Discussion 6

Joins

Agenda

I. Joins
   A. SNLJ
   B. PNLJ
   C. BNLJ
   D. INLJ
   E. Sort-Merge Join
   F. Grace Hash Join
II. Worksheet

Joins

Joins

- We’ll be looking at inner (equi) joins
  - Algorithms can be pretty easily extended to left/right outer joins
  - Full joins require more thought - not in scope
  - Some algorithms work for non-equi-joins, others don’t
- A join is: taking one relation, and matching each tuple with tuples from another relation
- The **join condition/predicate** determines what rows in the other relation match to a row in the first relation

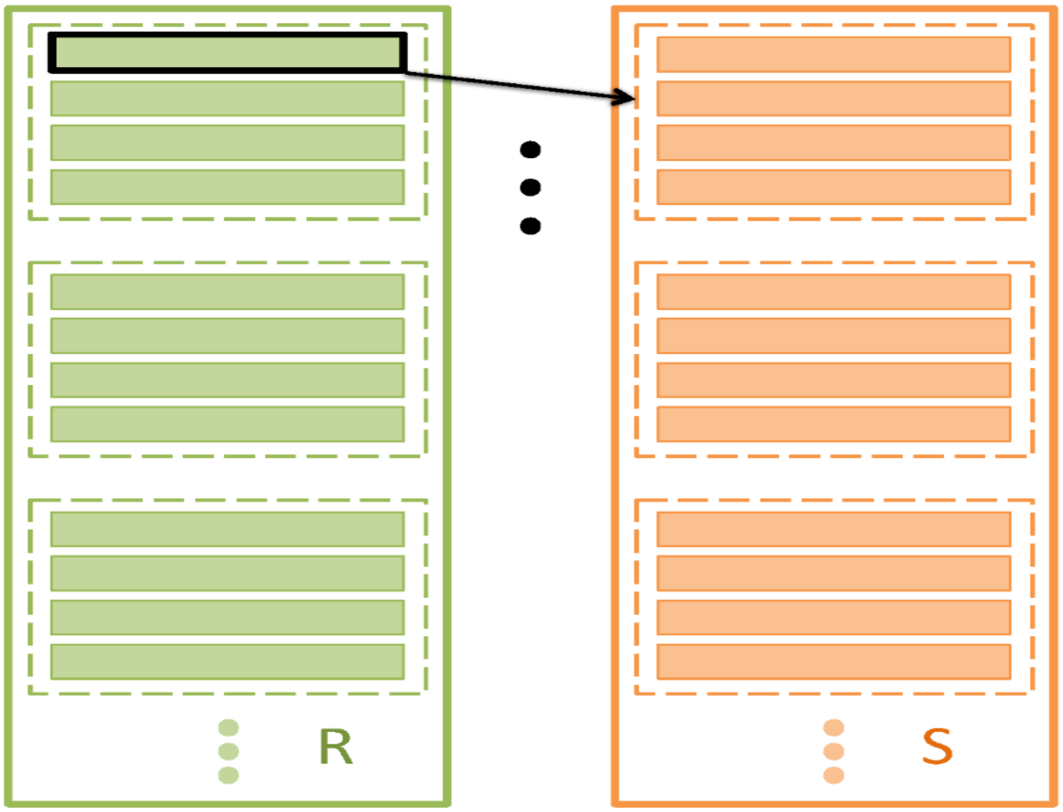
Joins

- Bit of notation:
  - [R] = number of pages in R
  - p_R = number of records per page in R
  - |R| = number of records in R (the **cardinality** of R)
    - $|R| = p_R * [R]$
- We typically *exclude* the final write's I/O cost
  - Don't add the cost of writing the joined output to disk
    - We might decide to stream it to the next operator instead of materializing results!

Simple Nested Loop Join (SNLJ)

- Direct translation of the definition of join into code
- To perform the join R $\bowtie_\theta$ S, just take each row in R, and scan through S to find the matching rows!
  - for each row r in R:
    - for each row s in S:
      - if θ(r, s): output r joined with s

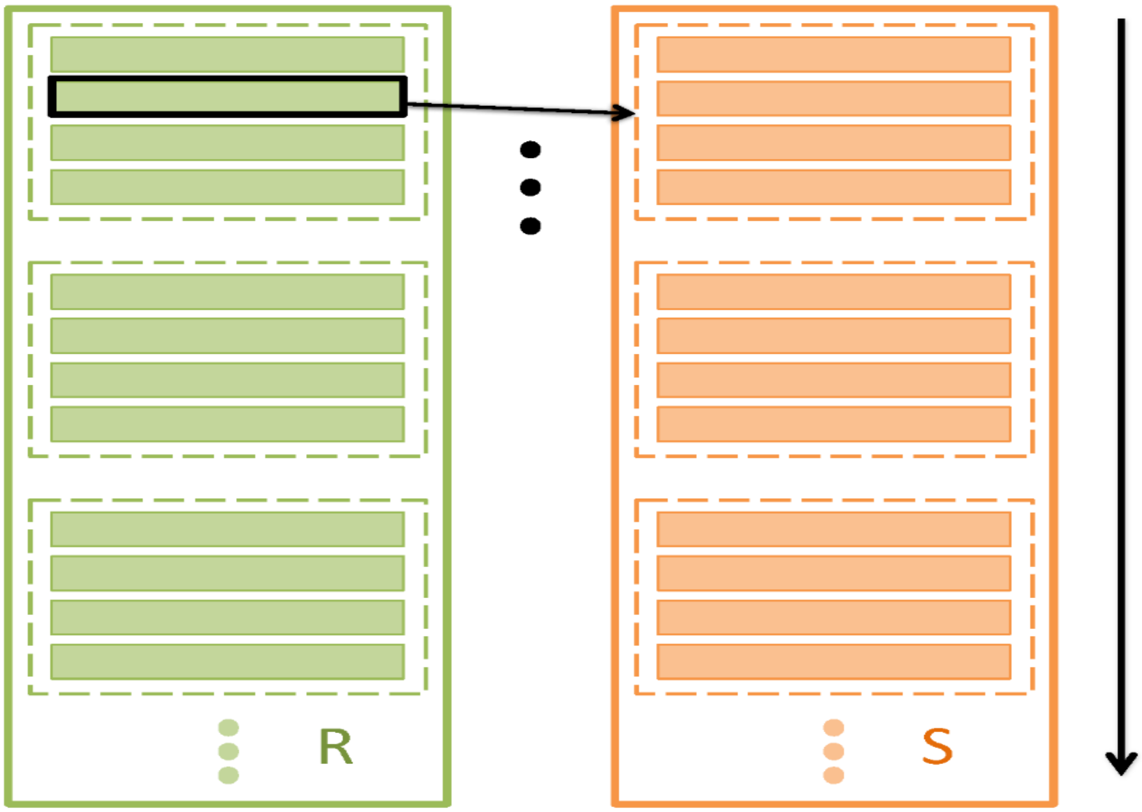
Simple Nested Loop Join



First iteration of outer loop…

Compare with all tuples in S
…and add matches to result

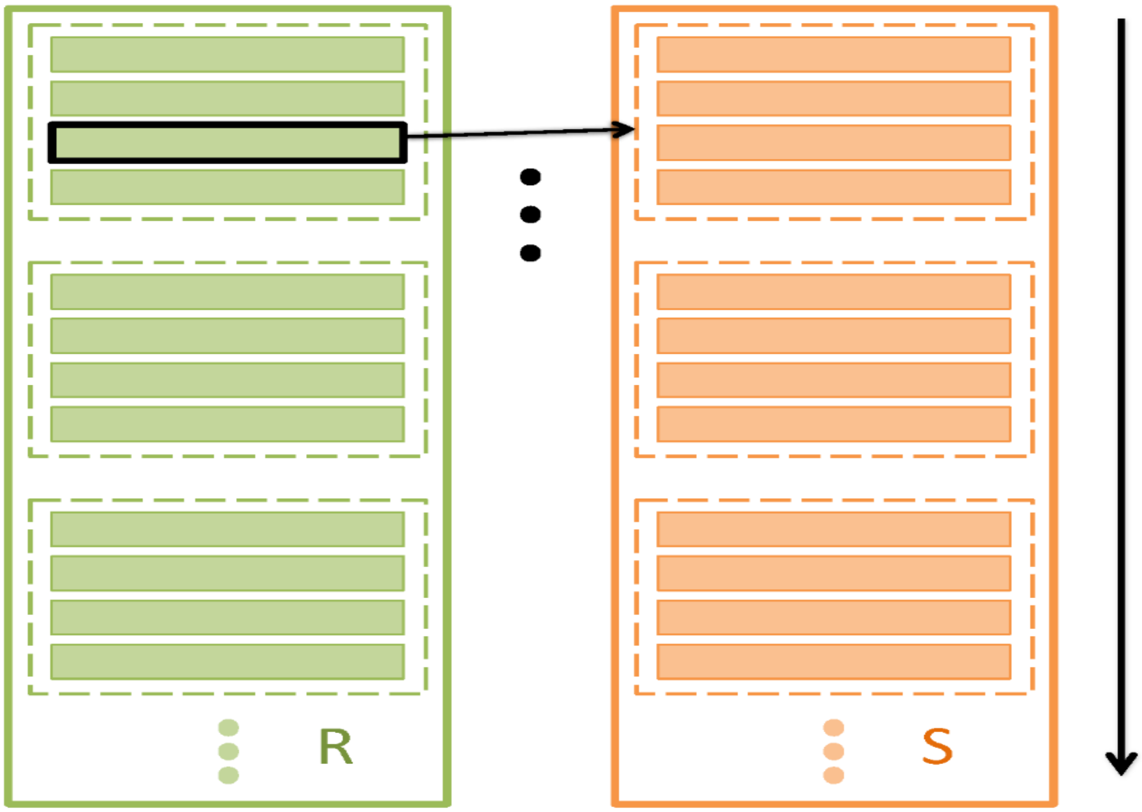
Simple Nested Loop Join



Second iteration of outer loop...

Compare with all tuples in S
...and add matches to result

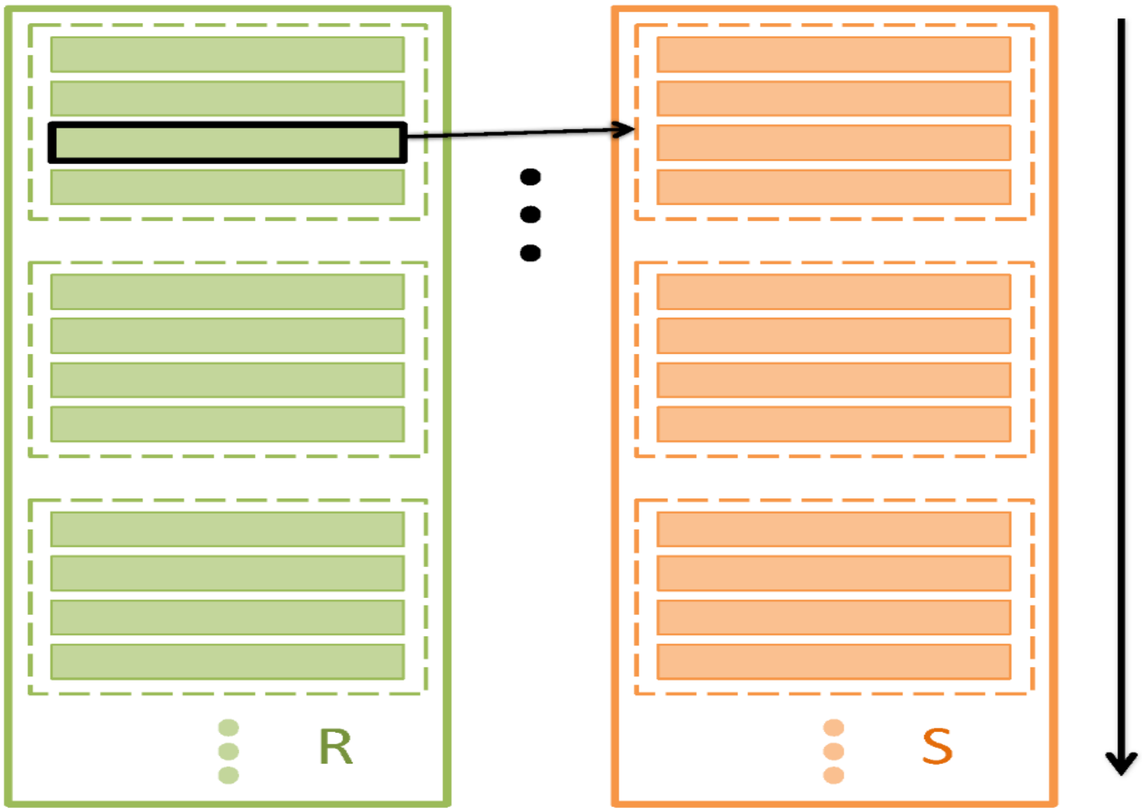
Simple Nested Loop Join



Cost =

$[R] + p_R[R][S]$

Simple Nested Loop Join



Which relation should we pick as R and S respectively?

Cost =

$[R] + p_R[R][S]$

Worksheet Q1a

How many disk I/Os are needed to perform a simple nested loops join?

```
Companies: (company_id, industry, ipo_date)
Nyse: (company_id, date, trade, quantity)
```

- 20 pages of memory
- Join Companies and NYSE on C.company_id = N.company_id
- company_id is the primary key for Companies
- For every tuple in Companies, assume there are 4 matching tuples in NYSE
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Unclustered B+ indexes on C.company_id and N.company_id
- For both indexes, assume it takes 2 I/Os to access a leaf

Worksheet Q1a

How many disk I/Os are needed to perform a simple nested loops join?

C ⋈ N

Cost is [C] + |C| * [N] = [C] + p_C [C] [N]

= 50 + 50 * 50 * 100 = 250,050 I/Os

N ⋈ C

Cost is [N] + |N| * [C] = [N] + p_N [N] [C]

= 100 + 100 * 100 * 50 = 500,100 I/Os

```
Companies: (company_id, industry, ipo_date)
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```

- 20 pages of memory
- We want to join Companies and NYSE on C.company_id = N.company_id
- company_id is the primary key for Companies
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- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Unclustered B+ indexes with height 1 on C.company_id and N.company_id

I/O cost for SNLJ: min(500,100, 250,050) = **250,050 I/Os**

Page Nested Loop Join (PNLJ)

- Can we do better?
  - We scan S for every row in R, but we had to load an entire page of R into memory to get that row!
  - Instead of finding the rows in S that match a row in R, do the check for *all* rows in a page in R at once

Page Nested Loop Join (PNLJ)

- SNLJ
    - for each row r in R:
        - for each row s in S:
            - if θ(r, s): output r joined with s

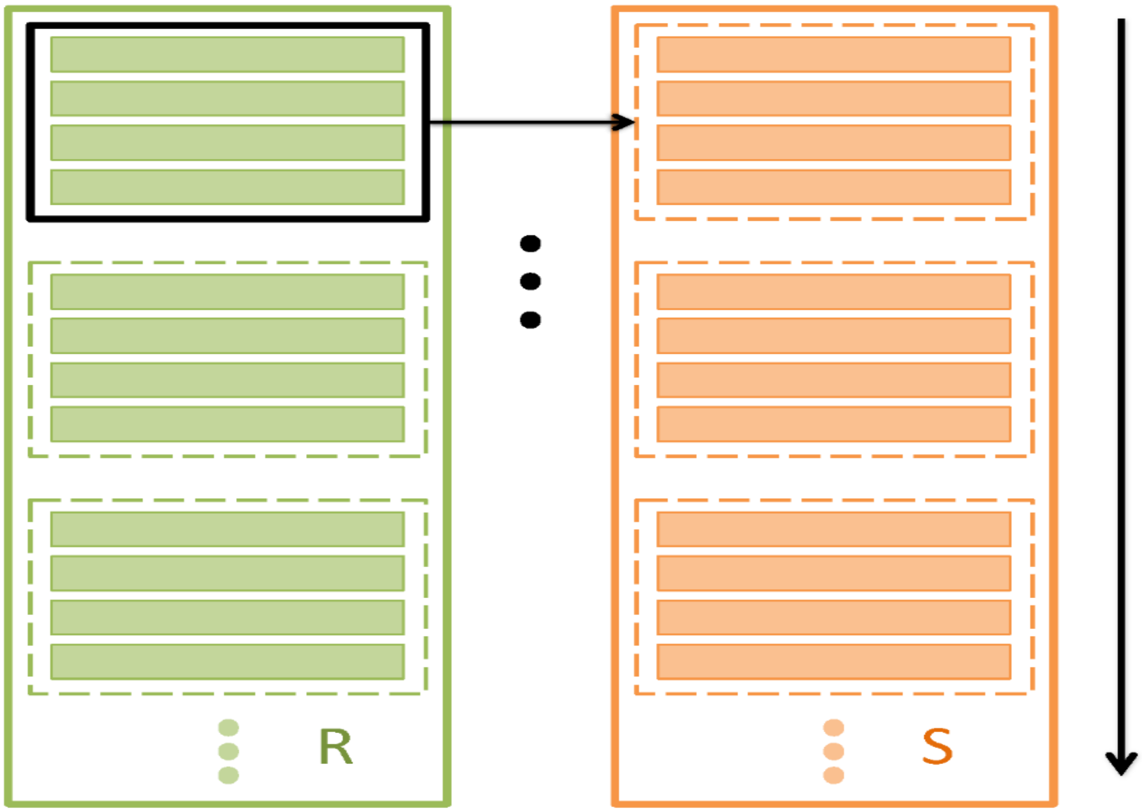
Page Nested Loop Join (PNLJ)

- SNLJ (but with page fetches written out explicitly)
  - for each page P_R in R:
    - for each row r in P_R:
      - for each page P_S in S:
        - for each row s in P_S:
          - if θ(r, s): output r joined with s

Page Nested Loop Join (PNLJ)

- **PNLJ**
  - for each page P_R in R:
    - **for each page P_S in S:**
      - **for each row r in P_R:**
        - for each row s in P_S:
          - if θ(r, s): output r joined with s

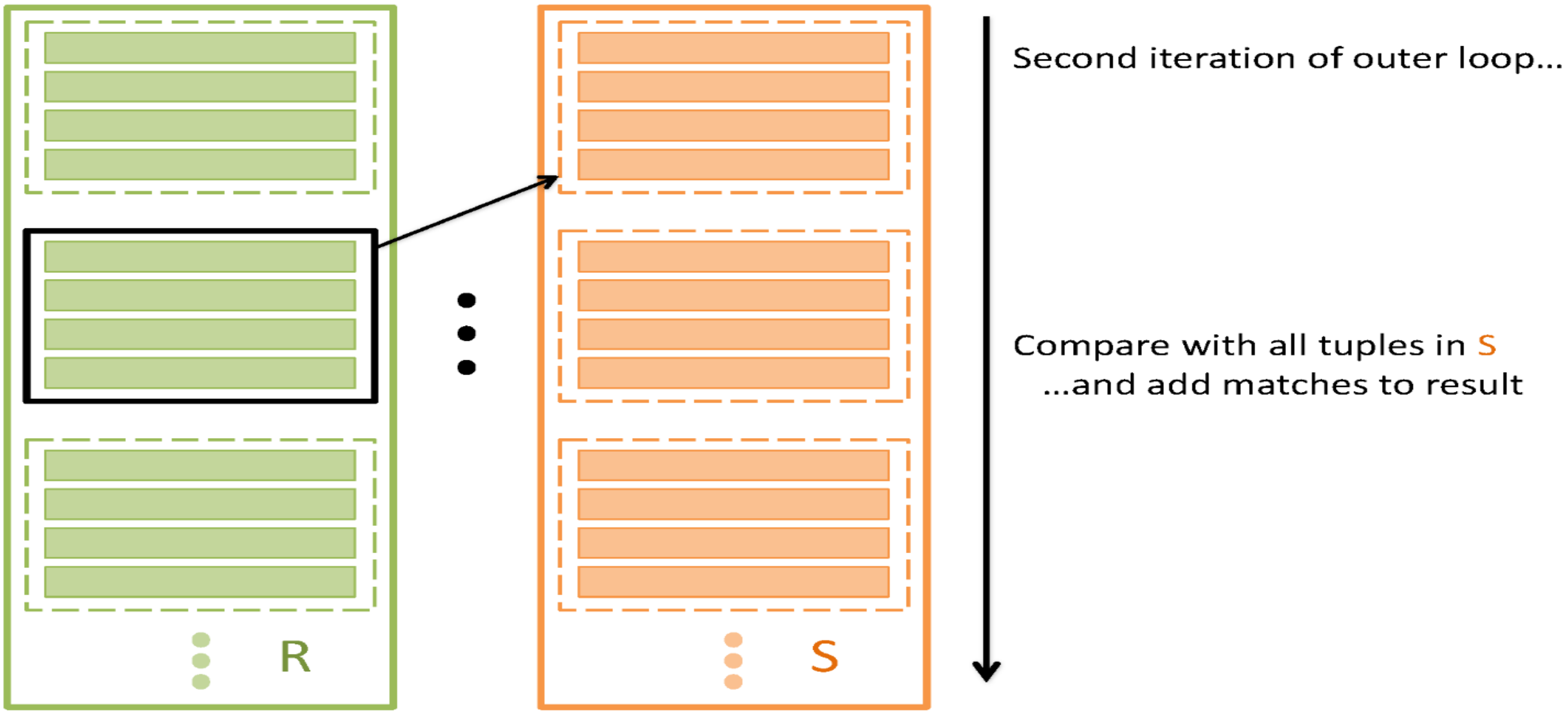
Page-Oriented Nested Loop Join



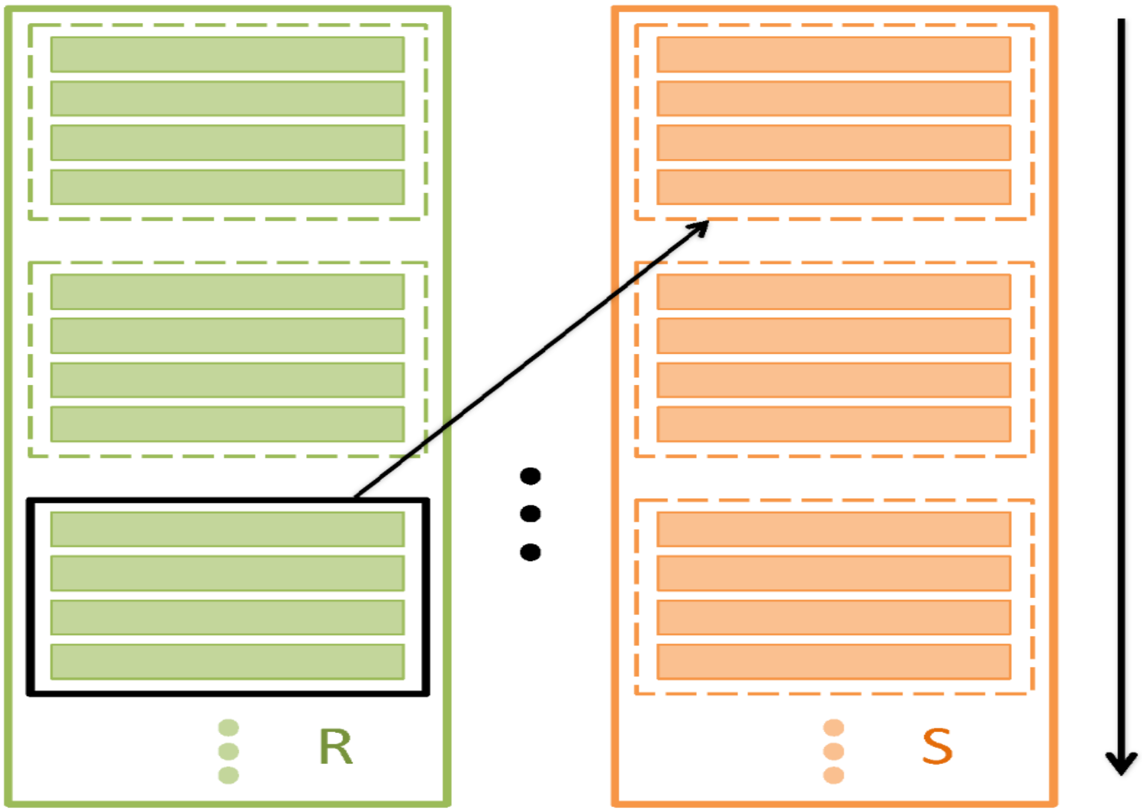
First iteration of outer loop…

Compare with all tuples in S
…and add matches to result

Page-Oriented Nested Loop Join



Page-Oriented Nested Loop Join



Cost =

[R] + [R][S]

Block Nested Loop Join (BNLJ)

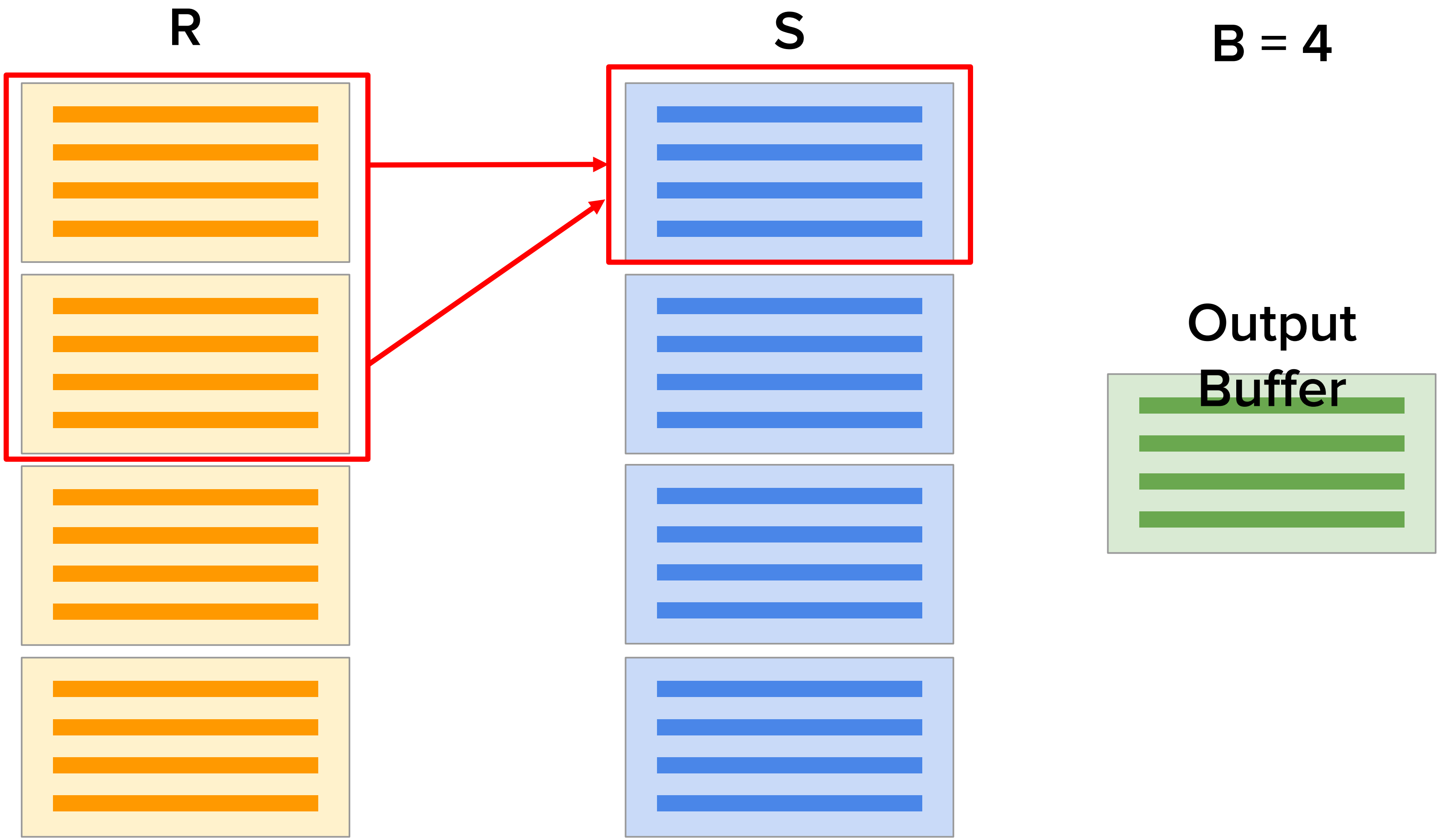
- Can we do even better?
  - We only use three page of memory for PNLJ (one buffer for R, one buffer for S, one output buffer), but we usually have more memory!
  - Instead of fetching one *page* of R at a time, why not fetch as many pages of R as we can fit (B - 2 pages)!

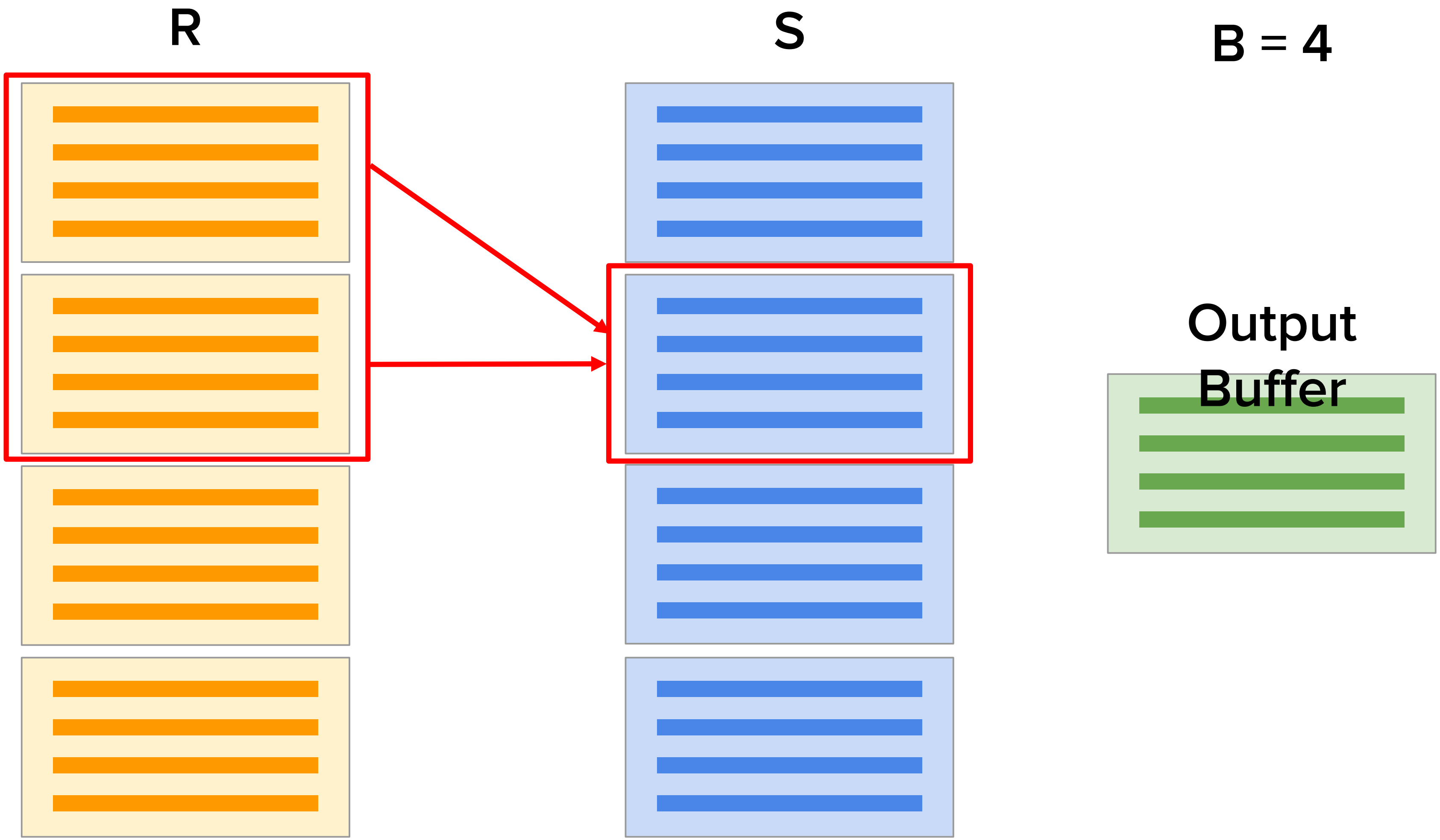
Block Nested Loop Join (BNLJ)

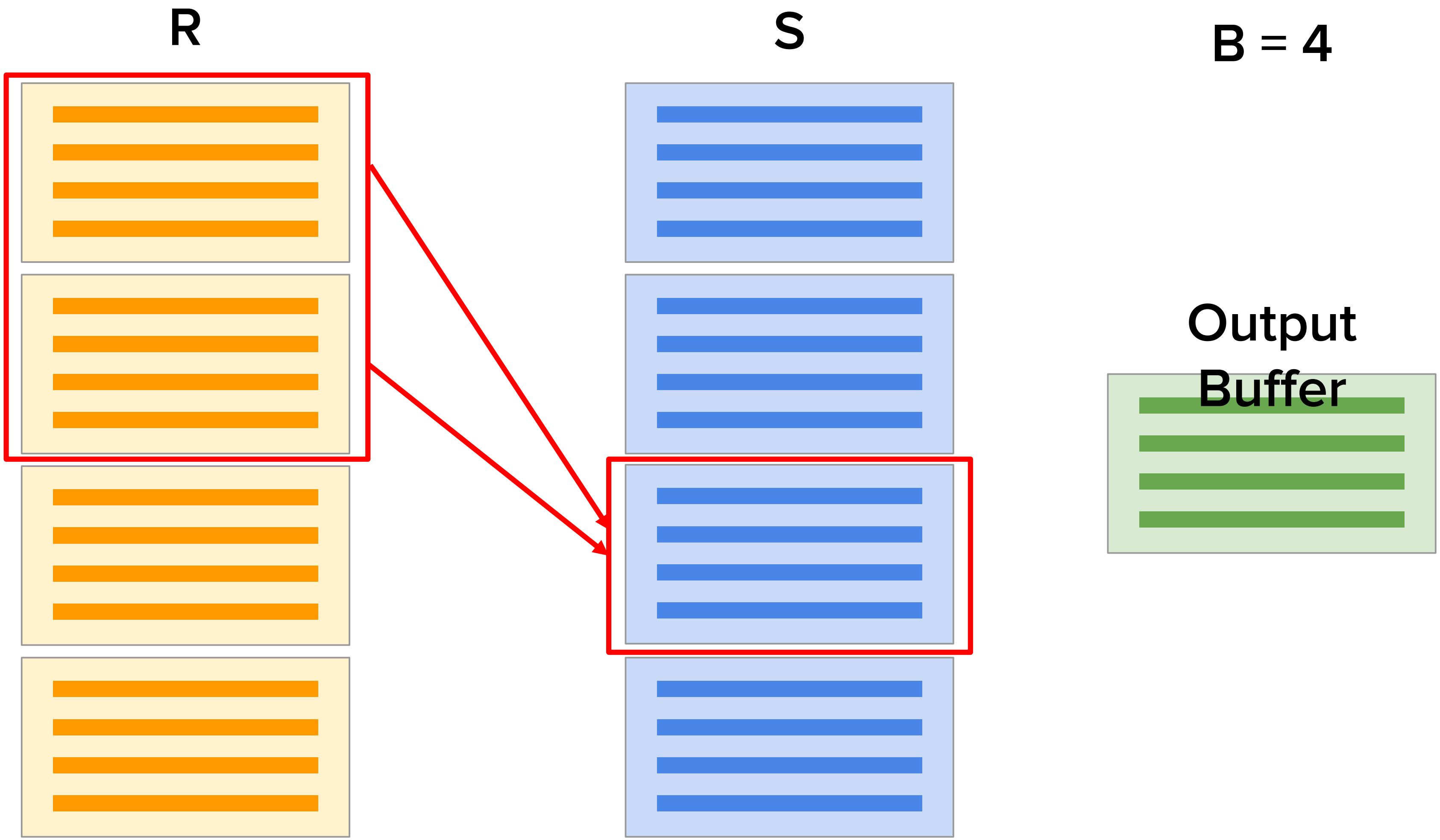
- PNLJ
  - for each page P_R in R:
    - for each page P_S in S:
      - for each row r in P_R:
        - for each row s in P_S:
          - if θ(r, s): output r joined with s

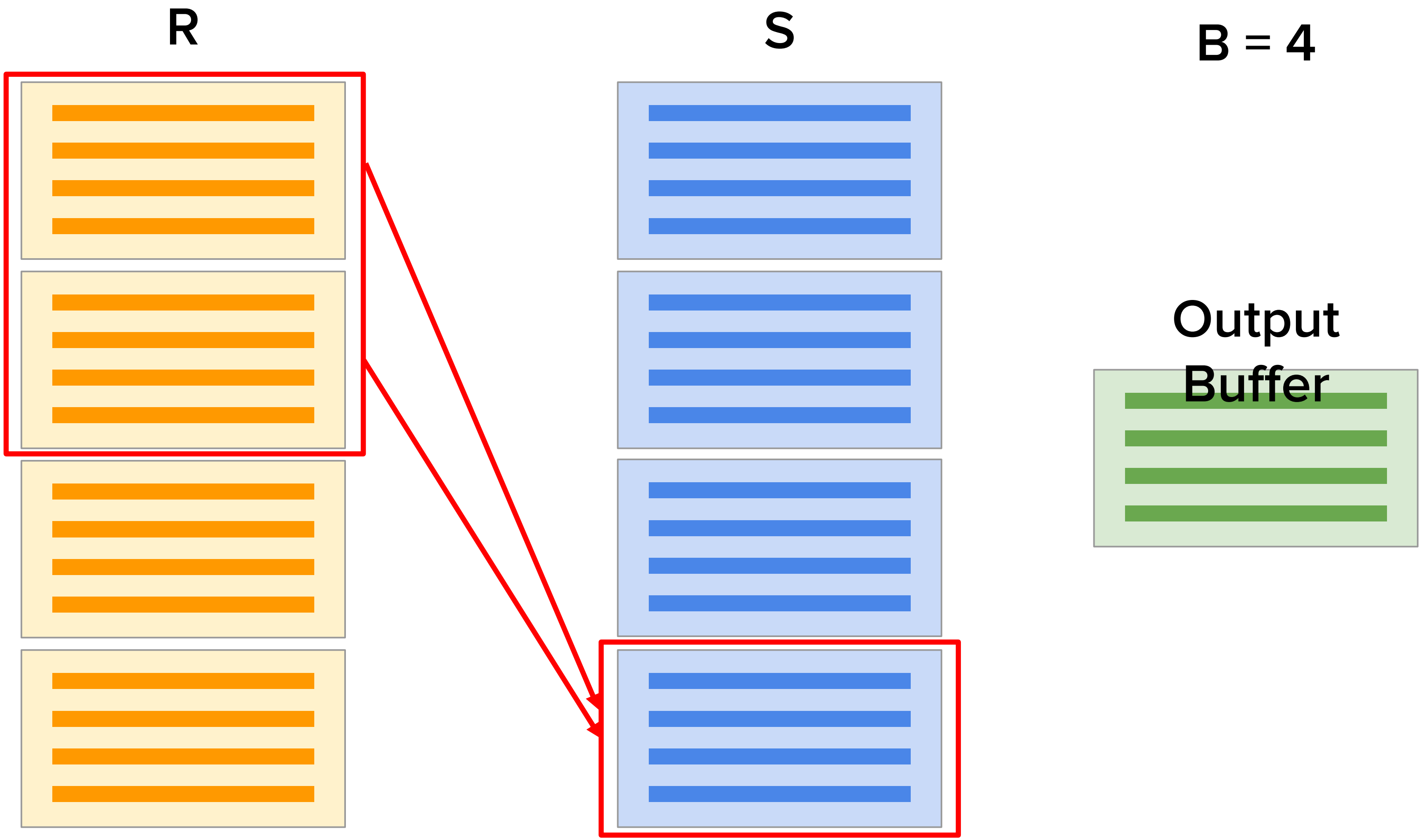
Block Nested Loop Join (BNLJ)

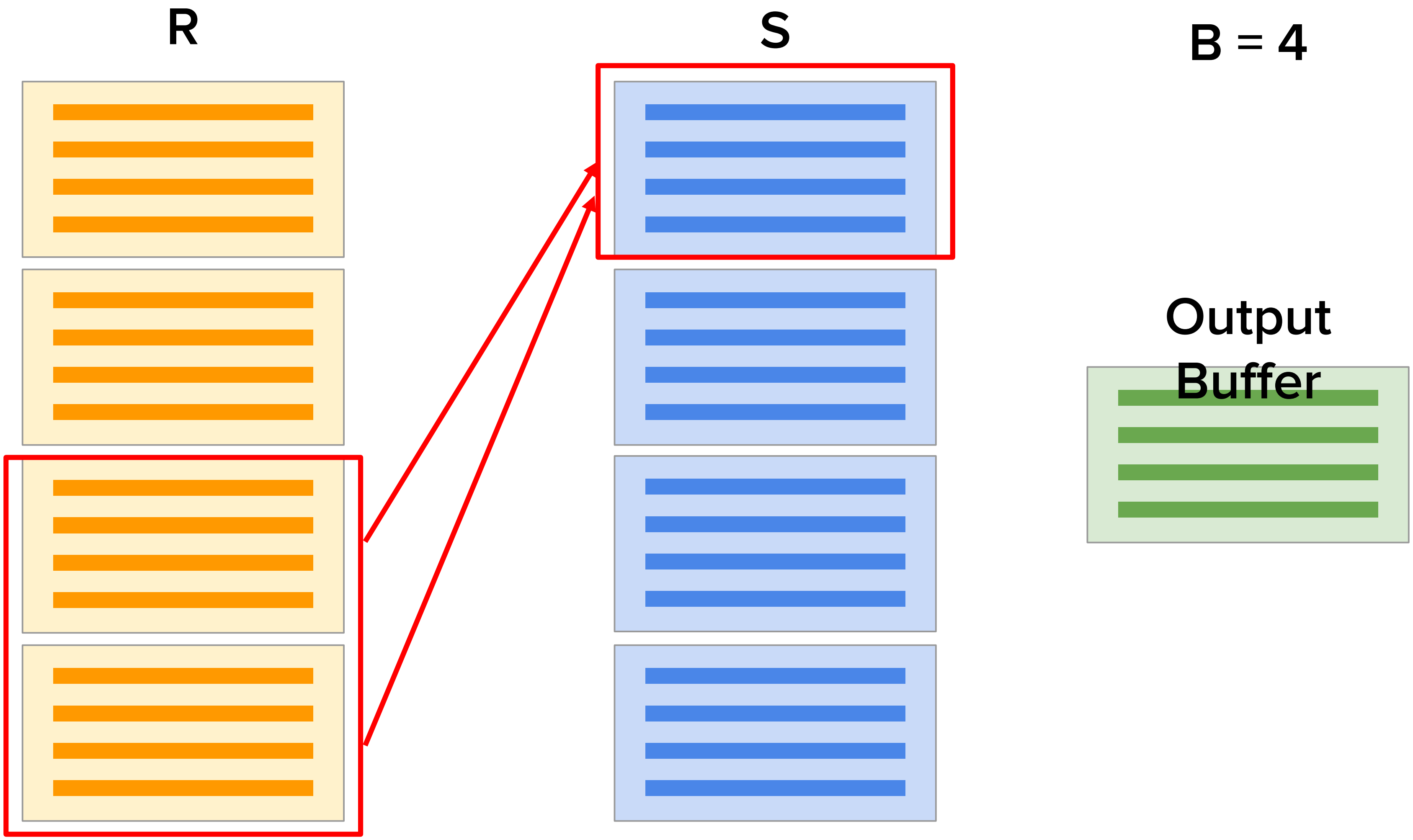
- **BNLJ**
  - **for each block of B - 2 pages $C_R = \{P_1, P_2, \ldots, P_{B-2}\}$ in R:**
    - for each page P_S in S:
      - **for each row r in C_R:**
        - for each row s in P_S:
          - if θ(r, s): output r joined with s

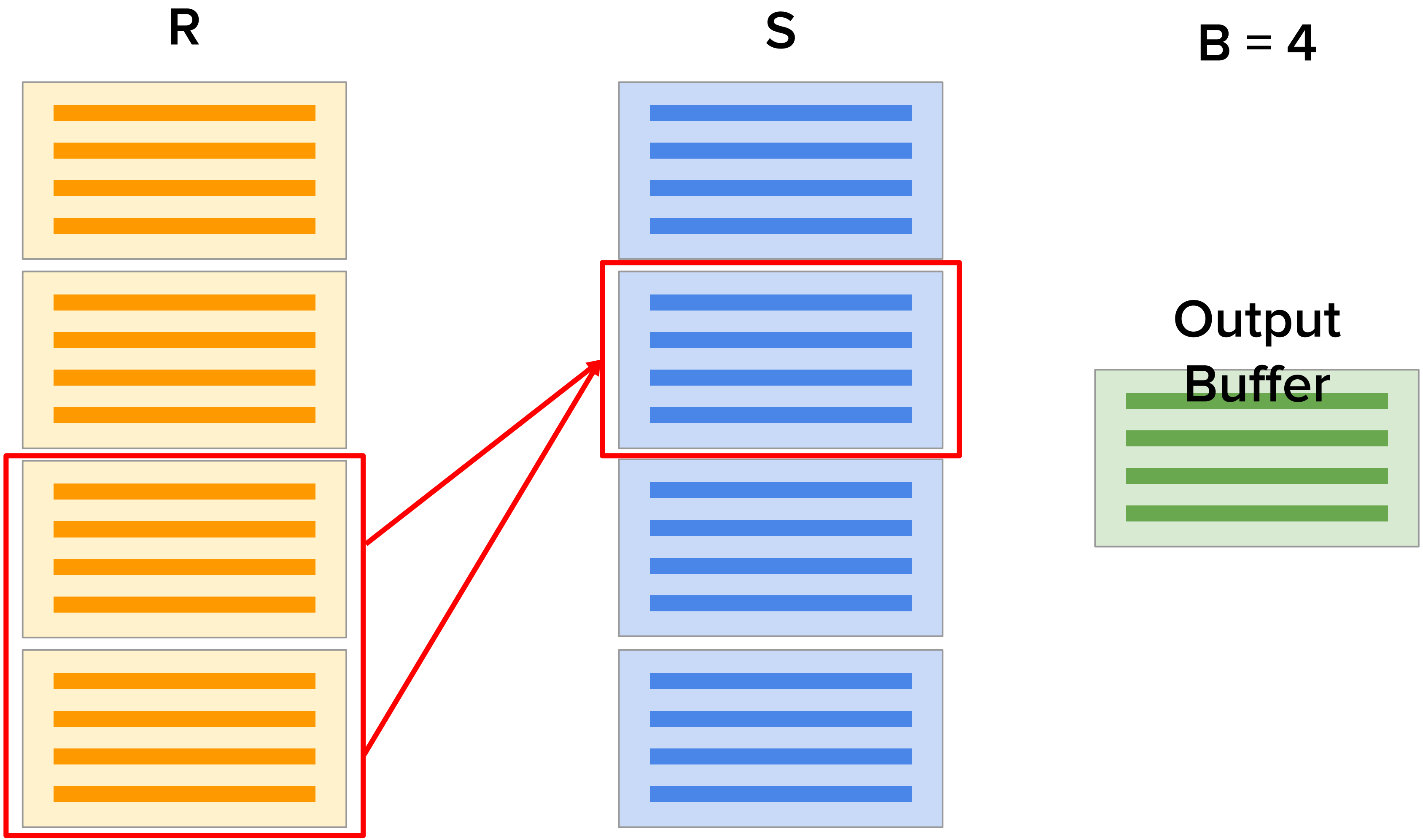

R
S
B = 4
Output
Buffer

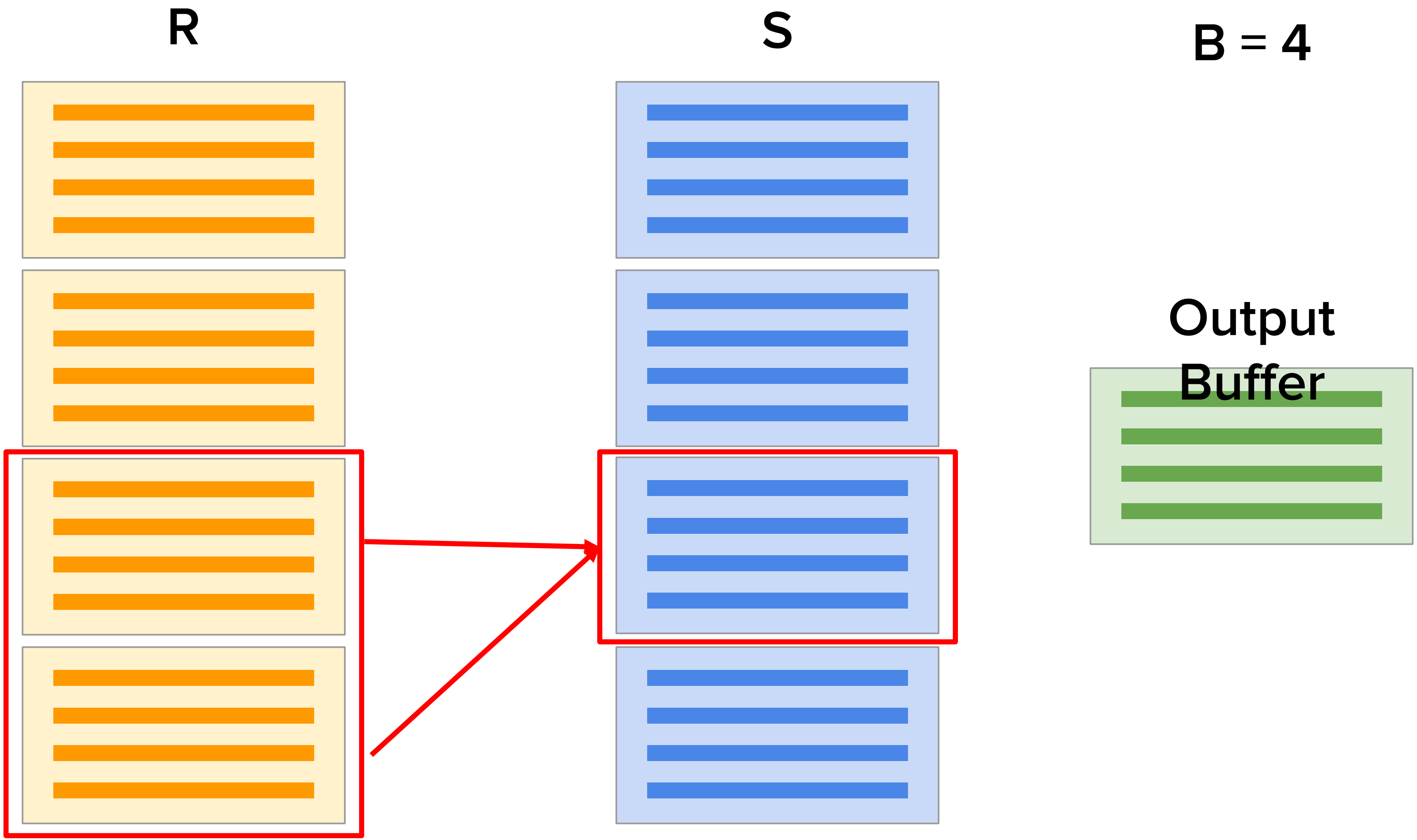

R
S
B = 4
Output
Buffer

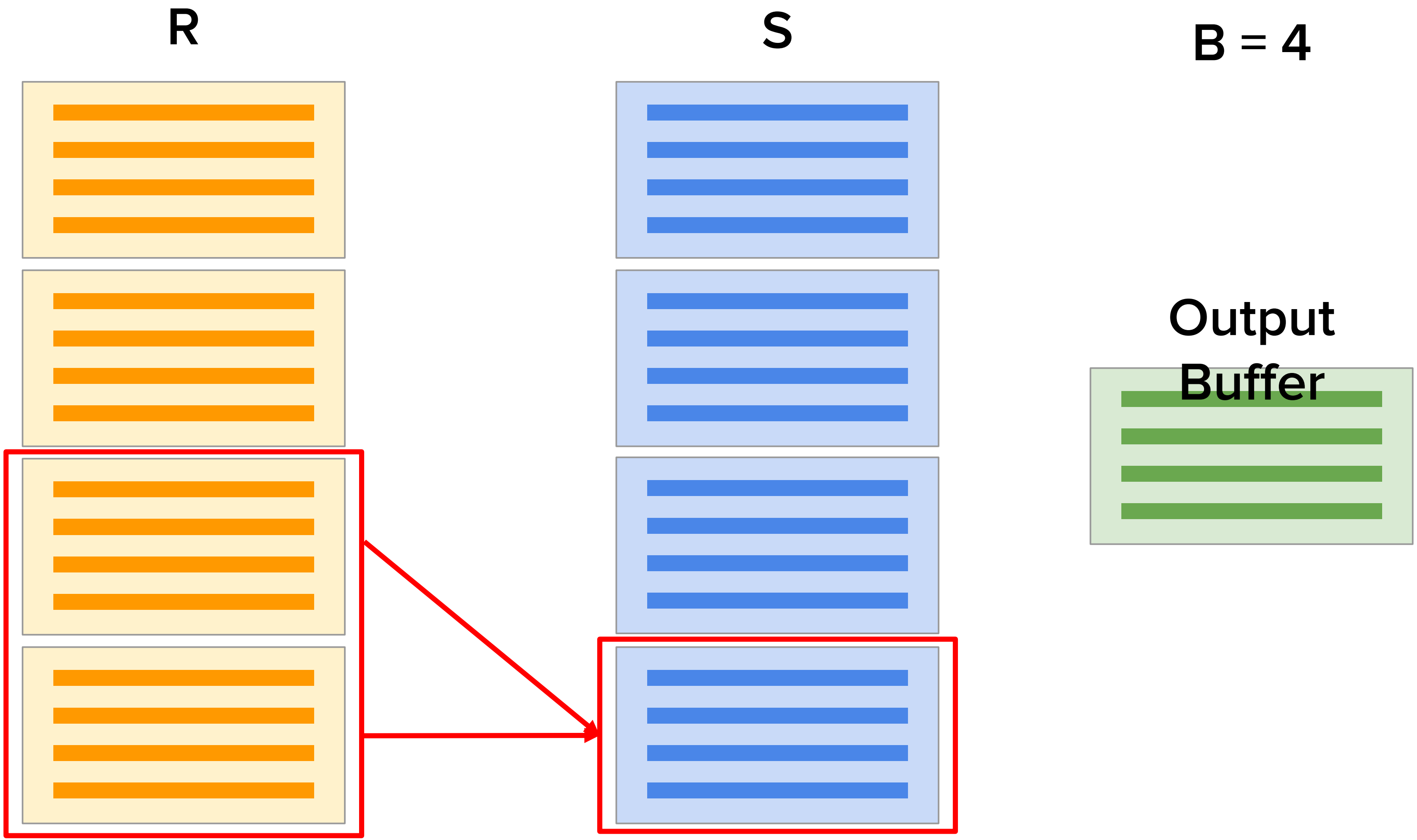

R
S
B = 4
Output
Buffer


R
S
B = 4
Output
Buffer

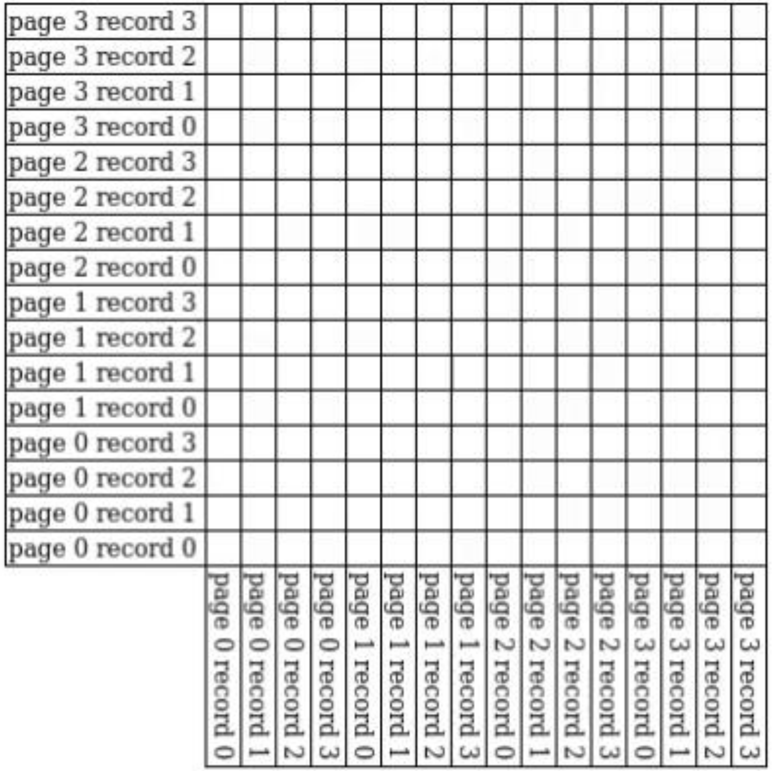

R
S
B = 4
Output
Buffer


R
S
B = 4
Output
Buffer


R
S
B = 4
Output
Buffer


R
S
B = 4
Output
Buffer

BNLJ



leftRecordIterator: Iterator over left block
rightRecordIterator: Iterator over right page
leftRecord:
rightRecord :

Cost of BNLJ?

$$[R] + (\#\text{ blocks in } R) * [S]$$

$$= [R] + \lceil {}^{[R]}/_{\text{chunksize}} \rceil * [S]$$

$$\boxed{= [R] + \lceil {}^{[R]}/_{(B-2)} \rceil [S]}$$

Worksheet Q1b

How many disk I/Os are needed to perform a block nested loops join?

```
Companies: (company_id, industry, ipo_date)
Nyse: (company_id, date, trade, quantity)
```

- 20 pages of memory
- We want to join Companies and NYSE on C.company_id = N.company_id
- company_id is the primary key for Companies
- For every tuple in Companies, assume there are 4 matching tuples in NYSE
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Unclustered B+ indexes with height 1 on C.company_id and N.company_id

Worksheet Q1b

How many disk I/Os are needed to perform a block nested loops join?

B = 20, block size = B - 2 = 18

C ⋈ N

Cost is [C] + [[C] / B - 2] * [N]

= 50 + [50 / 18] * 100 = 350 I/Os

N ⋈ C

Cost is [N] + [[N] / B - 2] * [C]

= 100 + [100 / 18] * 50 = 400 I/Os

I/O cost for BNLJ: min(350, 400) I/Os = **350 I/Os**

```
Companies: (company_id, industry, ipo_date)
Nyse: (company_id, date, trade, quantity)
```

- 20 pages of memory
- We want to join Companies and NYSE on C.company_id = N.company_id
- company_id is the primary key for Companies
- For every tuple in Companies, assume there are 4 matching tuples in NYSE
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Unclustered B+ indexes with height 1 on C.company_id and N.company_id

Index Nested Loop Join (INLJ)

- A join is essentially:
  - for each row r in R:
    - for each row s in S that satisfies θ(r, s):
      - output r joined with s

Index Nested Loop Join (INLJ)

- An *index on S* allows us to do the inner loop efficiently!
  - for each row r in R:
    - for each row s in S that satisfies θ(r, s) ***(found using the index)***:
      - output r joined with s

Index Nested Loop Join (INLJ)

- What's the I/O cost?
  - [R] + |R| * cost to find matching S tuples
    - [R] from scanning through R
  - Cost to find matching S tuples:
    - Alternative 1: cost to traverse root to leaf + read all the leaves with matching tuples
    - Alternative 2/3: cost of retrieving RIDs (similar to Alternative 1) + cost to fetch actual records
      - 1 I/O per **page** if clustered, 1 I/O per **tuple** if not

Index Nested Loop Join (INLJ)

- What's the I/O cost?
  - [R] + |R| * cost to find matching S tuples
    - [R] from scanning through R
  - **If we have no index,** then the only way to search for matching S tuples is by scanning all of S → SNLJ
    - Cost to find matching S tuples is then [S], giving us the formula for SNLJ cost

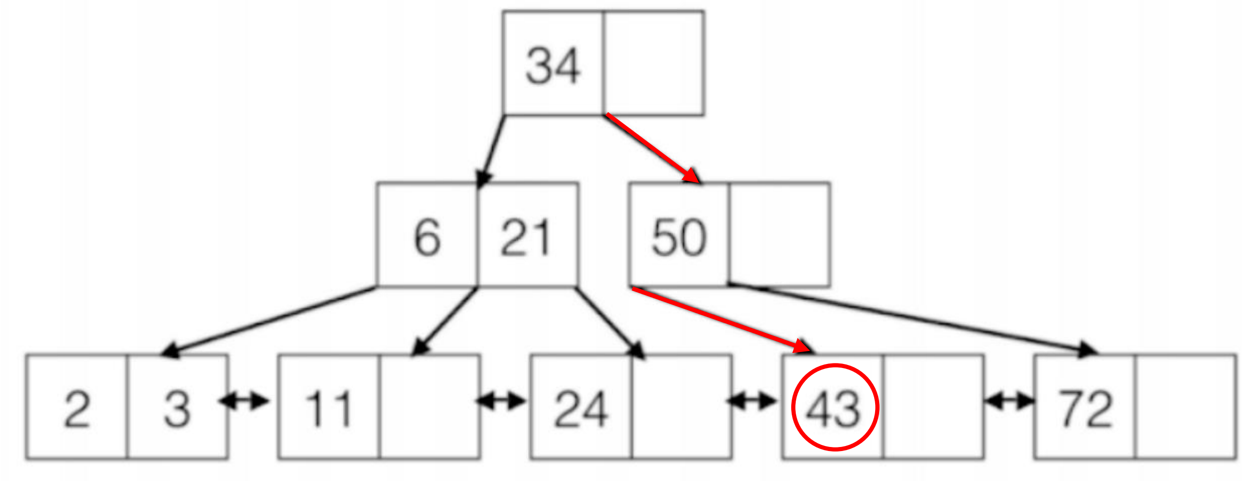
Index Nested Loop Join (INLJ)

R.col

43
5
11

Output

Index on S.col

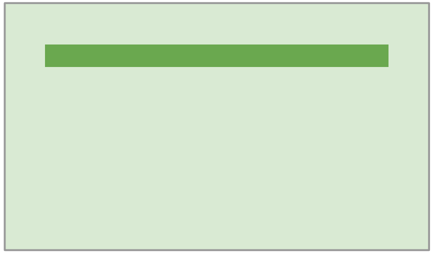


Index Nested Loop Join (INLJ)

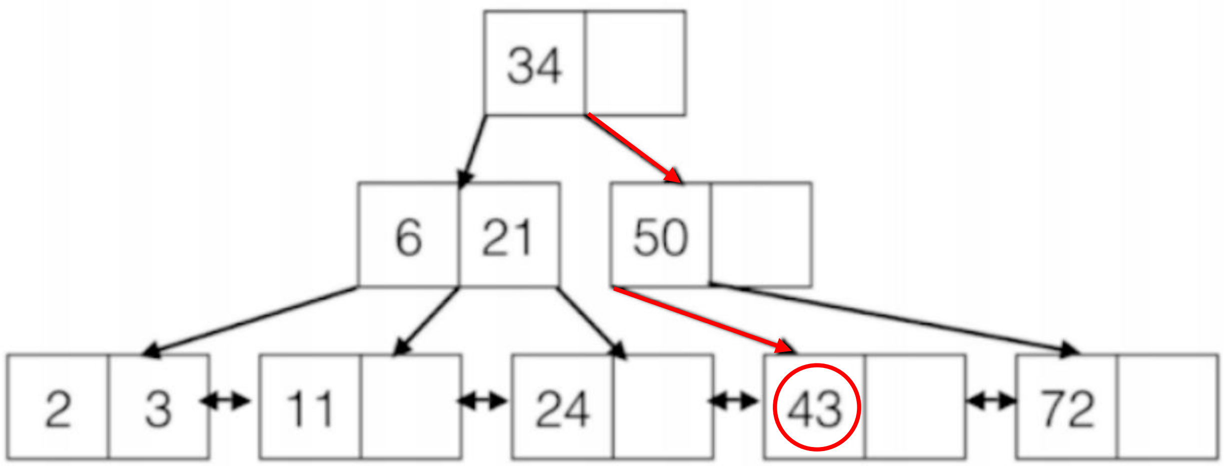
R.col

43
5
11

Output



Index on S.col



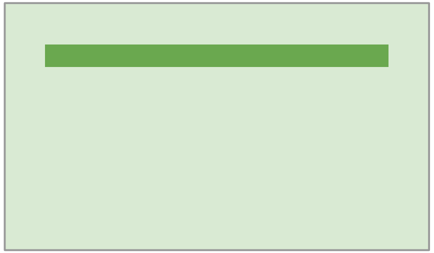
Index Nested Loop Join (INLJ)

R.col

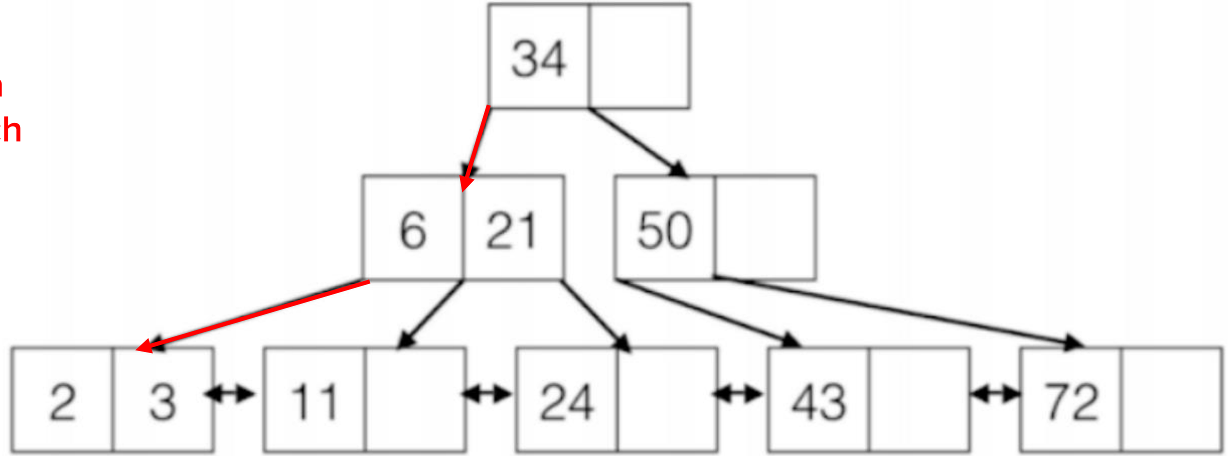
43
5
11

not a match

Output



Index on S.col



Index Nested Loop Join (INLJ)

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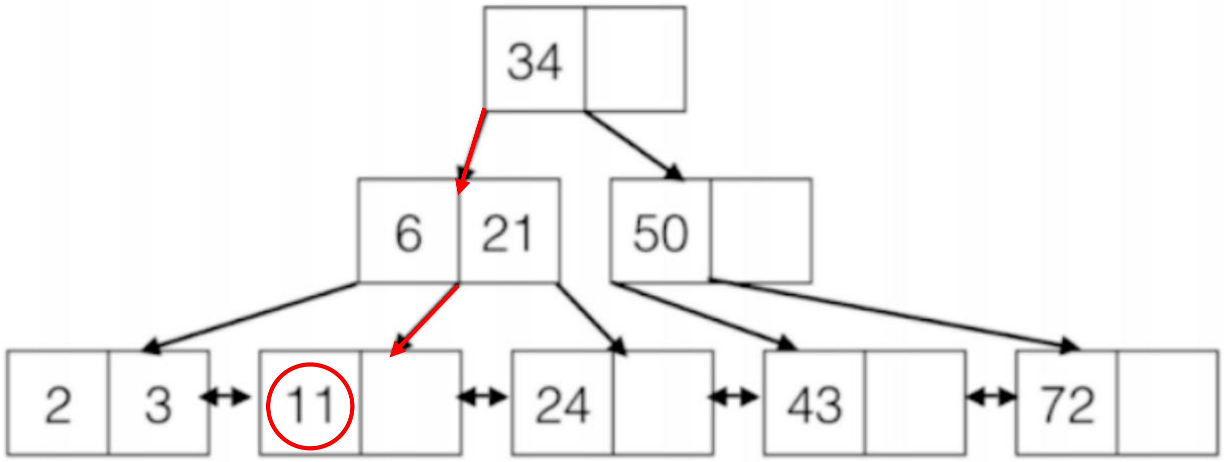
Output

Index on S.col



Index Nested Loop Join (INLJ)

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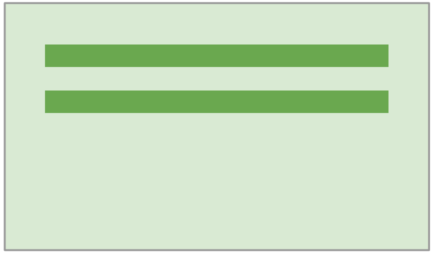
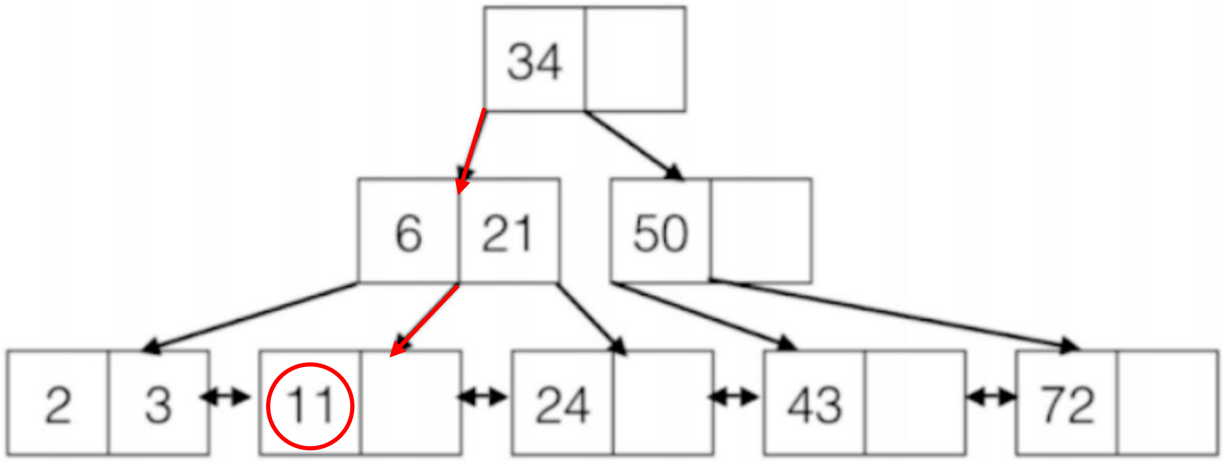
5
11

Output



Index on S.col



Worksheet Q1c

How many disk I/Os are needed to perform an index nested loops join?

```
Companies: (company_id, industry, ipo_date)
Nyse: (company_id, date, trade, quantity)
```

- 20 pages of memory
- We want to join Companies and NYSE on C.company_id = N.company_id
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- For every tuple in Companies, assume there are 4 matching tuples in NYSE
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Unclustered B+ indexes with height 1 on C.company_id and N.company_id

Worksheet Q1c

How many disk I/Os are needed to perform an index nested loops join?

C ⋈ N

Cost is [C] + |C| * cost of searching N

= 50 + (50 * 50) * (2 + 4) = 15,050 I/Os

N ⋈ C

Cost is [N] + |N| * cost of searching C

= 100 + (100 * 100) * (2 + 1) = 30,100 I/Os

I/O cost: min(30,100, 15,050) = **15,050 I/Os**

```
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Nyse: (company_id, date, trade, quantity)
```

- 20 pages of memory
- We want to join Companies and NYSE on C.company_id = N.company_id
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- Unclustered B+ indexes with height 1 on C.company_id and N.company_id

Sort-Merge Join (SMJ)

- What if we process the data a bit before we join things together?
  - For example, sort both relations first! Then we can join them efficiently
  - In some cases, we might even have one of the relations already sorted on the right key, and then we don't even have to spend time sorting it!

Sort-Merge Join (SMJ)

- First step: **sort** both R and S (with external sorting)
- Second step: **merge** matching tuples from R and S together
  - We do this efficiently by moving iterators over sorted R and sorted S in lockstep: move the iterator with the smaller key
    - We know that this key is smaller than *all* remaining key values in the other relation, so we're completely done joining that tuple!

Sort-Merge Join (SMJ)

- First step: **sort** both R and S (with external sorting)
- Second step: **merge** matching tuples from R and S together
  - Need a bit more care than this: we might have multiple rows in R matching with multiple rows in S
    - **Mark** the first matching row in S, match tuples with the first matching row in R, then **reset** the iterator to the mark so we can go through the rows in S again for the second matching row in R

Sort-**Merge** Join

```
while not done {
  while (r < s) { advance r }
  while (r > s) { advance s }

  mark s // save start of "block"
  while (r == s) {
    // Outer loop over r
    while (r == s) {
      // Inner loop over s
      yield <r, s>
      advance s
    }
    reset s to mark
    advance r
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
57	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

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Sort-Merge Join (SMJ)

- I/O cost?
  - Cost of sorting R
  - Cost of sorting S
  - The merge step: [R] + [S]
    - Only one pass (if we assume there aren't a lot of duplicates)

Sort-Merge Join (SMJ)

- An optimization we can sometimes make
  - We only have to (assuming no duplicate values in R) make *one* pass through the sorted relation → we don't *need* the sorted relations to be materialized!
  - In the final merge pass of sorting both relations, instead of writing the sorted relations to disk, we can stream them into the second part of SMJ!
    - Reduces I/O cost by 2*([R] + [S])!

Sort-Merge Join (SMJ)

- An optimization we can sometimes make
  - In the final merge pass of sorting both relations, instead of writing the sorted relations to disk, we can stream them into the second part of SMJ!
    - We have to be able to fit the input buffers of the last merge pass of sorting R *and* sorting S in memory, as well as have one output buffer for joined tuples
    - Need: # runs in last merge pass for R + # runs in

Worksheet Q1e

How many disk I/Os are needed to perform a sort-merge join (unoptimized/optimized)?

```
Companies: (company_id, industry, ipo_date)
Nyse: (company_id, date, trade, quantity)
```

- 20 pages of memory
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page

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Unoptimized:

Sorting N:

Pass 0 - ceil(100/20) = 5 sorted runs of 20 pages each

Pass 1 - ceil(5/19) = 1 sorted run of 100 pages each

Total I/Os: 4 * (100 pages) = 400 I/Os

Sorting C:

Pass 0 - ceil(50/20) = 3 sorted runs of 20 pages, 20 pages, and 10 pages

Pass 1 - ceil(3/19) = 1 sorted run of 50 pages

Total I/Os: 4 * (50 pages) = 200 I/Os

Merging: [C] + [N] = 150 I/Os

Total SMJ I/Os: 200 + 400 + 150 = 750 I/Os

Worksheet Q1e

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Can we perform the SMJ optimization?

Sorting N:

Pass 0 - ceil(100/20) = 5 sorted runs of 20 pages each

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Total I/Os: 4 * (100 pages) = 400 I/Os

Sorting C:

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Pass 1 - ceil(3/19) = 1 sorted run of 50 pages

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Can we perform the SMJ optimization?

Yes.

During the 2nd to last pass, we produce 5 sorted runs of N and 3 sorted runs of C. Since the number of runs of C + the number of runs of N ≤ 20 - 1, we can optimize sort merge join and combine the last sorting pass and final merging pass to save 2 * ([C] + [N]) I/Os.

Total I/Os = 750 - 2(50+100) = 450 I/Os

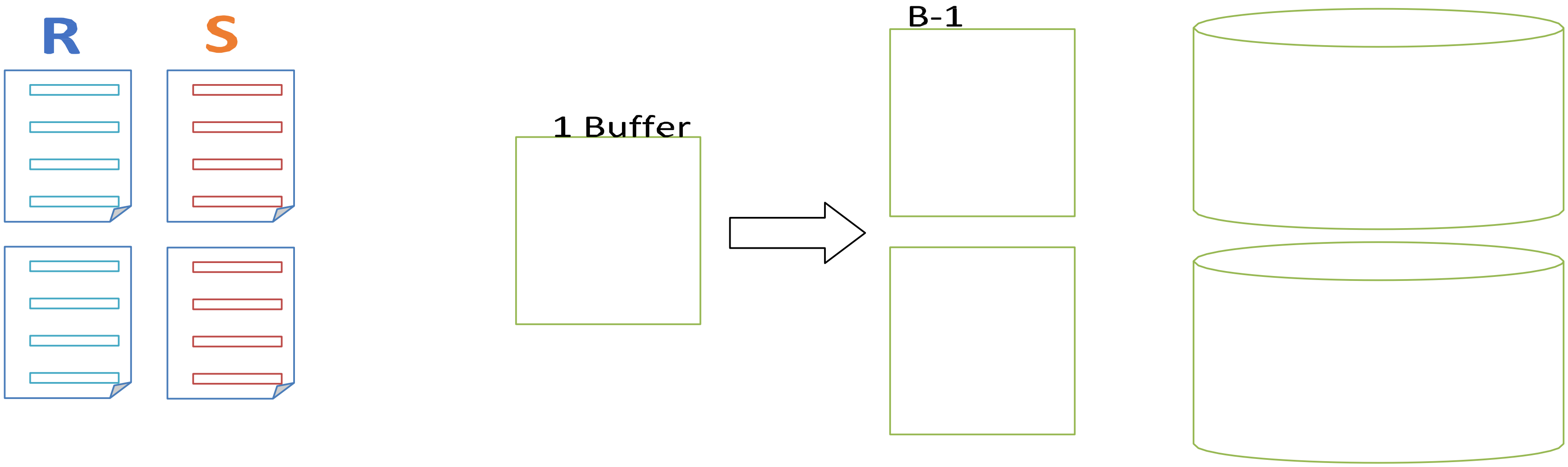
Grace Hash Join

- Same idea as SMJ, but let's build some hash tables instead
- Two passes: **partition** the data, then **build** an in-memory hash table and **probe** it
  - First, partition R and S into B - 1 partitions (like in external hashing), *using the same hash function*
    - All the tuples in R matching a tuple in S must be in the same partition → we can consider each partition independently

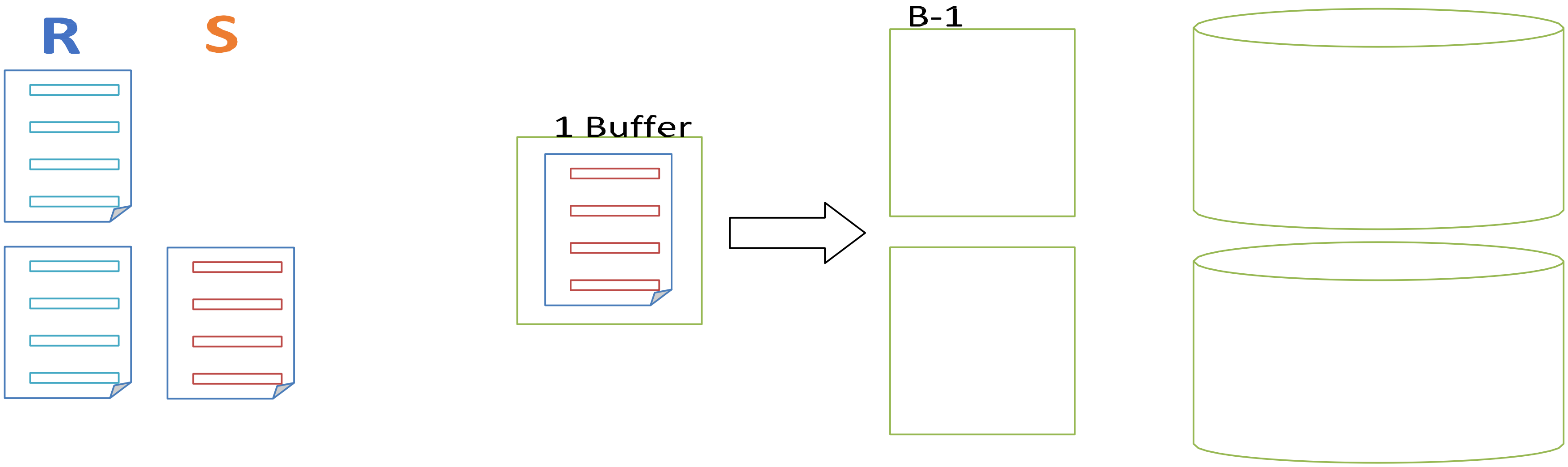
Grace Hash Join

- Same idea as SMJ, but let's build some hash tables instead
- Two passes: **partition** the data, then **build** an in-memory hash table and **probe** it
  - Then, build an in-memory hash table for a partition of R
  - We can use this in-memory hash table to find all the tuples in R that match a tuple in S
    - Stream in tuples of S, probe the hash table, output

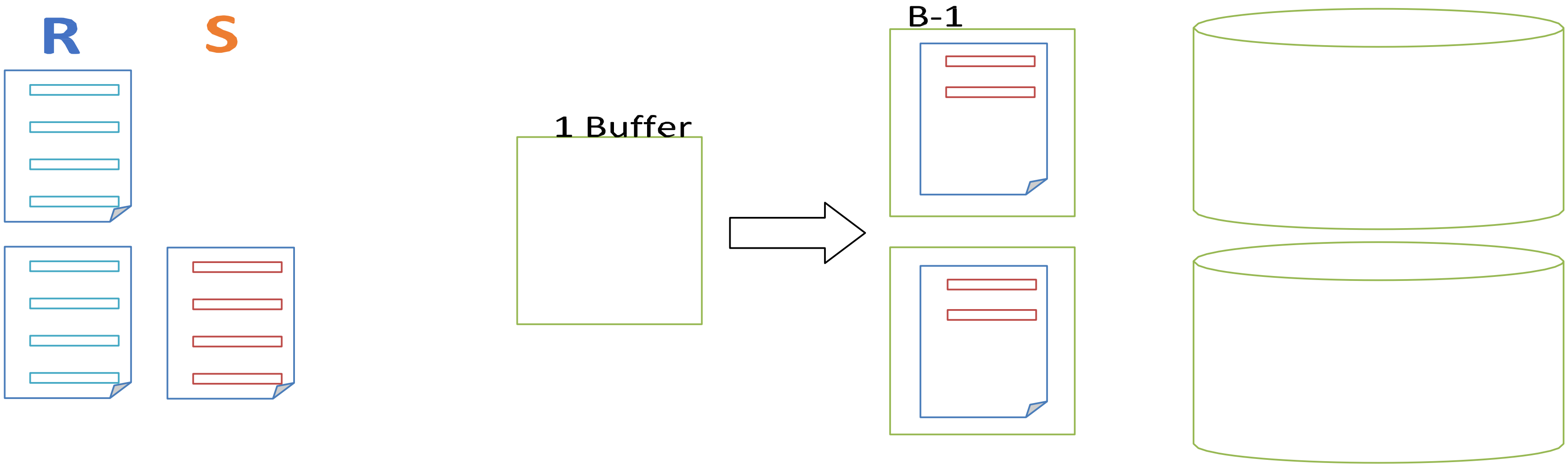
Grace Hash Join: ***Partition***



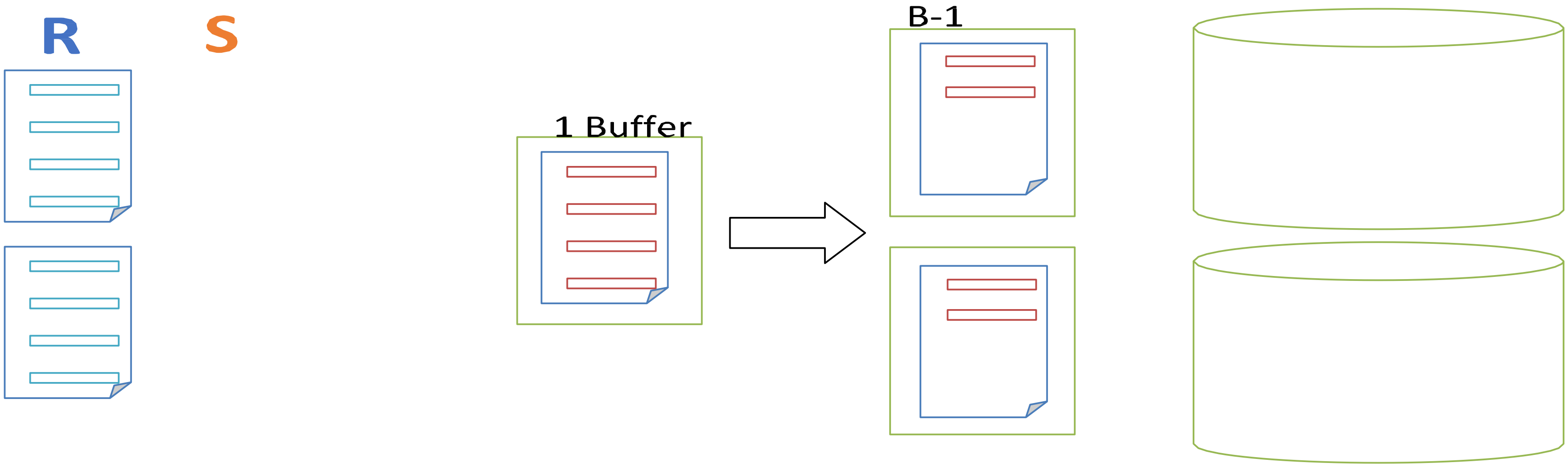
Grace Hash Join: ***Partition***



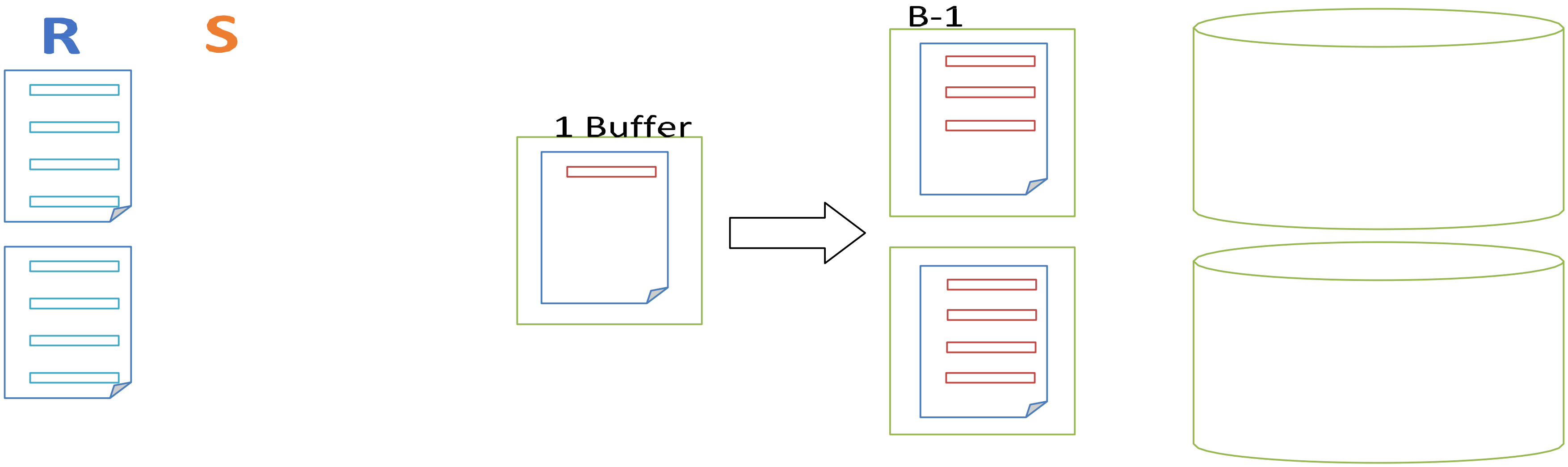
Grace Hash Join: *Partition*



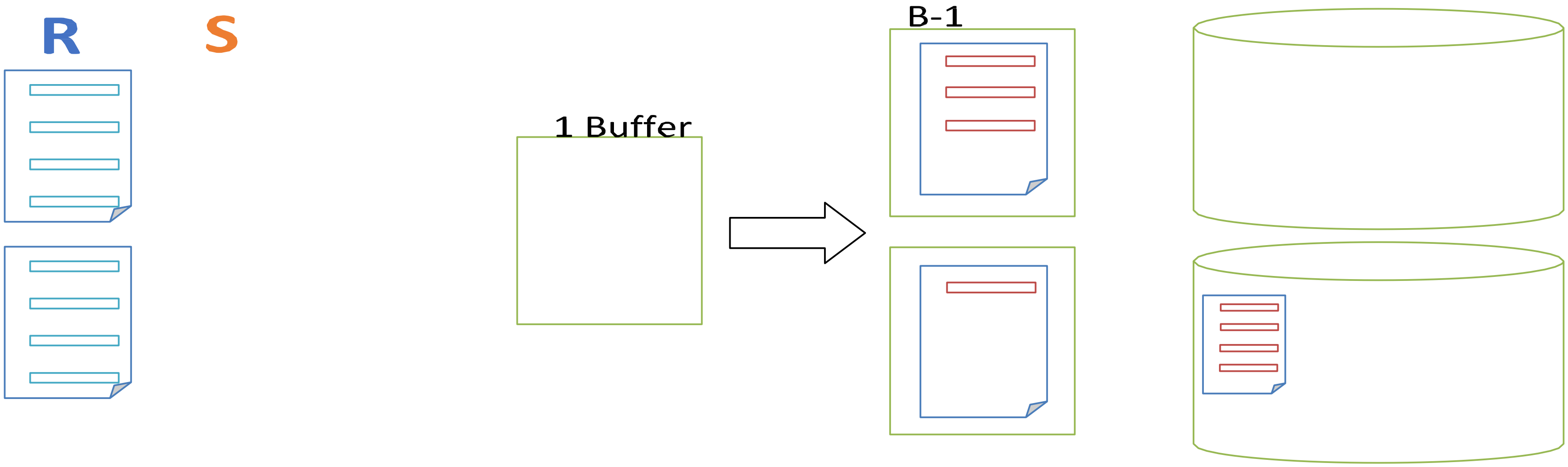
Grace Hash Join: ***Partition***



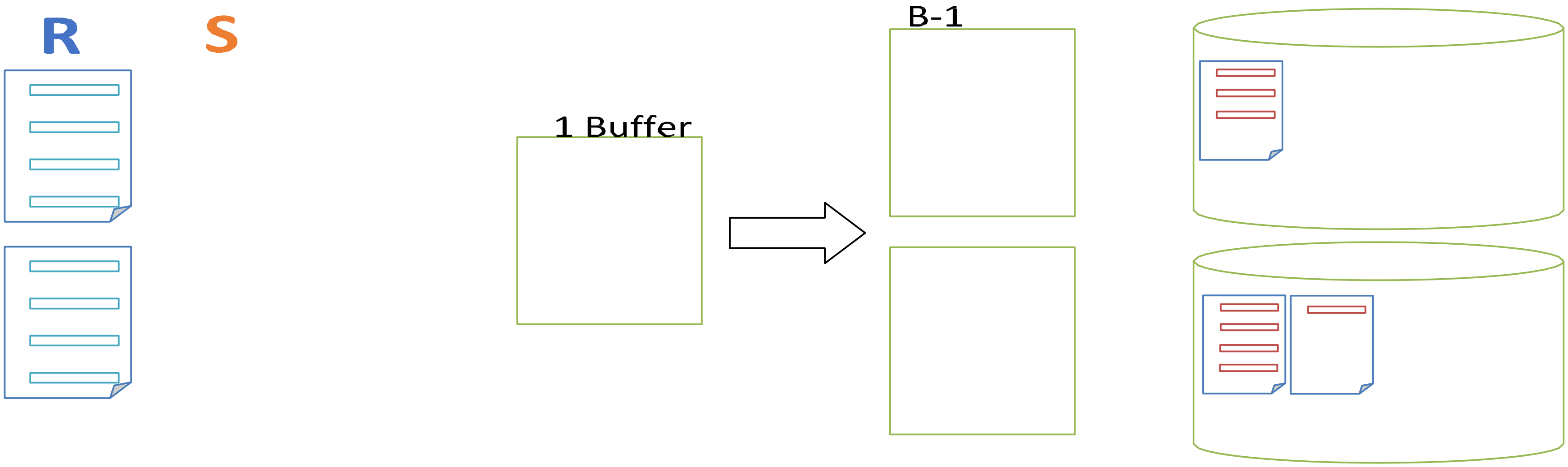
Grace Hash Join: *Partition*



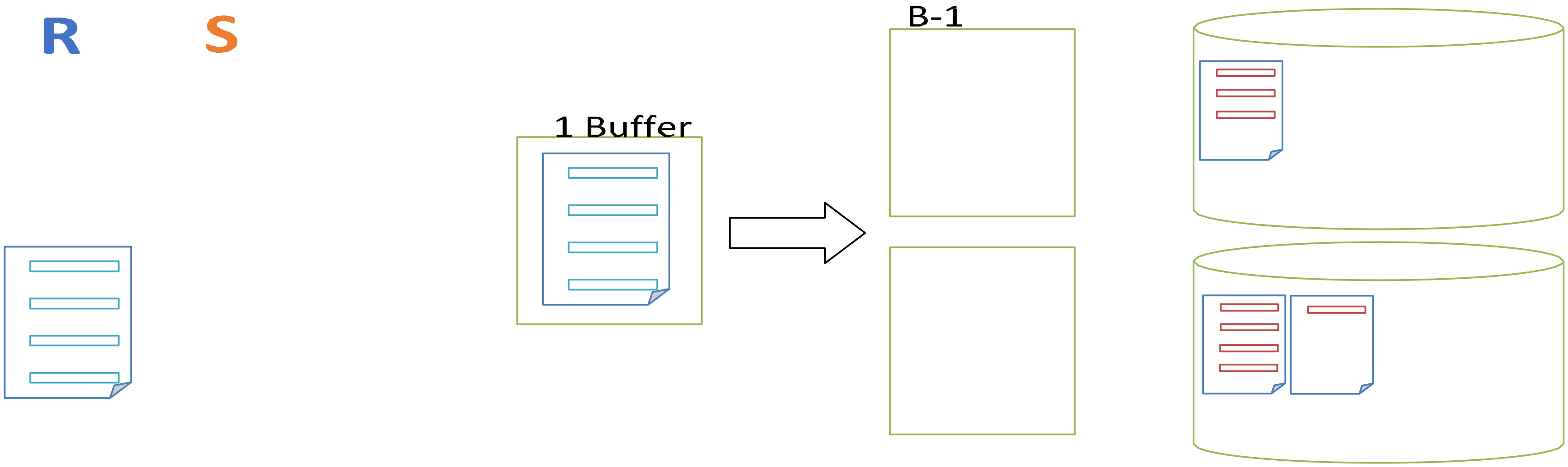
Grace Hash Join: *Partition*



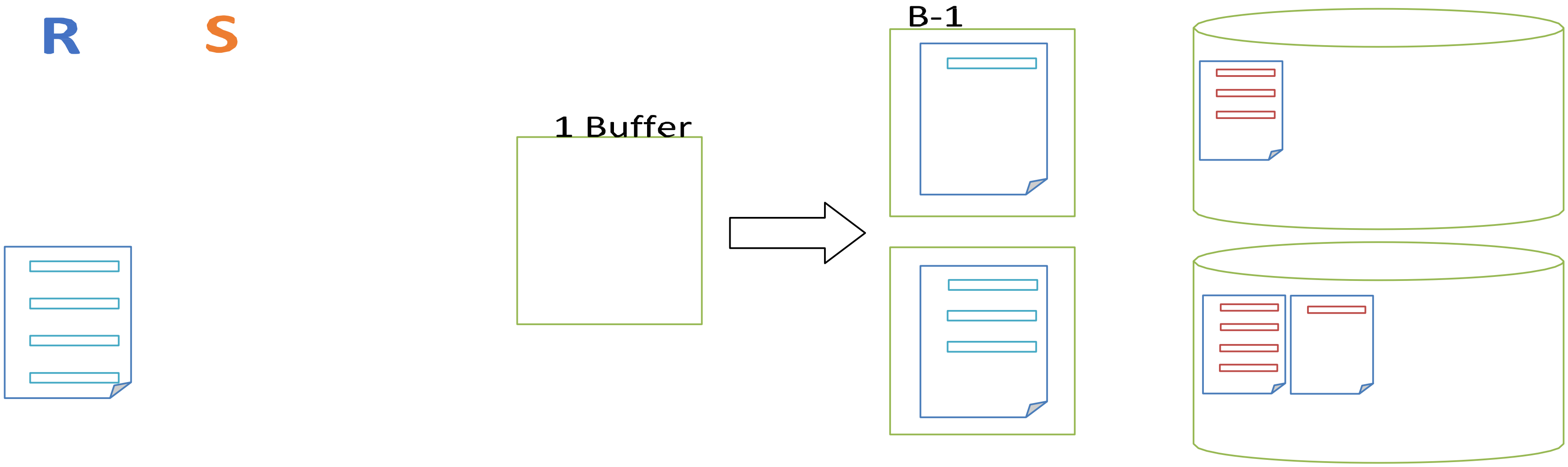
Grace Hash Join: ***Partition***



Grace Hash Join: *Partition*

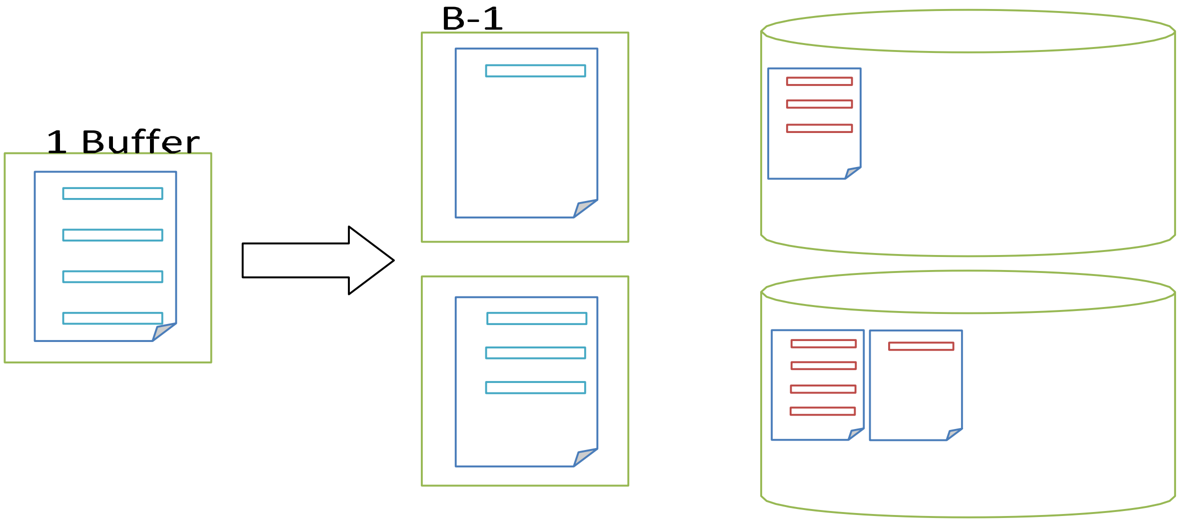


Grace Hash Join: *Partition*

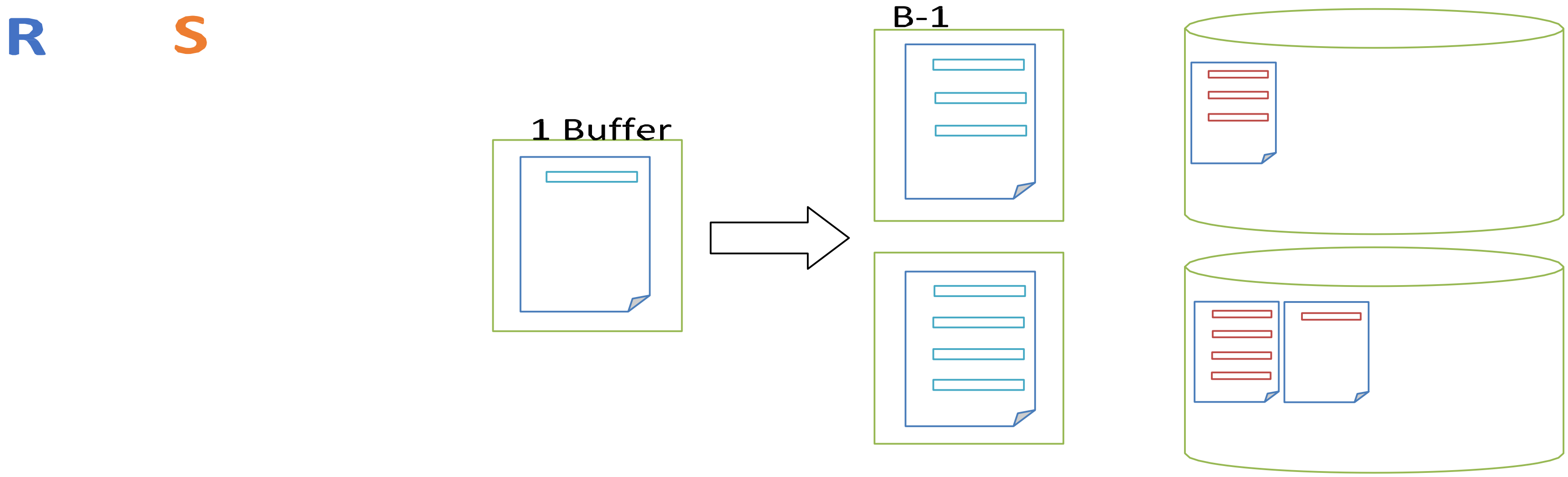


Grace Hash Join: ***Partition***

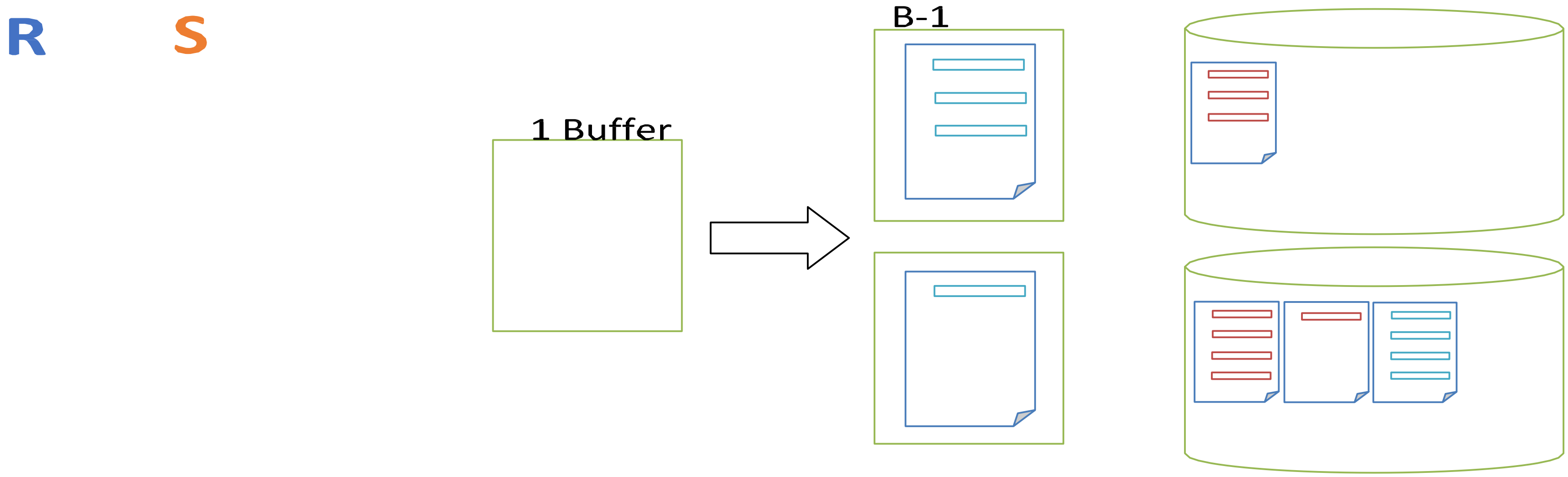
R S



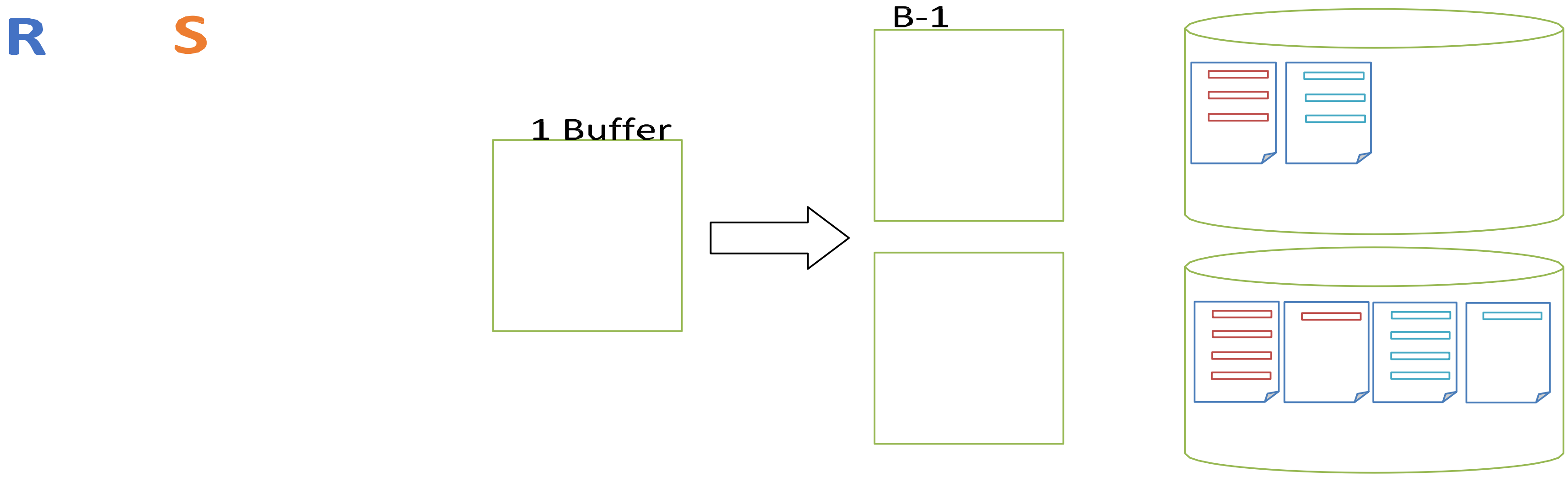
Grace Hash Join: ***Partition***



Grace Hash Join: ***Partition***



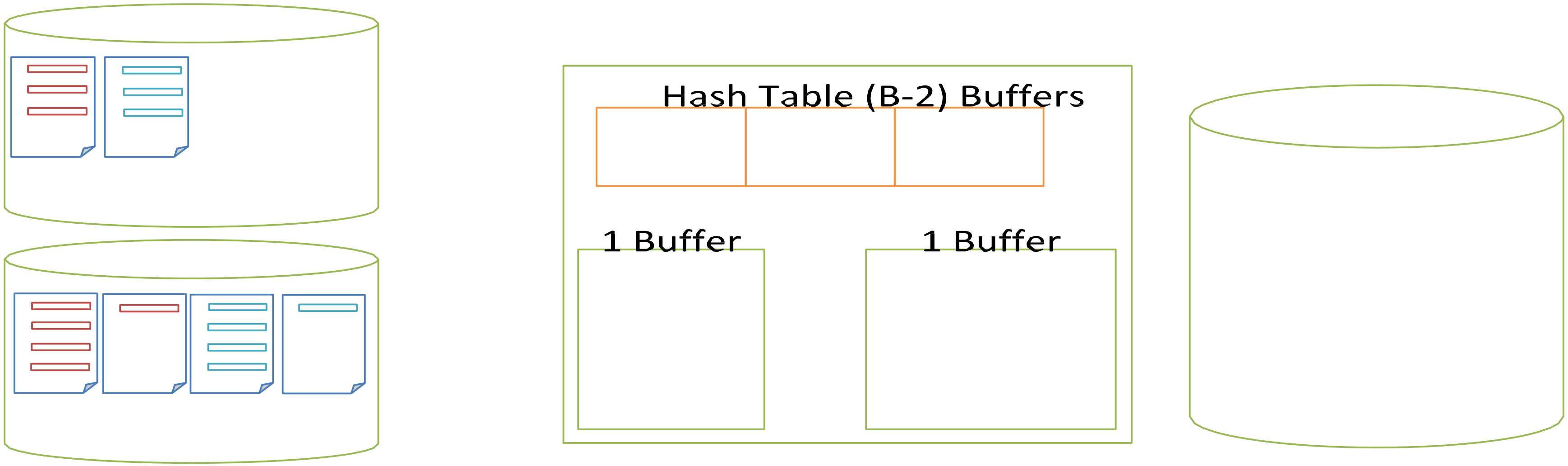
Grace Hash Join: ***Partition***



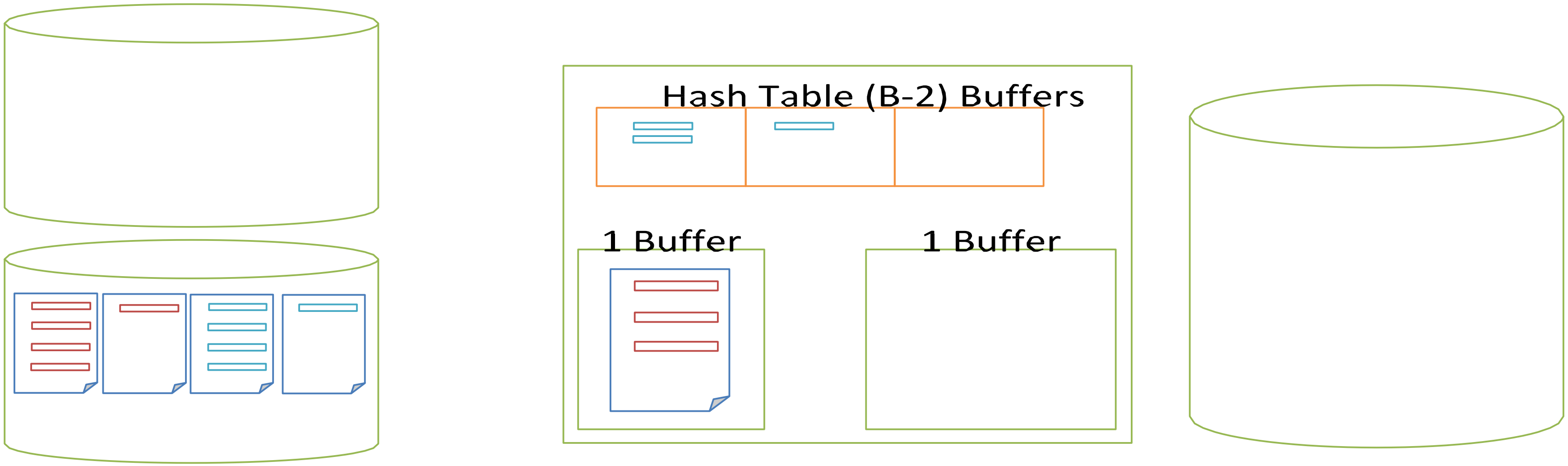
Grace Hash Join

- We need partitions of R (but not S!) to fit in B - 2 pages
  - 1 page reserved for streaming S partition
  - 1 page reserved for streaming output
- What if partitions of R are too big?
  - If S is smaller, do S $\bowtie_\theta$ R instead
  - Recursively partition! Make sure that for any partition of R you recursively partition, the matching S partition is also recursively partitioned!

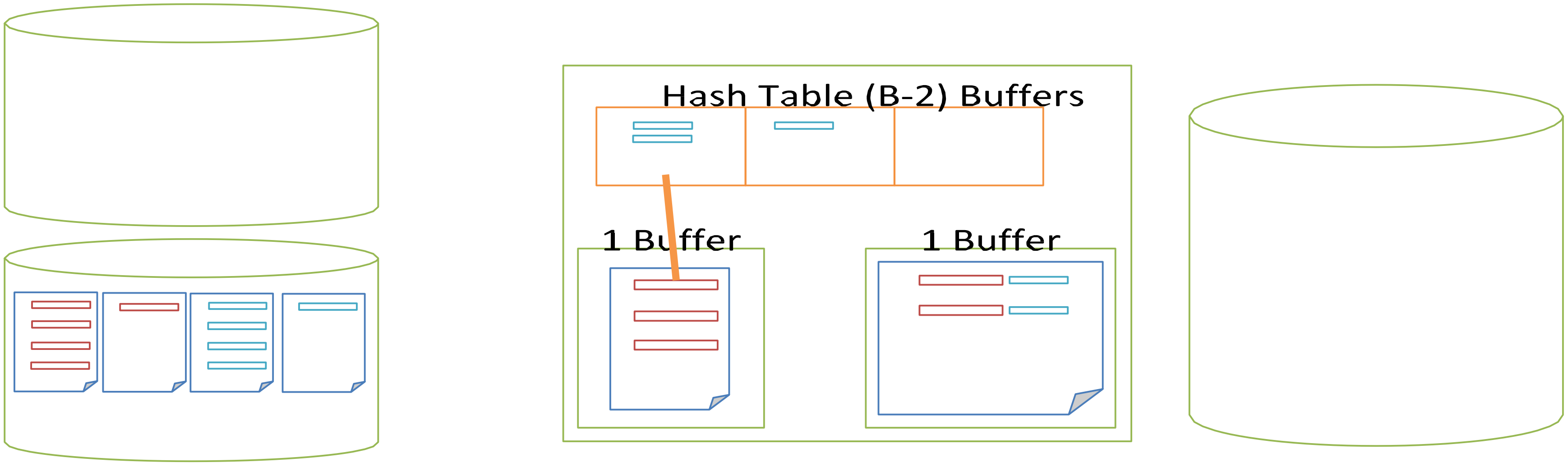
Grace Hash Join: ***<u>Build</u>* & *Probe***



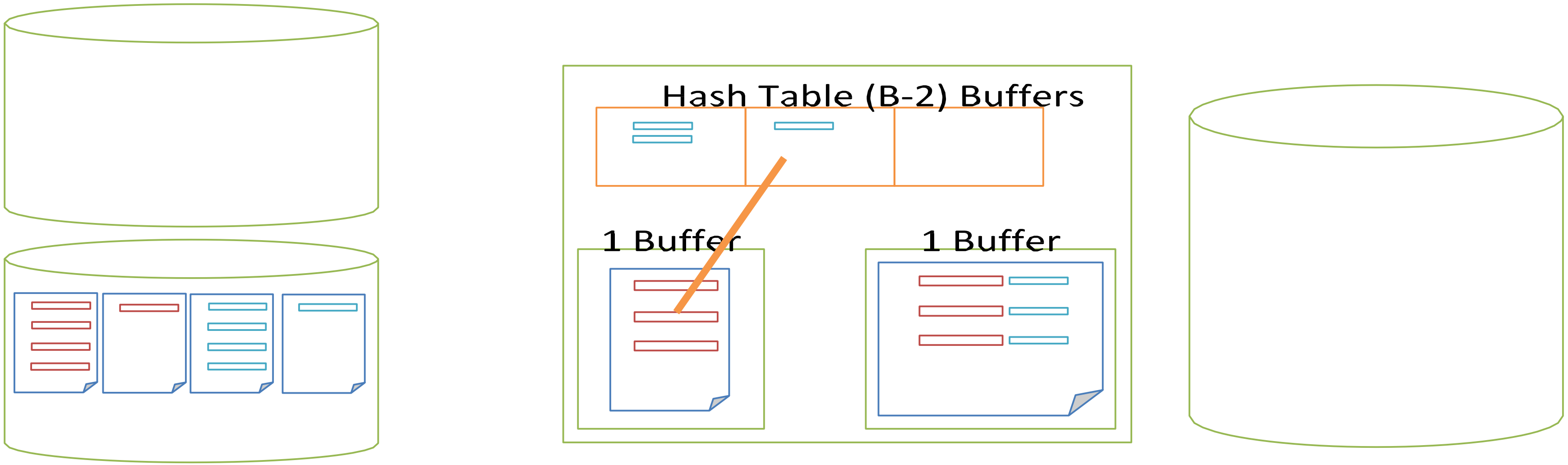
Grace Hash Join: ***Build*** & ***<u>Probe</u>***



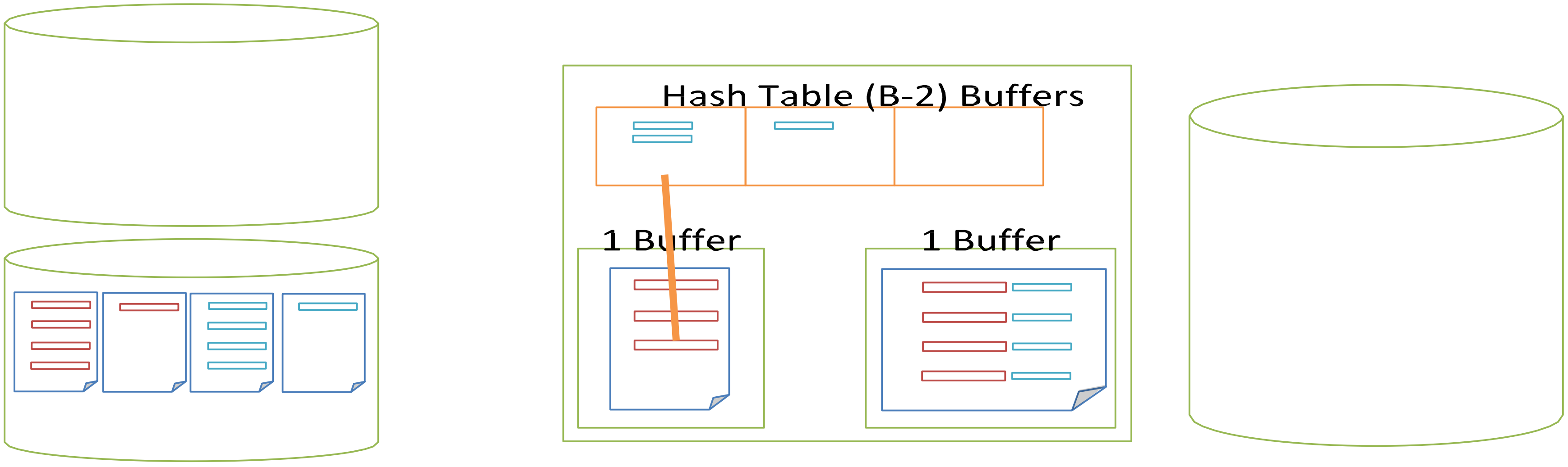
Grace Hash Join: ***Build*** & ***<u>Probe</u>***



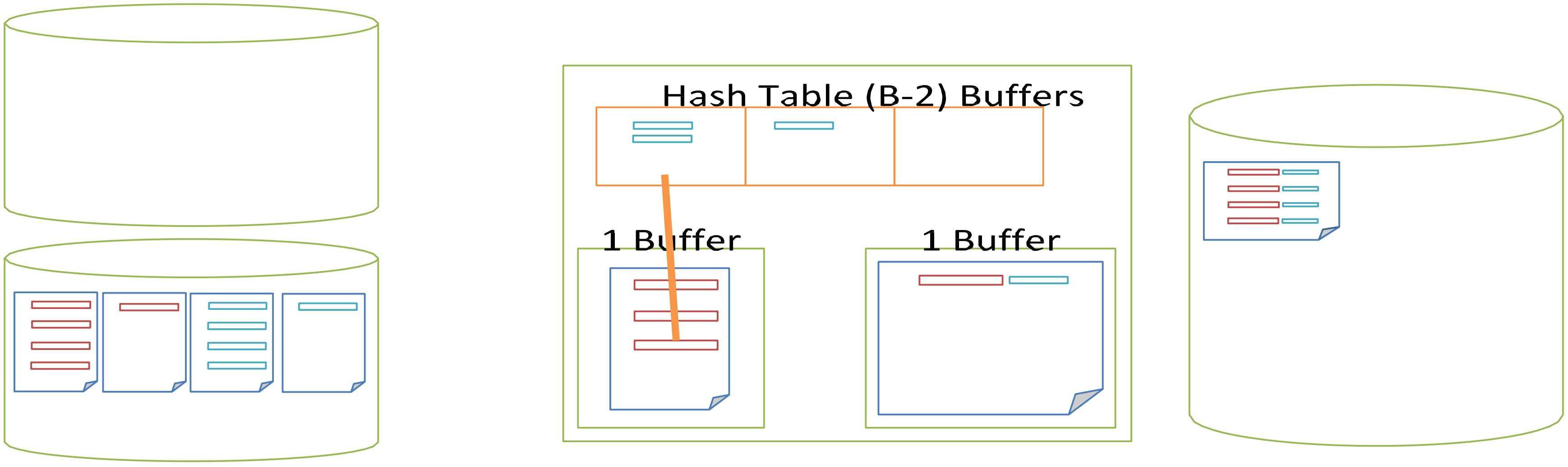
Grace Hash Join: ***Build*** **&** ***Probe***



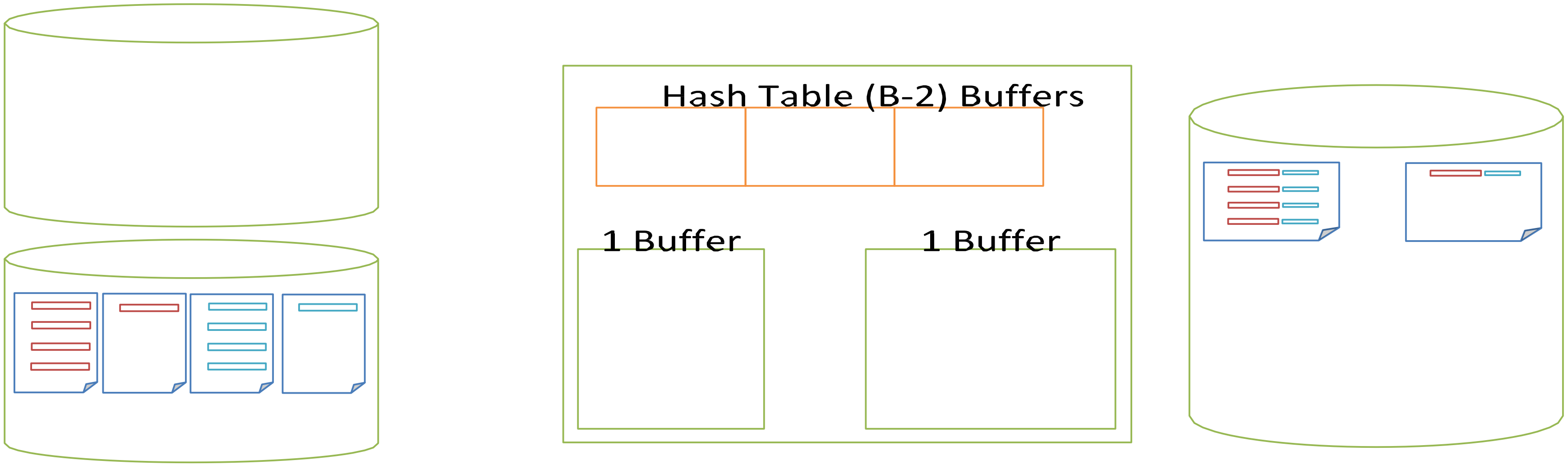
Grace Hash Join: ***Build*** & ***Probe***



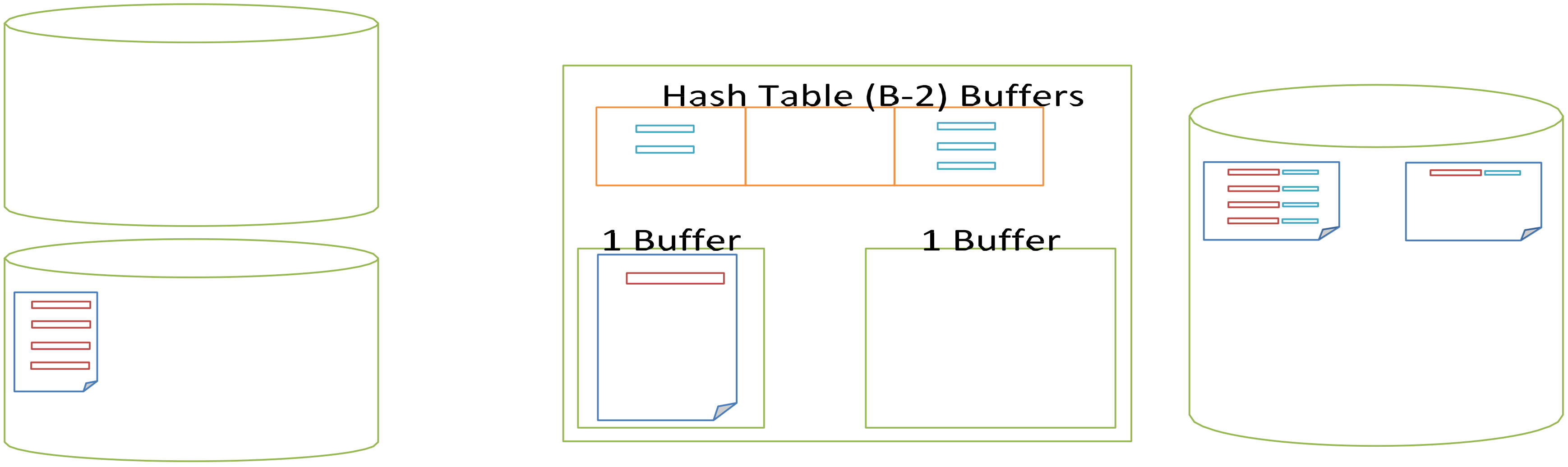
Grace Hash Join: ***Build*** & ***Probe***



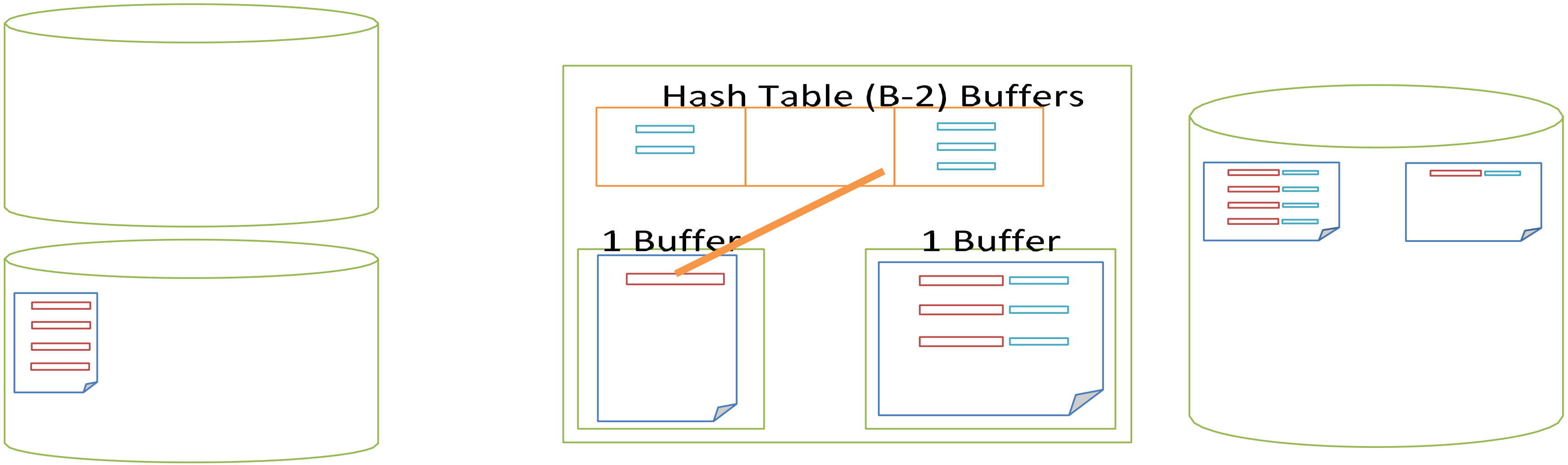
Grace Hash Join: ***Build*** *& Probe*



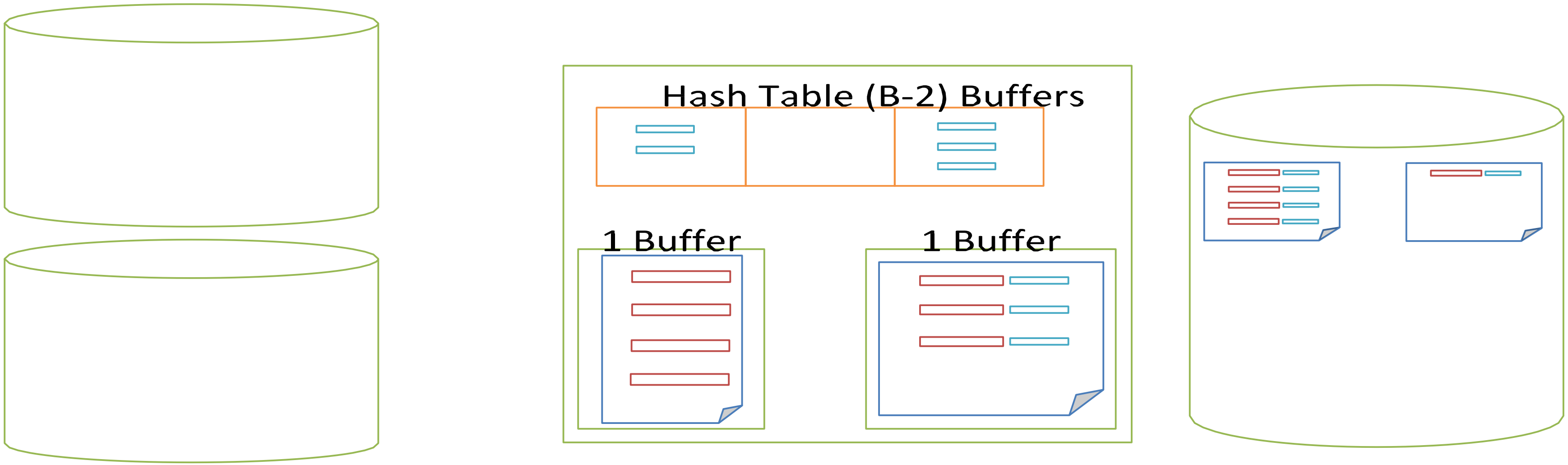
Grace Hash Join: ***Build*** & ***<u>Probe</u>***



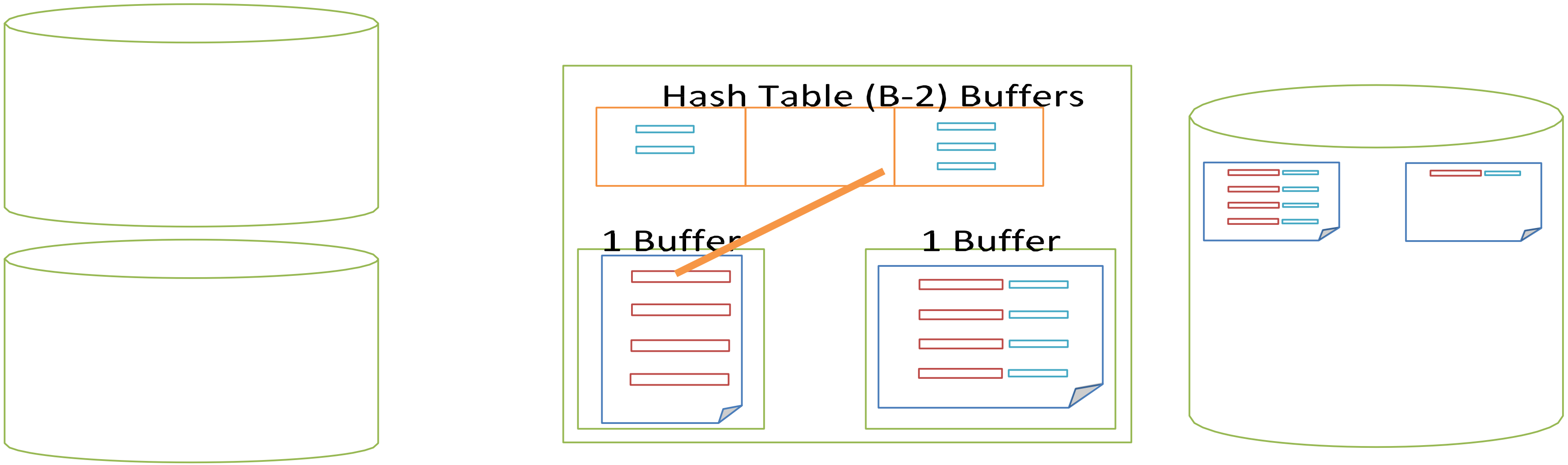
Grace Hash Join: ***Build*** & ***<u>Probe</u>***



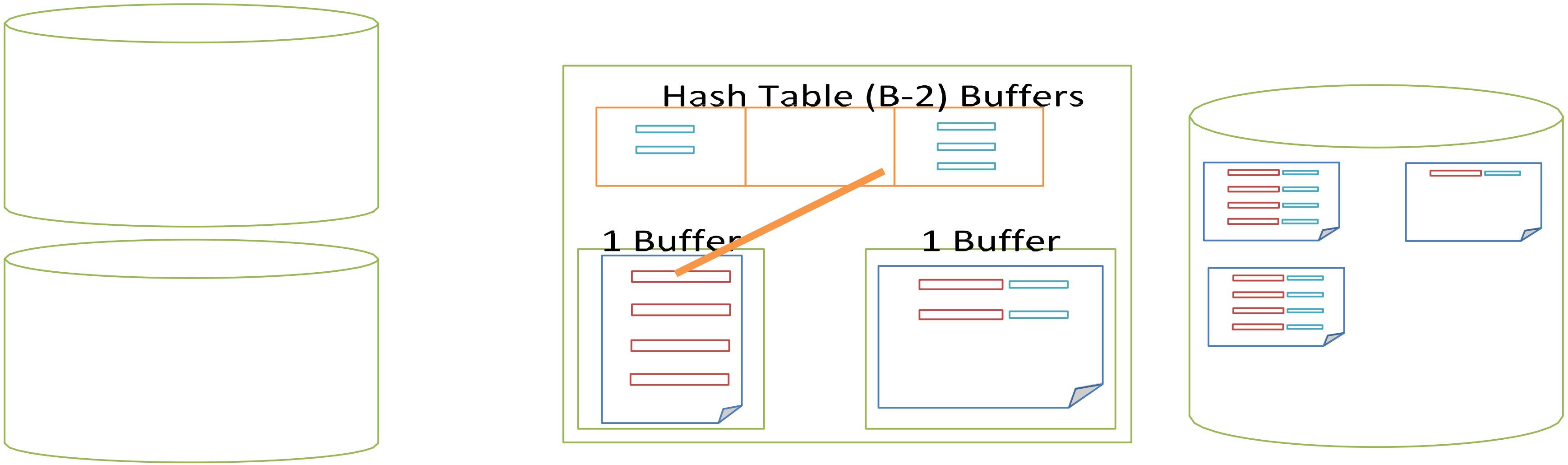
Grace Hash Join: ***Build*** **&** ***<u>Probe</u>***



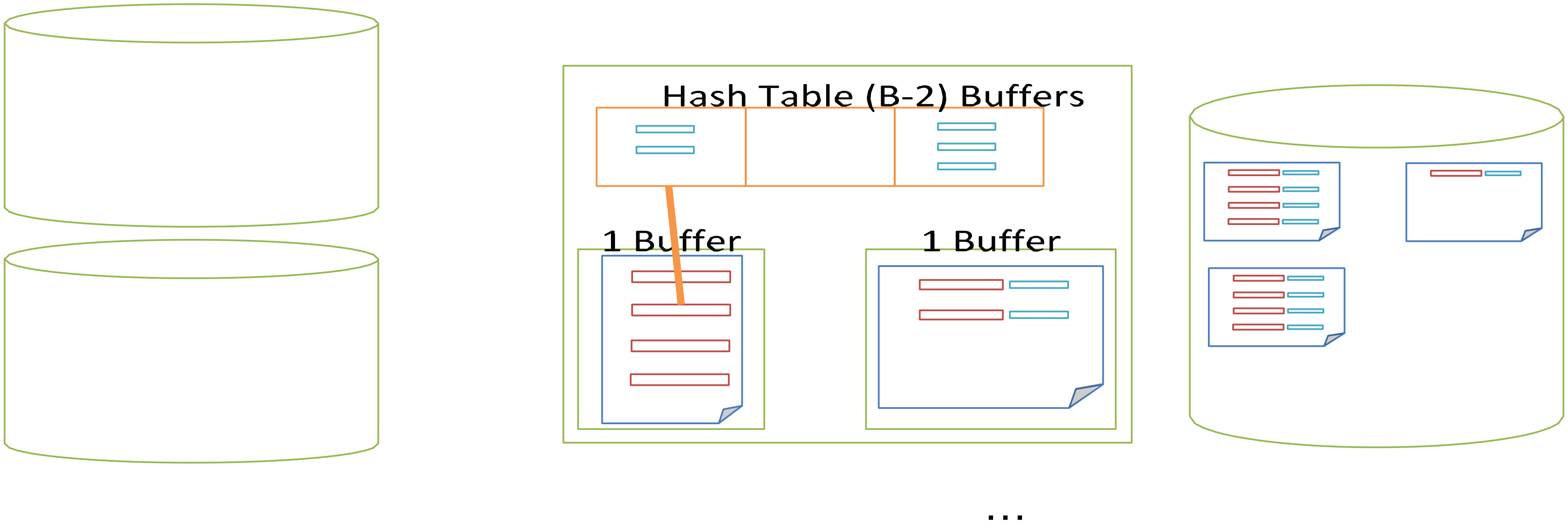
Grace Hash Join: ***Build & <u>Probe</u>***



Grace Hash Join: ***Build*** **&** ***<u>Probe</u>***



Grace Hash Join: ***Build & Probe***



Worksheet

Worksheet Q1f

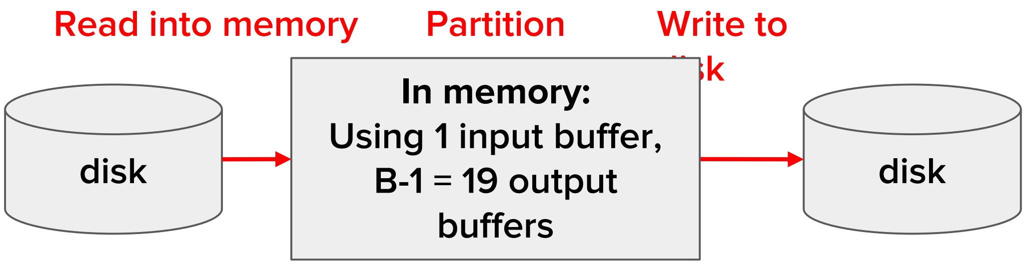
How many disk I/Os are needed to perform a hash join? Assume uniform partitioning.

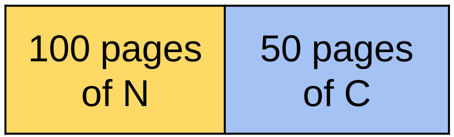
```
Companies: (company_id, industry, ipo_date)
Nyse: (company_id, date, trade, quantity)
```

- 20 pages of memory
- We want to join Companies and NYSE on C.company_id = N.company_id
- company_id is the primary key for Companies
- For every tuple in Companies, assume there are 4 matching tuples in NYSE
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Unclustered B+ indexes with height 1 on C.company_id and N.company_id

Worksheet Q1f

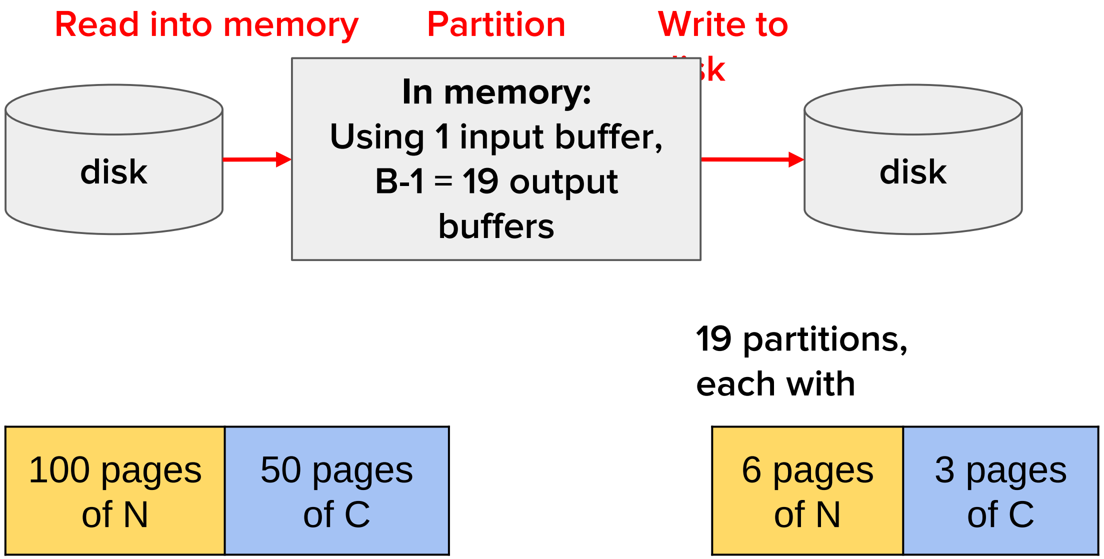
- B = 20
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Assume uniform partitioning





Worksheet Q1f

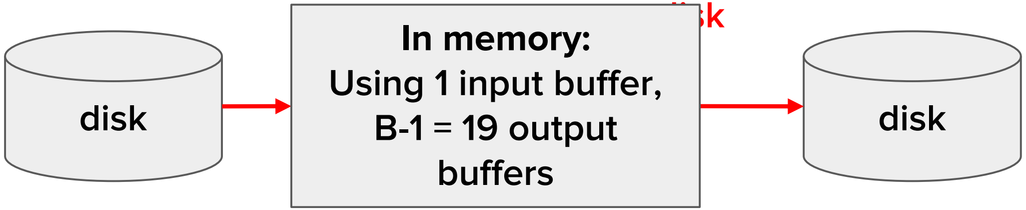
- B = 20
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Assume uniform partitioning



Worksheet Q1f

- B = 20
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Assume uniform partitioning

Read into memory | Partition | Write to



100 pages of N	50 pages of C

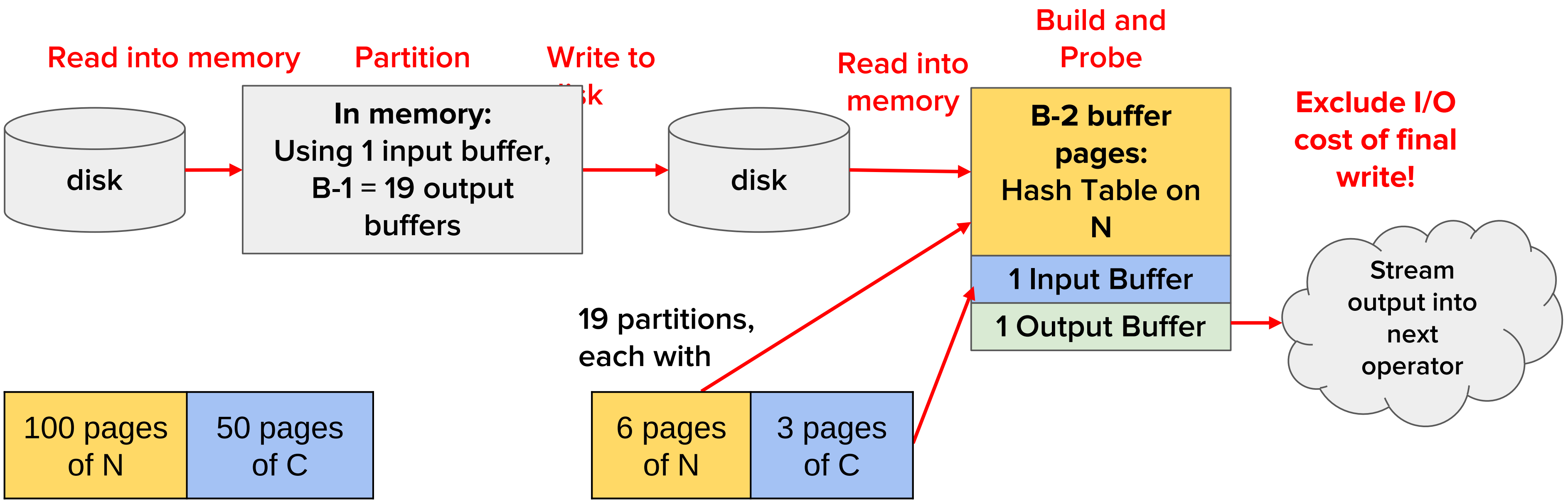
19 partitions,
each with

6 pages of N	3 pages of C

The partitions for at least 1 table fit in B-2 = 18 pages, so we can enter the Build and Probe phase.

Worksheet Q1f

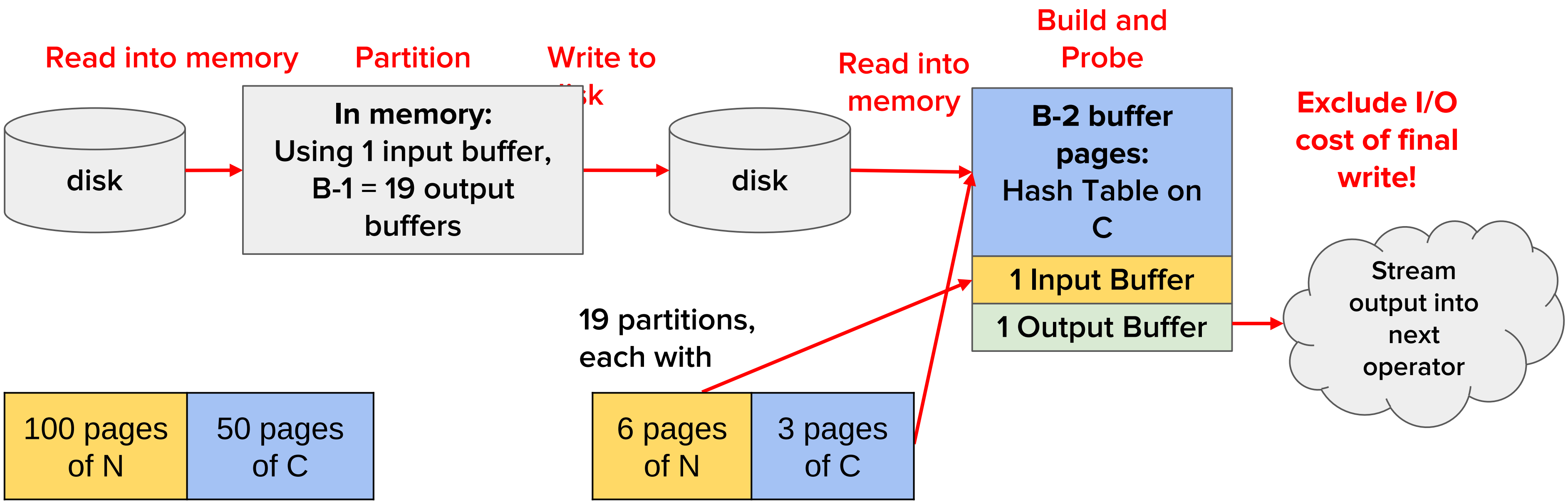
- B = 20
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Assume uniform partitioning



The partitions for at least 1 table fit in B-2 = 18 pages, so we can enter the Build and Probe phase.

Worksheet Q1f

- B = 20
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Assume uniform partitioning



Note: We can alternatively build a hash table on C and probe N since partitions for either relation fit in B-2 pages.

Worksheet Q1f

How many disk I/Os are needed to perform a hash join? Assume uniform partitioning.

- B = 20
- [N] = 100 pages, p_N = 100 tuples per page
- [C] = 50 pages, p_C = 50 tuples per page
- Assume uniform partitioning

No recursive partitioning required.

Partitioning phase:

ceil([N]/(B - 1))= 6 pages per partition for N, 19(6) pages

ceil([C]/(B - 1)) = 3 pages per partition for C, 19(3) pages

I/Os for Partitioning phase: 100 I/Os to read for N + 19(6) I/Os to write for N + 50 I/Os to read for C + 19(3) I/Os to write for C = 321 I/Os

I/Os for Build and Probe phase: 19(6) + 19(3) = 171 I/Os to read for N and C

Total: 321 + 171 = 492 I/Os

Worksheet Q2a

If we had 10 buffer pages, how many partitioning phases would we require for grace hash join?

- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

Worksheet Q2a

If we had 10 buffer pages, how many partitioning phases would we require for grace hash join?

- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

T is smaller, so we need its partitions to be at most B - 2 = 8 pages. After 1 partitioning pass, we have partitions of size 6, which is <= 8 so we only need **1 partitioning pass.**

Worksheet Q2b

What is the IO cost for the grace hash join then? Assume uniform partitioning.

- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

Worksheet Q2b

What is the IO cost for the grace hash join then? Assume uniform partitioning.

- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

We need 1 partitioning pass.

Partitioning phase:

ceil([C]/(B - 1)) = 12 pages per partition for C, 12(9) pages in total after partitioning

ceil([T]/(B - 1)) = 6 pages per partition for T, 6(9) pages in total after partitioning

Partitioning IOs: 100 I/Os to read from Catalog + 12(9) to write for Catalog + 50 I/Os to read from Transactions + 6(9) to write for Transactions = 312 I/Os

Probing phase: 12(9) + 6(9) = 162 I/Os to read from Catalog and Transactions

Total: 312 + 162 = 474 I/Os

Worksheet Q2c

If we only had 8 buffer pages, how many partitioning phases would there be?

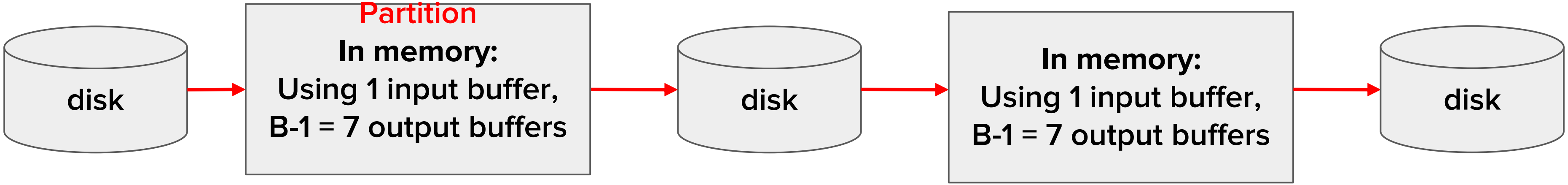
- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

Worksheet Q2c,d

- B = 8
- [C] = 100 pages
- [T] = 50 pages
- Assume the hash functions uniformly distribute the data for both tables.

Pass 1: Partition

Pass 2: Partition



Read into memory

100 pages of C	50 pages of T

Write to disk

7 partitions, each with

15 pages of C	8 pages of T

The partitions for neither table fit in B-2 = 6 pages, so we must **recursively partition.**

Read into memory

Write to disk

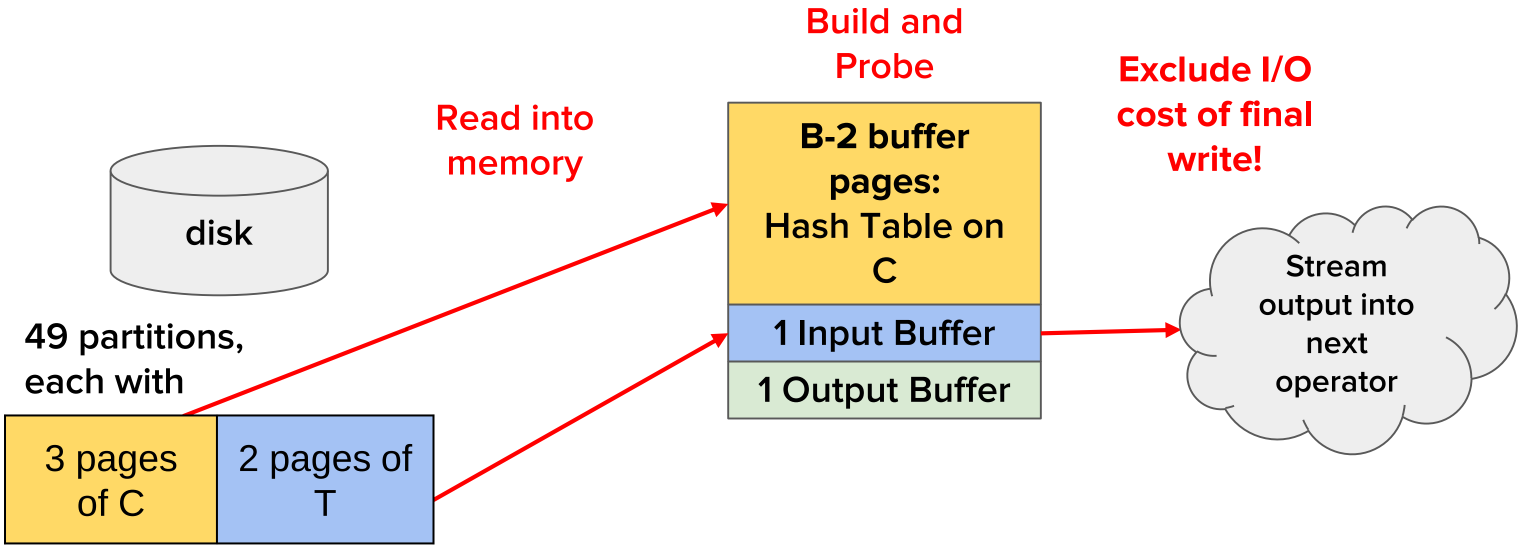
49 partitions, each with

3 pages of C	2 pages of T

The partitions for at least 1 table fit in B-2 = 6 pages, so we can enter the Build and Probe phase.

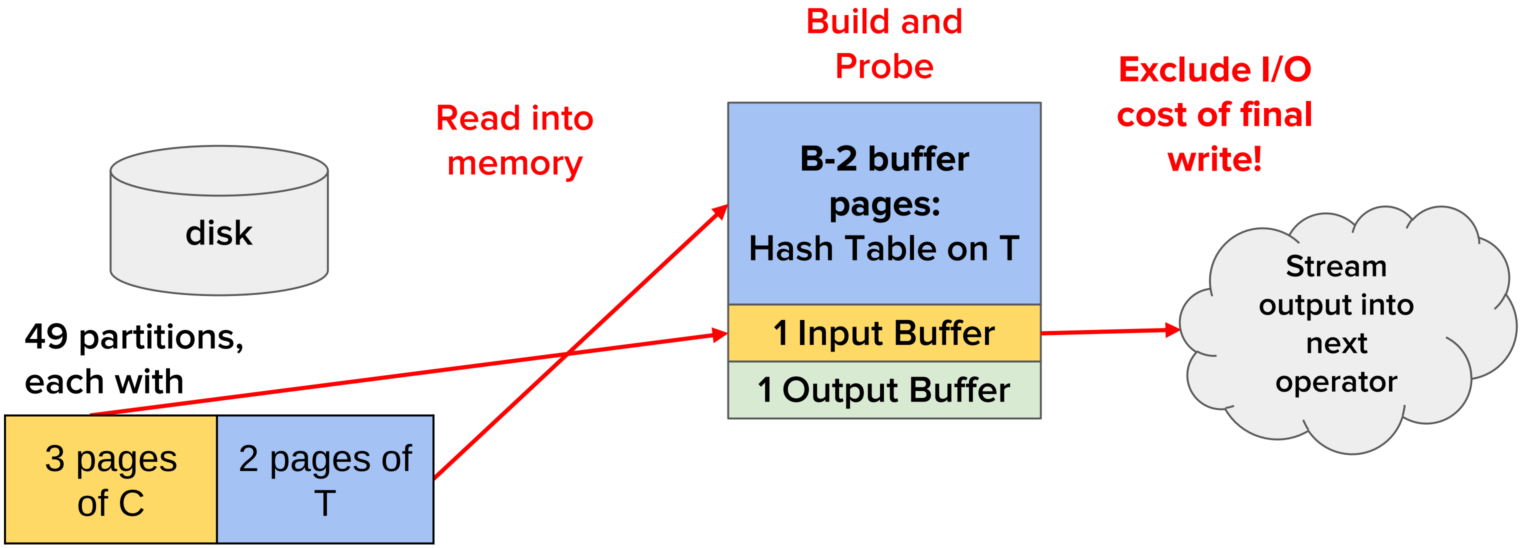
Worksheet Q2c,d

- B = 8
- [C] = 100 pages
- [T] = 50 pages
- Assume the hash functions uniformly distribute the data for both tables.



Worksheet Q2c,d

- B = 8
- [C] = 100 pages
- [T] = 50 pages
- Assume the hash functions uniformly distribute the data for both tables.



Note: We can alternatively build a hash table on T and probe C since partitions for either relation fit in B-2 pages.

Worksheet Q2c

If we only had 8 buffer pages, how many partitioning phases would there be?

- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

T is smaller, so we need its partitions to be at most B - 2 = 6 pages. After 1 partitioning pass,

we have partitions of size 8, which is too big to fit in B-2 buffer pages. We need a second

partitioning pass. 8 / 7 = 1.1→2 pages, which is small enough to fit in B-2 buffer pages.

Therefore, we need **2 passes in total.**

Worksheet Q2d

What will be the IO cost?

- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

Worksheet Q2d

What will be the IO cost?

- 2 tables: Catalog and Transactions
- [C] = 100 pages, p_C = 20 tuples per page
- [T] = 50 pages, p_T = 50 tuples per page
- Assume the hash functions uniformly distribute the data for both tables.

Partitioning phase:

ceil([C]/(B - 1)) = 15 pages per partition for C

ceil([T]/(B - 1)) = 8 pages per partition for T

ceil([C]/(B - 1)) = 3 pages per partition for second pass for C

ceil([T]/(B - 1)) = 2 pages per partition for second pass for T

	Read 1st	Write 1st	Read 2nd	Write 2nd	
Partitioning IOs:	[100 + 50] +	[15(7) + 8(7)] +	[15(7) + 8(7)] +	[3(49) + 2(49)]	= 717 I/Os

Build and Probe Phase: 3(49) + 2(49) = 245 IOs

Total: 717 + 245 = **962 I/Os**