Carnegie Mellon University

11 Join Algorithms

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

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ADMINISTRIVIA

Homework #2 is due Sunday Oct 4th

Project #2 is now released:
→ Checkpoint #1: Due Sunday Oct 11th
→ Checkpoint #2: Due Sunday Oct 25th

Mid-Term Exam is Wed Oct 21st
→ Download + Submit via Gradescope.
→ We will offer two sessions based on your reported timezone in S3.

WHY DO WE NEED TO JOIN?

We normalize tables in a relational database to avoid unnecessary repetition of information.

We use the join operate to reconstruct the original tuples without any information loss.

JOIN ALGORITHMS

We will focus on performing binary joins (two tables) using **inner equijoin** algorithms.

→ These algorithms can be tweaked to support other joins..

→ Multi-way joins exist only in research literature.

In general, we want the smaller table to always be the left table ("outer table") in the query plan.

JOIN OPERATORS

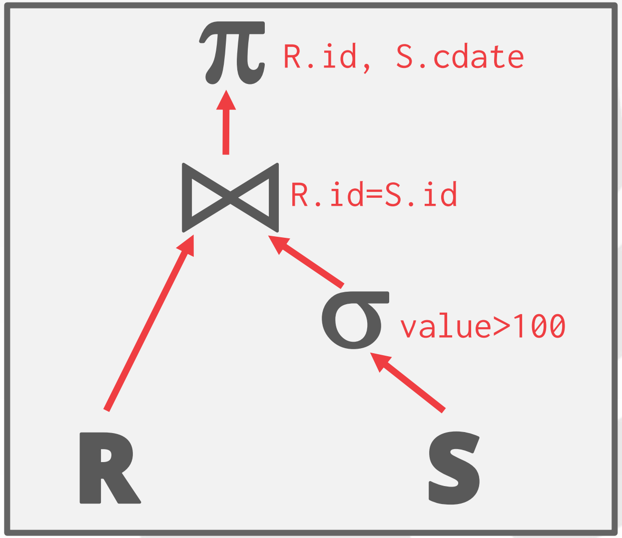
Decision #1: Output

→ What data does the join operator emit to its parent operator in the query plan tree?

Decision #2: Cost Analysis Criteria

→ How do we determine whether one join algorithm is better than another?

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```



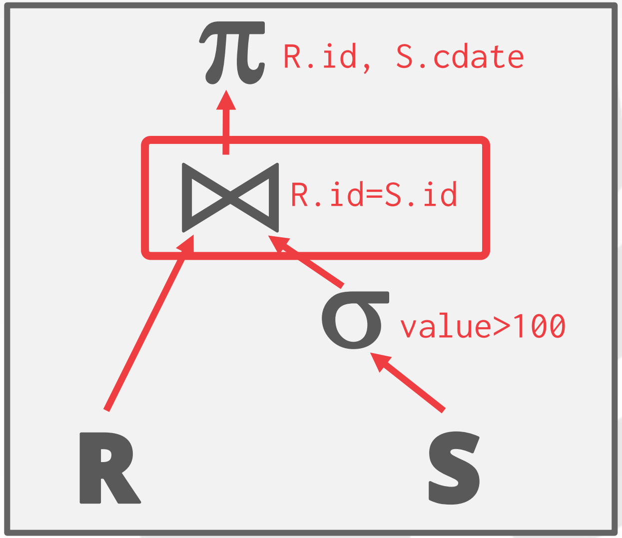
OPERATOR OUTPUT

For tuple **r** ∈ **R** and tuple **s** ∈ **S** that match on join attributes, concatenate **r** and **s** together into a new tuple.

Output contents can vary:

→ Depends on processing model
→ Depends on storage model
→ Depends on data requirements in query

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```



OPERATOR OUTPUT: DATA

Early Materialization:

→ Copy the values for the attributes in outer and inner tuples into a new output tuple.

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

R(id,name)

id	name
123	abc

⋈

S(id,value,cdate)

id	value	cdate
123	1000	10/7/2020
123	2000	10/7/2020

R.id	R.name	S.id	S.value	S.cdate
123	abc	123	1000	10/7/2020
123	abc	123	2000	10/7/2020

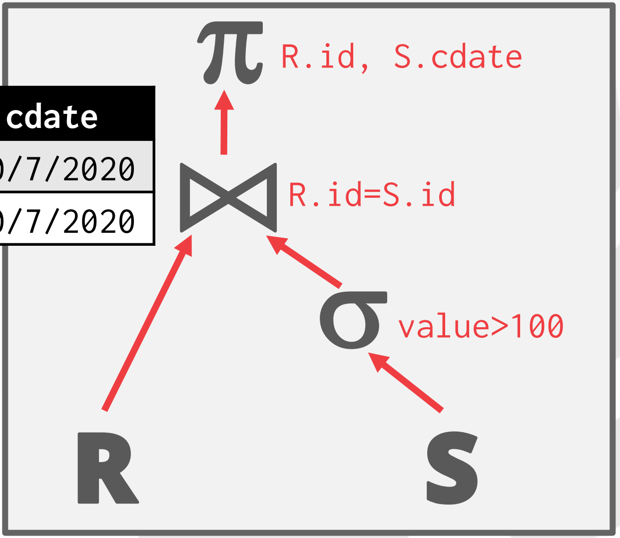
OPERATOR OUTPUT: DATA

Early Materialization:

→ Copy the values for the attributes in outer and inner tuples into a new output tuple.

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

R.id	R.name	S.id	S.value	S.cdate
123	abc	123	1000	10/7/2020
123	abc	123	2000	10/7/2020



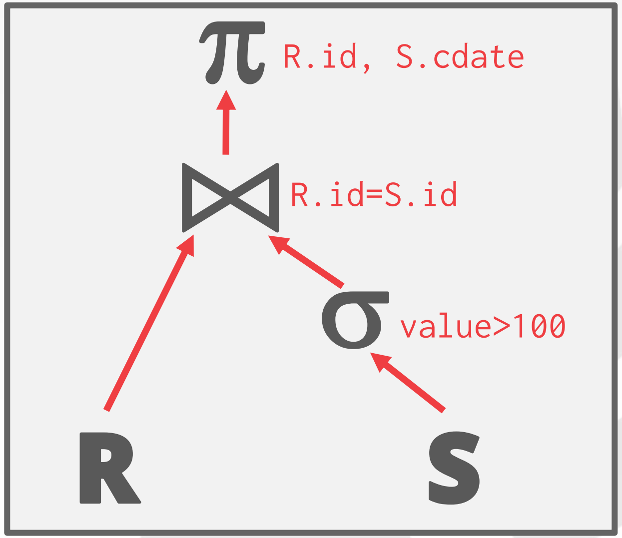
OPERATOR OUTPUT: DATA

Early Materialization:

→ Copy the values for the attributes in outer and inner tuples into a new output tuple.

Subsequent operators in the query plan never need to go back to the base tables to get more data.

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```



OPERATOR OUTPUT: RECORD IDS

Late Materialization:

→ Only copy the joins keys along with the record ids of the matching tuples.

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

R(id,name)

id	name
123	abc

⋈

S(id,value,cdate)

id	value	cdate
123	1000	10/7/2020
123	2000	10/7/2020

R.id	R.RID	S.id	S.RID
123	R.###	123	S.###
123	R.###	123	S.###

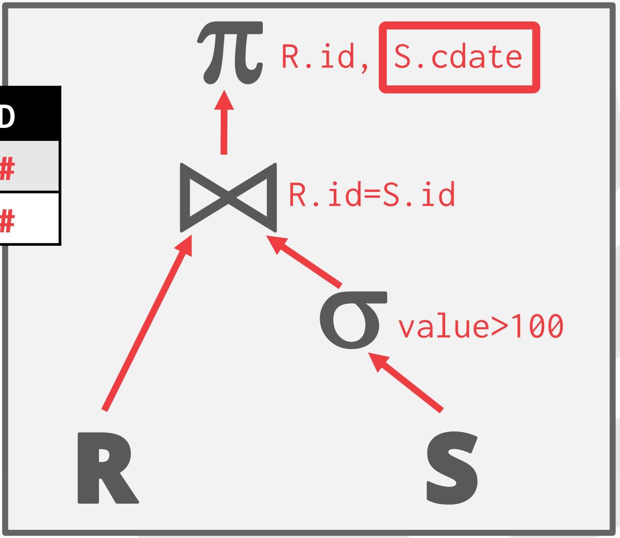
OPERATOR OUTPUT: RECORD IDS

Late Materialization:

→ Only copy the joins keys along with the record ids of the matching tuples.

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

R.id	R.RID	S.id	S.RID
123	R.###	123	S.###
123	R.###	123	S.###



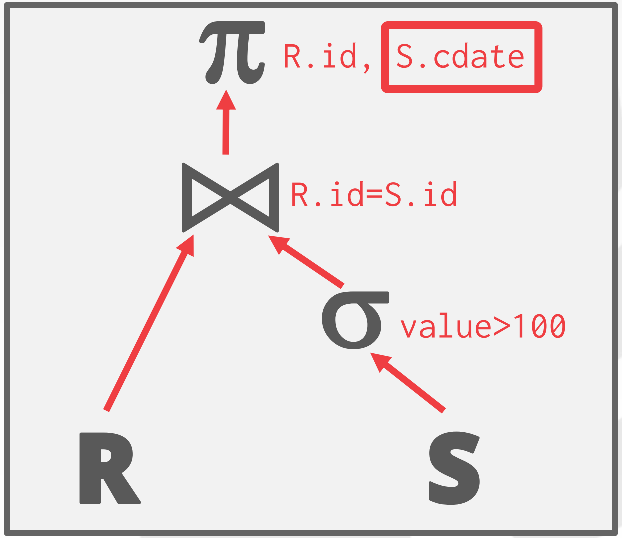
OPERATOR OUTPUT: RECORD IDS

Late Materialization:

→ Only copy the joins keys along with the record ids of the matching tuples.

Ideal for column stores because the DBMS does not copy data that is not need for the query.

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```



COST ANALYSIS CRITERIA

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

Assume:

→ ***M*** pages in table **R**, ***m*** tuples in **R**

→ ***N*** pages in table **S**, ***n*** tuples in **S**

Cost Metric: # of IOs to compute join

We will ignore output costs since that depends on the data and we cannot compute that yet.

JOIN VS CROSS-PRODUCT

$R \bowtie S$ is the most common operation and thus must be carefully optimized.

$R \times S$ followed by a selection is inefficient because the cross-product is large.

There are many algorithms for reducing join cost, but no algorithm works well in all scenarios.

JOIN ALGORITHMS

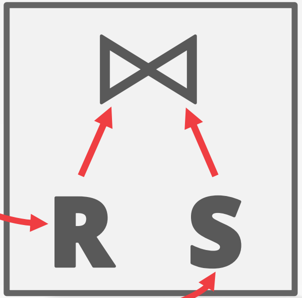
Nested Loop Join
→ Simple / Stupid
→ Block
→ Index

Sort-Merge Join

Hash Join

NESTED LOOP JOIN

```
foreach tuple r ∈ R:      ← Outer
  foreach tuple s ∈ S:    ← Inner
    emit, if r and s match
```



R(id,name)

id	name
600	MethodMan
200	GZA
100	Andy
300	ODB
500	RZA
700	Ghostface
400	Raekwon

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
500	7777	10/7/2020
400	6666	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020

STUPID NESTED LOOP JOIN

Why is this algorithm stupid?

→ For every tuple in **R**, it scans **S** once

Cost: M + (m · N)

M pages
m tuples

R(id,name)

id	name
600	MethodMan
200	GZA
100	Andy
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700	Ghostface
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S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
500	7777	10/7/2020
400	6666	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020

N pages
n tuples

STUPID NESTED LOOP JOIN

Example database:
→ **Table R**: $M = 1000$, $m = 100{,}000$
→ **Table S**: $N = 500$, $n = 40{,}000$

4 KB pages → 6 MB

Cost Analysis:
→ $M + (m \cdot N) = 1000 + (100000 \cdot 500) =$ **50,001,000 IOs**
→ At 0.1 ms/IO, Total time ≈ 1.3 hours

What if smaller table (**S**) is used as the outer table?
→ $N + (n \cdot M) = 500 + (40000 \cdot 1000) =$ **40,000,500 IOs**
→ At 0.1 ms/IO, Total time ≈ 1.1 hours

BLOCK NESTED LOOP JOIN

```
foreach block B_R ∈ R:
  foreach block B_S ∈ S:
    foreach tuple r ∈ B_R:
      foreach tuple s ∈ B_S:
        emit, if r and s match
```

R(id,name)

M pages
m tuples

id	name
600	MethodMan
200	GZA
100	Andy
300	ODB
500	RZA
700	Ghostface
400	Raekwon

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
500	7777	10/7/2020
400	6666	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020

N pages
n tuples

BLOCK NESTED LOOP JOIN

This algorithm performs fewer disk accesses.
→ For every block in **R**, it scans **S** once

Cost: $M + (M \cdot N)$

R(id,name)

id	name
600	MethodMan
200	GZA
100	Andy
300	ODB
500	RZA
700	Ghostface
400	Raekwon

M pages
m tuples

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
500	7777	10/7/2020
400	6666	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020

N pages
n tuples

BLOCK NESTED LOOP JOIN

The smaller table should be the outer table.

We determine size based on the number of pages <u>not</u> the number of tuples.

R(id,name)

M pages
m tuples

id	name
600	MethodMan
200	GZA
100	Andy
300	ODB
500	RZA
700	Ghostface
400	Raekwon

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
500	7777	10/7/2020
400	6666	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020

N pages
n tuples

BLOCK NESTED LOOP JOIN

Example database:

→ **Table R**: M = 1000, m = 100,000

→ **Table S**: N = 500, n = 40,000

Cost Analysis:

→ $M + (M \cdot N)$ = 1000 + (1000 · 500) = **501,000 IOs**

→ At 0.1 ms/IO, Total time ≈ 50 seconds

BLOCK NESTED LOOP JOIN

What if we have ***B*** buffers available?

→ Use ***B*-2** buffers for scanning the outer table.

→ Use one buffer for the inner table, one buffer for storing output.

M pages
m tuples

`R(id,name)`

id	name
600	MethodMan
200	GZA
100	Andy
300	ODB
500	RZA
700	Ghostface
400	Raekwon

`S(id,value,cdate)`

id	value	cdate
100	2222	10/7/2020
500	7777	10/7/2020
400	6666	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020

N pages
n tuples

BLOCK NESTED LOOP JOIN

```
foreach B-2 blocks bR ∈ R:
  foreach block bS ∈ S:
    foreach tuple r ∈ B-2 blocks:
      foreach tuple s ∈ bs:
        emit, if r and s match
```

R(id,name)

M pages
m tuples

id	name
600	MethodMan
200	GZA
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S(id,value,cdate)

N pages
n tuples

id	value	cdate
100	2222	10/7/2020
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400	6666	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020

BLOCK NESTED LOOP JOIN

This algorithm uses ***B*-2** buffers for scanning **R**.

Cost: $M + (\lceil M / (B\text{-}2) \rceil \cdot N)$

What if the outer relation completely fits in memory ($B > M+2$)?

→ **Cost:** $M + N$ = 1000 + 500 = **1500 IOs**

→ At 0.1ms/IO, Total time ≈ 0.15 seconds

NESTED LOOP JOIN

Why does the basic nested loop join suck?

→ For each tuple in the outer table, we must do a sequential scan to check for a match in the inner table.

We can avoid sequential scans by using an index to find inner table matches.

→ Use an existing index for the join.

→ Build one on the fly (hash table, B+Tree).

INDEX NESTED LOOP JOIN

```
foreach tuple r ∈ R:
  foreach tuple s ∈ Index(r_i = s_j):
    emit, if r and s match
```

R(id,name)

M pages
m tuples

id	name
600	MethodMan
200	GZA
100	Andy
300	ODB
500	RZA
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S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
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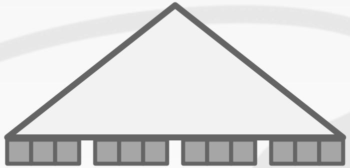
100	9999	10/7/2020
200	8888	10/7/2020

N pages
n tuples

Index(S.id)

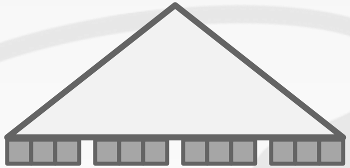


INDEX NESTED LOOP JOIN

Assume the cost of each index probe is some constant C per tuple.

Cost: $M + (m \cdot C)$

Index(S.id)



R(id,name)

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N pages
n tuples

NESTED LOOP JOIN

Pick the smaller table as the outer table.

Buffer as much of the outer table in memory as possible.

Loop over the inner table or use an index.

SORT-MERGE JOIN

Phase #1: Sort

→ Sort both tables on the join key(s).
→ We can use the external merge sort algorithm that we talked about last class.

Phase #2: Merge

→ Step through the two sorted tables with cursors and emit matching tuples.
→ May need to backtrack depending on the join type.

SORT-MERGE JOIN

```
sort R,S on join keys
cursorR ← Rsorted, cursorS ← Ssorted
while cursorR and cursorS:
  if cursorR > cursorS:
    increment cursorS
  if cursorR < cursorS:
    increment cursorR
  elif cursorR and cursorS match:
    emit
    increment cursorS
```

SORT-MERGE JOIN

R(id,name)

id	name
600	MethodMan
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400	Raekwon

Sort!

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
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Sort!

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

SORT-MERGE JOIN

R(id,name)

id	name
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Sort!

S(id,value,cdate)

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Sort!

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SELECT R.id, S.cdate
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SORT-MERGE JOIN

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SELECT R.id, S.cdate
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SORT-MERGE JOIN

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500	7777	10/7/2020

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

Output Buffer

R.id	R.name	S.id	S.value	S.cdate
100	Andy	100	2222	10/7/2020

SORT-MERGE JOIN

R(id,name)

id	name
100	Andy
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SELECT R.id, S.cdate
  FROM R JOIN S
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```

Output Buffer

R.id	R.name	S.id	S.value	S.cdate
100	Andy	100	2222	10/7/2020
100	Andy	100	9999	10/7/2020

SORT-MERGE JOIN

R(id,name)

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Output Buffer

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SORT-MERGE JOIN

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Output Buffer

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SORT-MERGE JOIN

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SORT-MERGE JOIN

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Output Buffer

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SORT-MERGE JOIN

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Output Buffer

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100	Andy	100	9999	10/7/2020
200	GZA	200	8888	10/7/2020
200	GZA	200	8888	10/7/2020

SORT-MERGE JOIN

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Output Buffer

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100	Andy	100	9999	10/7/2020
200	GZA	200	8888	10/7/2020
200	GZA	200	8888	10/7/2020
400	Raekwon	200	6666	10/7/2020

SORT-MERGE JOIN

R(id,name)

id	name
100	Andy
200	GZA
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100	2222	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020
400	6666	10/7/2020
500	7777	10/7/2020

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

Output Buffer

R.id	R.name	S.id	S.value	S.cdate
100	Andy	100	2222	10/7/2020
100	Andy	100	9999	10/7/2020
200	GZA	200	8888	10/7/2020
200	GZA	200	8888	10/7/2020
400	Raekwon	200	6666	10/7/2020

SORT-MERGE JOIN

R(id,name)

id	name
100	Andy
200	GZA
200	GZA
300	ODB
400	Raekwon
500	RZA
600	MethodMan
700	Ghostface

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2020
100	9999	10/7/2020
200	8888	10/7/2020
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SORT-MERGE JOIN

Sort Cost (R): $2M \cdot (1 + \lceil \log_{B-1} \lceil M / B \rceil \rceil)$

Sort Cost (S): $2N \cdot (1 + \lceil \log_{B-1} \lceil N / B \rceil \rceil)$

Merge Cost: $(M + N)$

Total Cost: Sort + Merge

SORT-MERGE JOIN

Example database:

→ **Table R**: M = 1000, m = 100,000

→ **Table S**: N = 500, n = 40,000

With B=100 buffer pages, both **R** and **S** can be sorted in two passes:

→ Sort Cost (**R**) = $2000 \cdot (1 + \lceil \log_{99} 1000 / 100 \rceil)$ = **4000 IOs**

→ Sort Cost (**S**) = $1000 \cdot (1 + \lceil \log_{99} 500 / 100 \rceil)$ = **2000 IOs**

→ Merge Cost = (1000 + 500) = **1500 IOs**

→ Total Cost = 4000 + 2000 + 1500 = **7500 IOs**

→ At 0.1 ms/IO, Total time ≈ 0.75 seconds

SORT-MERGE JOIN

The worst case for the merging phase is when the join attribute of all the tuples in both relations contain the same value.

Cost: $(M \cdot N)$ + (sort cost)

WHEN IS SORT-MERGE JOIN USEFUL?

One or both tables are already sorted on join key.

Output must be sorted on join key.

The input relations may be sorted by either by an explicit sort operator, or by scanning the relation using an index on the join key.

HASH JOIN

If tuple $r \in R$ and a tuple $s \in S$ satisfy the join condition, then they have the same value for the join attributes.

If that value is hashed to some partition i, the R tuple must be in r_i and the S tuple in s_i.

Therefore, R tuples in r_i need only to be compared with S tuples in s_i.

BASIC HASH JOIN ALGORITHM

Phase #1: Build

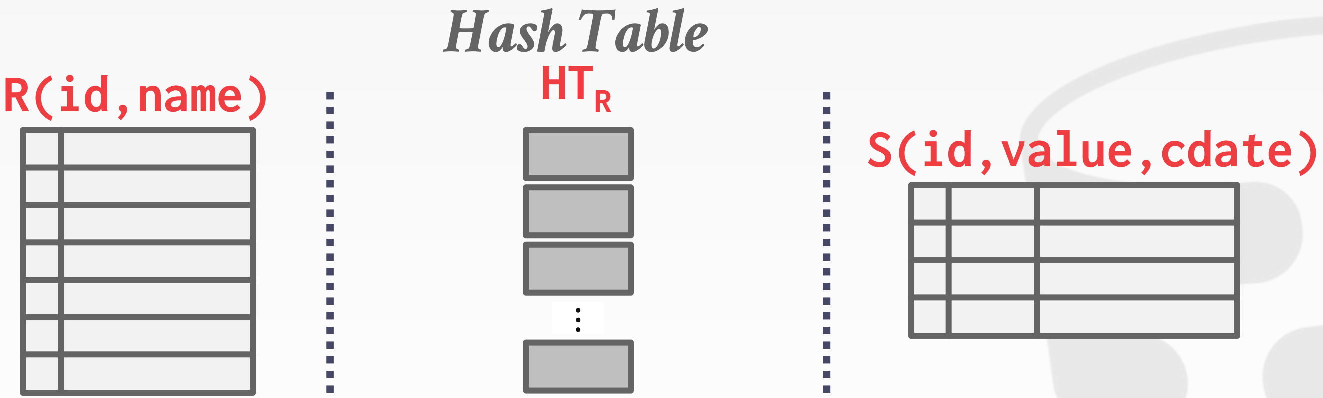
→ Scan the outer relation and populate a hash table using the hash function h_1 on the join attributes.

Phase #2: Probe

→ Scan the inner relation and use h_1 on each tuple to jump to a location in the hash table and find a matching tuple.

BASIC HASH JOIN ALGORITHM

```
build hash table HT_R for R
foreach tuple s ∈ S
  output, if h_1(s) ∈ HT_R
```



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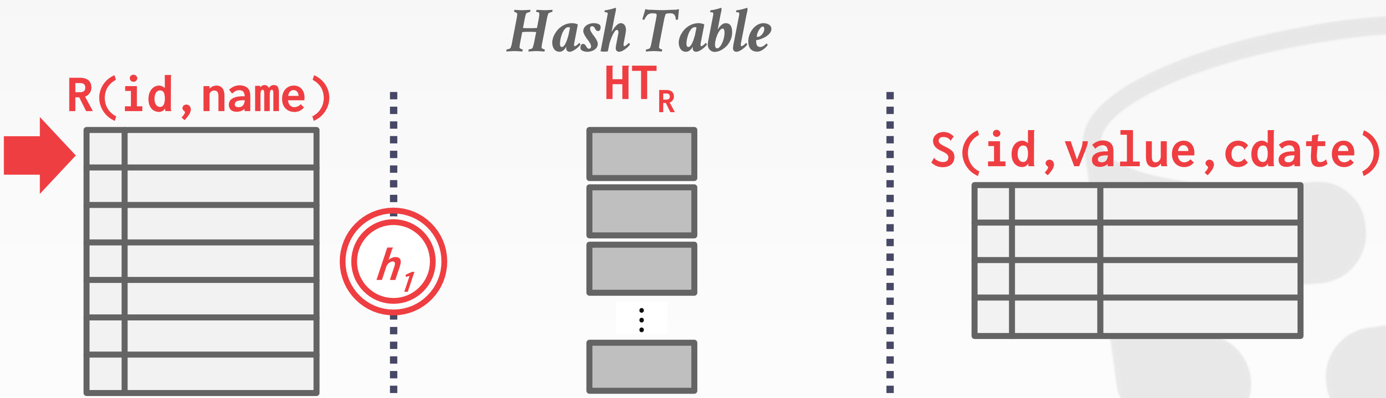

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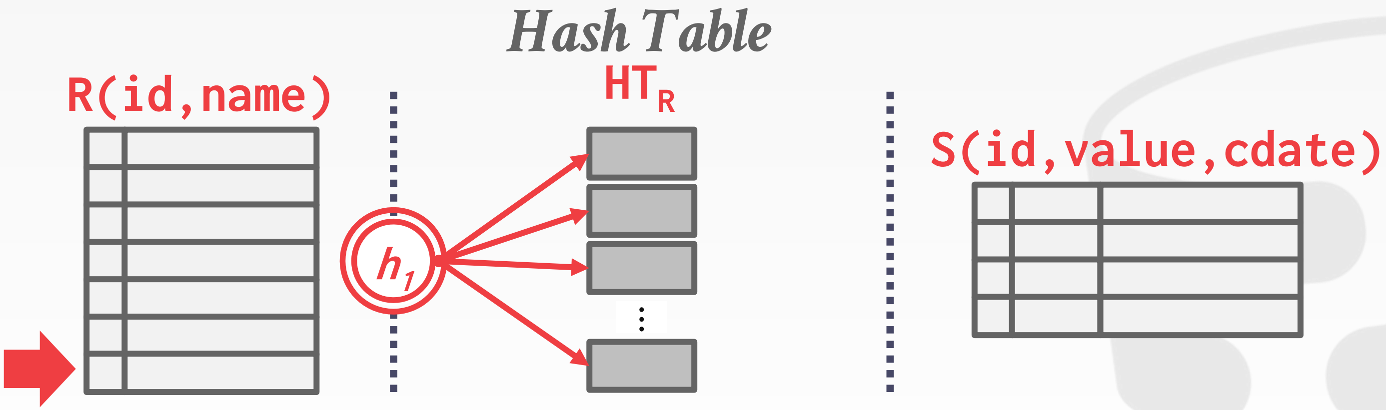

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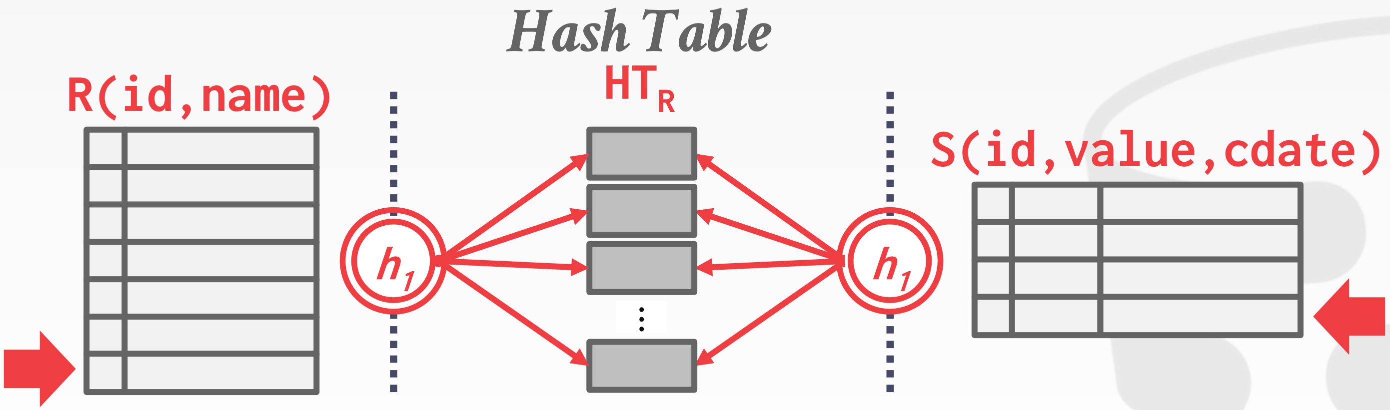

HASH TABLE CONTENTS

Key: The attribute(s) that the query is joining the tables on.

Value: Varies per implementation.
→ Depends on what the operators above the join in the query plan expect as its input.

HASH TABLE VALUES

Approach #1: Full Tuple

→ Avoid having to retrieve the outer relation's tuple contents on a match.
→ Takes up more space in memory.

Approach #2: Tuple Identifier

→ Could be to either the base tables or the intermediate output from child operators in the query plan.
→ Ideal for column stores because the DBMS does not fetch data from disk it does not need.
→ Also better if join selectivity is low.

PROBE PHASE OPTIMIZATION

Create a Bloom Filter during the build phase when the key is likely to not exist in the hash table.

→ Threads check the filter before probing the hash table. This will be faster since the filter will fit in CPU caches.

→ Sometimes called ***sideways information passing.***

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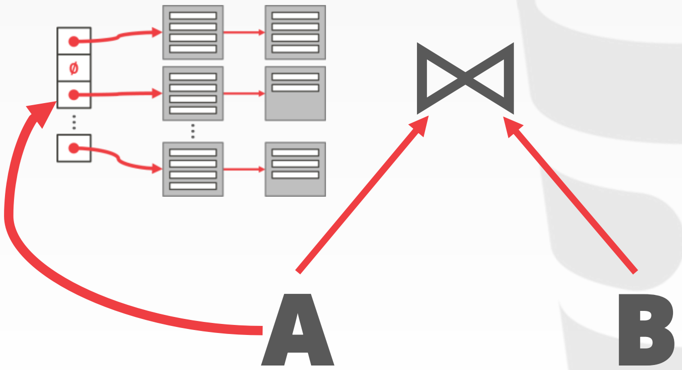

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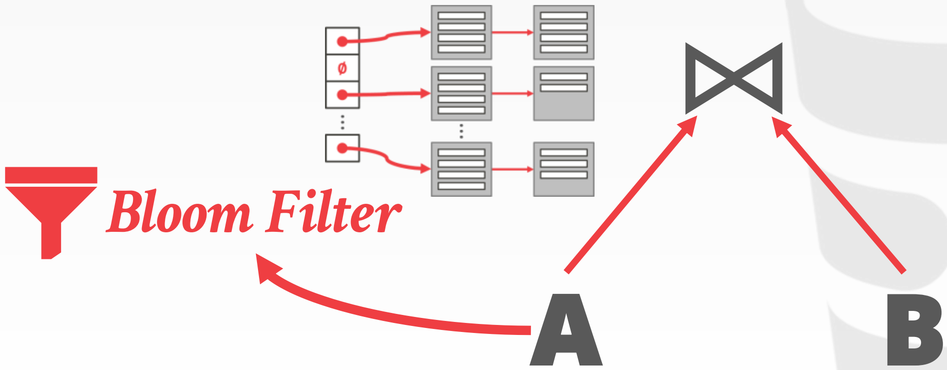

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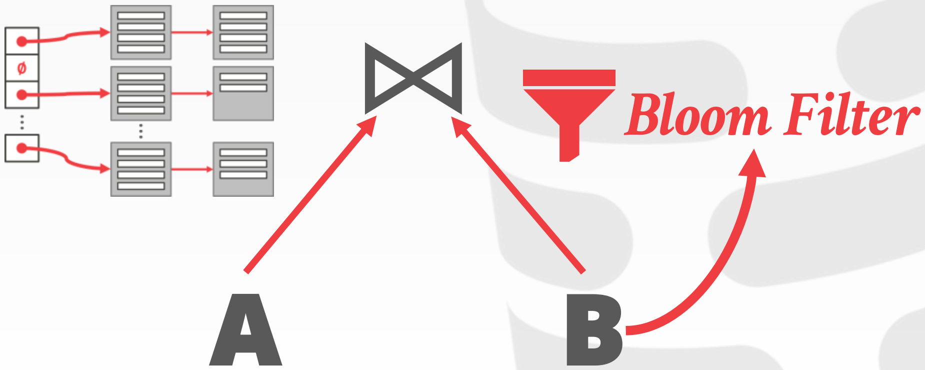

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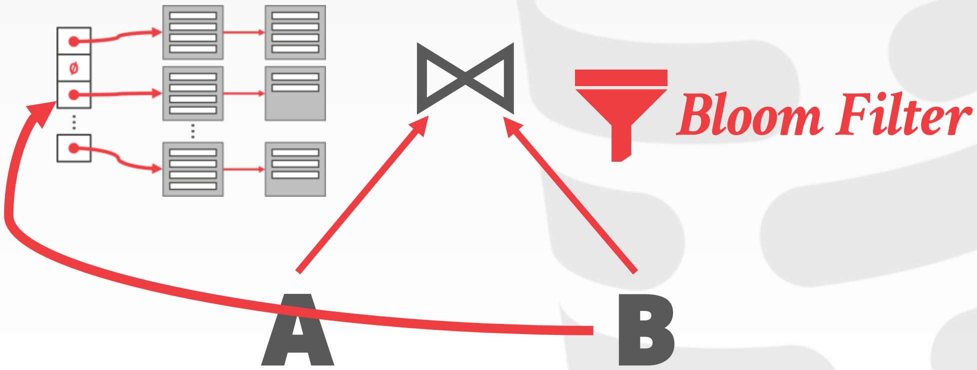


COST ANALYSIS

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

→ ***B*-1** "spill partitions" in Phase #1

→ Each should be no more than ***B*** blocks big

Answer: $B \cdot (B\text{-}1)$

→ A table of ***N*** pages needs about **sqrt(*N*)** buffers

→ Assumes hash distributes records evenly. Use a "fudge factor" f>1 for that: we need $B \cdot \mathrm{sqrt}(f \cdot N)$

HASH JOIN

What happens if we do not have enough memory to fit the entire hash table?

We do not want to let the buffer pool manager swap out the hash table pages at a random.

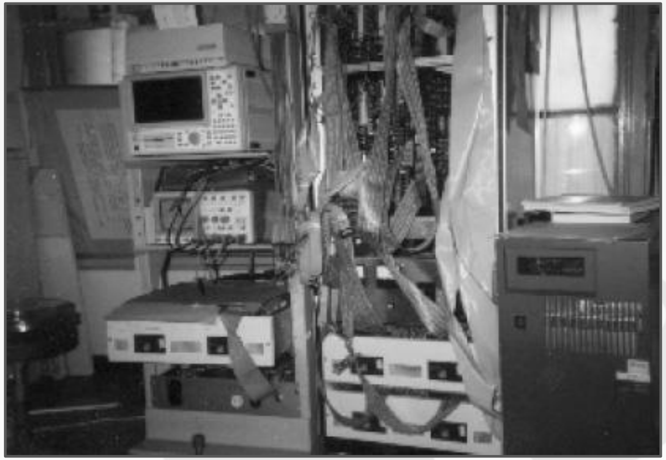
GRACE HASH JOIN

Hash join when tables do not fit in memory.

→ **Build Phase:** Hash both tables on the join attribute into partitions.

→ **Probe Phase:** Compares tuples in corresponding partitions for each table.

Named after the GRACE database machine from Japan in the 1980s.



GRACE
University of Tokyo

GRACE HASH JOIN

Hash **R** into (0, 1, ..., *max*) buckets.

Hash **S** into the same # of buckets with the same hash function.

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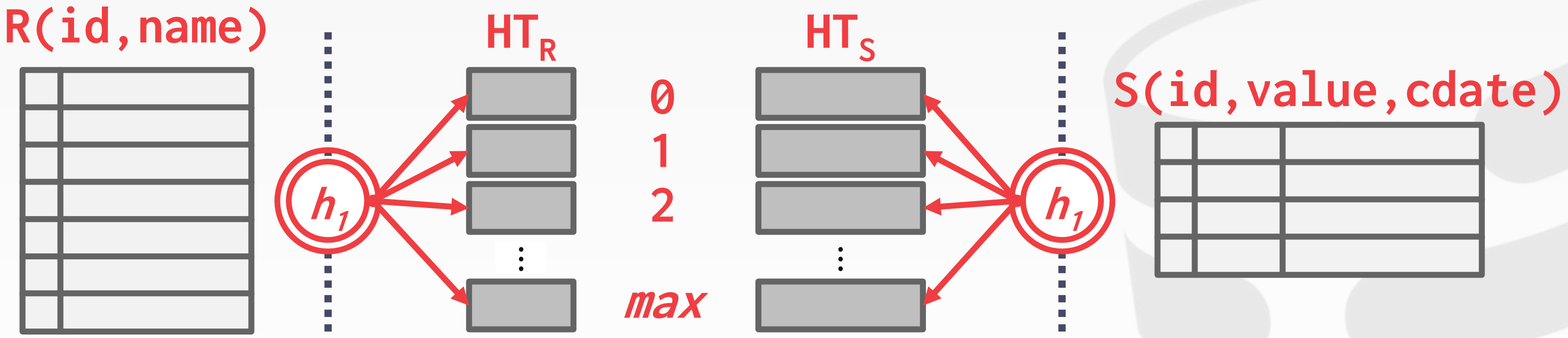
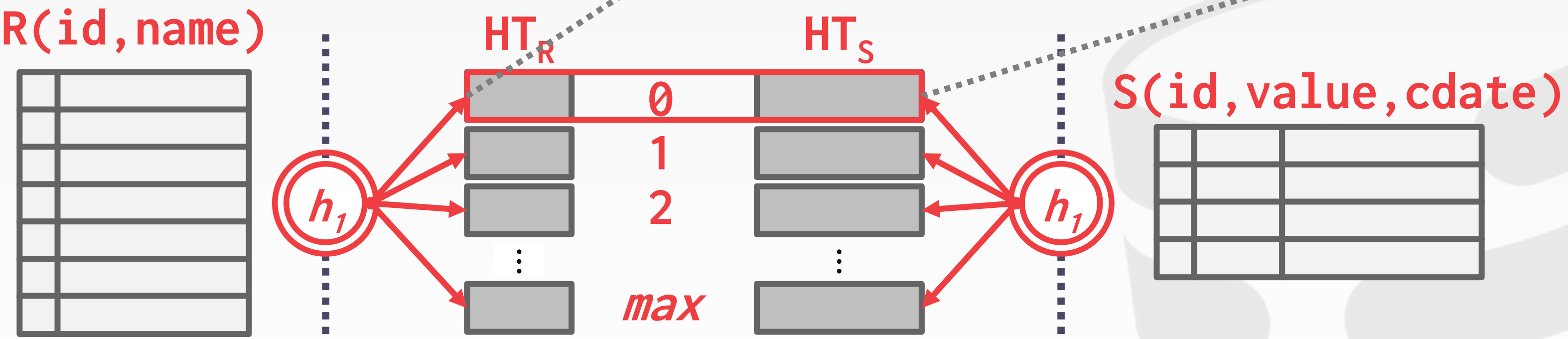


GRACE HASH JOIN

Perform nested loop join on each pair of matching buckets in the same level between **R** and **S**.

```
foreach tuple r ∈ bucket_{R,0}:
  foreach tuple s ∈ bucket_{S,0}:
    emit, if match(r, s)
```

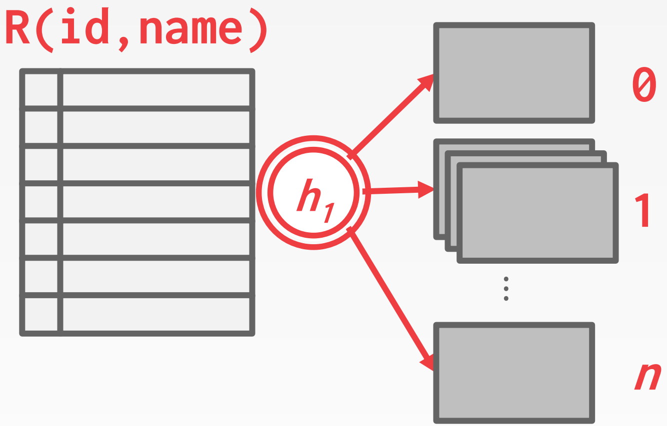


GRACE HASH JOIN

If the buckets do not fit in memory, then use **recursive partitioning** to split the tables into chunks that will fit.

- → Build another hash table for **$\text{bucket}_{R,i}$** using hash function **h_2** (with **$h_2 \neq h_1$**).
- → Then probe it for each tuple of the other table's bucket at that level.

RECURSIVE PARTITIONING



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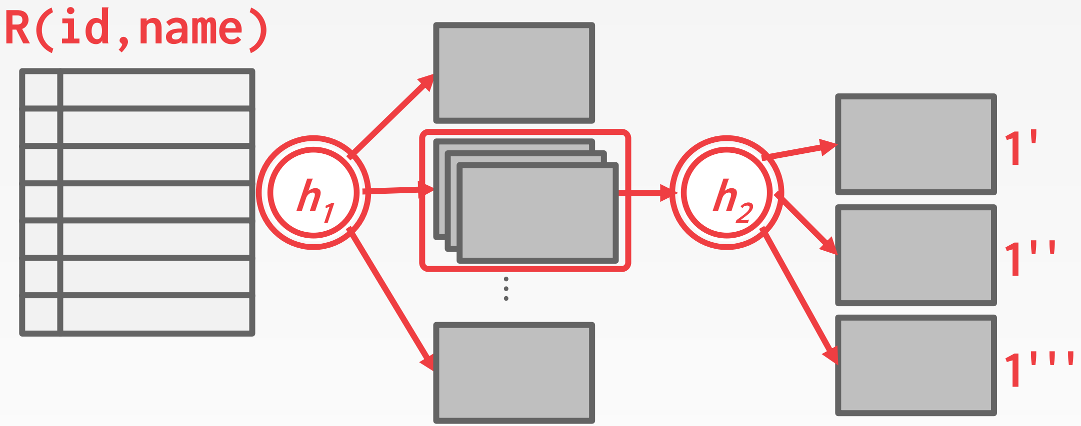

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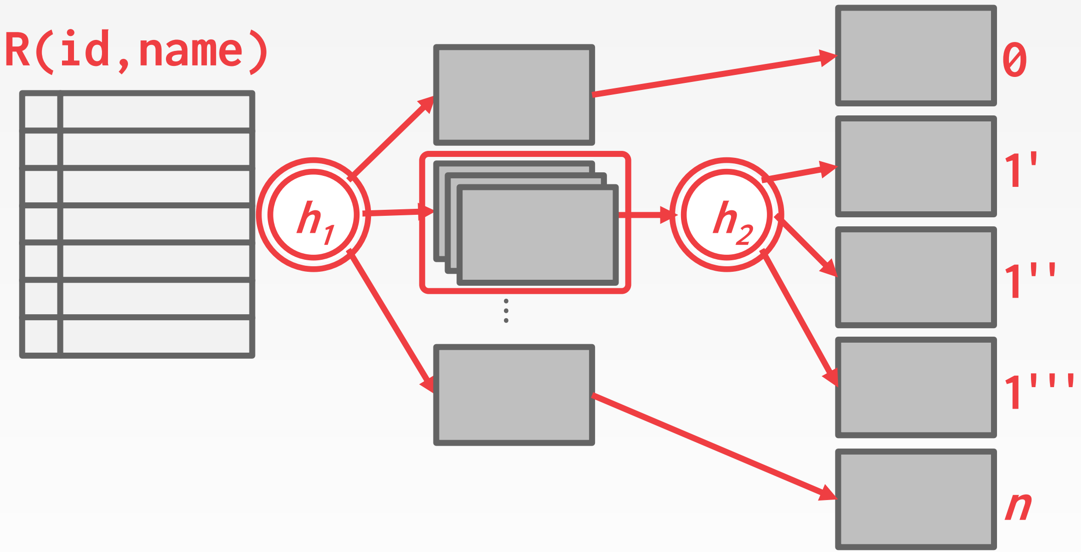

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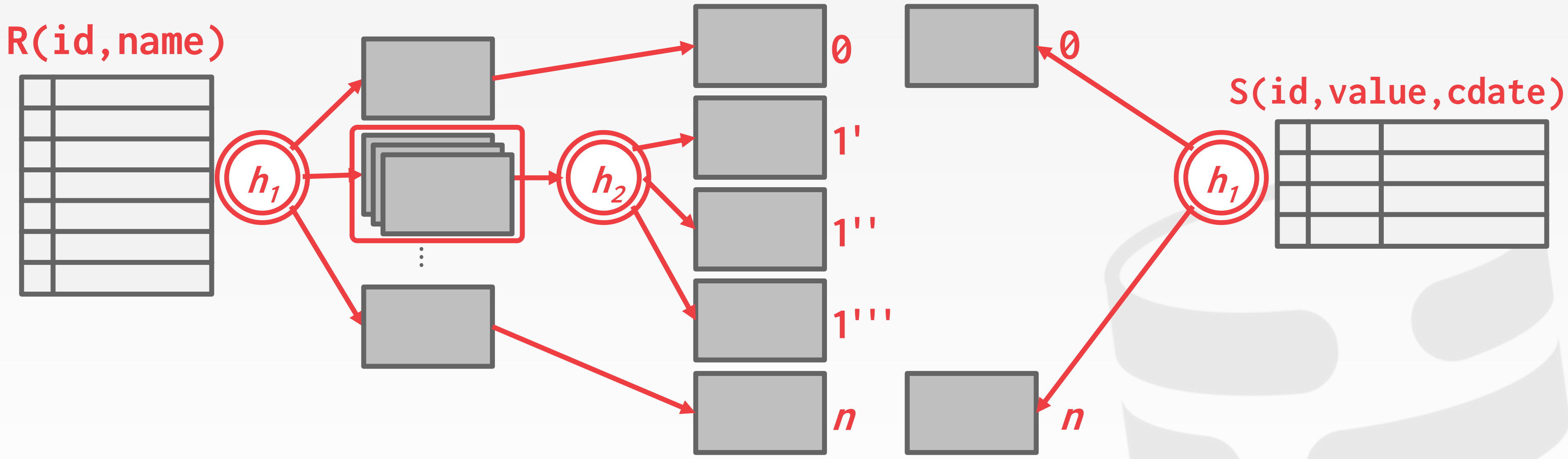

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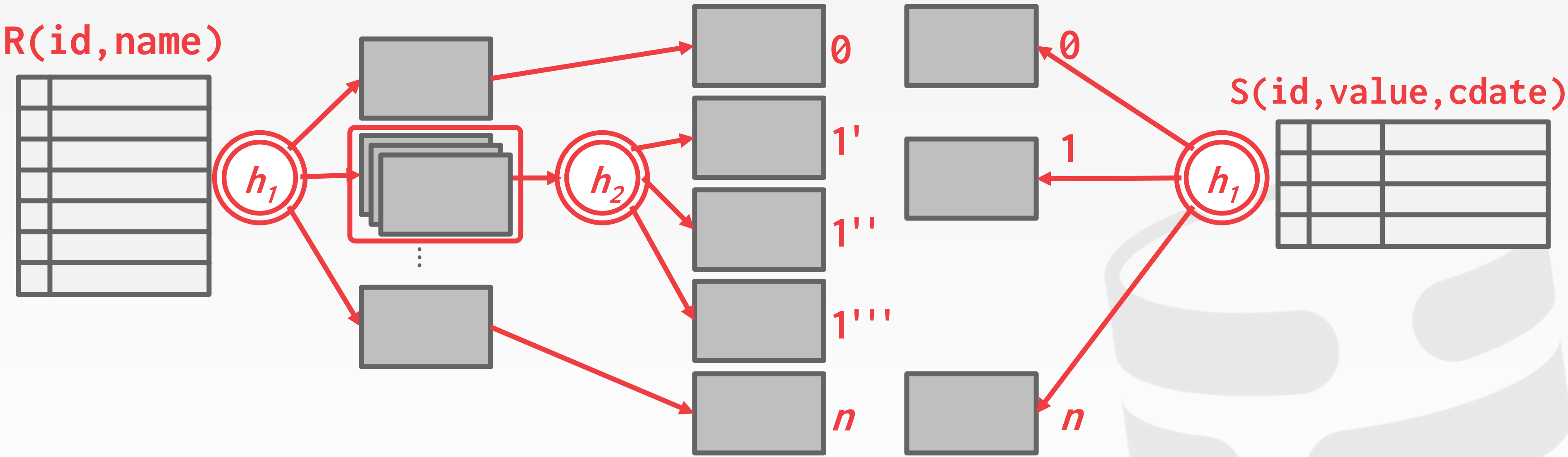

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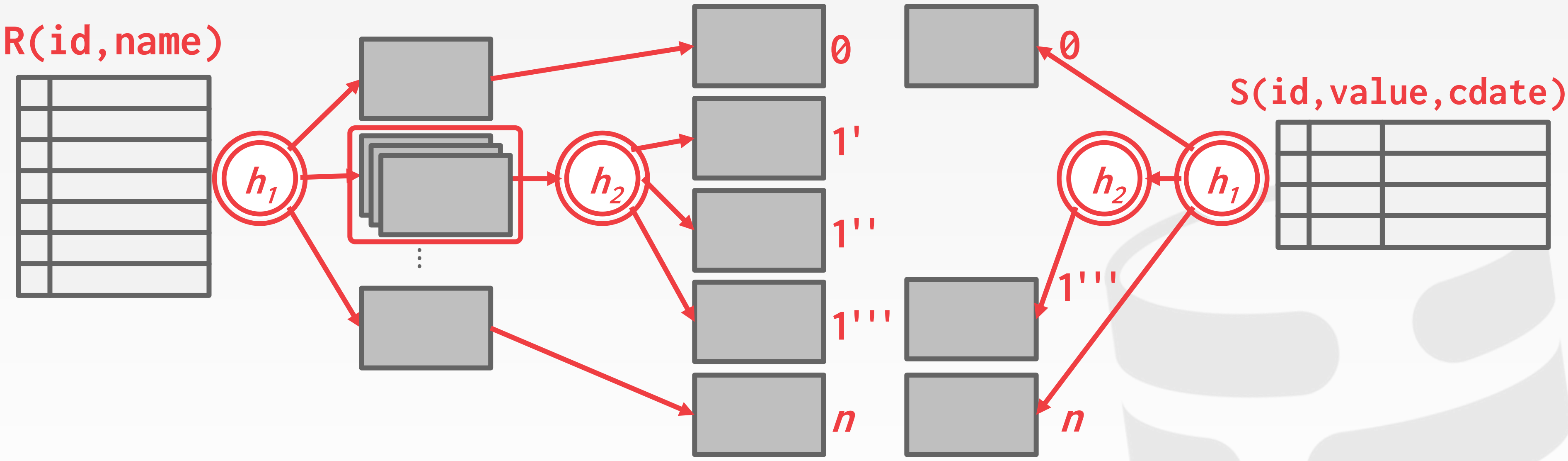

GRACE HASH JOIN

Cost of hash join?
- → Assume that we have enough buffers.
- → Cost: $3(M + N)$

Partitioning Phase:
- → Read+Write both tables
- → $2(M+N)$ IOs

Probing Phase:
- → Read both tables
- → M+N IOs

GRACE HASH JOIN

Example database:

→ $M = 1000$, $m = 100{,}000$

→ $N = 500$, $n = 40{,}000$

Cost Analysis:

→ $3 \cdot (M + N) = 3 \cdot (1000 + 500) =$ **4,500 IOs**

→ At 0.1 ms/IO, Total time ≈ 0.45 seconds

OBSERVATION

If the DBMS knows the size of the outer table, then it can use a static hash table.

→ Less computational overhead for build / probe operations.

If we do not know the size, then we must use a dynamic hash table or allow for overflow pages.

JOIN ALGORITHMS: SUMMARY

Algorithm	IO Cost	Example
Simple Nested Loop Join	$M + (m \cdot N)$	1.3 hours
Block Nested Loop Join	$M + (M \cdot N)$	50 seconds
Index Nested Loop Join	$M + (M \cdot C)$	Variable
Sort-Merge Join	$M + N + (\text{sort cost})$	0.75 seconds
Hash Join	$3(M + N)$	0.45 seconds

CONCLUSION

Hashing is almost always better than sorting for operator execution.

Caveats:
→ Sorting is better on non-uniform data.
→ Sorting is better when result needs to be sorted.

Good DBMSs use either or both.

NEXT CLASS

Composing operators together to execute queries.