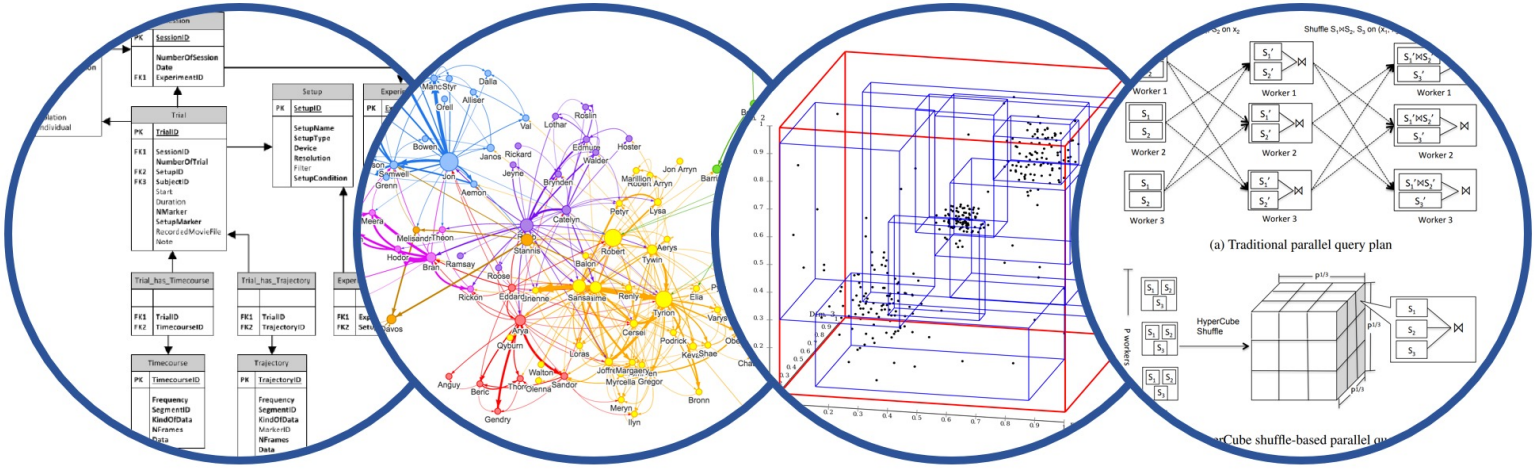


Database System Internals

Operator Algorithms (part 2)

Paul G. Allen School of Computer Science and Engineering
University of Washington, Seattle

Today's Outline

Query Execution Algorithms:

- Catch-up from last lecture
- Finish operator implementation

Operator Algorithms

Design criteria

- Cost: IO, CPU, Network
- Memory utilization
- Load balance (for parallel operators)

Cost Parameters

- **Cost = total number of I/Os**
  - This is a simplification that ignores CPU, network

- **Parameters:**
  - **B(R)** = # of blocks (i.e., pages) for relation R
  - **T(R)** = # of tuples in relation R
  - **V(R, a)** = # of distinct values of attribute a
    - When **a** is a key, **V(R,a) = T(R)**
    - When **a** is not a key, **V(R,a)** can be anything < **T(R)**

Convention

- Cost = the cost of reading operands from disk, plus cost to read/write intermediate results
- Cost of writing the final result to disk is *not included*; need to count it separately when applicable

Outline

- **Join operator algorithms**
  - One-pass algorithms (Sec. 15.2 and 15.3)
  - Index-based algorithms (Sec 15.6)
  - Two-pass algorithms (Sec 15.4 and 15.5)

- Note about readings:
  - In class, we discuss only algorithms for joins
  - Other operators are easier: book has extra details

Join Algorithms

- Hash join
- Nested loop join
- Sort-merge join

Hash Join

Hash join: $R \bowtie S$

- Scan R, build buckets in main memory
- Then scan S and join
- Cost: B(R) + B(S)

- One-pass algorithm when $B(R) \leq M$

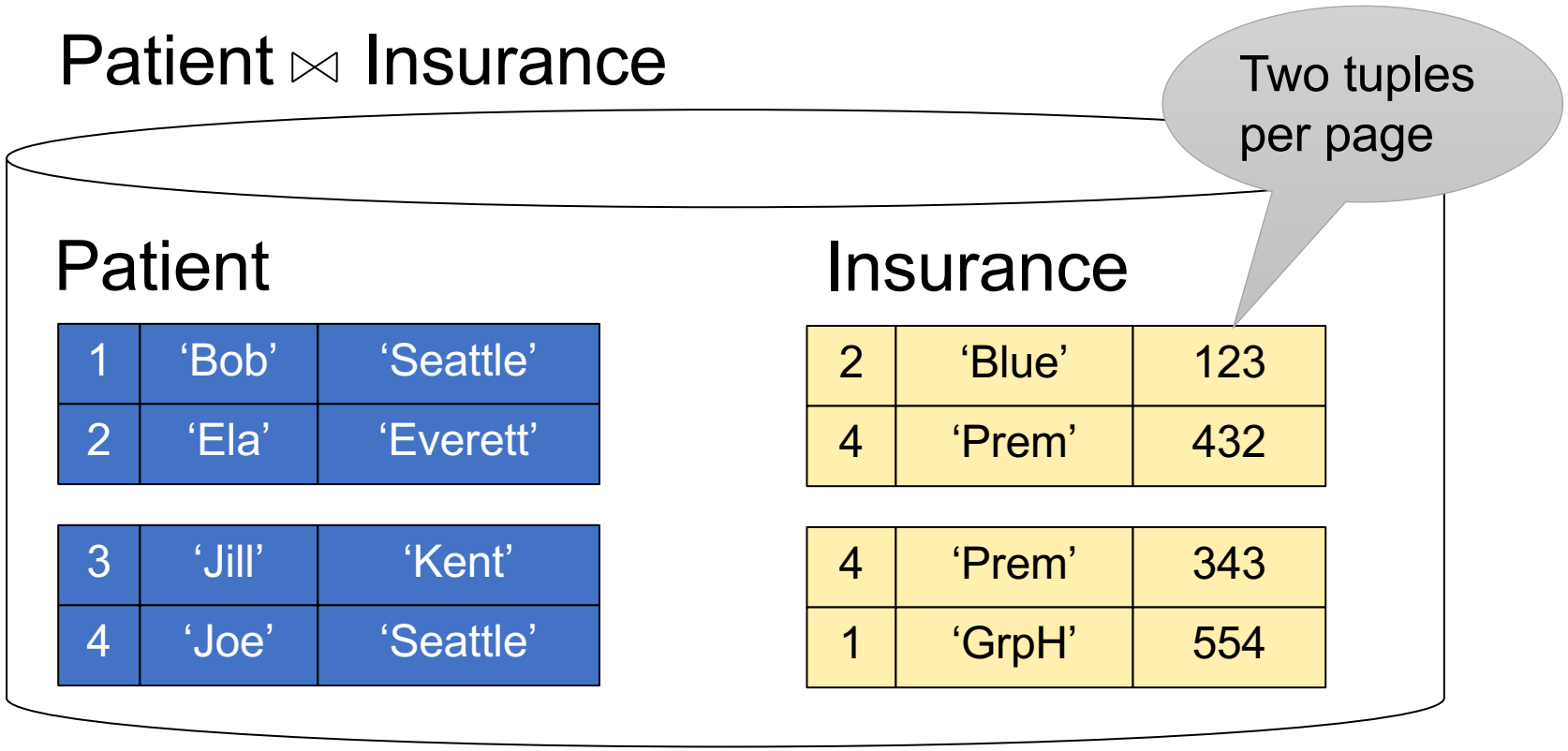
Note: the *inner* relation is the relation on which we build the hash table
- Usually this is the *right* relation of $R \bowtie S$, i.e. S.
- But the following slides choose the *left* relation, i.e. R

Hash Join Example

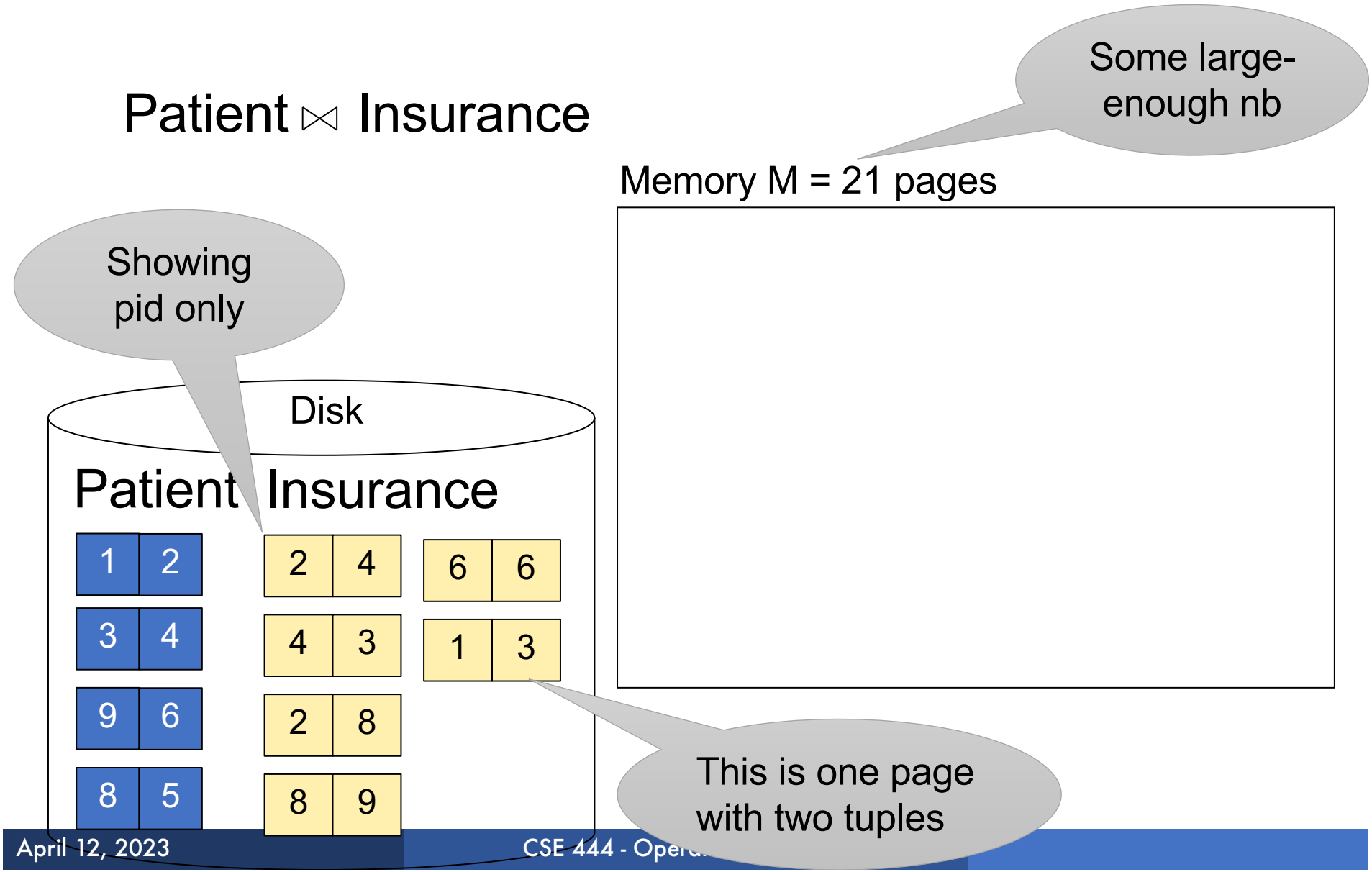
Patient(pid, name, address)

Insurance(pid, provider, policy_nb)

Patient ⋈ Insurance

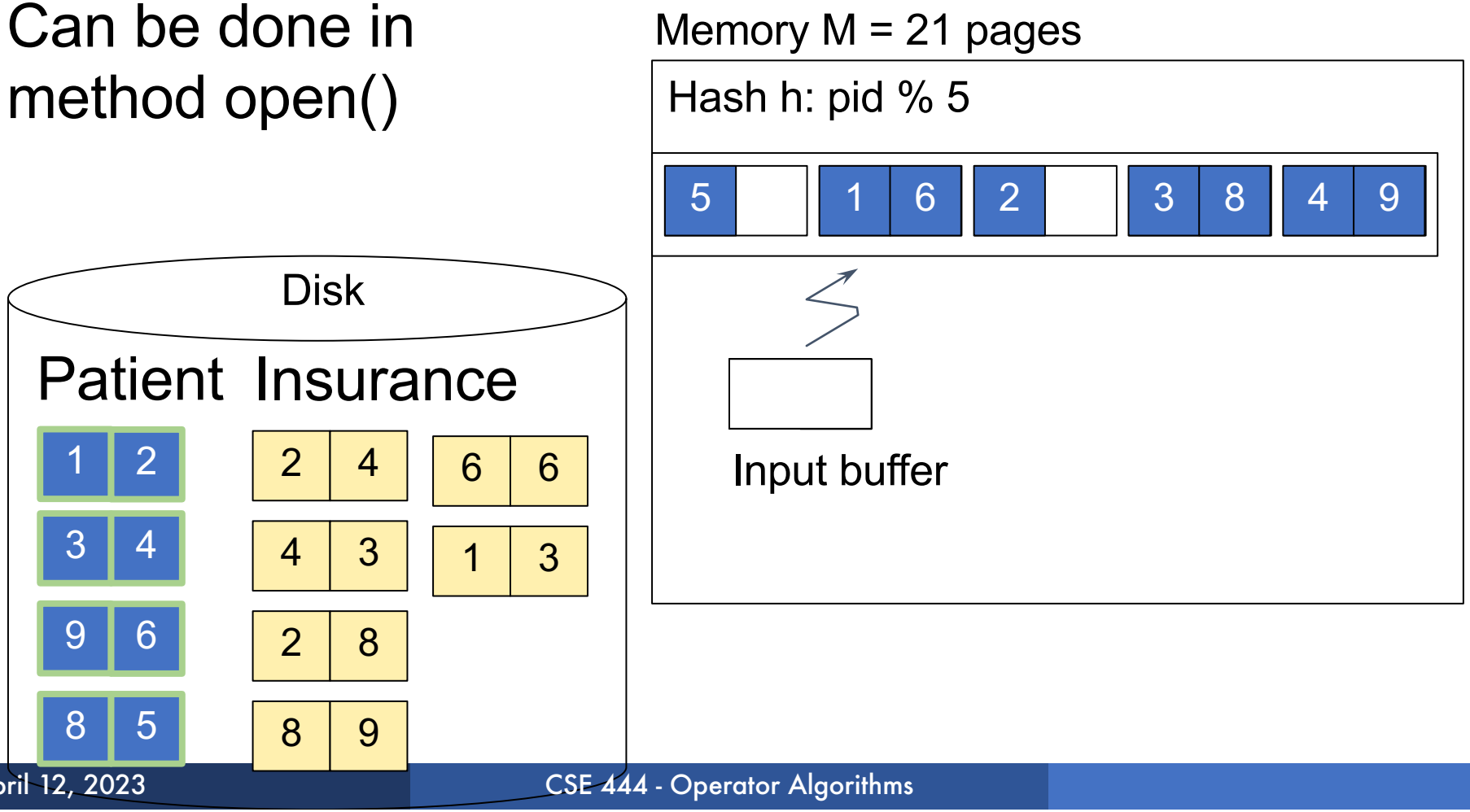


Hash Join Example



Hash Join Example

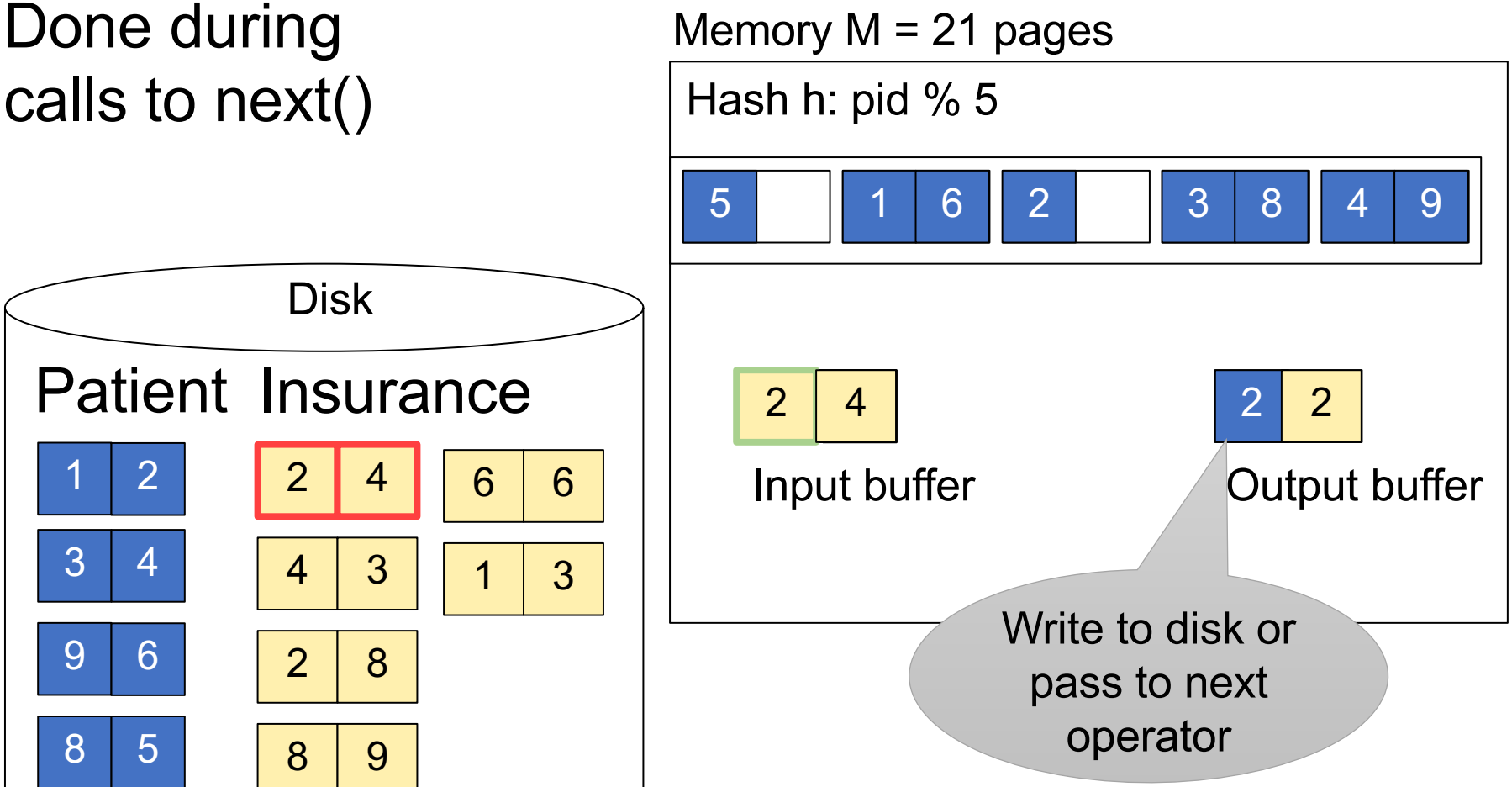
Step 1: Scan Patient and build hash table in memory
Can be done in
method open()



Hash Join Example

Step 2: Scan Insurance and probe into hash table

Done during
calls to next()



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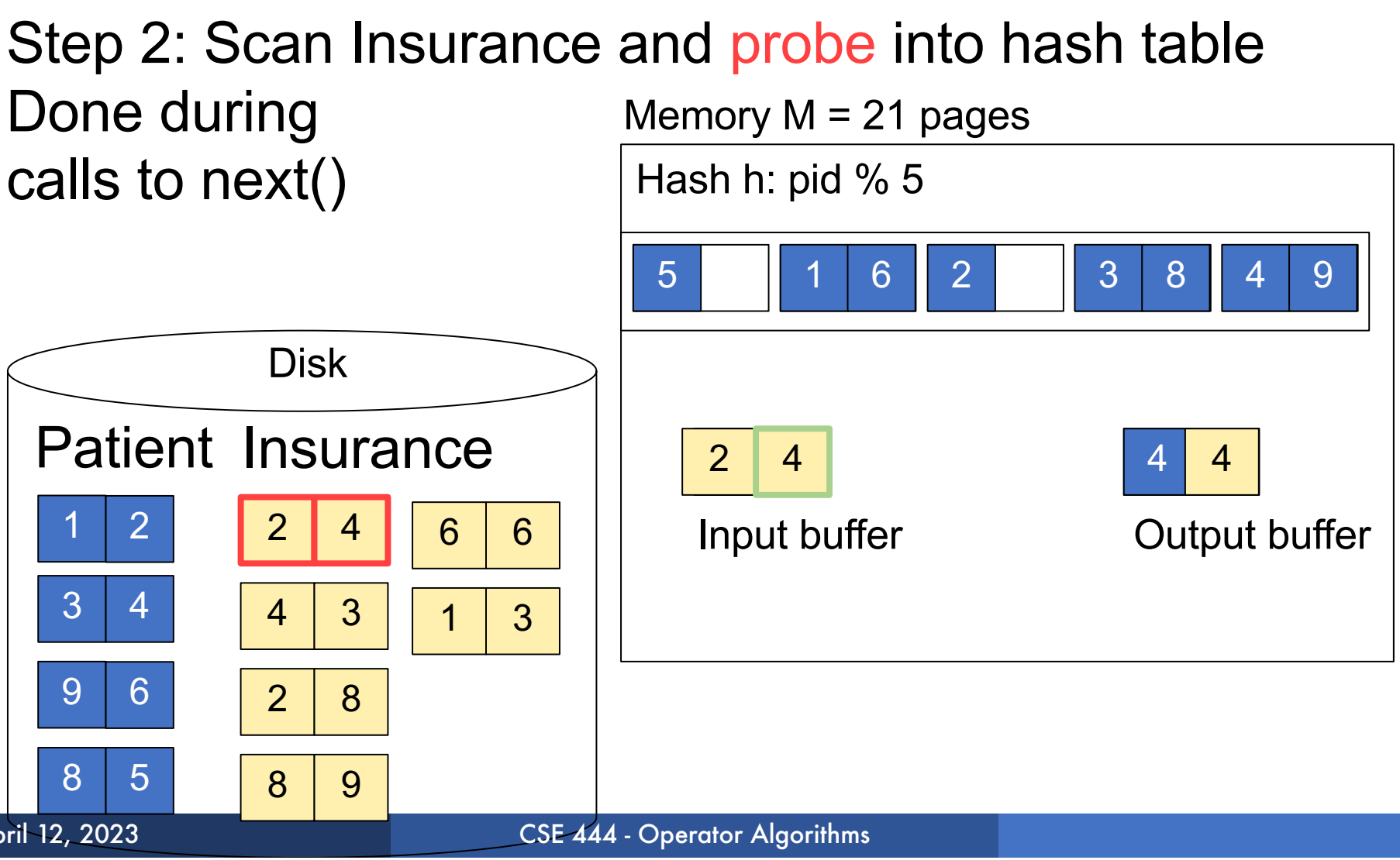

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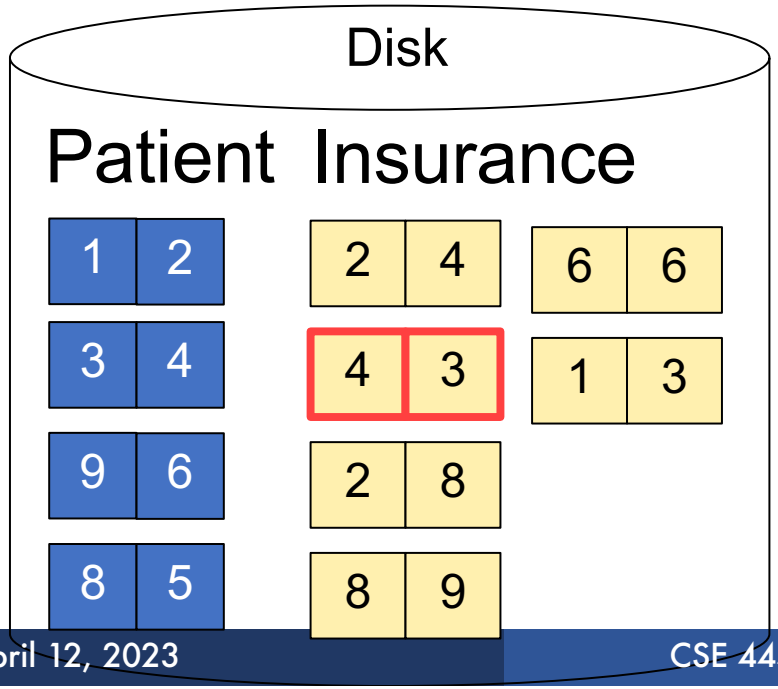
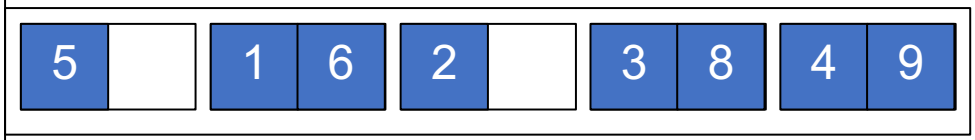
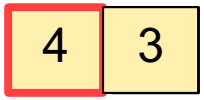


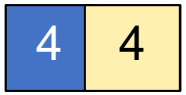
Memory M = 21 pages

Hash h: pid % 5





Input buffer



Output buffer

Keep going until read all of Insurance

Cost: B(R) + B(S)

Discussion

- Hash-join is the workhorse of database systems

- The hash table is built on the heap, not in BP;
  hence it is not organized in pages,
  but pages are still convenient to measure its size

- Hash-join works great when:
  - The inner table fits in main memory
  - The hash function is good (never write your own!)
  - The data has no skew (discuss in class…)

Nested Loop Joins

- Tuple-based nested loop R ⋈ S
- R is the outer relation, S is the inner relation

```
for each tuple t1 in R do
   for each tuple t2 in S do
      if t1 and t2 join then output (t1,t2)
```

What is the Cost?

Nested Loop Joins

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for each tuple t1 in R do
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```

What is the Cost?

- Cost: B(R) + T(R) B(S)
- Multiple-pass since S is read many times

Page-at-a-time Refinement

```
for each page of tuples r in R do
   for each page of tuples s in S do
      for all pairs of tuples t1 in r, t2 in s
            if t1 and t2 join then output (t1,t2)
```

What is the Cost?

Page-at-a-time Refinement

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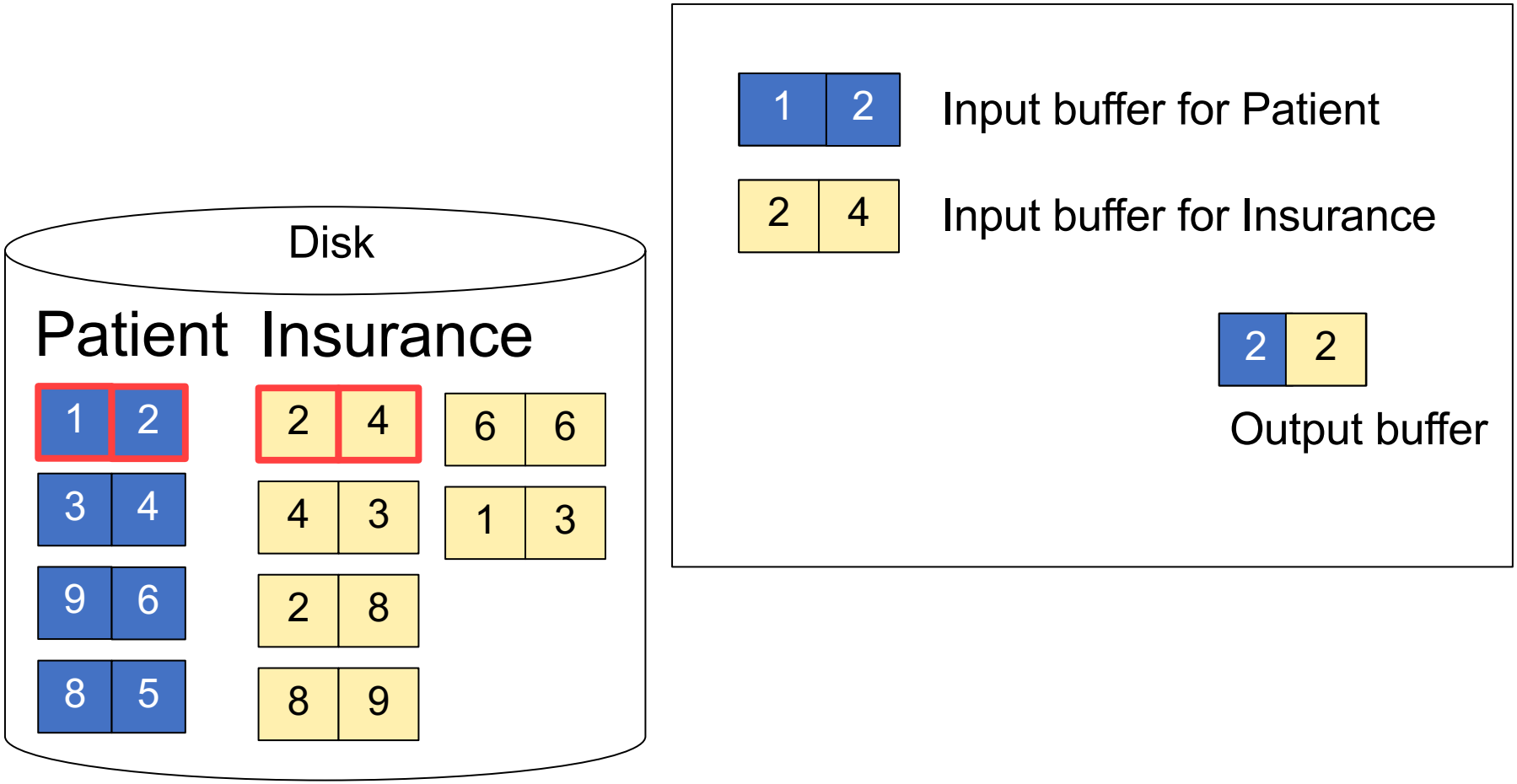
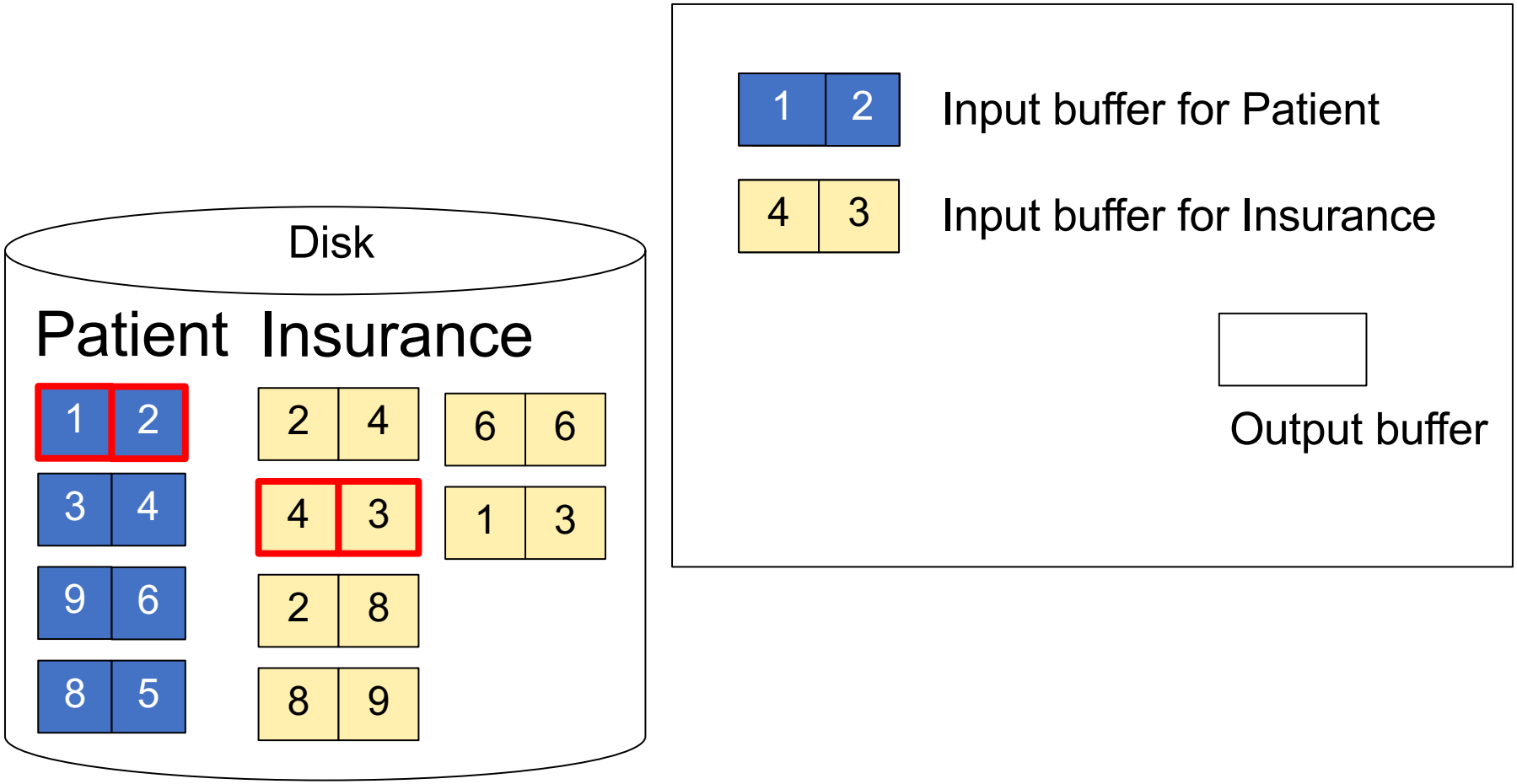
Page-at-a-time Refinement



Page-at-a-time Refinement



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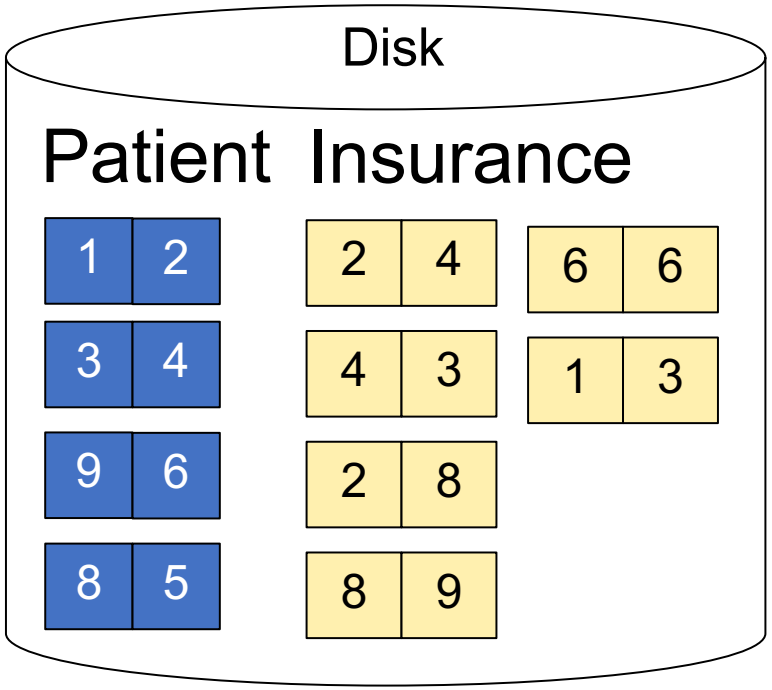

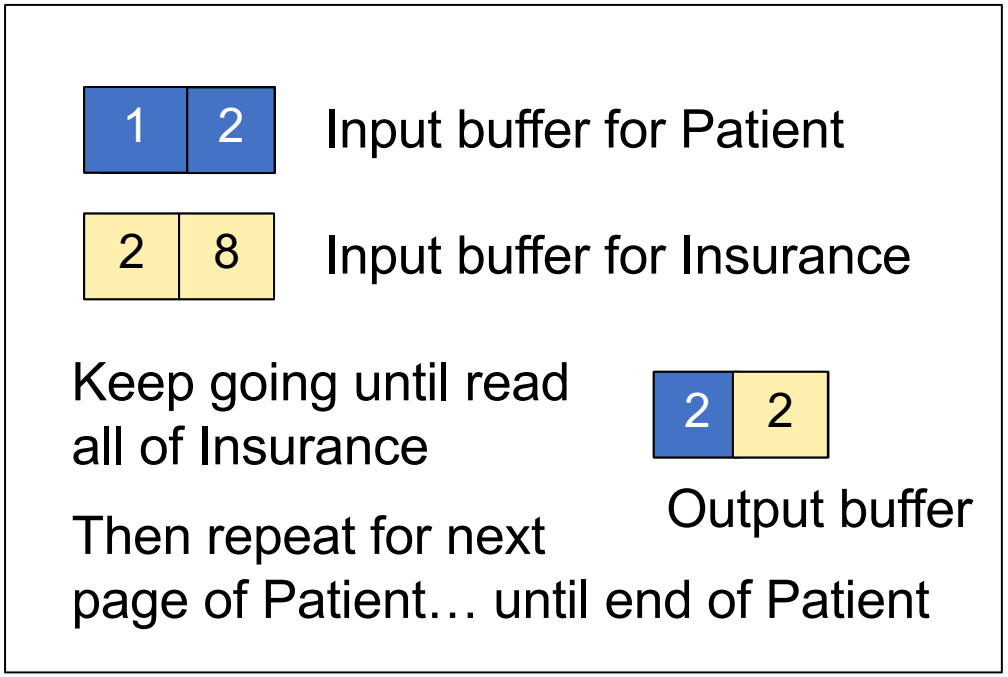

Cost: B(R) + B(R)B(S)

Block-Memory Refinement

```
for each group of M-1 pages r in R do
    for each page of tuples s in S do
        for all pairs of tuples t1 in r, t2 in s
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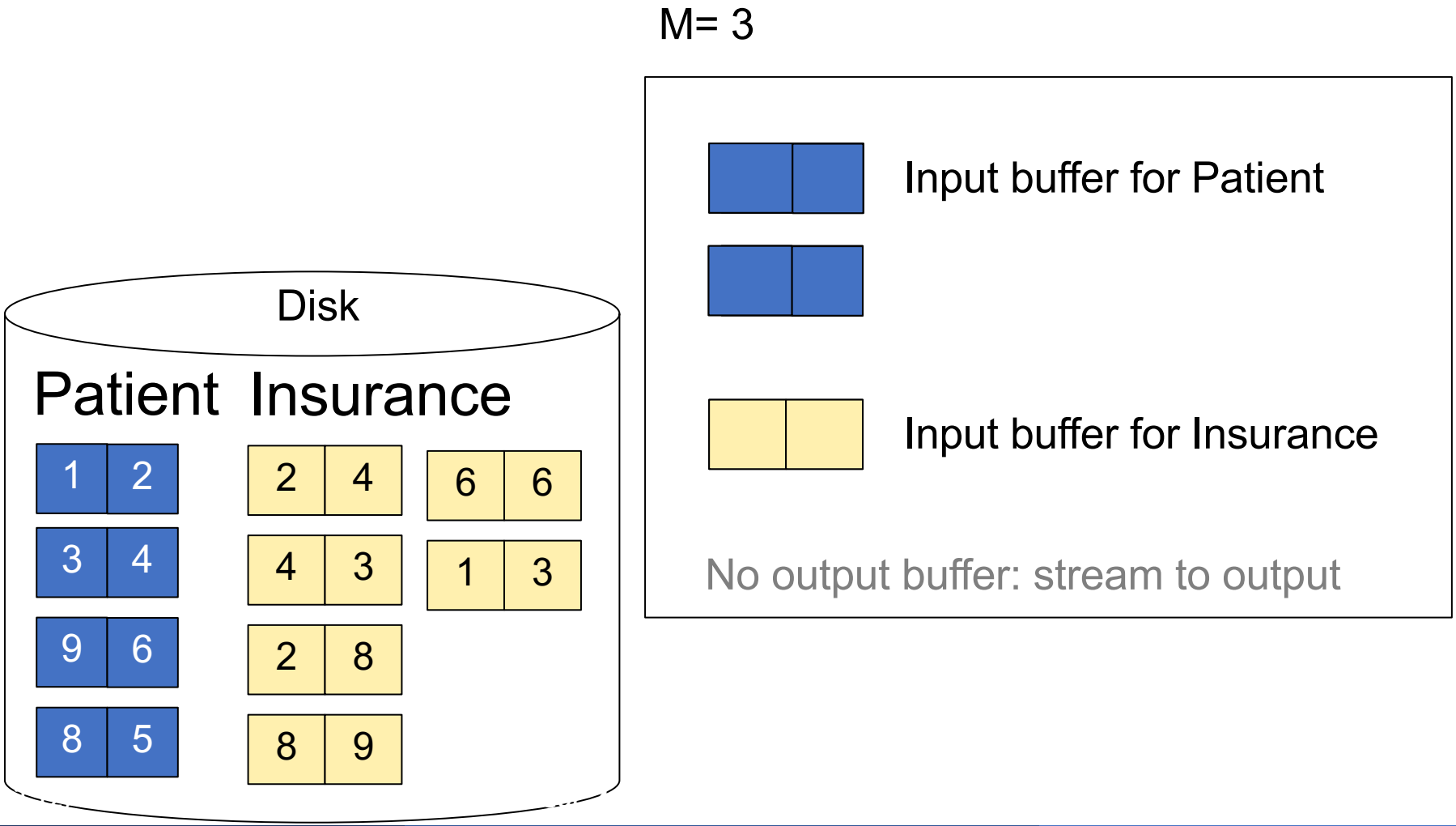
What is the Cost?

Block Memory Refinement



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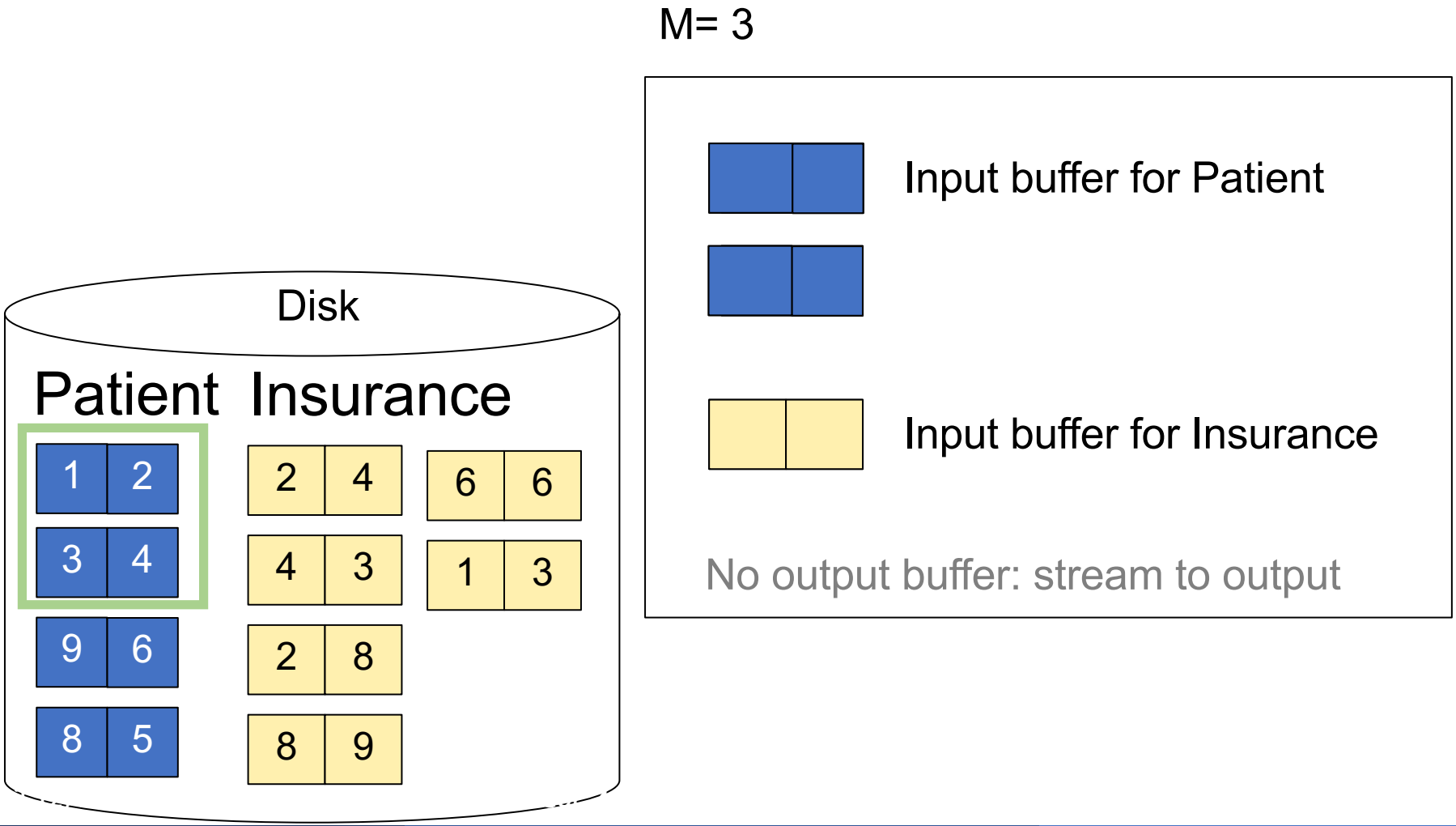

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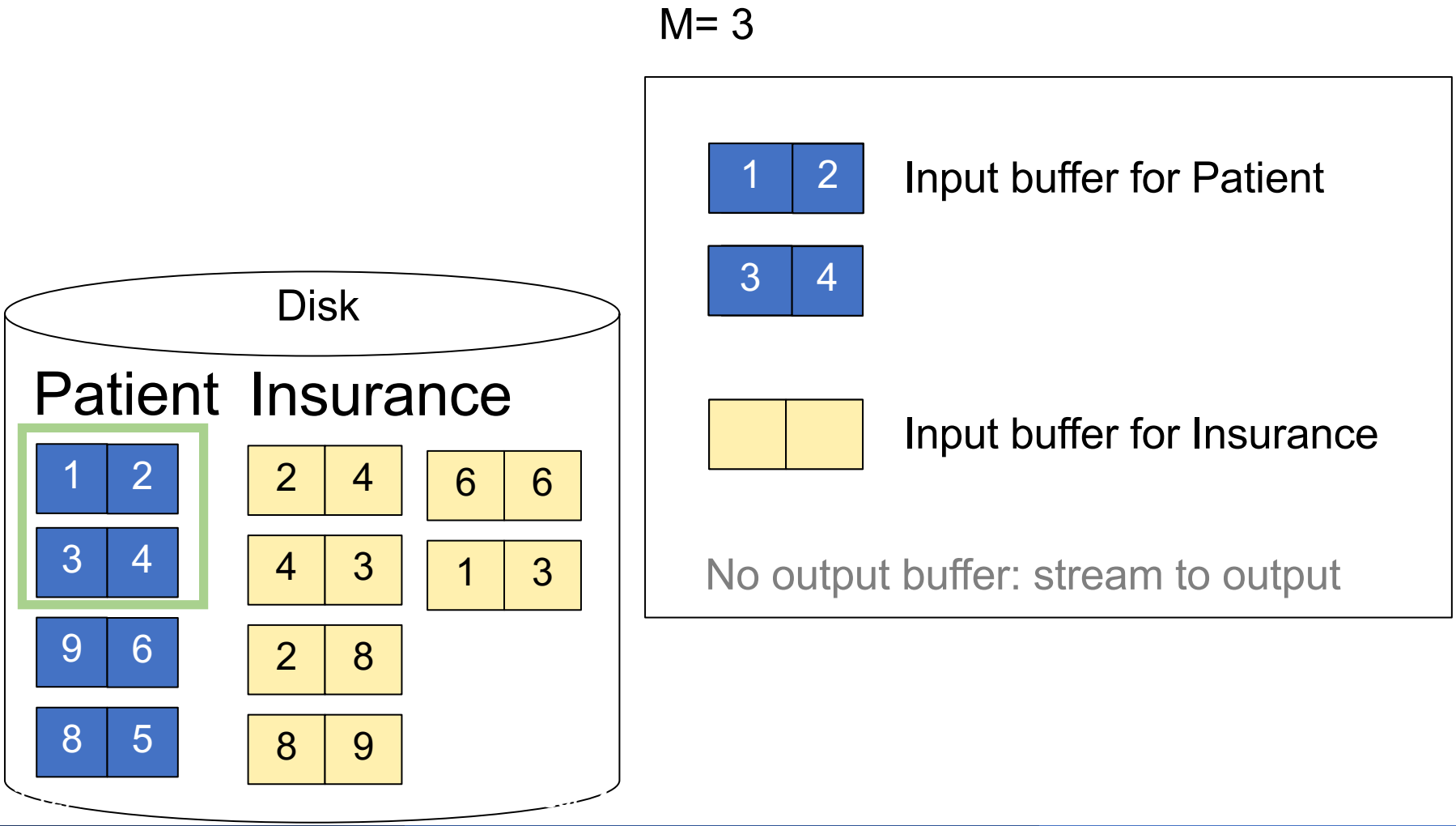
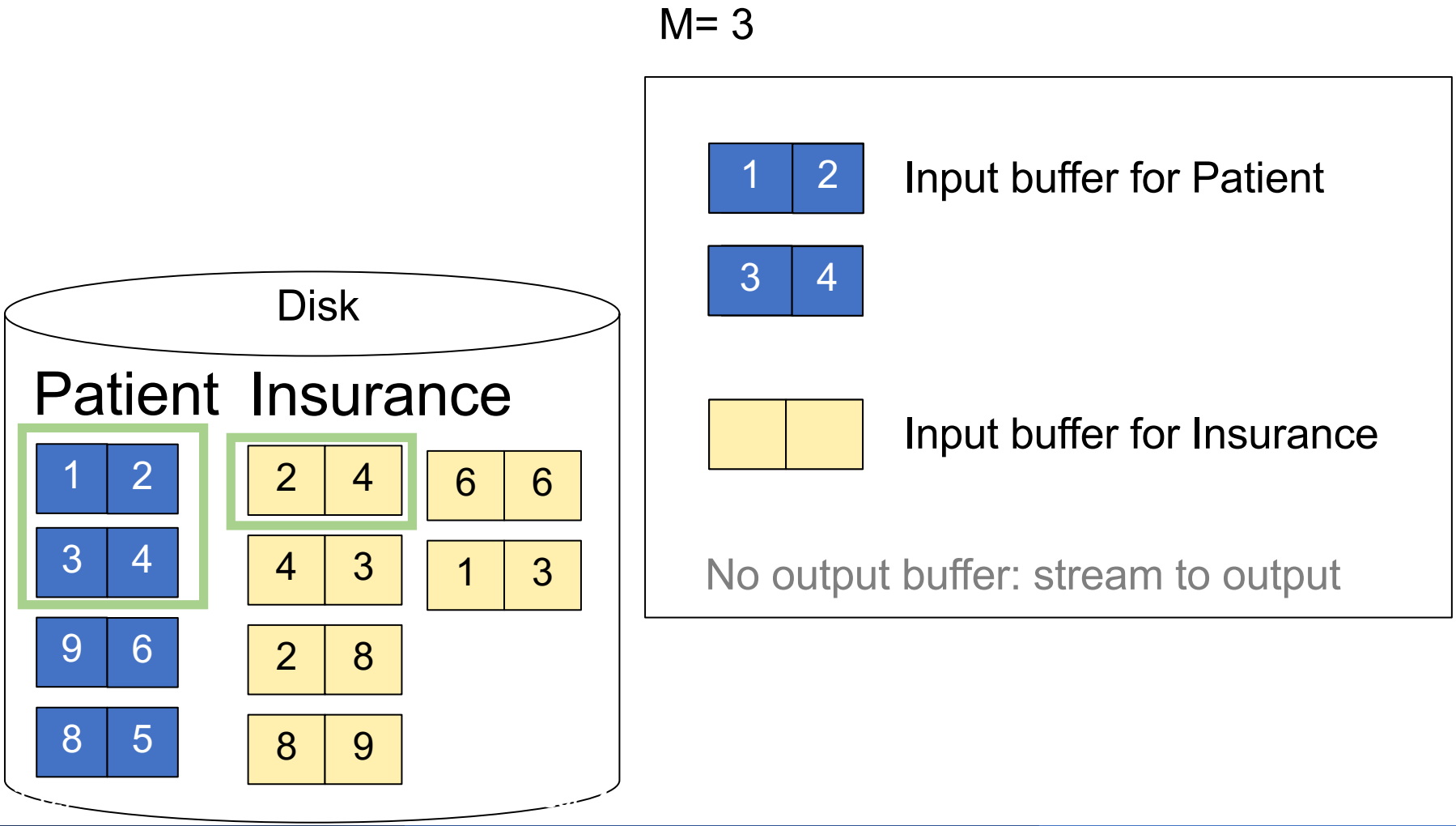


Block Memory Refinement



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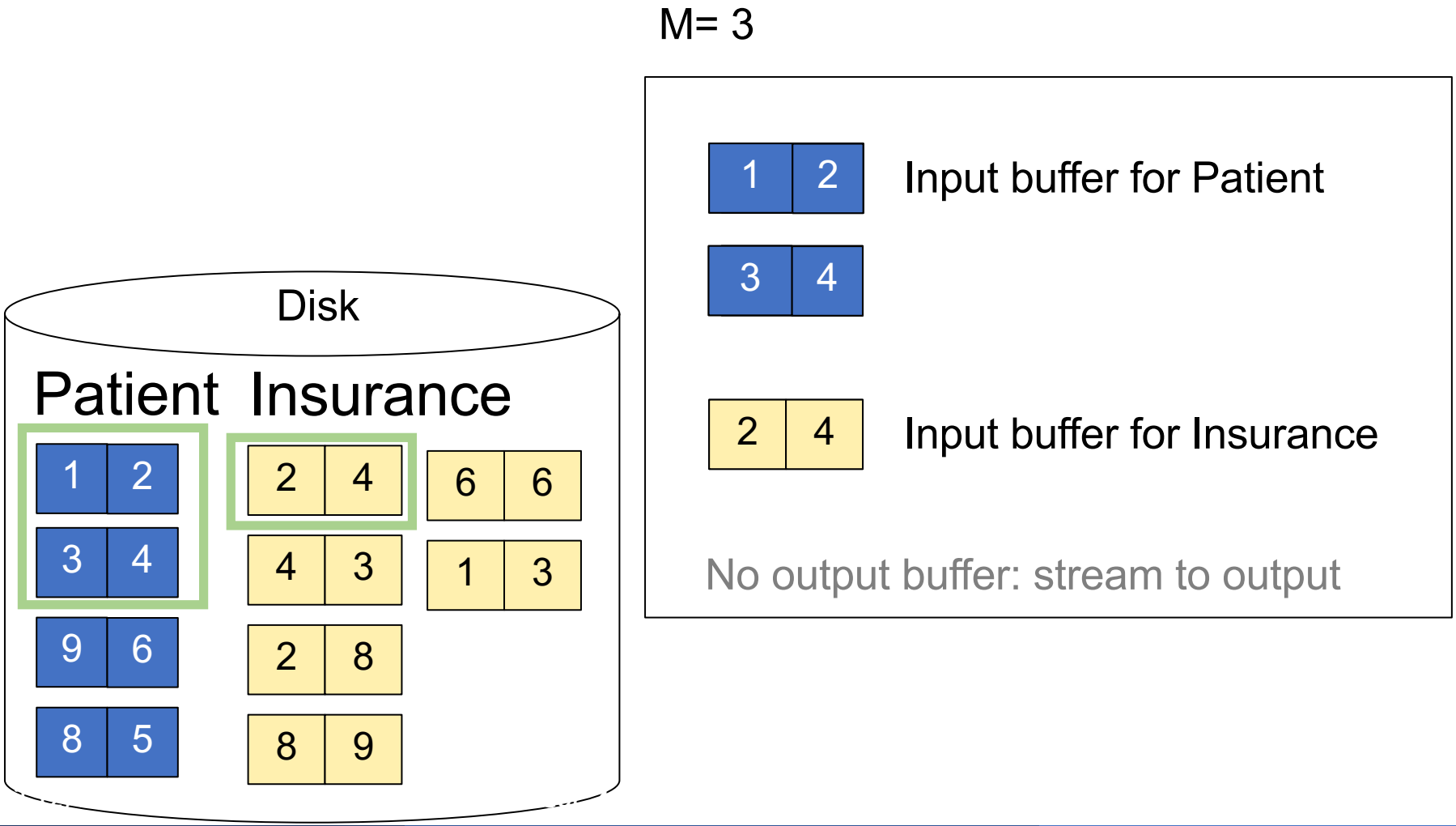

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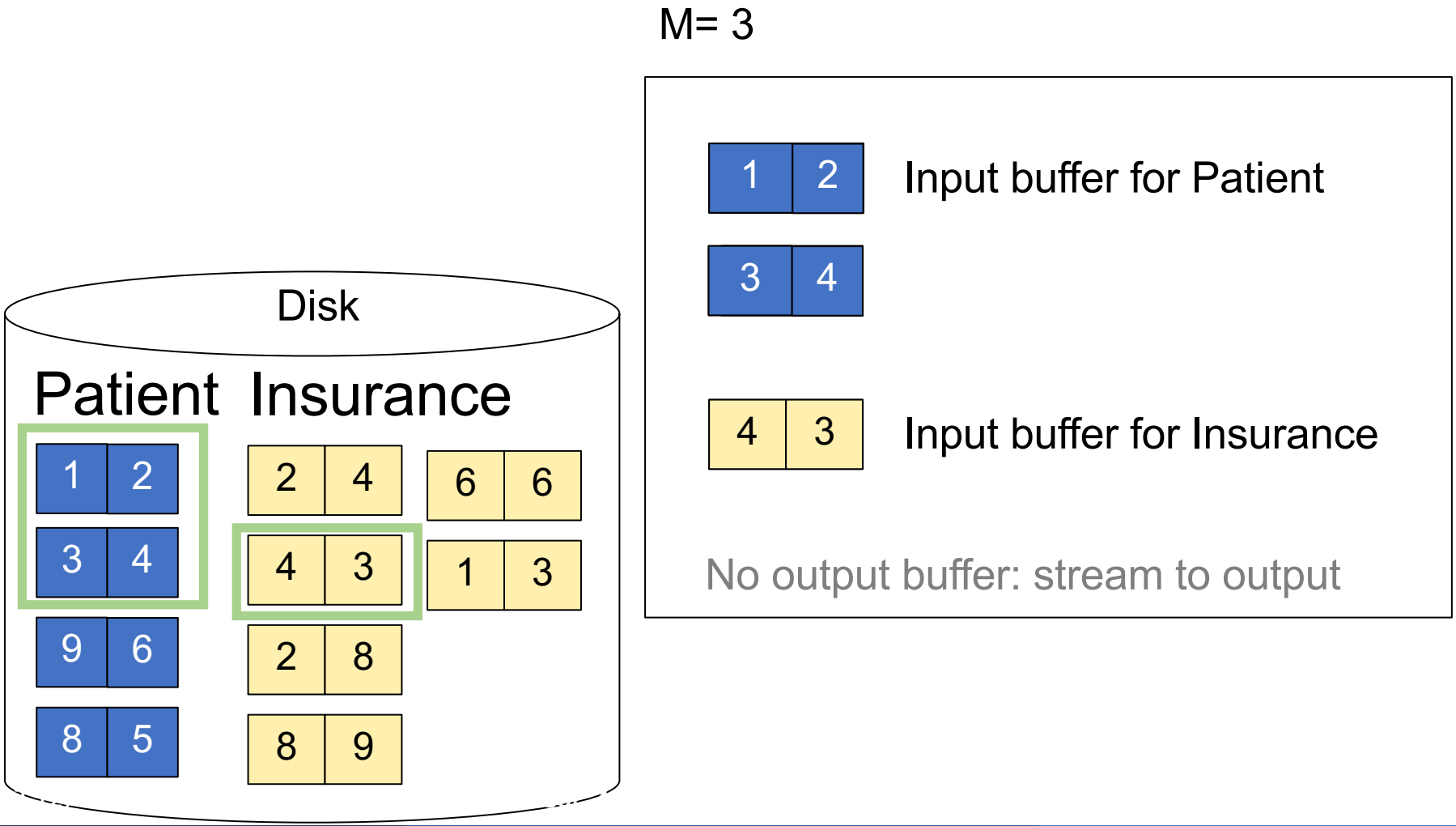

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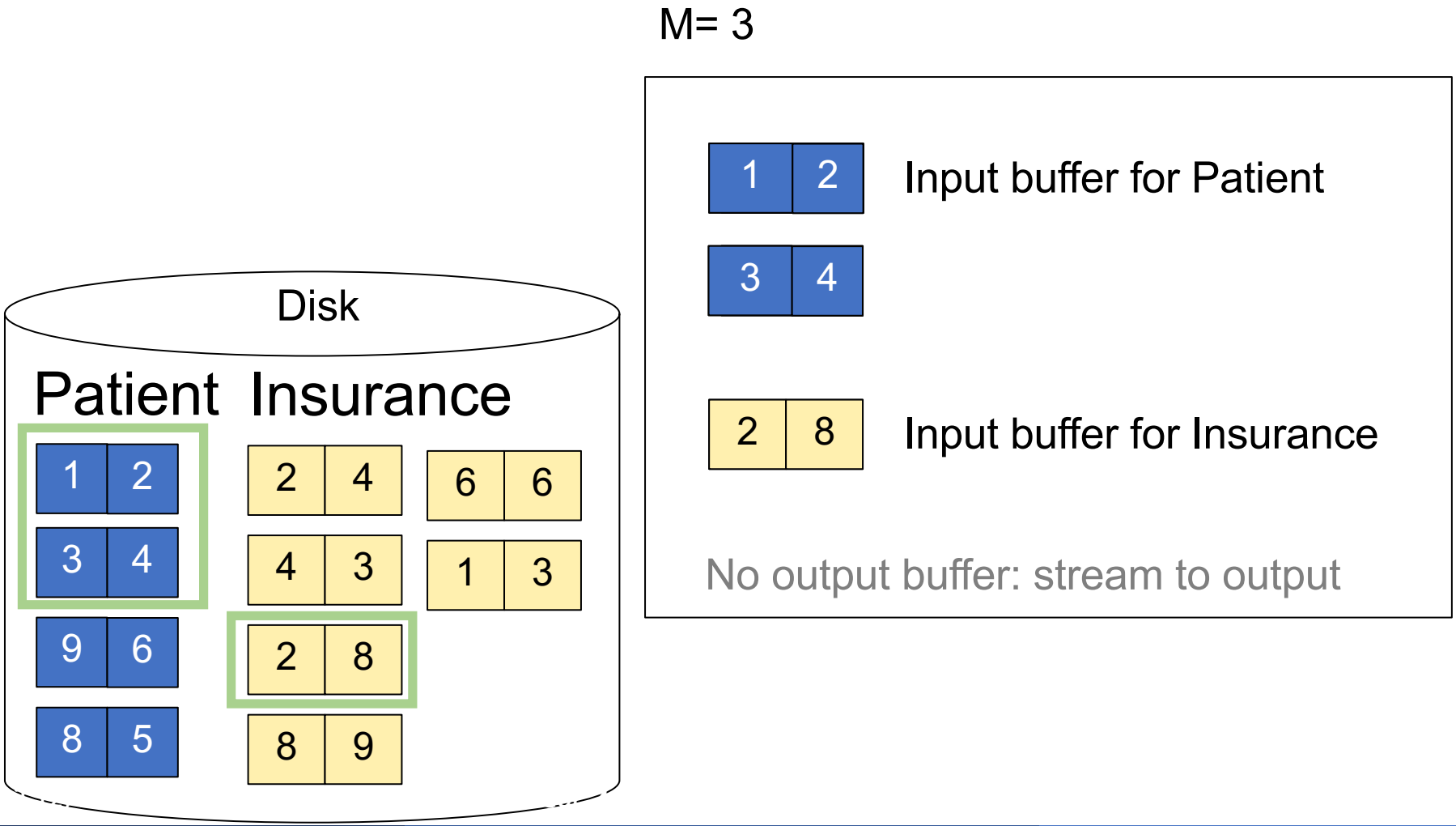

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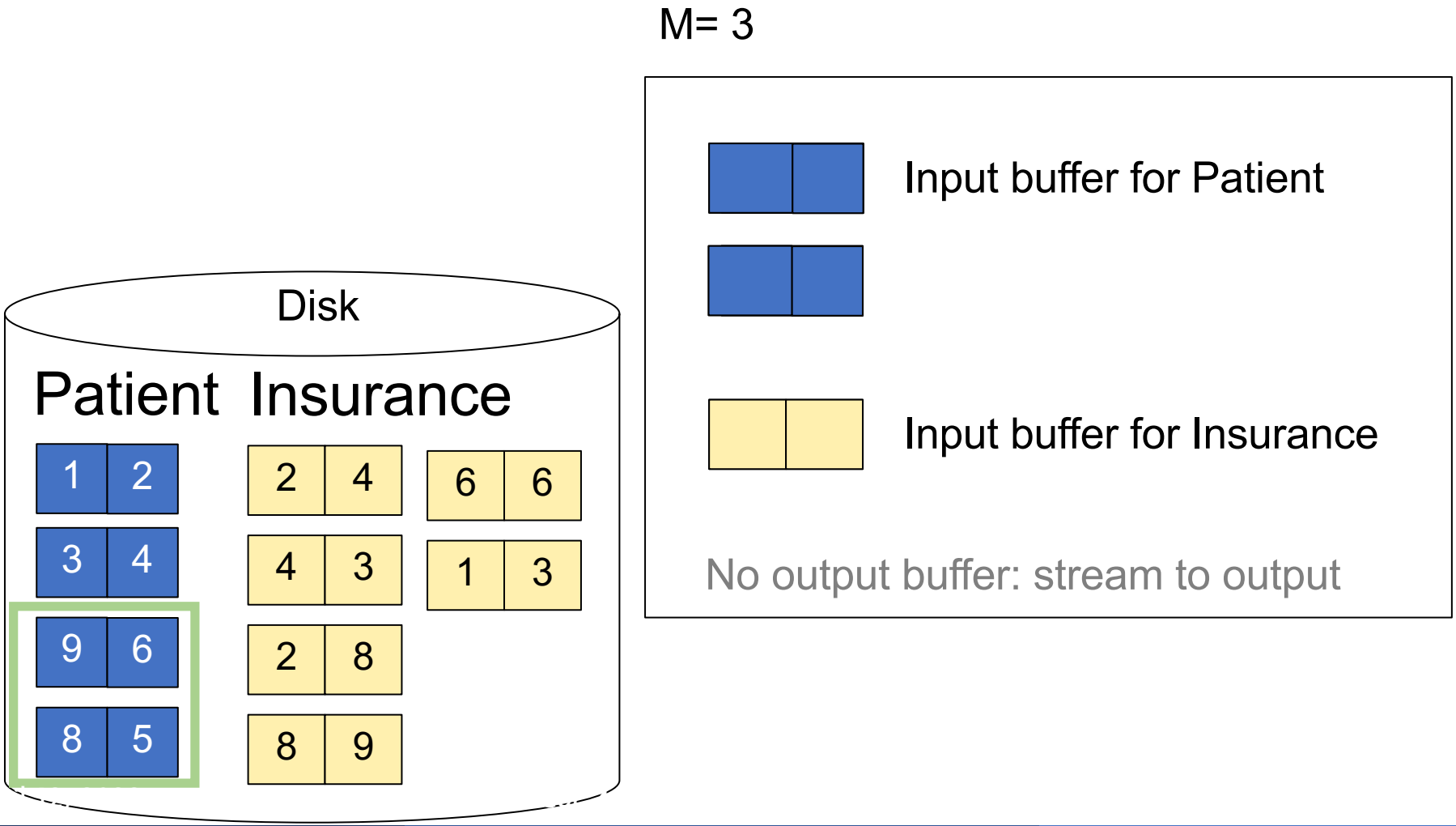

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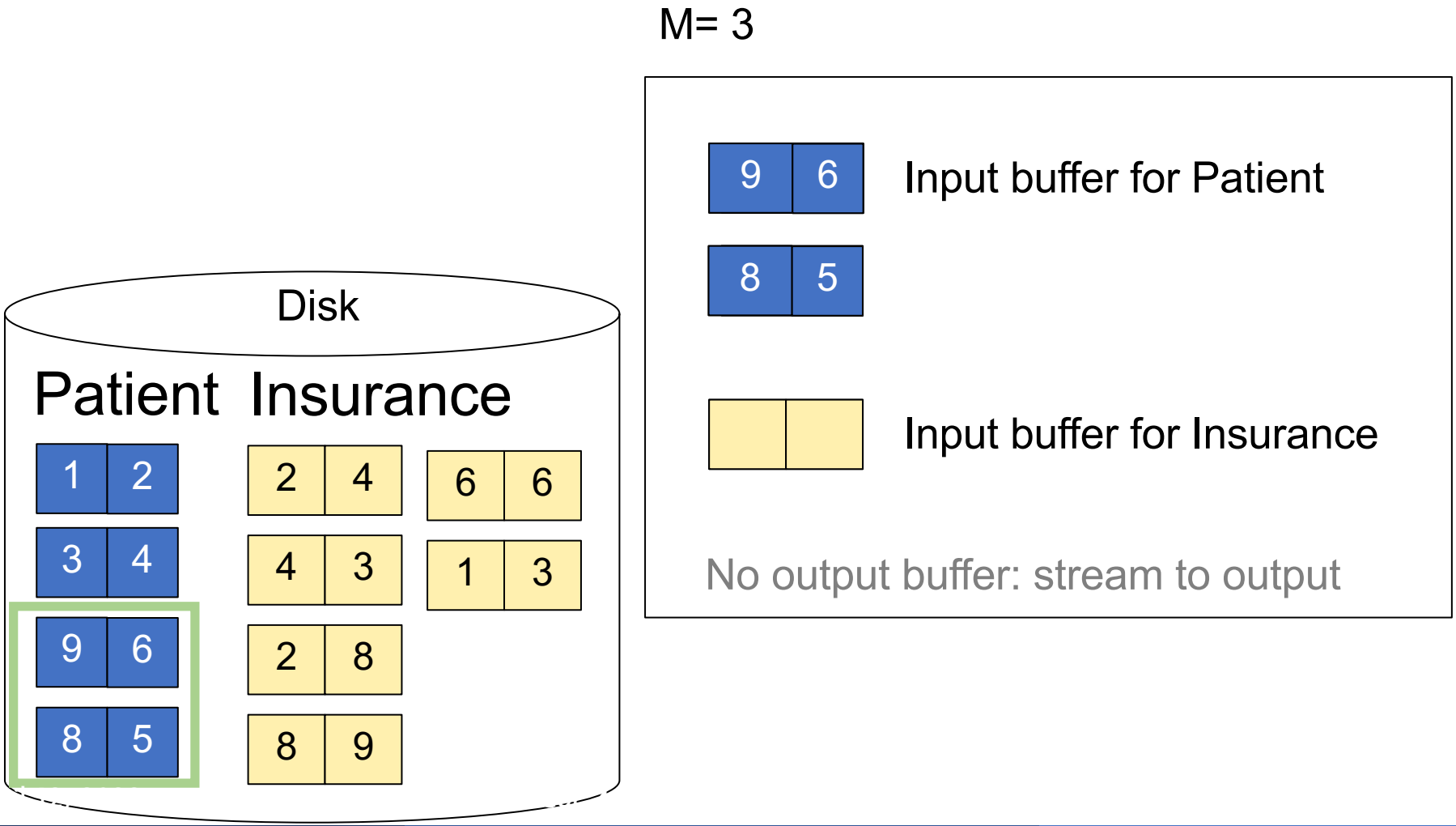

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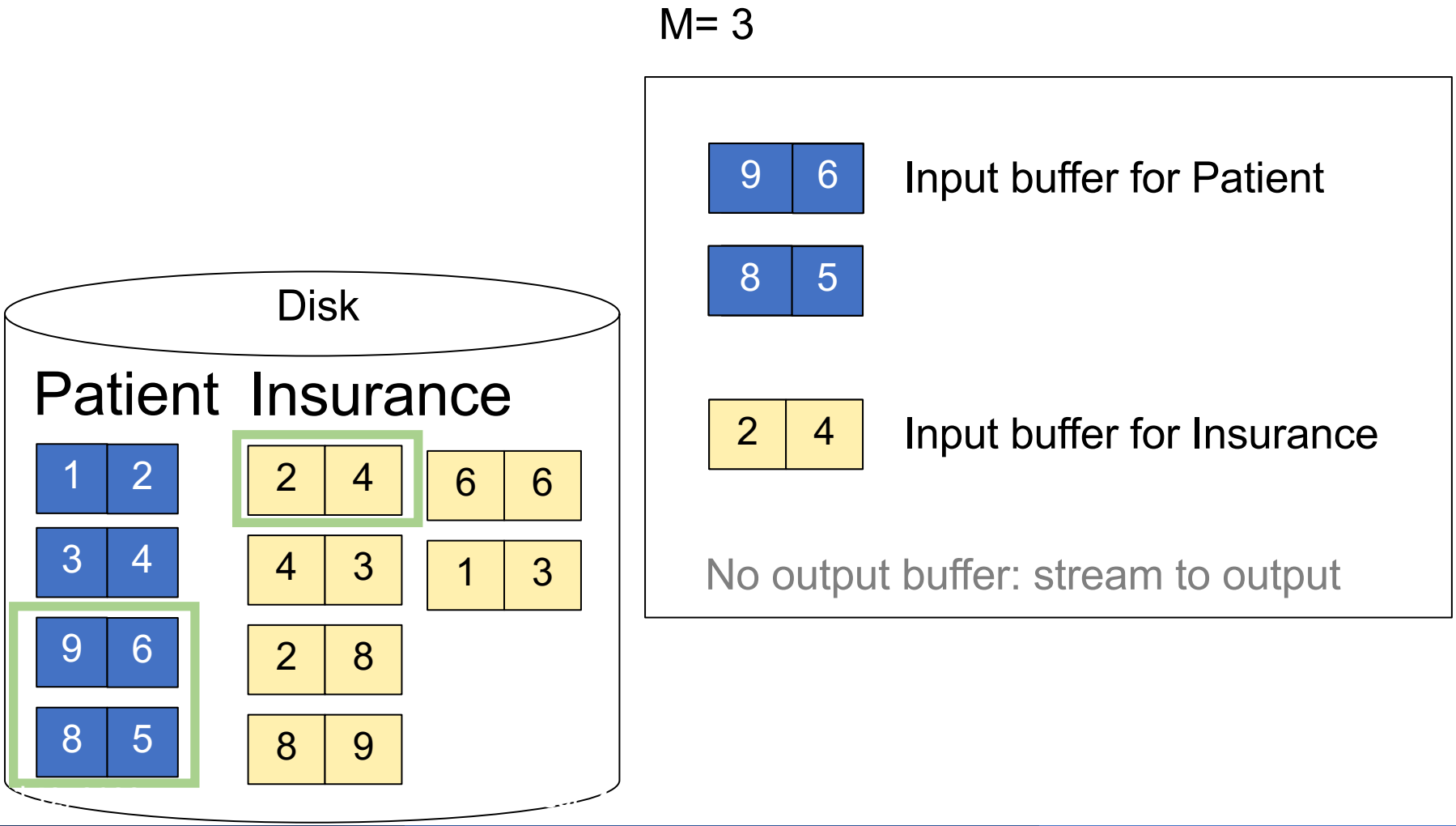

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What is the Cost

Block Memory Refinement

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        for all pairs of tuples t1 in r, t2 in s
            if t1 and t2 join then output (t1,t2)
```

- Cost: B(R) + B(R)B(S)/(M-1)

What is the Cost

Discussion

R ⋈ S: R=outer table, S=inner table

- Tuple-based nested loop join is never used
- Page-at-a-time nested loop join:
  - Usually combined with index access to inner table
  - Efficient when the outer table is small
- Block memory refinement nested loop:
  - Usually builds a hash table on the outer table
  - Efficient when the outer table is small

Sort-Merge Join

Sort-merge join: $R \bowtie S$

- Scan R and sort in main memory
- Scan S and sort in main memory
- Merge R and S

Sort-Merge Join

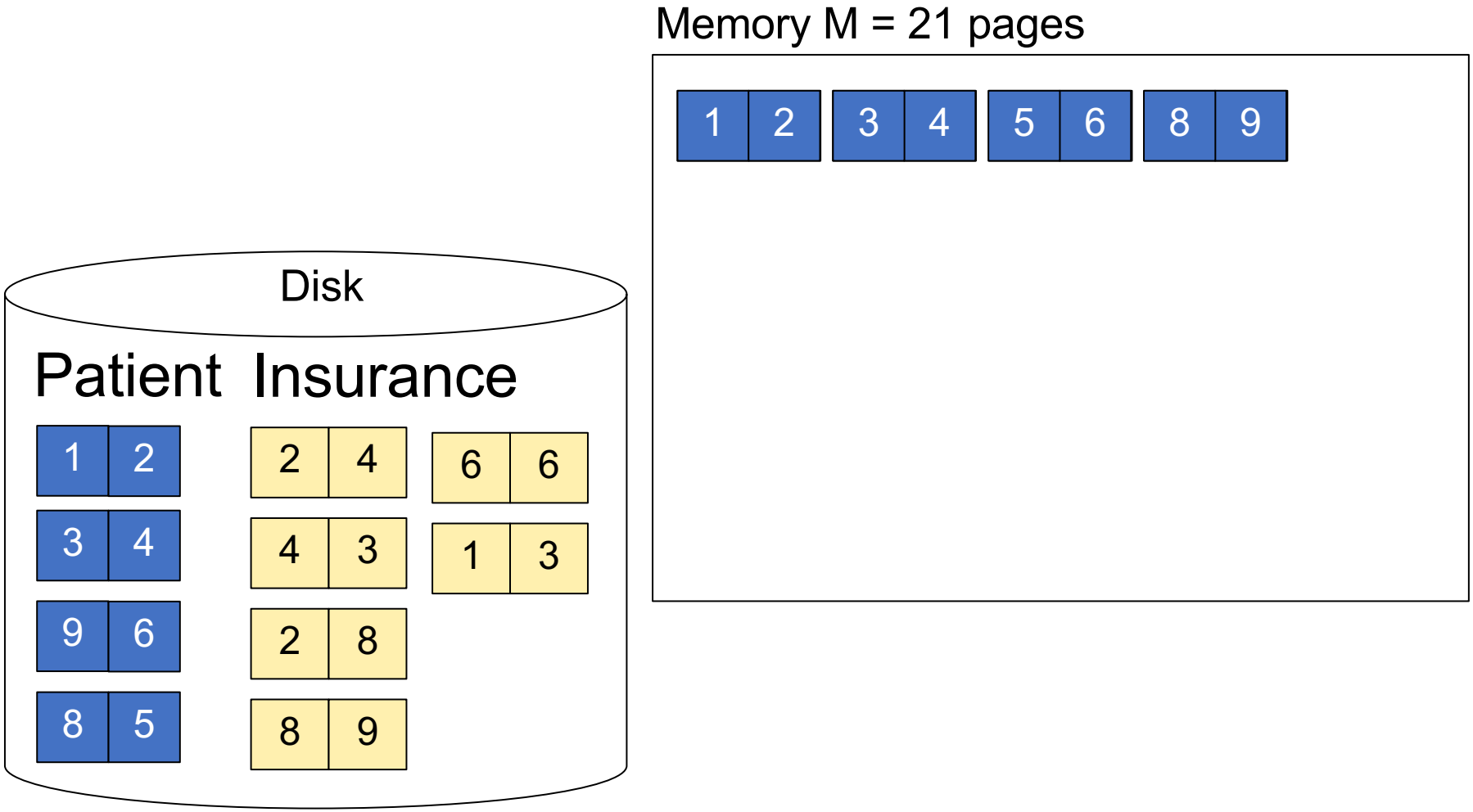
Sort-merge join: $R \bowtie S$

- Scan R and sort in main memory
- Scan S and sort in main memory
- Merge R and S

- Cost: B(R) + B(S)
- One pass algorithm when B(S) + B(R) <= M
- Typically, this is NOT a one pass algorithm,
  - We'll see the multi-pass version next lecture

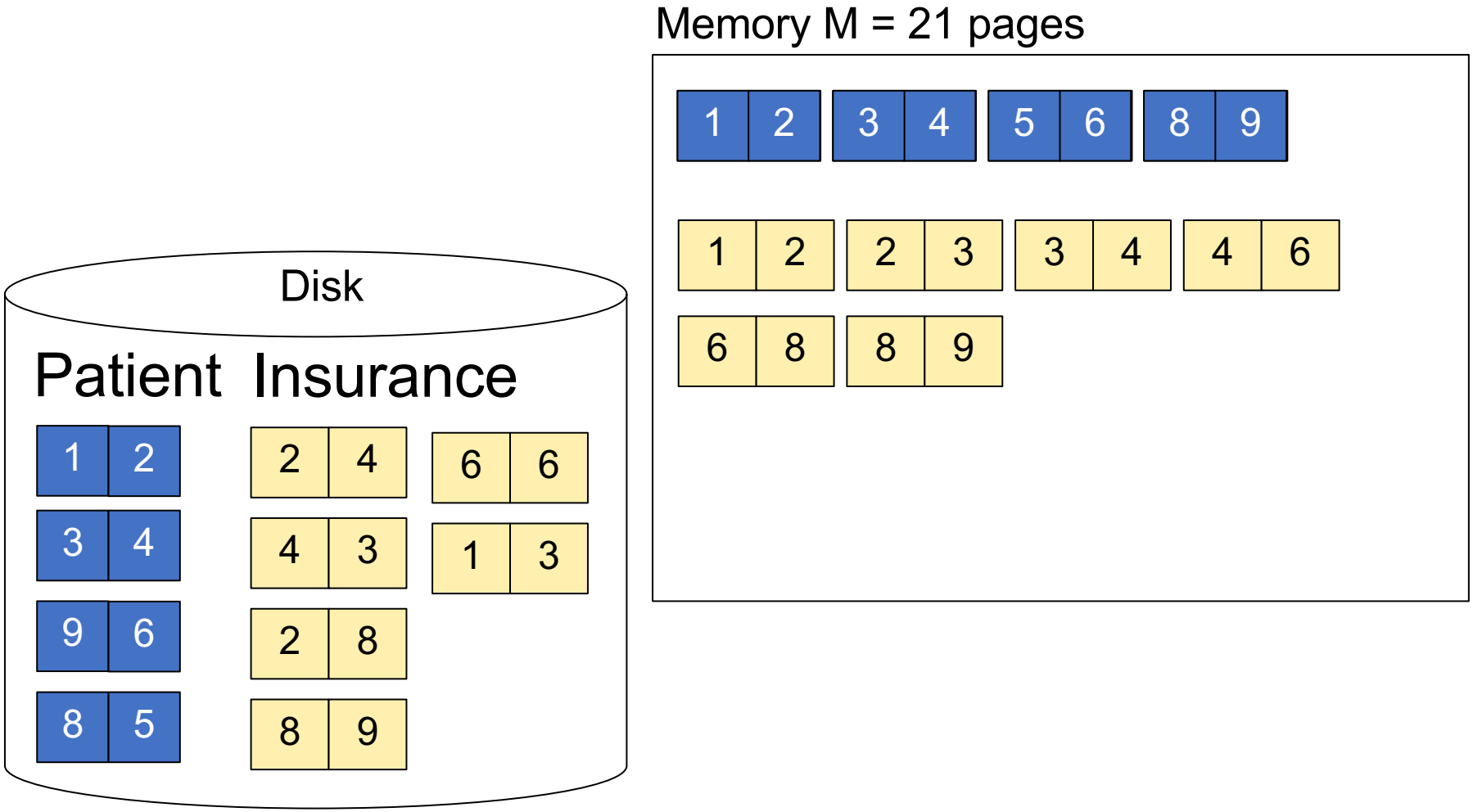
Sort-Merge Join Example

Step 1: Scan Patient and sort in memory



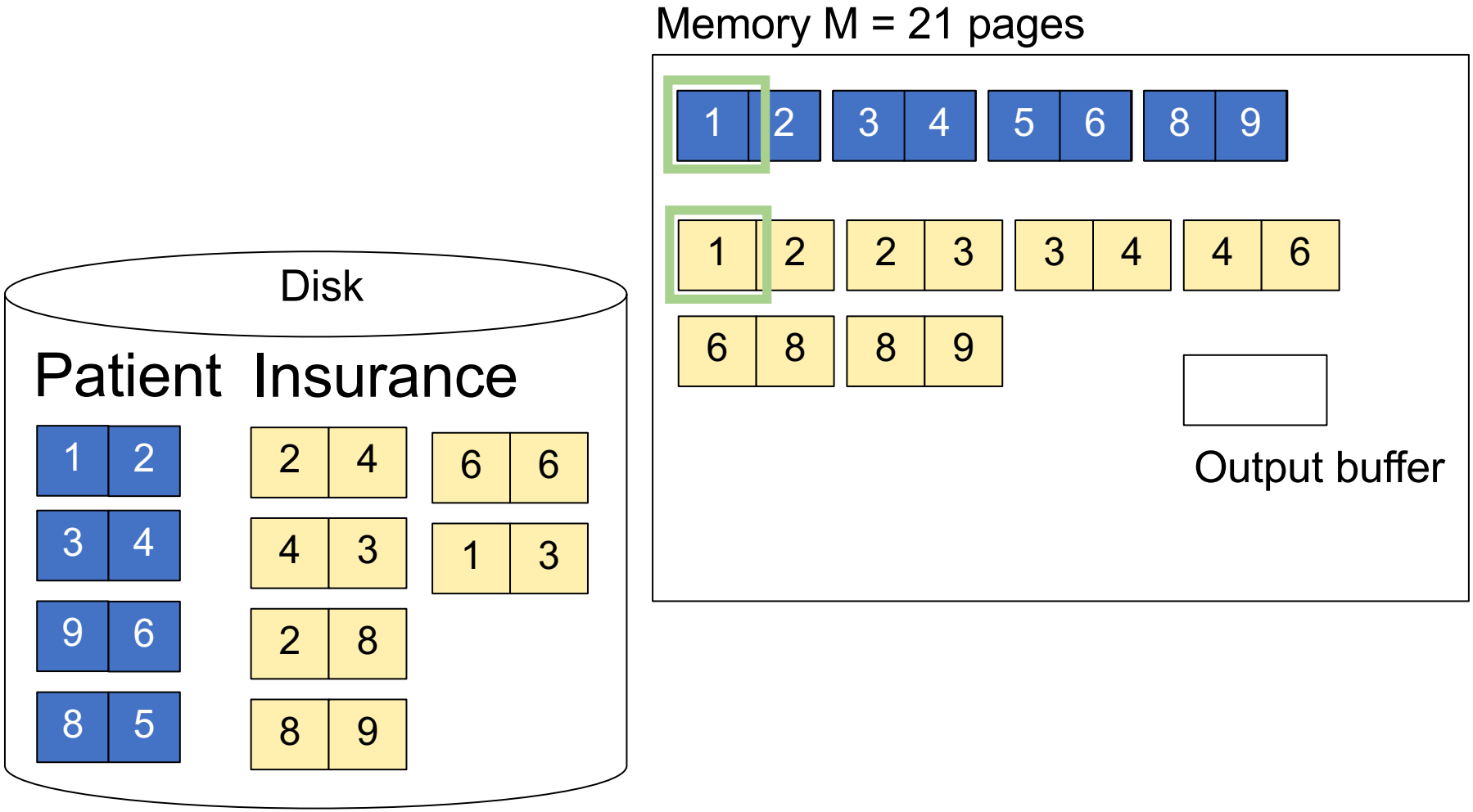
Sort-Merge Join Example

Step 2: Scan Insurance and sort in memory



Sort-Merge Join Example

Step 3: Merge Patient and Insurance



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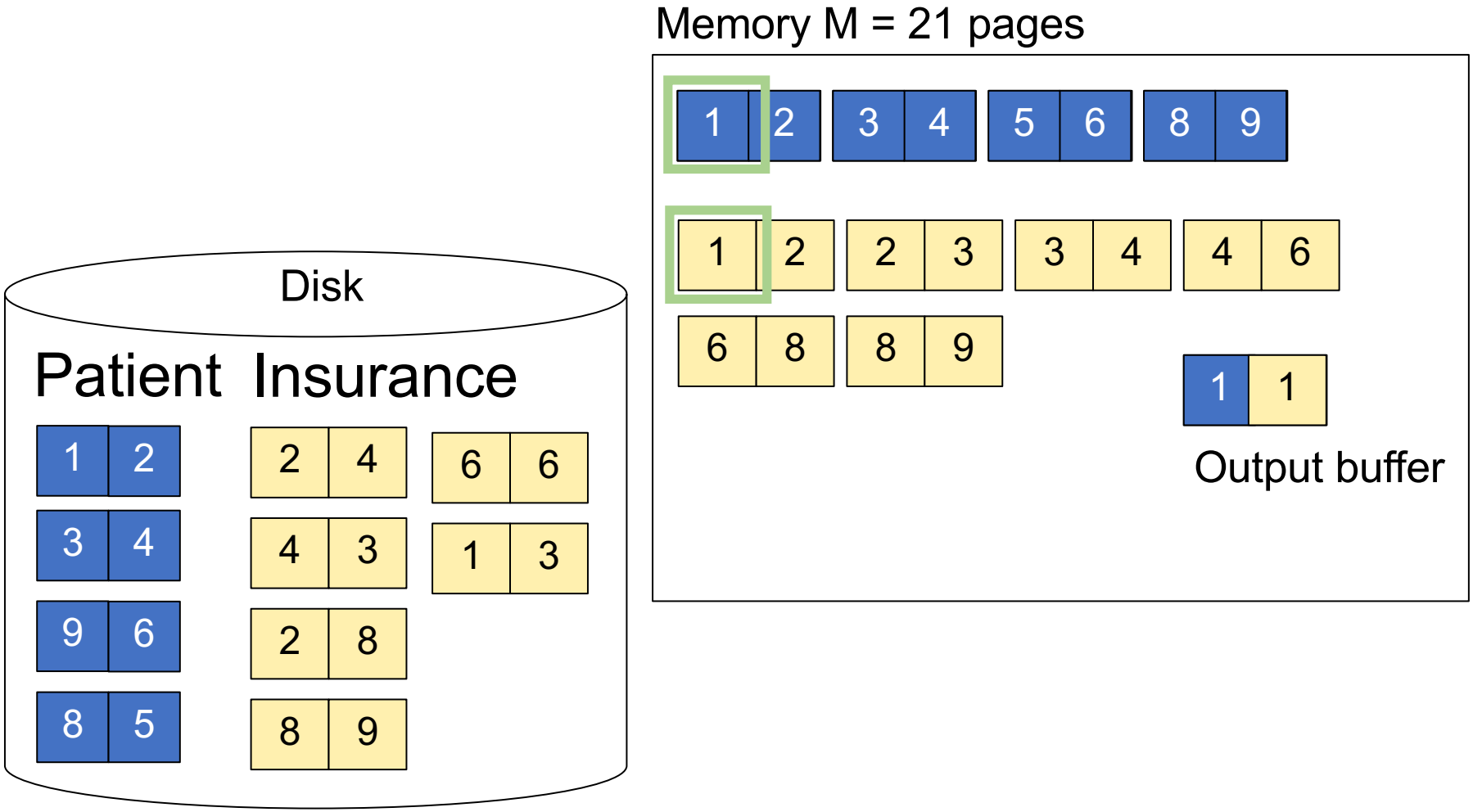

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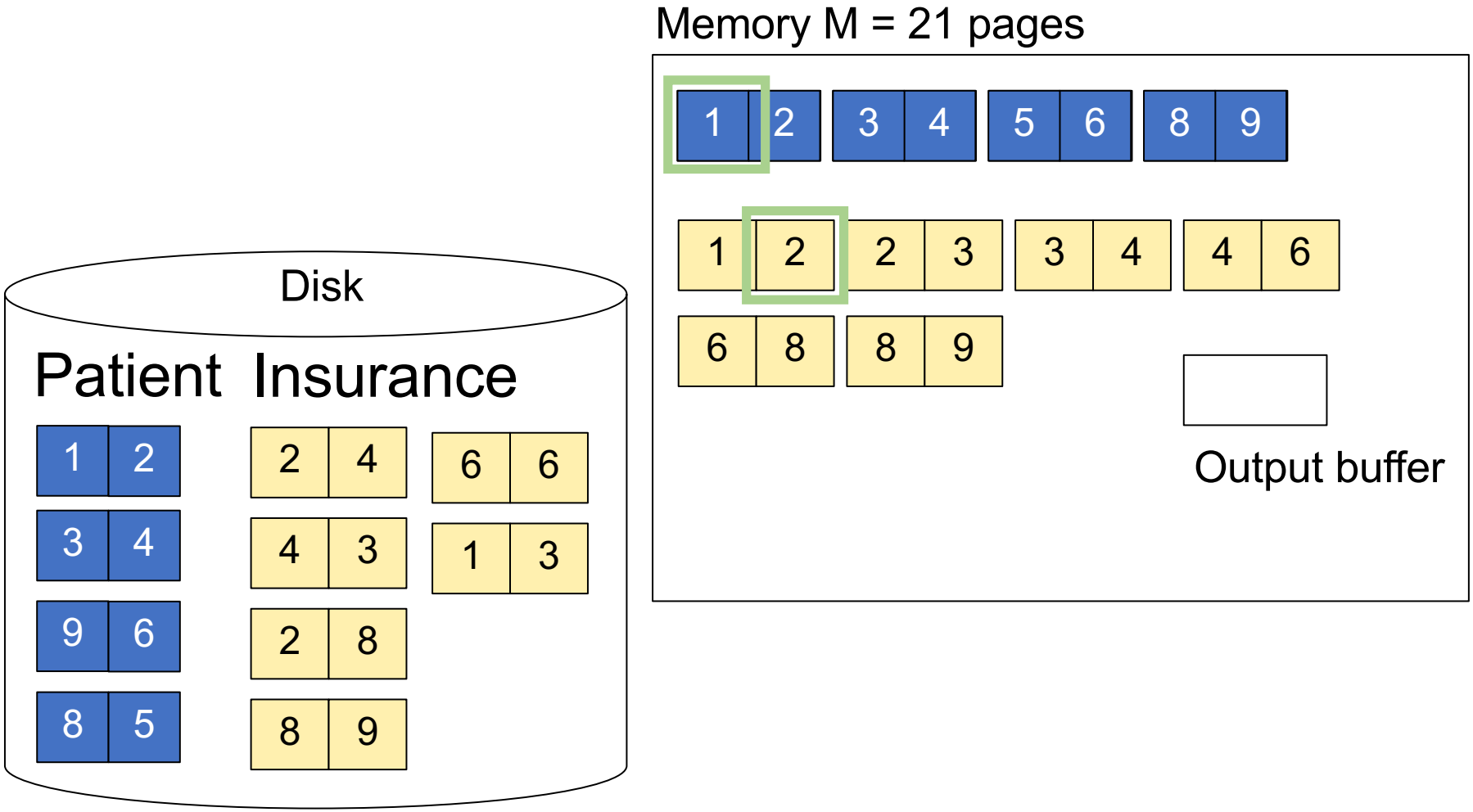

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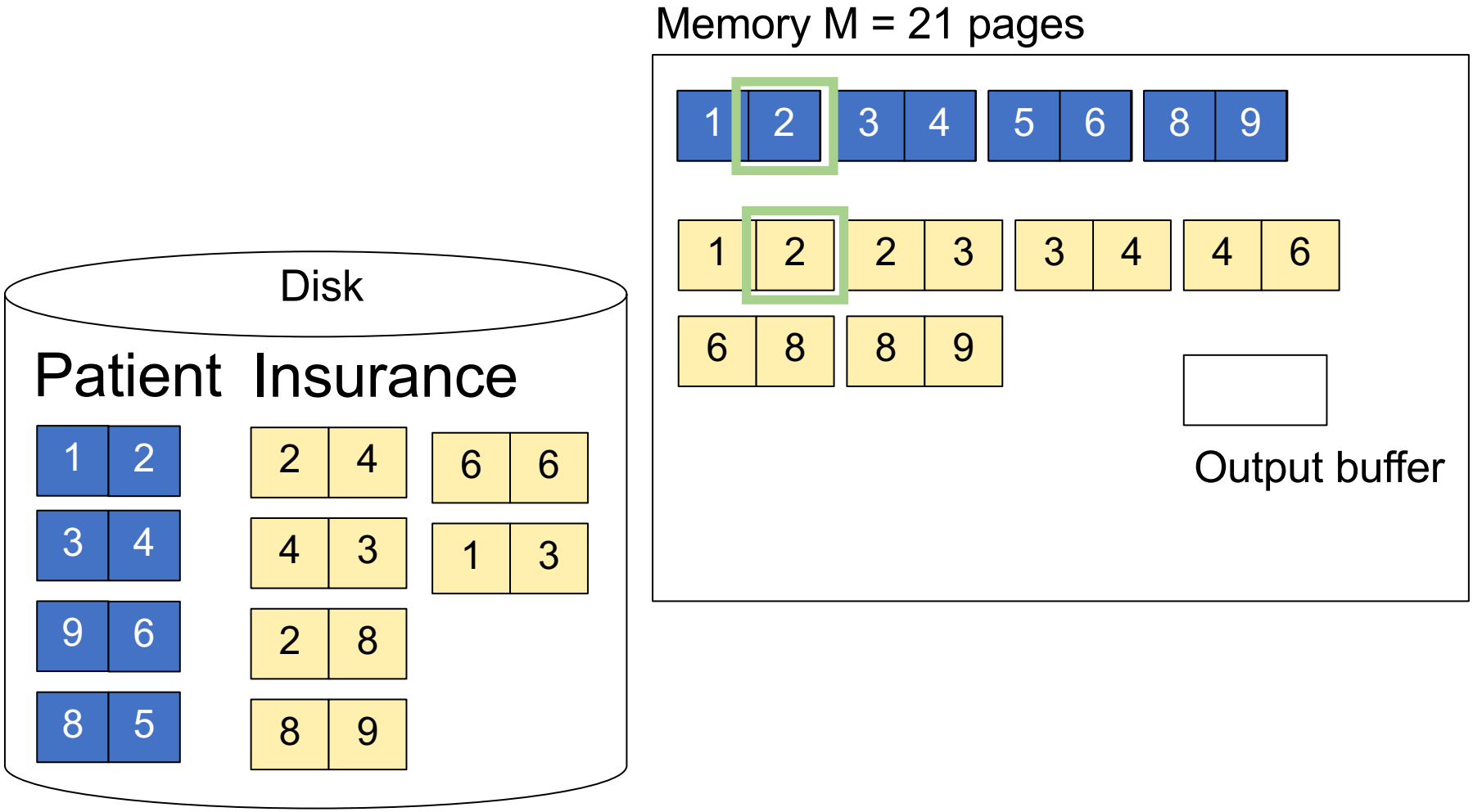

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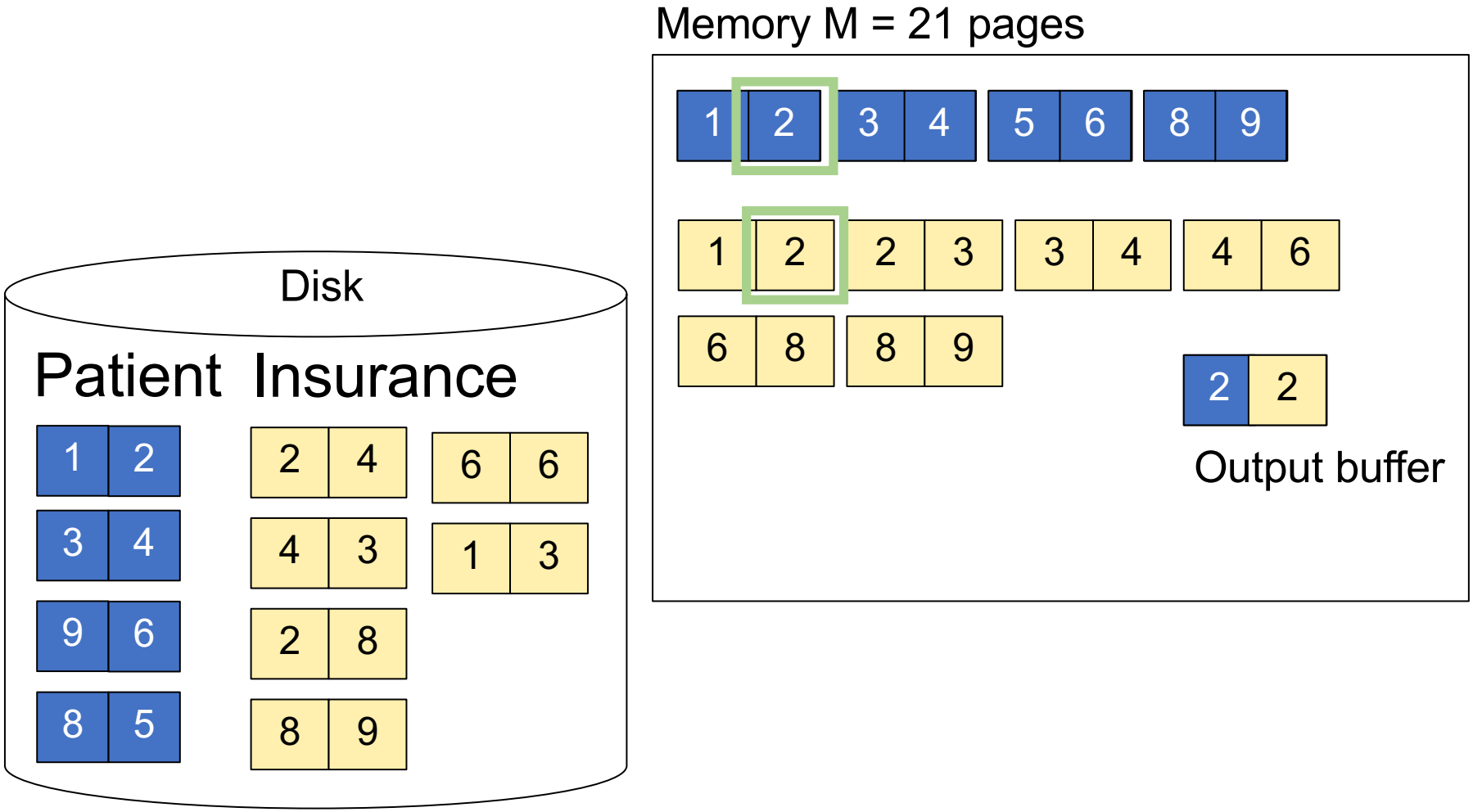

Sort-Merge Join Example

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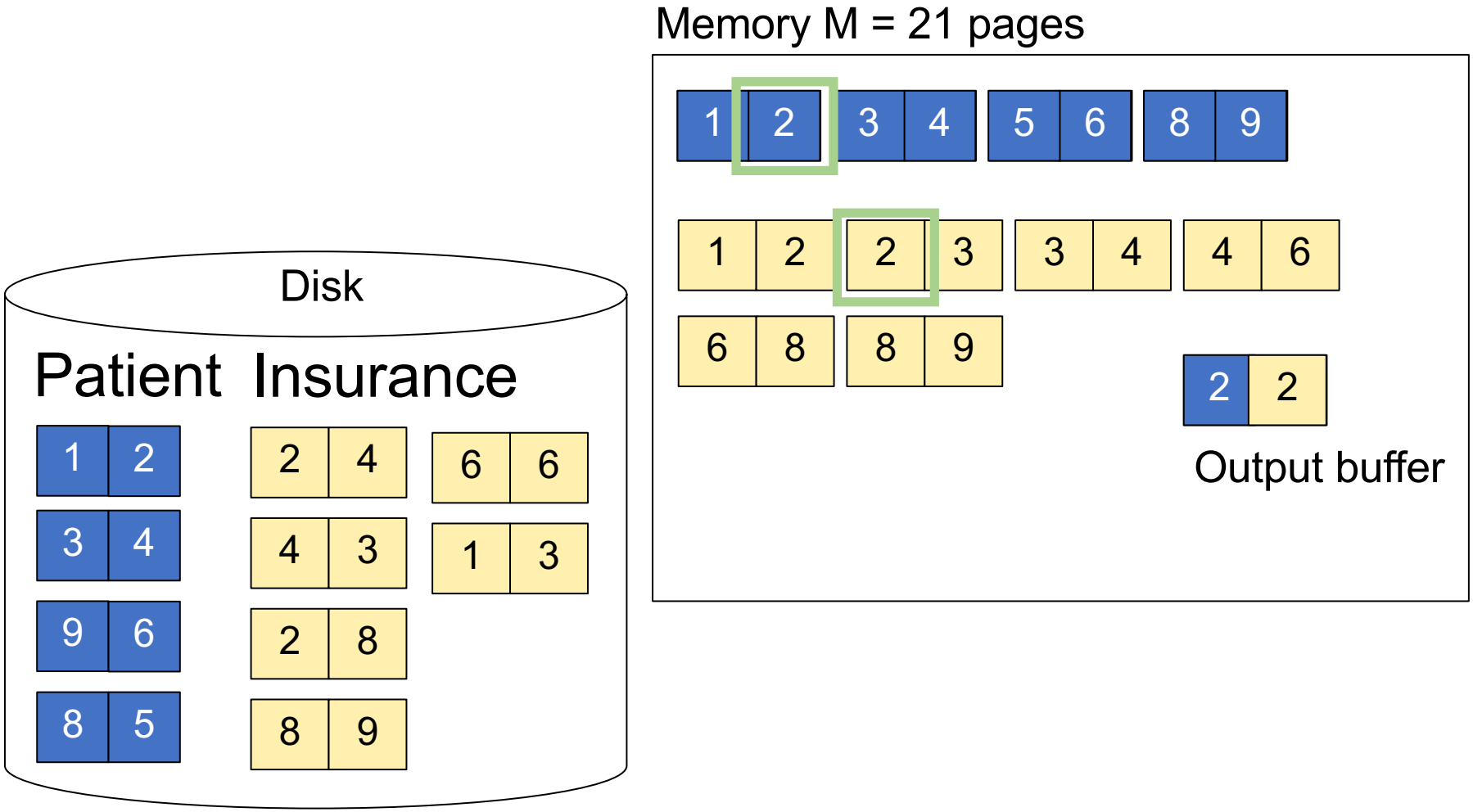

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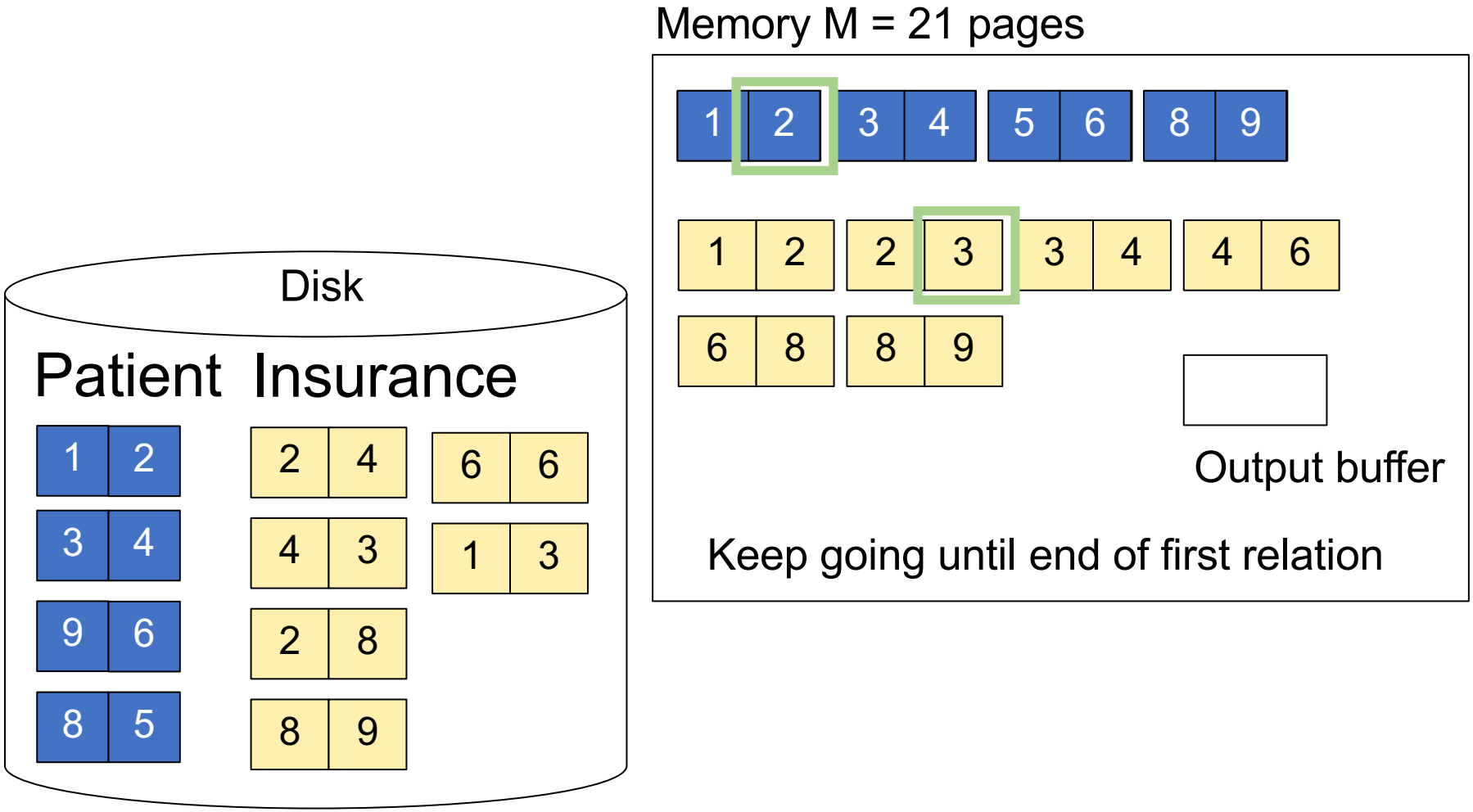

Outline

- **Join operator algorithms**
  - One-pass algorithms (Sec. 15.2 and 15.3)
  - Index-based algorithms (Sec 15.6)
  - Two-pass algorithms (Sec 15.4 and 15.5)

Index Based Selection

Selection on equality: $\sigma_{a=v}(R)$

- B(R)= size of R in blocks
- T(R) = number of tuples in R
- V(R, a) = # of distinct values of attribute a

Note: we ignore I/O cost for index pages

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What is the cost in each case?

- Clustered index on a:
- Unclustered index on a:

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What is the cost in each case?

- Clustered index on a: B(R)/V(R,a)
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Index Based Selection

- Example:

B(R) = 2000
T(R) = 100,000
V(R, a) = 20

cost of $\sigma_{a=v}(R) = ?$

- Table scan:
- Index based selection:

Index Based Selection

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  - If index is clustered: B(R)/V(R,a) = 100 I/Os
  - If index is unclustered: T(R)/V(R,a) = 5,000 I/Os

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  - If index is unclustered: T(R)/V(R,a) = 5,000 I/Os!

Lesson: Don't build unclustered indexes when V(R,a) is small !

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Lesson: Don't build unclustered indexes when V(R,a) is small !

Index Nested Loop Join

R ⋈ S

- Assume S has an index on the join attribute
- Iterate over R, for each tuple fetch corresponding tuple(s) from S

- Previous nested loop join: cost
  - B(R) + T(R)*B(S)
- Index Nested Loop Join Cost:
  - If index on S is clustered: B(R) + T(R)B(S)/V(S,a)
  - If index on S is unclustered: B(R) + T(R)T(S)/V(S,a)

Outline

- **Join operator algorithms**
  - One-pass algorithms (Sec. 15.2 and 15.3)
  - Index-based algorithms (Sec 15.6)
  - Two-pass algorithms (Sec 15.4 and 15.5)

Two-Pass Algorithms

- Fastest algorithm seen so far is one-pass hash join
  What if data does not fit in memory?
- Need to process it in multiple passes

- Two key techniques
  - Sorting
  - Hashing

Basic Terminology

- A run in a sequence is an increasing subsequence

- What are the runs?

  2, 4, 99, 103, 88, 77, 3, 79, 100, 2, 50

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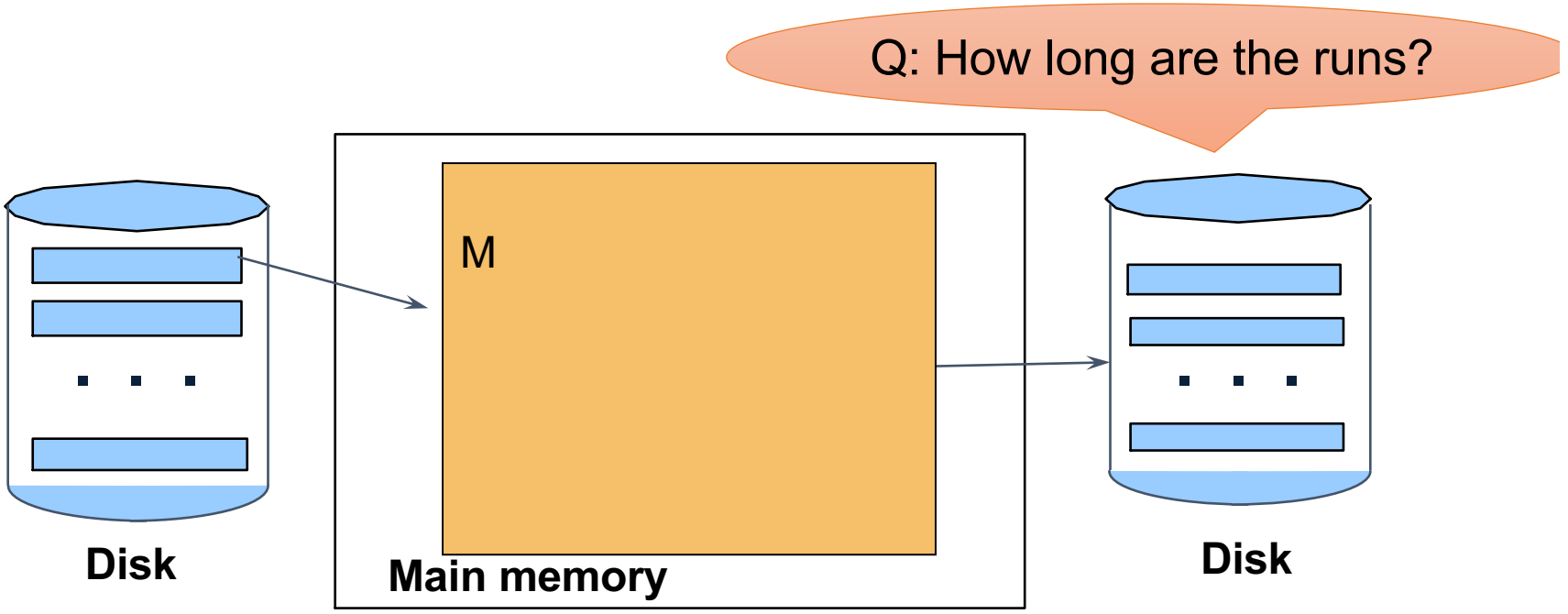
External Merge-Sort: Step 1

Phase one: load M blocks in memory, sort, send to disk, repeat

External Merge-Sort: Step 1

Phase one: load M blocks in memory, sort, send to disk, repeat



External Merge-Sort: Step 1

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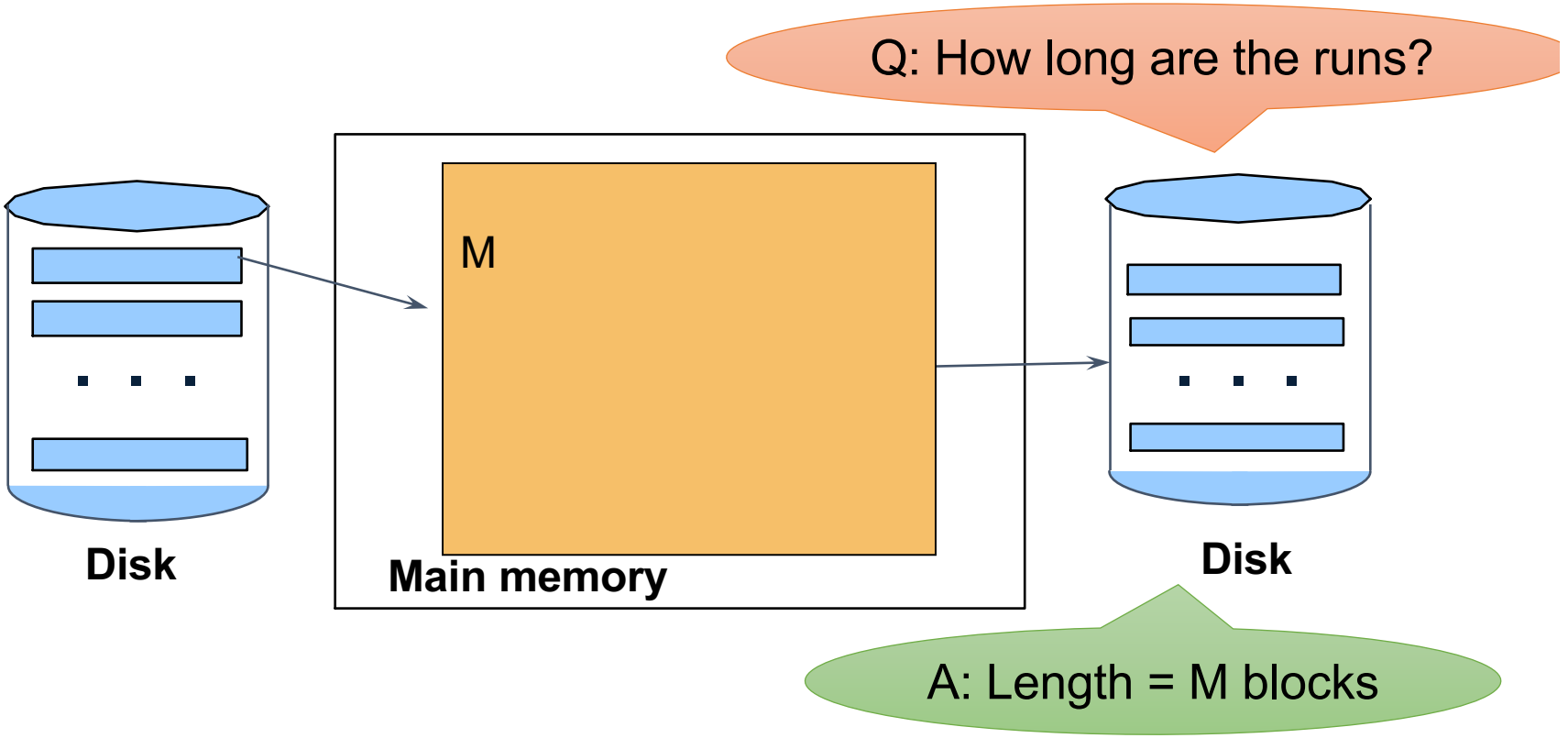
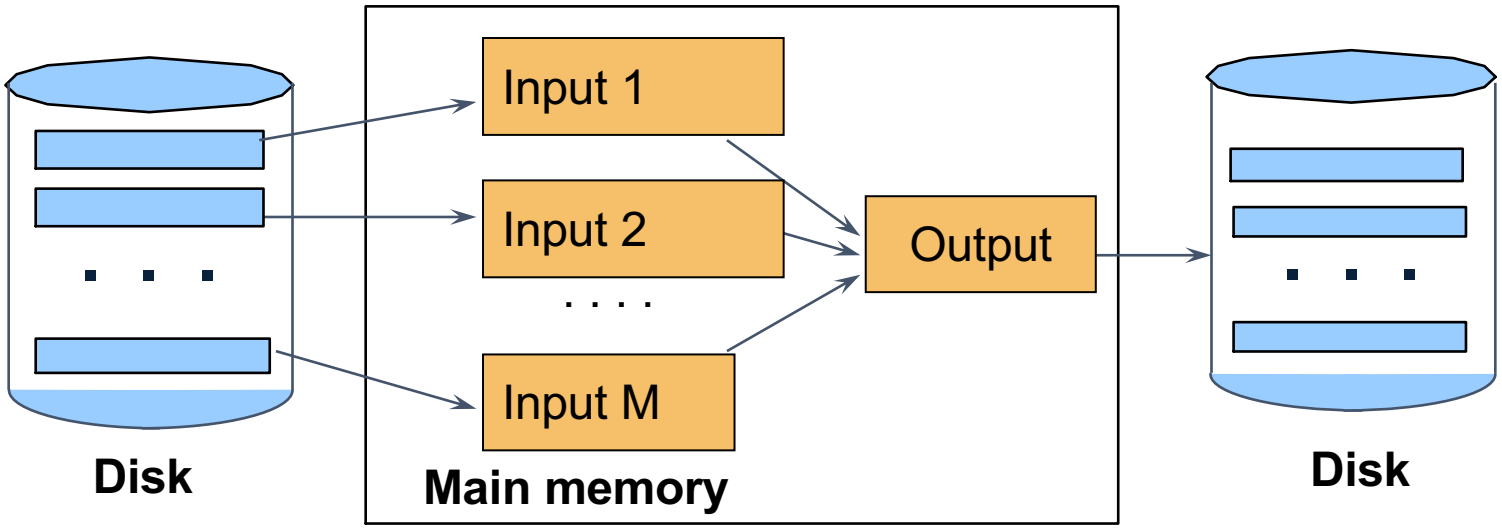


Phase two: merge M runs into a bigger run

- Merge M – 1 runs into a new run
- Result: runs of length M (M – 1) ≈ M^2



Example

- Merging three runs to produce a longer run:

0, 14, 33, 88, 92, 192, 322
2, 4, 7, 43, 78, 103, 523
1, 6, 9, 12, 33, 52, 88, 320

Output:
0

Example

- Merging three runs to produce a longer run:

0, **14**, **33, 88, 92, 192, 322**
2, **4, 7, 43, 78, 103, 523**
1, **6, 9, 12, 33, 52, 88, 320**

Output:
0, ?

Example

- Merging three runs to produce a longer run:

0, **14**, **33, 88, 92, 192, 322**
2, 4, 7, 43, 78, 103, 523
1, **6, 9, 12, 33, 52, 88, 320**

Output:
0, 1, ?

Example

- Merging three runs to produce a longer run:

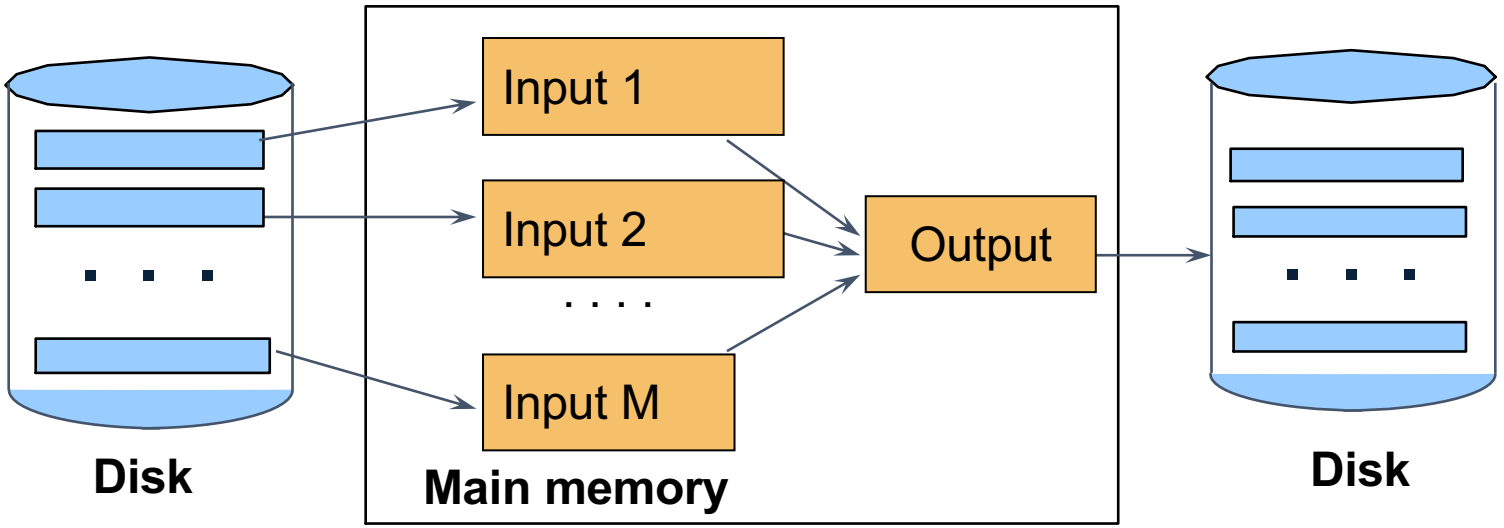
0, **14**, **33**, **88**, **92**, **192**, **322**
2, 4, 7, **43**, **78**, **103**, **523**
1, 6, **9**, **12**, **33**, **52**, **88**, **320**

Output:
0, 1, 2, 4, 6, 7, ?

External Merge-Sort: Step 2

Phase two: merge M runs into a bigger run

- Merge M – 1 runs into a new run
- Result: runs of length M (M – 1) ≈ M^2



If approx. B <= M^2 then we are done

Cost of External Merge Sort

- Assumption: $B(R) <= M^2$
- Read+write+read = 3B(R)

Discussion

- What does B(R) <= M^2 mean?
- How large can R be?

Discussion

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- How large can R be?

- Example:
  - Page size = 32KB
  - Memory size 32GB: M = 10^6-pages

Discussion

- What does B(R) <= M^2 mean?
- How large can R be?

- Example:
  - Page size = 32KB
  - Memory size 32GB: M = 10^6 pages

- R can be as large as 10^{12} pages
  - 32 × 10^{15} Bytes = 32 PB

Merge-Join

Join R ⋈ S

- How?....

Merge-Join

Join R ⋈ S

- Step 1a: generate initial runs for R
- Step 1b: generate initial runs for S
- Step 2: merge and join
  - Either merge first and then join
  - Or merge & join at the same time

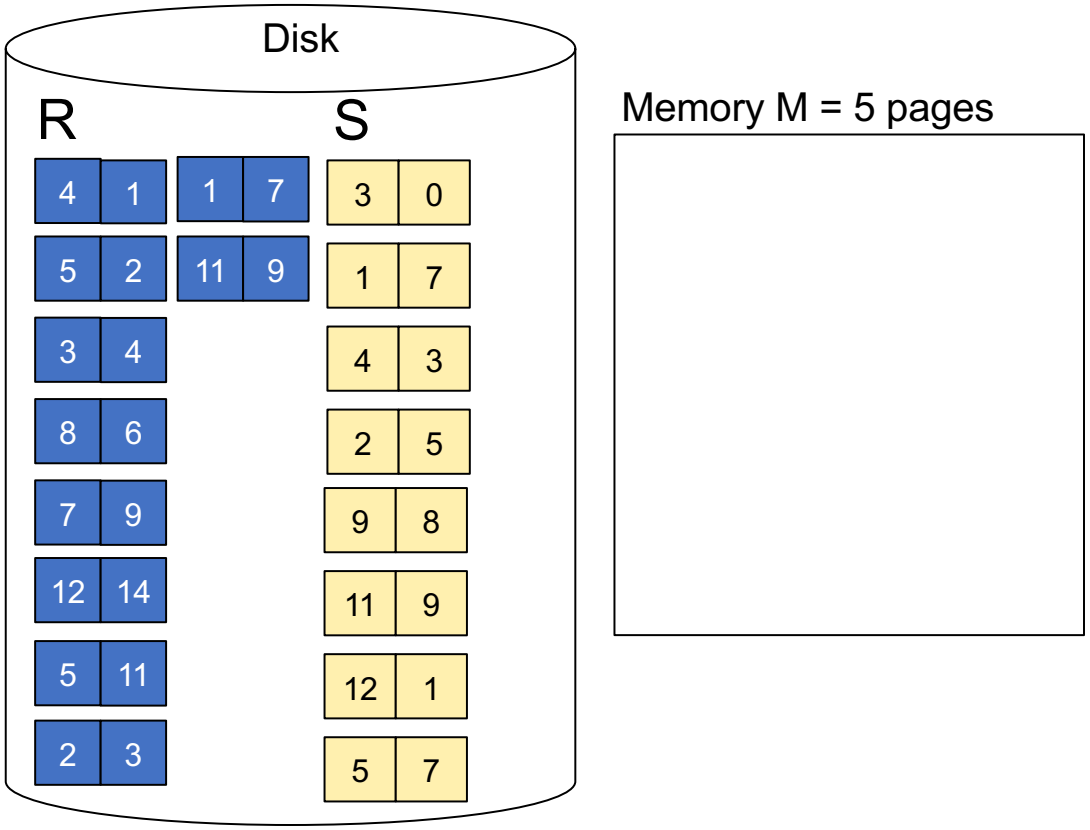
Merge-Join Example

Setup: Want to join R and S

Relation R has 10 pages with 2 tuples per page

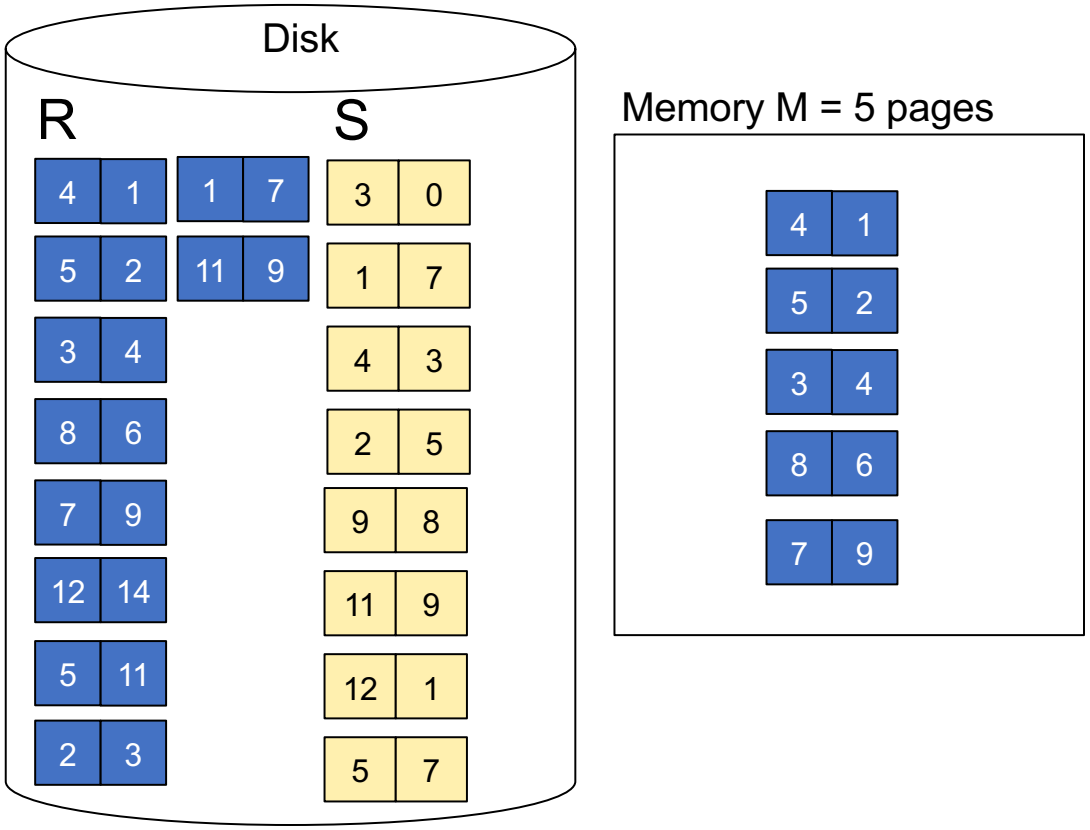
Relation S has 8 pages with 2 tuples per page

Values shown are values of join attribute for each given tuple



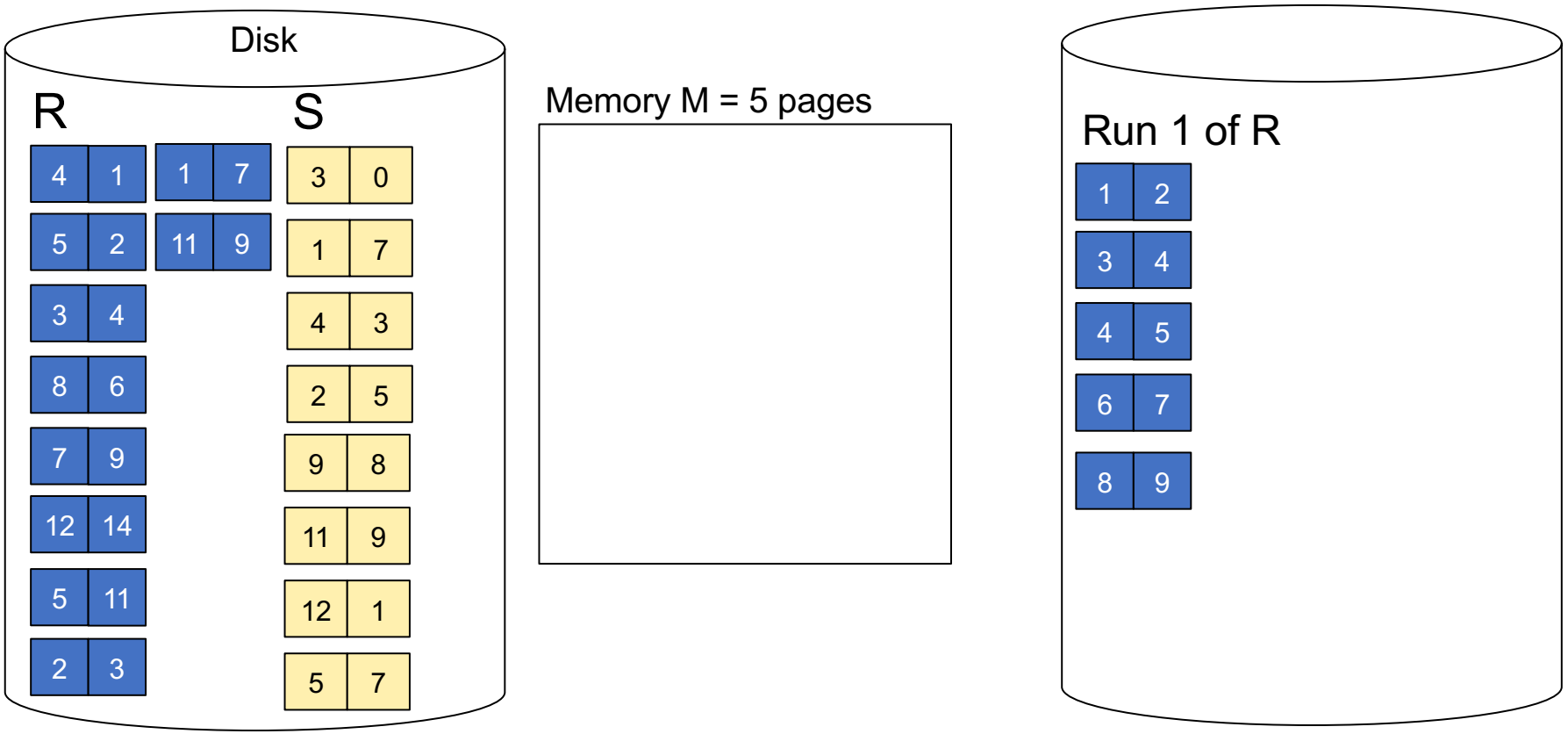
Merge-Join Example

Step 1: Read M pages of R and sort in memory



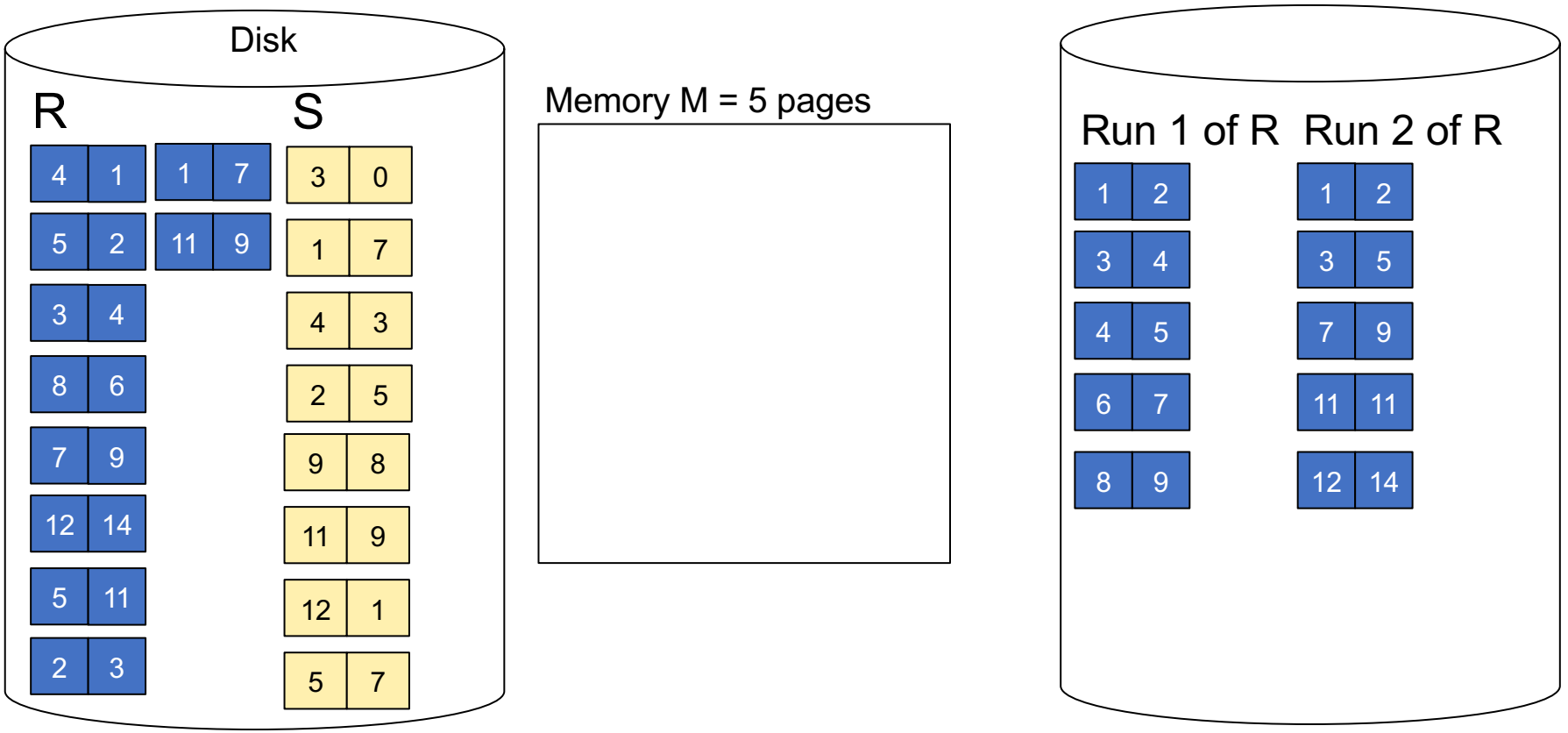
Merge-Join Example

Step 1: Read M pages of R and sort in memory, then write to disk



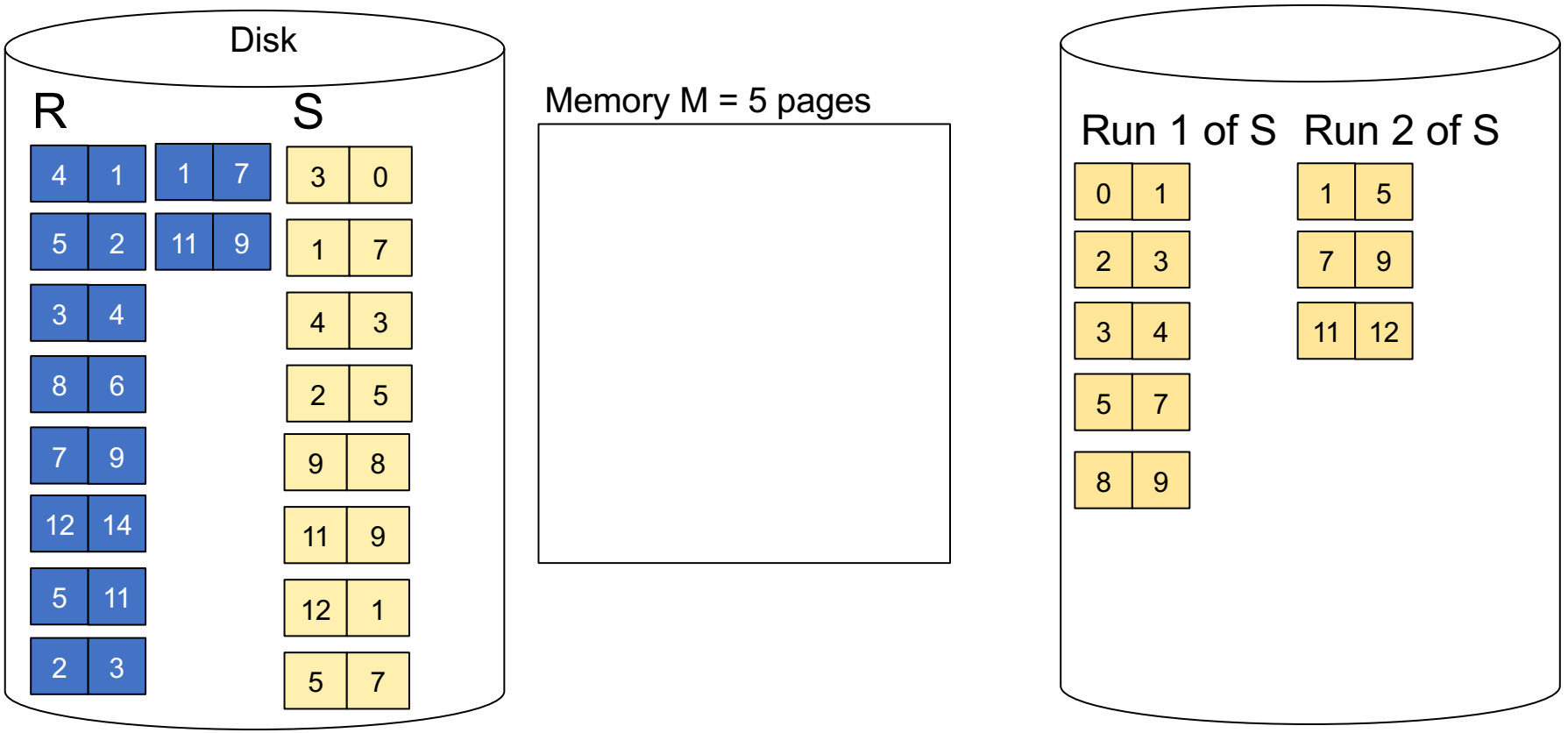
Merge-Join Example

Step 1: Repeat for next M pages until all R is processed



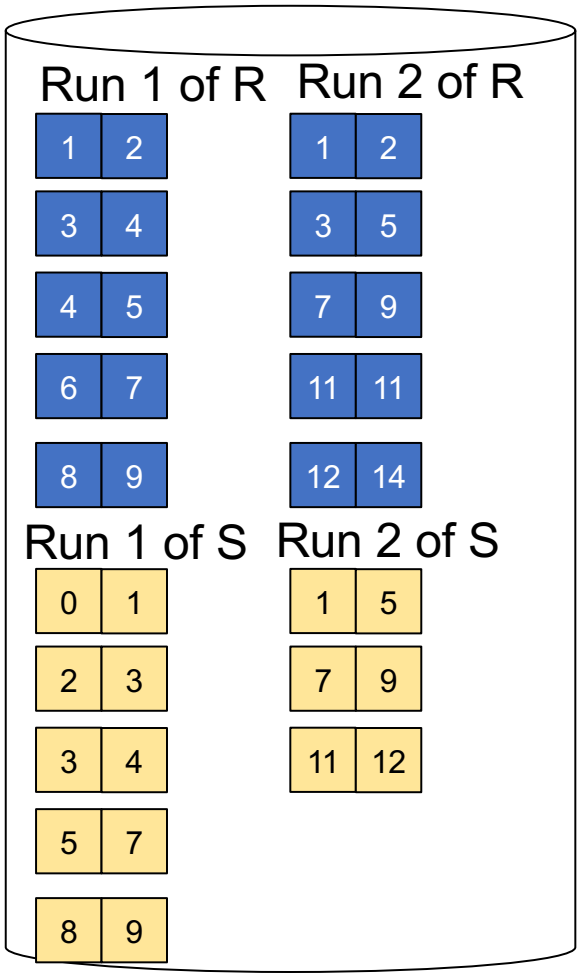
Merge-Join Example

Step 1: Do the same with S

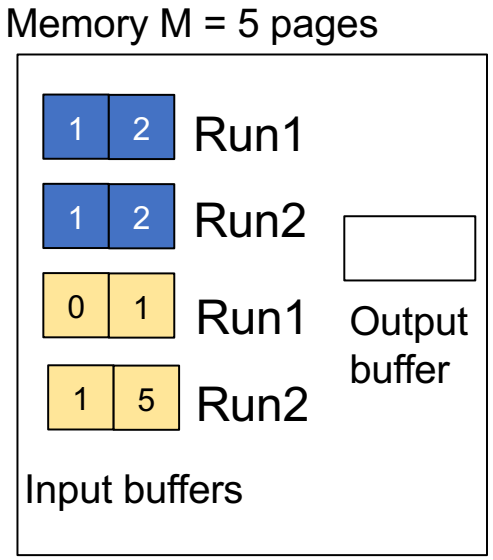


Merge-Join Example

Step 2: Join while merging sorted runs



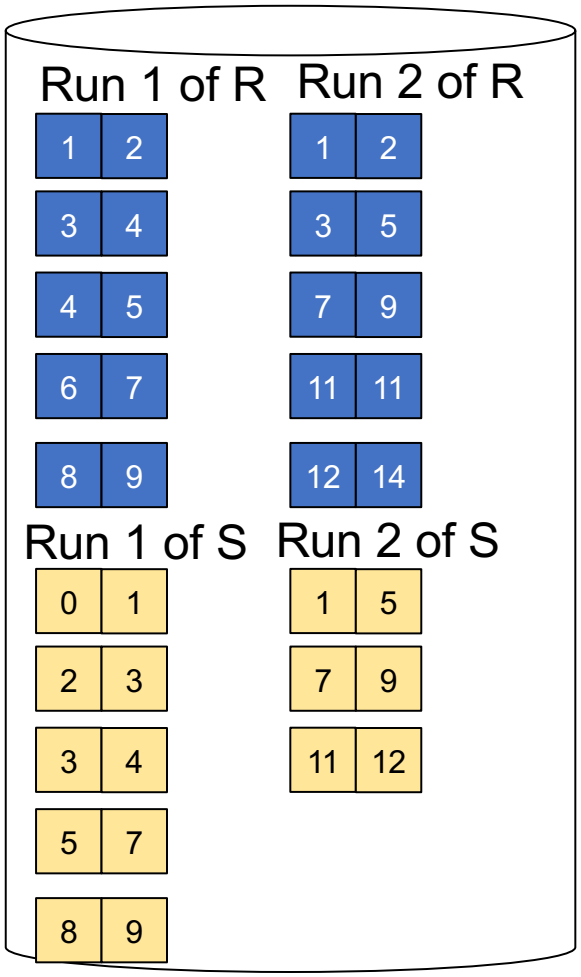
Total cost: 3B(R) + 3B(S)



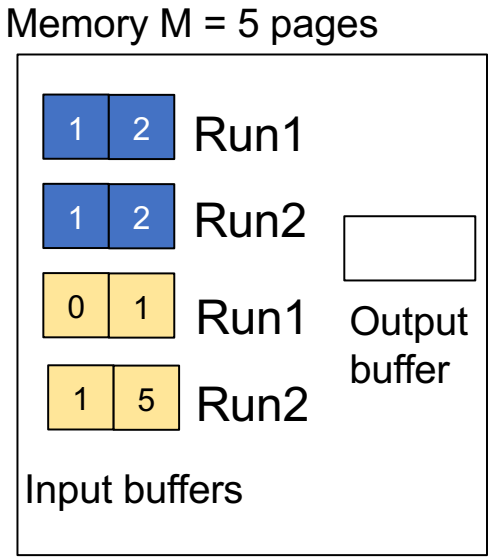
Step 2: Join while merging
Output tuples

Merge-Join Example

Step 2: Join while merging sorted runs



Total cost: 3B(R) + 3B(S)



Step 2: Join while merging
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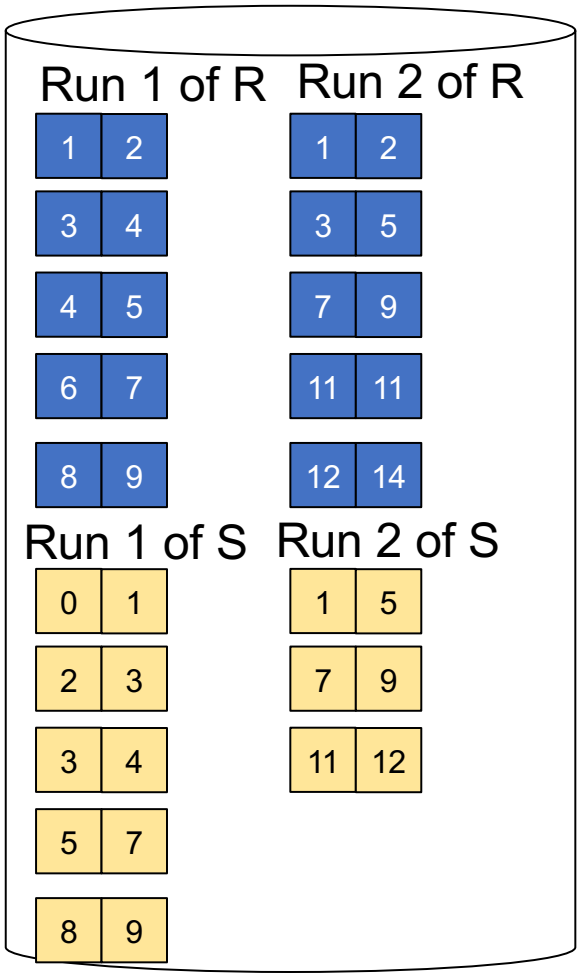
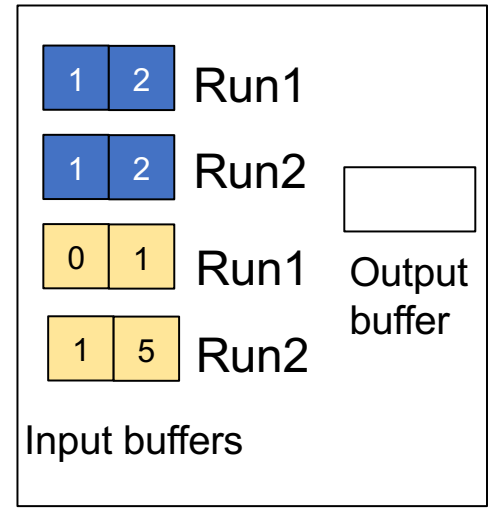
Merge-Join Example

Step 2: Join while merging sorted runs



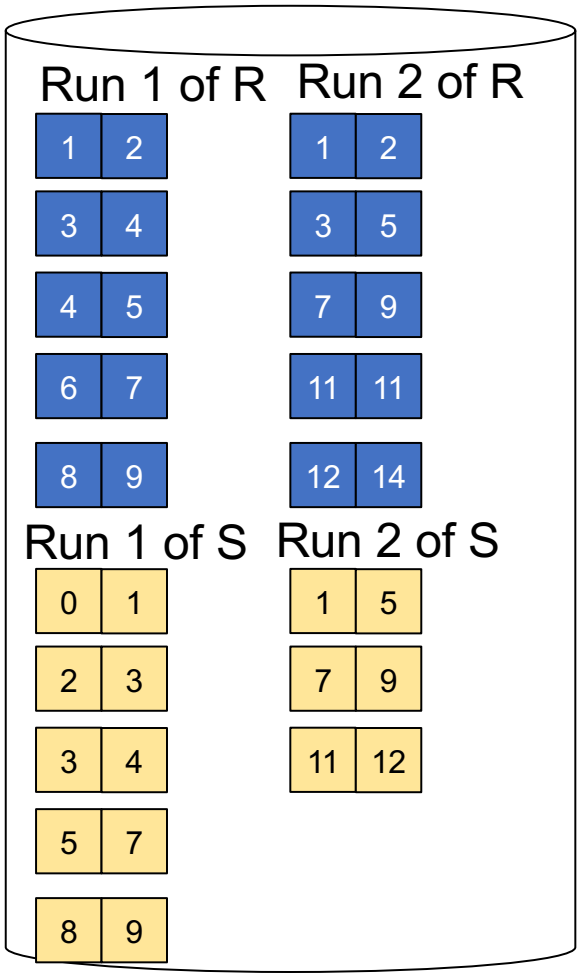
Total cost: 3B(R) + 3B(S)

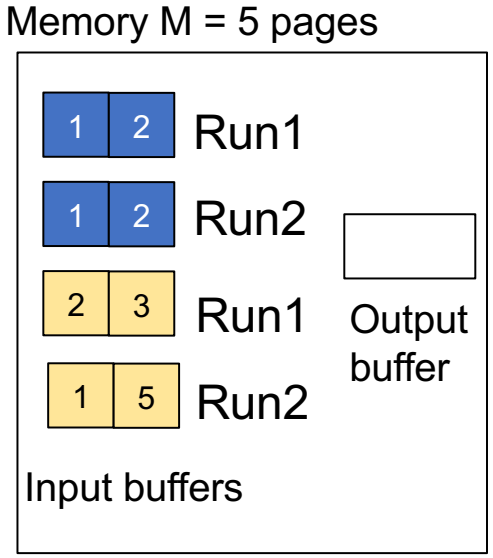


Step 2: Join while merging
Output tuples
(1,1)
(1,1)
(1,1)
(1,1)

Merge-Join Example

Step 2: Join while merging sorted runs



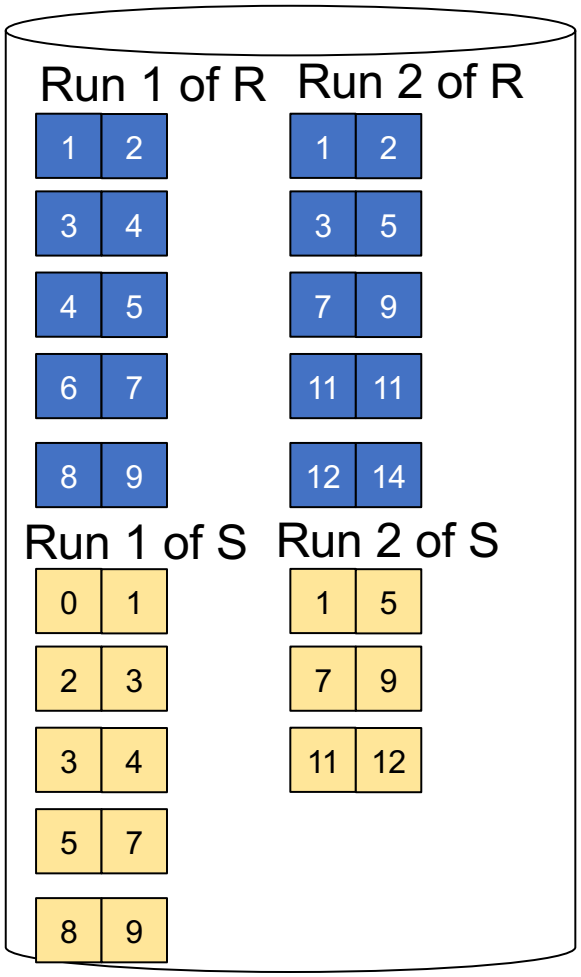


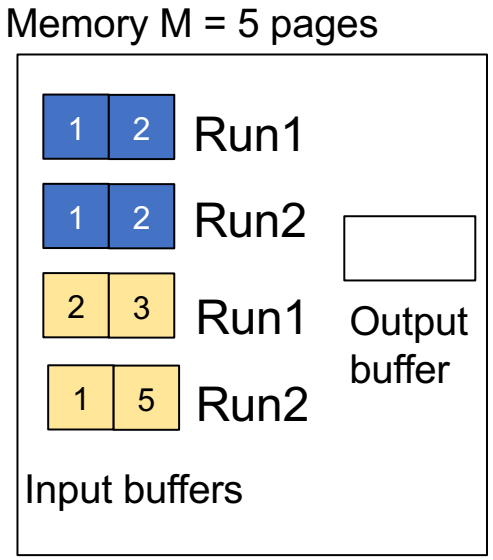
Total cost: 3B(R) + 3B(S)

Step 2: Join while merging
Output tuples
(1,1)
(1,1)
(1,1)
(1,1)

Merge-Join Example

Step 2: Join while merging sorted runs



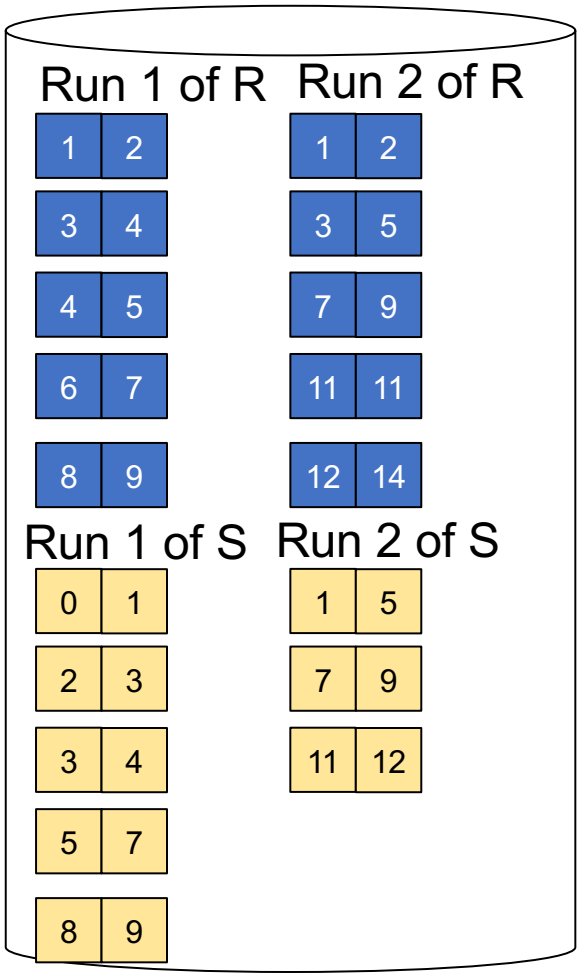


Total cost: 3B(R) + 3B(S)

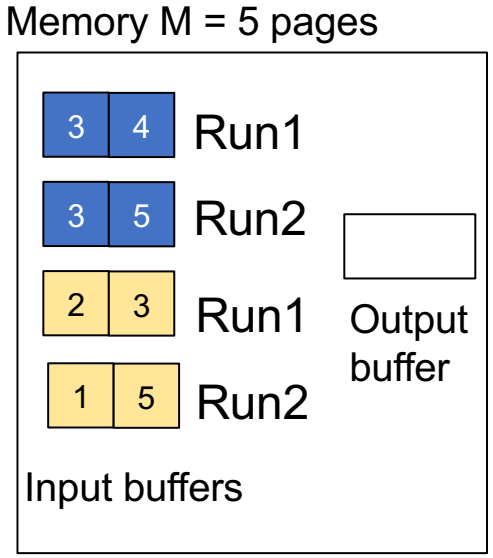
Step 2: Join while merging
Output tuples
(1,1)
(1,1)
(1,1)
(1,1)
(2,2)
(2,2)

Merge-Join Example

Step 2: Join while merging sorted runs

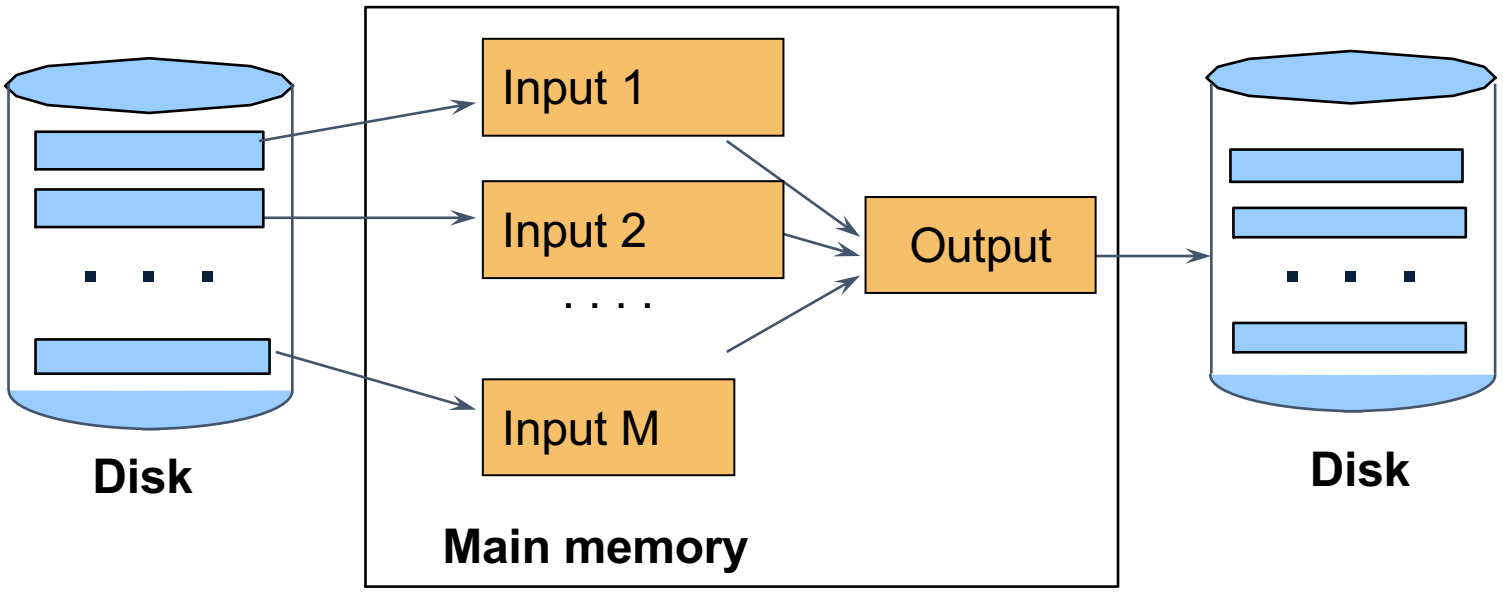


Total cost: 3B(R) + 3B(S)



Step 2: Join while merging
Output tuples
(1,1)
(1,1)
(1,1)
(1,1)
(2,2)
(2,2)
(3,3)
(3,3)
...

Merge-Join



M_1 = B(R)/M runs for R
M_2 = B(S)/M runs for S
Merge-join M_1 + M_2 runs;
need M_1 + M_2 <= M to process all runs
i.e. B(R) + B(S) <= M^2

B(R)/M <= M