CS 4440 A

Emerging Database Technologies

Lecture 10

02/12/25

Announcement

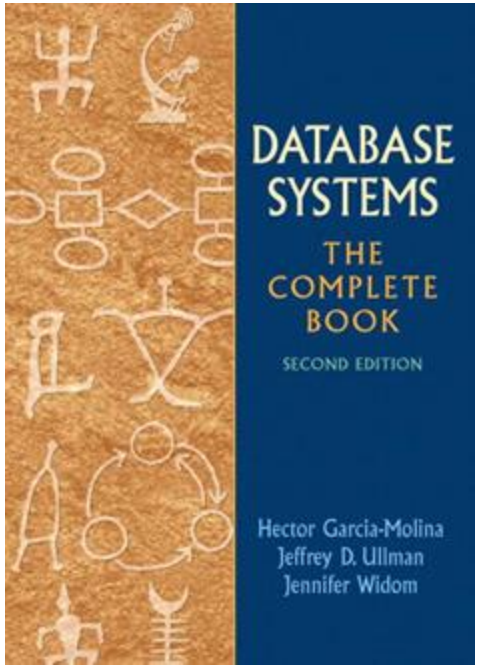
Assignment 2 released

- Groups with 3-5 members

Reading Materials

Database Systems: The Complete Book (2nd edition)

- Chapter 15: Query Execution



Acknowledgement: The following slides have been adapted from CS145 (Intro to Big Data Systems) taught by Peter Bailis.

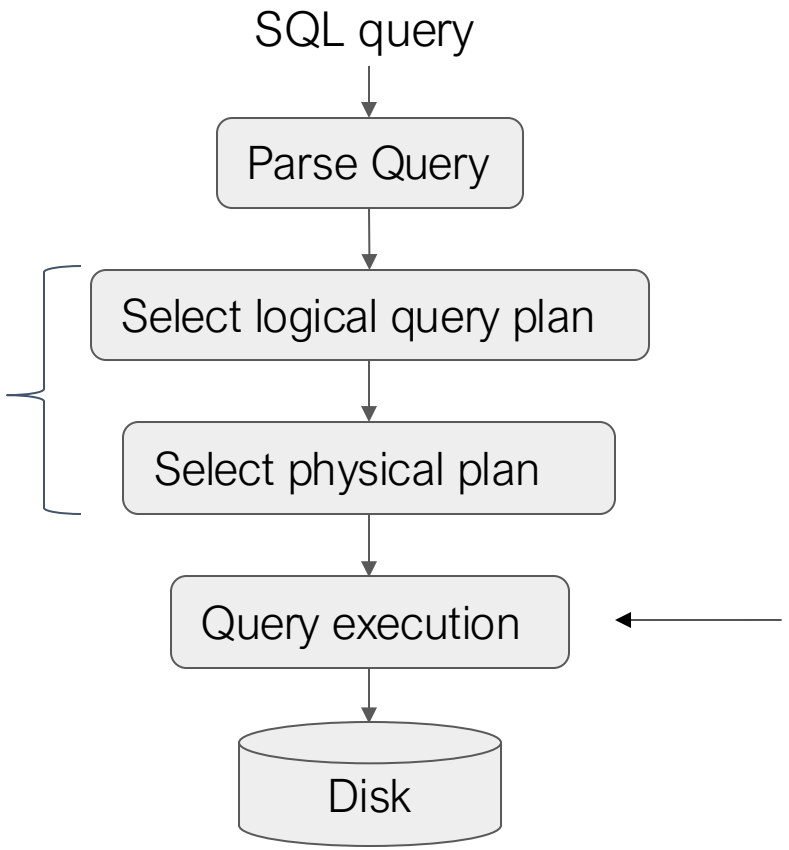
Agenda

RECAP: Joins

1. Nested Loop Join (NLJ)
2. Sort-Merge Join (SMJ)
3. Hash Join (HJ)

RDBMS Architecture

How does a SQL engine work ?



Query optimization (next two lectures)

Query execution (this lecture): algorithms that manipulate the data of the database

We will use JOIN algorithms as an example

- Arguable one of the most computational expensive operations in relational databases

- As we will see, different implementations of JOINs can make a huge difference in performance.

Joins: Example

$\mathbf{R} \bowtie \boldsymbol{S}$

```
SELECT R.A,B,C,D
FROM   R, S
WHERE  R.A = S.A
```

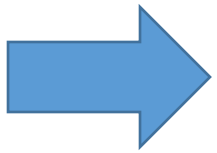
Example: Returns all pairs of tuples $r \in R, s \in S$ such that $r.A = s.A$

R

A	B	C
1	0	1
2	3	4
2	5	2
3	1	1

S

A	D
3	7
2	2
2	3



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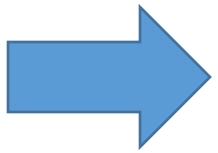

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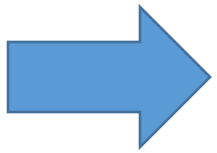

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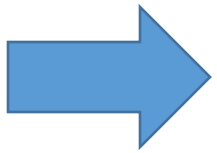

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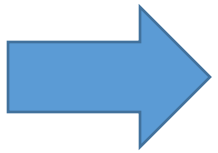

A	B	C	D
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Semantically: A Subset of the Cross Product

$\mathbf{R} \bowtie \boldsymbol{S}$

```
SELECT R.A,B,C,D
FROM   R, S
WHERE  R.A = S.A
```

Example: Returns all pairs of tuples $r \in R, s \in S$ such that $r.A = s.A$

R

A	B	C
1	0	1
2	3	4
2	5	2
3	1	1

×

S

A	D
3	7
2	2
2	3

→ Cross Product → … → Filter by conditions (r.A = s.A)

A	B	C	D
2	3	4	2
2	3	4	3
2	5	2	2
2	5	2	3
3	1	1	7

Can we actually implement a join in this way?

1. Nested Loop Joins

Notes

- We write $\mathbf{R} \bowtie \boldsymbol{S}$ to mean *join R and S by returning all tuple pairs where* ***all shared attributes*** *are equal*

- We write $\mathbf{R} \bowtie \boldsymbol{S}$ on A to mean *join R and S by returning all tuple pairs where* ***attribute(s) A*** *are equal*

- For simplicity, we'll consider joins on **two tables** and with **equality constraints** ("equijoins")

Join can involve > 2 tables, and some algorithms do support non-equality constraints!

Notes

- We are considering “IO aware” algorithms: ***care about disk IO***

- Given a relation R, let:
  - T(R) = # of tuples in R
  - P(R) = # of pages in R

Recall that we read / write entire pages with disk IO

- Note also that we omit ceilings in calculations… good exercise to put back in!

Nested Loop Join (NLJ)

Compute $R \bowtie S \; on \; A$:

```
for r in R:
  for s in S:
    if r[A] == s[A]:
      yield (r,s)
```

Nested Loop Join (NLJ)

Compute $R \bowtie S \; on \; A$:

```
for r in R:
  for s in S:
    if r[A] == s[A]:
      yield (r,s)
```

Cost:

$P(R)$

1. Loop over the tuples in R

Note that our IO cost is based on the number of pages loaded, not the number of tuples!

Nested Loop Join (NLJ)

Compute $R \bowtie S$ *on* A:

```
for r in R:
  for s in S:
    if r[A] == s[A]:
      yield (r,s)
```

Cost:

$$P(R) + T(R)*P(S)$$

1. Loop over the tuples in R
2. For every tuple in R, loop over all the tuples in S

Have to read all of S from disk for every tuple in R!

Nested Loop Join (NLJ)

Compute $R \bowtie S$ *on* A:

```
for r in R:
  for s in S:
    if r[A] == s[A]:
      yield (r,s)
```

Cost:

$$P(R) + T(R)*P(S)$$

1. Loop over the tuples in R
2. For every tuple in R, loop over all the tuples in S
3. Check against join conditions

Note that NLJ can handle things other than equality constraints… just check in the if statement!

Nested Loop Join (NLJ)

Compute $R \bowtie S$ *on* A:

```
for r in R:
  for s in S:
    if r[A] == s[A]:
      yield (r,s)
```

What would OUT be if our join condition is trivial (if TRUE)?

OUT could be P(R)*P(S)… but usually not that bad

Cost:

$$P(R) + T(R)*P(S) + OUT$$

1. Loop over the tuples in R
2. For every tuple in R, loop over all the tuples in S
3. Check against join conditions
4. Write out (to page, then when page full, to disk)

Nested Loop Join (NLJ)

Compute $R \bowtie S$ *on* A:

```
for r in R:
  for s in S:
    if r[A] == s[A]:
      yield (r,s)
```

Cost:

$$P(R) + T(R)*P(S) + OUT$$

What if R ("outer") and S ("inner") switched?

$$P(S) + T(S)*P(R) + OUT$$

Outer vs. inner selection makes a huge difference- DBMS needs to know which relation is smaller!

Block Nested Loop Join (IO-Aware Approach)

Block Nested Loop Join (BNLJ)

Given B+1 pages of memory

Compute $R \bowtie S$ *on* A:

```
for each B-1 pages pr of R:
  for page ps of S:
    for each tuple r in pr:
      for each tuple s in ps:
        if r[A] == s[A]:
          yield (r,s)
```

Cost:

$$P(R)$$

1. Load in B-1 pages of R at a time (leaving 1 page free for S & output)

Note: There could be some speedup here due to the fact that we're reading in multiple pages sequentially however we'll ignore this here!

Block Nested Loop Join (BNLJ)

Given B+1 pages of memory

Compute $R \bowtie S$ *on* A:

```
for each B-1 pages pr of R:
  for page ps of S:
    for each tuple r in pr:
      for each tuple s in ps:
        if r[A] == s[A]:
          yield (r,s)
```

Cost:

$$P(R) + \frac{P(R)}{B-1} P(S)$$

1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)

2. For each (B-1)-page segment of R, load each page of S

Note: Faster to iterate over the smaller relation first!

Block Nested Loop Join (BNLJ)

Given B+1 pages of memory

Compute $R \bowtie S$ *on* A:

```
for each B-1 pages pr of R:
  for page ps of S:
    for each tuple r in pr:
      for each tuple s in ps:
        if r[A] == s[A]:
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```

Cost:

$$P(R) + \frac{P(R)}{B-1} P(S)$$

1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)
2. For each (B-1)-page segment of R, load each page of S
3. Check against the join conditions

BNLJ can also handle non-equality constraints

Block Nested Loop Join (BNLJ)

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Compute $R \bowtie S$ *on* A:

```
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  for page ps of S:
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          yield (r,s)
```

Cost:

$$P(R) + \frac{P(R)}{B-1} P(S) + \text{OUT}$$

1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)
2. For each (B-1)-page segment of R, load each page of S
3. Check against the join conditions
4. Write out

BNLJ vs. NLJ: Benefits of IO Aware

In BNLJ, by loading larger chunks of R, we minimize the number of full *disk reads* of S

- We only read all of S from disk for ***every (B-1)-page segment of R***!
- Still the full cross-product, but more done only *in memory*

NLJ

$$\mathrm{P(R) + T(R)*P(S) + OUT}$$

BNLJ

$$\mathrm{P}(R) + \frac{P(R)}{B-1} P(S) + \mathrm{OUT}$$

BNLJ is faster by roughly $\frac{(B-1)T(R)}{P(R)}$!

BNLJ vs. NLJ: Benefits of IO Aware

Example:

- R: 500 pages
- S: 1000 pages
- 100 tuples / page
- We have 12 pages of memory (B = 11)

Ignoring OUT here…

NLJ: Cost = 500 + **50,000*1000** = **50 Million IOs ~= 140 hours**

BNLJ: Cost = 500 + $\frac{500*1000}{10}$ = **50 *Thousand* IOs ~= 0.14 hours**

A real difference from a small change in the algorithm!

1. Nested Loop Joins

1.2. Smarter than Cross-Products

Index Nested Loop Join
(Smarter than Cross-Products)

Smarter than Cross-Products: From Quadratic to Nearly Linear

All joins that compute the ***full cross-product*** have some **quadratic** term

- For example we saw:

NLJ $\mathrm{P(R)} + \mathrm{T(R)P(S)} + \mathrm{OUT}$

BNLJ $\mathrm{P}(R) + \frac{\boldsymbol{P(R)}}{B-1}\boldsymbol{P(S)} + \mathrm{OUT}$

Now we'll see some (nearly) linear joins:

- ~ O(P(R) + P(S) + ***OUT***), where again ***OUT*** could be quadratic but is usually better

We get this gain by taking advantage of structure - equality constraints ("equijoin") only!

Index Nested Loop Join (INLJ)

Compute $R \bowtie S$ *on* A:

```
Given index idx on S.A:
  for r in R:
    if s in idx(r[A]):
      yield r,s
```

Cost:

P(R) + T(R)*L + OUT

where L is the IO cost to access all the distinct values in the index; assuming these fit on one page, $L \sim 3$ is good estimate

→ We can use an index (e.g., B+ Tree) to avoid doing the full cross-product!

2. Sort-Merge Join (SMJ)

Sort Merge Join (SMJ): Basic Procedure

To compute $\mathrm{R} \bowtie S \; on \; A$:

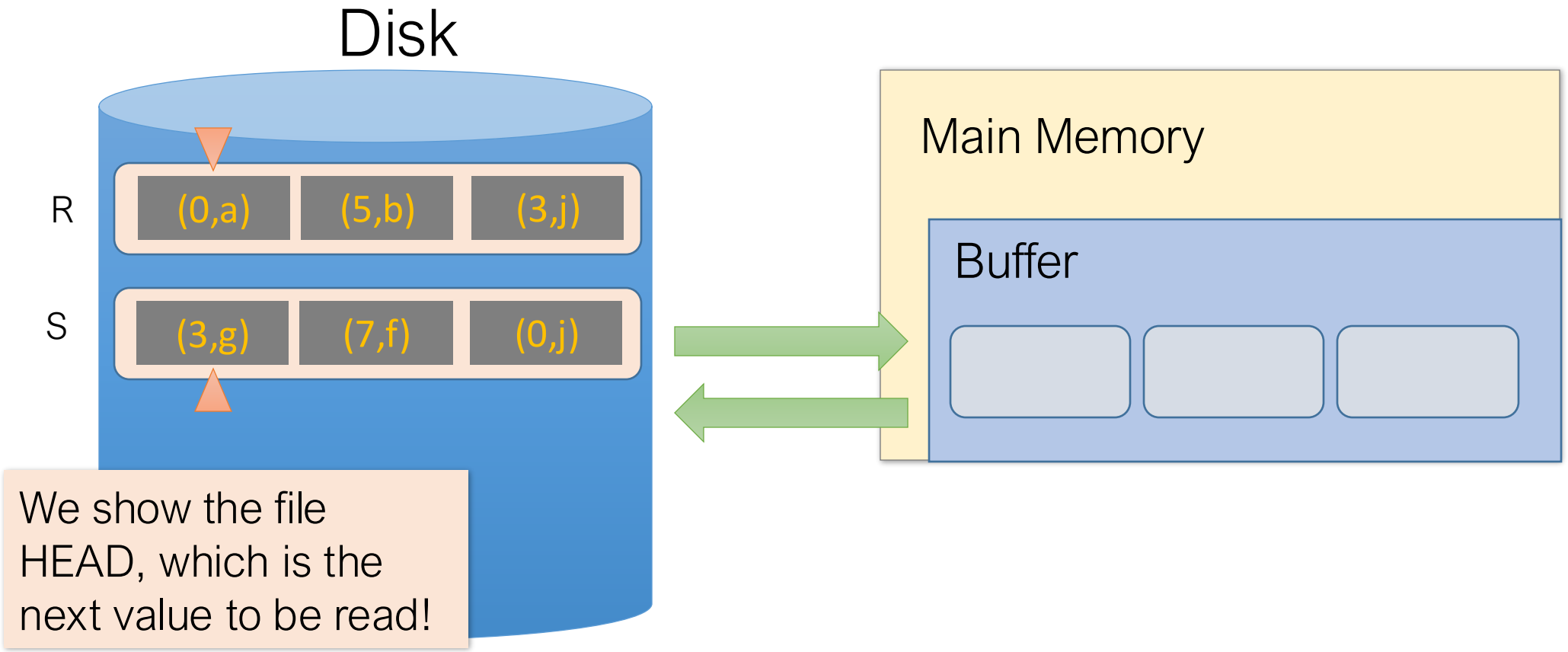
1. Sort R, S on A using ***external merge sort***
2. ***Scan*** sorted files and "merge"
3. *[May need to "backup"- see next subsection]*

Note that we are only considering equality join conditions here

Note that if R, S are already sorted on A, SMJ will be awesome!

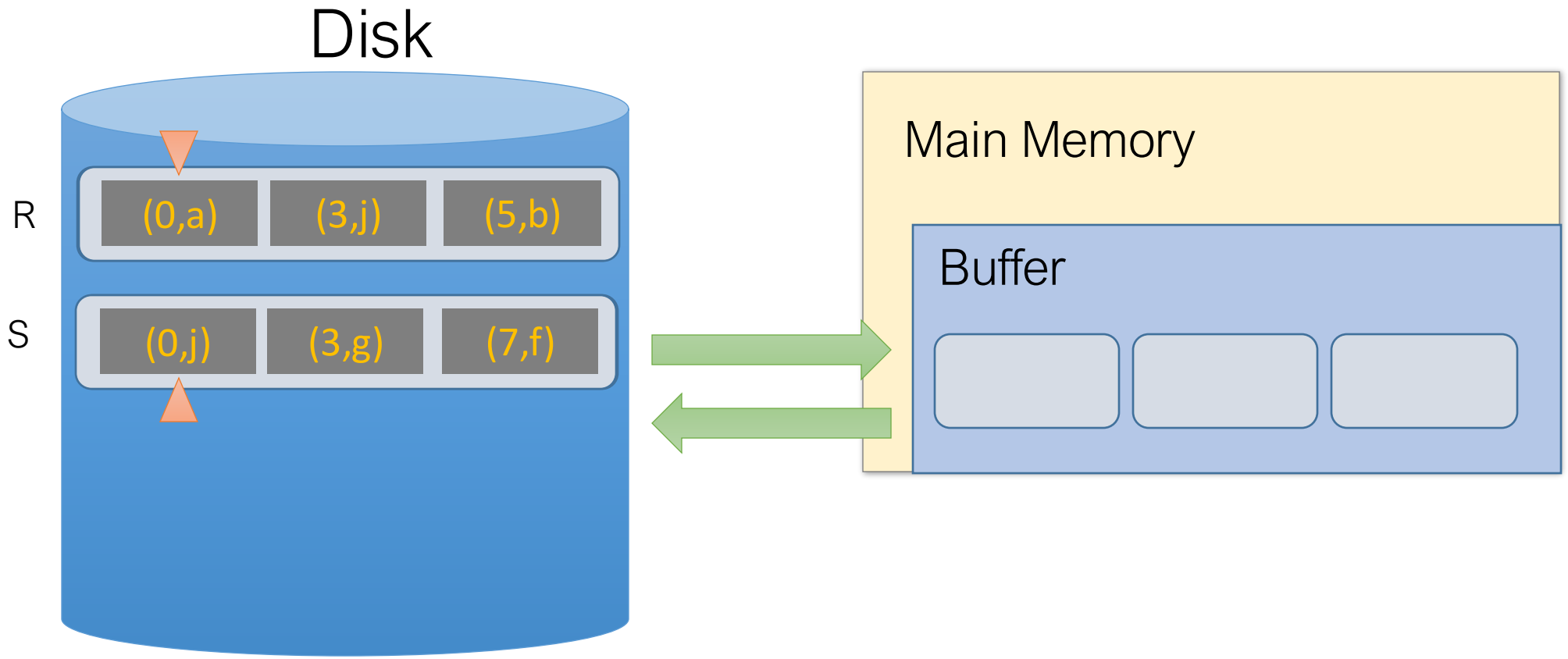
SMJ Example: $R \bowtie S$ *on* A with 3 page buffer

- For simplicity: Let each page be ***one tuple***, and let the first value be A



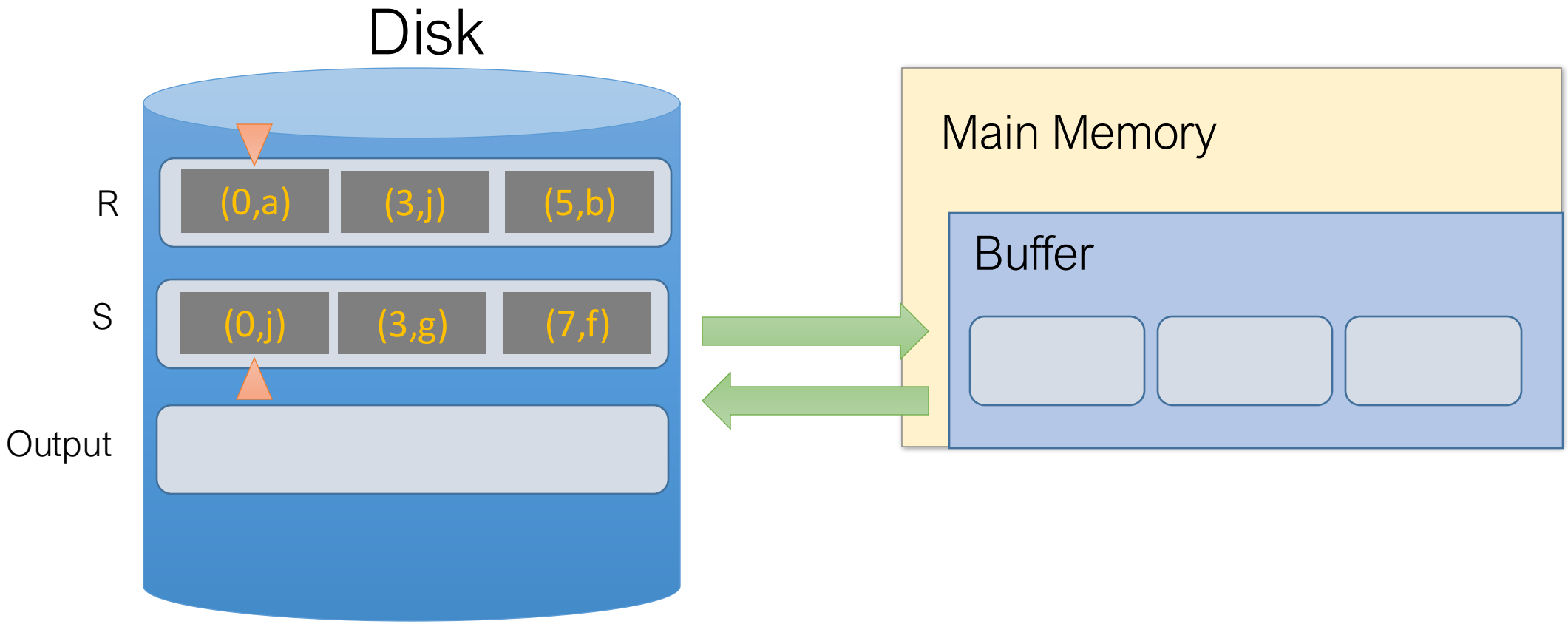
SMJ Example: $R \bowtie S$ *on* A with 3 page buffer

1. Sort the relations R, S on the join key (first value)



SMJ Example: $\mathrm{R} \bowtie S \; on \; A$ with 3 page buffer

2. Scan and “merge” on join key!



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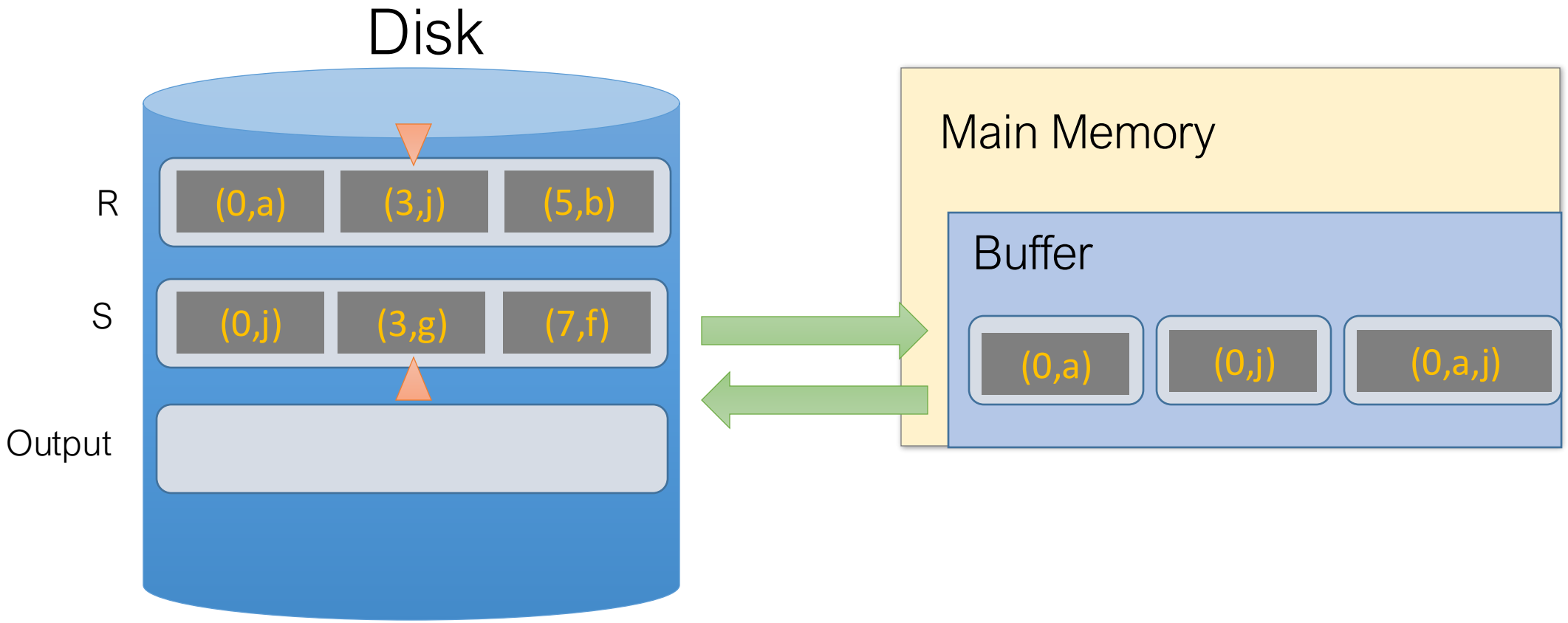

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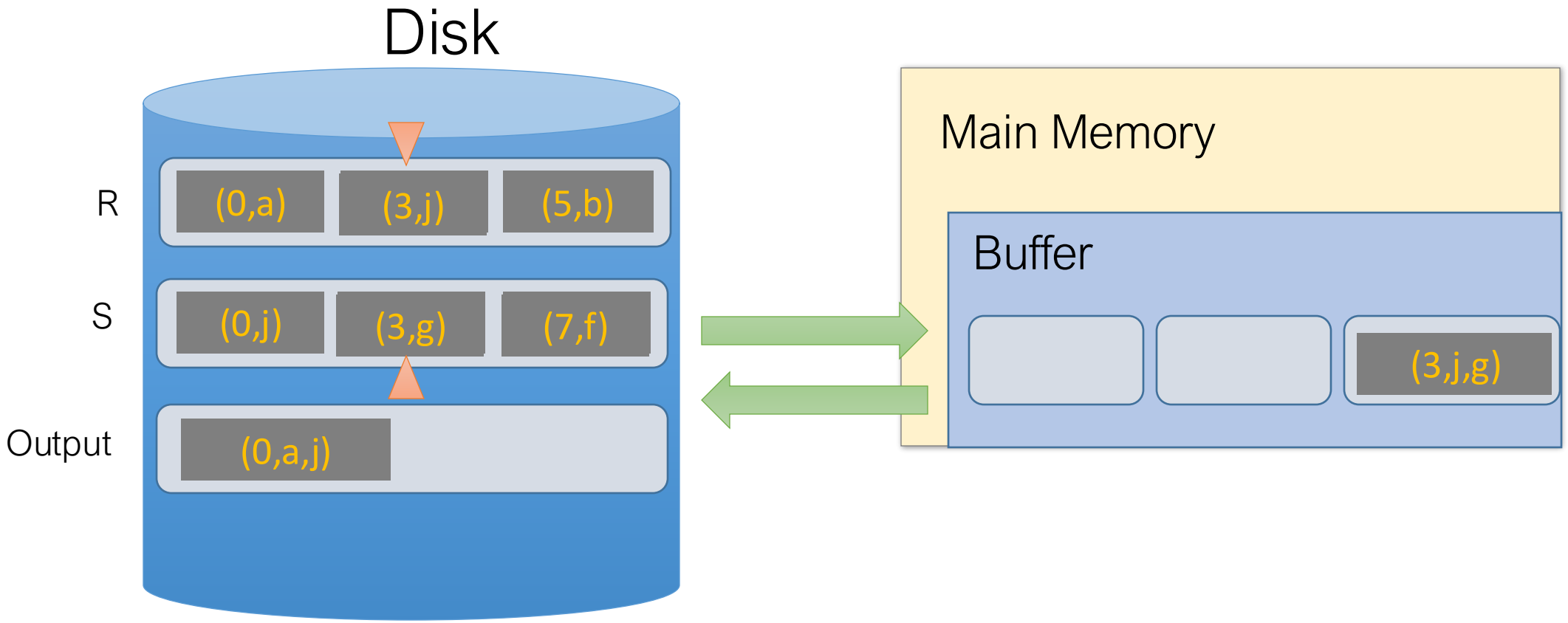
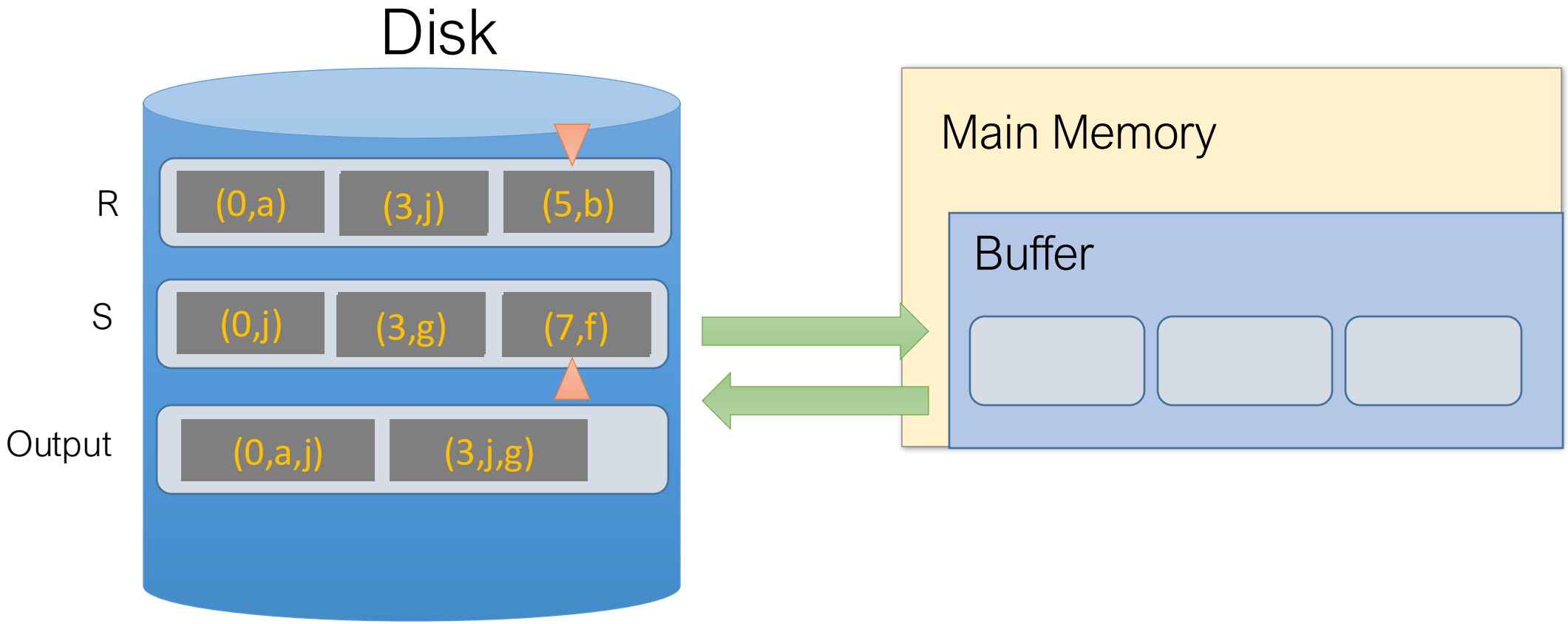


SMJ Example: $\mathrm{R} \bowtie S \; on \; A$ with 3 page buffer

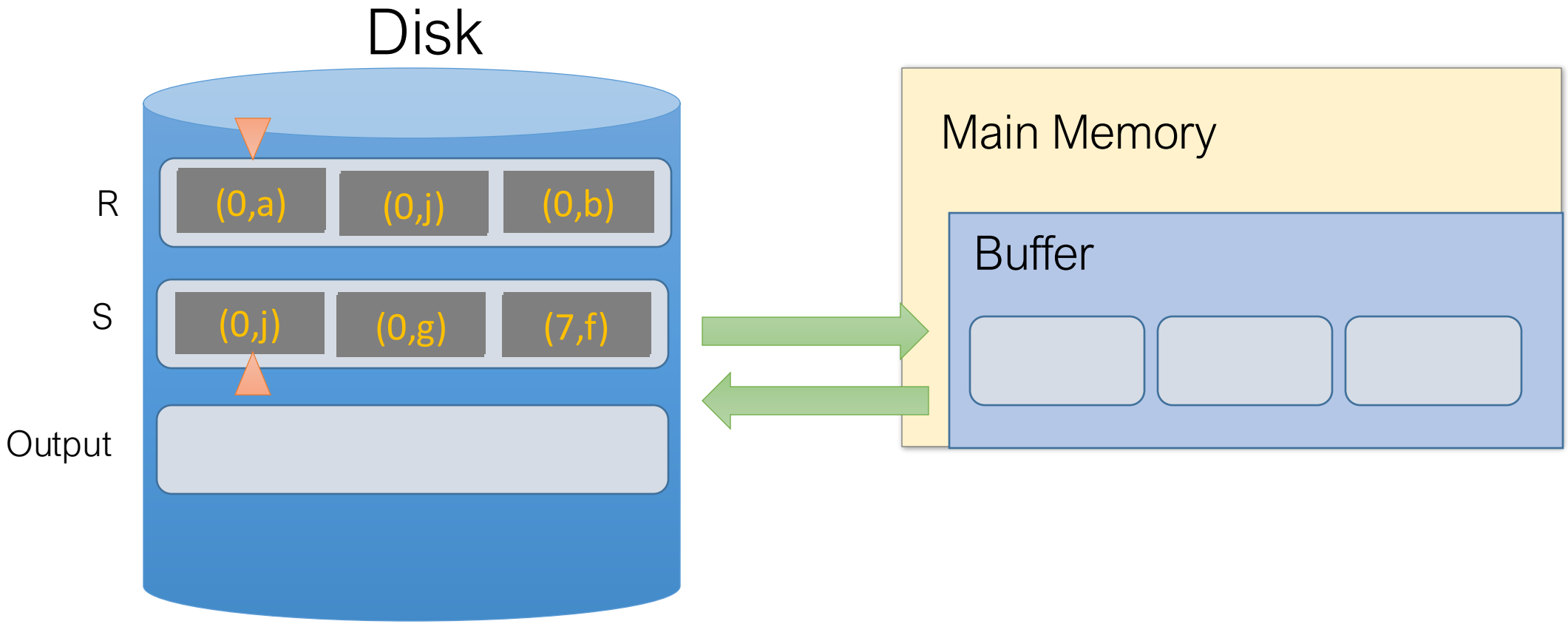
2. Done!



What happens with duplicate join keys?

Multiple tuples with Same Join Key: “Backup”

1. Start with sorted relations, and begin scan / merge…



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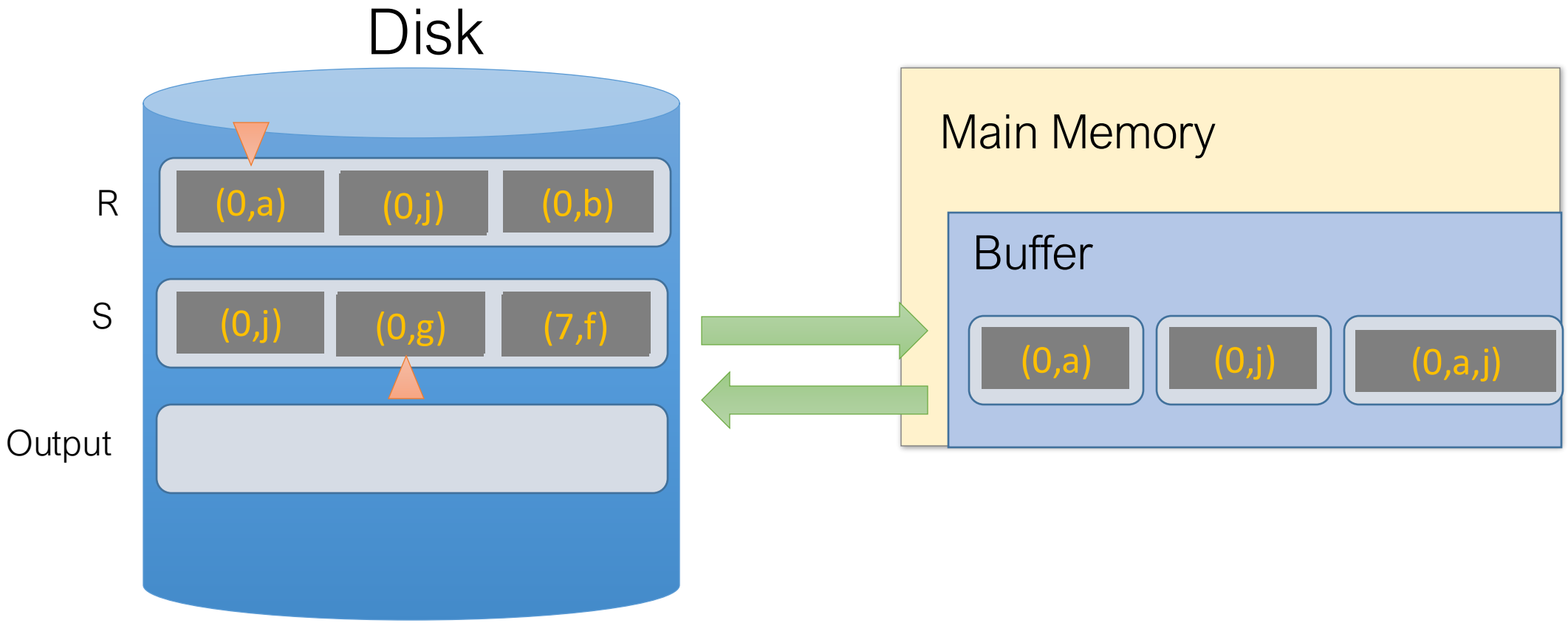

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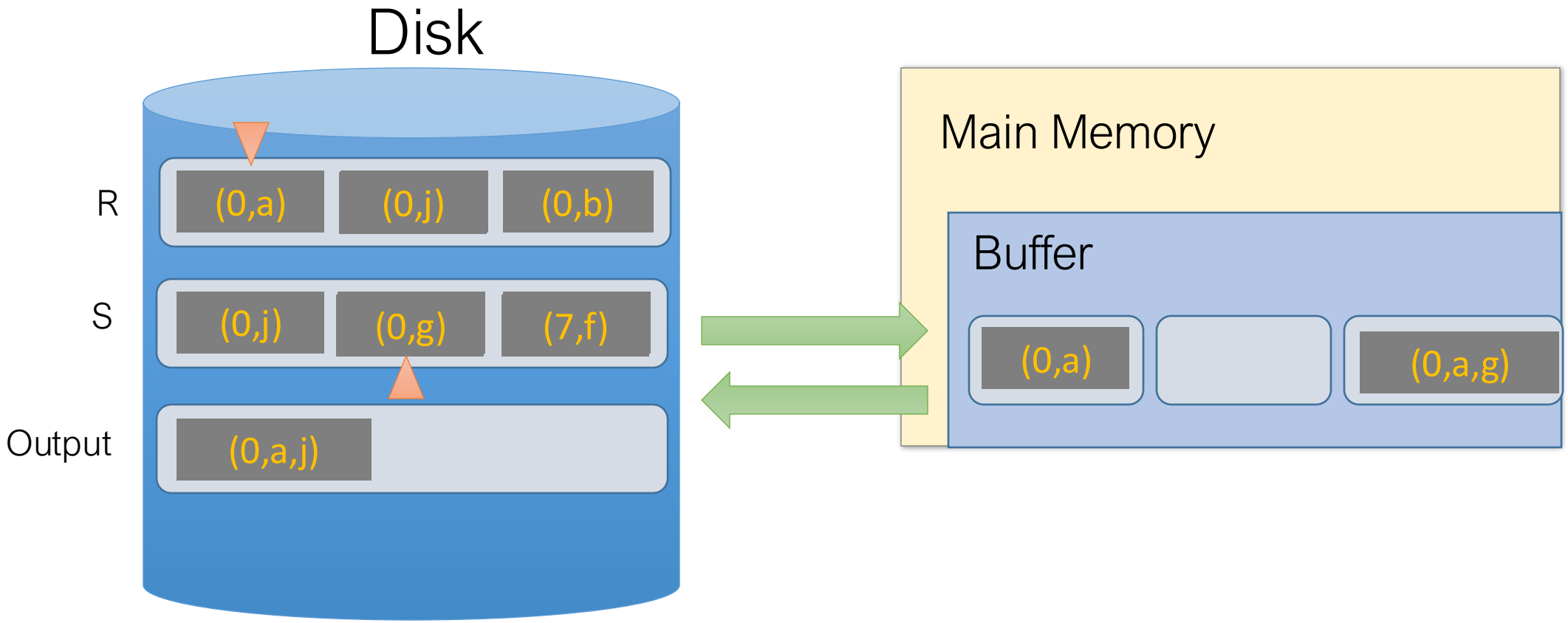

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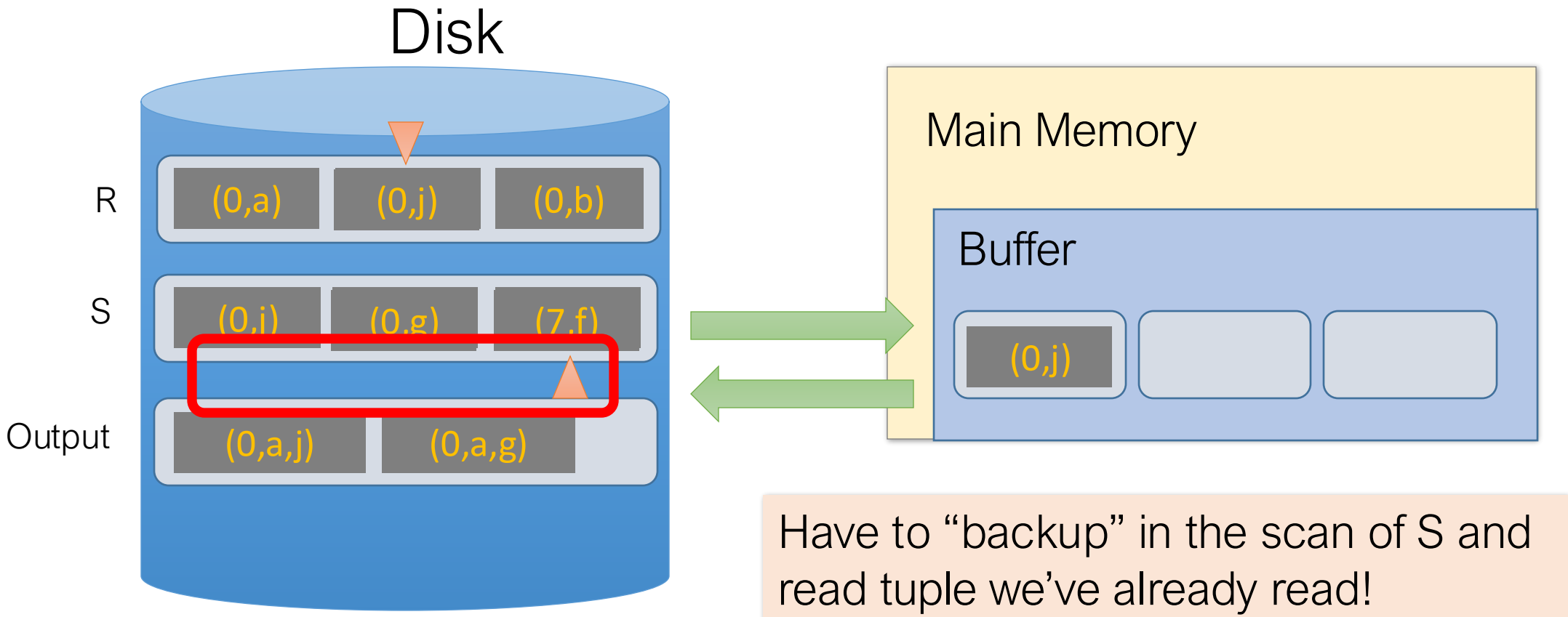


Have to “backup” in the scan of S and read tuple we’ve already read!

Backup

At best, no backup → scan takes P(R) + P(S) reads

- For ex: if no duplicate values in join attribute

At worst (e.g. full backup each time), scan could take P(R) * P(S) reads!

- For ex: if *all* duplicate values in join attribute, i.e. all tuples in R and S have the same value for the join attribute
- Roughly: For each page of R, we'll have to *back up* and read each page of S…

Often not that bad however, plus we can:

- Leave more data in buffer (for larger buffers)

SMJ: Total cost

Cost of SMJ is **cost of sorting** R and S…

What's the cost of sorting?

Plus the **cost of scanning**: ~P(R)+P(S)

- Because of *backup*: in worst case P(R)*P(S); but this would be very unlikely

Plus the **cost of writing out**

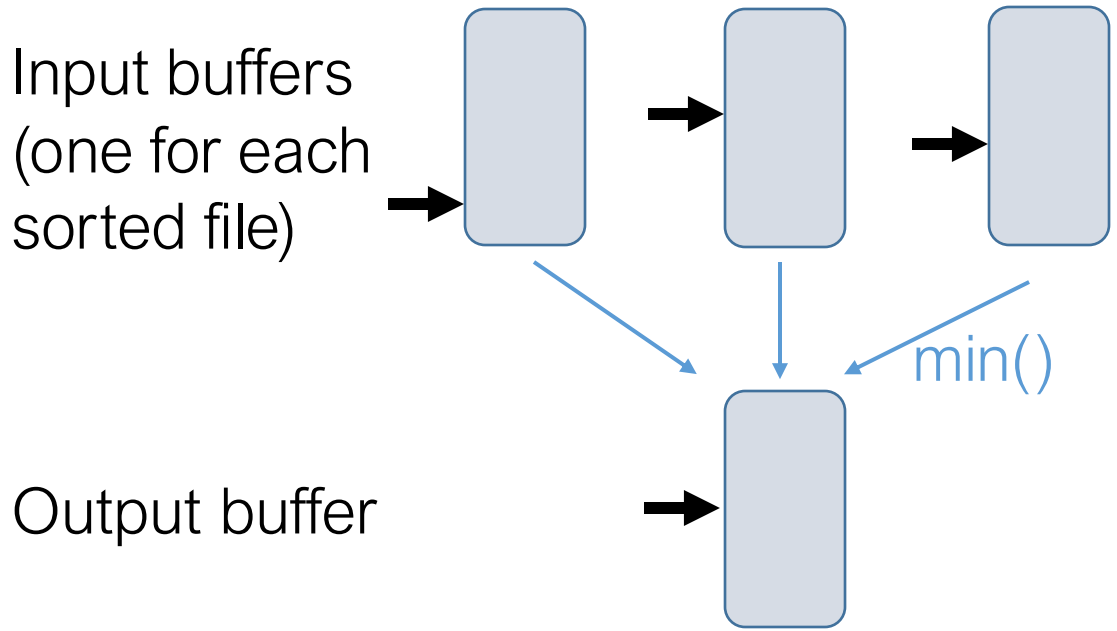
$$\sim \mathrm{Sort}(\mathrm{P}(\mathrm{R})) + \mathrm{Sort}(\mathrm{P}(\mathrm{S})) + \mathrm{P}(\mathrm{R}) + \mathrm{P}(\mathrm{S}) + \mathrm{OUT}$$

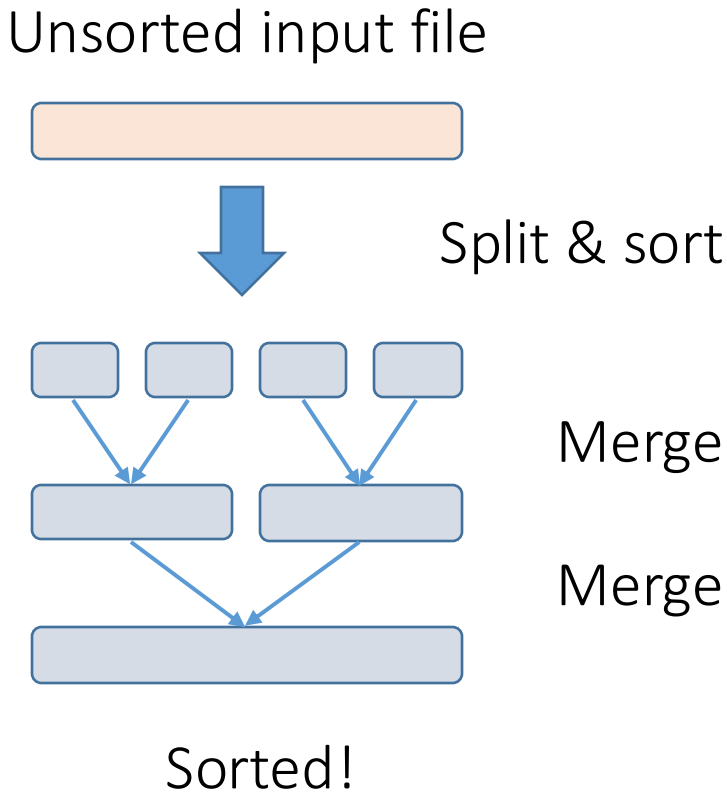
External Merge Sort

Given ***B+1*** buffer page

Phase 1. Split R into files small enough to sort in memory. Write sorted files to disk.

Phase 2. B-way merge of sorted files





External Merge Sort

Given ***B+1*** buffer page

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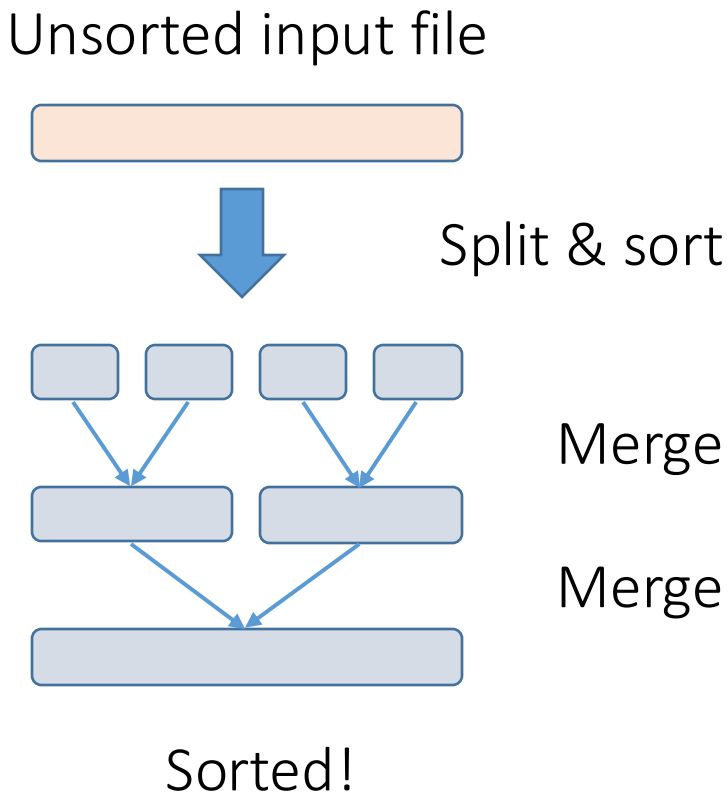


IO costs:

- Phase 1: 1 Read and 1 Write per page = 2N IOs
- Phase 2: 1 Read per page = N IOs

SMJ vs. BNLJ

If we have 100 buffer pages, P(R) = 1000 pages and P(S) = 500 pages:

- Sort both in two passes: 2 * 2 * (1000 + 500) = **6,000 IOs**
- Merge phase 1000 + 500 = 1,500 IOs
- **= 7,500 IOs + OUT**

What is BNLJ?

- 500 + 1000*$\left\lceil \frac{500}{98} \right\rceil$ = **6,500 IOs + OUT**

But, if we have 35 buffer pages?

- Sort Merge has same behavior (still 2 passes)
- BNLJ? ***15,500 IOs + OUT!***

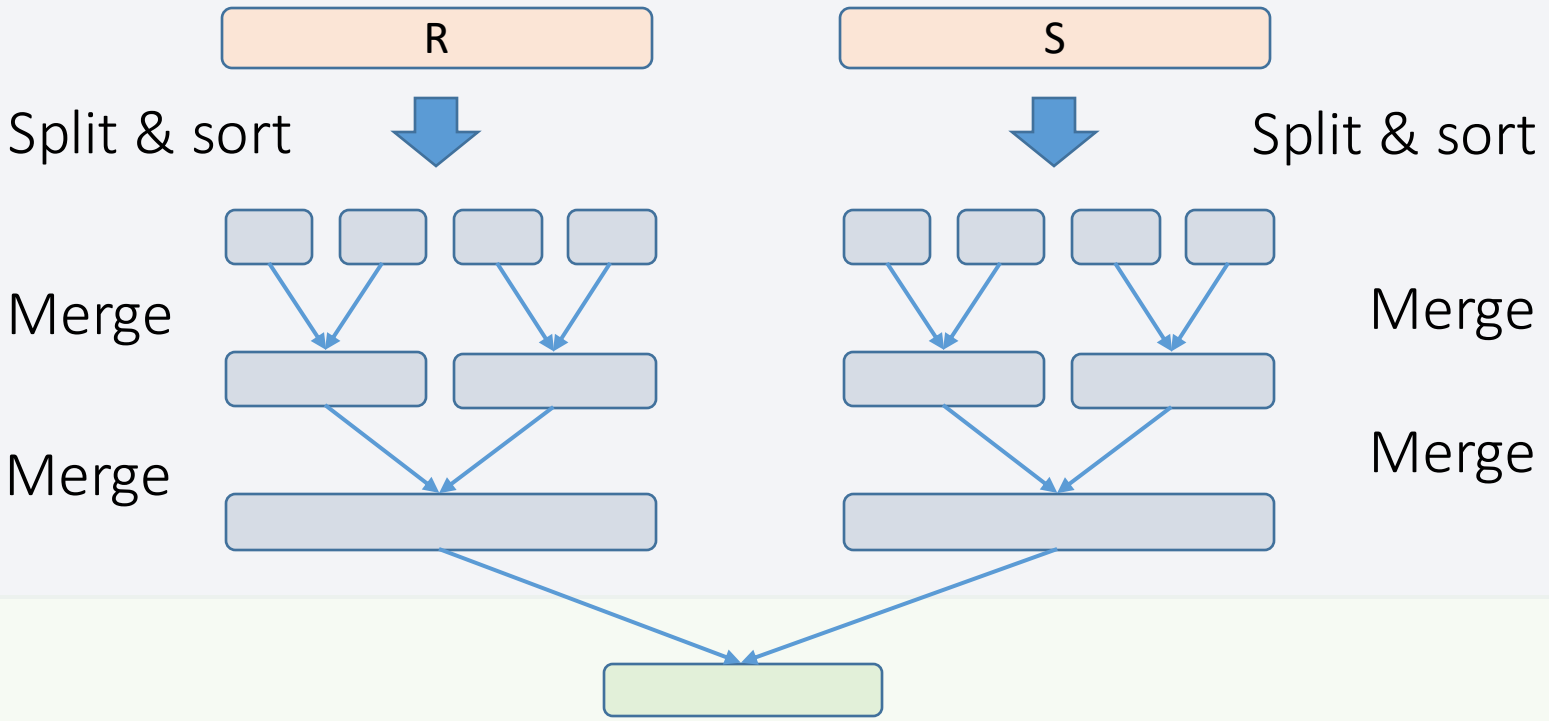
SMJ is ~ linear vs. BNLJ is quadratic…
But it's all about the memory.

Un-Optimized SMJ

Given ***B+1*** buffer pages

Unsorted input relations

Sort Phase
(Ext. Merge Sort)

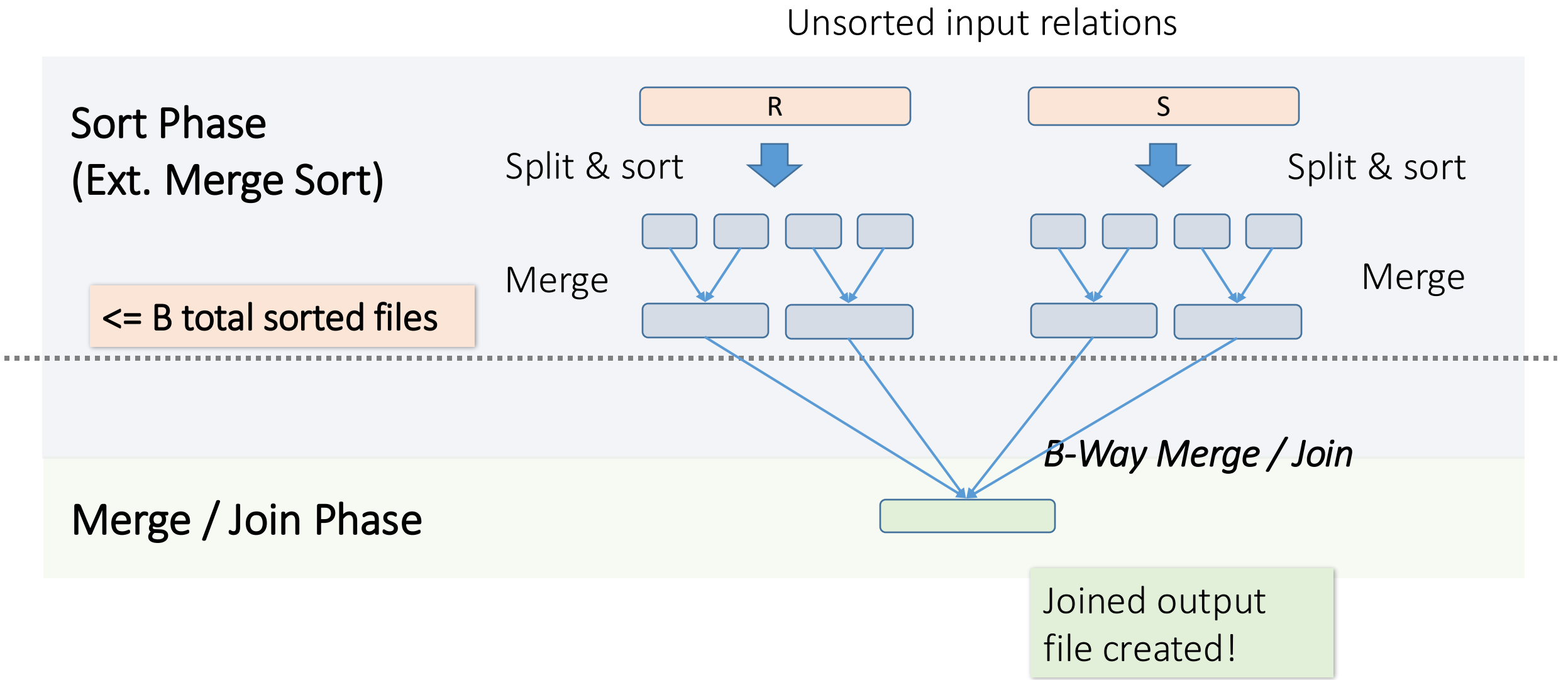


Merge / Join Phase

Joined output file created!

Simple SMJ Optimization

Given *B+1* buffer pages



Simple SMJ Optimization

Given ***B+1*** buffer pages

On this last pass, we only do P(R) + P(S) IOs to complete the join!

We are saving two disk I/O's per block by combining the second phase of the sorts with the join itself. ***3(P(R) + P(S)) + OUT*** for SMJ!

- 2 R/W per page to sort runs in memory, 1 R per page to B-way merge / join!

How much memory for this to happen?

- $\frac{P(R)+P(S)}{B} \leq B$
- Thus, $\mathbf{max\{P(R), P(S)\}} \leq \boldsymbol{B^2}$ is an approximate sufficient condition

If the larger of R,S has <= B^2 pages, then SMJ costs 3(P(R)+P(S)) + OUT!

Takeaway points from SMJ

If input already sorted on join key, skip the sorts.

- SMJ is basically linear.
- Nasty but unlikely case: Many duplicate join keys.

SMJ needs to sort **both** relations

- If max { P(R), P(S) } < B^2 then cost is 3(P(R)+P(S)) + OUT

3. Hash Join (HJ)

Recall: Hashing

- **Magic of hashing**:
  - A hash function h_B maps into [0, B-1]
  - And maps nearly uniformly

- A hash **collision** is when x != y but $h_B(x) = h_B(y)$
  - Note however that it will **never** occur that x = y but $h_B(x)$!= $h_B(y)$

- We hash on an attribute A, so our has function is $h_B(t)$ has the form $h_B(t.A)$.
  - **Collisions** may be more frequent.

Hash Join: High-level procedure

Given ***B+1*** buffer pages

To compute $\mathrm{R} \bowtie S \; on \; A$:

1. **Partition Phase:** Using one (shared) hash function h_B per pass partition R *and* S into ***B*** buckets.
   - Each phase creates B more buckets that are a factor of B smaller.
   - Repeatedly partition with a new hash function
   - Stop when all buckets for one relation are smaller than B-1 pages

Each pass takes $2(\mathrm{P(R)} + \mathrm{P(S)})$

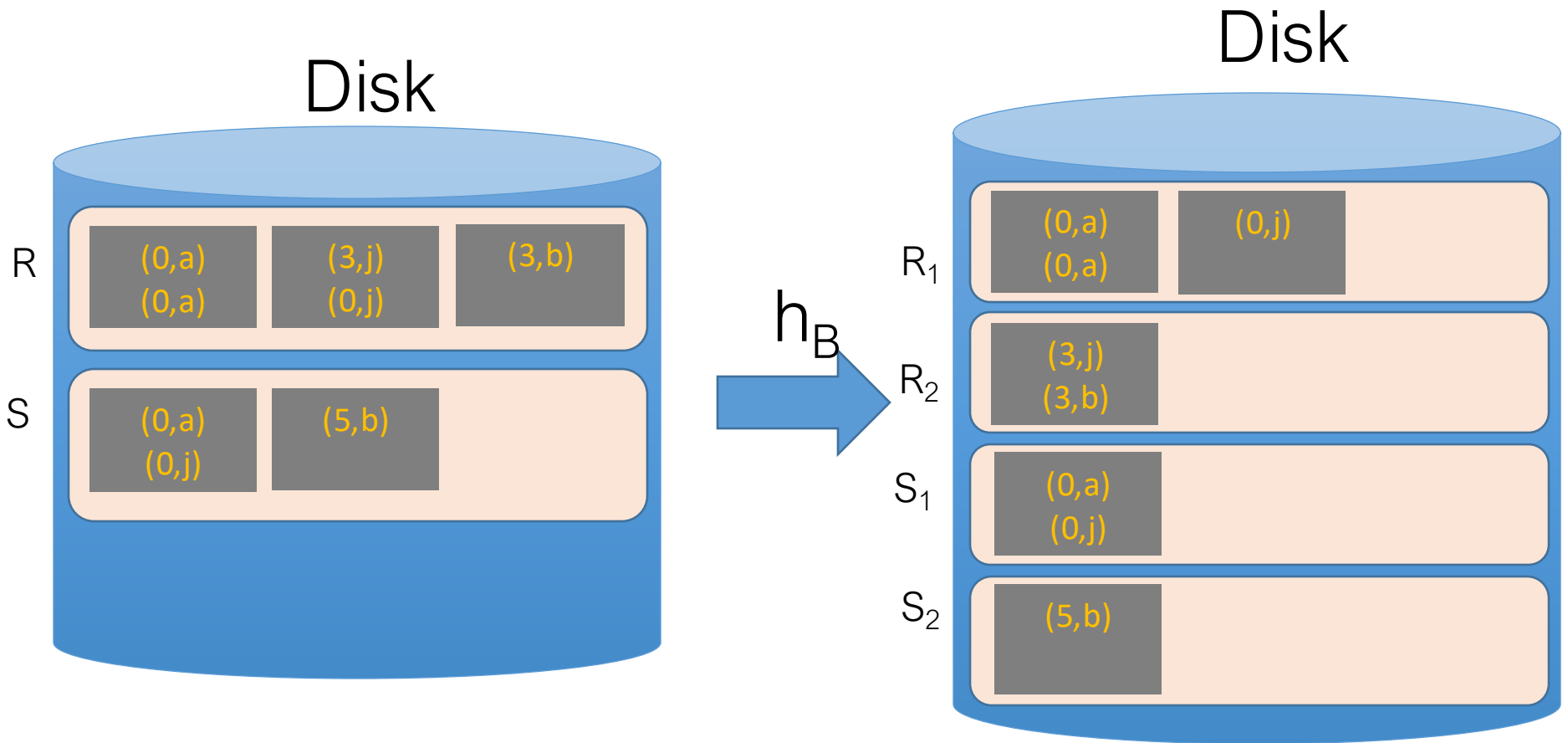
2. **Matching Phase:** Take pairs of buckets whose tuples have the same values for ***h***, and join these
   - Use BNLJ here for each matching pair.

$\mathrm{P(R)} + \mathrm{P(S)} + \mathrm{OUT}$

We ***decompose*** the problem using h_B, then complete the join

Hash Join: High-level procedure

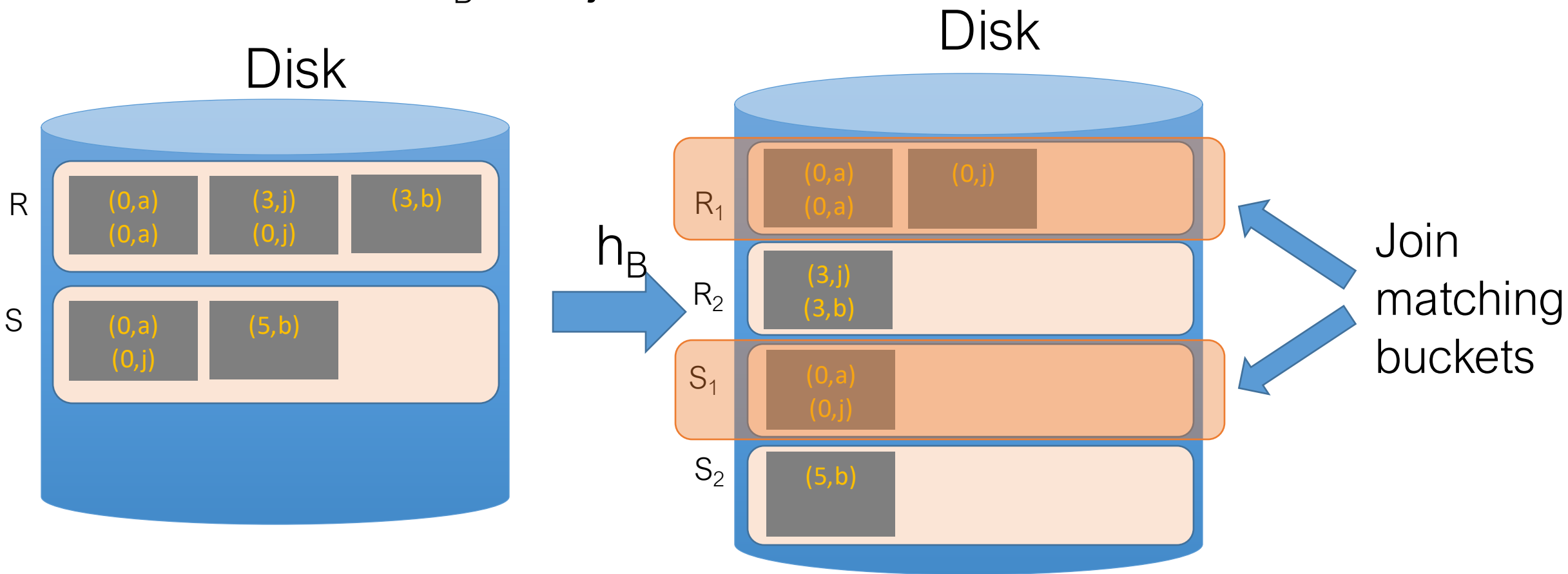
1. Partition Phase: Using one (shared) hash function h_B, partition R *and* S into ***B*** buckets



Suppose each pages has two tuples (one per row)

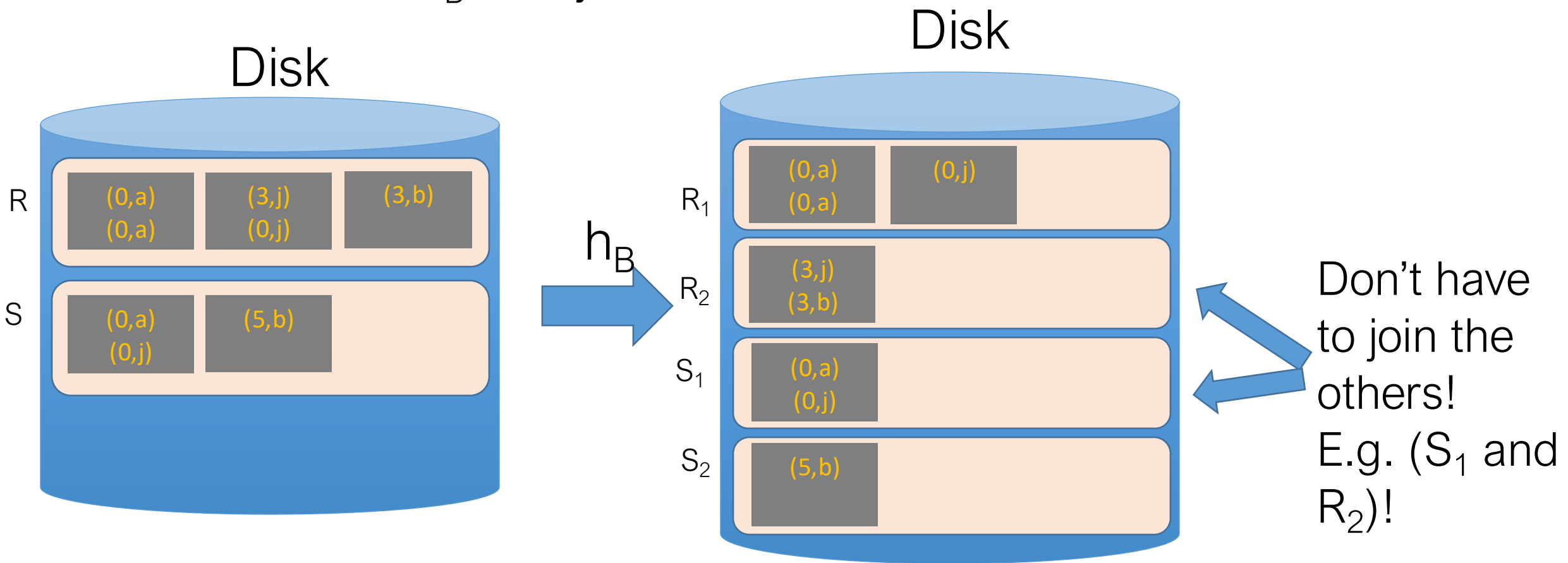
Hash Join: High-level procedure

2. Matching Phase: Take pairs of buckets whose tuples have the same values for h_B, and join these



Hash Join: High-level procedure

2. Matching Phase: Take pairs of buckets whose tuples have the same values for h_B, and join these

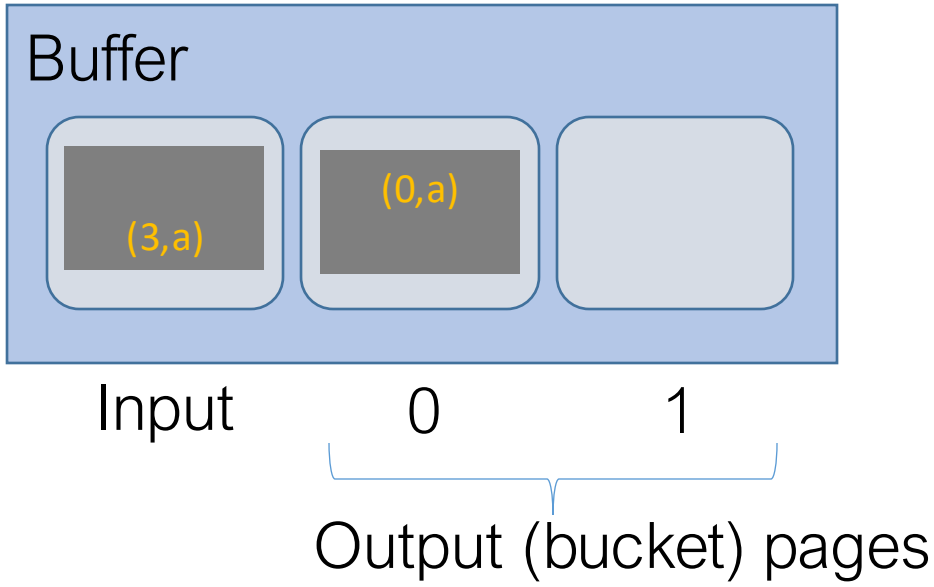


Hash Join Phase 1: Partitioning

Goal: For each relation, partition relation into **buckets** such that if $h_B(t.A) = h_B(t'.A)$ they are in the same bucket

Given B+1 buffer pages, we partition into B buckets:

- We use B buffer pages for output (one for each bucket), and 1 for input



How big *do we want* the resulting buckets?

Given B+1 buffer pages

Ideally, our buckets would be of size $\leq \boldsymbol{B-1}$ **pages**

Recall: If we want to join a bucket from R and one from S, we can do BNLJ **in linear time** if for *one of them (wlog say R),* $\boldsymbol{P(R) \leq B-1}$!

- And more generally, being able to fit bucket in memory is advantageous

Recall for BNLJ:

$$\mathrm{P}(R) + \frac{P(R)P(S)}{B-1}$$

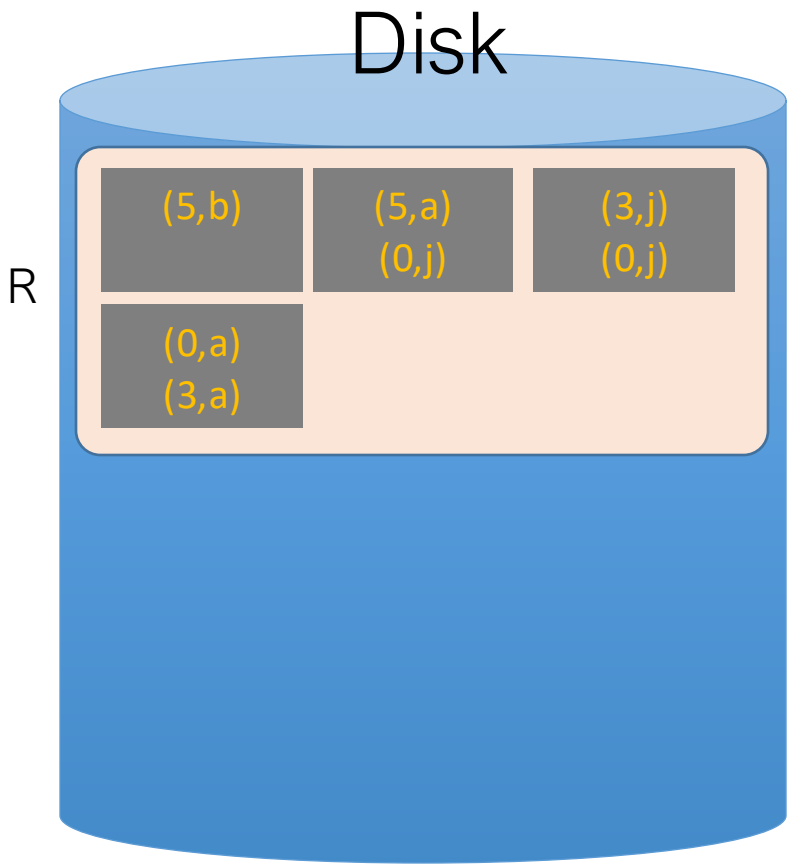
- We can keep partitioning buckets until they are $\leq \boldsymbol{B-1}$ **pages**
  - Using a new hash key which will split them…

We'll call each of these a "pass" again…

Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

We partition into ***B = 2*** buckets **using hash function h_2** so that we can have one buffer page for each partition (and one for input)



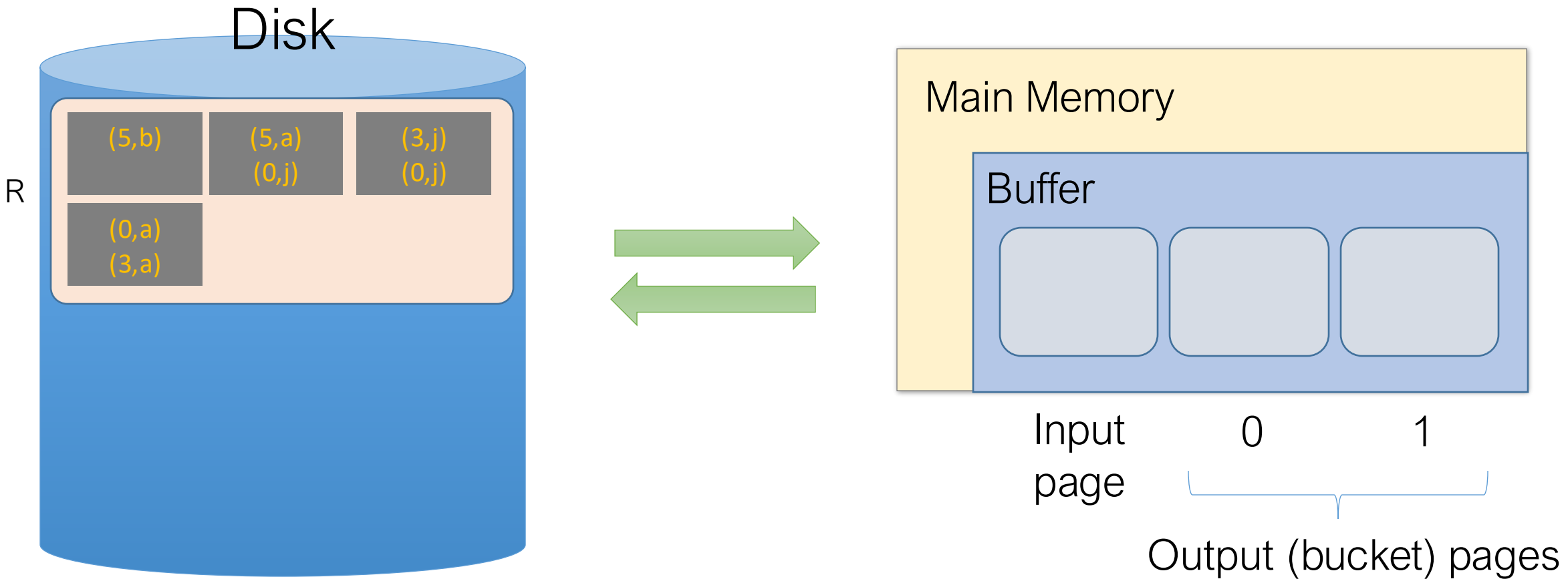
For simplicity, we'll look at partitioning one of the two relations- we just do the same for the other relation!

Recall: our goal will be to get B = 2 buckets of size <= B-1 → 1 page each

Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

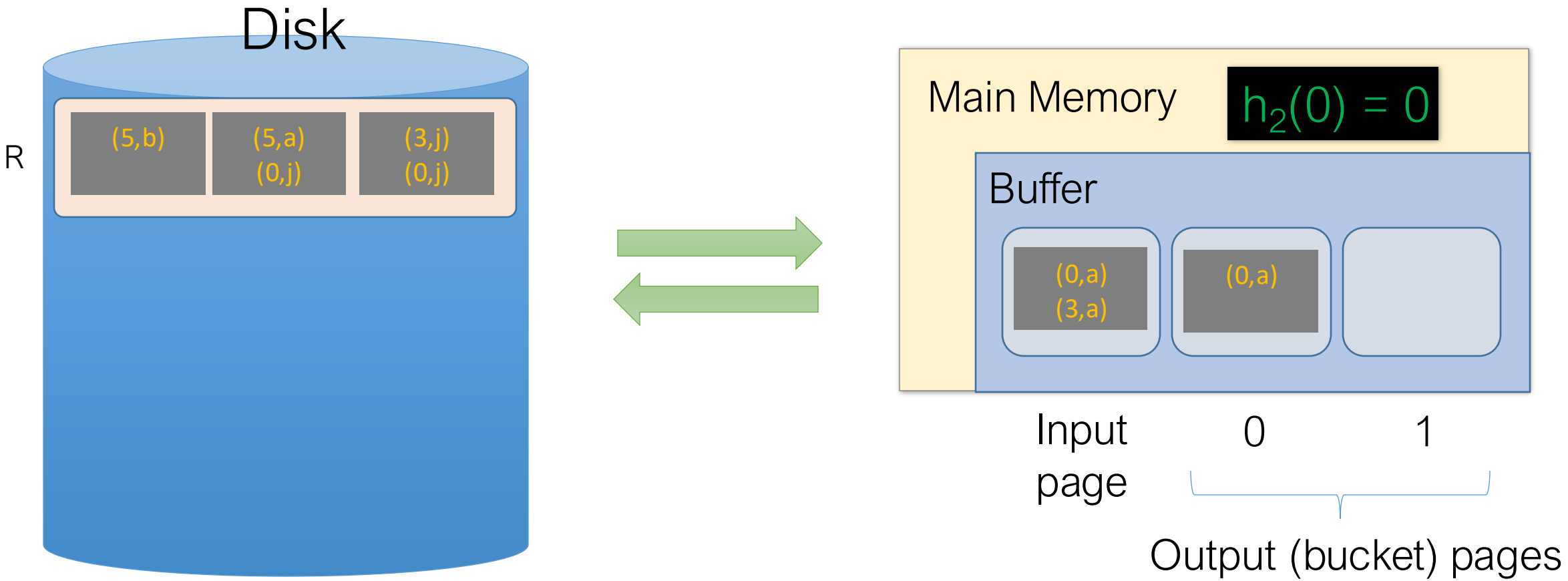
1. We read pages from R into the “input” page of the buffer…



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

2. Then we use **hash function h_2** to sort into the buckets, which each have one page in the buffer



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

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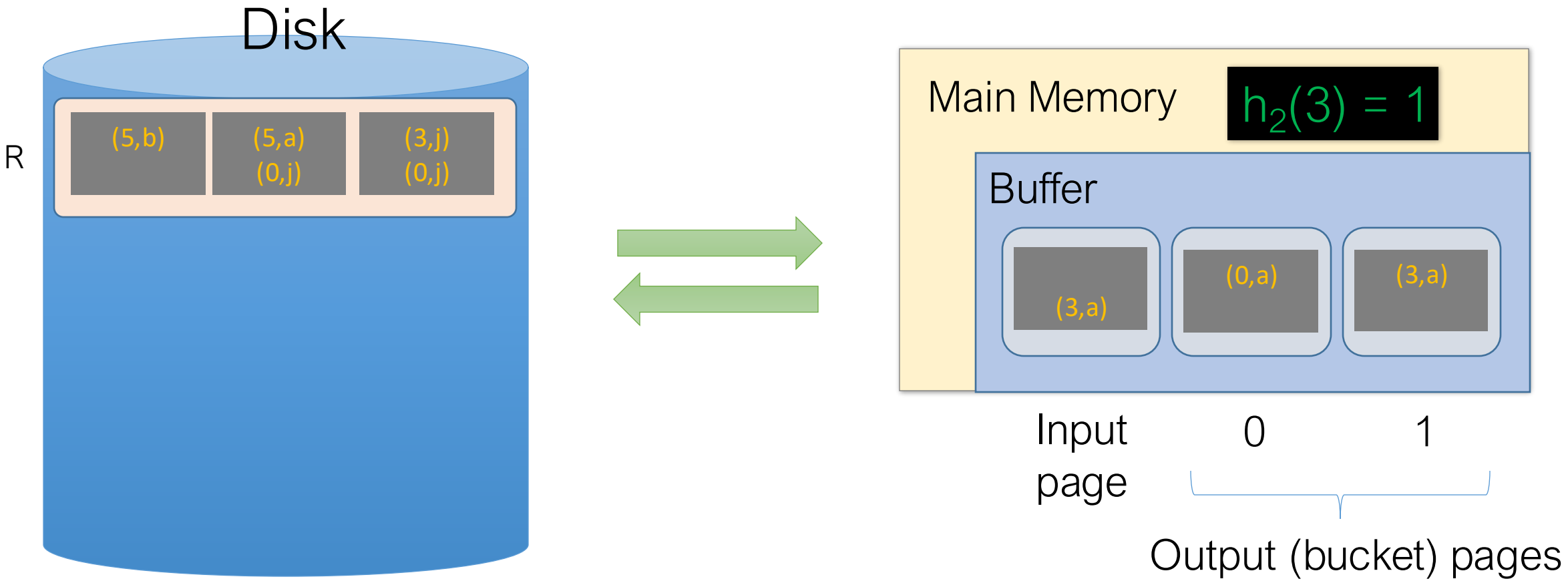
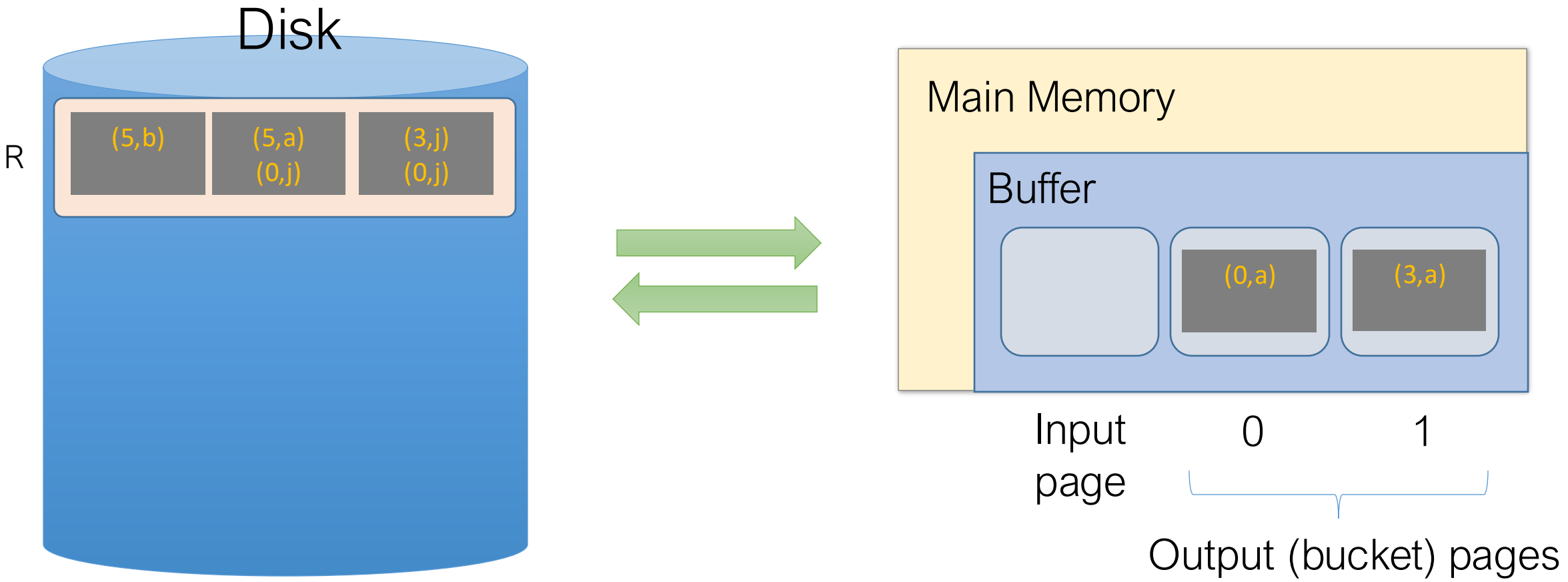


Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

3. We repeat until the buffer bucket pages are full…



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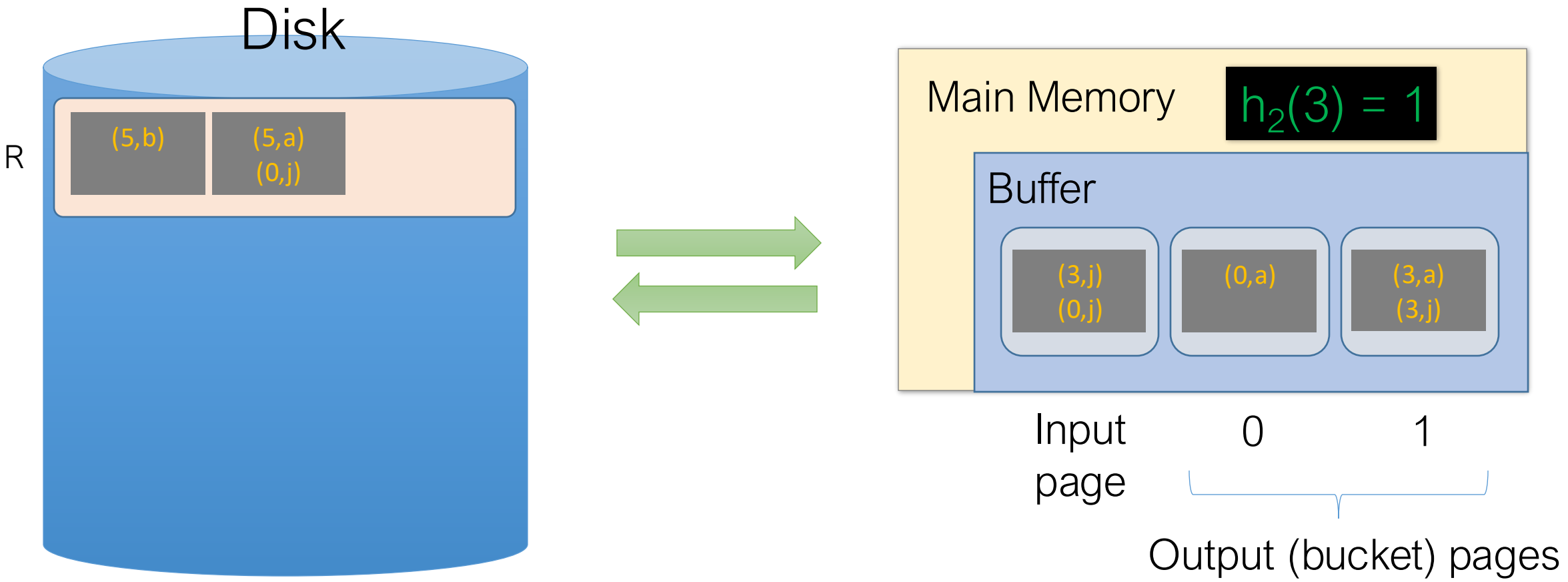

Hash Join Phase 1: Partitioning

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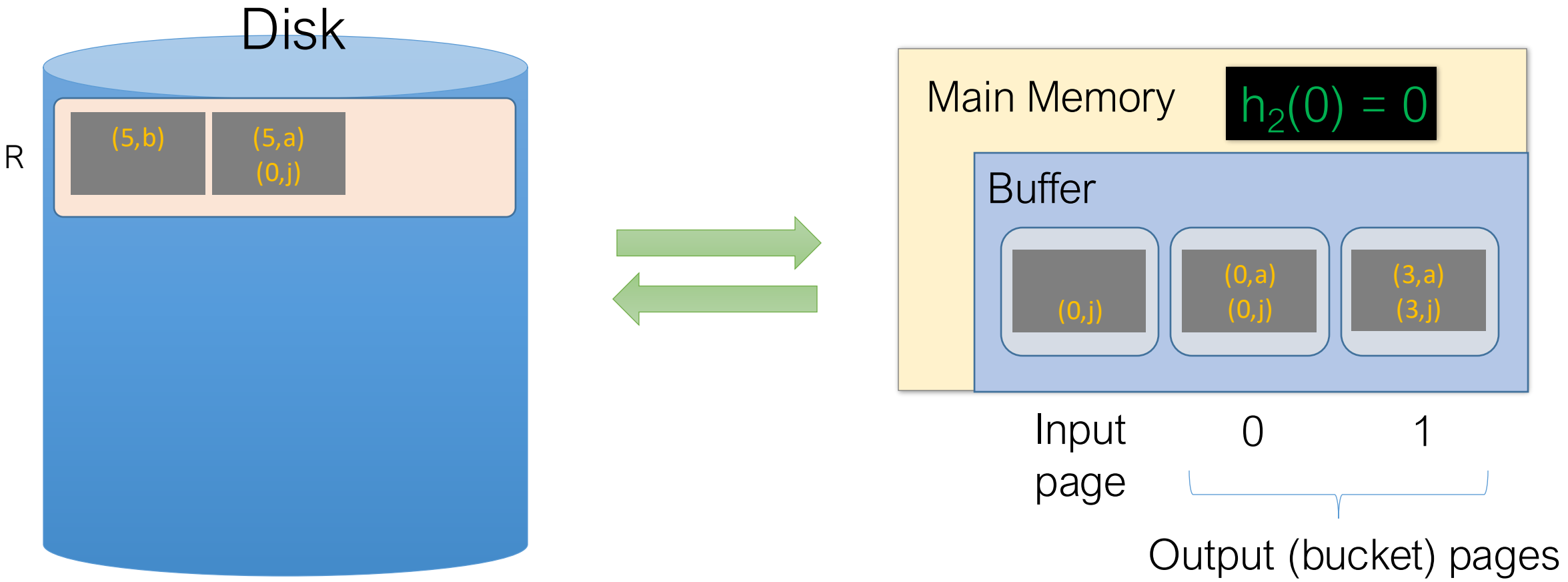
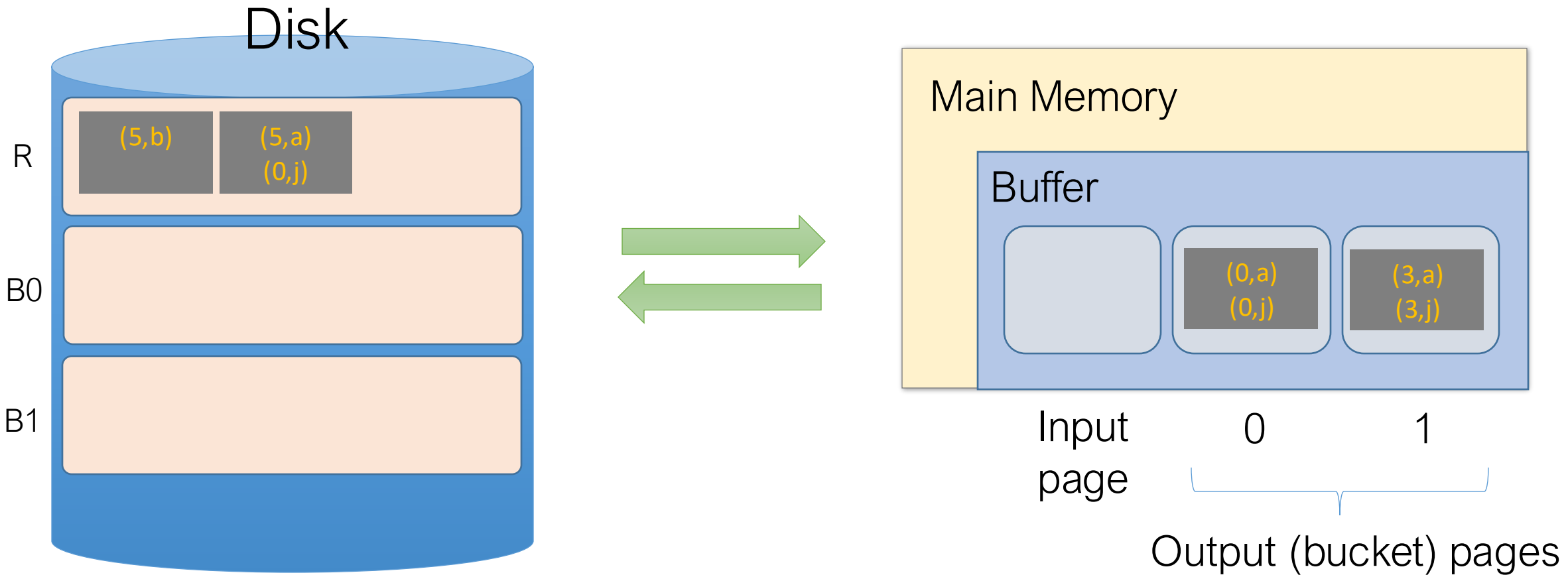


Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

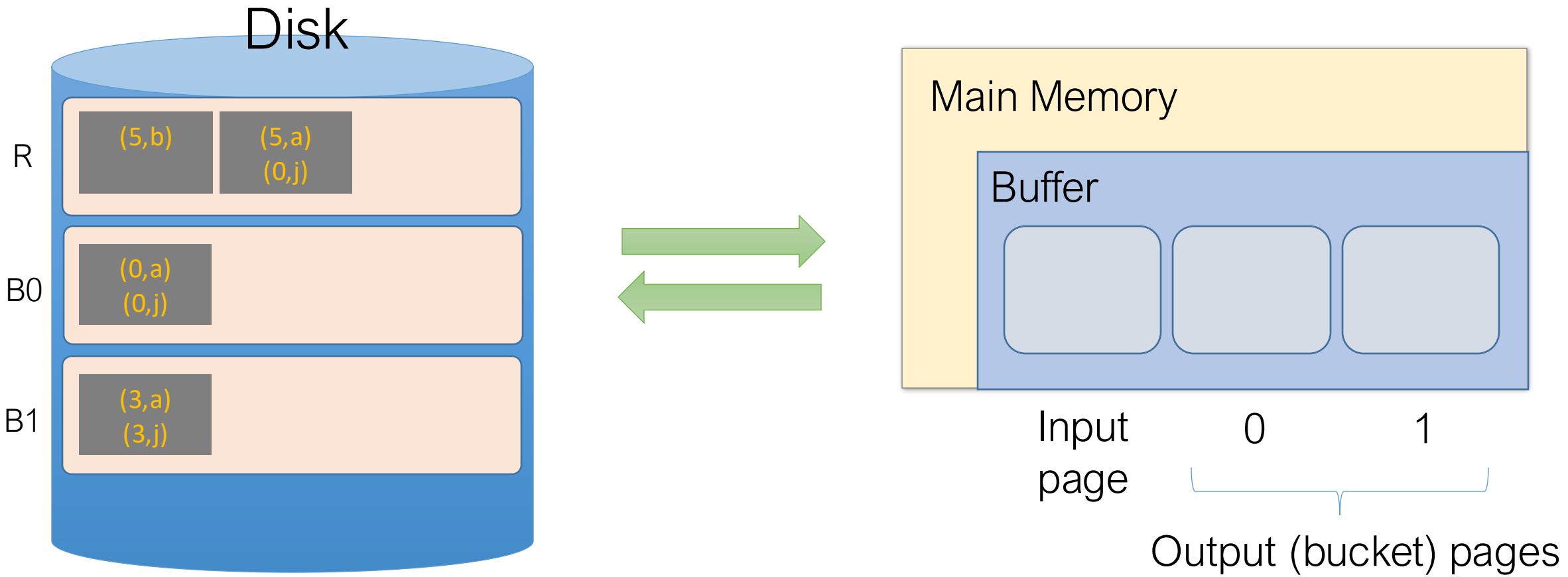
3. We repeat until the buffer bucket pages are full… then flush to disk



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

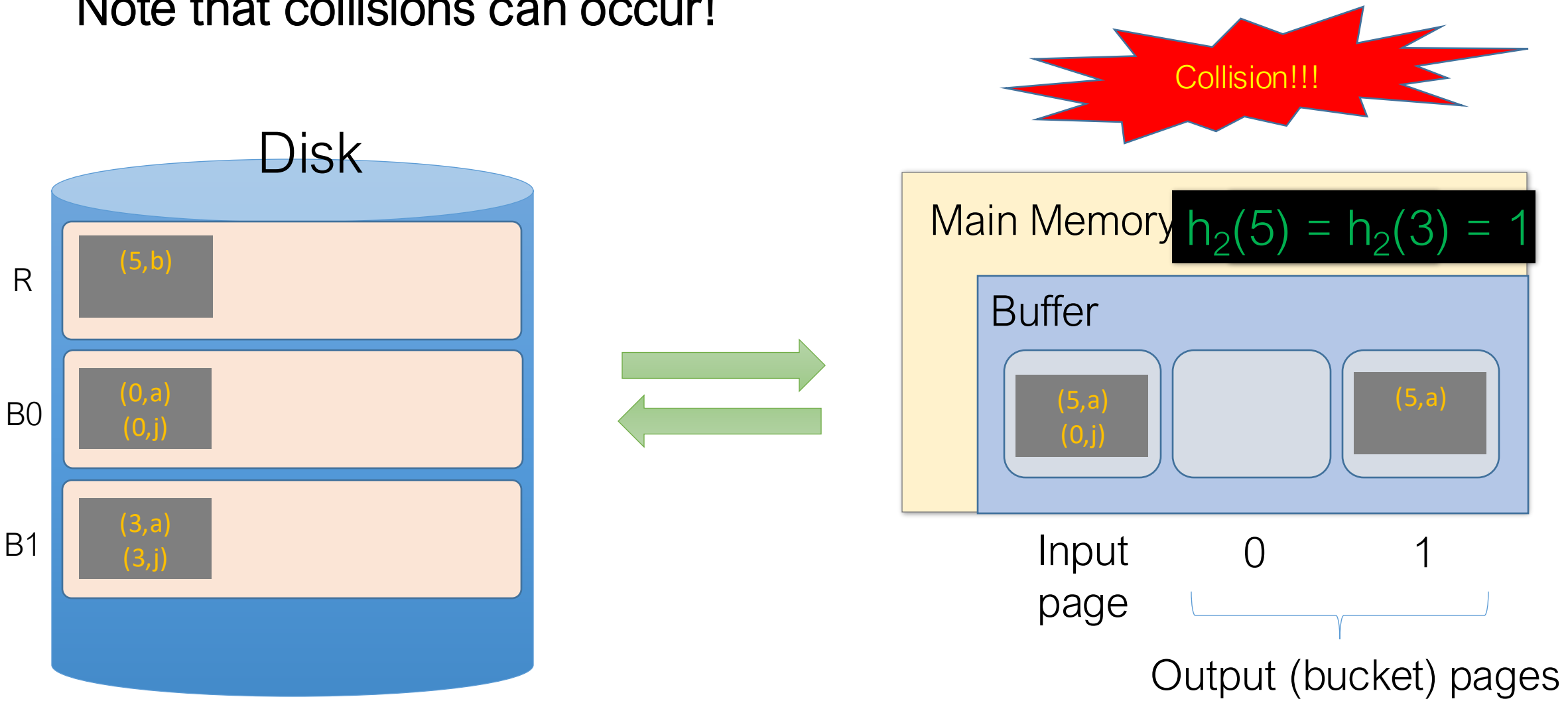
3. We repeat until the buffer bucket pages are full… then flush to disk



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

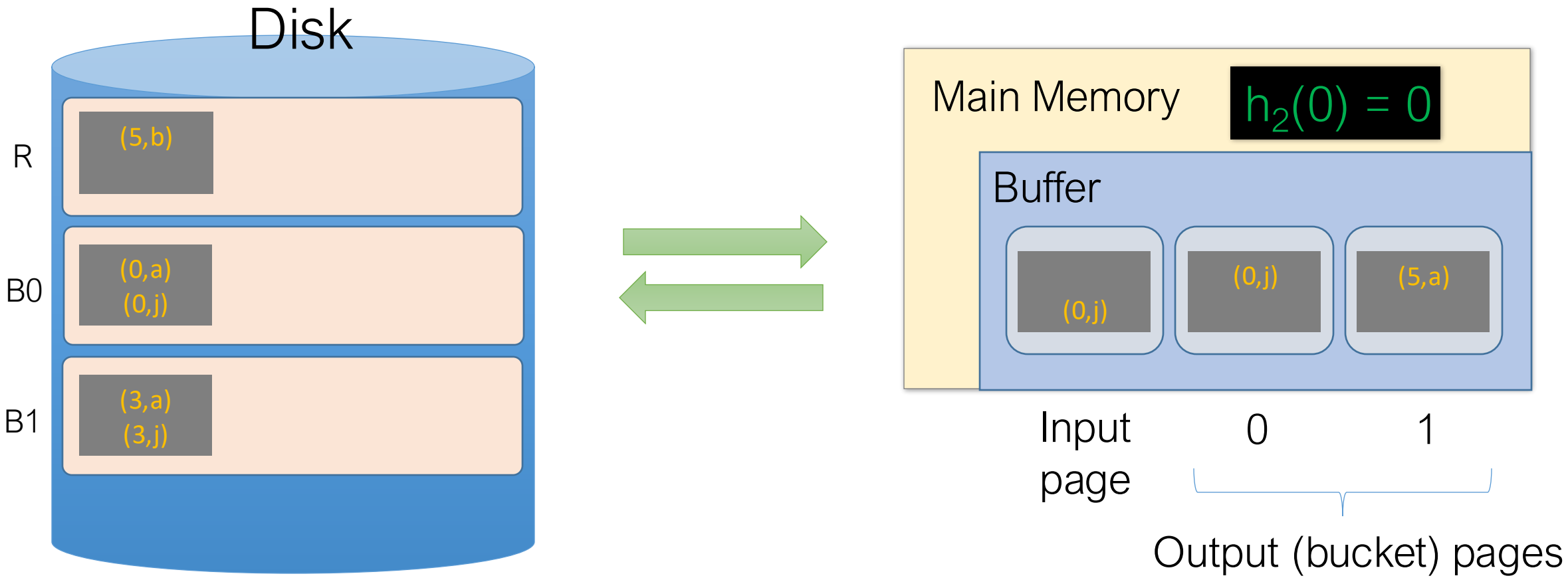
Note that collisions can occur!



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

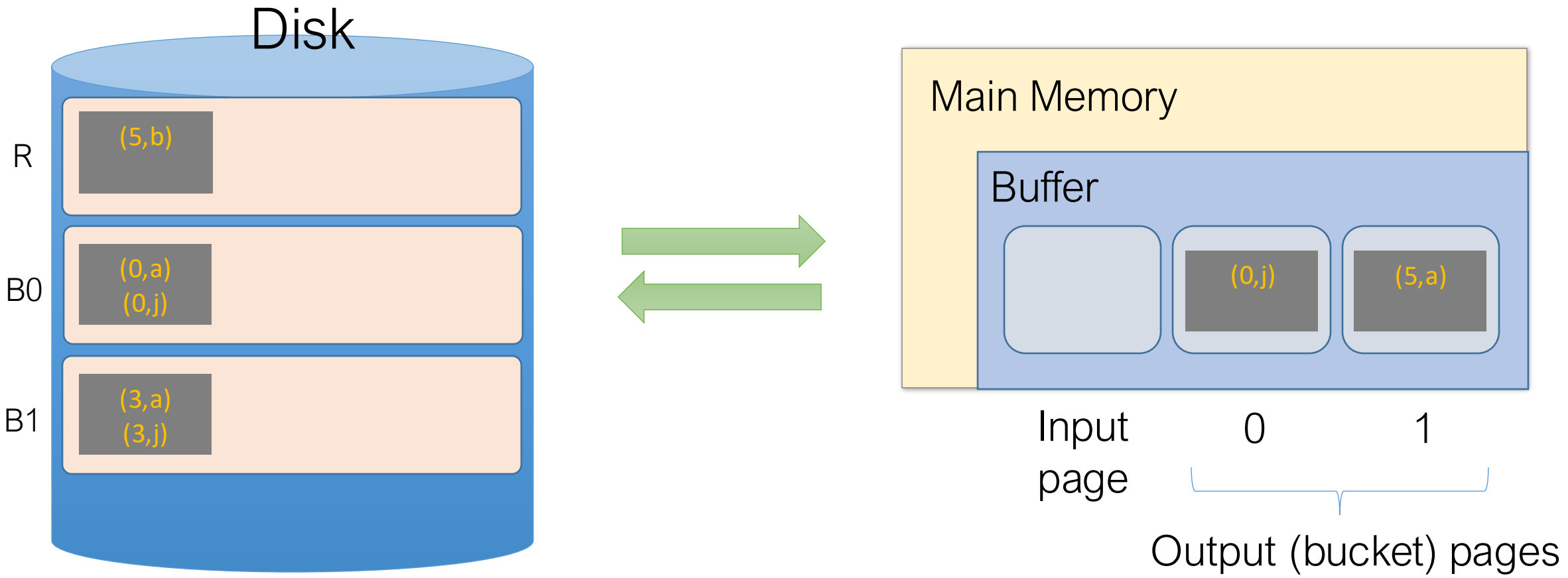
Finish this pass…



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

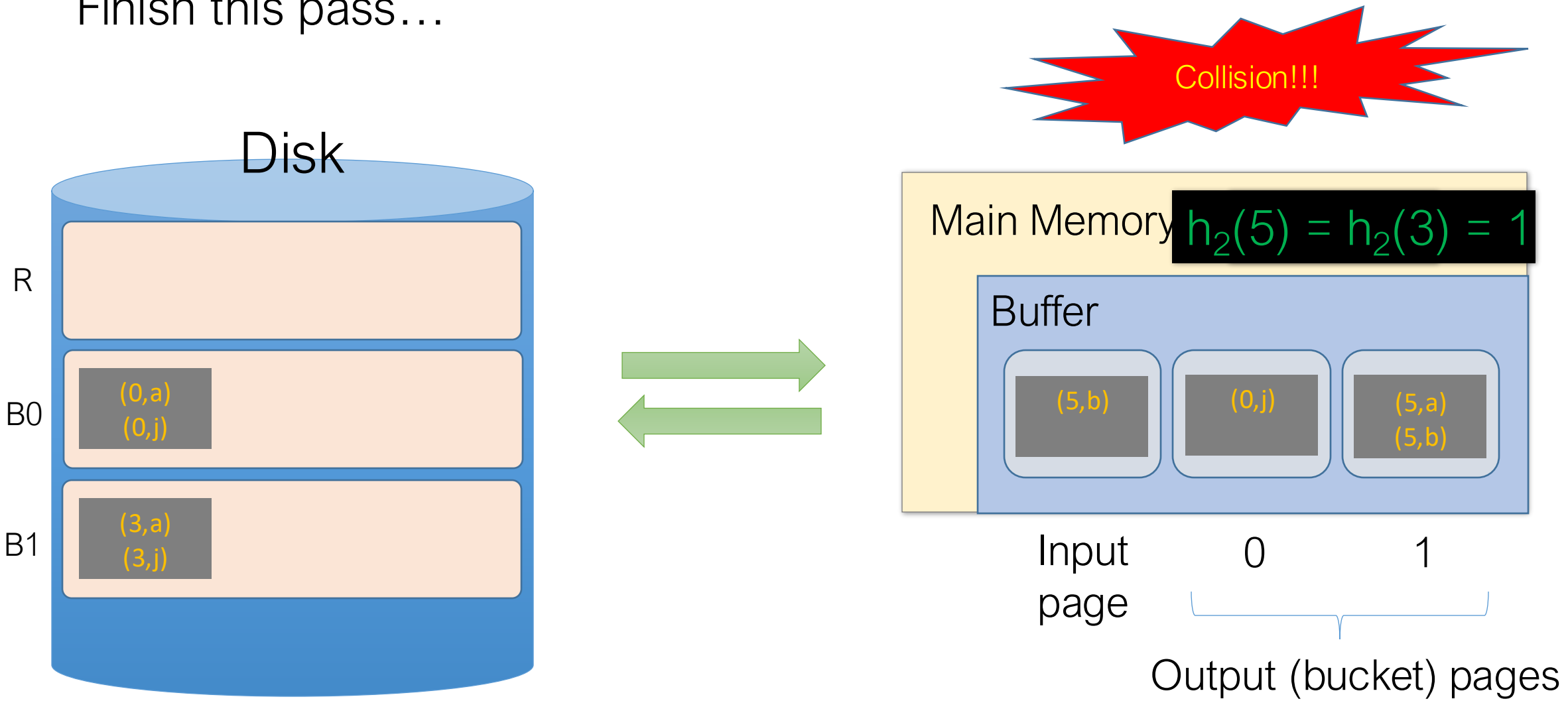
Finish this pass…



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages

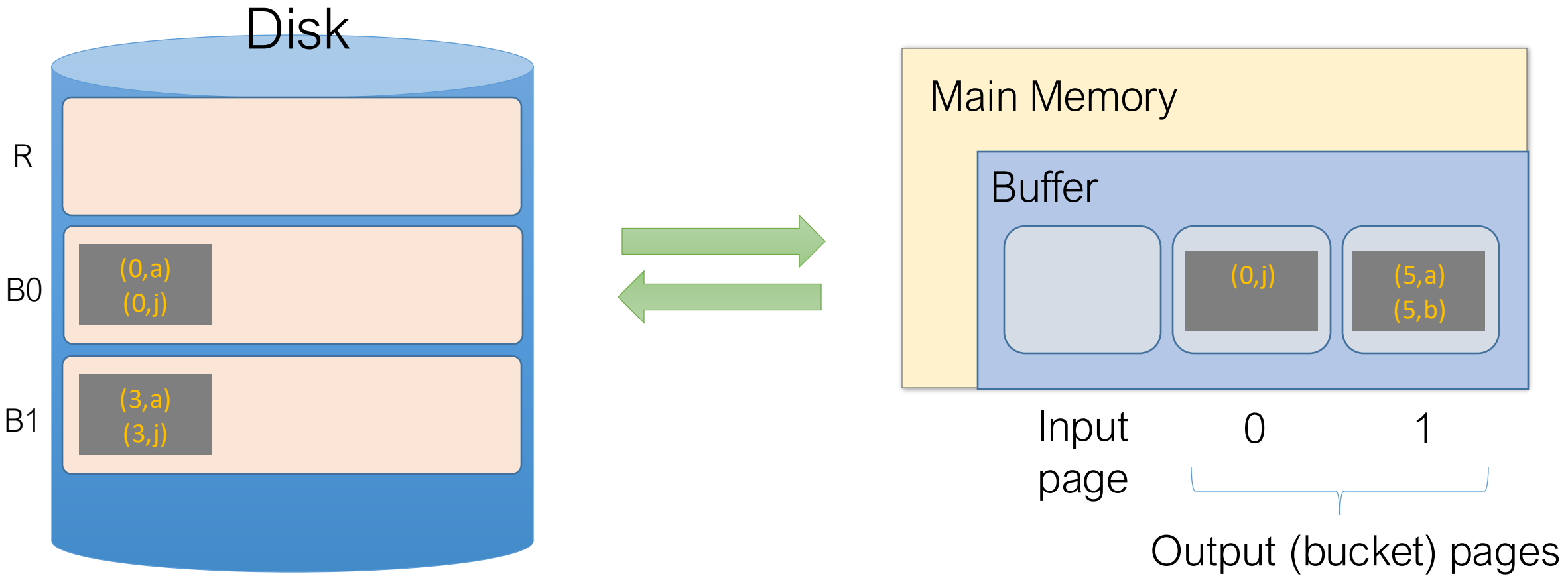
Finish this pass…



Hash Join Phase 1: Partitioning

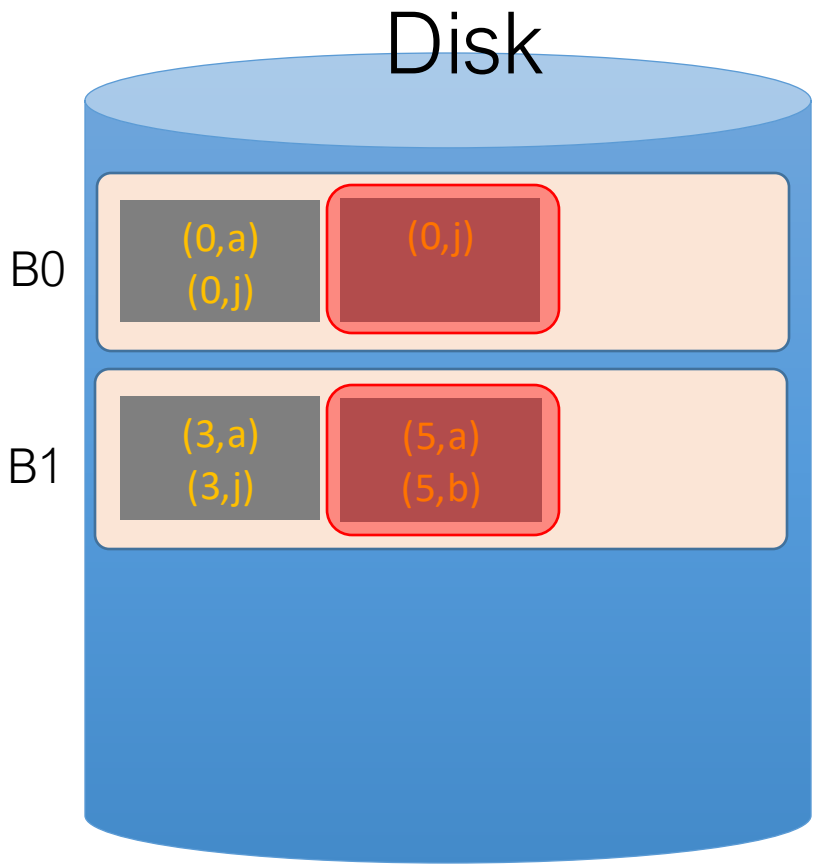
Given B+1 = 3 buffer pages

Finish this pass…



Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages



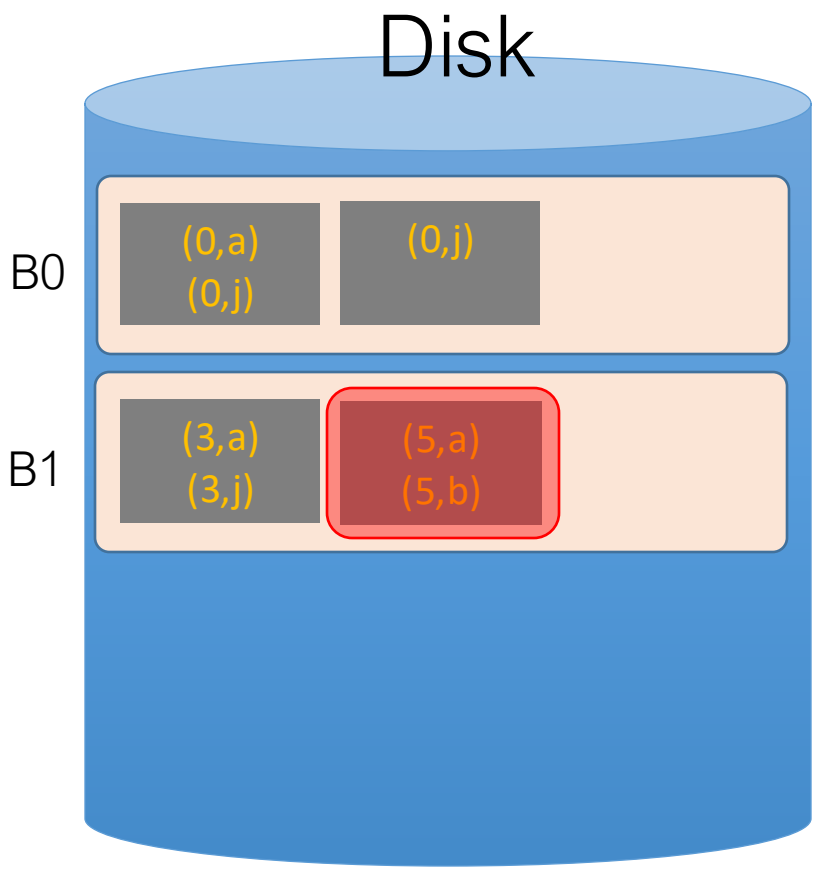
We wanted buckets of size B-1 = 1…
however we got larger ones due to:

(1) Duplicate join keys

(2) Hash collisions

Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages



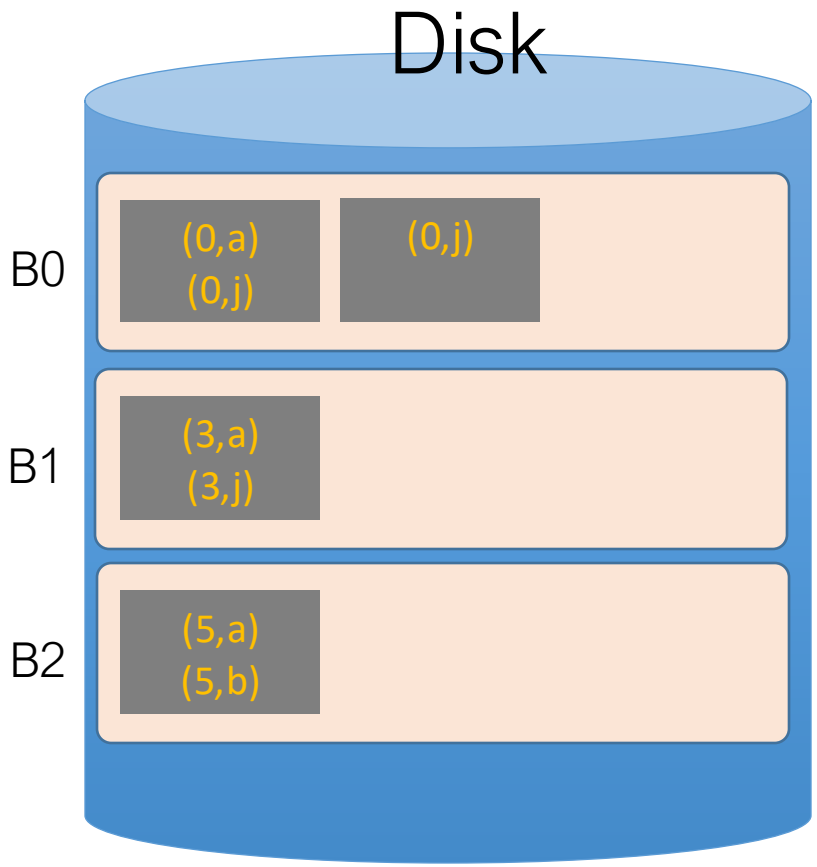
To take care of larger buckets caused by (2) hash collisions, we can just do another pass!

Do another pass with a different hash function, h'_2, ideally such that:

$$h'_2(3) \; != \; h'_2(5)$$

Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages



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Do another pass with a different hash function, h'_2, ideally such that:

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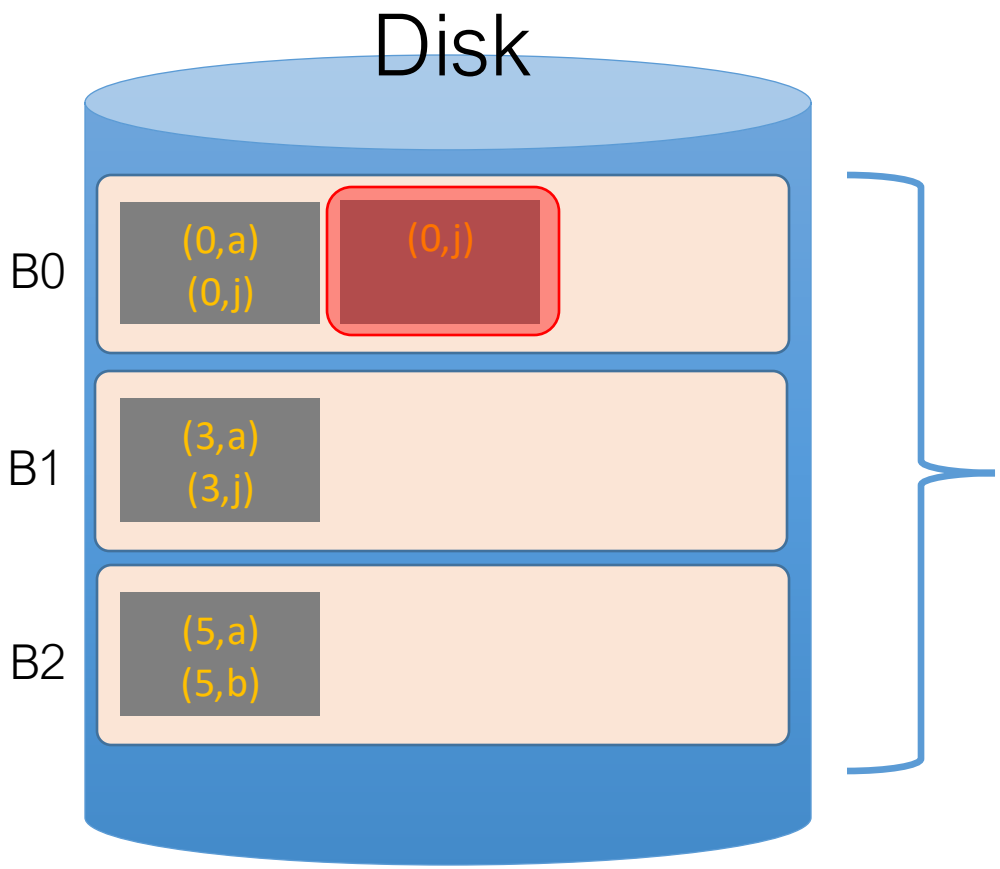
Hash Join Phase 1: Partitioning

Given B+1 = 3 buffer pages



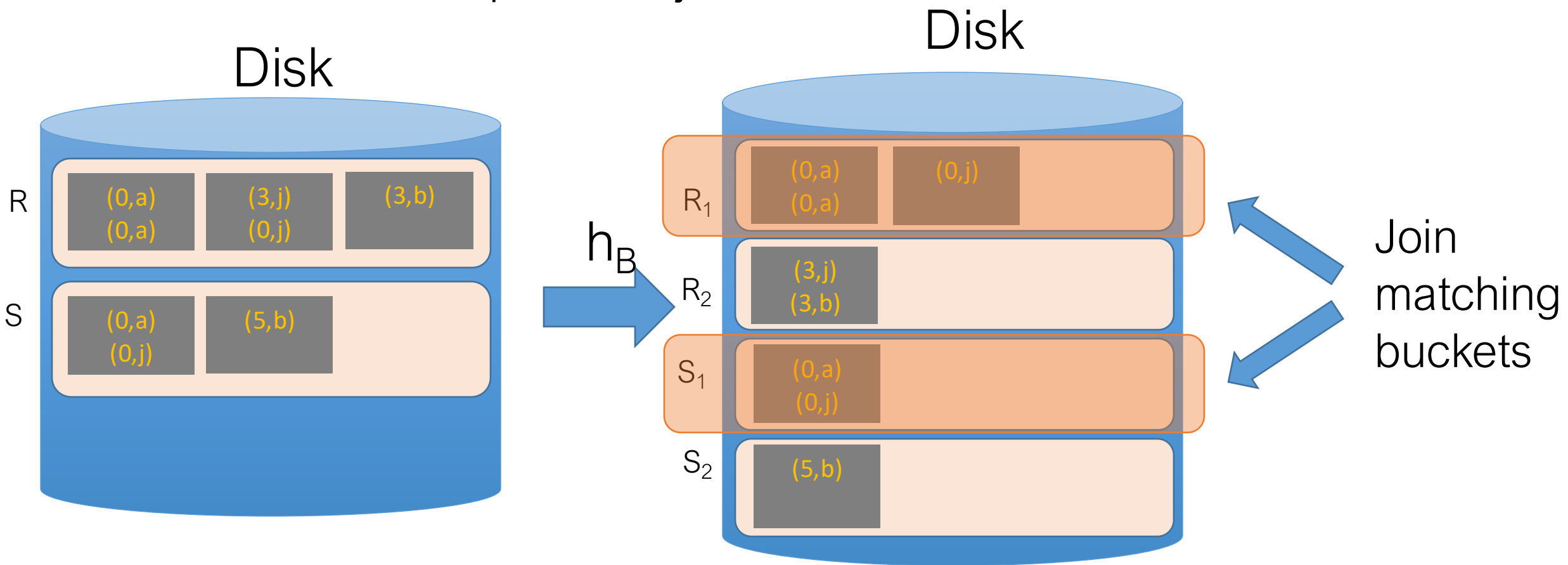
What about duplicate join keys? Unfortunately this is a problem… but usually not a huge one.

We call this unevenness in the bucket size skew

Now that we have partitioned R and S…

Hash Join Phase 2: Matching

- Now, we just join pairs of buckets from R and S that have the same hash value to complete the join!



Hash Join Phase 2: Matching

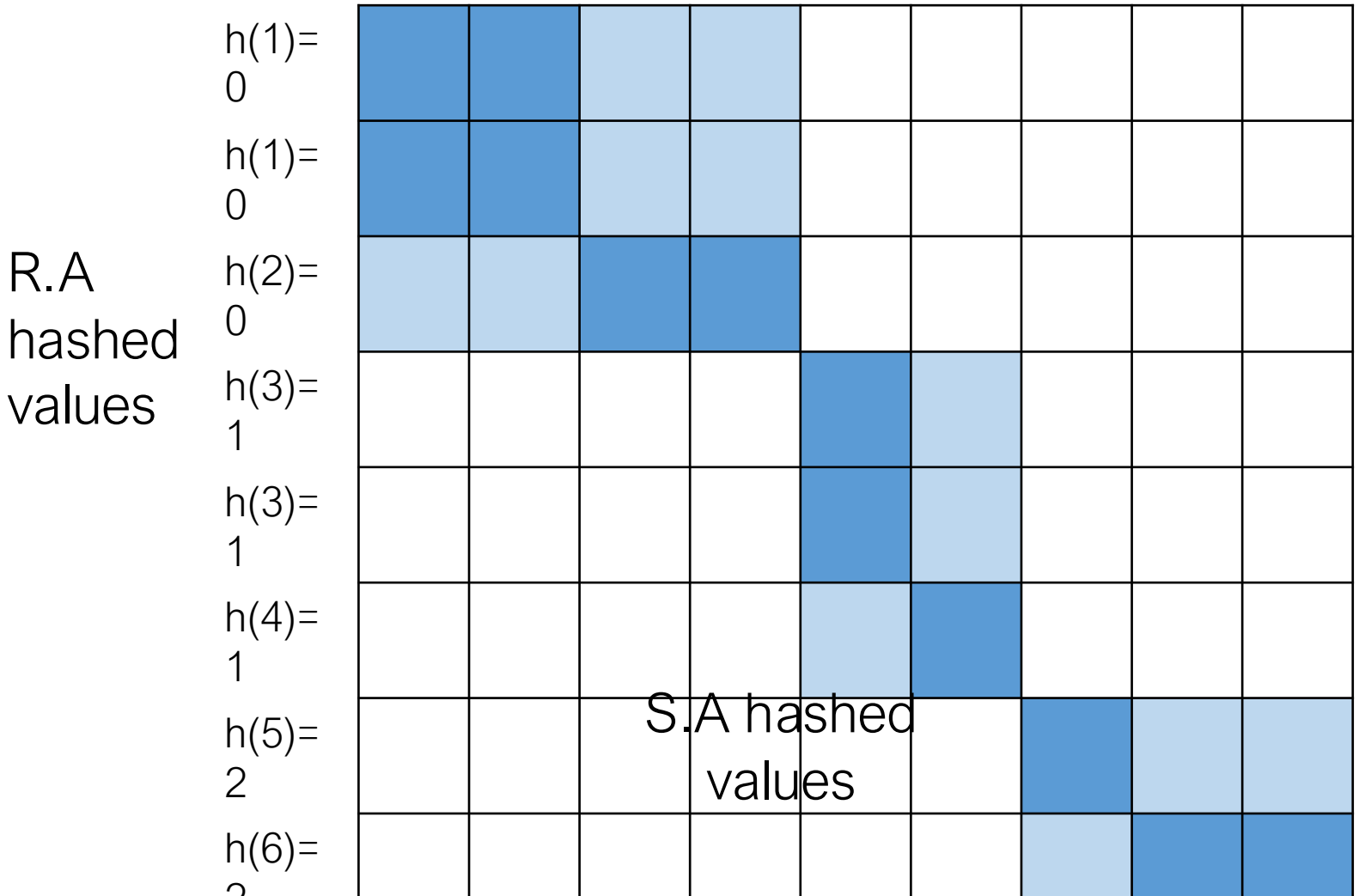
- Note that since x = y → h(x) = h(y), we only need to consider pairs of buckets (one from R, one from S) that have the same hash function value

- If our buckets are $\sim \boldsymbol{B-1}$ **pages,** can join each such pair using BNLJ ***in linear time***; recall (with P(R) = B-1):

BNLJ Cost: $\mathrm{P}(R) + \frac{P(R)P(S)}{B-1} = P(R) + \frac{(B-1)P(S)}{B-1}$ = P(R) + P(S)

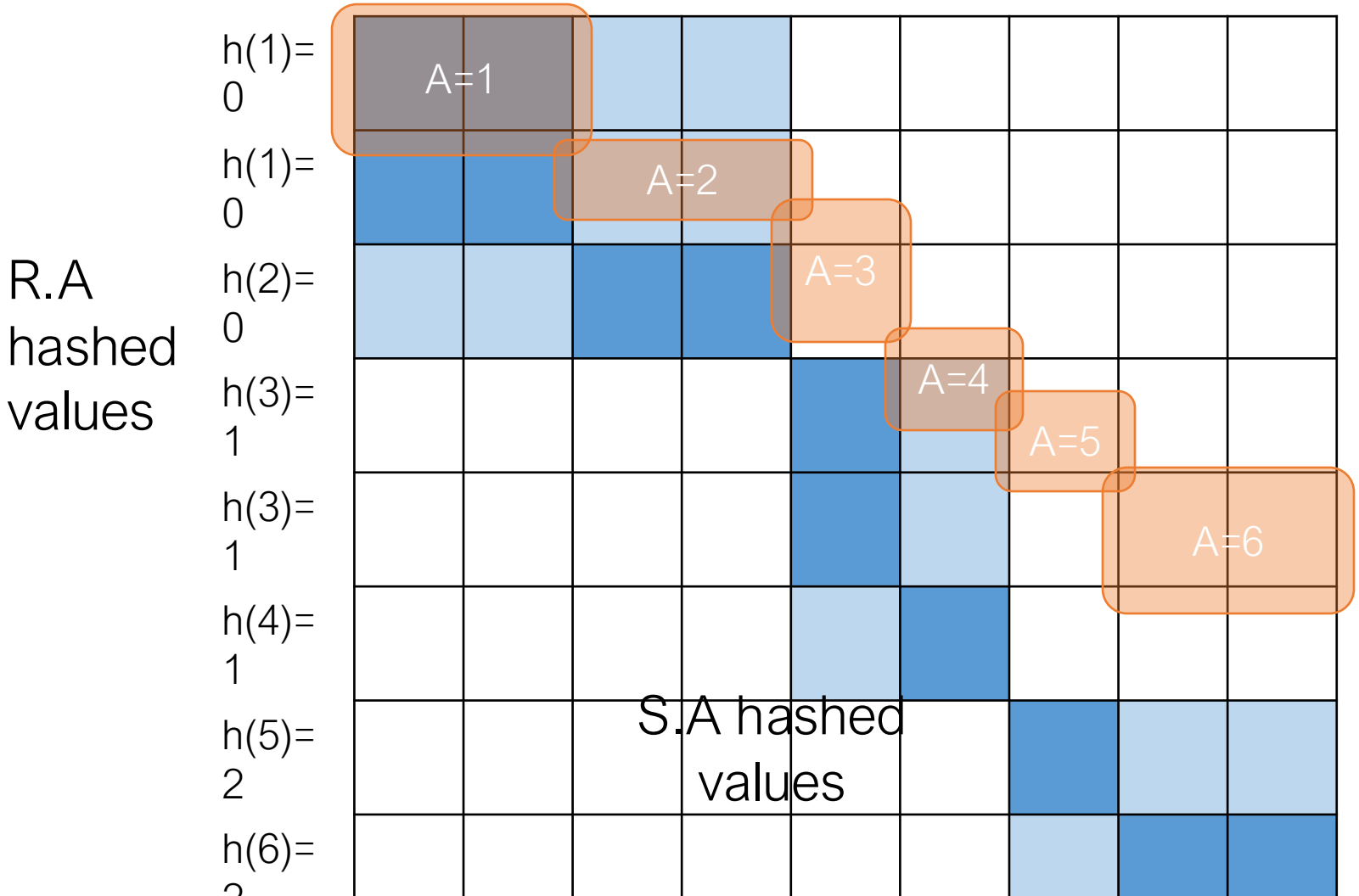
Joining the pairs of buckets is linear!
(As long as smaller bucket <= B-1 pages)

Hash Join Phase 2: Matching



$\mathrm{R} \bowtie S \; on \; A$

Hash Join Phase 2: Matching

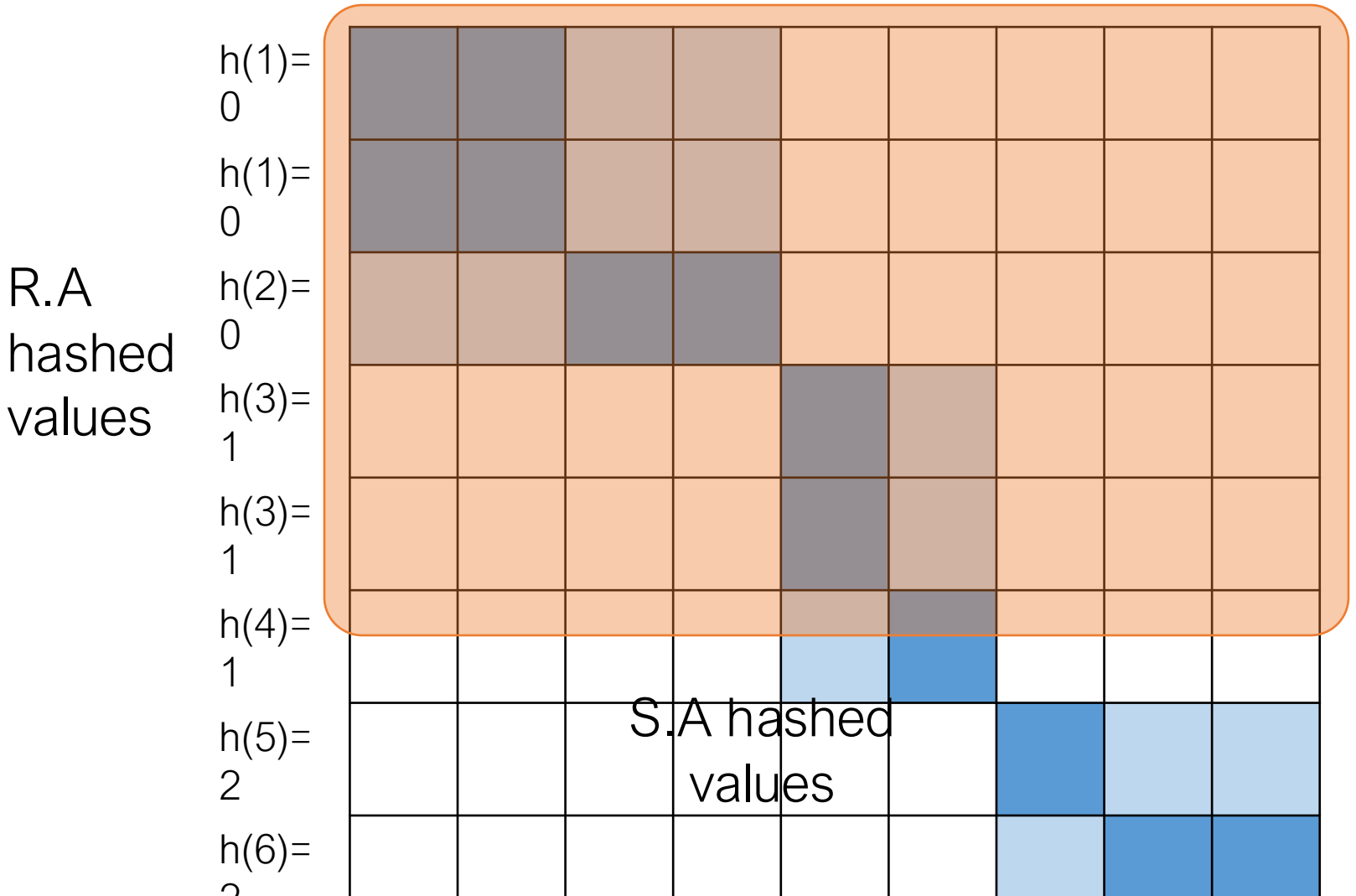


$R \bowtie S \; on \; A$

To perform the join, we ideally just need to explore the dark blue regions

= the tuples with same values of the join key A

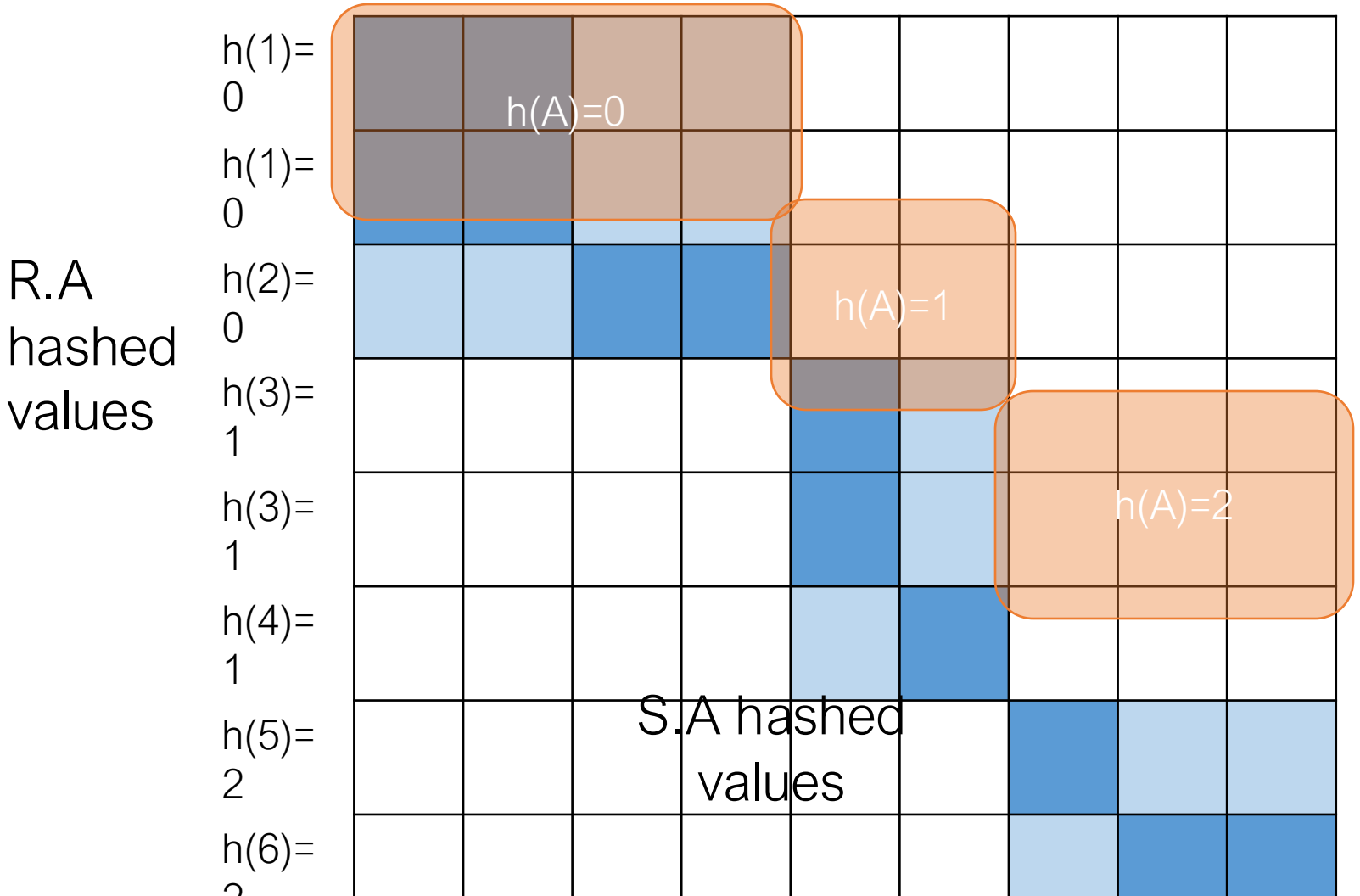
Hash Join Phase 2: Matching



$R \bowtie S \; on \; A$

With a join algorithm like BNLJ that doesn't take advantage of equijoin structure, we'd have to explore this whole grid!

Hash Join Phase 2: Matching



$R \bowtie S \; on \; A$

With HJ, we only explore the blue regions

= the tuples with same values of h(A)!

We can apply BNLJ to each of these regions

How much memory do we need for HJ?

- Given B+1 buffer pages

+ WLOG: Assume P(R) <= P(S)

- Suppose (reasonably) that we can partition into B buckets in 2 passes:
  - For R, we get B buckets of size ~P(R)/B
  - To join these buckets in linear time, we need these buckets to fit in B-1 pages, so we have:

$$B - 1 \geq \frac{P(R)}{B} \Rightarrow \sim \boldsymbol{B^2 \geq P(R)}$$

Quadratic relationship between smaller relation's size & memory!

Hash Join Summary

- *Given enough buffer pages as on previous slide…*
  - **Partitioning** requires reading + writing each page of R,S
    - → 2(P(R)+P(S)) IOs
  - **Matching** (with BNLJ) requires reading each page of R,S
    - → P(R) + P(S) IOs
  - **Writing out results** could be as bad as P(R)*P(S)… but probably closer to P(R)+P(S)

HJ takes ~3(P(R)+P(S)) + OUT IOs!

Sort-Merge v. Hash Join

Given enough memory, both SMJ and HJ have performance:

$$\sim 3(P(R)+P(S)) + OUT$$

"Enough" memory =

- SMJ: $B^2 > \max\{P(R), P(S)\}$
- HJ: $B^2 > \min\{P(R), P(S)\}$

Hash Join superior if relation sizes differ greatly. Why?

Further Comparisons of Hash and Sort Joins

- Hash Joins are highly parallelizable.

- Sort-Merge less sensitive to data skew and result is sorted