CS3223 Lecture 5
Query Evaluation: Projection & Join

Projection: $\pi_{A_1,\cdots,A_m}(R)$

- $\pi_L(R)$ projects columns given by list L from relation R
- Example: **select distinct** age **from** R

Relation R

name	age	weight	height
Alice	17	48	175
Bob	15	60	178
Curly	10	65	171
Larry	12	70	175
Lucy	17	45	170
Moe	10	55	180

$\pi_{\mathbf{age}}(\mathbf{R})$

age
17
15
10
12

- $\pi_L^*(R)$ same as $\pi_L(R)$ but preserves duplicates

$\pi^*_{\mathbf{age}}(\mathbf{R})$

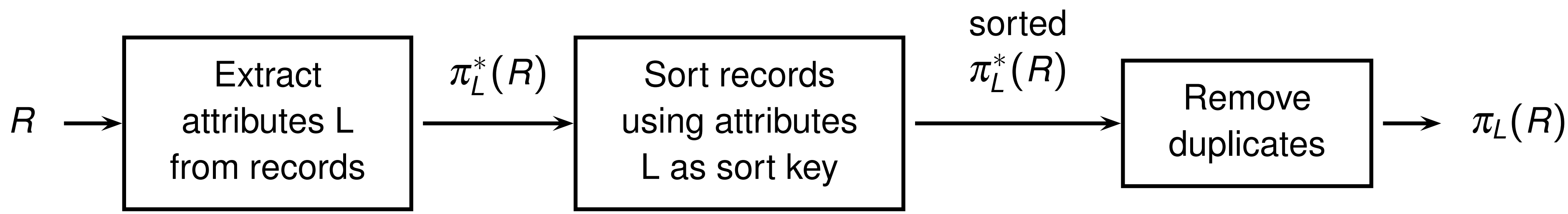
age
17
15
10
12
17
10

Projection Operation, $\pi_{A_1,\cdots,A_m}(R)$

- Projection involves two tasks:
  1. remove unwanted attributes
  2. eliminate any duplicate tuples produced
- Two approaches:
  - Projection based on sorting
  - Projection based on hashing

Sort-based Approach

Consider $\pi_L(R)$ where L denote some sequence of attributes of R



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$\pi^*_{\textbf{age}}(\mathbf{R})$

age
17
15
10
12
17
10

Sorted $\pi^*_{\textbf{age}}(\mathbf{R})$

age
10
10
12
15
17
17

$\pi_{\textbf{age}}(\mathbf{R})$

age
10
12
15
17

Sort-based Approach

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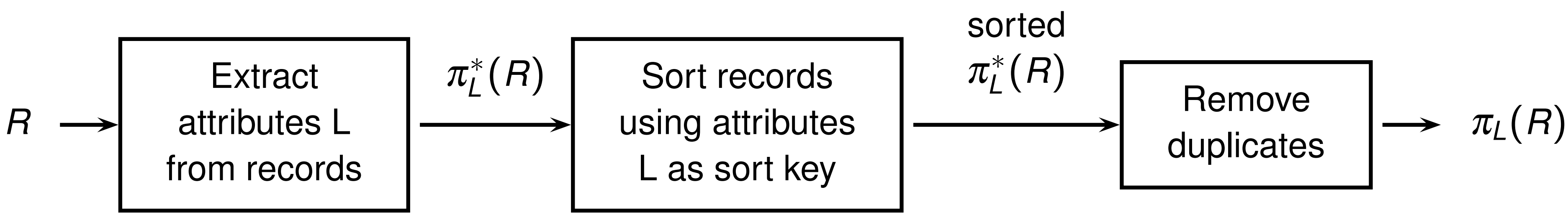
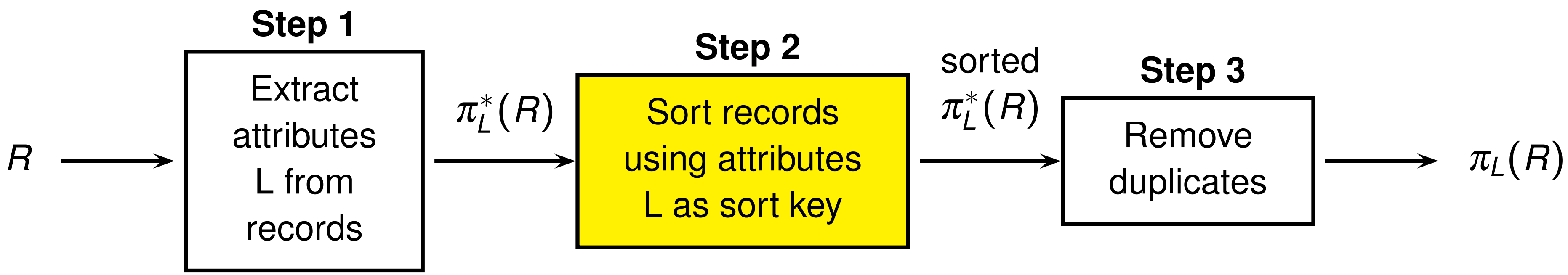


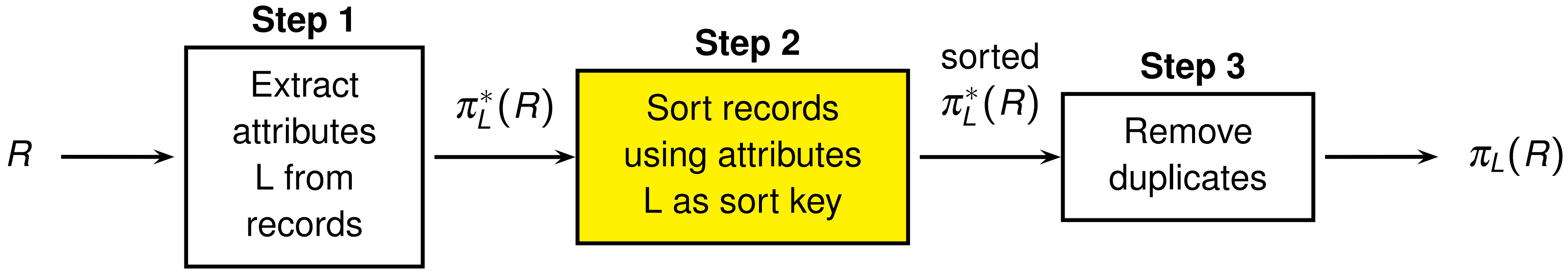
Cost Analysis

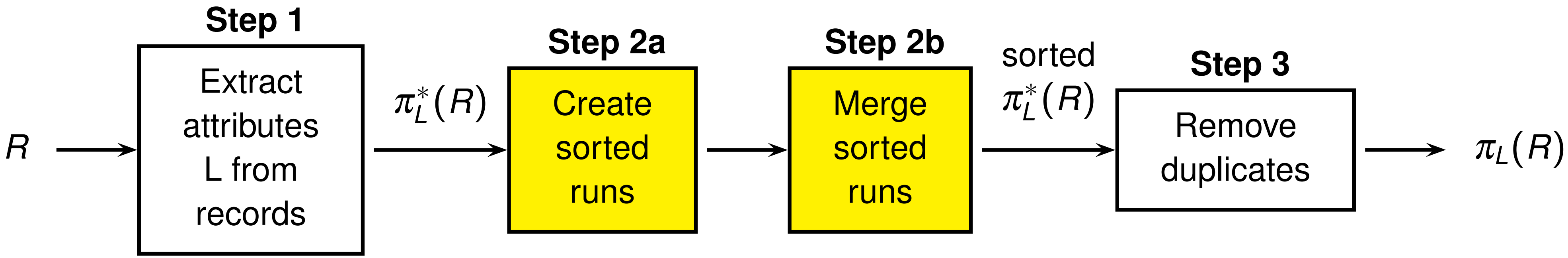
- **Step 1**:
  - Cost to scan records = $|R|$
  - Cost to output temporary result = $|\pi_L^*(R)|$
- **Step 2**:
  - Cost to sort records = $2|\pi_L^*(R)|\ (\log_m(N_0) + 1)$
  - $N_0 =$ number of initial sorted runs, $\quad m =$ merge factor
- **Step 3**:
  - Cost to scan records = $|\pi_L^*(R)|$

Optimized Sort-based Approach



Optimized Sort-based Approach





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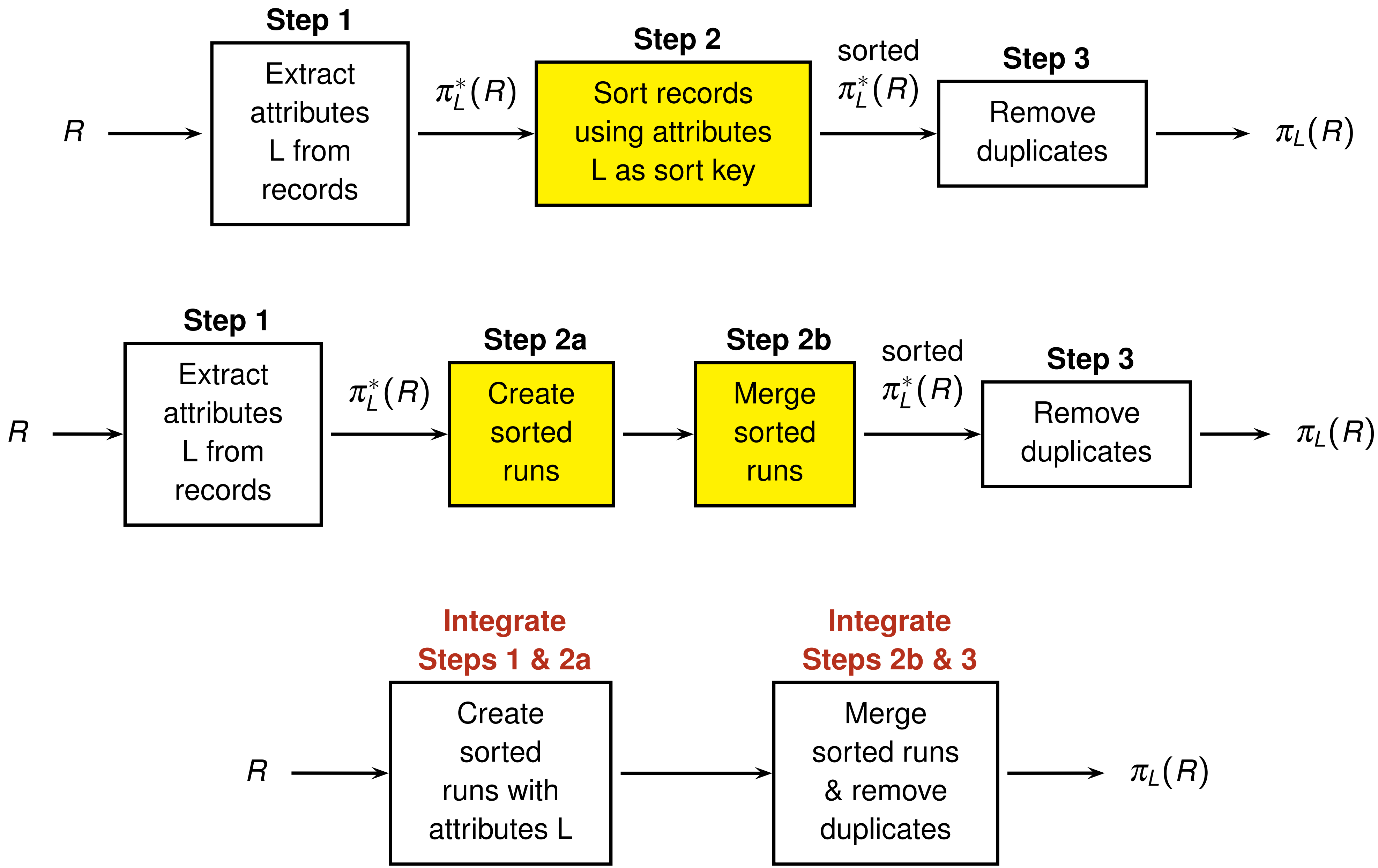


Hash-based Approach

- Consider $\pi_L(R)$
- Build a main-memory hash table to detect & remove duplicates

initialize an empty hash table T
for each tuple t in R do
    apply hash function h on $\pi_L(t)$
    let t be hashed to bucket B_i in T
    if ($\pi_L(t)$ is not in B_i) then
        insert $\pi_L(t)$ into B_i
return all entries in T

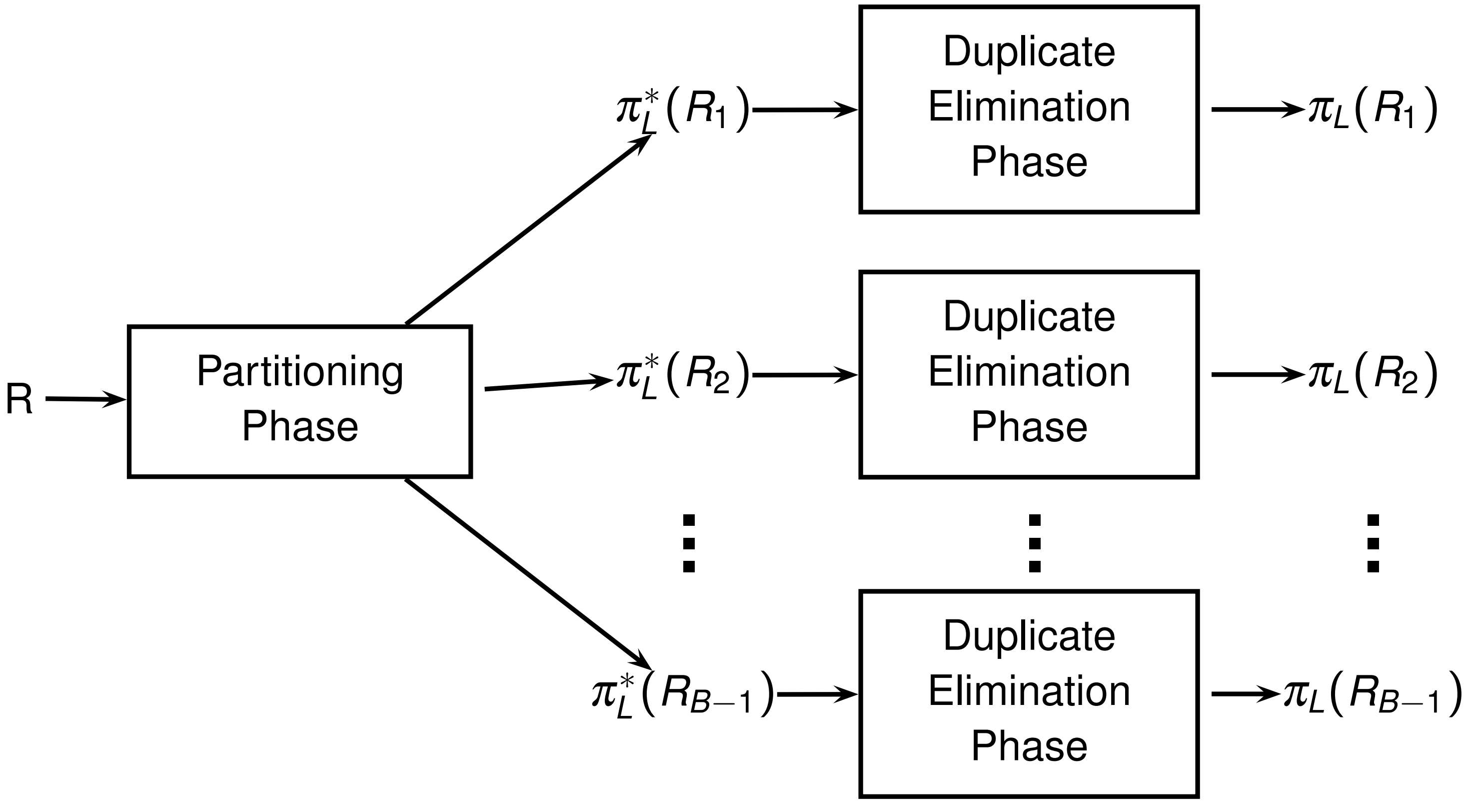
Hash-based Approach

Consists of two phases:

1. Partitioning phase: partitions R into $R_1, R_2, \cdots, R_{B-1}$
    - Hash on $\pi_L(t)$ for each tuple $t \in R$
    - $R = R_1 \cup R_2 \cup \cdots \cup R_{B-1}$
    - $\pi_L^*(R_i) \cap \pi_L^*(R_j) = \emptyset$ for each pair R_i & R_j, $i \neq j$
2. Duplicate elimination phase: eliminates duplicates from each $\pi_L^*(R_i)$

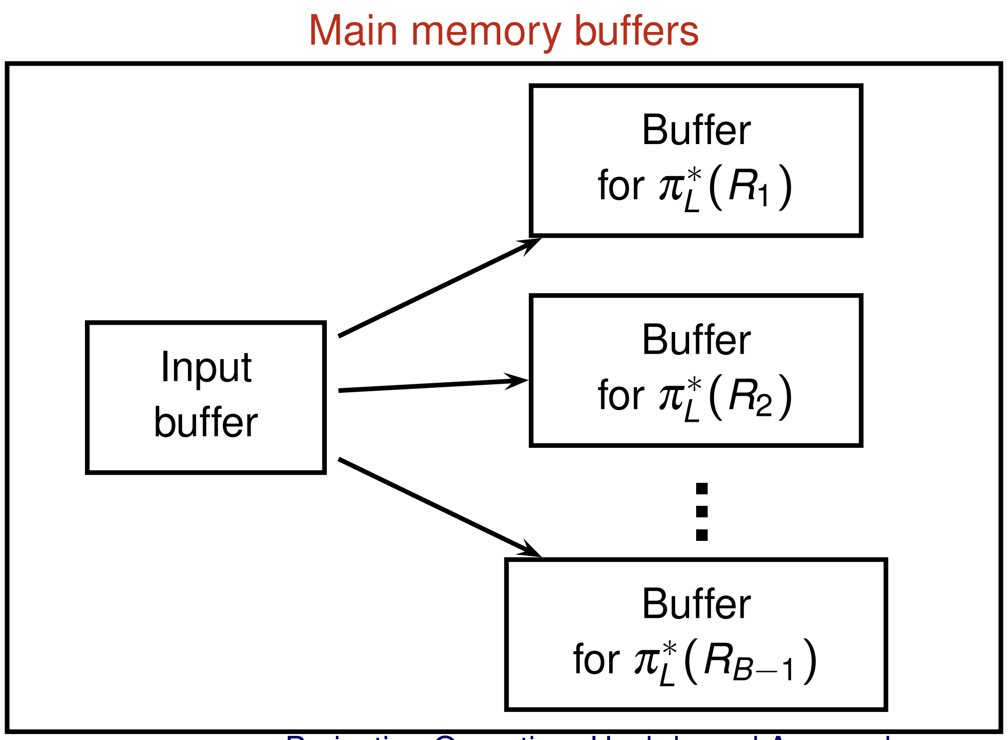
$\pi_L(R)$ = duplicate-free union of $\pi_L(R_1), \pi_L(R_2), \cdots, \pi_L(R_{B-1})$

Hash-based Approach (cont.)



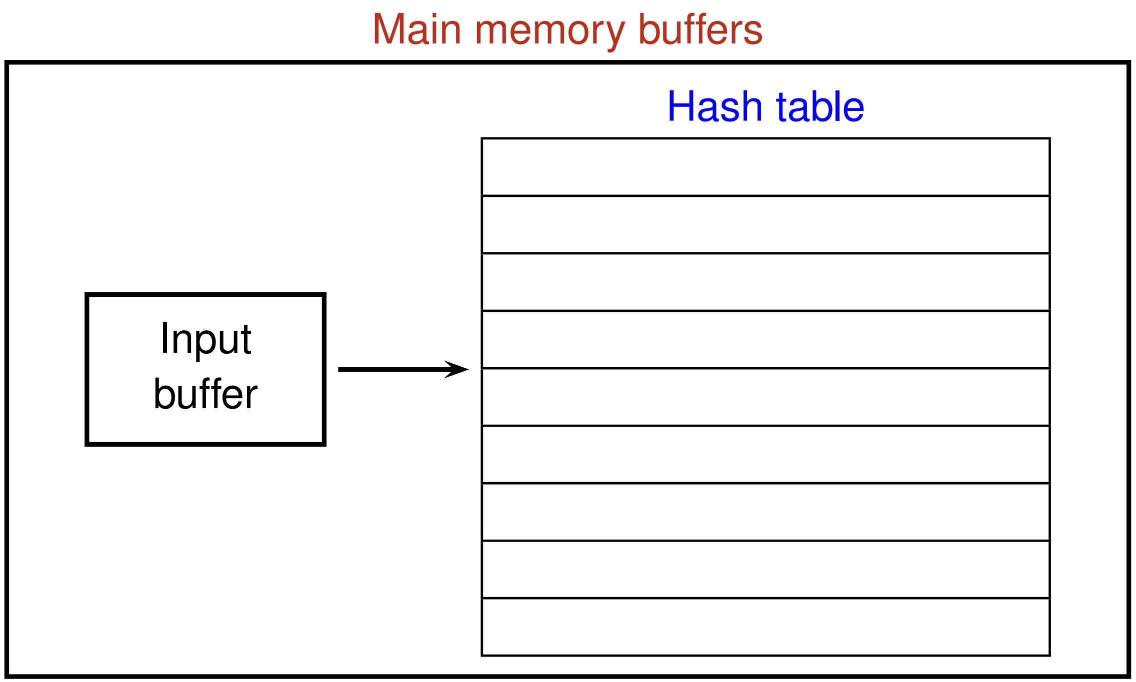
Partitioning Phase

- Use one buffer for input & $(B - 1)$ buffers for output
- Read R one page at a time into input buffer
- For each tuple t in input buffer,
  - project out unwanted attributes from t to form t'
  - apply a hash function h on t' to distribute t' into one output buffer
  - flush output buffer to disk whenever buffer is full

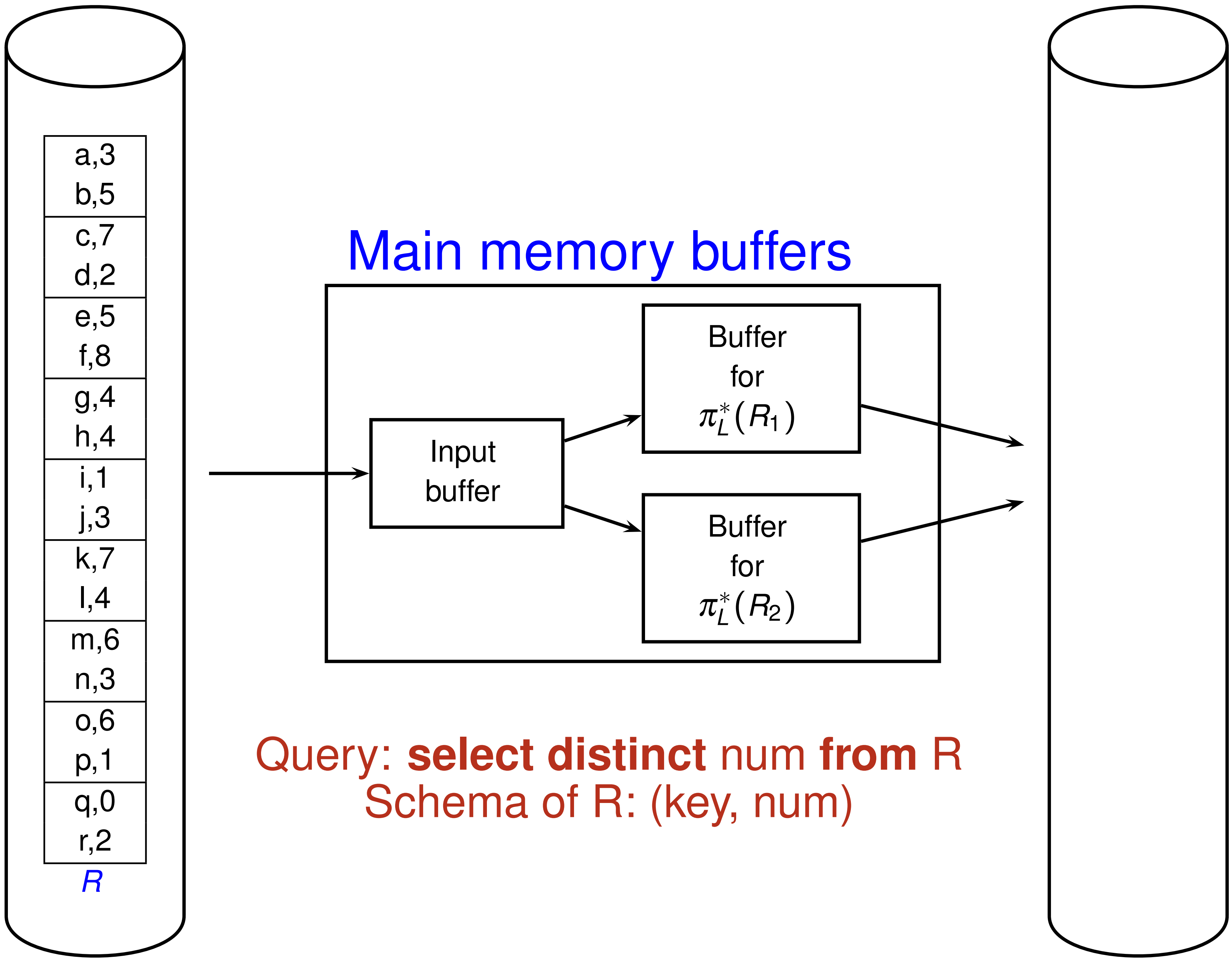


Duplicate Elimination Phase

- For each partition R_i,
  - Initialize an in-memory hash table
  - Read $\pi_L^*(R_i)$ one page at a time; for each tuple t read,
    - Hash t into bucket B_j with hash function h' ($h' \neq h$)
    - Insert t into B_j if $t \notin B_j$
  - Write out tuples in hash table to results

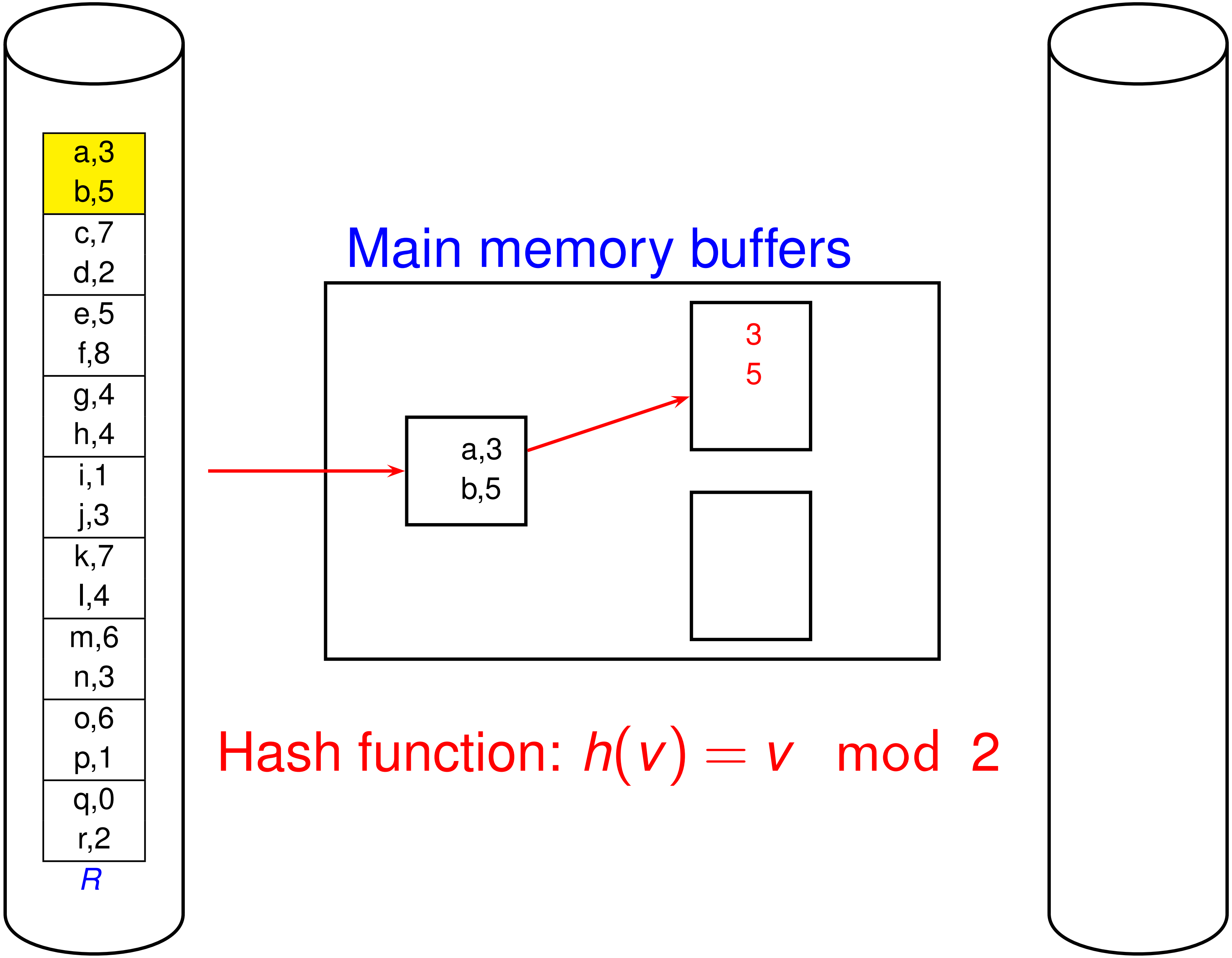


Partitioning Phase



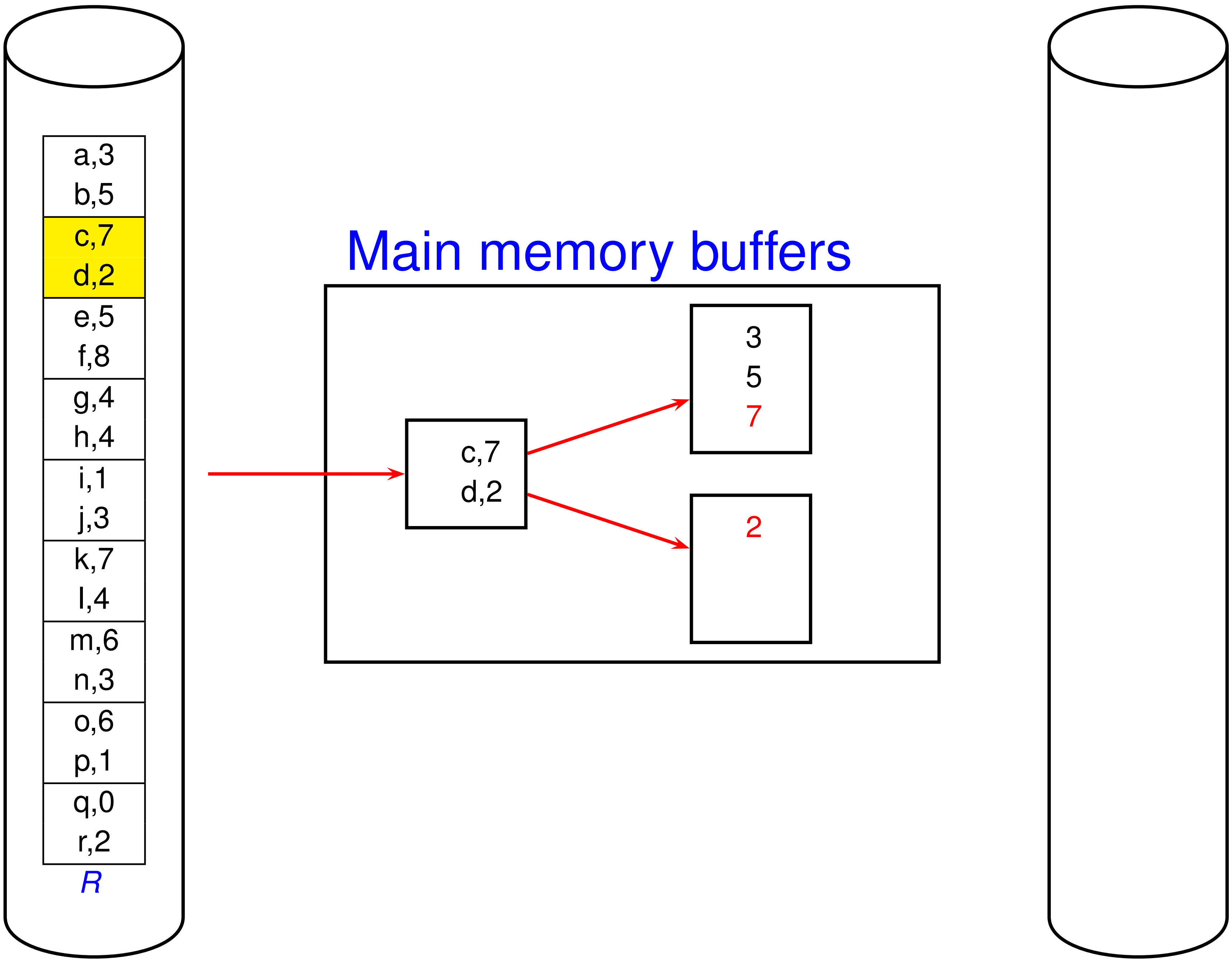
Query: **select distinct** num **from** R
Schema of R: (key, num)

Partitioning Phase

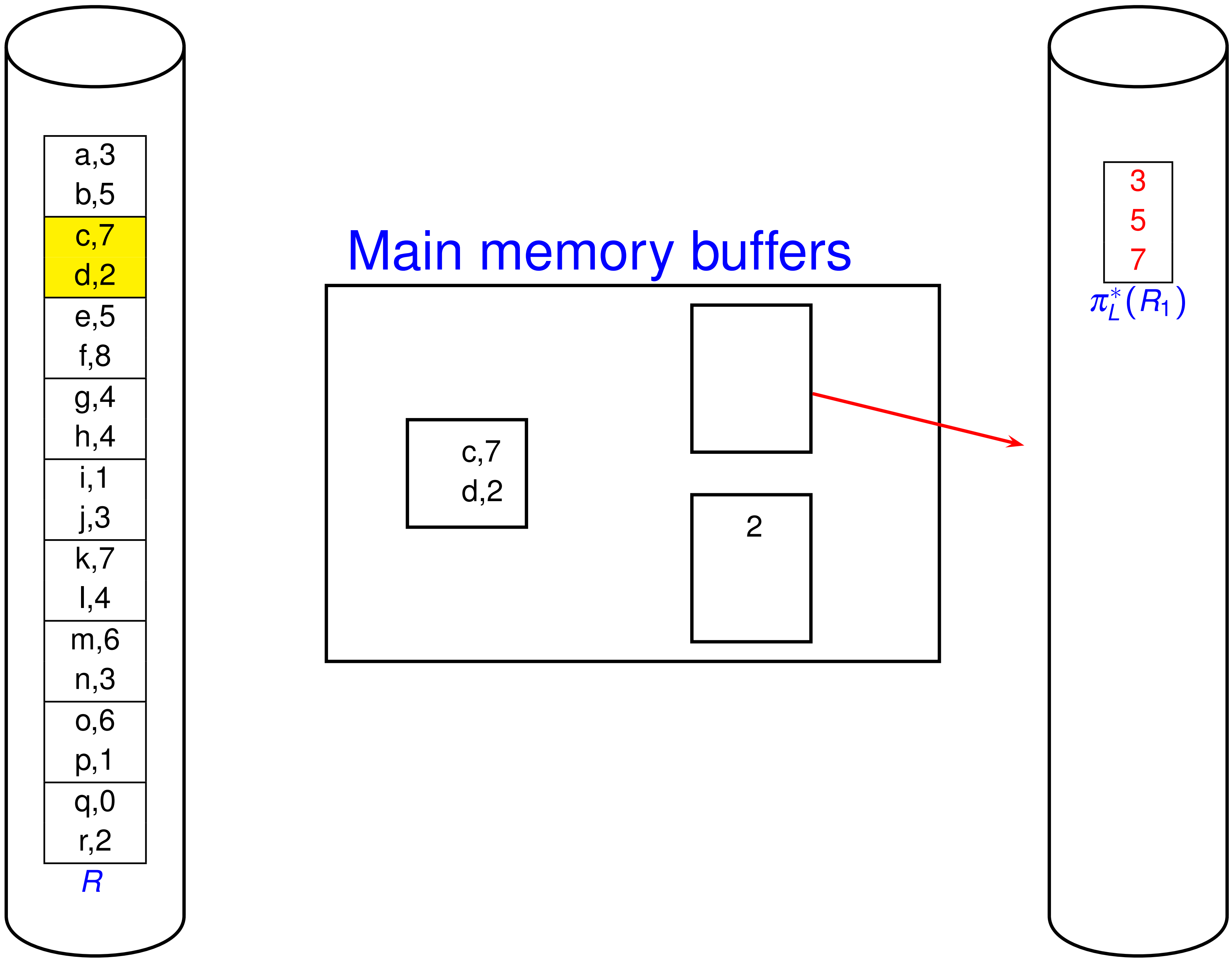


Hash function: $h(v) = v \mod 2$

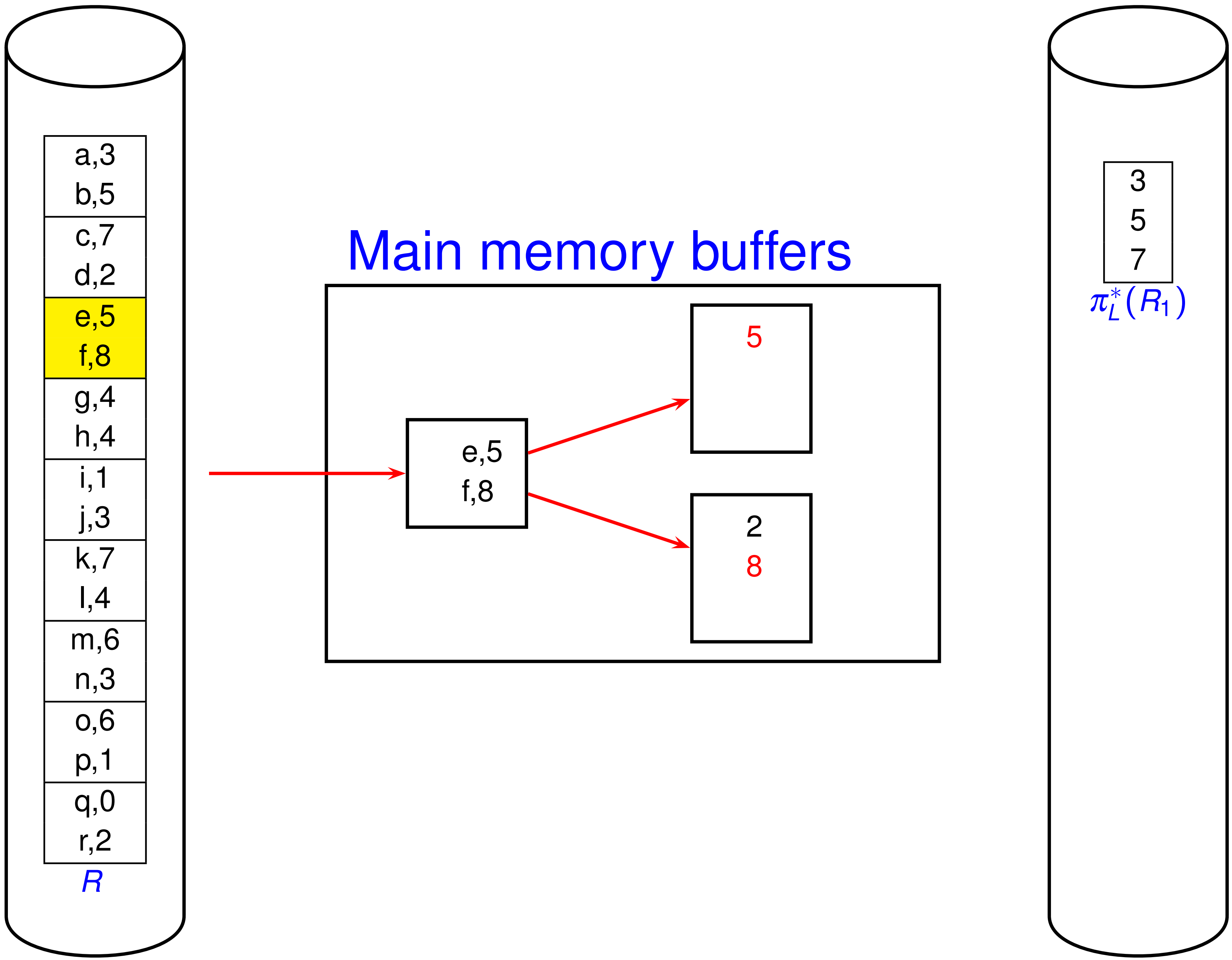
Partitioning Phase



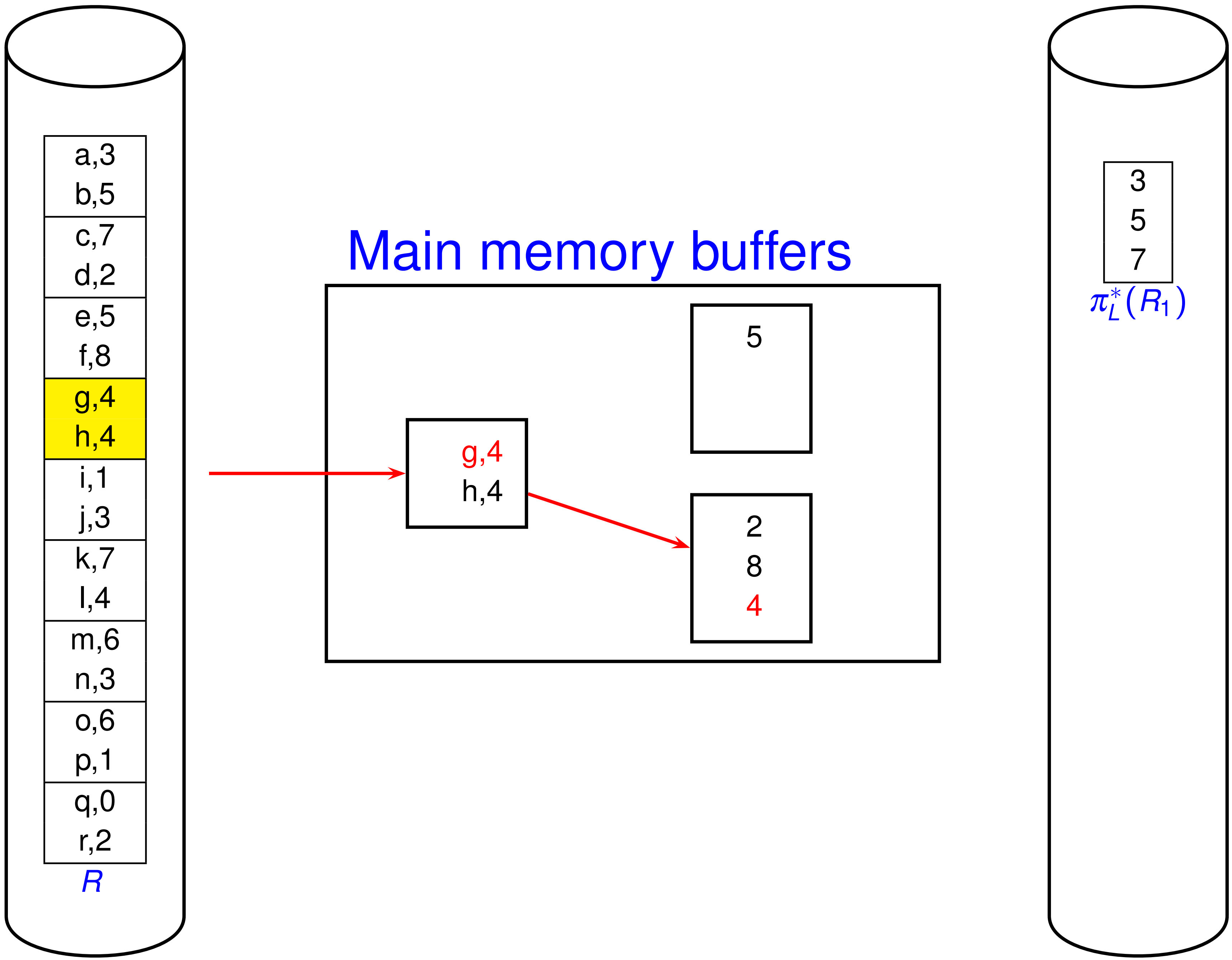
Partitioning Phase



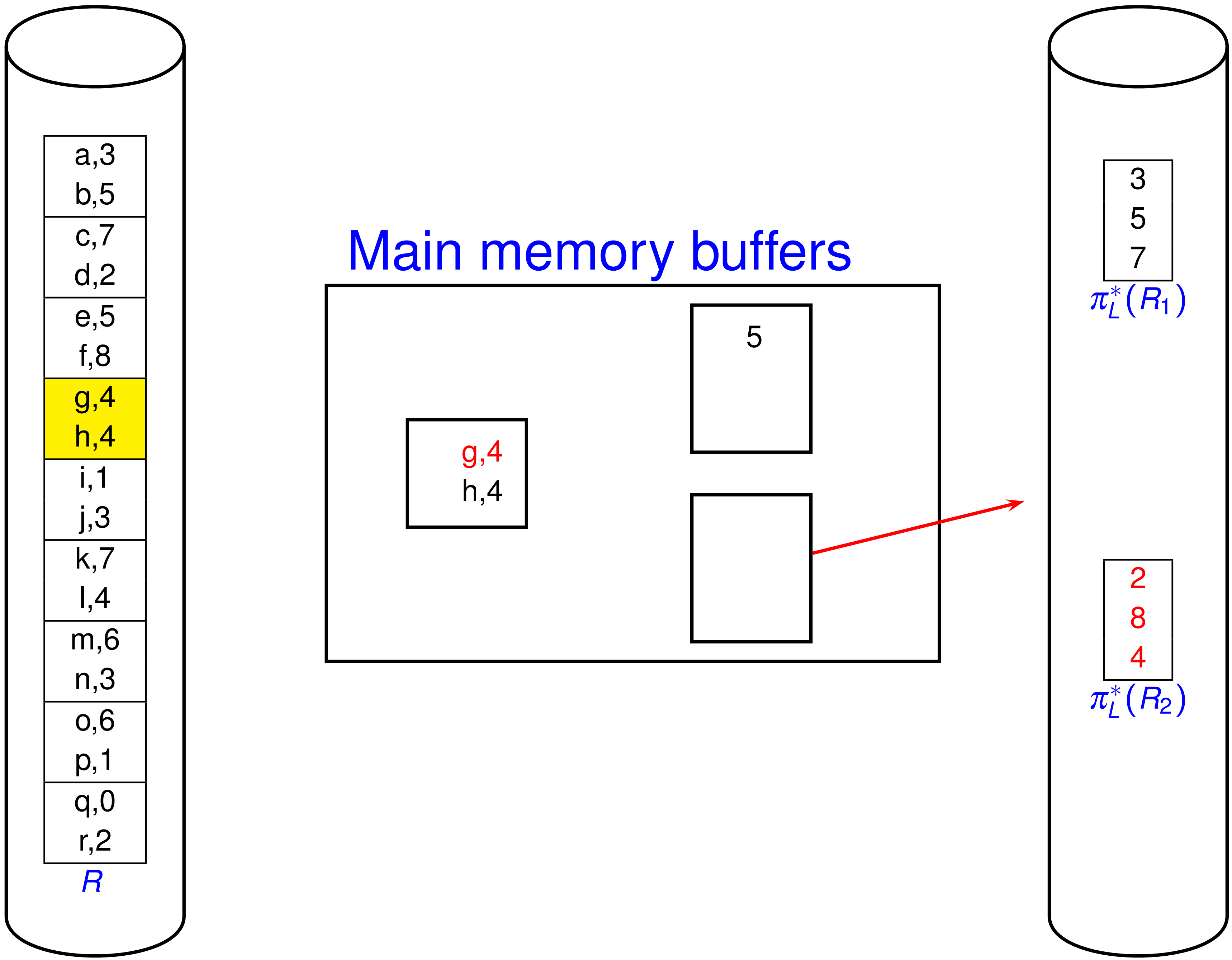
Partitioning Phase



Partitioning Phase



Partitioning Phase



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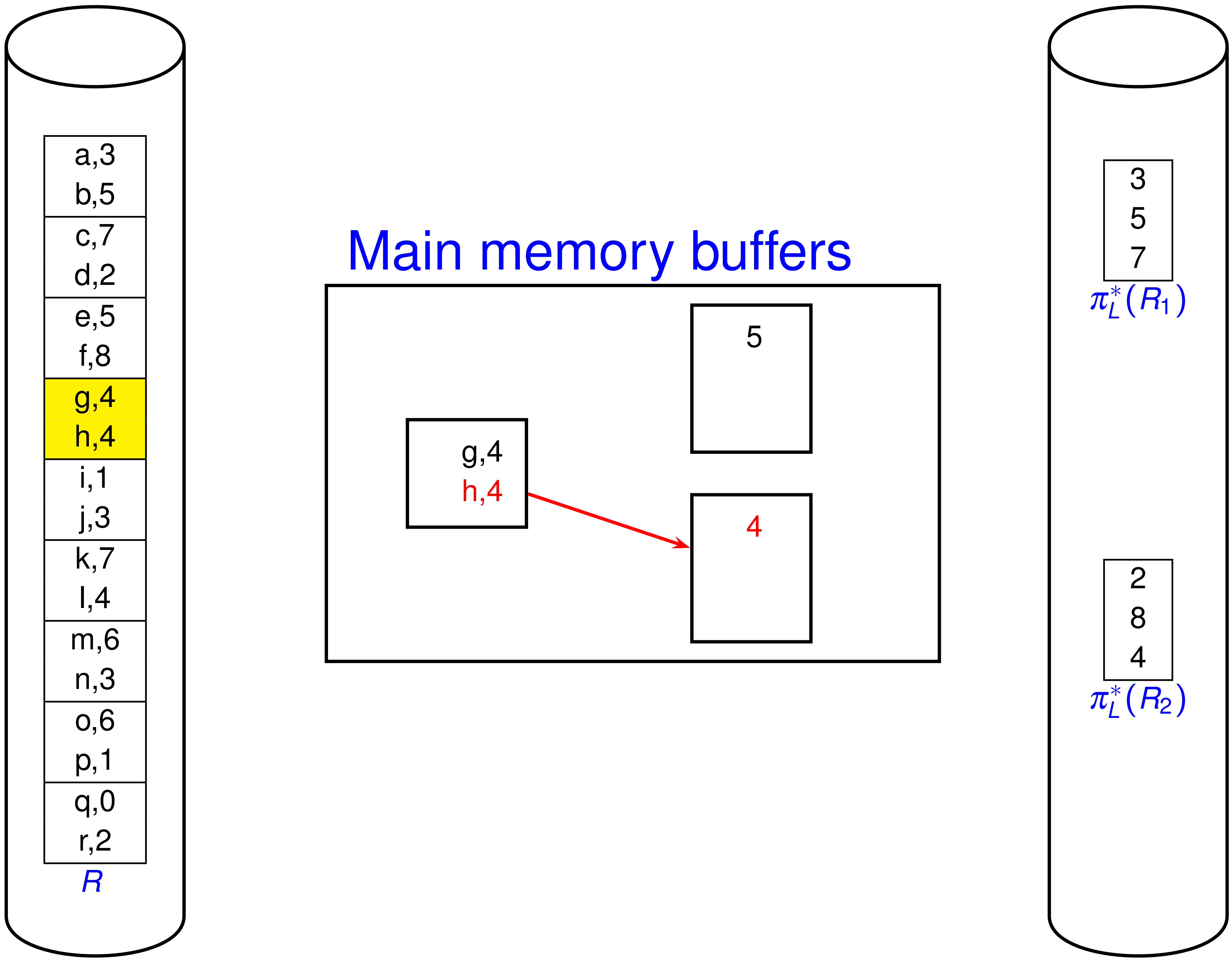

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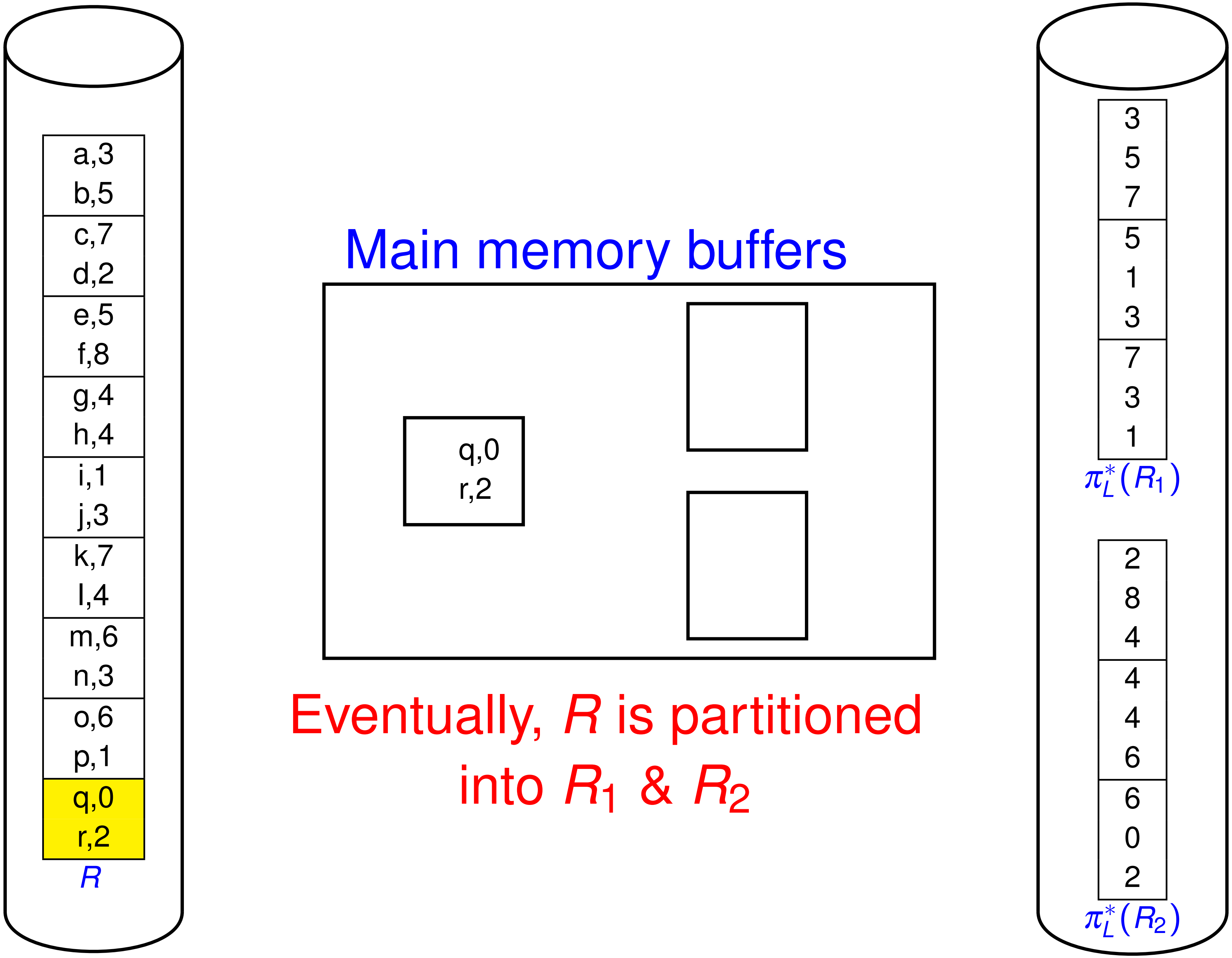
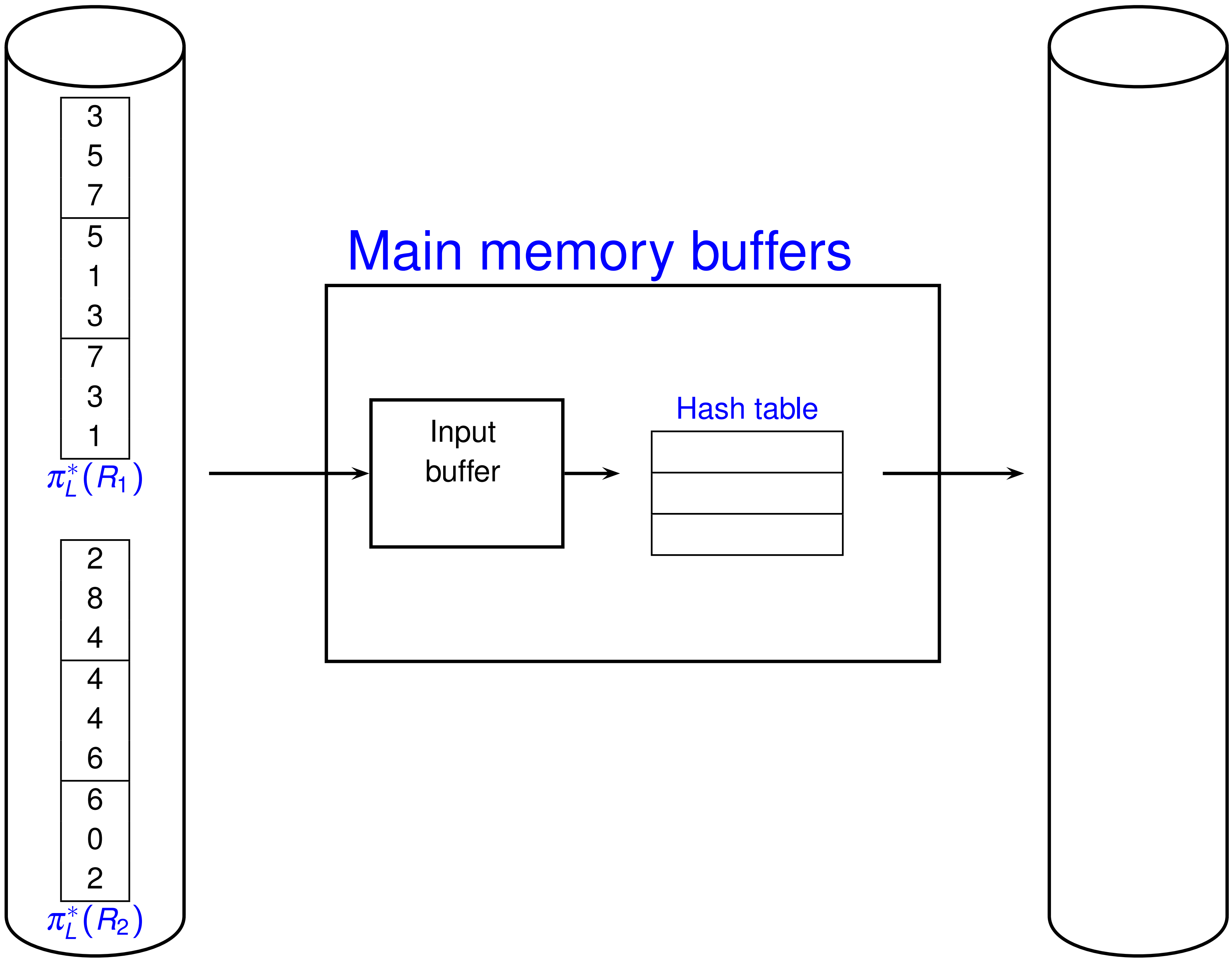


Duplicate Elimination Phase



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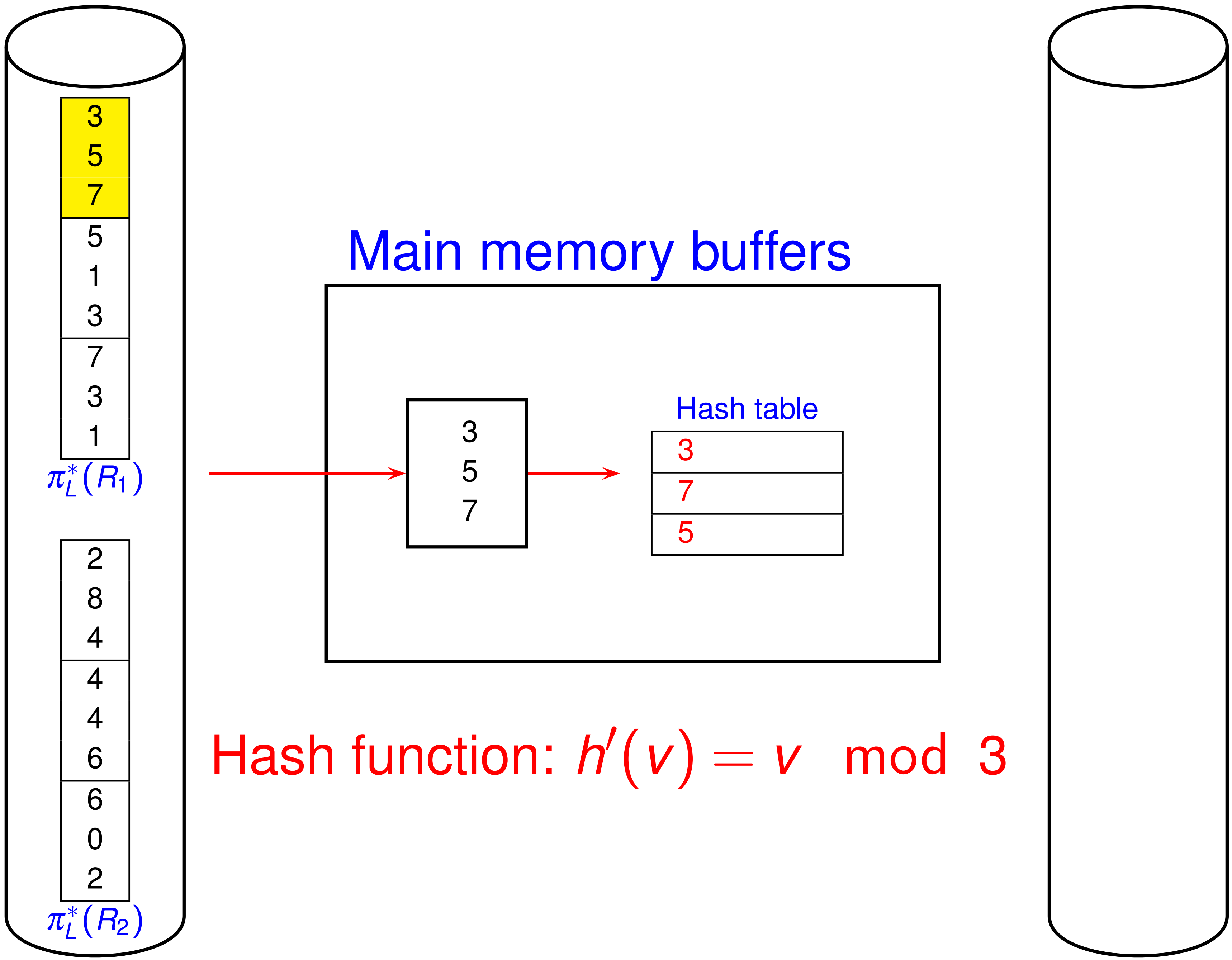

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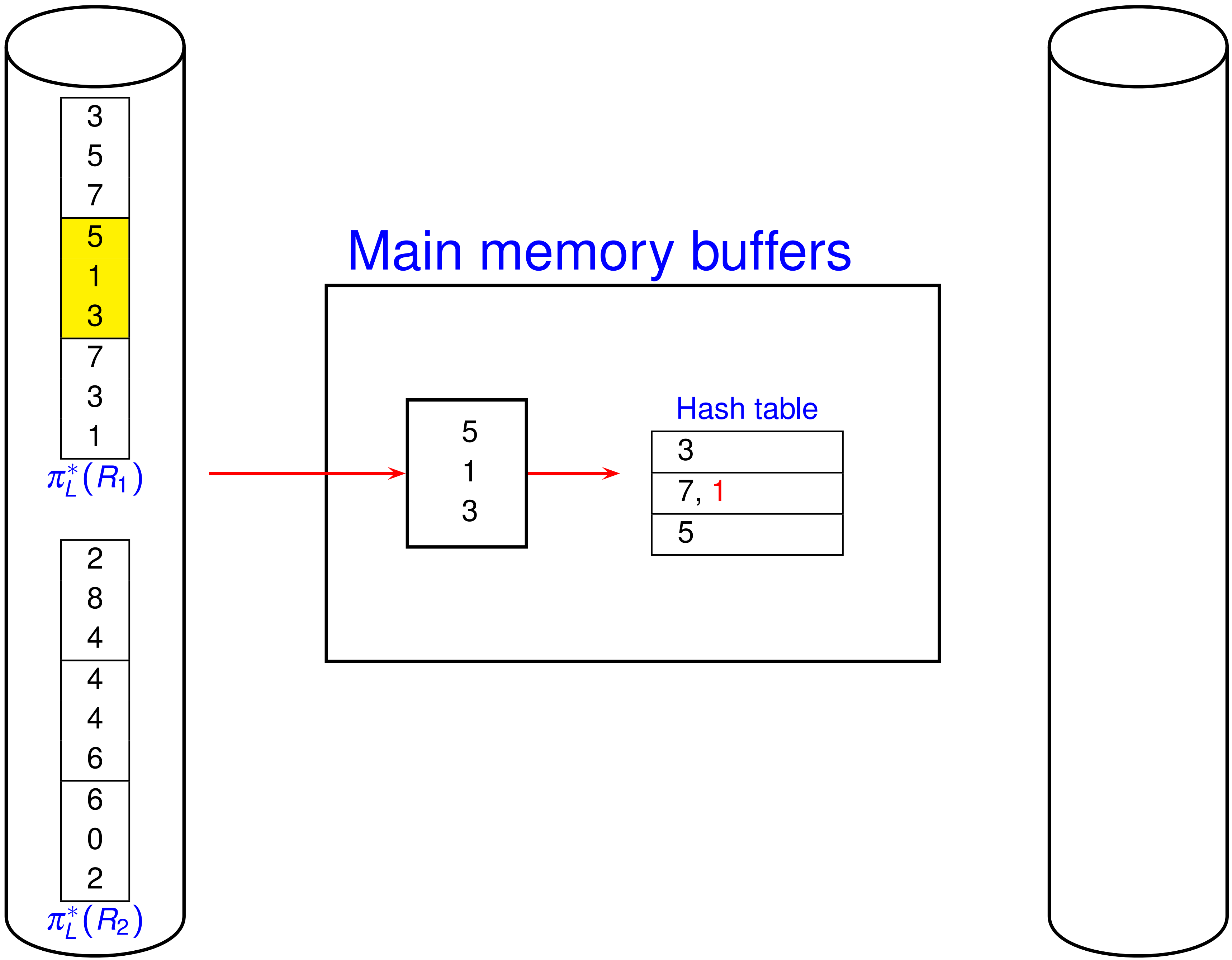

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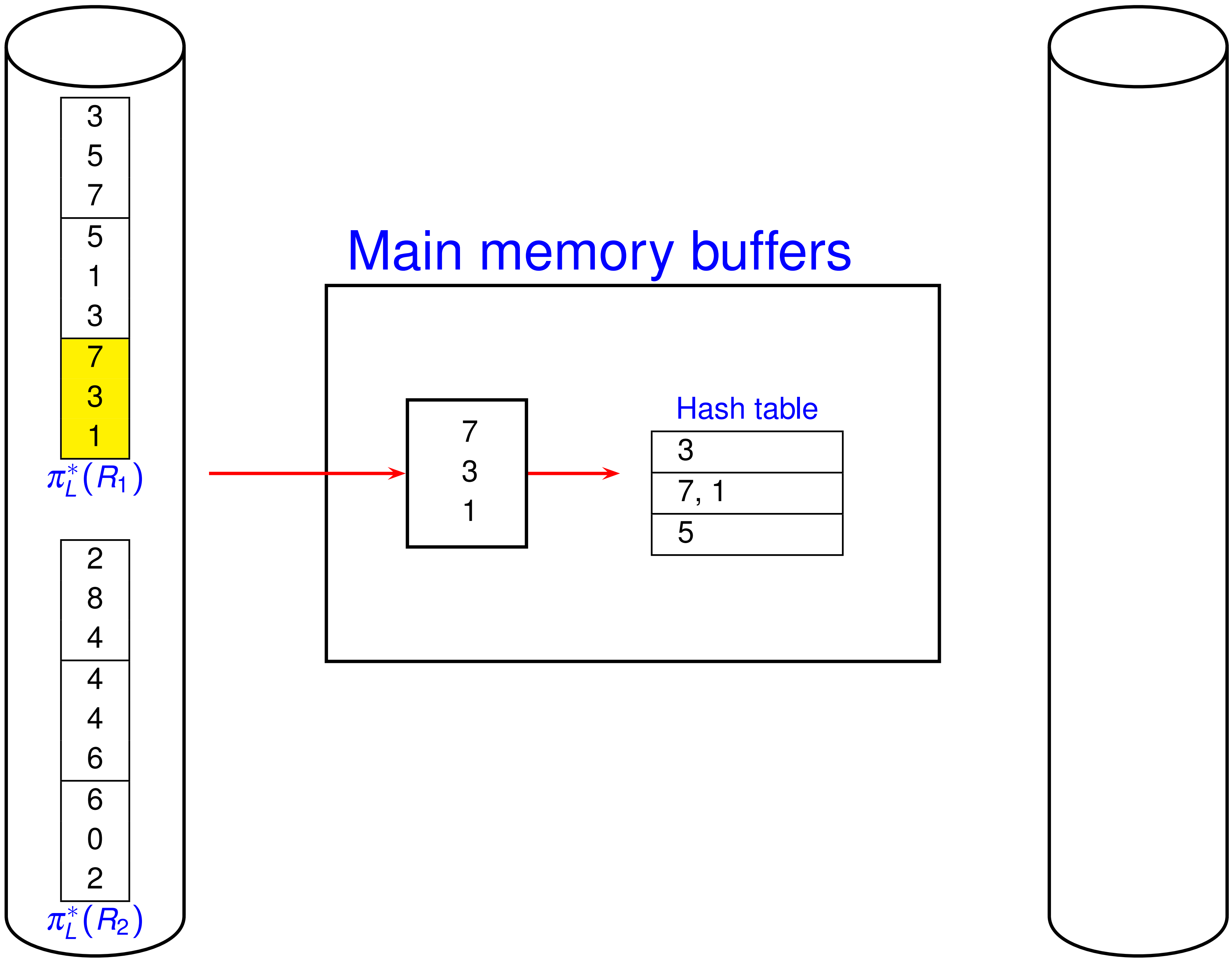

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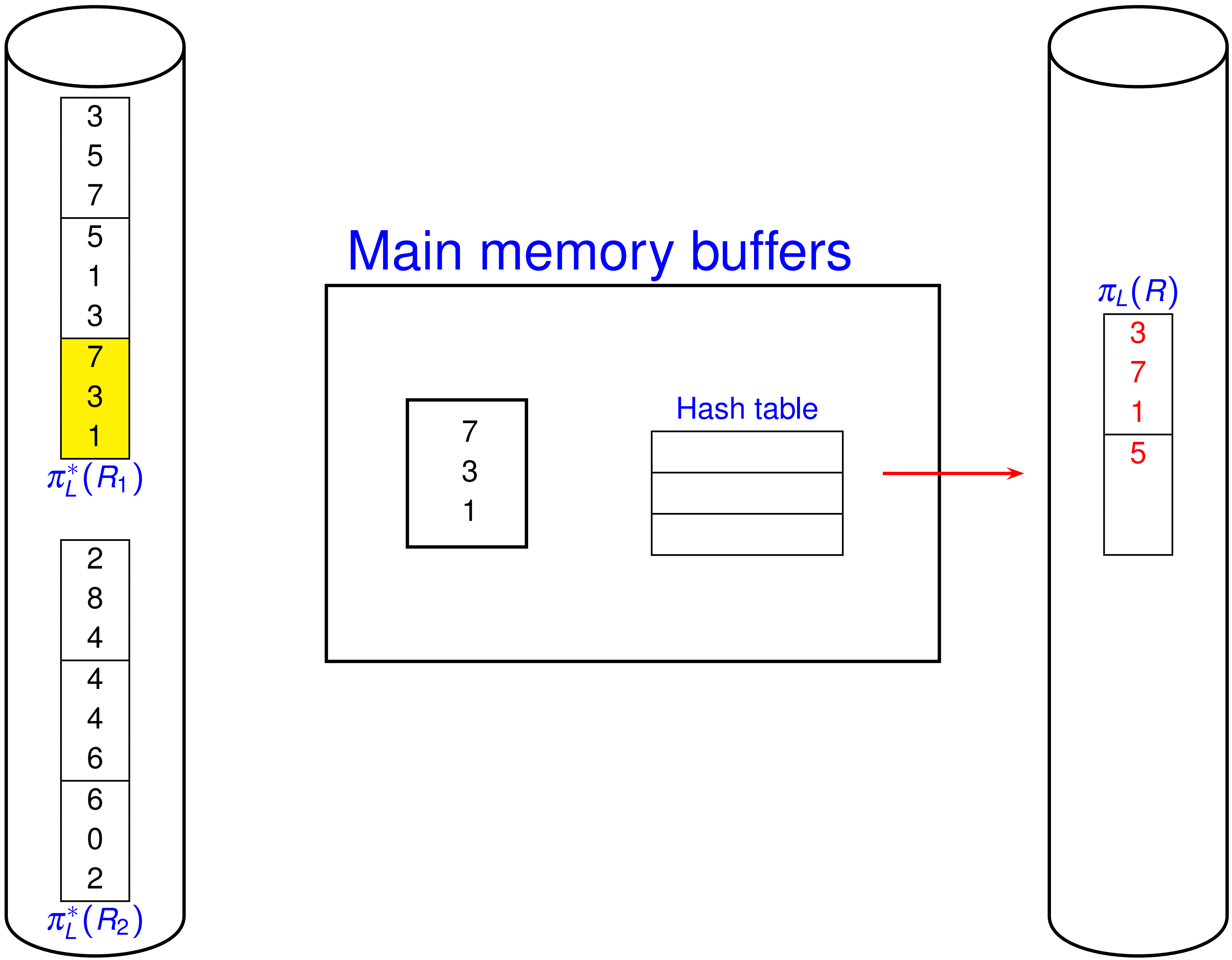

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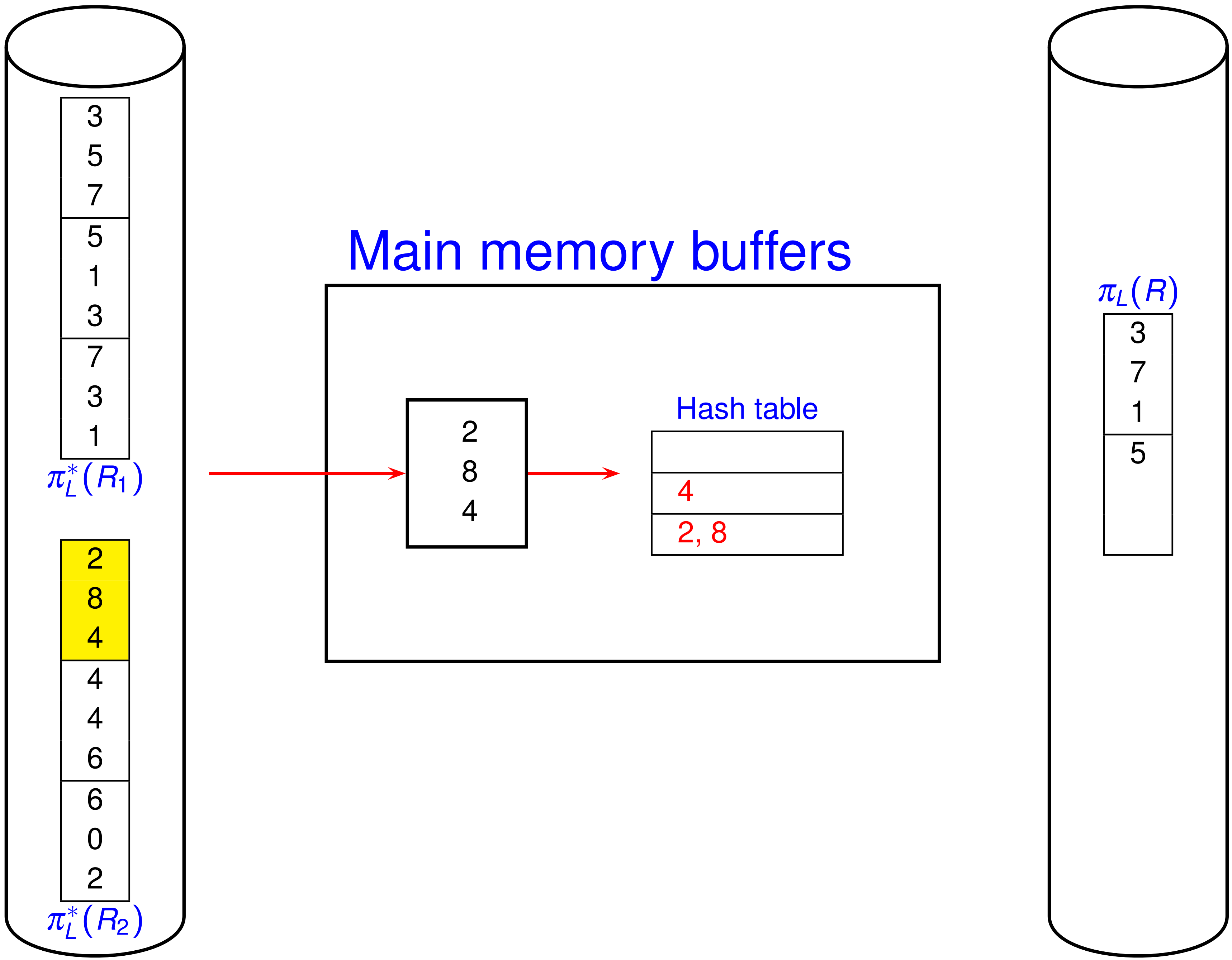

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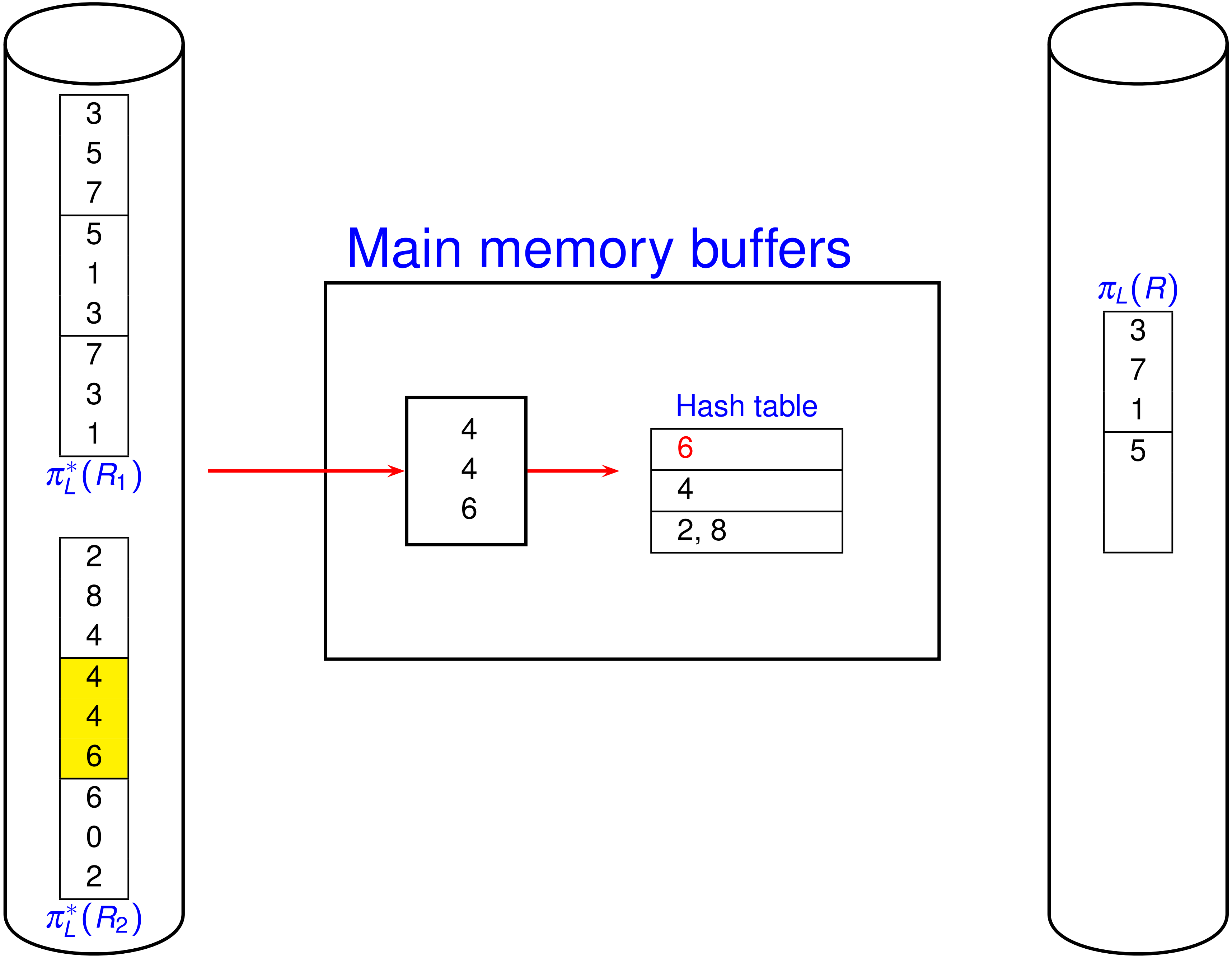

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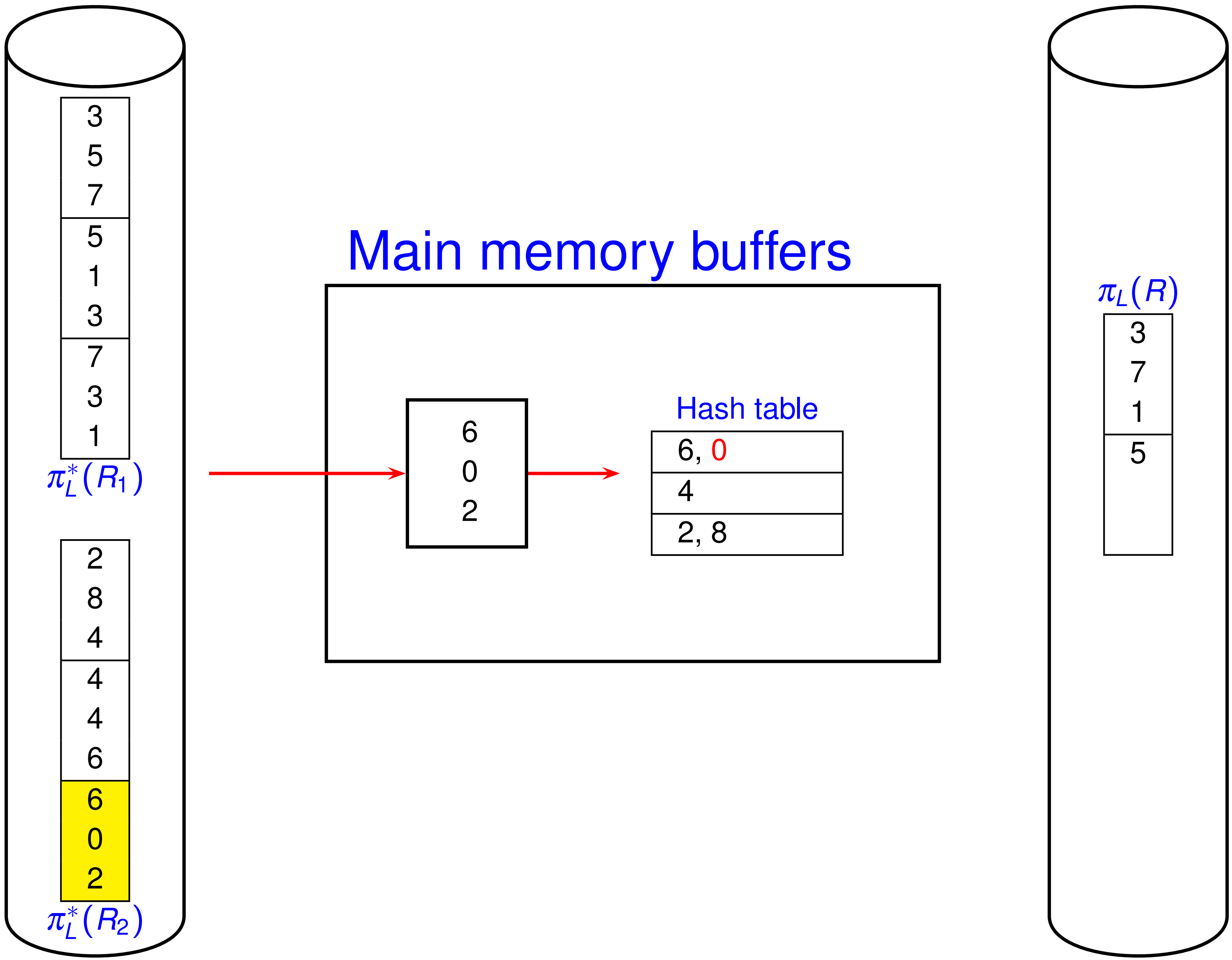

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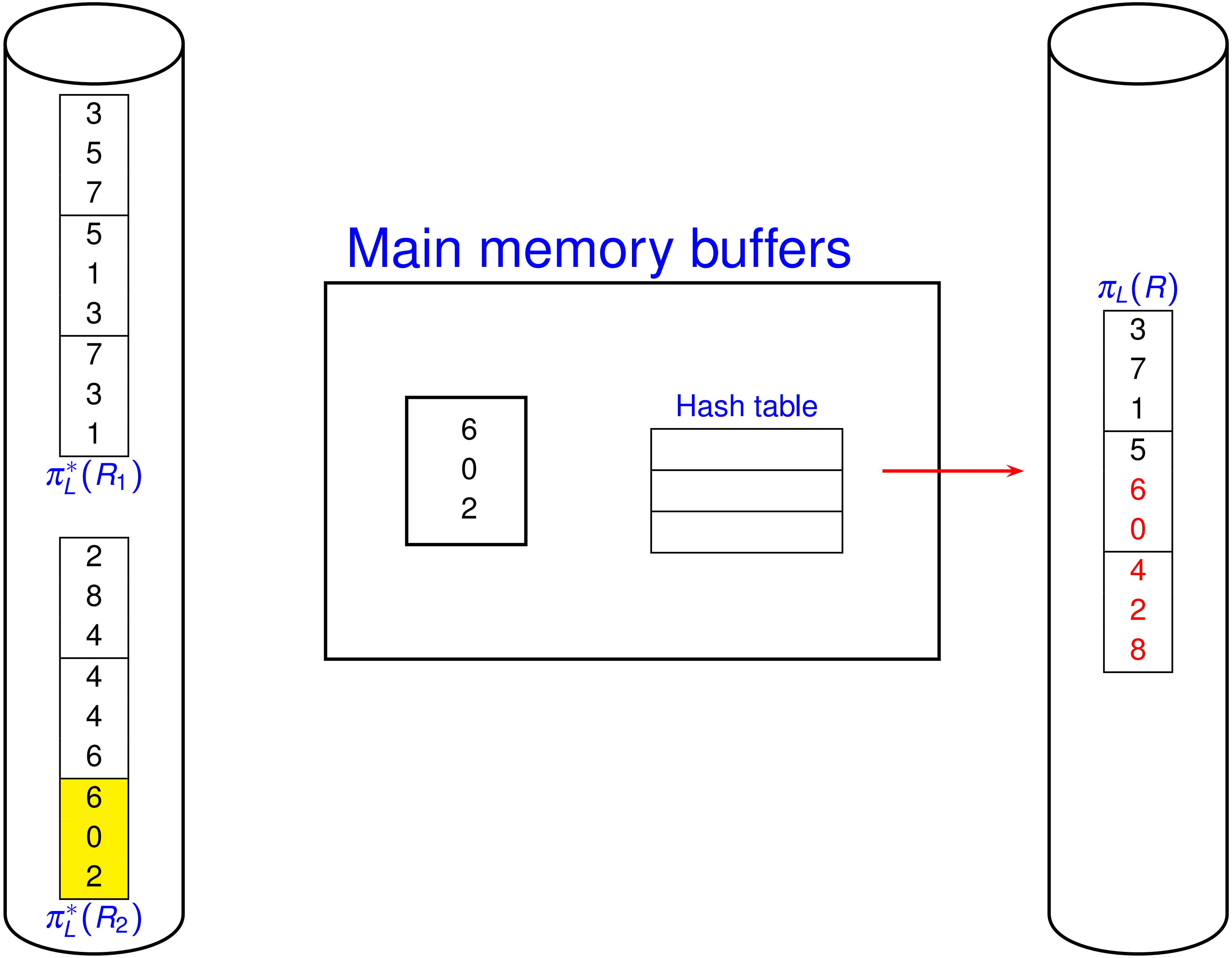
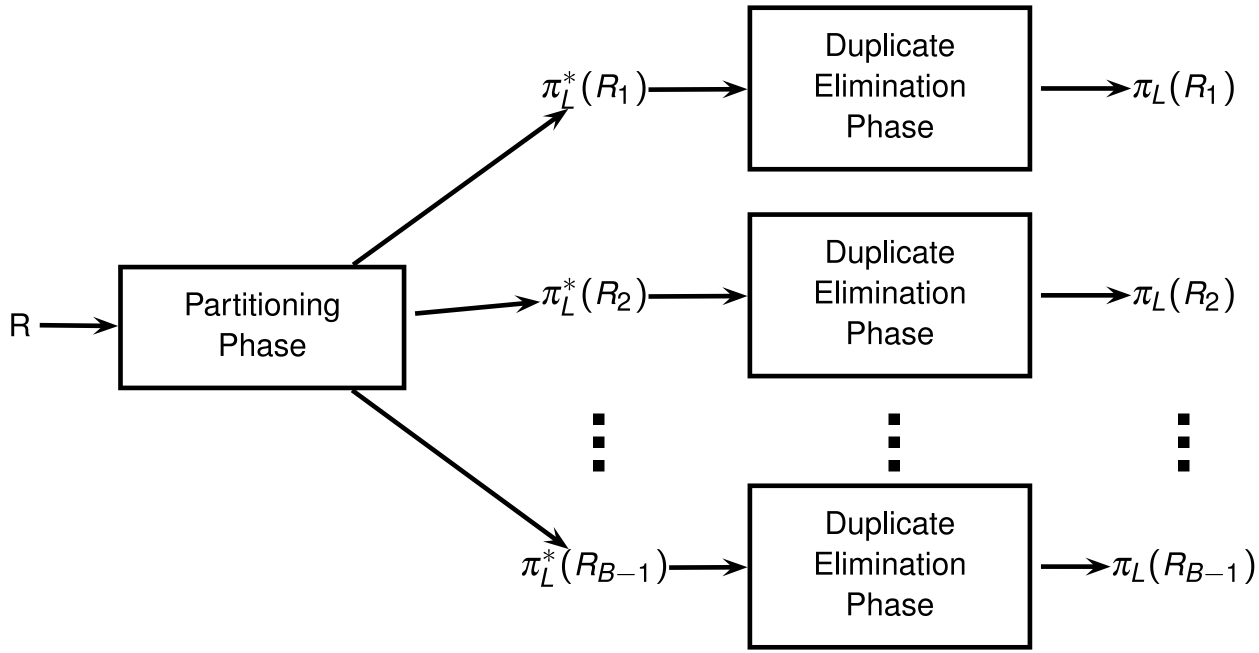


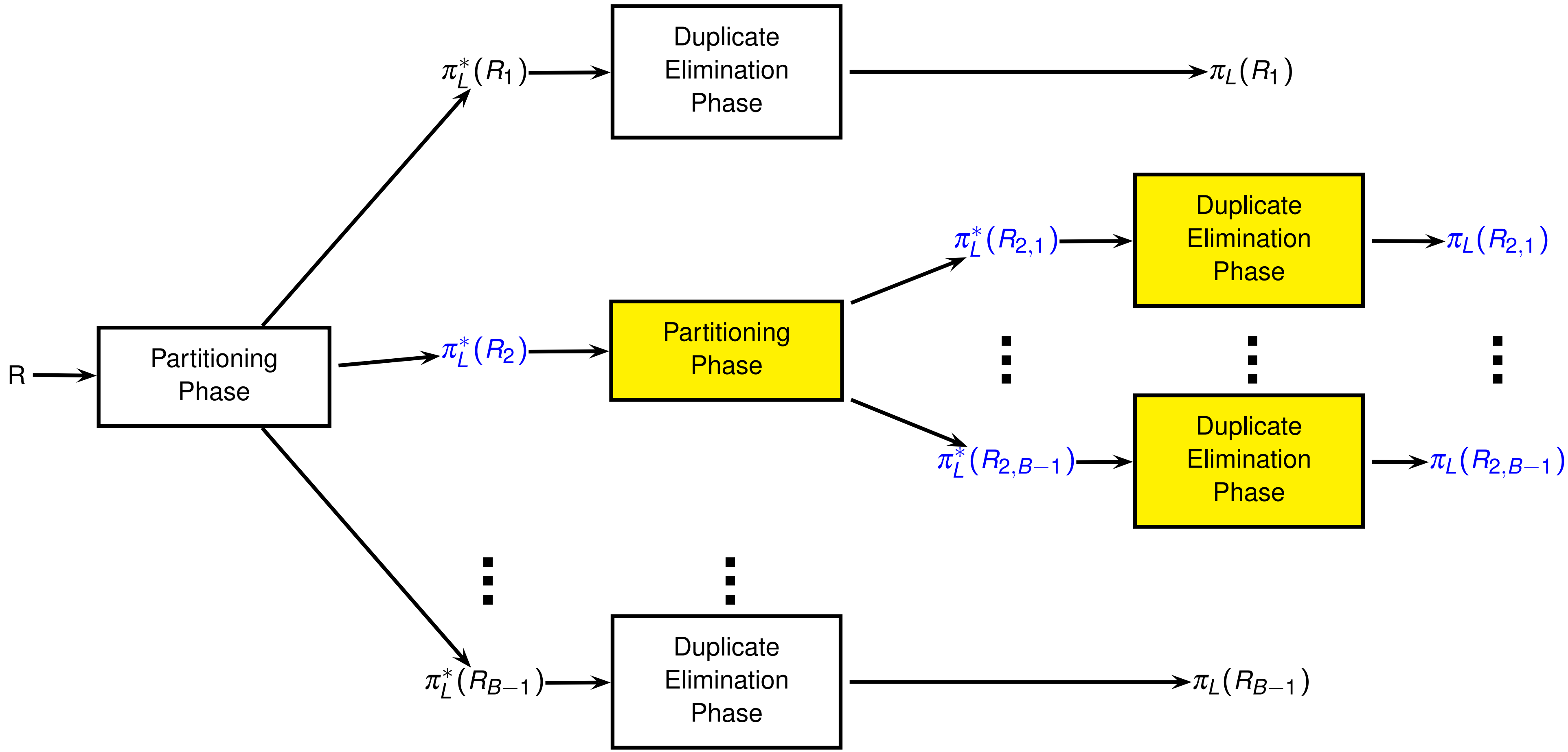
Hash-based Approach: Partition Overflow

- **Partition overflow problem**: Hash table for $\pi_L^*(R_i)$ is larger than available memory buffers
  - Recursively apply hash-based partitioning to the overflowed partition
- **Example**: Without partition overflow



Hash-based Approach: Partition Overflow

- **Example**: Partition R_2 overflows



Hash-based Approach: Analysis

- Approach is effective if B is large relative to $|R|$
- How large should B be?
  - Assume that h distributes tuples in R uniformly
  - Each R_i has $\frac{|\pi_L^*(R)|}{B-1}$ pages
  - Size of hash table for each R_i = $\frac{|\pi_L^*(R)|}{B-1} \times f$
    - ★ *f = fudge factor*
  - Therefore, to avoid partition overflow, $B > \frac{|\pi_L^*(R)|}{B-1} \times f$
    - ★ Approximately, $B > \sqrt{f \times |\pi_L^*(R)|}$
- Analysis: Assume there's no partition overflow
  - Cost of partitioning phase: $|R| + |\pi_L^*(R)|$
  - Cost of duplicate elimination phase: $|\pi_L^*(R)|$
  - Total cost = $|R| + 2|\pi_L^*(R)|$

Sort-based vs Hash-based

- Hash-based
  - Cost = $\underbrace{|R| + |\pi_L^*(R)|}_{\text{partitioning phase}} + \underbrace{|\pi_L^*(R)|}_{\text{duplicate elimination phase}}$
- Sort-based
  - Output is sorted
  - Good if there are many duplicates or if distribution of hashed values are non-uniform
  - If $B > \sqrt{|\pi_L^*(R)|}$,
    - ★ Number of initial sorted runs $N_0 = \lceil \frac{|R|}{B} \rceil \approx \sqrt{|\pi_L^*(R)|}$
    - ★ Number of merging passes = $log_{B-1}(N_0) \approx 1$
    - ★ Sort-based approach requires 2 passes for sorting
    - ★ Both hash-based & sort-based methods have same I/O cost

Projection Operation: Using Indexes

- If there is an index whose search key contains all the wanted attributes,
  - replace table scan with index scan!
- If index is ordered (e.g., B^+-tree) whose search key includes wanted attributes as a prefix,
  - scan data entries in order
  - compare adjacent data entries for duplicates
  - **Example**:
    - Use B^+-tree index on R with key (A, B) to evaluate query $\pi_A(R)$

Join: $R \bowtie_{\theta} S$

- **Database Schema**:
  - Employee (<u>eid</u>, ename, city, did)
  - Department (<u>did</u>, dname, city, managerId)

- **Example 1**: Find (eid, managerId) pairs where managerId is the manager of eid

$$\pi_{\text{eid,managerId}} \text{ (Employee } \bowtie_{\theta} \text{ Department)}$$
$$\text{where } \theta\text{: Employee.did = Department.did}$$

- **Example 2**: Find (eid, did) pairs where eid and did are co-located in the same city

$$\pi_{\text{eid,did}} \text{ (Employee } \bowtie_{\theta} \text{ Department)}$$
$$\text{where } \theta\text{: Employee.city = Department.city}$$

Join Algorithms

1. Iteration-based
   - block nested loop
2. Index-based
   - index nested loop
3. Partition-based
   - sort-merge join
   - hash join

Join Algorithms (cont.)

- Things to consider when choosing an algorithm:
  - Types of join predicates:
    - equality predicates (e.g. $R.A_i = S.B_j$)
    - inequality predicates: (e.g., $R.A_i < S.B_j$)
  - Sizes of join operands
  - Available buffer space
  - Available access methods
- Given a join $R \bowtie_\theta S$
  - R is referred to as the outer relation
  - S is referred to as the inner relation

Tuple-based Nested Loop Join

- Tuple-based Algorithm:

  for each tuple $r \in R$ do
      for each tuple $s \in S$ do
          if (r matches s) then
              output (r, s) to result

5, 10
2, 10
13, 7

R

4, 10
5, 10

S

Tuple-based Nested Loop Join

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R
$\boxed{5}$, 10
2, 10
13, 7

S
$\boxed{4}$, 10
5, 10

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R
$\boxed{5}$, 10
2, 10
13, 7

S
4, $\boxed{10}$
5, 10

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2, 10
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2, 10
13, 7

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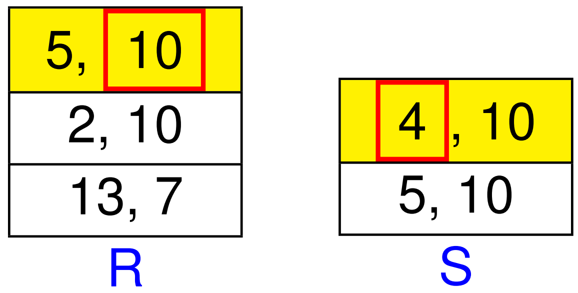

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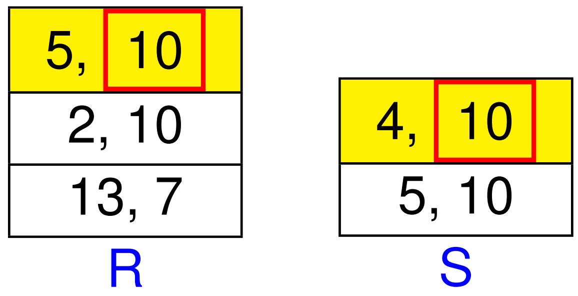

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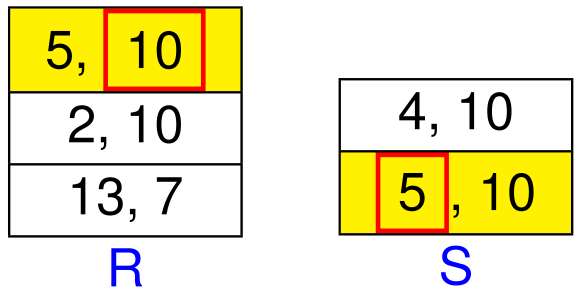

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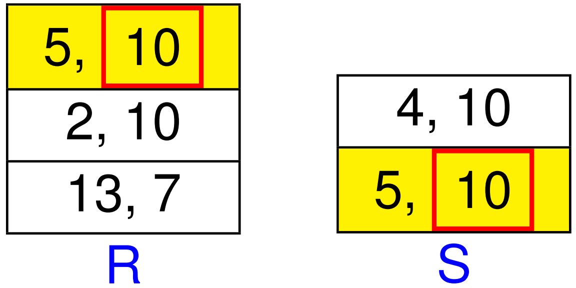

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R
5, 10
$\boxed{2}$, 10
13, 7

S
$\boxed{4}$, 10
5, 10

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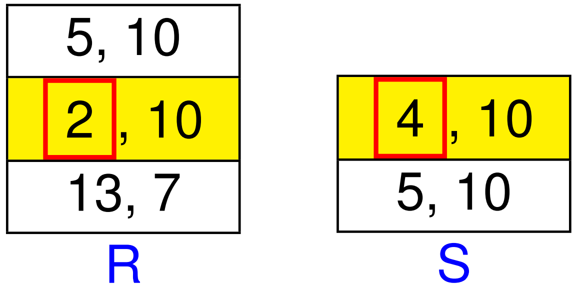

etc ...

Tuple-based Nested Loop Join

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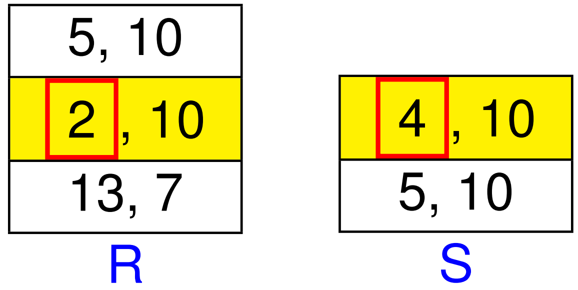

etc ...

- I/O Cost Analysis:

$$\underbrace{|R|}_{\text{scan R}} + \underbrace{||R|| \times |S|}_{\text{scan S}}$$

Page-based Nested Loop Join

- Page-based Algorithm:

for each page P_R of R do
    for each page P_S of S do
        for each tuple $r \in P_R$ do
            for each tuple $s \in P_S$ do
                if (r matches s) then
                    output (r, s) to result

5, 10
2, 10
13, 7

R

4, 10
5, 10

S

Page-based Nested Loop Join

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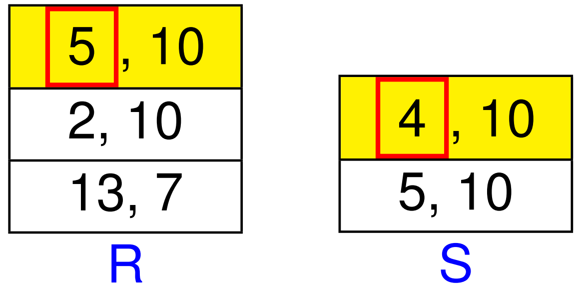

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R
$\boxed{5}$, 10
2, 10
13, 7

S
4, $\boxed{10}$
5, 10

Page-based Nested Loop Join

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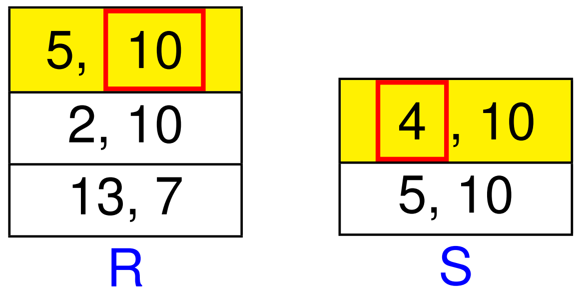

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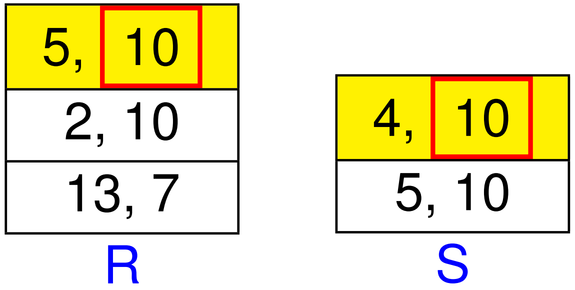

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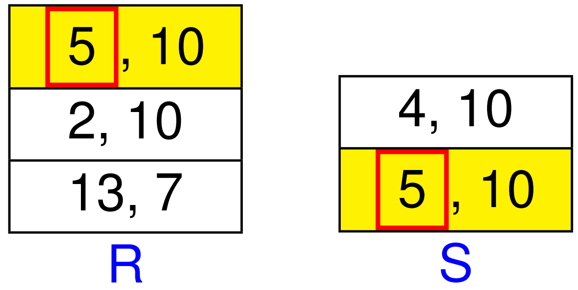

Page-based Nested Loop Join

- Page-based Algorithm:

for each page P_R of R do
    for each page P_S of S do
        for each tuple $r \in P_R$ do
            for each tuple $s \in P_S$ do
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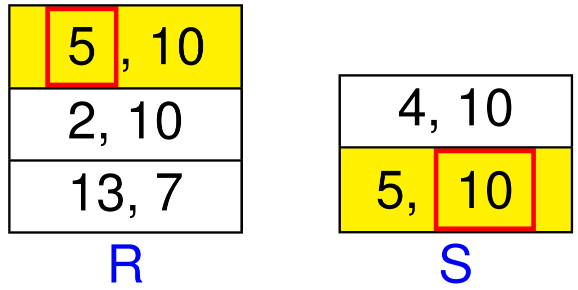

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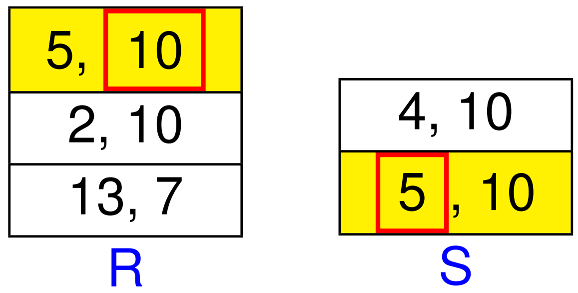

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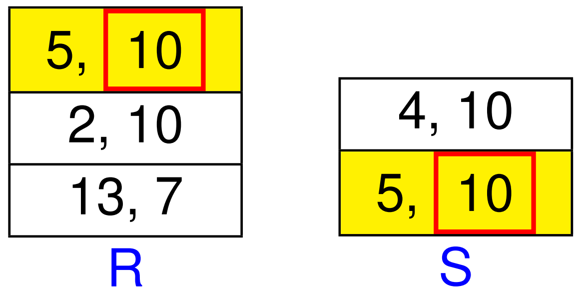

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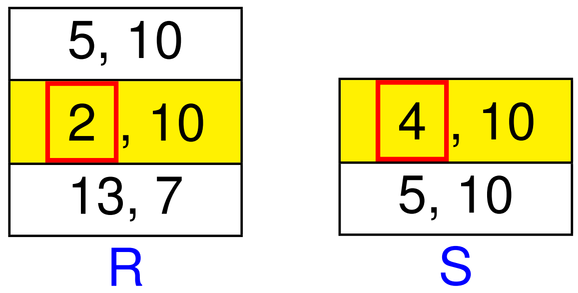

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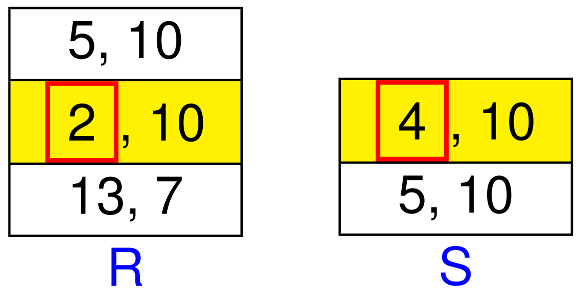

etc ...

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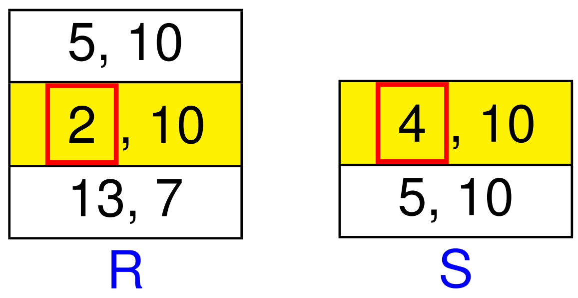


etc ...

- I/O Cost Analysis:

$$\underbrace{|R|}_{\text{scan R}} + \underbrace{|R| \times |S|}_{\text{scan S}}$$

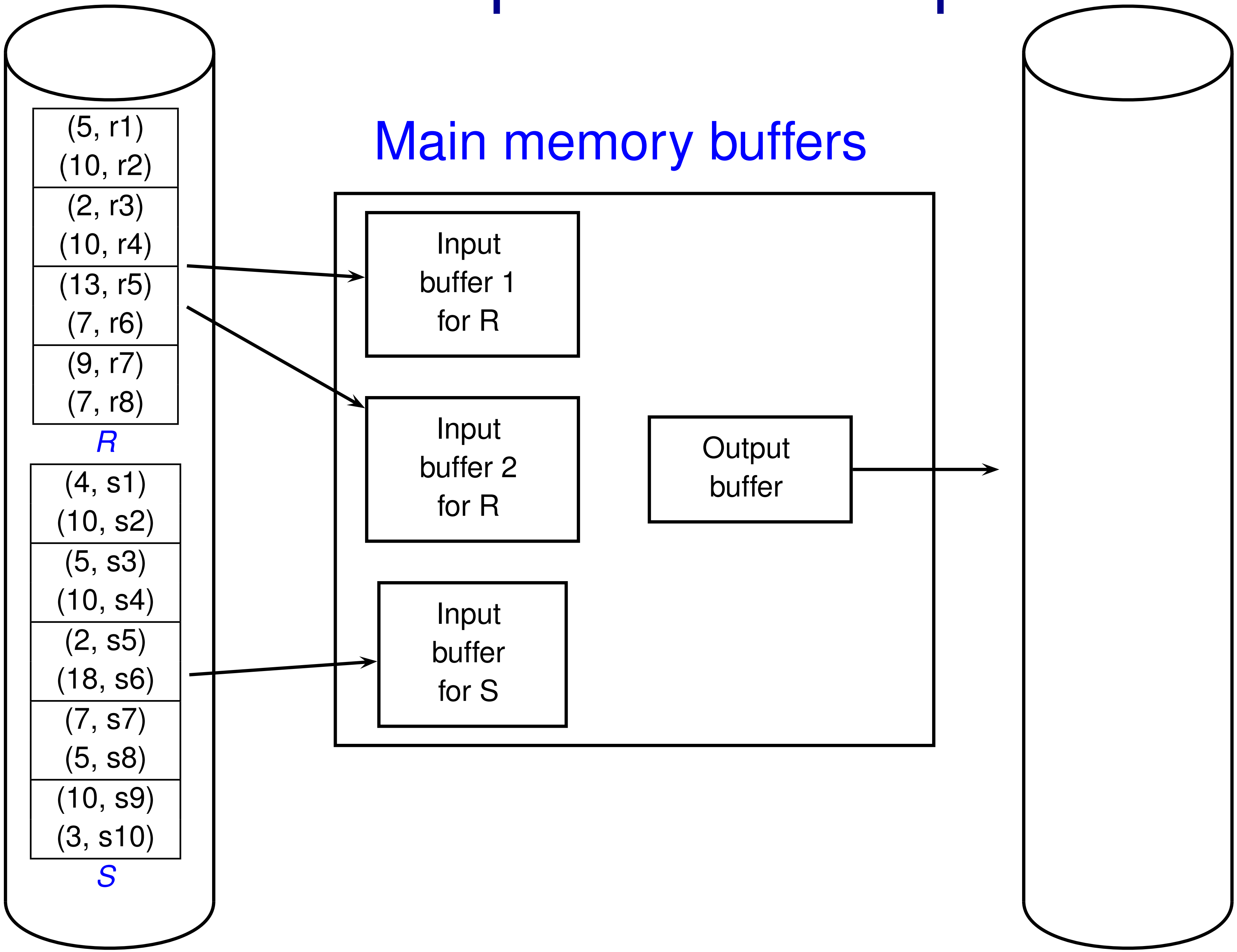
Block Nested Loop Join

- **Motivation**: How to better exploit buffer space to minimize number of I/Os?
- Assume $|R| \leq |S|$
- **Buffer space allocation**: Allocate one page for S, one page for output & remaining pages for R
- **Algorithm (using B buffer pages)**:

```
while (scan of R is not done) do
    read next (B − 2) pages of R into buffer
    for each page P_S of S do
        read P_S into buffer
        for each tuple r of R in buffer and each tuple s ∈ P_S do
            if (r matches s) then output (r, s) to result
```

- I/O Cost: $|R| + (\lceil \frac{|R|}{B-2} \rceil \times |S|)$

Block Nested Loop Join: Example



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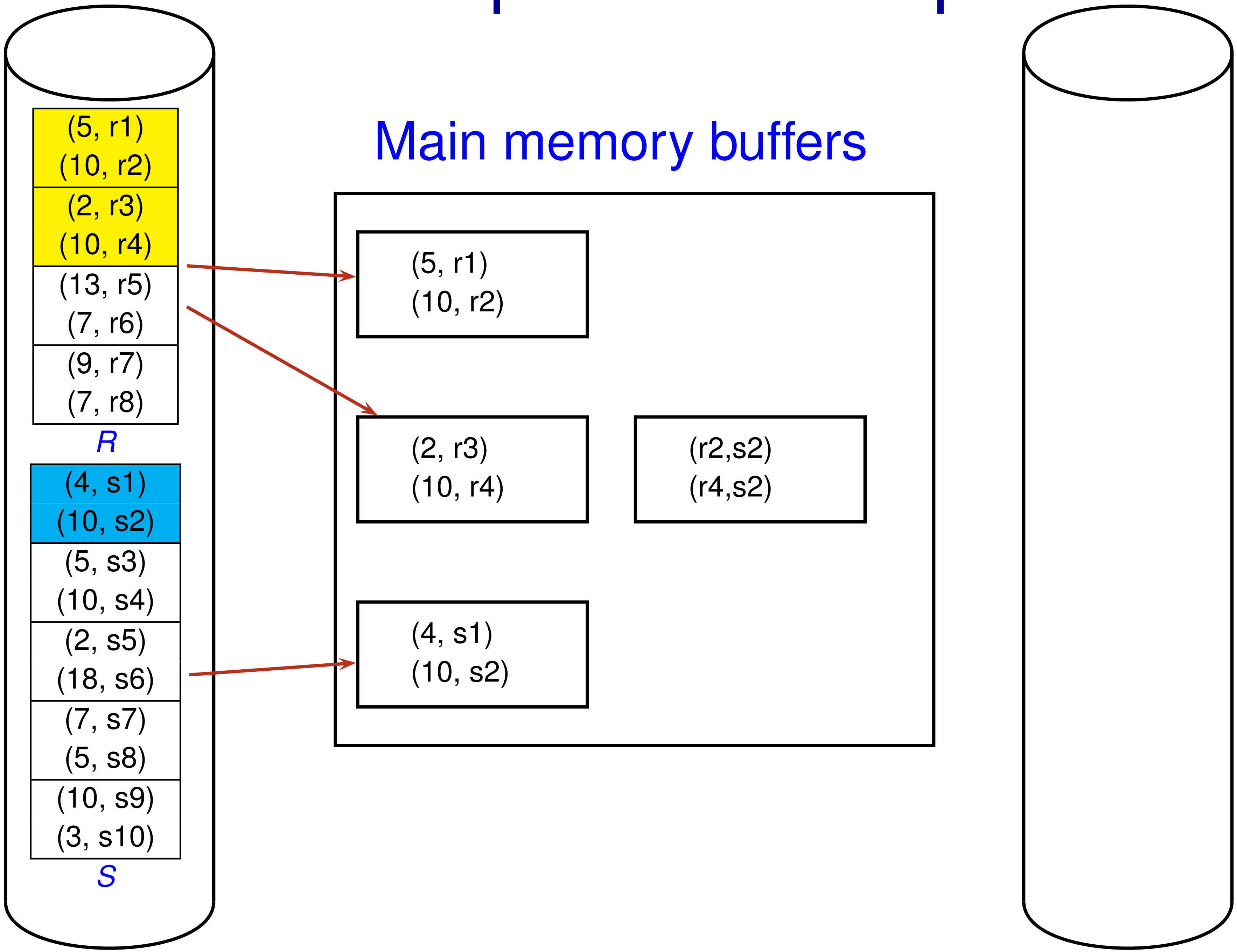

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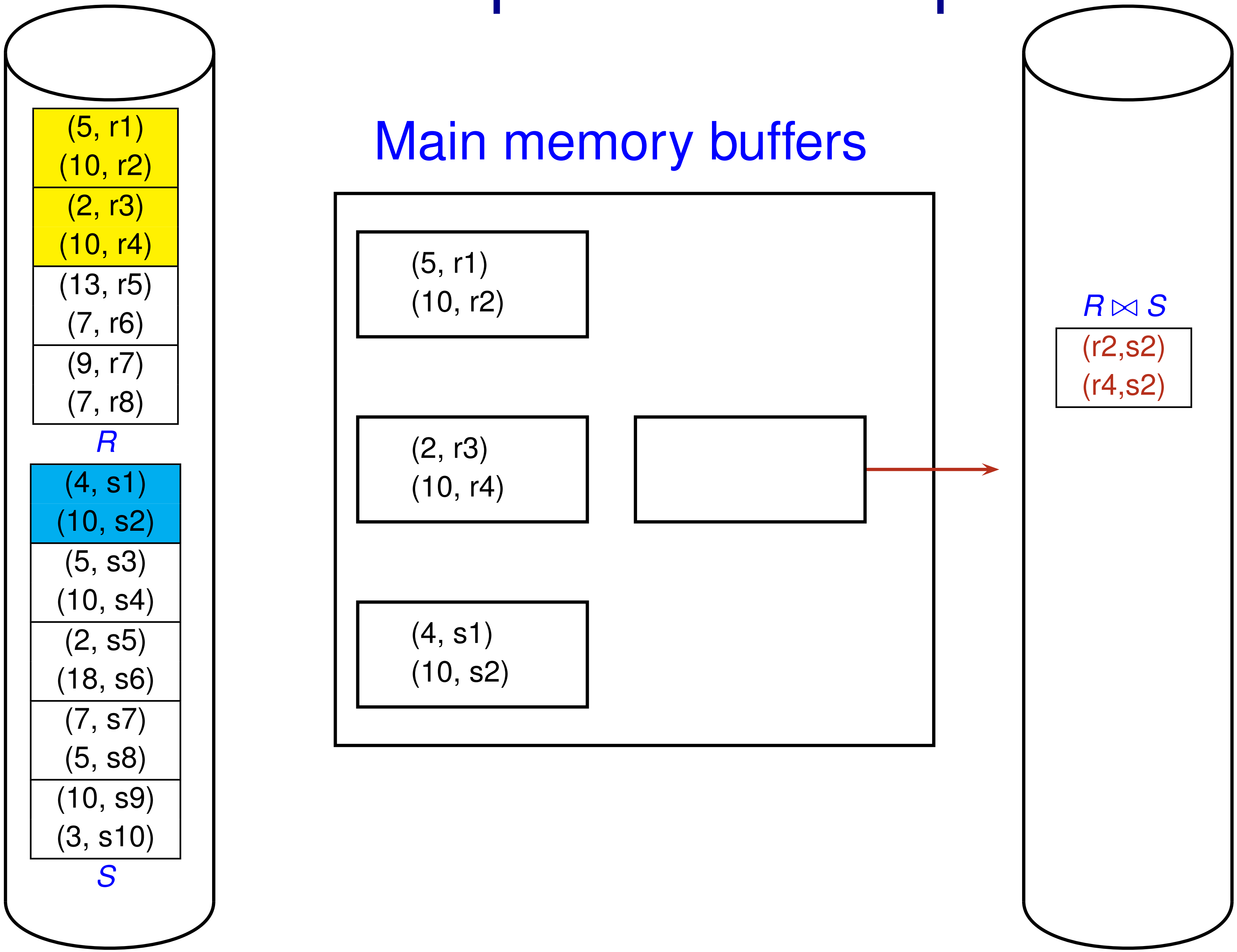

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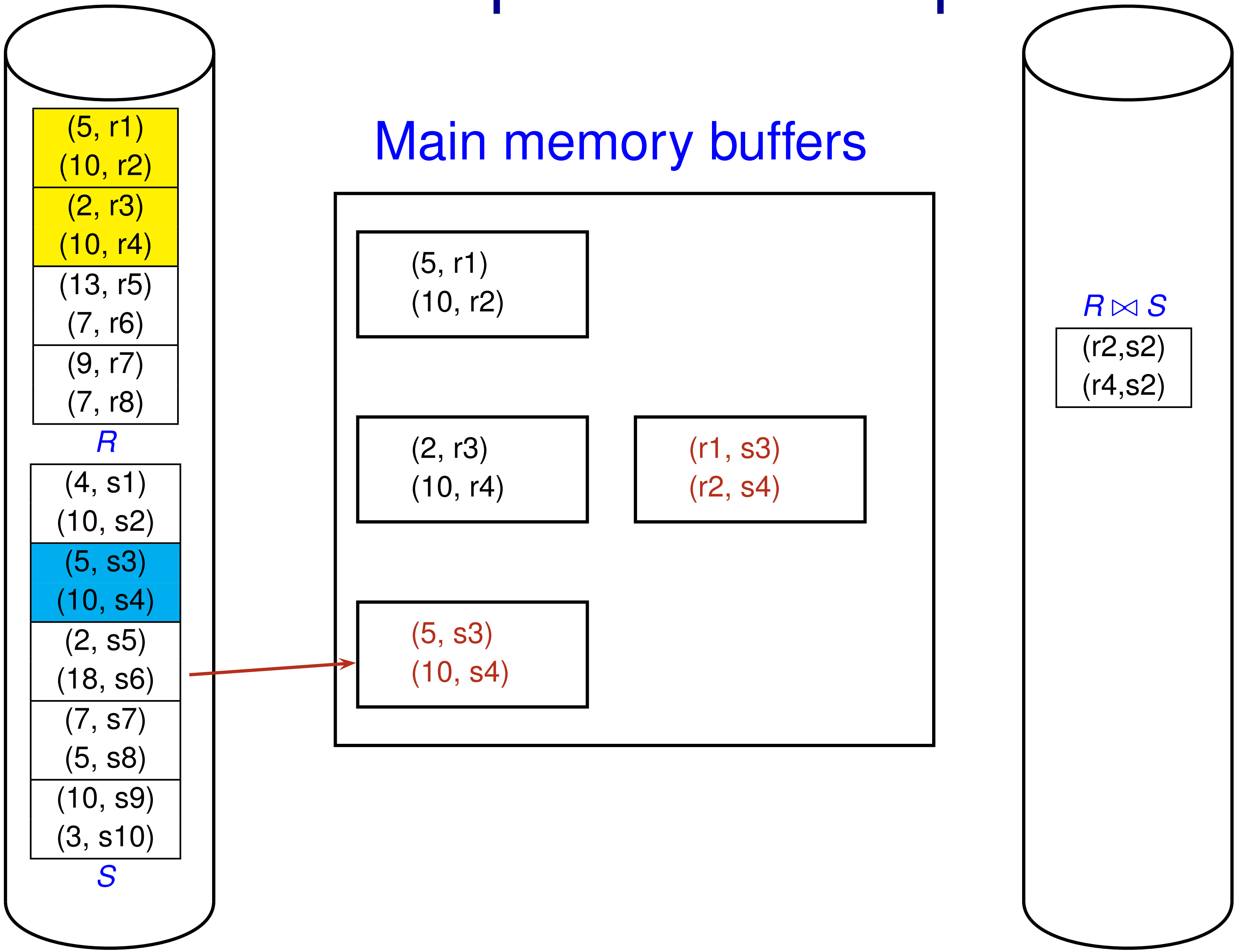

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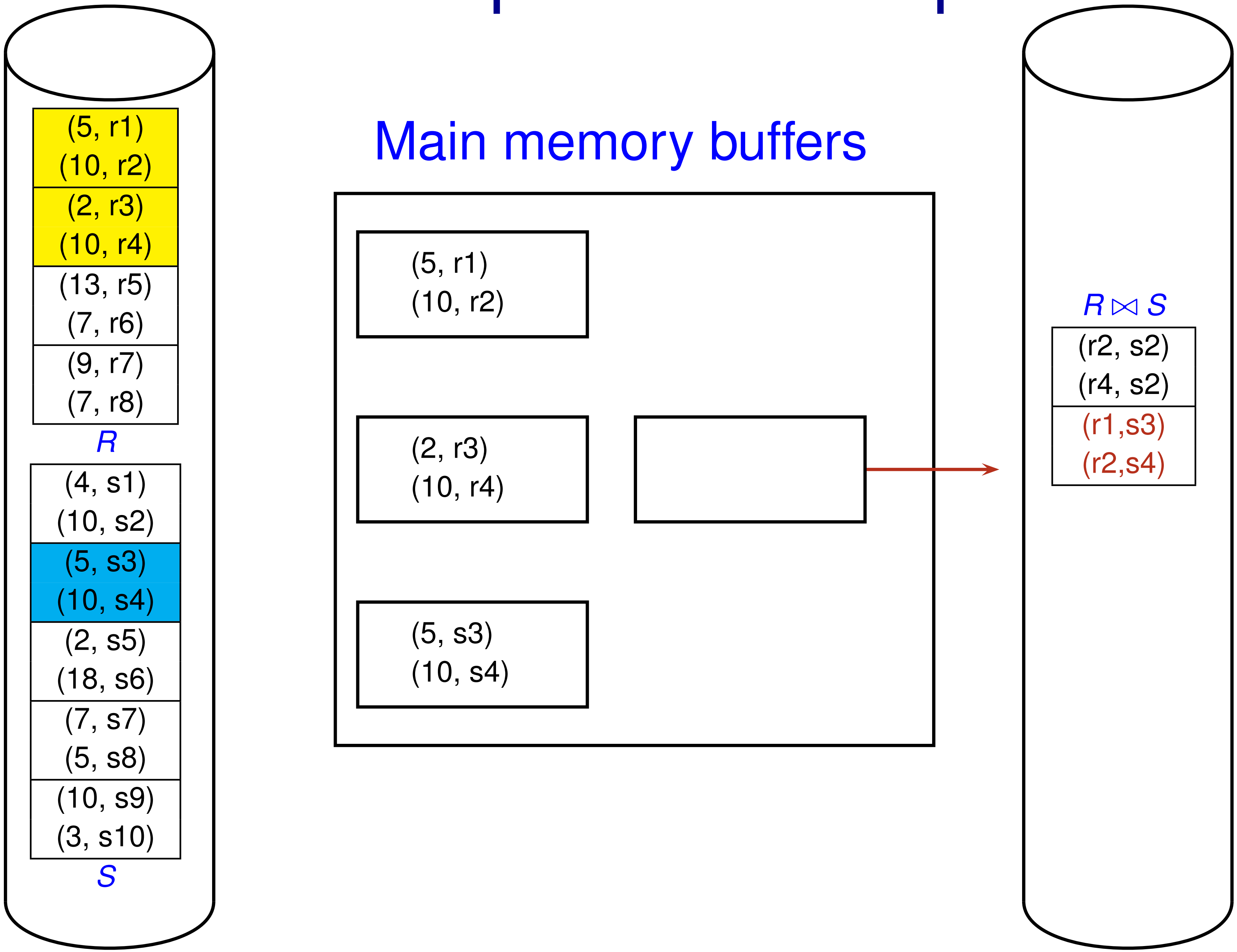

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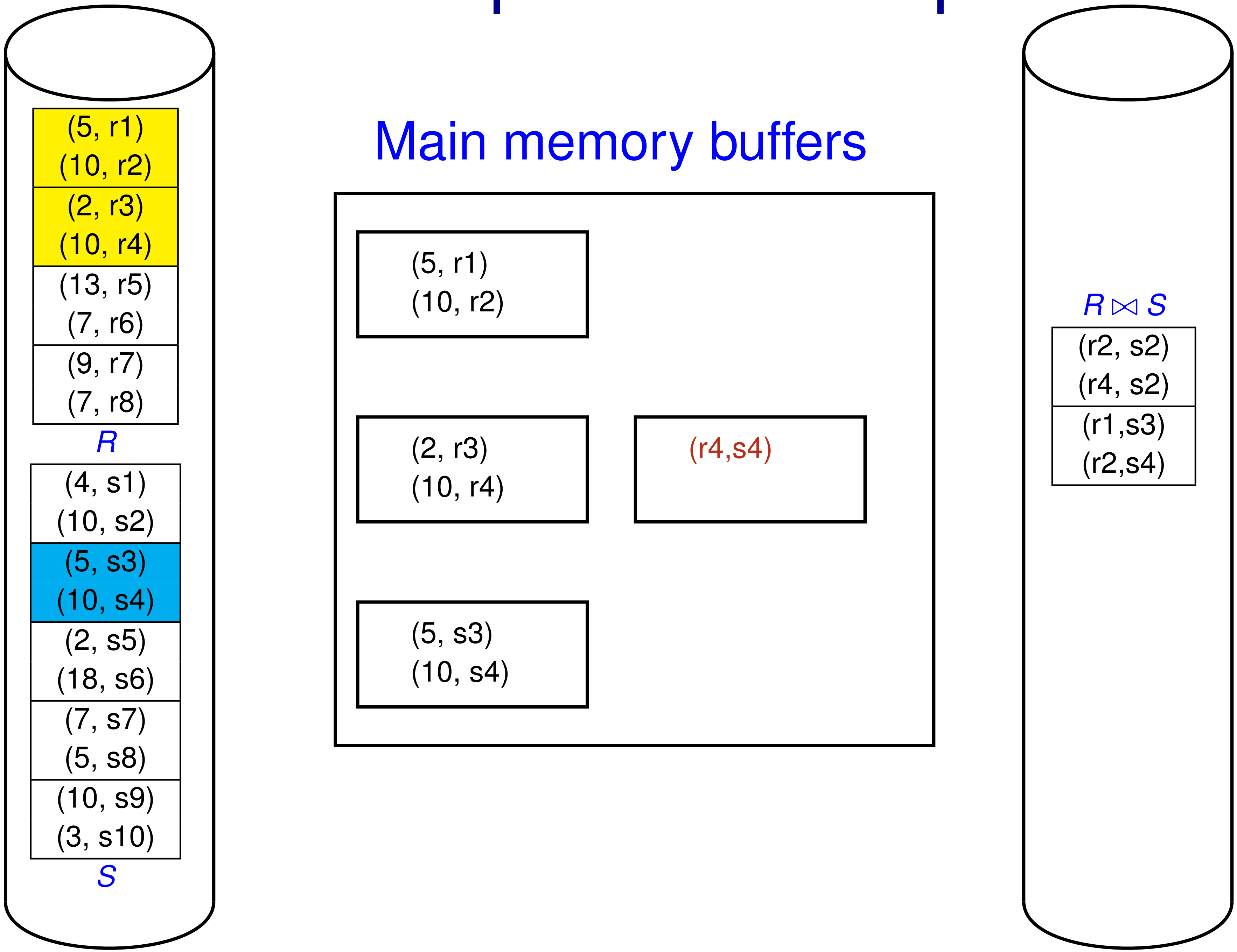

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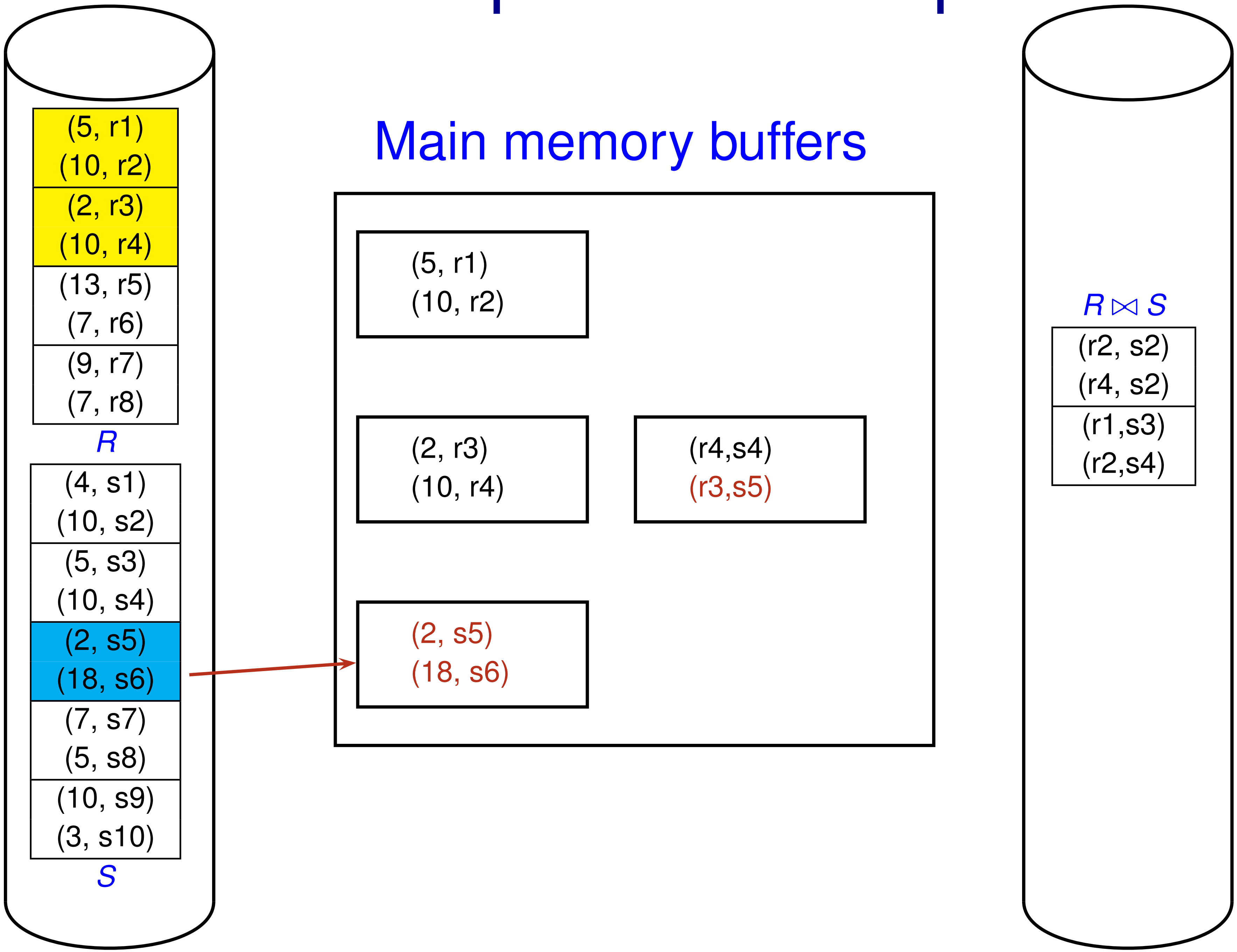

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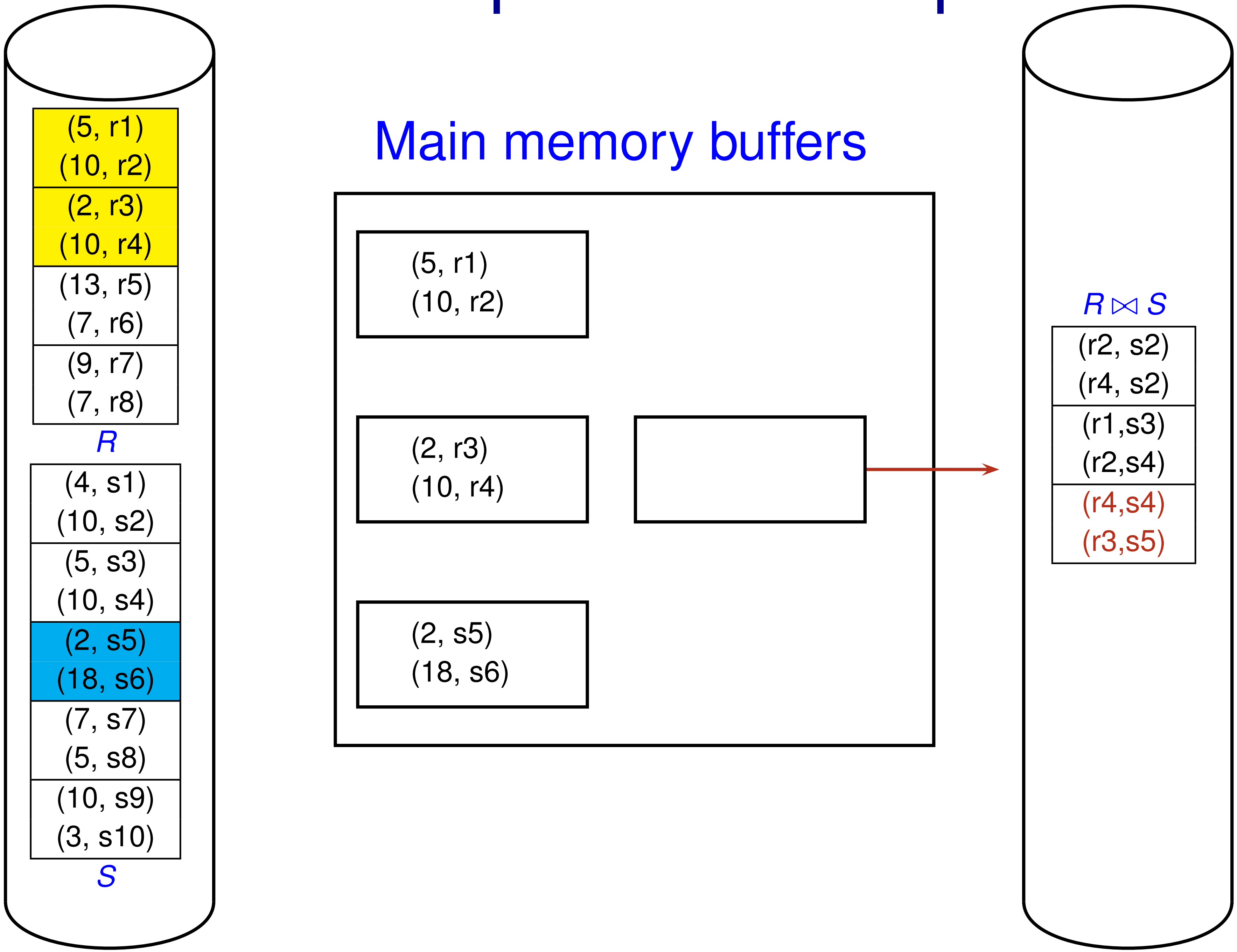

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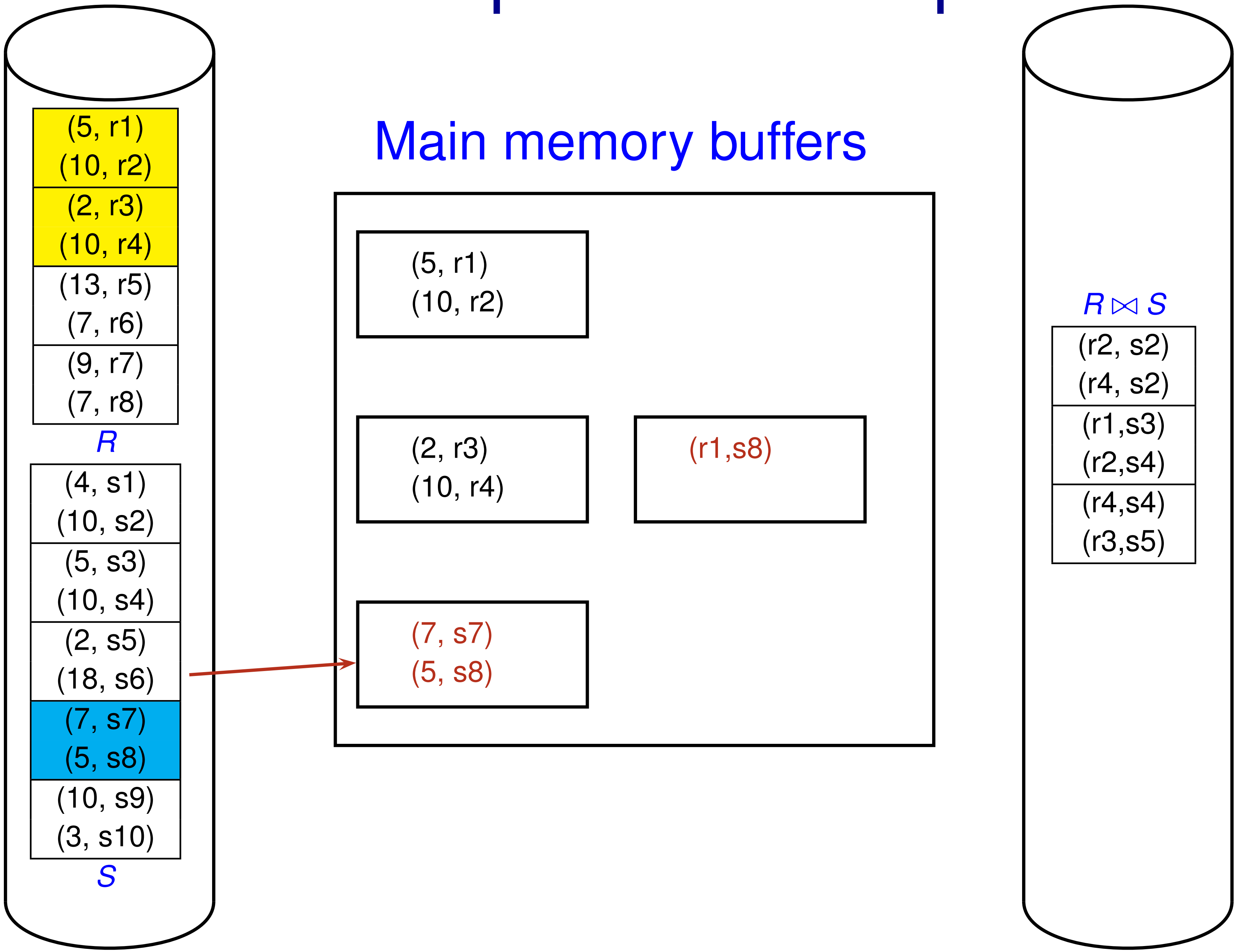

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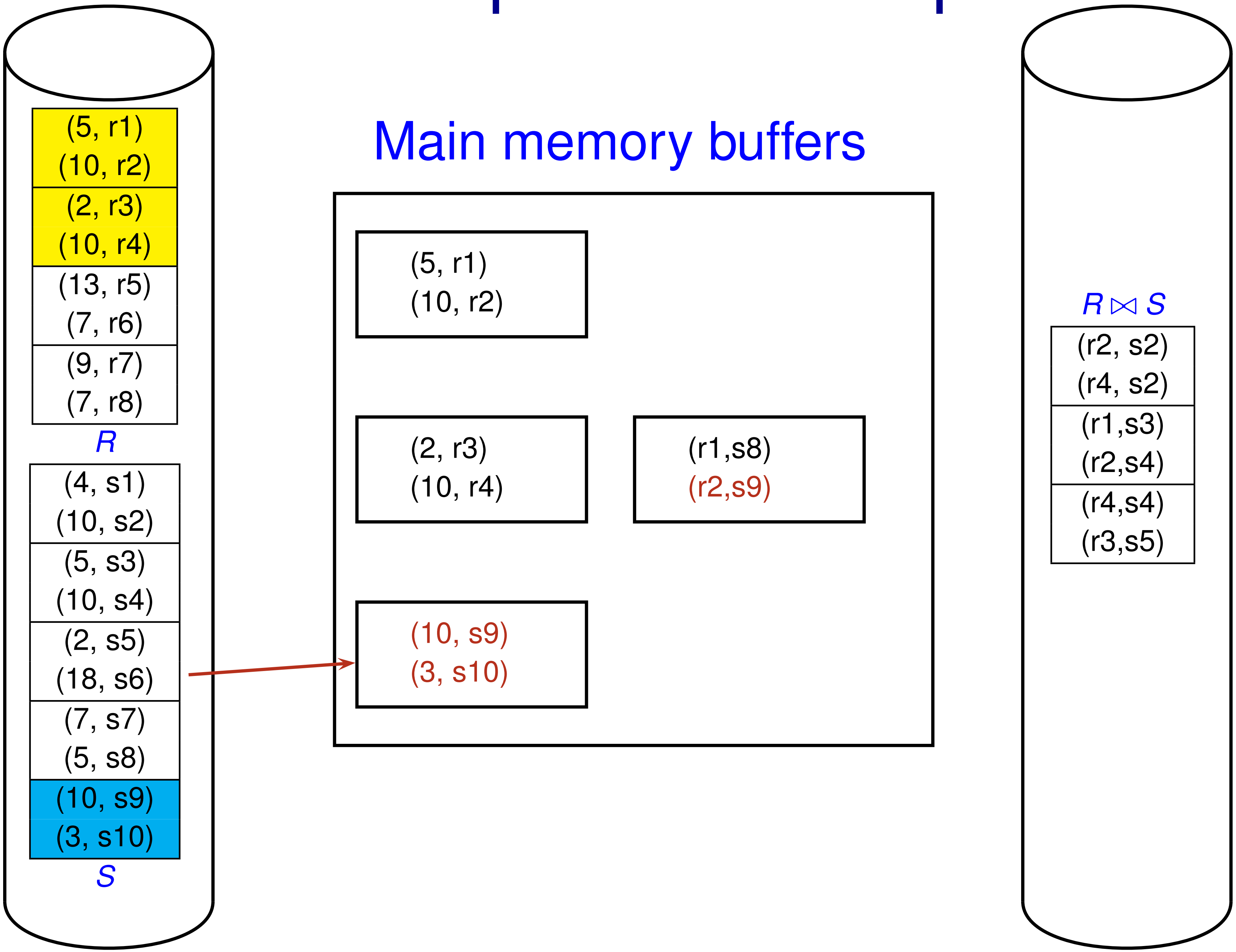

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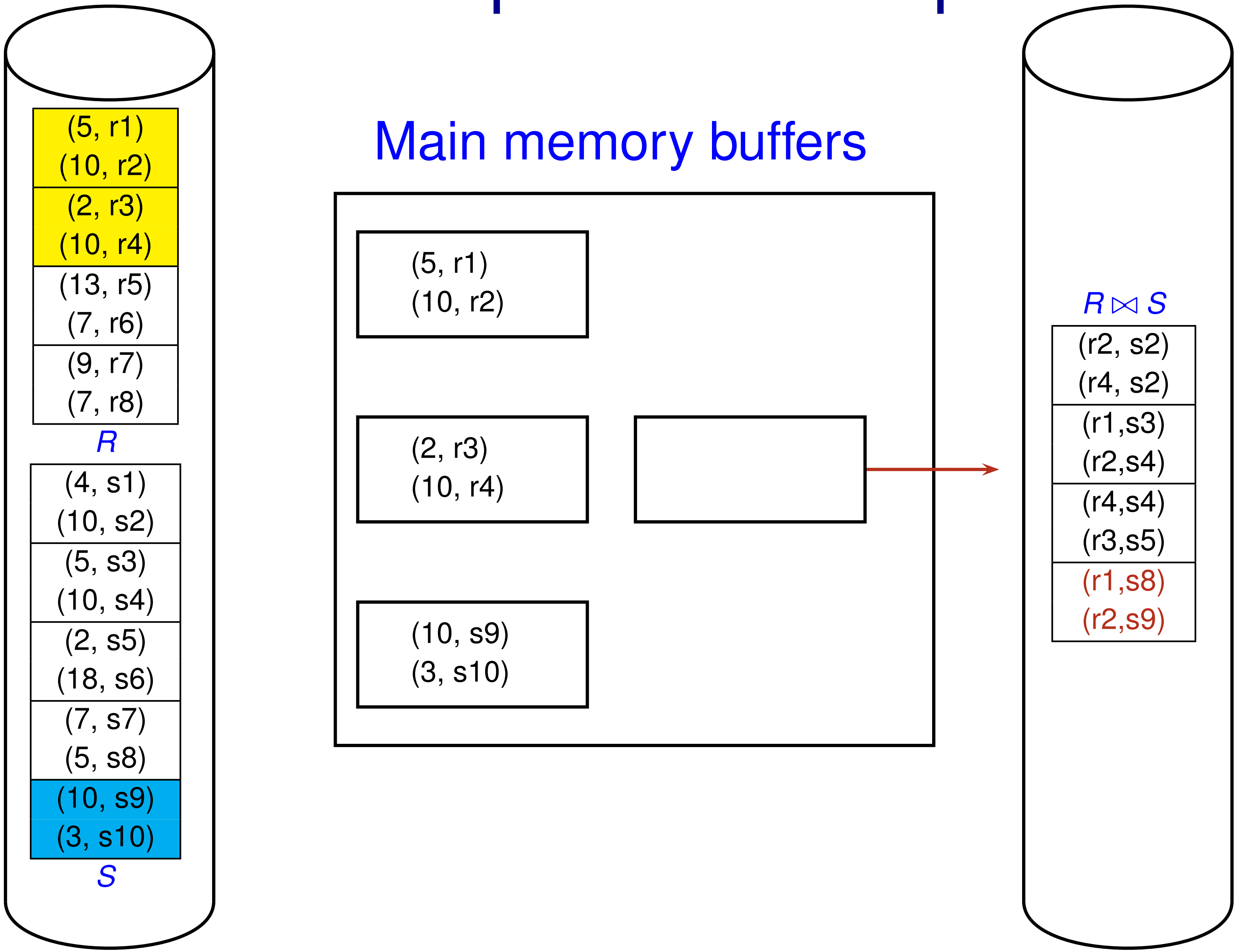

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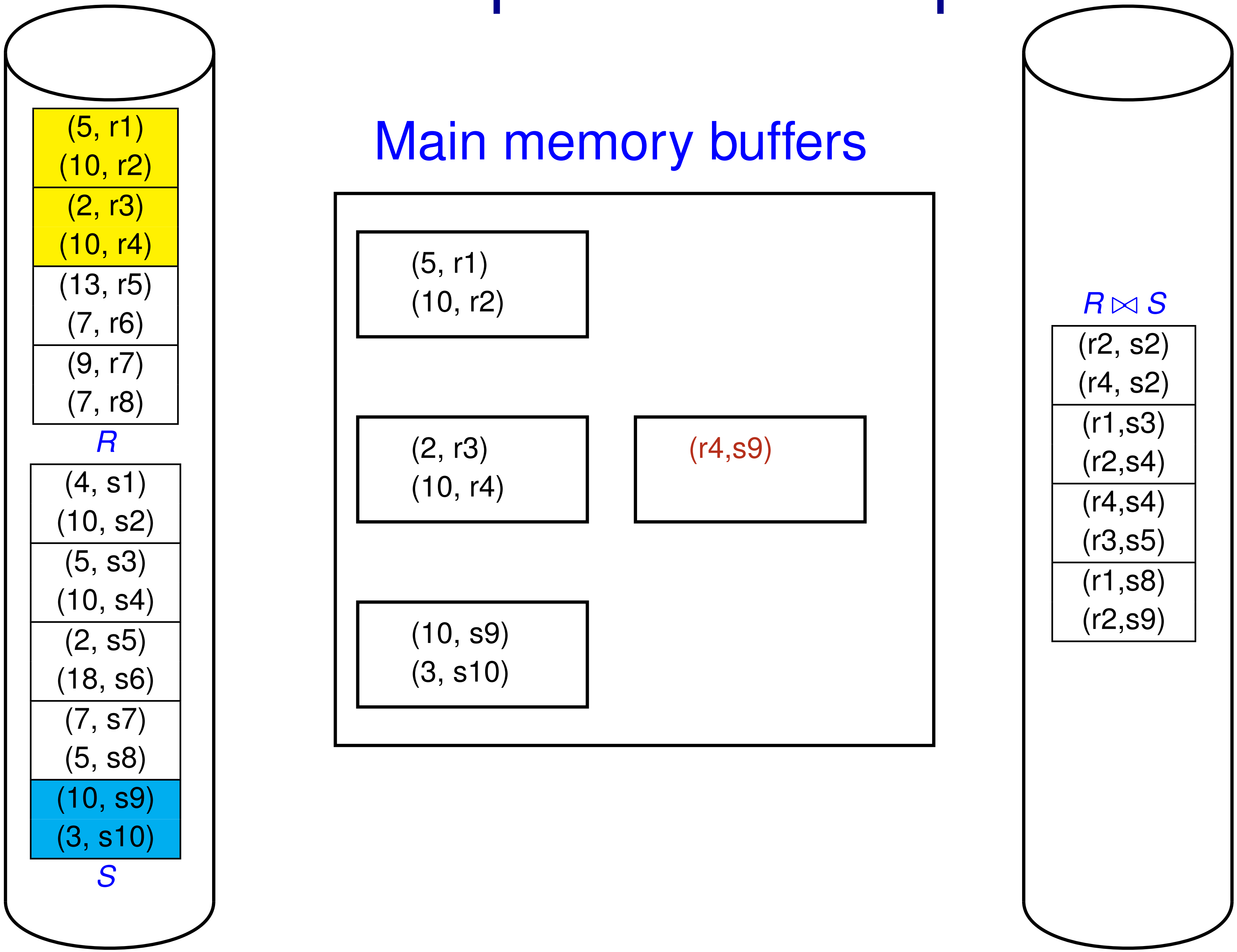

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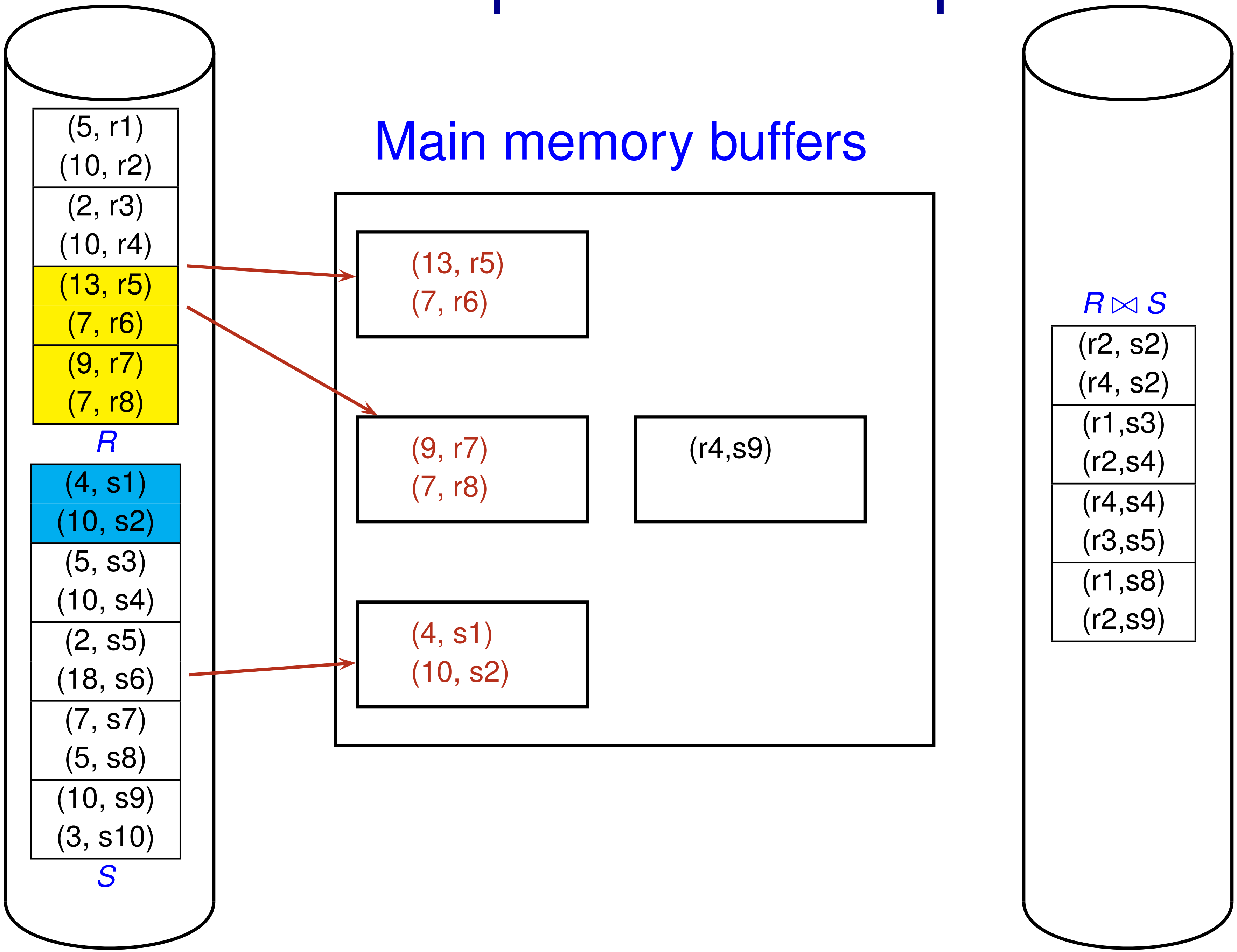
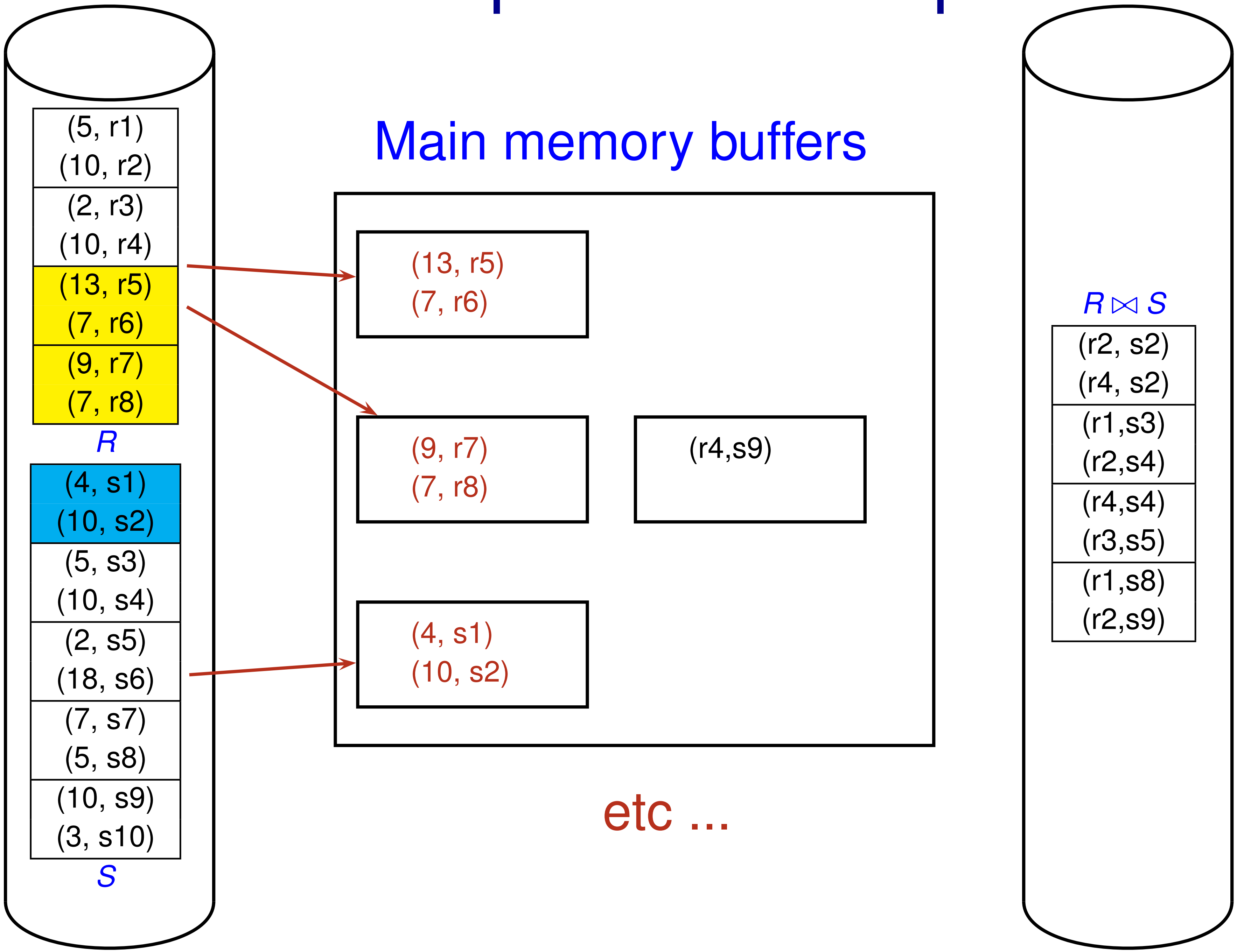
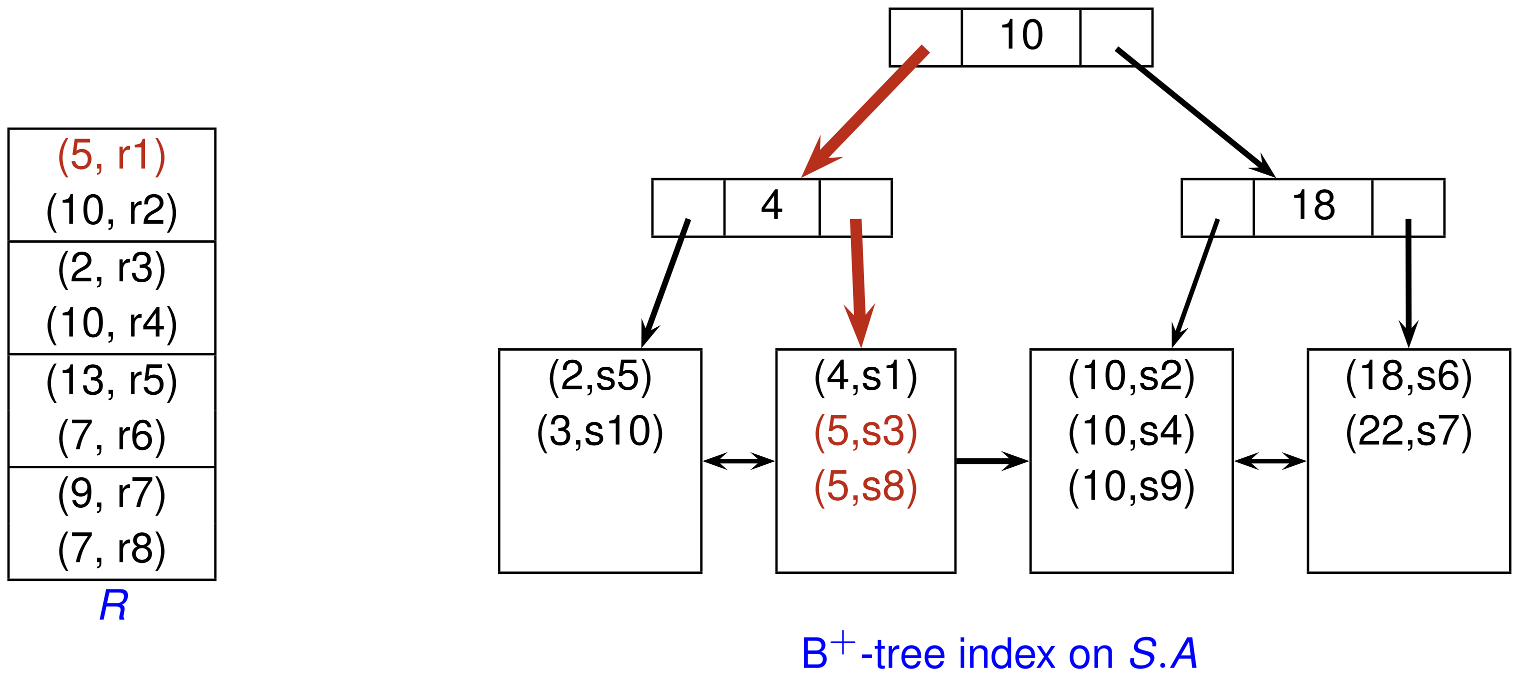


Block Nested Loop Join: Example



Index Nested Loop Join

- Consider $R(A, B) \bowtie_A S(A, C)$
- Assume that there's a B$^+$-tree index on $S.A$



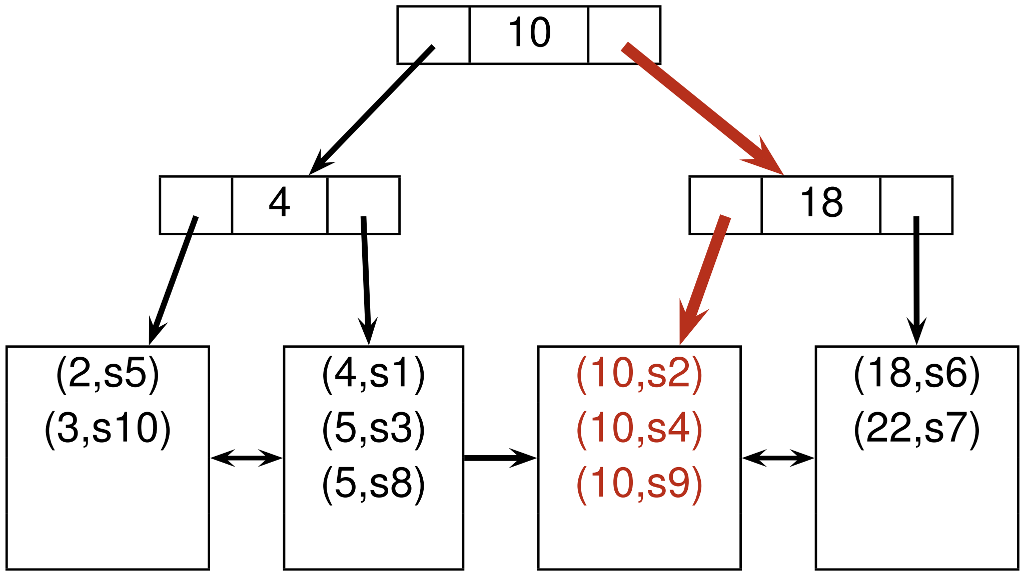
First, join $(5, r1) \in R$ with matching tuples in S

Index Nested Loop Join

- Consider $R(A, B) \bowtie_A S(A, C)$
- Assume that there's a B$^+$-tree index on $S.A$

(5, r1) (10, r2)
(2, r3) (10, r4)
(13, r5) (7, r6)
(9, r7) (7, r8)

R



B$^+$-tree index on $S.A$

Next, join $(10, r2) \in R$ with matching tuples in S, and so on ...

Index Nested Loop Join

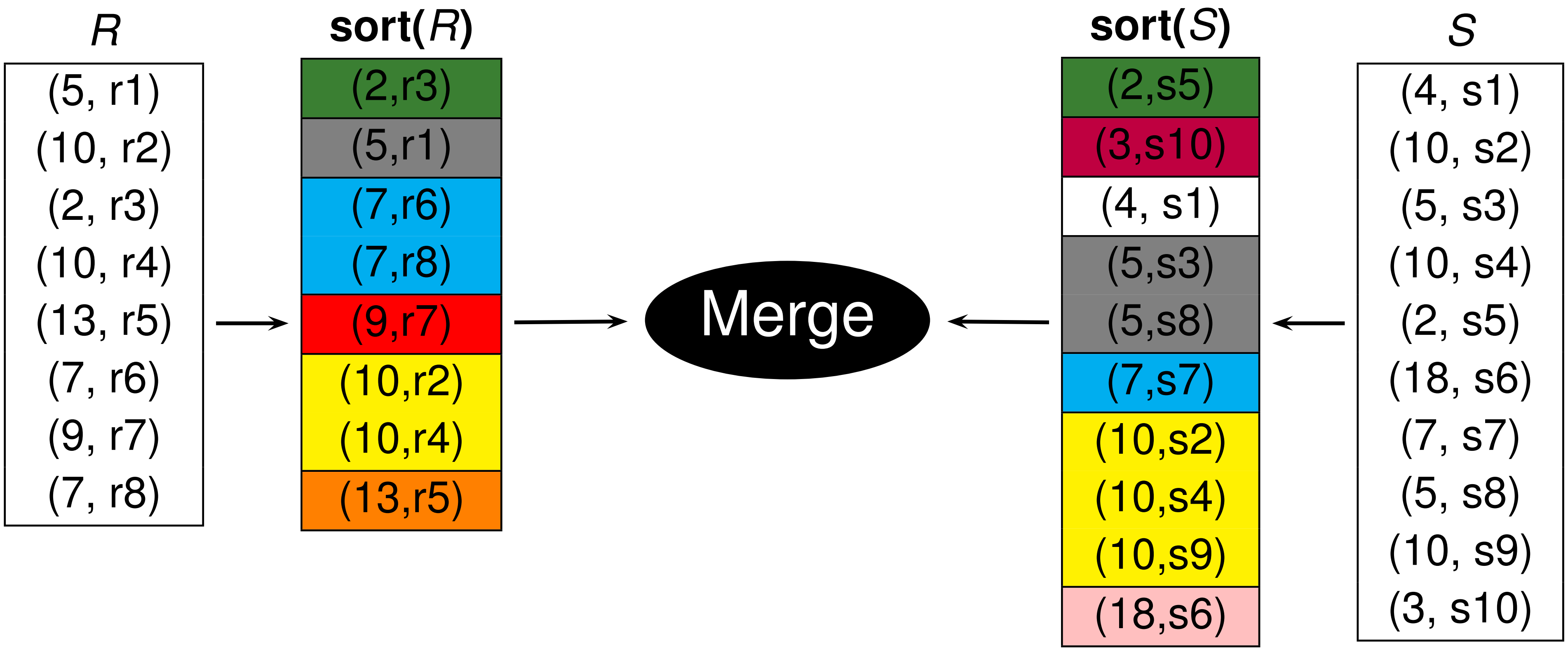
- Precondition: there is an index on the join attribute(s) of inner relation
- Idea:

  for each tuple $r \in R$ do

  use r to probe S's index to find matching tuples
- Analysis:
  - Let $R.A_i = S.B_j$ be the join condition
  - Uniform distribution assumption:
    each R-tuple joins with $\lceil \frac{||S||}{||\pi_{B_j}(S)||} \rceil$ number of S-tuples
  - For a format-1 B$^+$-tree index on S,
    - ★ I/O Cost = $\underbrace{|R|}_{\text{scan R}} + \underbrace{||R|| \times J}_{\text{join each R-tuple with S}}$
    - ★ $J = \underbrace{\log_F(\lceil \frac{||S||}{b_d} \rceil)}_{\text{search index's internal nodes}} + \underbrace{\lceil \frac{||S||}{b_d \; ||\pi_{B_j}(S)||} \rceil}_{\text{search index's leaf nodes}}$

Sort-Merge Join

- Idea: sort both relations based on join attributes & merge them
- A sorted relation R consists of partitions R_i of records where $r, r' \in R_i$ iff r and r' have the same values for the join attribute(s)



Sort-Merge Join: Merging Phase

- Each tuple in R-partition merges with all tuples in matching S-partition
- A *pointer* is maintained for each sorted join operand
- Each pointer is initialized to the first tuple in sorted operand
- Search for matching partitions by advancing the pointer that is pointing to a “smaller” tuple
- Need to remember position of first tuple in matching S-partition to enable rewinding of S-pointer
- **Example**:

R: 2 5 7 10 10 13

S: 4 5 5 10 10 18 22

$R \bowtie S$:

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$R \bowtie S$:(5,5)

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Sort-Merge Join Algorithm for $R \bowtie_{R.A_i = S.B_j} S$

if (R is not sorted) then sort R
if (S is not sorted) then sort S
t_r = first tuple in R
t_s = first tuple in S
p_s = first tuple in S partition
while ($t_r \neq null$) and ($p_s \neq null$) do
while ($t_r.A_i < p_s.B_j$) do
t_r = next tuple in R after t_r
while ($t_r.A_i > p_s.B_j$) do
p_s = next tuple in S afer p_s
$t_s = p_s$
while ($t_r.A_i = p_s.B_j$) do
$t_s = p_s$
while ($t_s.B_j = t_r.A_i$) do
add (t_r, t_s) to result
t_s = next tuple in S after t_s
t_r = next tuple in R after t_p
$p_s = t_s$

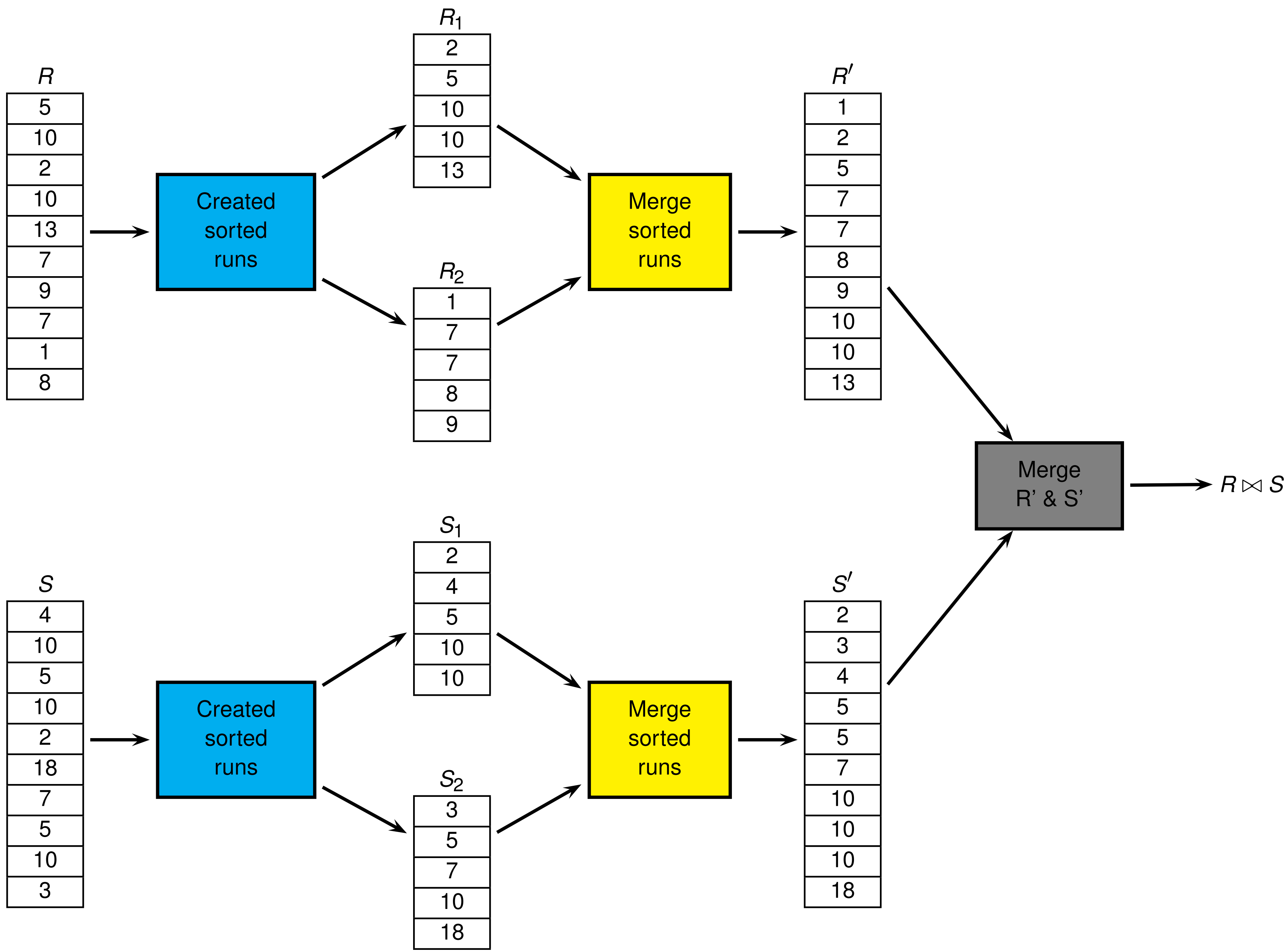
Sort-Merge Join: Analysis

- I/O cost = Cost to sort R + Cost to sort S + Merging cost
- **Cost to sort R** = $2|R|\ (\log_m(N_R) + 1)$ if using external merge sort
  - $N_R =$ number of initial sorted runs of R, $\quad m =$ merge factor
- **Cost to sort S** = $2|S|\ (\log_m(N_S) + 1)$ if using external merge sort
  - $N_S =$ number of initial sorted runs of S, $\quad m =$ merge factor
- If each S partition is scanned at most once during merging,
  - **Merging cost** = $|R| + |S|$
- Worst case occurs when each tuple of R requires scanning entire S!
  - **Merging cost** = $|R| + ||R|| \times |S|$

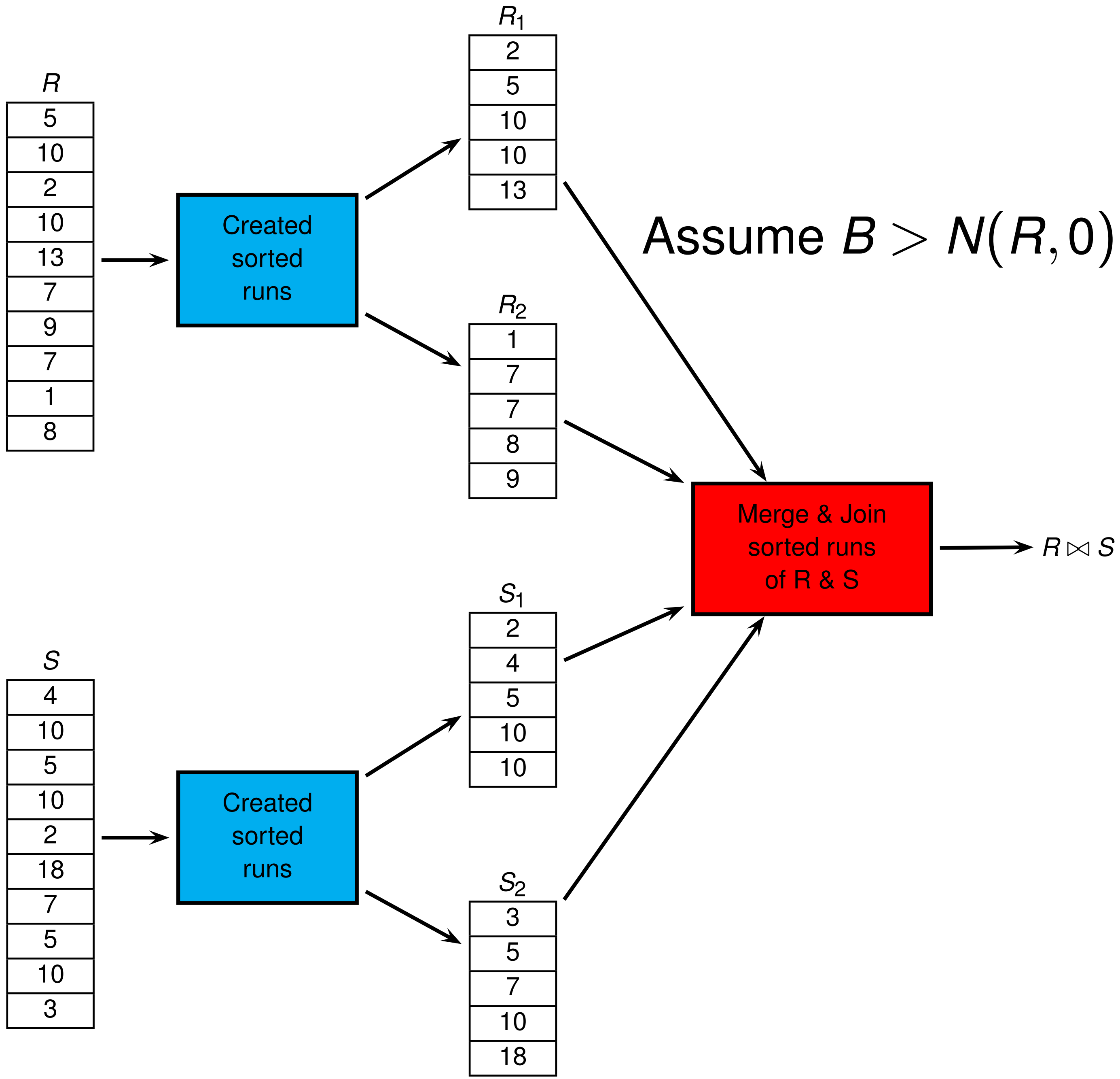
Sort-Merge Join: Optimization

- **Conventional Sort-Merge Join**
  - **Sort R**: create sorted runs of R; merge sorted runs of R
  - **Sort S**: create sorted runs of S; merge sorted runs of S
  - **Join R and S**: merge sorted R & sorted S
- Idea: Combine merge phase of sorting & merge phase of join
  - It's not necessary to merge sorted runs into a single run before performing join
  - If $B > N(R,i) + N(S,j)$ for some i & j, sorting of R and S can stop
    - N(R,i) = total number of sorted runs of R at the end of pass i of sorting R
- **Optimized Sort-Merge Join**
  - Create sorted runs of R; merge sorted runs of R partially
  - Create sorted runs of S; merge sorted runs of S partially
  - Merge remaining sorted runs of R & S and join them at the same time

Conventional Sort-Merge Join



Optimized Sort-Merge Join



Assume $B > N(R, 0) + N(S, 0)$

Optimized Sort-Merge Join: Analysis

- Assume $|R| \leq |S|$
- If $B > \sqrt{2|S|}$
  - Number of initial sorted runs of S < $\sqrt{\frac{|S|}{2}}$
  - Total number of initial sorted runs of R and S < $\sqrt{2|S|}$
  - One pass is sufficient to merge and join the initial sorted runs R & S
  - I/O Cost = $3 \times (|R| + |S|)$

Hash Join, $R \bowtie_{R.A=S.B} S$

- **Idea**:
  - Partition R and S into k partitions using some hash function h
    - ⋆ $R = R_1 \cup R_2 \cup \cdots \cup R_k,\ t \in R_i$ iff $h(t.A) = i$
    - ⋆ $S = S_1 \cup S_2 \cup \cdots \cup S_k,\ t \in S_i$ iff $h(t.B) = i$
    - ⋆ $\pi_A(R_i) \cap \pi_B(S_j) = \emptyset$ for each R_i & S_j, $i \neq j$
  - Joins corresponding pair of partitions
    - ⋆ $R \bowtie S = (R_1 \bowtie S_1) \cup (R_2 \bowtie S_2) \cup \cdots \cup (R_k \bowtie S_k)$
- **Algorithms**:
  - Grace hash join
  - Hybrid hash join (not covered in lecture)

Grace Hash Join, $R \bowtie_{R.A=S.B} S$

- Consists of three phases:
  1. Partition R into $R_1, \cdots, R_k$
  2. Partition S into $S_1, \cdots, S_k$
  3. Probing phase: probes each R_i with S_i
     - Read R_i to build a hash table
     - Read S_i to probe hash table
- R is called the build relation & S is called the probe relation

Grace Hash Join, $R \bowtie_{R.A=S.B} S$

- Consists of three phases:
  1. Partition R into $R_1, \cdots, R_k$
  2. Partition S into $S_1, \cdots, S_k$
  3. Probing phase: probes each R_i with S_i
     - Read R_i to build a hash table
     - Read S_i to probe hash table
- R is called the build relation & S is called the probe relation

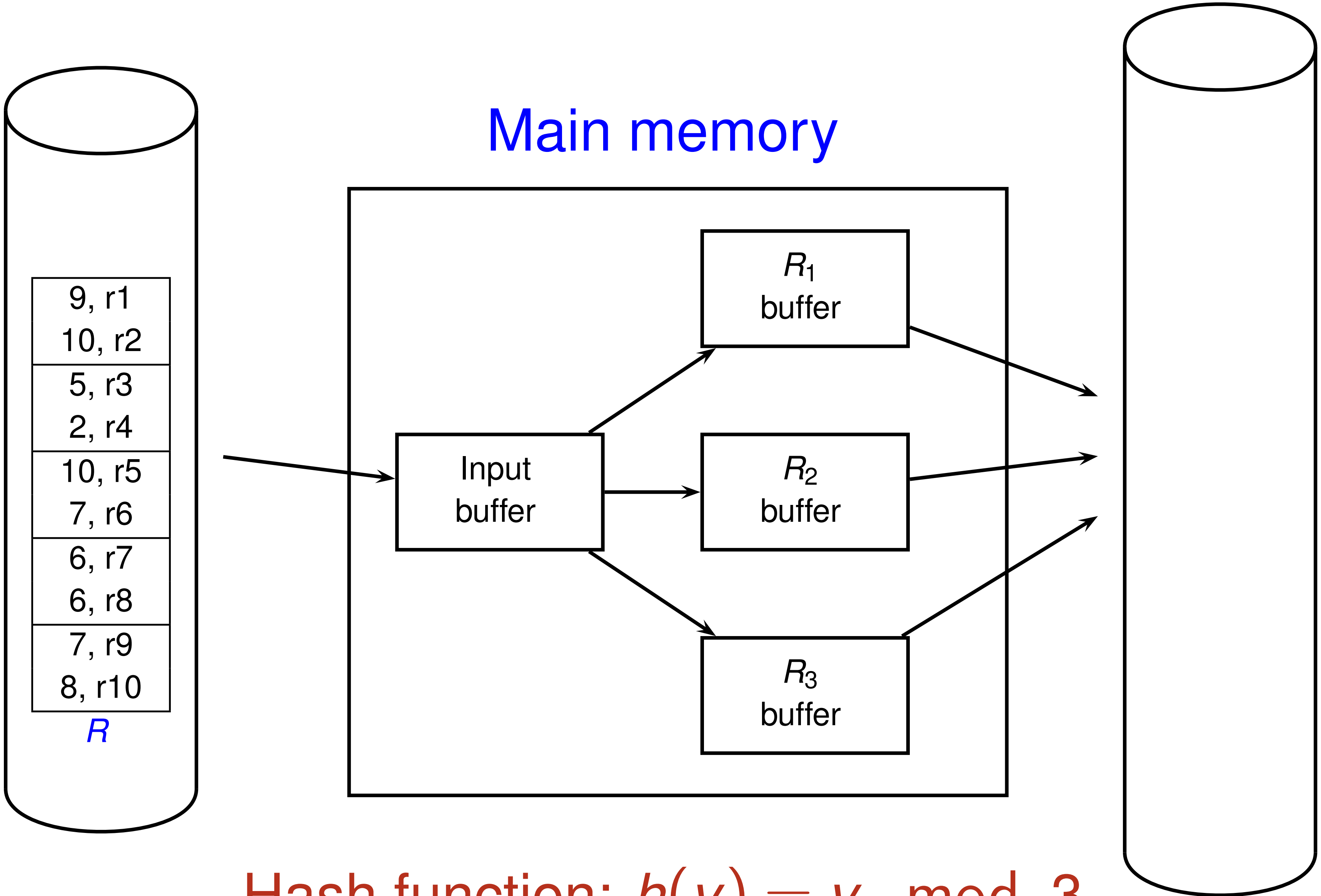
Partitioning (building) phases

```
initialize a hash table T with k buckets
for each tuple r ∈ R do
    insert r into bucket h(r.A) of T
write each bucket R_i of T to disk
initialize a hash table T with k buckets
for each tuple s ∈ S do
    insert s into bucket h(s.B) of T
write each bucket S_i of T to disk
```

Probing (matching) phase

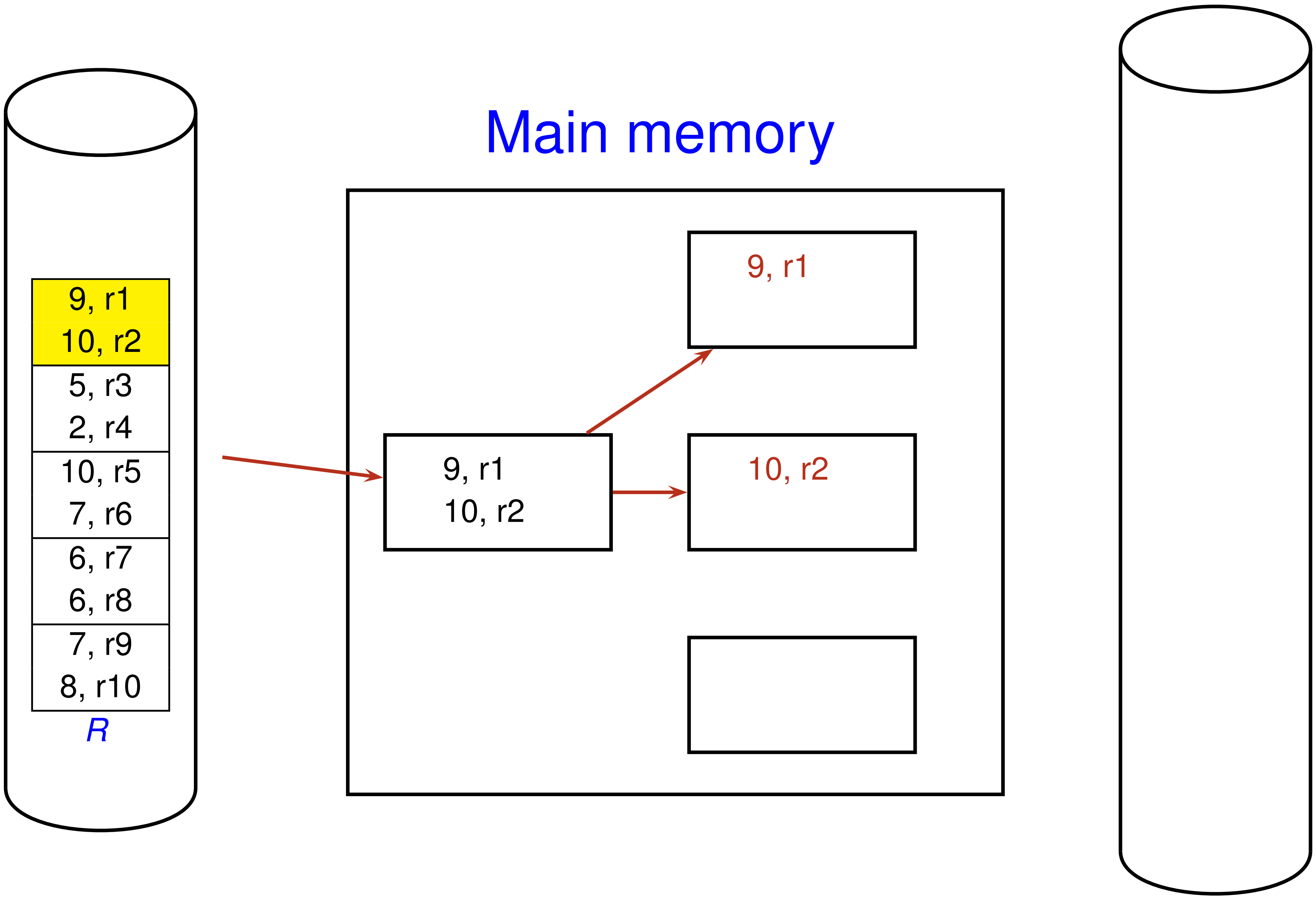
```
for i = 1 to k do
    initialize a hash table T
    for each tuple r in partition R_i do
        insert r into bucket h'(r.A) of T
    for each tuple s in partition S_i do
        for each tuple r in bucket h'(s.B) of T do
            if r and s matches then output (r, s)
```

Grace Hash Join: Partitioning Relation R

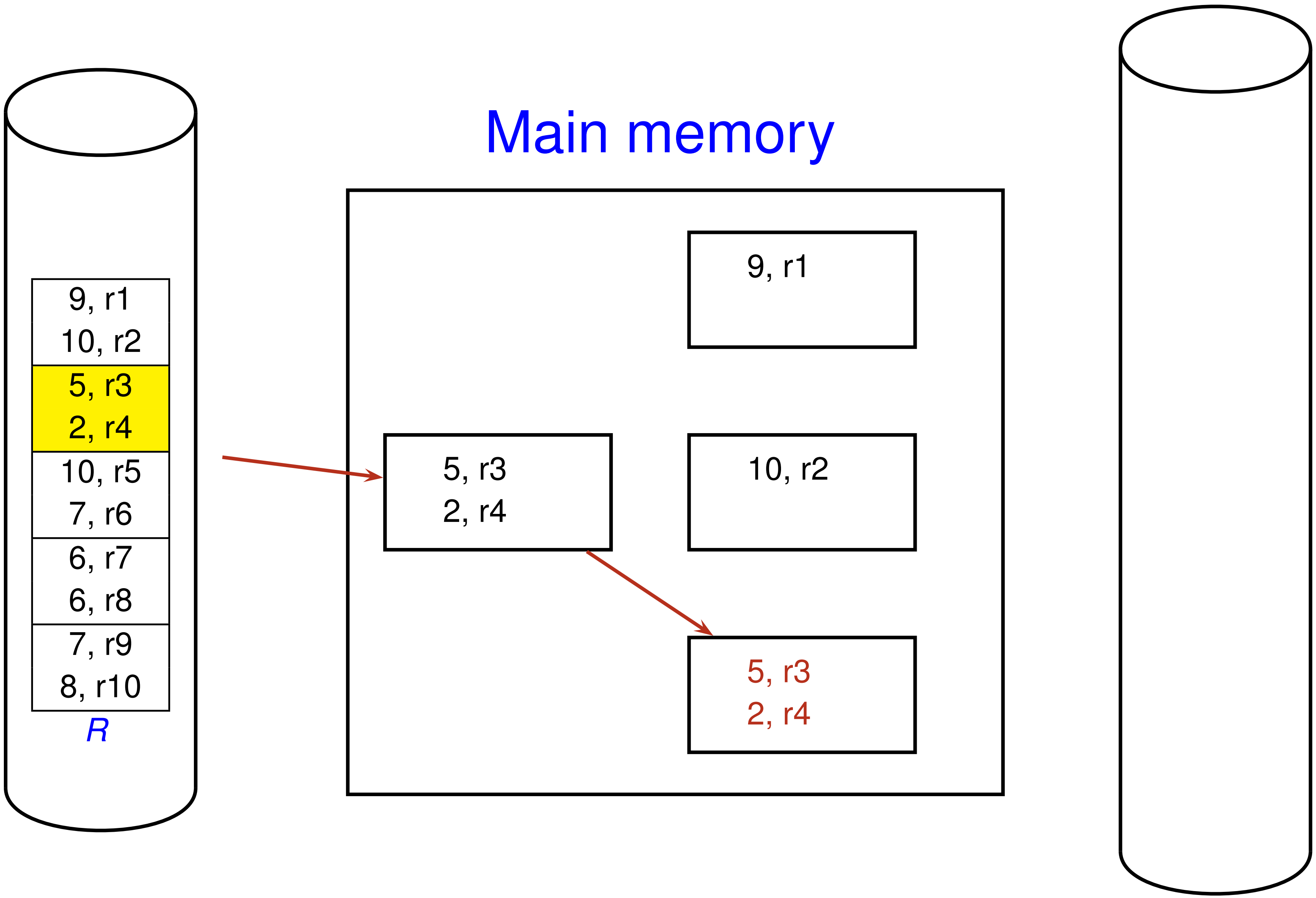


Hash function: $h(v) = v \mod 3$

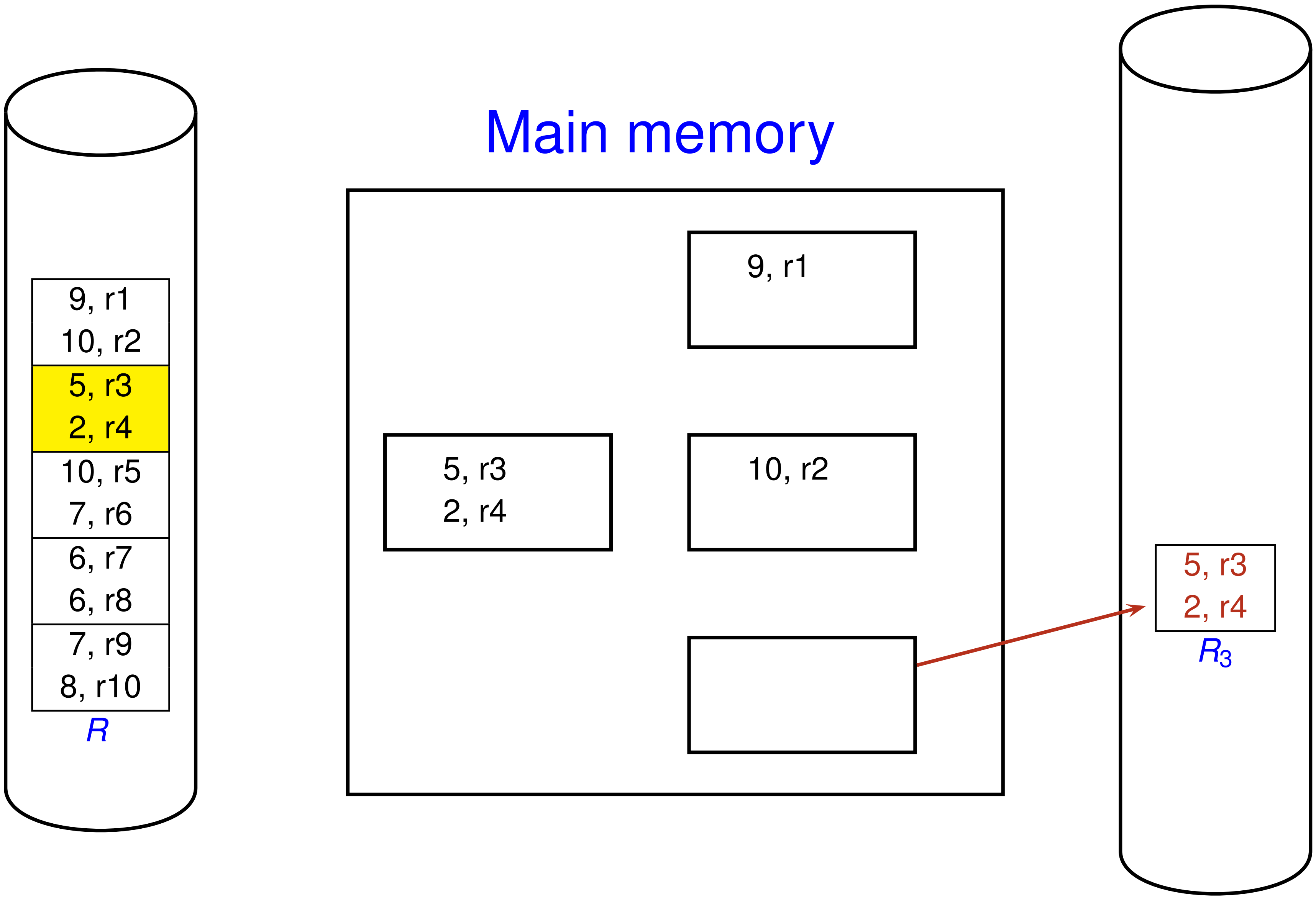
Grace Hash Join: Partitioning Relation R



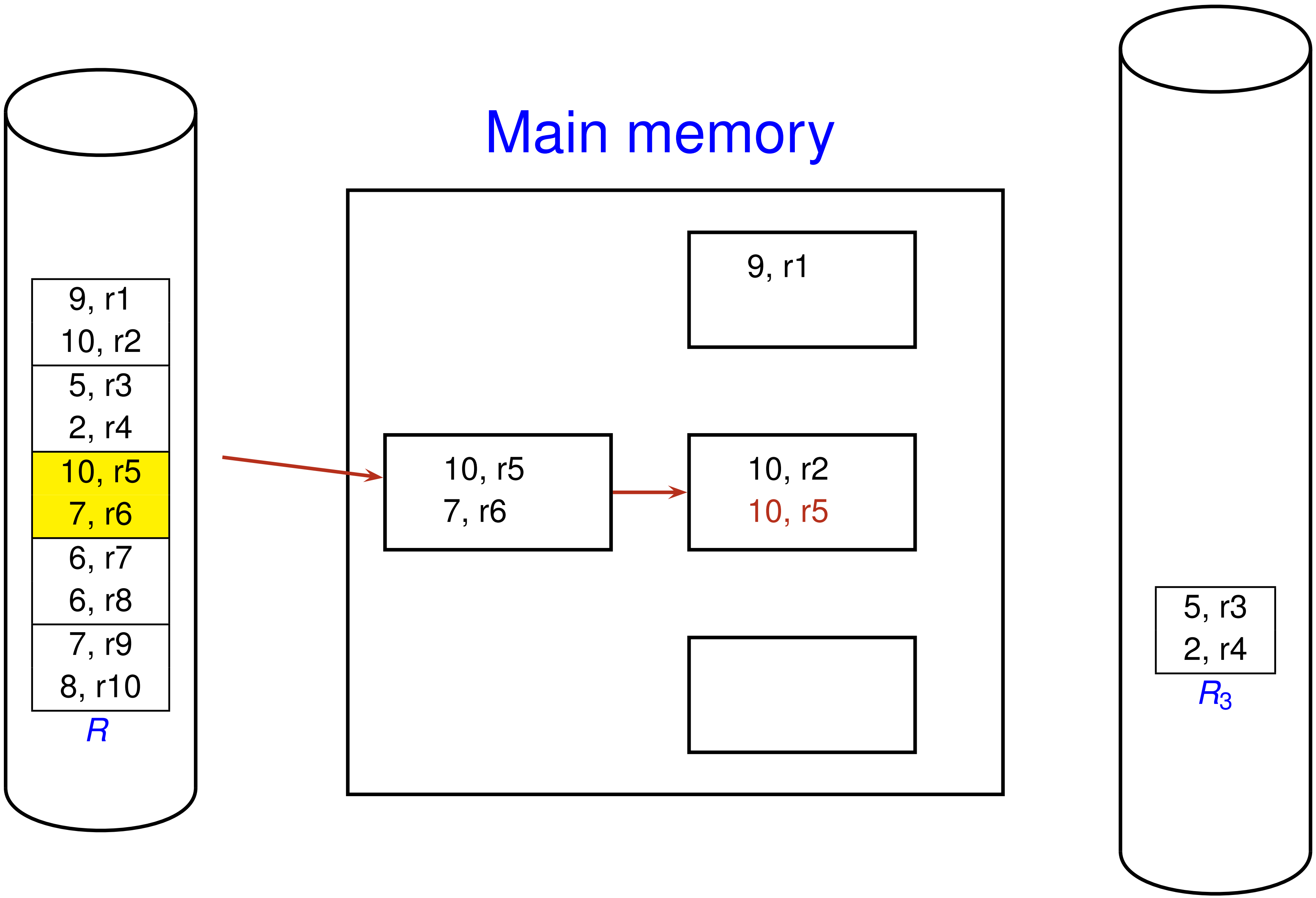
Grace Hash Join: Partitioning Relation R



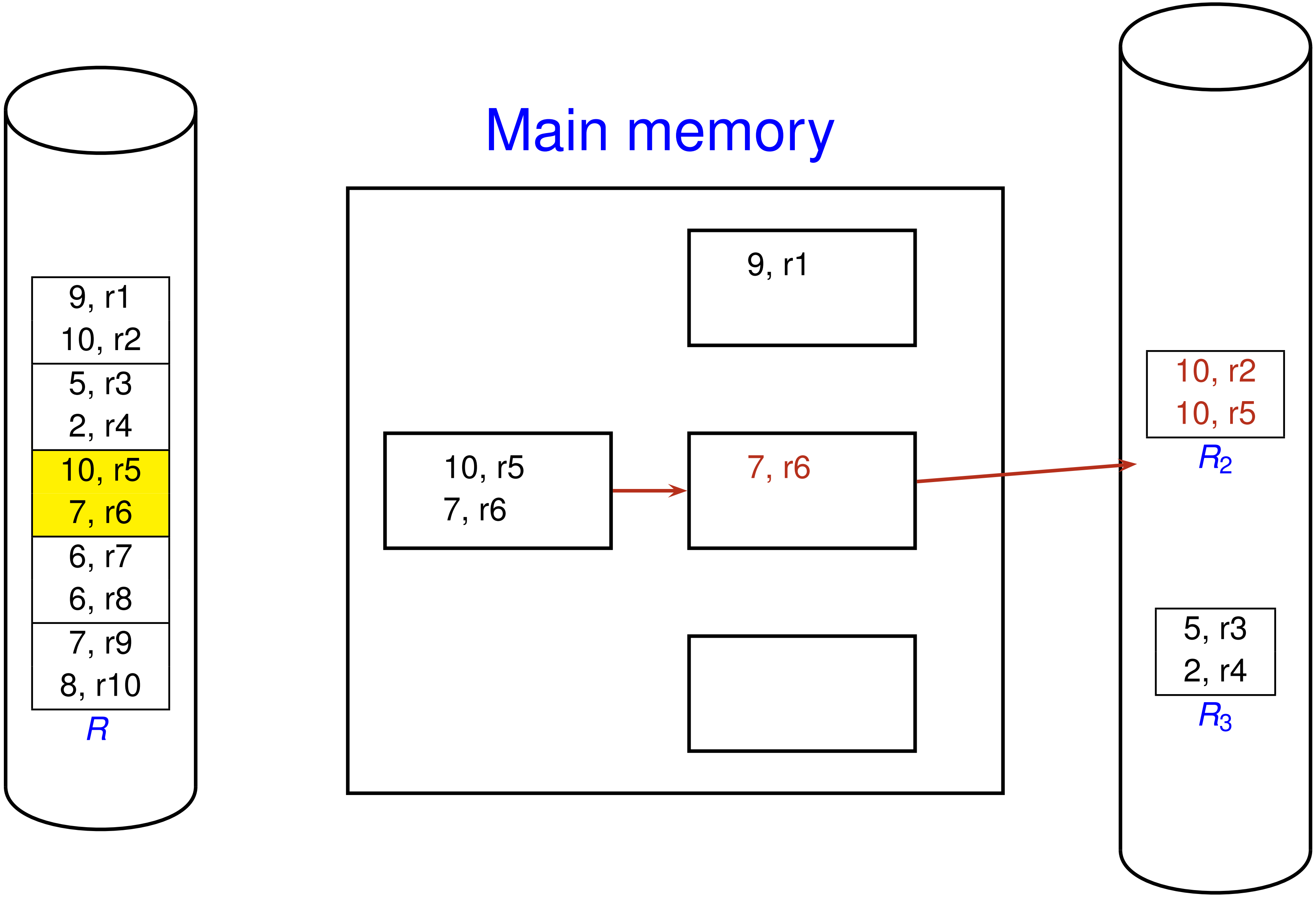
Grace Hash Join: Partitioning Relation R



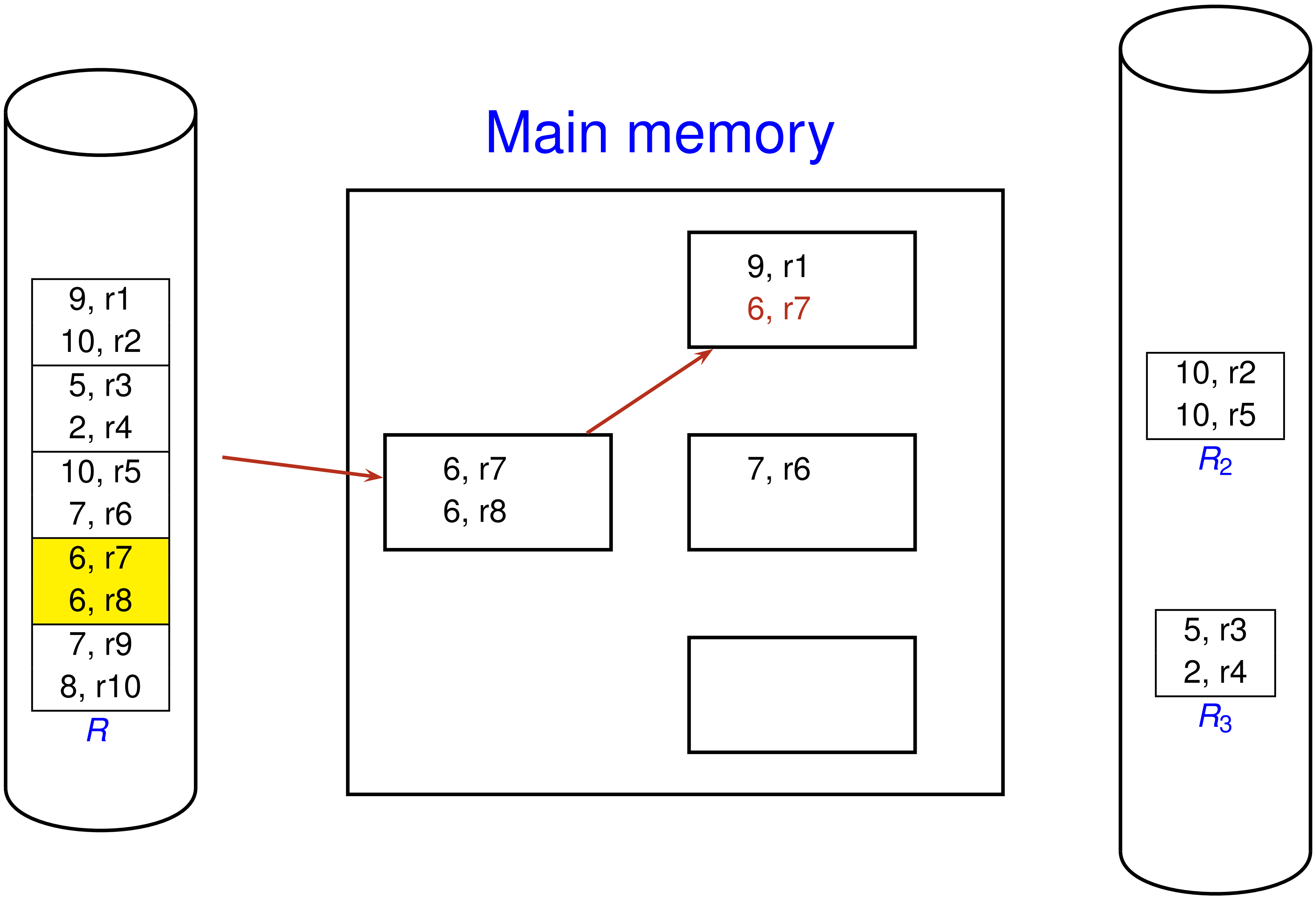
Grace Hash Join: Partitioning Relation R



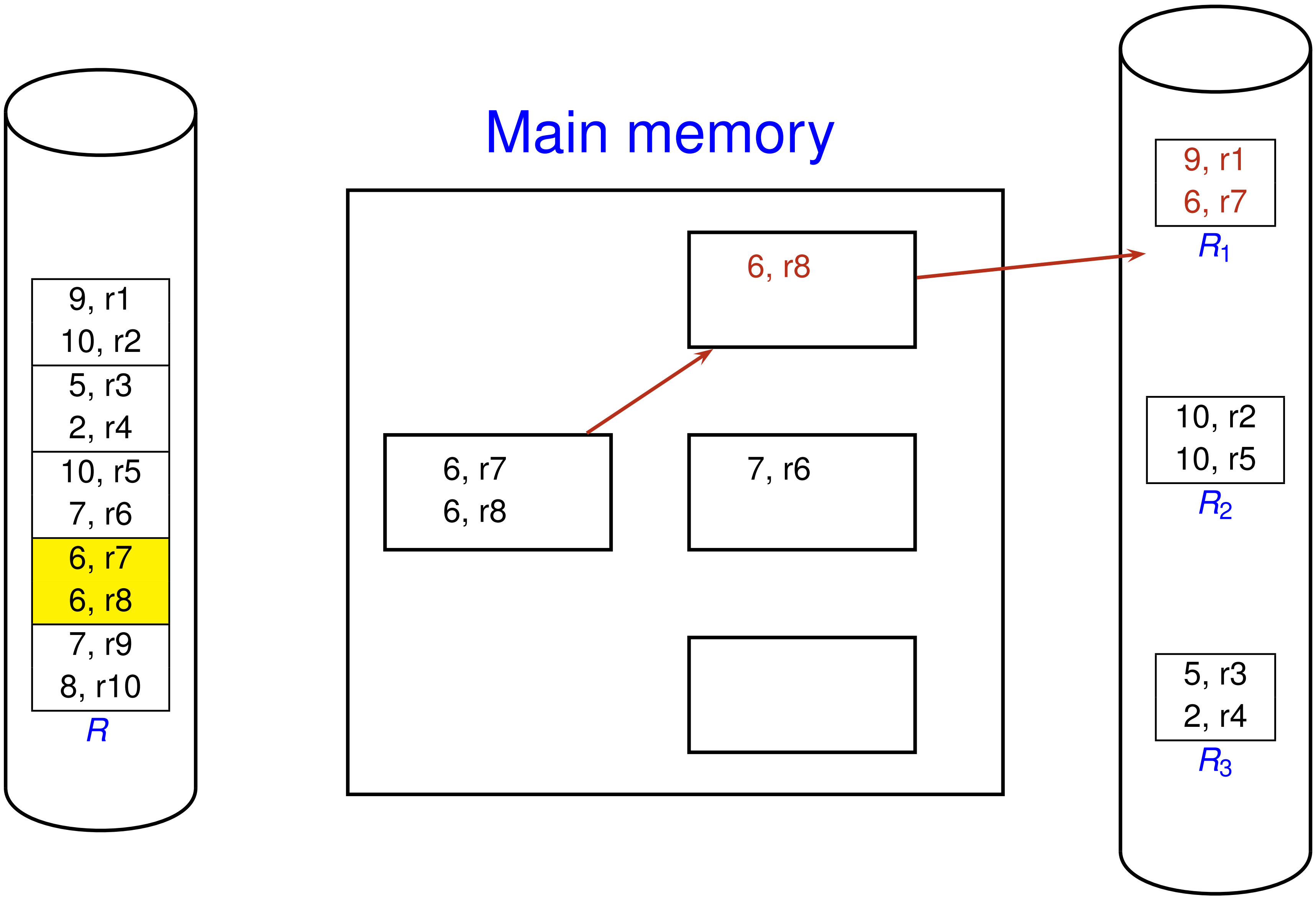
Grace Hash Join: Partitioning Relation R



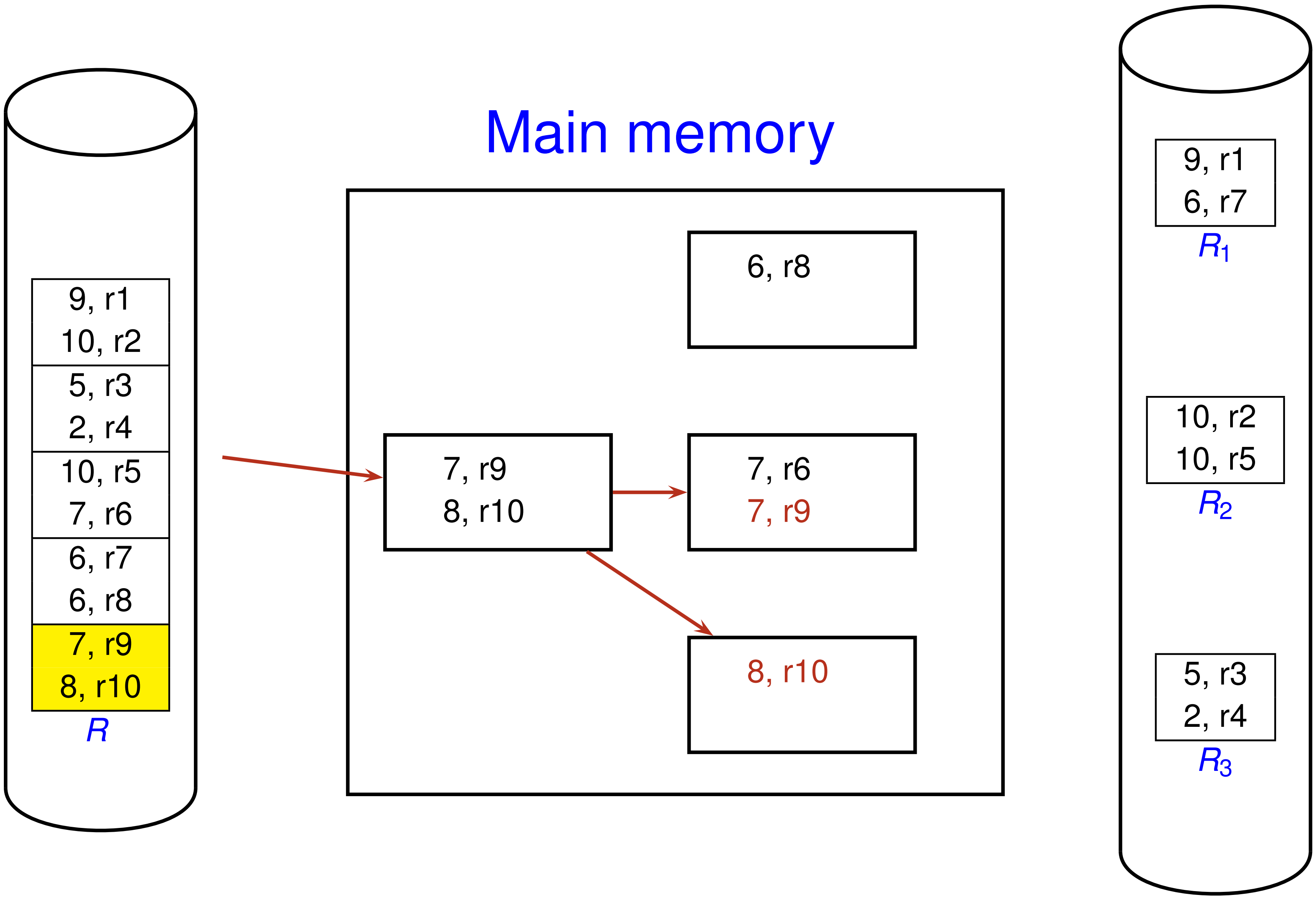
Grace Hash Join: Partitioning Relation R



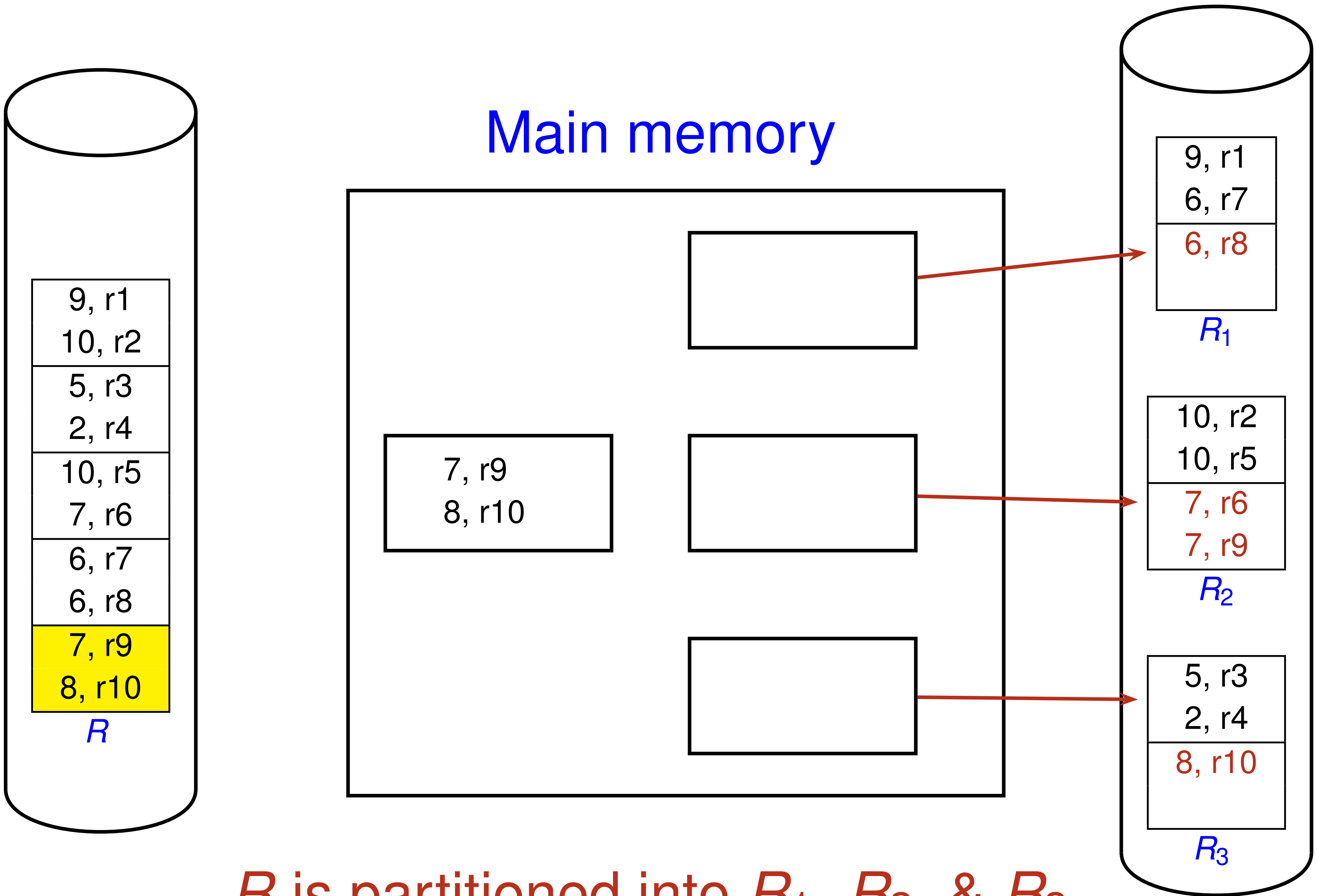
Grace Hash Join: Partitioning Relation R



Grace Hash Join: Partitioning Relation R

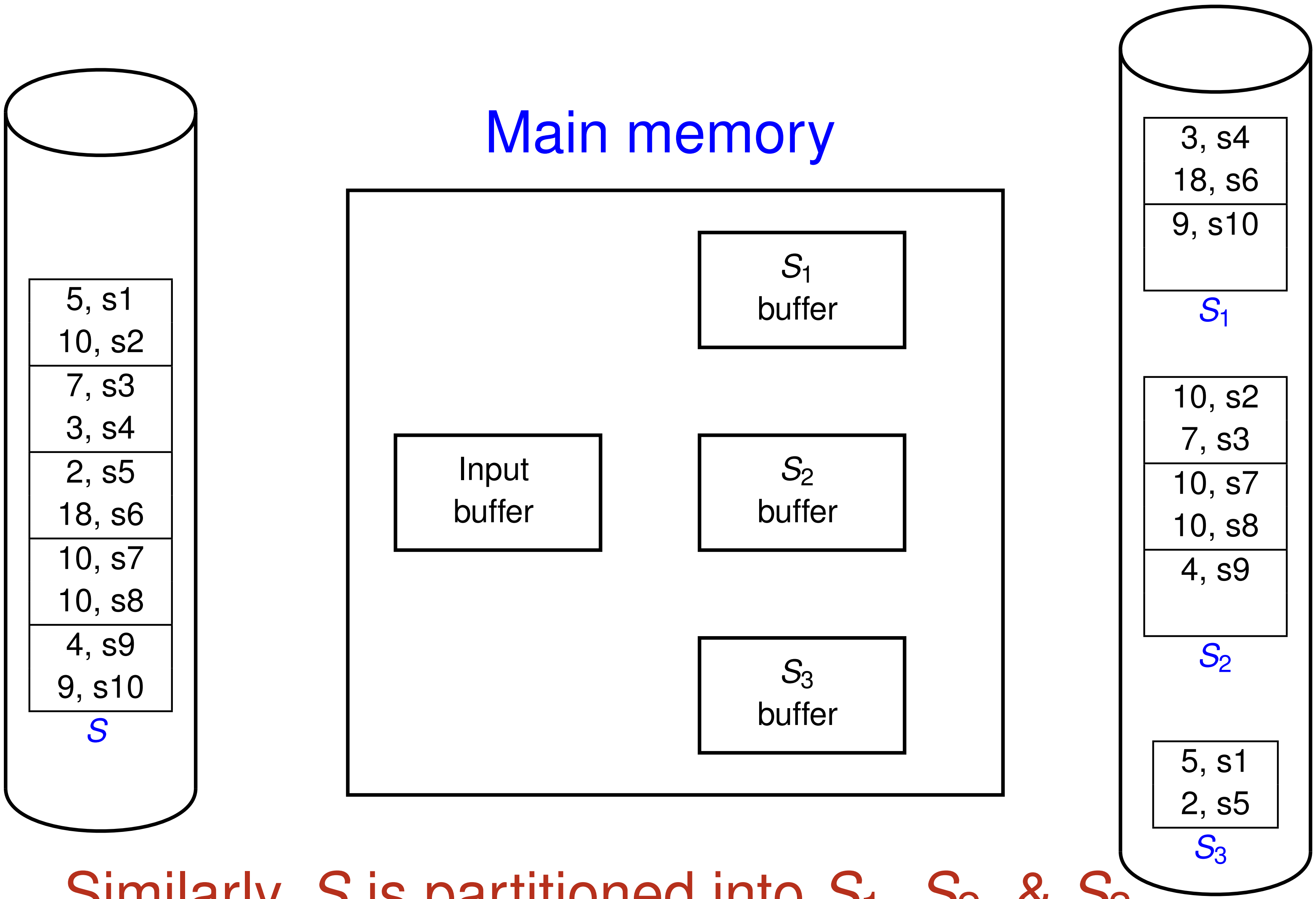


Grace Hash Join: Partitioning Relation R



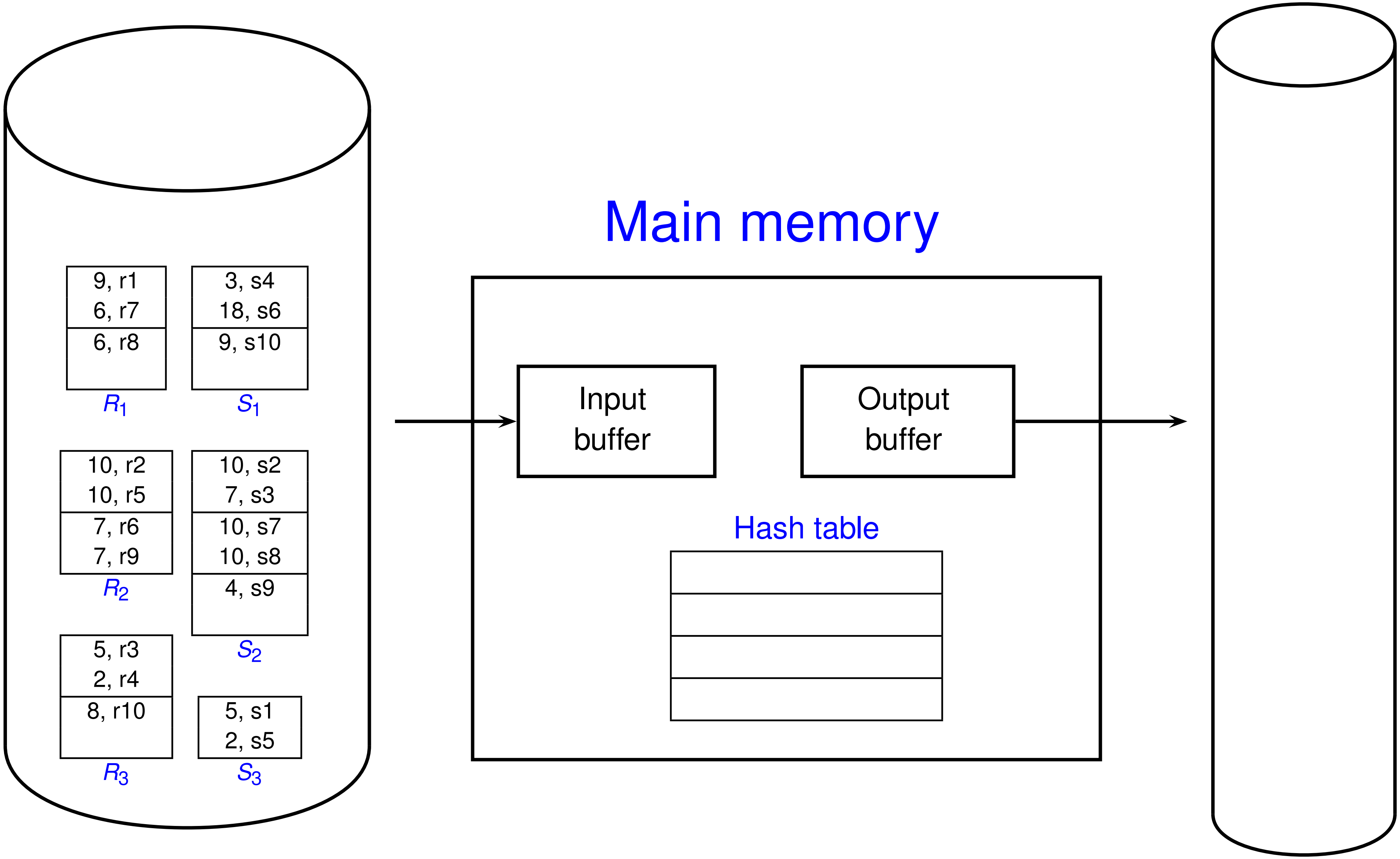
R is partitioned into R_1, R_2, & R_3

Grace Hash Join: Partitioning Relation S

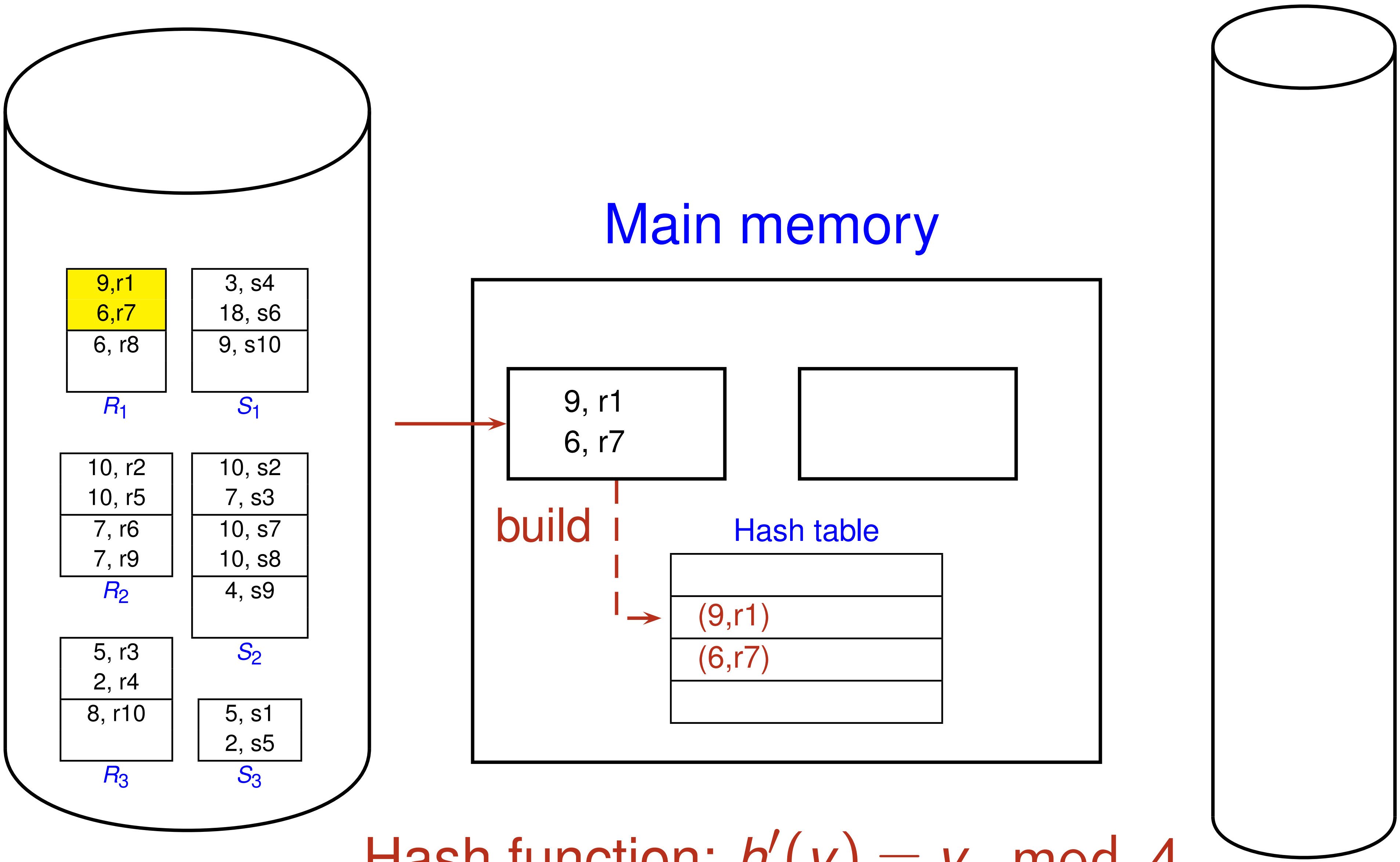


Similarly, S is partitioned into S_1, S_2, & S_3

Grace Hash Join: Probing Phase

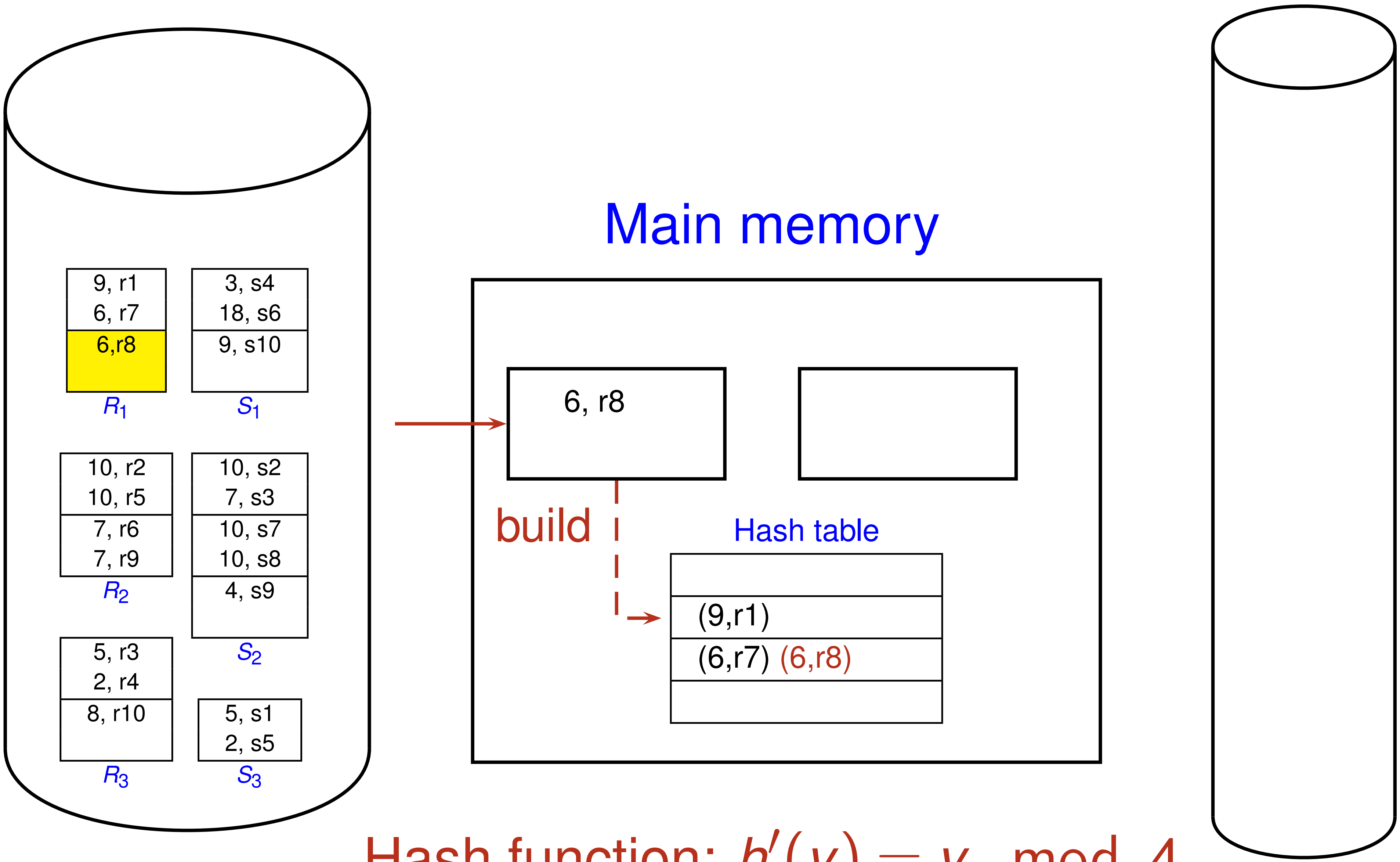


Grace Hash Join: Probing Phase



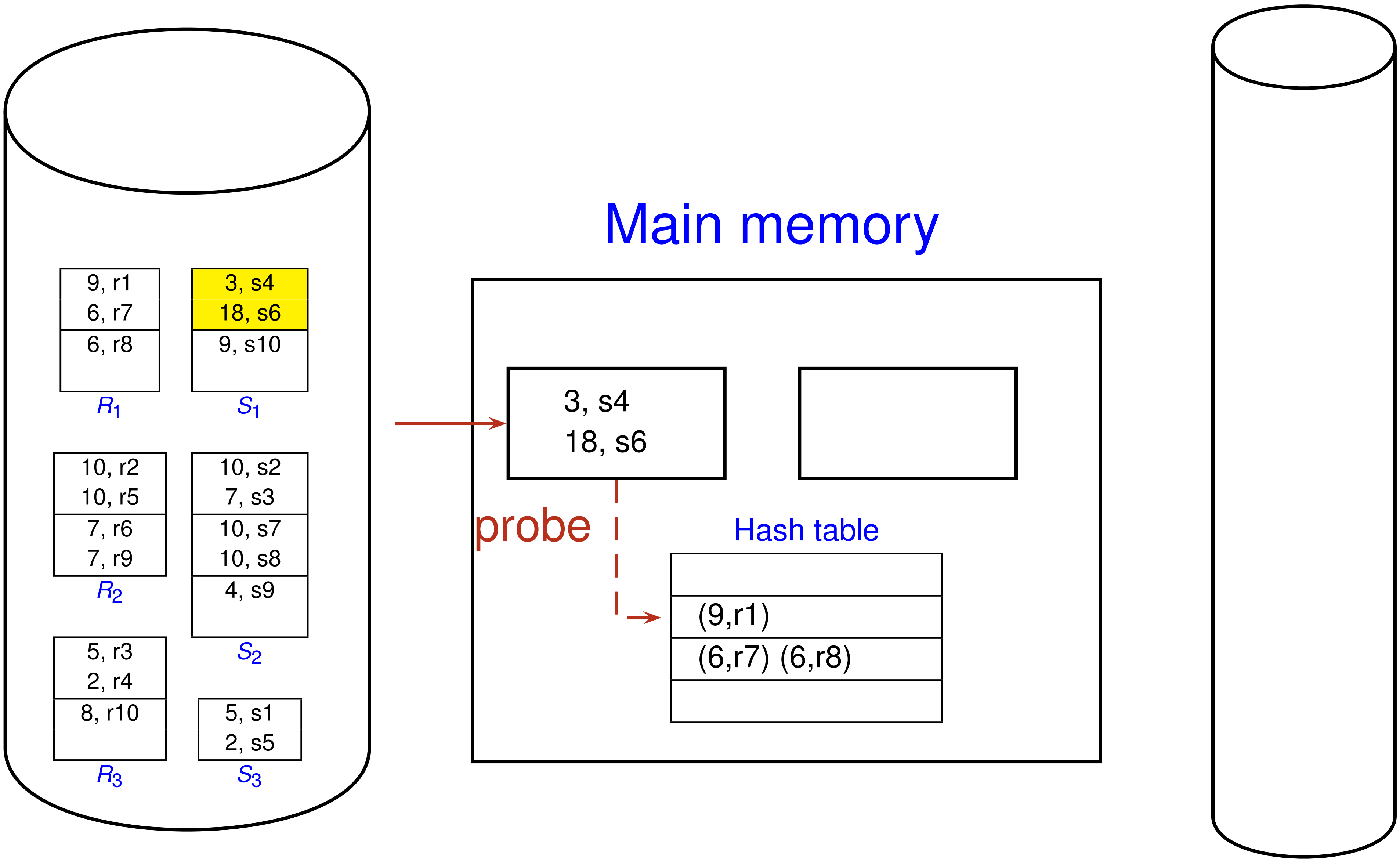
Hash function: $h'(v) = v \mod 4$

Grace Hash Join: Probing Phase

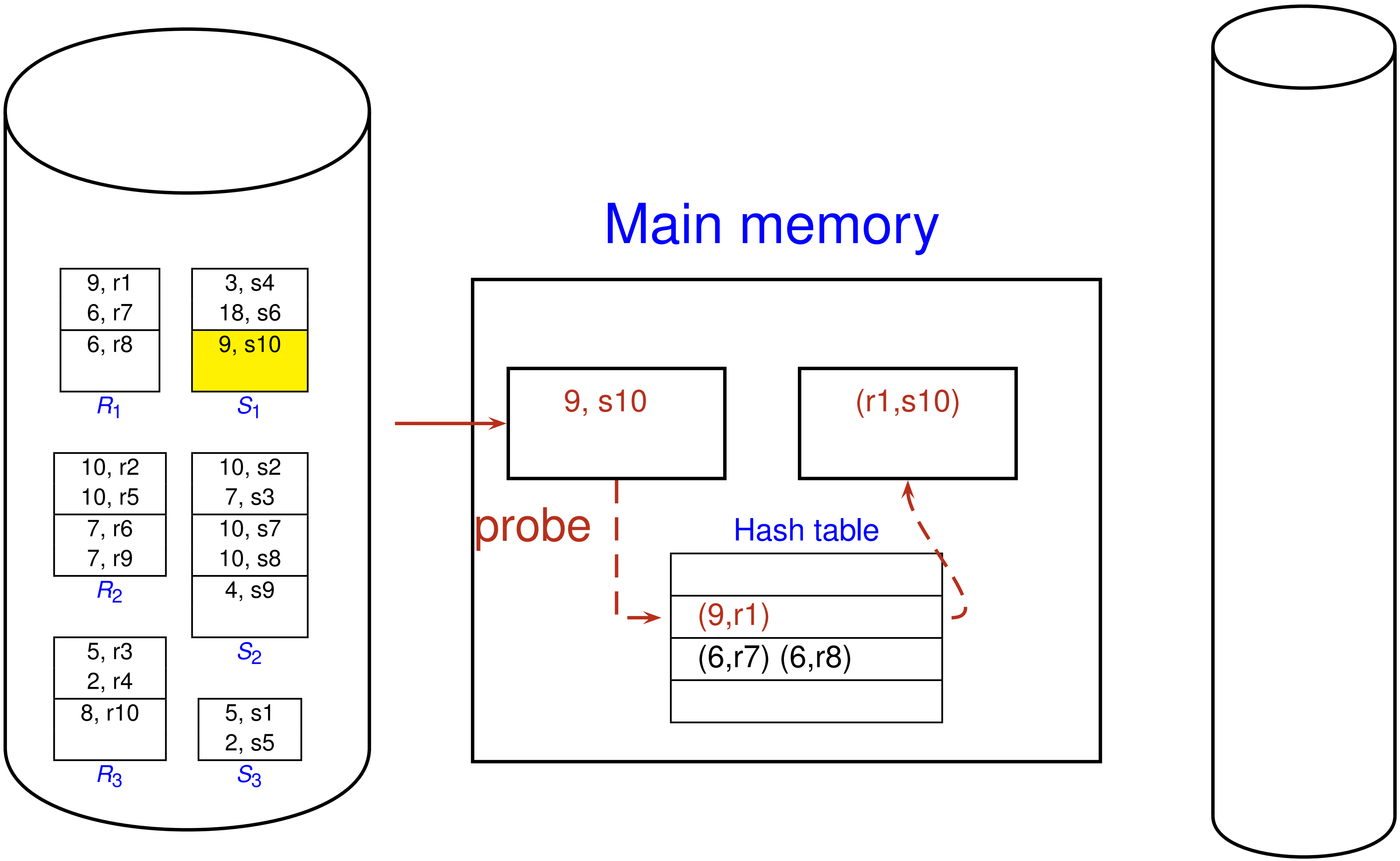


Hash function: $h'(v) = v \mod 4$

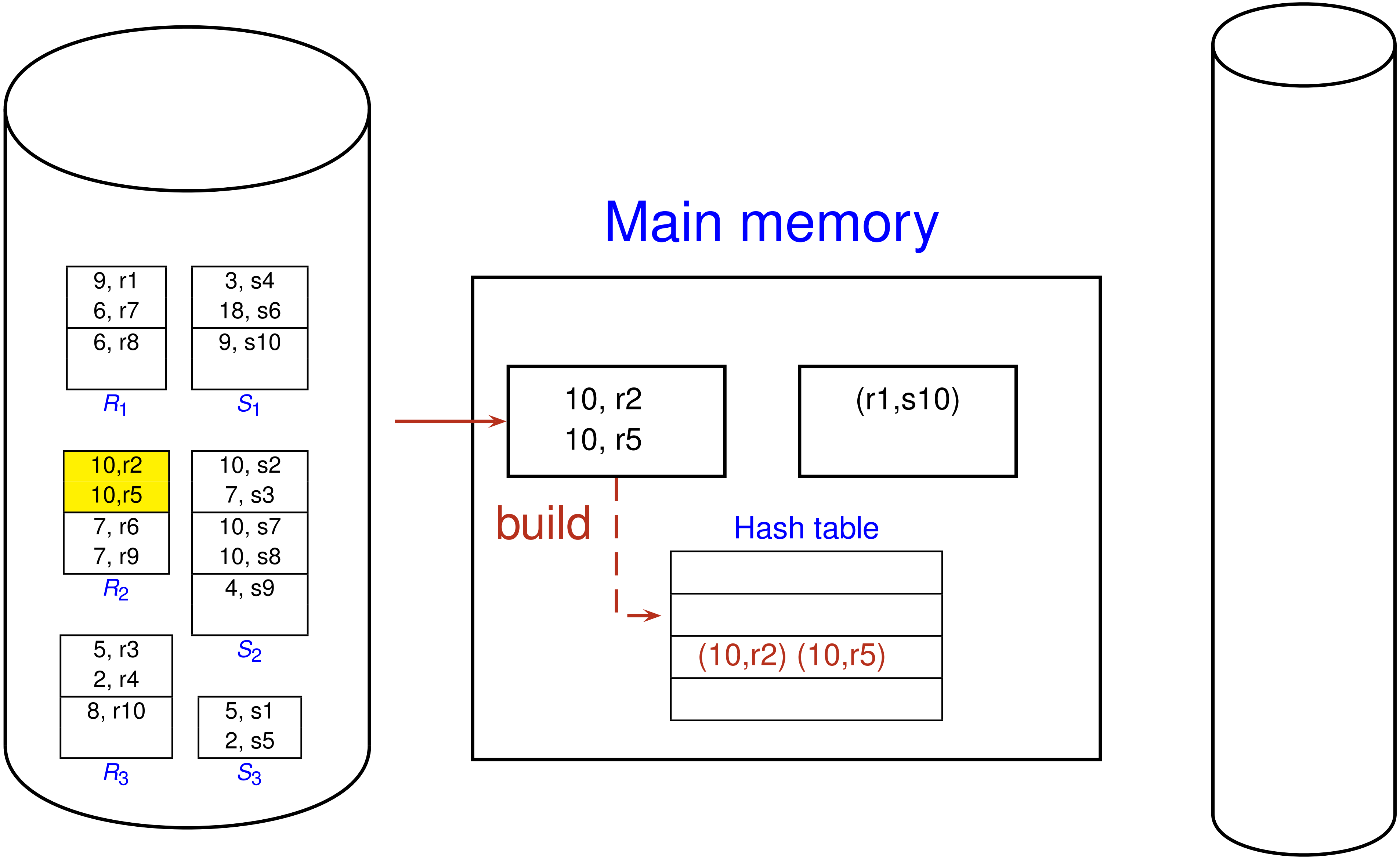
Grace Hash Join: Probing Phase



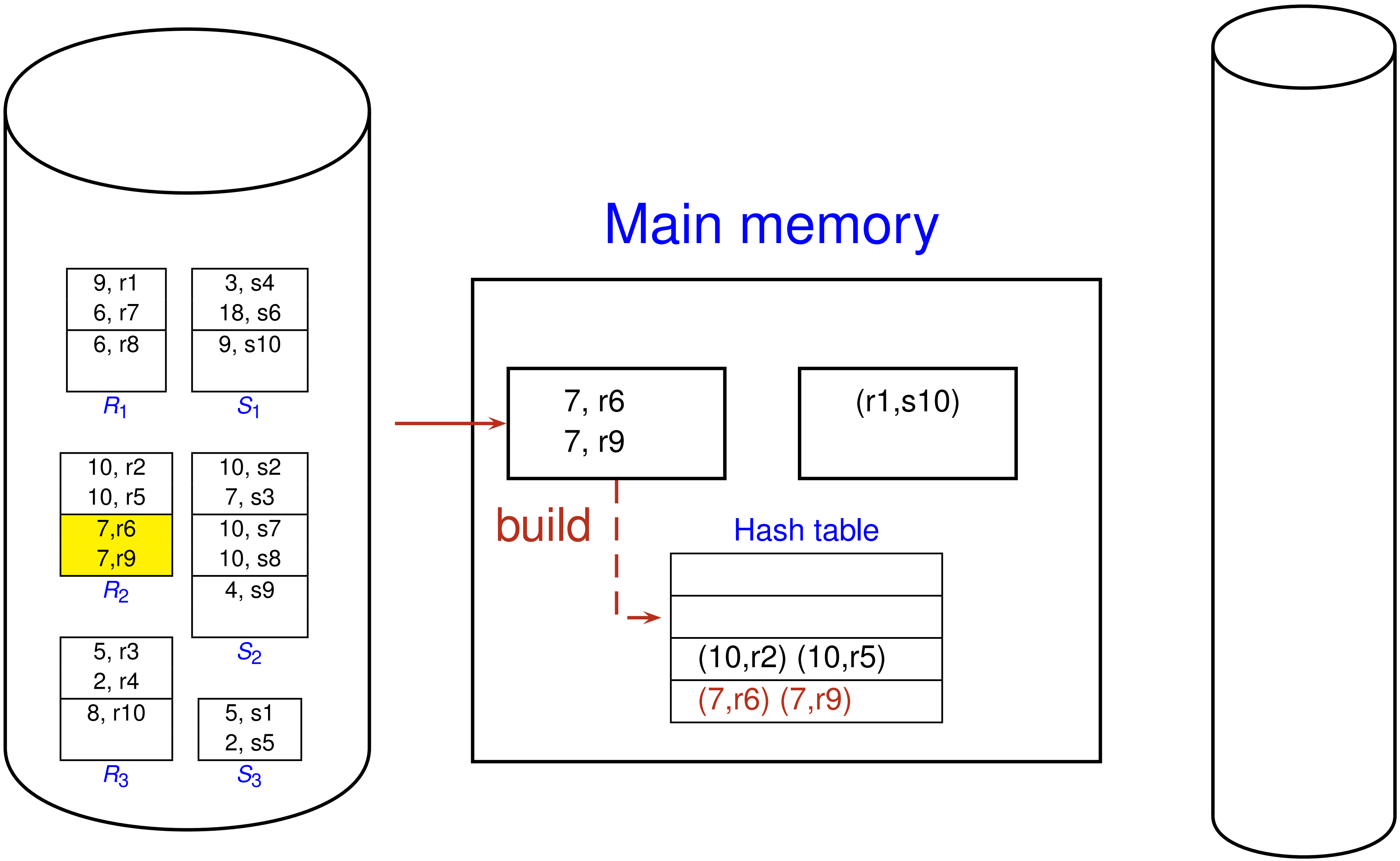
Grace Hash Join: Probing Phase



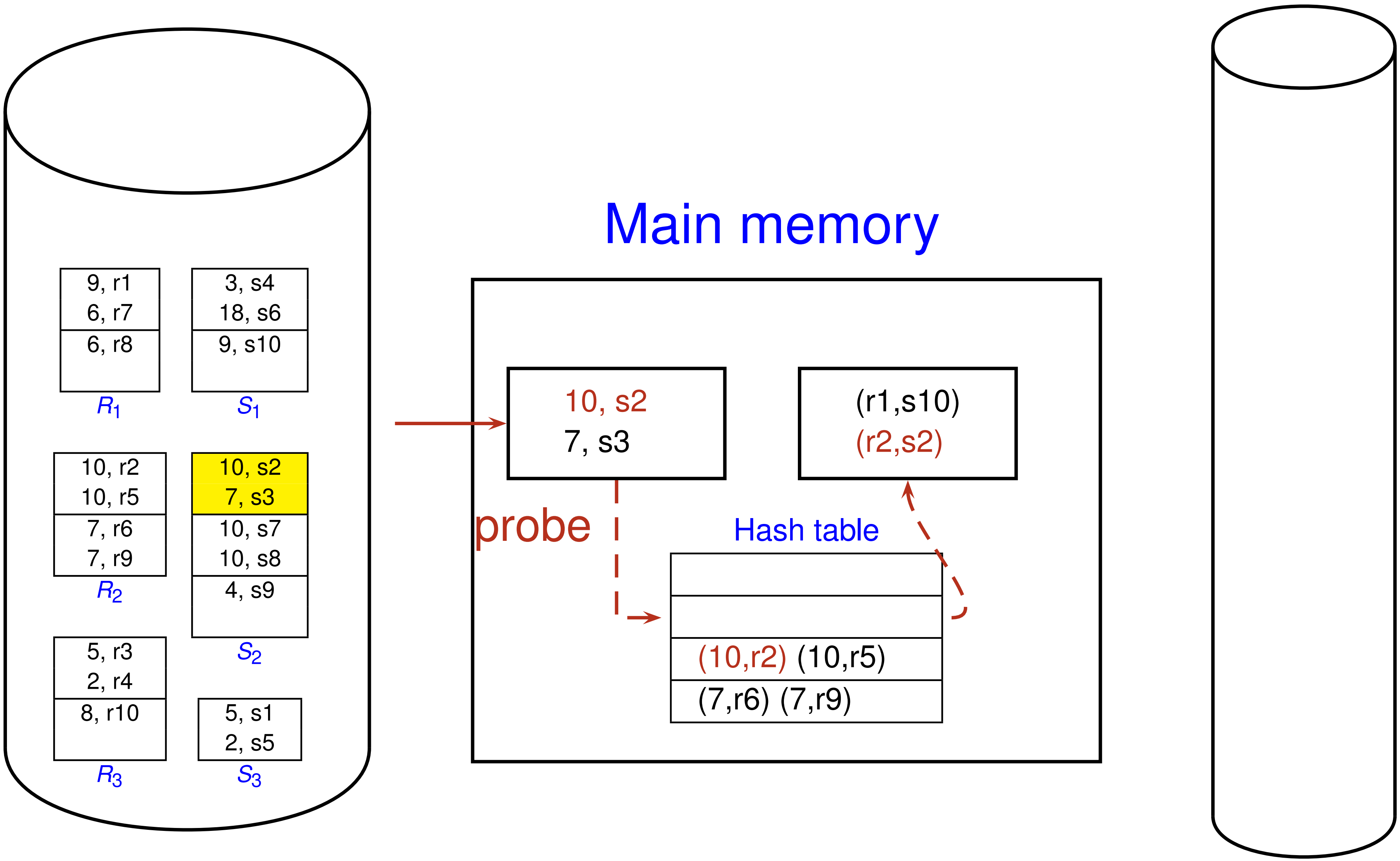
Grace Hash Join: Probing Phase



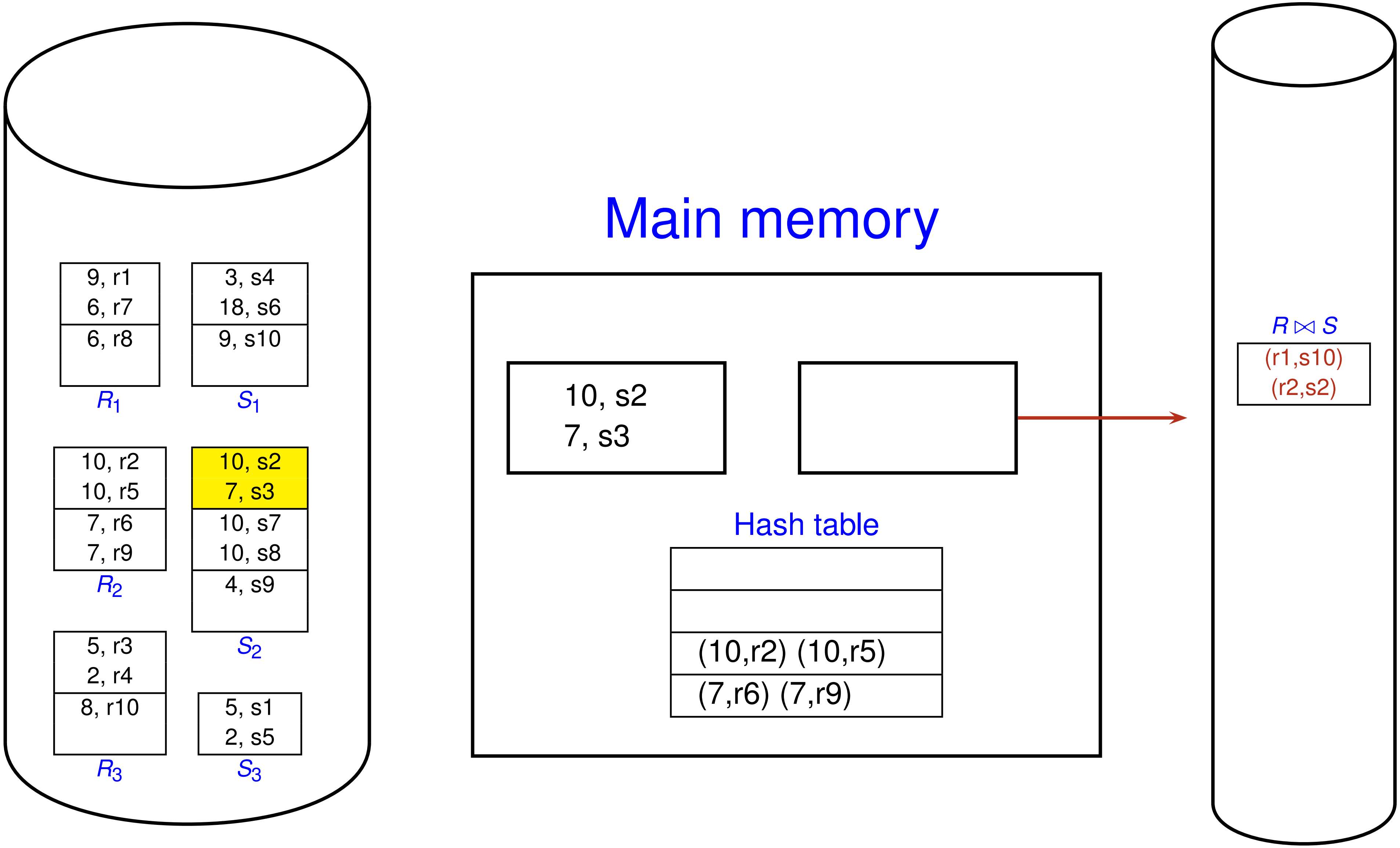
Grace Hash Join: Probing Phase



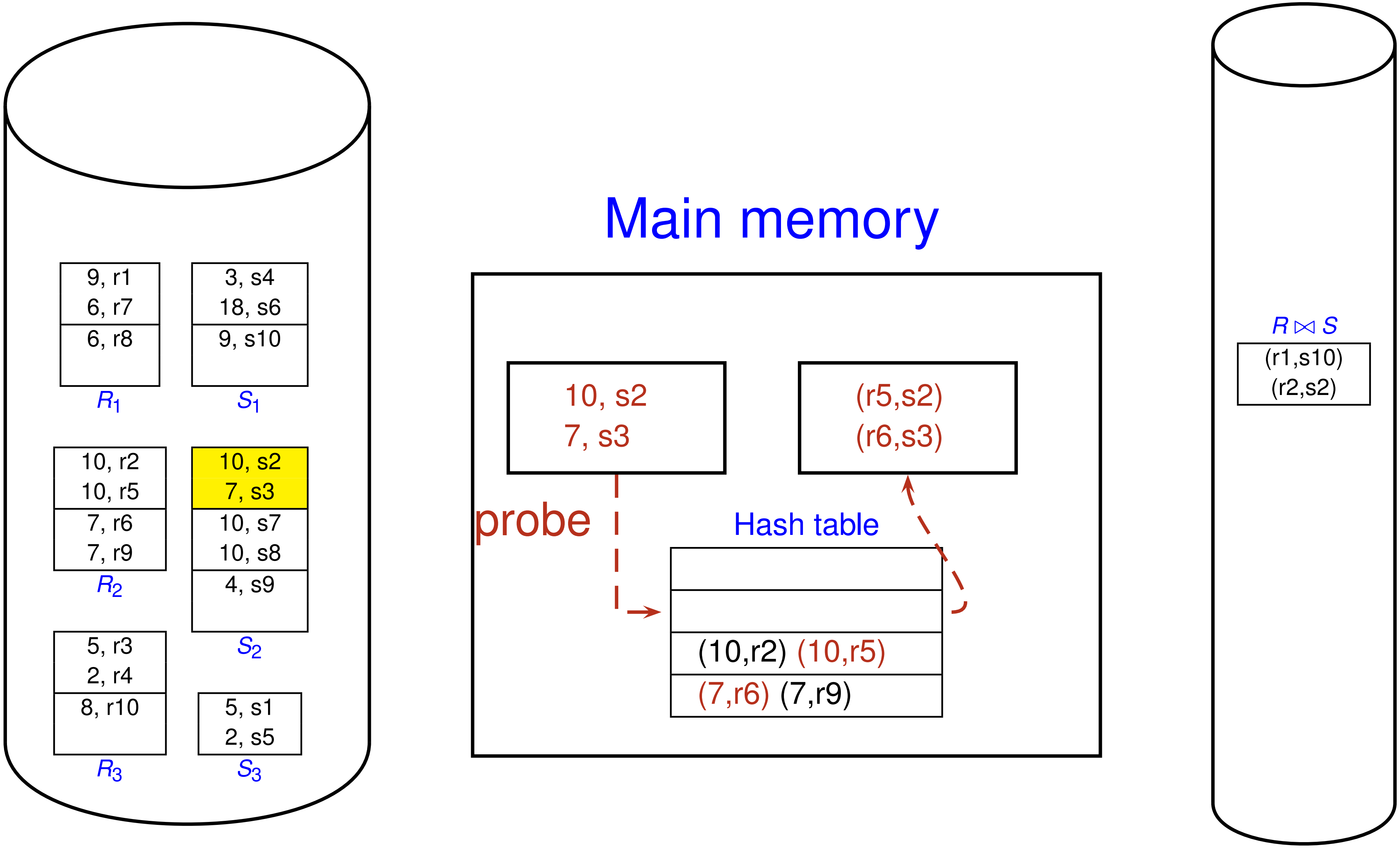
Grace Hash Join: Probing Phase



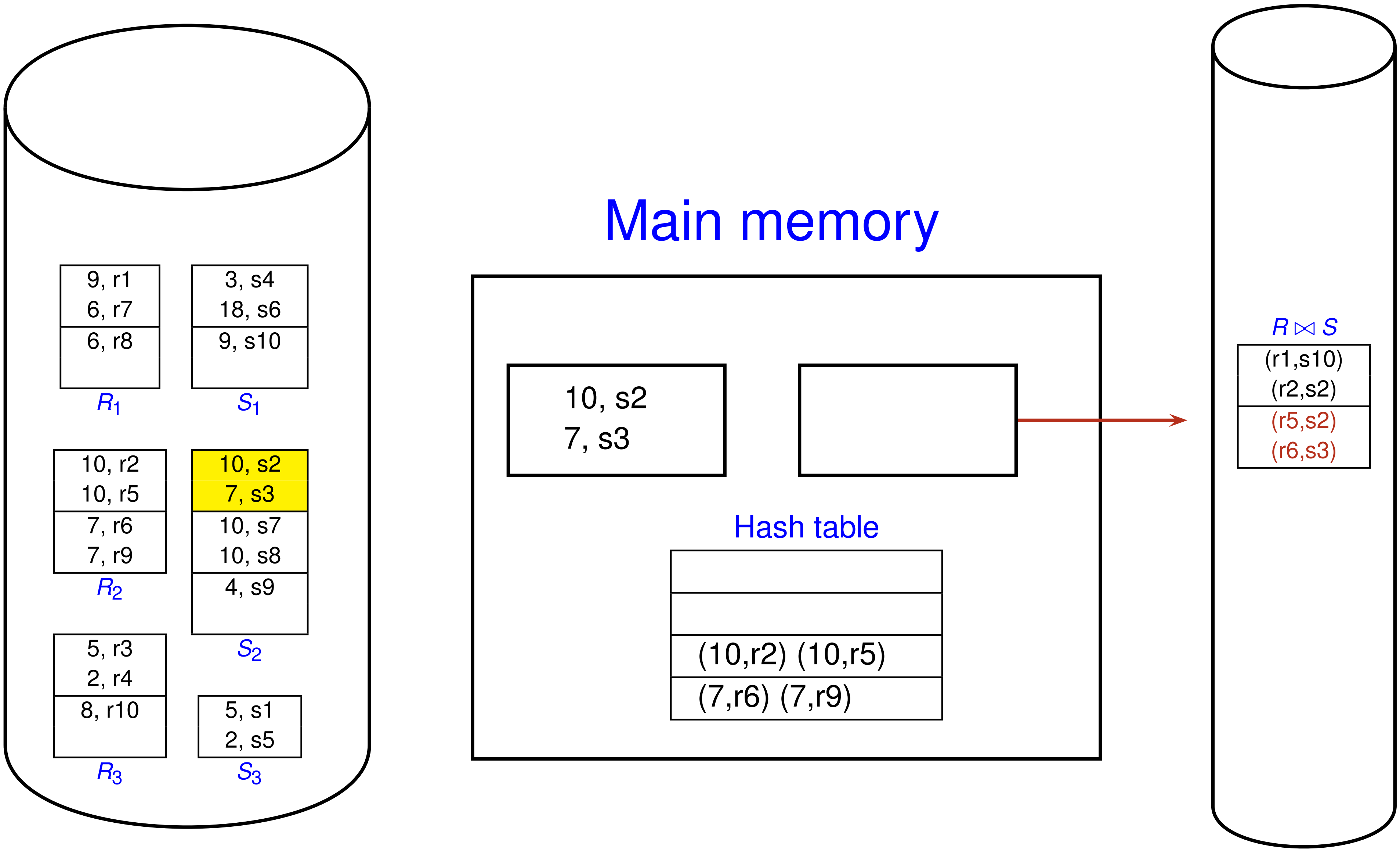
Grace Hash Join: Probing Phase



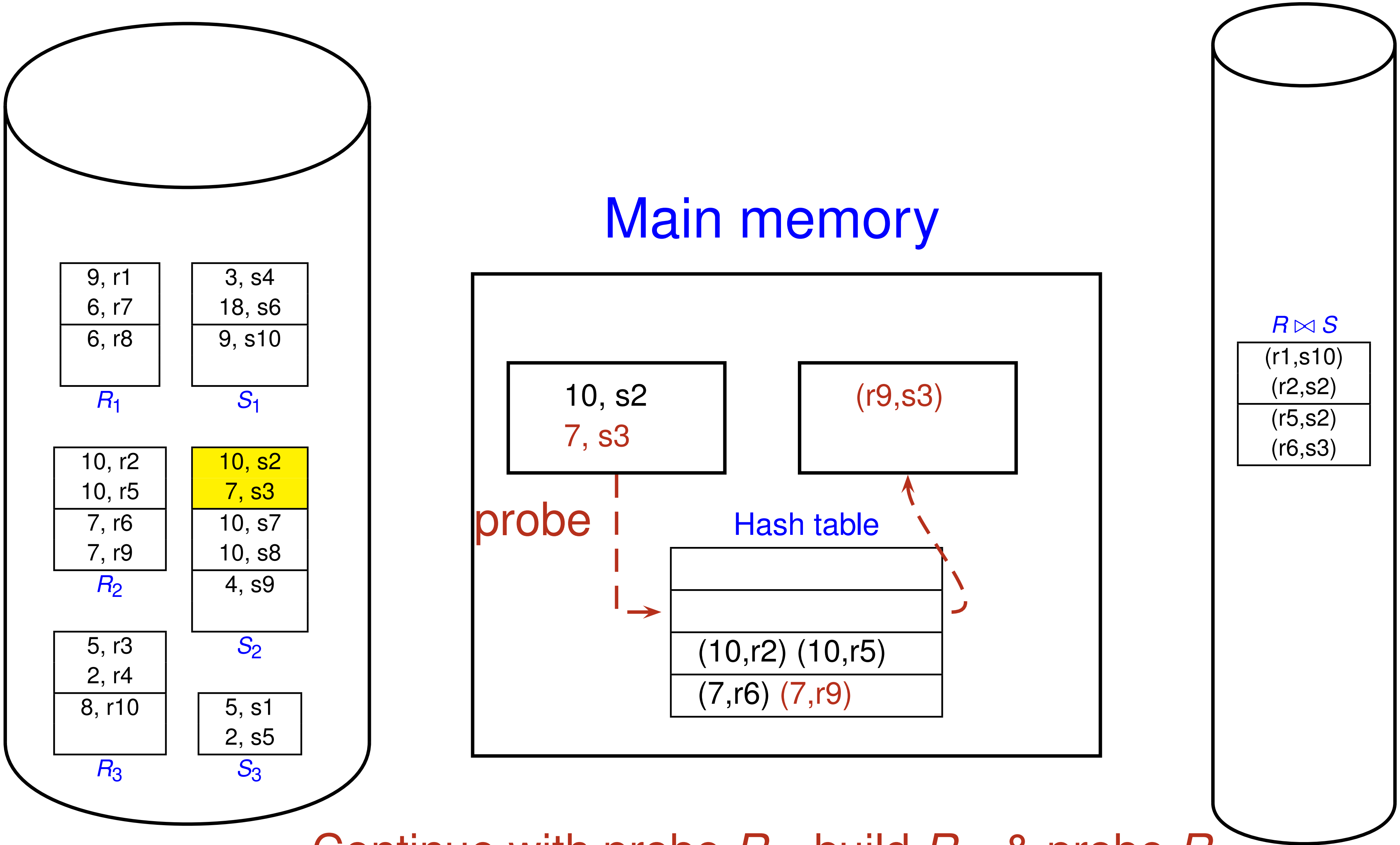
Grace Hash Join: Probing Phase



Grace Hash Join: Probing Phase



Grace Hash Join: Probing Phase



Continue with probe R_2, build R_3, & probe R_3

Grace Hash Join: Analysis

- To minimize size of each partition of R_i,
  - Set $k = B - 1$ given B buffer pages
- Assuming uniform hashing distribution,
  - size of each partition R_i is $\frac{|R|}{B-1}$
  - size of hash table for R_i is $\frac{f \times |R|}{B-1}$, where f is a fudge factor
  - During probing phase, $B > \frac{f \times |R|}{B-1} + 2$ (with one input buffer for S_i & one output buffer)
  - Approximately, $B > \sqrt{f \times |R|}$
- Partition overflow problem
  - Hash table for R_i does not fit in memory
  - Solution: recursively apply partitioning to overflow partitions
- I/O cost = Cost of partitioning phases + Cost of probing phase
  - I/O cost = $3(|R| + |S|)$ if there's no partition overflow problem

General Join Conditions

- Multiple equality-join conditions
  - Example: (R.A = S.A) `and` (R.B = S.B)
  - Algorithms:
    - **Index Nested Loop Join**: use index on all or some of join attributes
    - **Sort-Merge Join**: need to sort on combination of attributes
    - Other algorithms essentially unchanged
- Inequality-join conditions
  - Example: (R.A $<$ S.A)
  - Algorithms:
    - **Index Nested Loop Join**: requires a B^+-tree index
    - **Sort-Merge Join**: not applicable
    - **Hash-based Joins**: not applicable
    - Other algorithms essentially unchanged