Database Management Systems

Lecture 8

Evaluating Relational Operators

Query Optimization

- running example - schema
  - Students (SID: integer, SName: string, Age: integer)
  - Courses (CID: integer, CName: string, Description: string)
  - Exams (SID: integer, CID: integer, 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

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

  - Exams
    - every record has 40 bytes
    - there are 100 records / page
    - 1000 pages of Exams tuples

* <u>sorting</u>

- can be explicitly required (SELECT ... ORDER BY list), used to eliminate duplicates (SELECT DISTINCT), used by operators like:
    - join
    - union
    - intersection
    - set-difference
    - grouping

* sorting

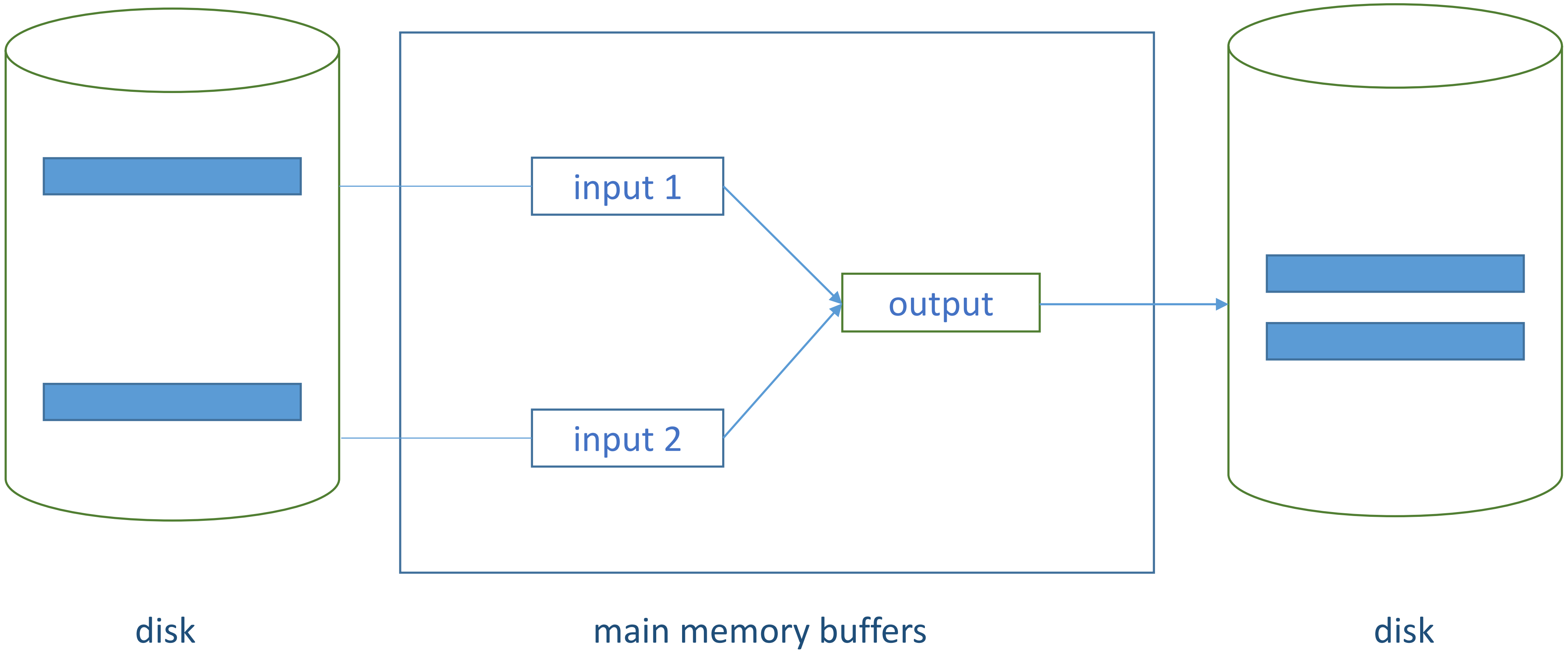
e.g., the user wants to sort the collection of Courses records by name

- if the data to be sorted fits into available main memory:
    - use an internal sorting algorithm (Quick Sort or any other in-memory sorting algorithm can be used to sort a collection of records that fits into main memory)

- if the data to be sorted doesn’t fit into available main memory:
    - use an external sorting algorithm
        - minimizes the cost of accessing the disk
        - breaks the data collection into subcollections of records
        - sorts the subcollections; a sorted subcollection of records is called a *run*
        - writes runs to disk
        - merges runs

Simple Two-Way Merge Sort

- uses 3 buffer pages
- passes over the data multiple times
- can sort large data collections using a small amount of main memory



Sabina S. CS

Simple Two-Way Merge Sort

- pass 0:
  - for each page P in the data collection:
    - read in page P -> sort page P -> save page P to disk

  => 1-page runs (runs that are 1 page long)

  example: - read in the 1st page from Courses, sort the 80 records on it by course name, write out the sorted page to disk (i.e., a *run* that is one page long);

  - read in the 2nd page from Courses, sort the 80 records on it by course name, write out sorted page to disk;

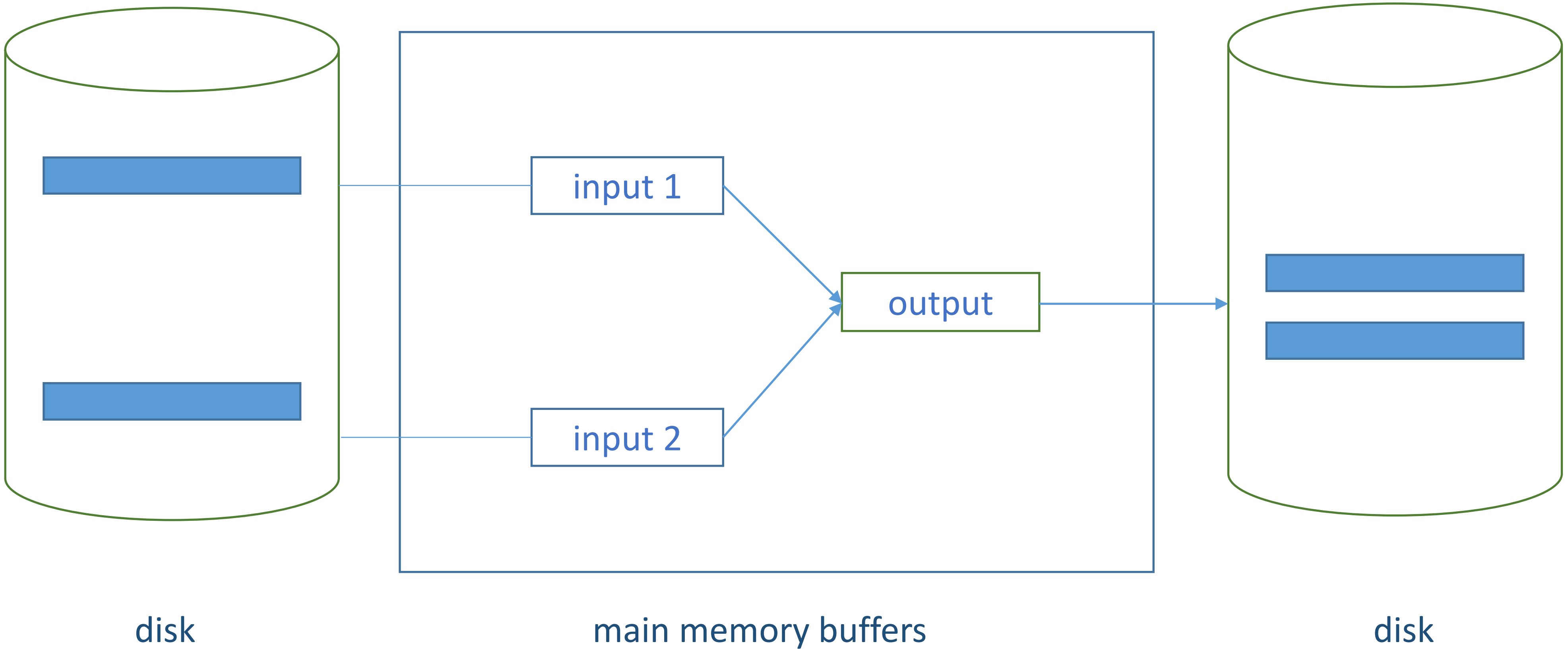
  …

  - read in the 100th page from Courses, sort the 80 records on it by course name, write out sorted page to disk

  => 100 1-page runs saved on disk

Simple Two-Way Merge Sort

- pass 1, 2, … etc:
  - use 3 buffer pages
  - read and merge pairs of runs from the previous pass
  - produce runs that are twice as long



Simple Two-Way Merge Sort

- e.g., pass 1 (pass 0 produced 100 1-page runs):
    - read in 2 runs from pass 0 (i.e., two pages holding Courses records, each of them sorted in pass 0), using 2 buffer pages
        - merge these runs writing to the 3rd available buffer page (the *output* buffer); when the output buffer fills up, write it out to disk (i.e., write a page of 80 sorted records to disk)

      => a run that is 2 pages long (it contains 160 Courses records, sorted by name)
    - read in and merge the next 2 runs from pass 0 … => another run that is 2 pages long
    - continue while there are runs to be processed (read in and merged) from pass 0
    - at the end of pass 1 there are 50 2-page runs (each run consists of 2 pages holding 160 records sorted by course name)

Simple Two-Way Merge Sort

- another example – sort data collection (file of records) with 7 pages:

3, 4	6, 2	9, 4	8, 7	5, 6	3, 1	2
page 1	page 2	...				

- only the value of the key is displayed (the key on which the user wants to sort the collection, an integer number in the example)
- simplifying assumption that allows us to focus on the idea of the algorithm: a page can hold 2 records

- pass 0
  - read in the collection one page at a time
  - sort each page that is read in
  - write out each sorted page to disk

  => 7 sorted runs that are 1 page long:

3, 4	2, 6	4, 9	7, 8	5, 6	1, 3	2

Simple Two-Way Merge Sort

- runs at the end of pass 0: 3, 4   2, 6   4, 9   7, 8   5, 6   1, 3   2

- pass 1
  - read in & merge pairs of runs from pass 0
  - produce runs that are twice as long
  - read in runs 3, 4 and 2, 6 :
    - merge the runs and write to the output buffer
    - write the output buffer to disk one page at a time

    => run 2, 3   4, 6

  - read in runs 4, 9 and 7, 8 :
    - merge the runs and write to the output buffer
    - write the output buffer to disk one page at a time

    => run 4, 7   8, 9

Simple Two-Way Merge Sort

- runs at the end of pass 0: [3, 4] [2, 6] [4, 9] [7, 8] [5, 6] [1, 3] [2]

- pass 1
  - read in runs [5, 6] and [1, 3] …

    => run [1, 3 | 5, 6]

  - read in run [2] (the last run from pass 0) …

    => run [2]

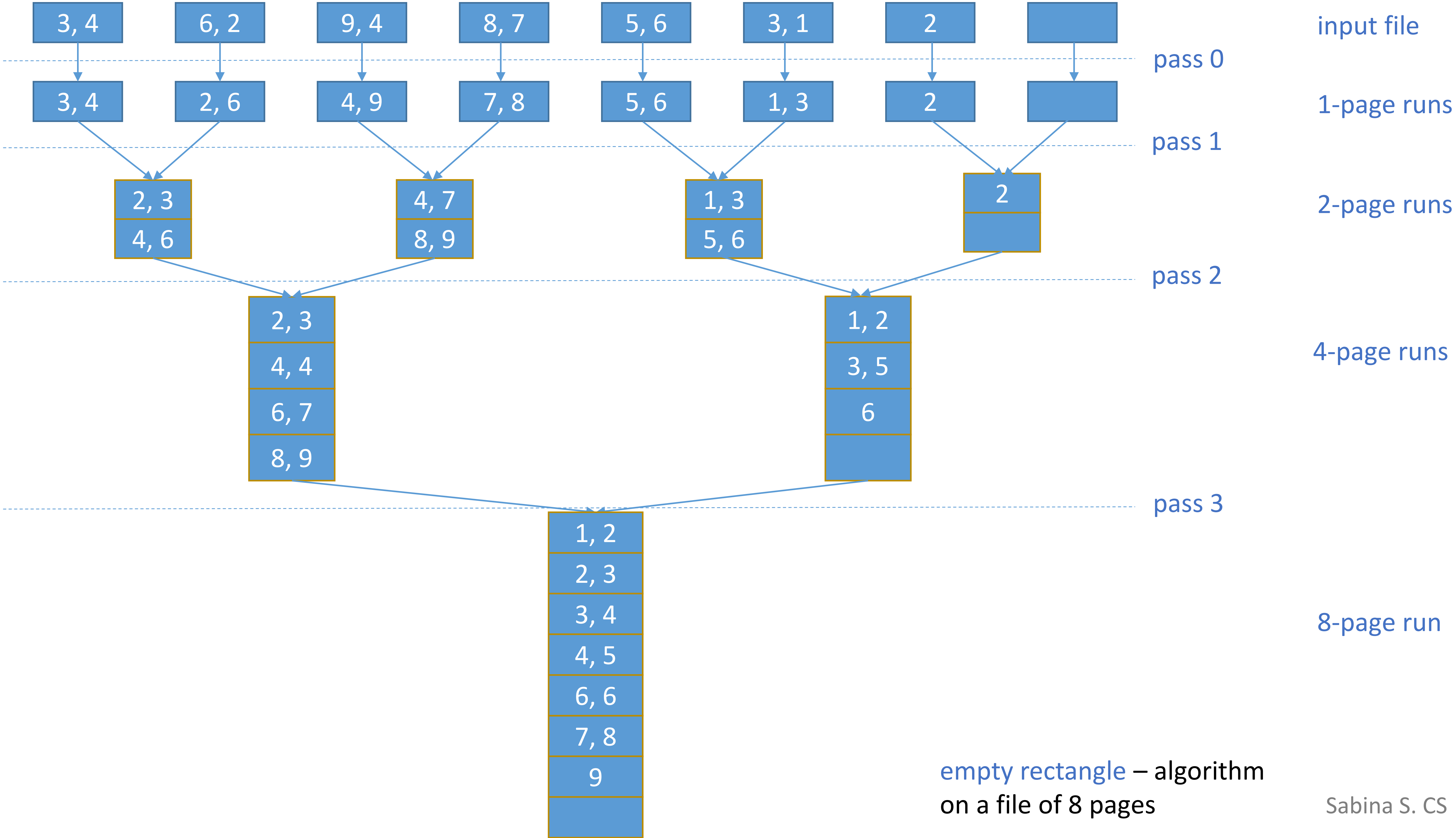
  => 4 sorted runs that are 2 pages long (except for the last run):

  [2, 3 | 4, 6] [4, 7 | 8, 9] [1, 3 | 5, 6] [2]

Simple Two-Way Merge Sort

- pass 2
    - read in & merge pairs of runs from pass 1
    - produce runs that are twice as long

  …
- complete example, with all passes of the algorithm, on the next page ->



input file

3, 4 | 6, 2 | 9, 4 | 8, 7 | 5, 6 | 3, 1 | 2

pass 0

1-page runs

3, 4 | 2, 6 | 4, 9 | 7, 8 | 5, 6 | 1, 3 | 2

pass 1

2-page runs

2, 3
4, 6 | 4, 7
8, 9 | 1, 3
5, 6 | 2

pass 2

4-page runs

2, 3
4, 4
6, 7
8, 9 | 1, 2
3, 5
6

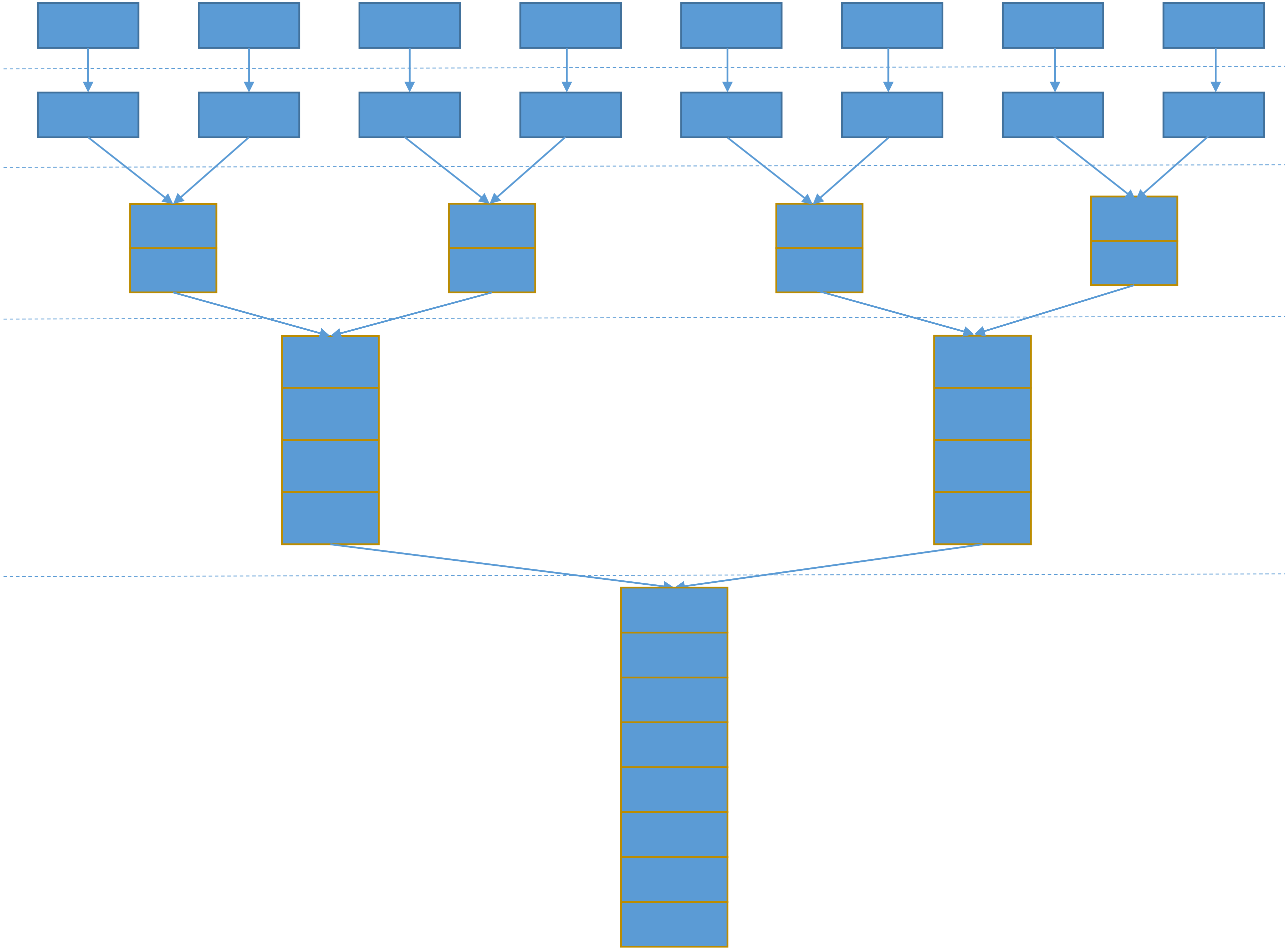
pass 3

8-page run

1, 2
2, 3
3, 4
4, 5
6, 6
7, 8
9

empty rectangle – algorithm
on a file of 8 pages

Sabina S. CS



input file: 2^k pages

pass 0

=> 2^k sorted runs (1-page)

pass 1

=> 2^{k-1} sorted runs (2-pages)

pass 2

=> 2^{k-2} sorted runs (4-pages)

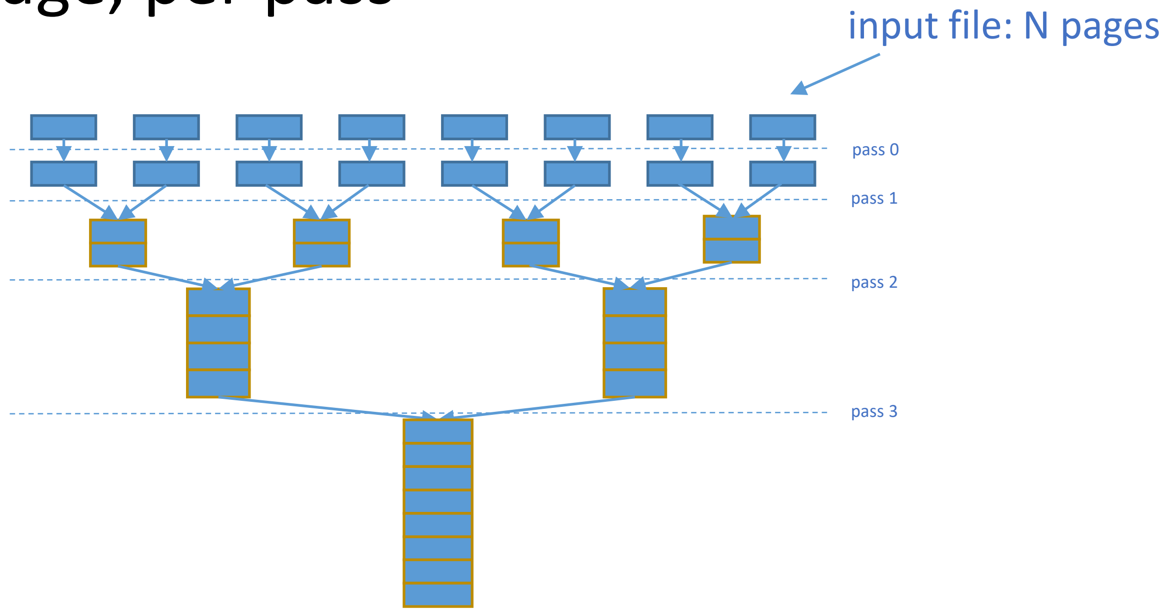
pass 3

=> 2^{k-3} sorted runs (8-pages)

i.e.,
pass k
=> one sorted run (2^k pages)

Simple Two-Way Merge Sort

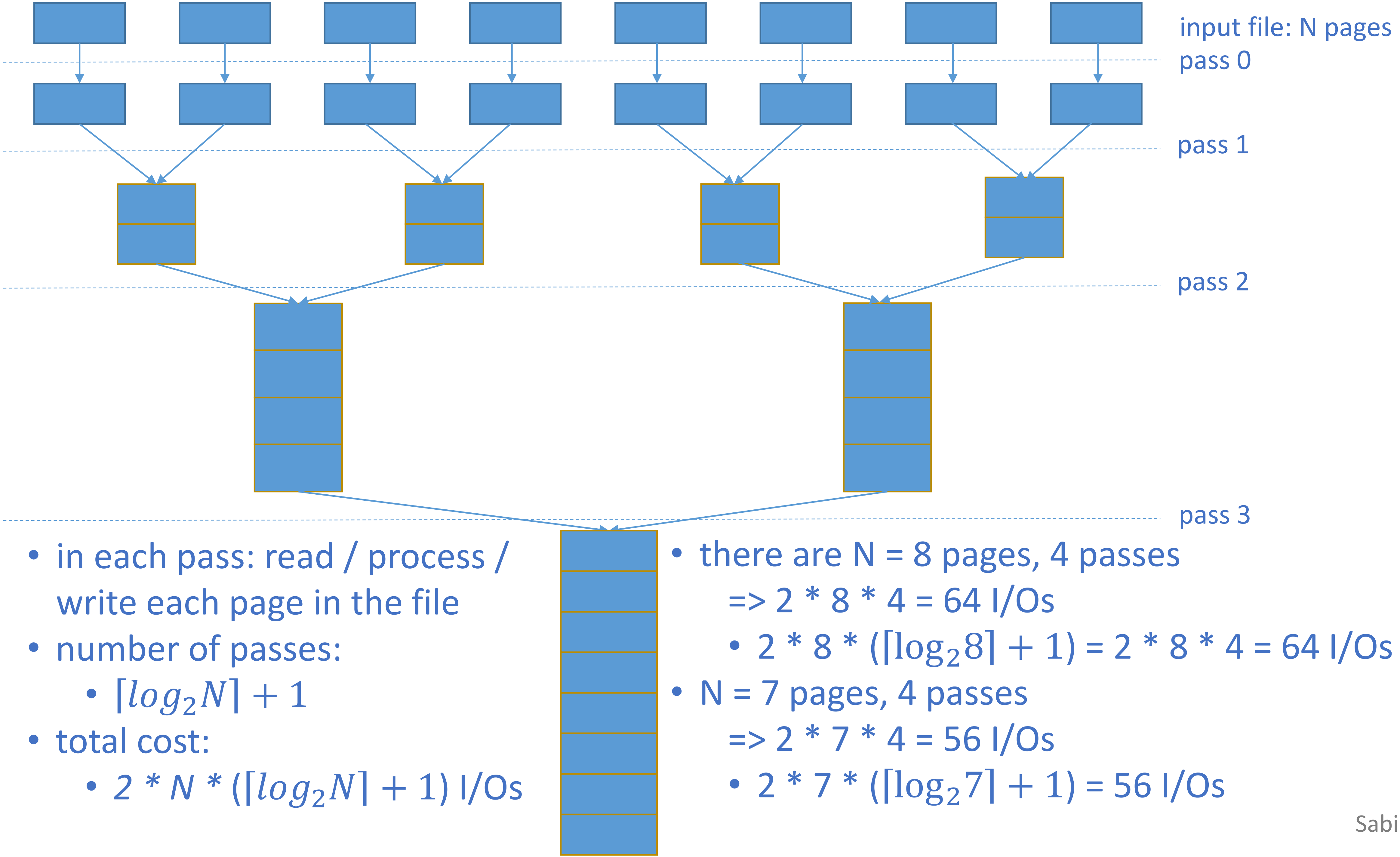
- in each pass, each page in the input file is: read in, processed, and written out; there are 2 I/O operations per page, per pass



- number of passes:
  - $\lceil log_2 N \rceil + 1$

  where *N* is the number of pages in the file to be sorted

- total cost:
  - 2 * number of pages * number of passes
  - $2 * N * (\lceil log_2 N \rceil + 1)$ I/Os



- in each pass: read / process / write each page in the file
- number of passes:
  - $\lceil log_2 N \rceil + 1$
- total cost:
  - $2 * N * (\lceil log_2 N \rceil + 1)$ I/Os

- there are N = 8 pages, 4 passes
  => 2 * 8 * 4 = 64 I/Os
  - $2 * 8 * (\lceil \log_2 8 \rceil + 1) = 2 * 8 * 4 = 64$ I/Os
- N = 7 pages, 4 passes
  => 2 * 7 * 4 = 56 I/Os
  - $2 * 7 * (\lceil \log_2 7 \rceil + 1) = 56$ I/Os

External Merge Sort

- Simple Two-Way Merge Sort: buffer pages are not used effectively
  - for instance, if 200 buffer pages are available, this algorithm still uses only 2 input buffers for passes 1, 2, …
- generalize the Two-Way Merge Sort algorithm to effectively use the available main memory and minimize the number of passes

->

External Merge Sort

- input file to be sorted: N pages
- B buffer pages are available
- pass 0:
  - use B buffer pages
  - read in B pages at a time and sort them in memory

=> $\left\lceil \frac{N}{B} \right\rceil$ runs of B pages each (except for the last one, which may be smaller)

->

External Merge Sort

- consider again the input file in the previous example:

3, 4	6, 2	9, 4	8, 7	5, 6	3, 1	2
page 1	page 2	…				

- N = 7 (number of pages in the file)
- B = 4 (there are 4 available buffer pages)
- pass 0 produces $\left\lceil \frac{N}{B} \right\rceil$ = $\left\lceil \frac{7}{4} \right\rceil = 2$ runs:
  - use all 4 buffer pages
  - read in 4 pages:

3, 4	6, 2	9, 4	8, 7

  - sort the pages in memory, write to disk a run that is 4 pages long:

2, 3	4, 4	6, 7	8, 9

  - read in remaining 3 pages:

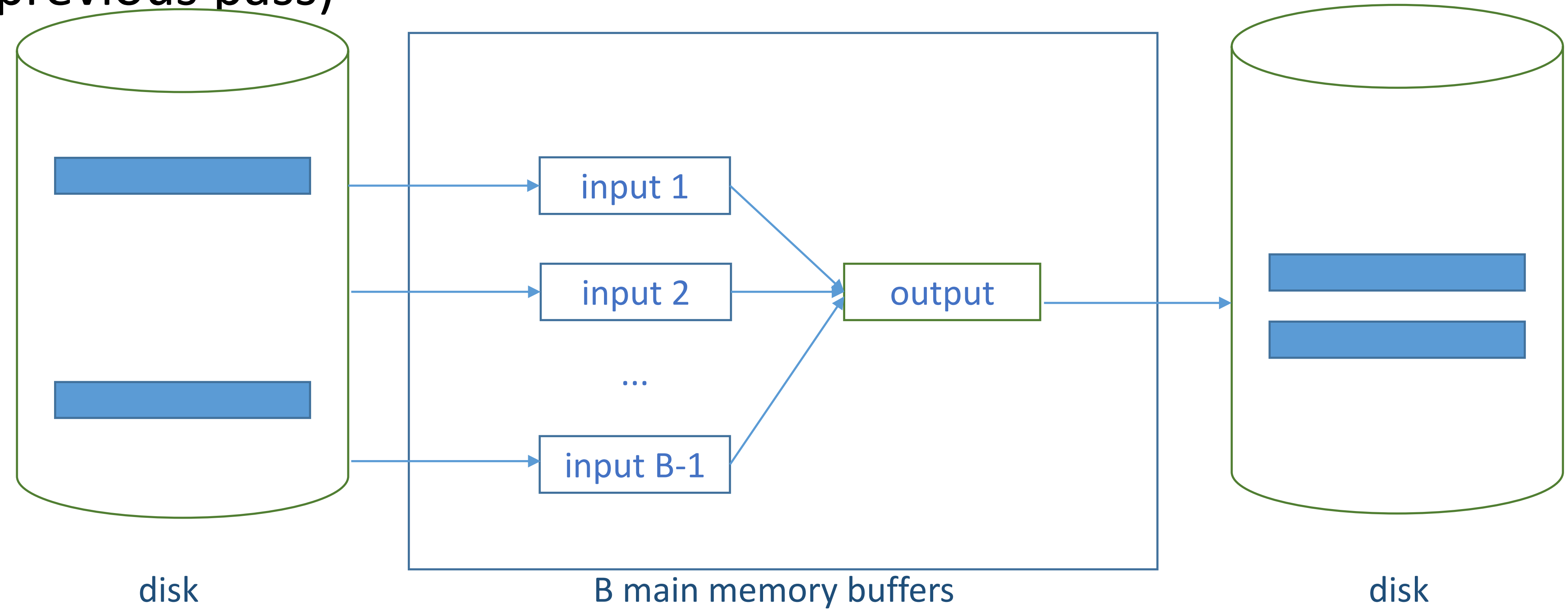
5, 6	3, 1	2

  - sort pages in memory, write to disk run of 3 pages:

1, 2	3, 5	6

External Merge Sort

- input file to be sorted: N pages
- B buffer pages are available
- pass 1, 2 ...:
  - use B-1 pages for input, and one page for output
  - perform a (B-1)-way merge in each pass (i.e., merge B-1 runs from the previous pass)



Sabina S. CS

External Merge Sort

- runs at the end of pass 0:

2, 3	4, 4	6, 7	8, 9

1, 2	3, 5	6

- pass 1
  - read in & merge the first B-1 = 4-1 = 3 runs from pass 0
  - pass 0 produced only 2 runs in this example; read in and merge these 2 runs:

    => run

1, 2	2, 3	3, 4	4, 5	6, 6	7, 8	9

External Merge Sort

- another example:
  - 5 buffer pages B = 5
  - sort file with 108 pages N = 108

- pass 0
  - use all 5 buffer pages
  - read in the first 5 pages of the file, sort them in memory, write the resulting run to disk (5 pages long)
  - read in the next 5 pages of the file, sort them in memory, write the resulting run to disk (5 pages long)
  - …
  - read in the remaining 3 pages of the file, sort them in memory, write the resulting run to disk (3 pages long)
  - 21 runs are 5 pages long; 1 run is 3 pages long

External Merge Sort

- another example: B = 5, N = 108
- pass 0
    - at the end of pass 0 there are $\left\lceil \frac{N}{B} \right\rceil = \left\lceil \frac{108}{5} \right\rceil$ = 22 runs
- pass 1
    - use B-1 = 5-1 = 4 pages for input, and one page for output
    - do a 4-way merge: read in and merge 4 runs from the previous pass
    - read in the first 4 runs from pass 0 (each run into an input buffer)
        - merge the runs and write to the output buffer
        - write the output buffer to disk one page at a time

    => a run that is 20 pages long (4 runs from pass 0 times 5 pages per run)
    - read in the next 4 runs from pass 0; merge the runs and write to the output buffer; write the output buffer to disk one page at a time

    => another run (20 pages long)

    …

External Merge Sort

- another example: B = 5, N = 108
- pass 0
  - at the end of pass 0 there are 22 runs

- pass 1
  - read in the last 2 runs from pass 0 (one has 5 pages, the other one has 3 pages)
    - merge the runs and write to the output buffer; write the output buffer to disk one page at a time

    => the last run (8 pages long)
  - at the end of pass 1 there are $\left\lceil \frac{22}{4} \right\rceil$ = 6 runs
  - 5 runs are 20 pages long; 1 run is 8 pages long

External Merge Sort

- another example: B = 5, N = 108
- pass 1
  - at the end of pass 1 there are 6 runs

- pass 2
  - 4-way merge
  - read in the first 4 runs from pass 1
    - merge the runs and write to the output buffer; write the output buffer to disk one page at a time

    => a run that is 80 pages long (4 runs from pass 1 times 20 pages per run)
  - read in the remaining 2 runs from pass 1 (20 and 8 pages, respectively)

    => a run that is 28 pages long
  - at the end of pass 2 there are $\left\lceil \frac{6}{4} \right\rceil$ = 2 runs

External Merge Sort

- another example: B = 5, N = 108
- pass 2
  - at the end of pass 2 there are 2 runs

- pass 3
  - read in the 2 runs from pass 2 and merge them
    => a run that is 108 pages long, representing the sorted file

External Merge Sort

- cost
  - N – number of pages in the input file, B – number of available pages in the buffer
  - in each pass: read / process / write each page
  - number of passes: $\lceil log_{B-1} \lceil N/B \rceil \rceil + 1$
  - total cost: $2 * N * \left(\left\lceil log_{B-1} \left\lceil \frac{N}{B} \right\rceil \right\rceil + 1 \right)$ I/Os

- previous example: B = 5 and N = 108, with 4 passes over the data
  - cost:
    2 * 108 * 4 = 864 I/Os
  - $2 * 108 * \left(\left\lceil log_{5-1} \left\lceil \frac{108}{5} \right\rceil \right\rceil + 1 \right) = 216 * (\lceil log_4 22 \rceil + 1) =$
    $216 * 4 = 864$ I/Os

- B buffer pages
- sort file with N pages

Simple Two-Way Merge Sort

pass 0 => N runs

number of passes = $\lceil log_2 N \rceil + 1$

External Merge Sort

pass 0 => $\left\lceil \frac{N}{B} \right\rceil$ runs

number of passes = $\left\lceil log_{B-1} \left\lceil \frac{N}{B} \right\rceil \right\rceil + 1$

- External Merge Sort – reduced number of:
  - runs produces by the 1st pass
  - passes over the data
- B is usually large => significant performance gains

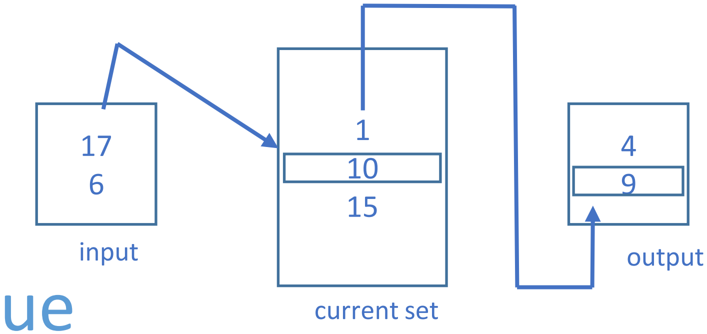
External Merge Sort – number of passes for different values of N and B

N	B = 3	B = 5	B = 9	B = 17	B = 129	B = 257
100	7	4	3	2	1	1
1,000	10	5	4	3	2	2
10,000	13	7	5	4	2	2
100,000	17	9	6	5	3	3
1,000,000	20	10	7	5	3	3
10,000,000	23	12	8	6	4	3
100,000,000	26	14	9	7	4	4
1,000,000,000	30	15	10	8	5	4

* minimize the number of runs - optional

- external merge sort
  - N pages in the file, B buffer pages => $\lceil N/B \rceil$ runs of B pages each
- improvement
  - algorithm known to produce runs of approximately 2*B pages (on average)
  - use 1 page as an input buffer, 1 page as an output buffer
  - the remaining buffer pages are collectively referred to as the *current set*

- example - sort file in ascending order on some key *k*:
  - repeatedly pick record *r* in the current set and append it to the output buffer
  - keep output buffer sorted: *r*'s *k* value >= largest *k* value in the output buffer
  - multiple such records in current set - choose the smallest one



* minimize the number of runs - optional

- example - sort file in ascending order on some key *k*:
  - use the extra space in the current set to bring in the next tuple from the input buffer
  - process all tuples in the input buffer, then read in the next page of the file
  - when the output buffer fills up, write it to disk (add its content to the run that is currently being built)
  - the current run is completed when every *k* value in the current set is < the largest *k* value in the output buffer; when this happens, the output buffer is written out (its content becomes the last page in the current run), and a new run is started

Sort-Merge Join

- equality join, one join column: $\mathrm{E} \otimes_{i=j} S$ (ith column's value in E = jth 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 ith and jth column, respectively)
    - there could be multiple tuples in E with the same value in the ith column as the current tuple *e* (same is true for S)

Sort-Merge Join

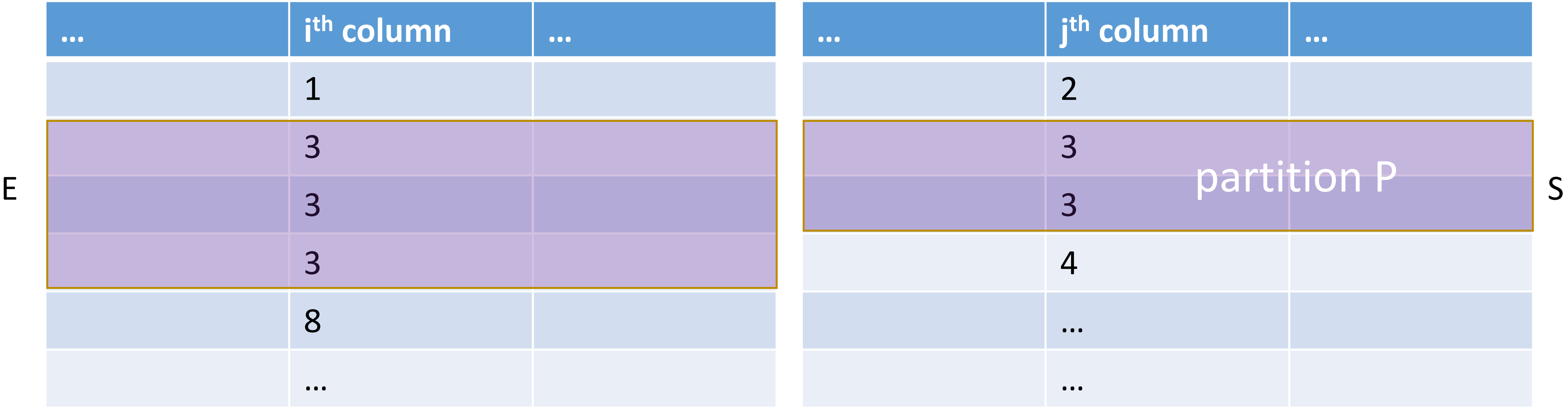
- partitions are illustrated on tables Students and Exams below (join column SID in both tables):

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	
	…	

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

S

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: 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 ($\text{Exams} \otimes_{Exams.SID=Students.SID} \text{Students}$)

- 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

* E - M pages, p_E records / page *	* 1000 pages *	* 100 records / page*
* S - N pages, p_S records / page *	* 500 pages *	* 80 records / page *

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

- 35 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
    - 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 *

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

- 300 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
        - 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 *

References

- [Ra02] RAMAKRISHNAN, R., GEHRKE, J., Database Management Systems (3rd Edition), McGraw-Hill, 2002
- [Da03] DATE, C.J., An Introduction to Database Systems (8th Edition), Addison-Wesley, 2003
- [Ga09] GARCIA-MOLINA, H., ULLMAN, J., WIDOM, J., Database Systems: The Complete Book (2nd Edition), Pearson, 2009
- [Ra07] RAMAKRISHNAN, R., GEHRKE, J., Database Management Systems, McGraw-Hill, 2007, http://pages.cs.wisc.edu/~dbbook/openAccess/thirdEdition/slides/slides3ed.html
- [Si19] SILBERSCHATZ, A., KORTH, H., SUDARSHAN, S., Database System Concepts (7th Edition), McGraw-Hill, 2019
- [Ul11] ULLMAN, J., WIDOM, J., A First Course in Database Systems, http://infolab.stanford.edu/~ullman/fcdb.html