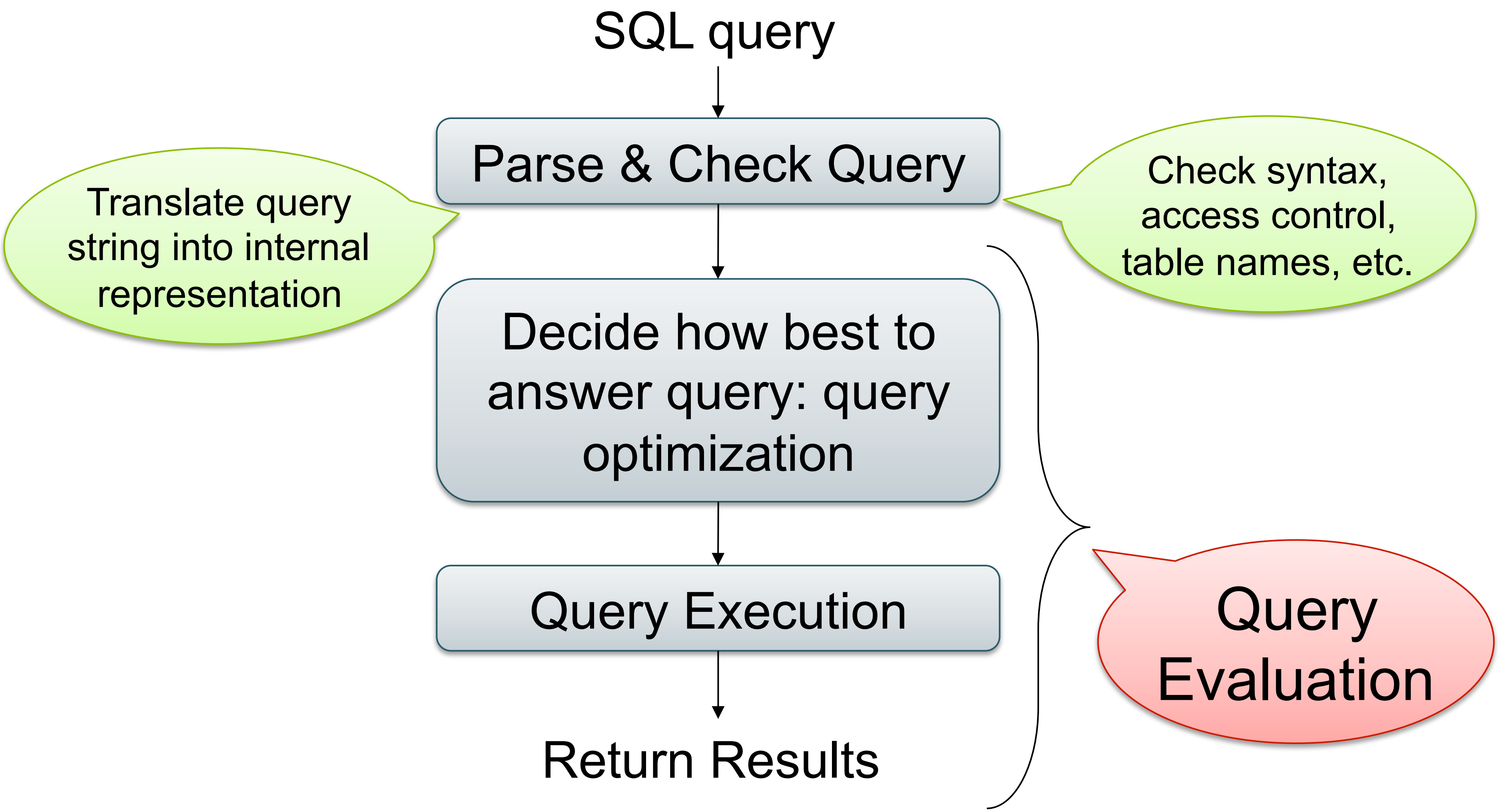
Introduction to Database Systems
CSE 414

Lectures 11-12:
Query Implementation

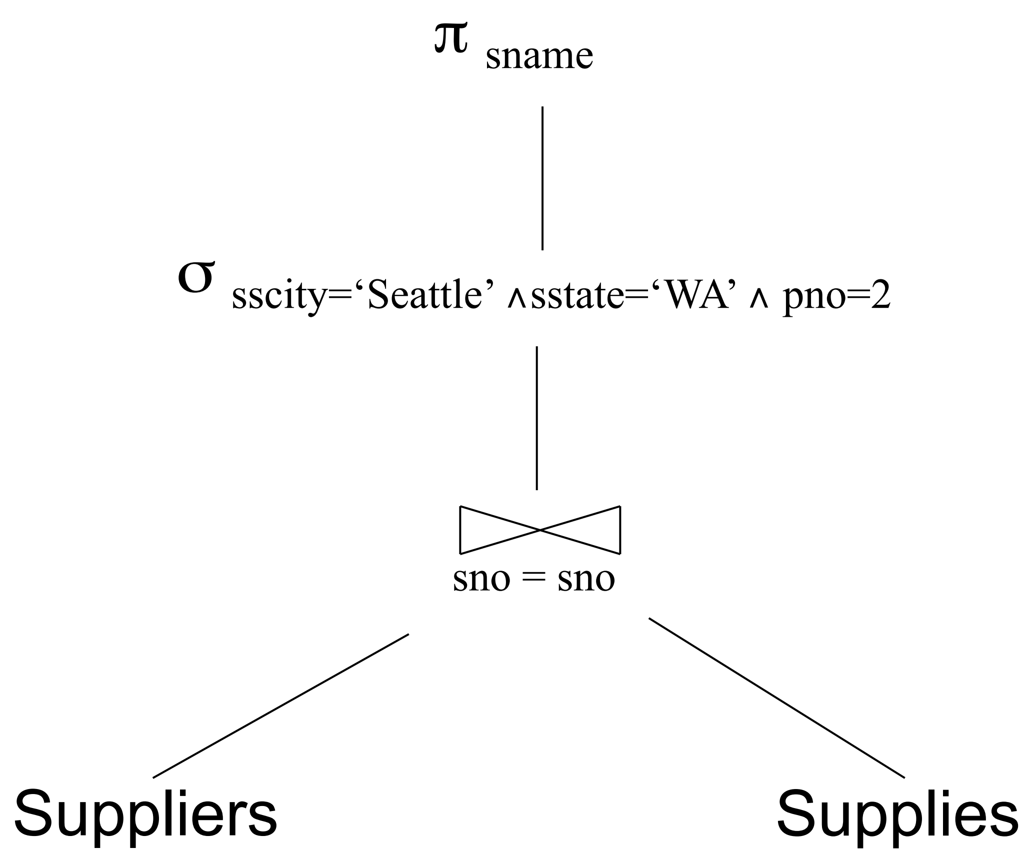
Announcements

- New HW and webquiz out later today
  - Due next week
- Next two lectures: query implementation and operator algorithms
  - Reading: sec. 15.1-15.6

SQL Query Evaluation Steps



Logical Plan



Query Processing

- **Query execution**
  - How to synchronize operators?
  - How to pass data between operators?

- Approach:
  - One thread per query
  - Iterator interface
  - Pipelined execution, or
  - Intermediate result materialization

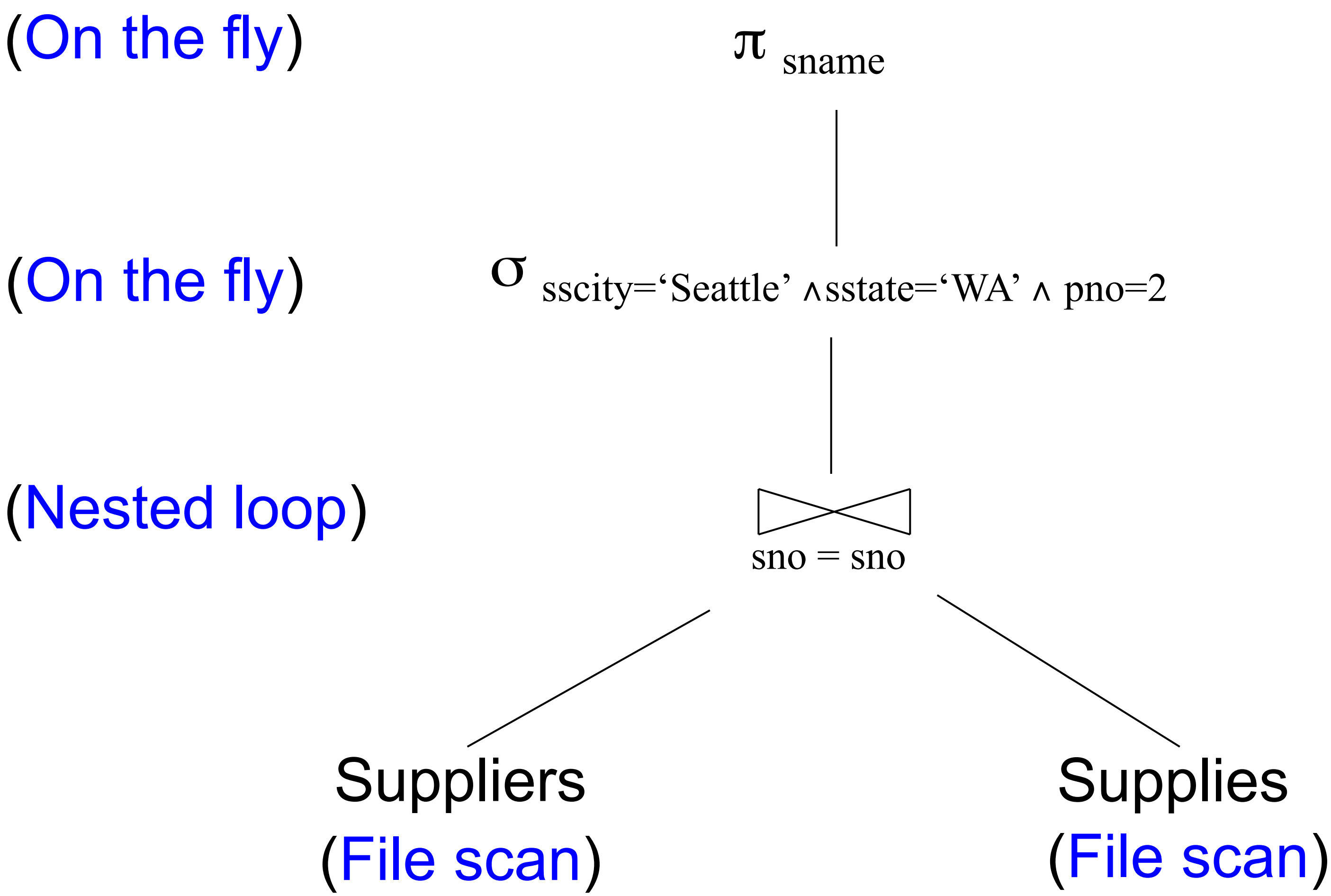
Iterator Interface

- Each **operator implements iterator interface**
- Interface has only three methods
- **open()**
  - Initializes operator state
  - Sets parameters such as selection condition
- **get_next()**
  - Operator invokes get_next() recursively on its inputs
  - Performs processing and produces an output tuple
- **close()**: cleans-up state

Pipelined Execution

- Applies parent operator to tuples directly as they are produced by child operators
- Benefits
  - No operator synchronization issues
  - Saves cost of writing intermediate data to disk
  - Saves cost of reading intermediate data from disk
  - Good resource utilizations on single processor
- This approach is used whenever possible

Pipelined Execution

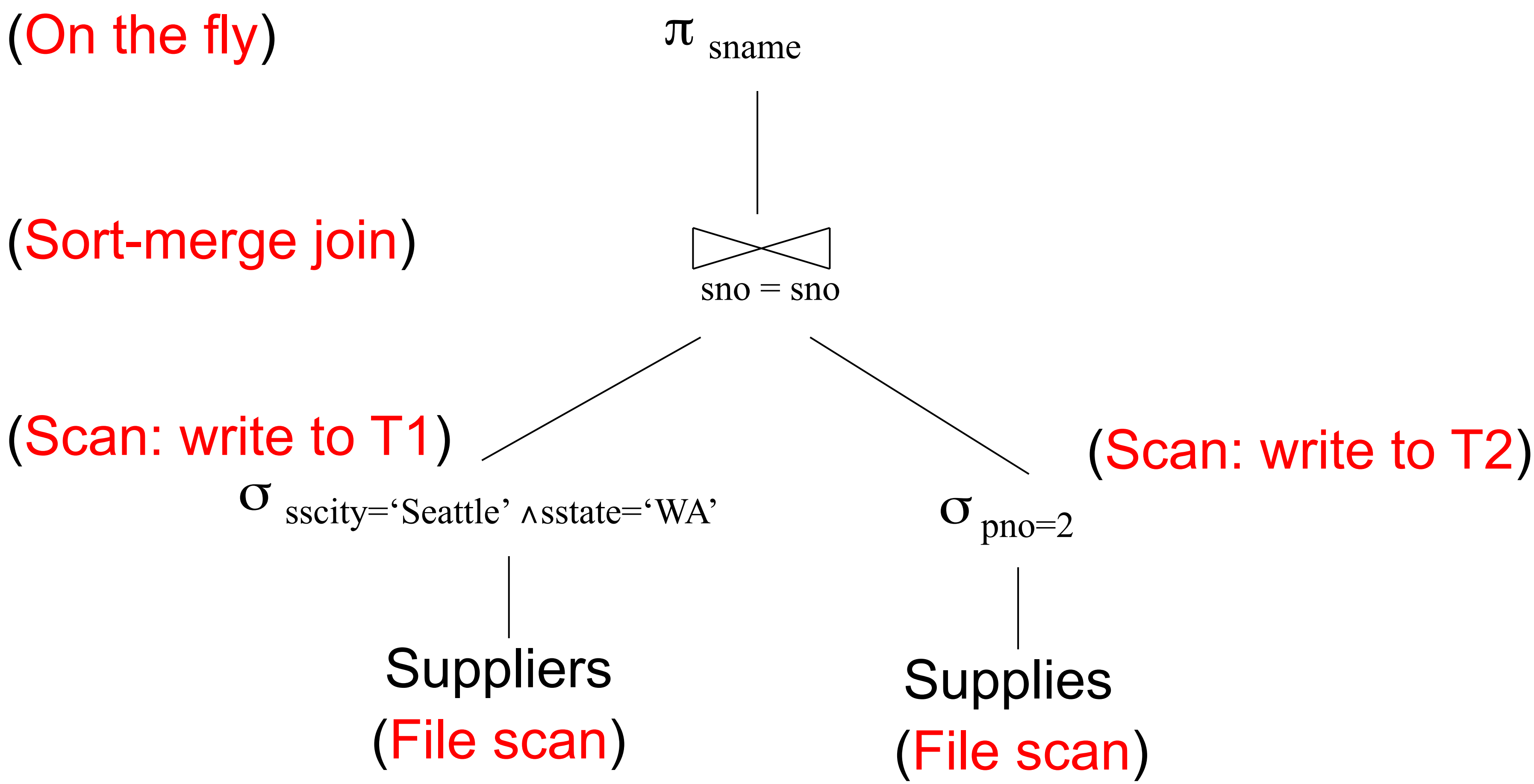


Intermediate Tuple Materialization

- Writes the results of an operator to an intermediate table on disk

- No direct benefit, but…
- Necessary for some operator implementations
- Also used when operator needs to examine the same tuples multiple times

Intermediate Tuple Materialization



Cost Parameters

- In database systems the data is on disk
- **Cost = total number of I/Os**
- 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)
- Main constraint: **M = # of memory (buffer) pages**

Cost

- Cost of an operation = number of disk I/Os to:
  - Read the operands
  - Compute the result
- Cost of writing the 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)
    (Quick overview only)

  - Note about readings:
    - In class, we will discuss only algorithms for join operator (because other operators are easier)
    - Book has more details about joins and descriptions of other operators

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) <= M
  – By "one pass", we mean that the operator reads its operands only once. It does not write intermediate results back to disk.

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’

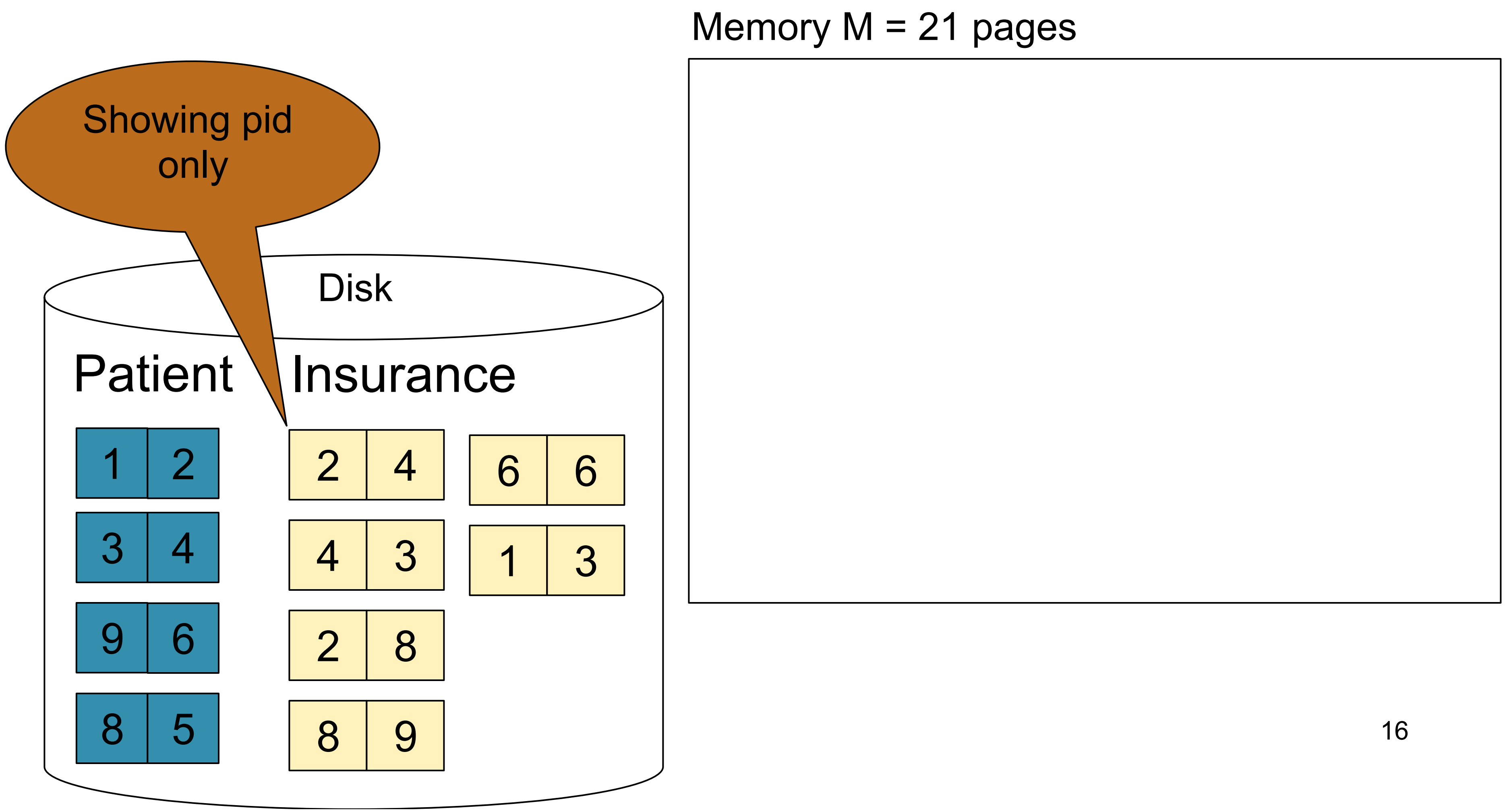
Insurance

2	‘Blue’	123
4	‘Prem’	432

4	‘Prem’	343
3	‘GrpH’	554

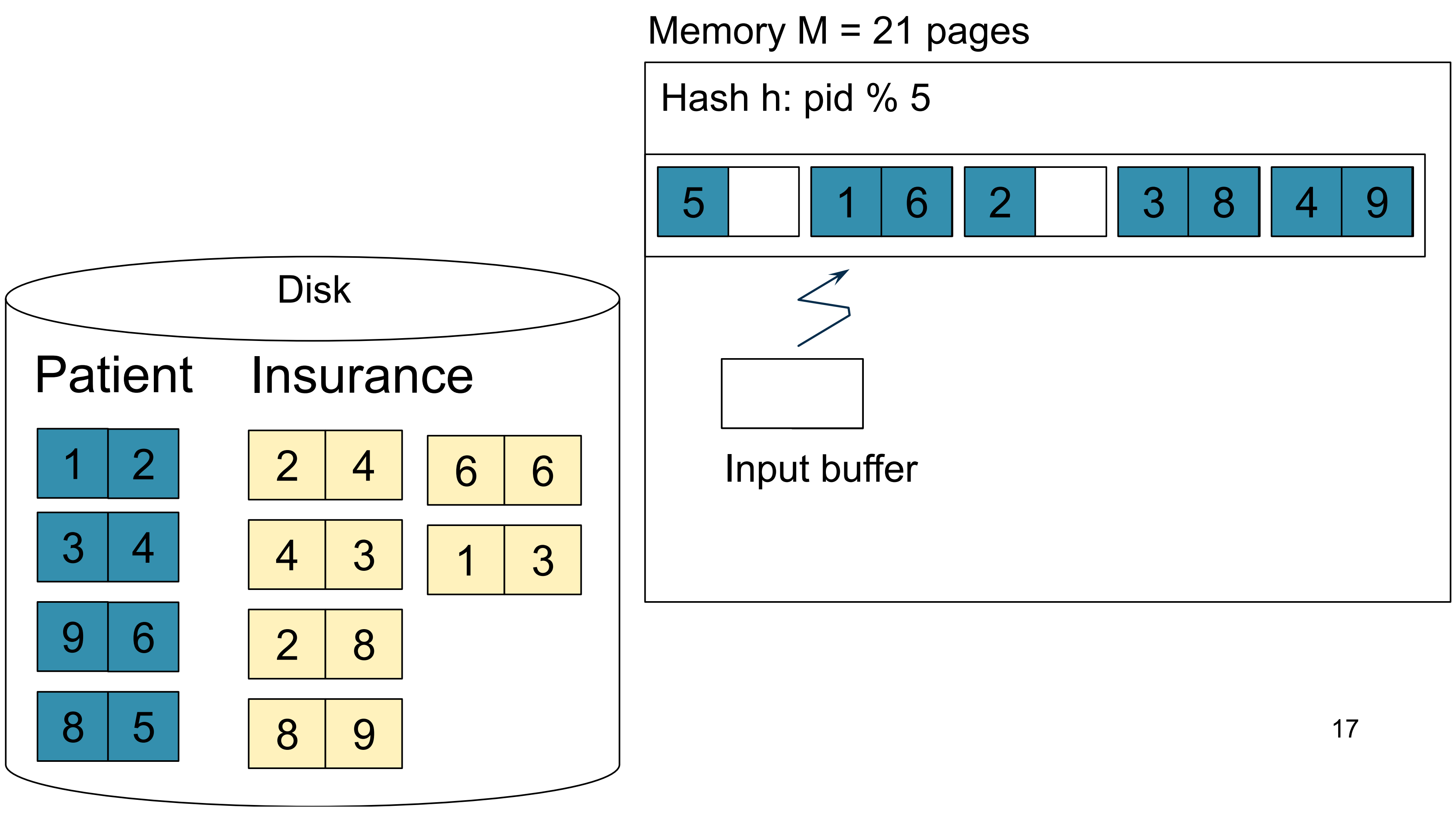
Hash Join Example

Patient $\bowtie$ Insurance



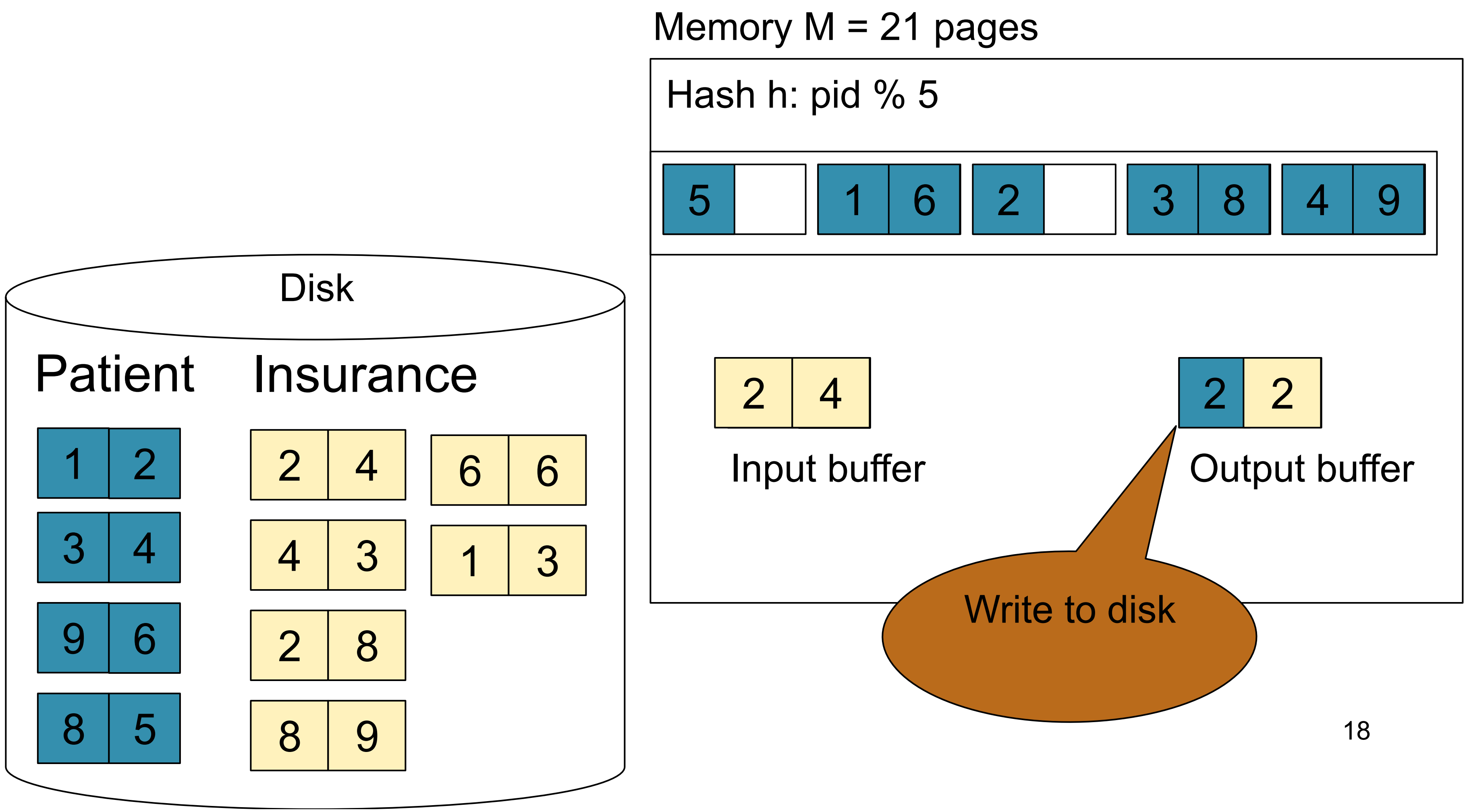
Hash Join Example

Step 1: Scan Patient and create hash table in memory



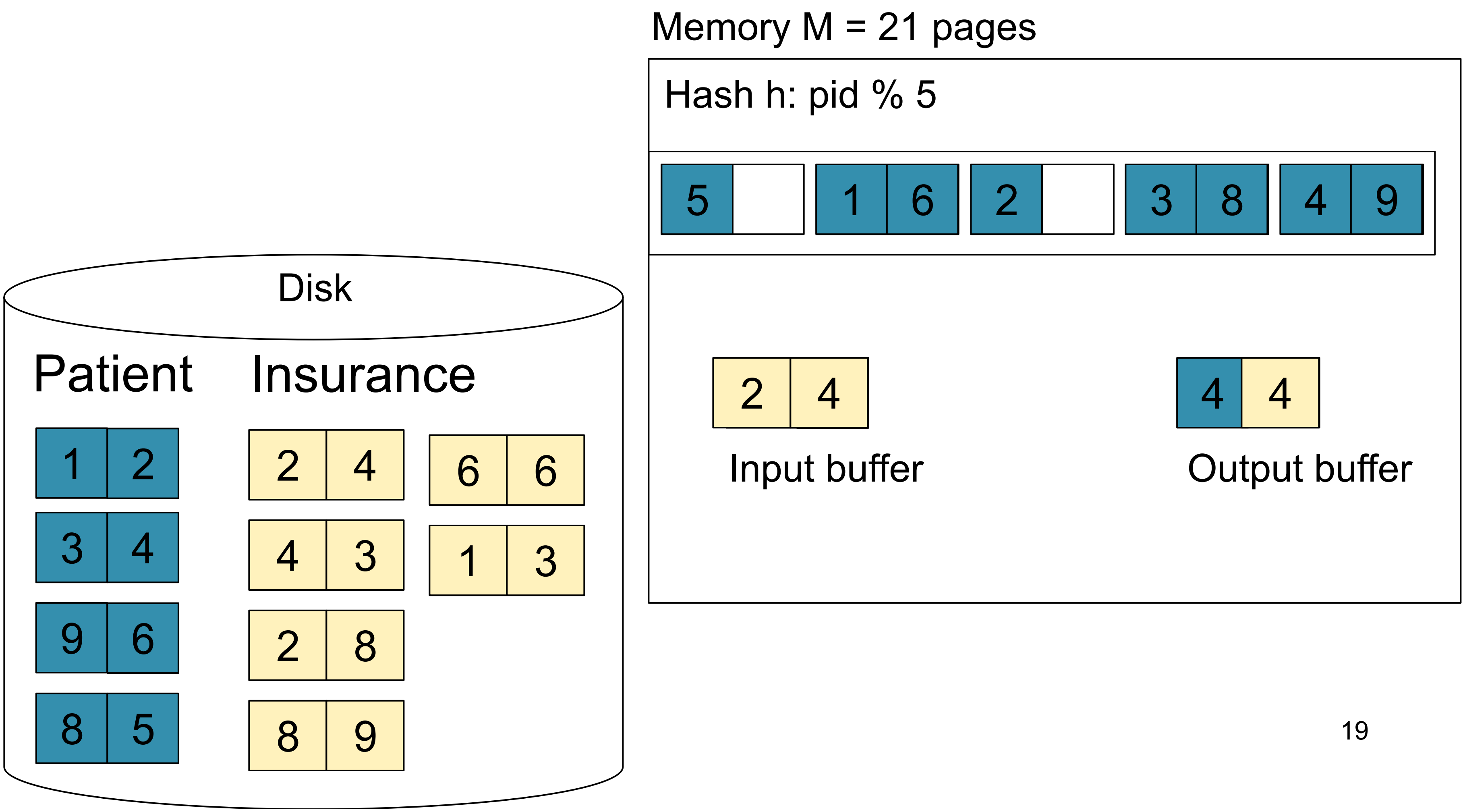
Hash Join Example

Step 2: Scan Insurance and probe into hash table



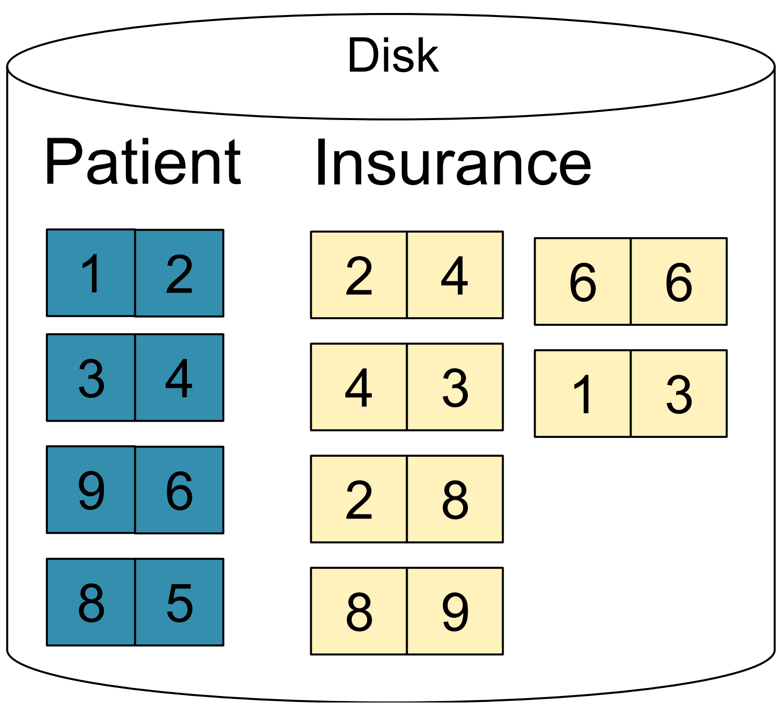
Hash Join Example

Step 2: Scan Insurance and probe into hash table

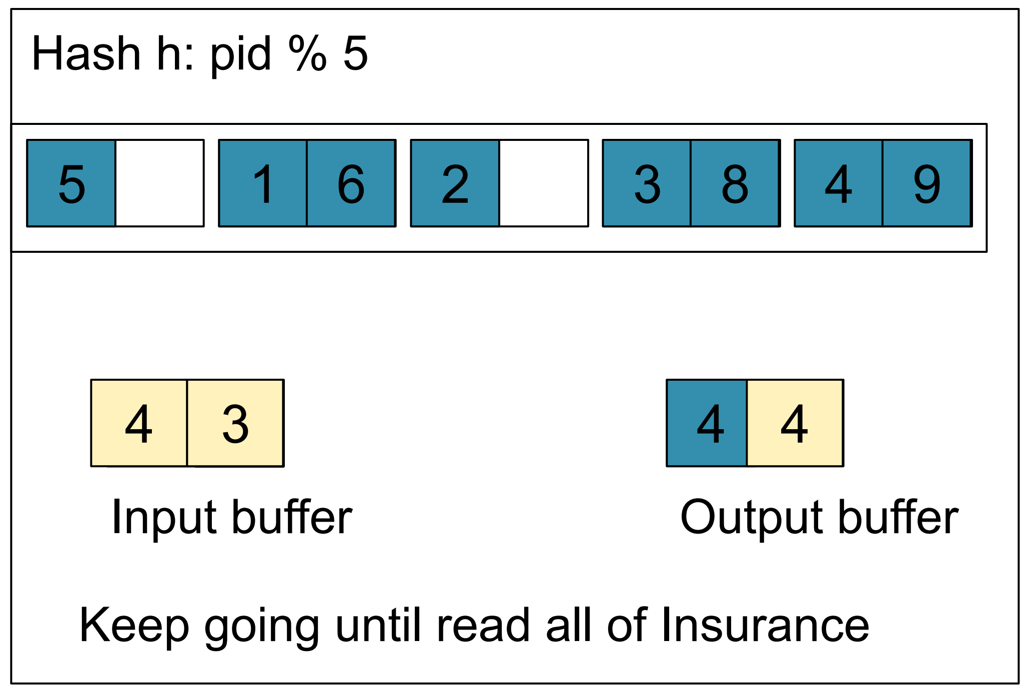


Hash Join Example

Step 2: Scan Insurance and probe into hash table



Memory M = 21 pages



Cost: B(R) + B(S)

Hash Join Details

```
Open( ) {
  H = newHashTable( );
  R.Open( );
  x = R.GetNext( );
  while (x != null) {
    H.insert(x);
    x = R.GetNext( );
  }
  R.Close( );
  S.Open( );
  buffer = [ ];
}
```

Hash Join Details

```
GetNext( ) {
  while (buffer == [ ]) {
        x = S.GetNext( );
        if (x==Null) return NULL;
        buffer = H.find(x);
  }
  z = buffer.first( );
  buffer = buffer.rest( );
  return z;
}
```

Hash Join Details

```
Close( ) {
  release memory (H, buffer, etc.);
  S.Close( )
}
```

Nested Loop Joins

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

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

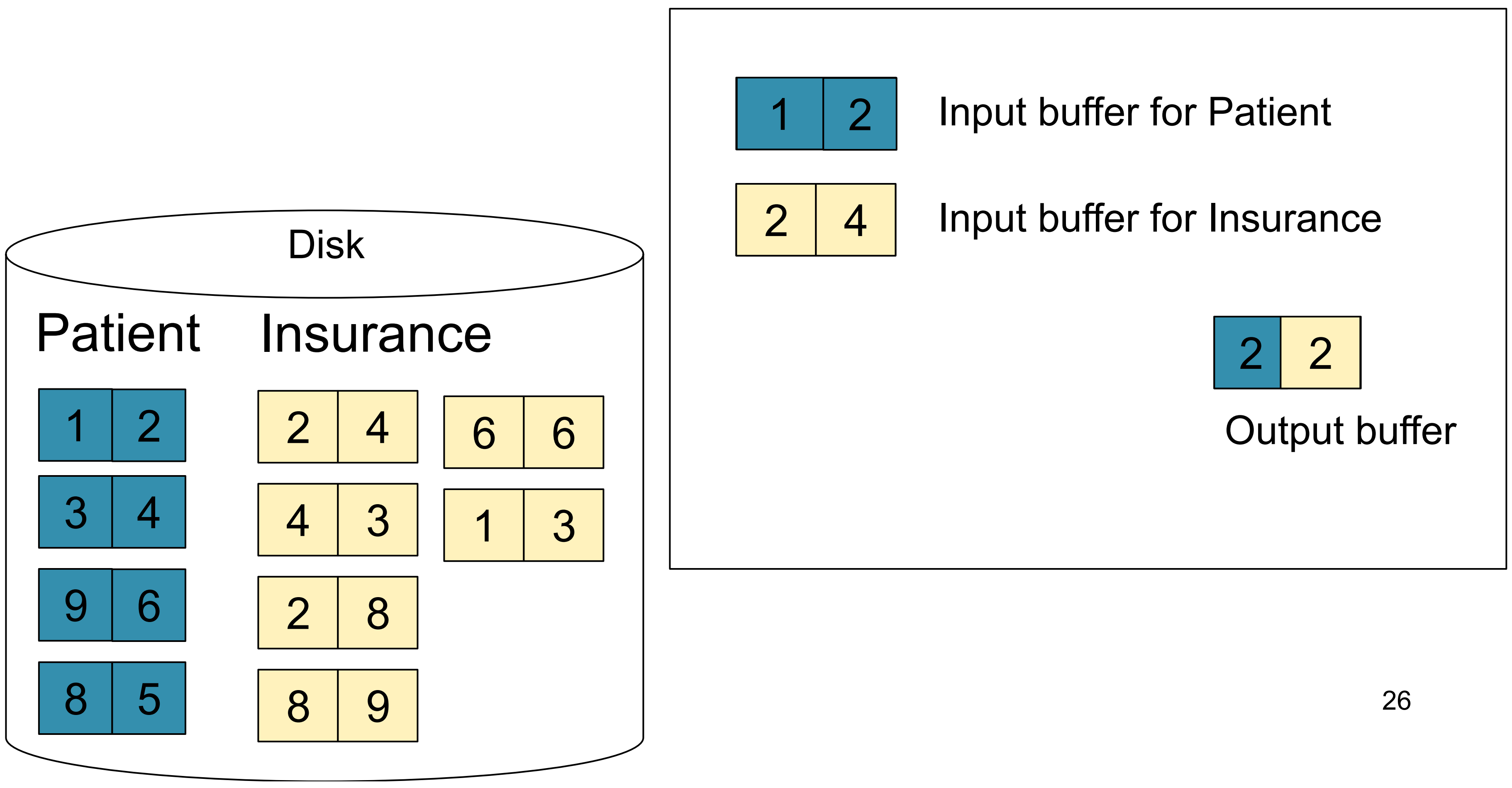
- Cost: B(R) + T(R) B(S)
- Not quite one-pass since S is read many times

Page-at-a-time Refinement

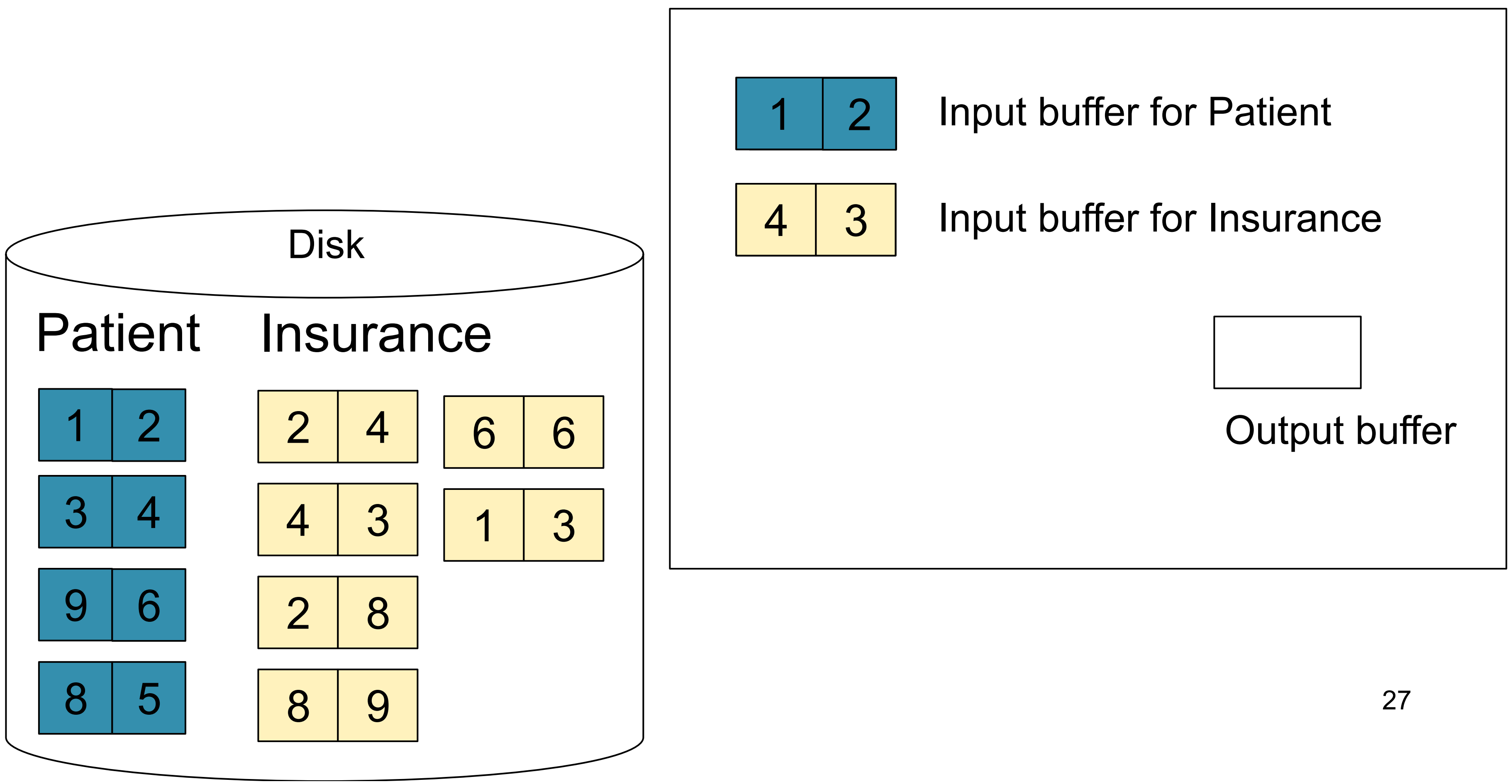
```
for each page of tuples r in R do
   for each page of tuples s in S do
                        for all pairs of tuples
                              if r and s join then output (r,s)
```

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

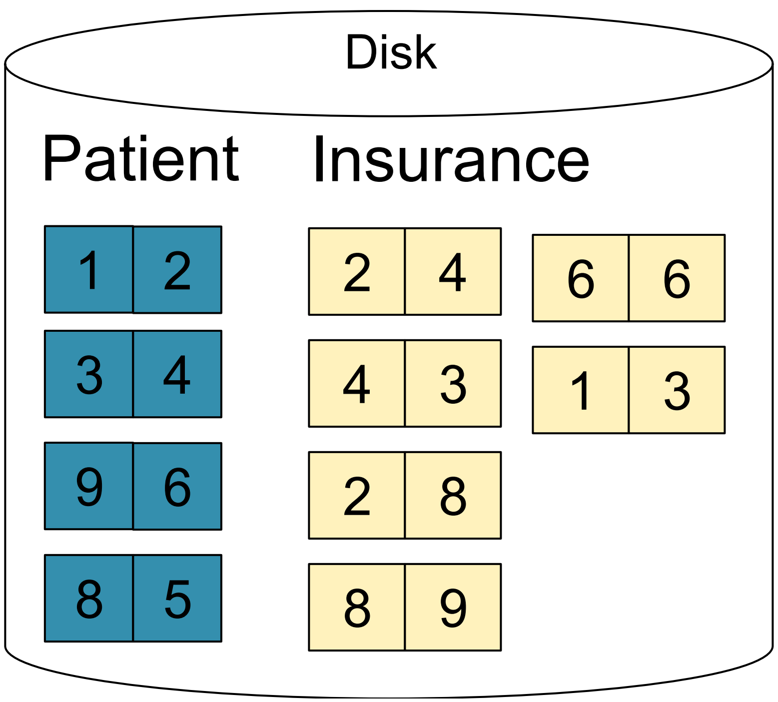
Nested Loop Example

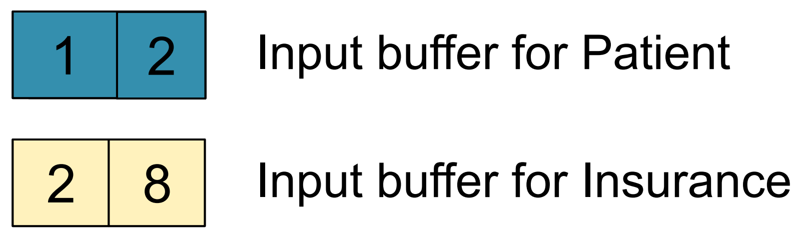


Nested Loop Example

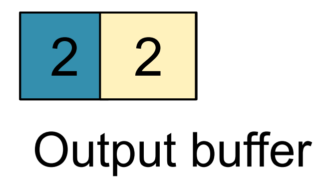


Nested Loop Example





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)

Sort-Merge Join

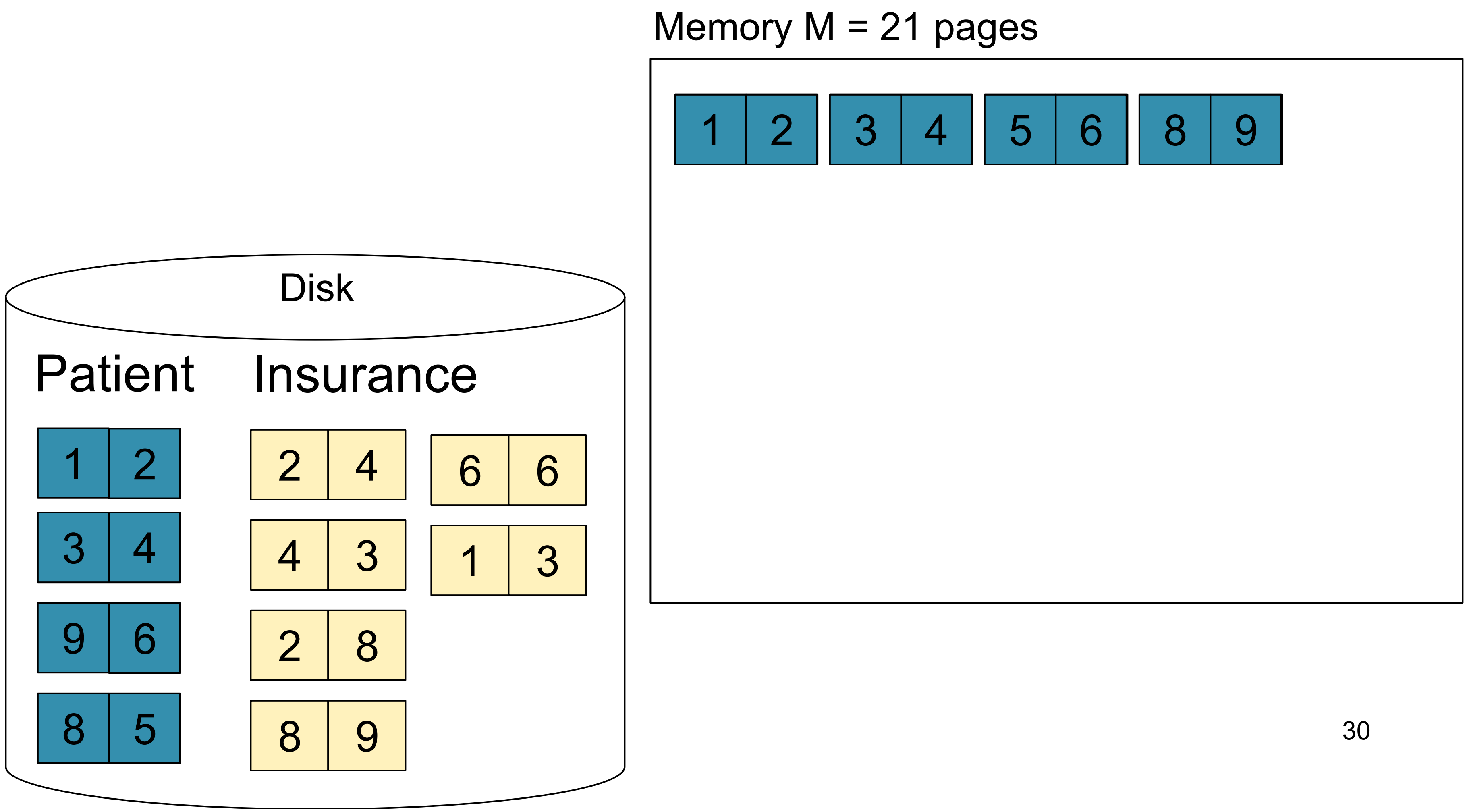
Sort-merge join: R $\bowtie$ S

- 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

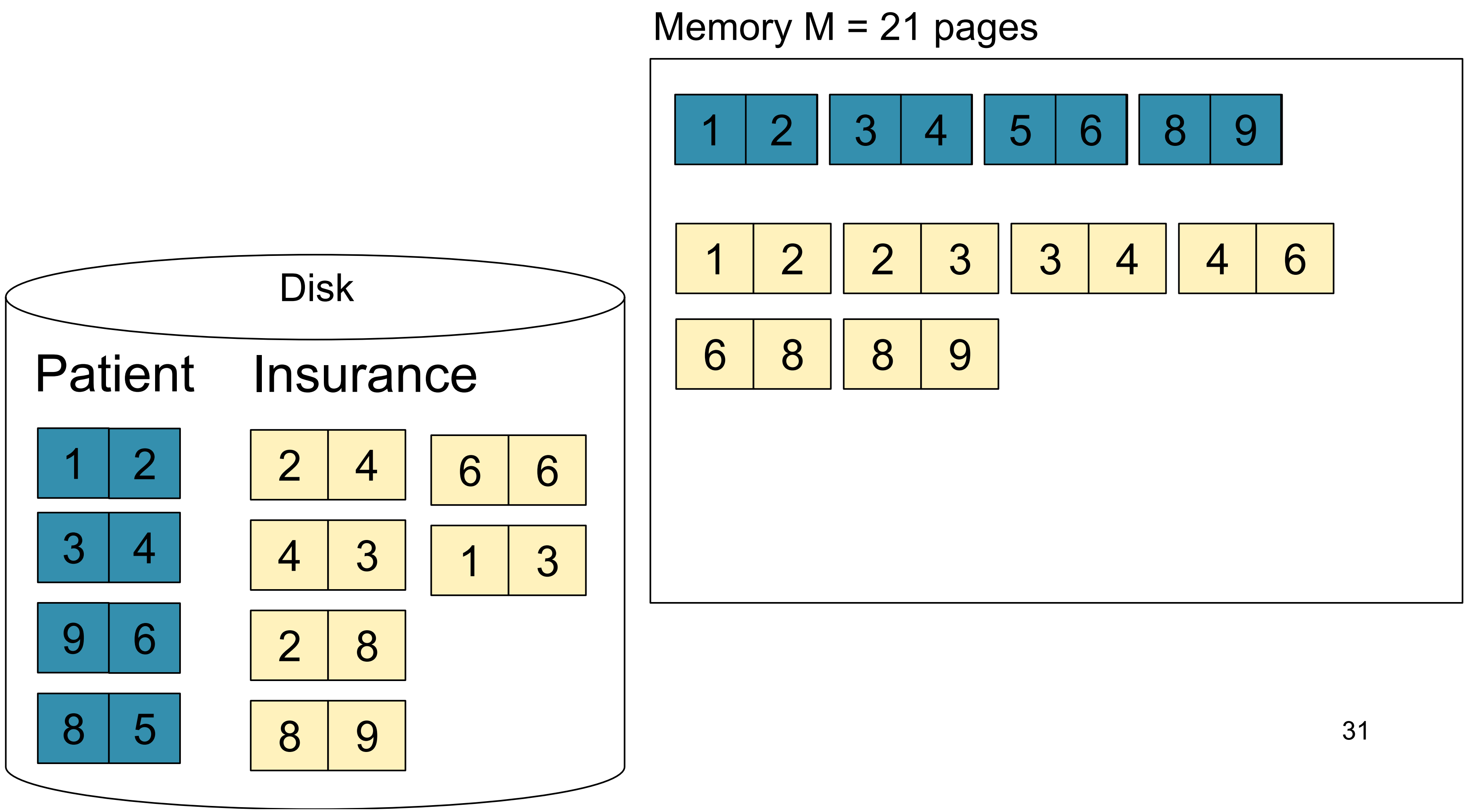
Sort-Merge Join Example

Step 1: Scan Patient and sort in memory



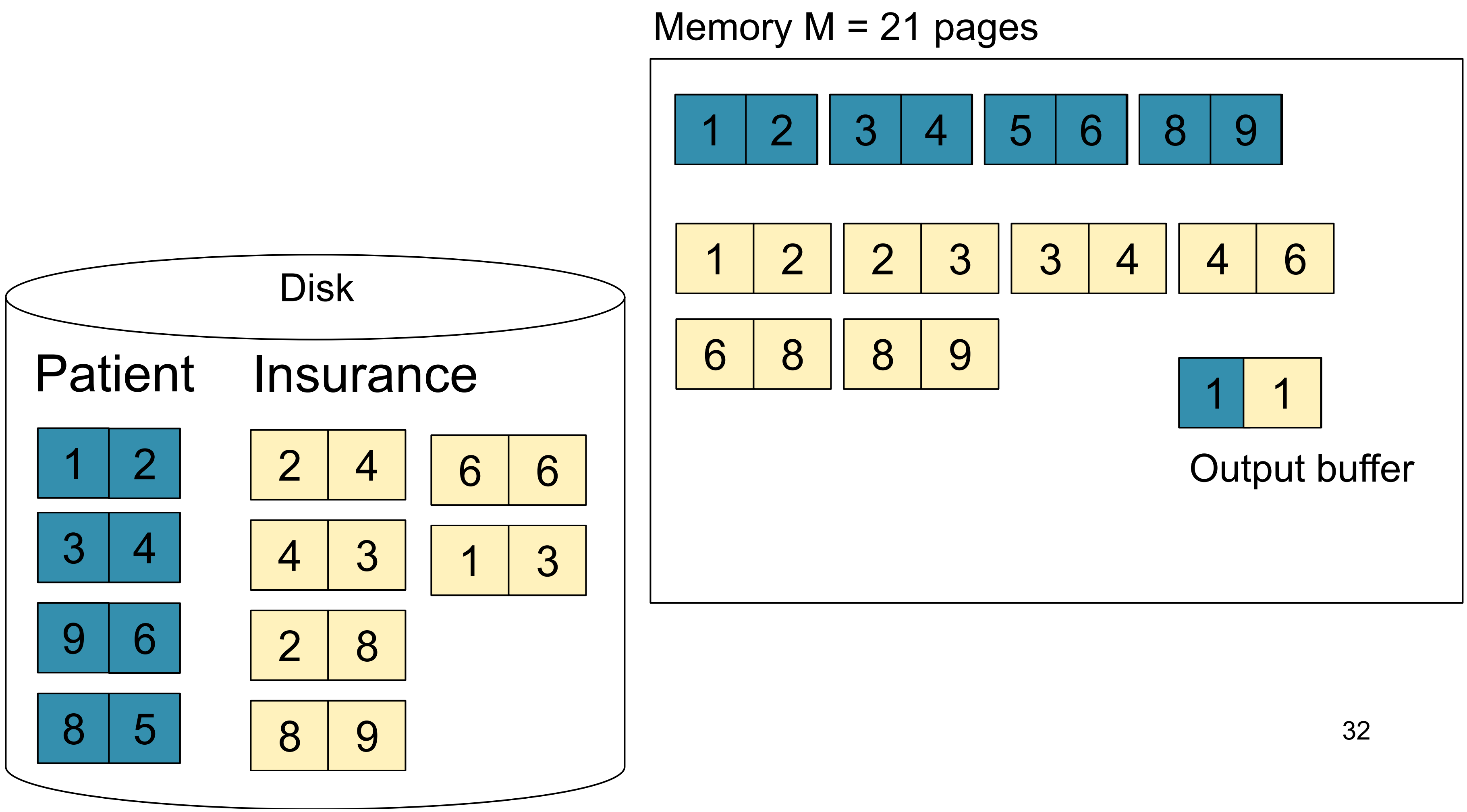
Sort-Merge Join Example

Step 2: Scan Insurance and sort in memory



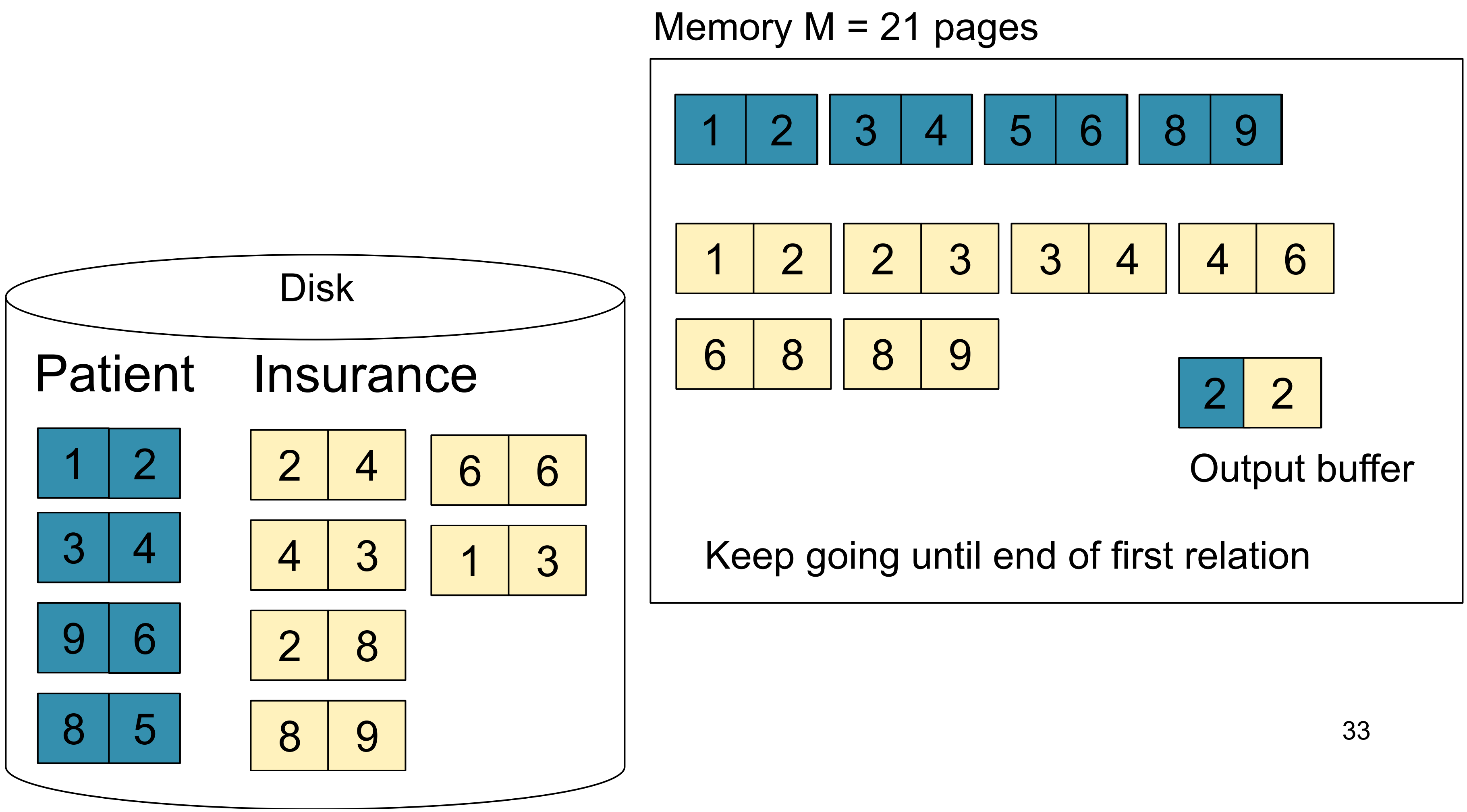
Sort-Merge Join Example

Step 3: Merge Patient and Insurance



Sort-Merge Join Example

Step 3: Merge Patient and Insurance



Outline for Today

- **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)

Review: Access Methods

- **Heap file**
  - Scan tuples one at the time
- **Hash-based index**
  - Efficient selection on equality predicates
  - Can also scan data entries in index
- **Tree-based index**
  - Efficient selection on equality or range predicates
  - Can also scan data entries in index

Index Based Selection

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

- V(R, a) = # of distinct values of attribute a

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

- Note: we ignored 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: B(R) = 2,000 I/Os
- Index based selection
  - 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
- 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: $B(R)+T(R)T(S)/V(S,a)$

Outline for Today

- **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)

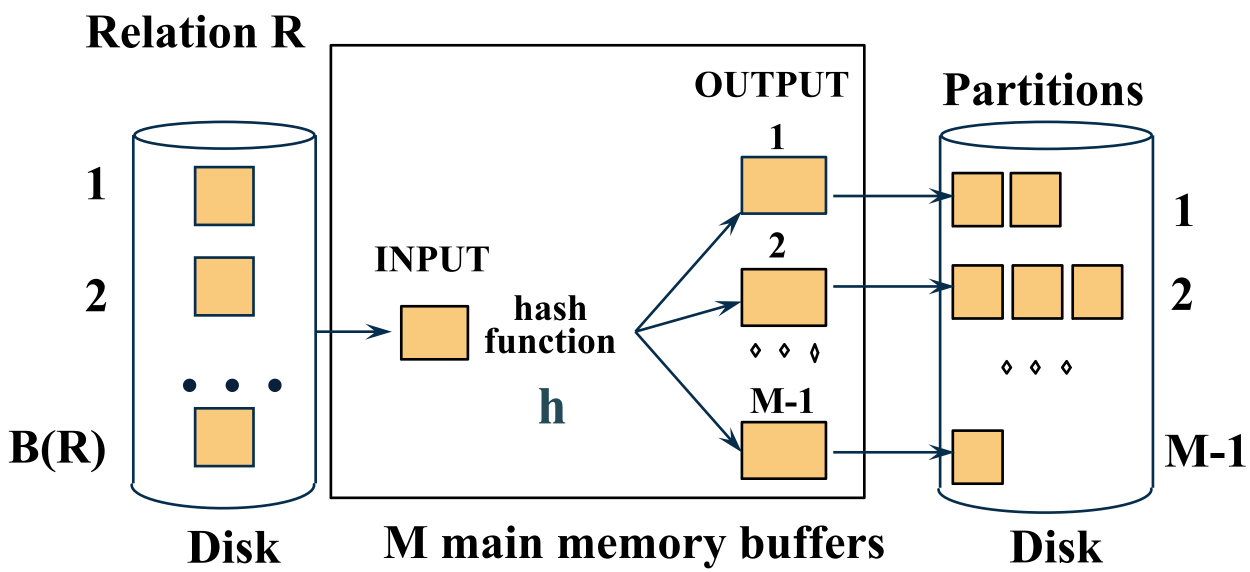
Two-Pass Algorithms

- What if data does not fit in memory?
- Need to process it in multiple passes

- Two key techniques
  - Hashing
  - Sorting

Two Pass Algorithms Based on Hashing

- Idea: partition a relation R into buckets, on disk
- Each bucket has size approx. B(R)/M



- Does each bucket fit in main memory ?
  - Yes if B(R)/M <= M, i.e. $B(R) <= M^2$

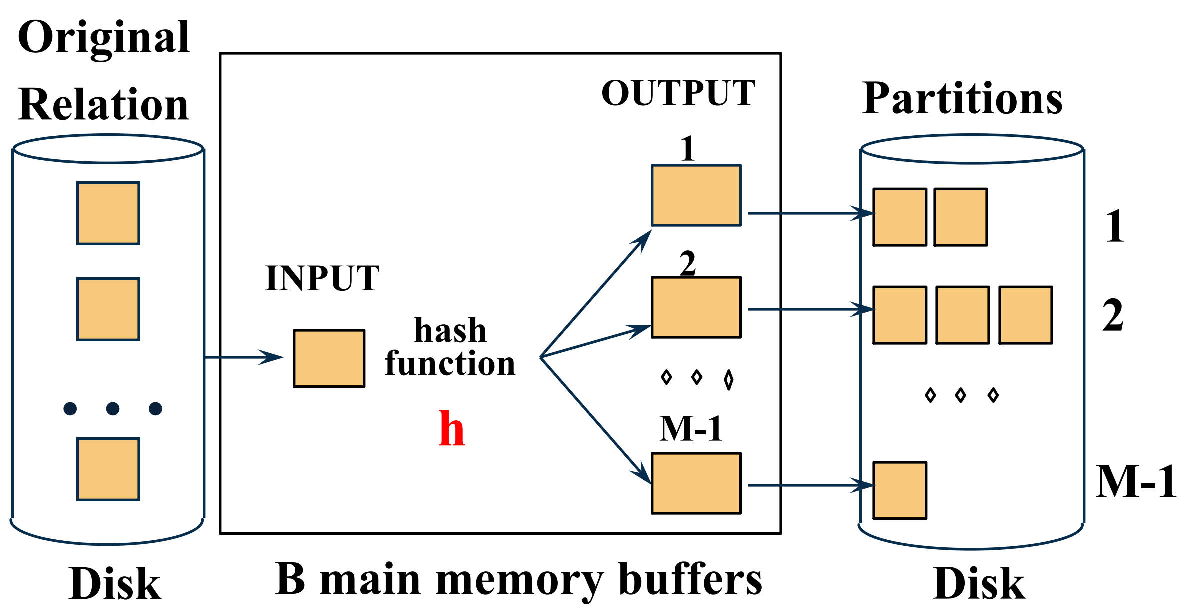
Partitioned (Grace) Hash Join

$R \bowtie S$

- Step 1:
  – Hash S into M-1 buckets
  – Send all buckets to disk
- Step 2
  – Hash R into M-1 buckets
  – Send all buckets to disk
- Step 3
  – Join every pair of buckets

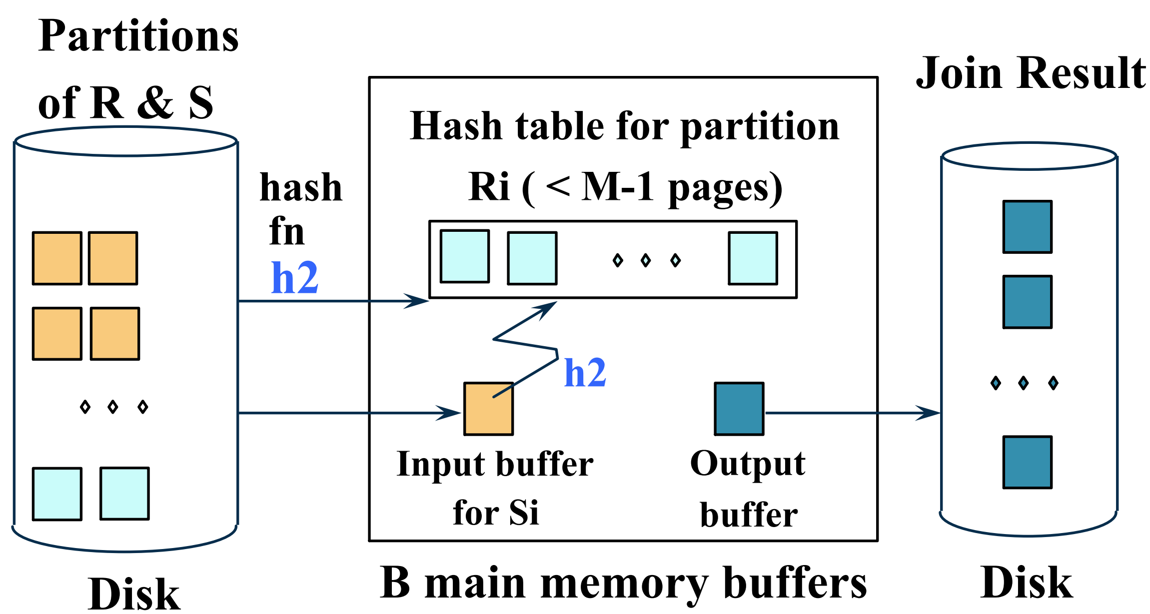
Partitioned Hash Join

- Partition both relations using hash fn **h**
- R tuples in partition i will only match S tuples in partition i.



Partitioned Hash Join

- Read in partition of R, hash it using **h2** (≠ h)
  - Build phase
- Scan matching partition of S, search for matches
  - Probe phase



Partitioned Hash Join

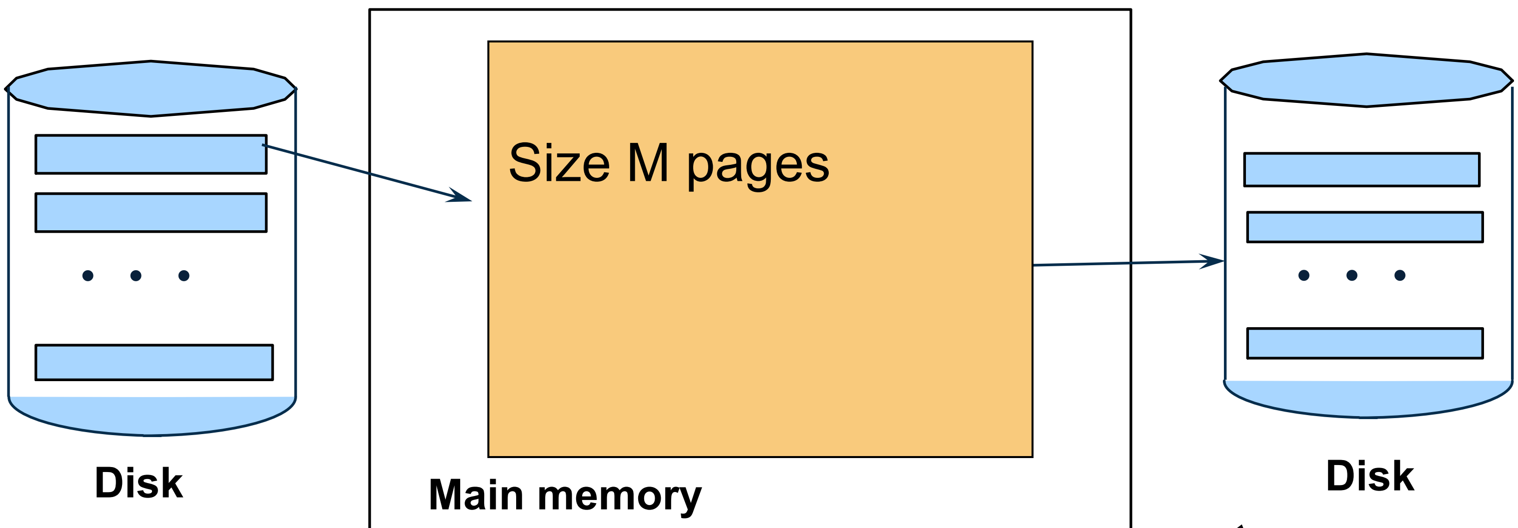
- Cost: 3B(R) + 3B(S)
- Assumption: min(B(R), B(S)) <= M^2

External Sorting

- Problem: Sort a file of size B with memory M
- Where we need this:
  - ORDER BY in SQL queries
  - Several physical operators
  - Bulk loading of B+-tree indexes.
- Sorting is two-pass when $B < M^2$

External Merge-Sort: Step 1

Phase one: load M pages in memory, sort

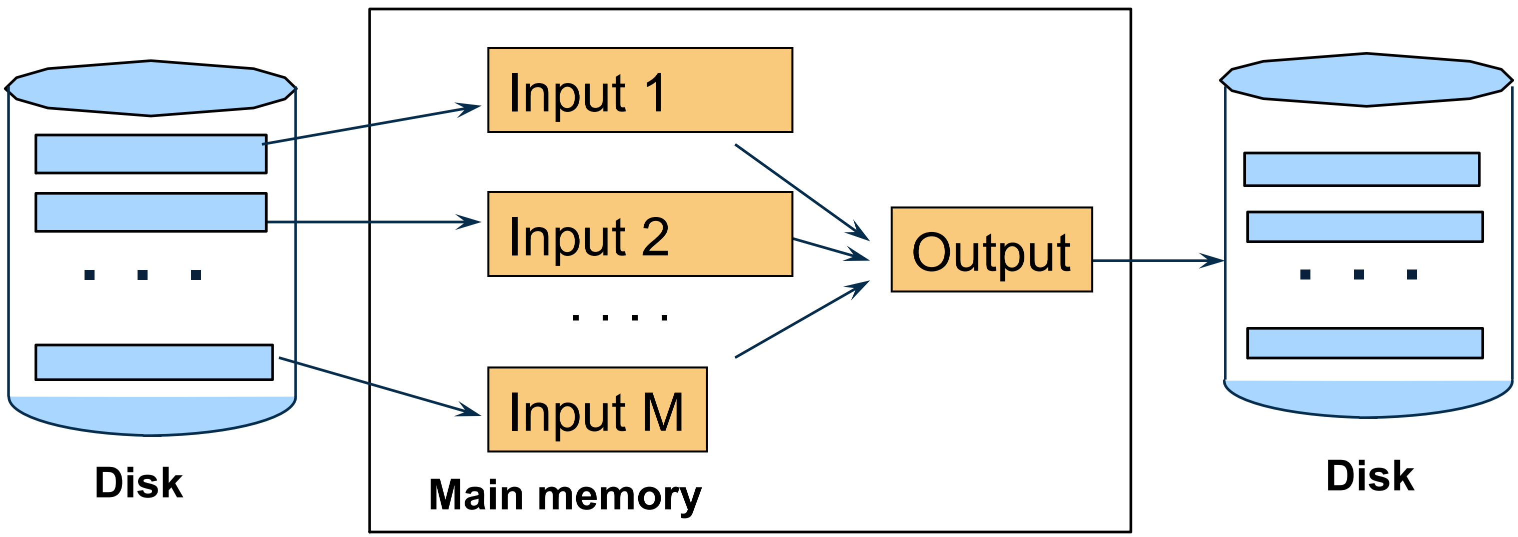


Runs of length M pages

External Merge-Sort: Step 2

Merge M – 1 runs into a new run

Result: runs of length M (M – 1) $\approx M^2$



If B <= M^2 then we are done

External Merge-Sort

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

- Other considerations
  - In general, a lot of optimizations are possible

Two-Pass Join Algorithm Based on Sorting

Join R ⋈ S

- Step 1: sort both R and S on the join attribute:
  - Cost: 4B(R)+4B(S) (because need to write to disk)
- Step 2: Read both relations in sorted order, match tuples
  - Cost: B(R)+B(S)
- Total cost: 5B(R)+5B(S)
- Assumption: B(R) <= M^2, B(S) <= M^2

Two-Pass Join Algorithm Based on Sorting

Join R ⋈ S

- If B(R) + B(S) <= M^2
  - Or if use a priority queue to create runs of length 2|M|
- If the number of tuples in R matching those in S is small (or vice versa)
- We can compute the join during the merge phase

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

Summary of Join Algorithms

- Nested Loop Join: B(R) + B(R)B(S)
  - Assuming page-at-a-time refinement
- Hash Join: 3B(R) + 3B(S)
  - Assuming: min(B(R), B(S)) <= M^2
- Sort-Merge Join: 3B(R)+3B(S)
  - Assuming B(R)+B(S) <= M^2
- Index Nested Loop Join: B(R)+T(R)B(S)/V(S,a)
  - Assuming S has clustered index on a

Summary of Query Execution

- For each logical query plan
  - There exist many physical query plans
  - Each plan has a different cost
  - Cost depends on the data
- Additionally, for each query
  - There exist several logical plans
- Explore on your own: query optimization
  - How to compute the cost of a complete plan?
  - How to pick a good query plan for a query?