CSE544
Data Management

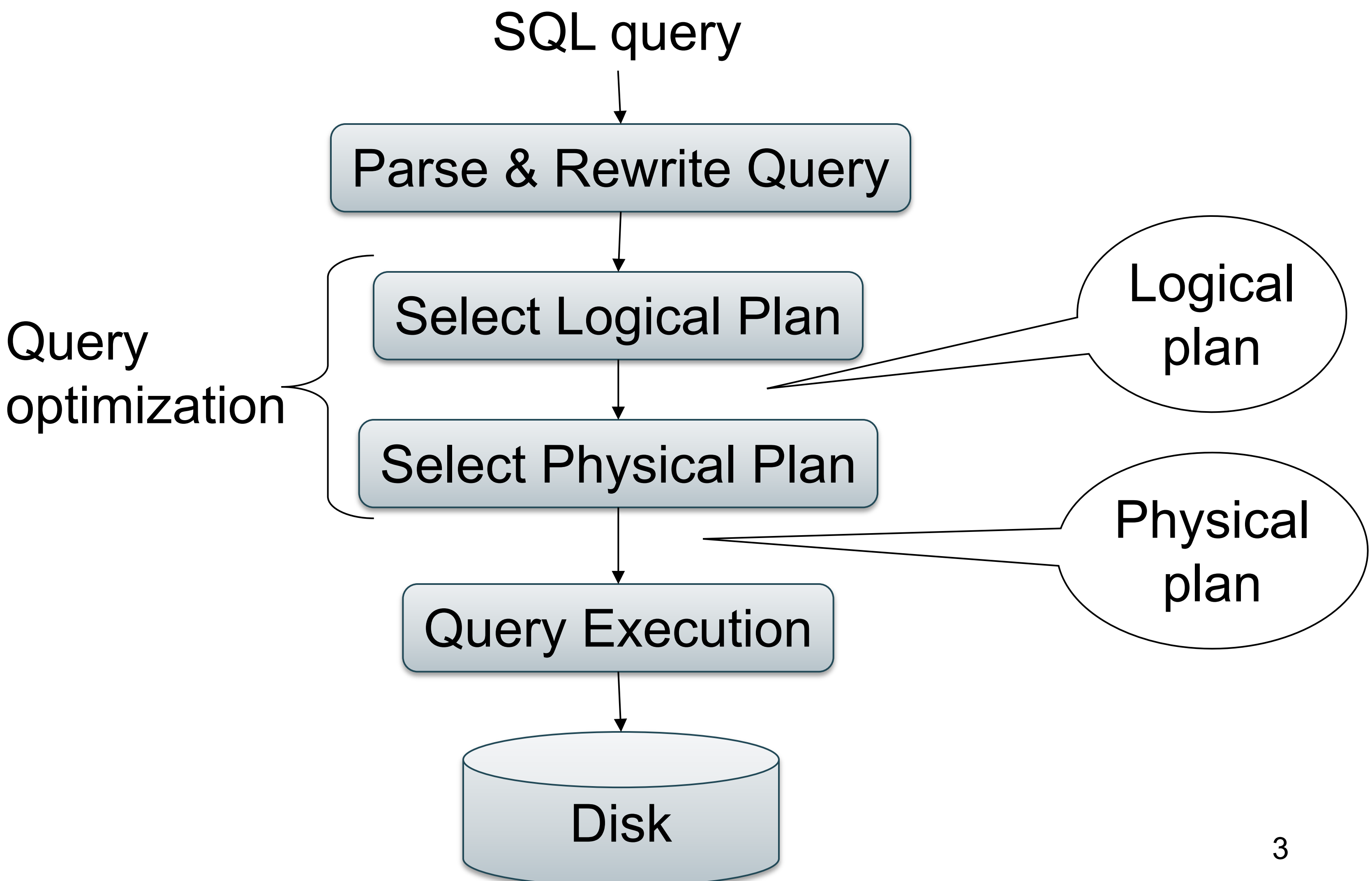
Lectures 8

Query Execution – Part 2

Announcements

- This Friday: Kyle's office hour moved
  - 1:30-2:20, Gates 274
- Project proposals due on Monday, 2/5
- HW2 due on Wednesday 2/7
- R3 pushed to Wednesday, 2/14

Lifecycle of a Query



Main Memory Operators

Supplier(sno,sname,scity,sstate)
Supply(sno,pno,price)
Part(pno,pname,psize,pcolor)

1. Nested Loop Join

Logical operator:

$$\text{Supplier} \bowtie_{\text{sno}=\text{sno}} \text{Supply}$$

```
for x in Supplier do
    for y in Supply do
        if x.sno = y.sno
            then output(x,y)
```

If |R|=|S|=n,
what is the runtime?

$O(n^2)$

Supplier(sno,sname,scity,sstate)
Supply(sno,pno,price)
Part(pno,pname,psize,pcolor)

1. Index Join

Logical operator:

$$\text{Supplier} \bowtie_{\text{sno}=\text{sno}} \text{Supply}$$

```
for x in Supplier do
    for y in SupplyIndex(x.sno) do
        output(x,y)
```

If |R|=|S|=n, what is the runtime?

O(n)

When data is on disk
then big difference between
clustered and unclustred

Supplier(sno,sname,scity,sstate)
Supply(sno,pno,price)
Part(pno,pname,psize,pcolor)

Clustered v.s. Unclustered

Logical operator:

$$\text{Supplier} \bowtie_{\text{sno=sno}} \text{Supply}$$

```
for x in Supplier do
   for y in SupplyIndex(x.sno) do
      output(x,y)
```

Rule of thumb:
Random reading 1-2% of Supply ≈ sequential scan entire file

Supplier(sno,sname,scity,sstate)
Supply(sno,pno,price)
Part(pno,pname,psize,pcolor)

2. Hash Join

Logical operator:

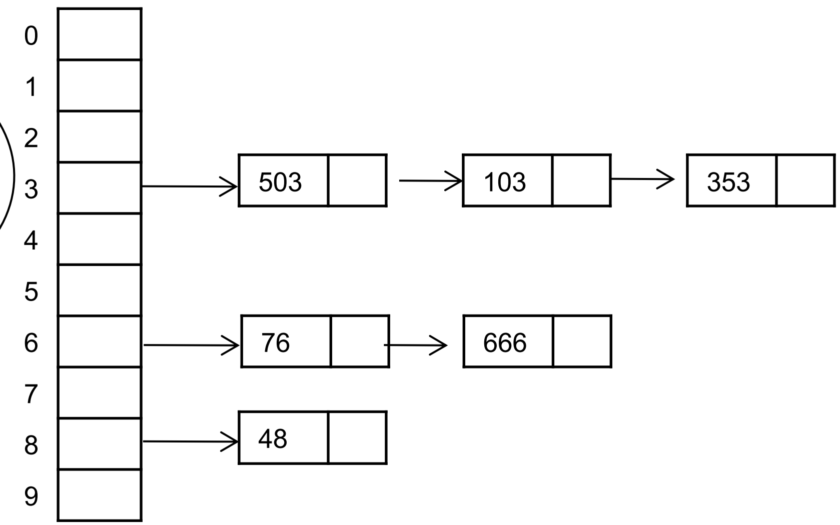
$$\text{Supplier} \bowtie_{\text{sno=sno}} \text{Supply}$$

Build phase

```
for x in Supplier do
     insert(x.sno, x)

for y in Supply do
     x = find(y.sno);
     output(x,y);
```

Probe phase



If |R|=|S|=n,
what is the runtime?

O(n)

Supplier(sno,sname,scity,sstate)
Supply(sno,pno,price)
Part(pno,pname,psize,pcolor)

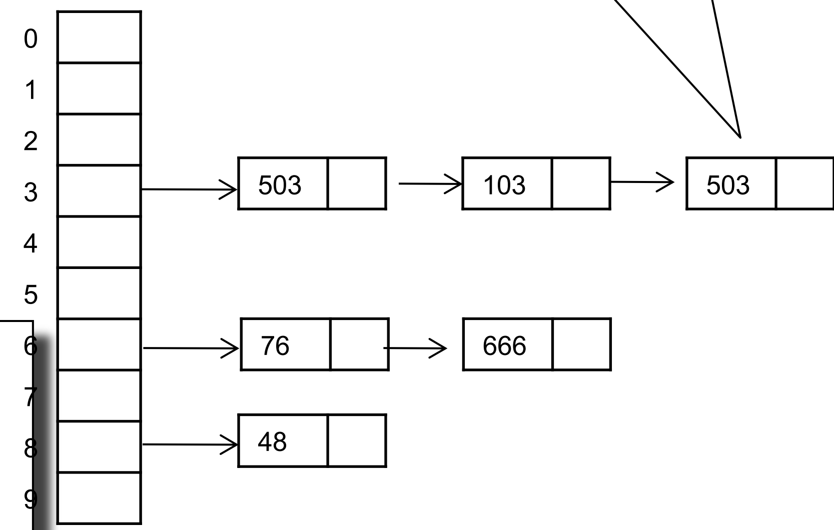
2. Hash Join

There may be duplicate sno's

Change join order

Logical operator:

$$\text{Supply} \bowtie_{sno=sno} \text{Supplier}$$




```
for y in Supply do
    insert(y.sno, y)

for x in Supplier do
    for y in find(x.sno) do
        output(x,y);
```

If |R|=|S|=n,
what is the runtime?

O(n)
But can be $O(n^2)$ why?

Supplier(sno,sname,scity,sstate)
Supply(sno,pno,price)
Part(pno,pname,psize,pcolor)

3. Merge Join

Logical operator:

$$\text{Supplier} \bowtie_{\text{sno}=\text{sno}} \text{Supply}$$

```
Sort(Supplier); Sort(Supply);
x = Supplier.first();
y = Supply.first();
while y != NULL do
  case:
    x.sno < y.sno: x = x.next()
    x.sno = y.sno: output(x,y); y = y.next();
    x.sno > y.sno: y = y.next();
```

If |R|=|S|=n,
what is the runtime?

O(n log(n))

Brief Review:
Hash Tables, Sorting

Hash Tables

- Array: map indices to memory locations
  – A[0], A[1], A[2], … sequential in memory

- How to map texts to memory locations?
  – A[“alice”], A[“bob”],A[“carl”]…???

- Hash function: maps strings to indices

Separate chaining:

Hash Tables

A (naïve) hash function:

$$\boxed{h(\text{“abc”}) = (\text{‘a’}+\text{’b’}+\text{’c’}) \bmod 10}$$

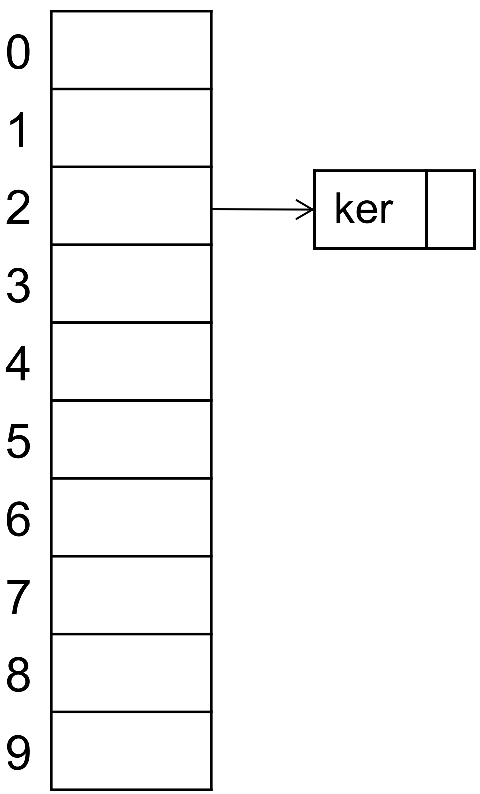
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	

Separate chaining:

Hash Tables

A (naïve) hash function:

h(“abc”) = (‘a’+’b’+’c’) mod 10



E.g. h(“ker”) = (‘k’+’e’+’r’) mod 10
= (107+101+114) mod 10
= 2

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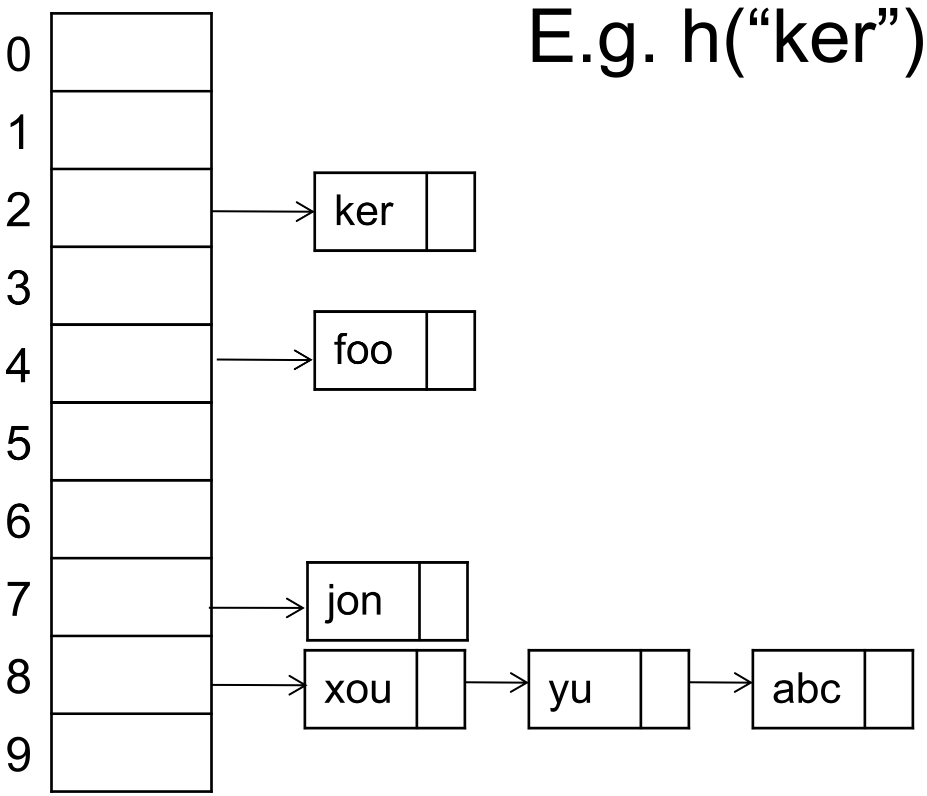

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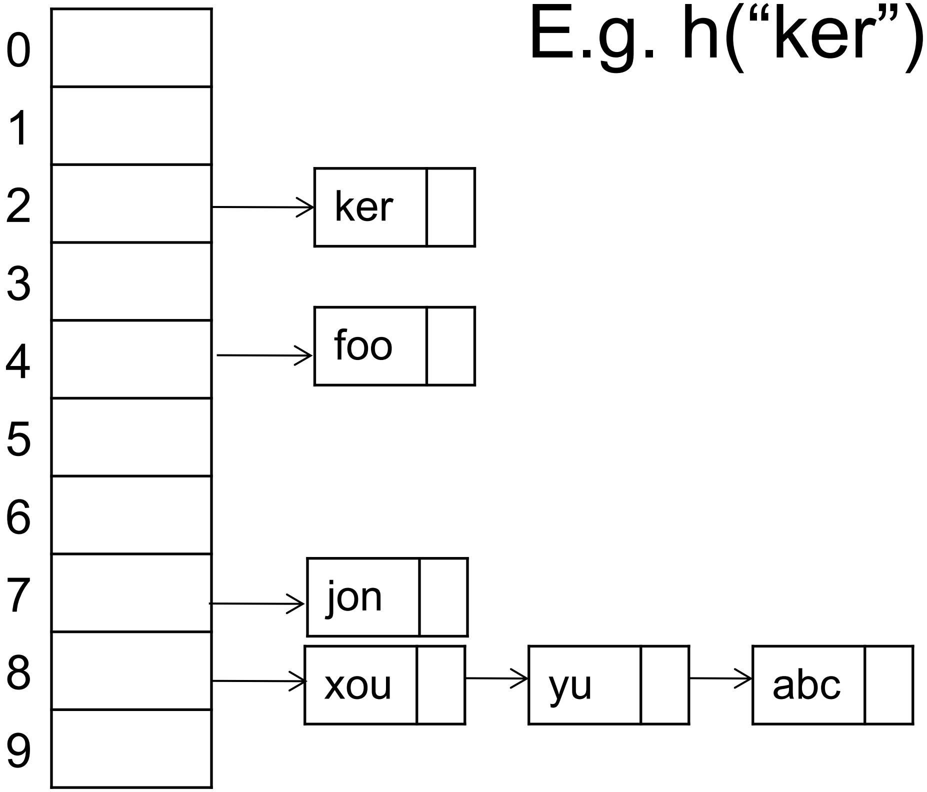

E.g. $h(\text{“ker”}) = (\text{‘k’}+\text{’e’}+\text{’r’}) \bmod 10$

$= (107+101+114) \bmod 10$

$= 2$

find(“yu”) = ??

insert(“alice”) = ??

Hash Table Takeaways

- Use good hash function, never your own. E.g. https://15445.courses.cs.cmu.edu/fall2023/slides/07-hashtables.pdf
  - Low probability of collision
- The vector needs to be pre-allocated:
  - Too big: waste space
  - To small: long chains
  - Extensible hash table: doubles the vector
- Skewed data leads to collisions: O(1)→O(N)

Sorting

- Given an array, sort it in increasingly

74	7	45	99	2	90	19	87	61	82

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2	7	19	45	61	74	82	87	90	99

Sorting

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- Simple algorithms: $O(N^2)$
- Quicksort: $O(N \log N)$
- Mergesort: $O(N \log N)$

Merge Sort: Overview

- A run is a subarray that is sorted
- Repeat:
  - Merge two runs
  - Store output in some array T
  - Switch A,T
- Stop when A is one single run

Merging two Arrays

Assume ∞ at the end

```
Merge(A, B)          // A, B are sorted
```

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Merge(A, B)              // A, B are sorted
  i=0;  j=0;  k=0;
  while i<n or j<n
    case:
        A[i]<B[j]:  T[k++] = A[i++];
```

Merging two Arrays

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```

Time = O(|A|+|B|)

Merge-Sort

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Merge-Sort

Runs

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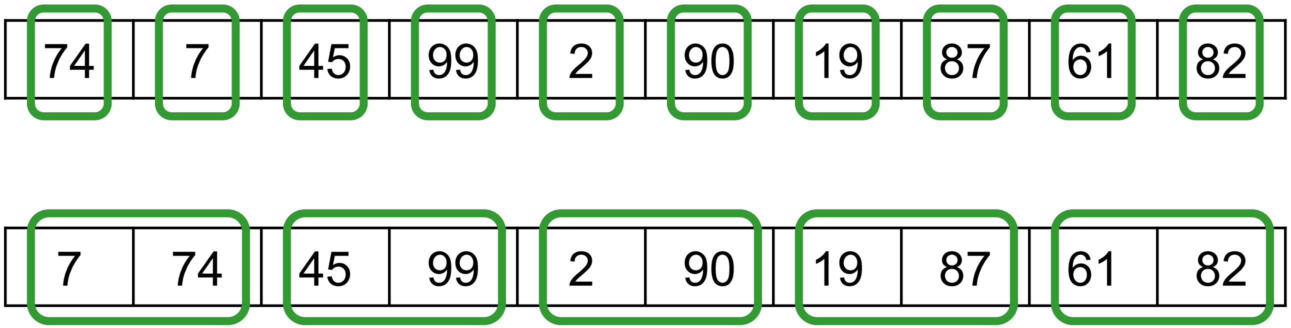
Merge-Sort

Runs



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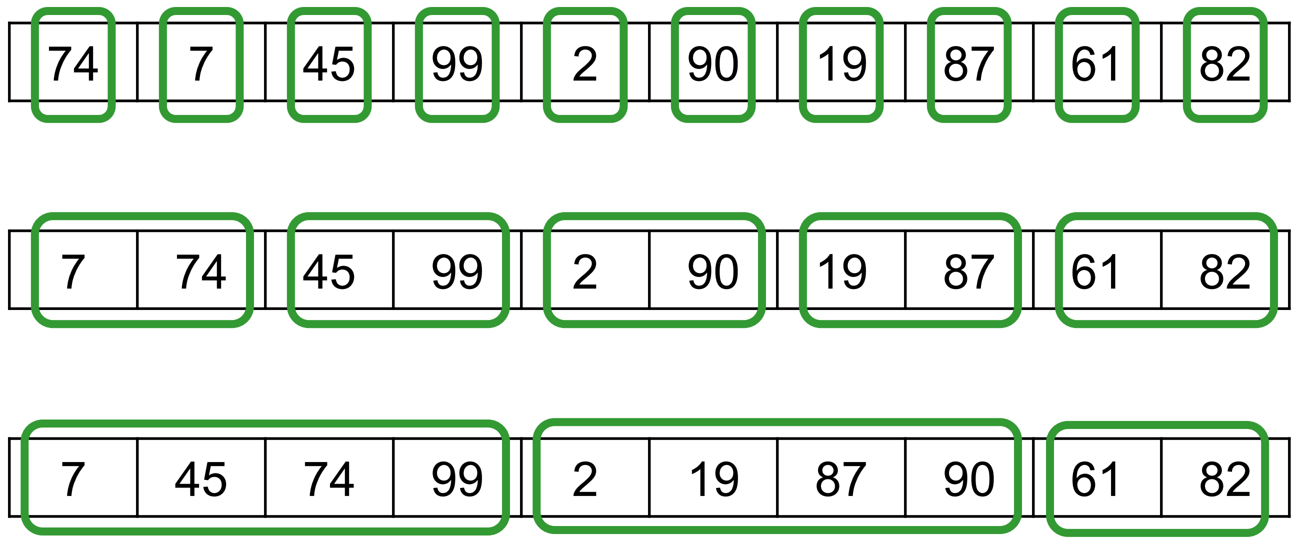

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Merge-Sort

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7	45	74	99	2	19	87	90	61	82

2	7	19	45	74	87	90	99	61	82

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Discussion

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- Main memory algorithms use quicksort
  - O(N log N) expected runtime
  - Problem: random access, not good for disk
- Merge-sort:
  - O(N log N) runtime
  - log N sequential reads   will improve
  - But: O(N) memory overhead; Not used for main memory, except for python's TimSort

External Memory Operators

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Main cost = number of disk I/O's
Always ignore the final write

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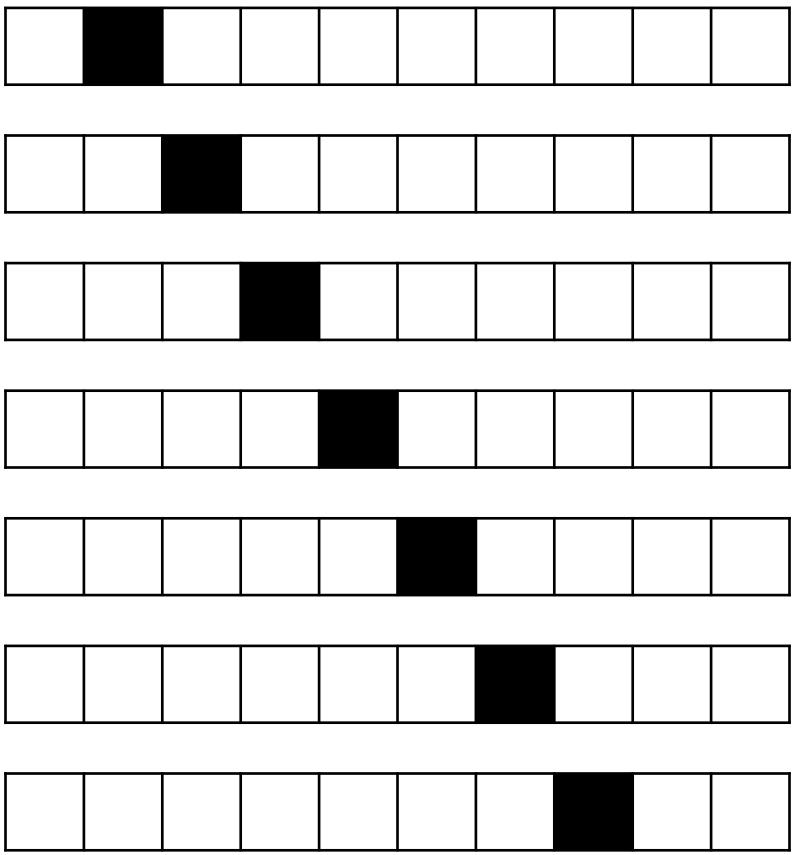
$$T(R) \gg B(R)$$

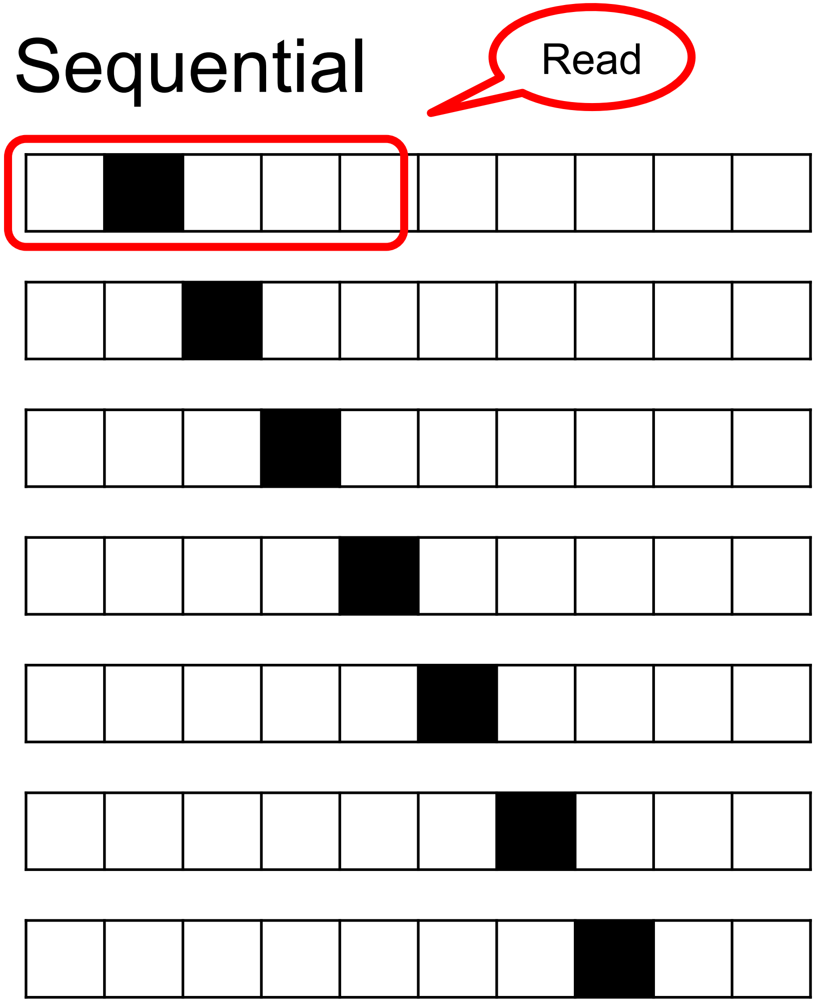
Sequential/Random Access

Sequential



Sequential/Random Access

Sequential



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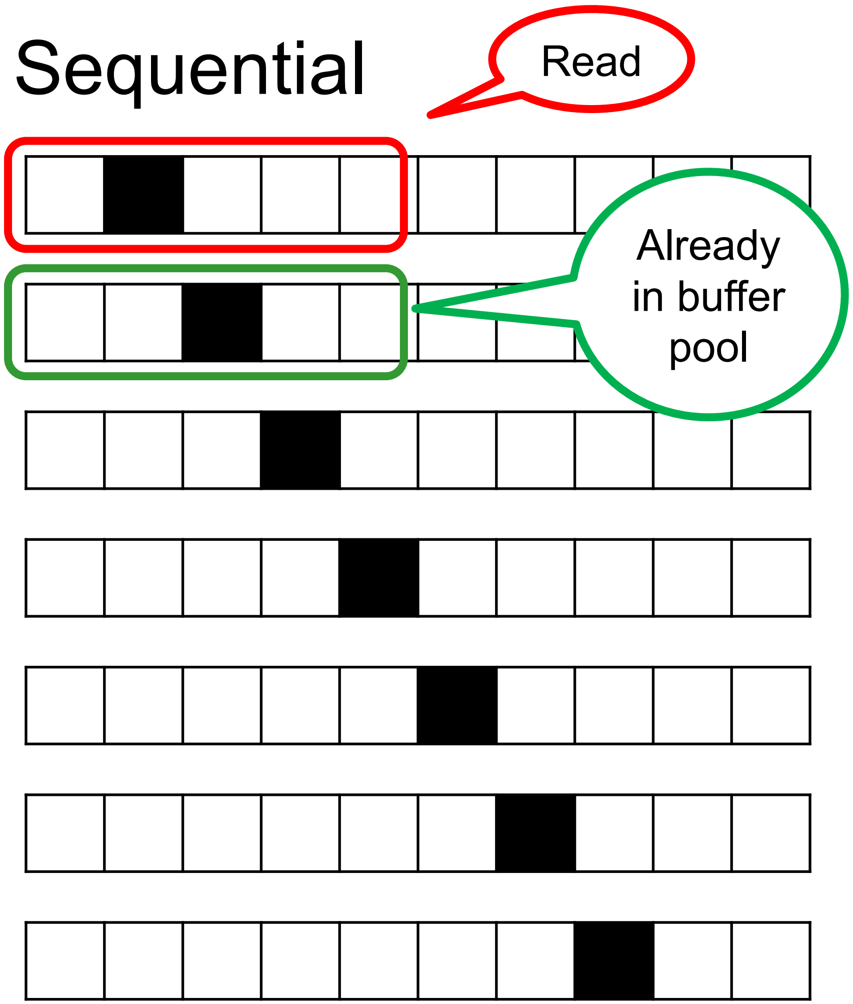

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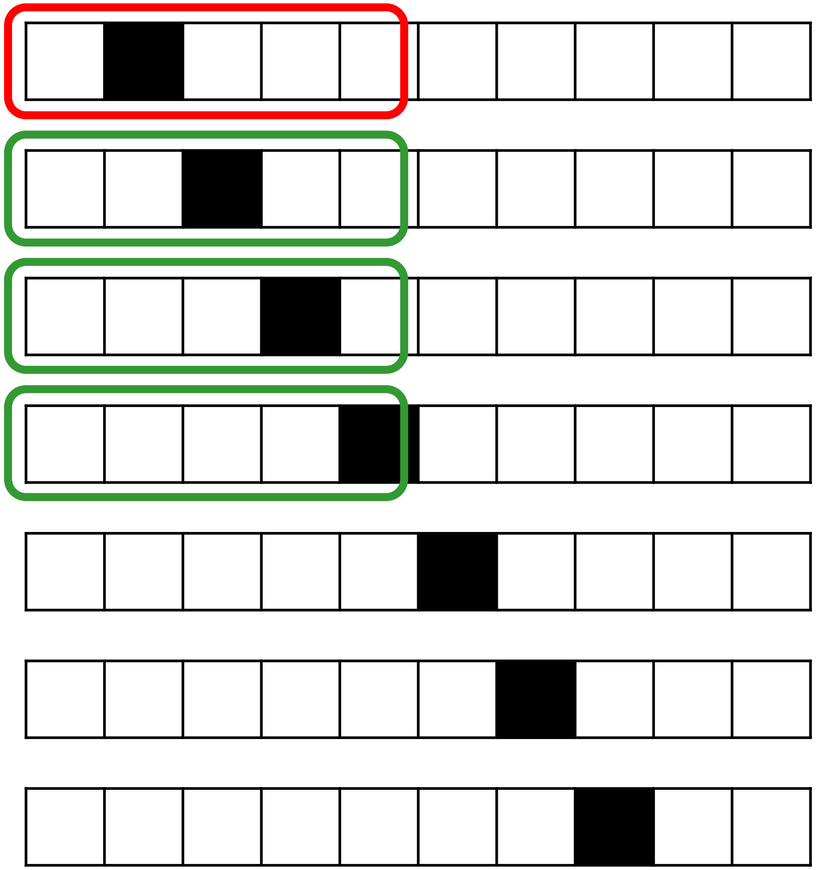
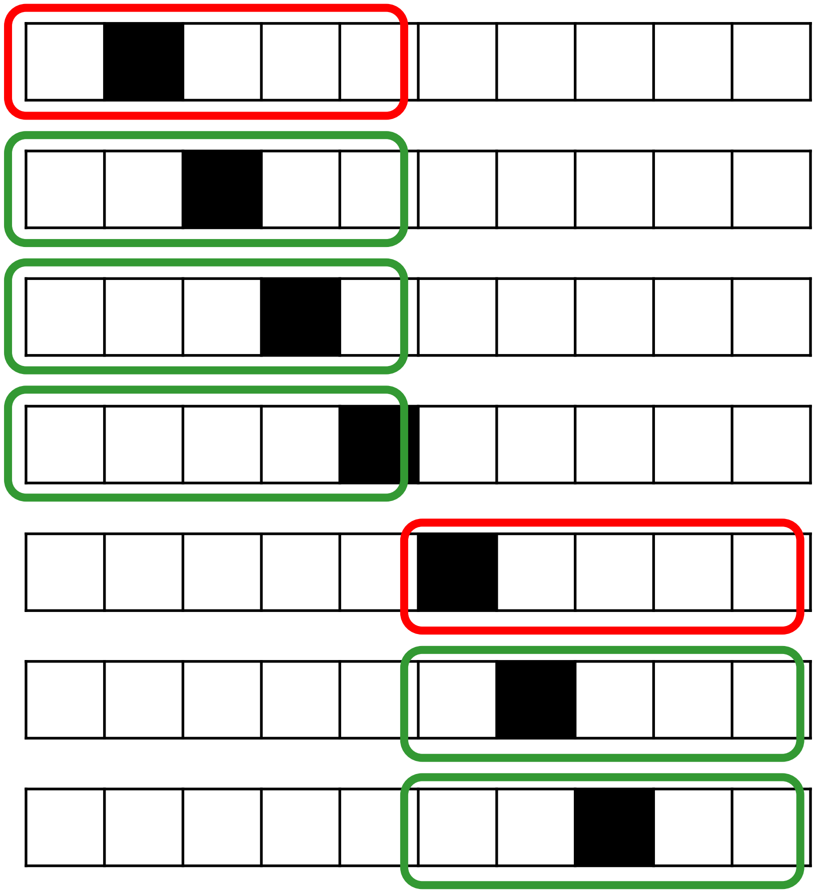


Sequential/Random Access

Sequential: B(R)=2 reads



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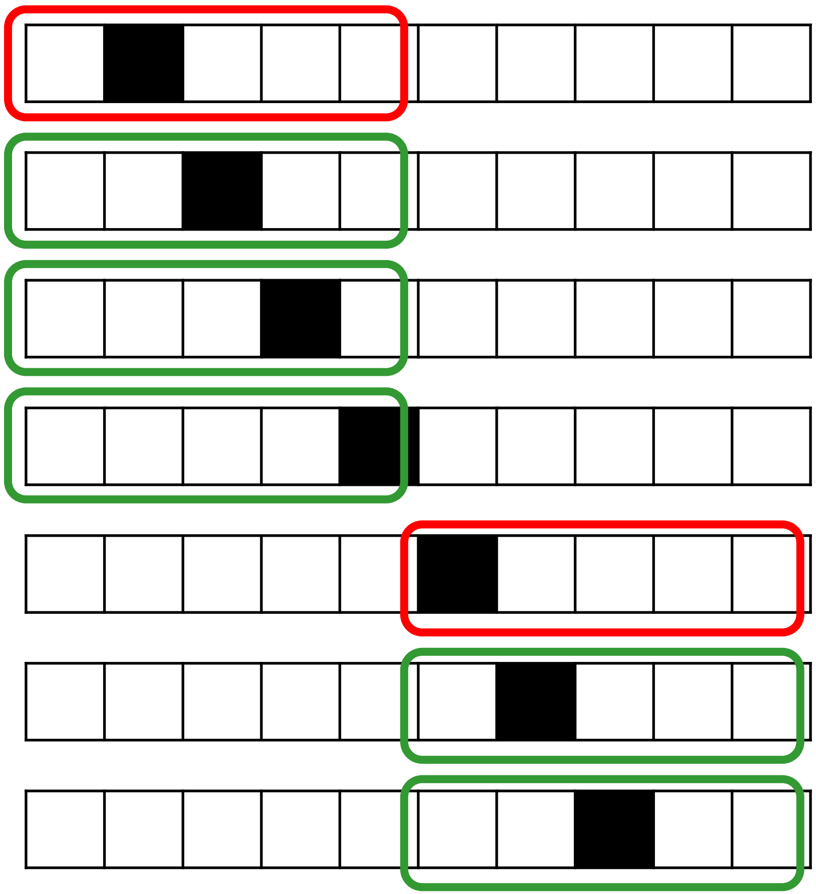
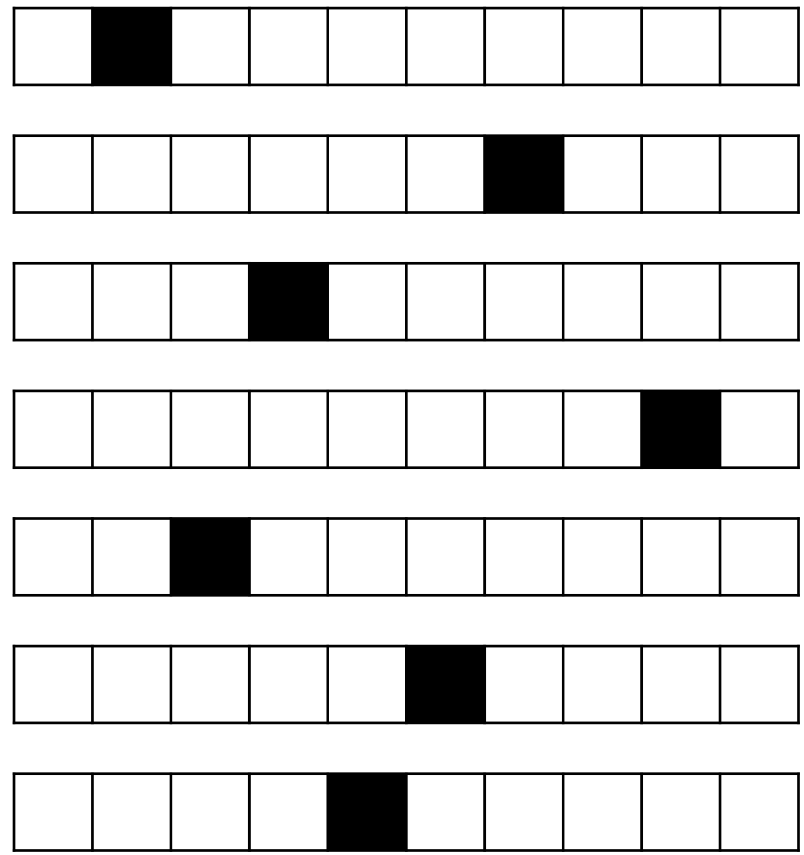


Random



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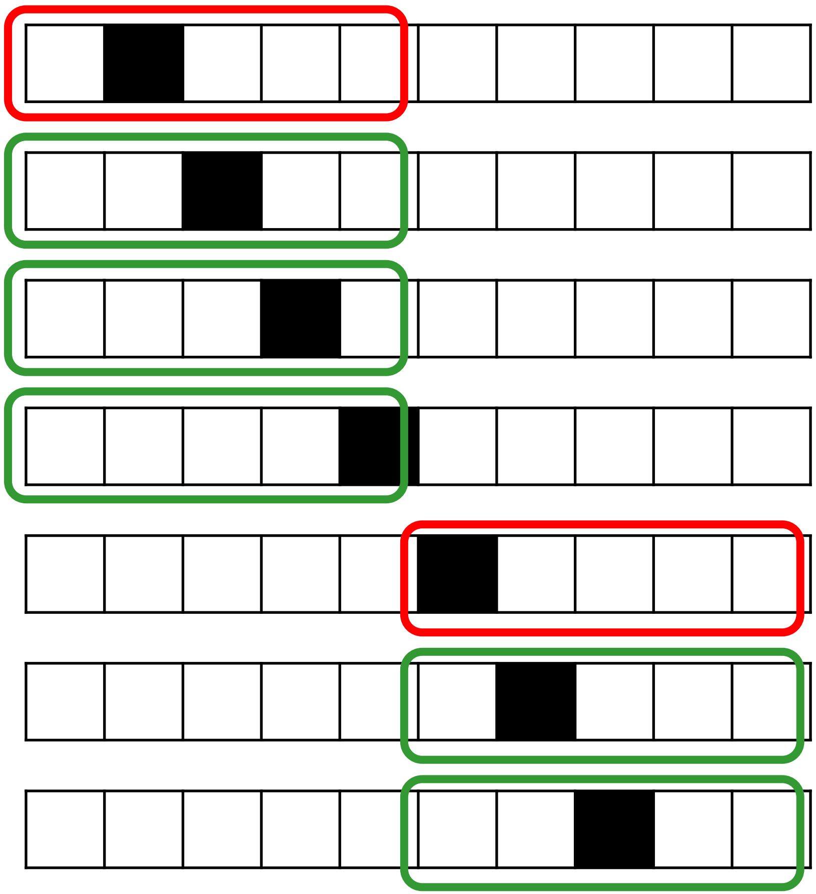

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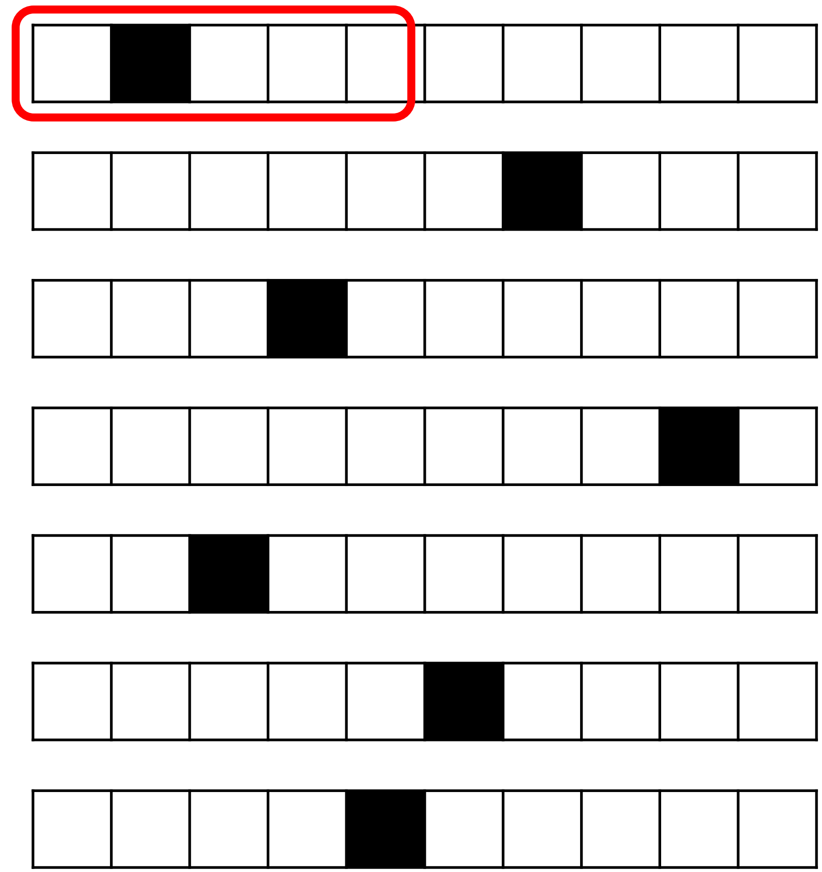

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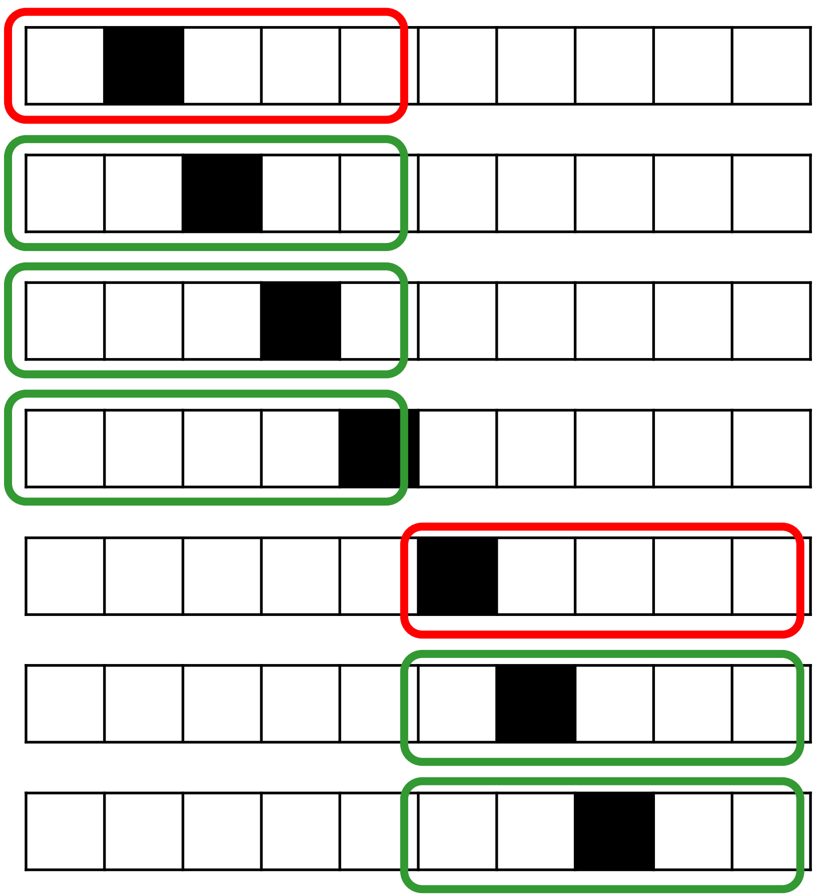
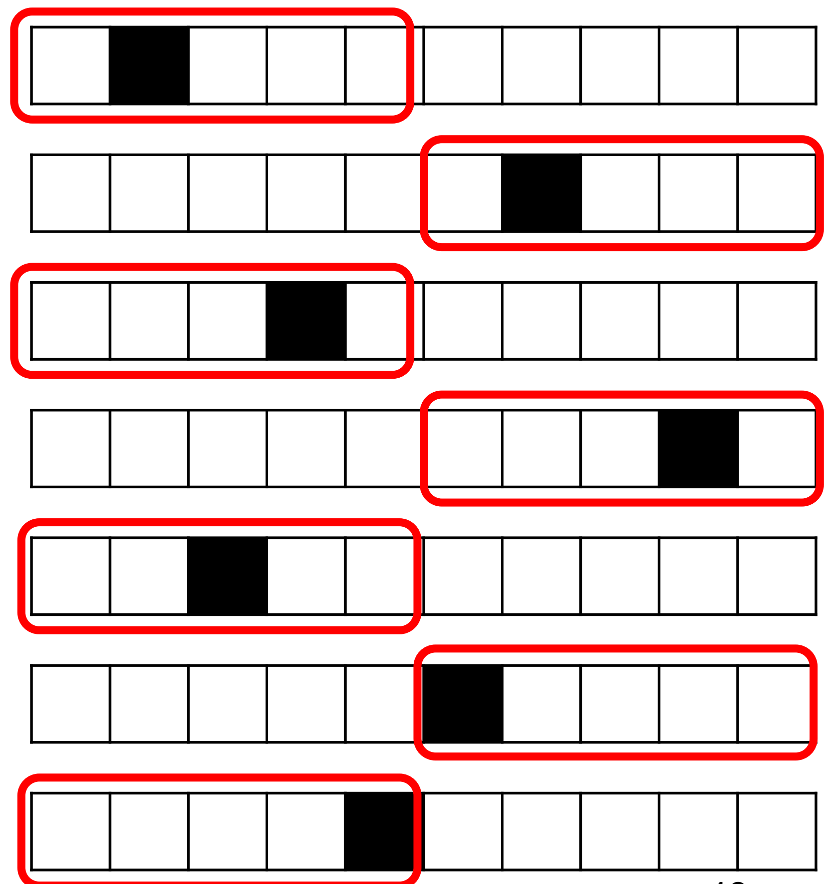


Random: T(R)=10 reads



External Memory Operators

- Block Nested Loop Join
- Merge Join
- Partitioned Hash Join

Block Nested Loop Join

Nested Loop Joins

$R \bowtie S$

```
for x in R do
   for y in S do
      if join(x,y): output(x,y)
```

- Naïve nested loop join: $B(R) + T(R) * B(S)$

- If T(R)=1,000,000 then this is terrible…

Block Nested Loop Join

Idea: better use of the available memory

- M = # of blocks that fit in main memory

Block Nested Loop Join

Group of (M-2) pages of R, called a "block"

<u>for</u> each (M-2) pages PR of R <u>do</u>
    <u>for</u> each page PS of S <u>do</u>
        Main memory join: PR $\bowtie$ PS

Block Nested Loop Join

Group of (M-2) pages of R, called a "block"

Why not use M-1 pages?

<u>for</u> each (M-2) pages PR of R <u>do</u>

  <u>for</u> each page PS of S <u>do</u>

    Main memory join: PR ⋈ PS

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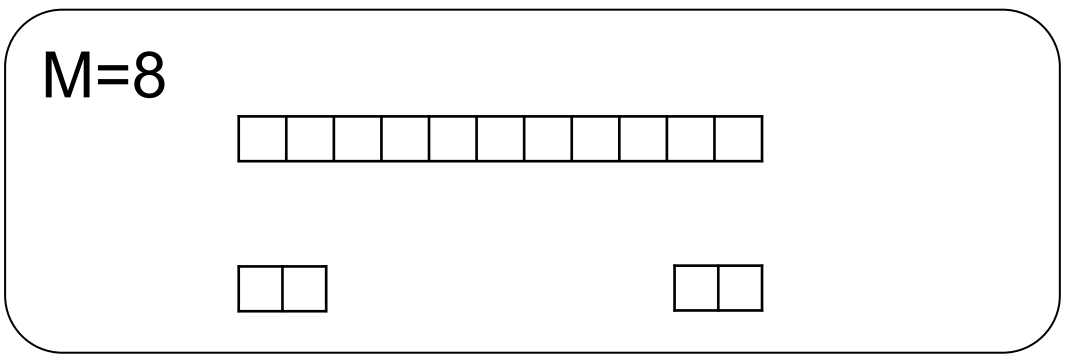
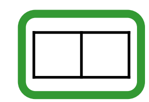
    <u>for</u> each page PS of S <u>do</u>
        Main memory join: PR $\bowtie$ PS
        use the remaining page for output

B(R) + B(R)B(S)/(M-2) disk I/Os. WHY?

Block Nested Loop Join

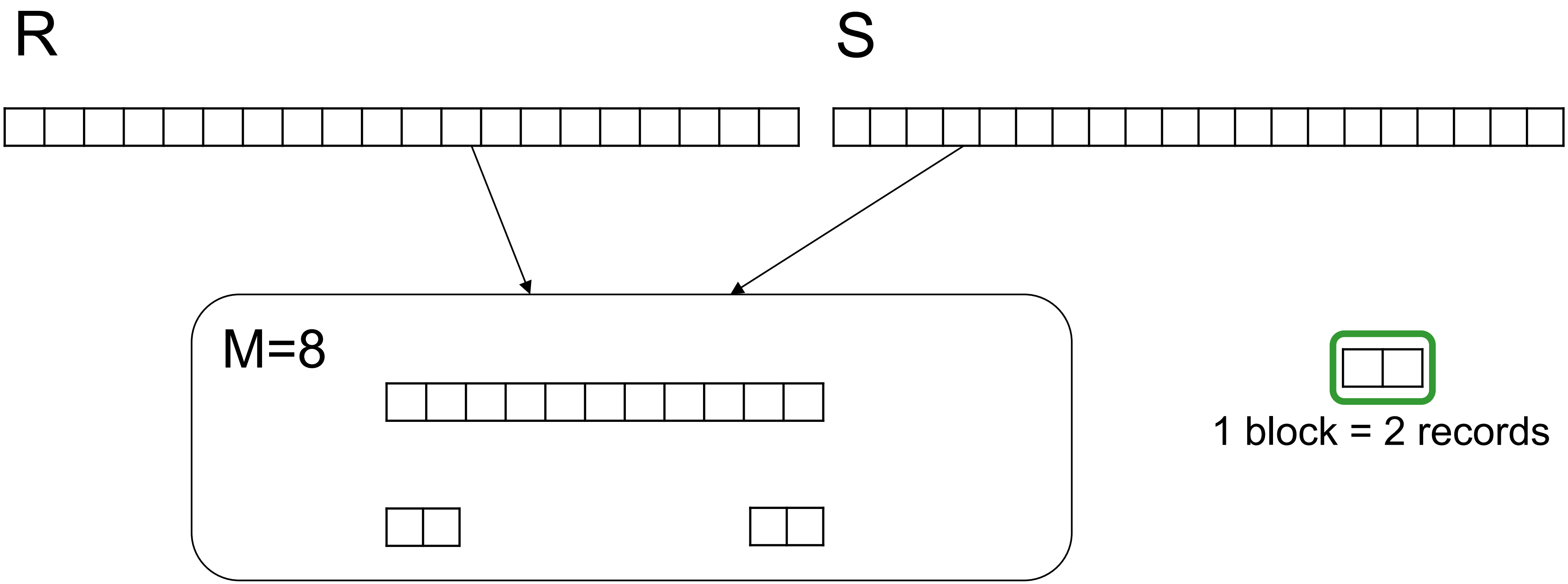




1 block = 2 records

$R \bowtie S$

Block Nested Loop Join



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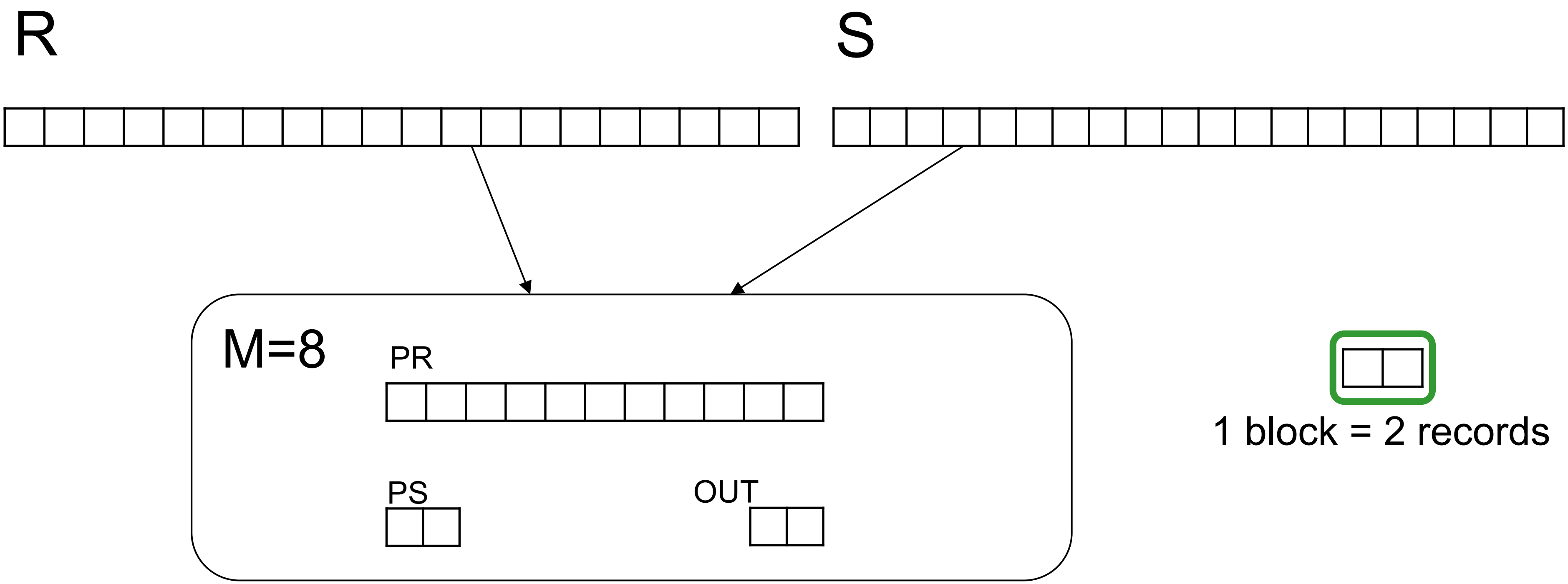

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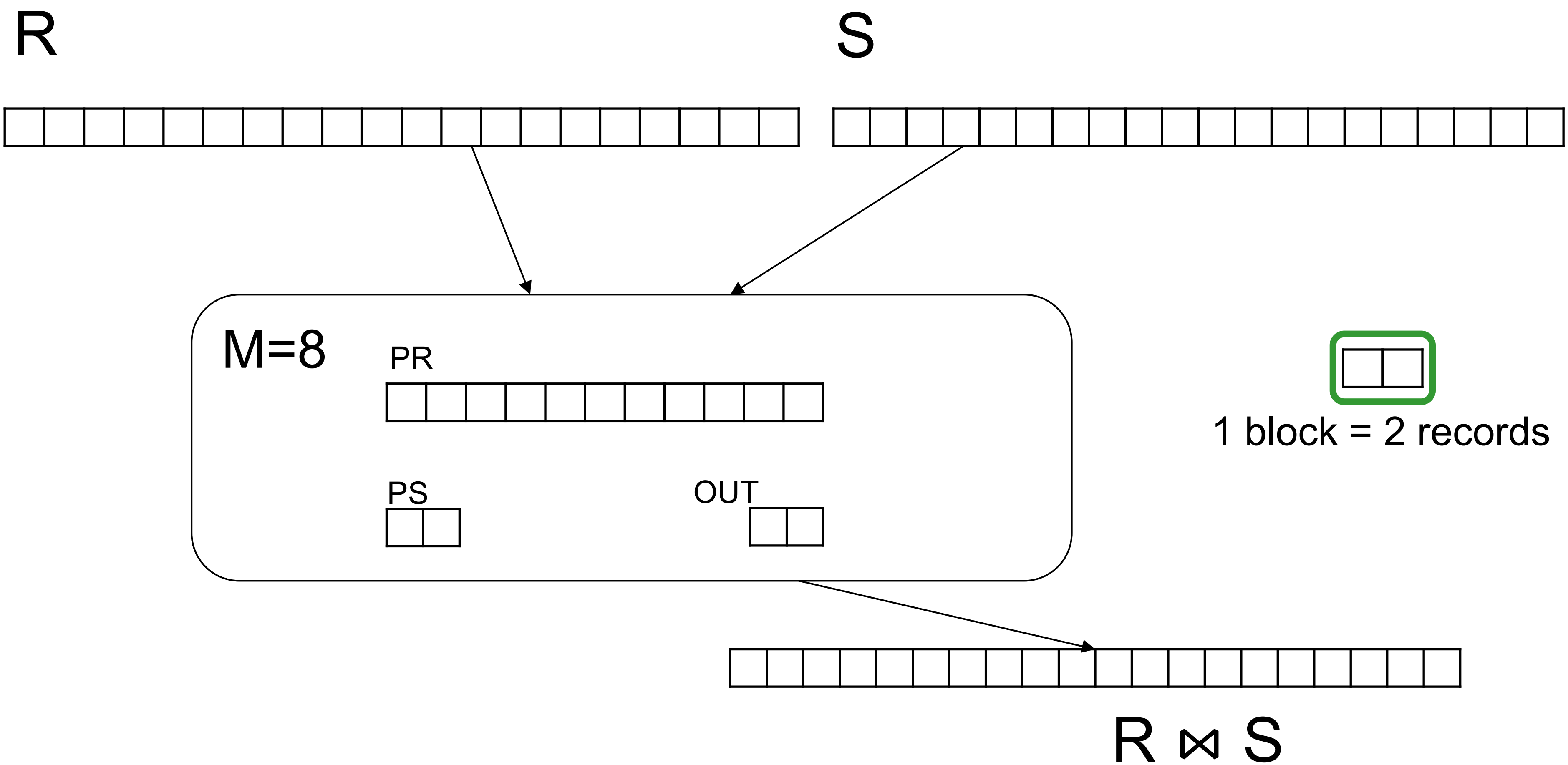

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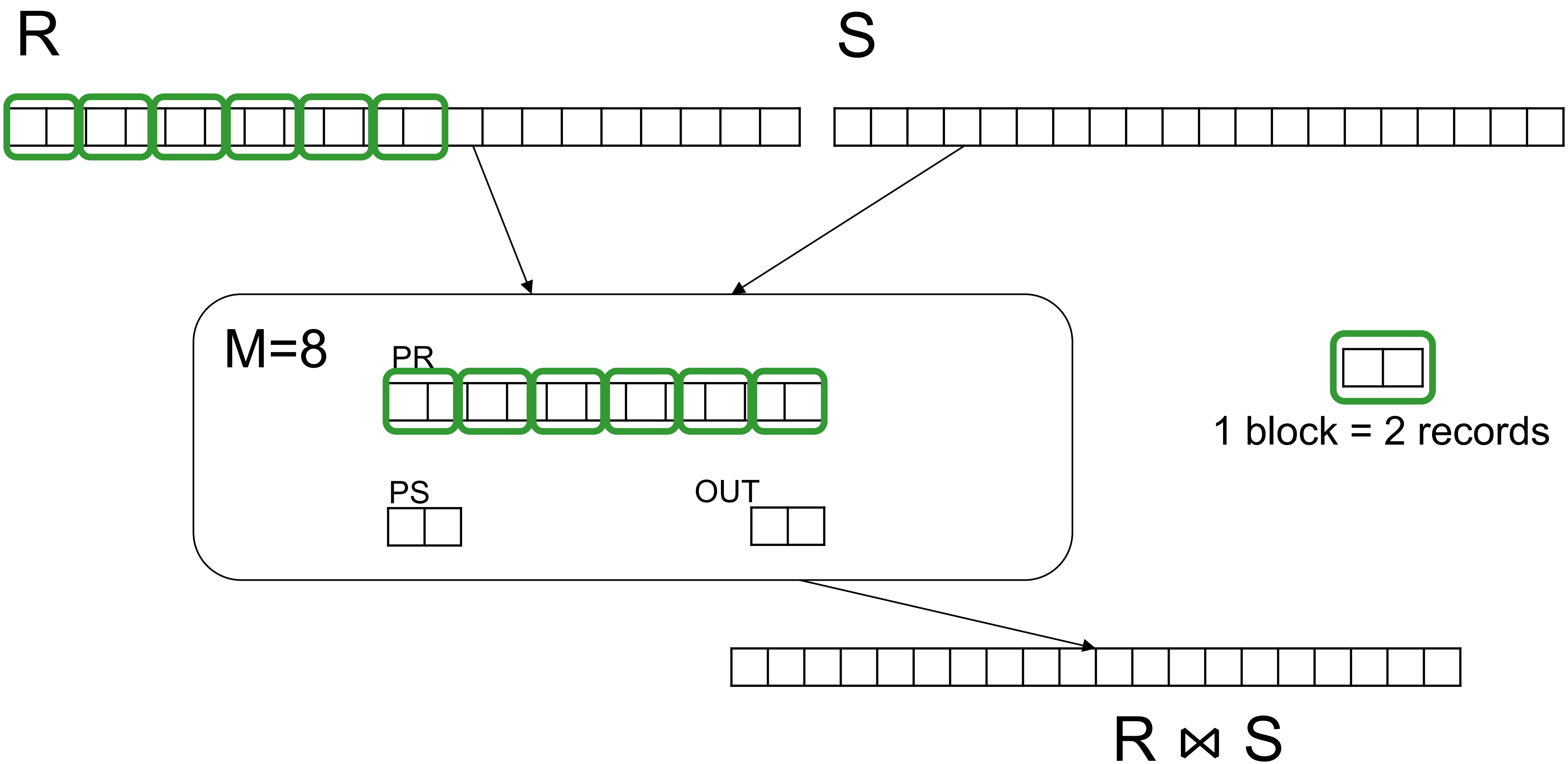

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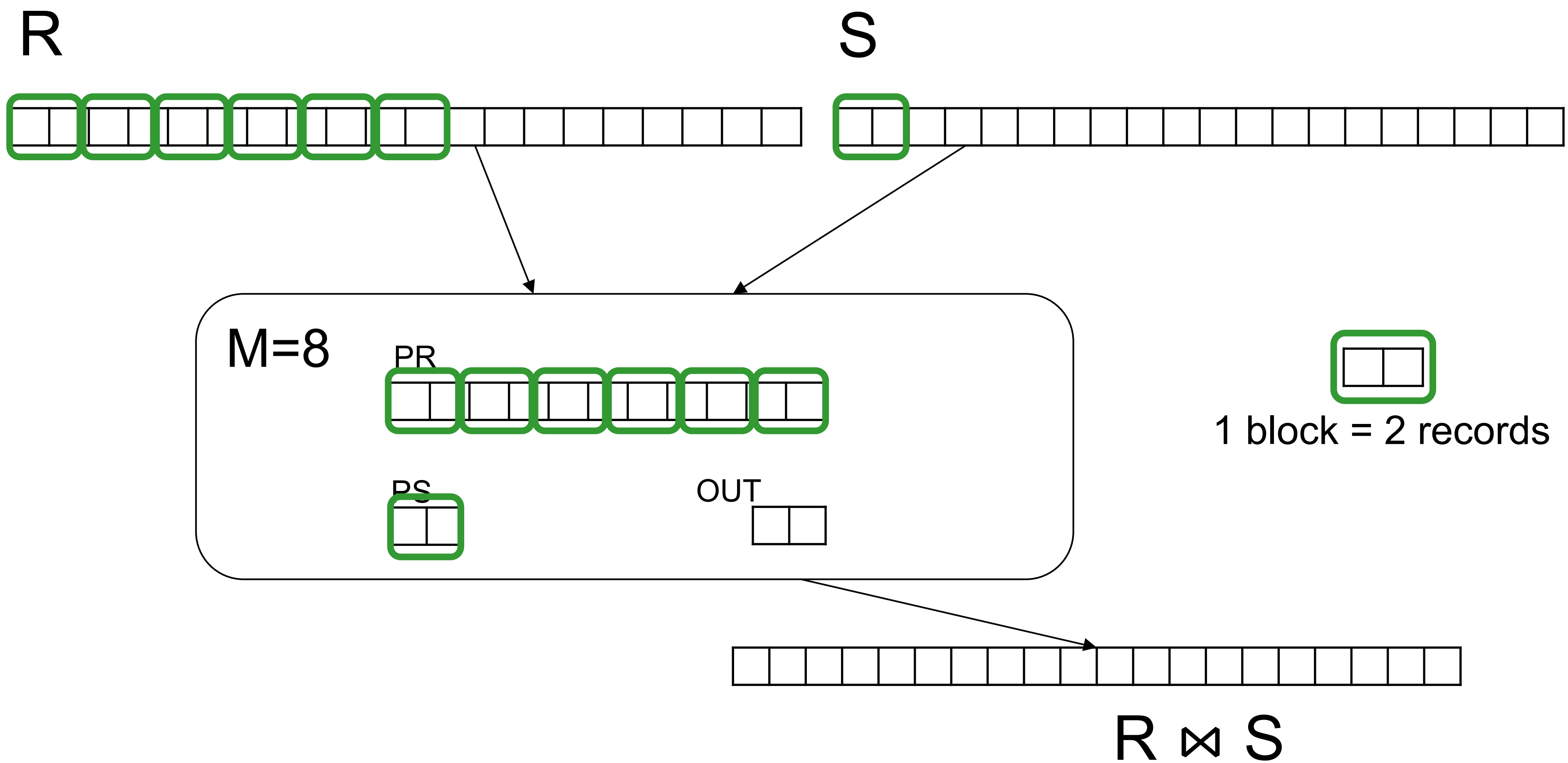

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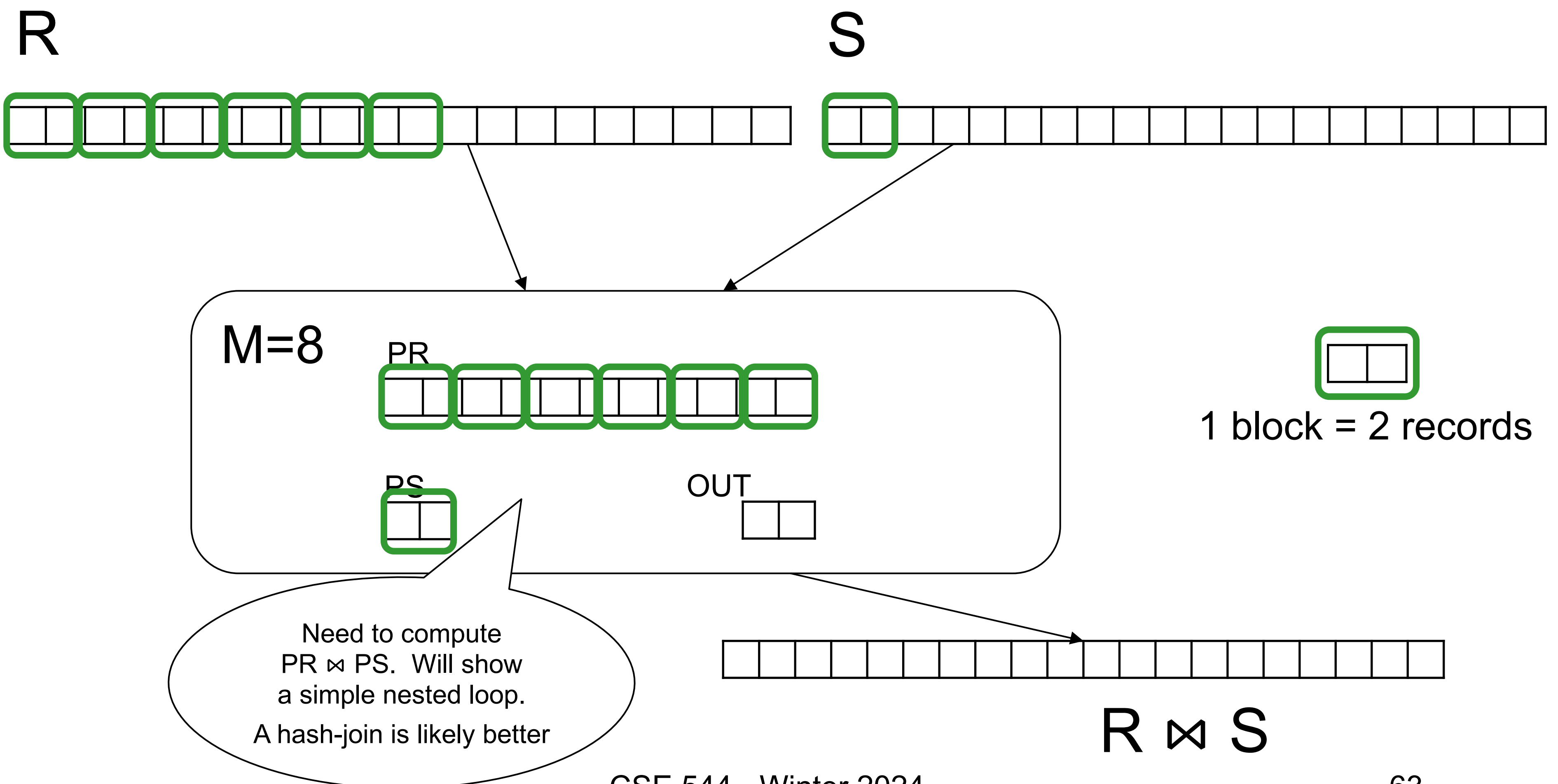

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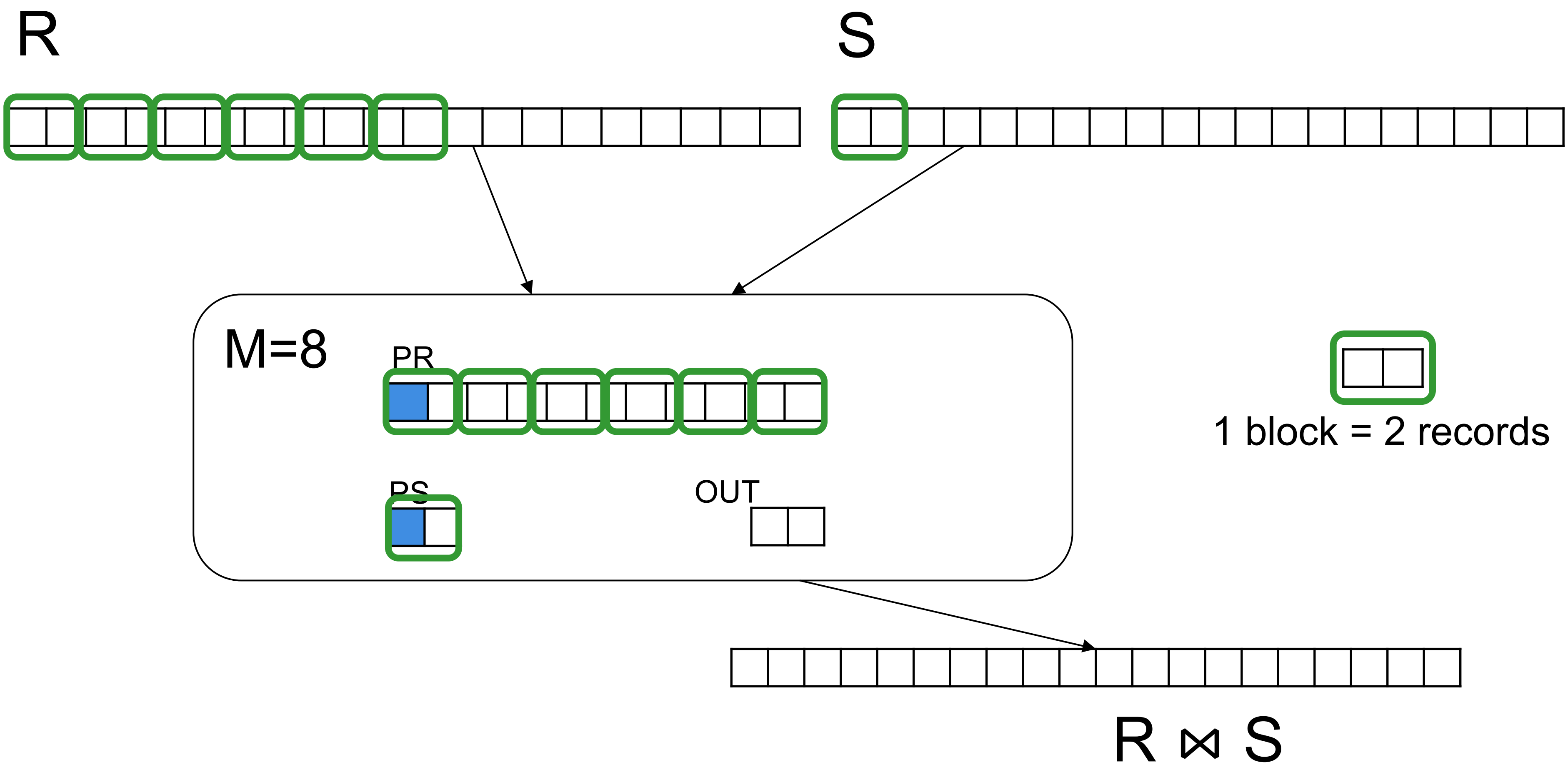

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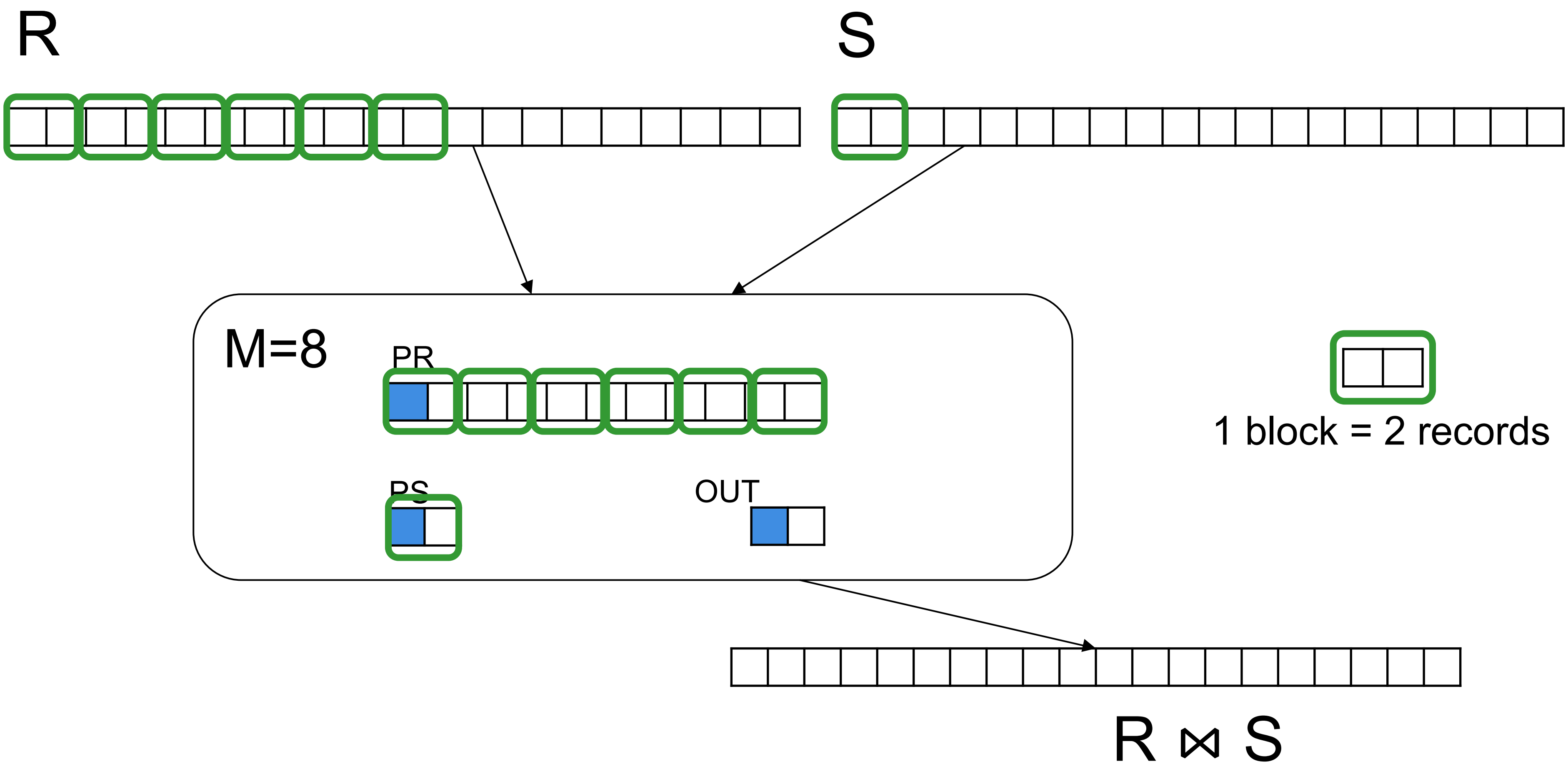

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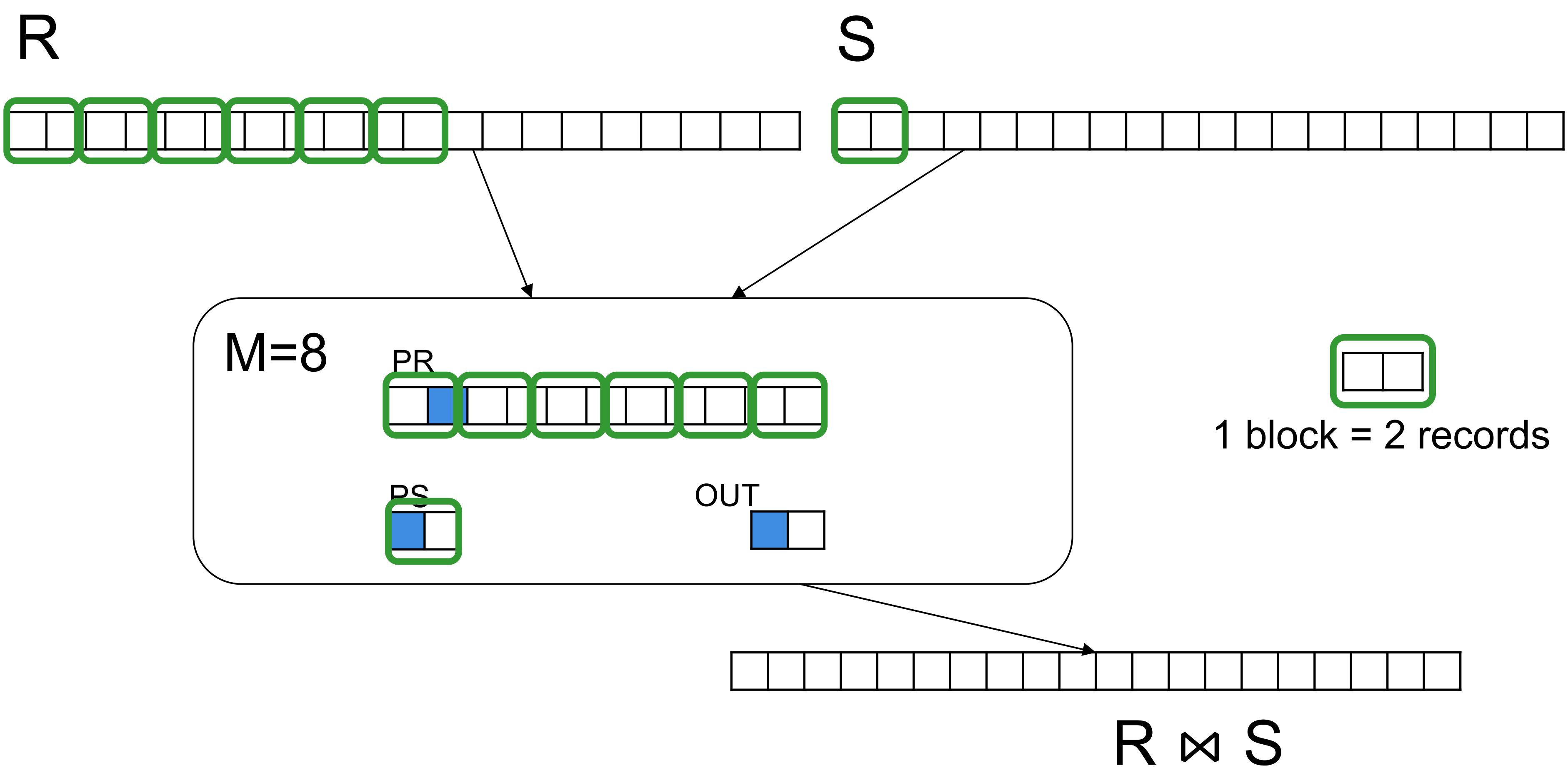

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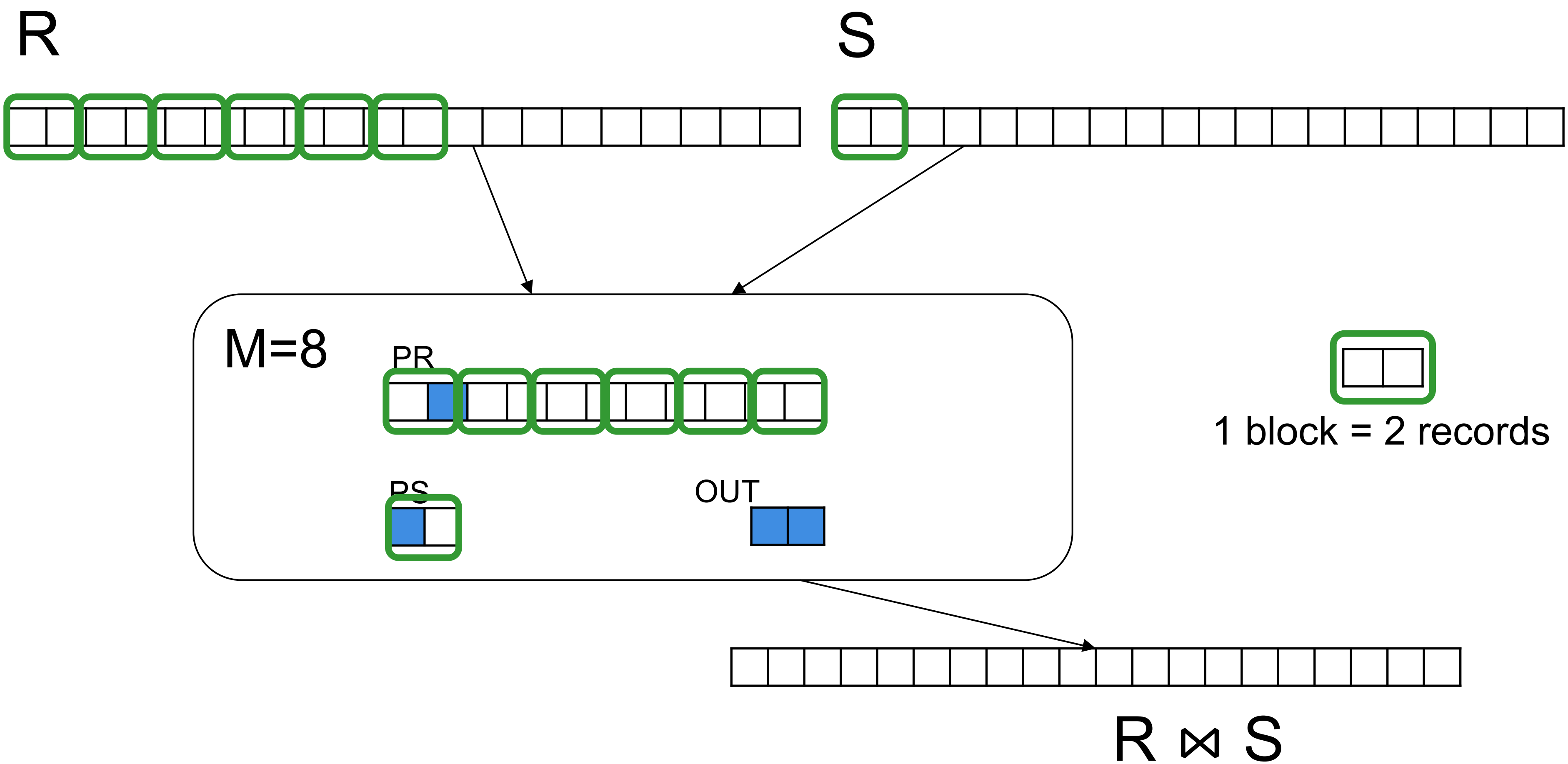

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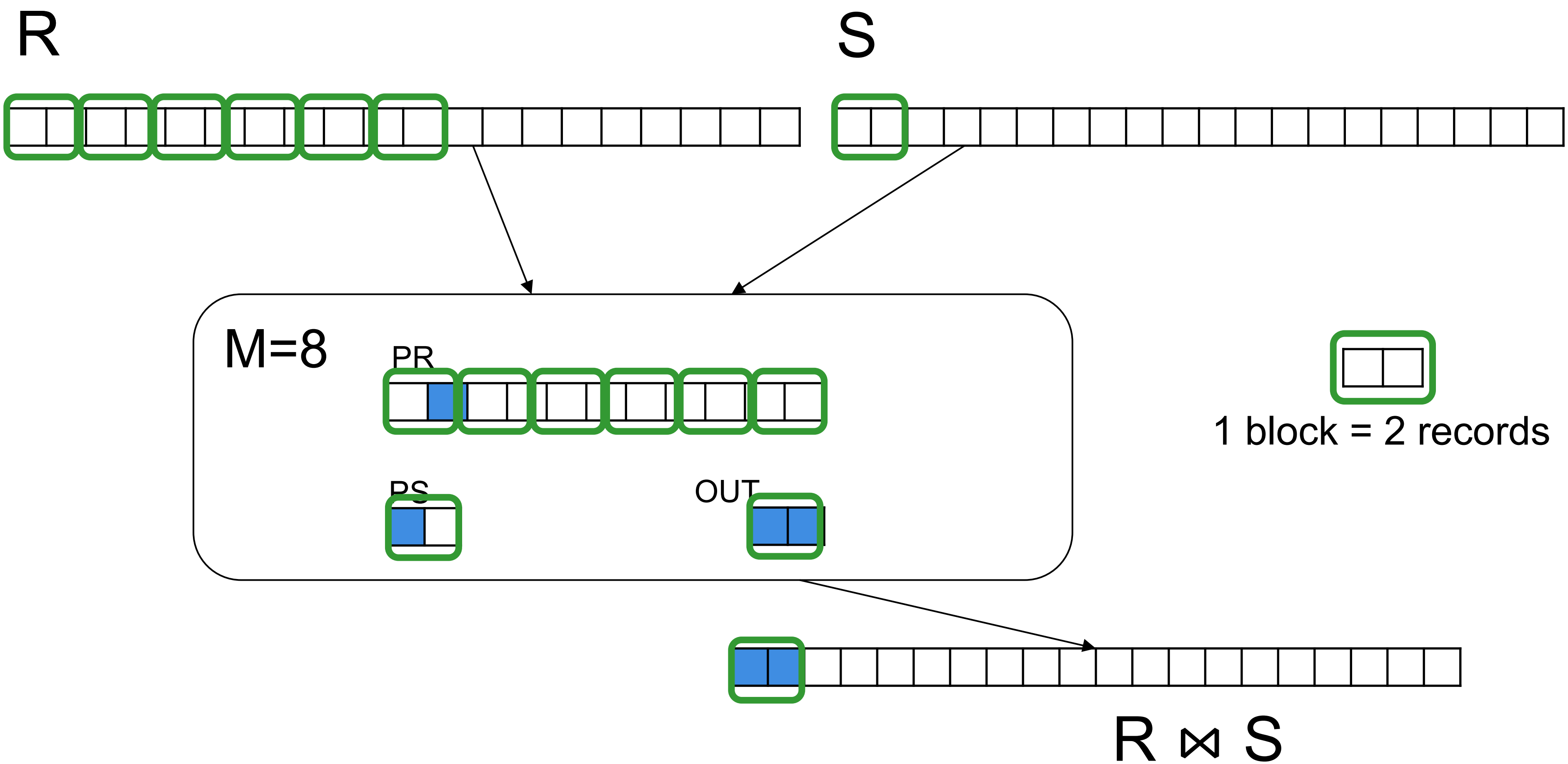

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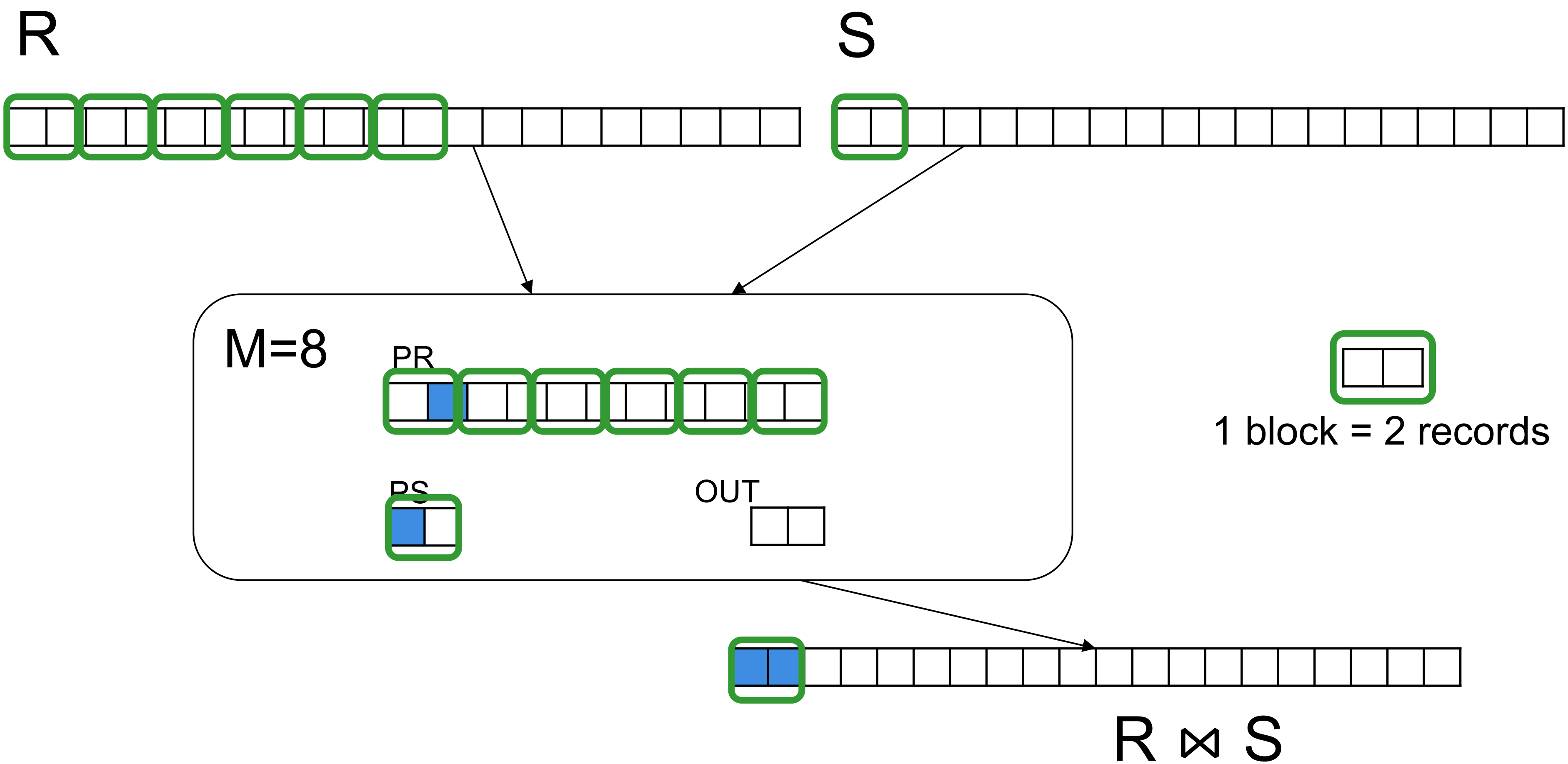

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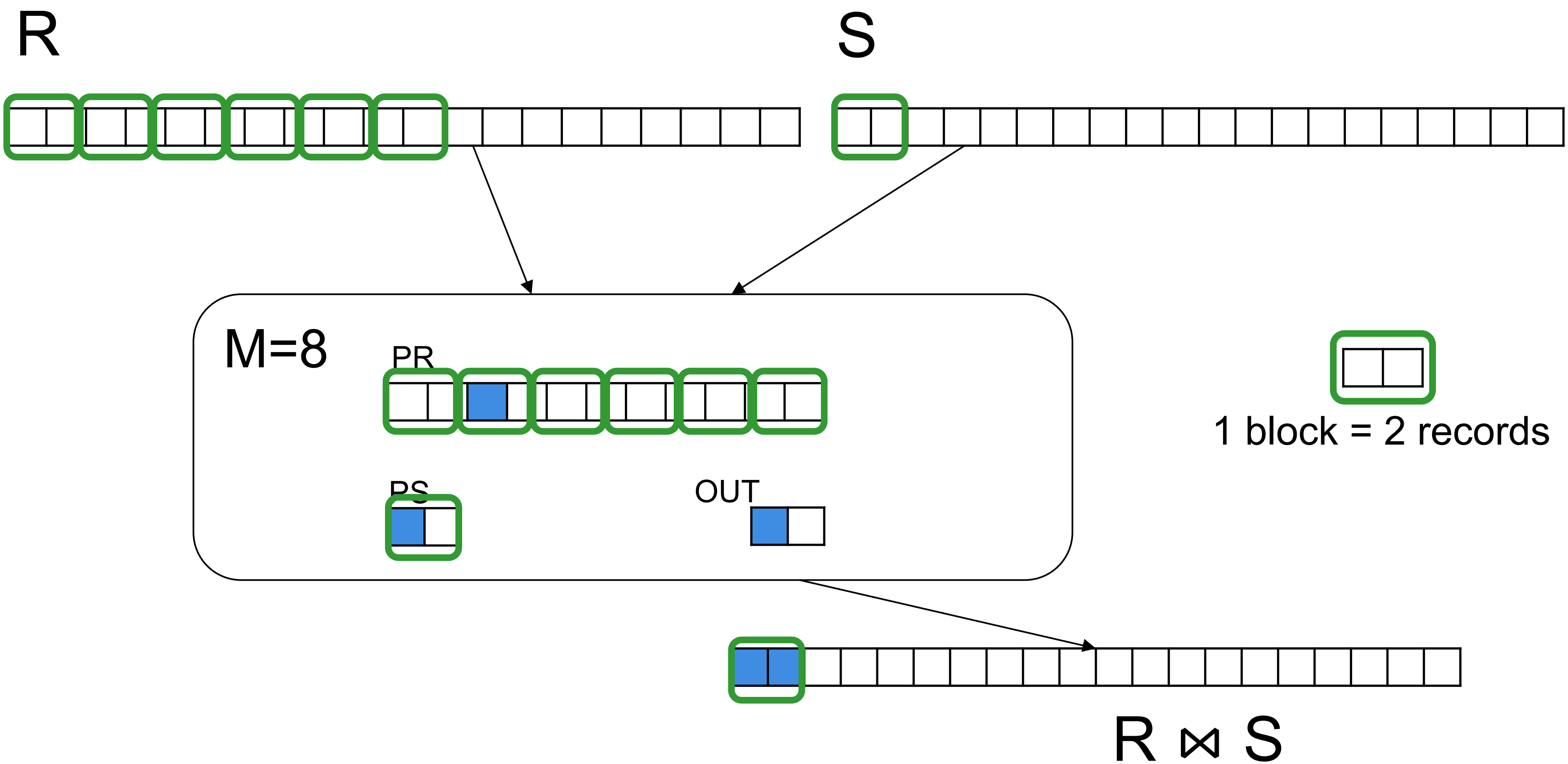

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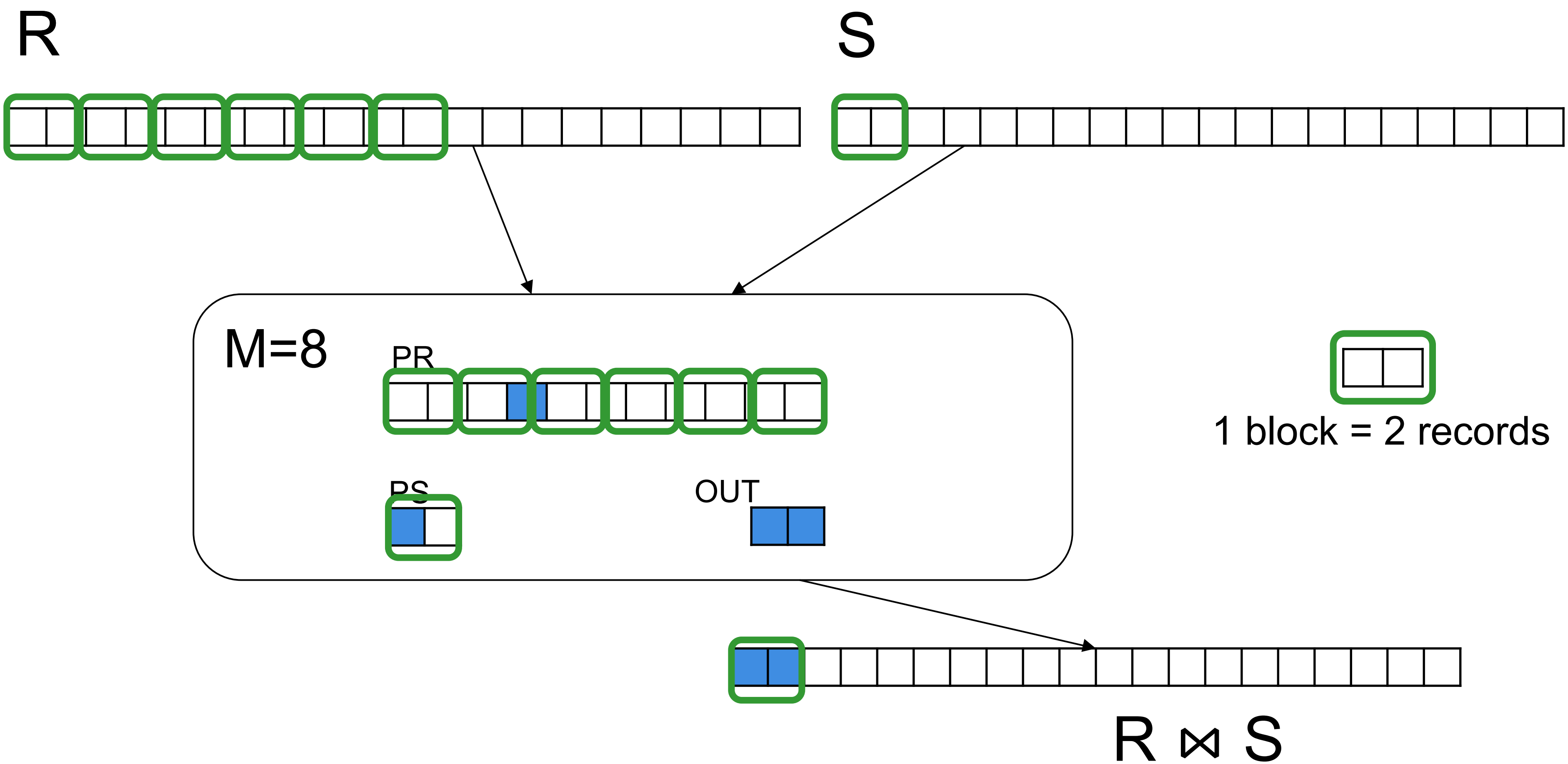

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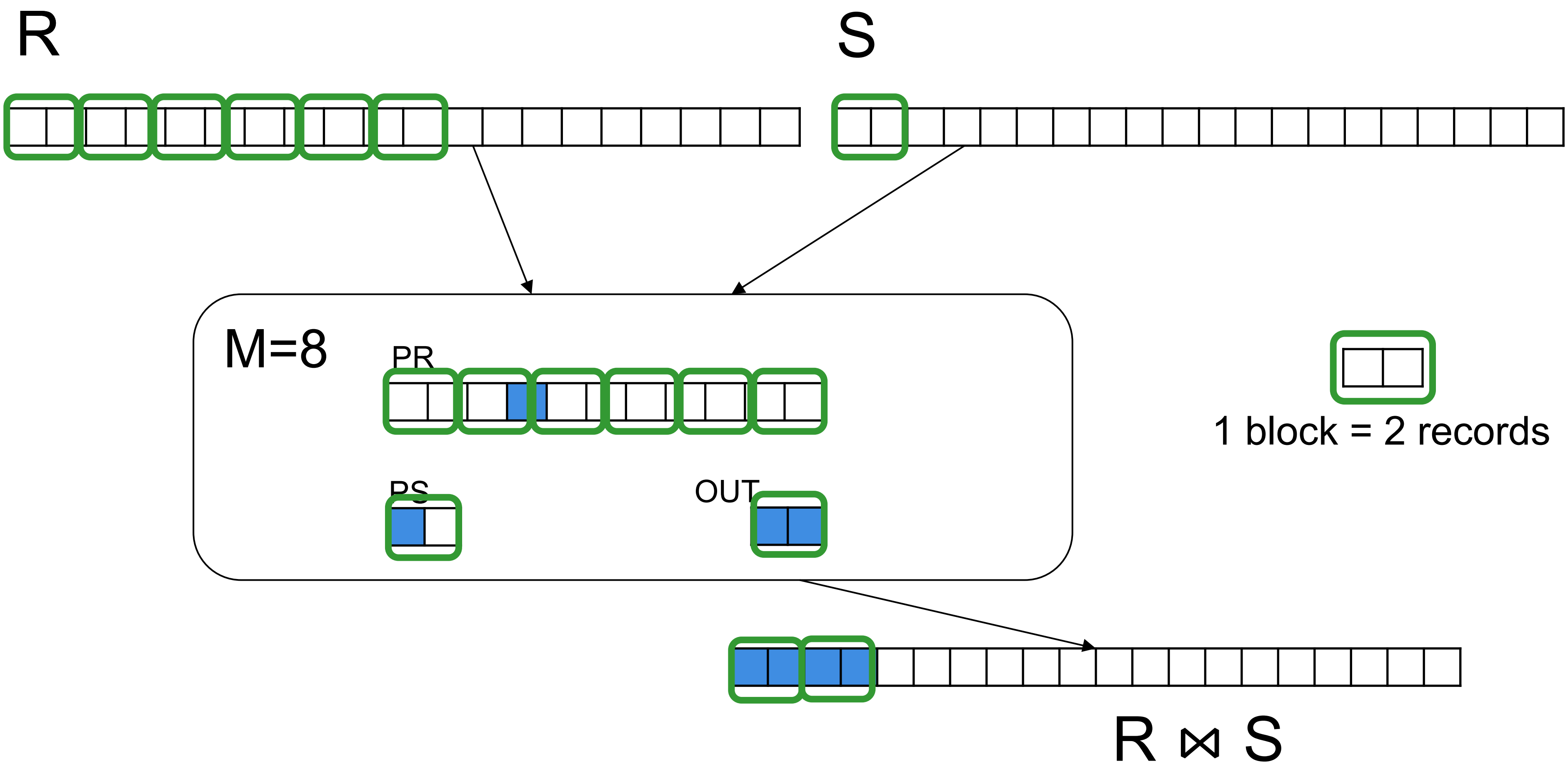

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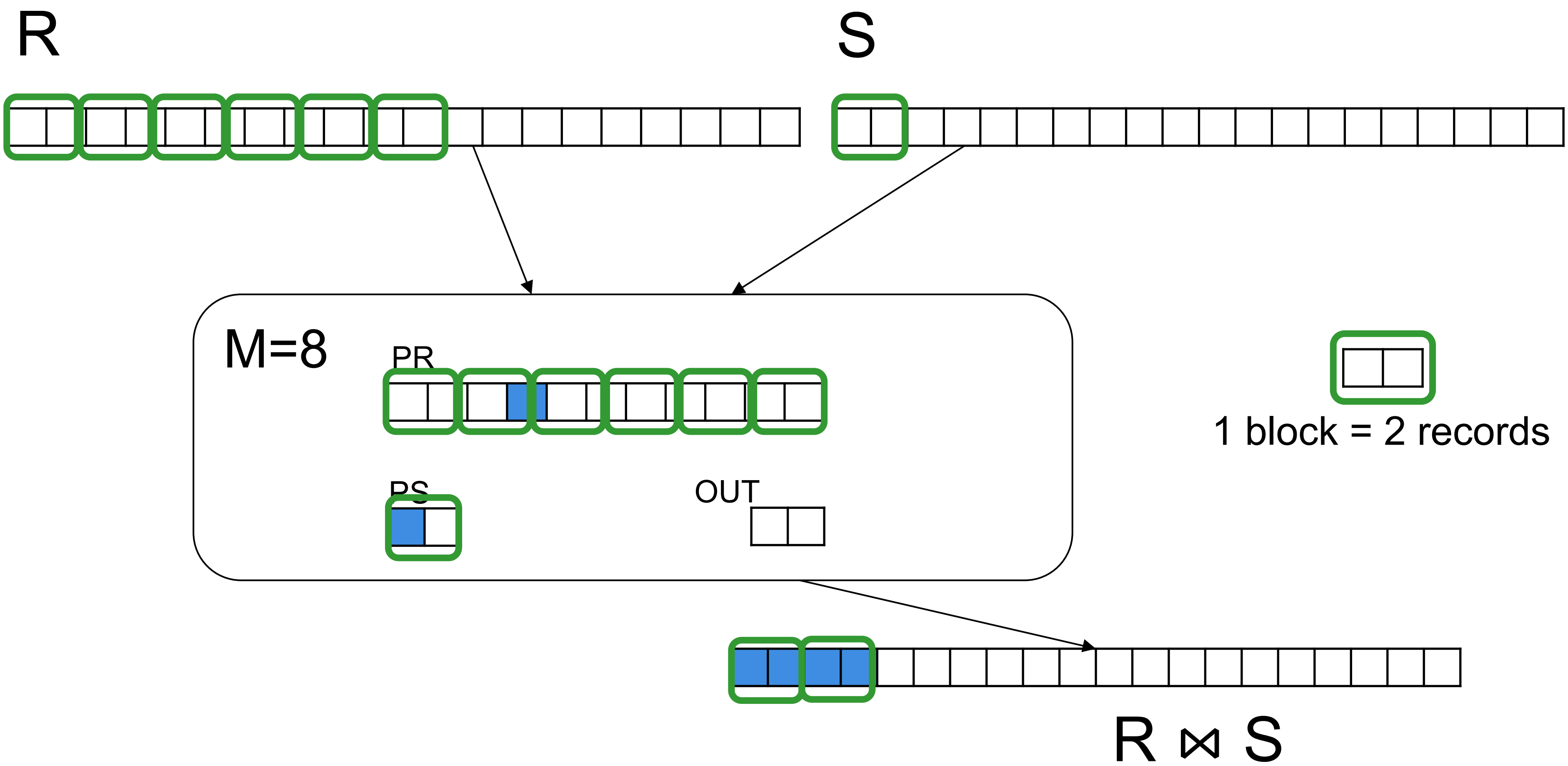

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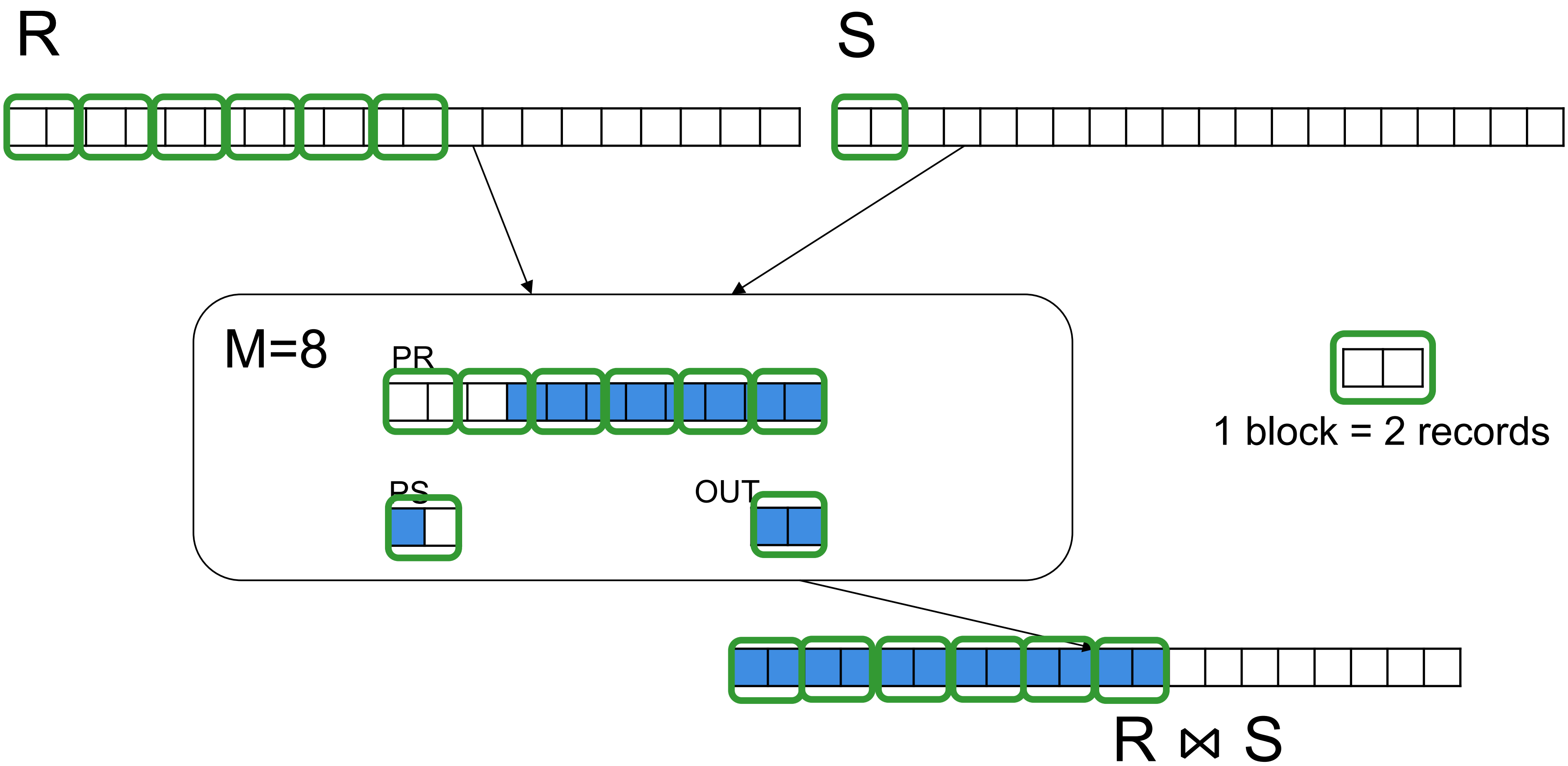

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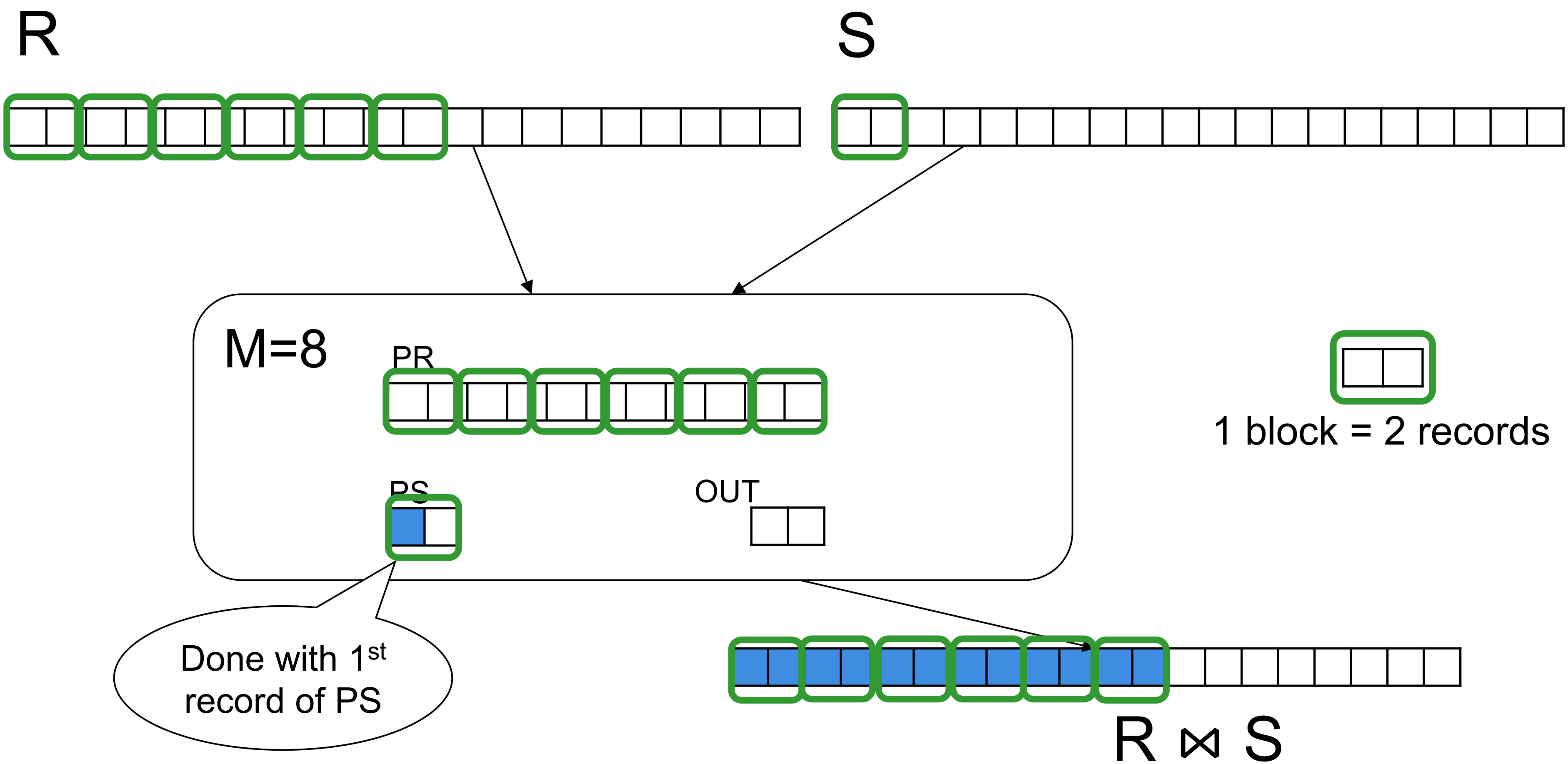
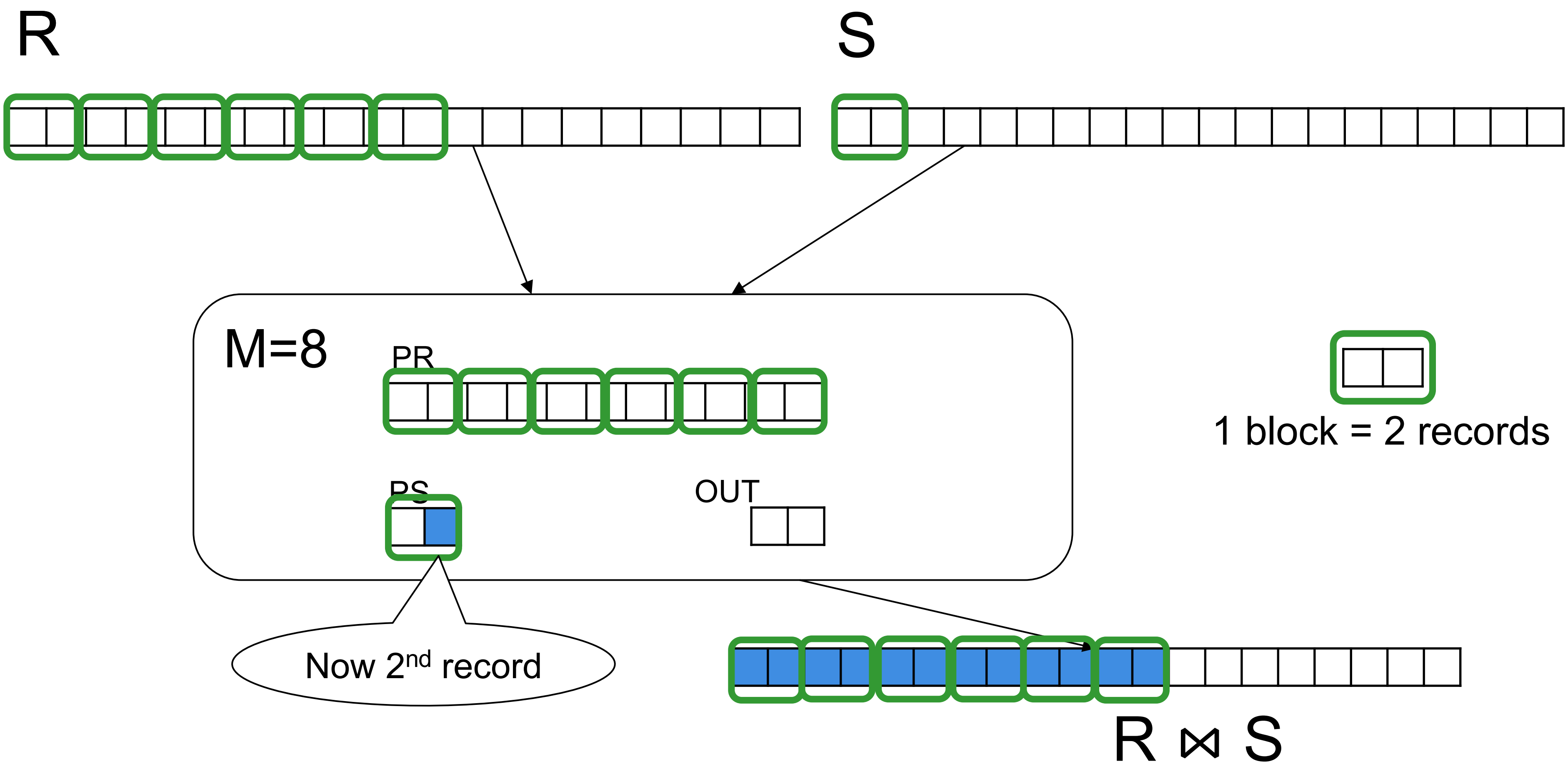


Block Nested Loop Join



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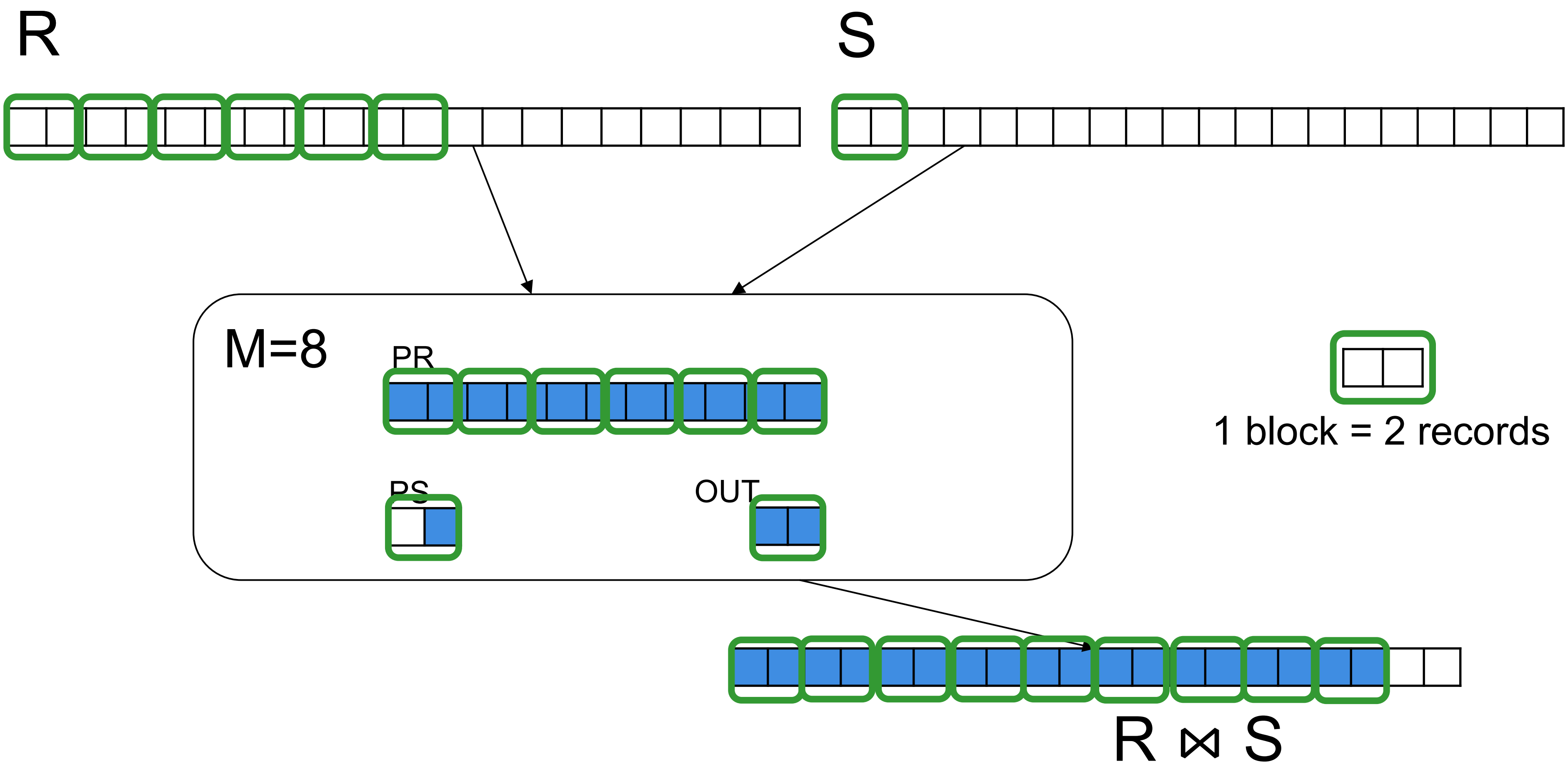

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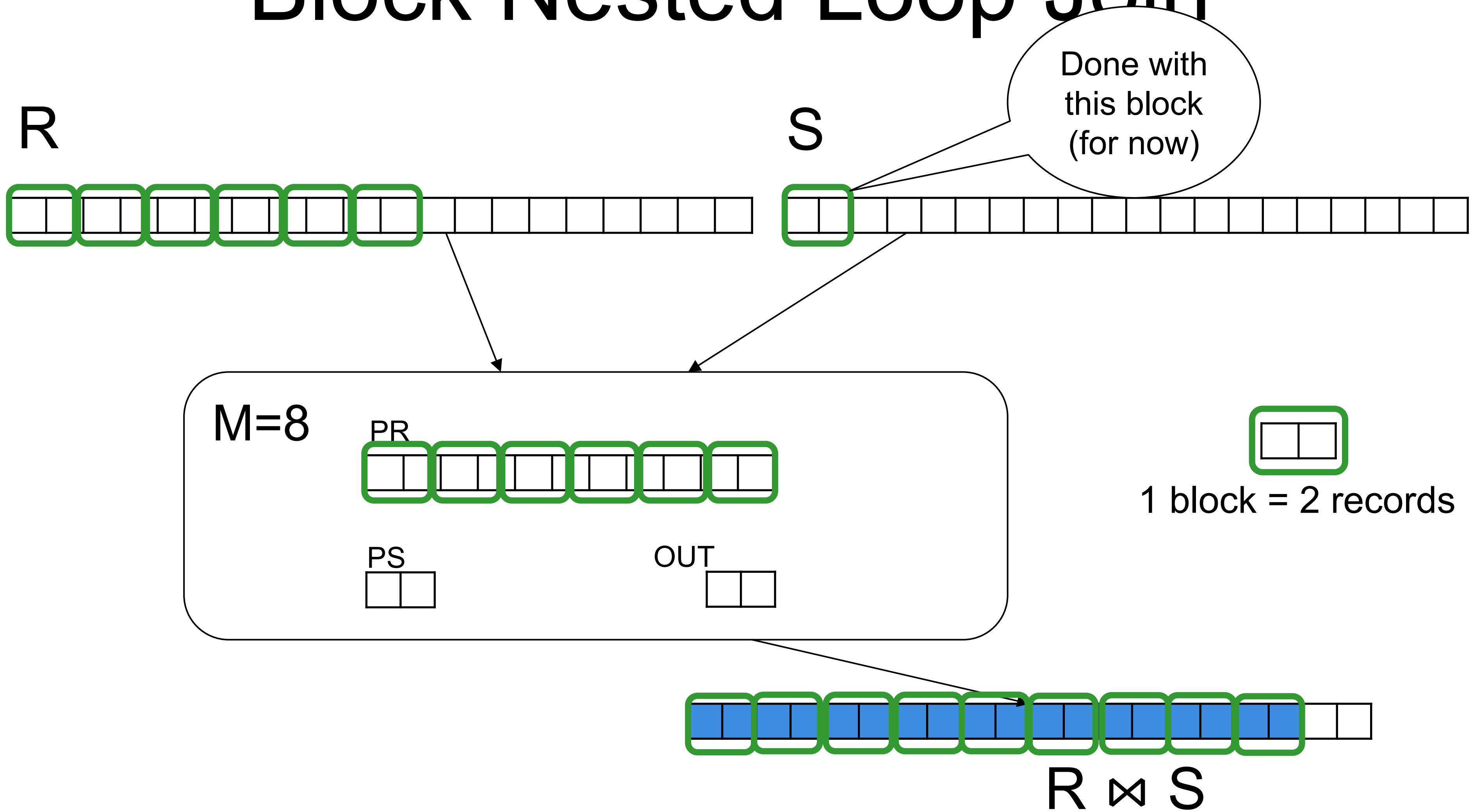

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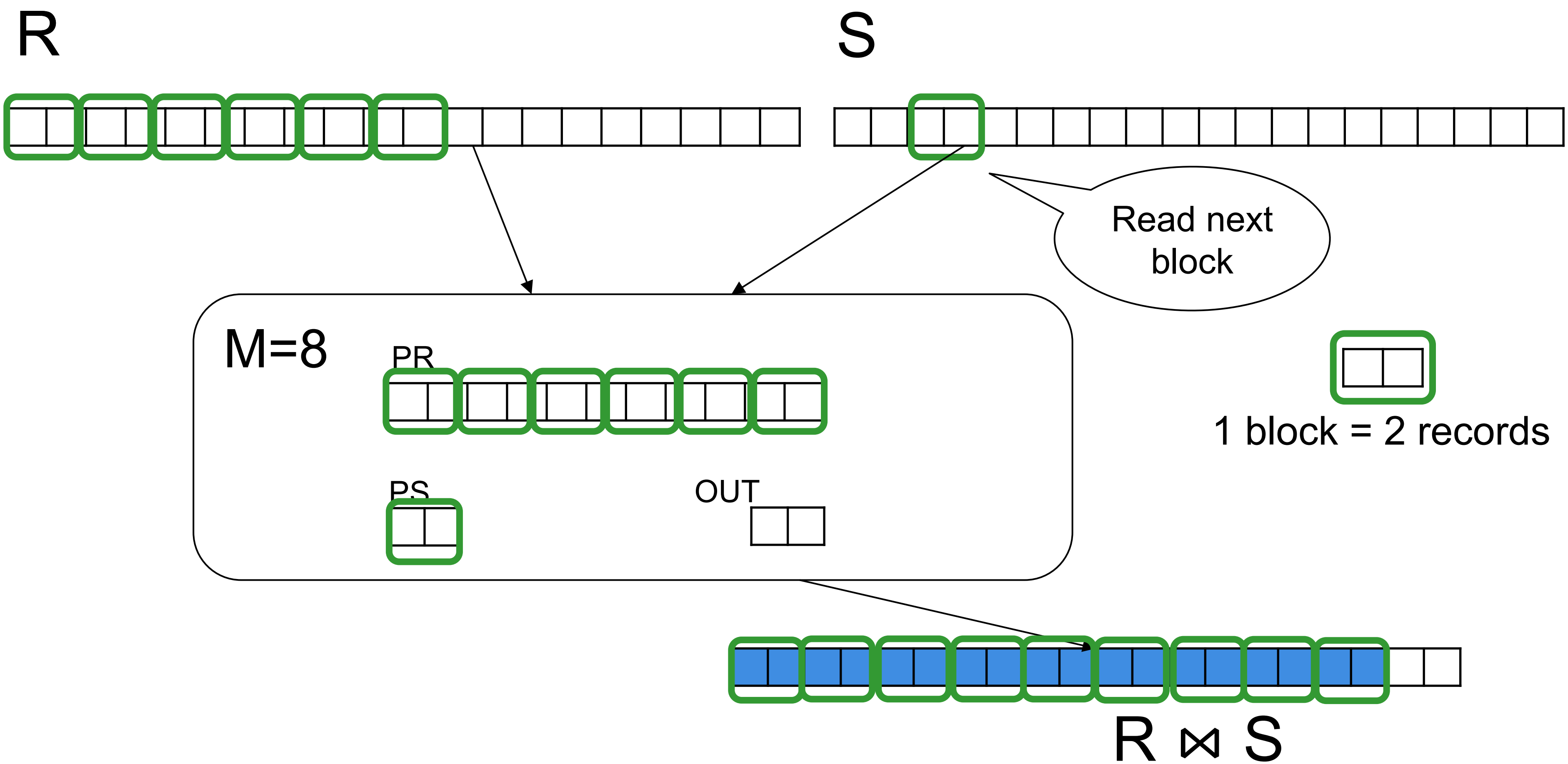

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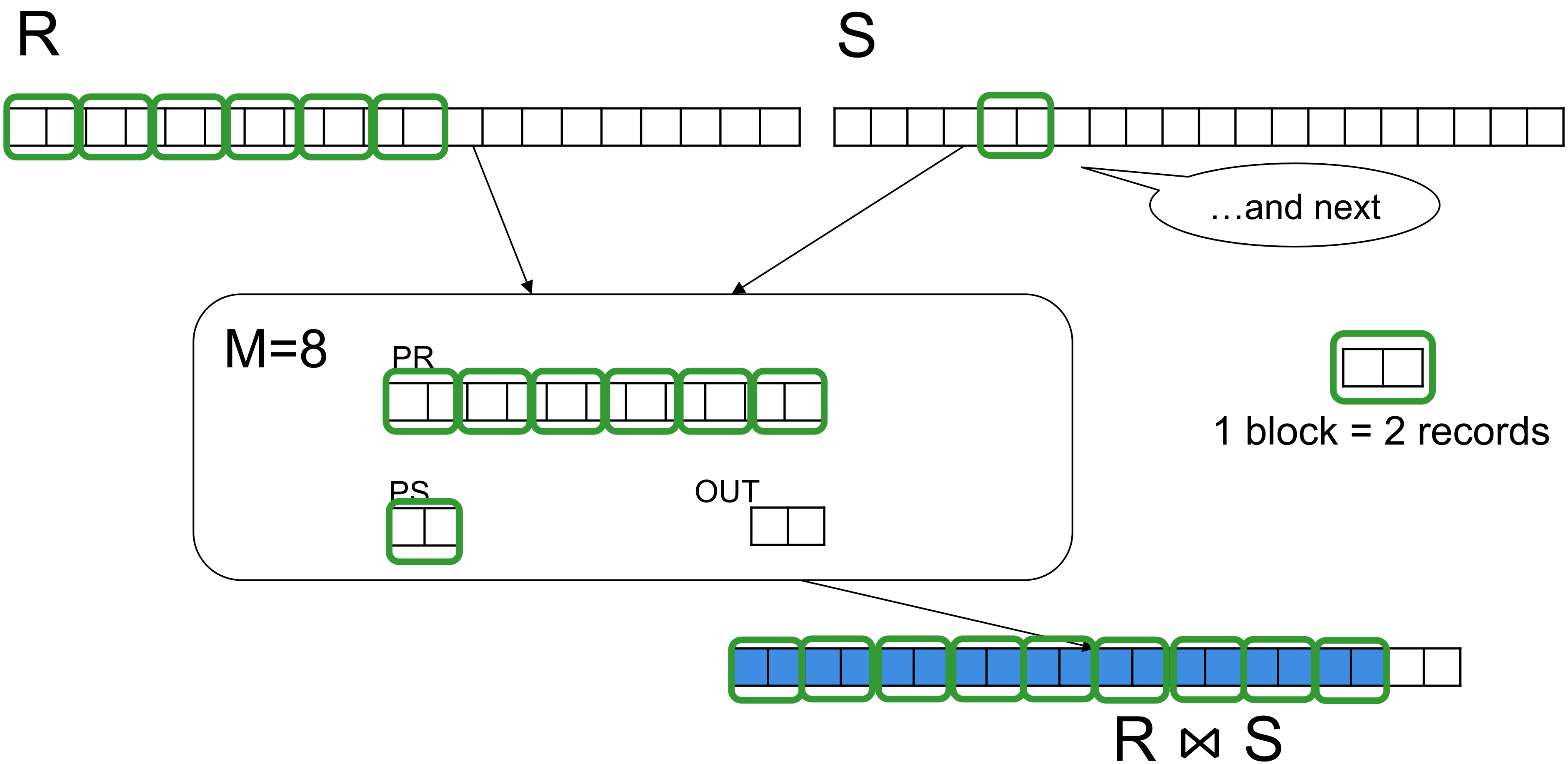

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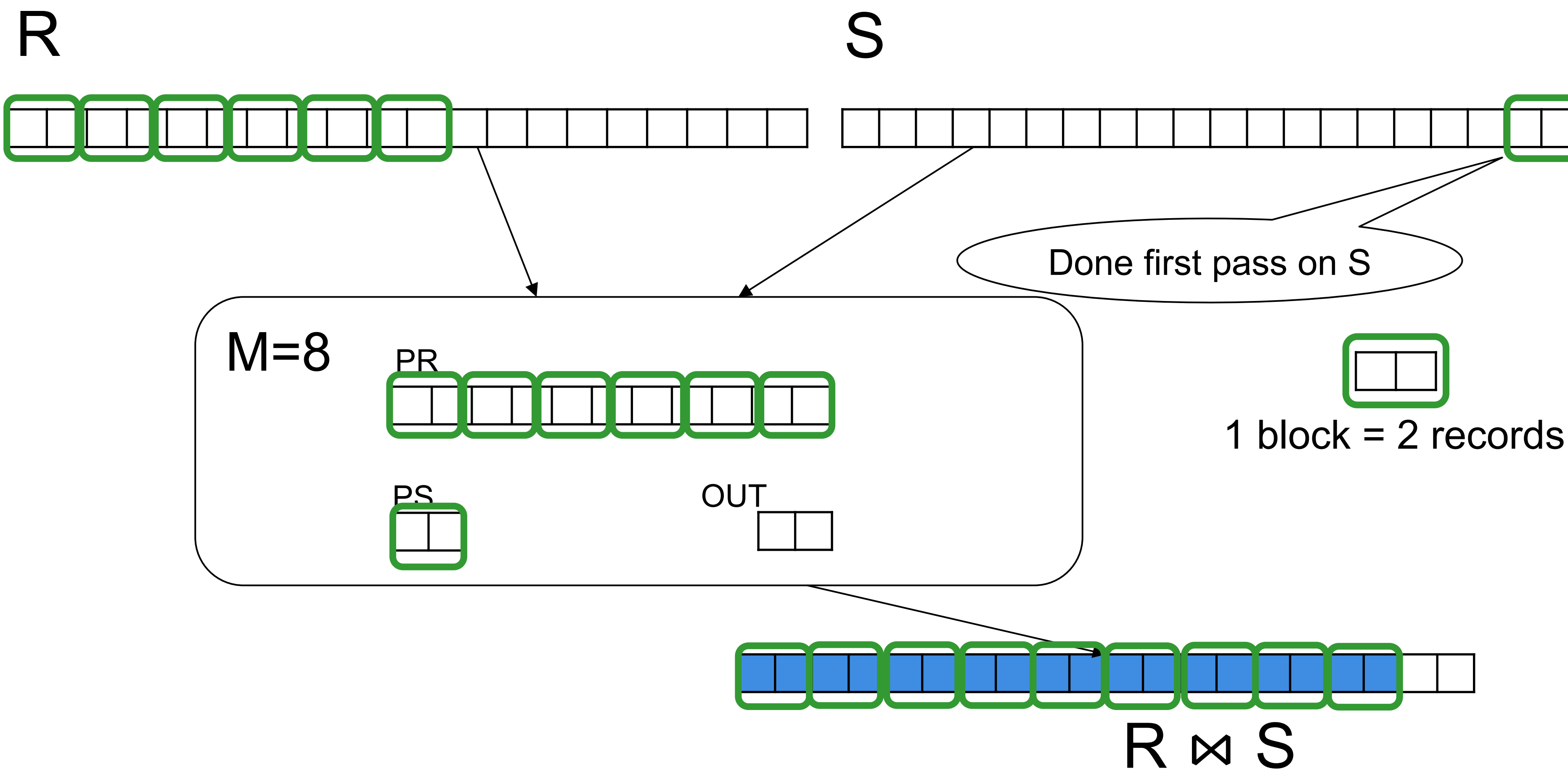

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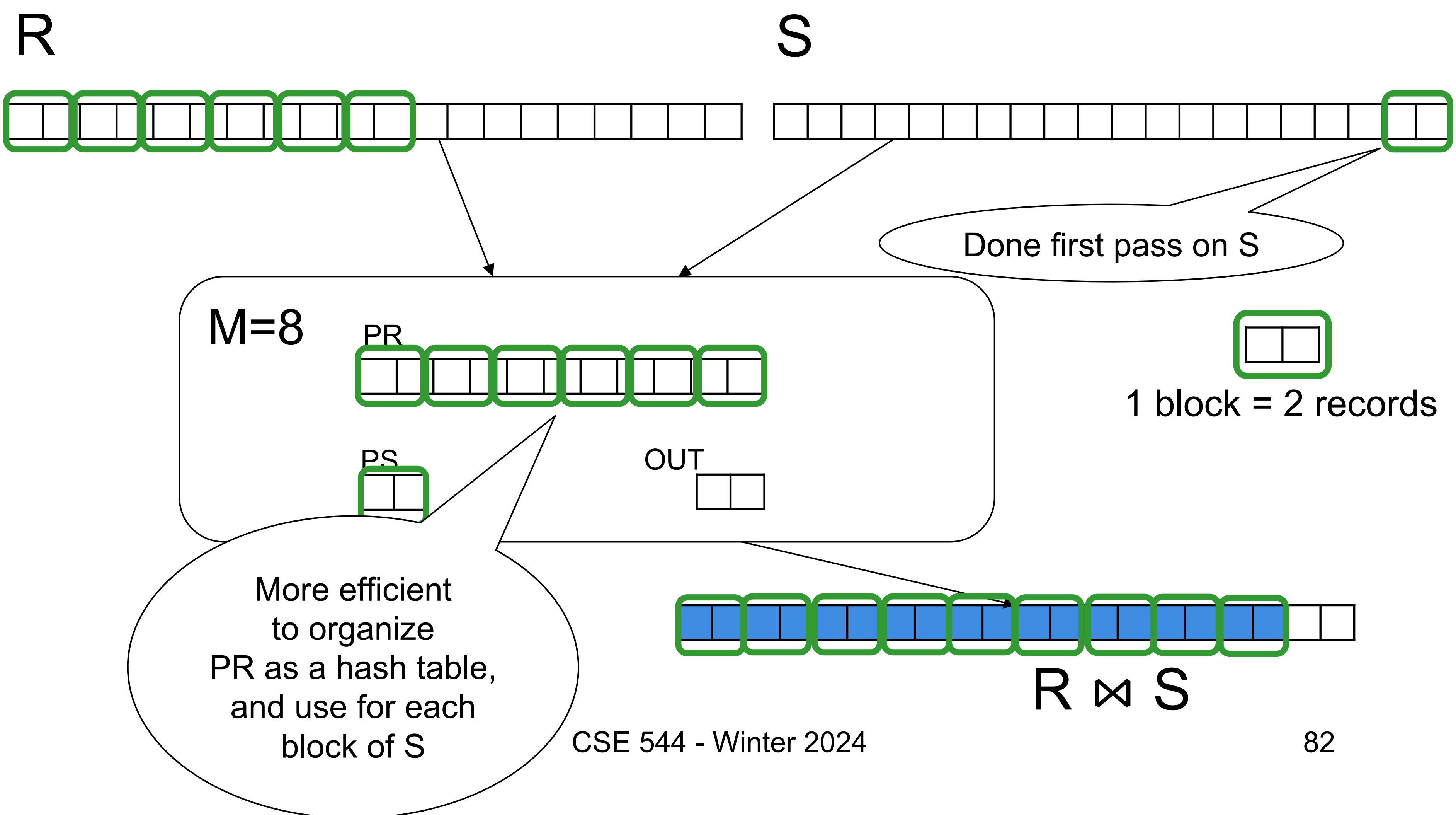

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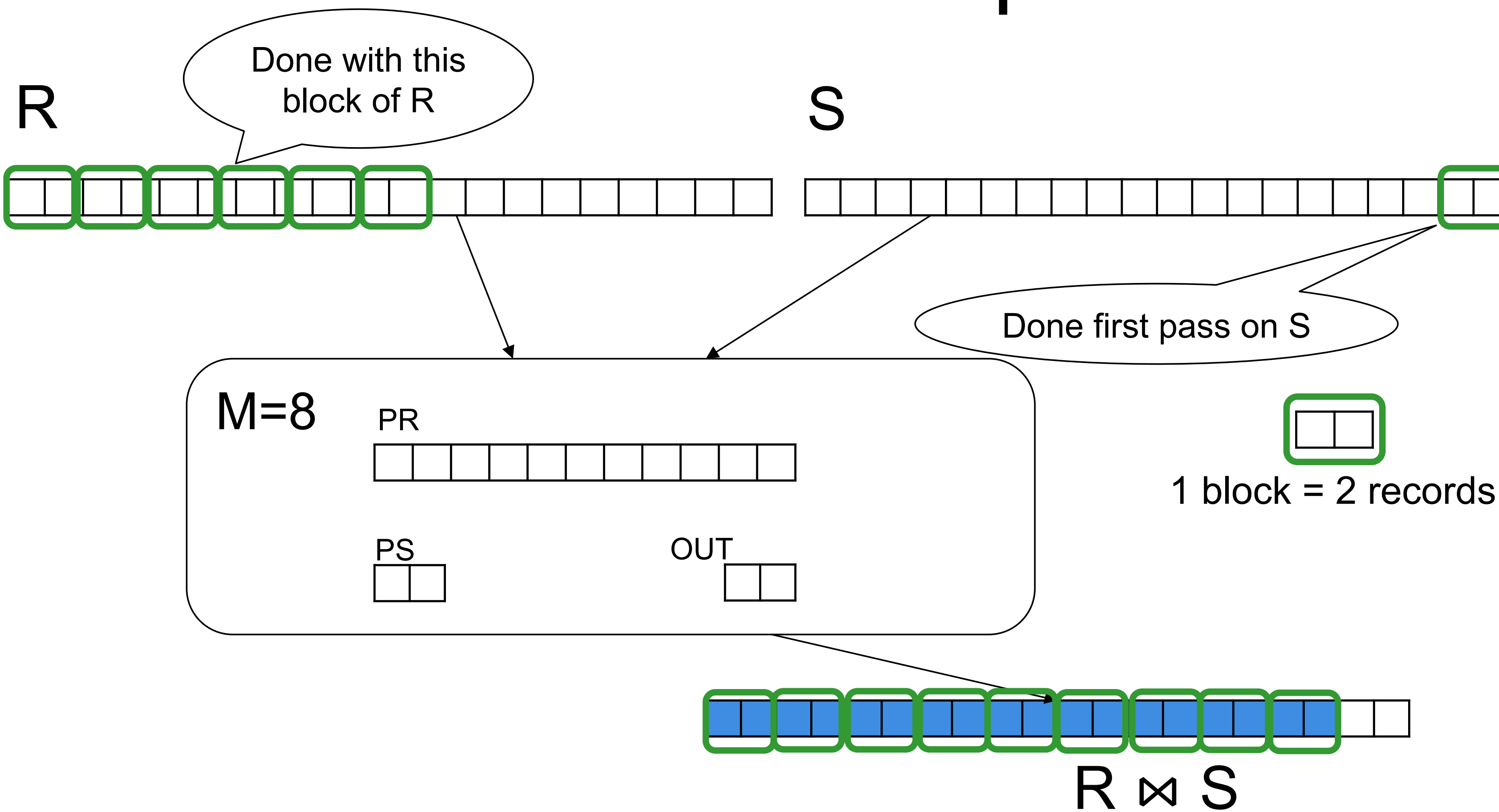

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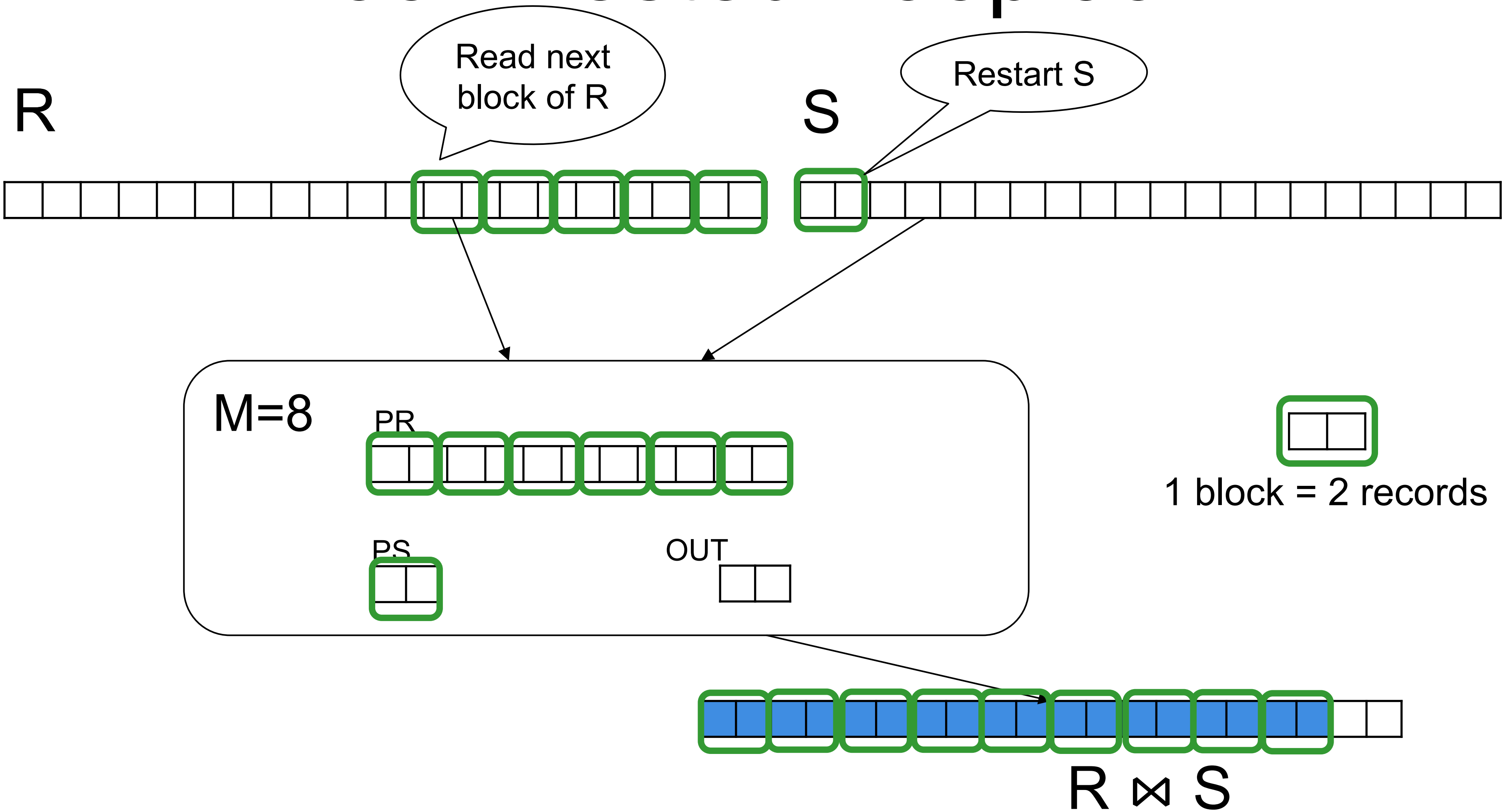

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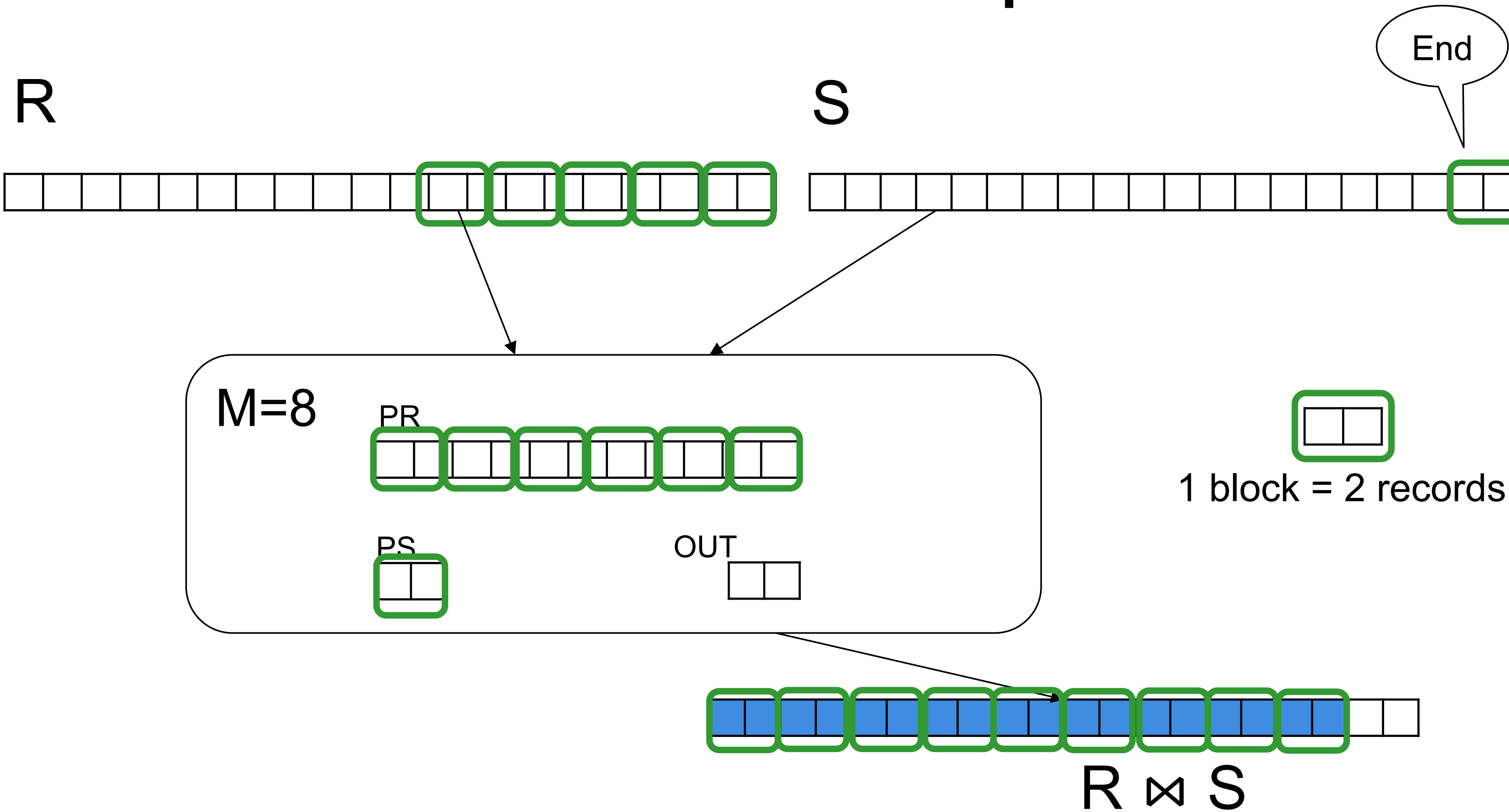

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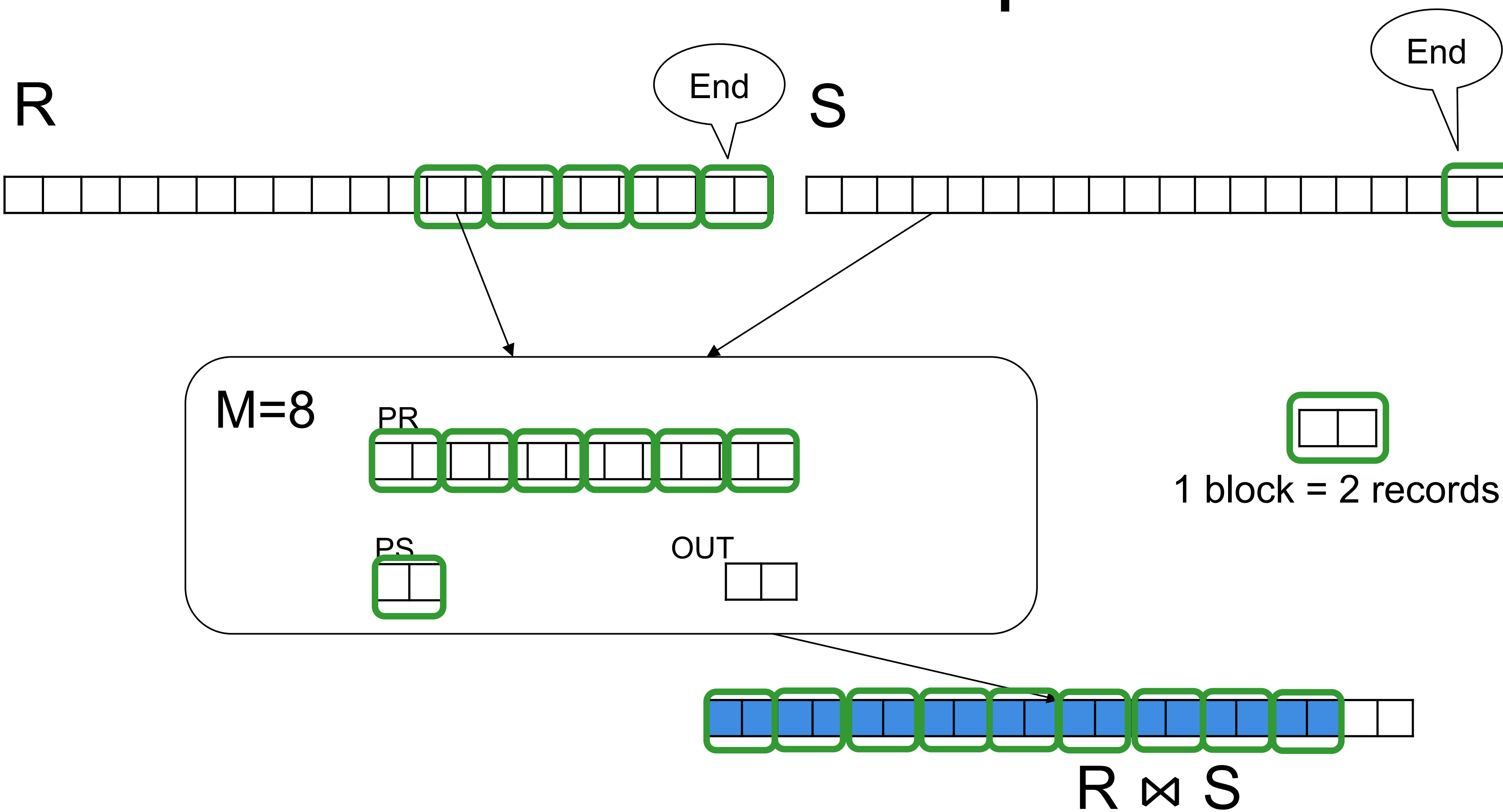

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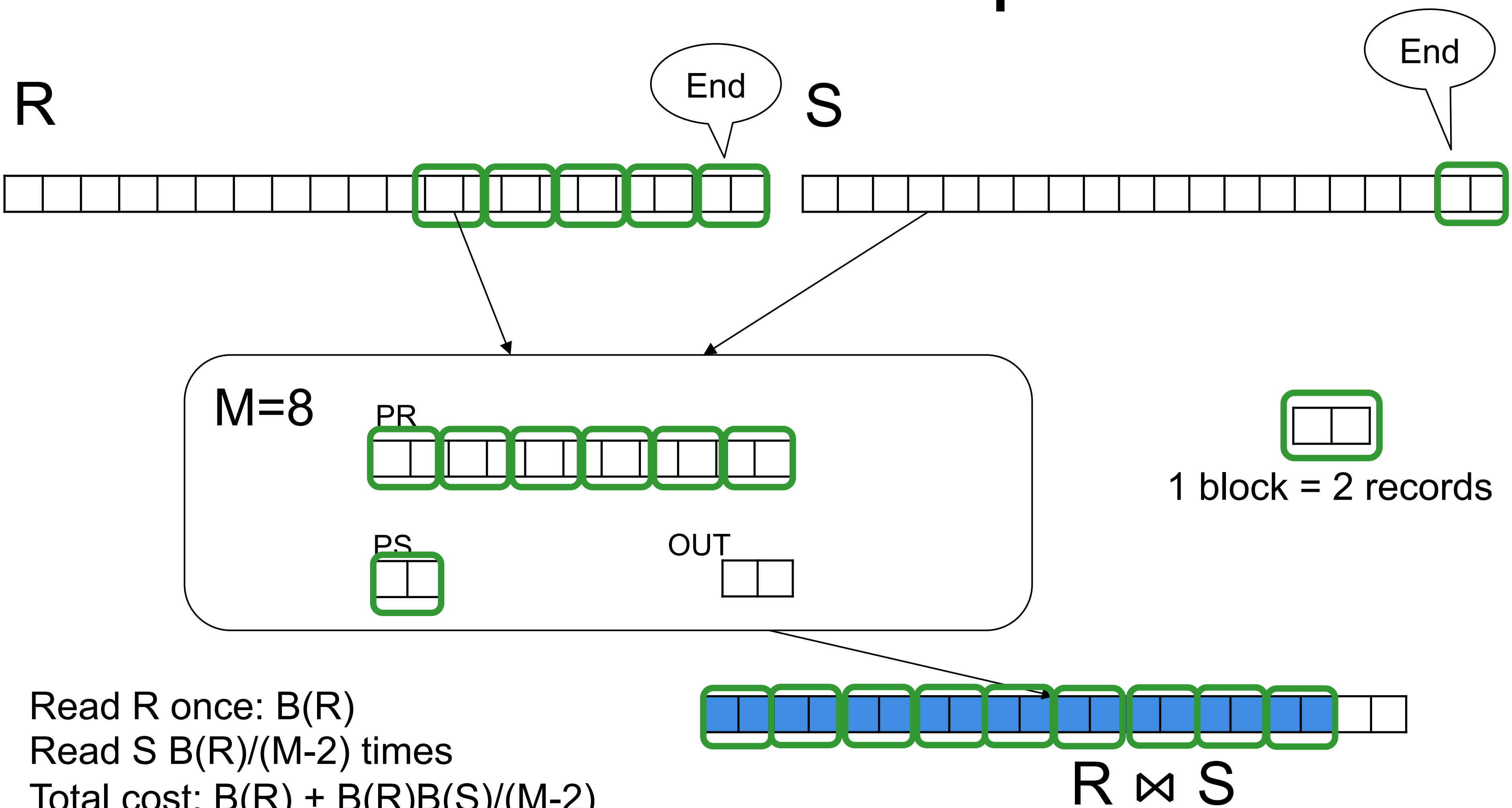

Read R once: B(R)
Read S B(R)/(M-2) times
Total cost: B(R) + B(R)B(S)/(M-2)
We ignore the final write

Merge Sort, Merge Join

Merge-Sort

Merge-sort reads/writes sequentially

- Run lengths: 2, 4, 8, 16, …
- Need log(N) sequential reads and writes

$$\text{Cost} = 2 \log(N)\, B(R)$$

Multi-Way Merge-Sort

N-Way Merge Sort: use entire memory M

- Merge M-1 runs at once; run lengths: $(M\text{-}1), (M\text{-}1)^2, (M\text{-}2)^3, \ldots$
- Need $\log_{M\text{-}1} N$ reads/writes; $\log_{M\text{-}1} N \approx 2$

Cost = 3 B(R)

Ignore final write

Merging n Arrays

Merge n sorted arrays

Merge(A_1, A_2, …, A_n)   // A_1, …, A_n are sorted

Merging n Arrays

```
Merge(A_1, A_2, …, A_n)          // A_1, …, A_n are sorted
   i_1 =0;  …, i_n = 0;  j=0
   while i_1 ≤ N or … or i_1 ≤ N
         let  A_k[i_k] = min(A_1[i_1], …, A_n[i_n])
```

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        T[k++] = A_k[i_k++]
```

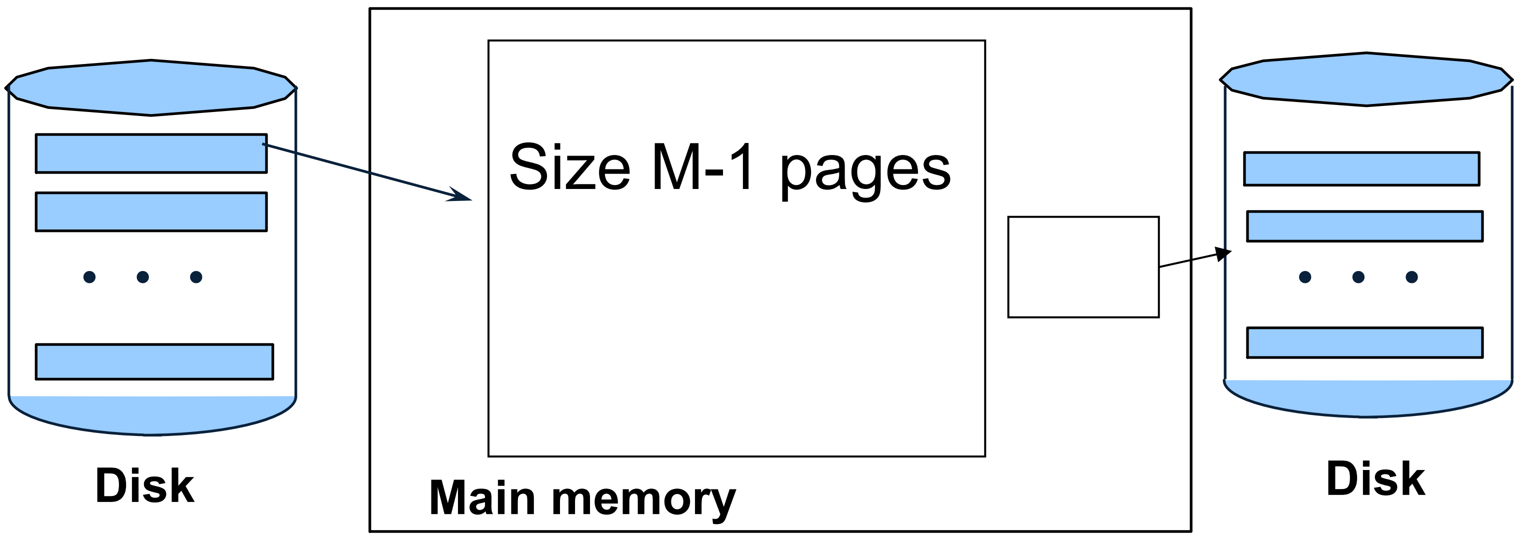
Important:
Need to read only one element from each array

Time = $O(|A_1| + |A_2| + \dots |A_n|)$

Additional log n factor to find min using priority queue

Merge-Sort: Step 1

- Phase 1: load M-1 blocks in memory, sort



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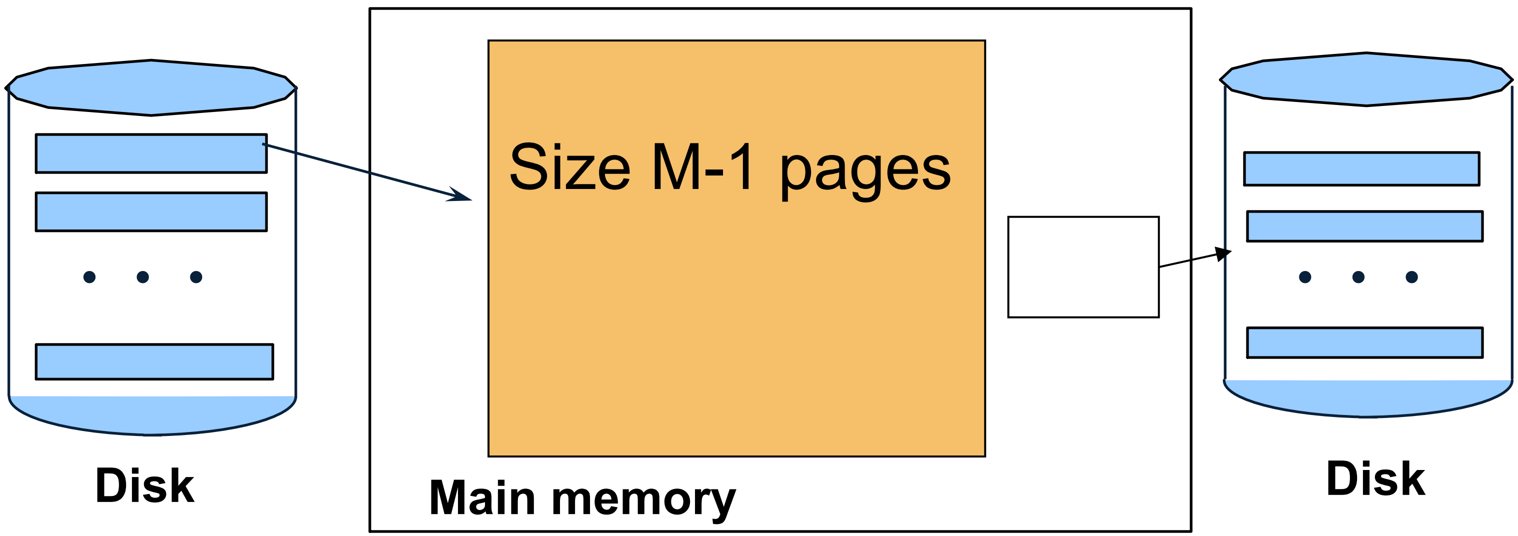

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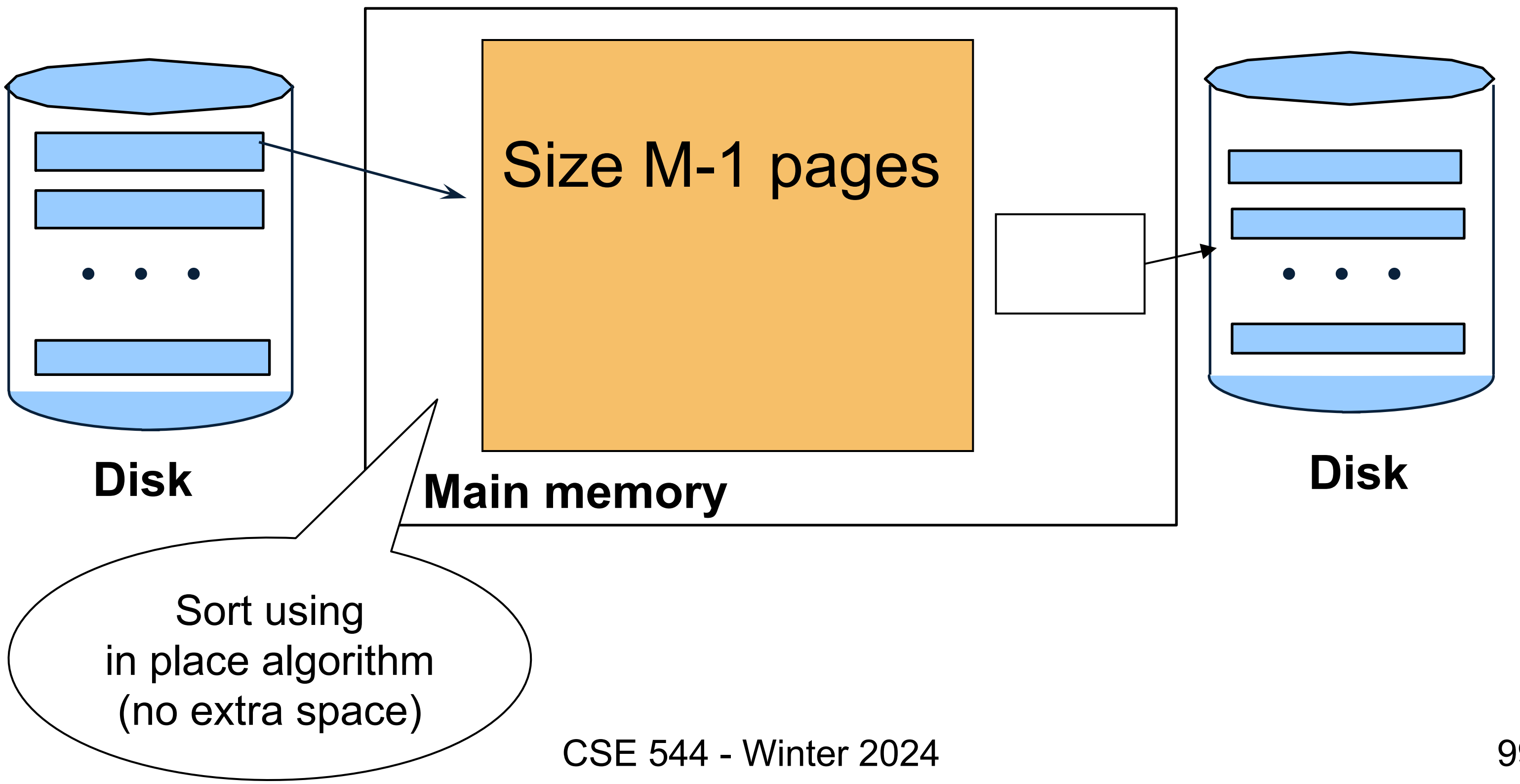

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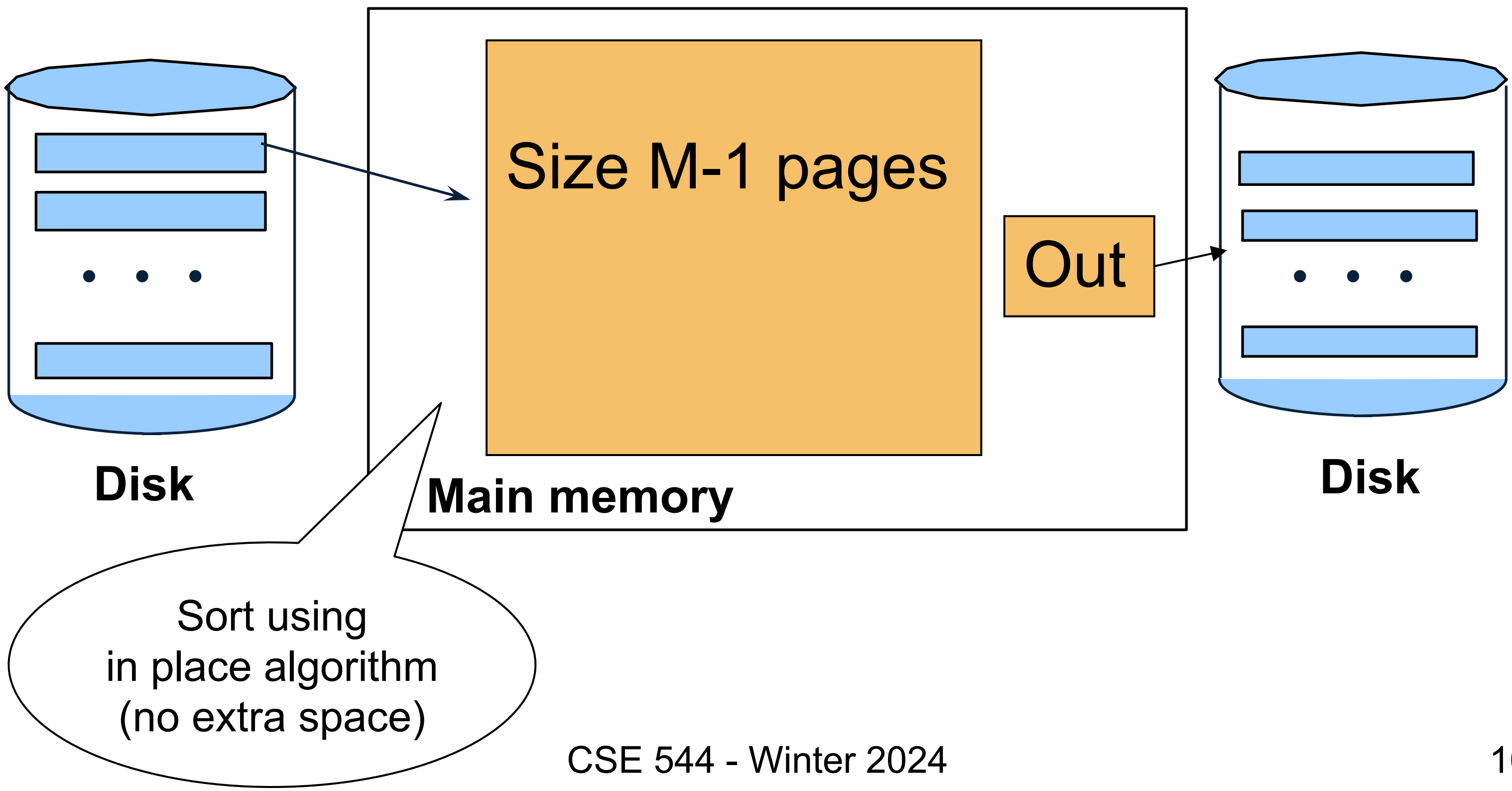

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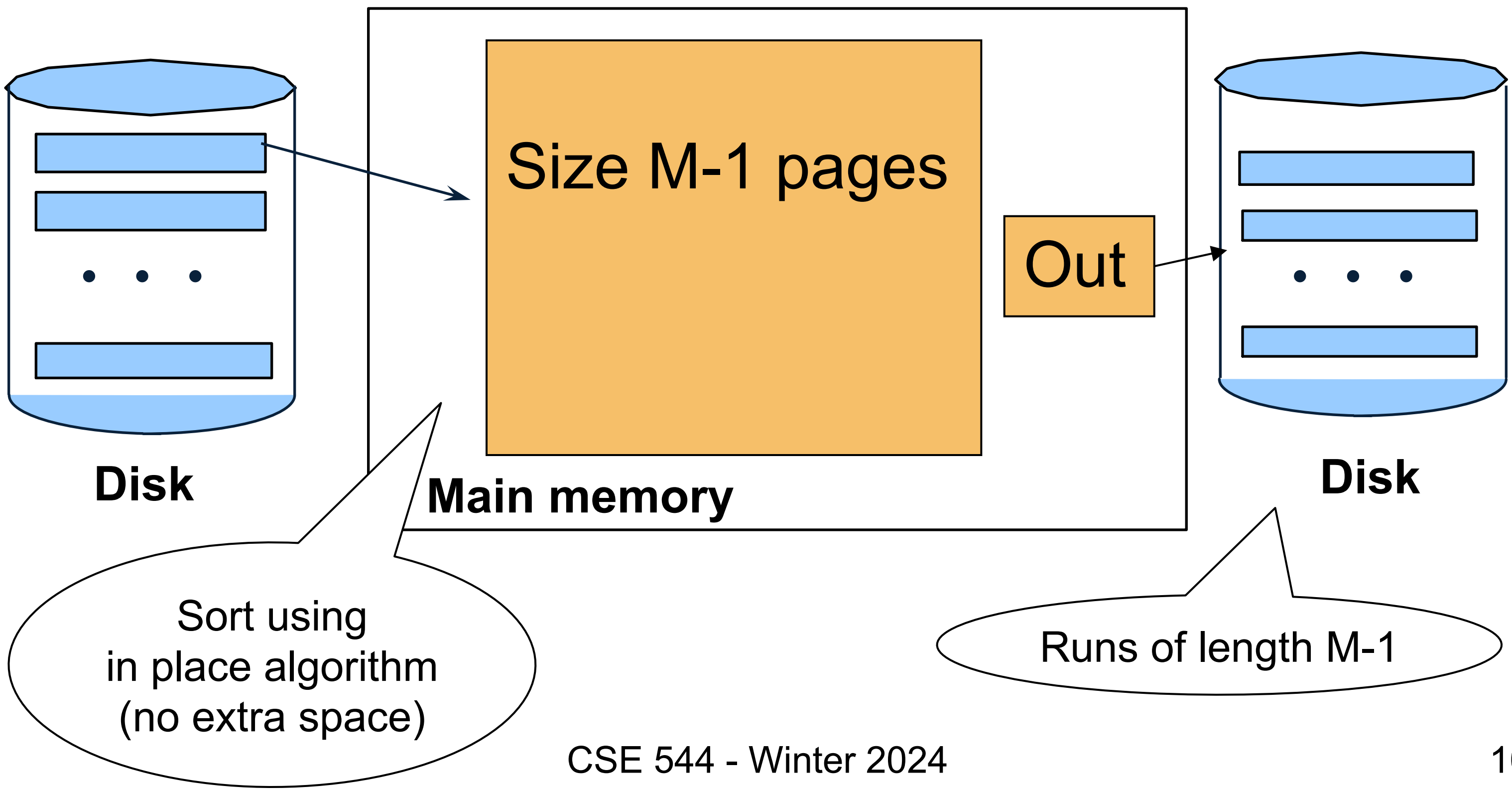

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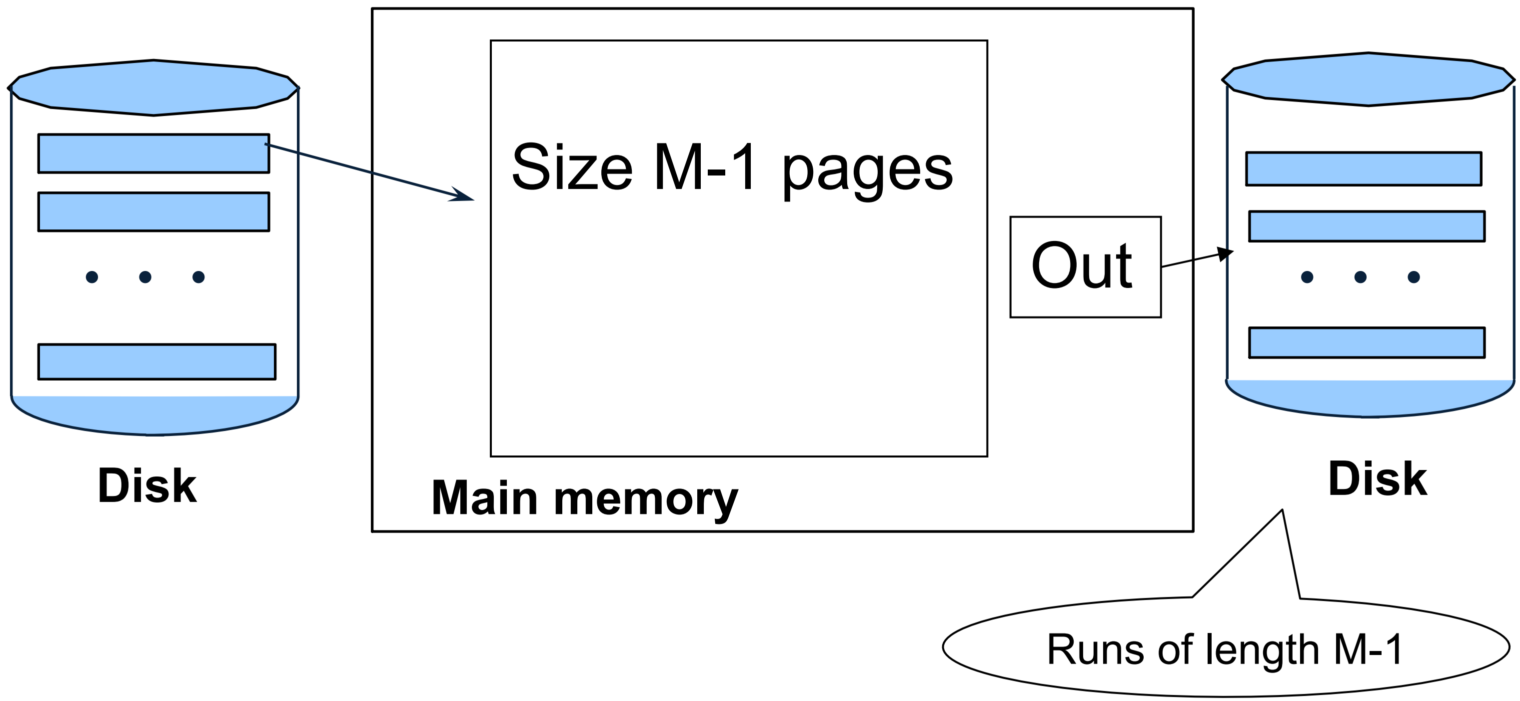

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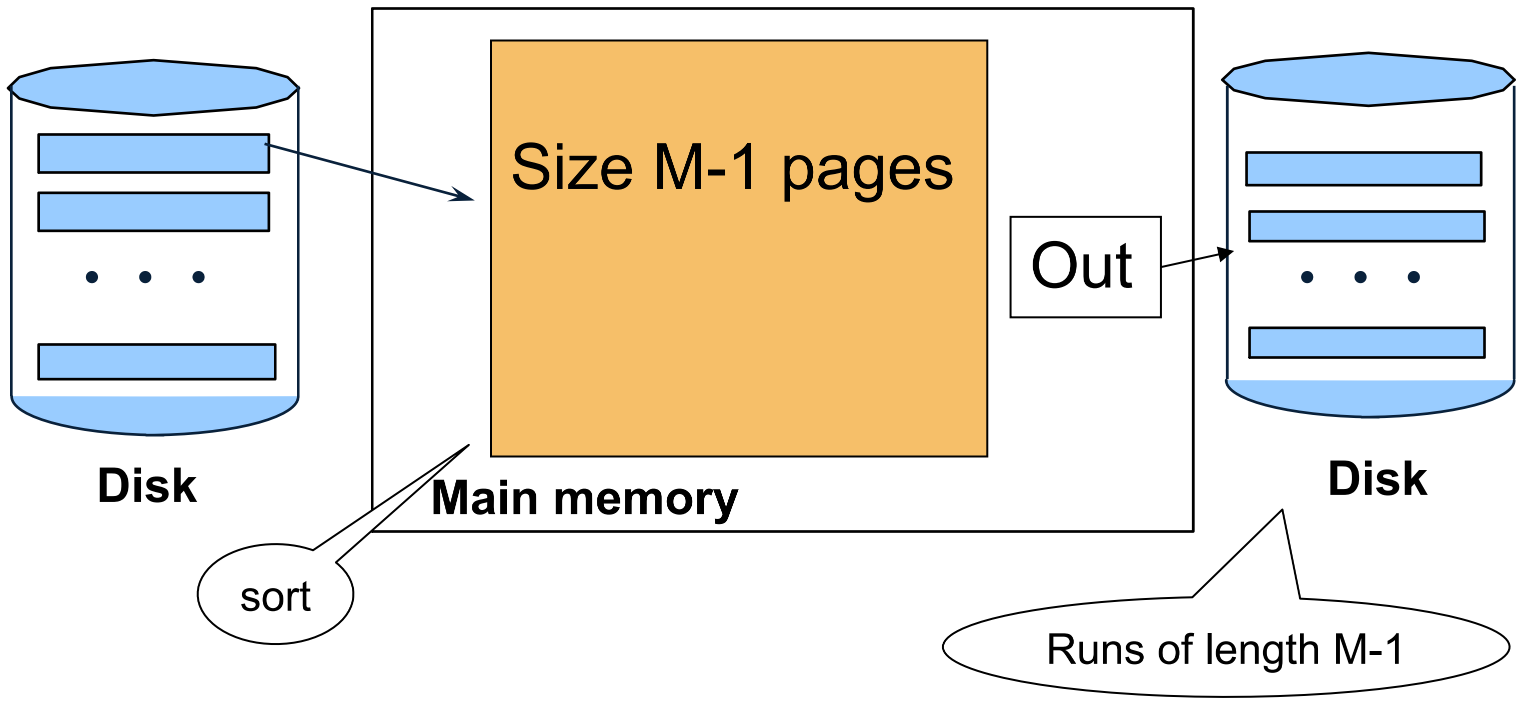

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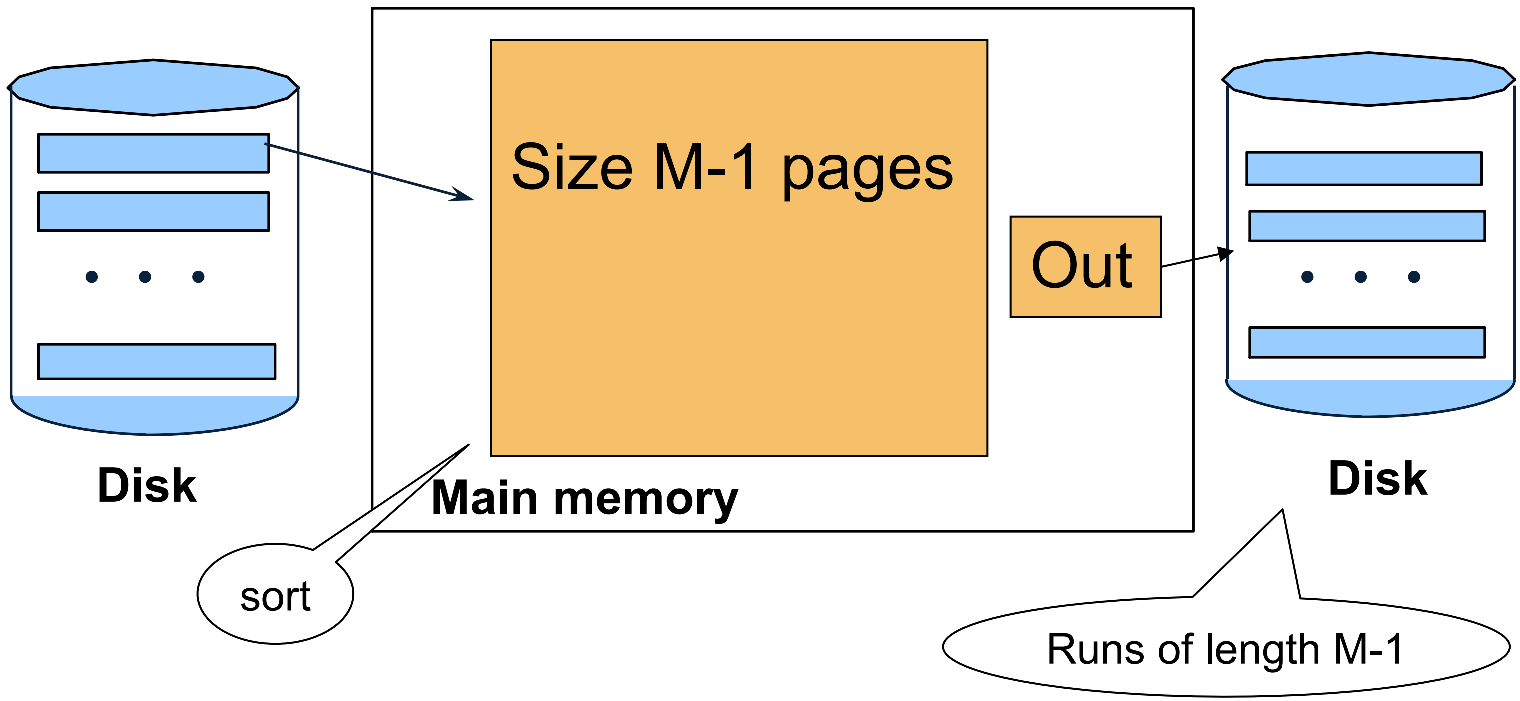
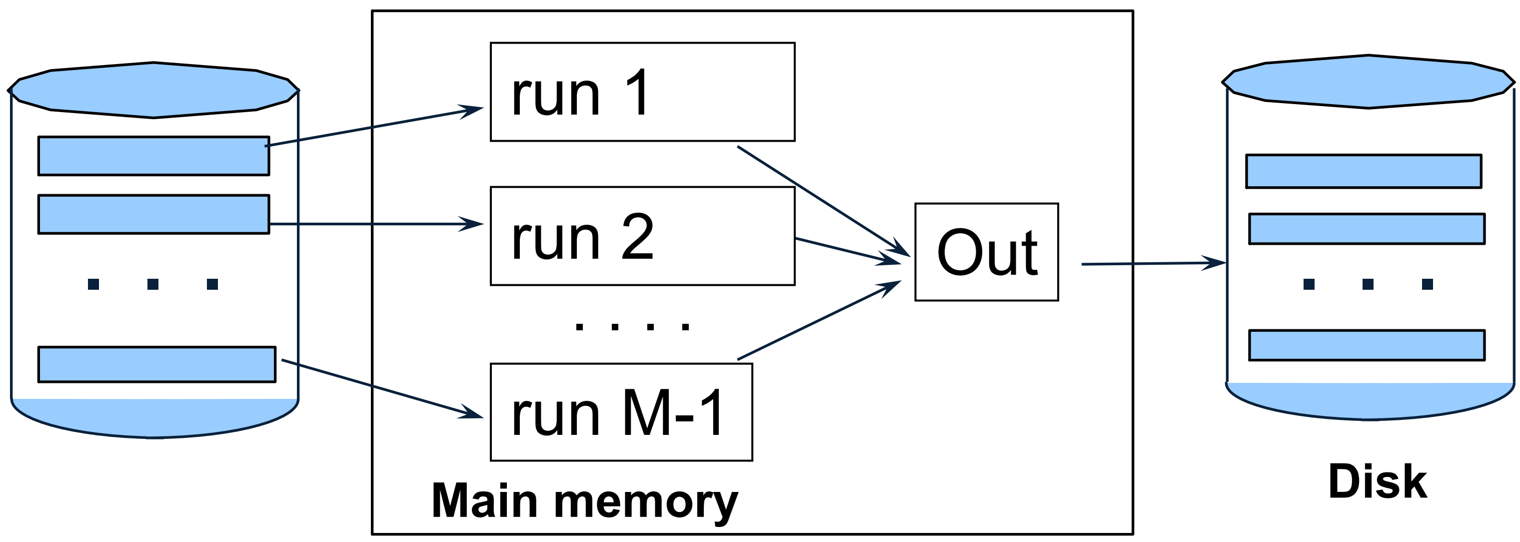


Merge-Sort: Steps 2, 3, …

- Merge M – 1 runs into a new run
- New runs of length $(M - 1)^2$, $(M - 1)^3$,…



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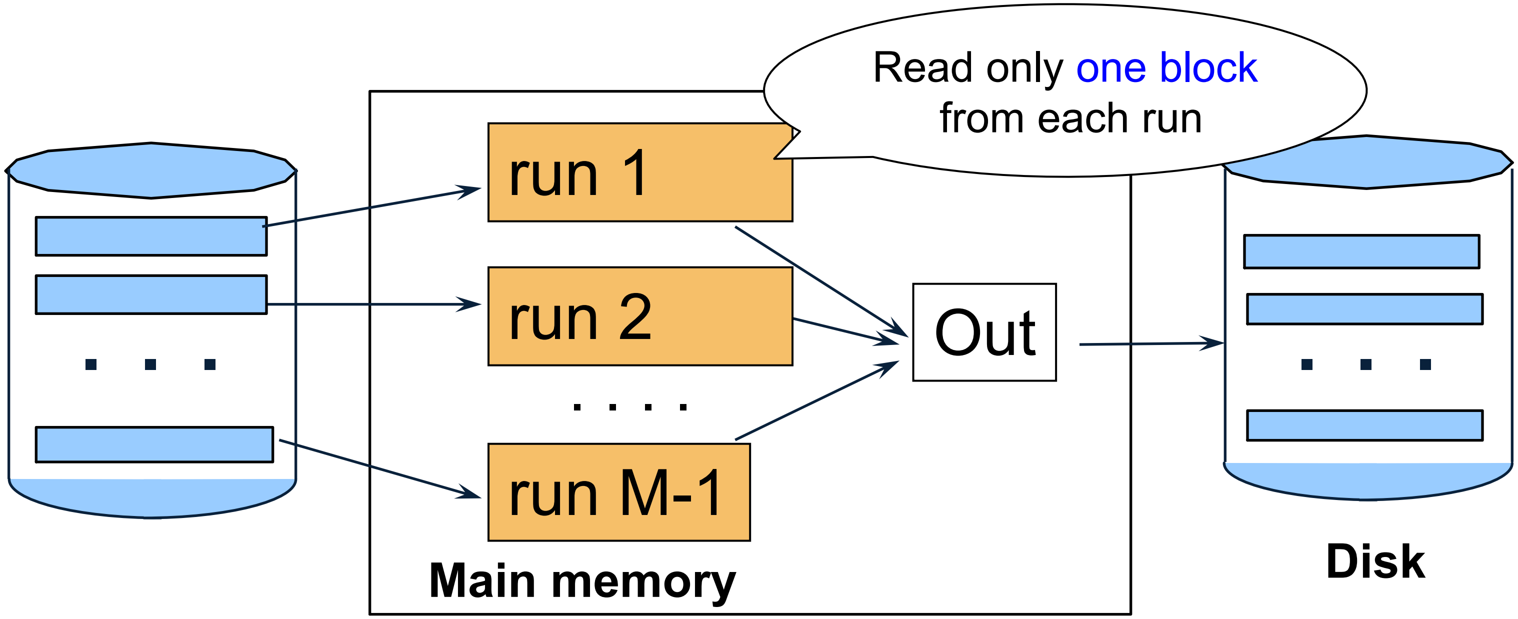

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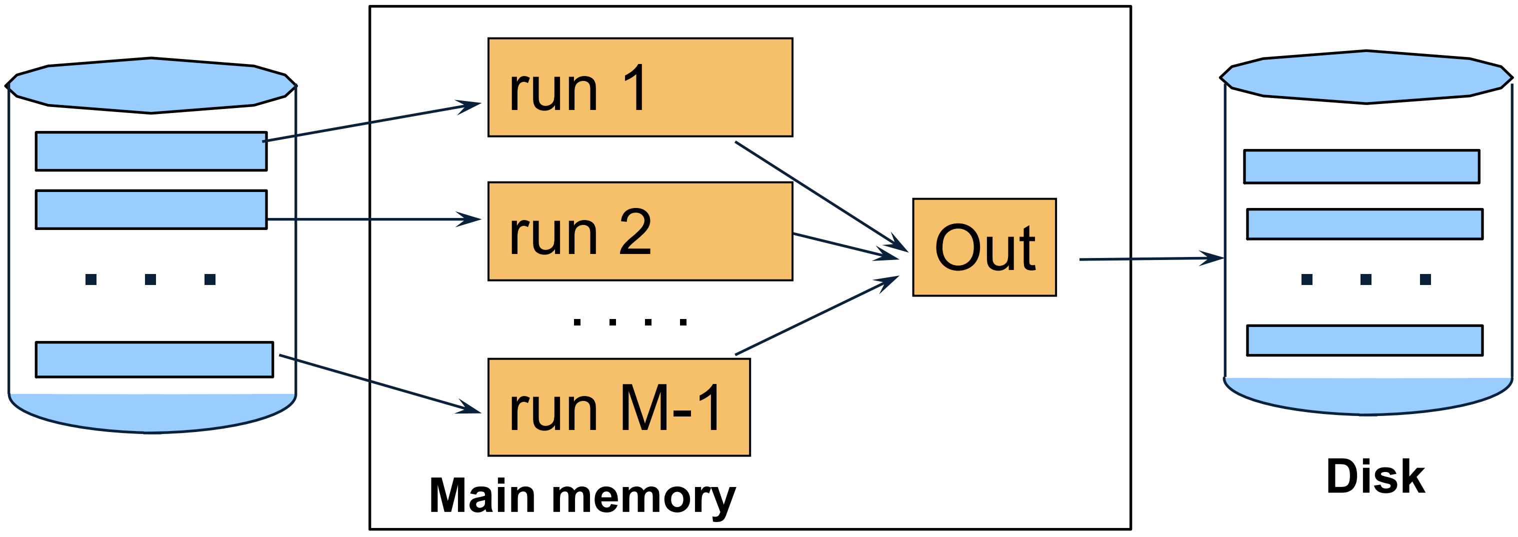

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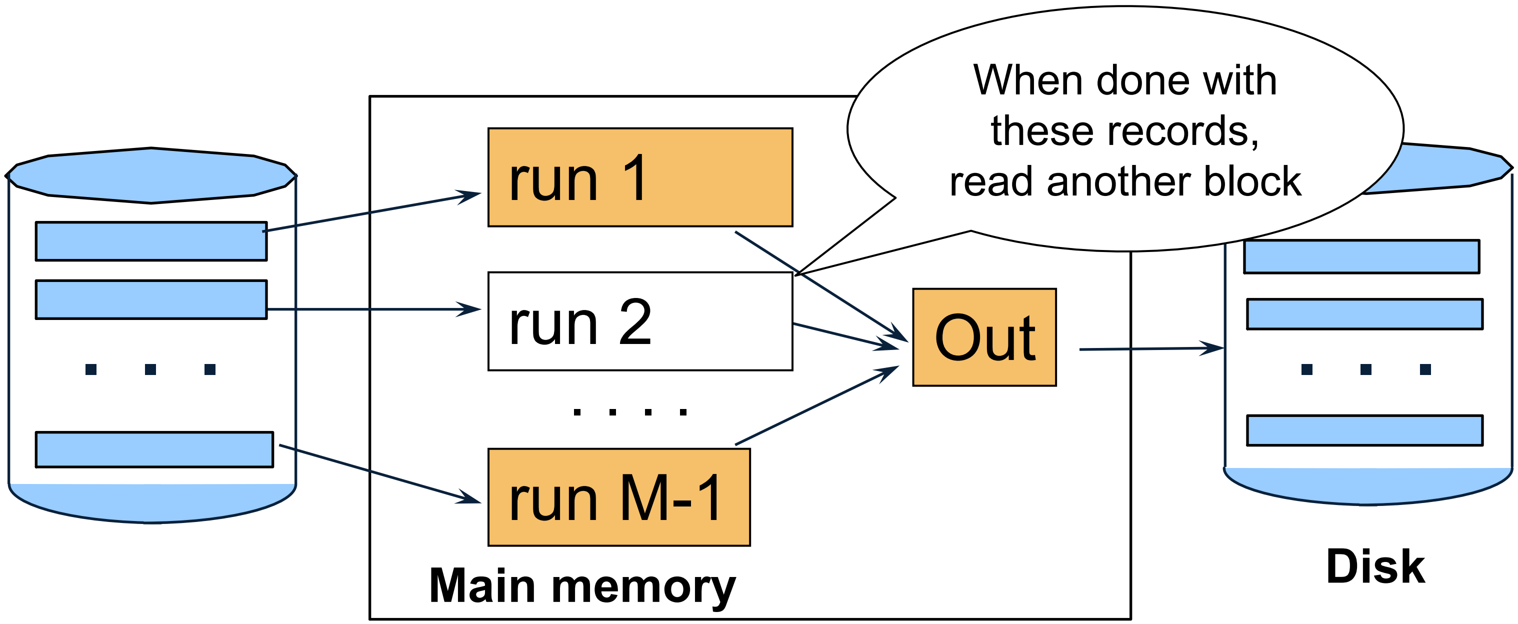

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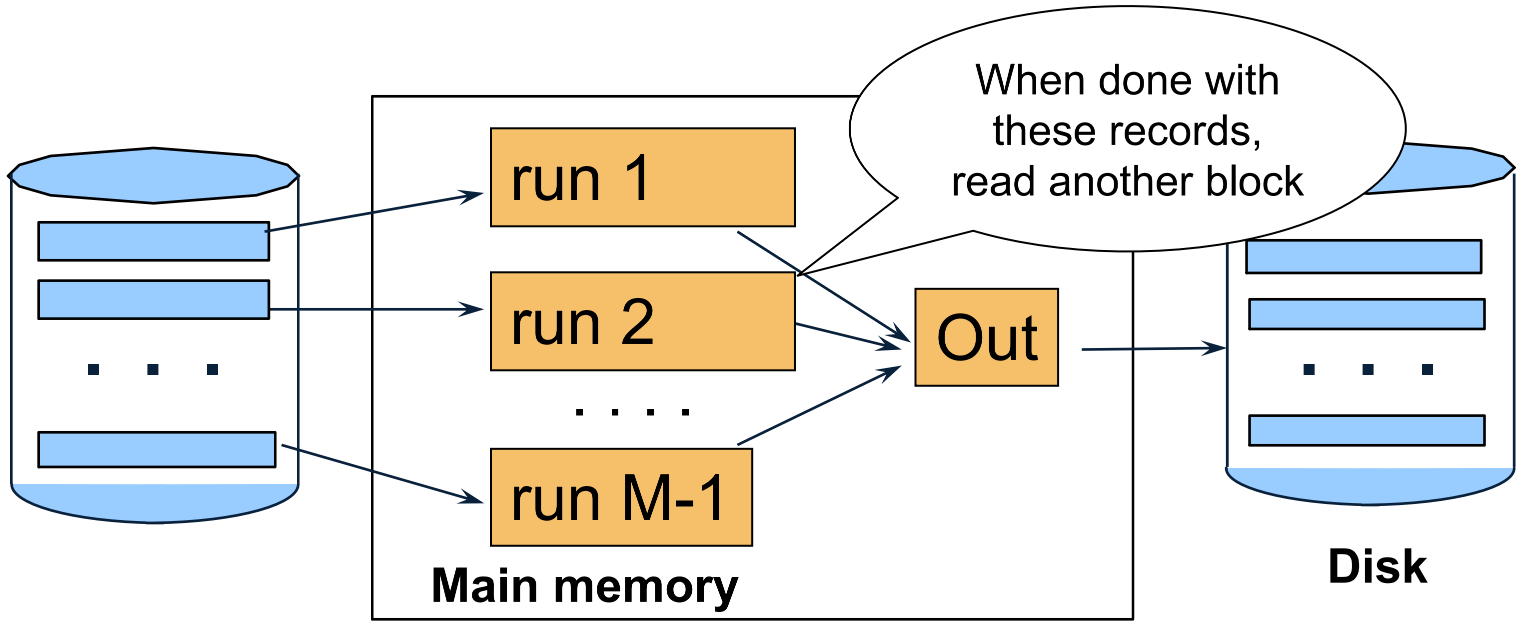

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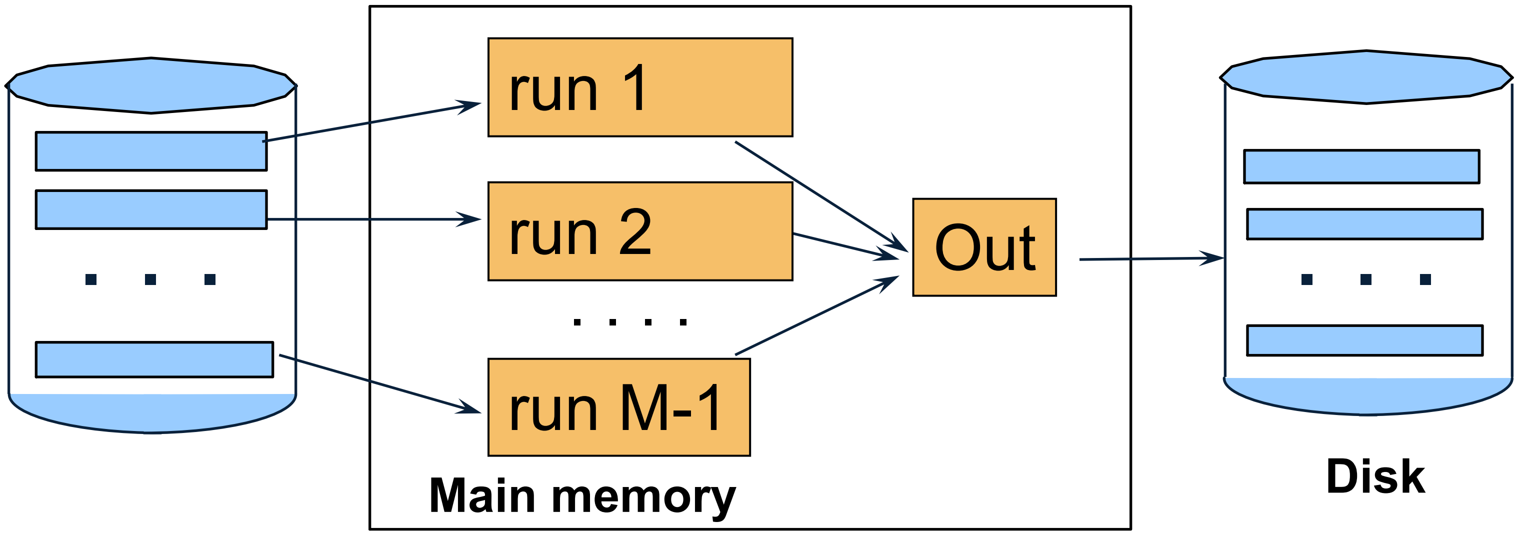

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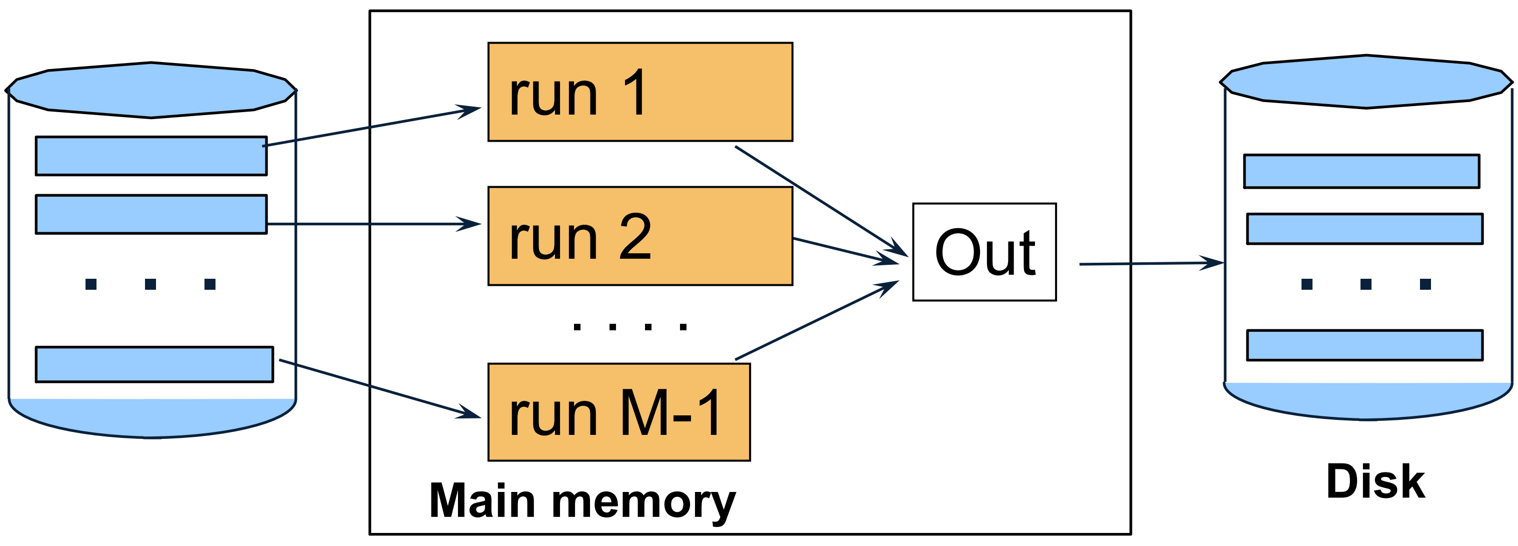

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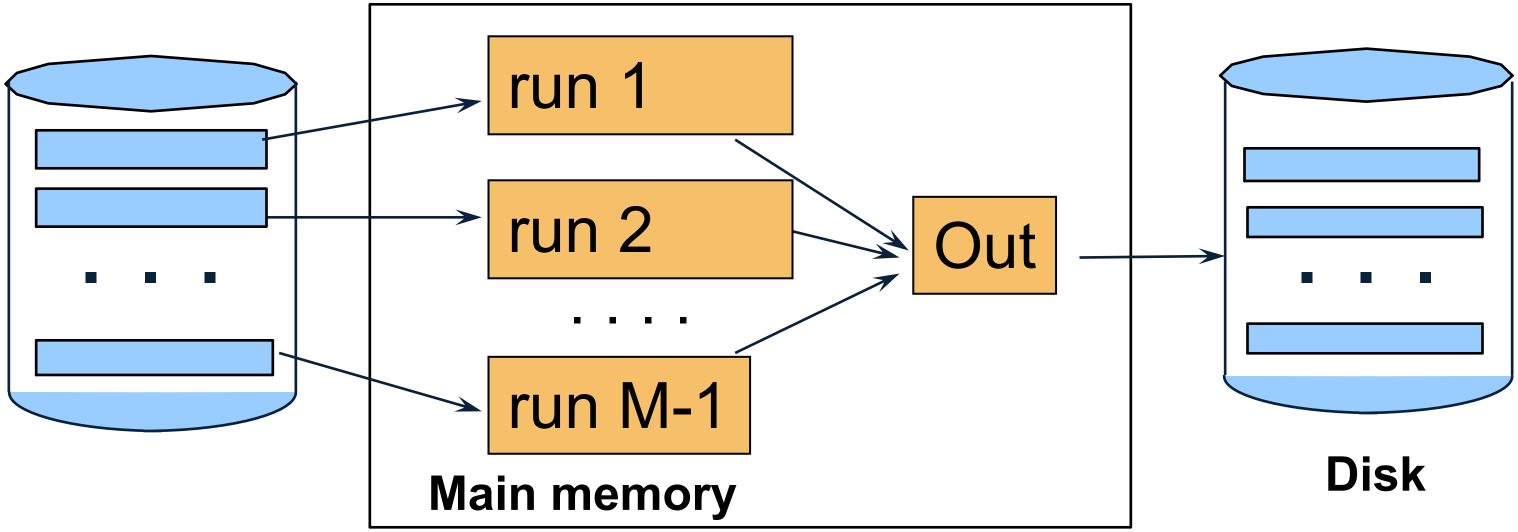

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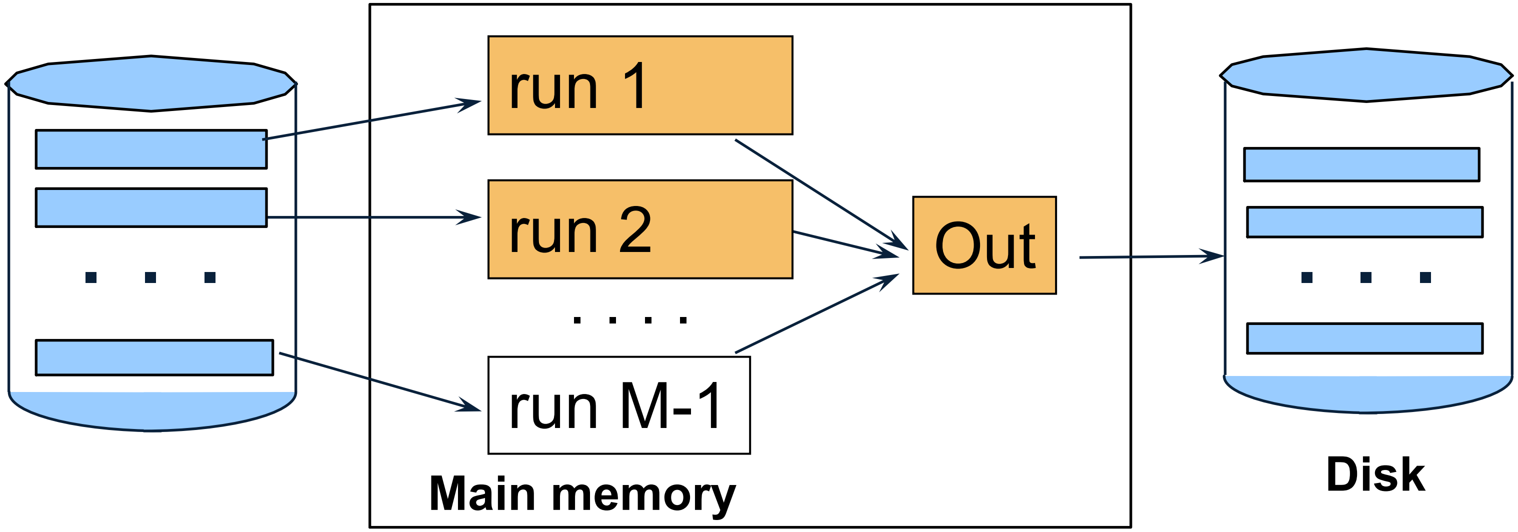

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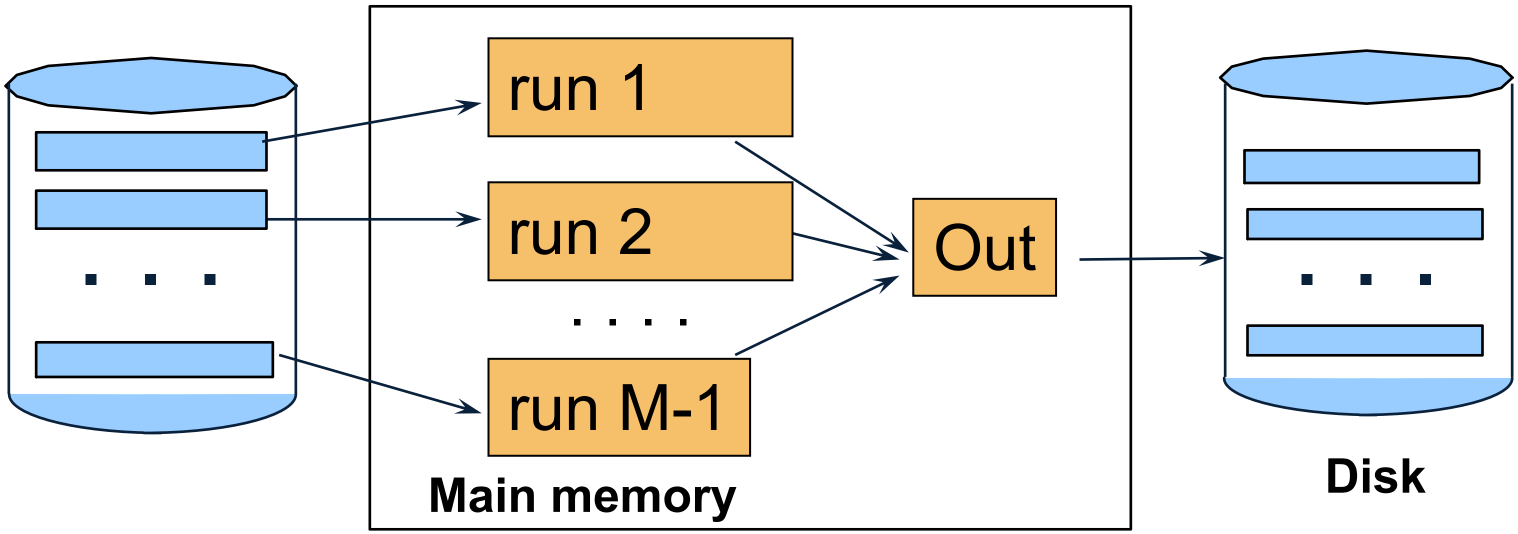

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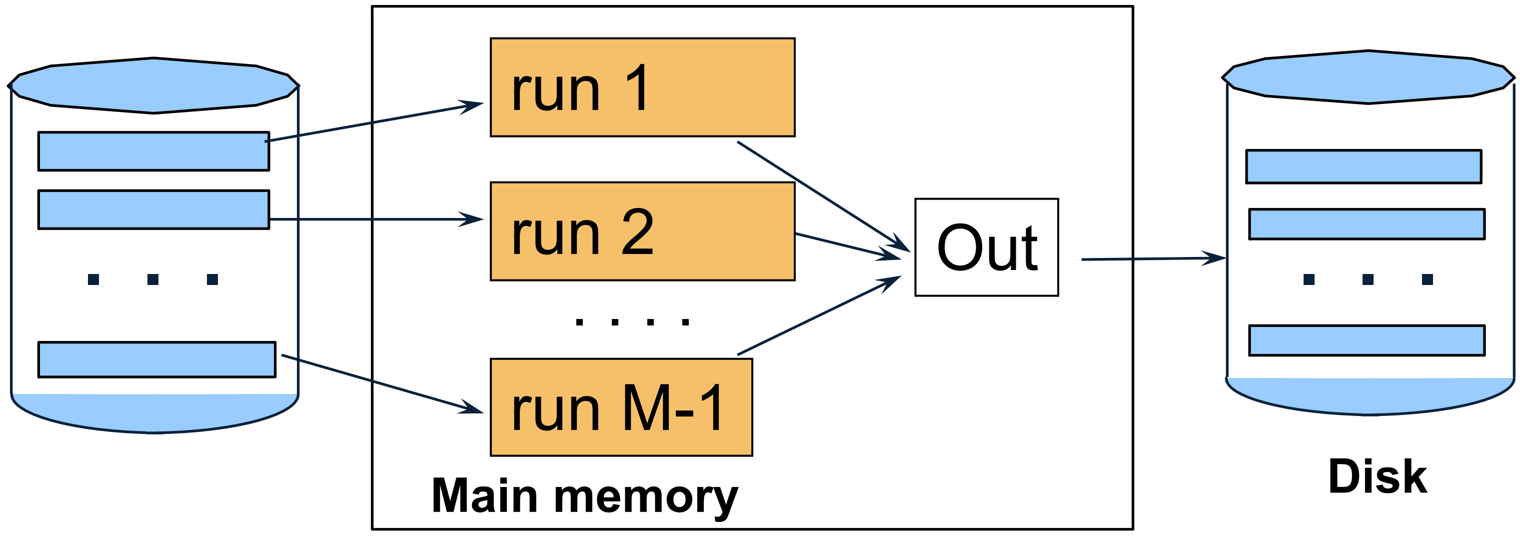

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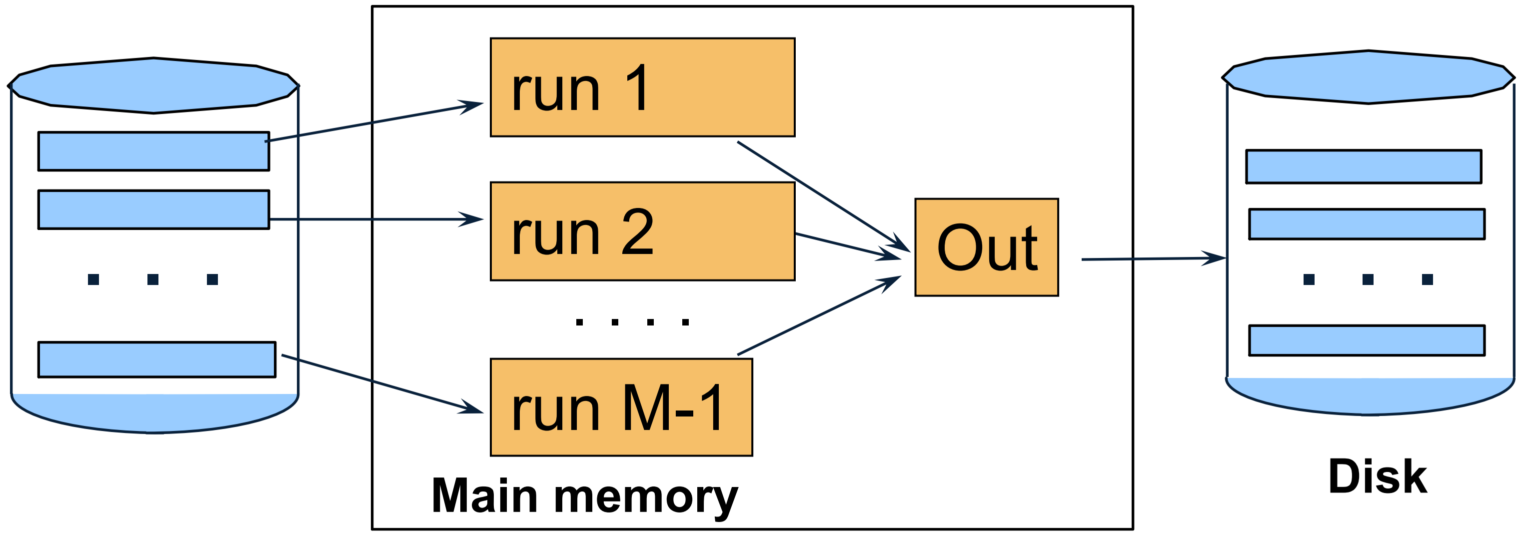

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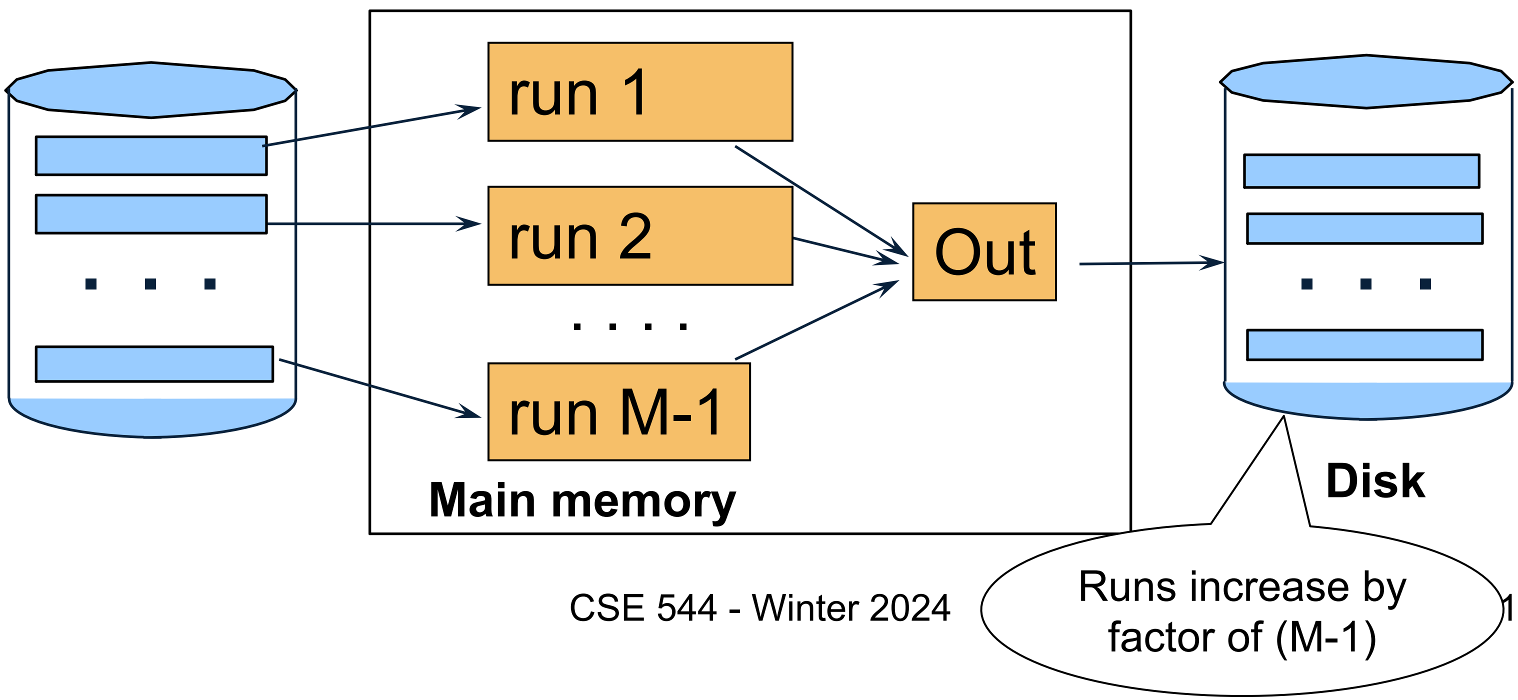

Merge-Sort: Discussion

Size of the runs increases fast

- Example: B=10001

Each block is 16Kb

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- Step 1: run length 10000 = 160Mb

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Merge-Sort: Discussion

Size of the runs increases fast

Each block is 16Kb

- Example: B=10001
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- …

Usually, 2 steps suffice

Cost = 3B(R)

Finally: Merge-Join

$R \bowtie S$

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- Create runs of R → B(R)/(M-1) runs
- Create runs of S → B(S)/(M-1) runs

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- Create runs of R → B(R)/(M-1) runs
- Create runs of S → B(S)/(M-1) runs
- Use N-way merge to compute the join

Finally: Merge-Join

$R \bowtie S$

- Create runs of R → $B(R)/(M-1)$ runs
- Create runs of S → $B(S)/(M-1)$ runs
- Use N-way merge to compute the join

- Need $B(R)+B(S) \leq (M-1)^2$ why?

$$\text{Cost} = 3(B(R)+B(S))$$

Partitioned Hash-Join

Hash-Partitioned Join

- The outer relation R needs to fit in main memory
- The inner relation S doesn't need to fit

```
for x in R do
    insert(x.key, x)

for y in S do
    x = find(y.key);
    output(x,y);
```

Partitioned Hash-Join

- $R \bowtie S$, both bigger than main memory

Partitioned Hash-Join

- R ⋈ S, both bigger than main memory
- Step 1:
  - Hash partition both R and S
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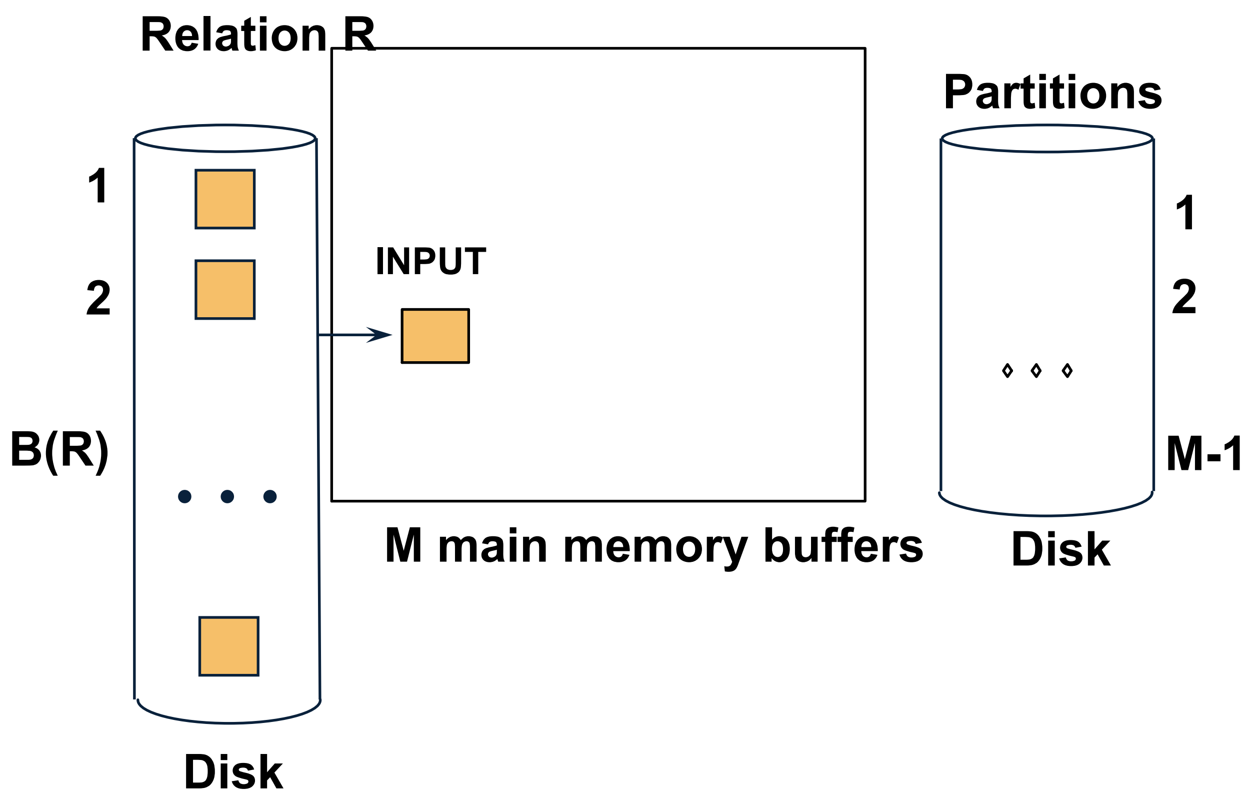
Partitioned Hash-Join

- R $\bowtie$ S, both bigger than main memory
- Step 1:
  - Hash partition both R and S
  - Store buckets on disk
- Step 2:
  - Read one R-bucket in main memory
  - Hash-Join with corresponding S-bucket
  - Repeat for all buckets

Step 1: Hash-partition

- Partition R into buckets, on disk



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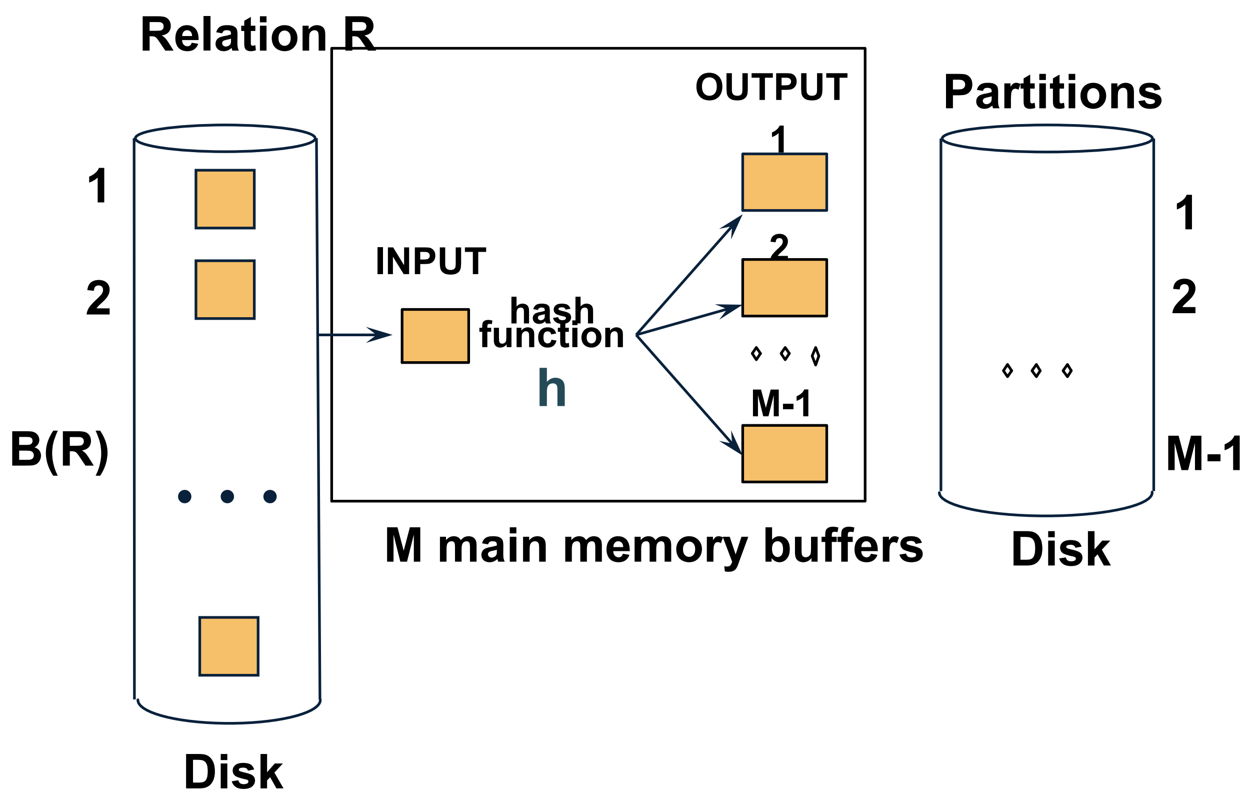

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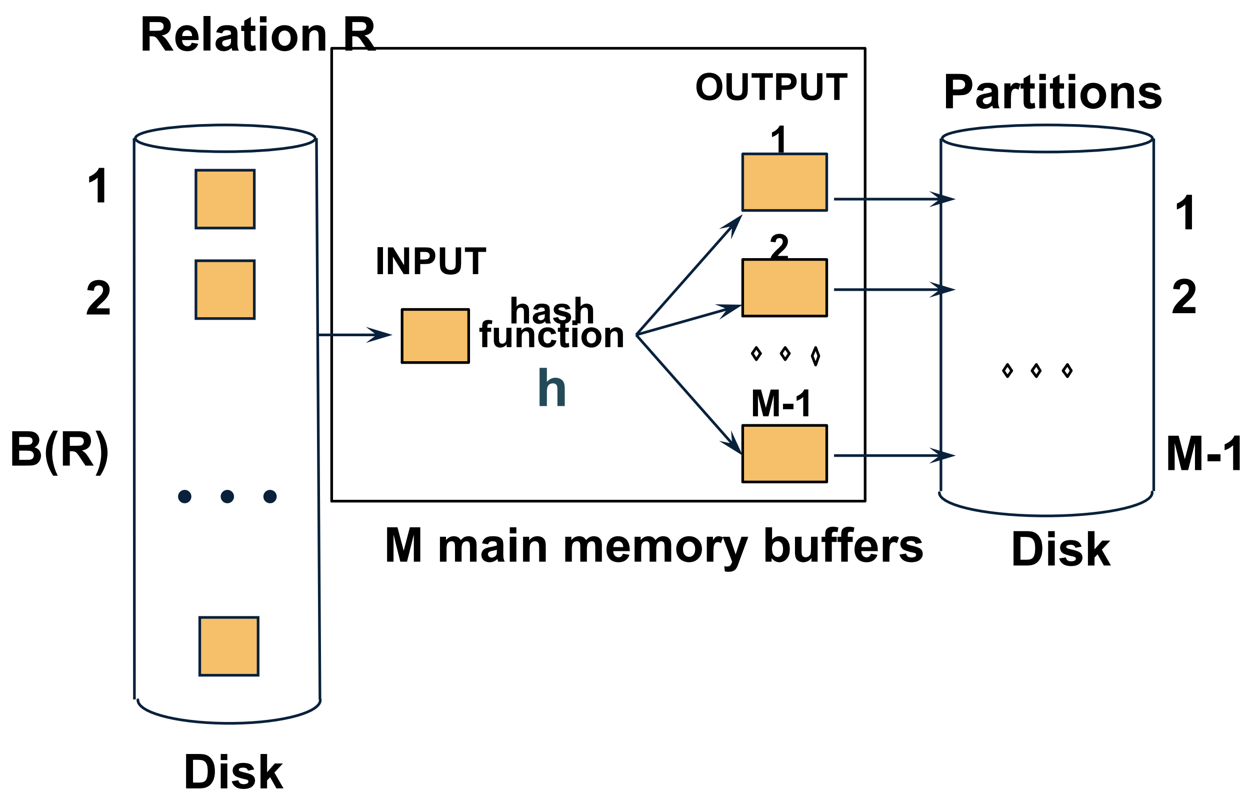

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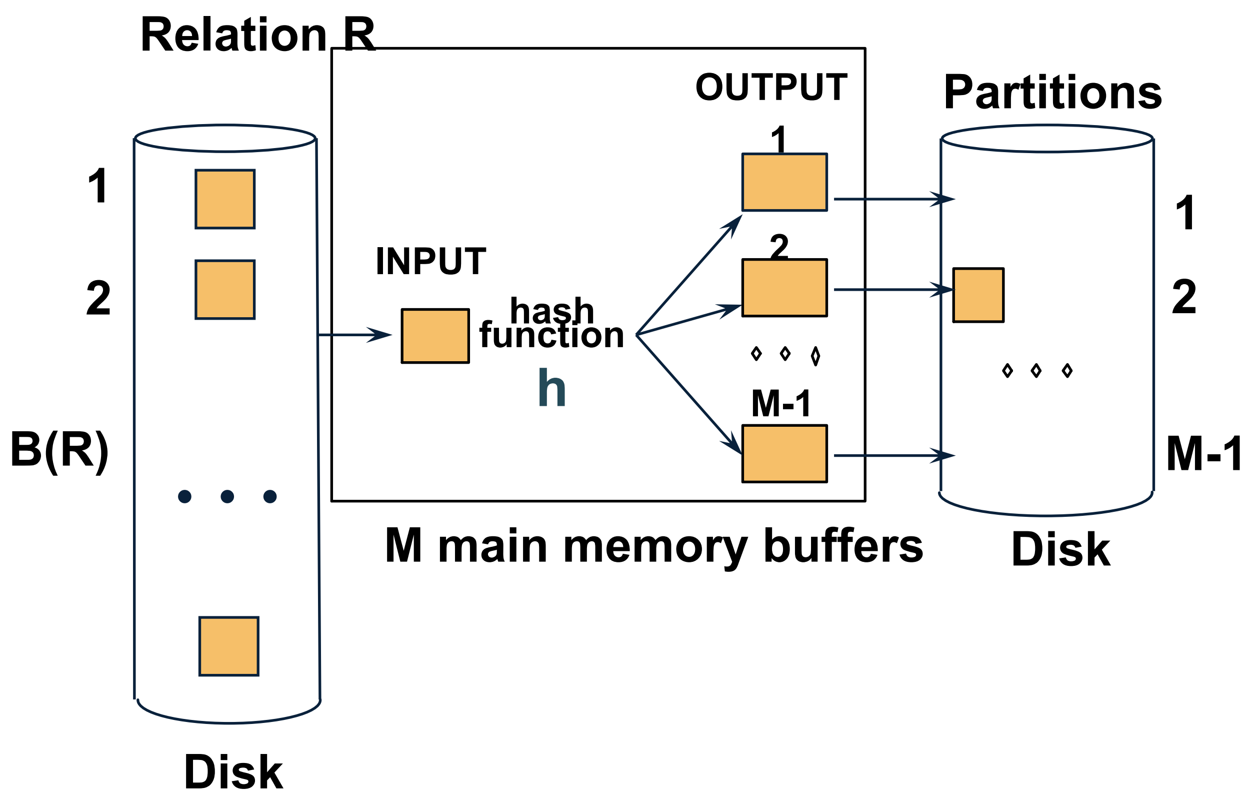

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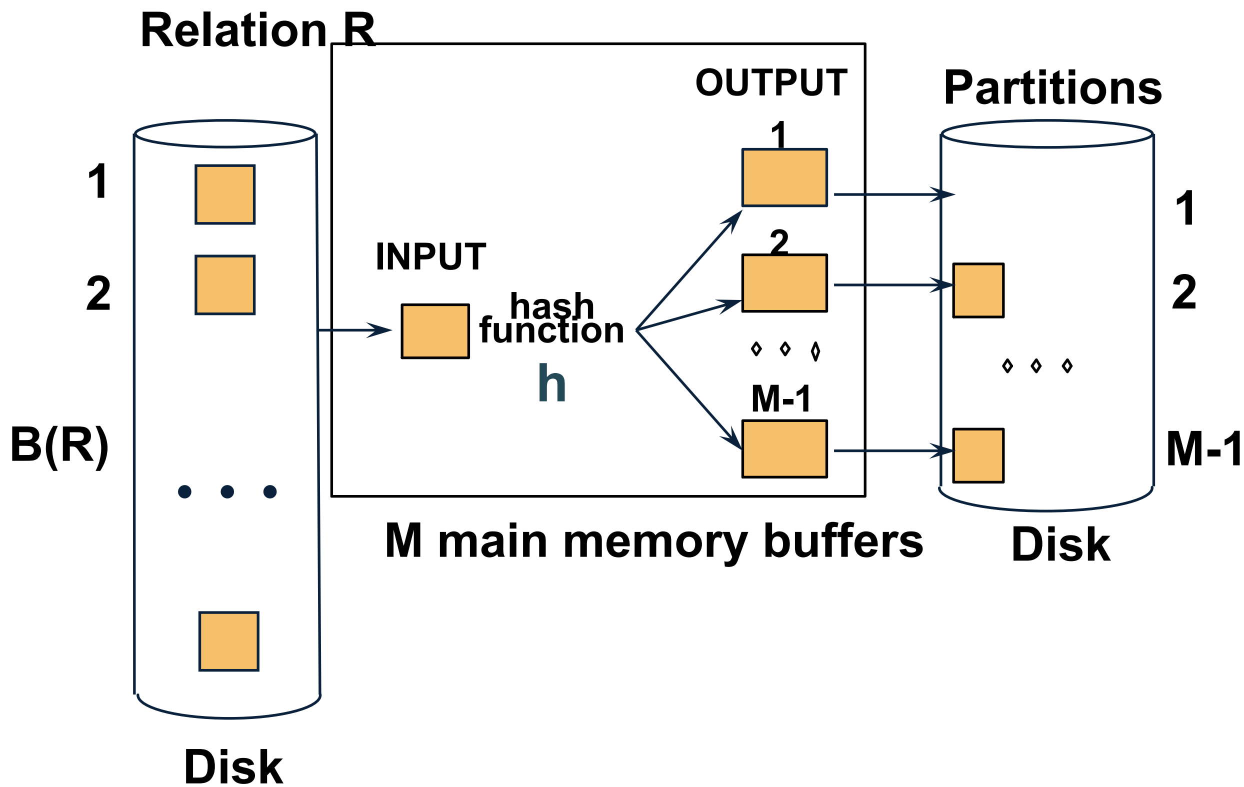

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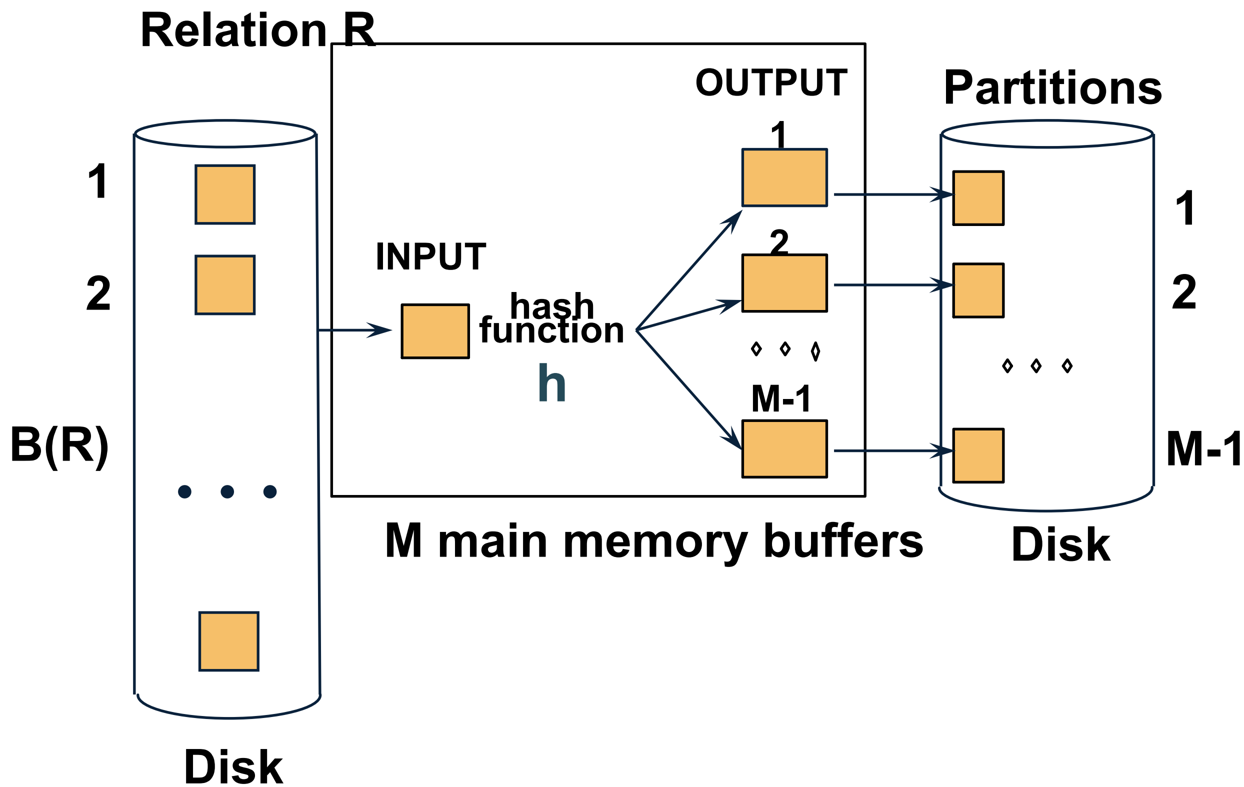

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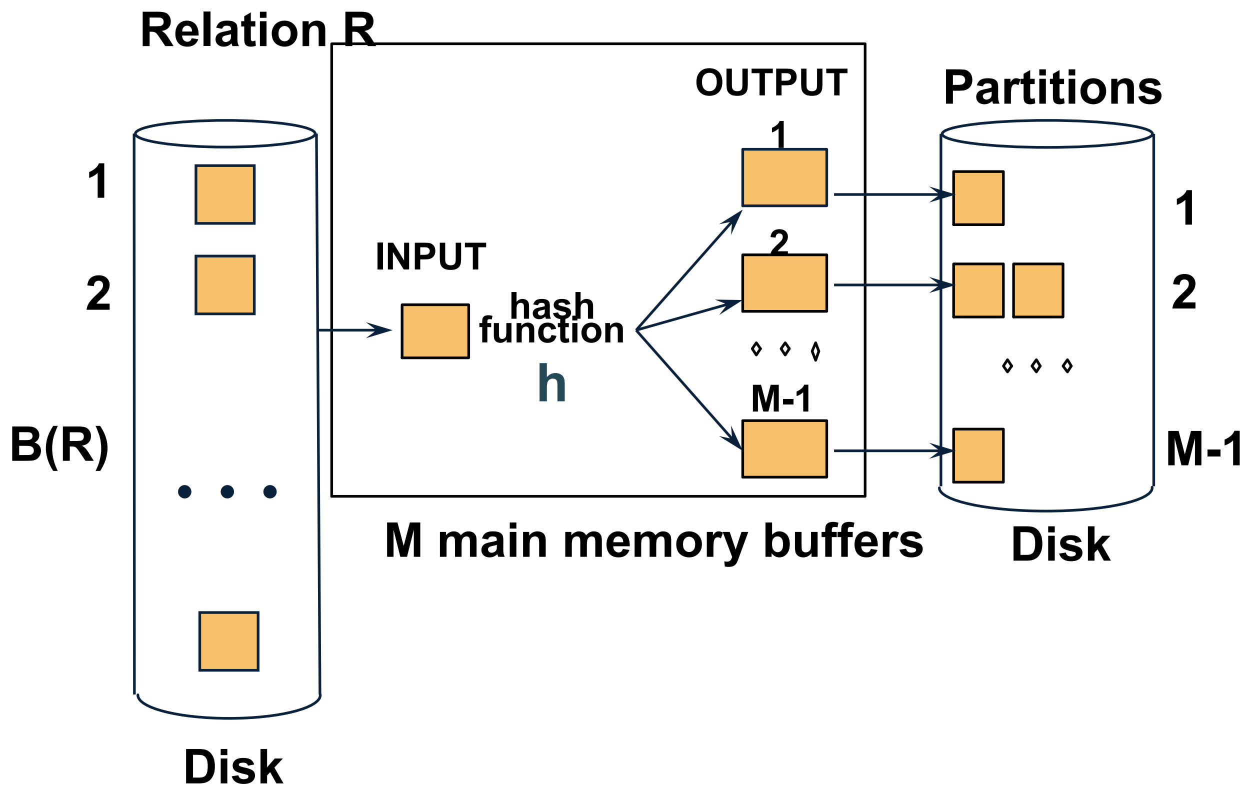

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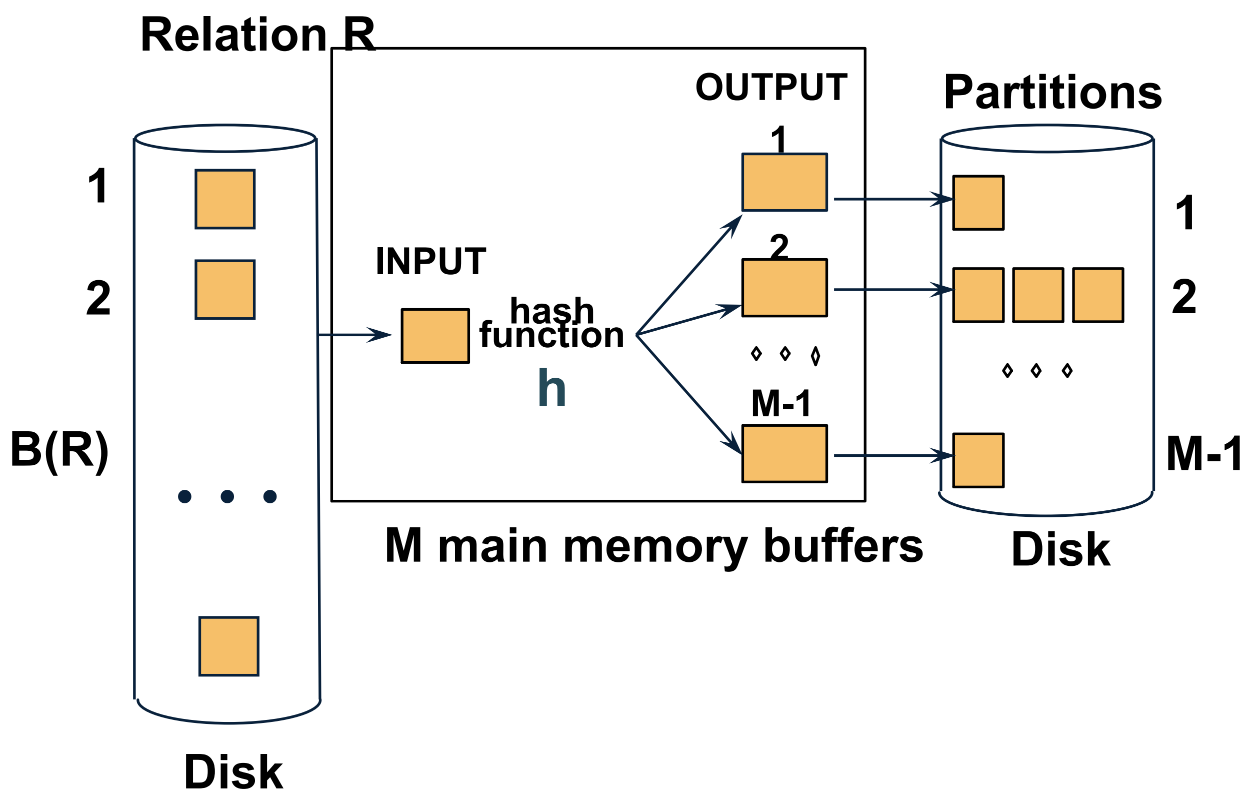

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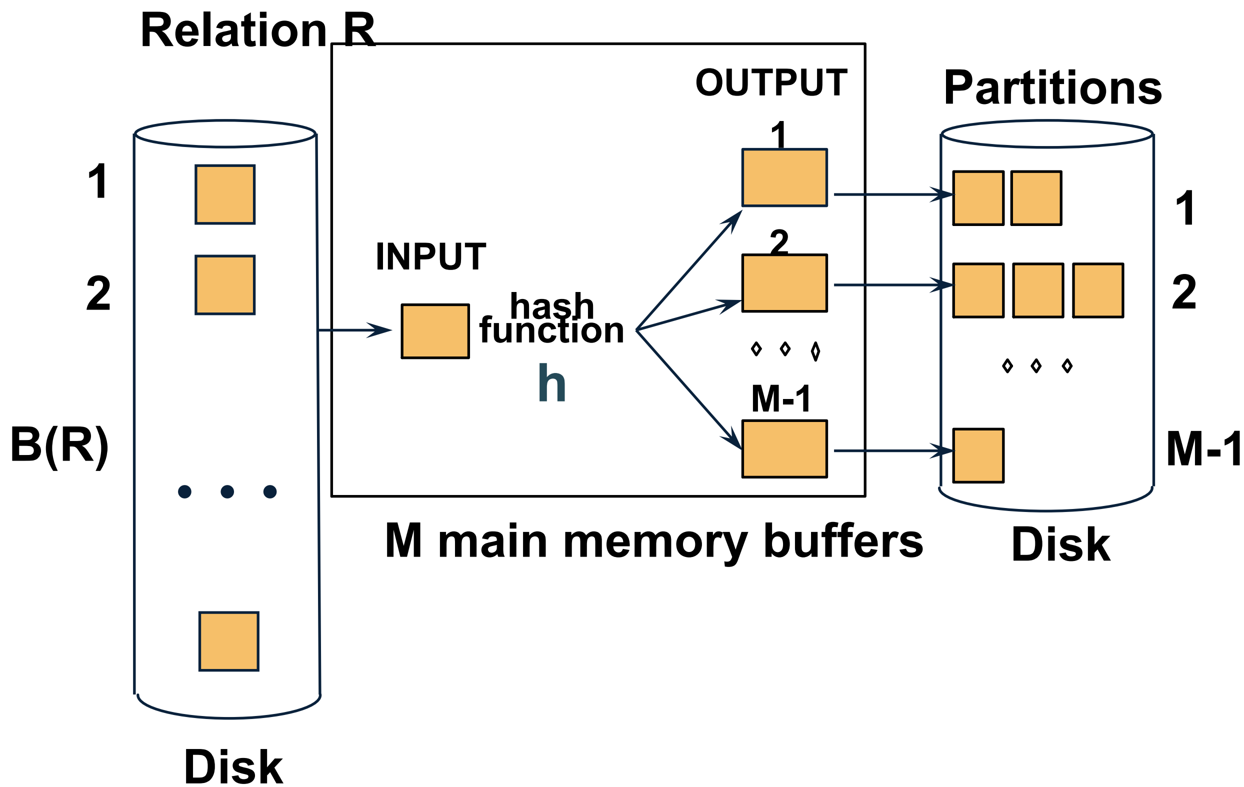

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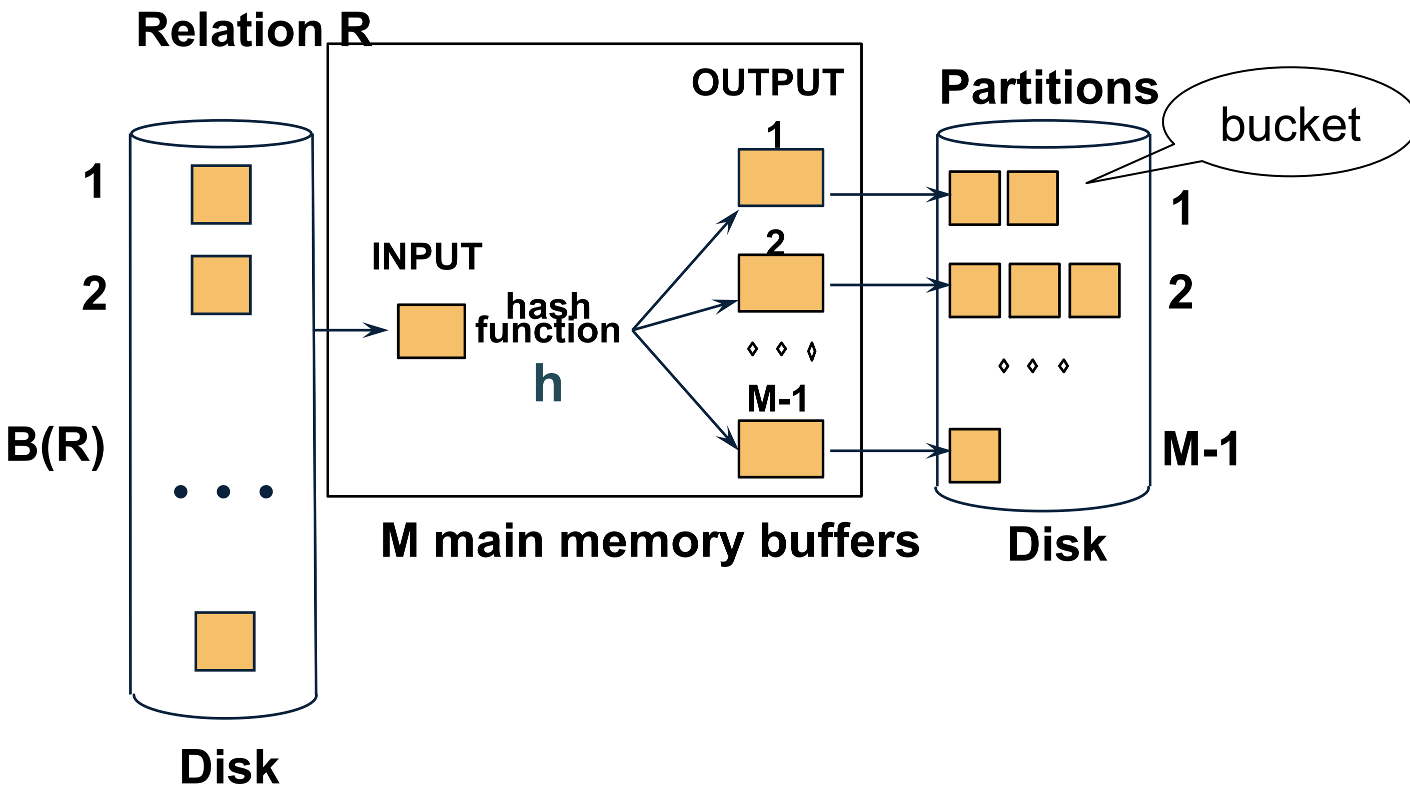
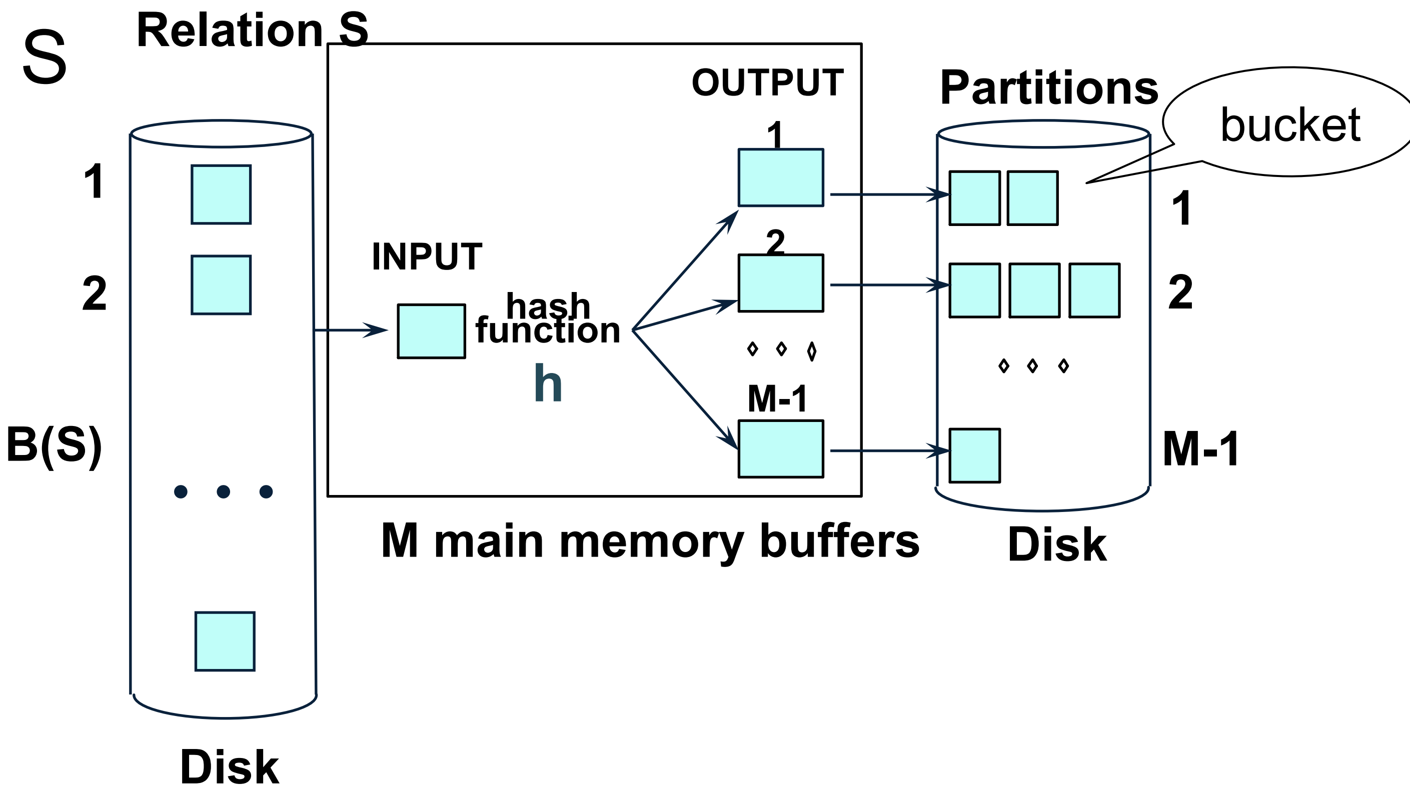


Step 1: Hash-partition

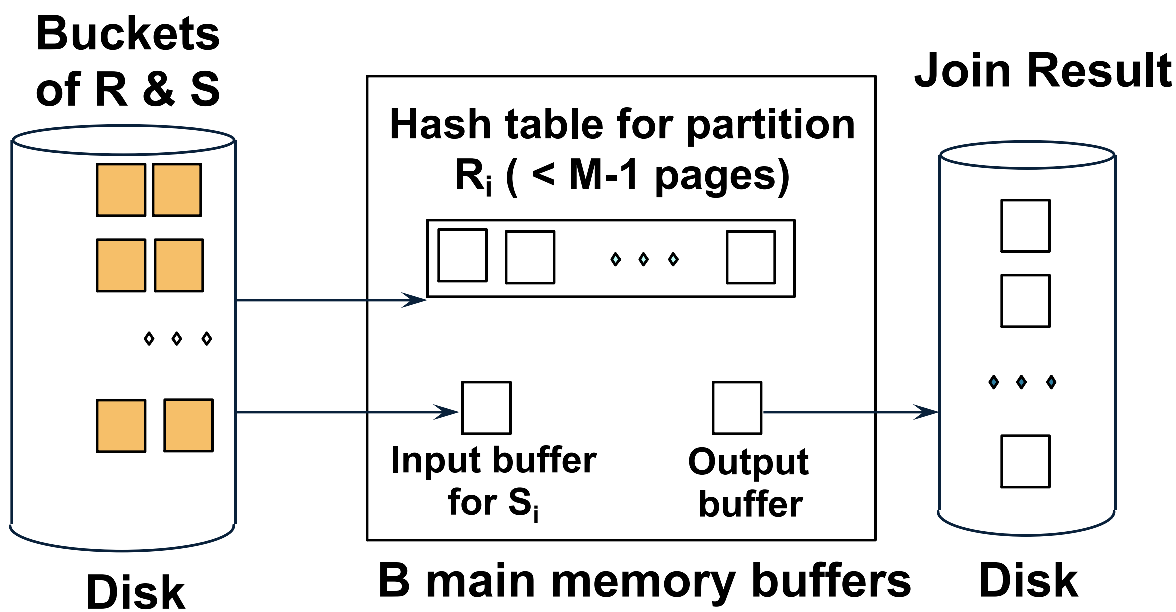
- Partition R into buckets, on disk
- Partition S



Step 2: Join Buckets

R ⋈ S

- Read one R-bucket; hash-partition it using h2 (≠ h)



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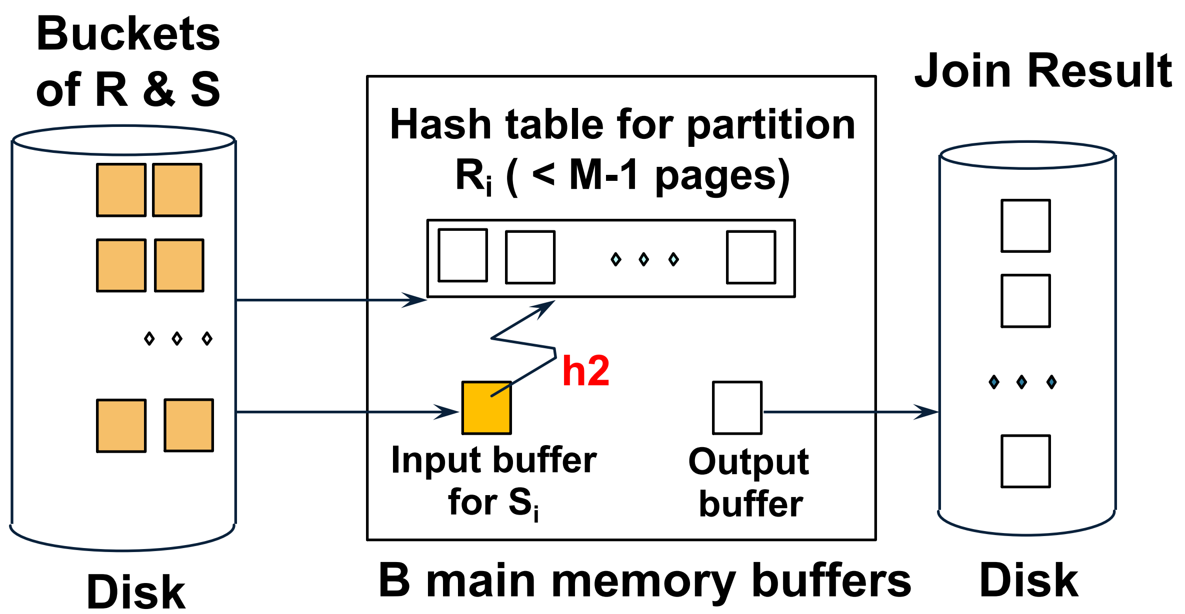

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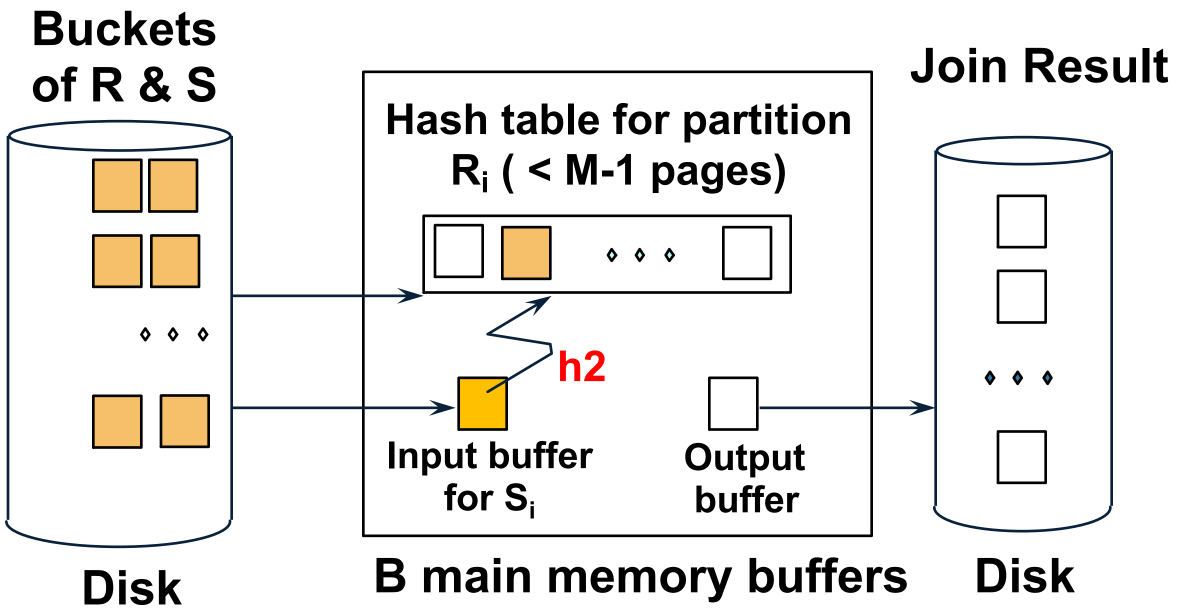

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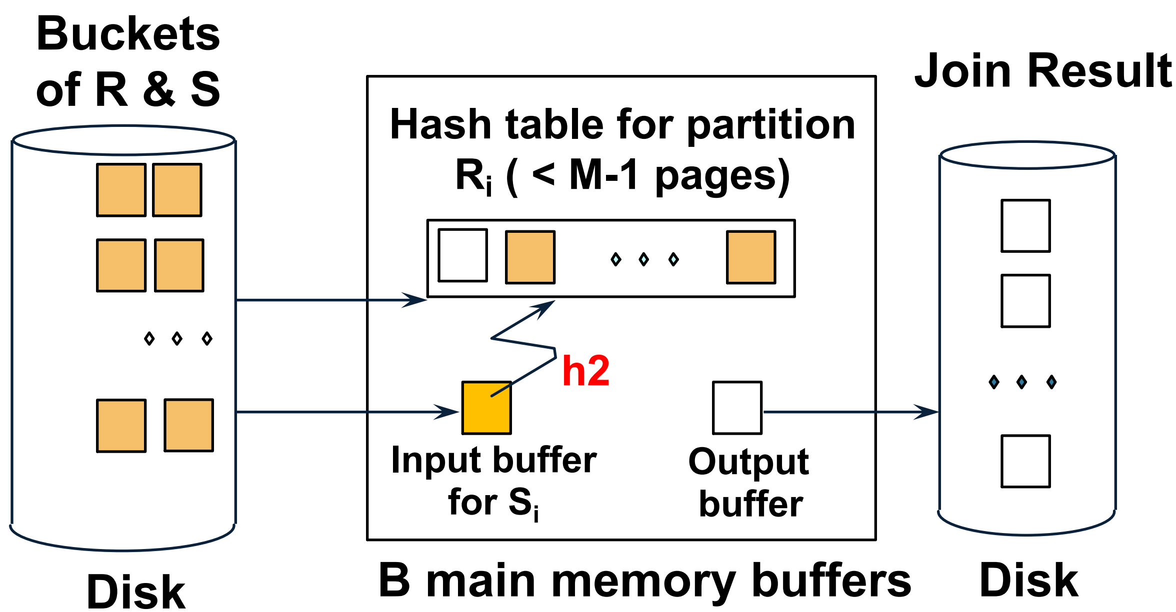
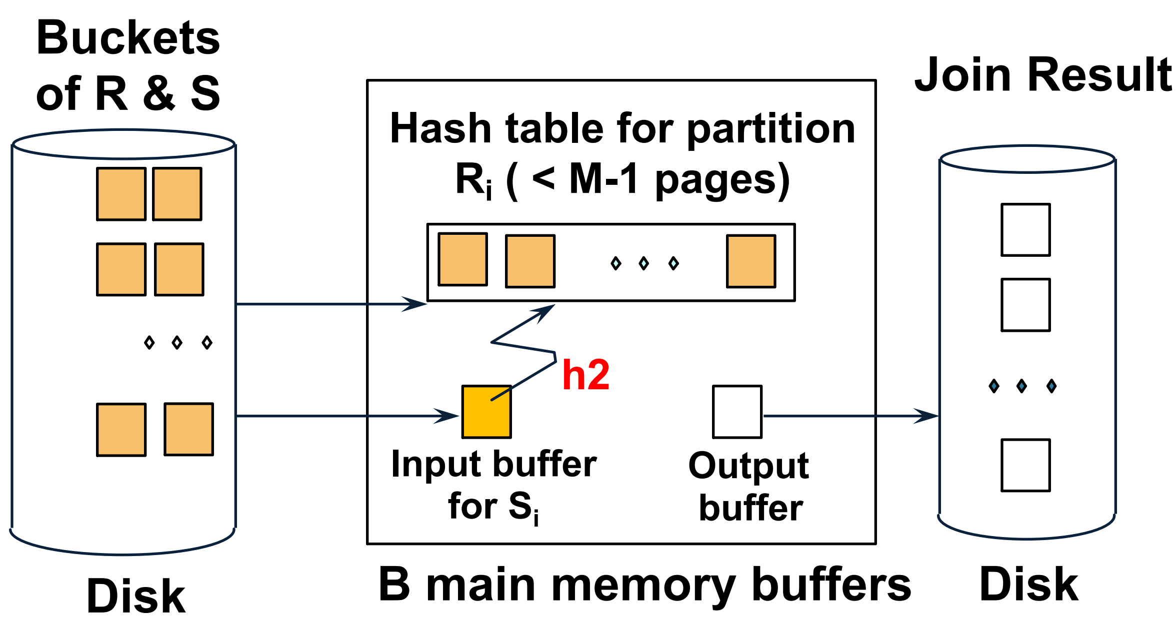


Step 2: Join Buckets

$R \bowtie S$

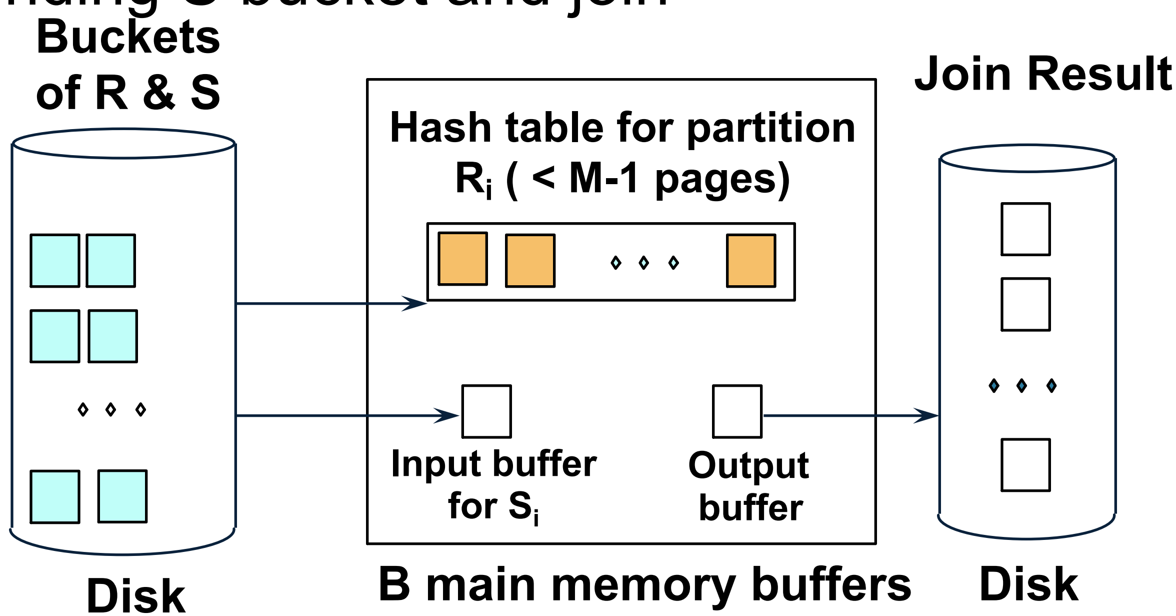
- Read one R-bucket; hash-partition it using h2 ($\neq$ h)



Step 2: Join Buckets

R ⋈ S

- Read one R-bucket; hash-partition it using h2 (≠ h)
- Scan corresponding S bucket and join



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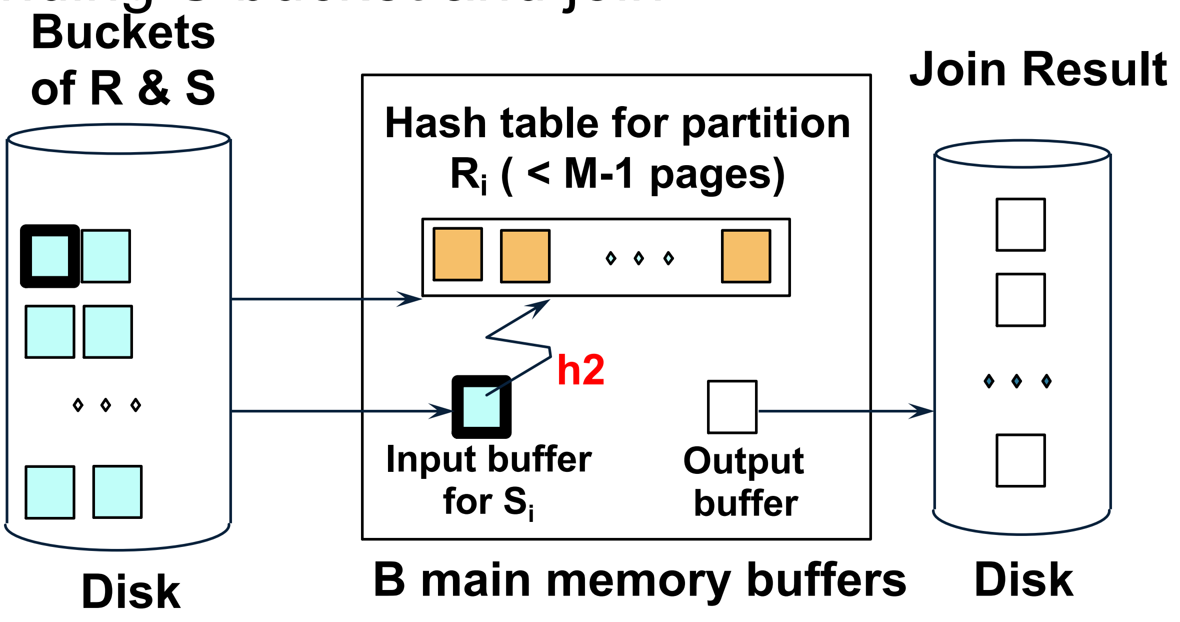

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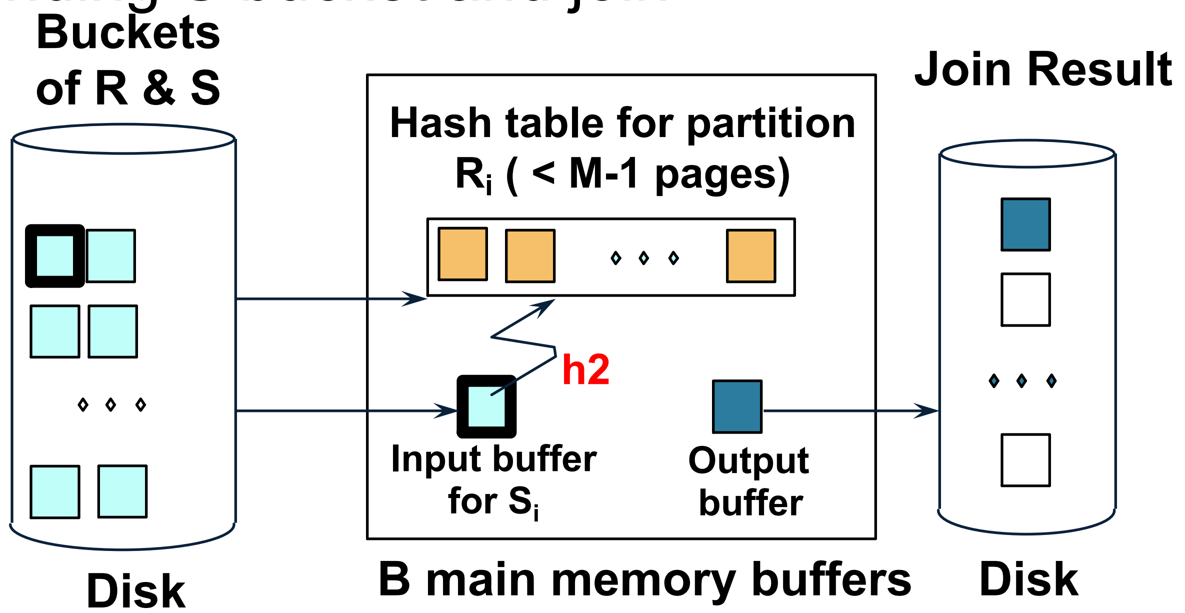
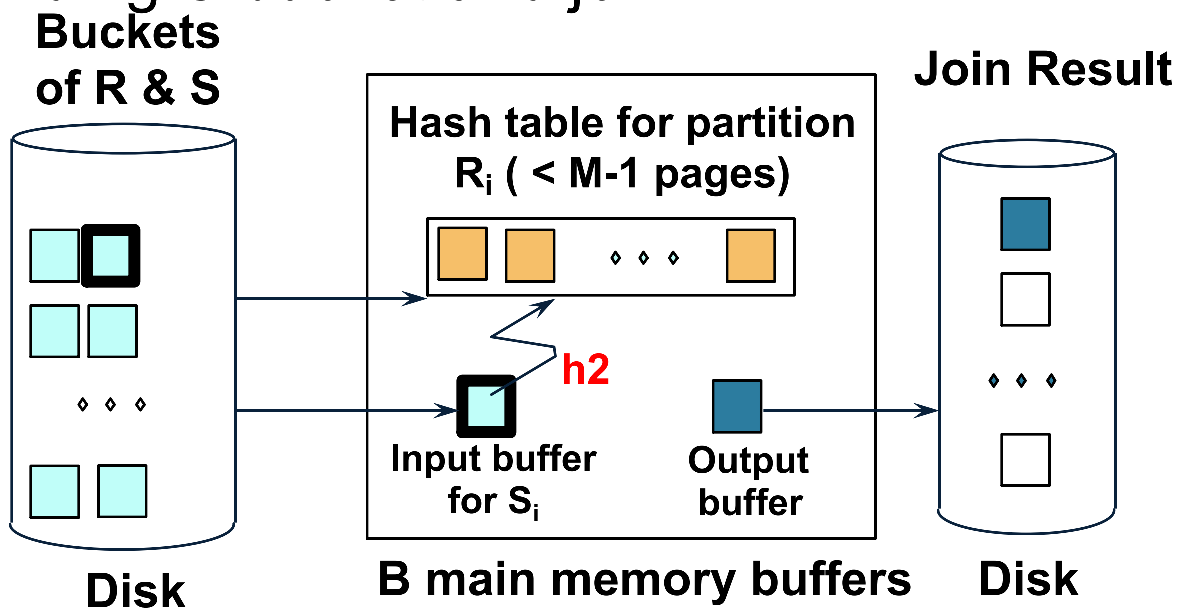
- Read one R-bucket; hash-partition it using h2 (≠ h)
- Scan corresponding S bucket and join



Step 2: Join Buckets

R ⋈ S

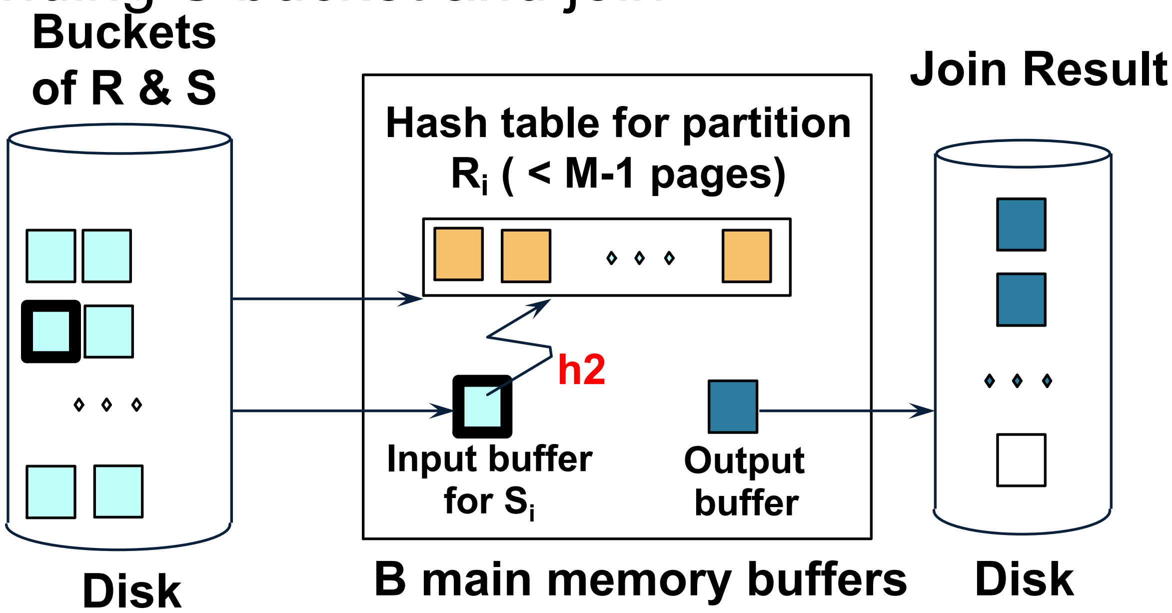
- Read one R-bucket; hash-partition it using h2 (≠ h)
- Scan corresponding S bucket and join



Step 2: Join Buckets

$R \bowtie S$

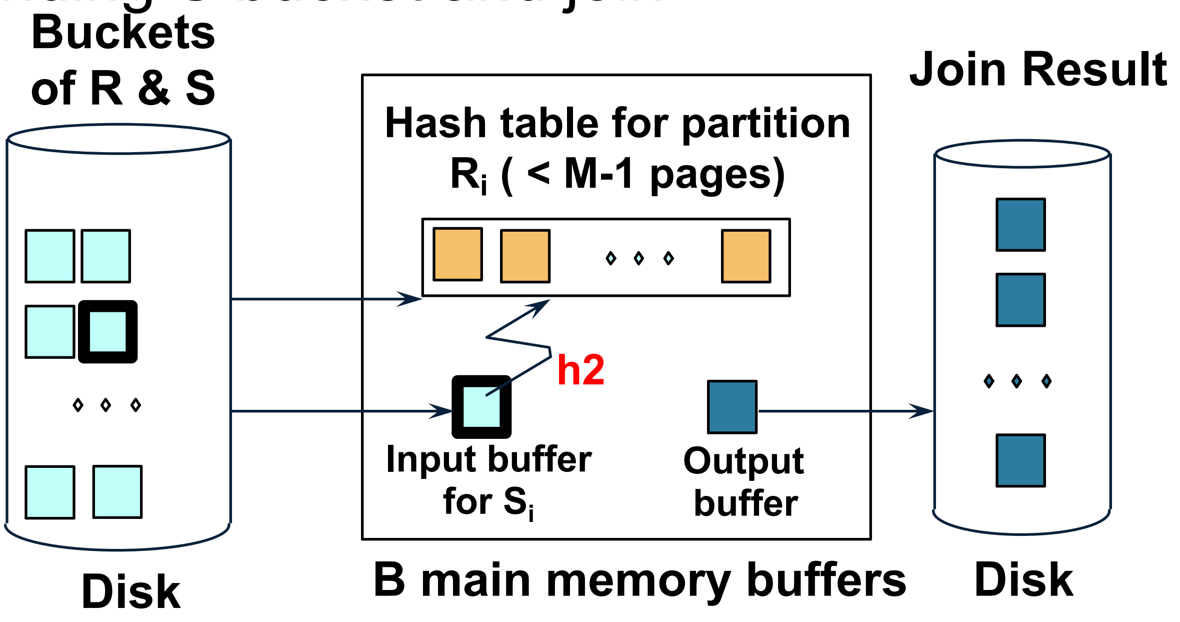
- Read one R-bucket; hash-partition it using h2 ($\neq$ h)
- Scan corresponding S bucket and join



Step 2: Join Buckets

$R \bowtie S$

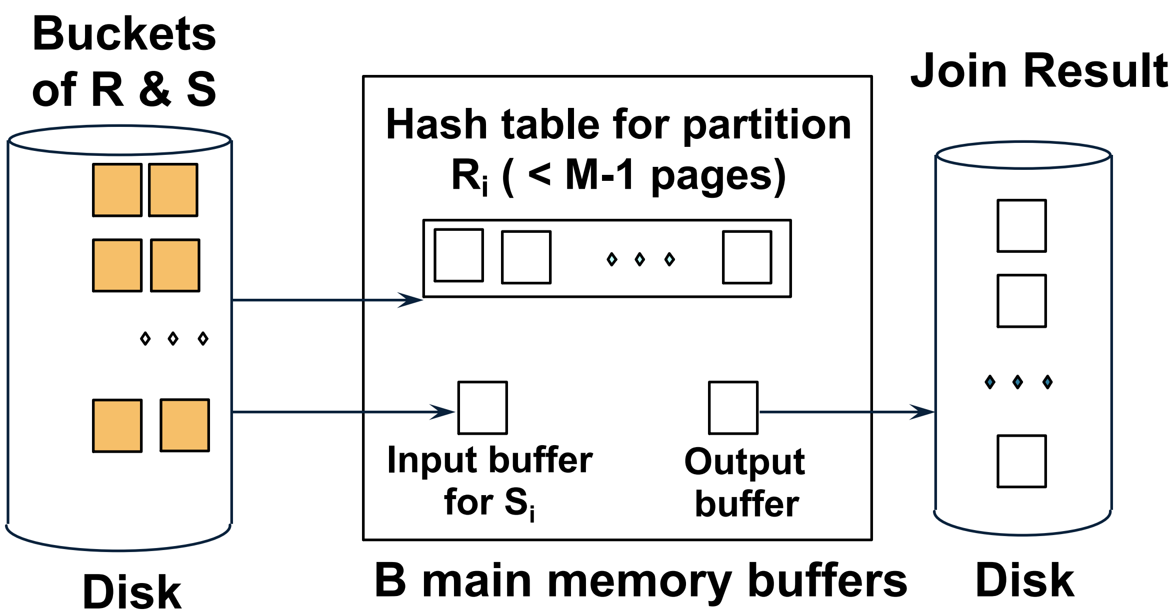
- Read one R-bucket; hash-partition it using h2 ($\neq$ h)
- Scan corresponding S bucket and join



Step 2: Join Buckets

$R \bowtie S$

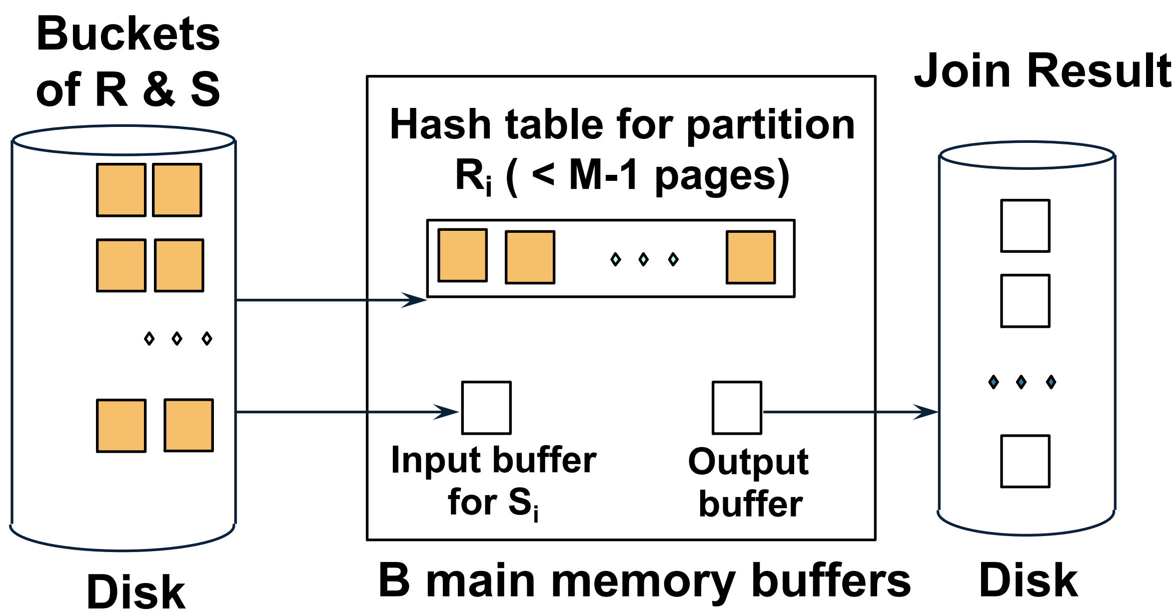
- Read the next R bucket



Step 2: Join Buckets

$R \bowtie S$

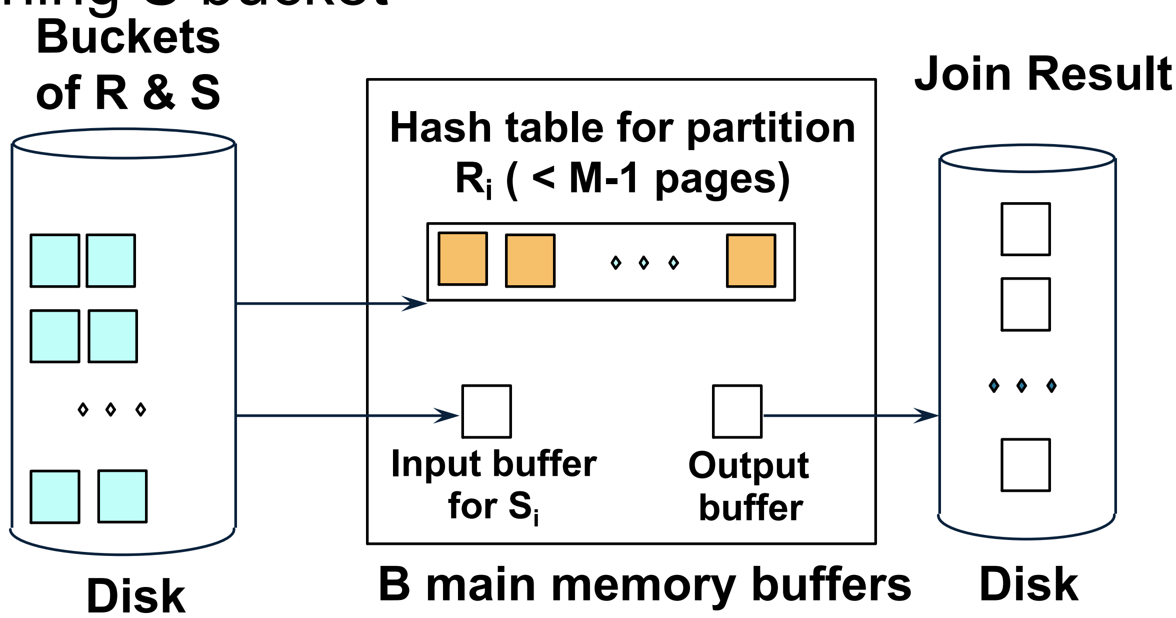
- Read the next R bucket



Step 2: Join Buckets

R ⋈ S

- Read the next R bucket
- Scan the matching S bucket



Partitioned Hash Join

- Cost: 3B(R) + 3B(S)
- Assumption: min(B(R), B(S)) ≤ $(M-1)^2$

Summary

- Basic algorithms:
  - Nested loop
  - Hash-based
  - Sort-based
- If larger than main memory, partition data by using temporary files on disk
- Usually one partitioning step suffices: create runs, or hash-partition