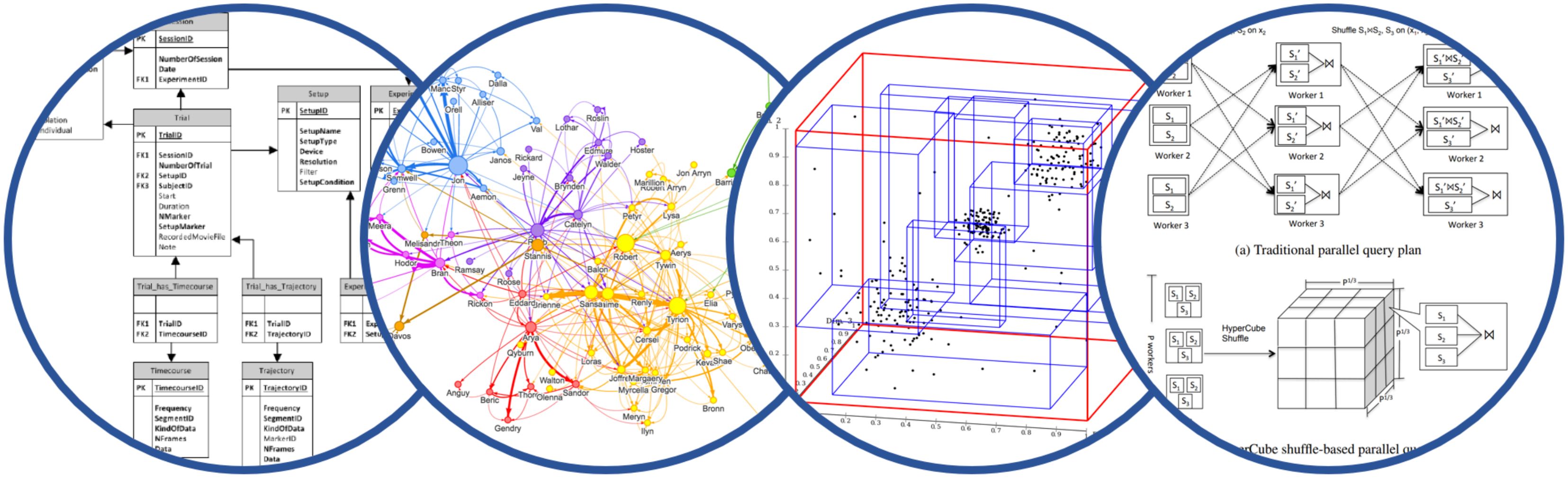

Database System Internals

Query Execution and Algorithms

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University of Washington, Seattle

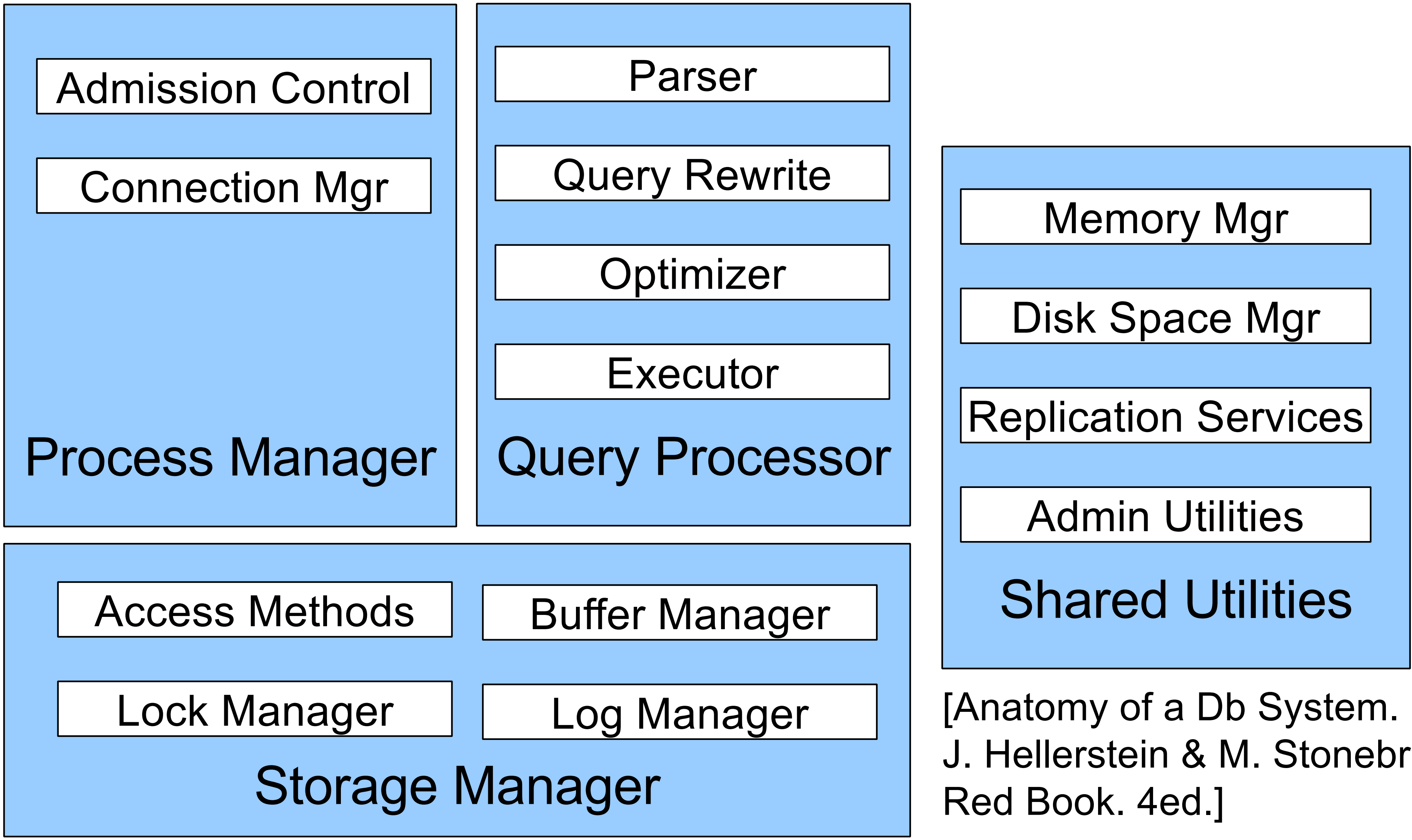
Announcements

- Lab1 due on Wednesday
- HW2 released, due Monday, 4/25

What We Have Learned So Far

- Overview of the architecture of a DBMS
- Access methods
  - Heap files, sequential files, Indexes (hash or B+ trees)
- Role of buffer manager
- Practiced the concepts in hw1 and lab1

DBMS Architecture



[Anatomy of a Db System.
J. Hellerstein & M. Stonebraker.
Red Book. 4ed.]

Query Processor

- Query optimization: find a good plan
- Query execution: execute the plan

We start with execution and analyze its cost.
That will inform how to optimize.

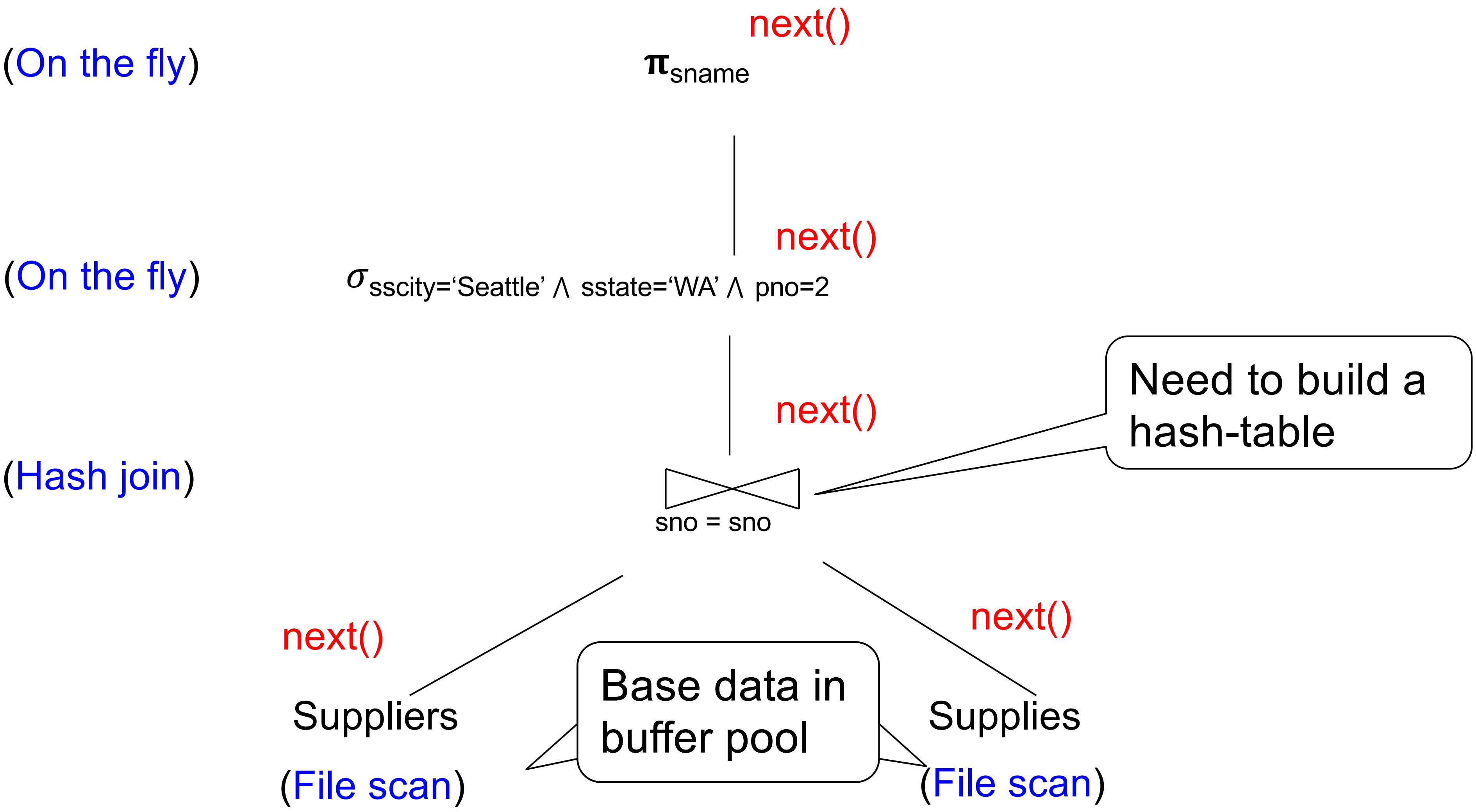
Query Execution Summary

SQL query transformed into physical plan

- Access path selection for each relation
- Implementation choice for each operator
- Scheduling decisions for operators:
  - Single-threaded or parallel
  - Pipelined or materialized

Operators given a limited amount of memory

Pipelined Query Execution



(On the fly)

next()

π_{sname}

(On the fly)

next()

$\sigma_{sscity='Seattle' \wedge sstate='WA' \wedge pno=2}$

(Hash join)

next()

$\bowtie_{sno = sno}$

Need to build a hash-table

next()

Suppliers

(File scan)

Base data in buffer pool

next()

Supplies

(File scan)

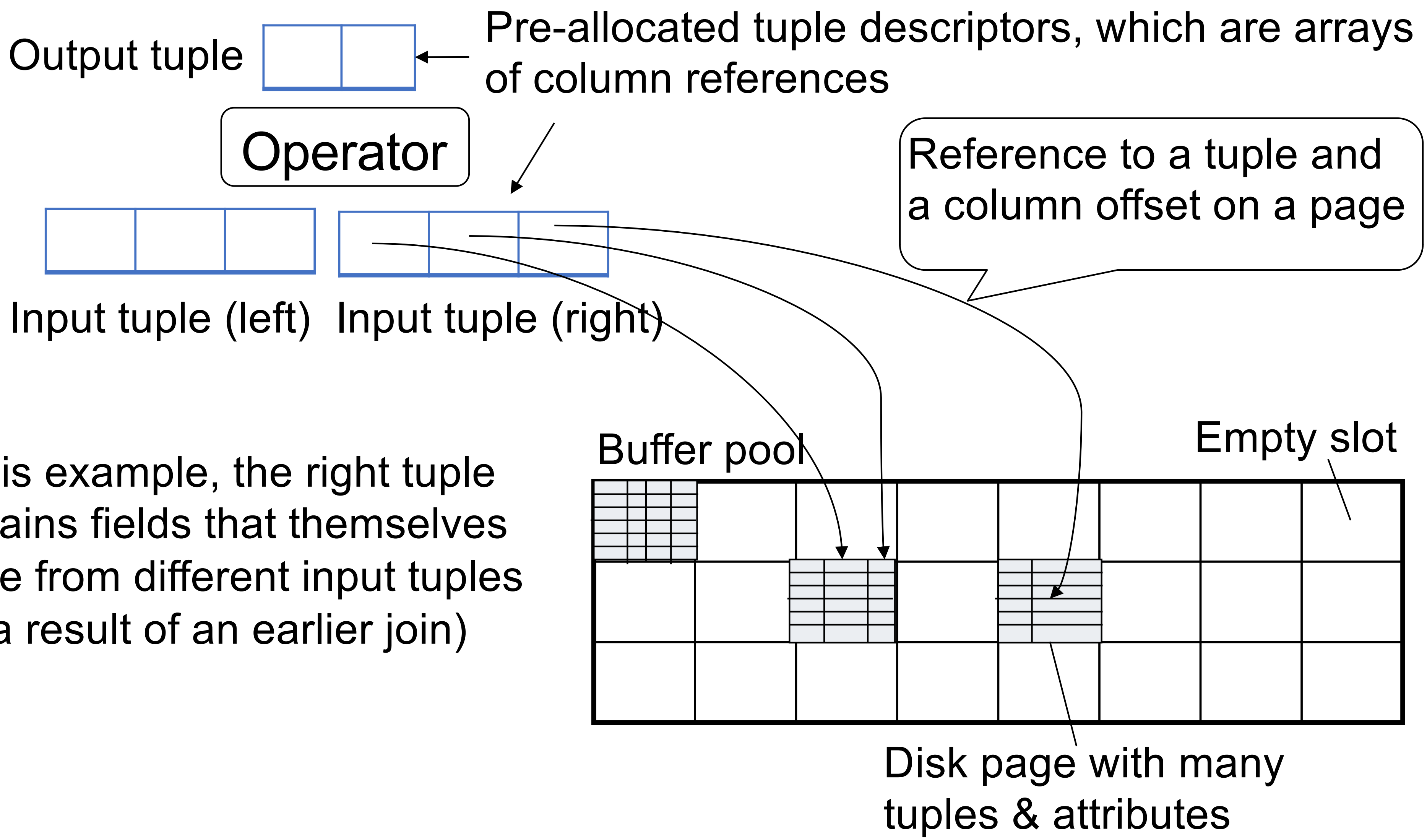
Memory Management

Each operator:

- Pre-allocates heap space for input/output tuples
  - Option 1, BP-tuples: pointers to data in buffer pool
  - Option 2, M-tuples: new tuples on the heap
- Allocates memory for its internal state
  - On heap

DMBS **limits** how much memory each operator, or each query can use

BP-tuples (option 1)



Output tuple

Pre-allocated tuple descriptors, which are arrays of column references

Operator

Reference to a tuple and a column offset on a page

Input tuple (left) Input tuple (right)

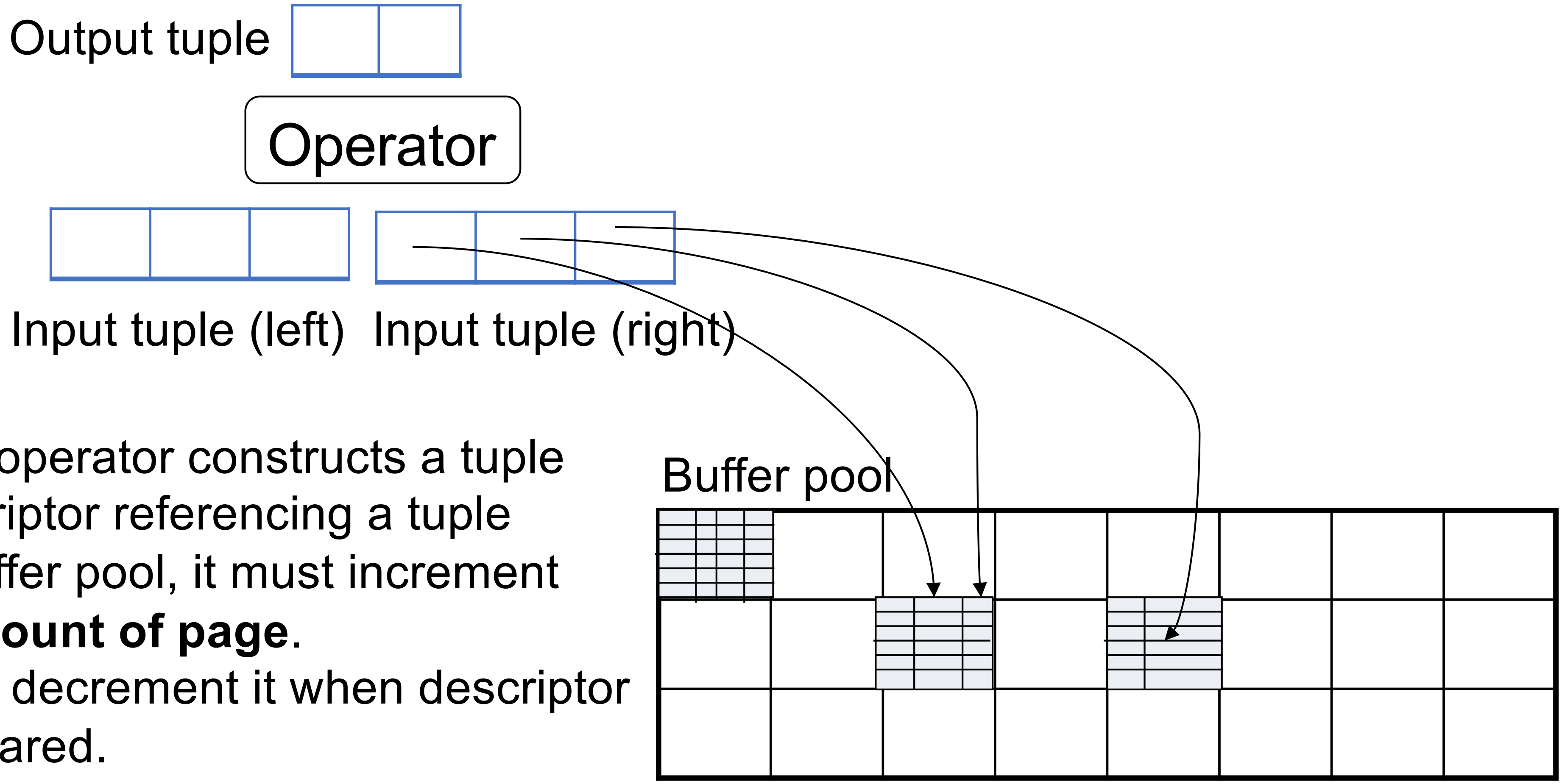
Buffer pool

Empty slot

Disk page with many tuples & attributes

In this example, the right tuple contains fields that themselves come from different input tuples (as a result of an earlier join)

BP-tuples (option 1)

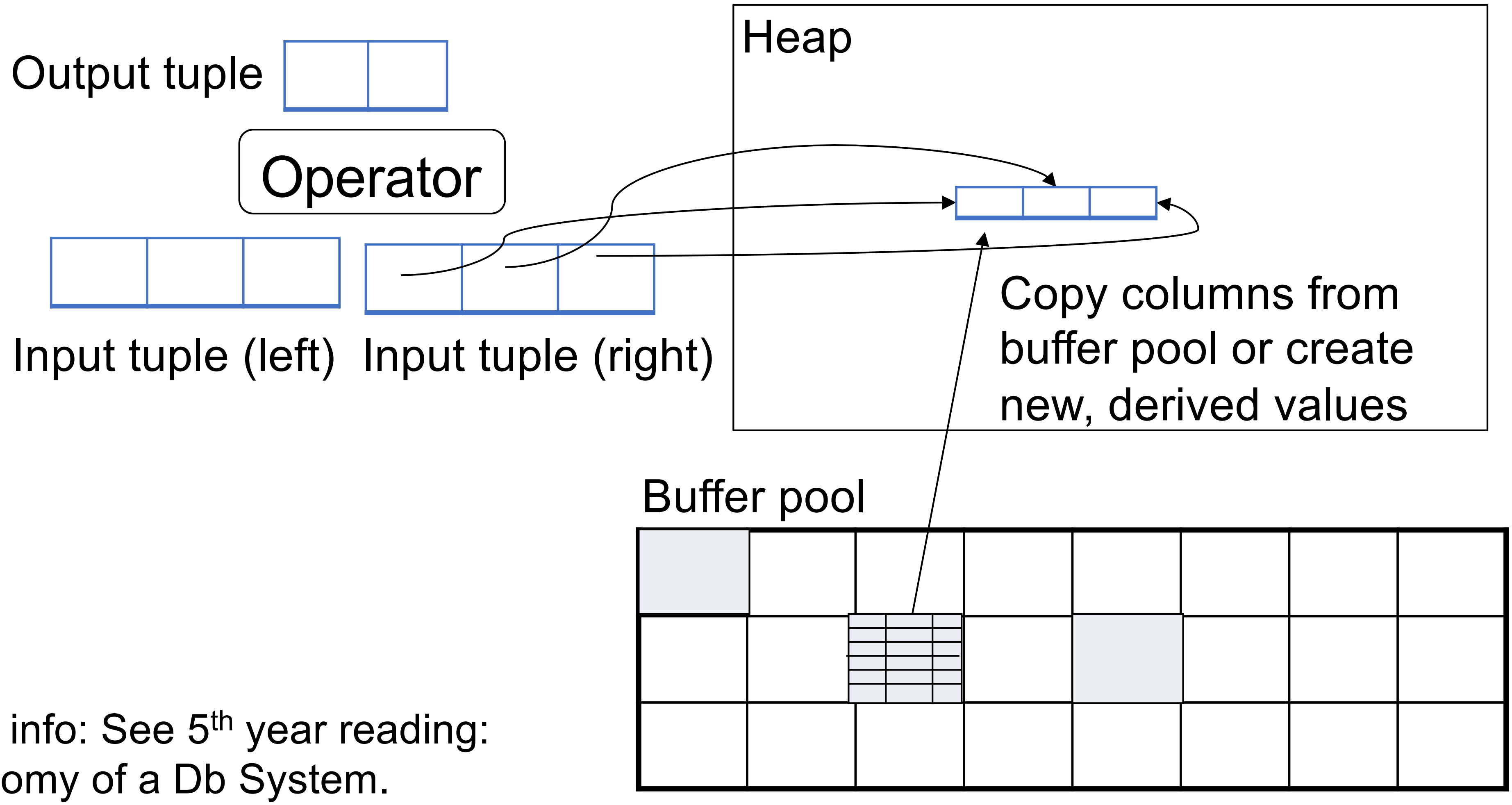


If an operator constructs a tuple descriptor referencing a tuple in buffer pool, it must increment **pin count of page**.

Then decrement it when descriptor is cleared.

(more details of pin count eviction policy in book)

M-Tuples (option 2)



More info: See 5th year reading:
[Anatomy of a Db System.
J. Hellerstein & M. Stonebraker.
Red Book. 4ed.]

Discussion

Buffer-Pool tuples (BP-tuples)

- Pros: don't copy the data (great performance)
- Cons:
  - Need to pin pages in the BP
  - Cannot compute new values:
    SELECT pid, price*quantity FROM …

Heap-tuples, or memory-tuples (M-tuples)

- Pros
  - No need to pin pages (except short period – why?)
  - Can represent new values: price*quanity
- Cons: data copying can degrade performance

Operator Algorithms (Quick review from 344 today & new algorithms next time)

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

- 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 ⋈ S

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

- One-pass algorithm when B(R) ≤ M

Note: the *inner* relation is the relation on which we build the hash table

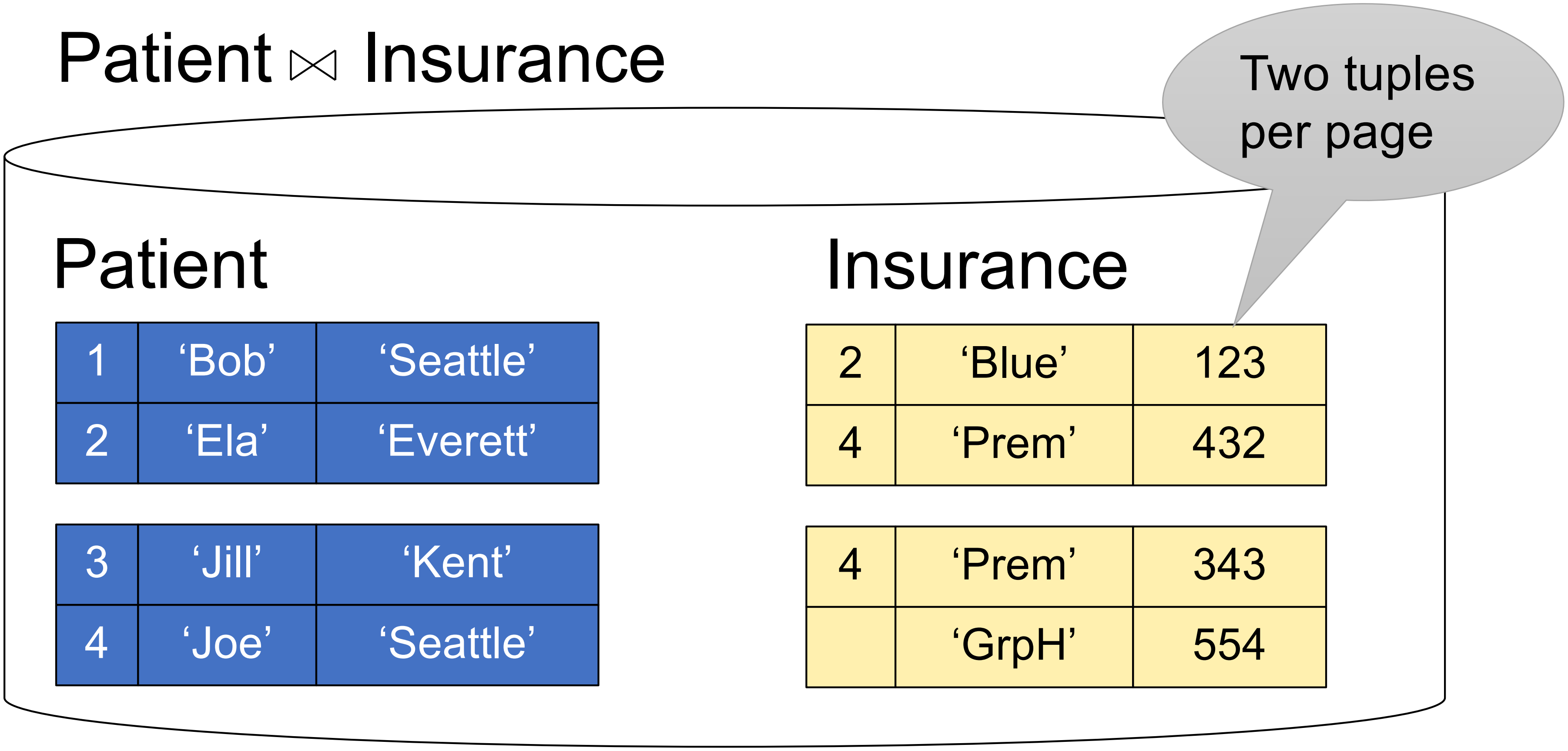
- Usually this is the *right* relation, i.e. S.
- But the following slides choose the *left* relation, i.e. R

Hash Join Example

Patient(pid, name, address)

Insurance(pid, provider, policy_nb)

Patient ⋈ Insurance



Two tuples per page

Patient

1	‘Bob’	‘Seattle’
2	‘Ela’	‘Everett’

3	‘Jill’	‘Kent’
4	‘Joe’	‘Seattle’

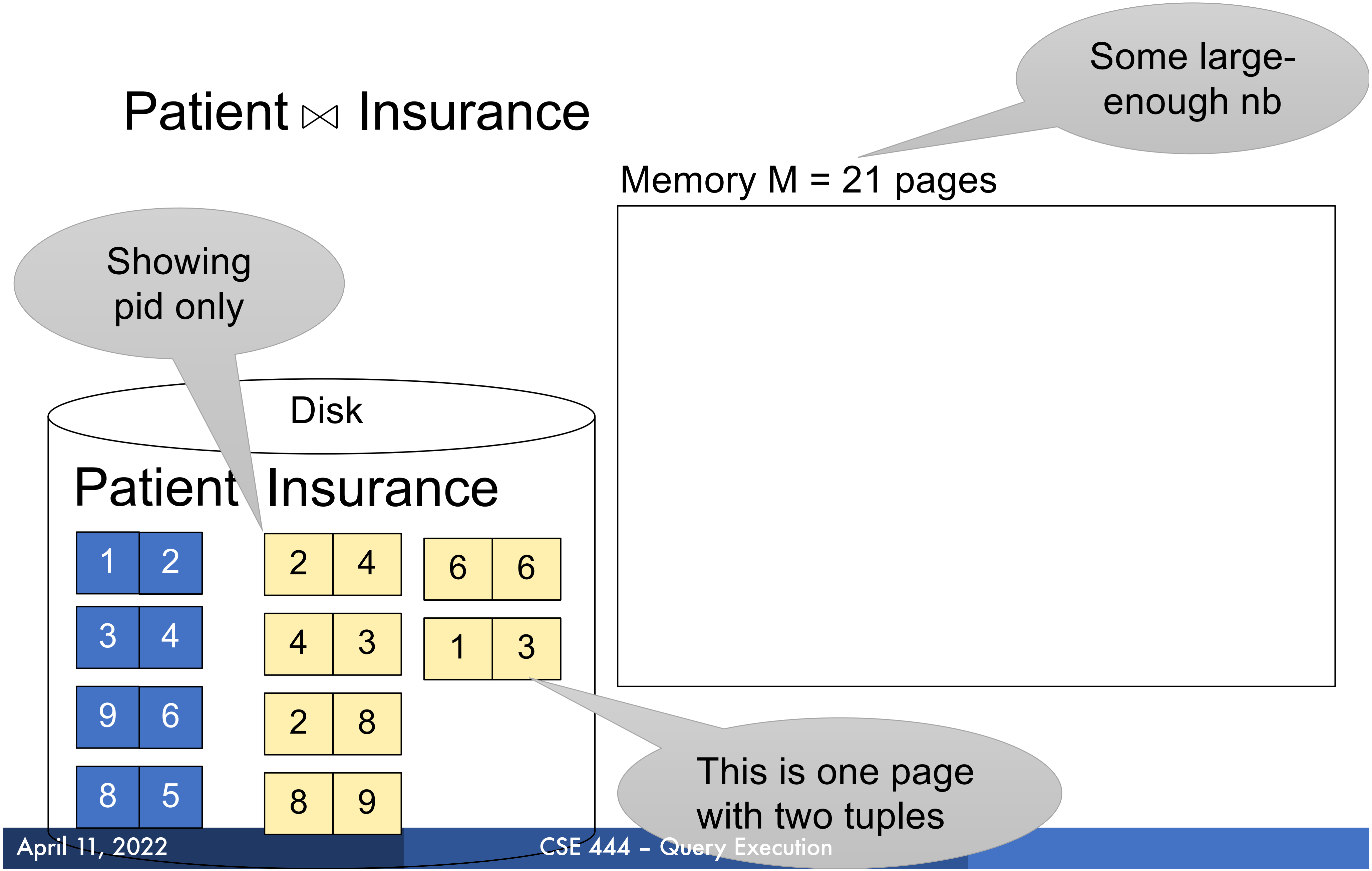
Insurance

2	‘Blue’	123
4	‘Prem’	432

4	‘Prem’	343
	‘GrpH’	554

Hash Join Example

Patient $\bowtie$ Insurance



Some large-enough nb

Memory M = 21 pages

Showing pid only

Disk

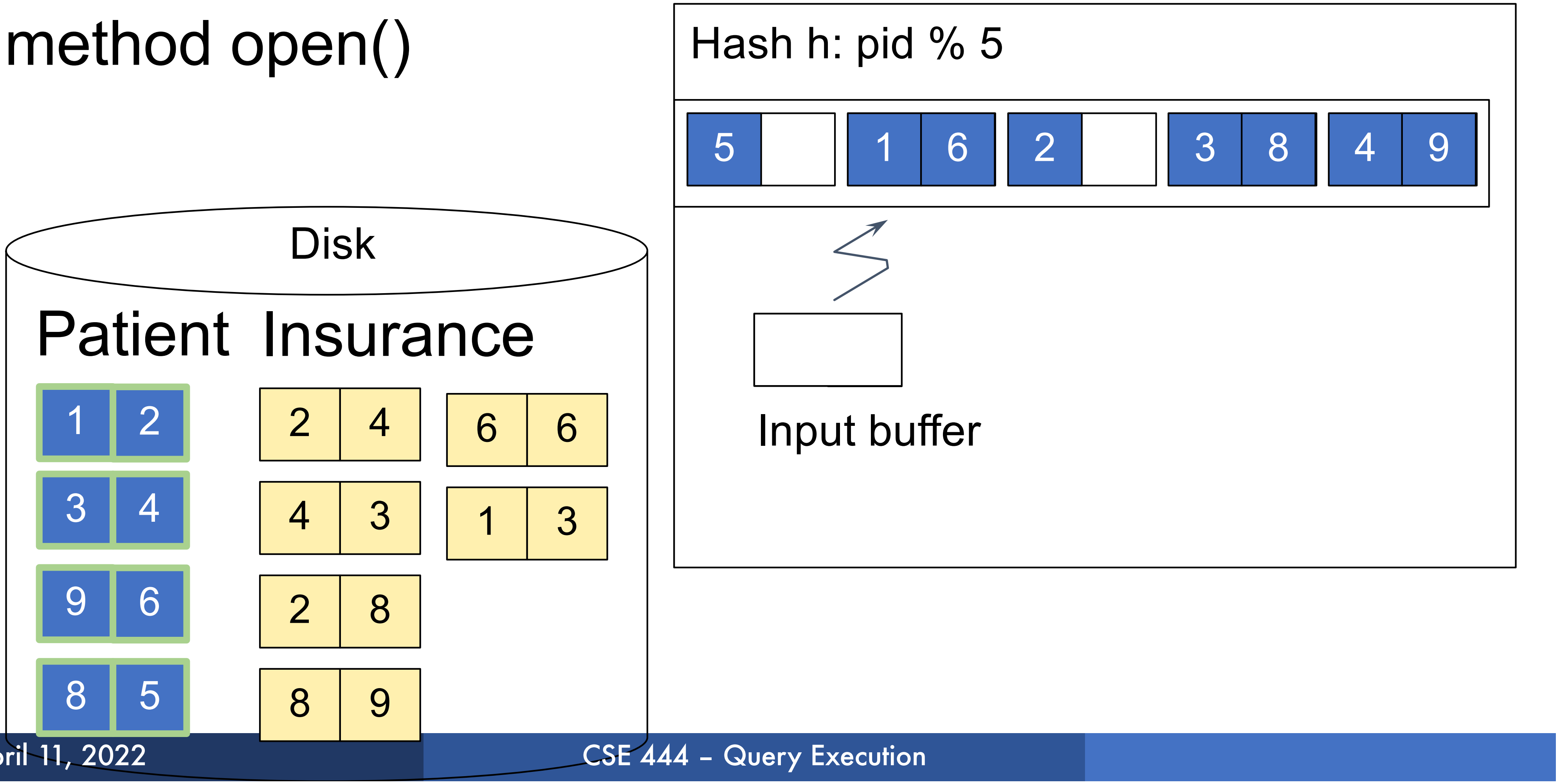
Patient	Insurance	
1 2	2 4	6 6
3 4	4 3	1 3
9 6	2 8	
8 5	8 9	

This is one page with two tuples

Hash Join Example

Step 1: Scan Patient and build hash table in memory

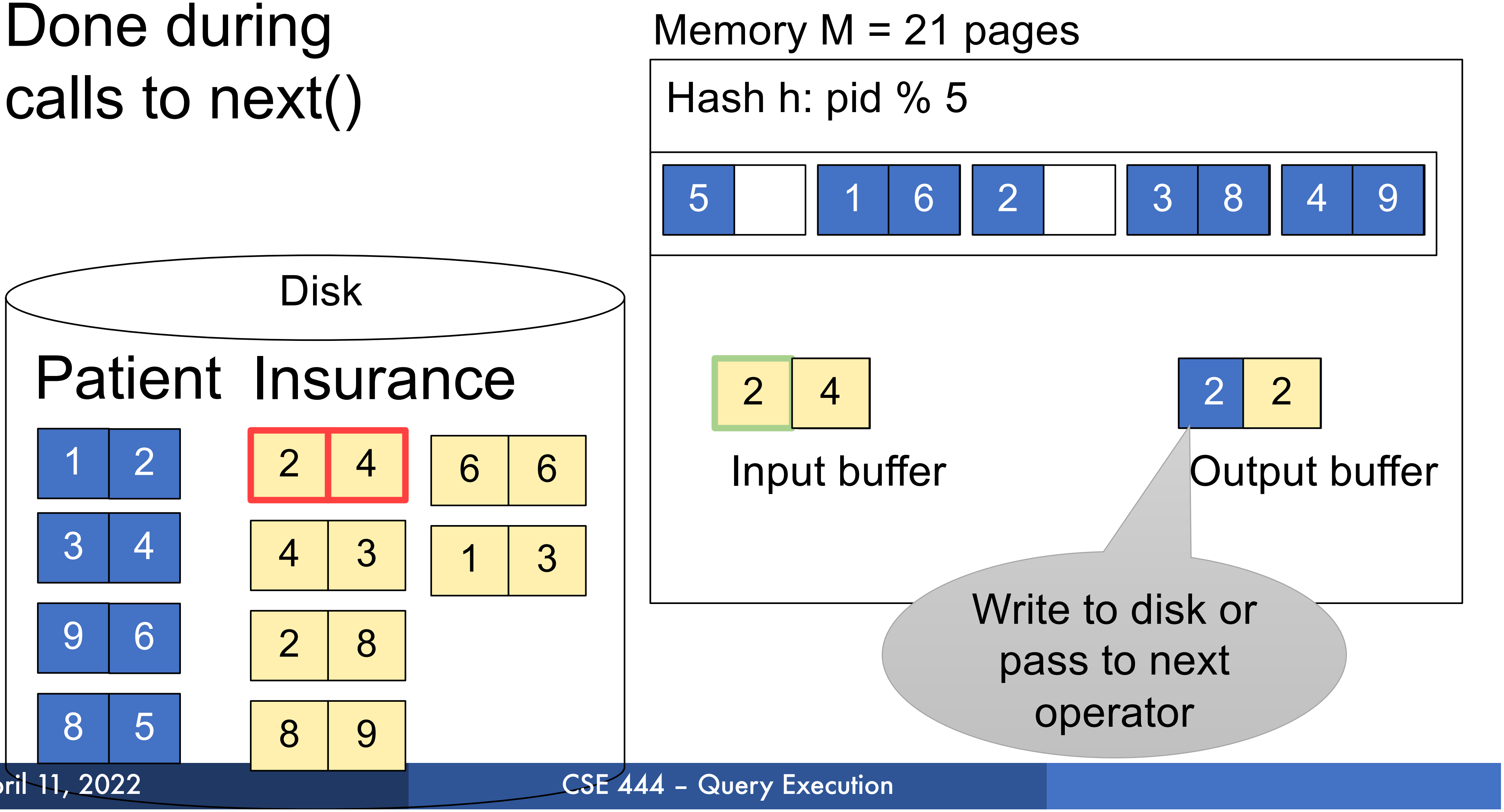
Can be done in method open()



Hash Join Example

Step 2: Scan Insurance and probe into hash table

Done during calls to next()



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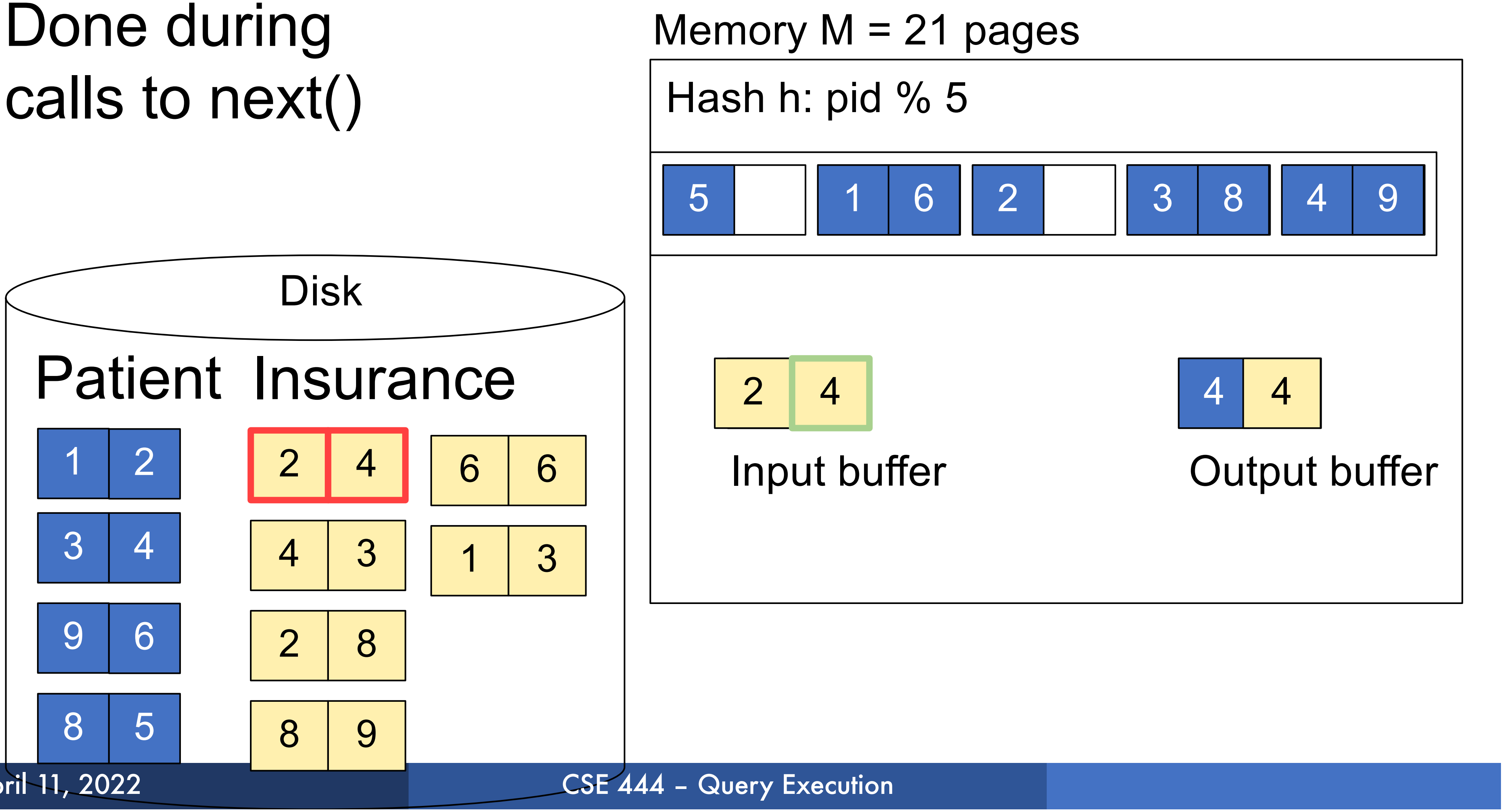

Hash Join Example

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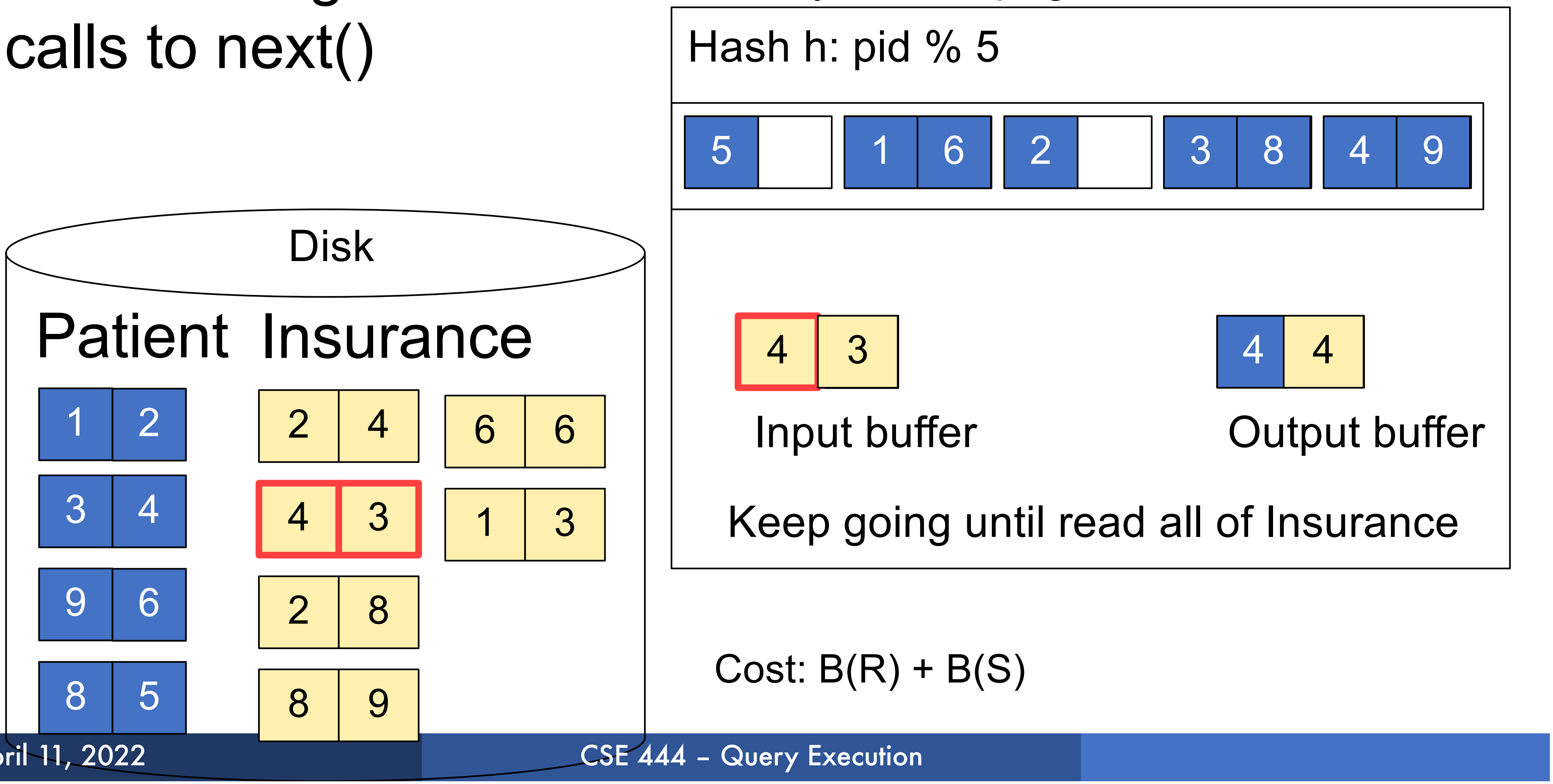

Keep going until read all of Insurance

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 think about it

- 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 $R \bowtie S$
- R is the outer relation, S is the inner relation

```
for each tuple $t_1$ in R do
   for each tuple $t_2$ in S do
      if $t_1$ and $t_2$ join then output $(t_1,t_2)$
```

What is the Cost?

Nested Loop Joins

- Tuple-based nested loop $R \bowtie S$
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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 $t_1$ in r, $t_2$ in s
        if $t_1$ and $t_2$ join then output ($t_1$,$t_2$)
```

What is the Cost?

Page-at-a-time Refinement

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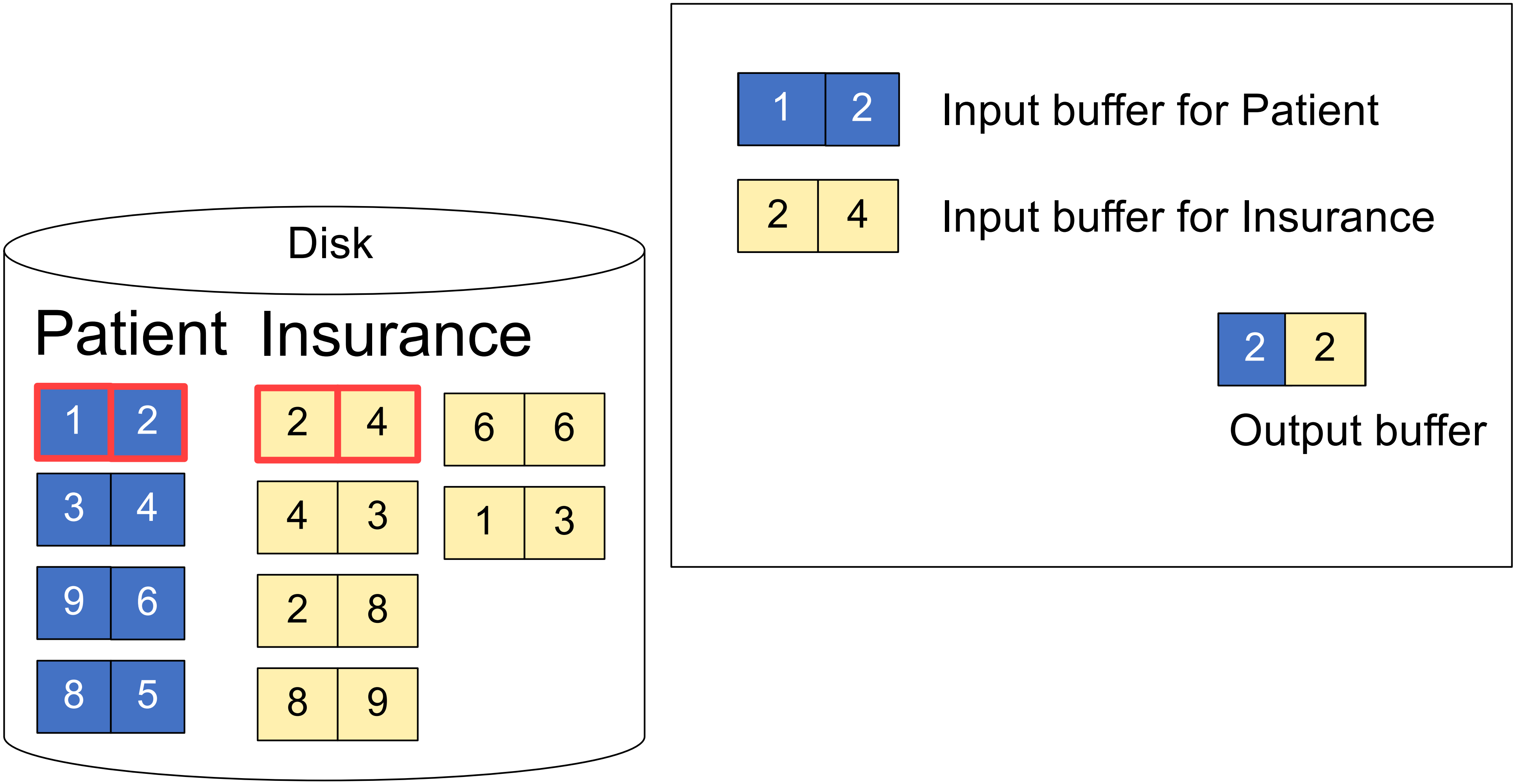
- Cost: B(R) + B(R)B(S)

What is the Cost?

Page-at-a-time Refinement



Disk

Patient

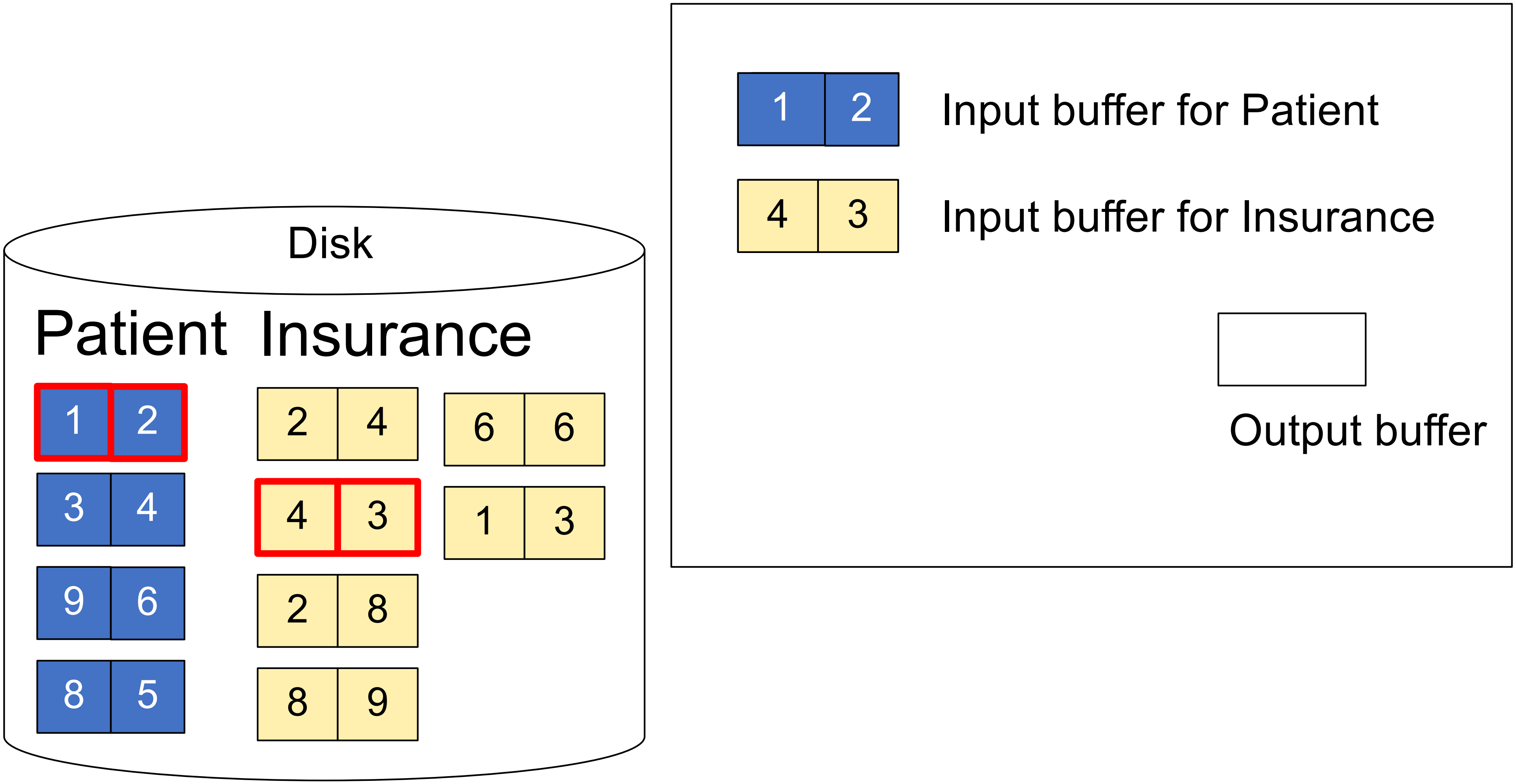
Insurance

Input buffer for Patient

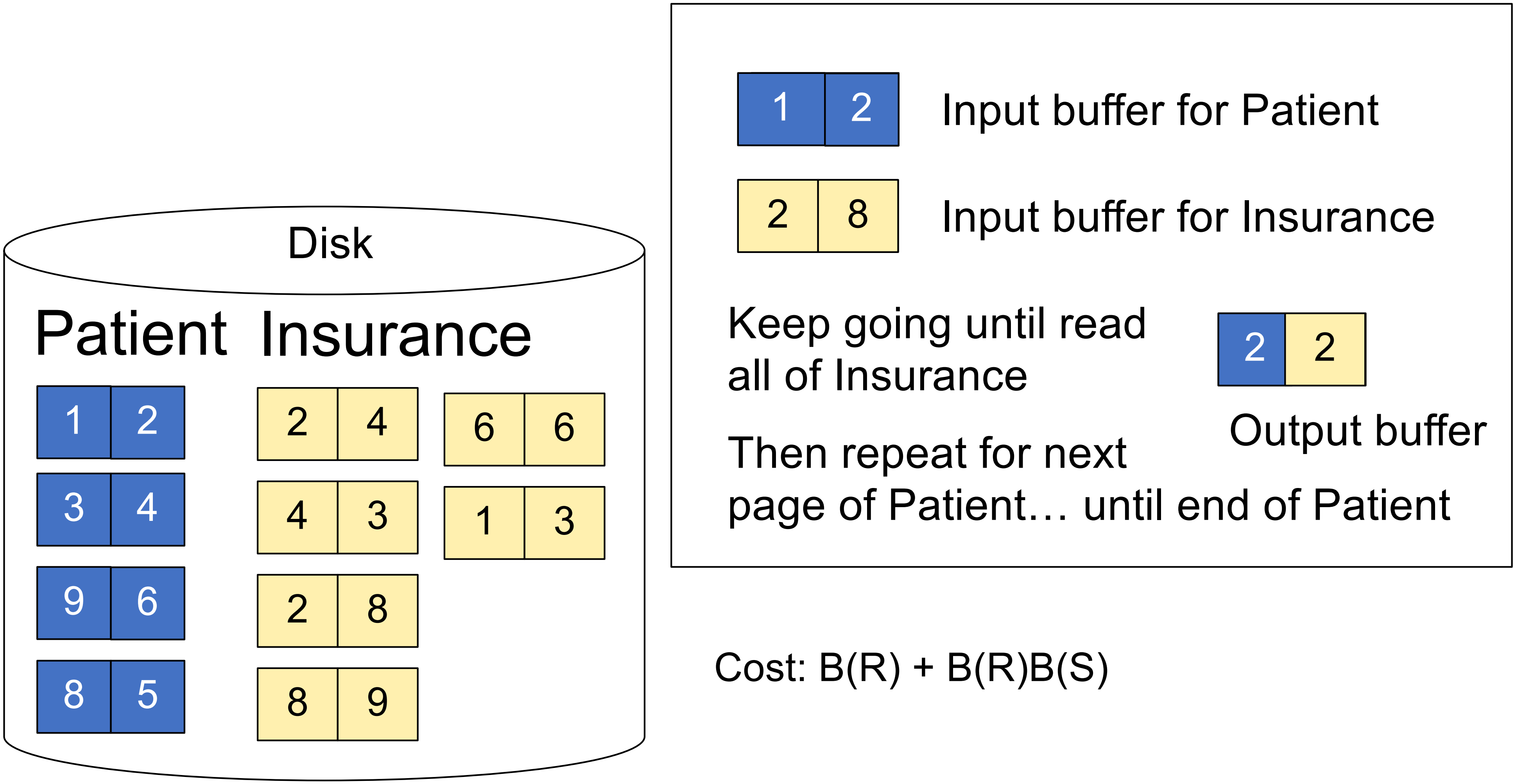
Input buffer for Insurance

Output buffer

Page-at-a-time Refinement



Page-at-a-time Refinement



Keep going until read all of Insurance

Then repeat for next page of Patient… until end of Patient

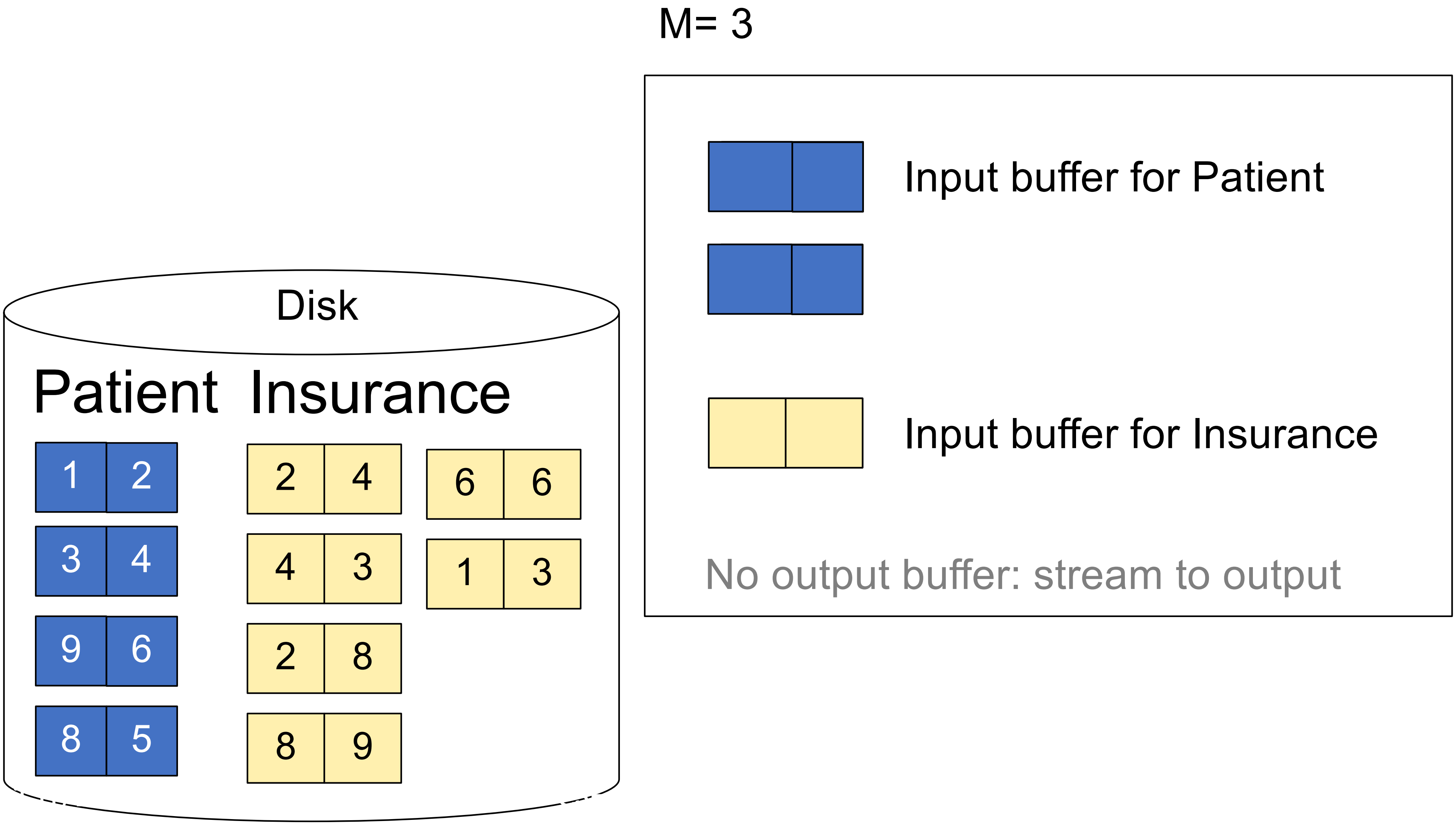
Cost: B(R) + B(R)B(S)

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 $t_1$ in r, $t_2$ in s
      if $t_1$ and $t_2$ join then output ($t_1$,$t_2$)
```

What is the Cost?

Block Memory Refinement



M= 3

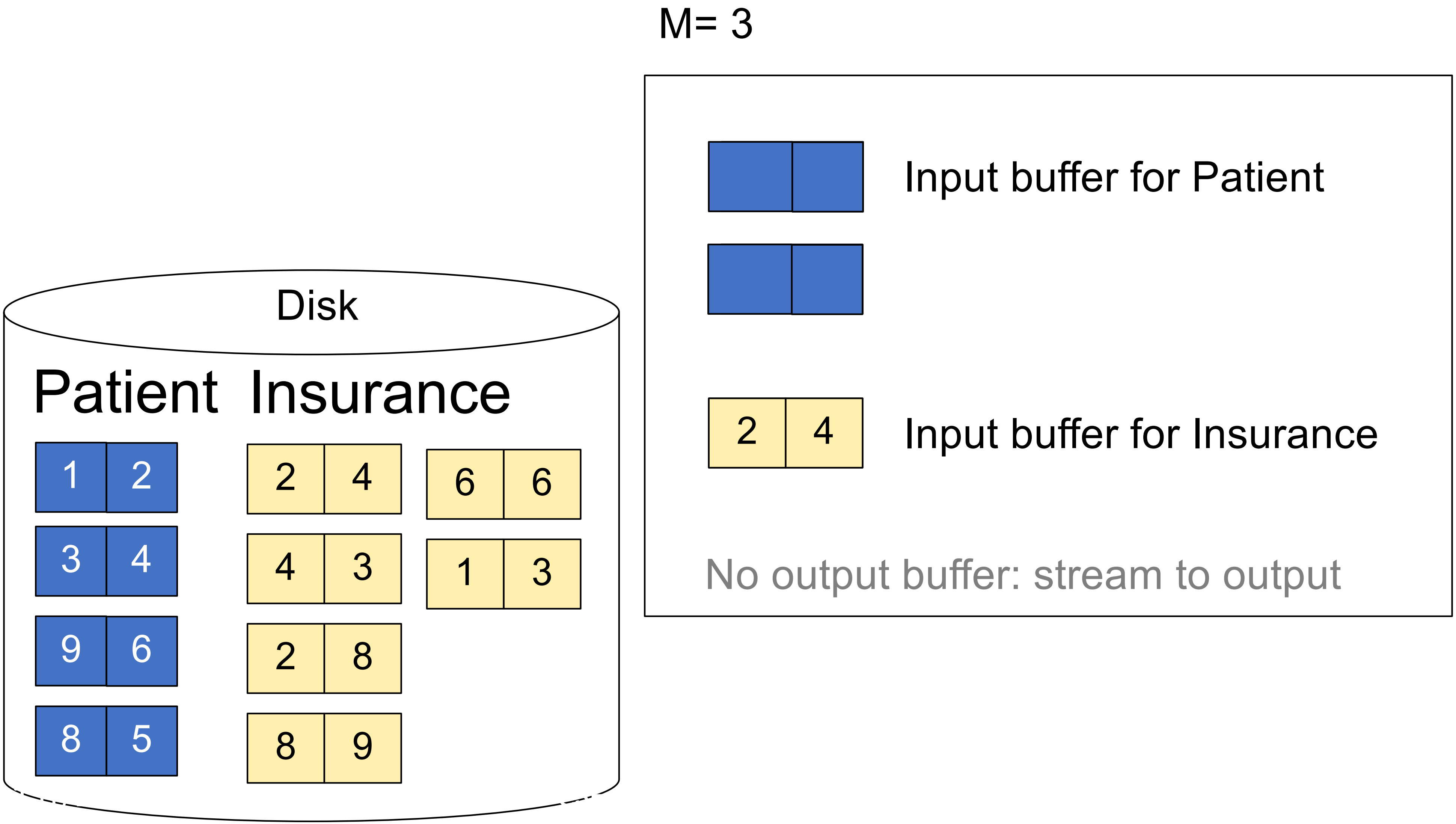
Input buffer for Patient

Input buffer for Insurance

No output buffer: stream to output

Disk

Block Memory Refinement



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Disk

Patient Insurance

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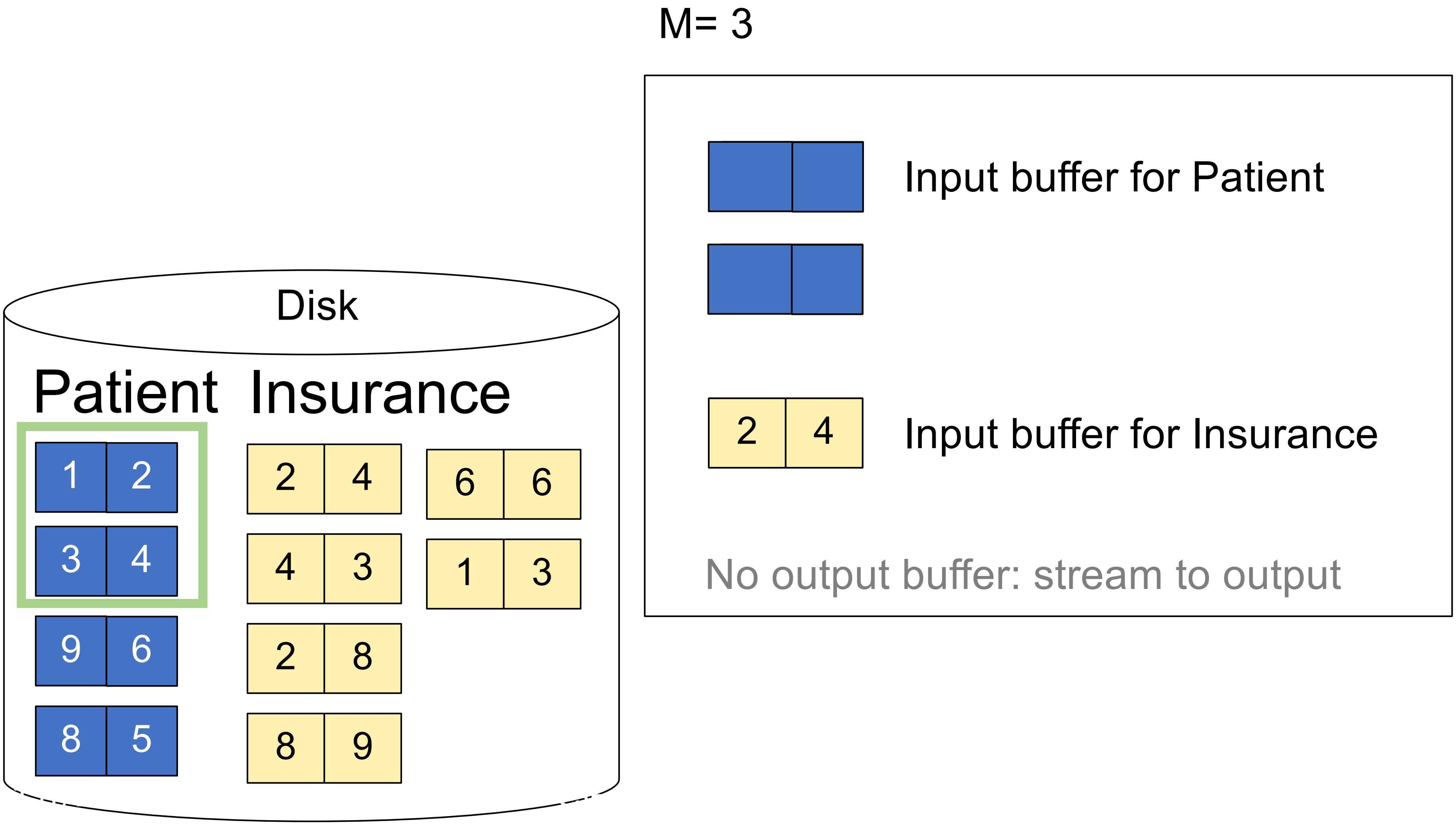
Block Memory Refinement



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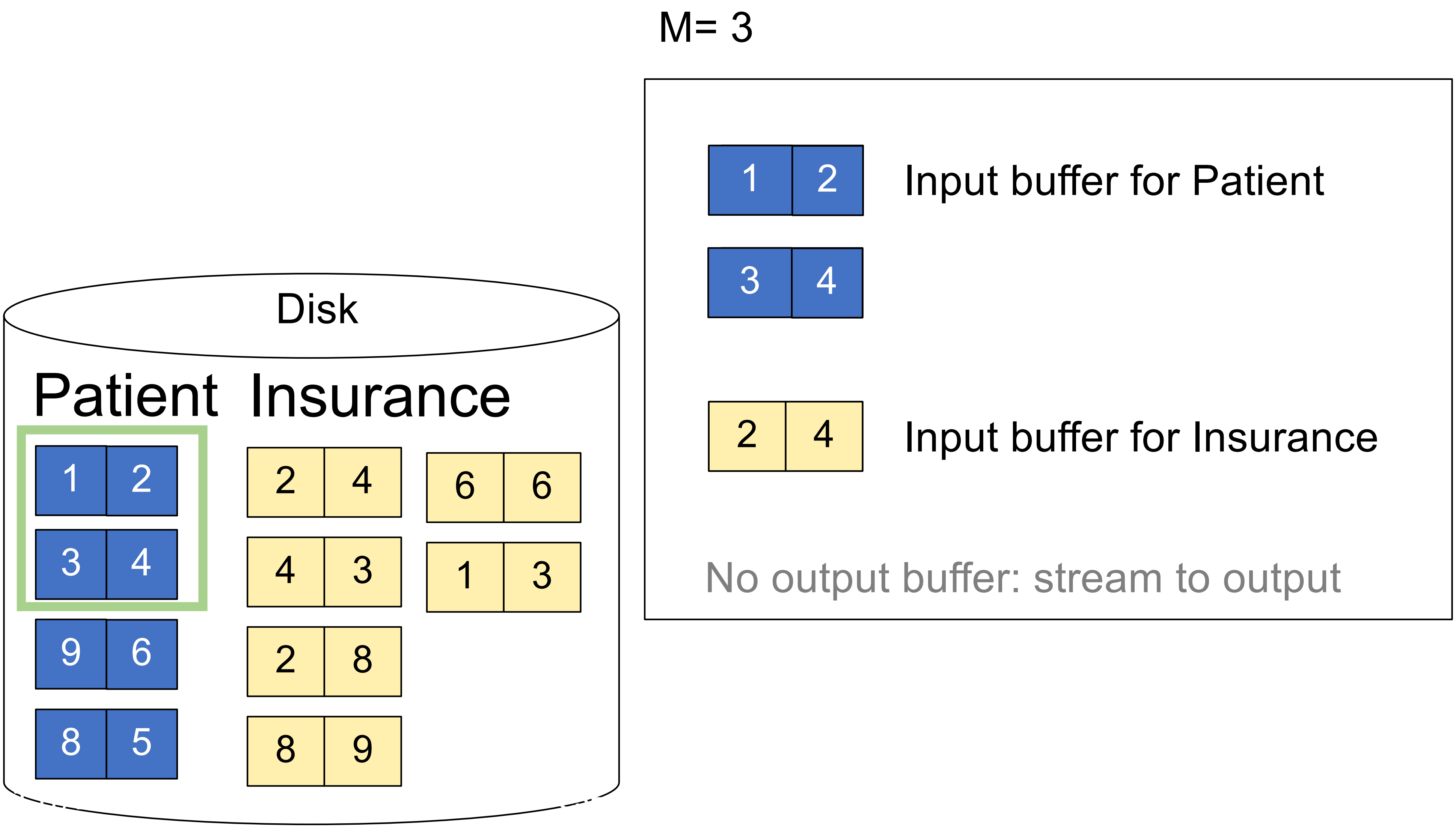
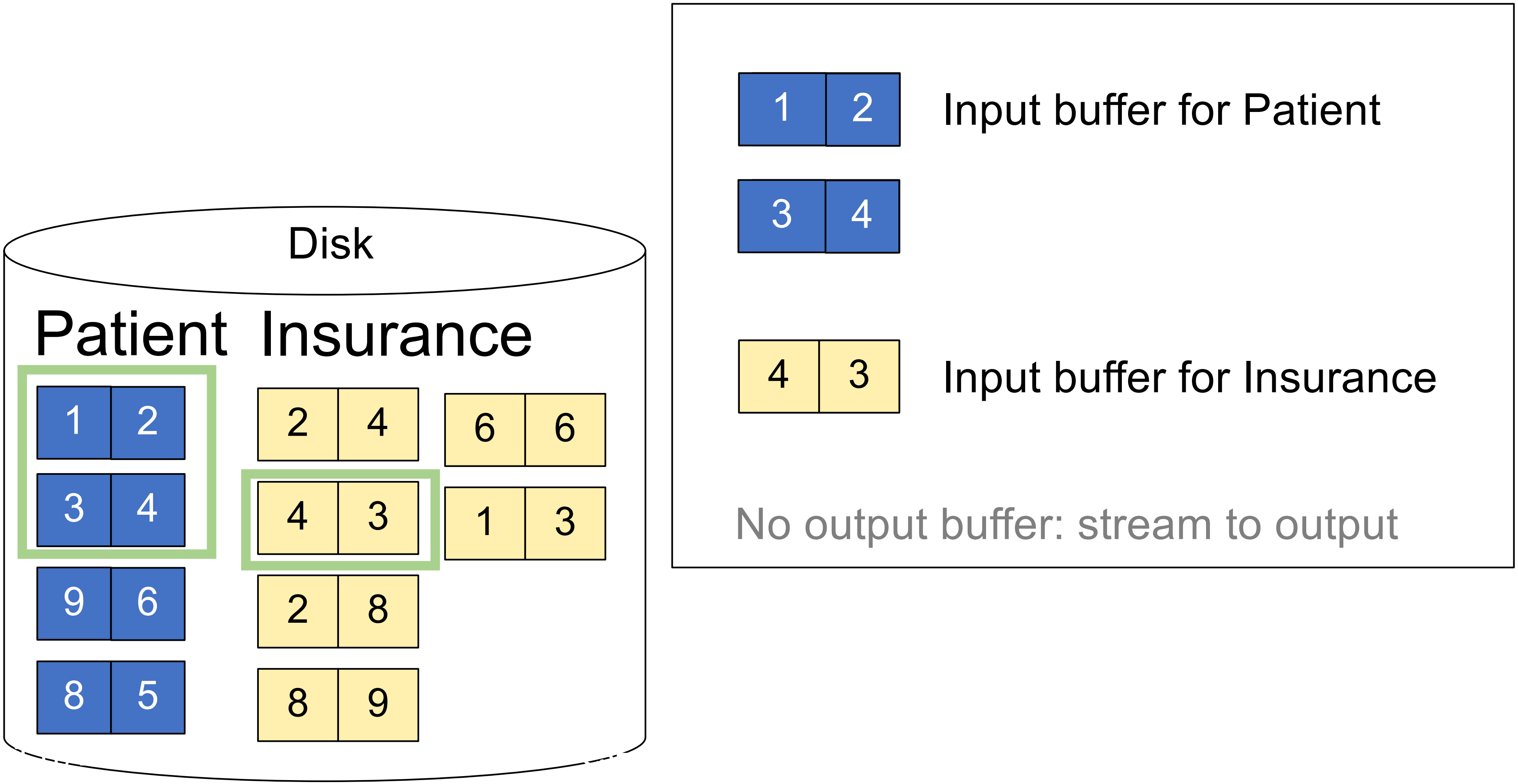


Block Memory Refinement

M= 3



Disk

Patient Insurance

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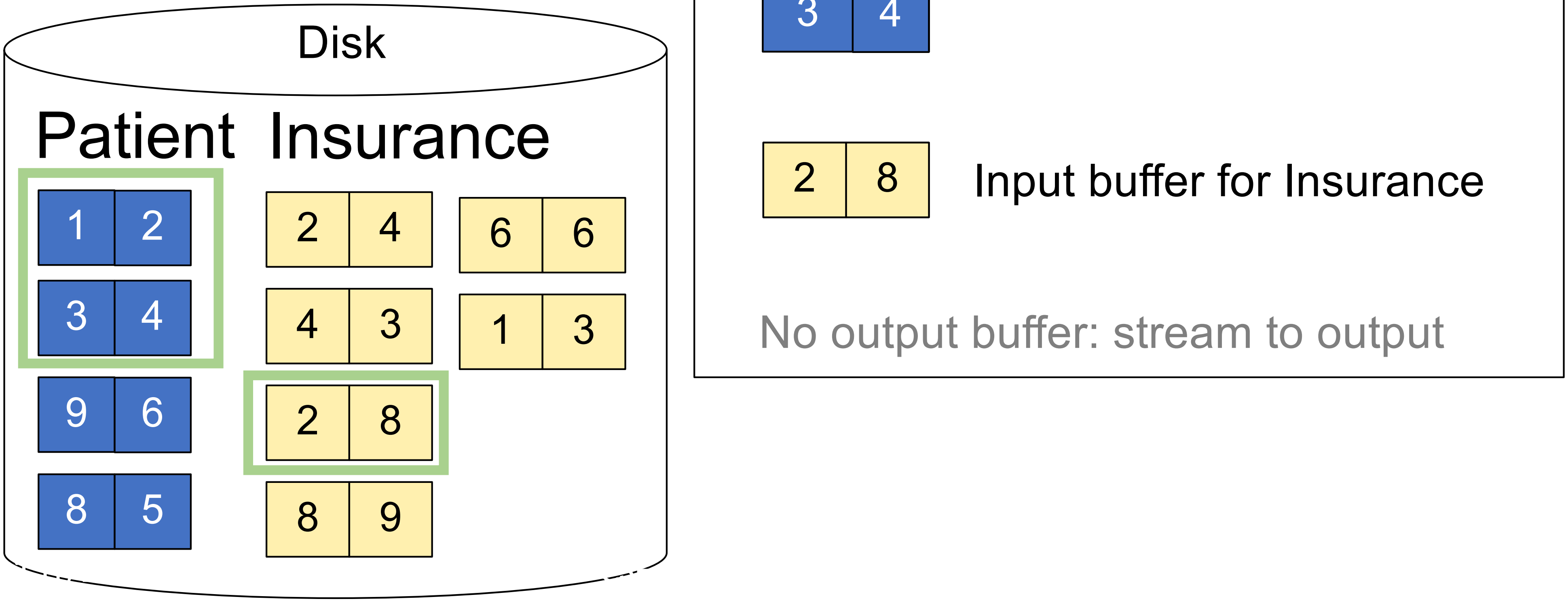

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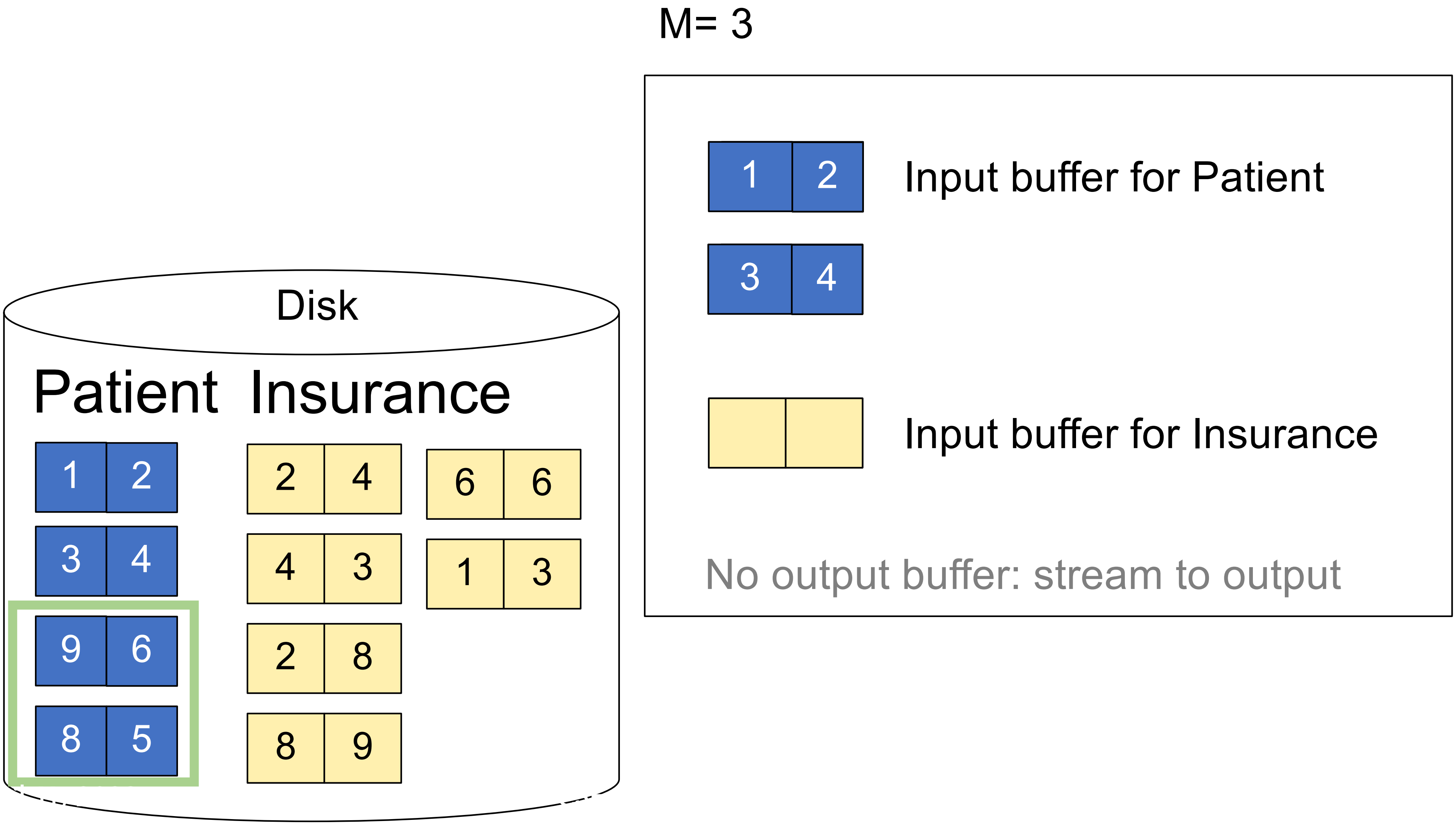

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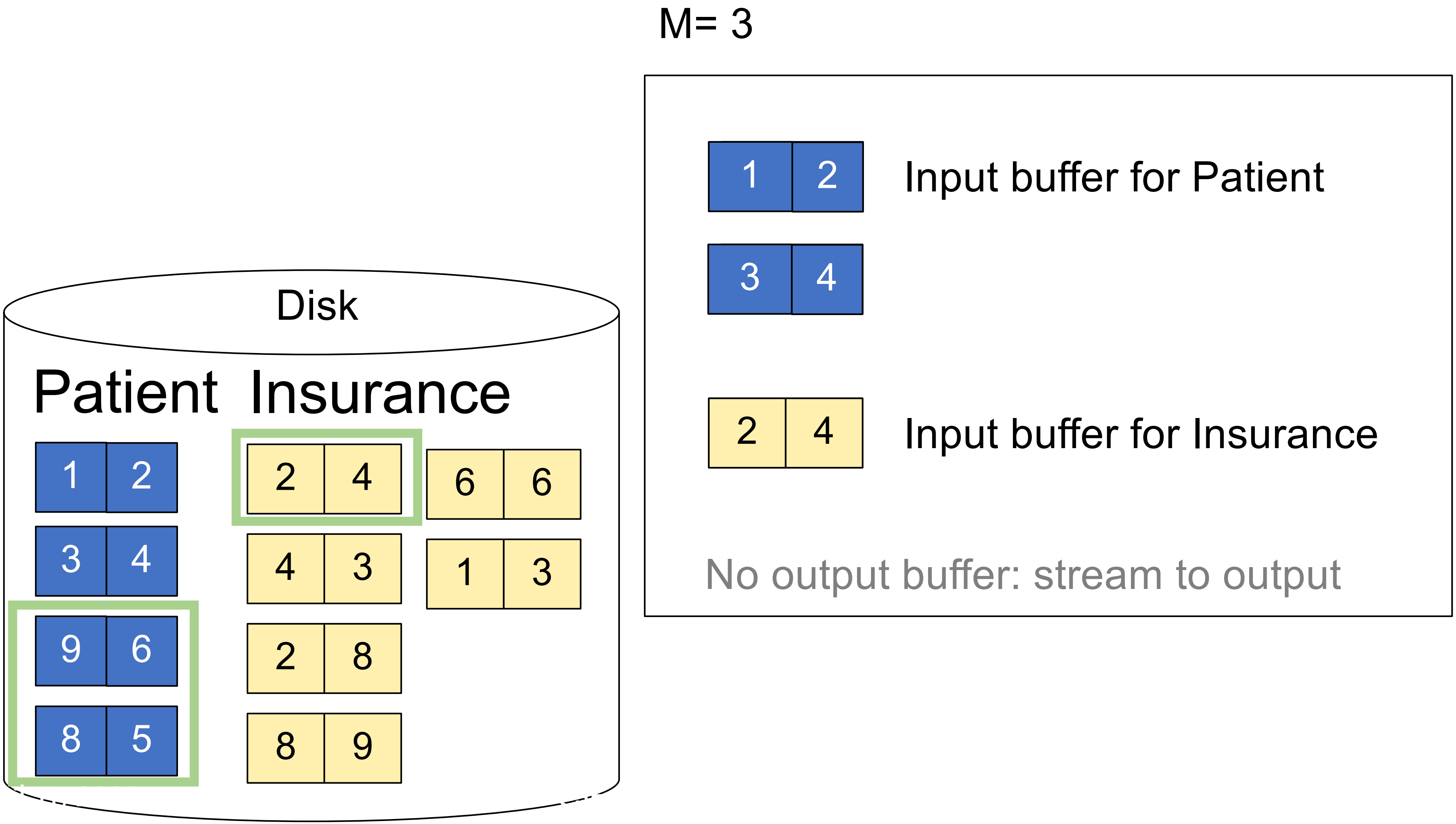

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No output buffer: stream to output

Block Memory Refinement

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Block Memory Refinement

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          if $t_1$ and $t_2$ join then output $(t_1,t_2)$
```

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

What is the Cost

Discussion

R $\bowtie$ 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

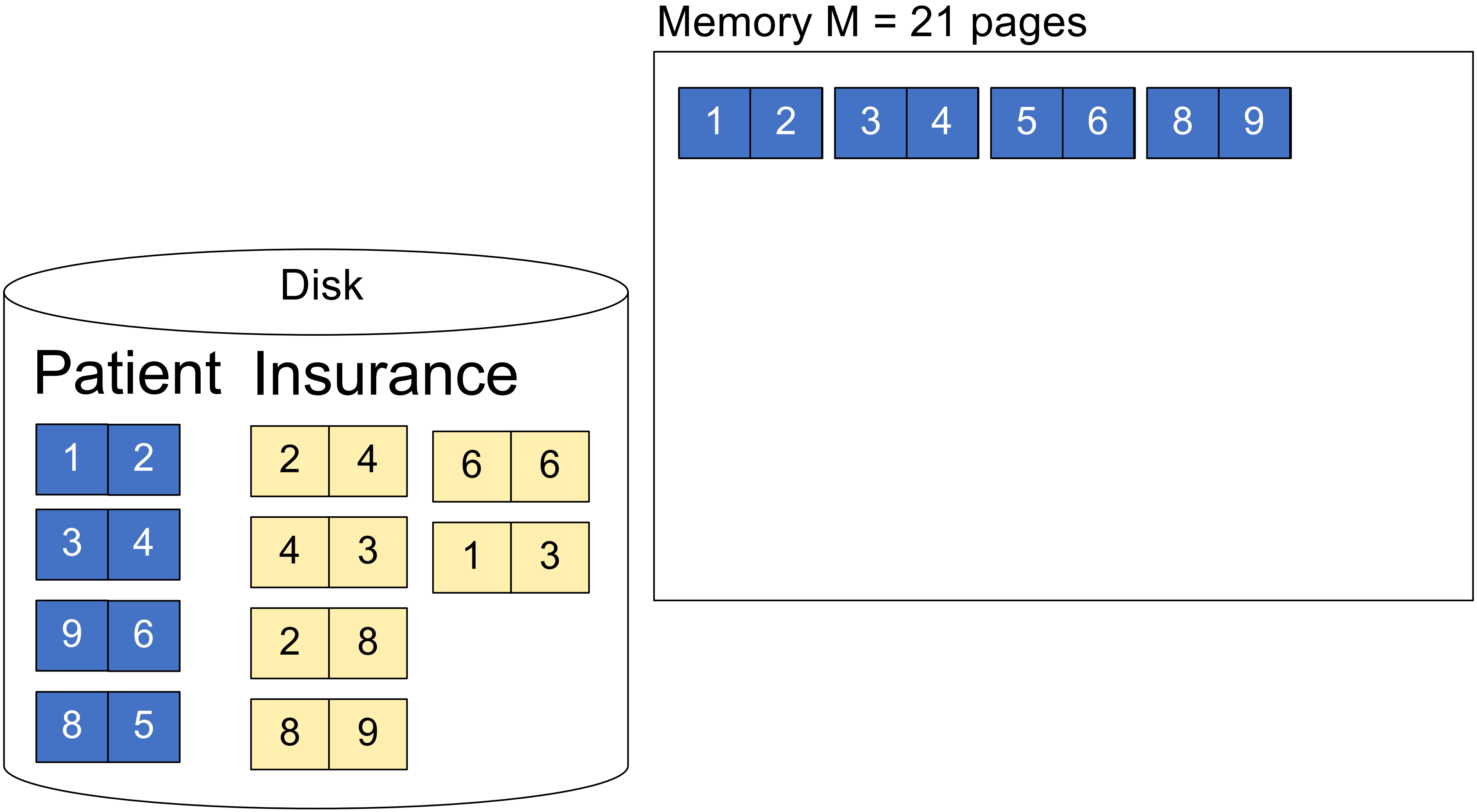
Sort-merge join: R ⋈ S

- 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

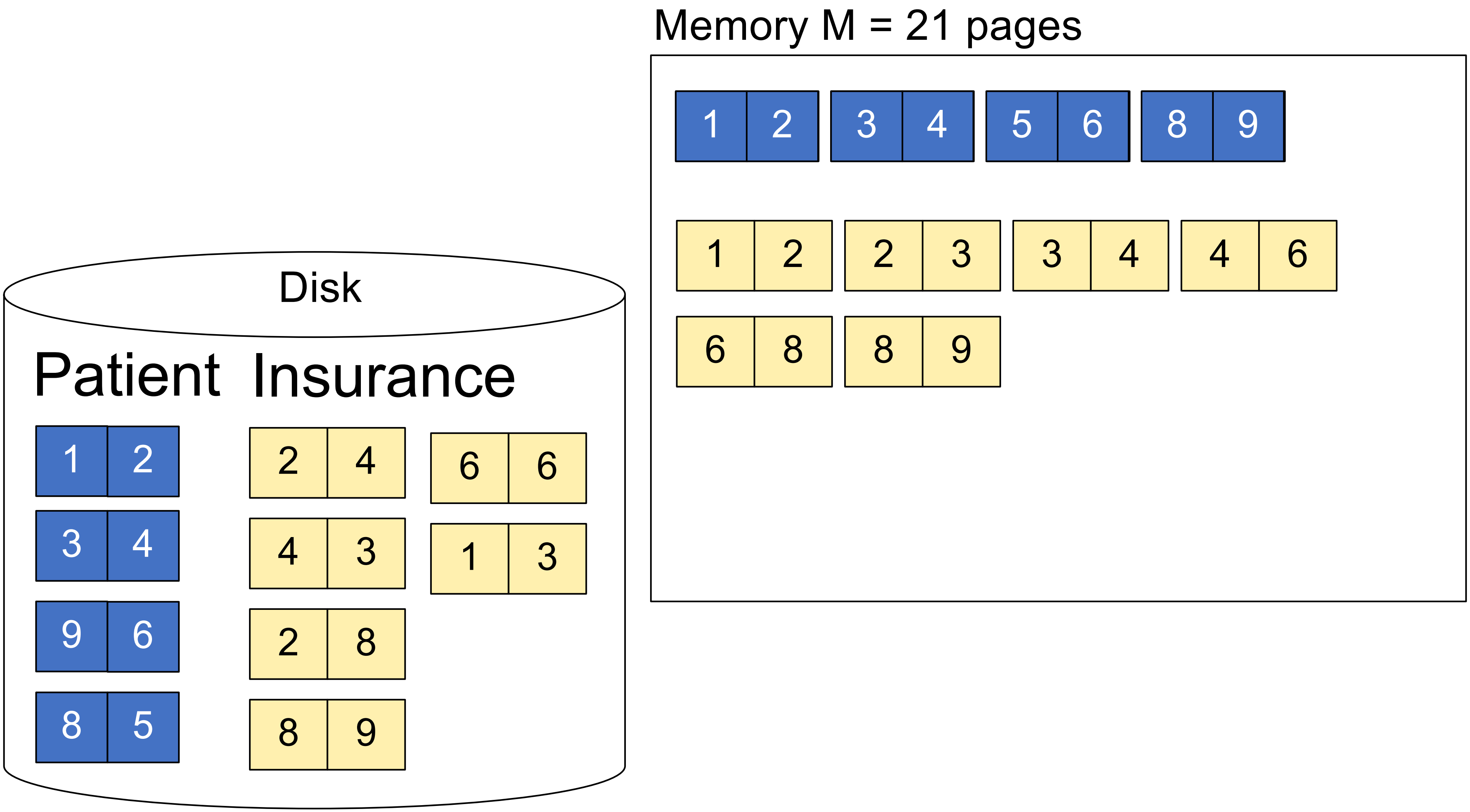
Sort-Merge Join Example

Step 1: Scan Patient and sort in memory



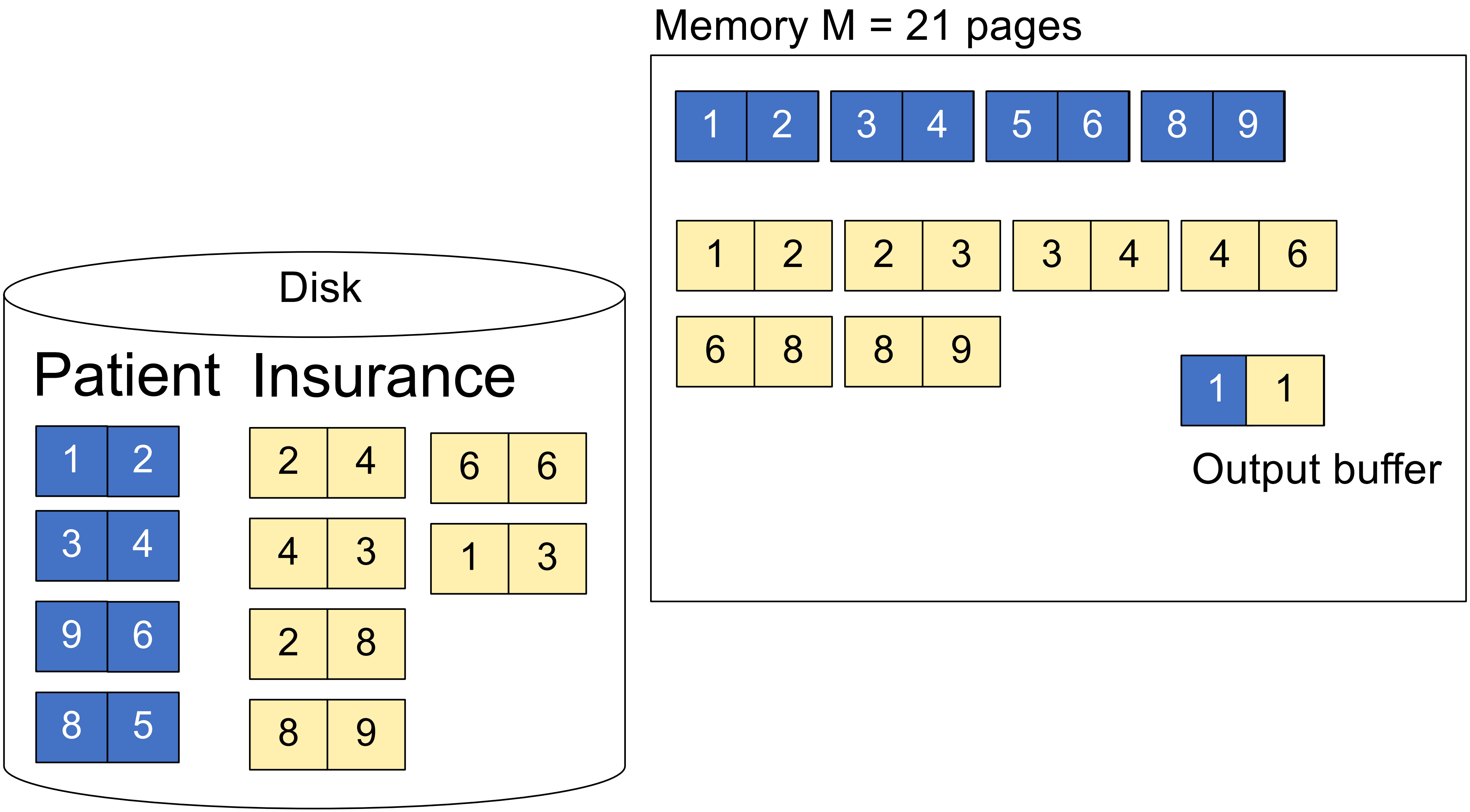
Sort-Merge Join Example

Step 2: Scan Insurance and sort in memory



Sort-Merge Join Example

Step 3: Merge Patient and Insurance



Memory M = 21 pages

Output buffer

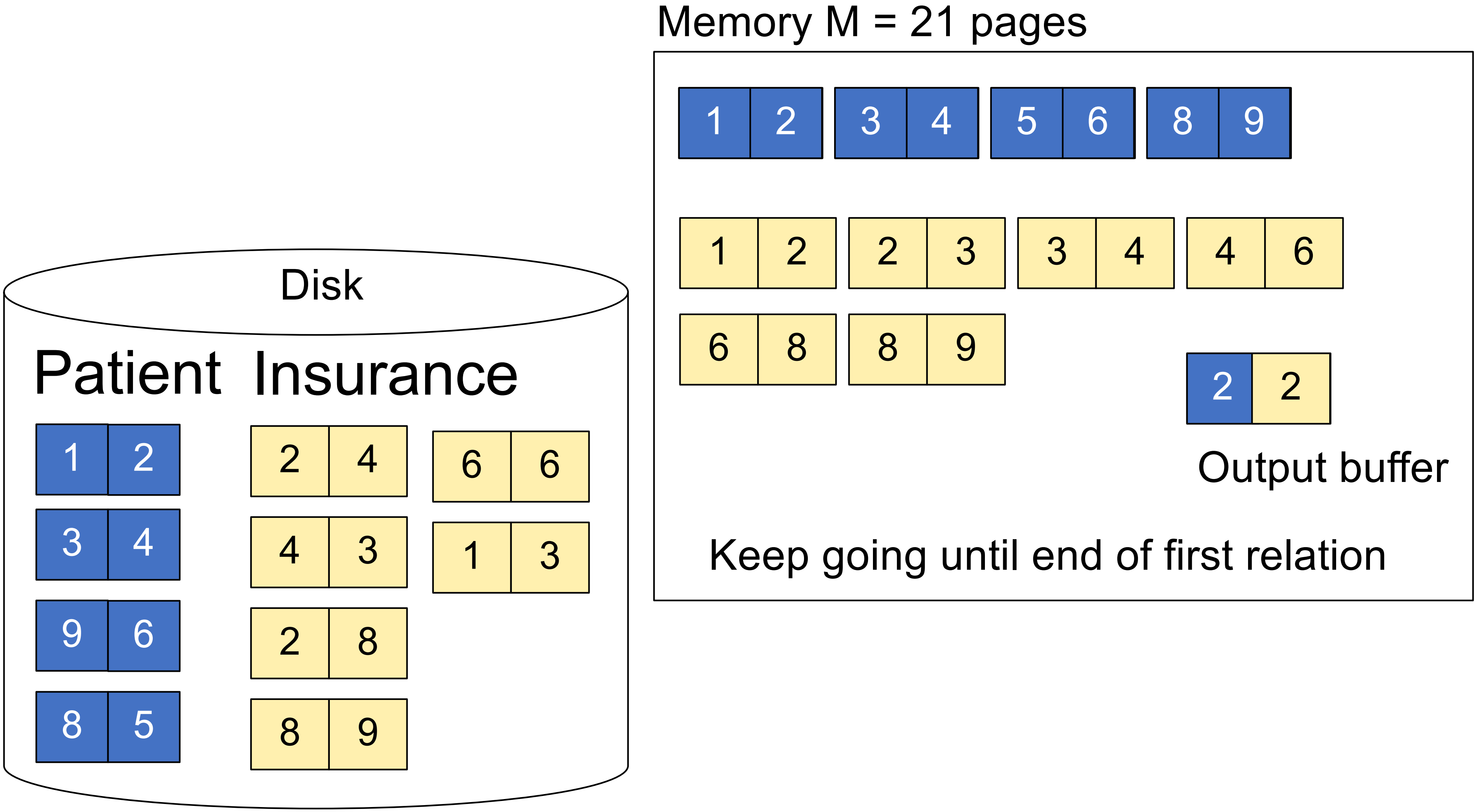
Disk

Patient

Insurance

Sort-Merge Join Example

Step 3: Merge Patient and Insurance



Keep going until end of first relation

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

Index Based Selection

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What is the cost in each case?

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

Index Based Selection

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

What is the cost in each case?

- Clustered index on a: B(R)/V(R,a)
- Unclustered index on a: T(R)/V(R,a)

Index Based Selection

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What is the cost in each case?

- Clustered index on a: B(R)/V(R,a)
- Unclustered index on a: T(R)/V(R,a)

Note: we ignore I/O cost for index pages

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

- Example:

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

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

- Table scan: B(R) = 2,000 I/Os
- Index based selection:

Index Based Selection

- Example:

B(R) = 2000
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cost of $\sigma_{a=v}(R) = ?$

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  - If index is clustered:
  - If index is unclustered:

Index Based Selection

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Index Based Selection

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

Index Based Selection

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

Index Nested Loop Join

$R \bowtie S$

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

- Cost:
  - If index on S is clustered: $B(R) + T(R)B(S)/V(S,a)$
  - If index on S is unclustered: $B(R) + T(R)T(S)/V(S,a)$