Lecture 14: Joins!

Announcements: Two Hints

- You may want to do *Trigger activity* for project 2.
  - We've noticed those who do it have less trouble with project!
  - Seems like we're good here ☺ Exciting for us!
- We posted an activity for you to do on your own... it may overlap heavily with a ps #3 problem... (*this is not necessary but helpful*).
  - The solutions will **not** be posted.
- Sorry the Google lecture was not recorded! Last minute thing...

1. Nested Loop Joins

What you will learn about in this section

1. RECAP: Joins

1. Nested Loop Join (NLJ)

1. Block Nested Loop Join (BNLJ)

1. Index Nested Loop Join (INLJ)

RECAP: Joins

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 $\mathbf{r} \in R, s \in S$ *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

A	B	C	D
2	3	4	2

Joins: Example

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2	2
2	3

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2	3	4	3

Joins: Example

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S

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

Semantically: A Subset of the Cross Product

$\mathbf{R} \bowtie S$

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

Example: Returns all pairs of tuples $\mathrm{r} \in R, s \in S$ *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?

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")

However joins *can* merge > 2 tables, and some algorithms do support non-equality constraints!

Nested Loop Joins

Notes

- We are again 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)
```

<u>Cost:</u>

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

1. **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 $R \bowtie S \; on \; A$:

```
Compute R ⋈ 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
1. For every tuple in R, loop over all the tuples in S
1. **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)
```

Cost:

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

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

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

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

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!

IO-Aware Approach

Block Nested Loop Join (BNLJ)

Given ***B+1*** pages of memory

```
Compute R ⋈ 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:

$\mathrm{P}(R)$

1. **Load in B-1 pages of R at a time (leaving 1 page each 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 $\mathrm{R} \bowtie S \text{ on } A$:

```
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:

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

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

1. **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 ⋈ 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)

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

1. **Check against the join conditions**

BNLJ can also handle non-equality constraints

Block Nested Loop Join (BNLJ)

Given ***B+1*** pages of memory

```
Compute R ⋈ 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)
```

Again, ***OUT*** could be bigger than P(R)*P(S)… but usually not that bad

Cost:

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

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

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

1. Check against the join conditions

1. **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

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

BNLJ

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

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 ~=** **<u>140 hours</u>**

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

A very real difference from a small change in the algorithm!

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

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

- 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***- moving to equality constraints ("equijoin") only!

Index Nested Loop Join (INLJ)

```
Compute R ⋈ S on A:
  Given index idx on S.A:
    for r in R:
      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 est.

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

Joins: A Cage Match

Message: It's all about the memory!

Today’s Lecture

1. Sort-Merge Join (SMJ)

1. Hash Join (HJ)

1. The Cage Match: SMJ vs. HJ

1. Sort-Merge Join (SMJ)

What you will learn about in this section

1. Sort-Merge Join

1. “Backup” & Total Cost

1. Optimizations

1. ACTIVITY: Sequential Flooding

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]*

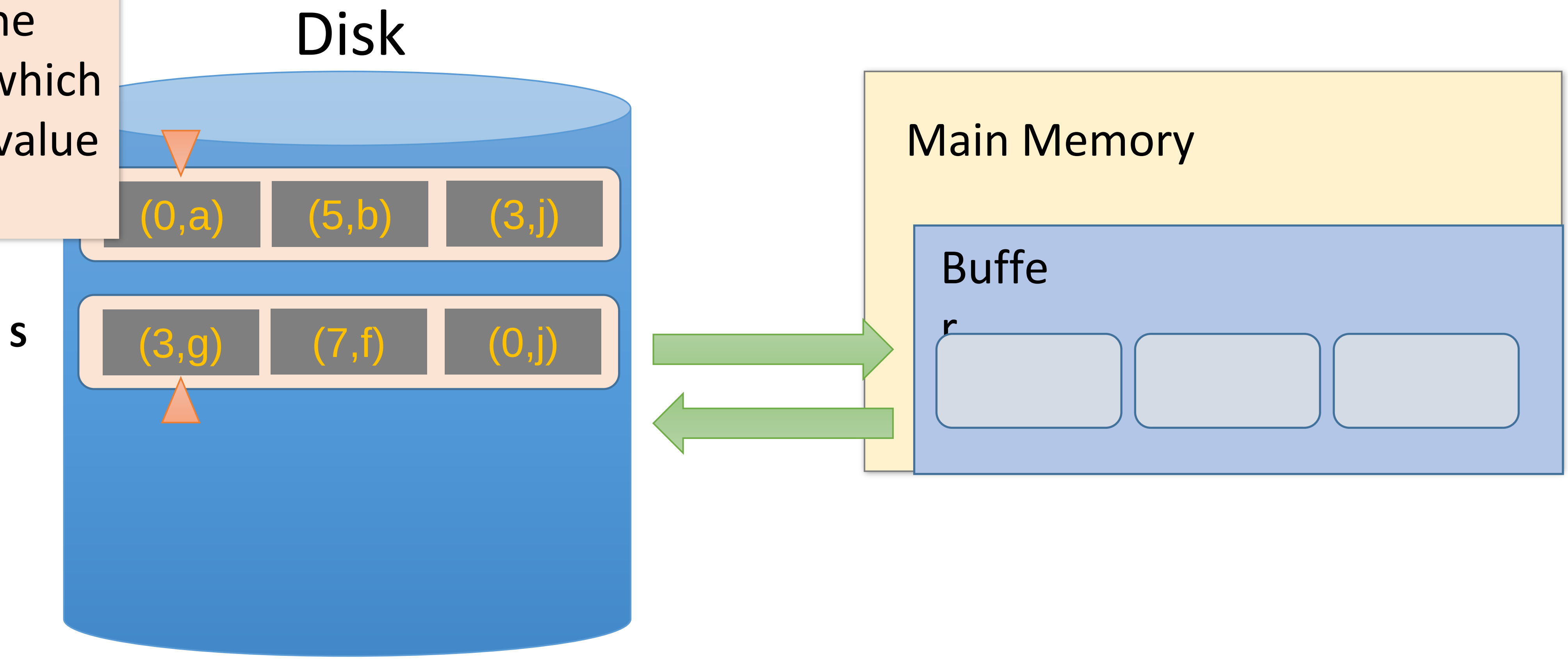
Note that we are only considering equality join conditions here

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

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

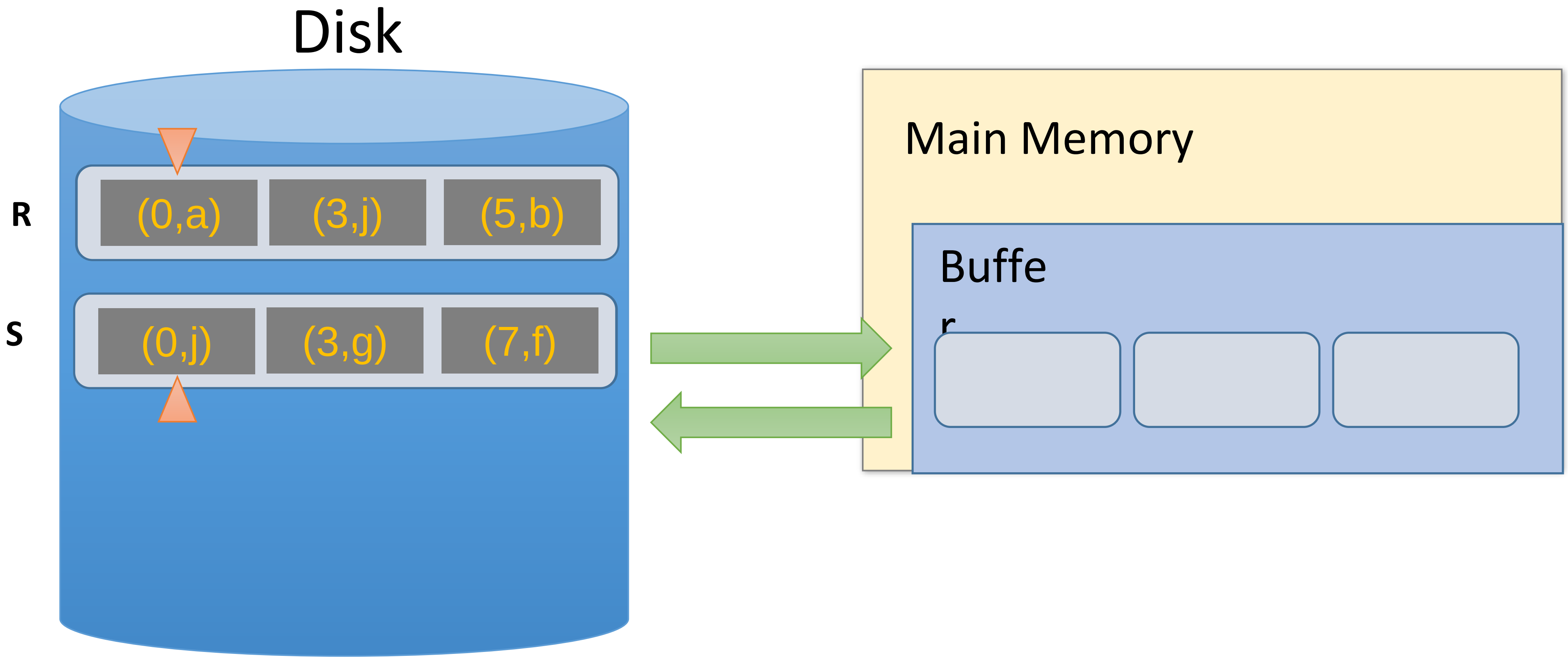
- For simplicity: Let each page be ***one tuple***, and let the first value be A

We show the file HEAD, which is the next value to be read!



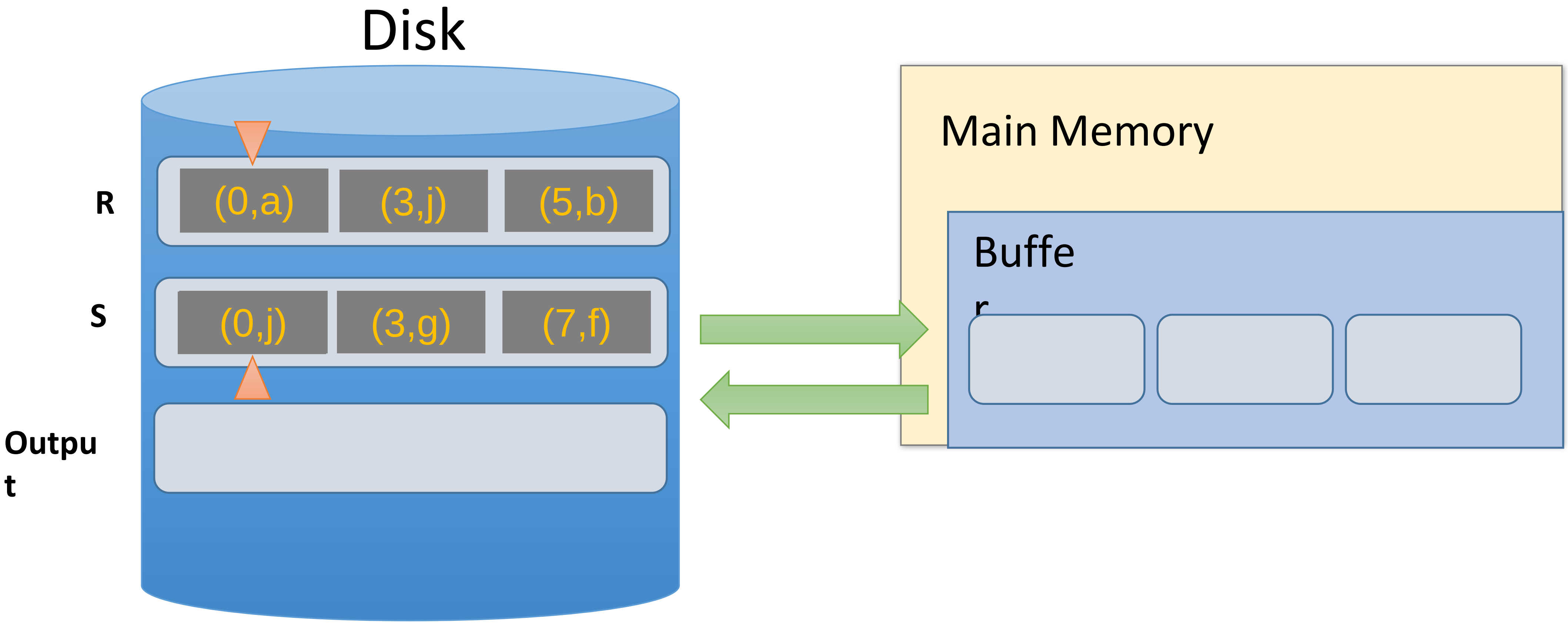
SMJ Example: $\mathrm{R} \bowtie S\ on\ A$ with 3 page buffer

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



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

2. Scan and “merge” on join key!



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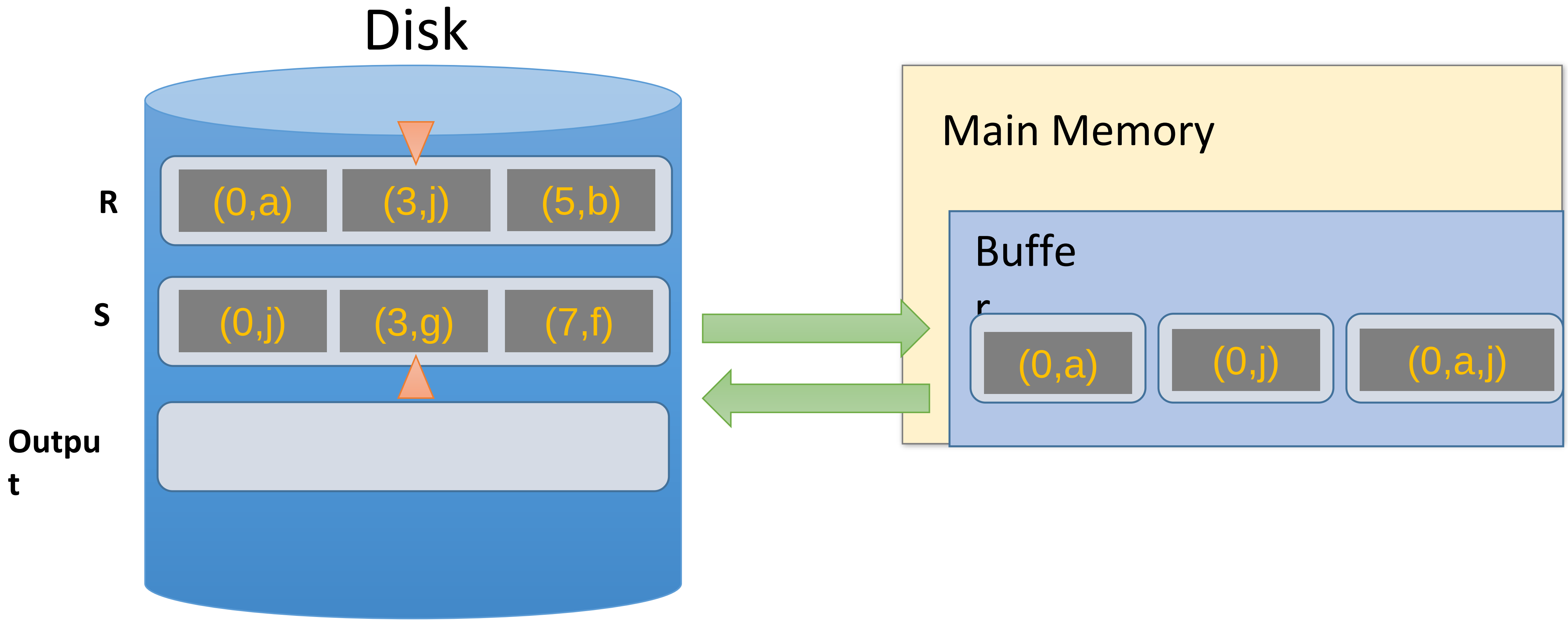

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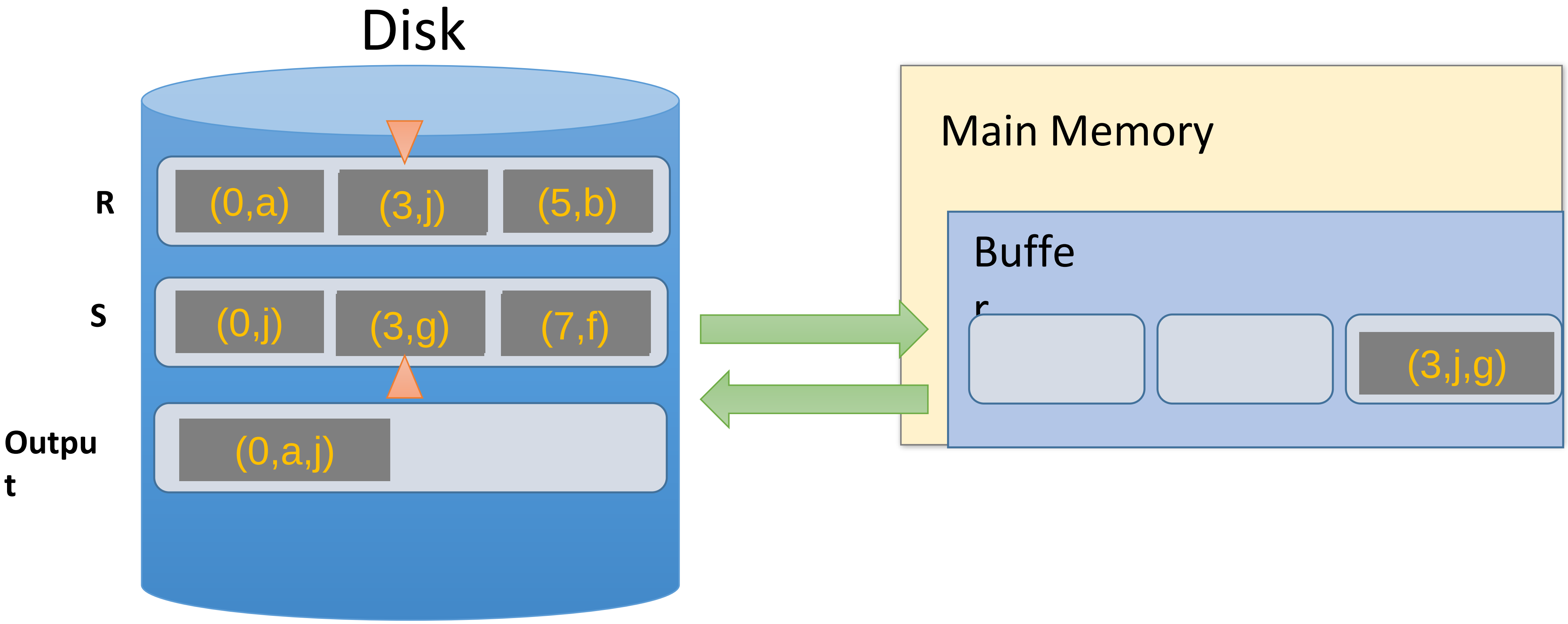
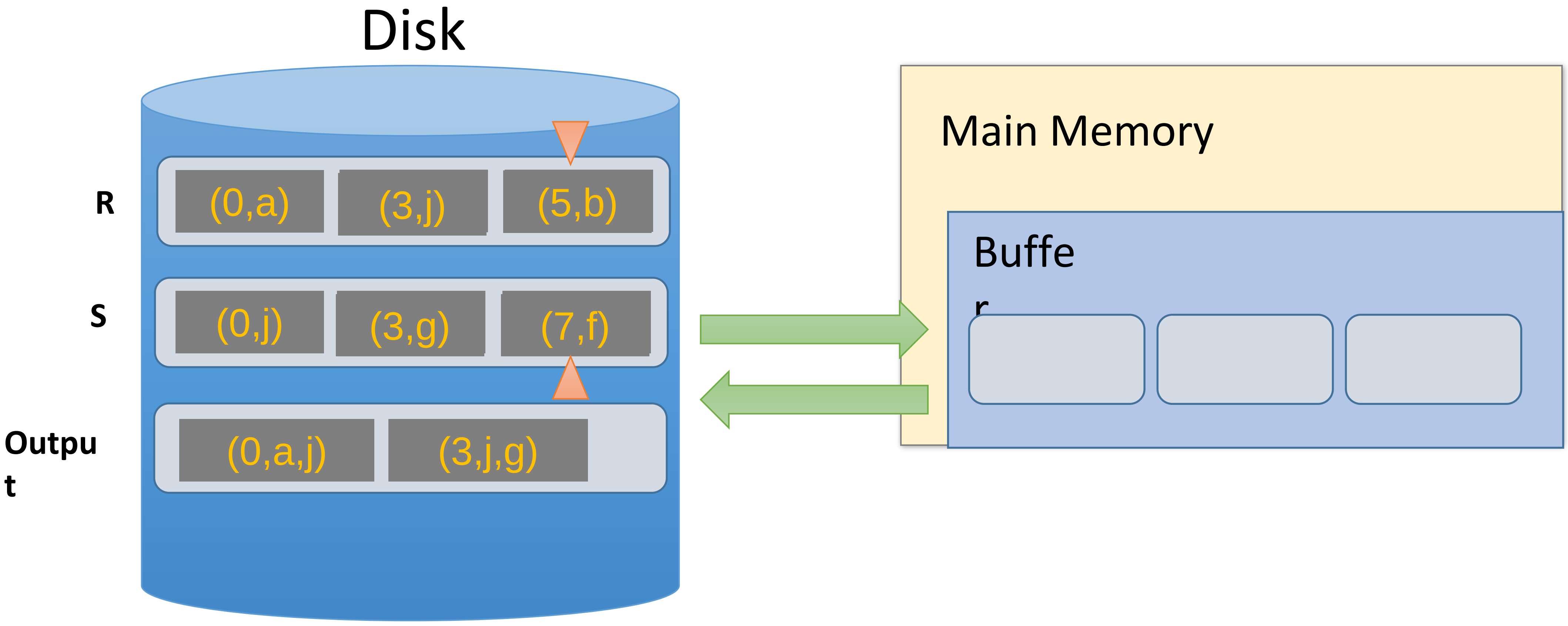
2. Scan and “merge” on join key!



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

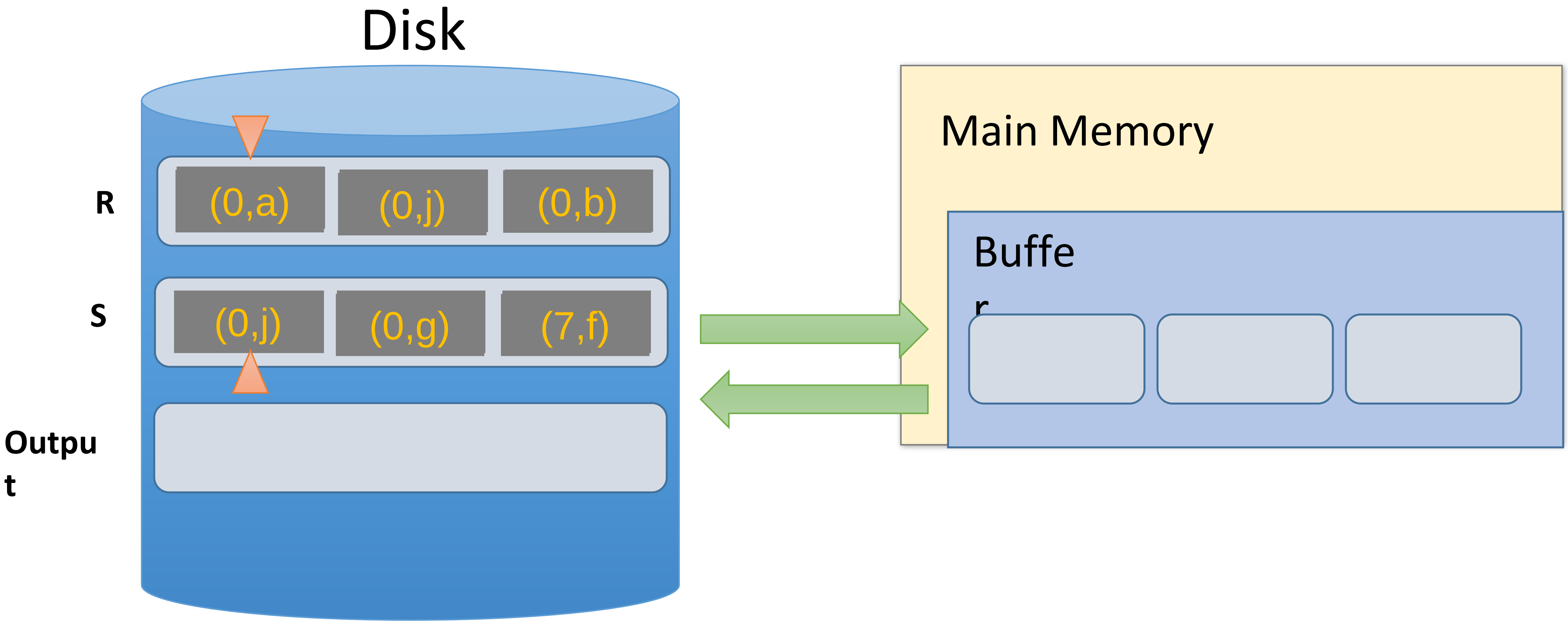
2. Done!



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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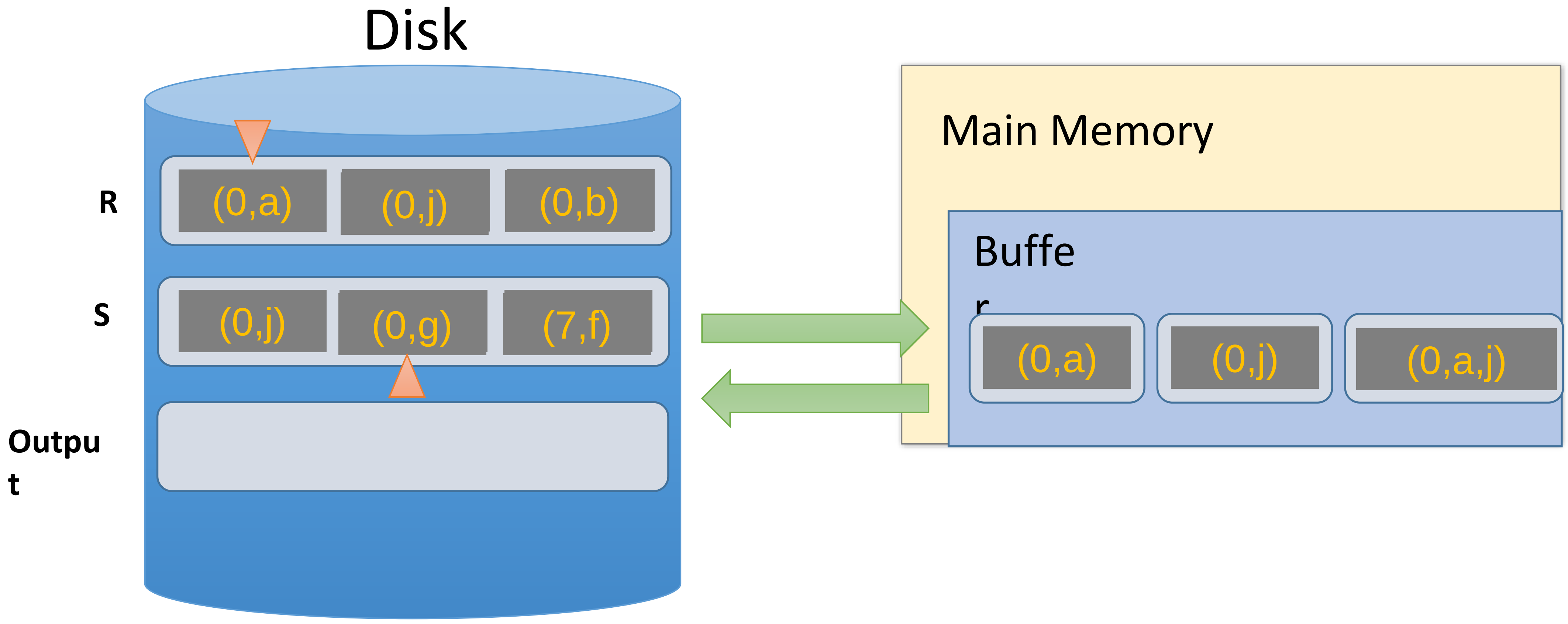

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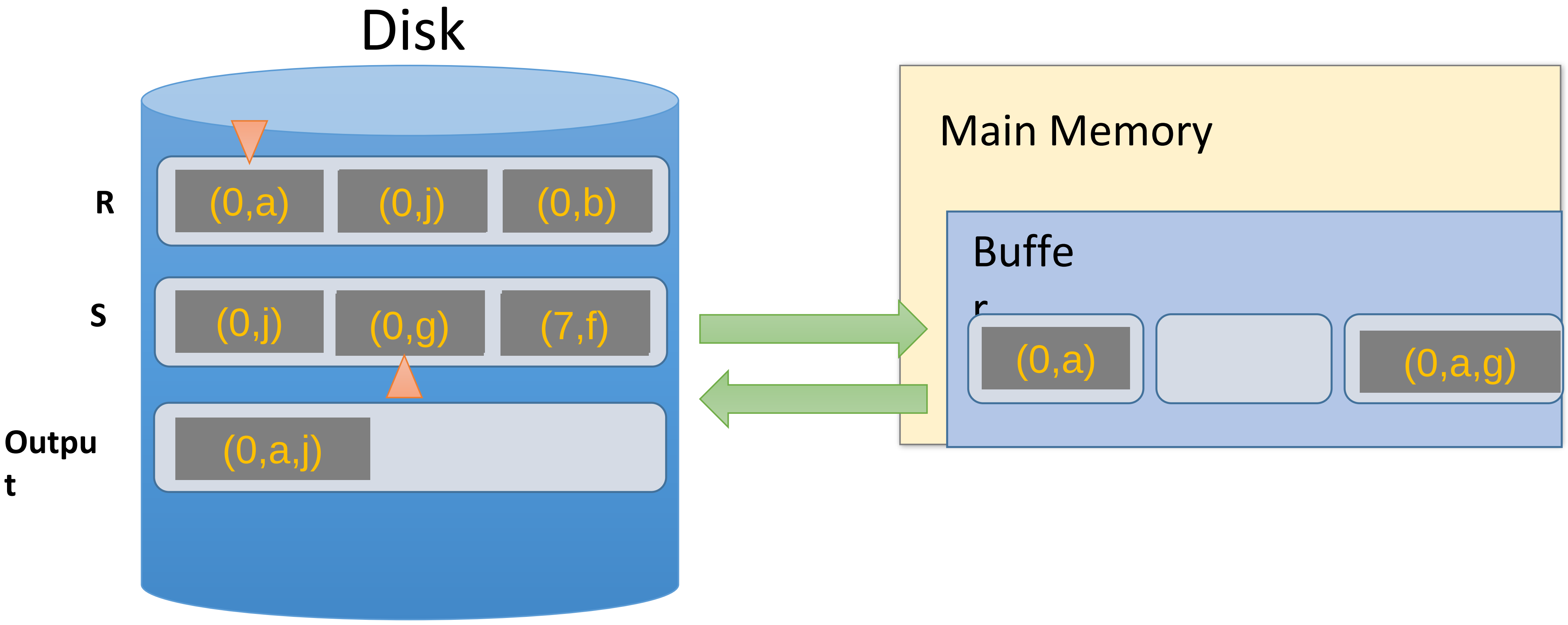

Multiple tuples with Same Join Key: "Backup"

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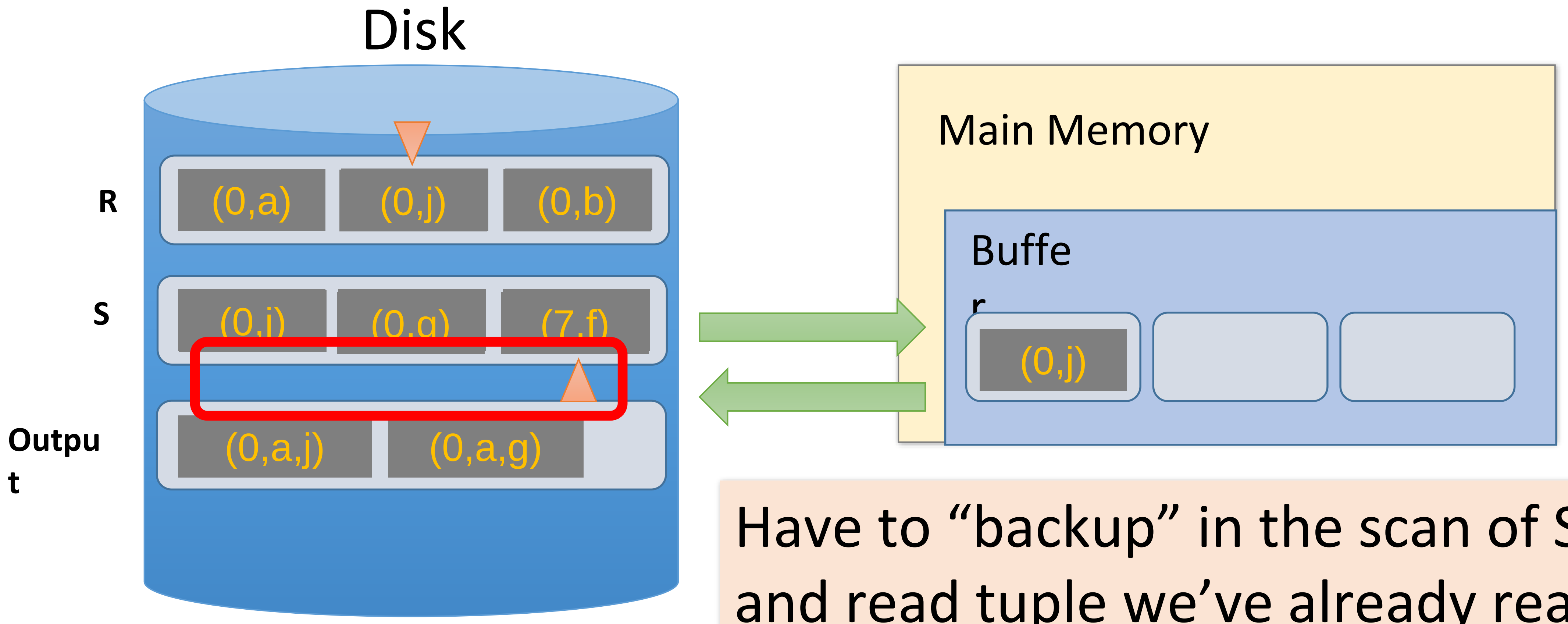


Have to "backup" in the scan of S and read tuple we've already read!

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)
  - Can "zig-zag" (see animation)

SMJ: Total cost

- Cost of SMJ is **cost of sorting** R and S…
- 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**: ~P(R)+P(S) but in worst case T(R)*T(S)

~ Sort(P(R)) + Sort(P(S)) + P(R) + P(S) + OUT

Recall: Sort(N) $\approx 2N\left(\left\lceil \log_B \frac{\boldsymbol{N}}{\boldsymbol{2(B+1)}} \right\rceil + 1\right)$

Note: this is using repacking, where we estimate that we can create initial runs of length ~2(B+1)

SMJ vs. BNLJ: Steel Cage Match

- If we have 100 buffer pages, P(R) = 1000 pages and P(S) = 500 pages:
  - Sort both in two passes: 2 * 2 * 1000 + 2 * 2 * 500 = **6,000 IOs**
  - Merge phase 1000 + 500 = 1,500 IOs
  - **<u>= 7,500 IOs + OUT</u>**

What is BNLJ?

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

- But, if we have 35 buffer pages?
  - Sort Merge has same behavior (still 2 passes)
  - BNLJ? ***<u>15,500 IOs + OUT!</u>***

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

A Simple Optimization: Merges Merged!

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

- SMJ is composed of a ***sort phase*** and a ***merge phase***

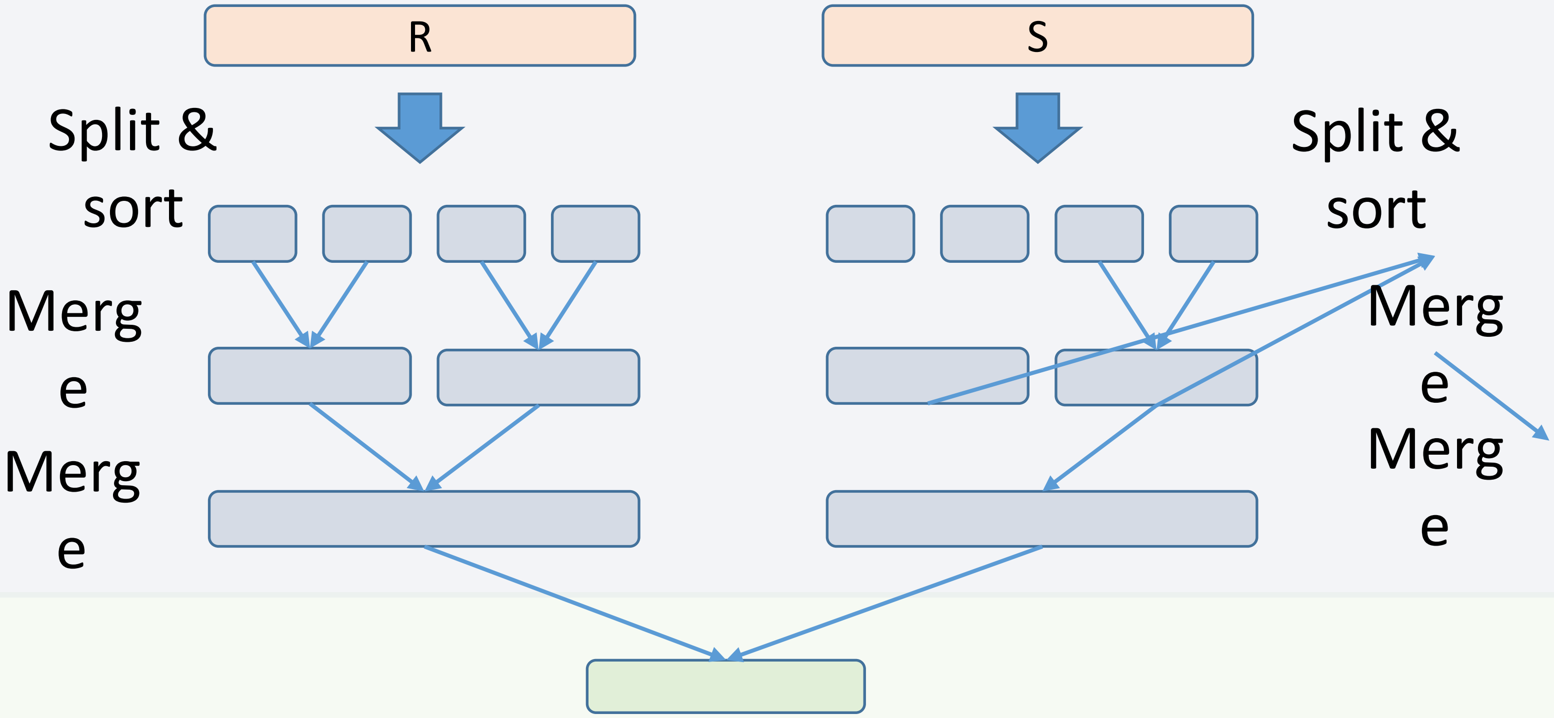
- During the ***sort phase***, run passes of external merge sort on R and S
  - Suppose at some point, R and S have <= ***B*** (sorted) runs in total
  - We could do two merges (for each of R & S) at this point, complete the sort phase, and start the merge phase…
  - OR, we could combine them: do **one** B-way merge and complete the join!

Un-Optimized SMJ

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

Unsorted input relations

Sort Phase (Ext. Merge Sort)

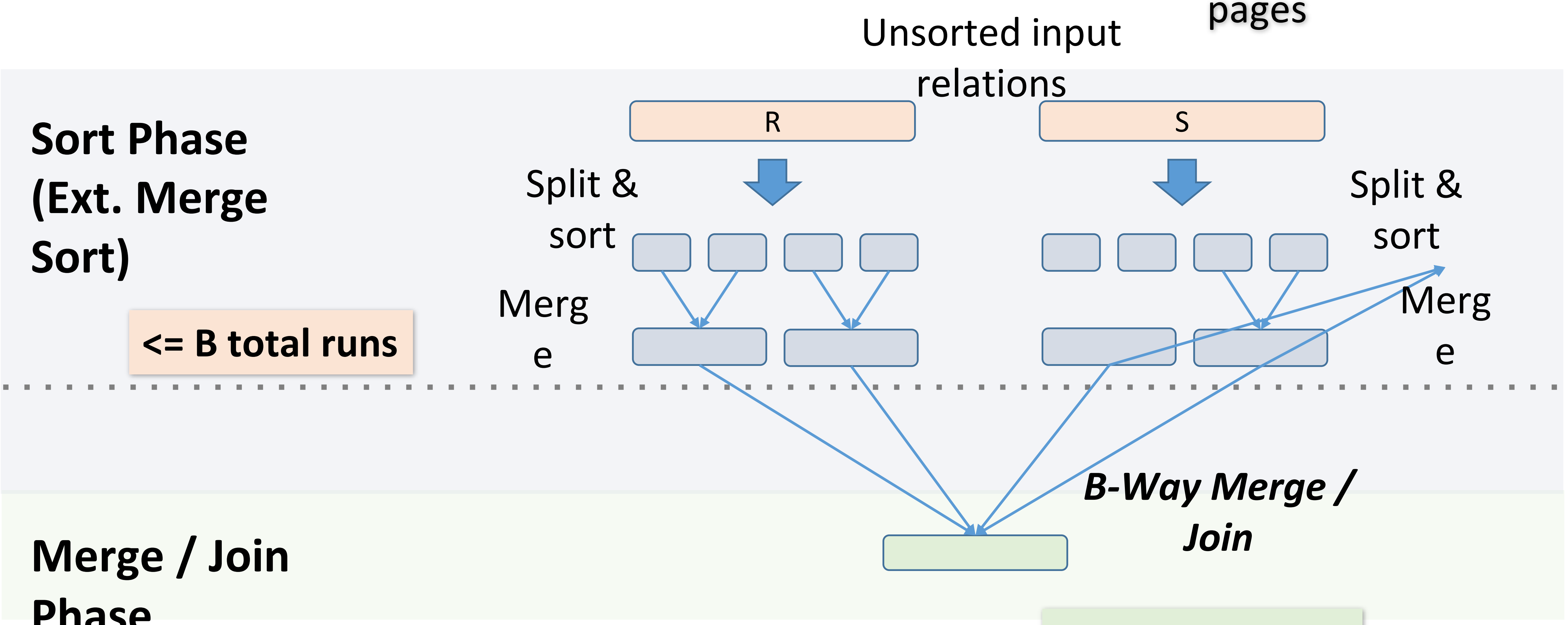


Merge / Join Phase

Joined output file created!

Simple SMJ Optimization

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



Joined output file created!

Simple SMJ Optimization

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

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

- If we can initially split R and S into **B total runs each of length approx. <= 2(B+1)**, *assuming repacking lets us create initial runs of ~2(B+1)*- then we only need ***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?
  - $\frac{P(R)+P(S)}{B} \leq 2(B+1) \Rightarrow \sim \mathrm{P(R)} + \mathrm{P(S)} \leq 2B^2$
  - **Thus,** $\mathbf{max\{P(R), P(S)\}} \leq \boldsymbol{B^2}$ **is an approximate sufficient condition**

See Lecture 15, Slide 13-14 – to clarify this slide.

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

4. Hash Join (HJ)

What you will learn about in this section

1. Hash Join

1. Memory requirements

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 $h_B(x) \mathrel{!}= h_B(y)$

- 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.

Recall: Mad Hash Collisions

Say something here to justify this slide’s existence? [TODO]

Hash Join: High-level procedure

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

Note again that we are only considering equality constraints here

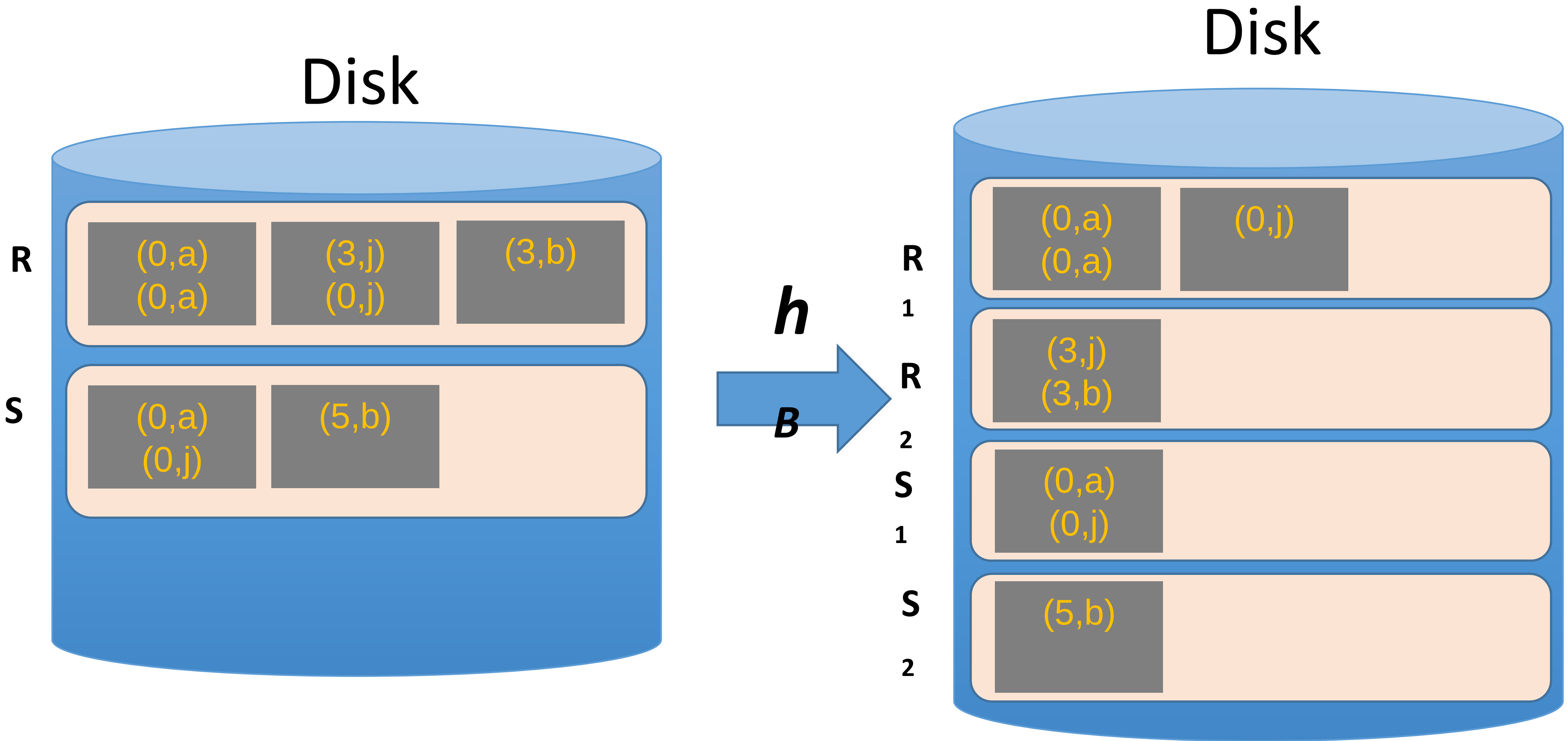
1. **Partition Phase:** Using one (shared) hash function $\boldsymbol{h_B}$, partition R *and* S into ***B*** buckets

2. **Matching Phase:** Take pairs of buckets whose tuples have the same values for ***h***, and join these
   1. Use BNLJ here; or hash again → either way, operating on small partitions so fast!

We ***decompose*** the problem using $\boldsymbol{h_B}$, 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

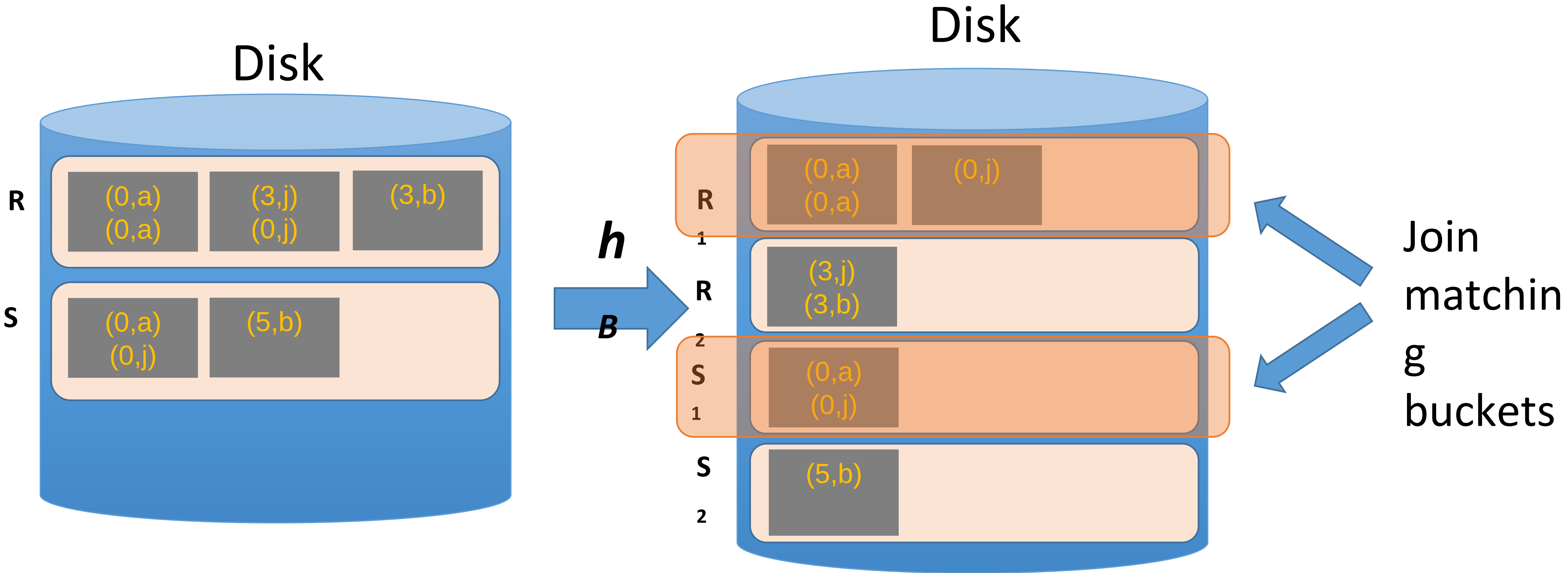


Note our new convention: pages each have two tuples (one per row)

More detail in a second…

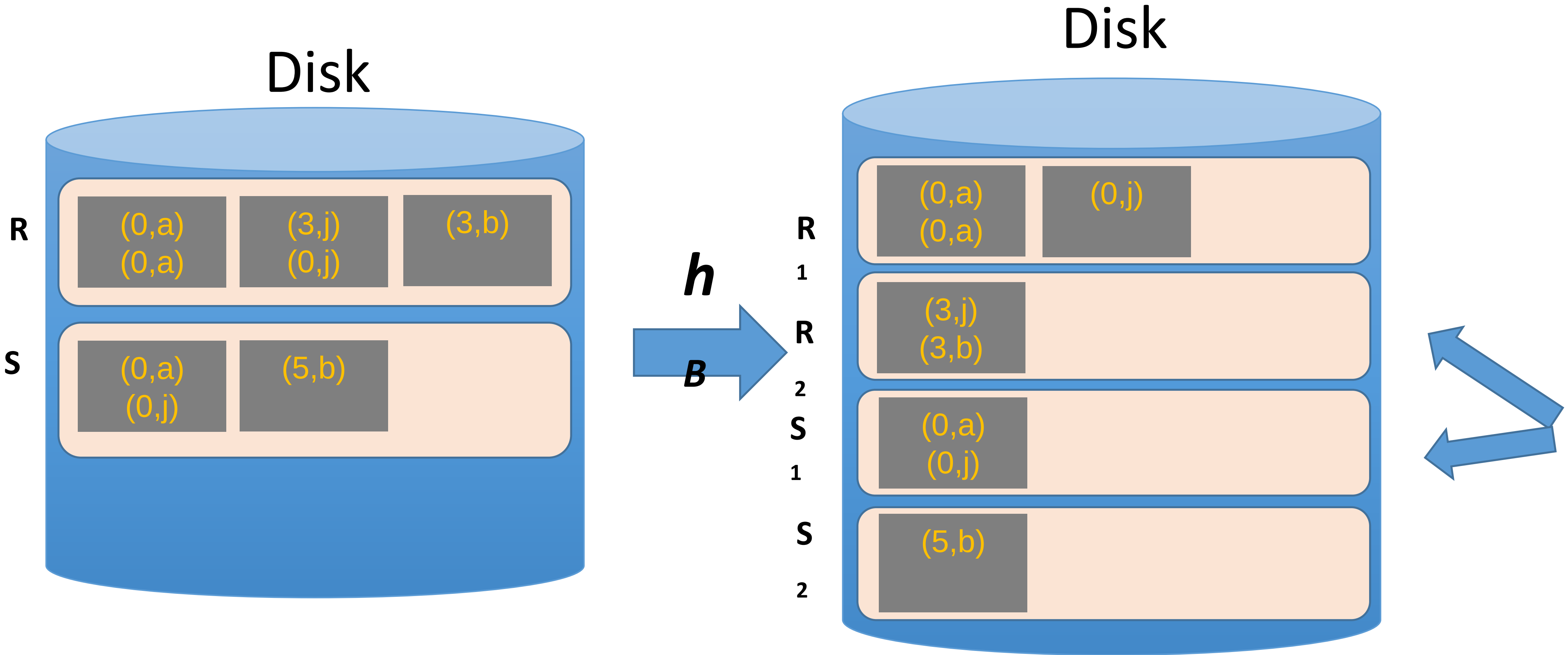
Hash Join: High-level procedure

2. Matching Phase: Take pairs of buckets whose tuples have the same values for $\boldsymbol{h_B}$, 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



Don't have to join the others! E.g. (S_1 and R_2)!

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
  - The "dual" of sorting.
  - For each tuple t in input, copy to buffer page for $h_B(t.A)$
  - When page fills up, flush to disk.

How big are the resulting buckets?

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

- Given **N input pages, we partition into B buckets**:
  - ⍰ Ideally our buckets are each of size **~ N/B pages**
- What happens if there are **hash collisions**?
  - Buckets could be > N/B
  - **We'll do several passes…**
- What happens if there are **duplicate join keys?**
  - Nothing we can do here… could have some **skew** in size of the buckets

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**
  - ***1*** for input page, ***1*** for output page, ***B-1*** for each bucket
- 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:

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

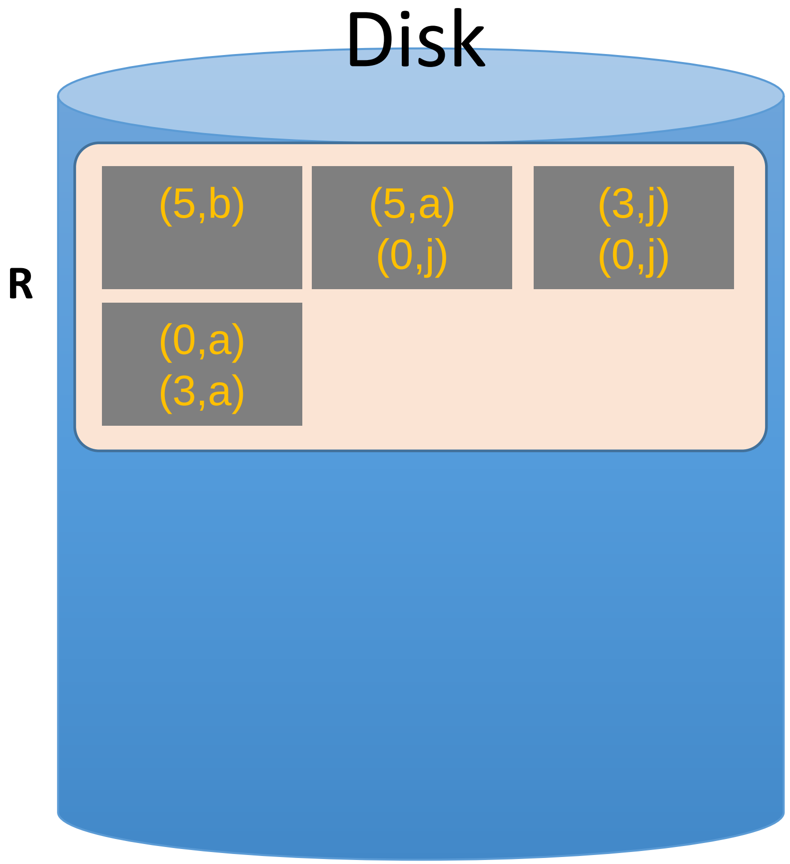
- We can keep partitioning buckets that are > B-1 pages, until they are $\leq \boldsymbol{B-1}$ **pages**
  - Using a new hash key which will split them…

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)



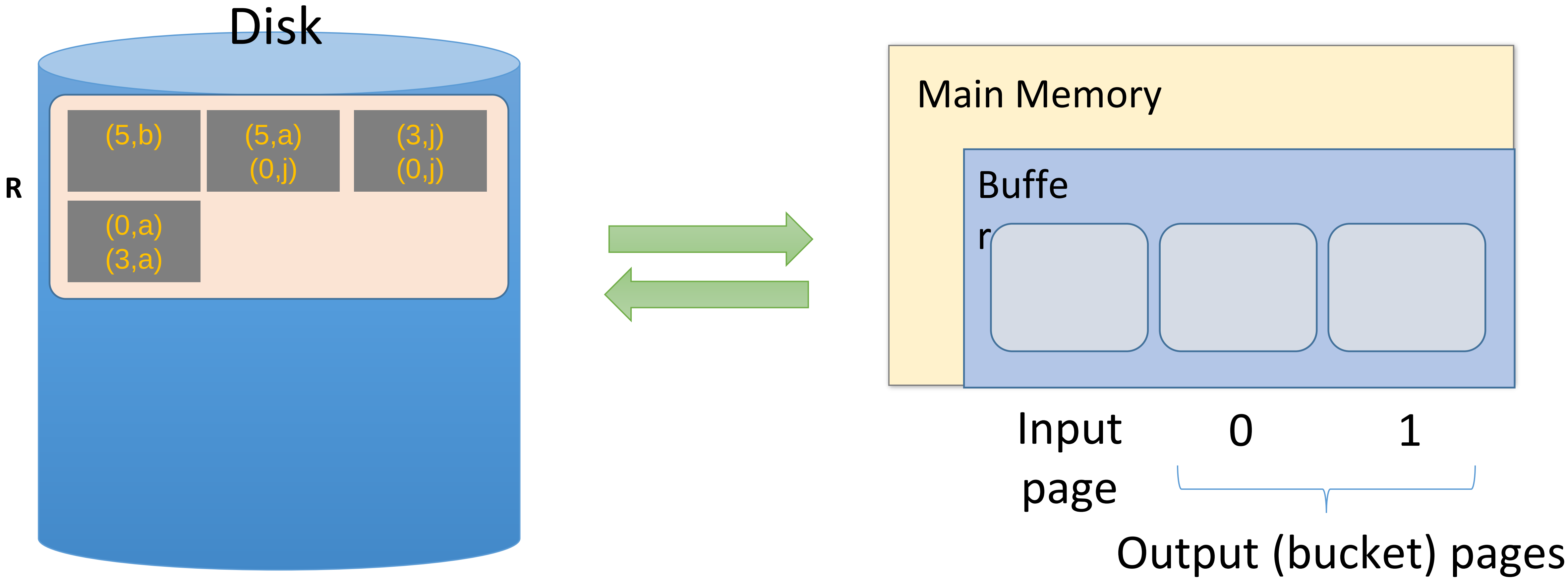
For simplicity, we'll look at partitioning one of the two relations- we just do the same for the other relation!

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

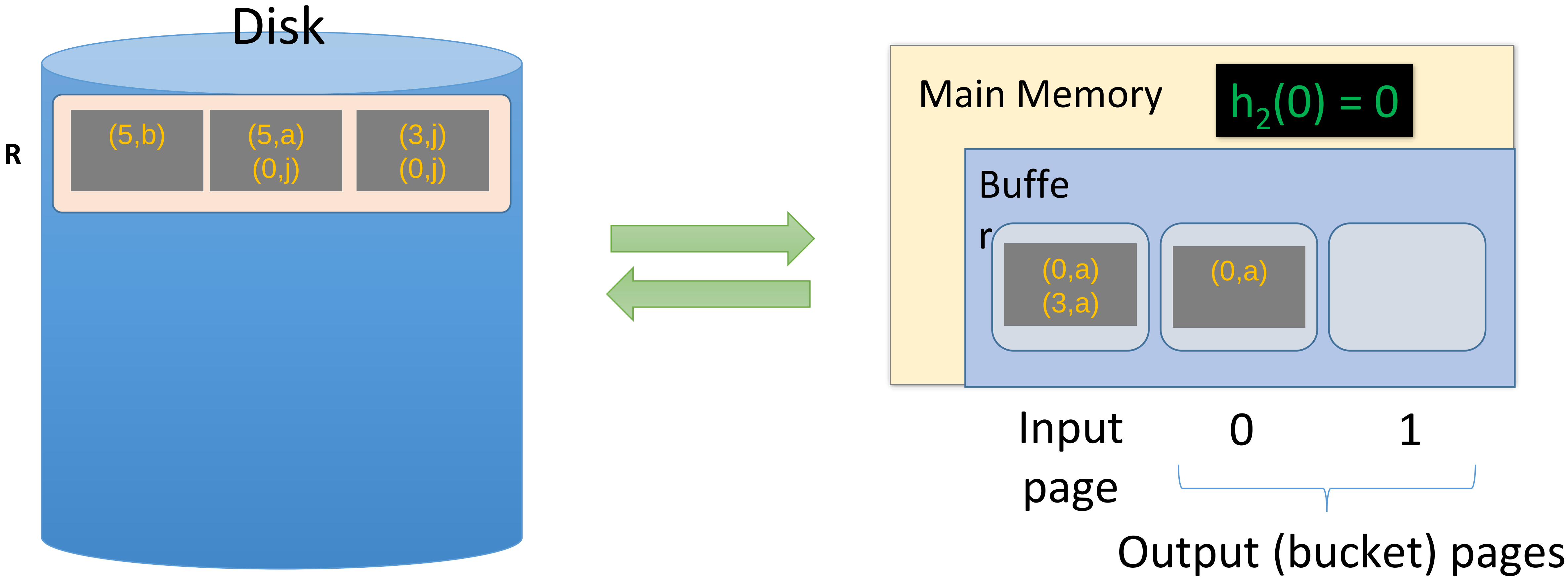
1. We read pages from R into the "input" page of the buffer…



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

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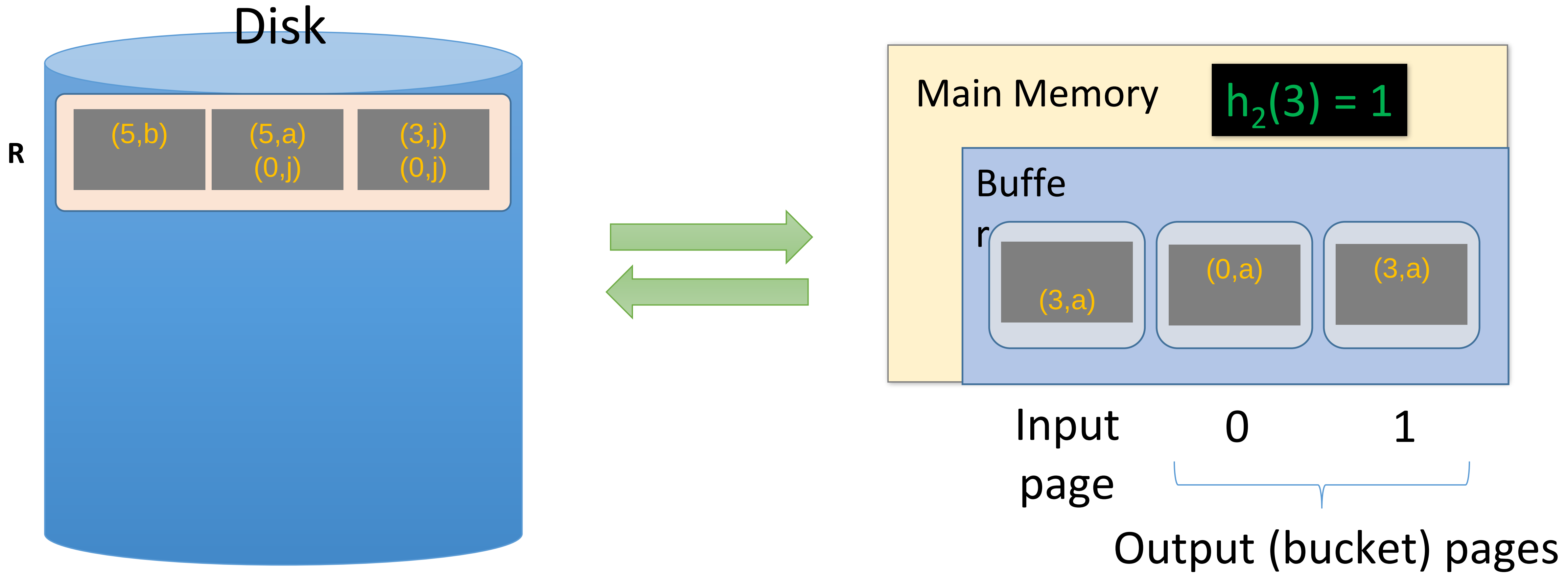
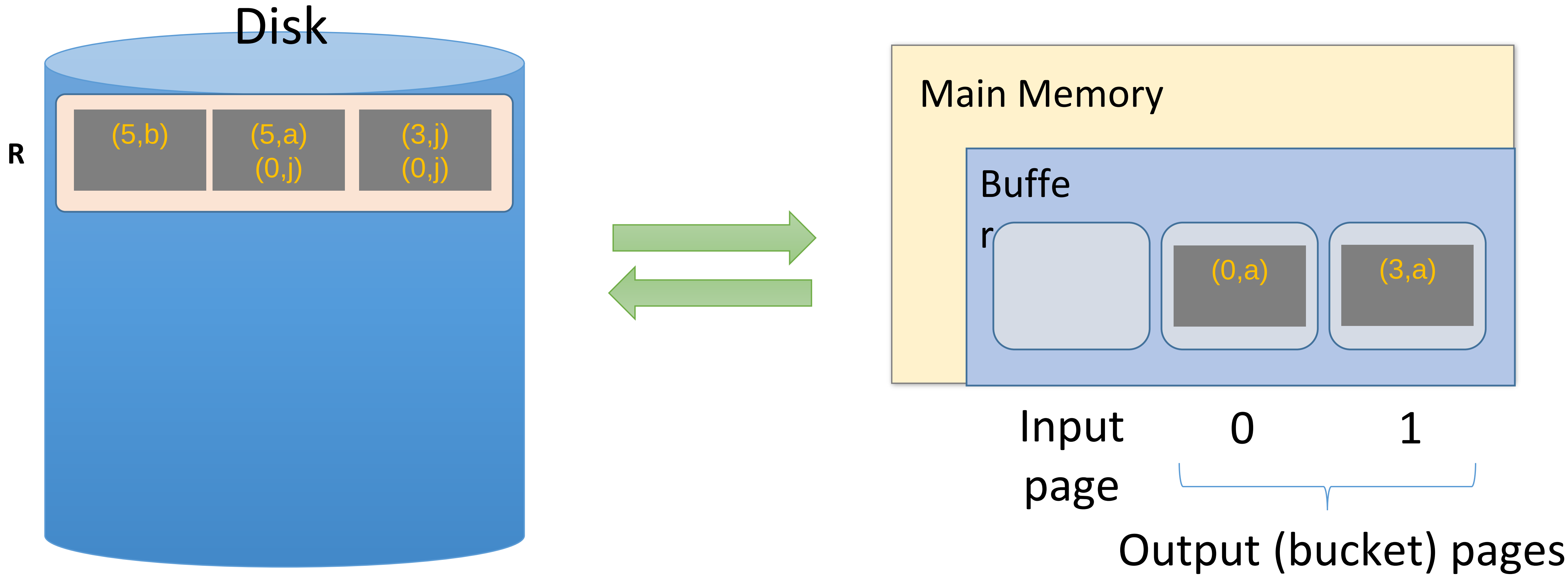


Hash Join Phase 1: Partitioning

Given ***B+1 = 3*** buffer pages

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



Hash Join Phase 1: Partitioning

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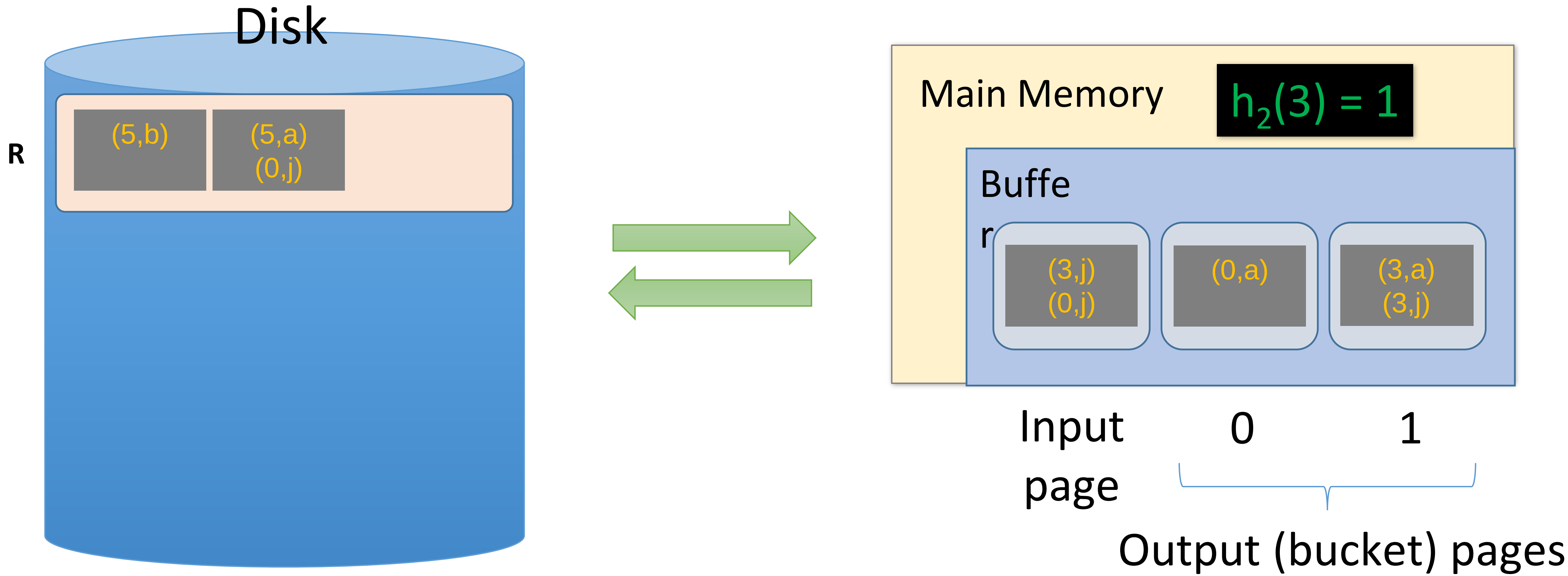

Hash Join Phase 1: Partitioning

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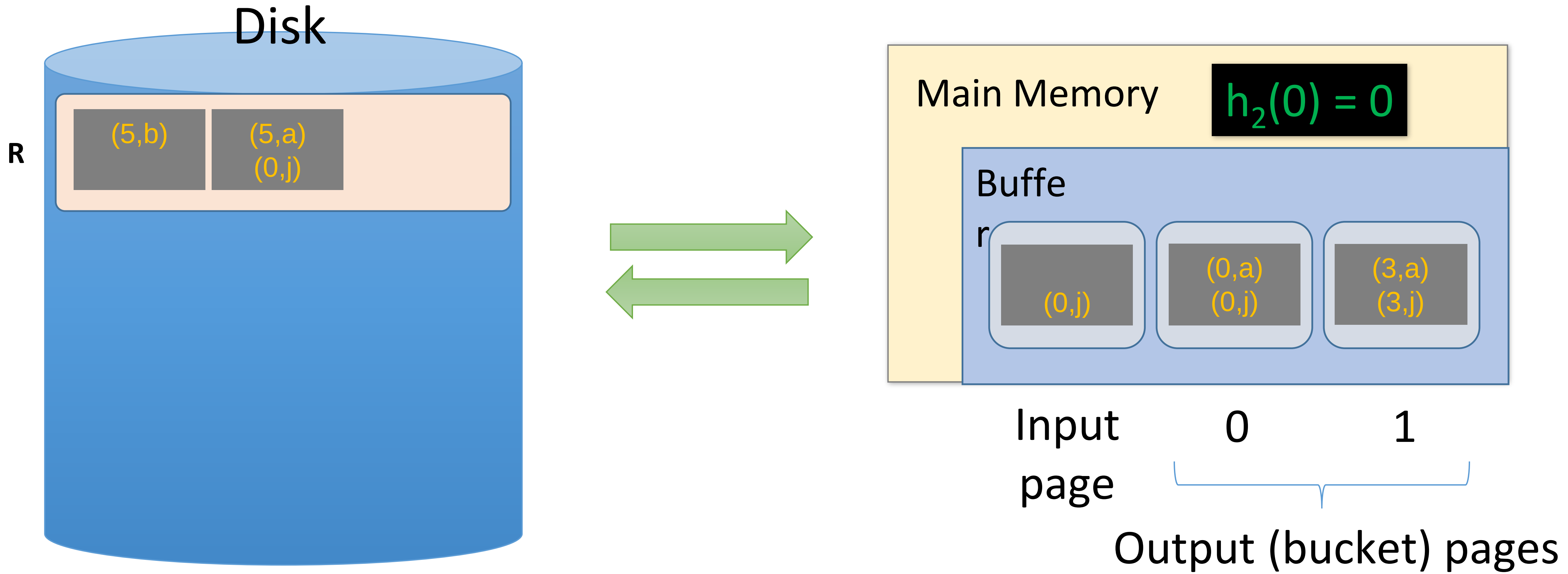
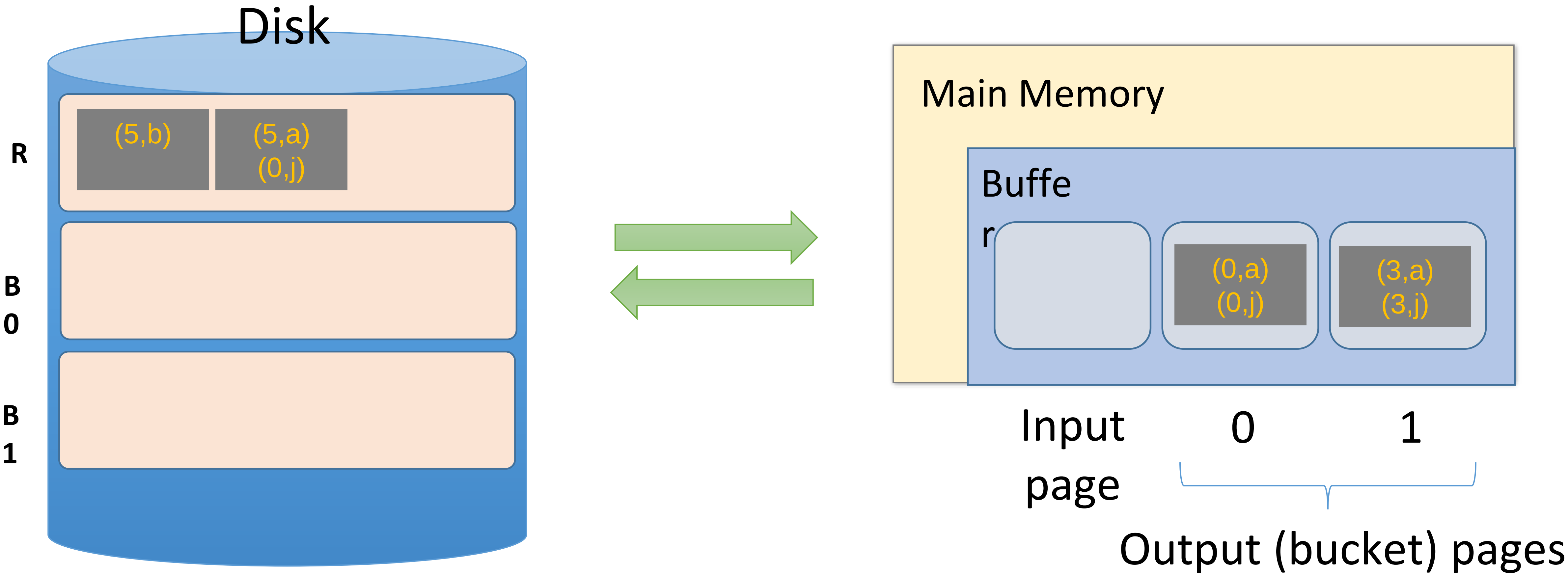


Hash Join Phase 1: Partitioning

Given ***B+1 = 3*** buffer pages

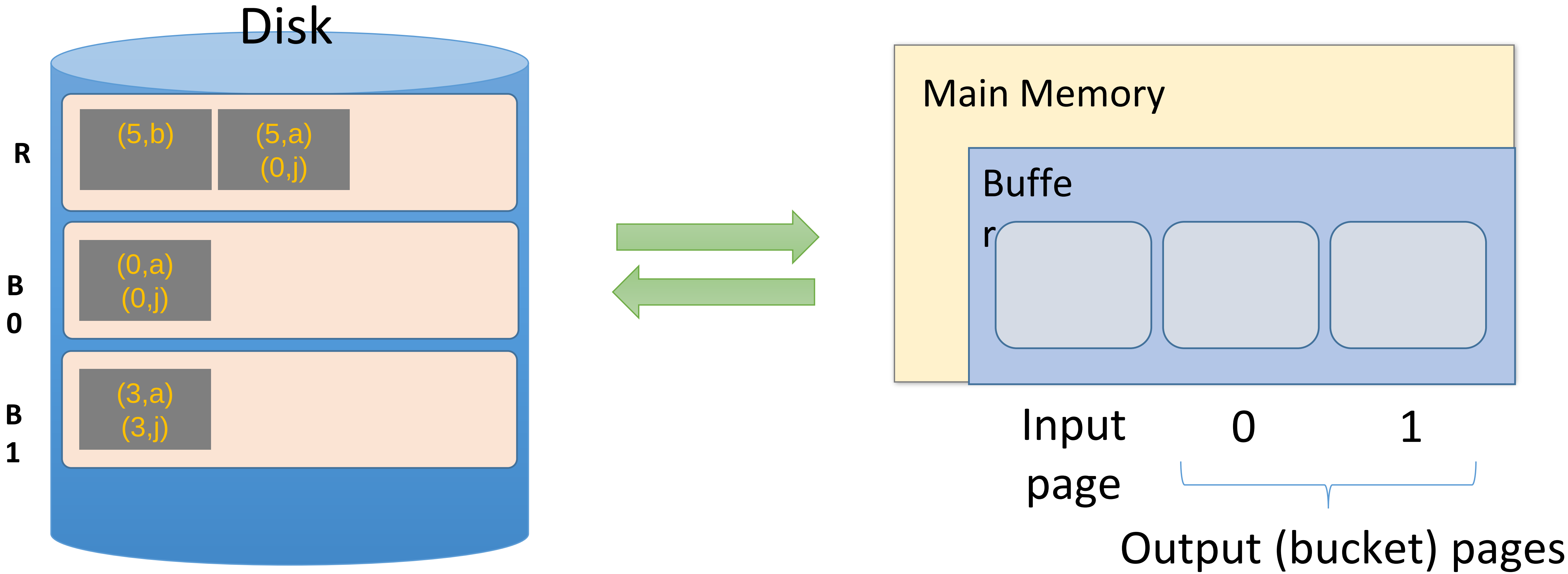
3. We repeat until the buffer bucket pages are full… then flush to disk



Hash Join Phase 1: Partitioning

Given ***B+1 = 3*** buffer pages

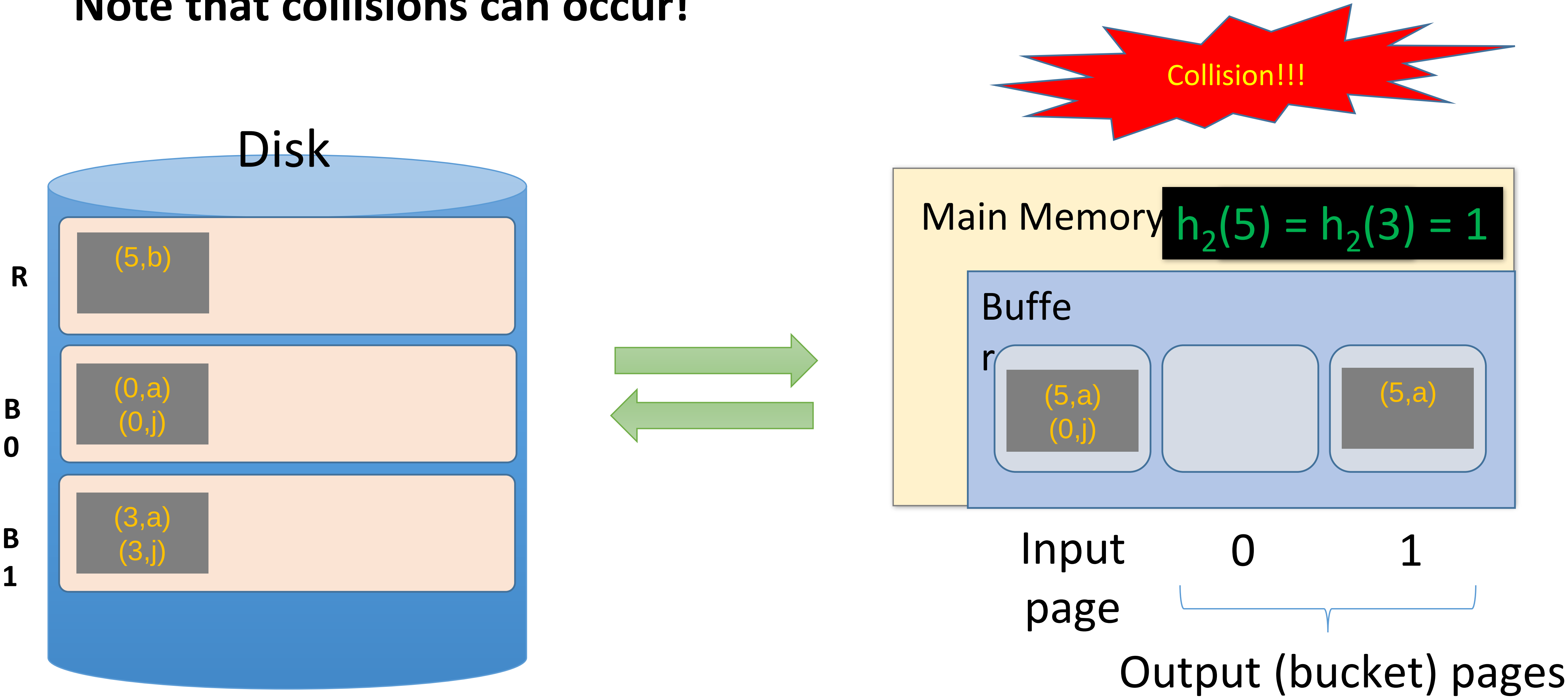
3. We repeat until the buffer bucket pages are full… then flush to disk



Hash Join Phase 1: Partitioning

Given ***B+1 = 3*** buffer pages

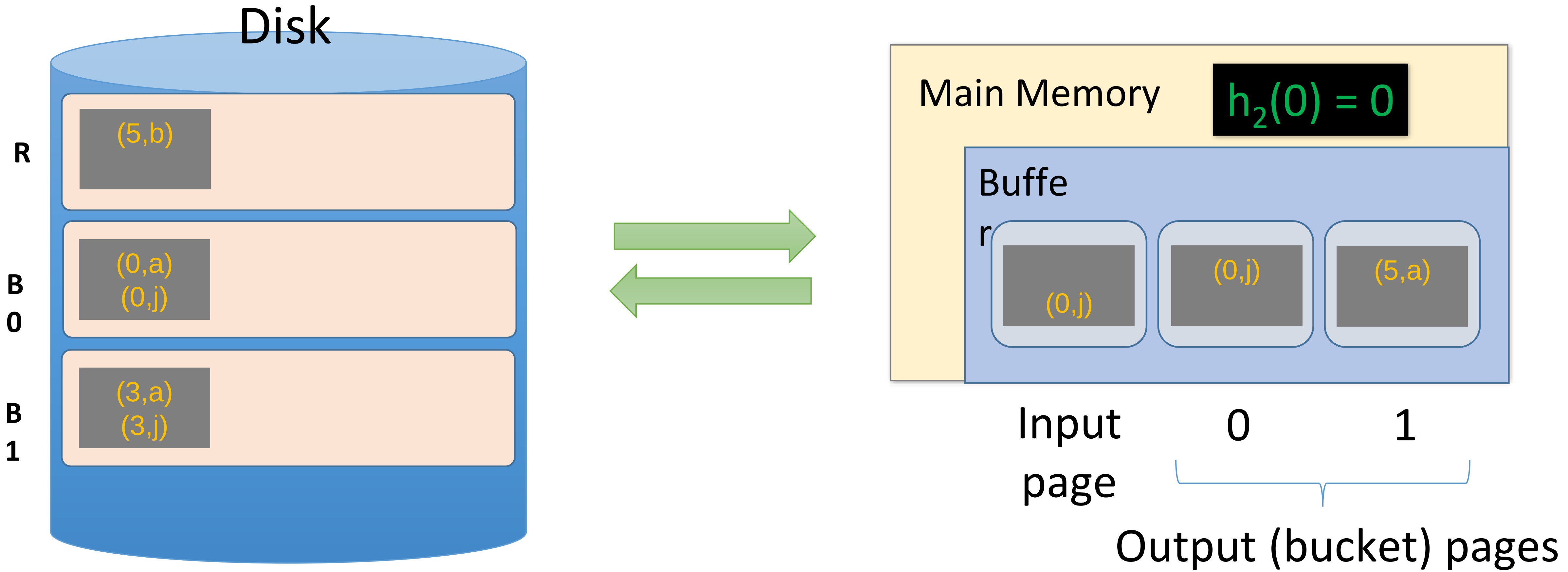
Note that collisions can occur!



Hash Join Phase 1: Partitioning

Given ***B+1* = *3*** buffer pages

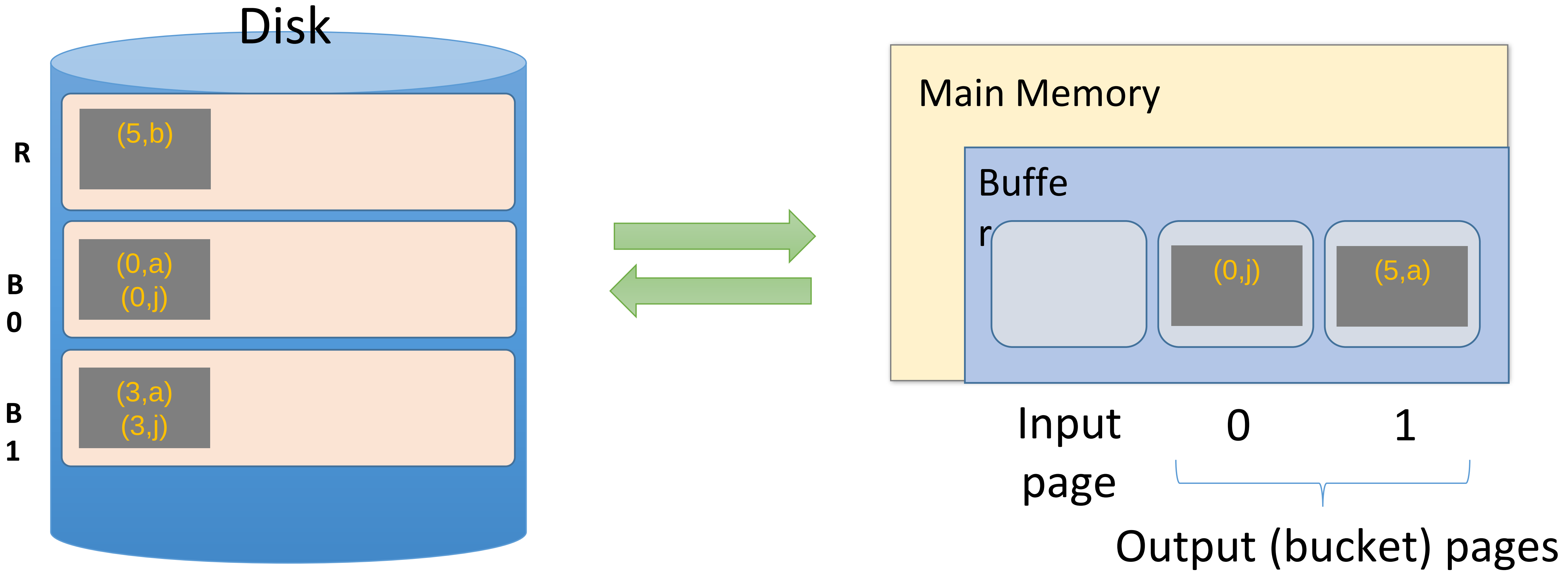
Finish this pass…



Hash Join Phase 1: Partitioning

Given ***B+1 = 3*** buffer pages

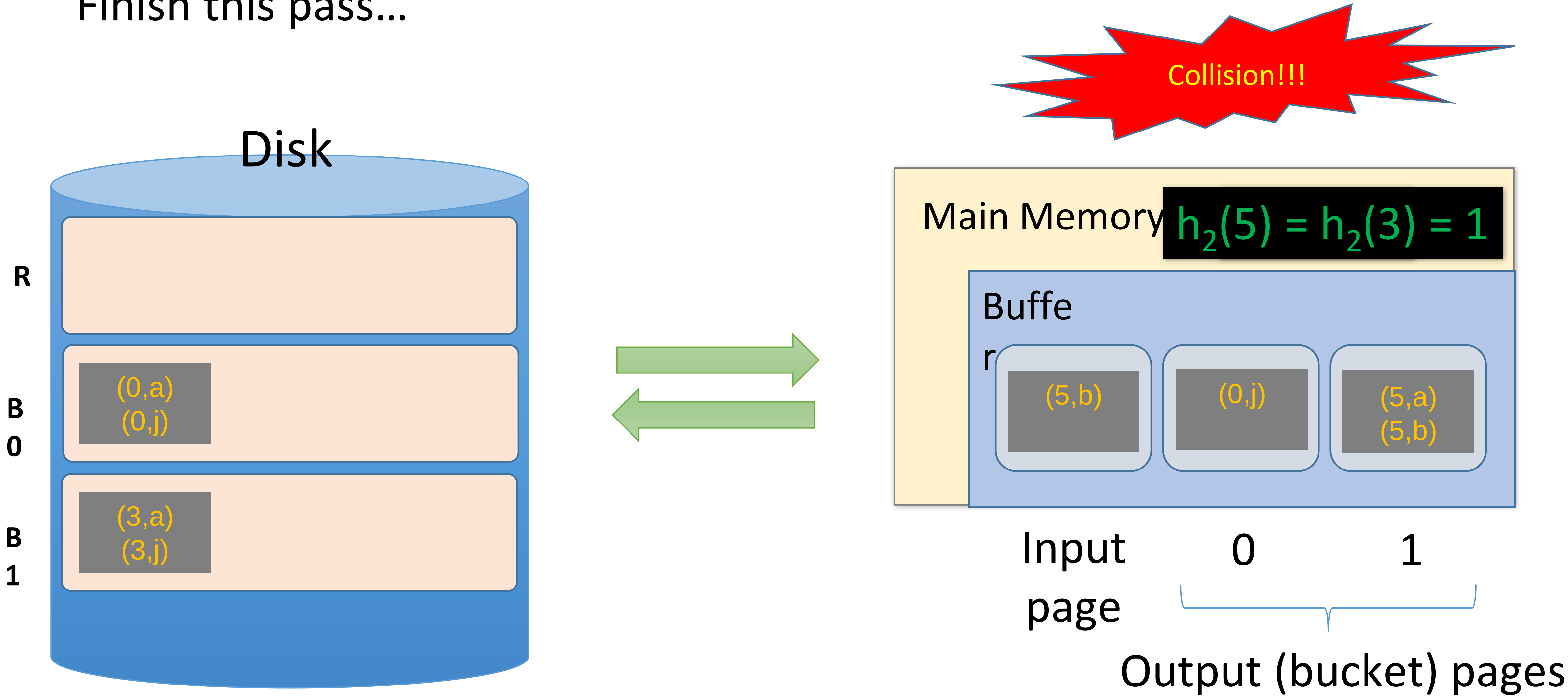
Finish this pass…



Hash Join Phase 1: Partitioning

Given ***B+1 = 3*** buffer pages

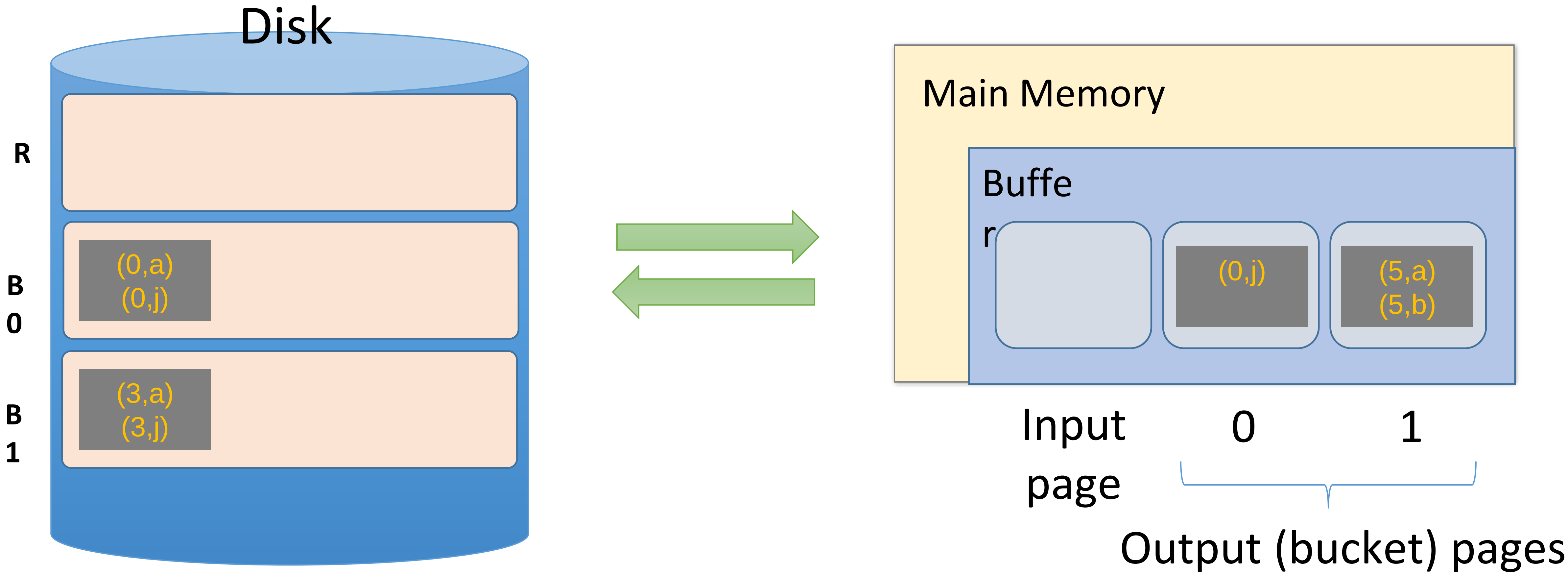
Finish this pass…



Hash Join Phase 1: Partitioning

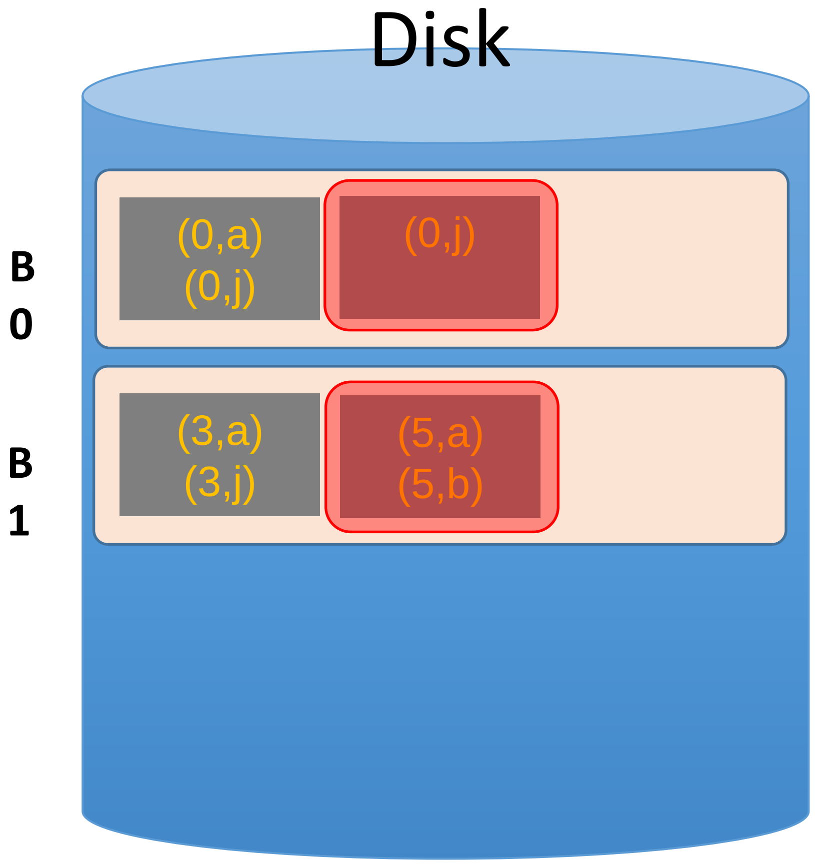
Given ***B+1 = 3*** buffer pages

Finish this pass…



Hash Join Phase 1: Partitioning

Given ***B+1 = 3*** buffer pages



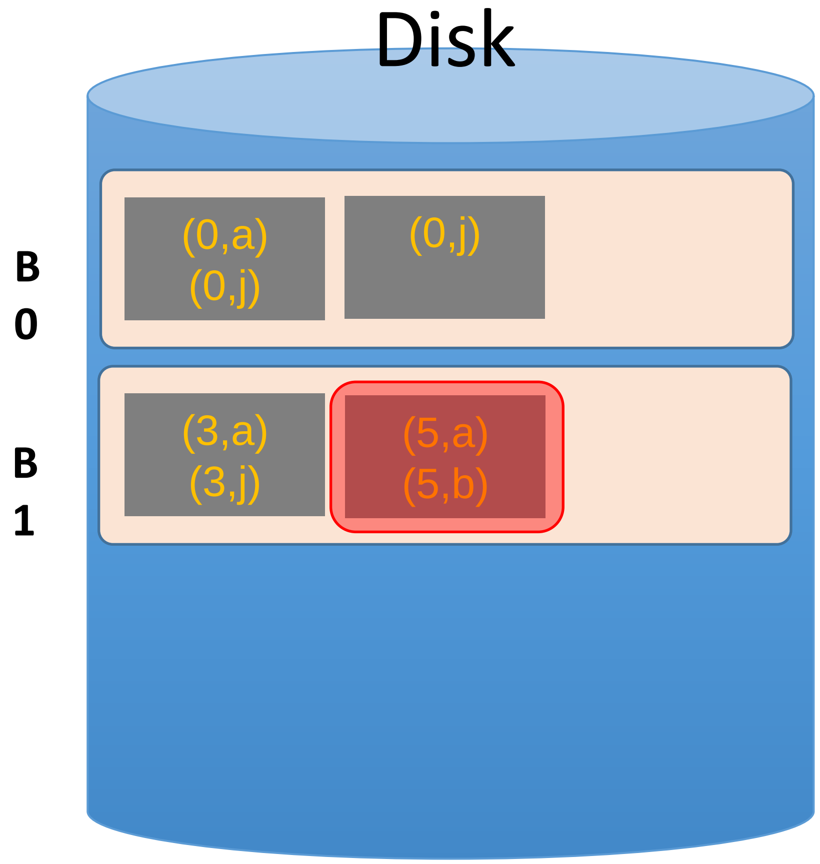
We wanted buckets of size ***B-1 = 1…***
however we got larger ones due to:

(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!

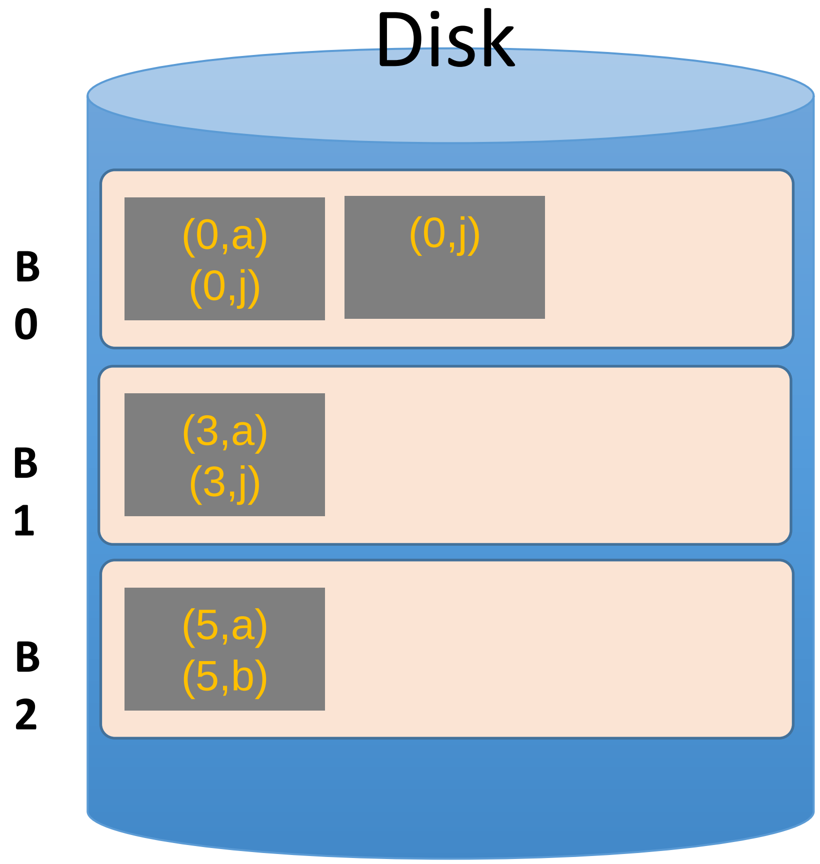
What hash function should we use?

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

$$h'_2(3) \mathrel{!=} h'_2(5)$$

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!

What hash function should we use?

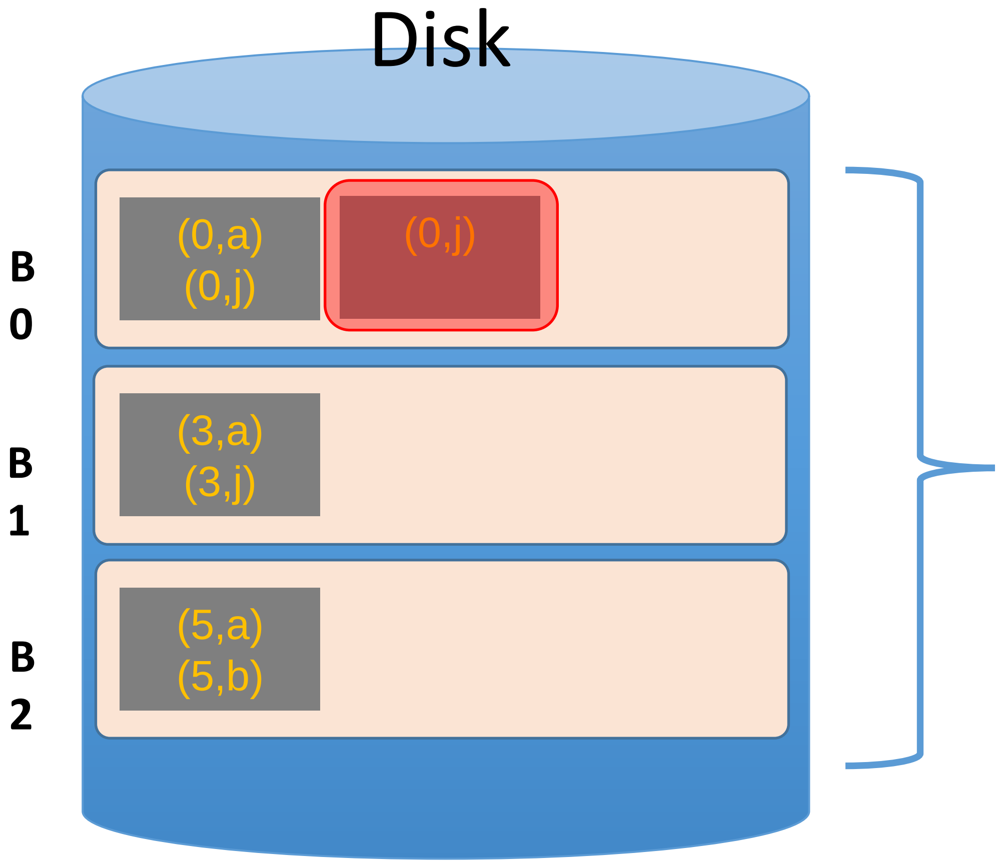
Do another pass with a different hash function, h'_2, ideally such that:

$$h'_2(3) \neq h'_2(5)$$

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.

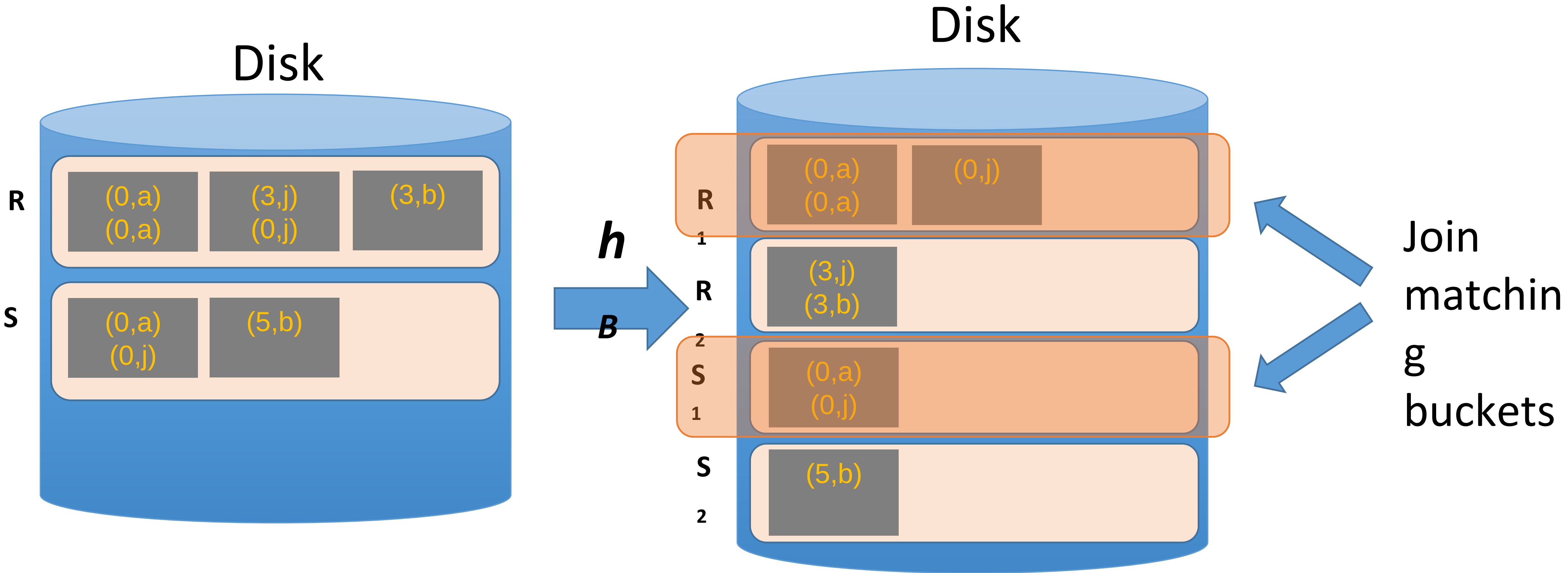


We call this unevenness in the bucket size **skew**

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

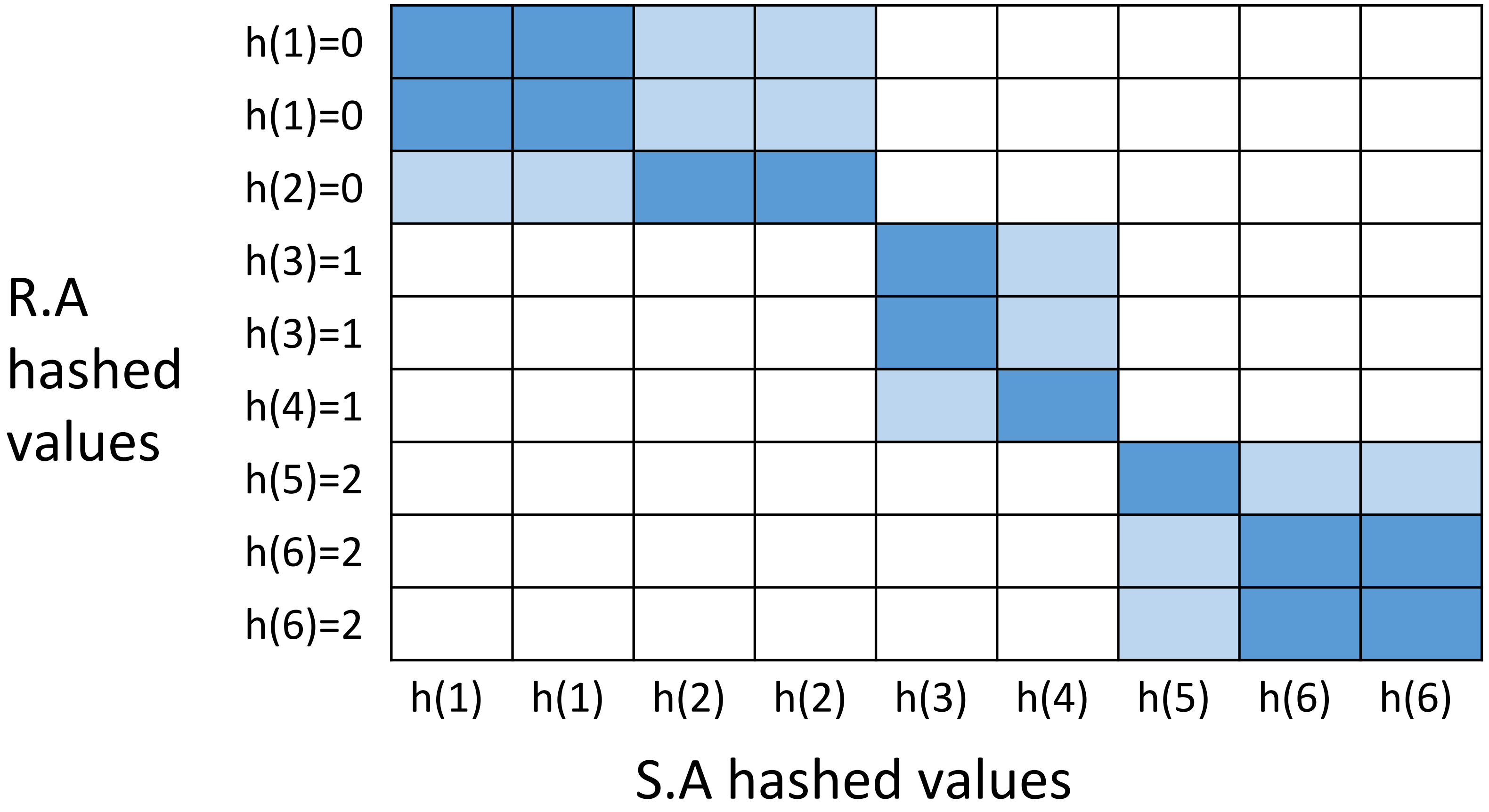
- Note that since x = y → h(x) = h(y), we only need to consider pairs of buckets (one from R, one from S) that have the same hash function value

- 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):

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

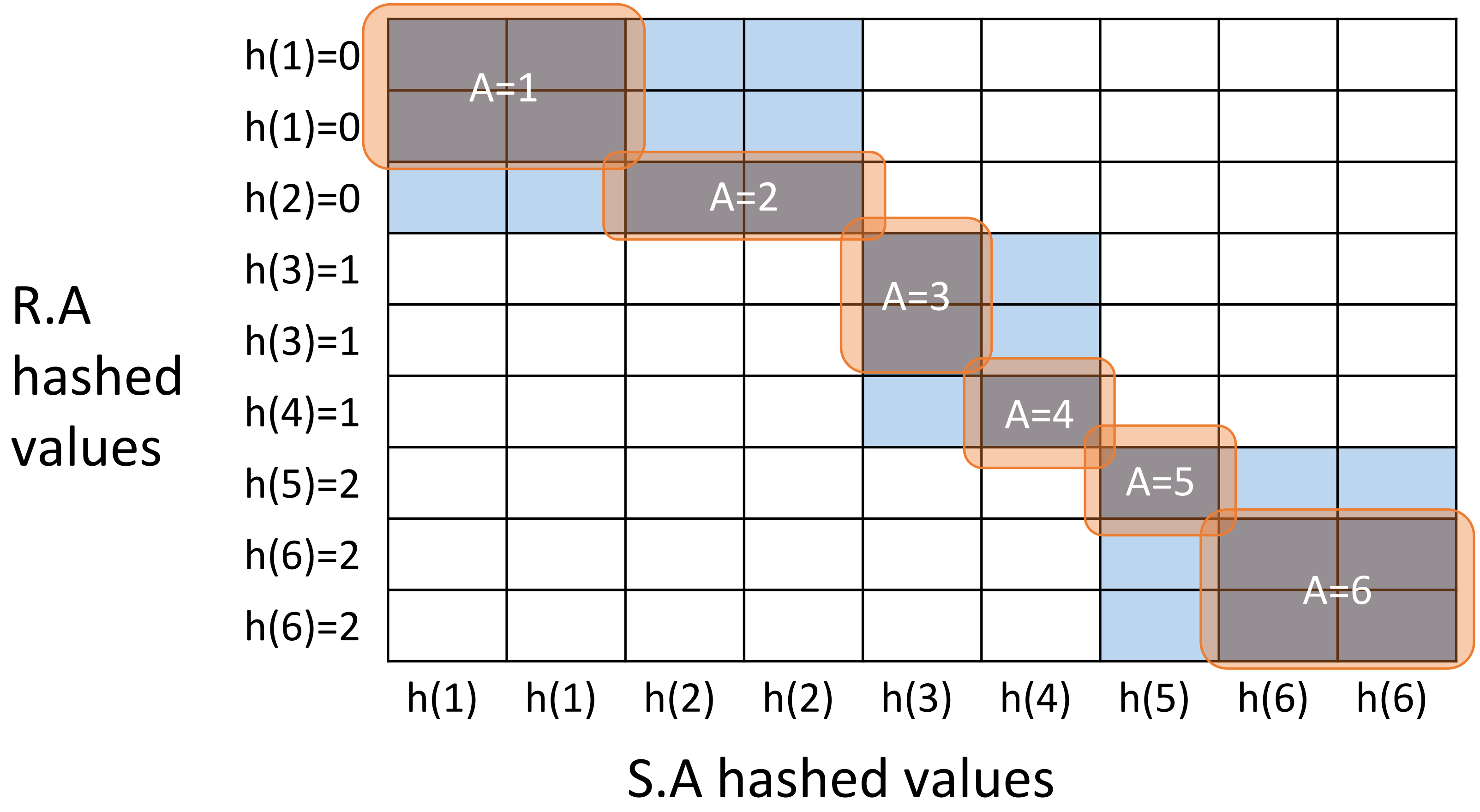
Joining the pairs of buckets is linear!
(As long as smaller bucket <= B-1 pages)

Hash Join Phase 2: Matching



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

Hash Join Phase 2: Matching

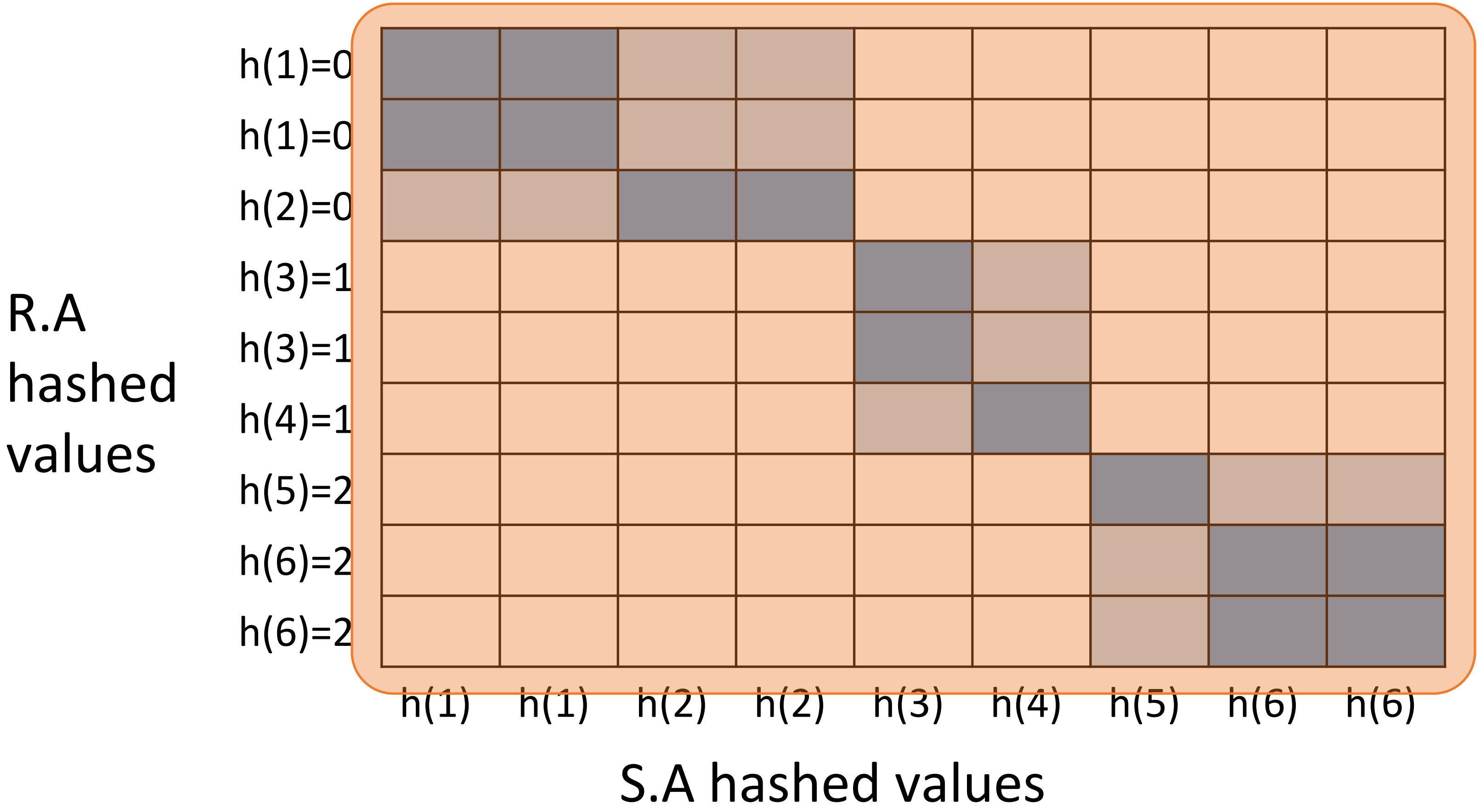


$\mathrm{R} \bowtie S \text{ on } A$

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

= the tuples with same values of the join key A

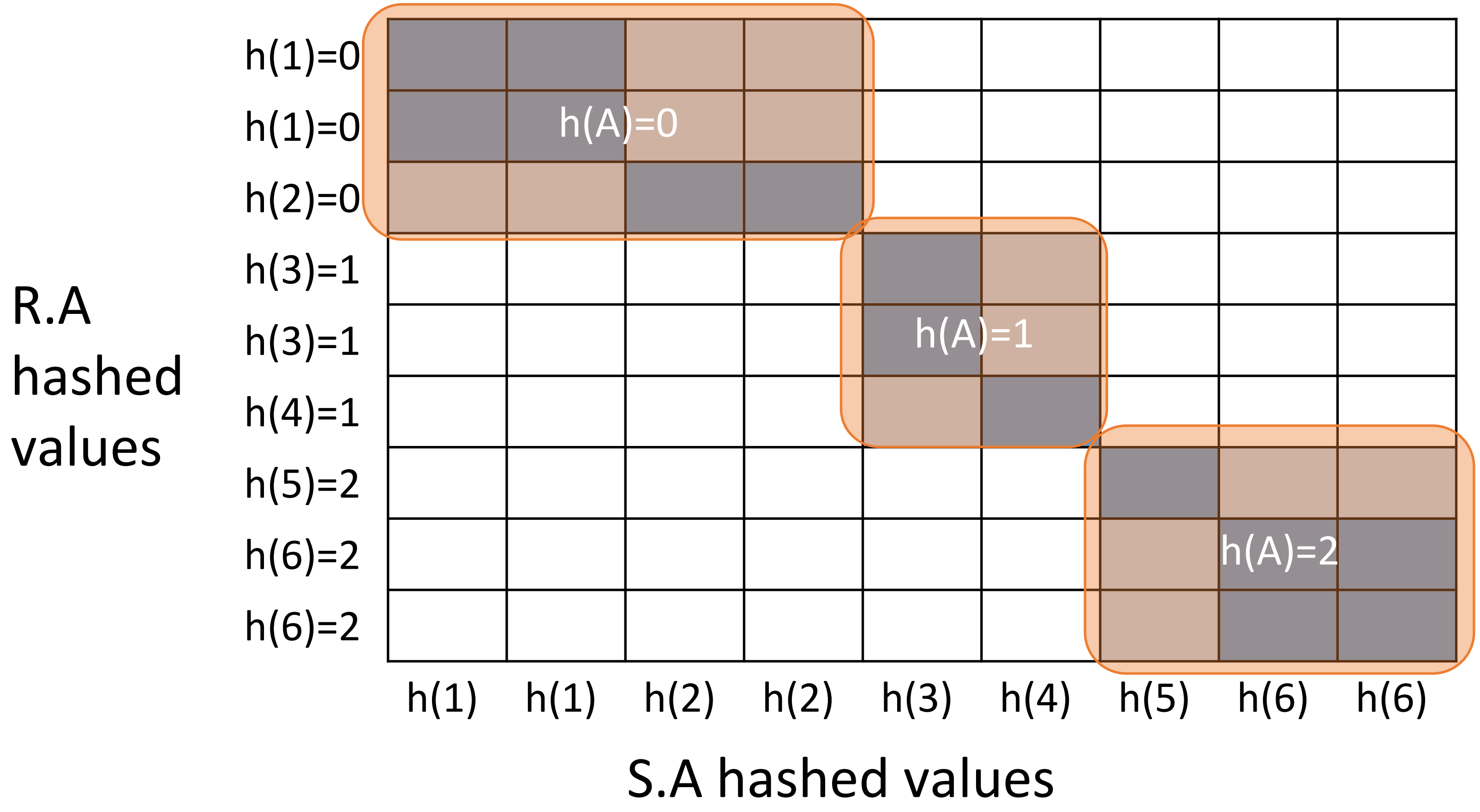
Hash Join Phase 2: Matching



$R \bowtie S$ 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



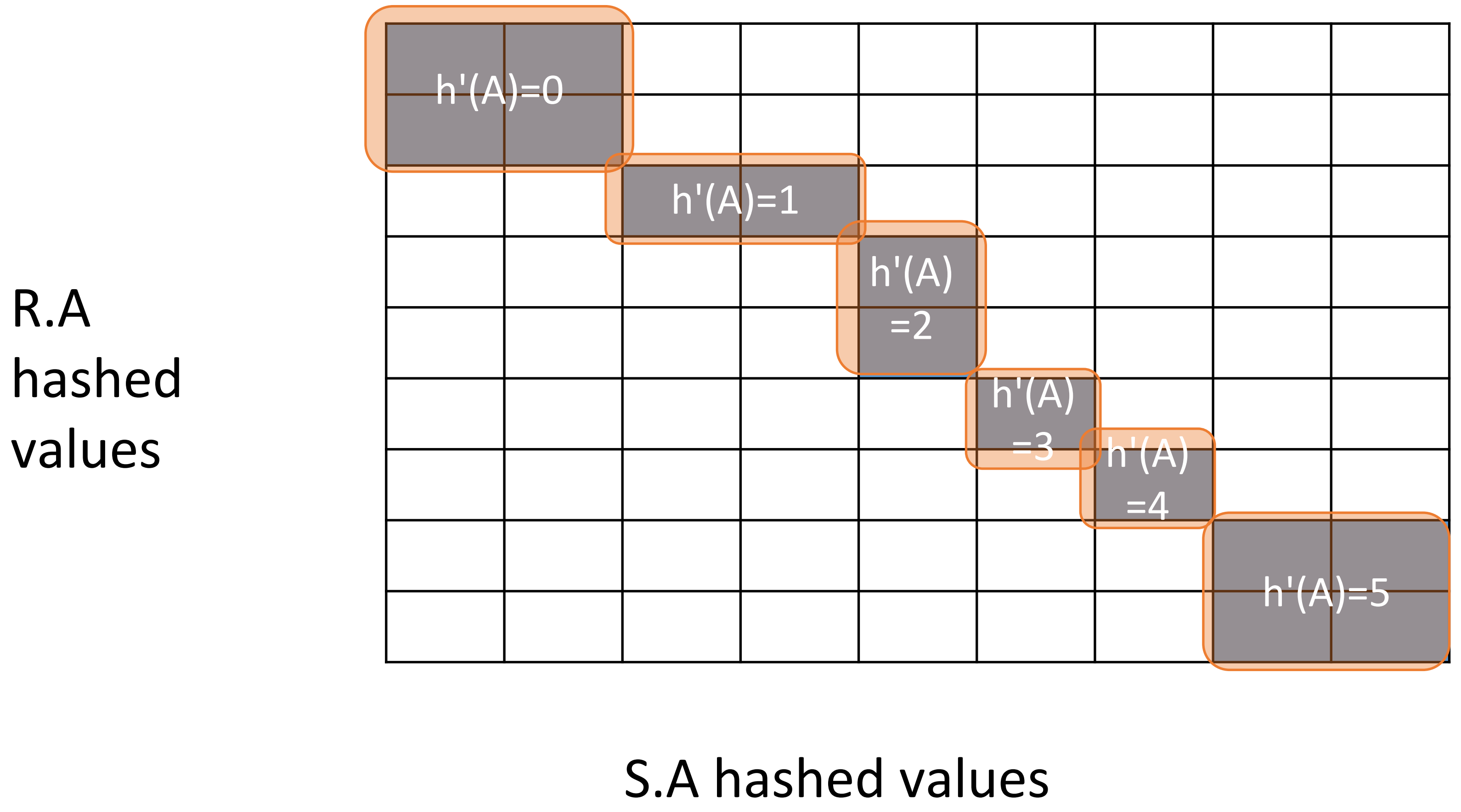
$R \bowtie S \text{ on } A$

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

Hash Join Phase 2: Matching



$R \bowtie S \ on \ A$

An alternative to applying BNLJ:

We could also hash again, and keep doing passes in memory to reduce further!

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:

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

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!

3. The Cage Match

Sort-Merge v. Hash Join

- ***Given enough memory***, both SMJ and HJ have performance:

~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

Summary

- Saw IO-aware join algorithms
  - Massive difference
- Memory sizes key in hash versus sort join
  - Hash Join = Little dog (depends on smaller relation)
- Skew is also a major factor