Lecture 13:
Joins Part II

Today's Lecture

1. Sort-Merge Join (SMJ)

2. Hash Join (HJ)

3. The Cage Match: SMJ vs. HJ

1. Sort-Merge Join (SMJ)

What you will learn about in this section

1. Sort-Merge Join
2. "Backup" & Total Cost
3. Optimizations
4. ACTIVITY: Sequential Flooding

Sort Merge Join (SMJ): Basic Procedure

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

Note that we are only considering equality join conditions here

1. Sort R, S on A using ***external merge sort***

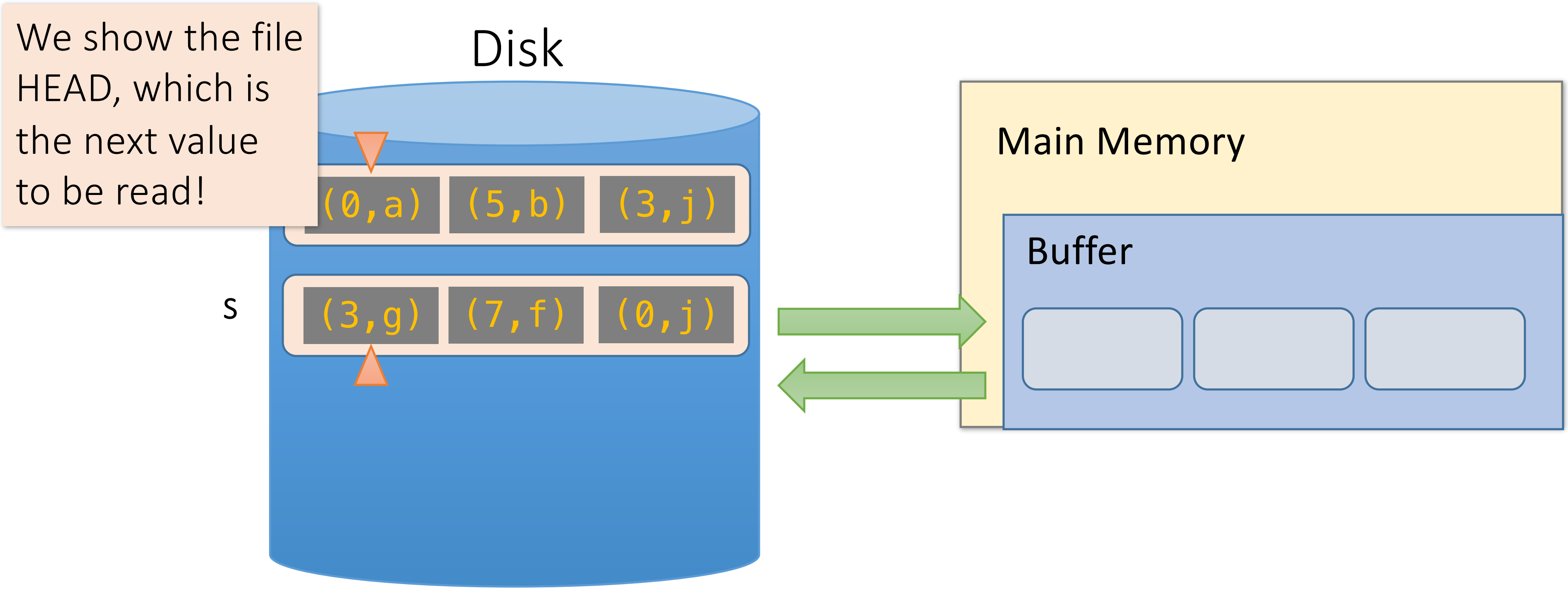
2. Scan sorted files and "merge"

3. [May need to "backup"- see next subsection]

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

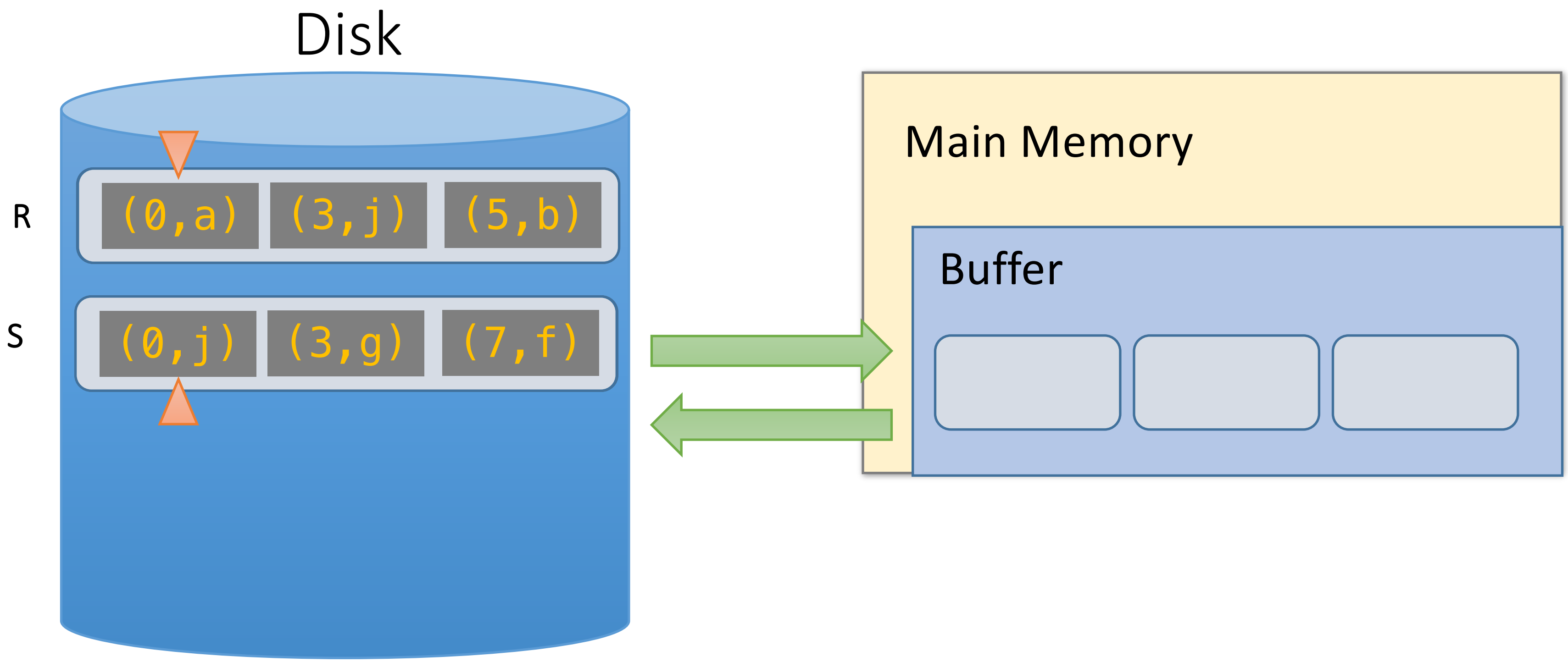
SMJ Example: $\mathrm{R} \bowtie S \ on \ A$ with 3 page buffer

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



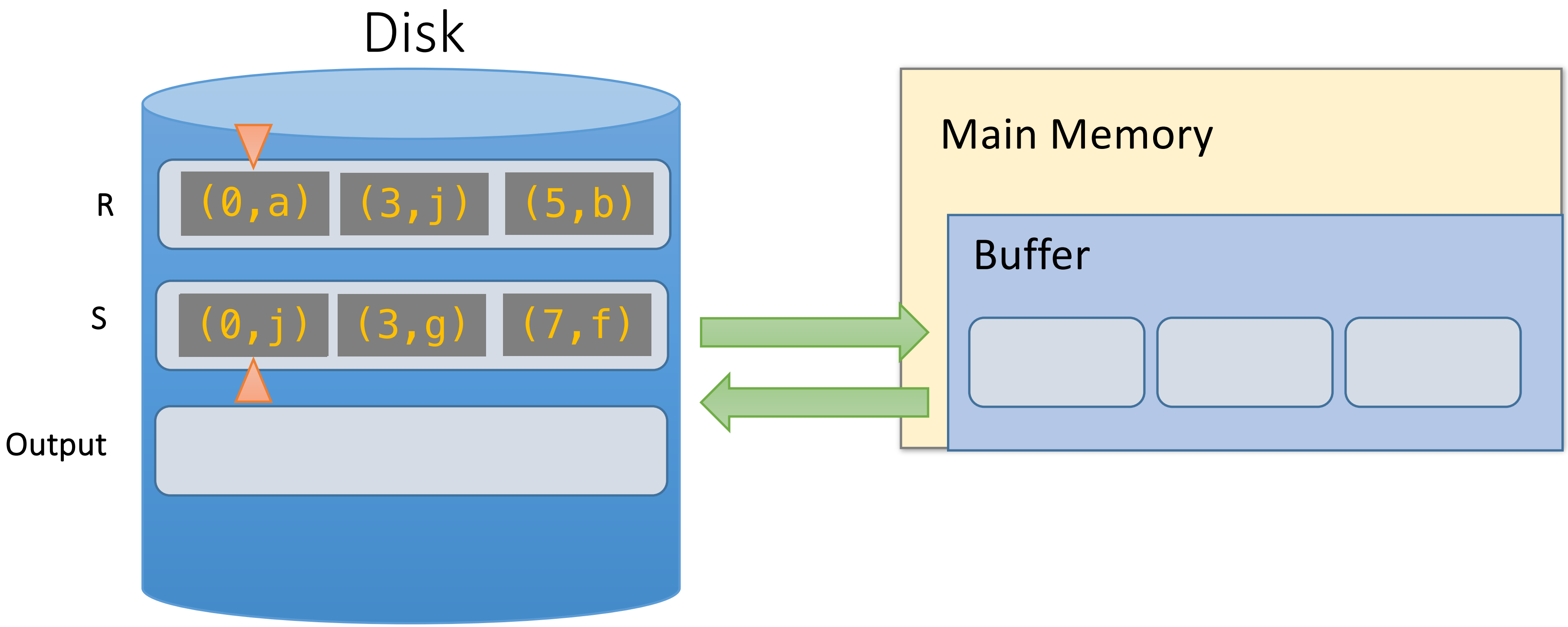
SMJ Example: $\mathrm{R} \bowtie S\ on\ A$ with 3 page buffer

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



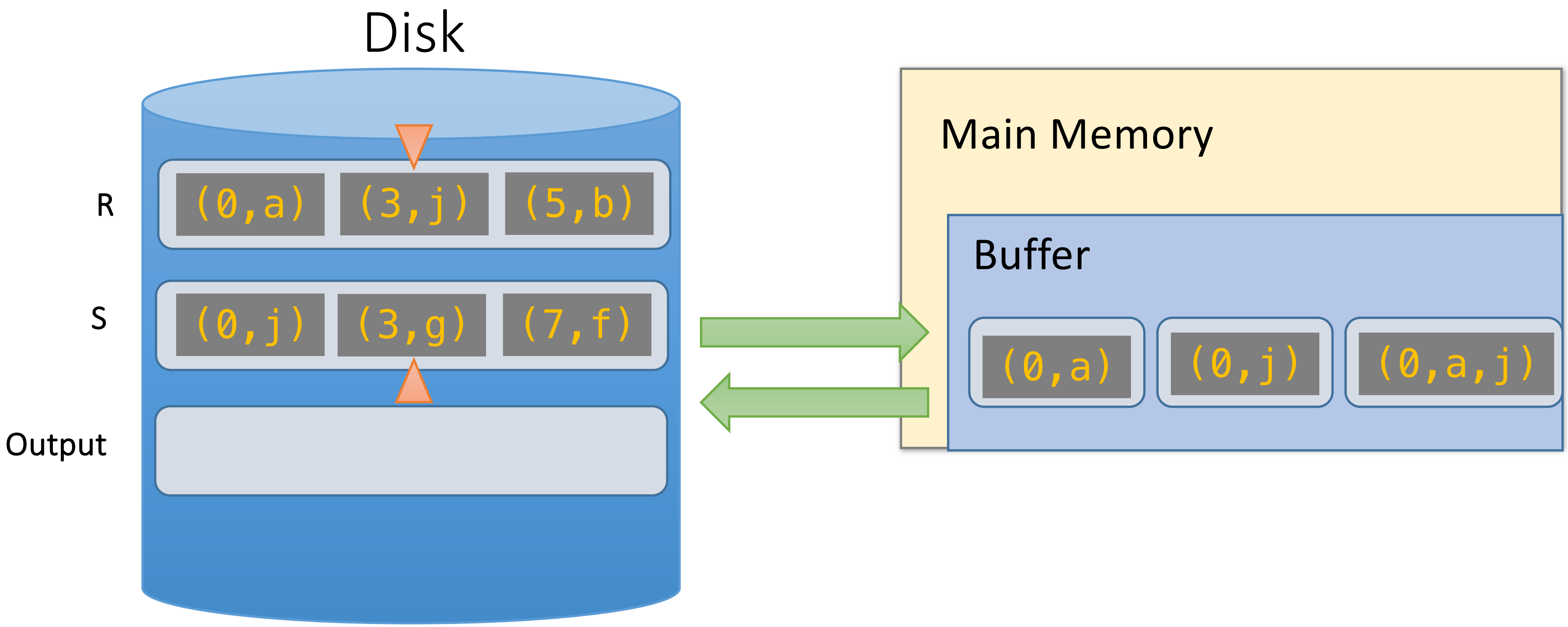
SMJ Example: $\mathrm{R} \bowtie S \text{ on } A$ with 3 page buffer

2. Scan and “merge” on join key!



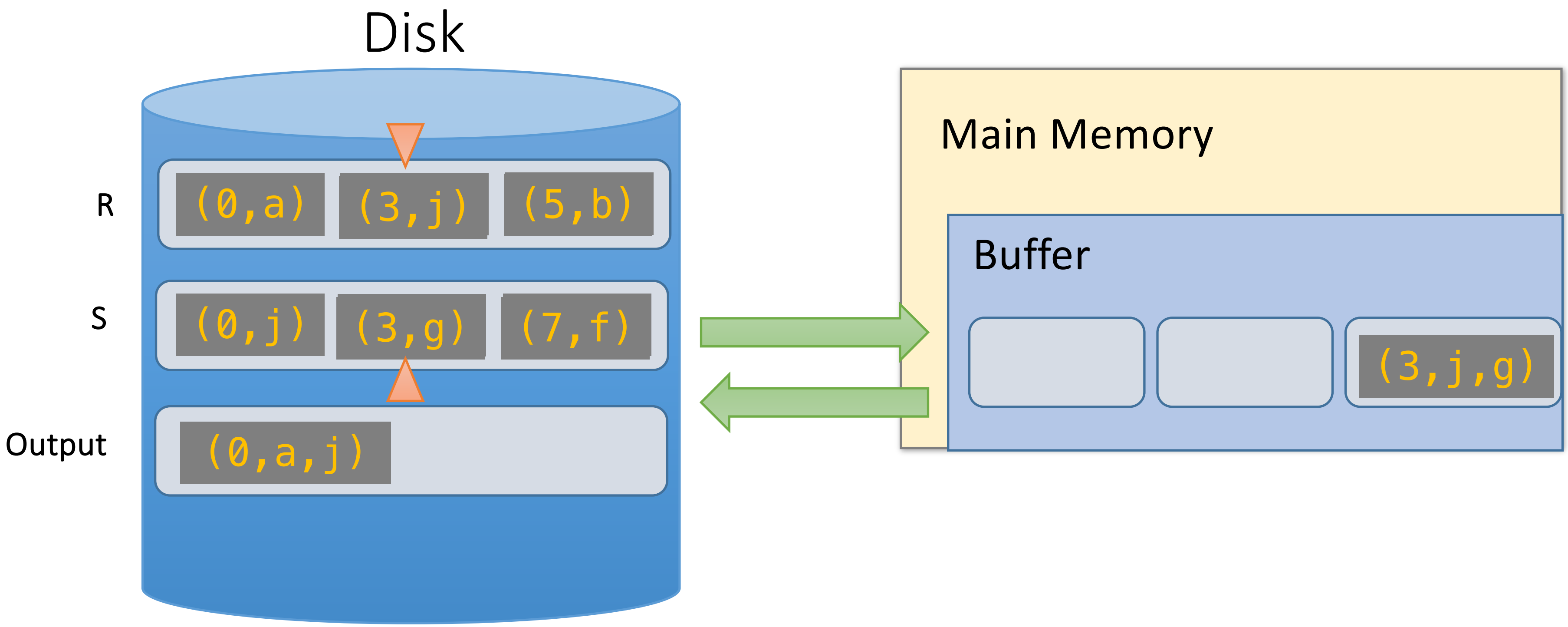
SMJ Example: $R \bowtie S\ on\ A$ with 3 page buffer

2. Scan and "merge" on join key!



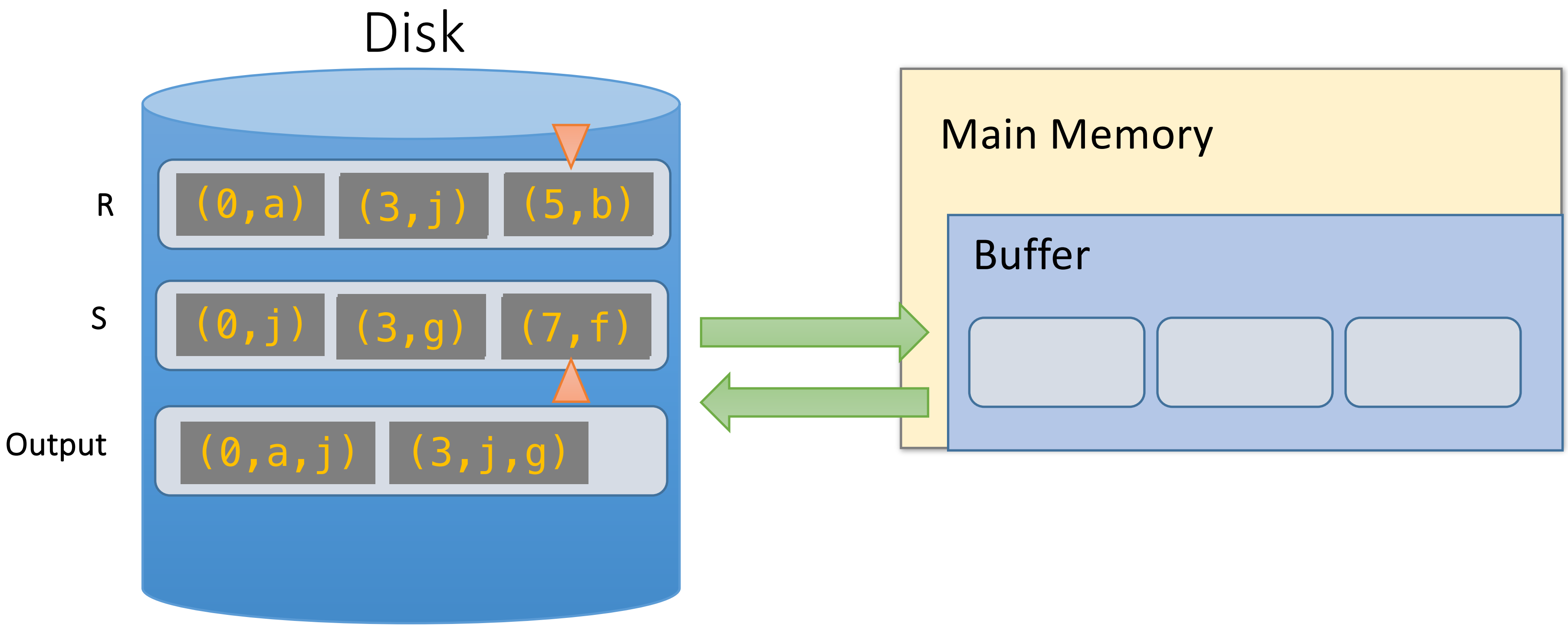
SMJ Example: $\mathrm{R} \bowtie S\ on\ A$ with 3 page buffer

2. Scan and "merge" on join key!



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

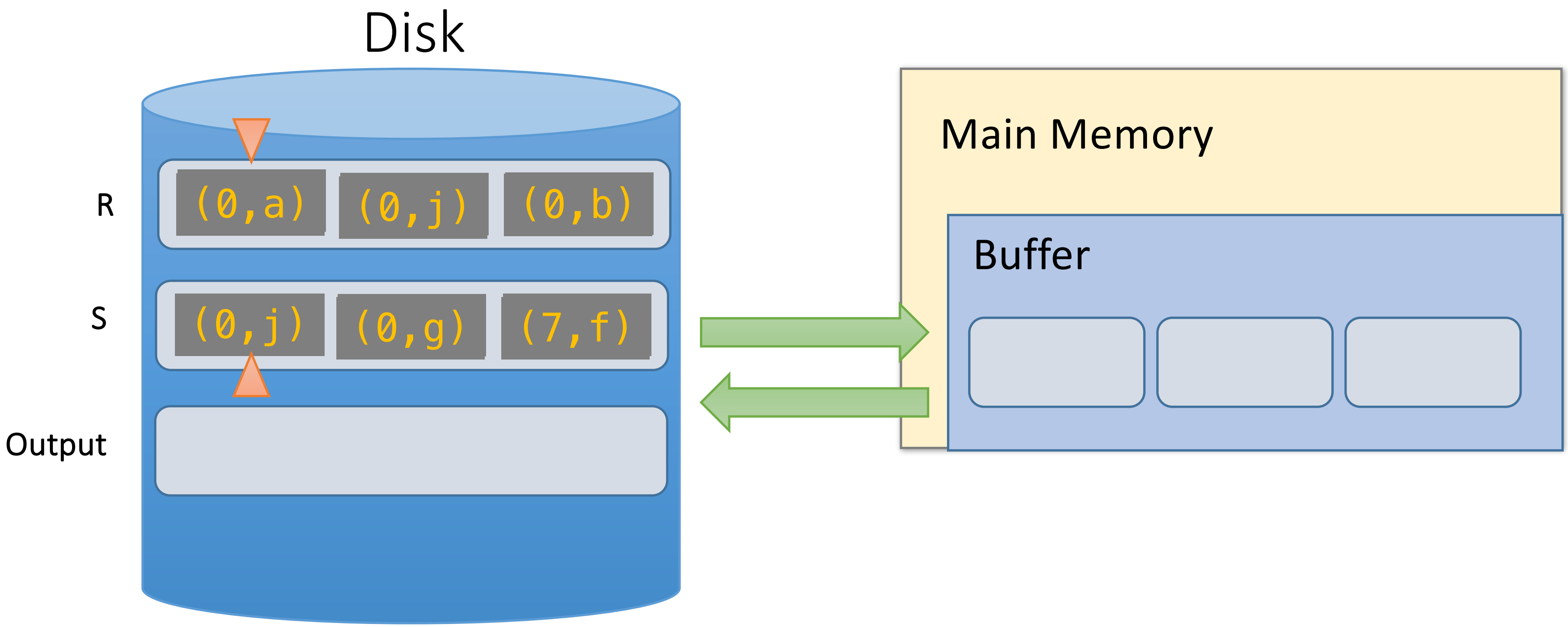
2. Done!



What happens with duplicate join keys?

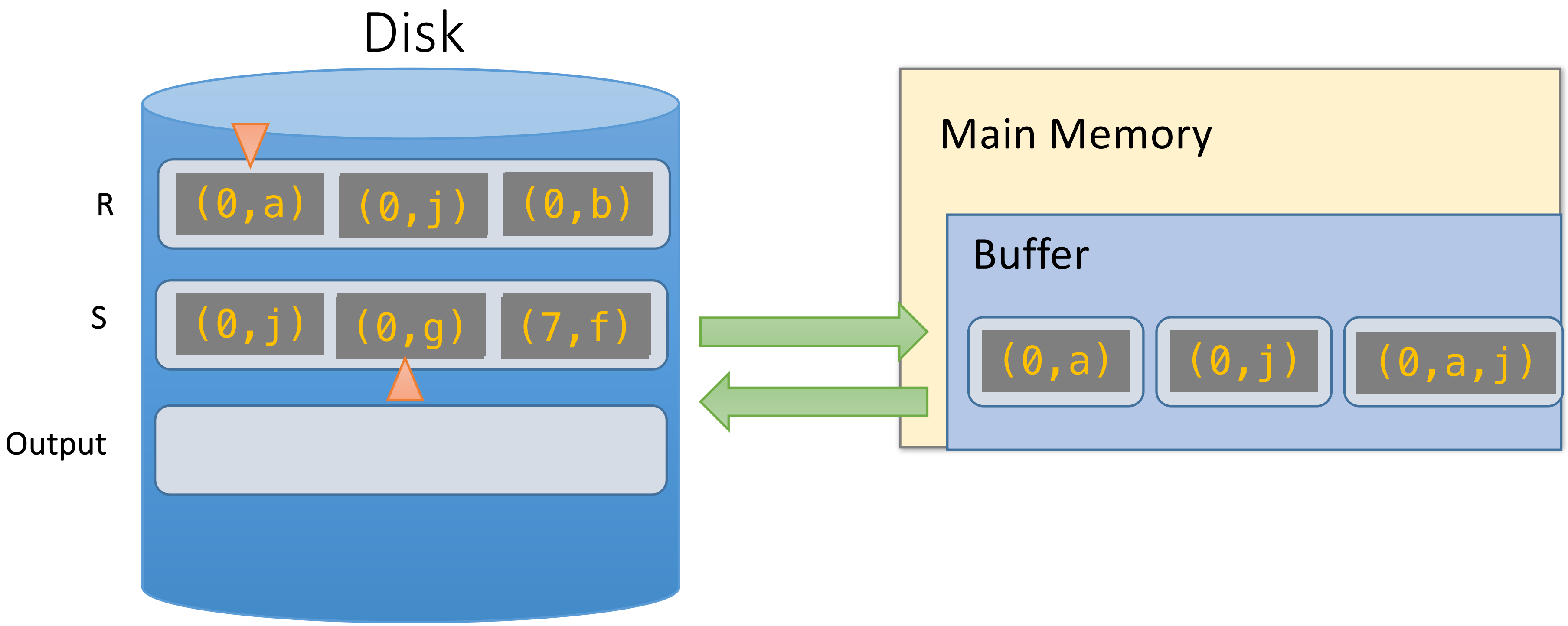
Multiple tuples with Same Join Key: “Backup”

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



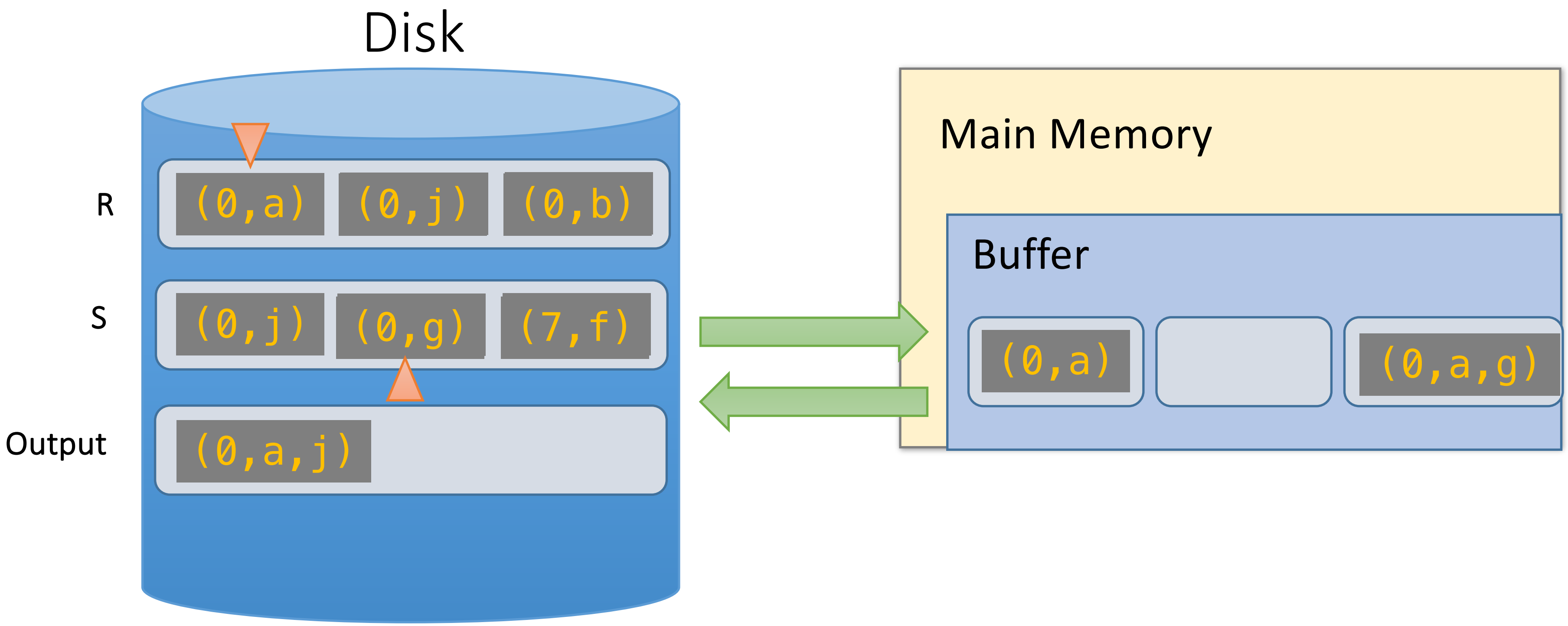
Multiple tuples with Same Join Key: "Backup"

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



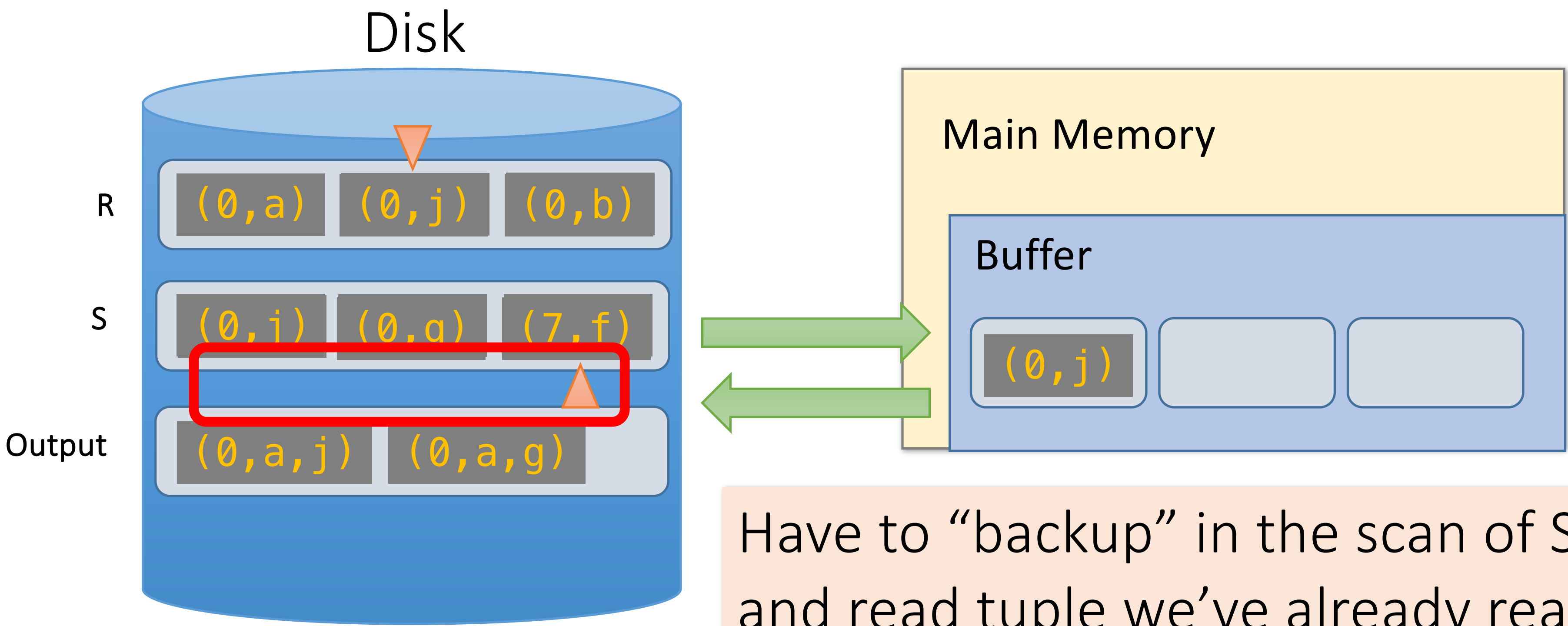
Multiple tuples with Same Join Key: "Backup"

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



Multiple tuples with Same Join Key: "Backup"

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



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
  - **= 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.

A Simple Optimization: Merges Merged!

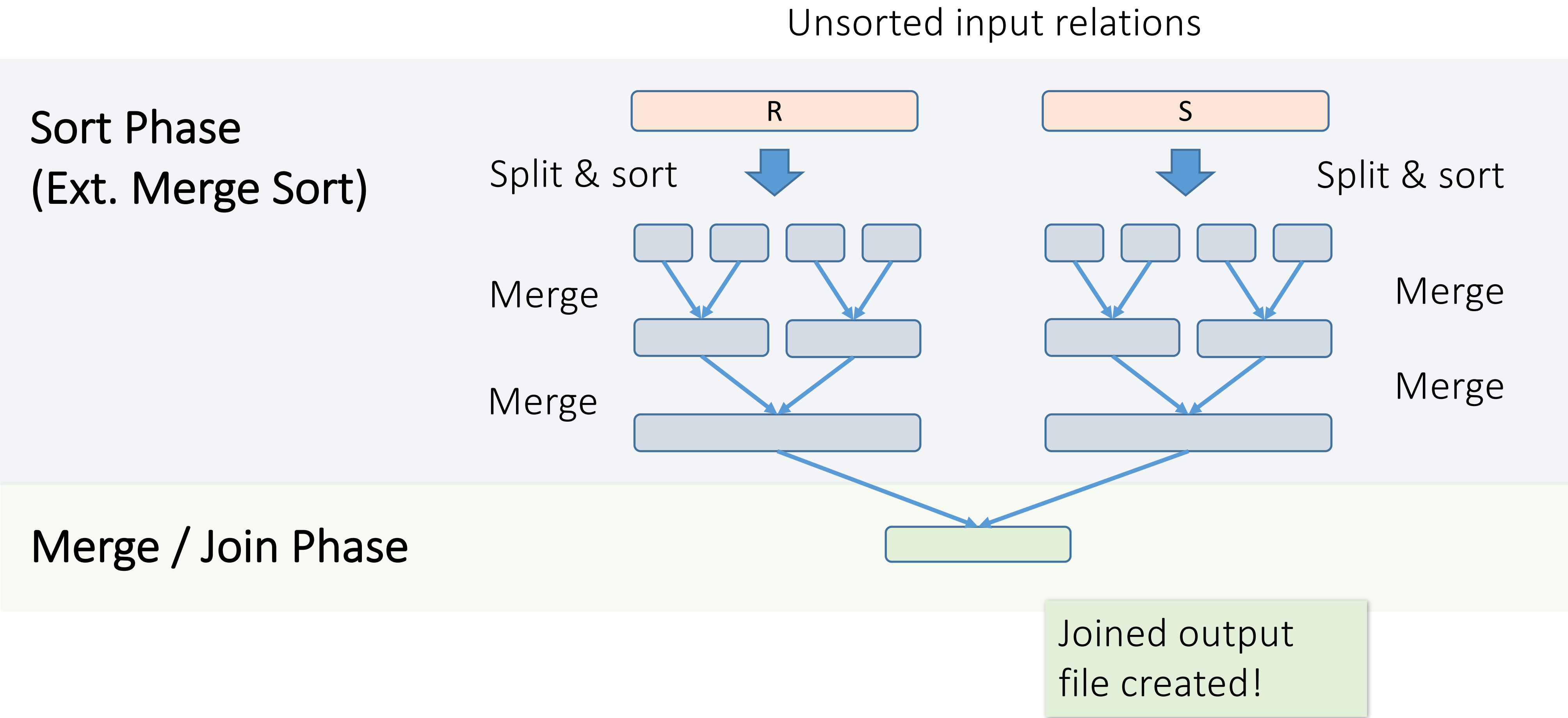
Given ***B+1*** buffer pages

- 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!

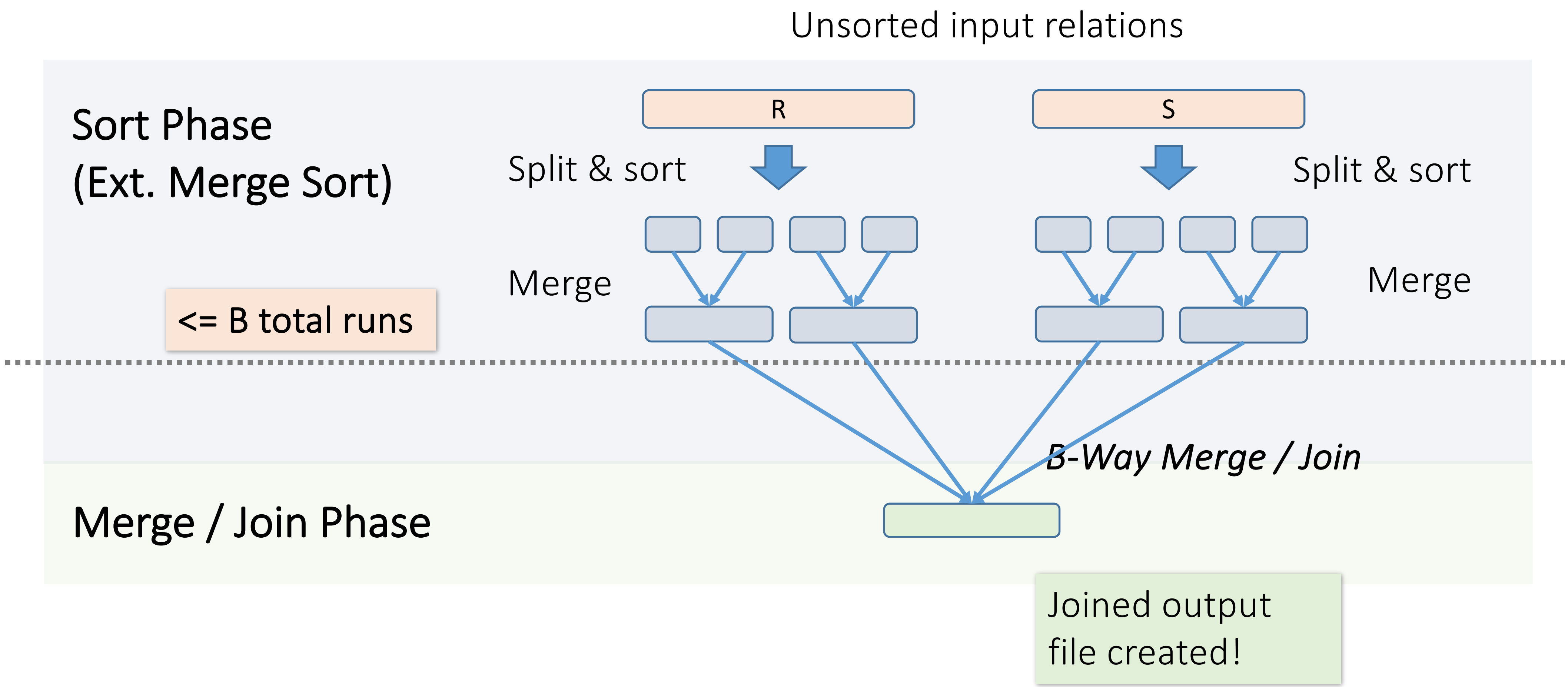
Un-Optimized SMJ

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



Simple SMJ Optimization

Given *B+1* buffer pages



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 13, 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

Bonus questions.

- Q1: Fast dog.
  - If max {P(R), P(S)} < B^2 then SMJ takes 3(P(R) + P(S)) + OUT
  - What is the similar condition to obtain 5(P(R) + P(S)) + OUT?
  - What is the condition for (2k+1)(P(R) + P(S)) + OUT

- Q2: BNLJ V. SMJ
  - Under what conditions will BNLJ outperform SMJ?
    - Size of R, S and # of buffer pages

- Discuss! And We'll put up a google form.

2. Hash Join (HJ)

What you will learn about in this section

1. Hash Join

2. 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 <u>**never**</u> 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.

Recall: Mad Hash Collisions

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

Hash Join: High-level procedure

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

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

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

1. **Partition Phase:** Using one (shared) hash function $\boldsymbol{h_B}$ 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 (Why?)

Each pass takes 2(P(R) + P(S))

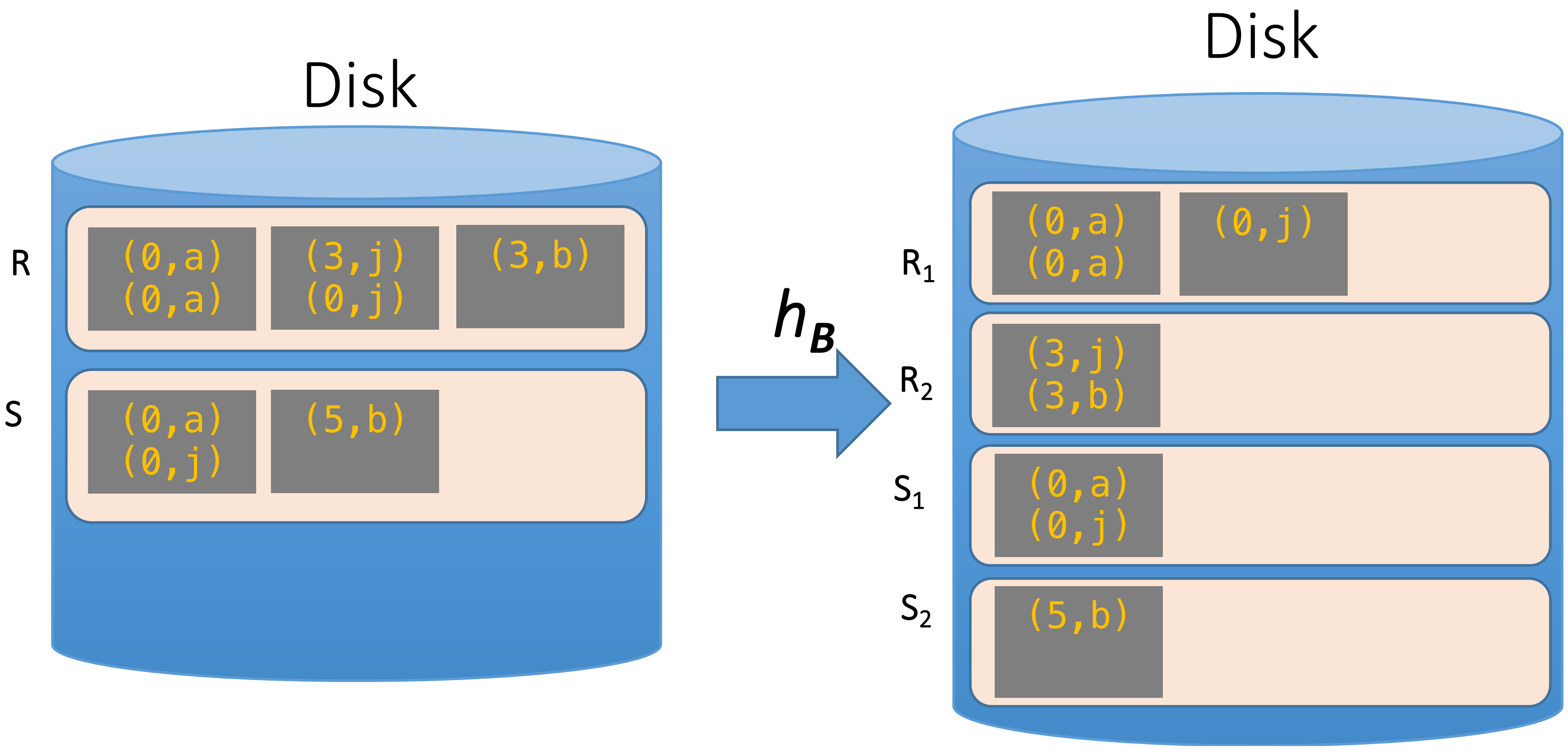
2. **Matching Phase:** Take pairs of buckets whose tuples have the same values for ***h***, and join these
   - Use BNLJ here for each matching pair.

P(R) + P(S) + OUT

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 $\boldsymbol{h_B}$, partition R *and* S into ***B*** buckets

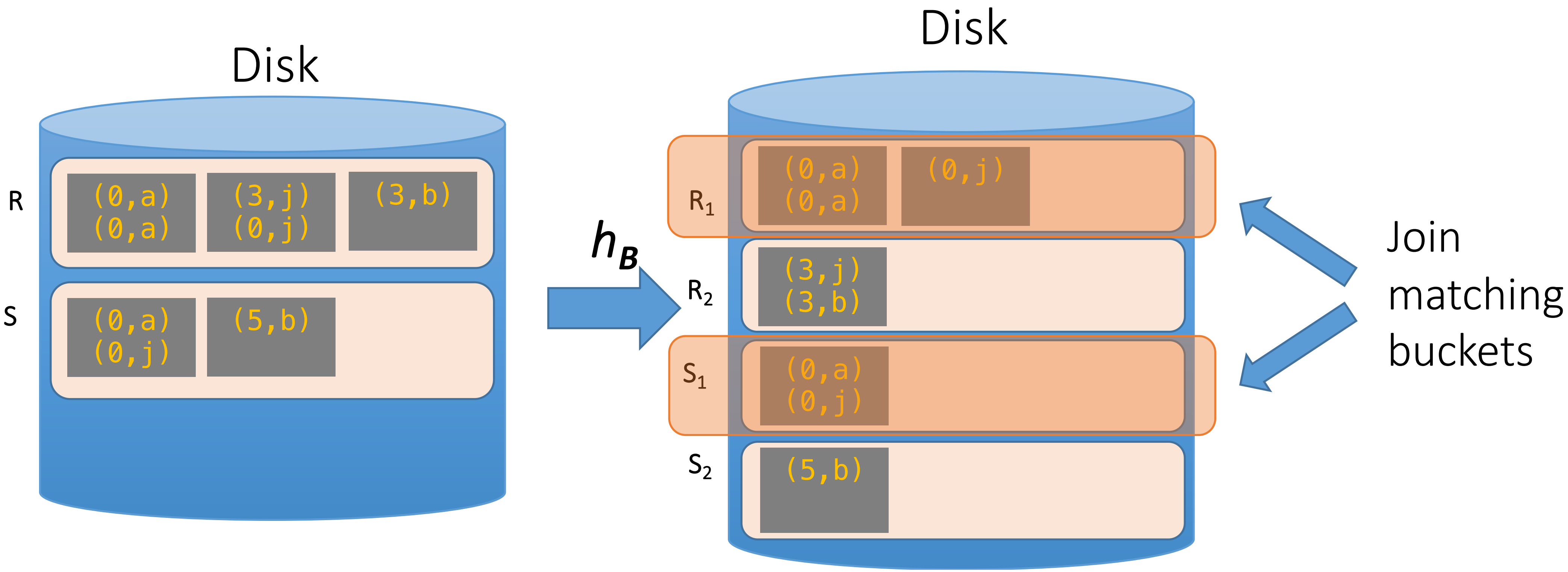


Note our new convention: pages each have two tuples (one per row)

More detail in a second…

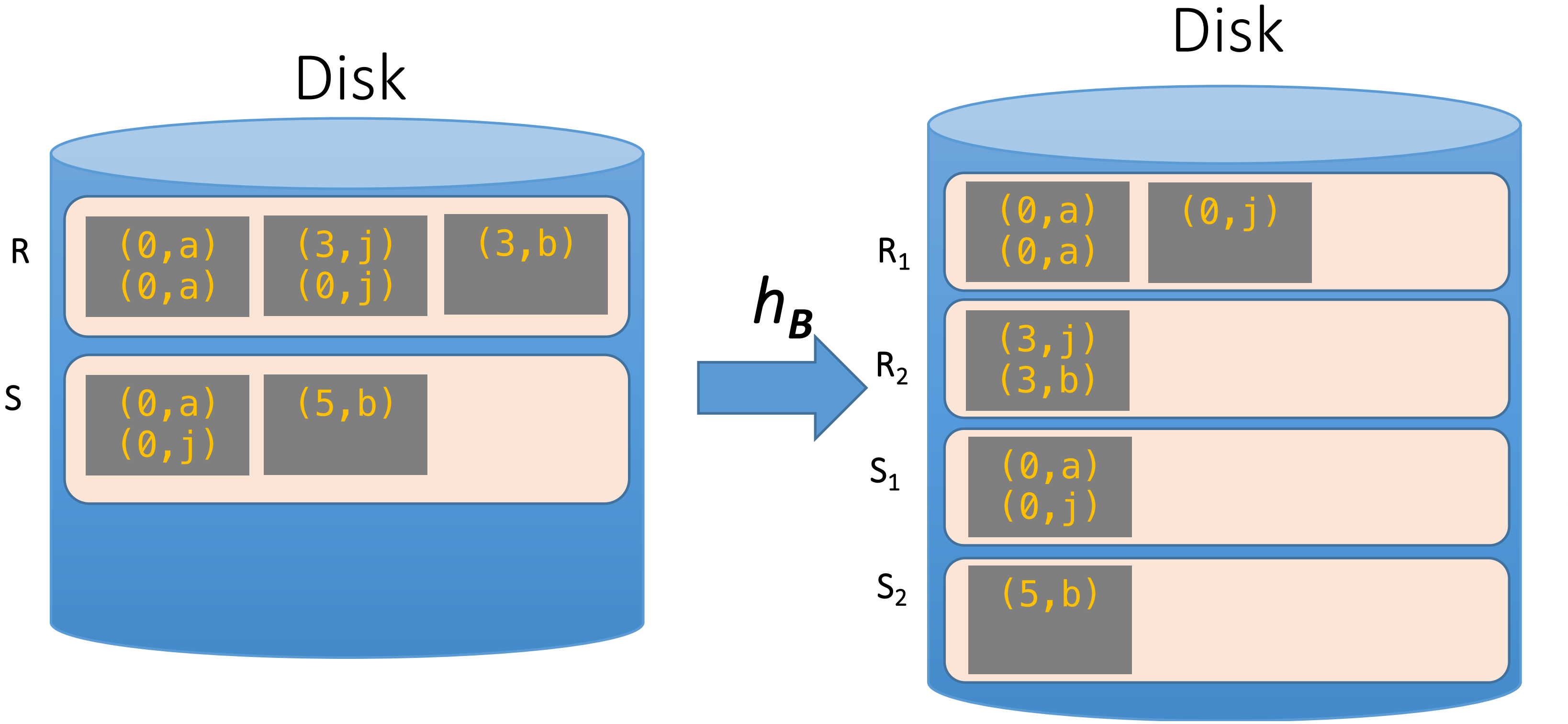
Hash Join: High-level procedure

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



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



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:

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

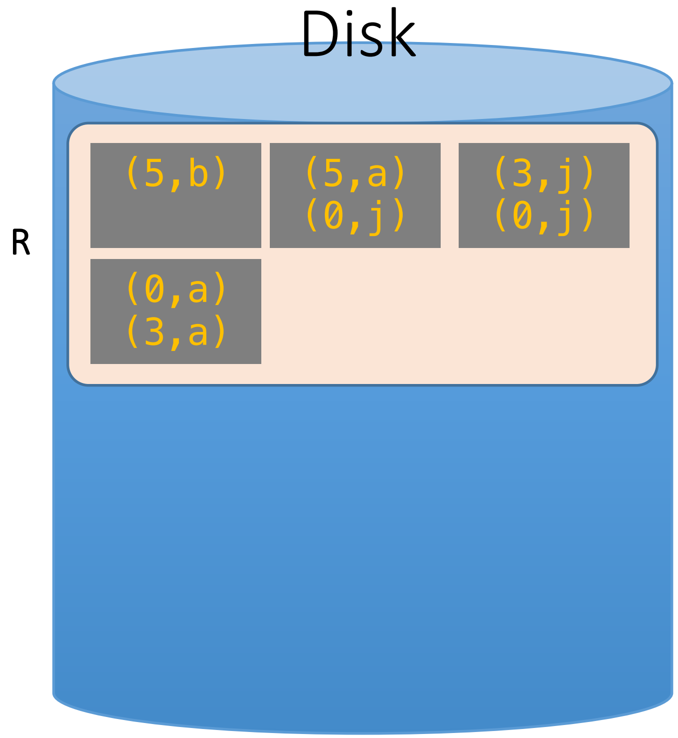
- We can keep partitioning buckets that are > B-1 pages, until they are $\leq \boldsymbol{B-1}$ **pages**
  - Using a new hash key which will split them…

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)



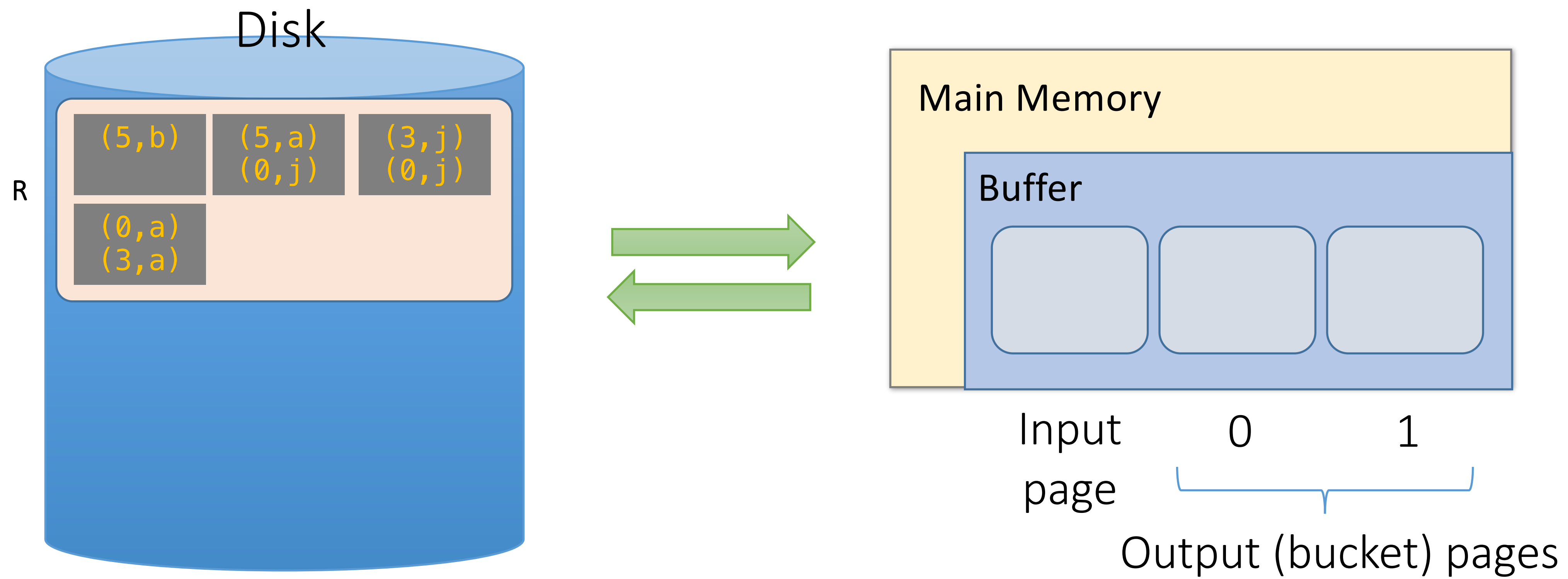
For simplicity, we'll look at partitioning one of the two relations- we just do the same for the other relation!

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

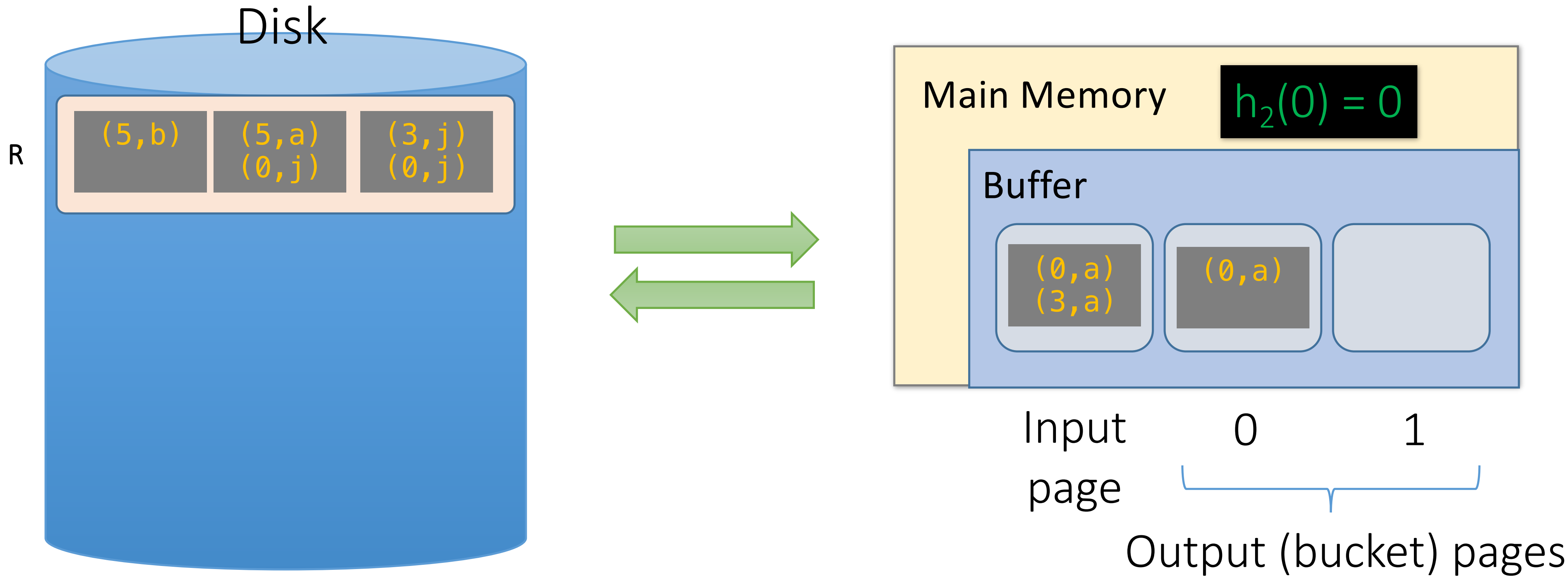
1. We read pages from R into the “input” page of the buffer…



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

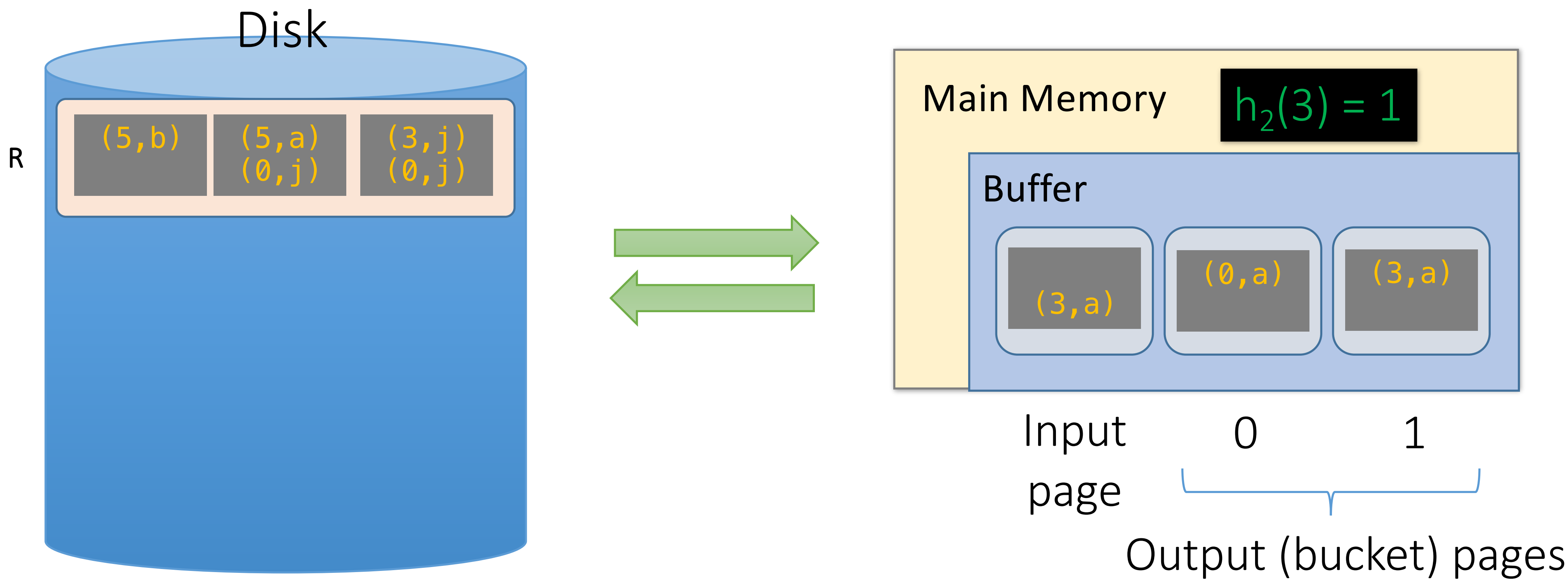
2. Then we use **hash function h_2** to sort into the buckets, which each have one page in the buffer



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

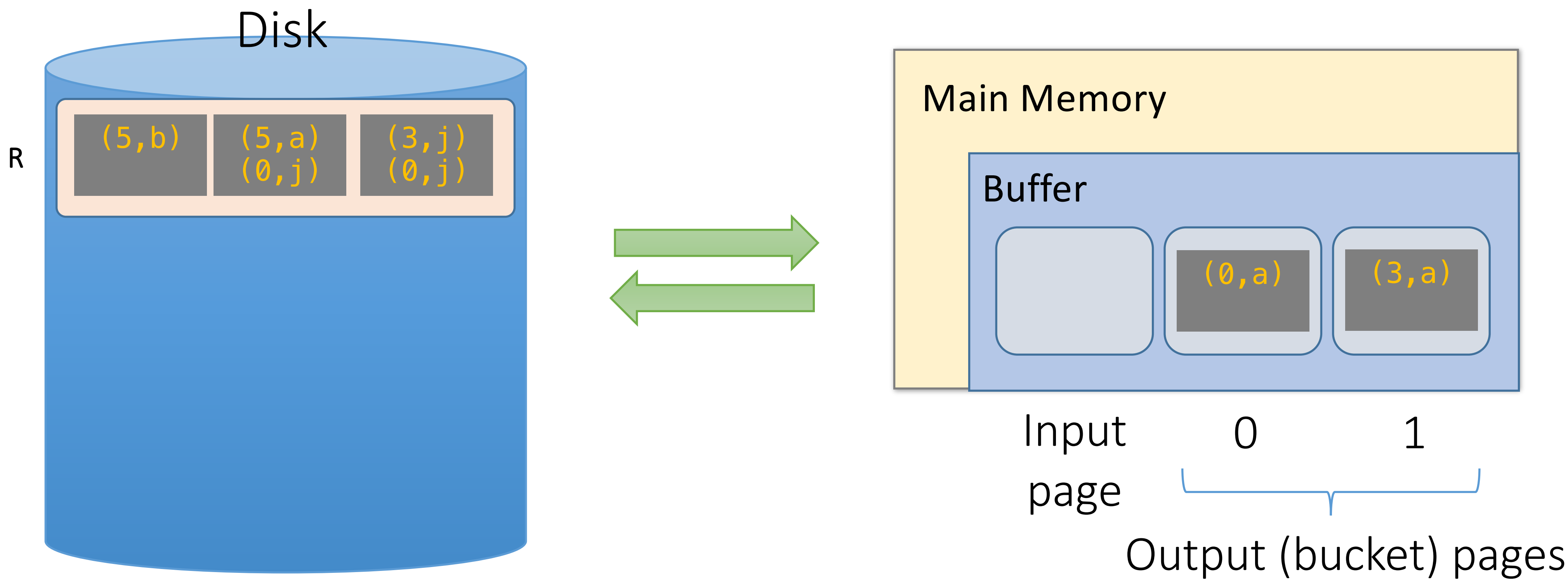
2. Then we use **hash function h_2** to sort into the buckets, which each have one page in the buffer



Hash Join Phase 1: Partitioning

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

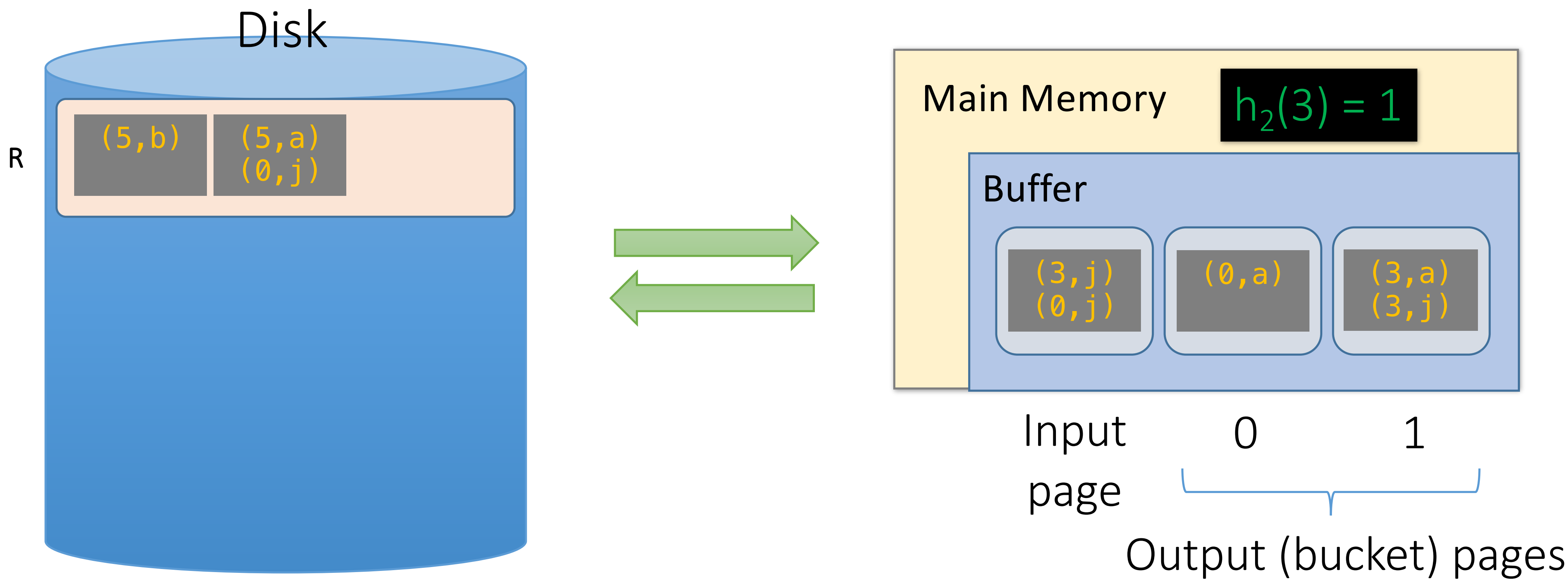
3. We repeat until the buffer bucket pages are full…



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

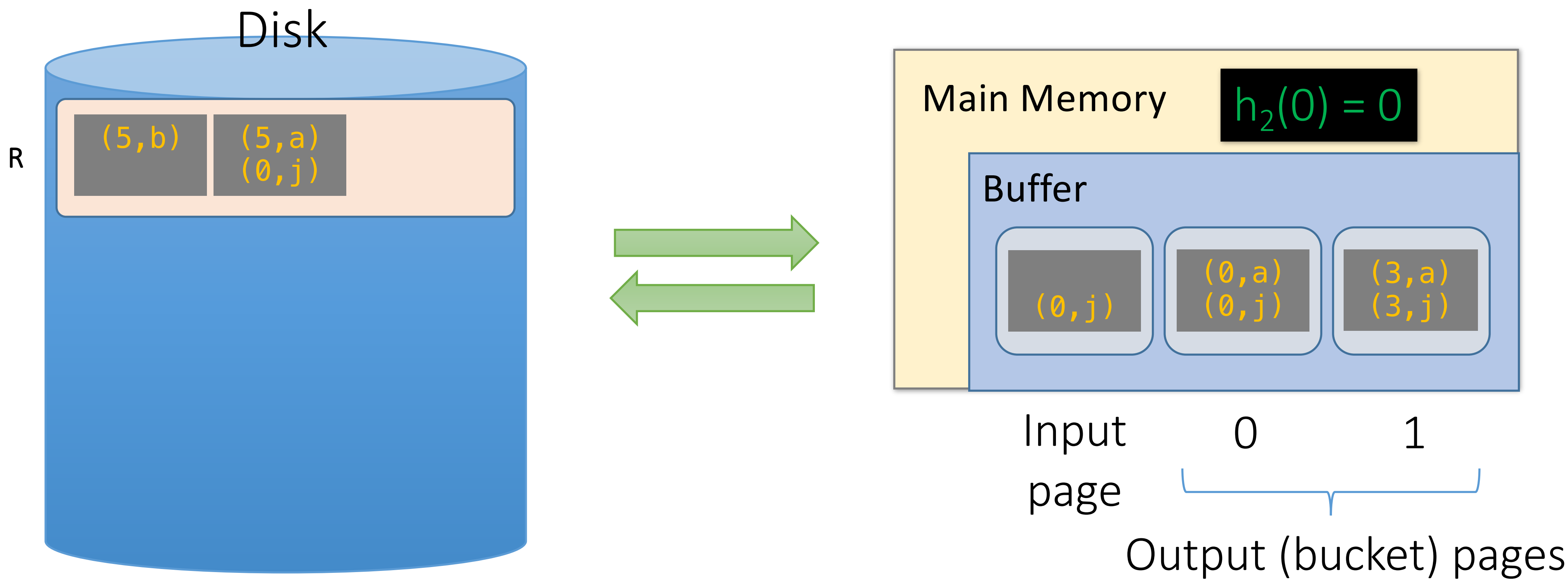
3. We repeat until the buffer bucket pages are full…



Hash Join Phase 1: Partitioning

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

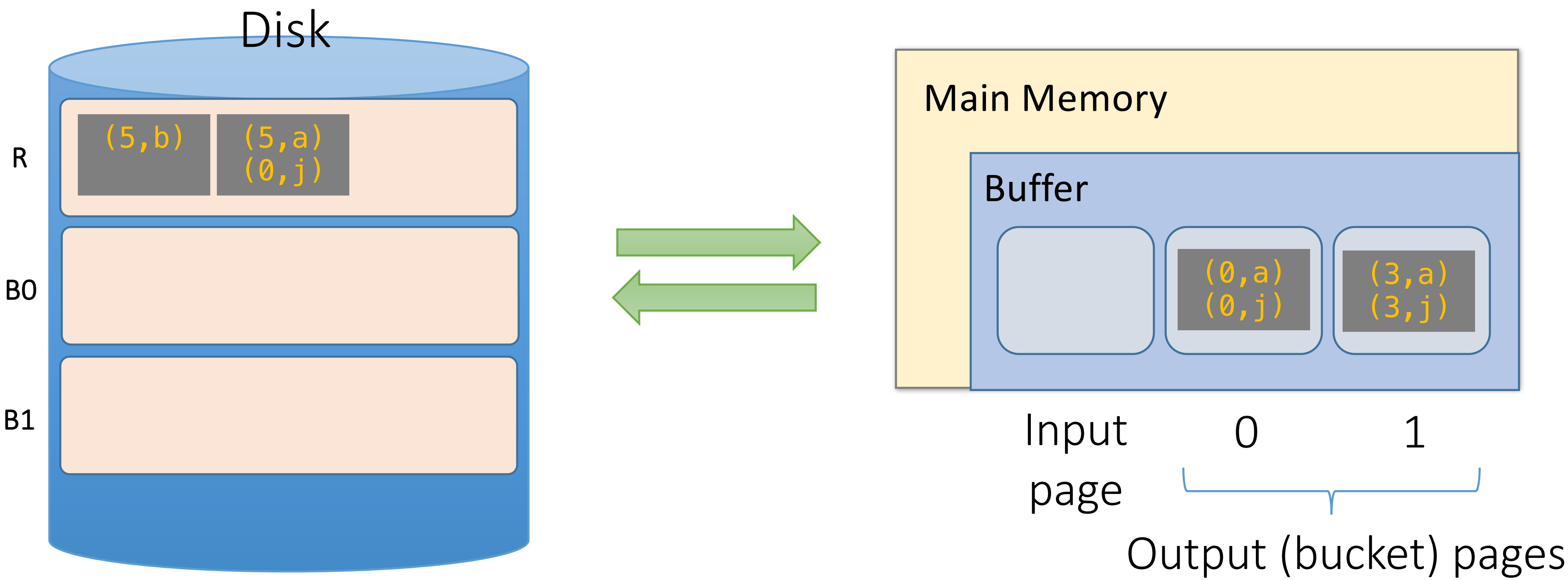
3. We repeat until the buffer bucket pages are full…



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

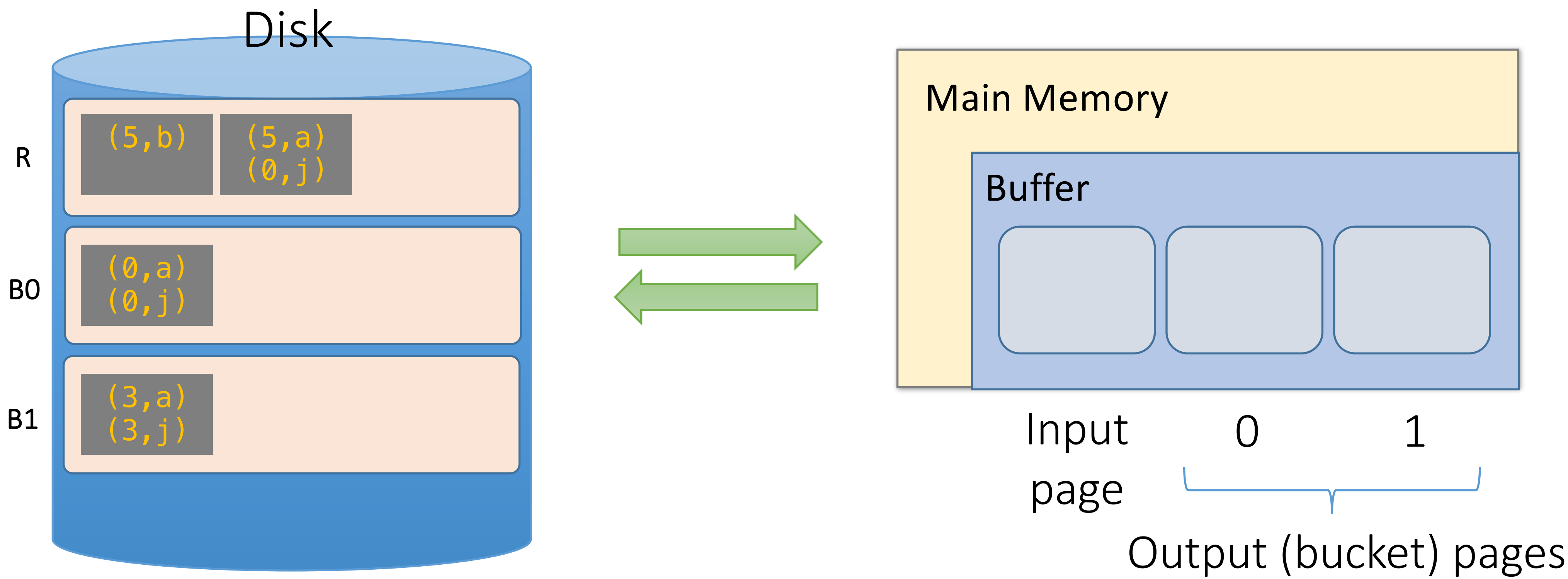
3. We repeat until the buffer bucket pages are full… then flush to disk



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

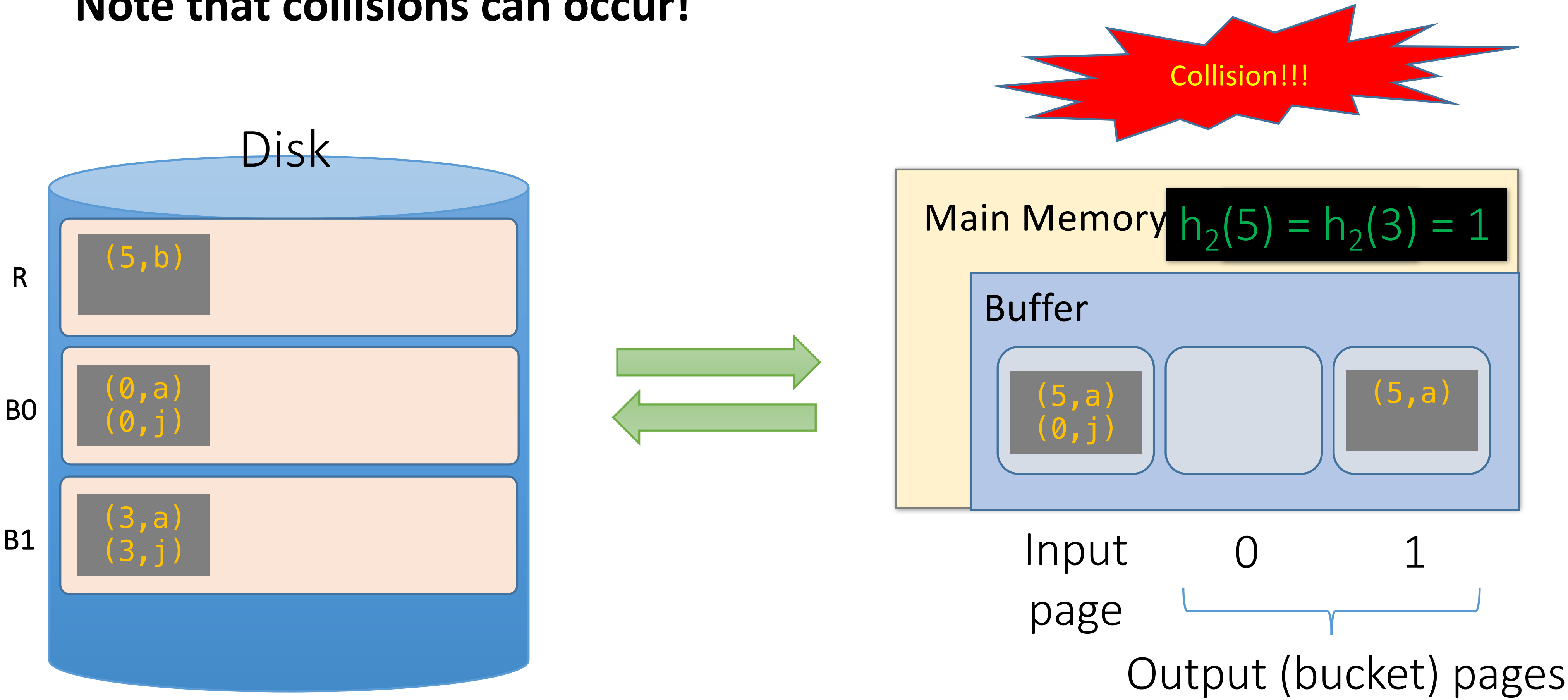
3. We repeat until the buffer bucket pages are full… then flush to disk



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

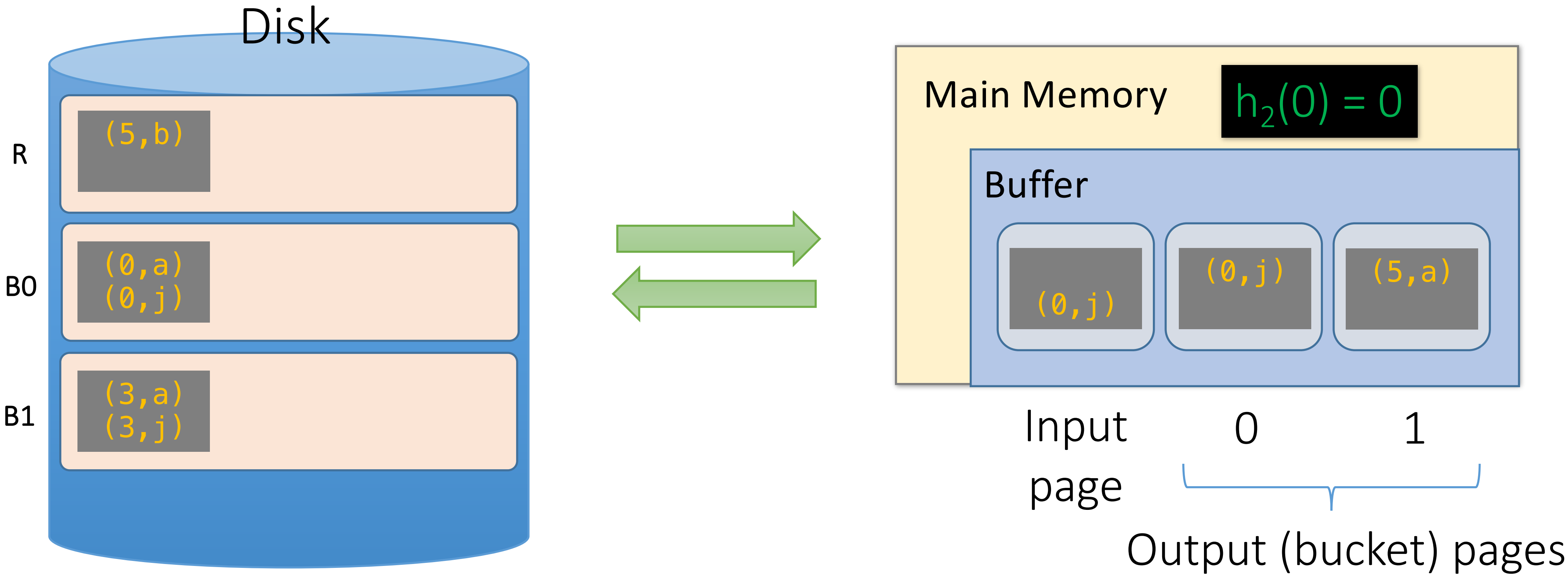
Note that collisions can occur!



Hash Join Phase 1: Partitioning

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

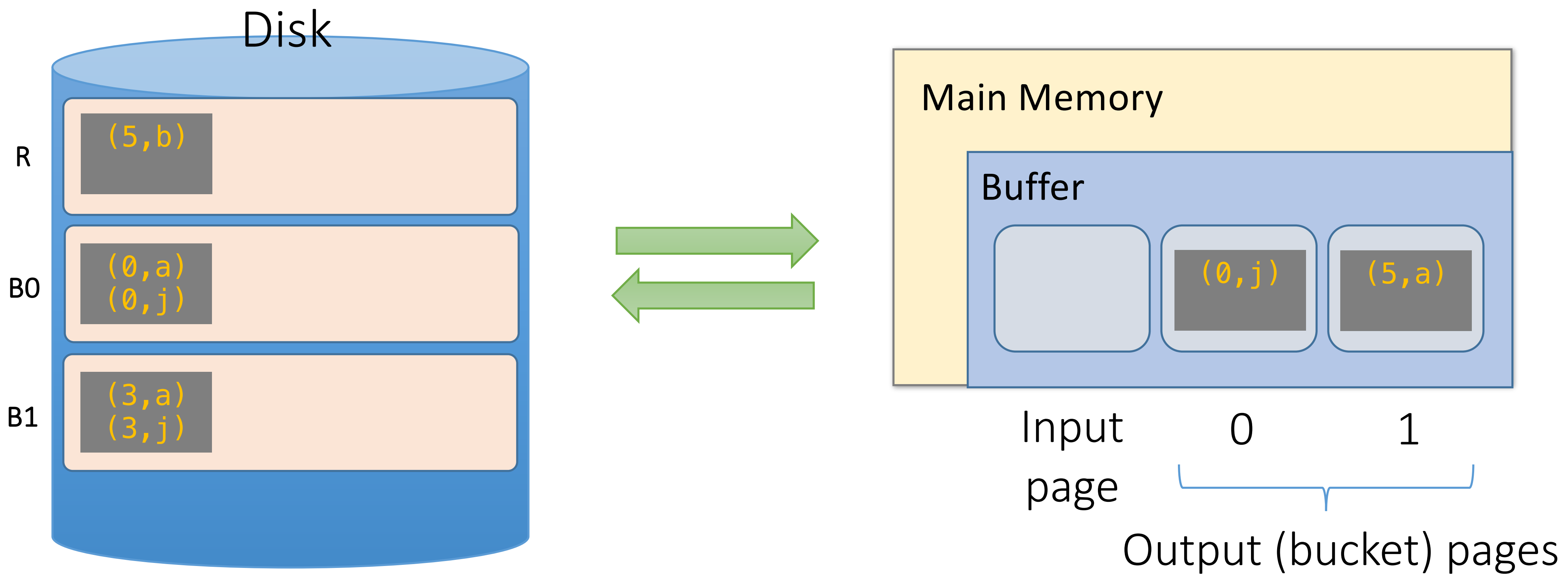
Finish this pass…



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

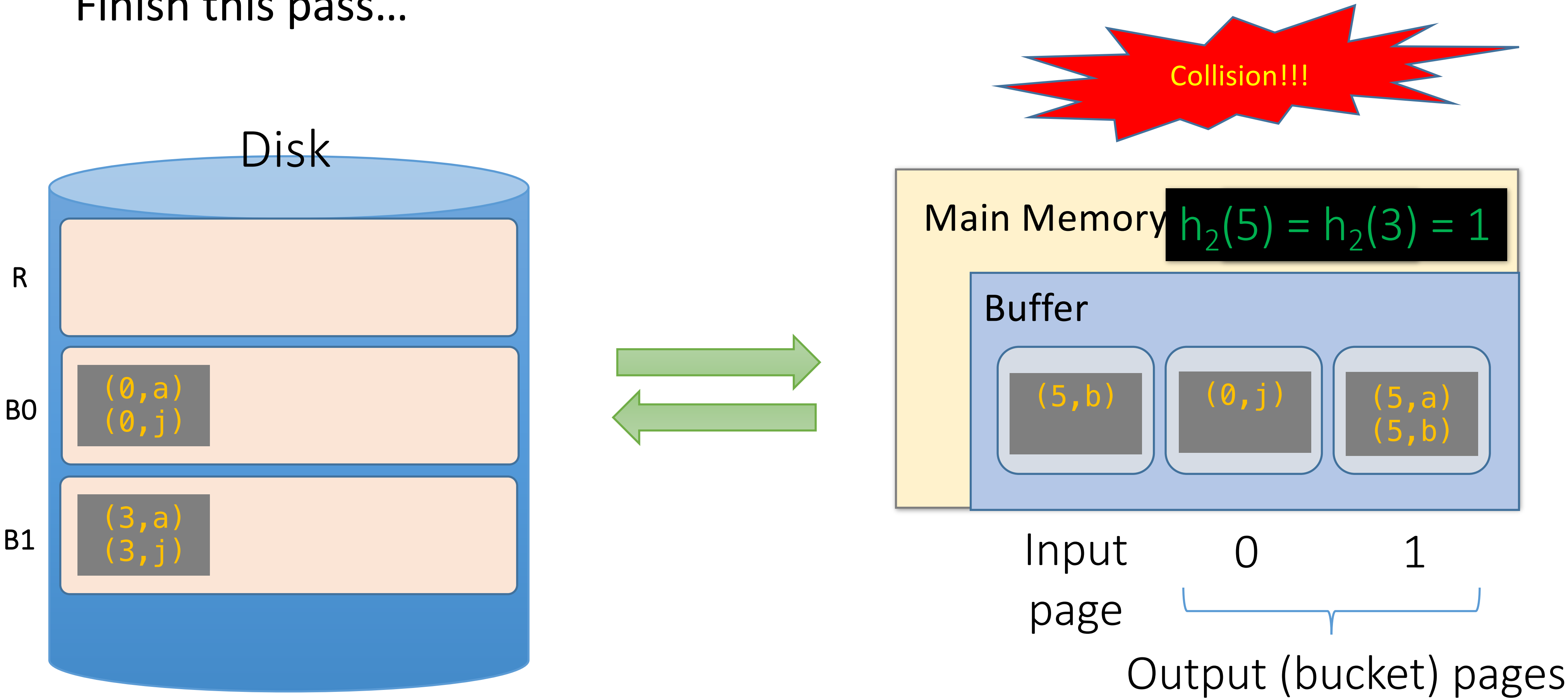
Finish this pass…



Hash Join Phase 1: Partitioning

Given *B+1 = 3* buffer pages

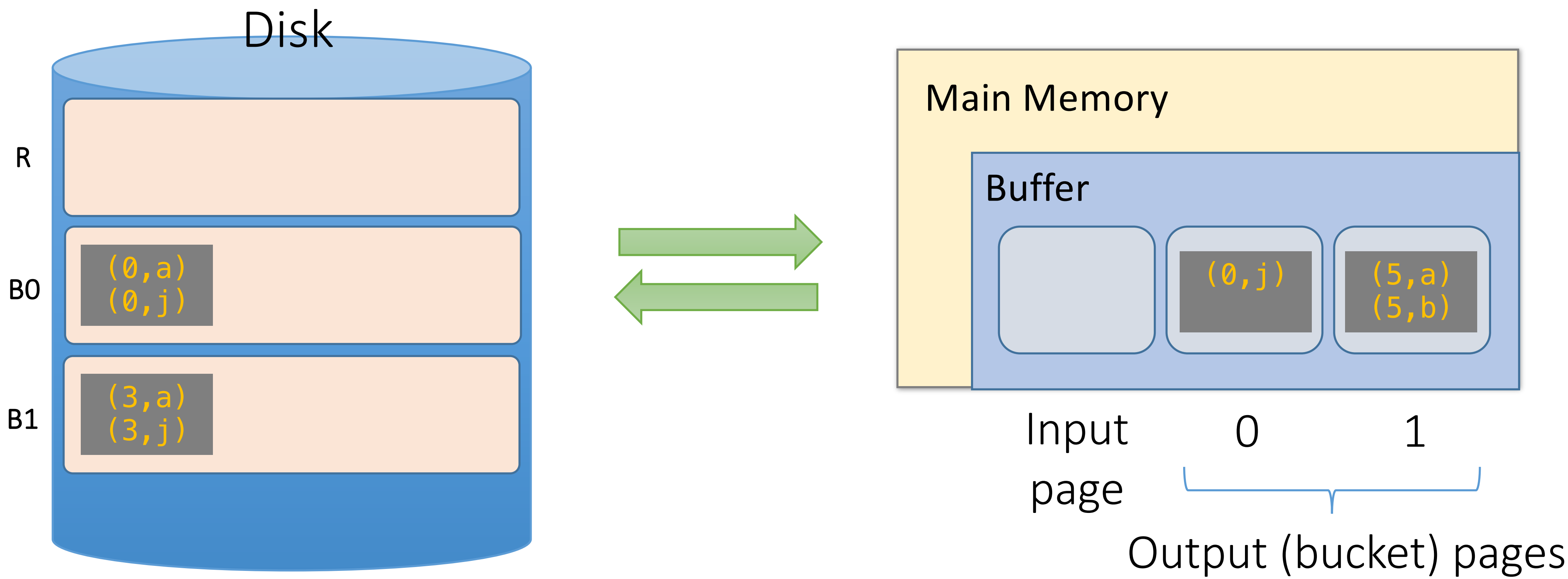
Finish this pass…



Hash Join Phase 1: Partitioning

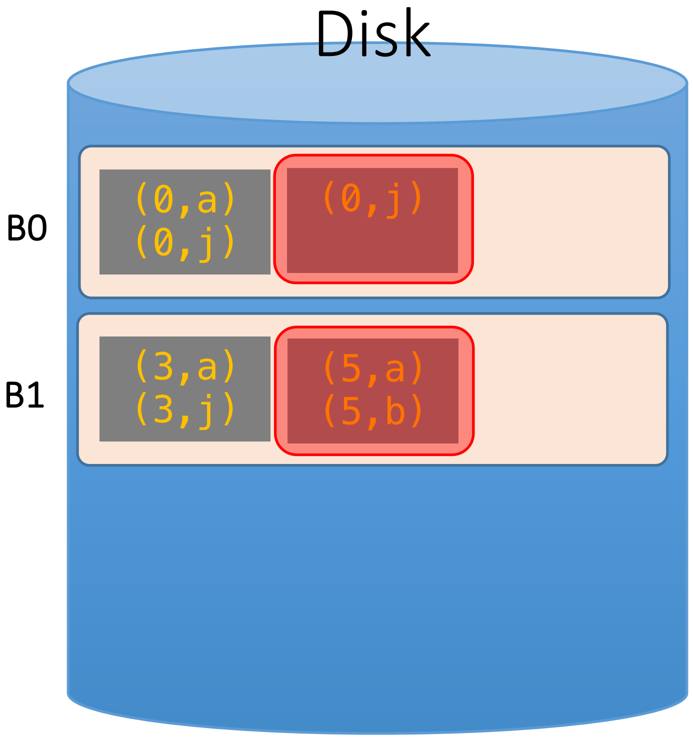
Given *B+1 = 3* buffer pages

Finish this pass…



Hash Join Phase 1: Partitioning

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



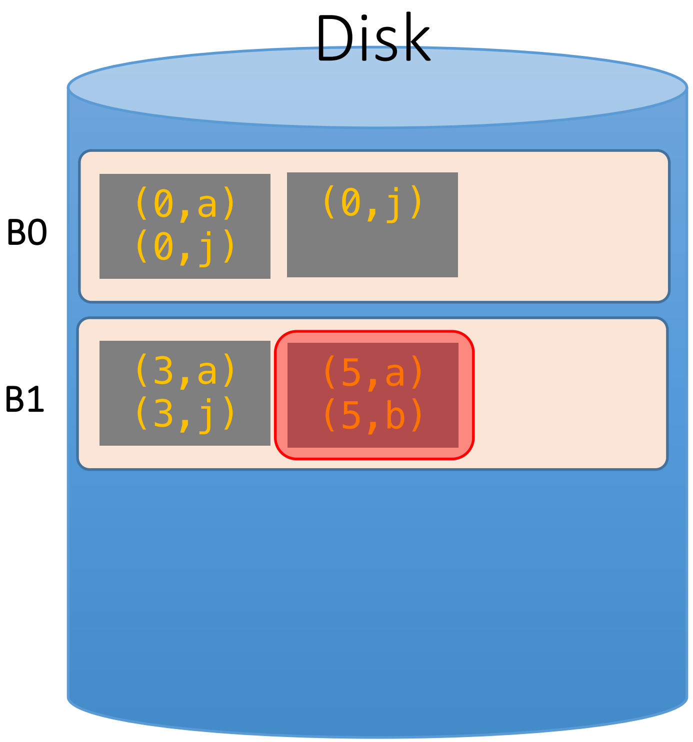
We wanted buckets of size ***B-1 = 1…***
however we got larger ones due to:

(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!

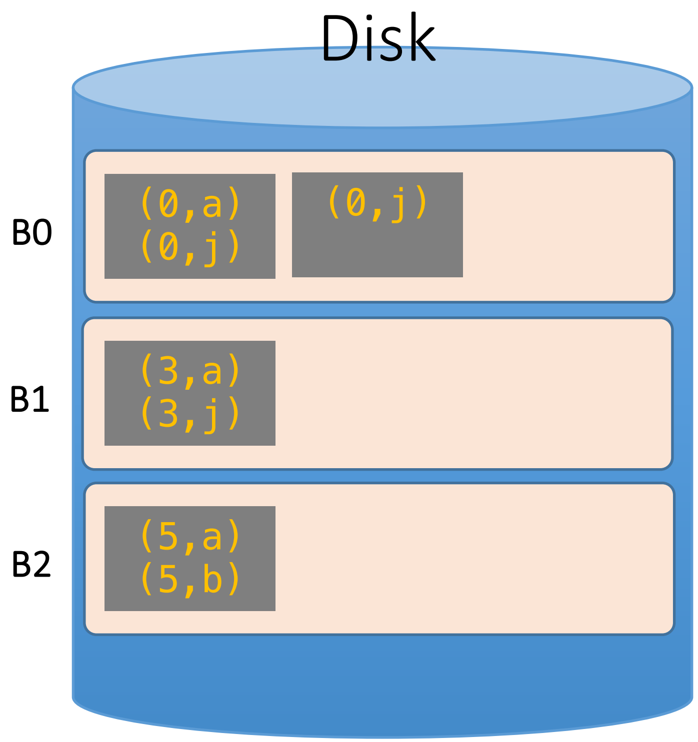
What hash function should we use?

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

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

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?

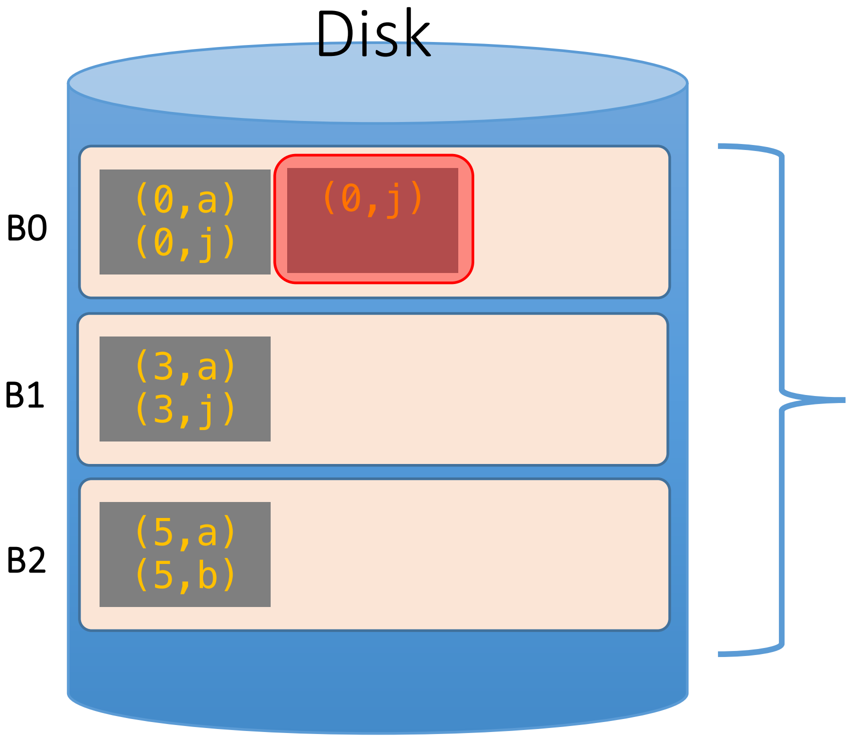
Do another pass with a different hash function, h'_2, ideally such that:

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

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.

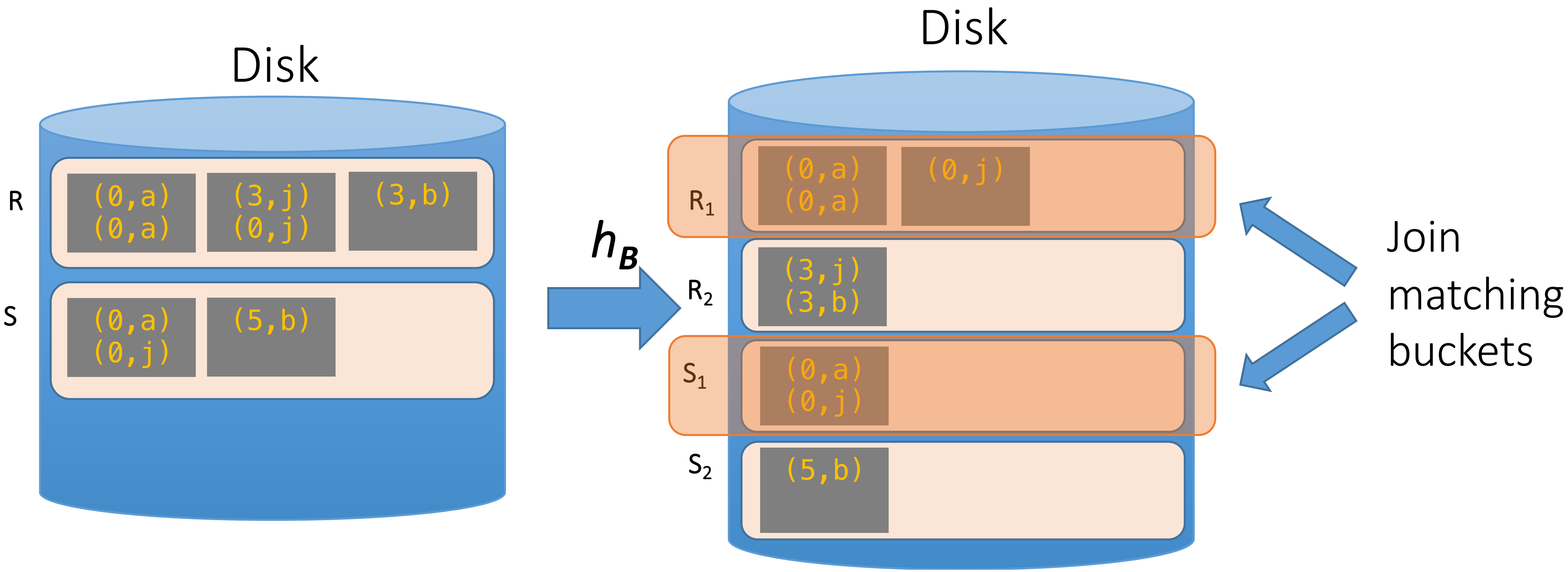


We call this unevenness in the bucket size **skew**

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

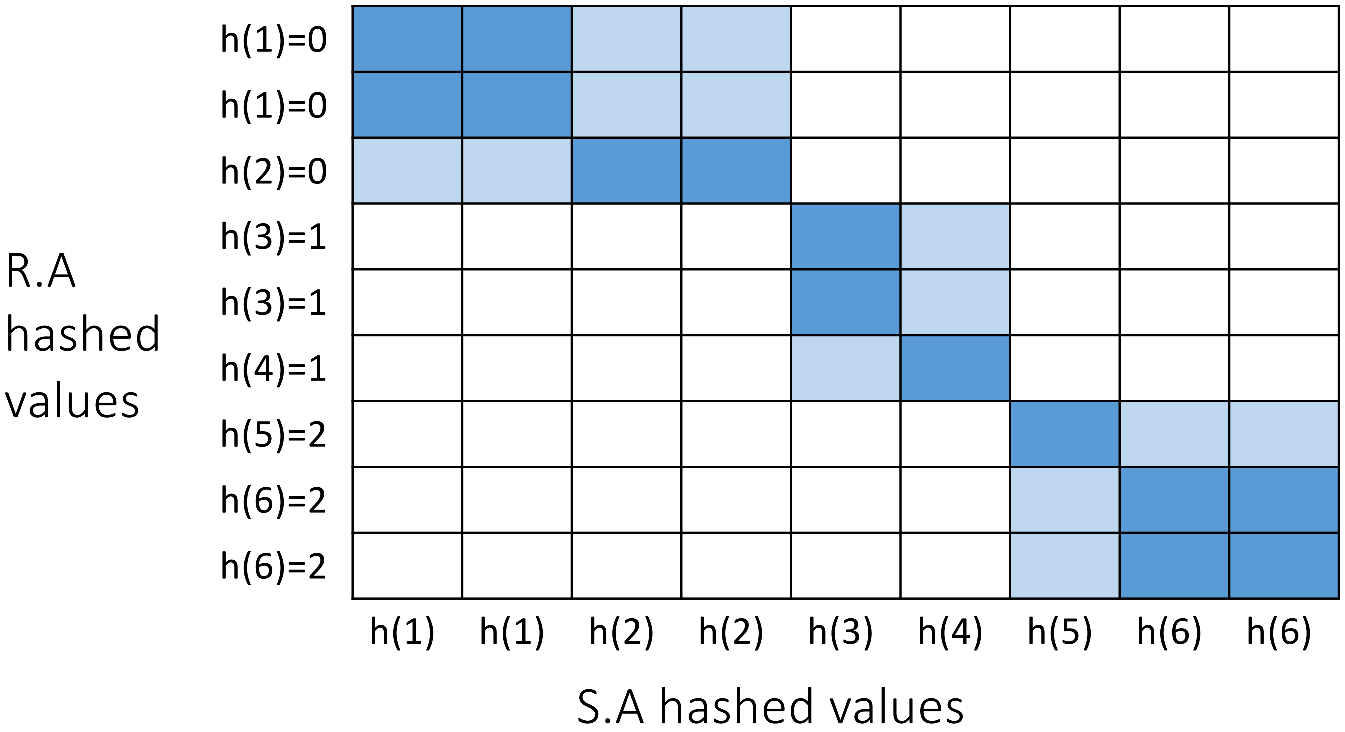
- If our buckets are $\sim\boldsymbol{B-1}$ **pages,** can join each such pair using BNLJ ***in linear time***; recall (with P(R) = B-1):

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)

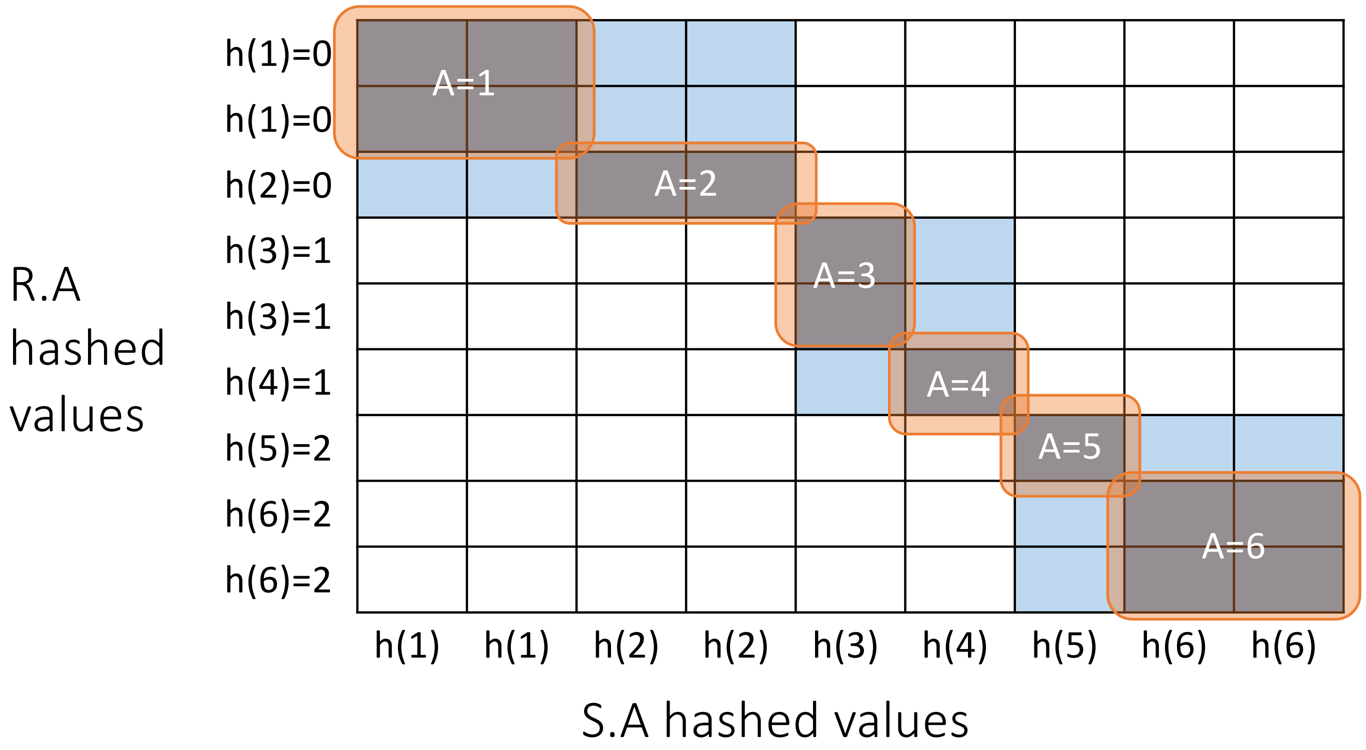
Joining the pairs of buckets is linear!
(As long as smaller bucket <= B-1 pages)

Hash Join Phase 2: Matching

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



Hash Join Phase 2: Matching

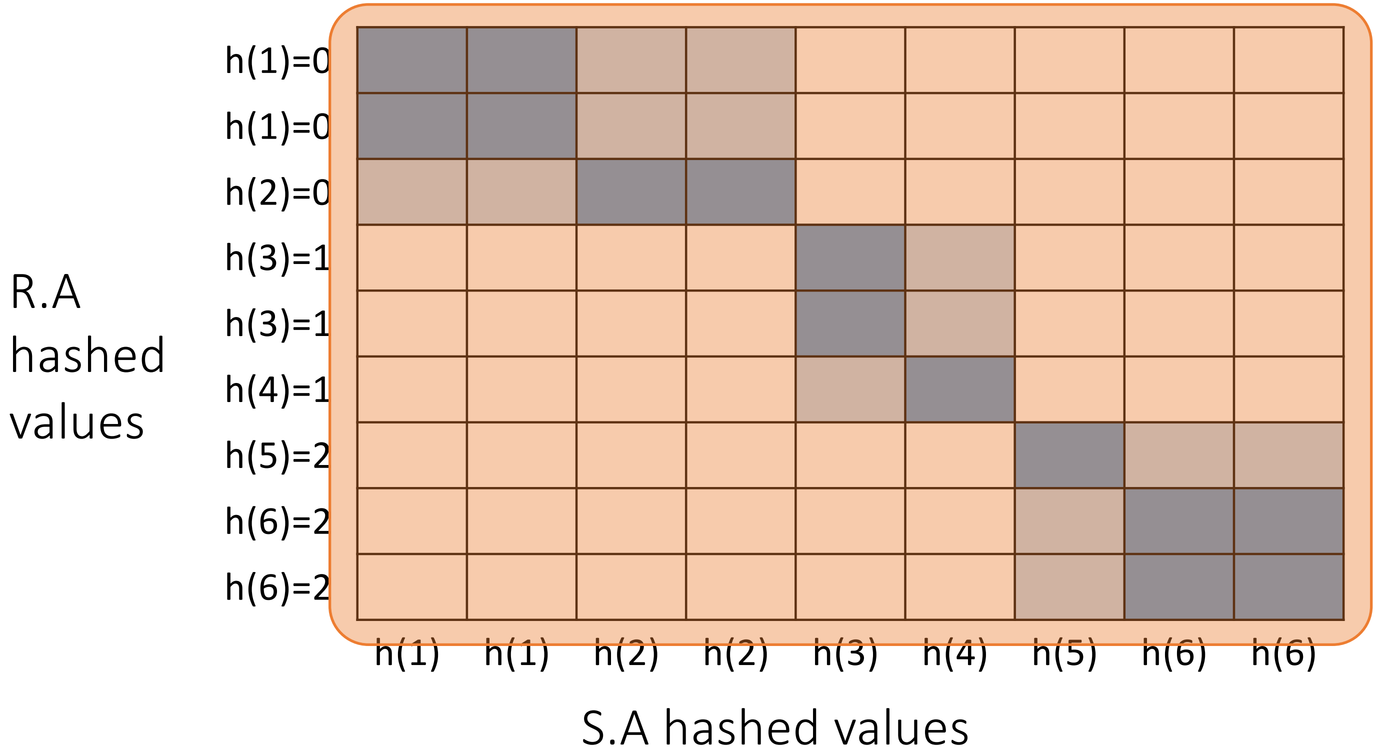


$R \bowtie S \text{ on } A$

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

= the tuples with same values of the join key A

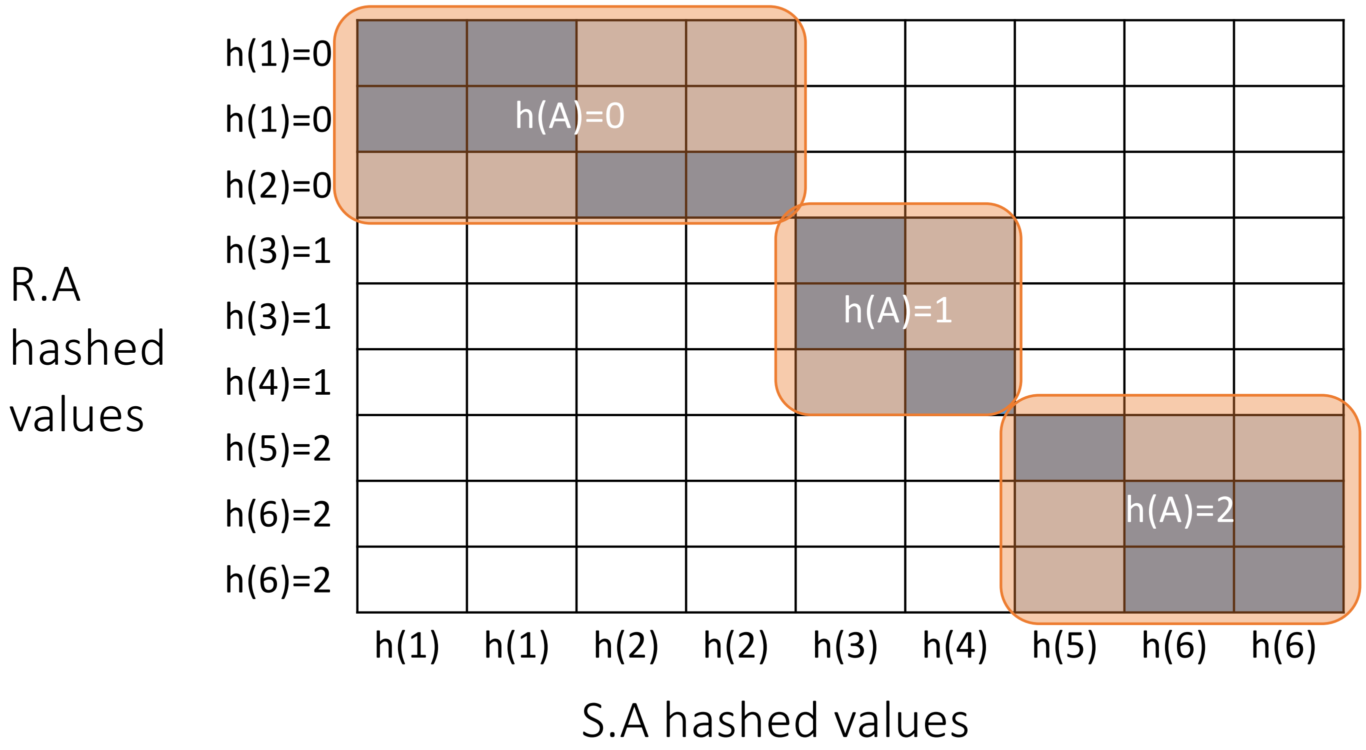
Hash Join Phase 2: Matching



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

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

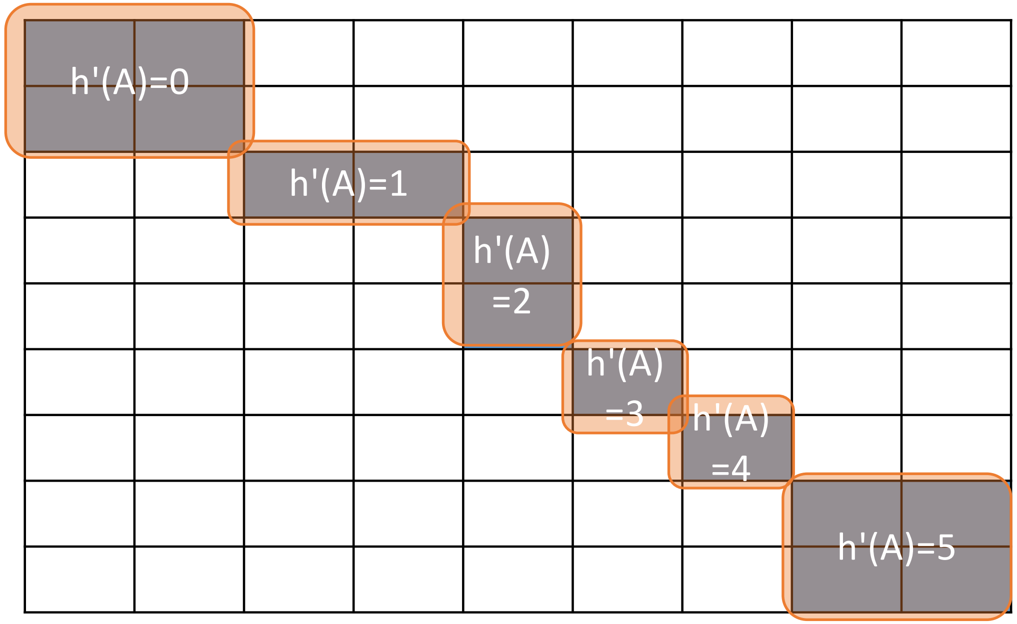
With HJ, we only explore the ***blue*** regions

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

We can apply BNLJ to each of these regions

Hash Join Phase 2: Matching

R.A hashed values



S.A hashed values

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

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:

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

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!

Bonus questions #2

- Q1: Fast little dog.
  - If min {P(R), P(S)} < B^2 then HJ takes 3(P(R) + P(S)) + OUT
  - What is the similar condition to obtain 5(P(R) + P(S)) + OUT?
  - What is the condition for (2k+1)(P(R) + P(S)) + OUT

- Q2: SMJ V. HJ
  - Under what conditions will HJ outperform SMJ?
  - Under what conditions will SMJ outperform SMJ?
    - Size of R, S and # of buffer pages

- Discuss! And We'll put up a google form.

3. The Cage Match

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

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

- Message: The database can compute IO costs, and these are different than a traditional system