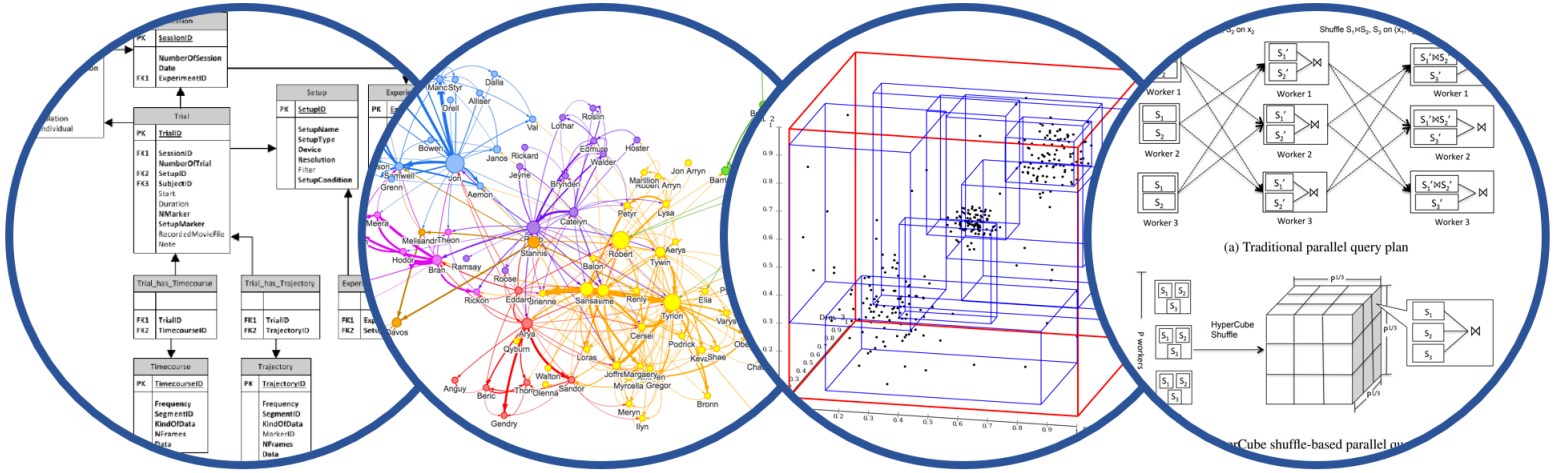

Database System Internals

Query Execution and Algorithms

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University of Washington, Seattle

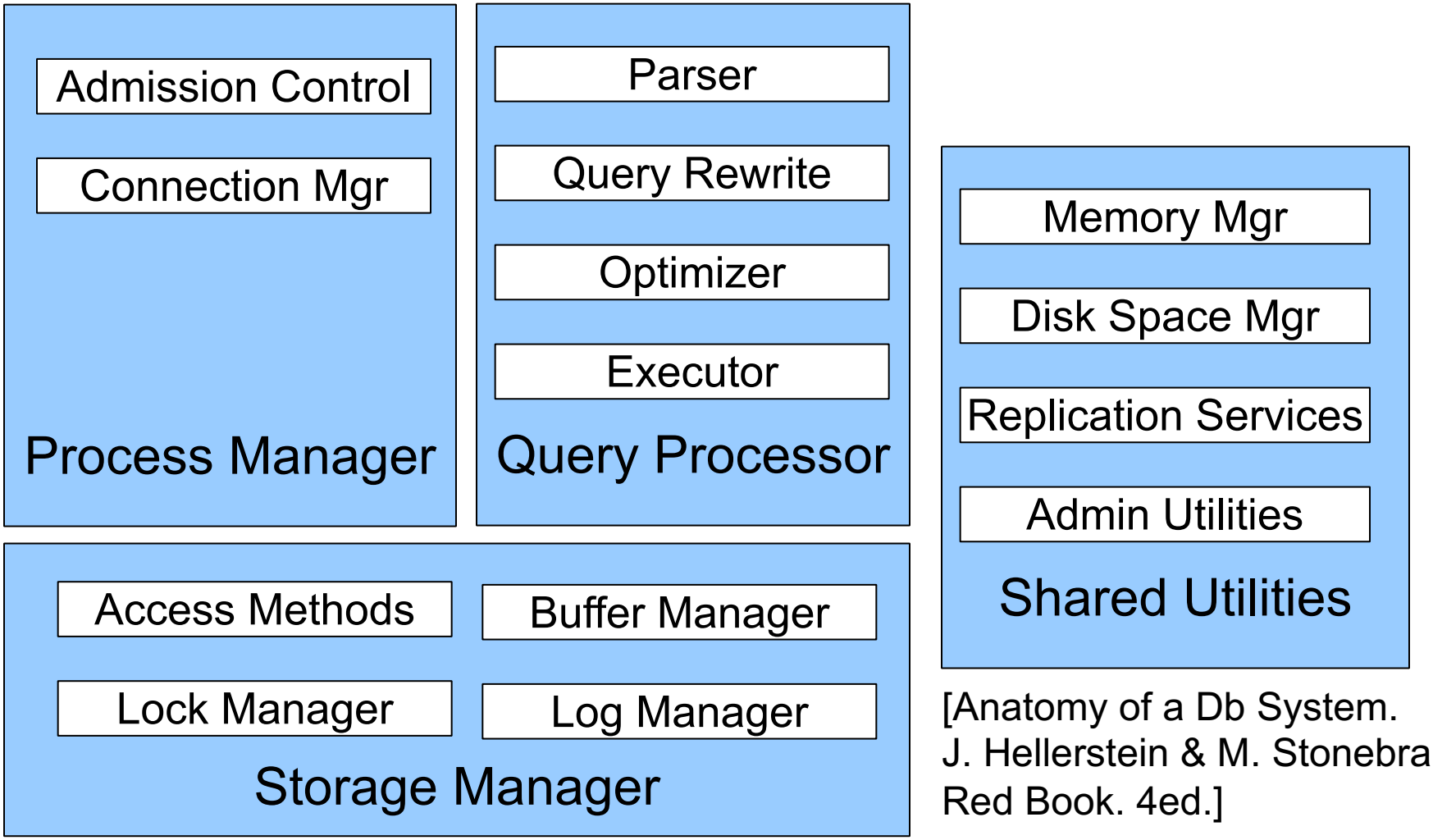
Announcements

- Lab1 due on Wednesday
- 544 paper 1 report due Friday
- HW2 will be released soon, due Monday, 4/27

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.]

Next Lectures

How to answer queries efficiently

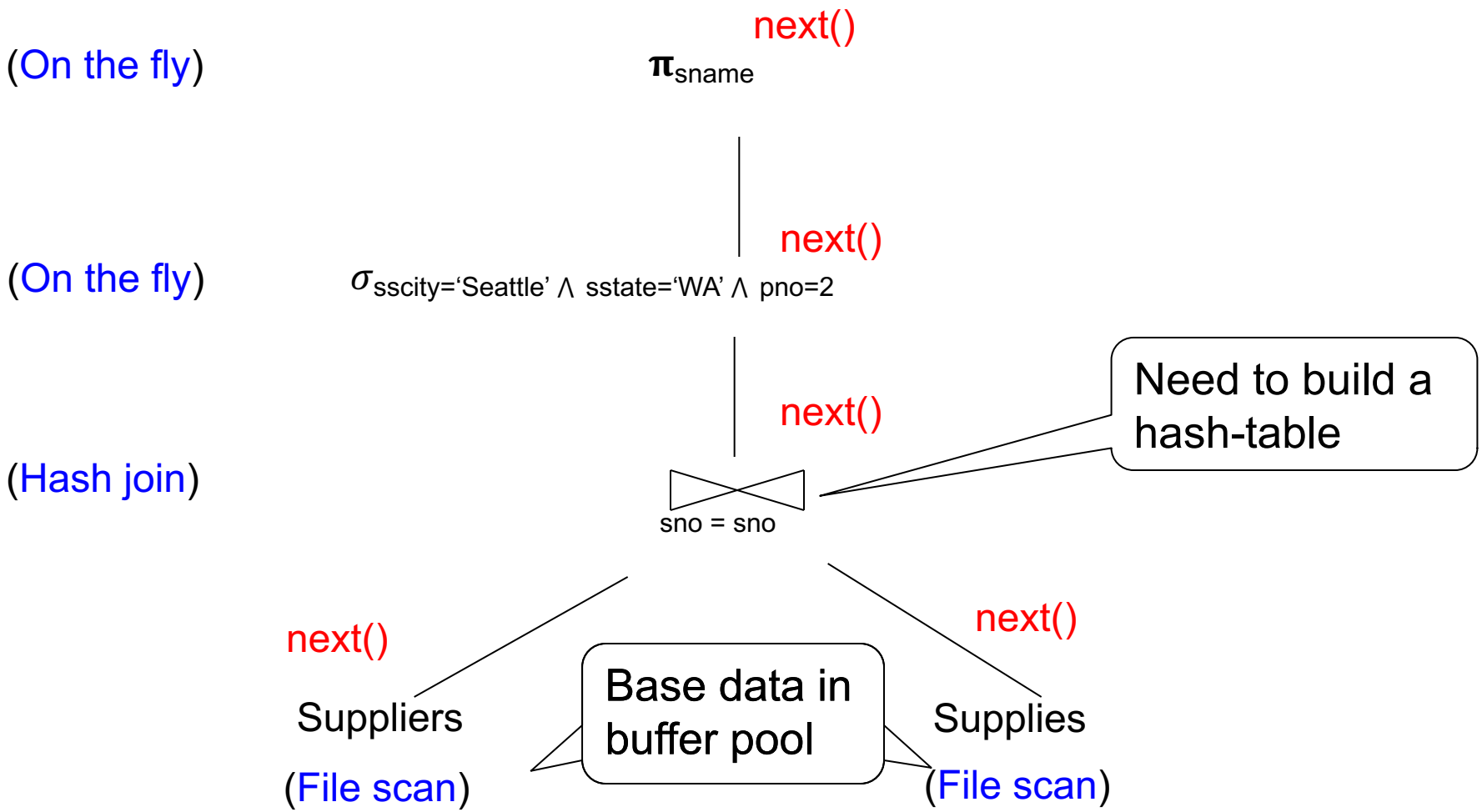
- Query optimization: find a good plan
- Query execution: execute the plan

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
- Execution of the physical plan is pull-based
- Operators given a limited amount of memory

Pipelined Query Execution



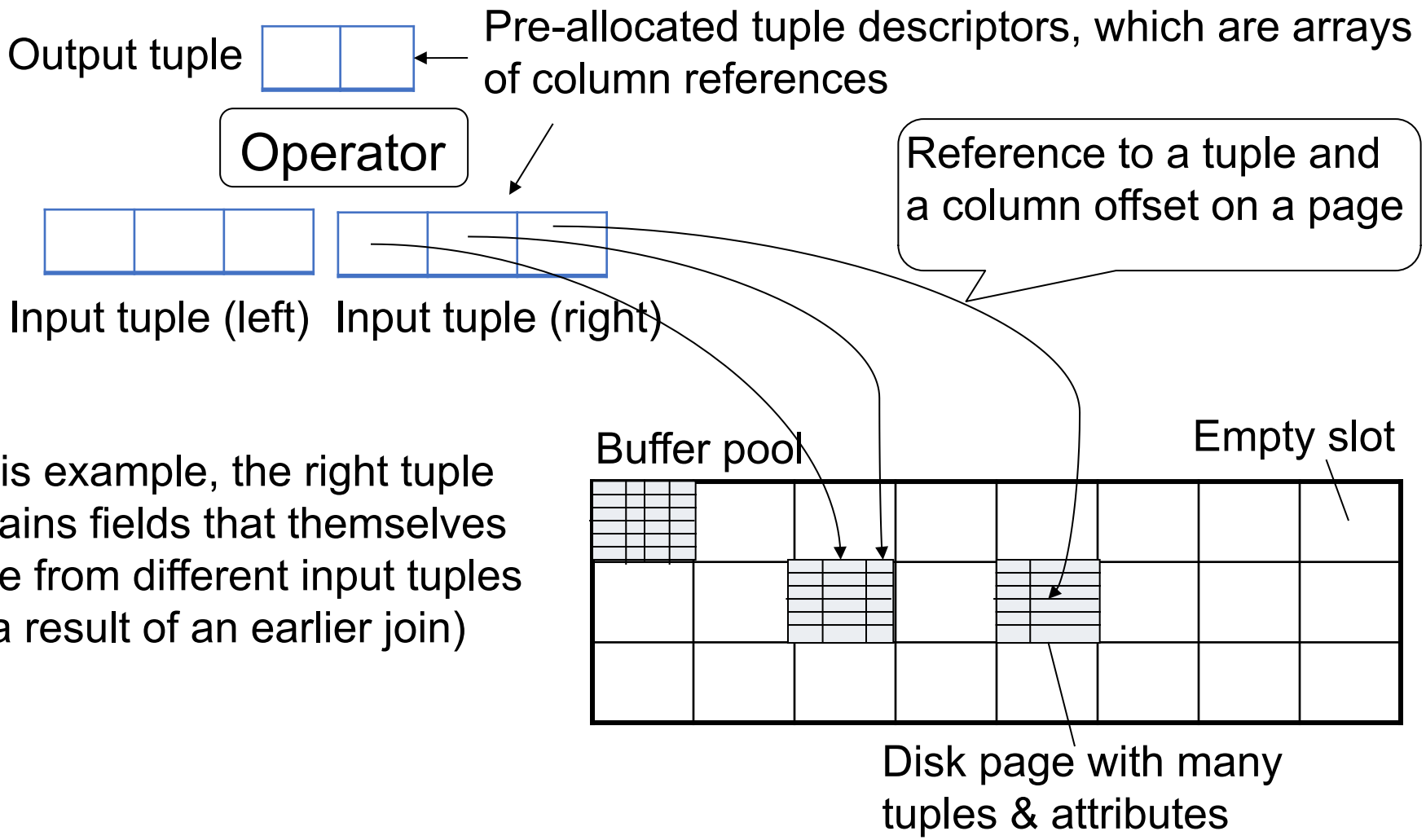
Memory Management

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
  - Either on heap or in buffer pool (depends on system)

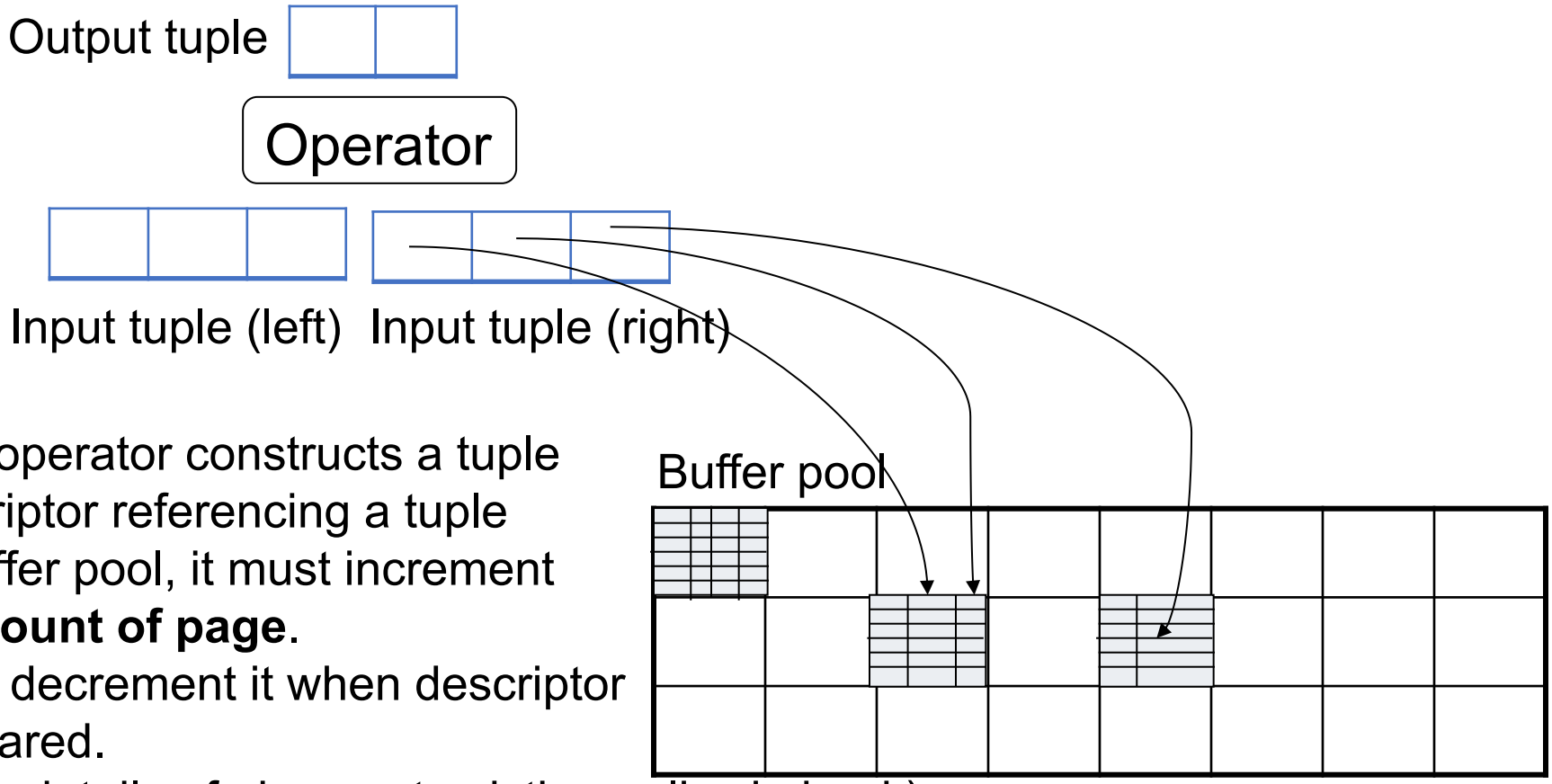
DMBS **limits** how much memory each operator, or each query can use

BP-tuples (option 1)



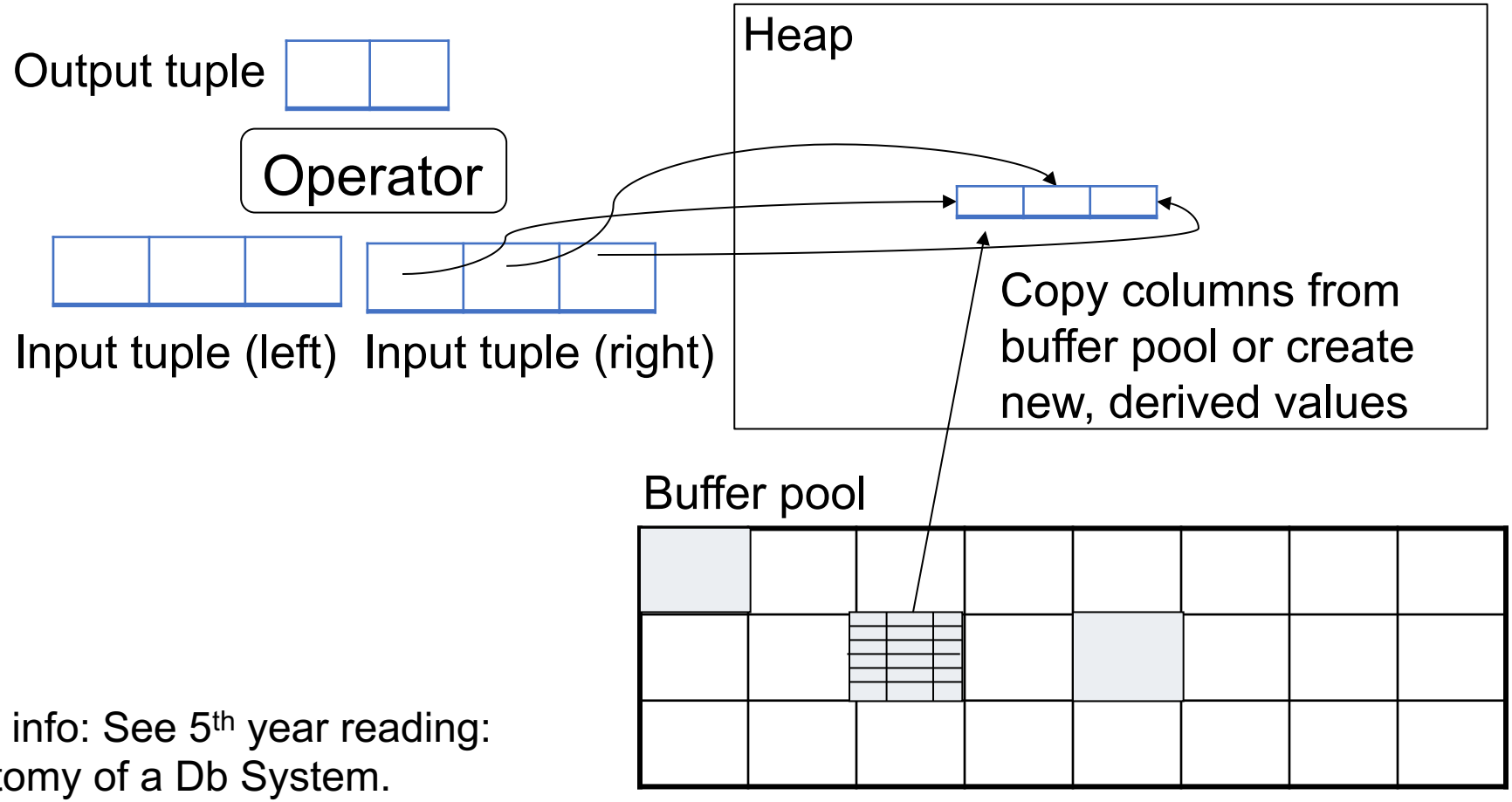
In this example, the right tuple contains fields that themselves come from different input tuples (as a result of an earlier join)

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 …

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: $R \bowtie S$

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

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

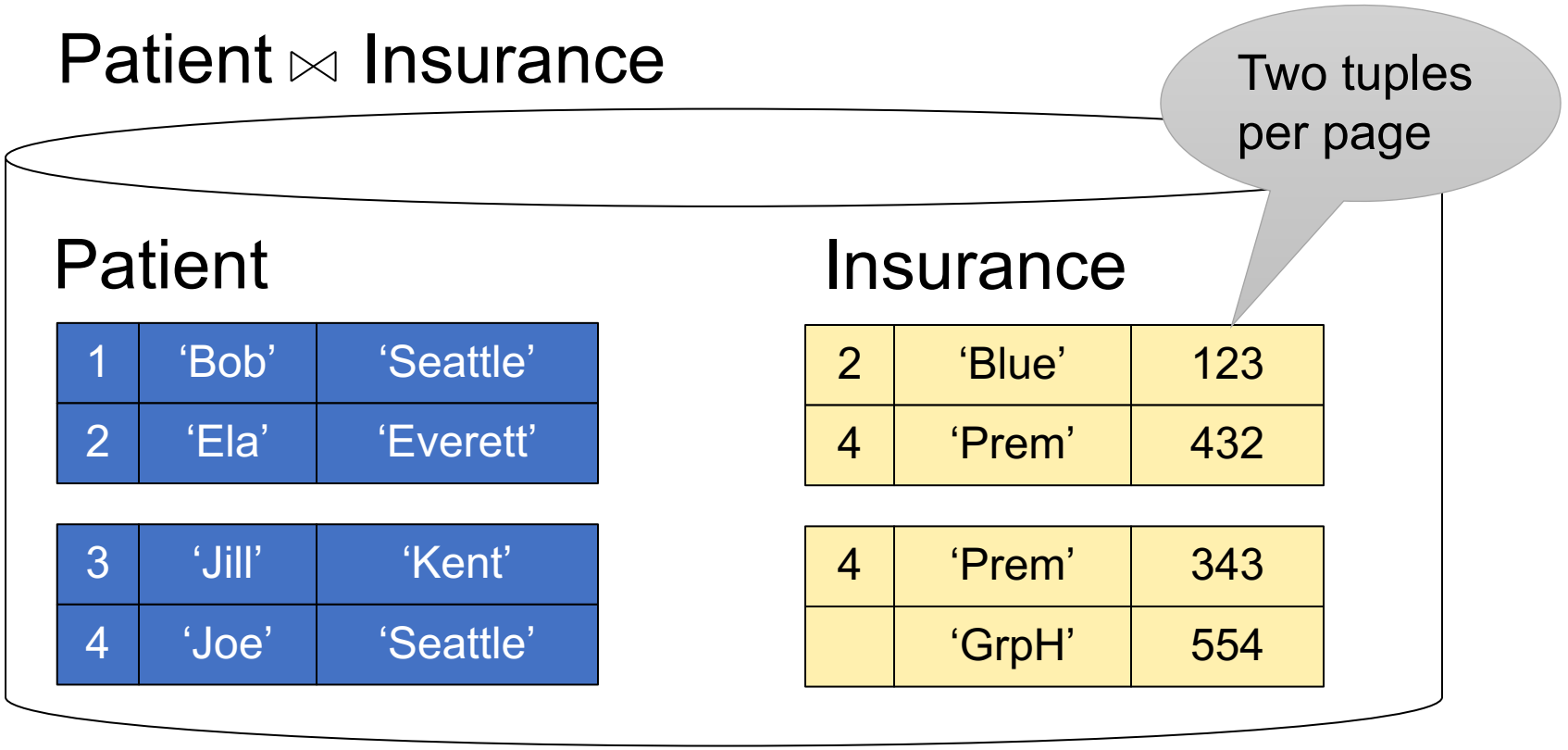
Note: the *inner* relation is the relation on which we build the hash table
- Usually this is the *right* relation, i.e. S.
- But the following slides choose the *left* relation, i.e. R

Hash Join Example

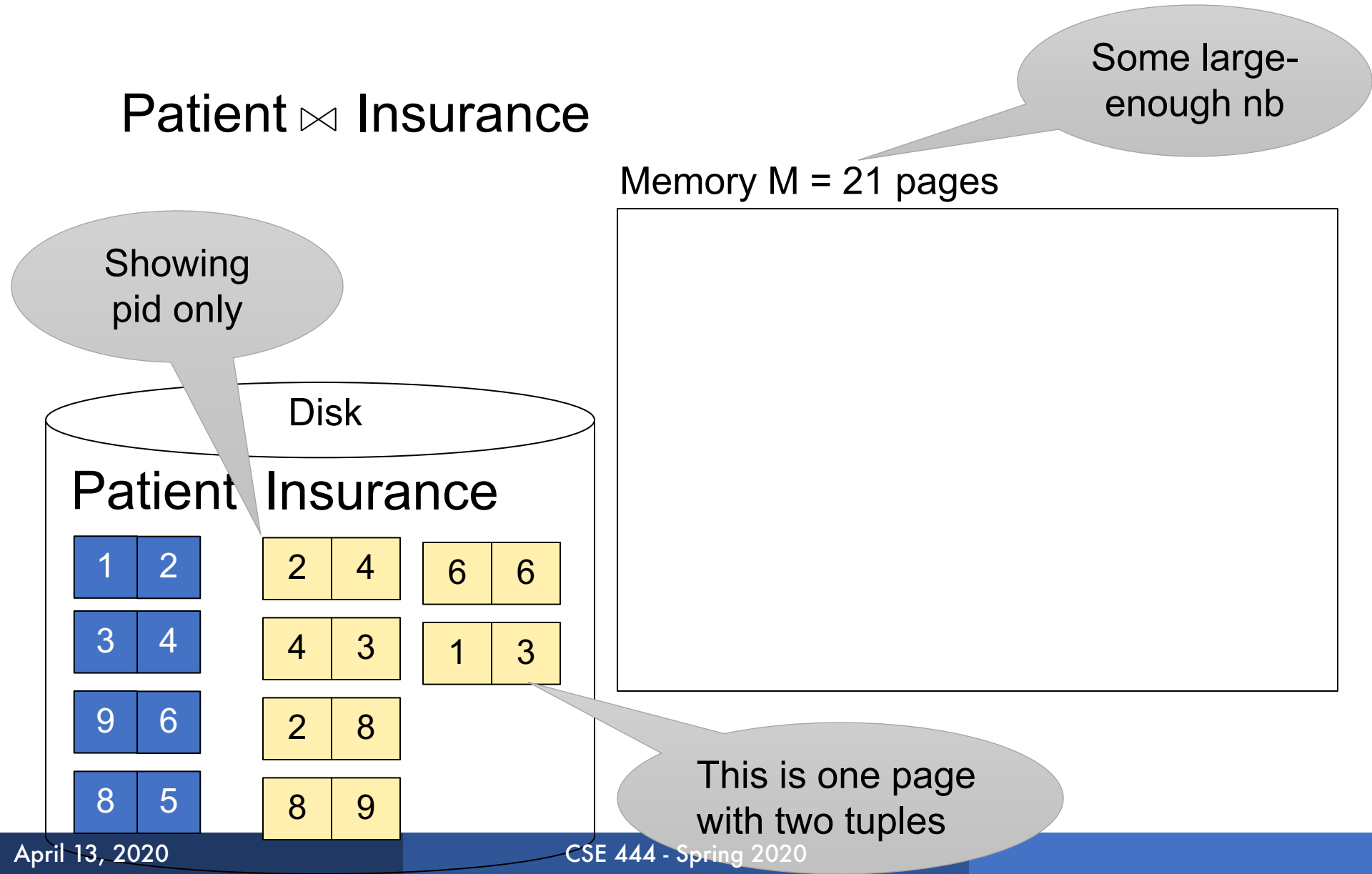
Patient(pid, name, address)

Insurance(pid, provider, policy_nb)

Patient ⋈ Insurance



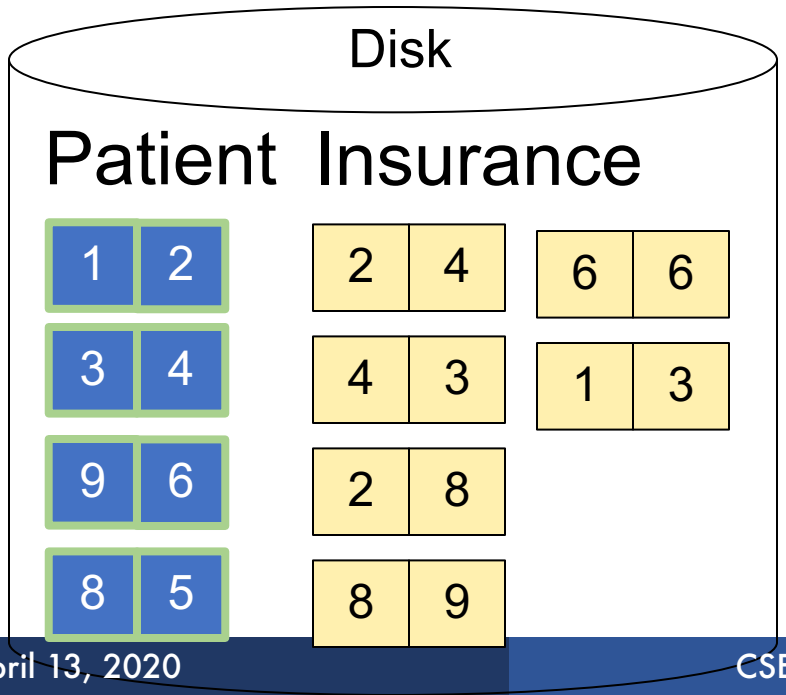
Hash Join Example

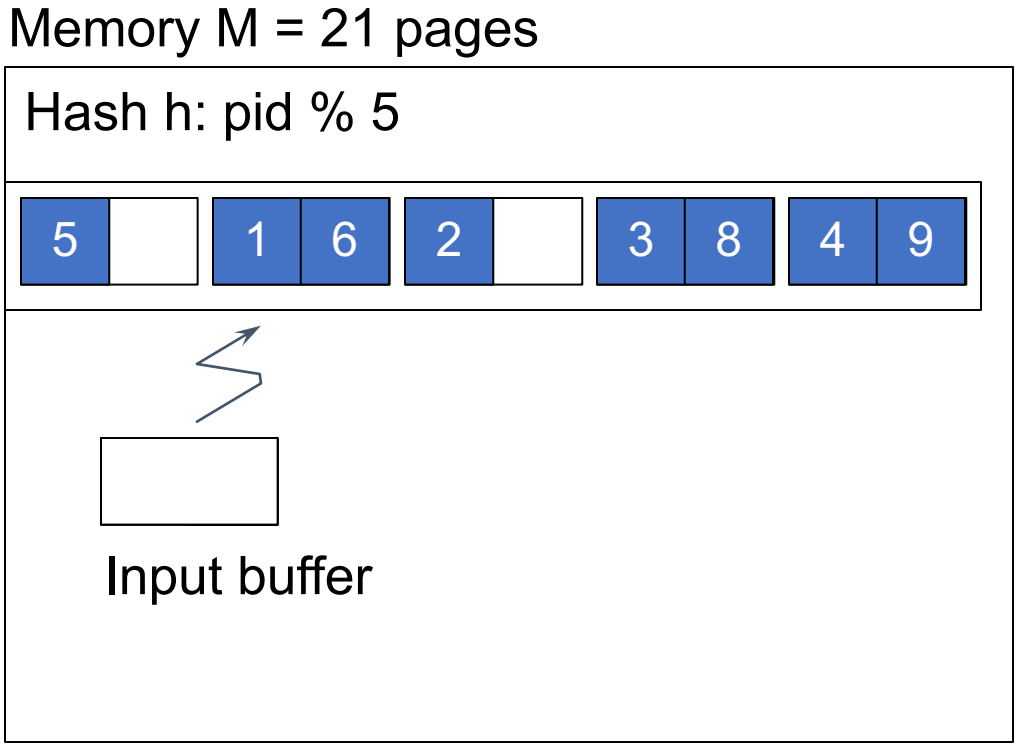


Hash Join Example

Step 1: Scan Patient and build hash table in memory

Can be done in method open()

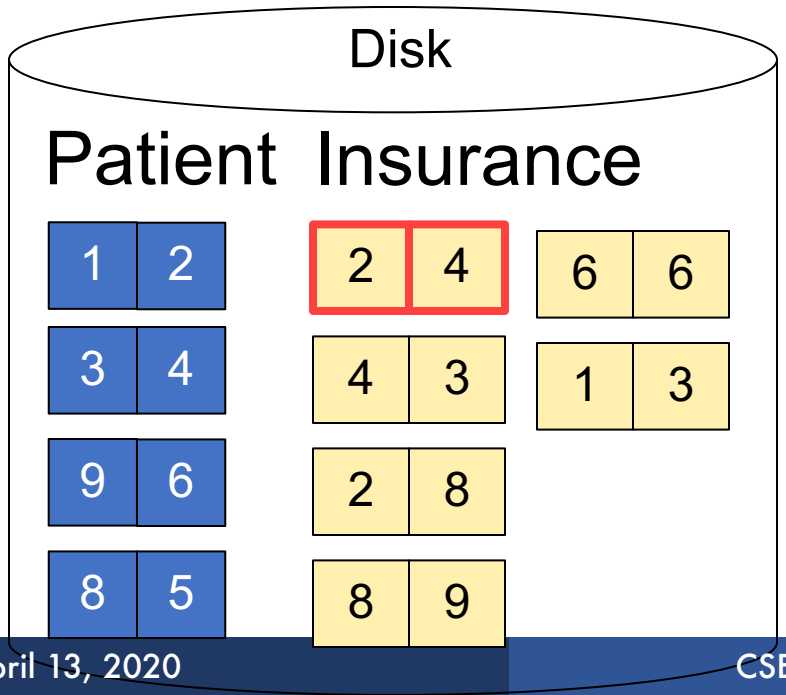


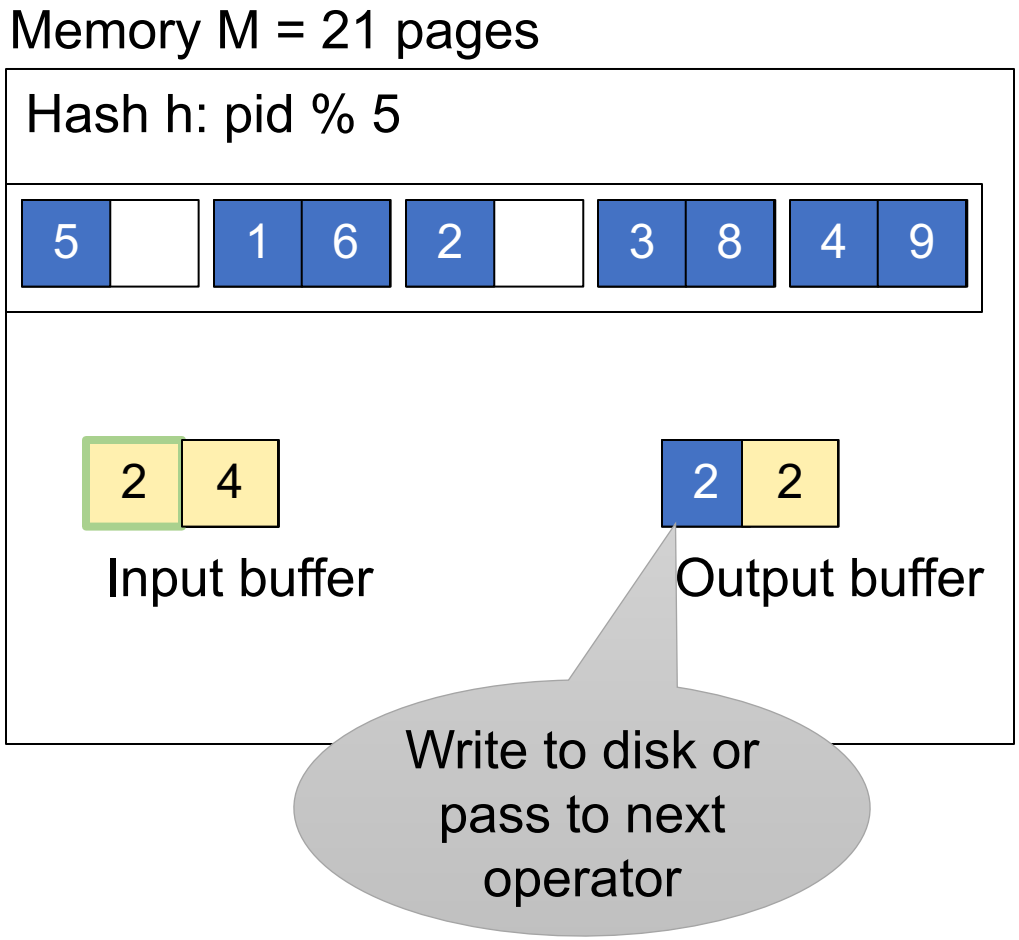


Hash Join Example

Step 2: Scan Insurance and probe into hash table

Done during calls to next()





Hash Join Example

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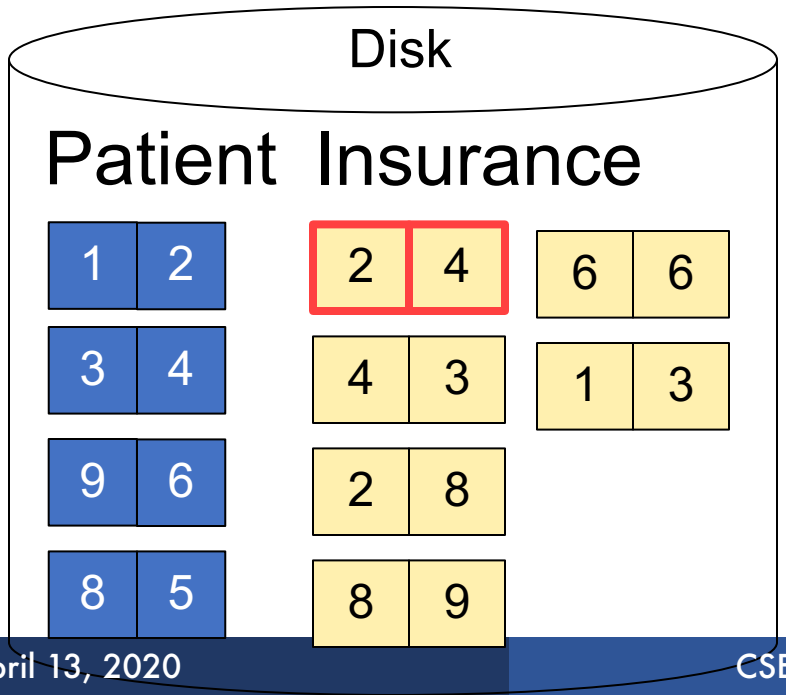

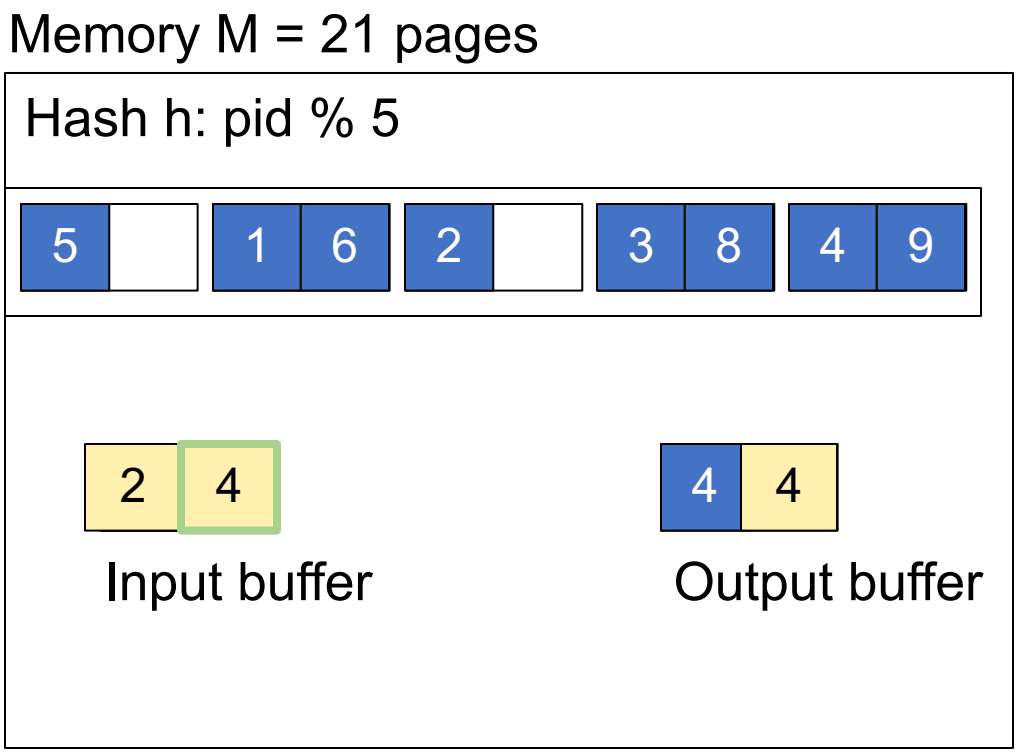

Hash Join Example

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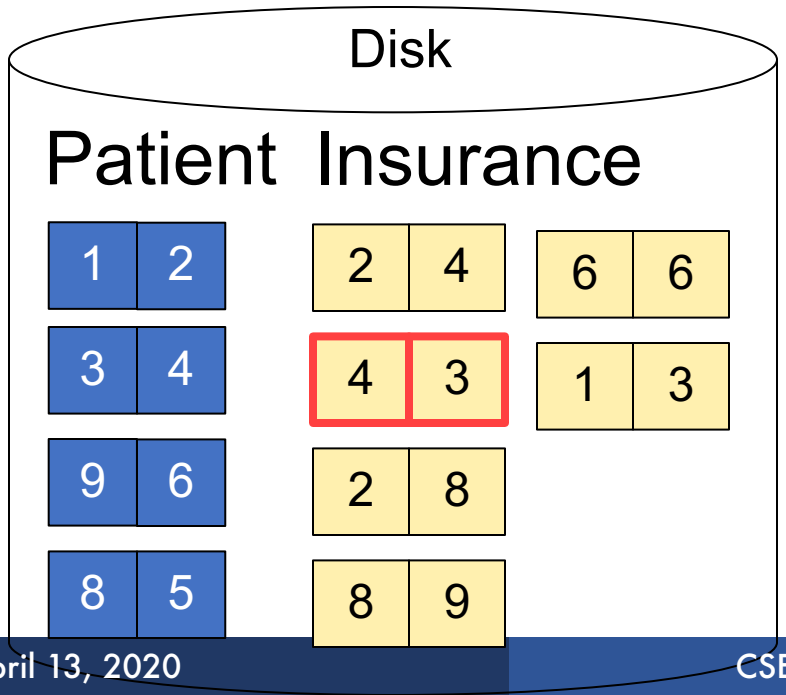
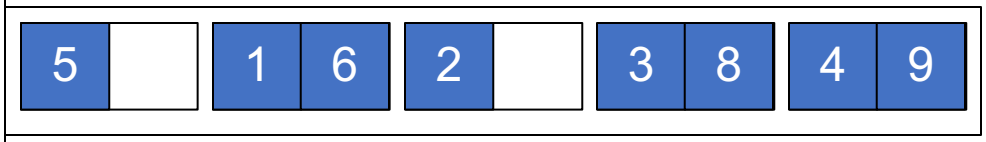
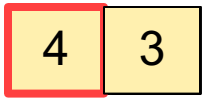


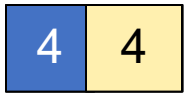
Memory M = 21 pages

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 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 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

- 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?

- 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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for each page of tuples r in R do
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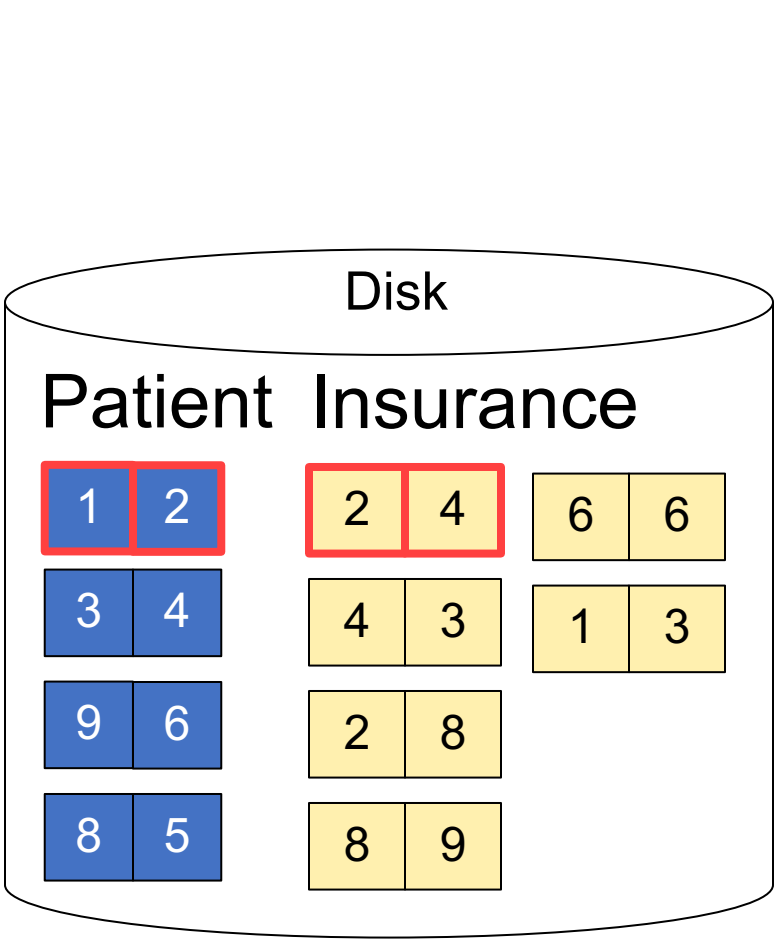
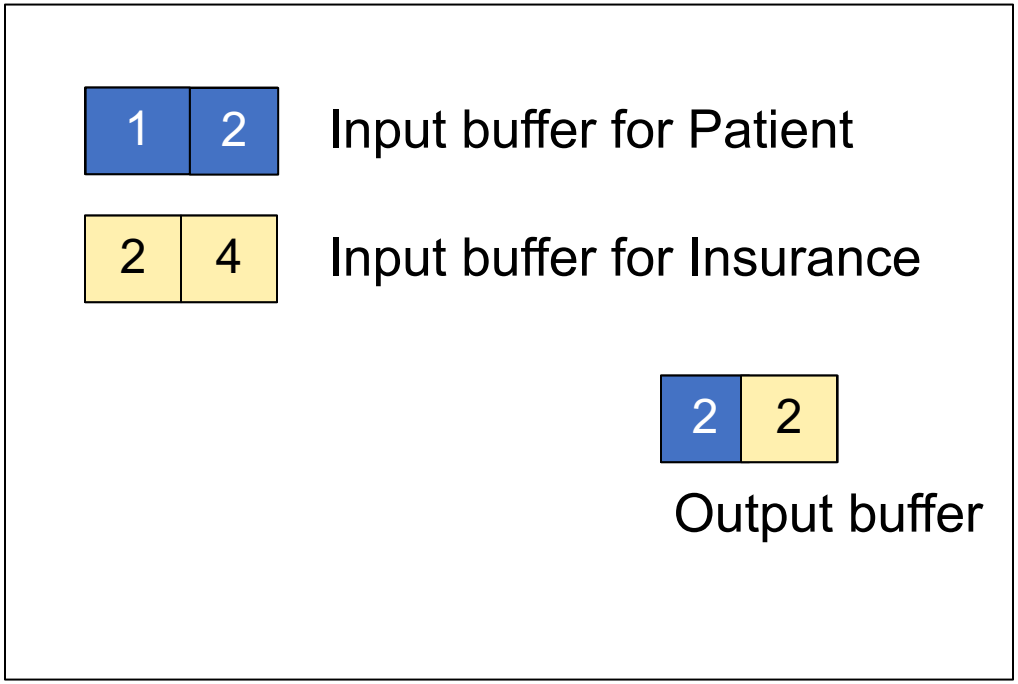
```

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

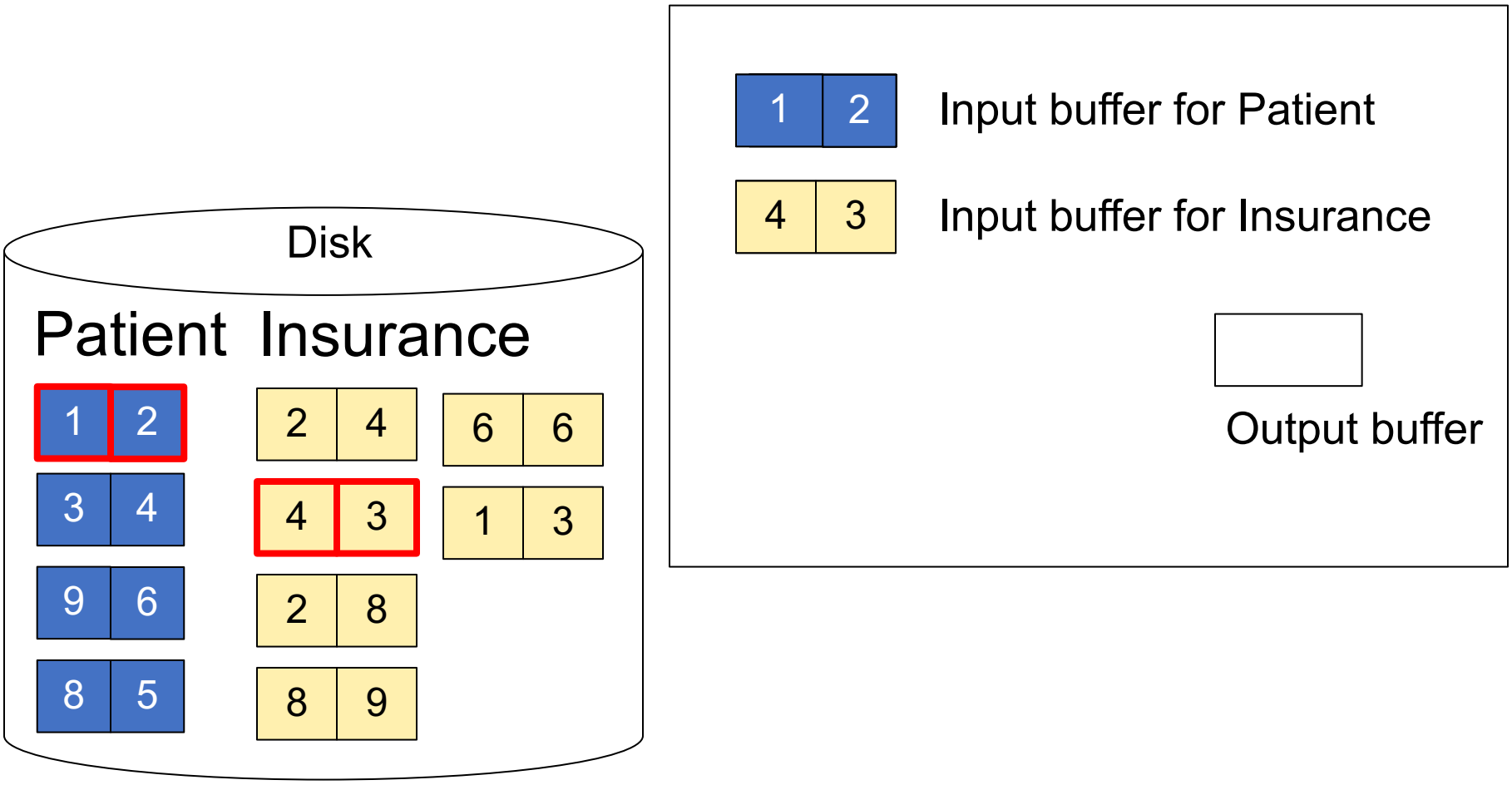
What is the Cost?

Page-at-a-time Refinement

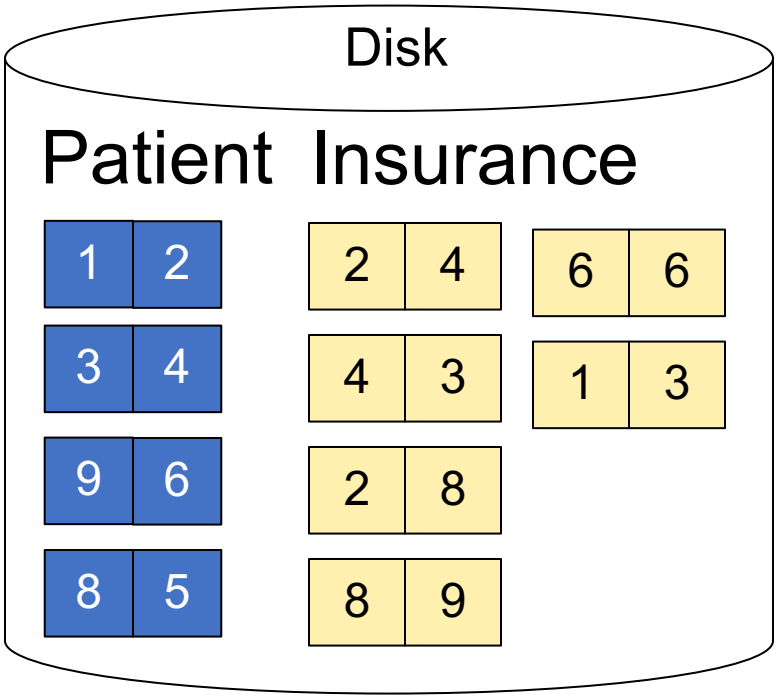


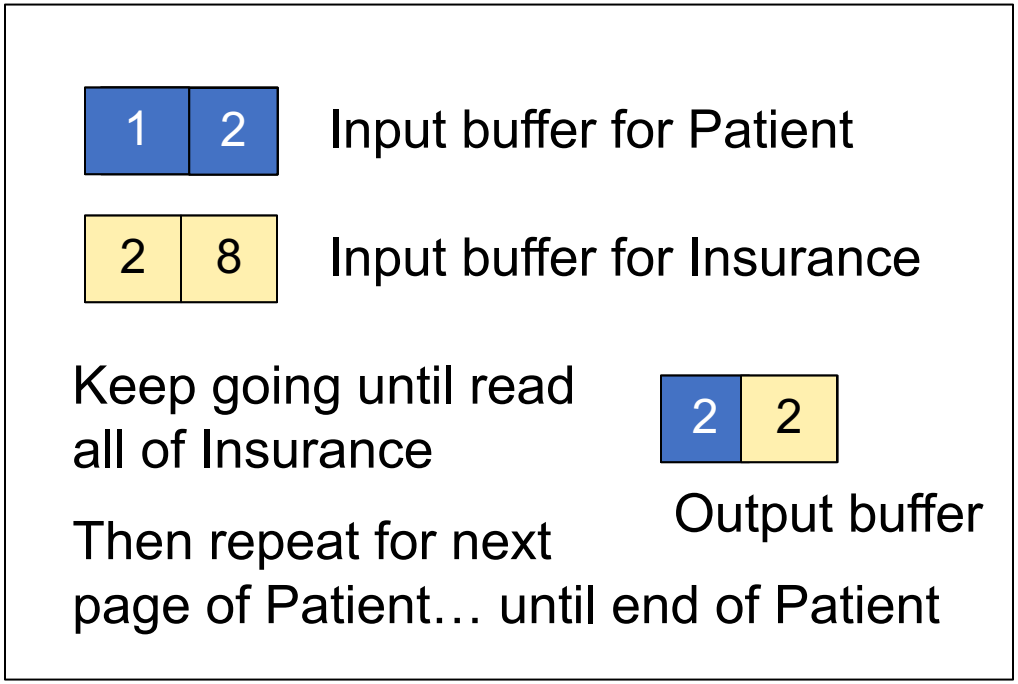


Page-at-a-time Refinement



Page-at-a-time Refinement





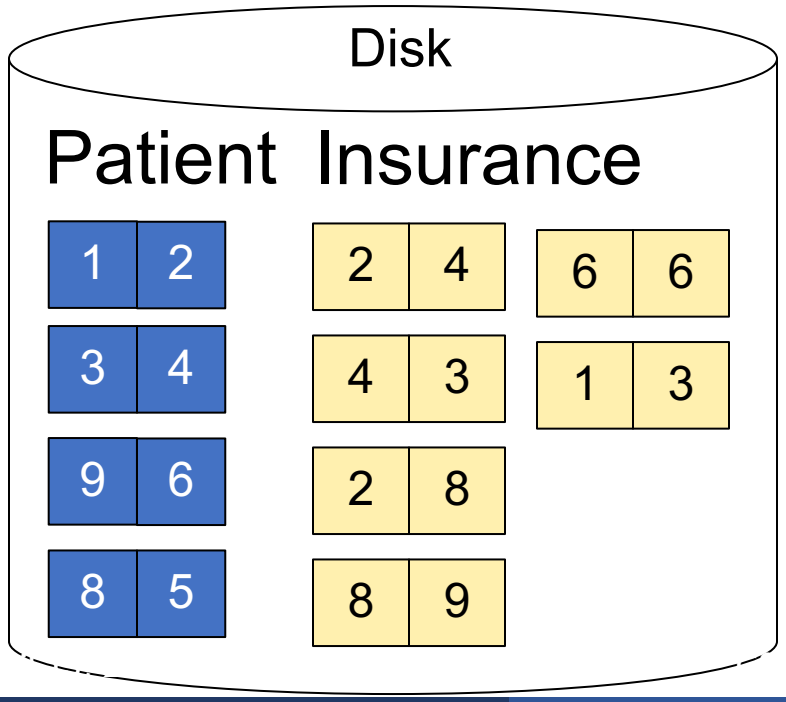
Cost: B(R) + B(R)B(S)

Block-Memory Refinement

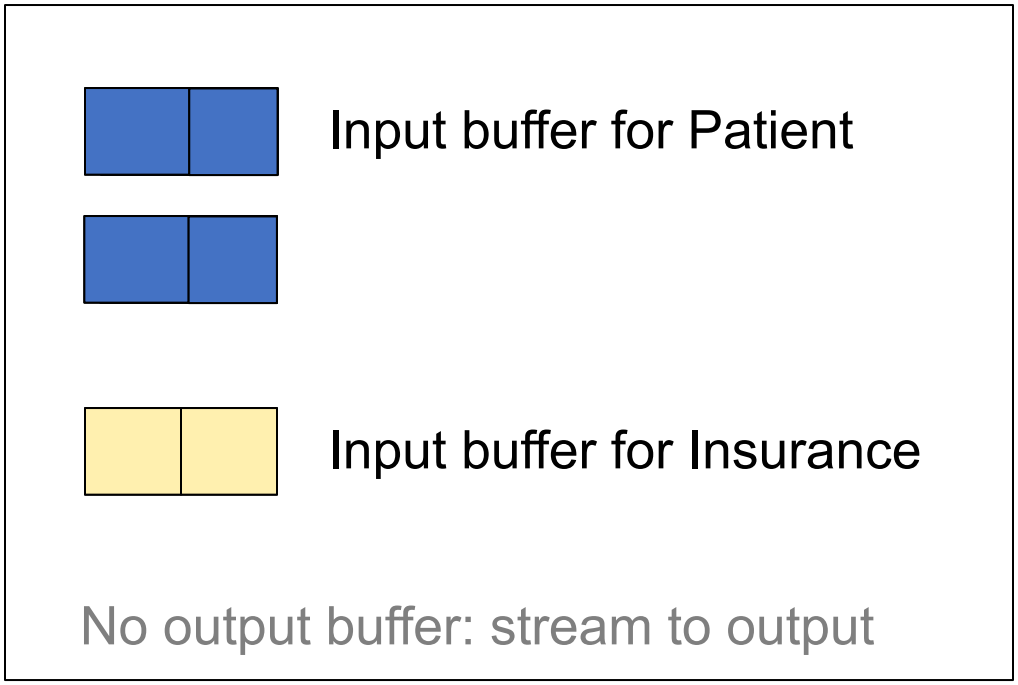
```
for each group of M-1 pages r in R do
    for each page of tuples s in S do
        for all pairs of tuples t1 in r, t2 in s
            if t1 and t2 join then output (t1,t2)
```

What is the Cost?

Block Memory Refinement



M= 3



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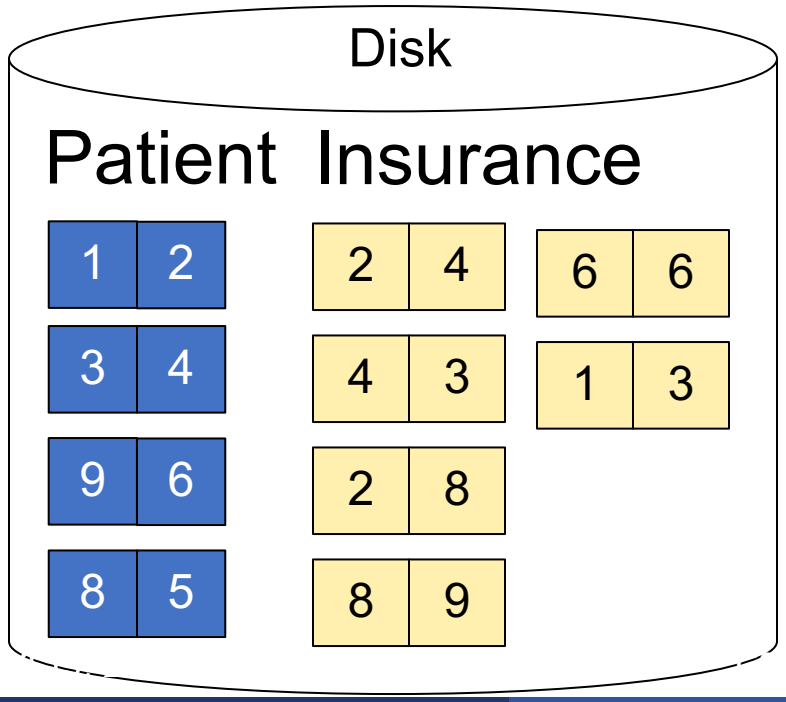

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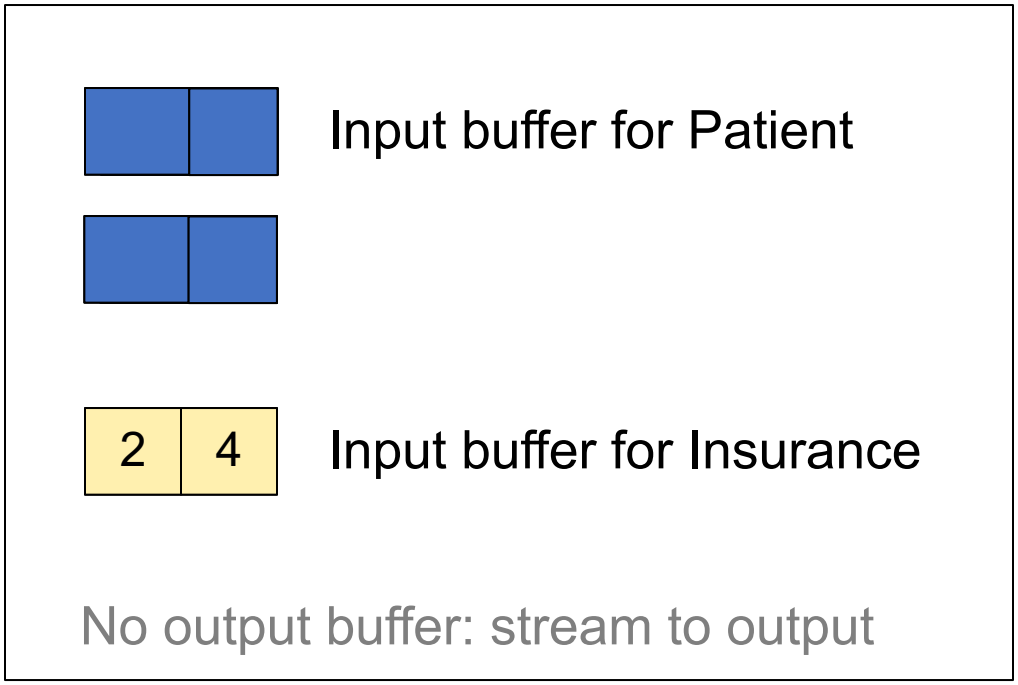

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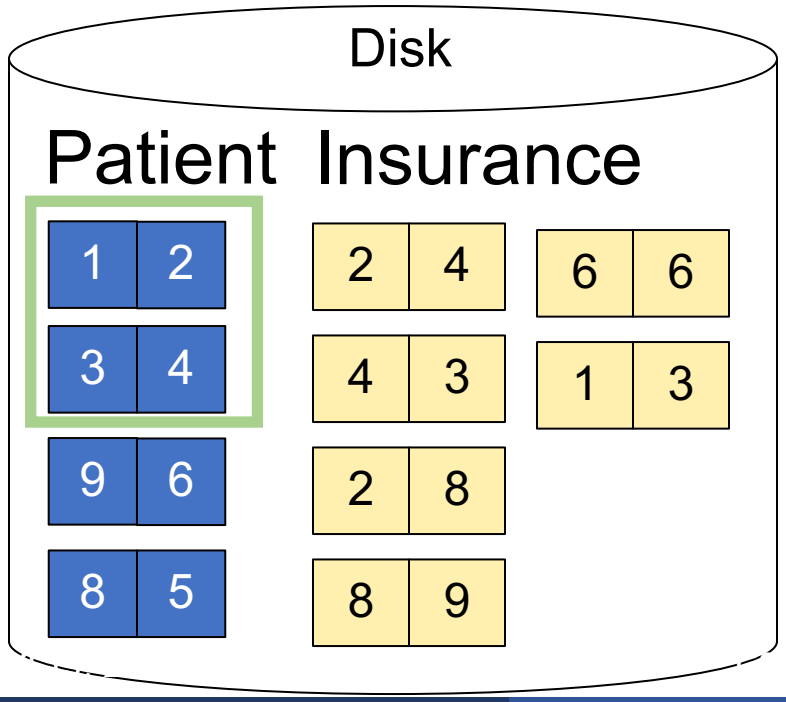

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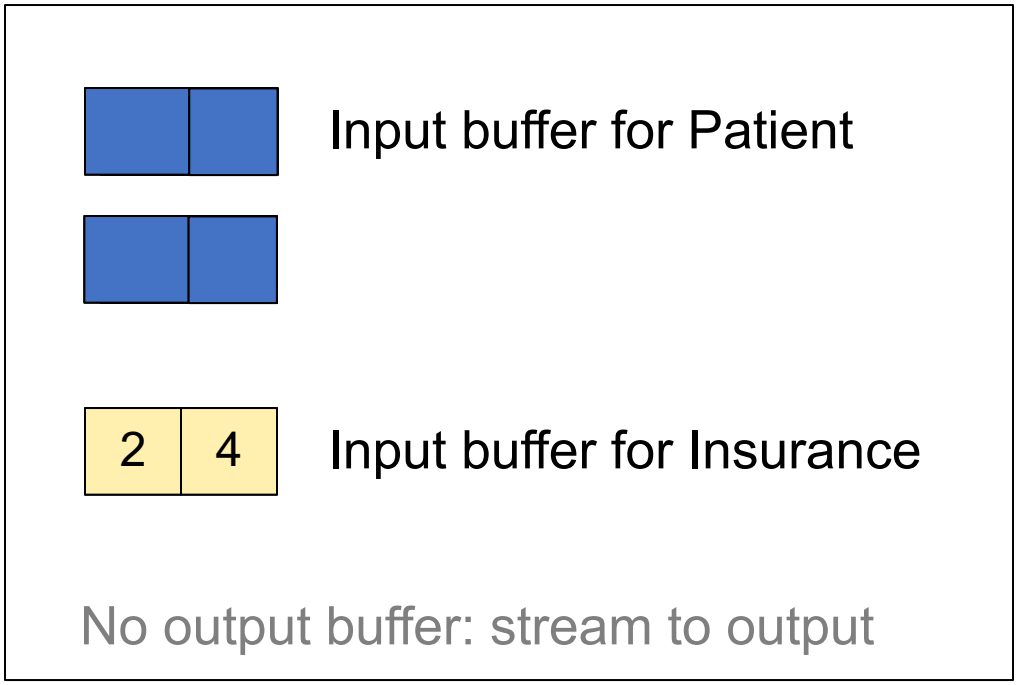

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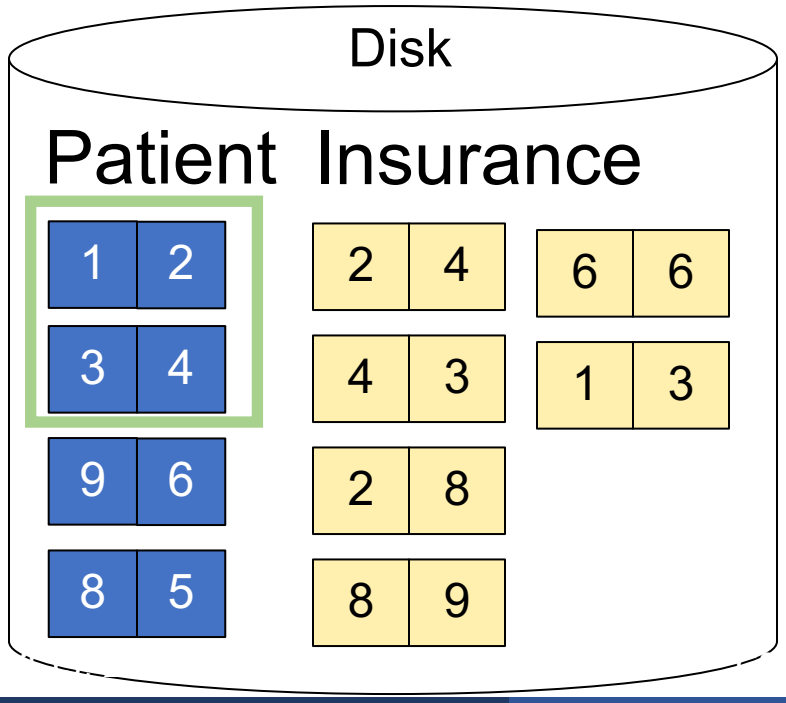

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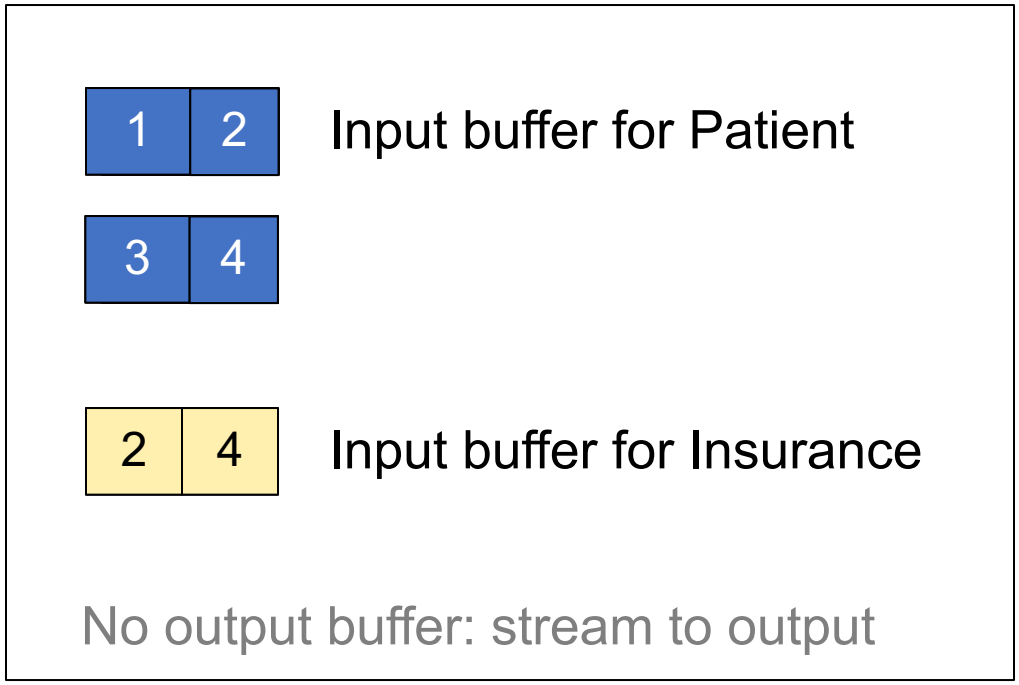

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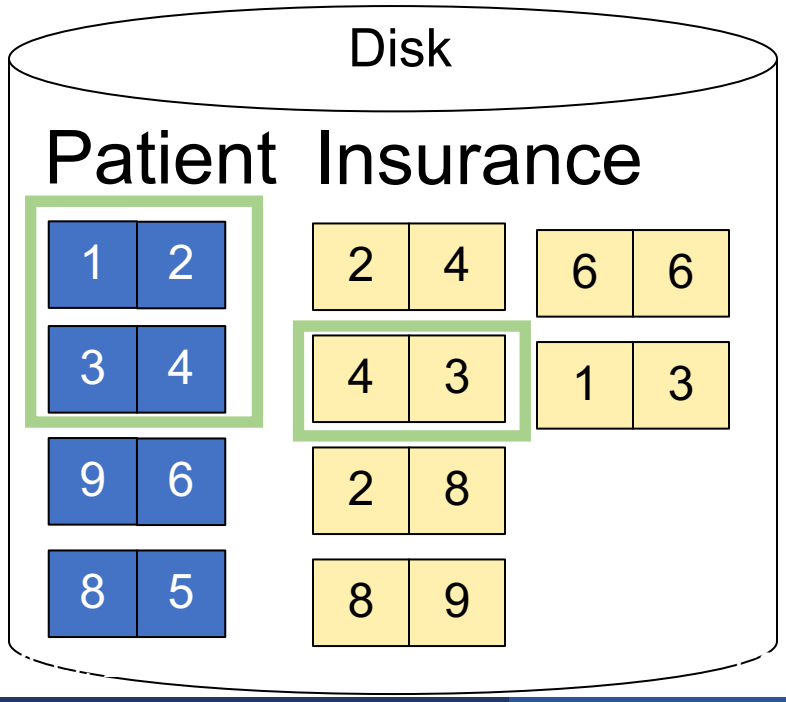

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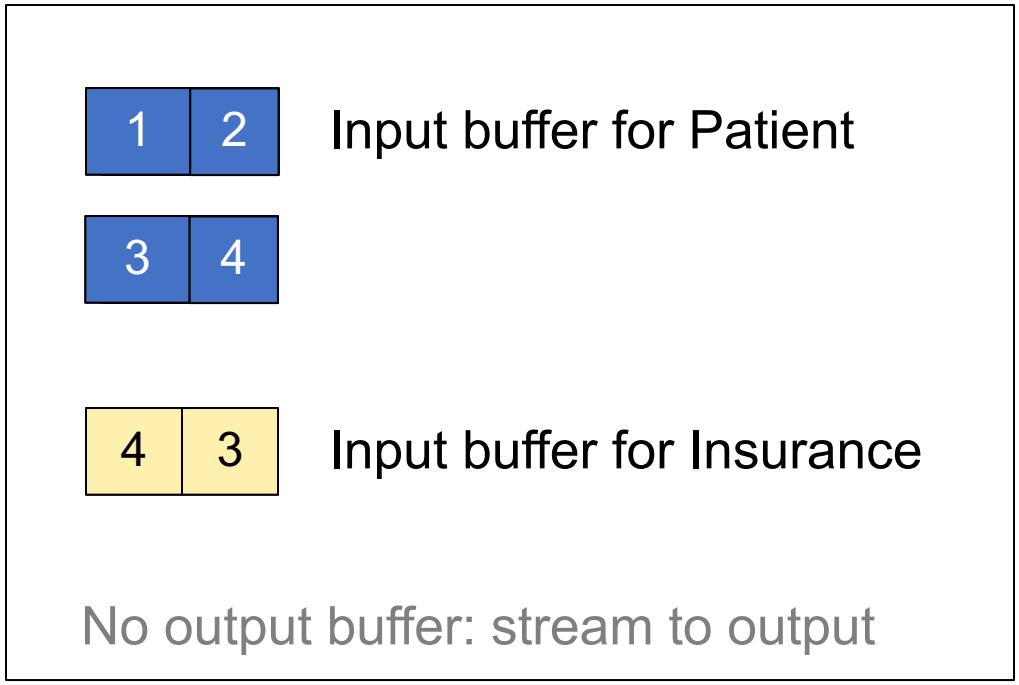

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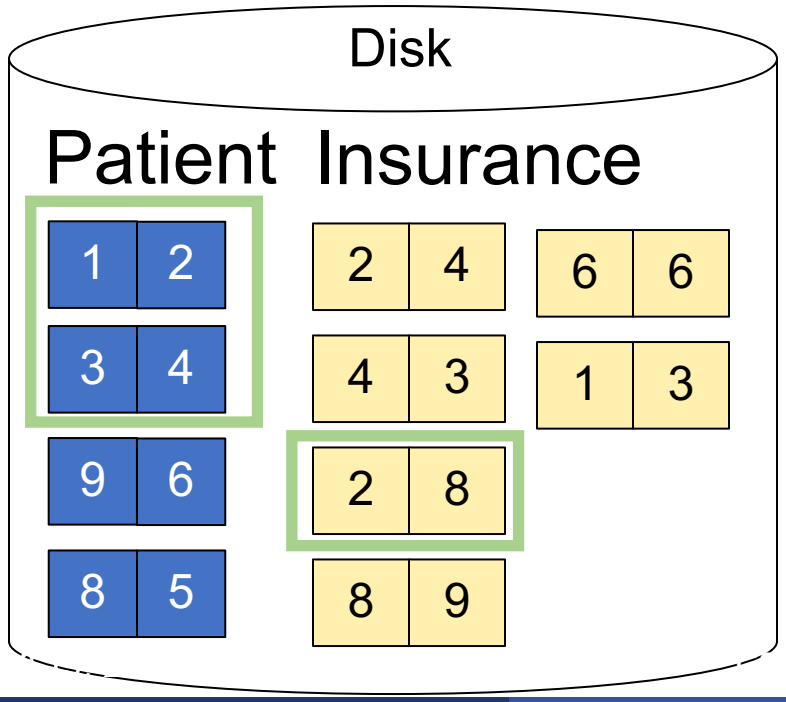

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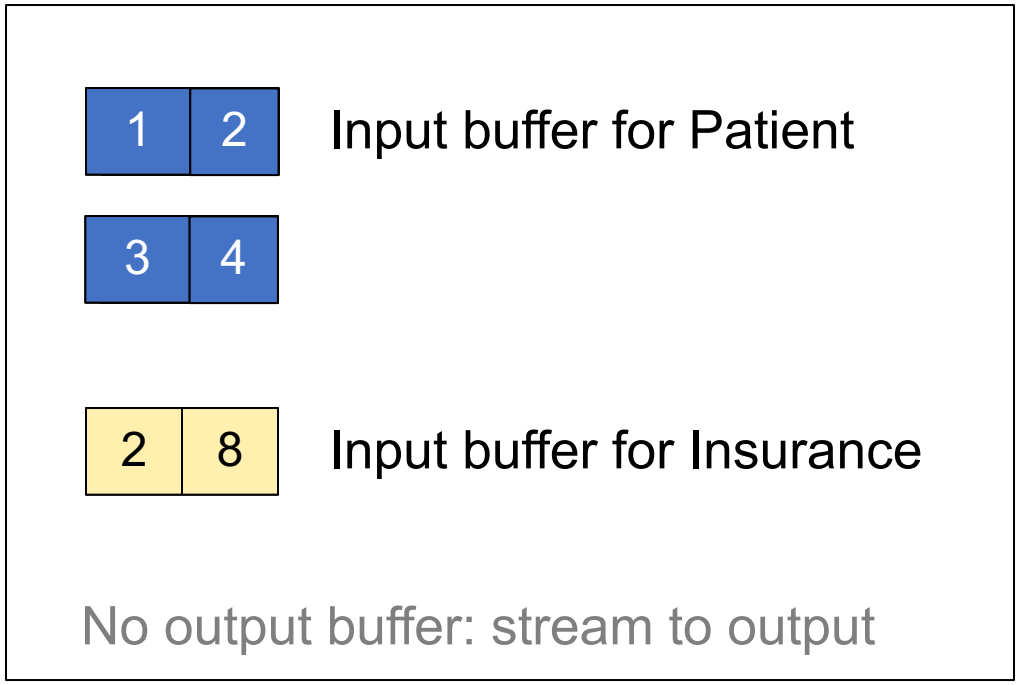

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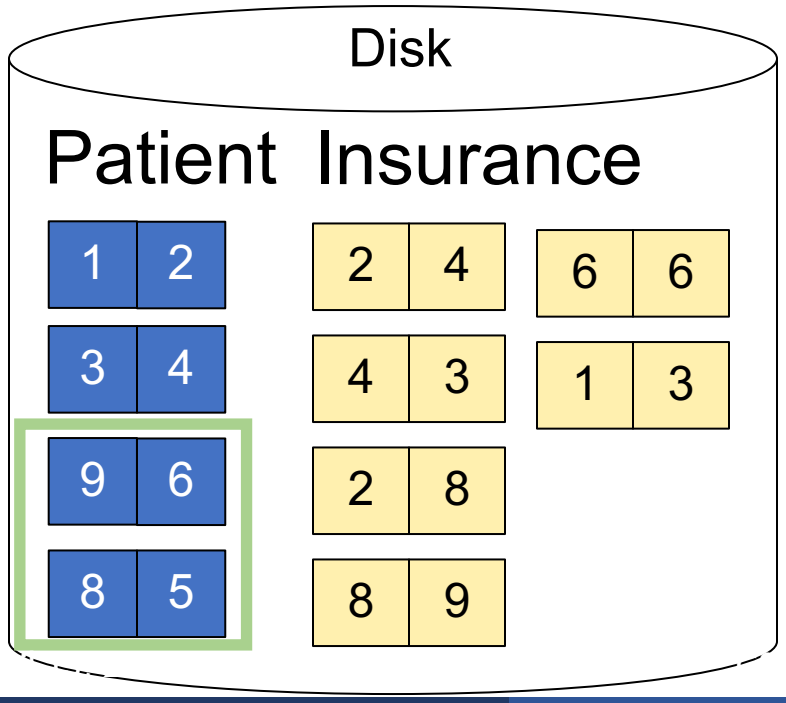

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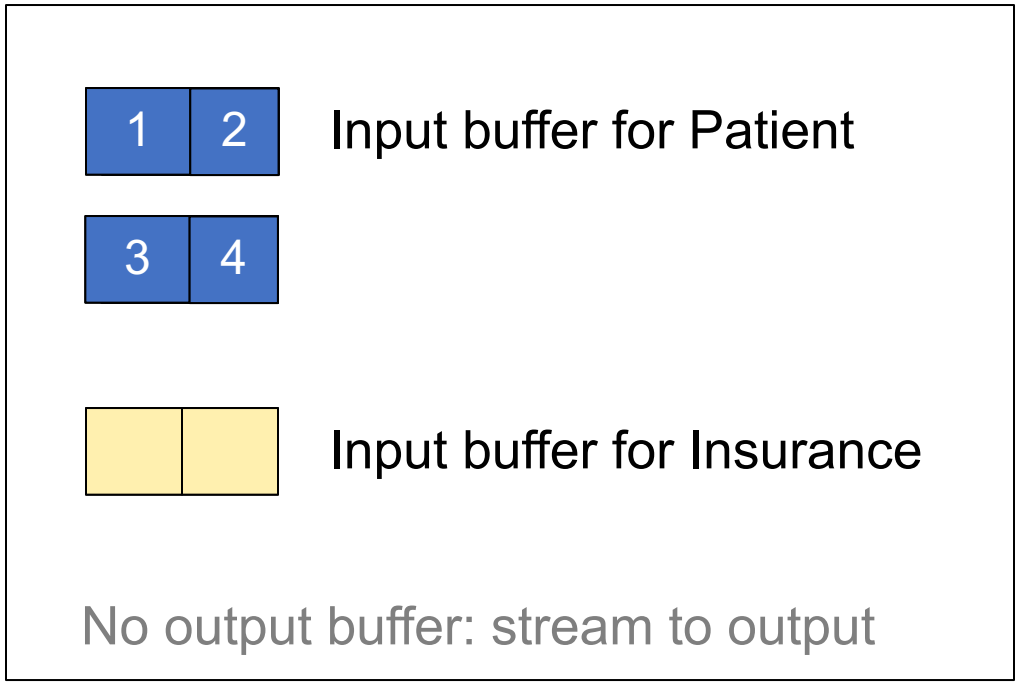

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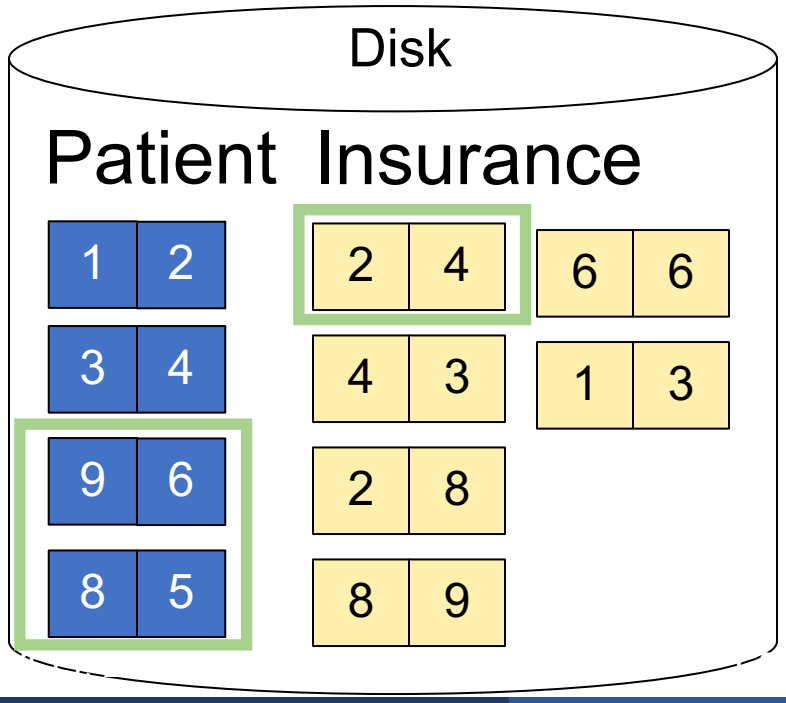

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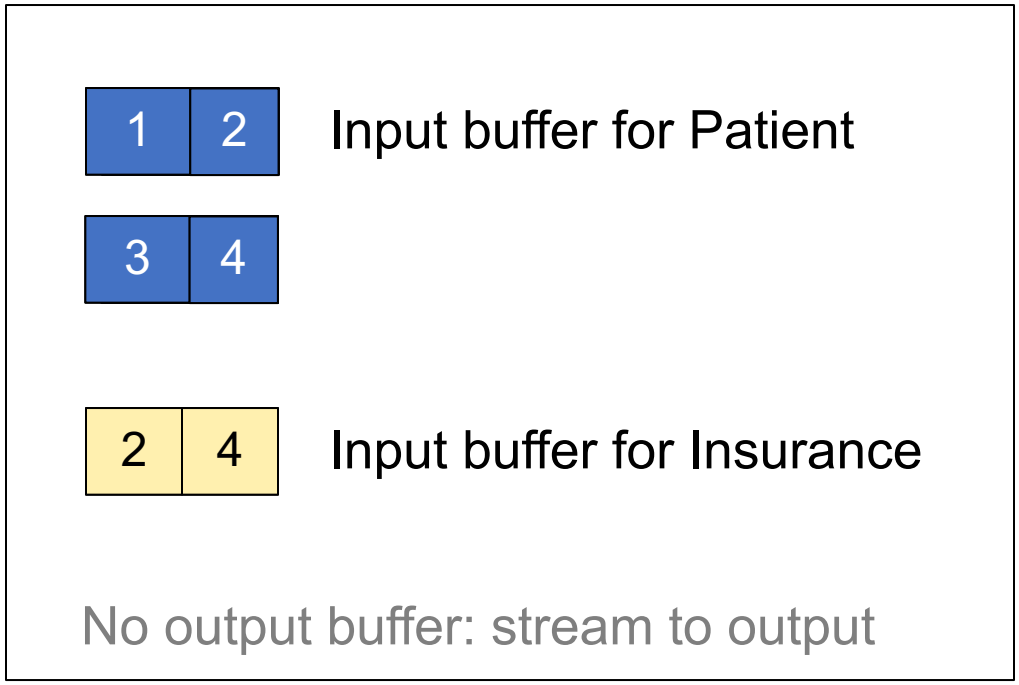

Block Memory Refinement

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```

What is the Cost

Block Memory Refinement

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```

- 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

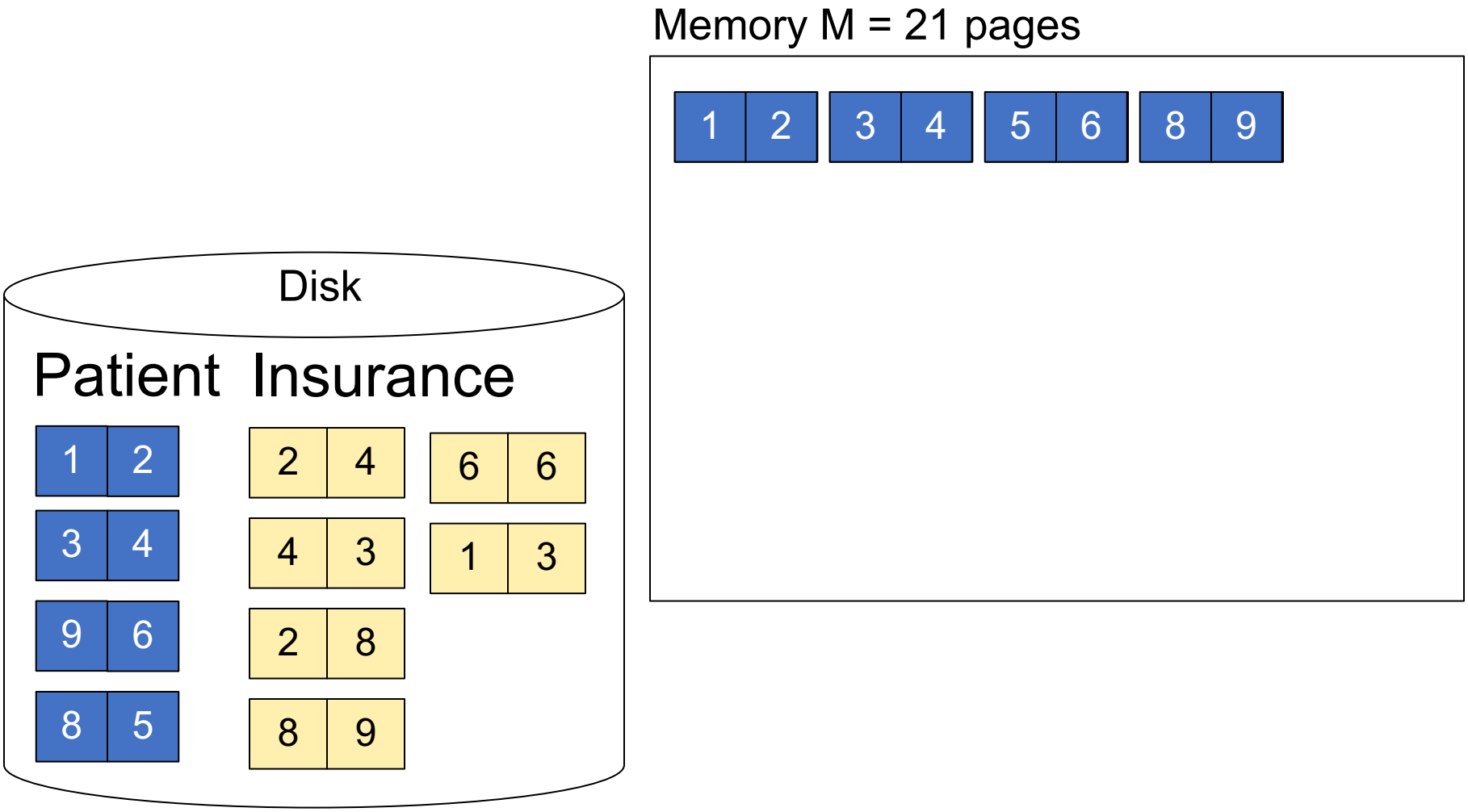
Sort-merge join: $R \bowtie S$

- 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

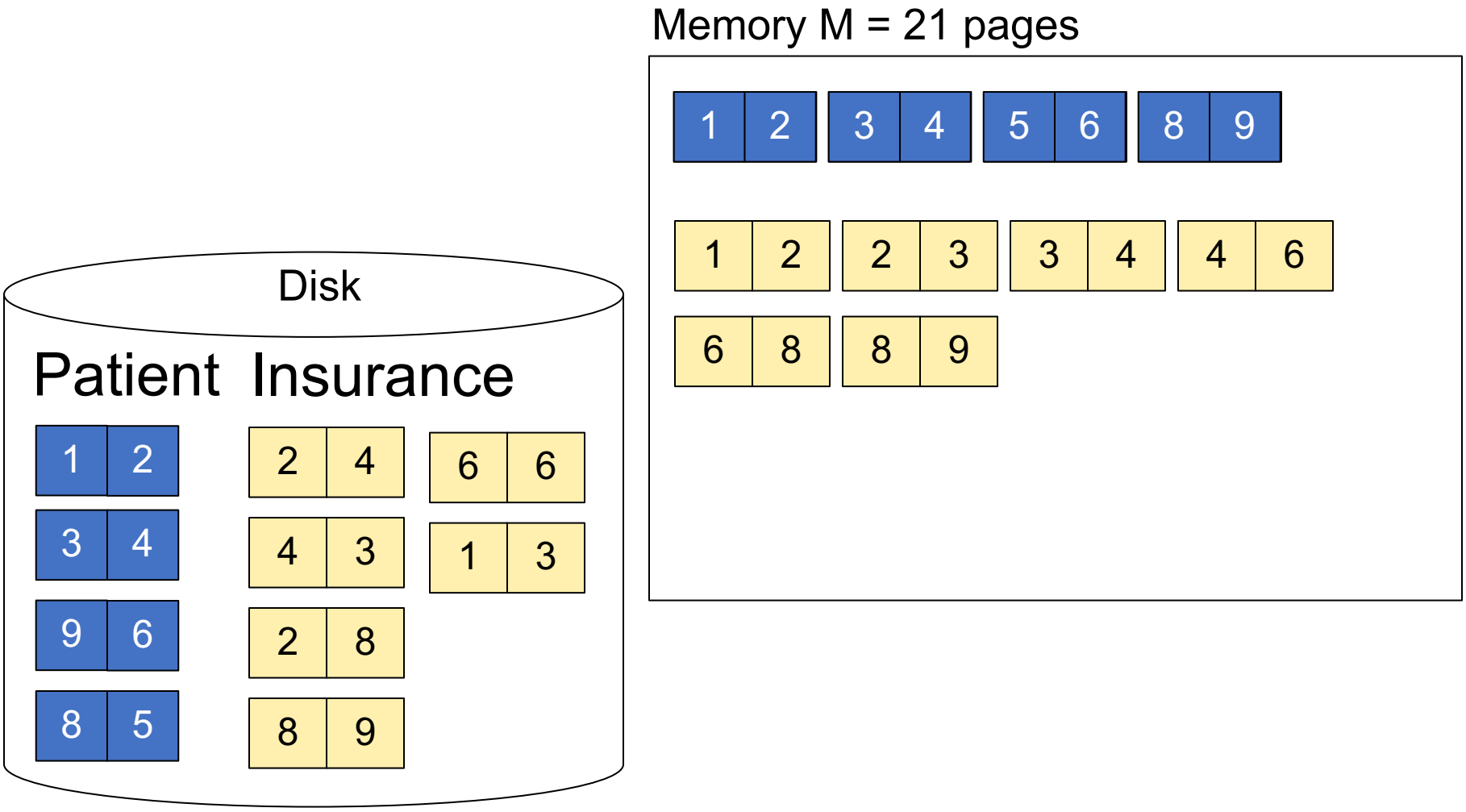
Sort-Merge Join Example

Step 1: Scan Patient and sort in memory



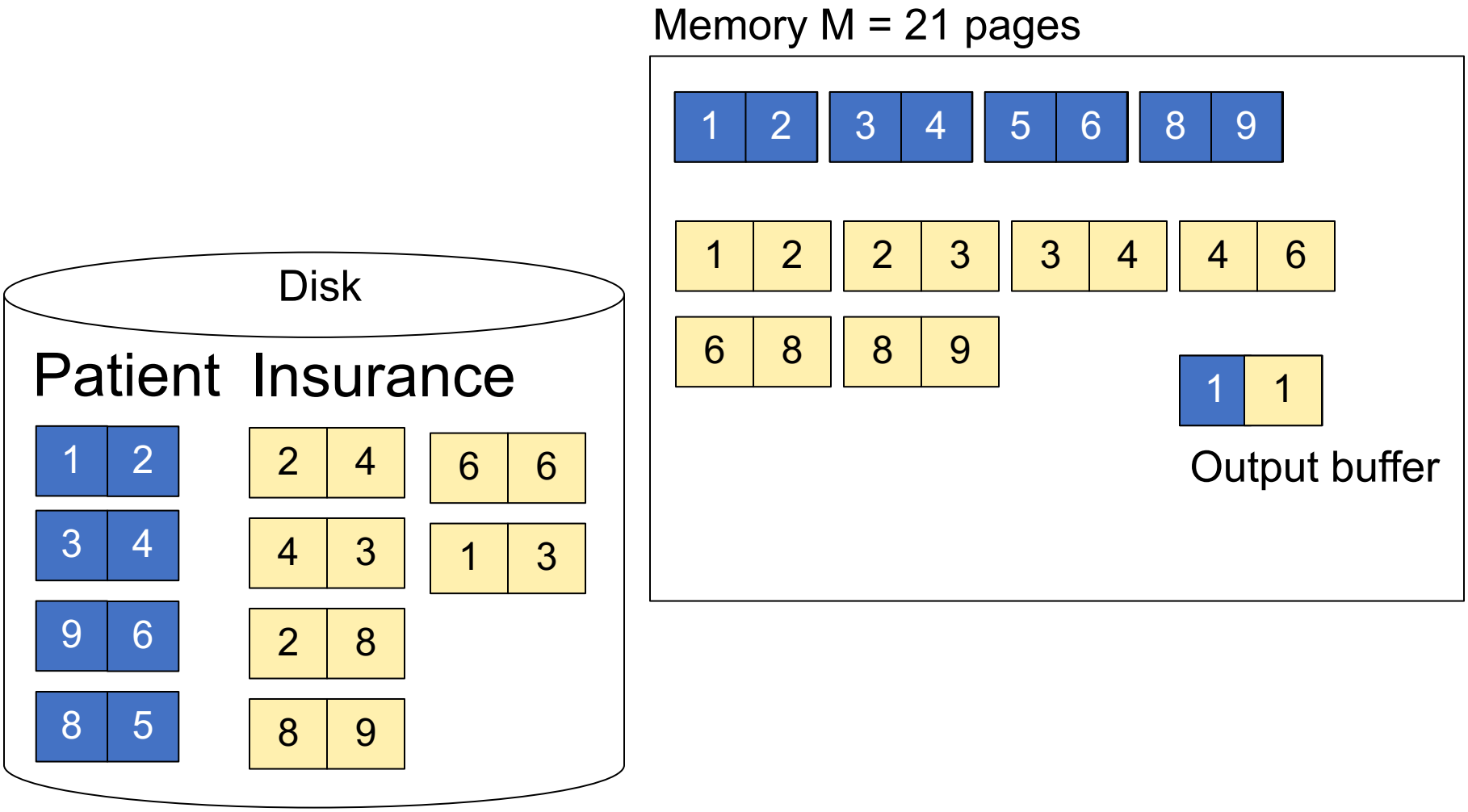
Sort-Merge Join Example

Step 2: Scan Insurance and sort in memory



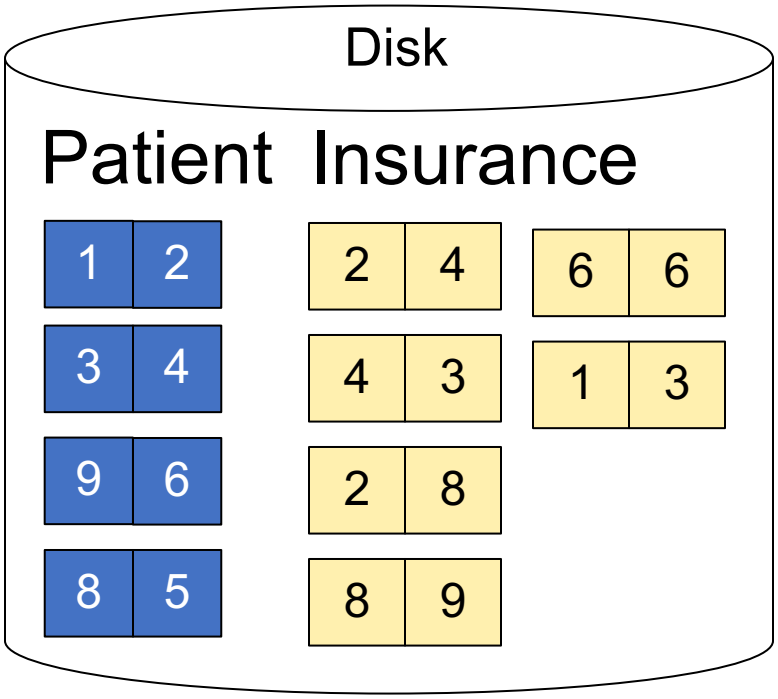
Sort-Merge Join Example

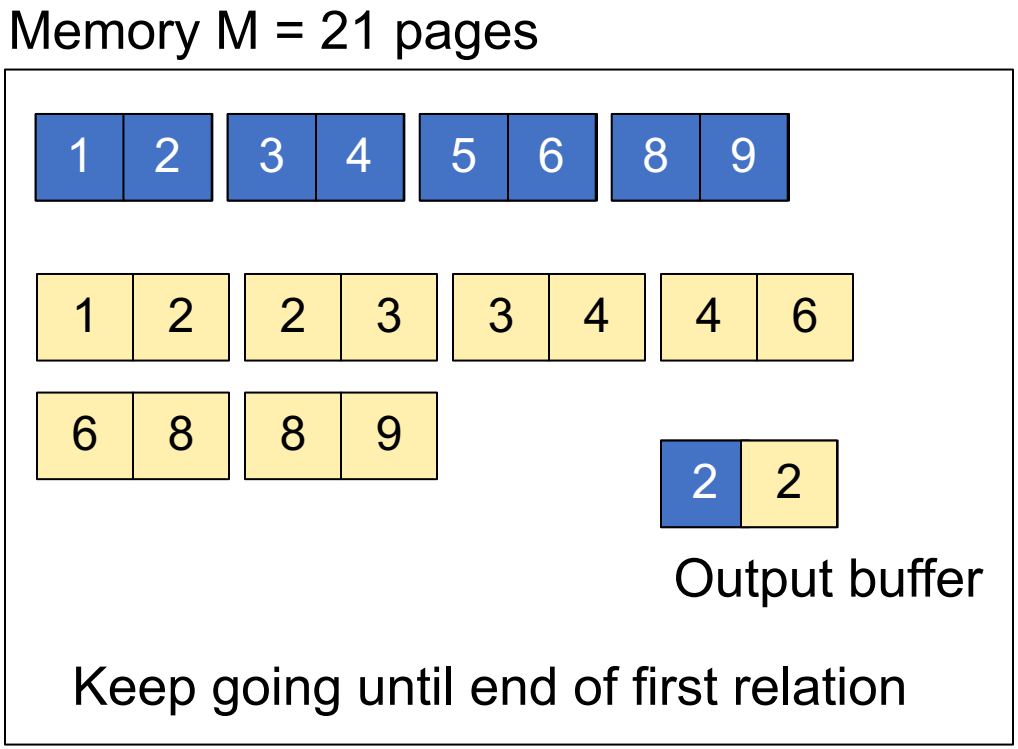
Step 3: Merge Patient and Insurance



Sort-Merge Join Example

Step 3: Merge Patient and Insurance





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

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

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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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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)