THE UNIVERSITY of EDINBURGH

Advanced Databases

Spring 2020

Lecture #07:

External Sorting & Aggregation

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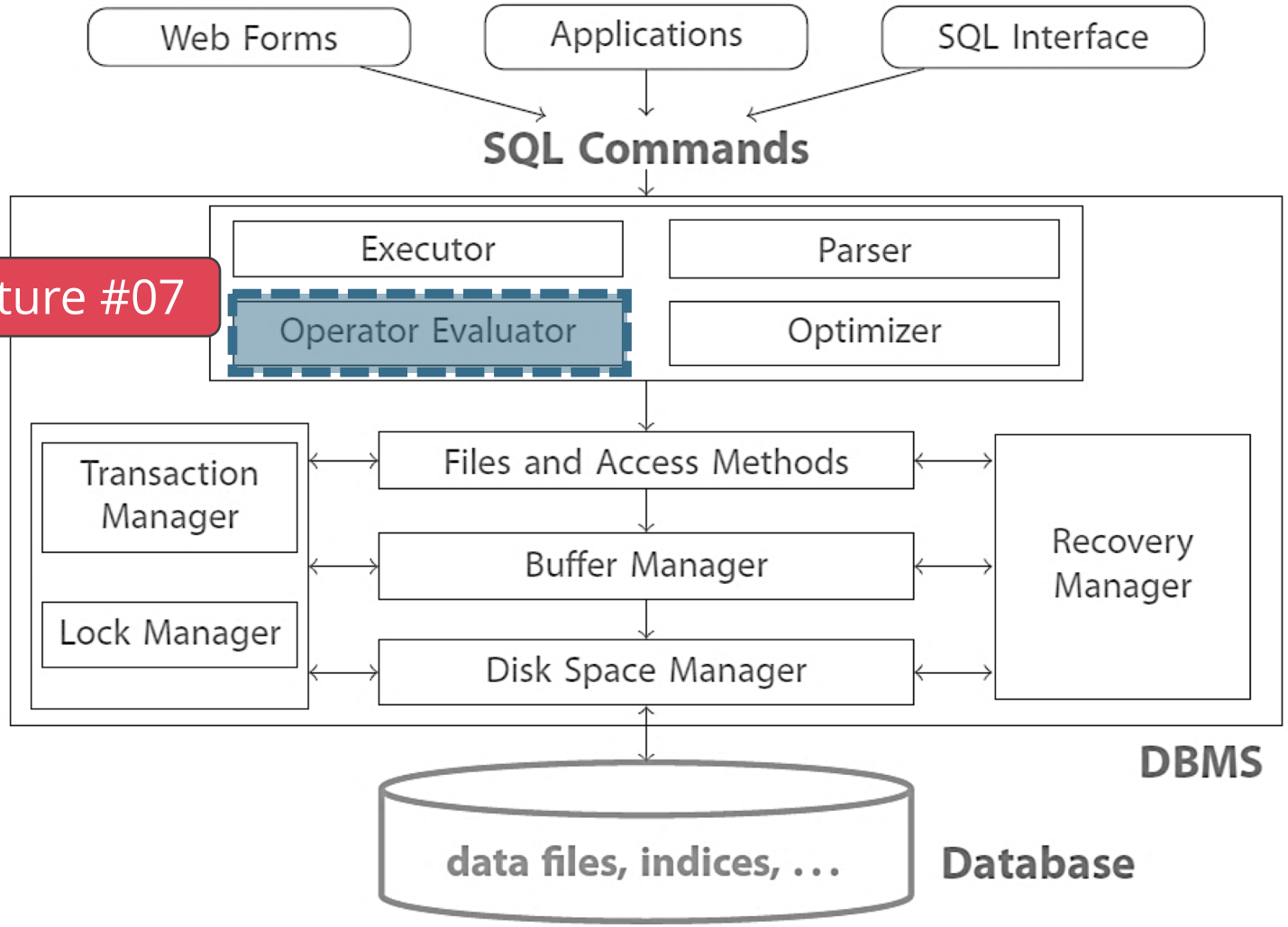
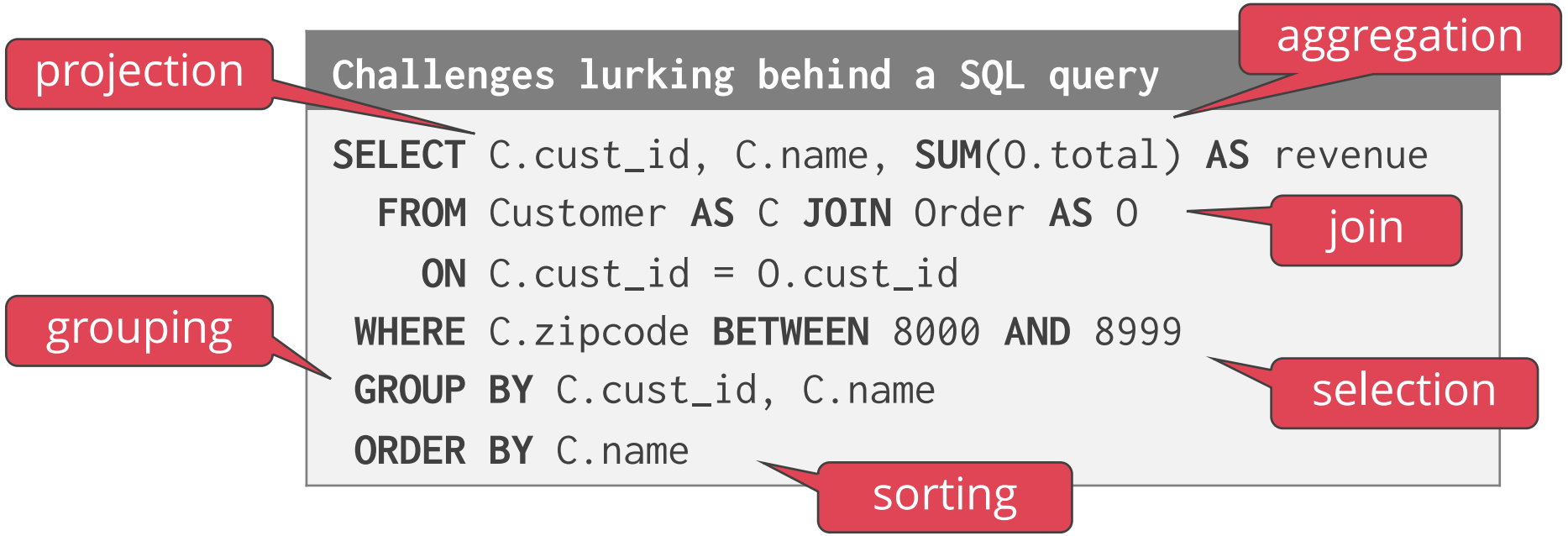
DATABASE ARCHITECTURE

Lecture #07



Query Processing



DBMS query processors need to perform various tasks

- with limited memory resources
- over large amounts of data
- yet as fast as possible

Query Plans and Operators

DBMSs do not execute a query as a large monolithic block but rather provide specialised routines, the **query operators**

Query plan = Network of operators able to evaluate a query

Each operator is carefully implemented to perform well for a specific task

Focus of this lecture:

- Implementation of one of the most basic and important operators: **sort**
- Implementation of (grouped by) **aggregation**

Why Do We Need Sorting?

Explicit sorting via the SQL ORDER BY clause

```
SELECT A, B, C FROM R ORDER BY A;
```

Implicit sorting, e.g., for duplicate elimination

```
SELECT DISTINCT A, B, C FROM R;
```

Implicit sorting, e.g., to prepare (sort-merge) equi-join

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

Grouping via **group by**, B+ tree **bulk loading**, **sorted** rid scans after access to unclustered indexes, etc.

Sorting

A file is **sorted** with respect to key ***k*** and ordering **Θ**, if for any two records r_1 and r_2 with r_1 preceding r_2 in the file, their corresponding keys are in **Θ**-order:

$$r_1 \Theta r_2 \Leftrightarrow r_1.k \Theta r_2.k$$

A key may be a single attribute or an ordered list of attributes. In the latter case, the order is **lexicographical**

Consider key (A,B) and **Θ** is <

$$r_1 < r_2 \Leftrightarrow r_1.A < r_2.A \vee (r_1.A = r_2.A \wedge r_1.B < r_2.B)$$

Sorting Algorithms

If data **fits** in memory, then we can use a standard sorting algorithm like quick-sort

If data **does not fit** in memory, then we need to use a technique that is aware of the cost of writing data out to disk

External Sorting

*How can we sort a file of records whose size **exceeds the available main memory space** (let alone the available buffer manager space) by far?*

Idea: **Divide and conquer**

- Sort chunks of data that fit in memory, then write back the sorted chunks to disk
- Combine sorted chunks into a single larger file

Approach the task in two phases:

1. Sorting a file of arbitrary size is possible using only three buffer pages
2. Refine this algorithm to make effective use of larger buffer sizes

OVERVIEW

We will start with a simple example of a 2-way external merge sort

Files are broken up into ***N*** pages

The DBMS has a finite number of ***B*** fixed-size buffer pages

2-Way External Merge Sort

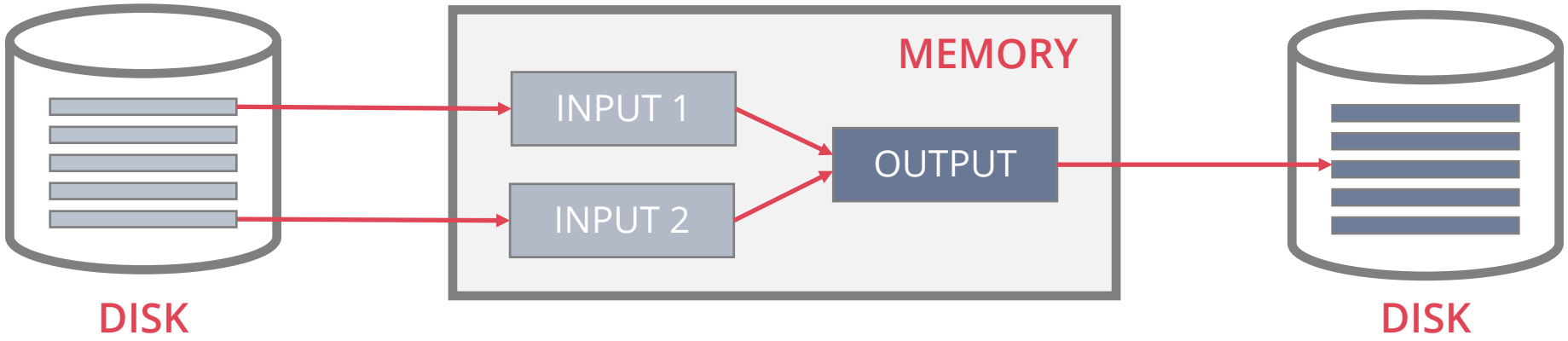
Pass #0

Read a page into memory, sort it, and write it back to disk (***uses 1 buffer page***)

Each sorted set of pages is called a **run**

Pass #1, #2, #3, ...

Recursively merge pairs of runs into runs twice as long (***uses 3 buffer pages***)

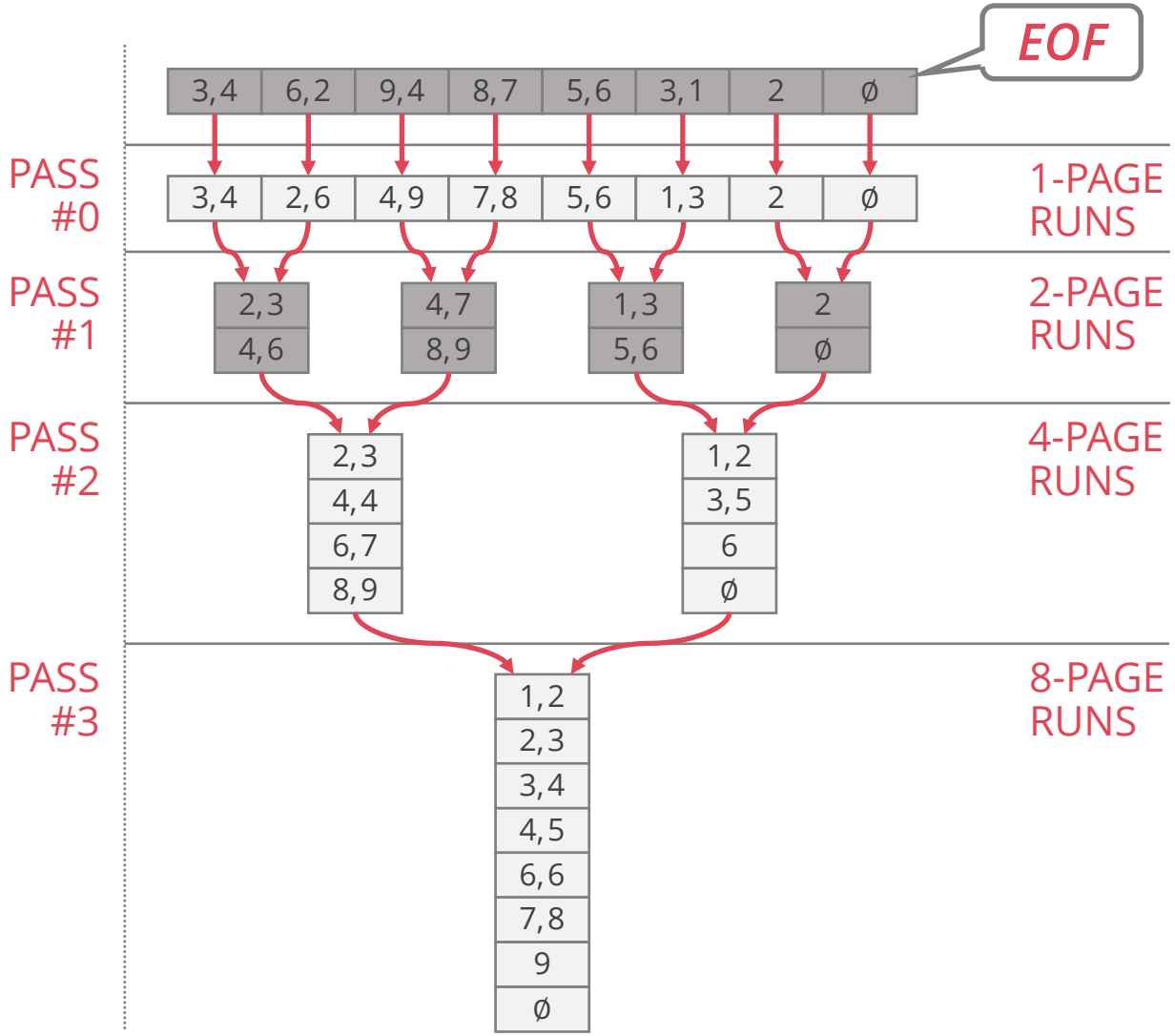


2-Way External Merge Sort

In each pass, we read and write each page in file

Number of passes
= $1 + \lceil \log_2 N \rceil$

Total I/O cost
= $2N \cdot$(# of passes)

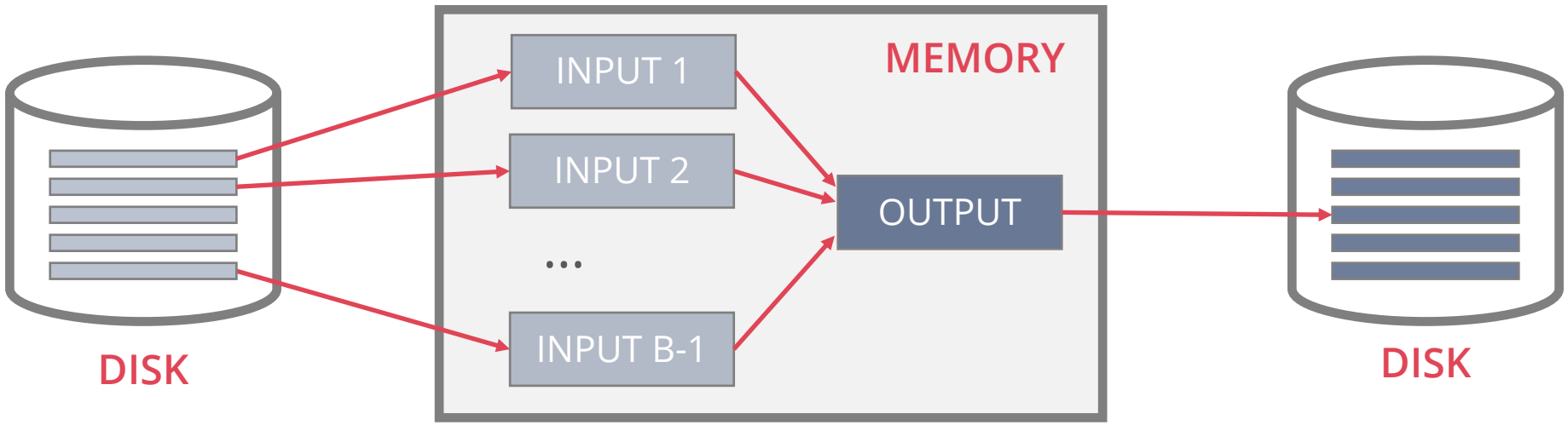


External Merge Sort

Previous algorithm uses only three buffer pages (*B = 3*)

How can we make effective use of a larger buffer pool (*B > 3*)?

- Reduce # of initial runs by using the full buffer space during in-memory sort
- Reduce # of passes by merging *B-1* runs at a time



External Merge Sort

Pass #0

Use B buffer pages

Produce $\lceil N / B \rceil$ sorted runs of size B

Pass #1, #2, #3, ...

Merge $B - 1$ runs (i.e., multi-way merge)

Number of passes = $1 + \lceil \log_{B-1} \lceil N / B \rceil \rceil$

Total I/O cost = $2N \cdot$ (# of passes)

Example

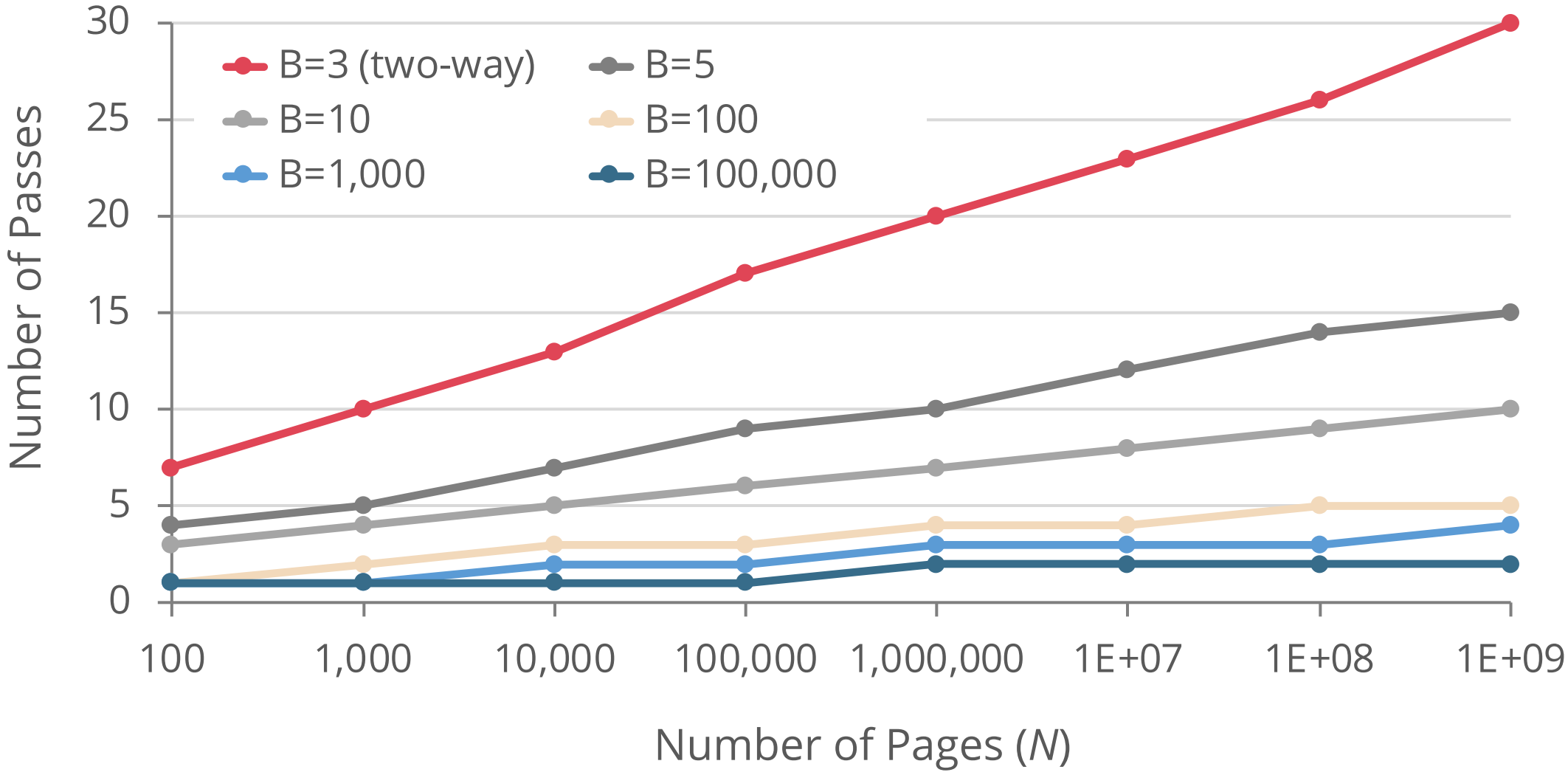
Sort N = 108 page file with B = 5 buffer pages

- **Pass #0**: $\lceil 108/5 \rceil$ = 22 sorted runs of 5 pages each (last run is only 3 pages)
- **Pass #1**: $\lceil 22/4 \rceil$ = 6 sorted runs of 20 pages each (last run is only 8 pages)
- **Pass #2**: $\lceil 6/4 \rceil$ = 2 sorted runs of 80 pages and 28 pages
- **Pass #3**: Sorted file of 108 pages

Number of passes = $1 + \lceil \log_{B-1} \lceil N / B \rceil \rceil = 1 + \lceil \log_4 22 \rceil = 1 + \lceil 2.229\ldots \rceil$
= **4 passes**

Total I/O cost = $2N \cdot$(# of passes) = $2 \cdot 108 \cdot 4 = 864$

Number of Passes of External Sort



I/O for External Merge Sort

Blocked I/O = Read blocks of ***b*** pages at once during the merge phase

Allocate ***b*** pages for each input (instead of just one)

Reduces per-page I/O cost by a factor of ***b***

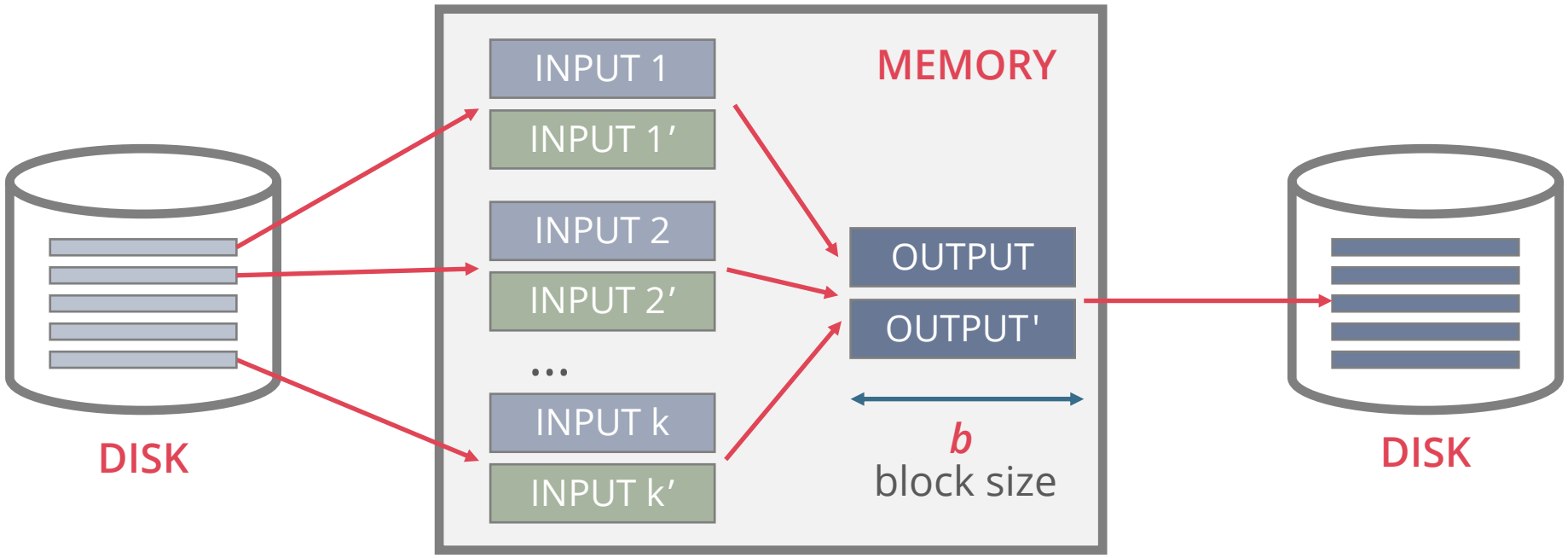
But this will reduce fan-out during the merge phase (resulting in more passes and I/O operations)

In practice, main memory sizes are large enough to sort files in **1-2 passes**

Double Buffering

To reduce wait time for I/O request to complete, **prefetch** pages into "**shadow block**"

Potentially more passes; in practice, most files **still** sorted in **1-2 passes**



B main memory buffers, k-way merge: $2b \cdot (k+1) \leq B$

Using B+ Trees for Sorting

If the table to be sorted has a B+ tree index on the sort attribute(s), we may be better off by accessing the index and avoid external sorting

Retrieve sorted records by simply traversing the leaf pages of the tree

Cases to consider

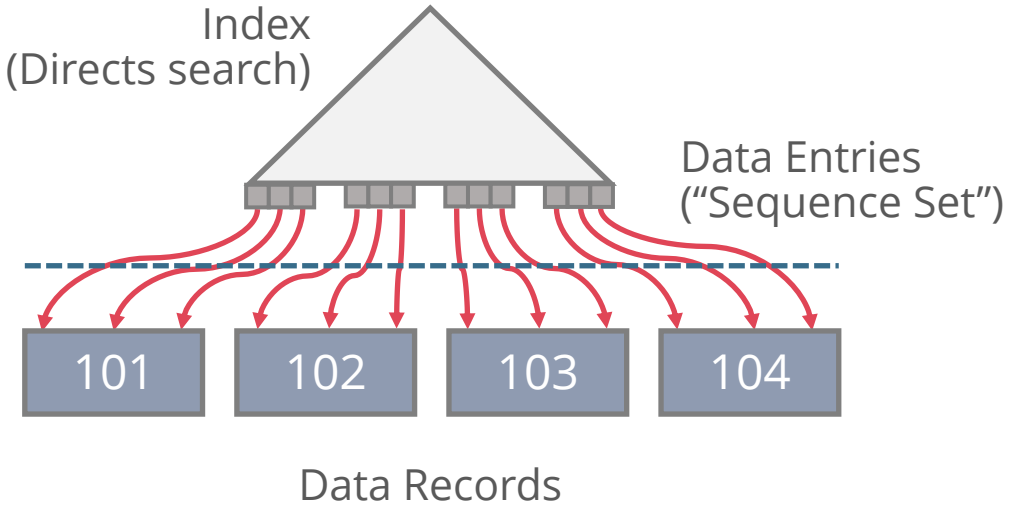
- Clustered B+ tree
- Unclustered B+ tree

Case 1: Clustered B+ Tree

Traverse to the left-most leaf page, then retrieve all leaf pages (variant **A**)

If variant **B** is used?
Additional cost of retrieving data records: each page fetched just once

Always better than external sorting!



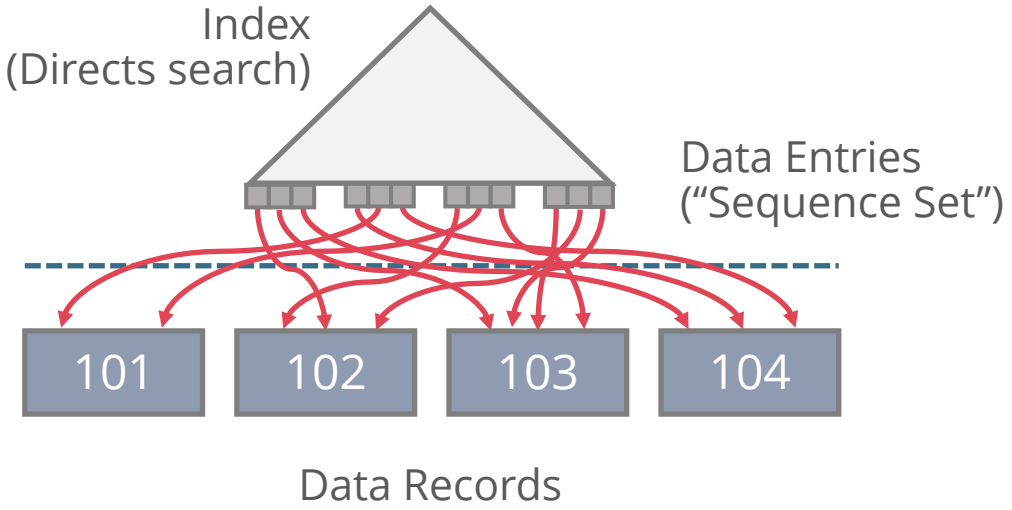
Case 2: Unclustered B+ Tree

Variant ***B*** for index data entries
(each contains *rid* of a data record)

Chase each pointer to the page
that contains the data

This is almost always a bad idea

In general, **one I/O per data record**



Duplicate Elimination using Sorting

```
SELECT DISTINCT cid
  FROM enrolled
 WHERE grade < 90
```

enrolled(sid, cid, grade)

sid	cid	grade
123466	INFR-11011	65
123488	INFR-11122	95
123488	INFR-10070	80
123466	INFR-11122	70
123455	INFR-11011	75

Filter

sid	cid	grade
123466	INFR-11011	65
123488	INFR-10070	80
123466	INFR-11122	70
123455	INFR-11011	75

Remove Columns

cid
INFR-11011
INFR-10070
INFR-11122
INFR-11011

Sort

cid
INFR-10070
INFR-11011
INFR-11011
INFR-11122

Eliminate Duplicates

Alternative to Sorting

What if we do not need the data to be ordered?

- Forming groups in **GROUP BY** (no ordering)
- Removing duplicates in **DISTINCT** (no ordering)

Hashing is a better alternative in this scenario

- Only need to remove duplicates, no need for ordering
- Can be computationally cheaper than sorting

Aggregations

Collapse multiple tuples into a single scalar value (SUM, MIN, MAX, …)

Hashing aggregates:
Populate an ephemeral hash table as the DBMS scans the relation. For each record check whether there is already an entry in the hash table

DISTINCT: Discard duplicate

GROUP BY: Perform aggregate computation

If everything fits in memory, then it's easy

If we have to spill to disk, then we need to be smarter…

```
SELECT A, MAX(B) FROM R
GROUP BY A;
```

Hashing Aggregate

Partition phase

Divide tuples into buckets based on hash key

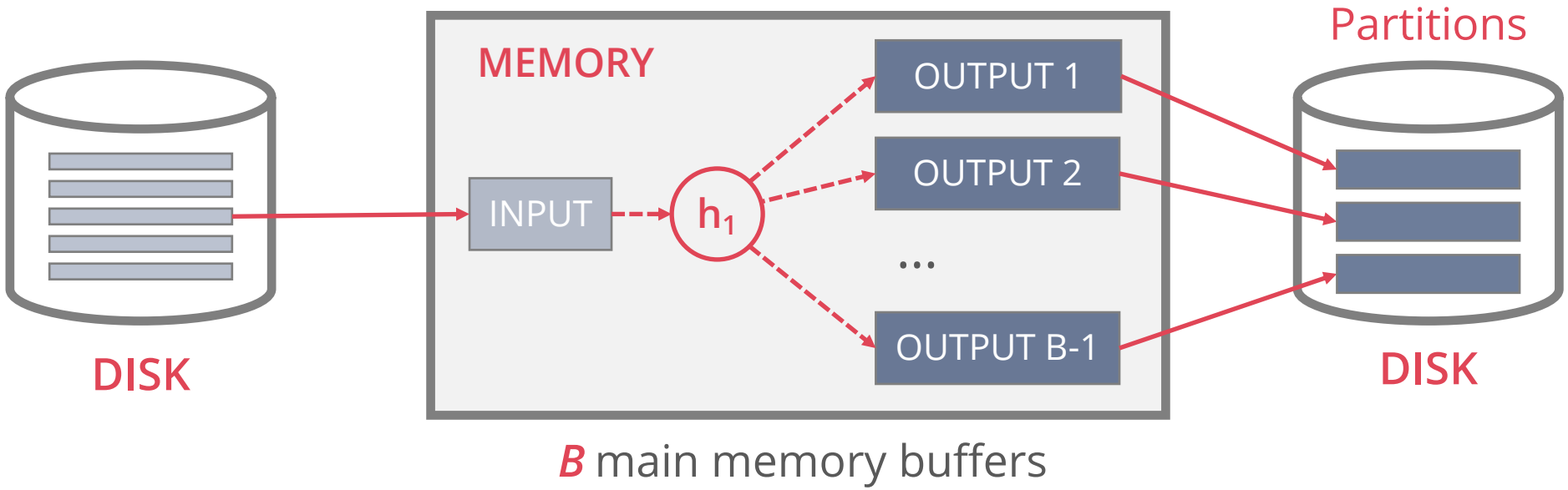
Rehash phase

Build in-memory hash table for each partition and compute the aggregate

Hashing Aggregate Phase #1: Partition

Use a hash function h_1 to split tuples into partitions on disk

- We know that all matches live in the same partition
- Partitions are "spilled" to disk via output buffers



Hashing Aggregate Phase #1: Partition

```
SELECT DISTINCT cid
  FROM enrolled
 WHERE grade < 90
```

enrolled(sid, cid, grade)

sid	cid	grade
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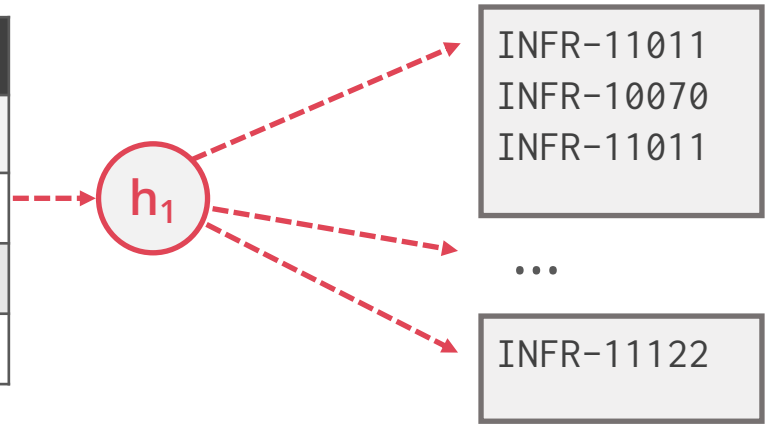
123488	INFR-11122	95
123488	INFR-10070	80
123466	INFR-11122	50
123455	INFR-11011	75

Filter

sid	cid	grade
123466	INFR-11011	80
123488	INFR-10070	80
123466	INFR-11122	50
123455	INFR-11011	75

Remove Columns

cid
INFR-11011
INFR-10070
INFR-11122
INFR-11011



B-1 partitions

Hashing Aggregate Phase #2: Rehash

For each partition on disk:

- Read it into memory and build an in-memory hash table based on a second hash function h_2 ($\neq h_1$)
- Then go through each bucket of this hash table to bring together matching tuples

No need to load the entire partition at once in memory

- Can load several pages at a time
- But the hash table built for each partition must fit in memory
- If not enough memory, repeat Phase #1 on each partition

Hashing Aggregate Phase #2: Rehash

```
SELECT DISTINCT cid
  FROM enrolled
 WHERE grade < 90
```

enrolled(sid, cid, grade)

sid	cid	grade
123466	INFR-11011	80
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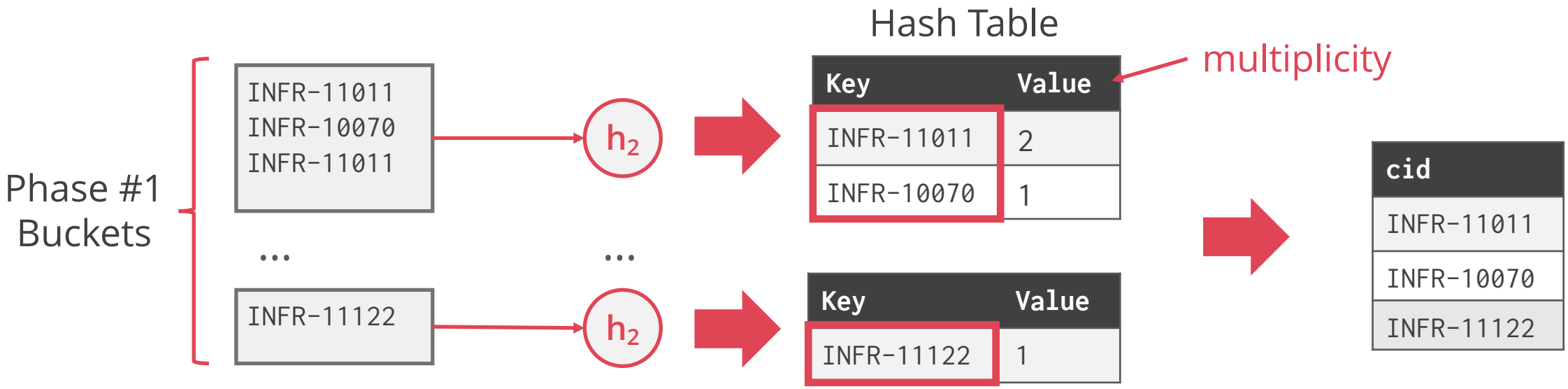

Hashing Summarisation

During the Rehash phase, store pairs of the form **GroupKey** ⟶ **RunningValue**

When we want to insert a new tuple into the hash table

- If we find a matching **GroupKey**, just update the **RunningValue** appropriately
- Else insert a new **GroupKey** ⟶ **RunningValue**

Hashing Summarisation

```
SELECT cid, AVG(grade)
  FROM enrolled
 GROUP BY cid
```

Running Totals

```
AVG(col)   ⟶ (COUNT,SUM)
MIN(col)   ⟶ (MIN)
MAX(col)   ⟶ (MAX)
SUM(col)   ⟶ (SUM)
COUNT(col) ⟶ (COUNT)
```

enrolled(sid, cid, grade)

sid	cid	grade
123466	INFR-11011	80
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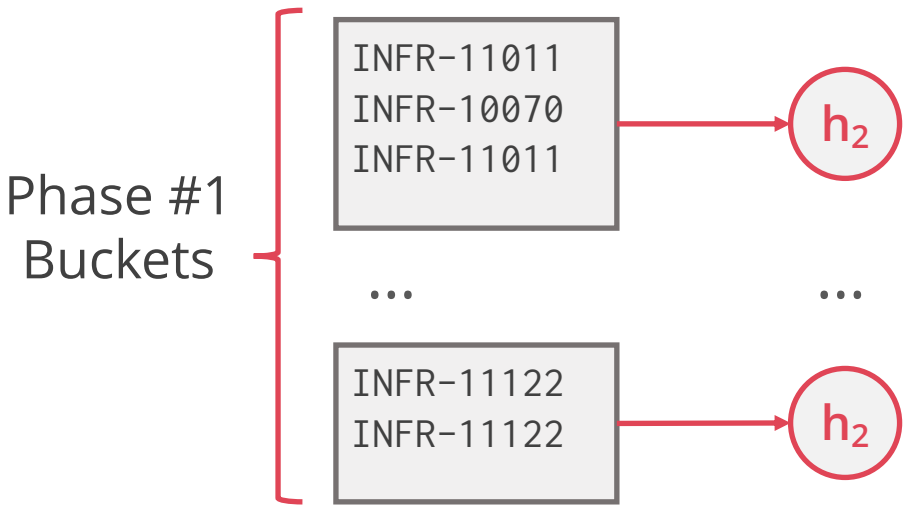
123488	INFR-10070	80
123466	INFR-11122	50
123455	INFR-11011	75



Hash Table

Key	Value
INFR-11011	(2,155)
INFR-10070	(1,80)

Key	Value
INFR-11122	(2,145)

Final Result

cid	AVG(grade)
INFR-11011	77.5
INFR-10070	80
INFR-11122	72.5

Cost Analysis

How big of a table can we hash using this approach?

- *B-1* "spill partitions" in Phase #1
- Each partition (i.e., its hash table) should be no more than *B* blocks big

Answer: ***B · (B-1)***

- A table of *N* pages needs about **sqrt(*N*)** buffer pages
- Assumes hash distributes records evenly
- Use a "fudge factor" ***f* > 1** to capture the (small) increase in size between the partition and a hash table for that partition
- Must be ***B* > *f* · *N* / (*B*-1)**; thus, we need approx. ***B* > sqrt(*f* · *N*)** buffer pages

Conclusion

Sorting has become a blood sport!

- Parallel sorting is the name of the game...
- Current world records at http://sortbenchmark.org/
  - **Gray Sort**: 100TB in 98.8 seconds, 60.7TB / minute
  - **Cloud Sort** : $1.44 / TB
  - **Minute Sort**: 55TB in one minute

External merge sort often finishes in 1-2 passes

Group-by aggregates are typically computed via hashing