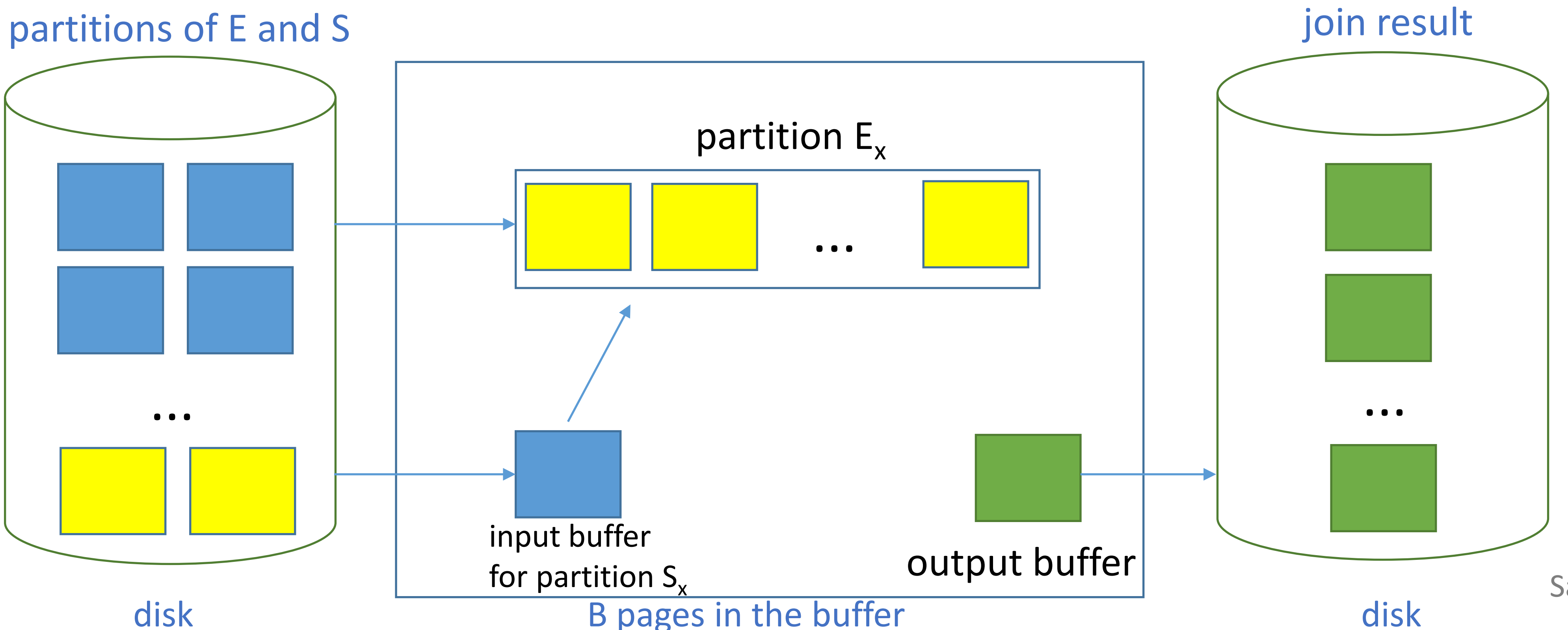
Hash Join

- partitioning phase => *partitions* of E (E_1, E_2, etc.) and S (S_1, S_2, etc.) on disk
- partition = collection of tuples that have the same hash value
- tuples in partition E_1 can only join with tuples in partition S_1 (they cannot join with tuples in partitions S_2 or S_3, for instance, since these tuples have a different hash value)
- so to compute the join, we need to scan E and S only once (provided any partition of E fits in main memory)
- when reading in a partition E_k of E, we must scan only the corresponding partition S_k of S to find matching tuples (compare tuples *e* in E_k with tuples *s* in S_k to test the join condition *value of i^th^ column in E = value of j^th^ column in S*)



Hash Join

- probing phase:
  - read in a partition of the smaller relation (e.g., E) and scan the corresponding partition of S for matching tuples
  - use one page as the input buffer for S, one page as the output buffer, and the remaining pages to read in partitions of E

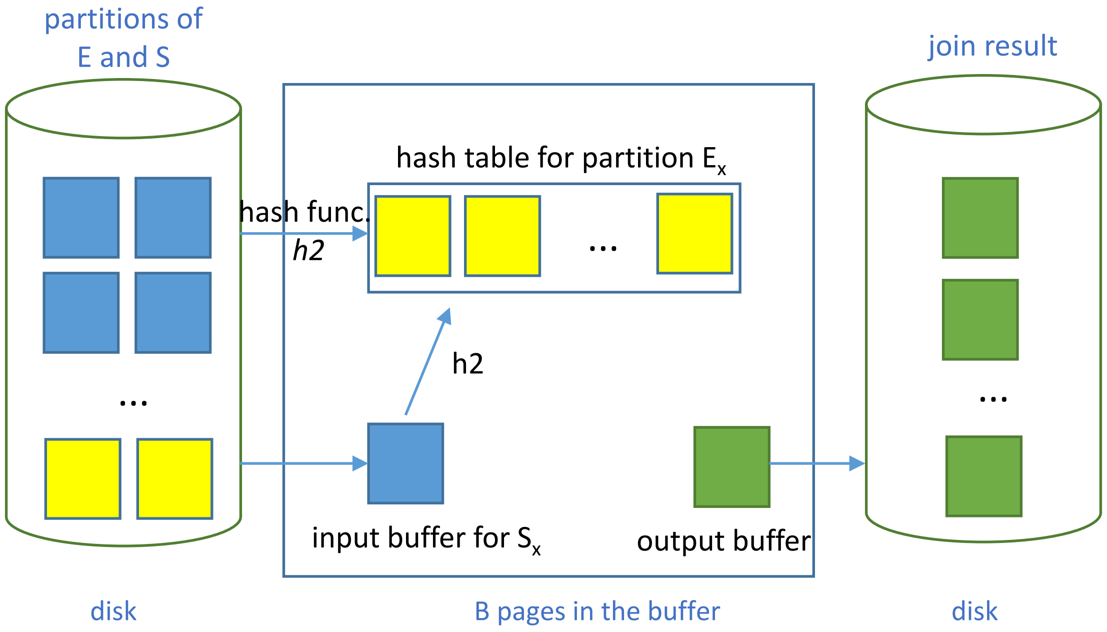


Sabina S. CS

Hash Join

- probing phase:
    - in practice, to reduce CPU costs, an in-memory hash table is built, using a different function *h2,* for the E partition

- consider a partition E_x of E
- build in-memory hash table for E_x using hash function *h2* (the function is applied to the join column of E)
- for each tuple *s* in partition S_x, find matching tuples in the hash table using the hash value $h2(s_j)$



- result tuples <e, s> are written to output buffer
- once partitions E_x and S_x are processed, the hash table is emptied (to prepare for the next partition)

Hash Join

- cost:
  - partitioning: both E and S are read and written once => cost: 2*(M+N) I/Os
  - probing: scan each partition once => cost: M+N I/Os

  => total cost: 3*(M+N) I/Os
    - assumption: each partition fits into memory during probing
  - 3*(1000 + 500) = 4500 I/Os

* E - M pages, p_E records / page * * 1000 pages * * 100 records / page*

* S - N pages, p_S records / page * * 500 pages * * 80 records / page *

- *partition overflow* – an E partition does not fit in memory during probing: apply hash join technique recursively:
  - divide E, S into subpartitions
  - join subpartitions pairwise
  - if subpartitions don't fit in memory, apply hash join technique recursively

Hash Join

- memory requirements - objective: partition in E fits into main memory (S - similarly)
  - B buffer pages; need one input buffer => maximum number of partitions: B-1
  - size of largest partition: B – 2 (need one input buffer for S, one output buffer)
  - assume uniformly sized partitions => size of each E partition: M/(B-1)

  => M/(B-1) < B-2 => we need approximately B > $\sqrt{M}$

  - if an in-memory hash table is used to speed up tuple matching => need a little more memory (because the hash table for a collection of tuples will be a little larger than the collection itself)

* E - M pages, p_E records / page *   * 1000 pages * * 100 records / page*

general join conditions

- equalities over several attributes
    - E.SID = S.SID AND E.attrE = S.attrS
        - index nested loops join
            - Exams – inner relation:
                - build index on Exams with search key <SID, attrE> (if not already created)
                - can also use index on SID or index on attrE
            - Students – inner relation (similar)
        - sort-merge join
            - sort Exams on <SID, attrE>, sort Students on <SID, attrS>
        - hash join
            - partition Exams on <SID, attrE>, partition Students on <SID, attrS>
        - other join algorithms
            - essentially unaffected

general join conditions

- inequality comparison
  - E.attrE < S.attrS
    - index nested loops join: B+ tree index required
    - sort-merge join: not applicable
    - hash join: not applicable
    - other join algorithms: essentially unaffected

* no join algorithm is uniformly superior to others

- choice of a good algorithm depends on:
  - size(s) of:
    - joined relations
    - buffer pool
  - available access methods

Selection

Q:

```
SELECT *
FROM Exams E
WHERE E.FacultyMember = 'Ionescu'
```

- use information in the selection condition to reduce the number of retrieved tuples
- e.g., |Q| = 4 (result set has 4 tuples), there's a B+ tree index on FacultyMember
  - it's expensive to scan E (1000 I/Os) to evaluate the query
  - should use the index instead

- selection algorithms based on the following techniques:
  - iteration, indexing

* E - M pages, p_E records / page * * 1000 pages * * 100 records / page*

Selection

- simple selections
  - $\sigma_{E.attr\ op\ val}(E)$

- no index on *attr*, data not sorted on *attr*
  - must scan E and test the condition for each tuple
  - access path: file scan

  => cost: M I/Os = 1000 I/Os

- no index, sorted data (E physically sorted on *attr)*
    - binary search to locate 1st tuple that satisfies condition

      and
    - scan E starting at this position until condition is no longer satisfied
  - access method: sorted file scan

Review lecture notes on *Relational Algebra, Indexes, DB – Physical Structure* (*Databases* course)

Selection

- simple selections
  - $\sigma_{E.attr\ op\ val}(E)$

- no index, sorted data (E physically sorted on *attr)*

  => cost:
  - binary search: $O(\log_2 M)$
  - scan cost: varies from 0 to M
  - binary search on E
    - $\log_2 1000 \approx 10$ I/Os

Selection

- simple selections
  - $\sigma_{E.attr\ op\ val}(E)$

- B+ tree index on *attr*
  * search tree to find 1st index entry pointing to a qualifying E tuple
    - cost: typically 2, 3 I/Os
  * scan leaf pages to retrieve all qualifying entries
    - cost: depends on the number of qualifying entries
  * for each qualifying entry - retrieve corresponding tuple in E
    - cost: depends on the number of tuples and the nature of the index (clustered / unclustered)

Selection

- simple selections
  - $\sigma_{E.attr\ op\ val}(E)$

- B+ tree index on *attr*
  - assumption
    - indexes use a2 or a3
    - a1-based index => data entry contains the data record => the cost of retrieving records = the cost of retrieving the data entries!
  - access path: B+ tree index
    - clustered index:
      - best access path when *op* is not *equality*
      - good access path when *op* is *equality*

<u>Selection</u>

- simple selections: $\sigma_{E.attr\ op\ val}(E)$
- B+ tree index on *attr*

Q

```
SELECT *
FROM Exams E
WHERE E.FacultyMember < 'C%'
```

- names uniformly distributed with respect to 1st letter

=> |Q| ≈ 10,000 tuples = 100 pages

- clustered B+ tree index on FacultyMember

=> cost of retrieving tuples: ≈ 100 I/Os (a few I/Os to get from root to leaf)

- non-clustered B+ tree index on FacultyMember

=> cost of retrieving tuples: up to 1 I/O per tuple (worst case) => up to 10.000 I/Os

* E - M pages, p_E records / page * * 1000 pages * * 100 records / page*

Selection

- simple selections: $\sigma_{E.attr\ op\ val}(E)$
- B+ tree index on *attr*

```
SELECT *
FROM Exams E
WHERE E.FacultyMemger < 'C%'
```

- non-clustered B+ tree index on FacultyMember
  - refinement - sort rids in qualifying data entries by page-id
    => a page containing qualifying tuples is retrieved only once
    - cost of retrieving tuples: number of pages containing qualifying tuples (but such tuples are probably stored on more than 100 pages)
- range selections
  - non-clustered indexes can be expensive
  - could be less costly to scan the relation (in our example: 1000 I/Os)

Selection

- general selections
  - selections without disjunctions
- C - CNF condition without disjunctions
  - evaluation options:

  1. use the most selective access path
     - if it's an index I:
       - apply conjuncts in C that match I
       - apply rest of conjuncts to retrieved tuples
     - example
       - *c < 100 AND a = 3 AND b = 5*
         - can use a B+ tree index on *c* and check *a = 3 AND b = 5* for each retrieved tuple
         - can use a hash index on *a* and *b* and check *c < 100* for each retrieved tuple

Selection

- general selections - selections without disjunctions
  - evaluation options:

  2. use several indexes - when several conjuncts match indexes using a2 / a3
     - compute sets of rids of candidate tuples using indexes
     - intersect sets of rids, retrieve corresponding tuples
     - apply remaining conjuncts (if any)
     - example: *c < 100 AND a = 3 AND b = 5*
       - use a B+ tree index on *c* to obtain rids of records that meet condition *c < 100* (R_1)
       - use a hash index on *a* to retrieve rids of records that meet condition *a = 3* (R_2)
       - compute $R_1 \cap R_2 = R_{int}$
       - retrieve records with rids in R_{int} (R)
       - check *b = 5* for each record in *R*

Selection

- general selections
  - selections with disjunctions
- C - CNF condition with disjunctions, i.e., some conjunct *J* is a disjunction of terms
  - if some term *T* in *J* requires a file scan, testing *J* by itself requires a file scan
    - example: $a < 100 \vee b = 5$
      - hash index on *b*, hash index on *c*

    => check both terms using a file scan (i.e., best access path: file scan)
  - compare with the example below:
      - $(a < 100 \vee b = 5) \wedge c = 7$
      - hash index on *b*, hash index on *c*

    => use index on *c*, apply $a < 100 \vee b = 5$ to each retrieved tuple (i.e., most selective access path: index)

Selection

- general selections
  - selections with disjunctions

- C - CNF condition with disjunctions
  - every term *T* in a disjunction matches an index

  => retrieve tuples using indexes, compute union
  - example
    - $a < 100 \vee b = 5$
    - B+ tree indexes on *a* and *b*
    - use index on *a* to retrieve records that meet condition $a < 100$ (R_1)
    - use index on *b* to retrieve records that meet condition $b = 5$ (R_2)
    - compute $R_1 \cup R_2 = R$
    - if all matching indexes use a2 or a3 => take union of rids, retrieve corresponding tuples

Projection

- $\Pi_{\text{SID, CID}}$(Exams)

```
SELECT DISTINCT E.SID, E.CID
FROM Exams E
```

- to implement projection:
  - eliminate:
    - unwanted columns
    - duplicates
- projection algorithms - *partitioning* technique:
  - sorting
  - hashing

Projection Based on Sorting

- step 1
  - scan E => set of tuples containing only desired attributes (E')
  - cost:
    - scan E: M I/Os
    - write temporary relation E': T I/Os
      - T depends on: number of columns and their sizes, T is O(M)
- step 2
  - sort tuples in E'
  - sort key: all columns
  - cost: O(TlogT)   (also O(MlogM))
- step 3
  - scan sorted E', compare adjacent tuples, eliminate duplicates
  - cost: T
- total cost: O(MlogM)

Projection Based on Sorting

* example

```
SELECT DISTINCT E.SID, E.CID
FROM Exams E
```

- scan Exams: 1000 I/Os
- size of tuple in E': 10 bytes

=> cost of writing temporary relation E': 250 I/Os

- available buffer pages: 20
  - E' can be sorted in 2 passes
  - sorting cost: 2 * 2 * 250 = 1000 I/Os

- final scan of E' - cost: 250 I/Os

=> total cost: 1000 + 250 + 1000 + 250 = 2500 I/Os

* E – record size = 40 bytes *   * 1000 pages *   * 100 records / page*

Projection Based on Sorting

* example

```
SELECT DISTINCT E.SID, E.CID
FROM Exams E
```

- scan Exams: 1000 I/Os
- size of tuple in E': 10 bytes

=> cost of writing temporary relation E': 250 I/Os

- available buffer pages: 257
  - E' can be sorted in 1 pass
  - sorting cost: 2 * 1 * 250 = 500 I/Os

- final scan of E' - cost: 250 I/Os

=> total cost: 1000 + 250 + 500 + 250 = 2000 I/Os

* E – record size = 40 bytes *   * 1000 pages *   * 100 records / page*

Projection Based on Sorting

- improvement
  - adapt the sorting algorithm to do projection with duplicate elimination
    - modify pass 0 of External Merge Sort: eliminate unwanted columns
      - read in B pages from E
      - write out (T/M) * B internally sorted pages of E'
        - refinement: write out 2*B internally sorted pages of E' (on average)
      - tuples in runs - smaller than input tuples
    - modify merging passes: eliminate duplicates
      - number of result tuples is smaller than number of input tuples

Projection Based on Sorting

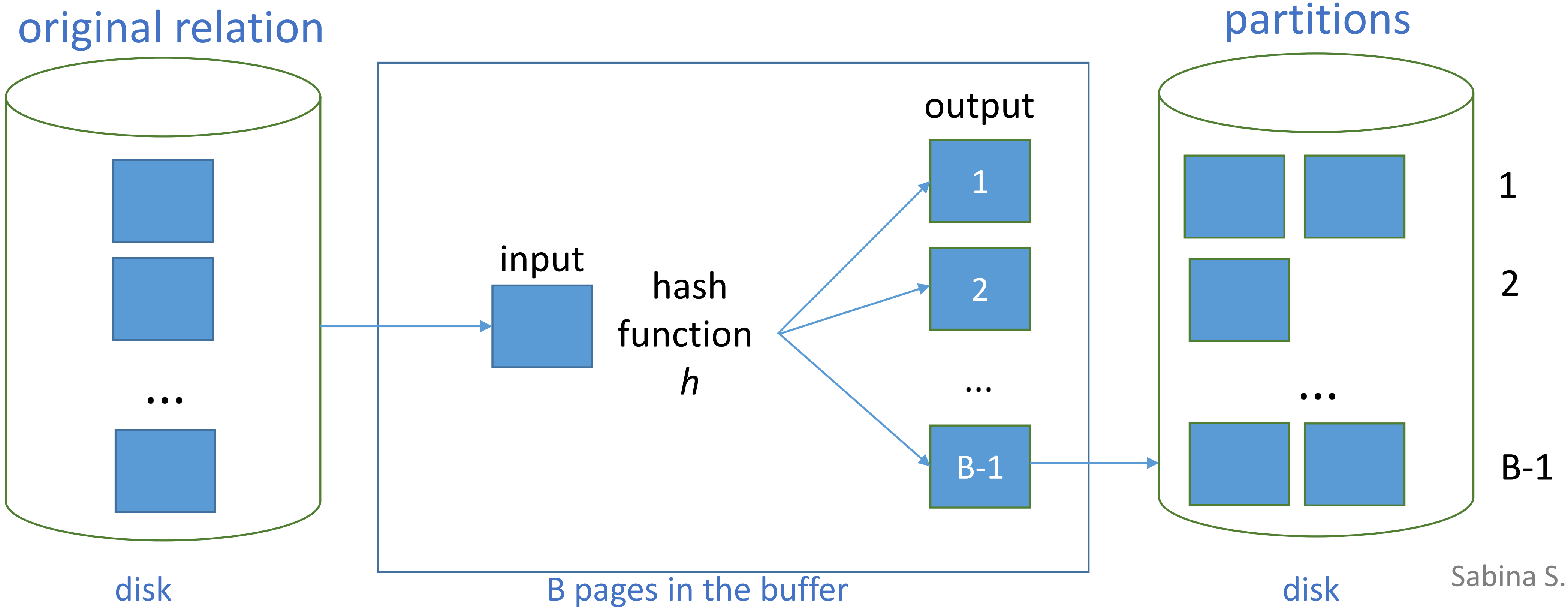
- improvement

  * example

  - pass 0:
    - scan Exams: 1000 I/Os
    - write out 250 pages:
      - 20 available buffer pages
        - 250 pages => 7 sorted runs about 40 pages long (except the last one, which is about 10 pages long)
  - pass 1:
    - read in all runs – cost: 250 I/Os
    - merge runs
  - total cost : 1000 + 250 + 250 = 1500 I/Os

Projection Based on Hashing

- phases: partitioning & duplicate elimination
- partitioning phase:
  - 1 input buffer page – read in the relation one page at a time
  - hash function *h* – distribute tuples uniformly to one of B-1 partitions
  - B-1 output buffer pages – one output page / partition



<u>Projection Based on Hashing</u>

- <u>partitioning phase</u>:
  - read the relation using the input buffer page
  - for each tuple *t*:
    - discard unwanted fields => tuple *t′*
    - apply hash function *h* to *t′*
    - write *t′* to the output buffer page that it is hashed to by *h*

  => B-1 partitions
  - <u>partition</u>:
    - collection of tuples with:
      - common hash value
      - no unwanted fields
  - tuples in different partitions are guaranteed to be distinct

Projection Based on Hashing

- duplicate elimination phase:
  - process all partitions:
    - read in partition P, one page at a time
      - build in-memory hash table with hash function *h2* ($\neq$ *h*) on all fields:
        - if a new tuple hashes to the same value as an existing tuple, compare them to check if they are distinct
        - eliminate duplicates
      - write duplicate-free hash table to result file
      - clear in-memory hash table

  - partition overflow
    - apply hash-based projection technique recursively (subpartitions)

Projection Based on Hashing

- cost
  - partitioning:
    - read E: M I/Os
    - write E': T I/Os
  - duplicate elimination:
    - read in partitions: T I/Os

  => total cost: M + 2*T I/Os

- Exams:
  - 1000 + 2*250 = 1500 I/Os

Set Operations

- intersection, cross-product
    - special cases of join (join condition for intersection - equality on all fields, no join condition for cross-product)

- union, set-difference
    - similar

- union: R ∪ S
    - sorting
        - sort R and S on all attributes
        - scan the sorted relations in parallel; merge them, eliminating duplicates
        - refinement
            - produce sorted runs of R and S, merge runs in parallel

Set Operations

- union: R ∪ S
  - hashing
    - partition R and S with the same hash function *h*
    - for each S-partition
      - build in-memory hash table (using *h2*) for the S-partition
      - scan corresponding R-partition, add tuples to hash table, discard duplicates
      - write out hash table
      - clear hash table

Aggregate Operations

- without grouping
  - scan relation
  - maintain *running information* about scanned tuples
    - COUNT - count of values retrieved
    - SUM - *total* of values retrieved
    - AVG - *<total, count>* of values retrieved
    - MIN, MAX - smallest / largest value retrieved
- with grouping
  - sort relation on the grouping attributes
  - scan relation to compute aggregate operations for each group
  - improvement: combine sorting with aggregation computation
  - alternative approach based on hashing

Aggregate Operations

- using existing indexes
    - index with a search key that includes all the attributes required by the query
        - work with the data entries in the index (instead of the data records)
    - attribute list in the GROUP BY clause is a prefix of the index search key (tree index)
        - get data entries (and records, if necessary) in the required order (i.e., avoid sorting)

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