Carnegie Mellon University

10 Sorting & Aggregations

Intro to Database Systems
15-445/15-645
Fall 2020

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ADMINISTRIVIA

Homework #3 is due Sunday Oct 18th

Mid-Term Exam is Wed Oct 21st

→ Download + Submit via Gradescope.

→ We will offer two sessions based on your reported timezone in S3.

ADMINISTRIVIA

Project #2 is now released:

→ Checkpoint #1: Due Sunday Oct 11th

→ Checkpoint #2: Due Sunday Oct 25th

Q&A Session about the project on **Tuesday Oct 6th @ 8:00pm ET**.

→ In-Person: GHC 4401

→ https://cmu.zoom.us/j/98100285498?pwd=a011L0E2eWFwTndKMG9KNVhzb2tDdz09

UPCOMING DATABASE TALKS

Apache Arrow
→ Monday Oct 5th @ 5pm ET

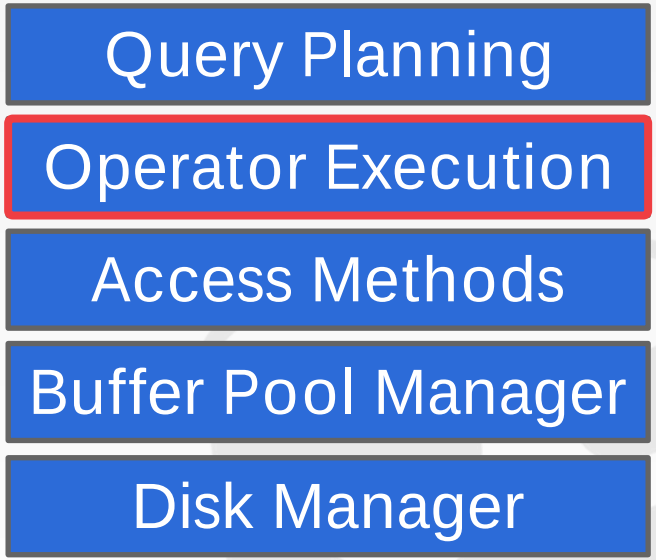
DataBricks Query Optimizer
→ Monday Oct 12th @ 5pm ET

FoundationDB Testing
→ Monday Oct 19th @ 5pm ET

COURSE STATUS

We are now going to talk about how to execute queries using table heaps and indexes.

Next two weeks:
→ Operator Algorithms
→ Query Processing Models
→ Runtime Architectures



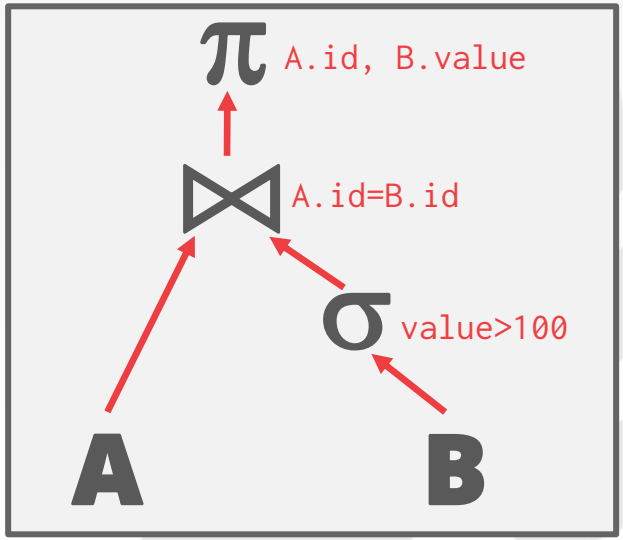
QUERY PLAN

The operators are arranged in a tree.

Data flows from the leaves of the tree up towards the root.

The output of the root node is the result of the query.

```
SELECT A.id, B.value
  FROM A, B
 WHERE A.id = B.id
   AND B.value > 100
```



DISK-ORIENTED DBMS

Just like it cannot assume that a table fits entirely in memory, a disk-oriented DBMS cannot assume that the results of a query fits in memory.

We are going use on the buffer pool to implement algorithms that need to spill to disk.

We are also going to prefer algorithms that maximize the amount of sequential I/O.

TODAY'S AGENDA

External Merge Sort

Aggregations

WHY DO WE NEED TO SORT?

Queries may request that tuples are sorted in a specific way (**ORDER BY**).

But even if a query does not specify an order, we may still want to sort to do other things:

→ Trivial to support duplicate elimination (**DISTINCT**).
→ Bulk loading sorted tuples into a B+Tree index is faster.
→ Aggregations (**GROUP BY**).

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 reading and writing from the disk in pages…

EXTERNAL MERGE SORT

Divide-and-conquer algorithm that splits the data set into separate **runs**, sorts them individually, and then combine into larger sorted runs.

Phase #1 – Sorting

→ Sort blocks of data that fit in main-memory and then write back the sorted blocks to a file on disk.

Phase #2 – Merging

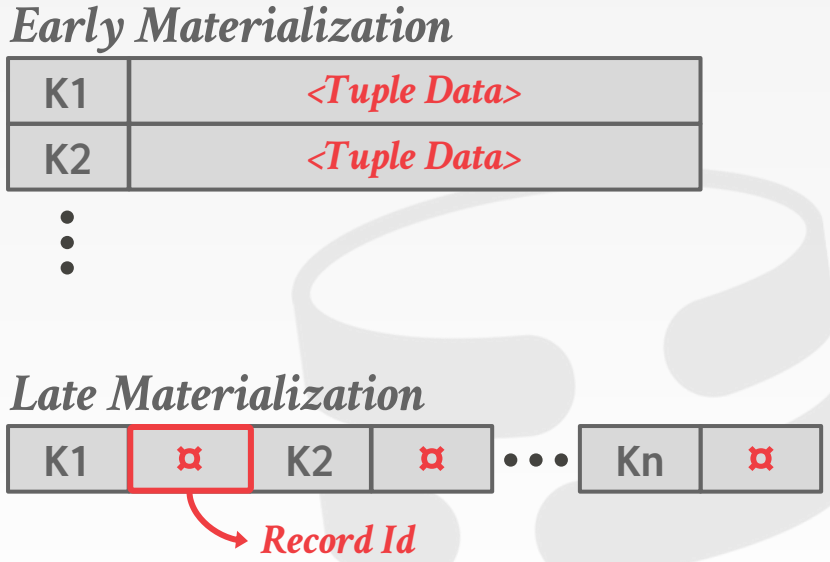
→ Combine sorted sub-files into a single larger file.

SORTED RUN

A run is a list of key/value pairs.

Key: The attribute(s) to compare to compute the sort order.

Value: Two choices
→ Record Id (***late materialization***).
→ Tuple (***early materialization***).



2-WAY EXTERNAL MERGE SORT

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

→ "2" represents the number of runs that we are going to merge into a new run for each pass.

Data set is broken up into ***N*** pages.

The DBMS has a finite number of ***B*** buffer pages to hold input and output data.

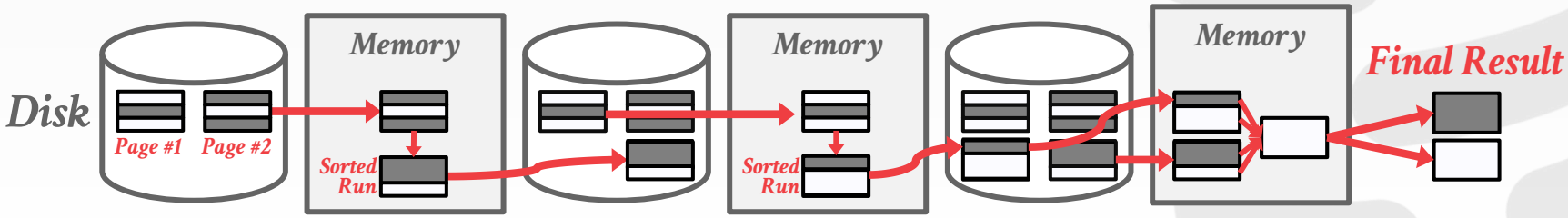
2-WAY EXTERNAL MERGE SORT

Pass #0

→ Read every ***B*** pages of the table into memory
→ Sort pages into runs and write them back to disk.

Pass #1,2,3,...

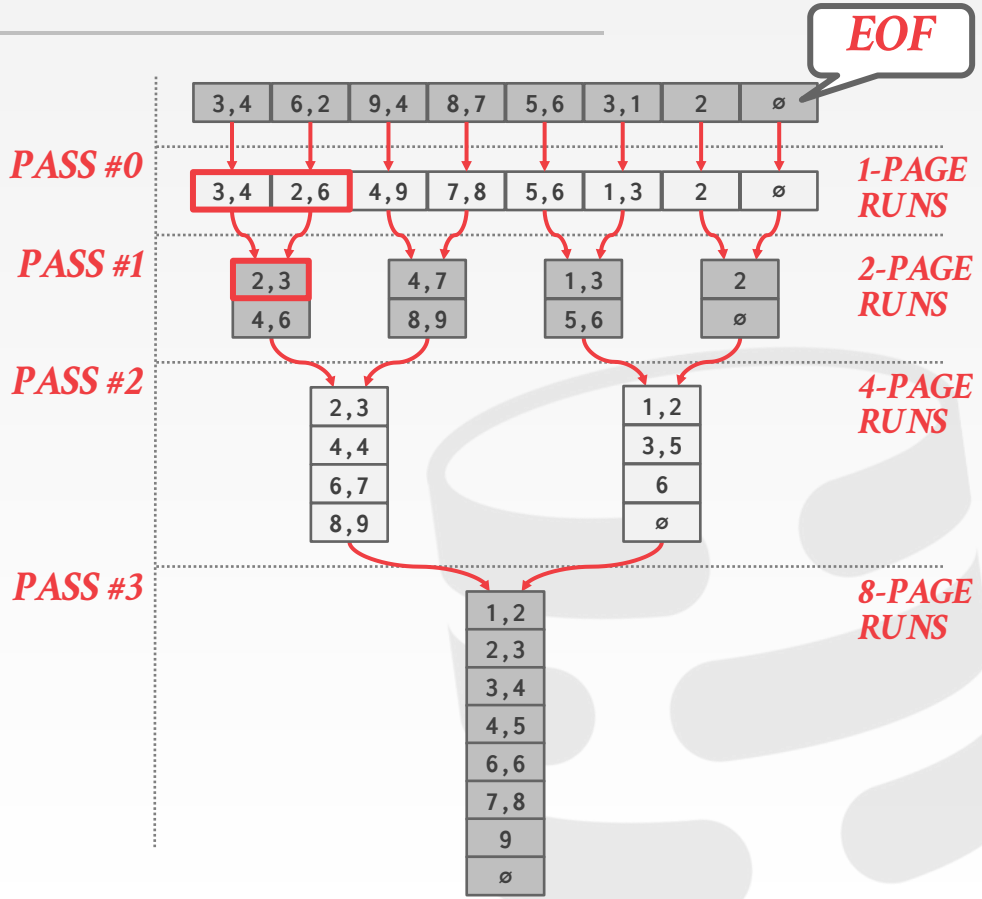
→ Recursively merges pairs of runs into runs twice as long.
→ Uses three buffer pages (2 for input pages, 1 for output).



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)



2-WAY EXTERNAL MERGE SORT

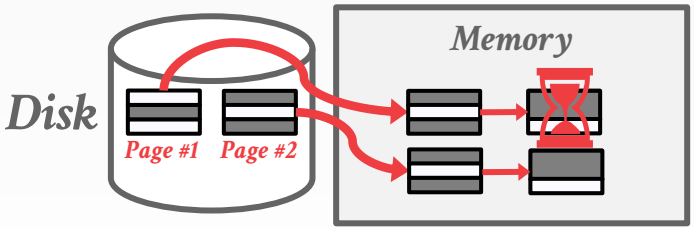
This algorithm only requires three buffer pages to perform the sorting (***B=3***).
→ Two Input Pages, One Output Page

But even if we have more buffer space available (***B>3***), it does not effectively utilize them if the worker must block on disk I/O…

DOUBLE BUFFERING OPTIMIZATION

Prefetch the next run in the background and store it in a second buffer while the system is processing the current run.

→ Reduces the wait time for I/O requests at each step by continuously utilizing the disk.



GENERAL 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., K-way merge).

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

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

EXAMPLE

Determine how many passes it takes to sort 108 pages with 5 buffer pages: $N=108$, $B=5$

→ **Pass #0:** $\lceil N / B \rceil = \lceil 108 / 5 \rceil = 22$ sorted runs of 5 pages each (last run is only 3 pages).

→ **Pass #1:** $\lceil N' / B\text{-}1 \rceil = \lceil 22 / 4 \rceil = 6$ sorted runs of 20 pages each (last run is only 8 pages).

→ **Pass #2:** $\lceil N'' / B\text{-}1 \rceil = \lceil 6 / 4 \rceil = 2$ sorted runs, first one has 80 pages and second one has 28 pages.

→ **Pass #3:** Sorted file of 108 pages.

$$1+\lceil \log_{B-1} \lceil N / B \rceil \rceil = 1+\lceil \log_4 22 \rceil = 1+\lceil 2.229... \rceil$$

$$= \mathbf{4\ passes}$$

USING B+TREES FOR SORTING

If the table that must be sorted already has a B+Tree index on the sort attribute(s), then we can use that to accelerate sorting.

Retrieve tuples in desired sort order by simply traversing the leaf pages of the tree.

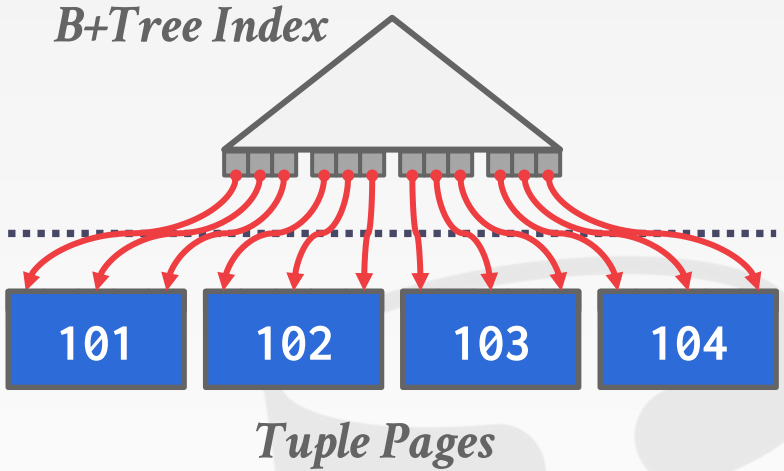
Cases to consider:

→ Clustered B+Tree
→ Unclustered B+Tree

CASE #1 – CLUSTERED B+TREE

Traverse to the left-most leaf page, and then retrieve tuples from all leaf pages.

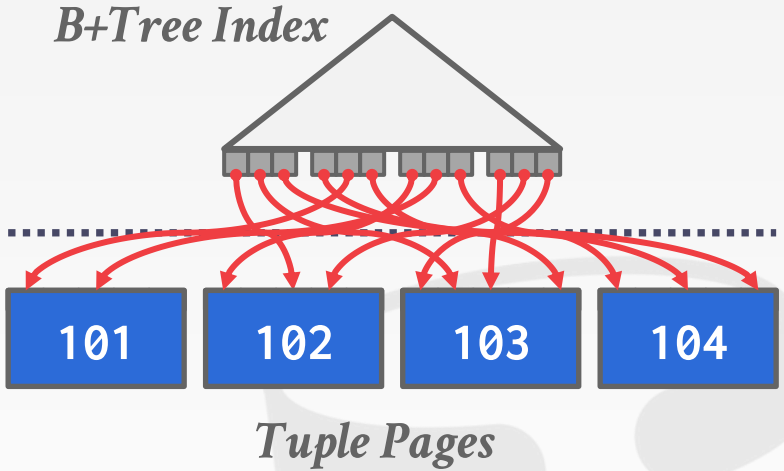
This is always better than external sorting because there is no computational cost, and all disk access is sequential.



CASE #2 – UNCLUSTERED B+TREE

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.



AGGREGATIONS

Collapse values for a single attribute from multiple tuples into a single scalar value.

Two implementation choices:
→ Sorting
→ Hashing

SORTING AGGREGATION

```
SELECT DISTINCT cid
  FROM enrolled
 WHERE grade IN ('B','C')
 ORDER BY cid
```

enrolled(sid,cid,grade)

sid	cid	grade
53666	15-445	C
53688	15-721	A
53688	15-826	B
53666	15-721	C
53655	15-445	C

Filter

sid	cid	grade
53666	15-445	C
53688	15-826	B
53666	15-721	C
53655	15-445	C

Remove Columns

cid
15-445
15-826
15-721
15-445

Sort

cid
15-445
15-445
15-721
15-826

Eliminate Dupes

ALTERNATIVES 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.

HASHING AGGREGATE

Populate an ephemeral hash table as the DBMS scans the table. 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 this is easy.

If the DBMS must spill data to disk, then we need to be smarter…

EXTERNAL HASHING AGGREGATE

Phase #1 – Partition

→ Divide tuples into buckets based on hash key.
→ Write them out to disk when they get full.

Phase #2 – ReHash

→ Build in-memory hash table for each partition and compute the aggregation.

PHASE #1 – PARTITION

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

→ A partition is one or more pages that contain the set of keys with the same hash value.

→ Partitions are "spilled" to disk via output buffers.

Assume that we have ***B*** buffers.

We will use ***B-1*** buffers for the partitions and ***1*** buffer for the input data.

PHASE #1 – PARTITION

```
SELECT DISTINCT cid
  FROM enrolled
 WHERE grade IN ('B','C')
```

enrolled(sid,cid,grade)

sid	cid	grade
53666	15-445	C
53688	15-721	A
53688	15-826	B
53666	15-721	C
53655	15-445	C

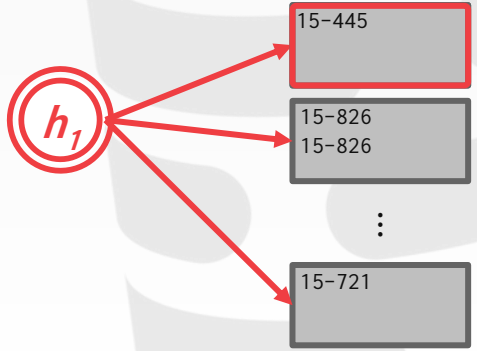
Filter

sid	cid	grade
53666	15-445	C
53688	15-826	B
53666	15-721	C
53655	15-445	C

Remove Columns

cid
15-445
15-826
15-721
15-445
⋮

B-1 partitions



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.

→ Then go through each bucket of this hash table to bring together matching tuples.

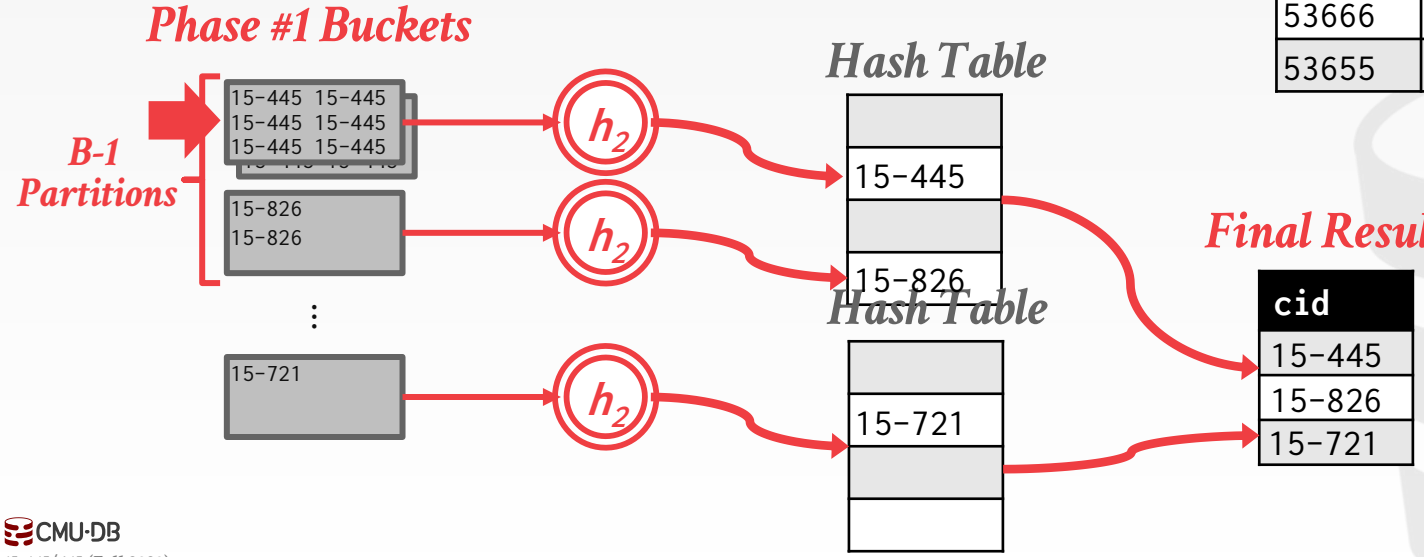
This assumes that each partition fits in memory.

PHASE #2 – REHASH

```
SELECT DISTINCT cid
  FROM enrolled
 WHERE grade IN ('B','C')
```

enrolled(sid,cid,grade)

sid	cid	grade
53666	15-445	C
53688	15-721	A
53688	15-826	B
53666	15-721	C
53655	15-445	C



HASHING SUMMARIZATION

During the ReHash phase, store pairs of the form (**GroupKey→RunningVal**)

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

→ If we find a matching **GroupKey**, just update the **RunningVal** appropriately

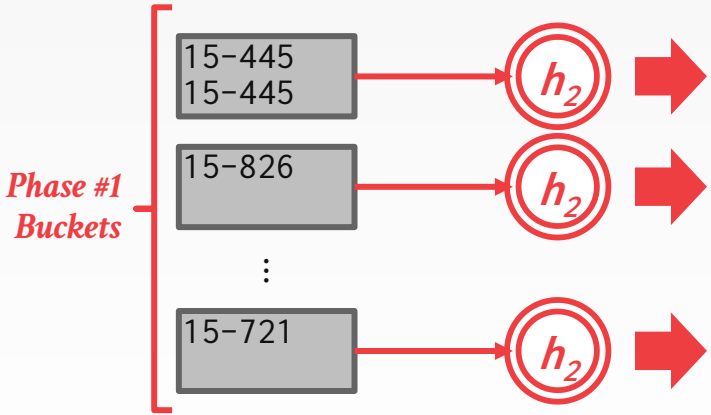
→ Else insert a new **GroupKey→RunningVal**

HASHING SUMMARIZATION

```
SELECT cid, AVG(s.gpa)
  FROM student AS s, enrolled AS e
 WHERE s.sid = e.sid
 GROUP BY cid
```

Running Totals

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



Hash Table

key	value
15-445	(2, 7.32)
15-826	(1, 3.33)
15-721	(1, 2.89)

Final Result

cid	AVG(gpa)
15-445	3.66
15-826	3.33
15-721	2.89

CONCLUSION

Choice of sorting vs. hashing is subtle and depends on optimizations done in each case.

We already discussed the optimizations for sorting:

→ Chunk I/O into large blocks to amortize costs.
→ Double-buffering to overlap CPU and I/O.

NEXT CLASS

Nested Loop Join

Sort-Merge Join

Hash Join