Carnegie Mellon University

Database Systems

Join Algorithms

15-445/645 FALL 2024 » PROF. ANDY PAVLO

ADMINISTRIVIA

Mid-term Exam on Wednesday Oct 9th @ 2:00pm
→ In-class in this room.
→ Study guide is available online (see @295)

Project #2 is due Sunday Oct 27th @ 11:59pm
→ Recitation on Thursday Oct 10th @ 8:00pm (Zoom)

UPCOMING DATABASE TALKS

ParadeDB (DB Seminar)
→ Monday Oct 7th @ 4:30pm ET
→ Zoom

Spice.ai (DB Seminar)
→ Monday Oct 21st @ 4:30pm
→ Zoom

Exon (DB Seminar)
→ Monday Oct 28th @ 4:30pm
→ Zoom

LAST CLASS

We started discussing how to implement algorithms to compute queries and handle data sets that are larger than available memory.

→ **Common Pattern:** Divide-and-Conquer

There are two high-level strategies to quickly find tuples with the same attribute values.

→ Sorting

→ Hashing

WHY DO WE NEED TO JOIN?

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

We then use the **join operator** 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 primarily in research literature (e.g., worst-case optimal joins).

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

→ The optimizer will (try to) figure this out when generating the physical plan.

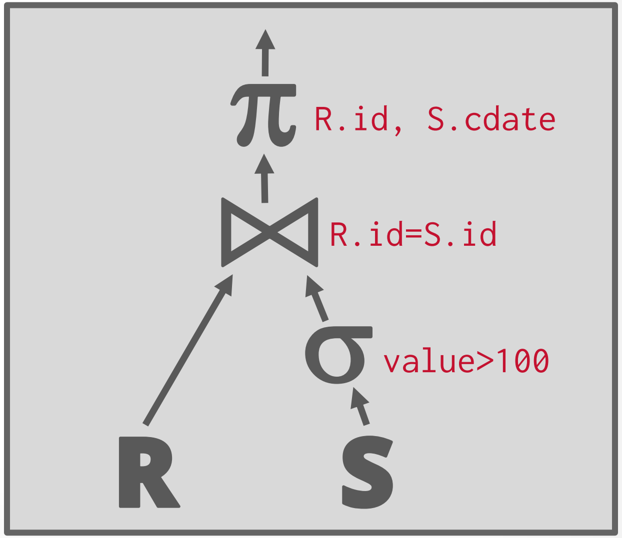
QUERY PLAN

The operators are arranged in a tree.

Data flows from the leaves of the tree up towards the root.
→ We will discuss the granularity of the data movement next lecture.

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

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



JOIN OPERATORS

Decision #1: Output

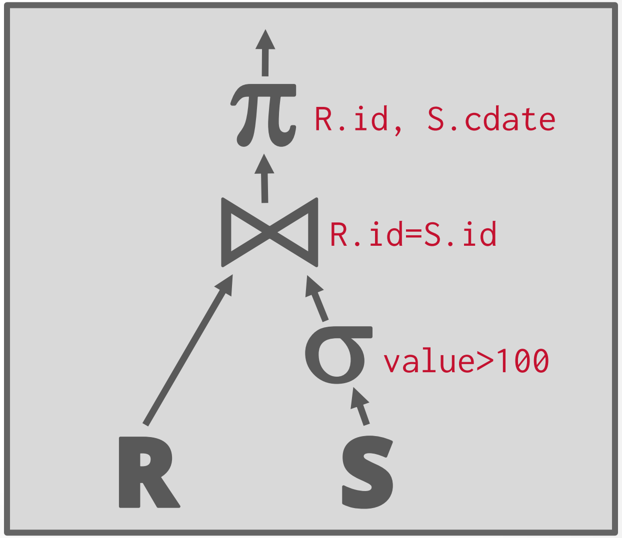
早期物化 VS 延迟物化

→ 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
```

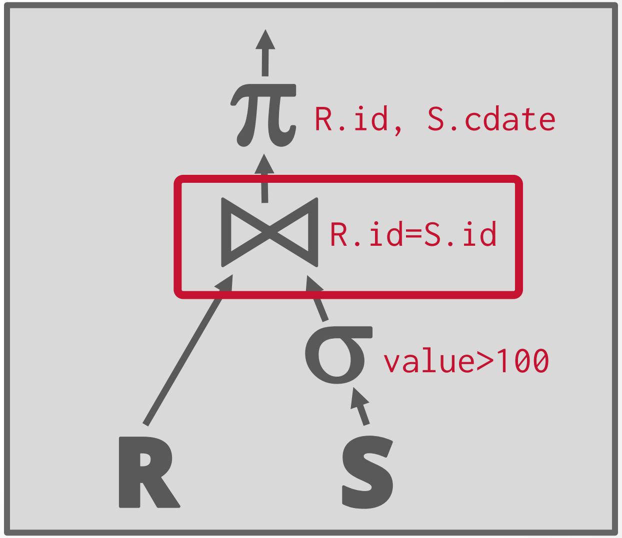


OPERATOR OUTPUT

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.

从源端获取数据后, 将元组内容全部构建出来.

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

R(id,name) ⋈ S(id,value,cdate)

id	name
123	abc

id	value	cdate
123	1000	10/7/2024
123	2000	10/7/2024

R.id	R.name	S.id	S.value	S.cdate
123	abc	123	1000	10/7/2024
123	abc	123	2000	10/7/2024

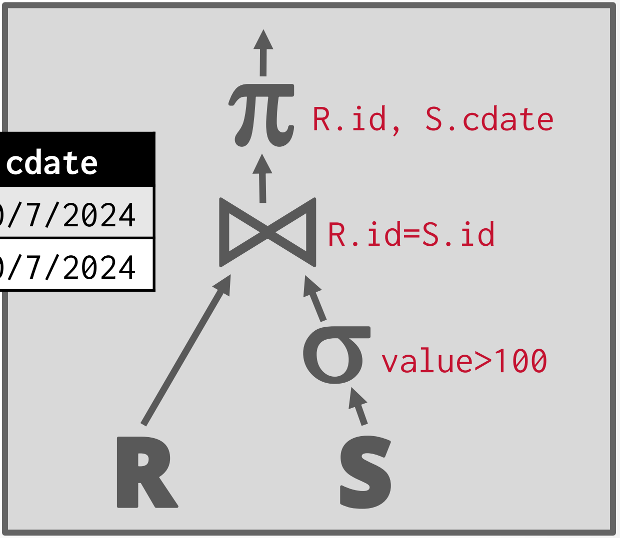
OPERATOR OUTPUT: DATA

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	10/7/2024
123	abc	123	2000	10/7/2024



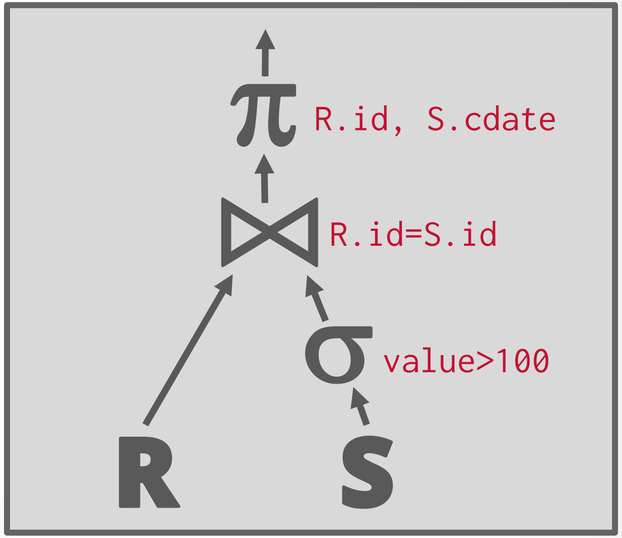
OPERATOR OUTPUT: DATA

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.
构建最小量数据.

```
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	10/7/2024
123	2000	10/7/2024

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

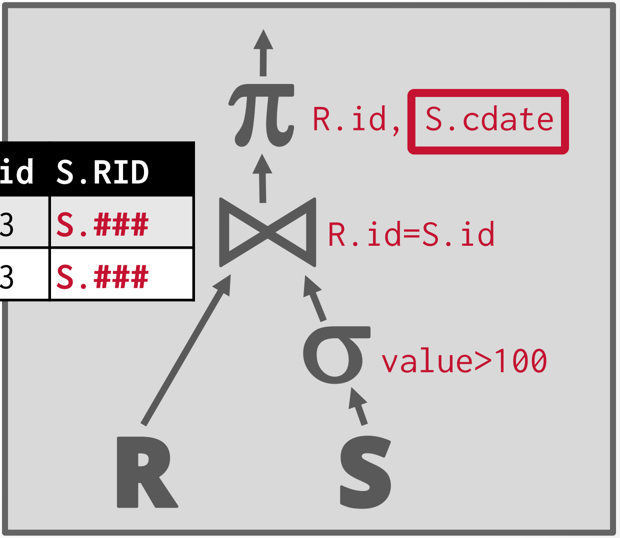
OPERATOR OUTPUT: RECORD IDS

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.###



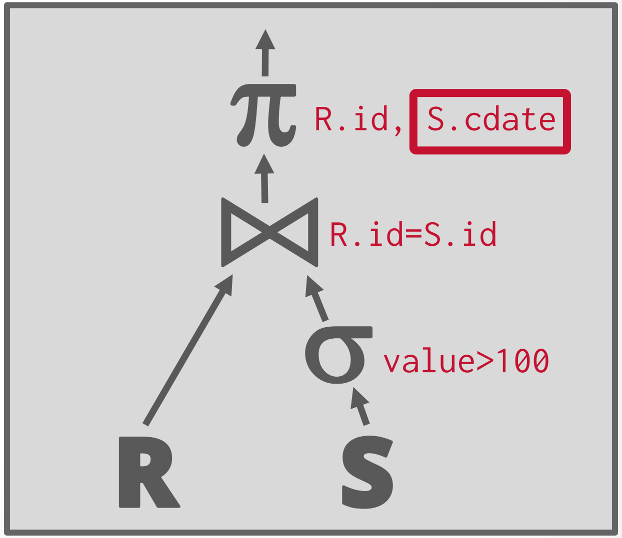
OPERATOR OUTPUT: RECORD IDS

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 needed 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
```

Given a query that joins table **R** with table **S**, assume the DBMS has the following information those tables:

→ ***M*** pages in table **R**, ***m*** tuples in **R**
→ ***N*** pages in table **S**, ***n*** tuples in **S**

Cost Metric: # of I/Os to compute join

→ Ignore result output costs because it depends on the data and is the same for all algorithms.
→ Ignore computation / network costs (for now).

JOIN ALGORITHMS

Nested Loop Join
- → Naïve
- → Block
- → Index

Sort-Merge Join

Hash Join
- → Simple
- → GRACE (Externally Partitioned)
- → Hybrid

NAÏVE NESTED LOOP JOIN

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

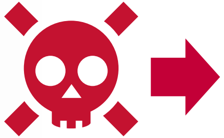
R(id,name)

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

S(id,value,cdate)

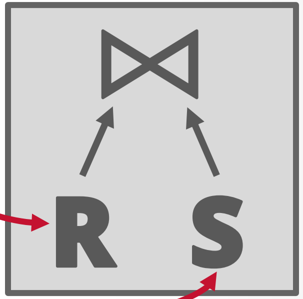
id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

NAÏVE NESTED LOOP JOIN



Don't Do This!

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



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	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

NAÏVE NESTED LOOP JOIN

Why is this algorithm bad?

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

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

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)

N pages
n tuples

id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

NAÏVE 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:
        if r and s match then emit
```

数据按块存储: 以块为单位进行遍历.

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	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

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)

M pages
m tuples

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

S(id,value,cdate)

N pages
n tuples

id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

BLOCK NESTED LOOP JOIN

The smaller table should be the outer table.

We determine size based on the number of pages, not 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)

N pages
n tuples

id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

BLOCK NESTED LOOP JOIN

If we have ***B*** buffers available:
→ Use ***B*-2** buffers for each block of the outer table.
→ Use one buffer for the inner table, one buffer for output.

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)

N pages
n tuples

id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

BLOCK NESTED LOOP JOIN

```
foreach B - 2 pages pR ∈ R:
  foreach page pS ∈ S:
    foreach tuple r ∈ B - 2 pages:
      foreach tuple s ∈ ps:
        if r and s match then emit
```

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)

N pages
n tuples

id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

BLOCK NESTED LOOP JOIN

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

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

If the outer relation fits in memory ($M < B\text{-}2$):

→ **Cost:** $M + N$ = 1000 + 500 = **1500 I/Os**

→ At 0.1ms per I/O, Total time ≈ 0.15 seconds

If we have B=102 buffer pages:

→ **Cost:** $M + (\lceil M / (B\text{-}2) \rceil \cdot N)$ = 1000 + 10·500 = **6000 I/Os**

→ Or can switch inner/outer relations, giving us cost:

500 + 5·1000 = **5500 I/Os**

NESTED LOOP JOIN

Why is the basic nested loop join so bad?
- → For each tuple in the outer table, we must do a sequential scan to check for a match in the inner table.

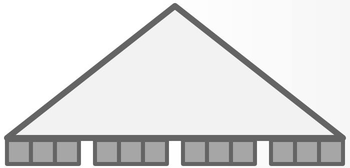
We can avoid sequential scans by using an index to find inner table matches.
- → Use an existing index for the join.

INDEX NESTED LOOP JOIN

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

内部表的 join key 上有索引.

Index(S.id)



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	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

N pages
n tuples

INDEX NESTED LOOP JOIN

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

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

R(id,name)

M pages
m tuples

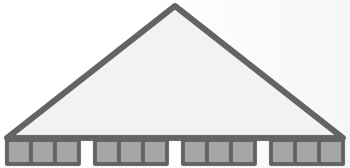
id	name
600	MethodMan
200	GZA
100	Andy
300	ODB
500	RZA
700	Ghostface
400	Raekwon

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

N pages
n tuples

Index(S.id)



NESTED LOOP JOIN SUMMARY

Key Takeaways

→ 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).

Algorithms

→ Naïve
→ Block
→ Index

SORT-MERGE JOIN

Phase #1: Sort

→ Sort both tables on the join key(s).
→ You can use any appropriate sort algorithm
→ These phases are distinct from the sort/merge phases of an external merge sort, from the previous 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
    backtrack cursors (if necessary)
  elif cursorR and cursorS match:
    emit
    increment cursorS
```

SORT-MERGE JOIN

R(id,name)

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

Sort!

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2024
500	7777	10/7/2024
400	6666	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024

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

Sort!

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

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
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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: ---

```
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
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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

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

Last Value: ---

Output Buffer

R.id	R.name	S.id	S.value	S.cdate
100	Andy	100	2222	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

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

Last Value: ---

Output Buffer

R.id	R.name	S.id	S.value	S.cdate
100	Andy	100	2222	10/7/2024
100	Andy	100	9999	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **100**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **100**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **200**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **200**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

***Last Value:* 200**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **200**

```sql
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **200**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024
400	Raekwon	200	6666	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **400**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024
400	Raekwon	200	6666	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **400**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024
400	Raekwon	200	6666	10/7/2024
500	RZA	500	7777	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **500**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024
400	Raekwon	200	6666	10/7/2024
500	RZA	500	7777	10/7/2024

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	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **500**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024
400	Raekwon	200	6666	10/7/2024
500	RZA	500	7777	10/7/2024

SORT-MERGE JOIN

R(id,name)

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

S(id,value,cdate)

id	value	cdate
100	2222	10/7/2024
100	9999	10/7/2024
200	8888	10/7/2024
400	6666	10/7/2024
500	7777	10/7/2024

Last Value: **500**

```
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	10/7/2024
100	Andy	100	9999	10/7/2024
200	GZA	200	8888	10/7/2024
200	GZA	200	8888	10/7/2024
400	Raekwon	200	6666	10/7/2024
500	RZA	500	7777	10/7/2024

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 I/Os**

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

→ Merge Cost = (1000 + 500) = **1500 I/Os**

→ Total Cost = 4000 + 2000 + 1500 = **7500 I/Os**

→ 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 contains 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 either by an explicit sort operator, or by scanning the relation using an index on the join key.

HASH JOIN

在外部表上构建哈希表, 内部表作探测表.

If tuple $r \in R$ and 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.

SIMPLE 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.

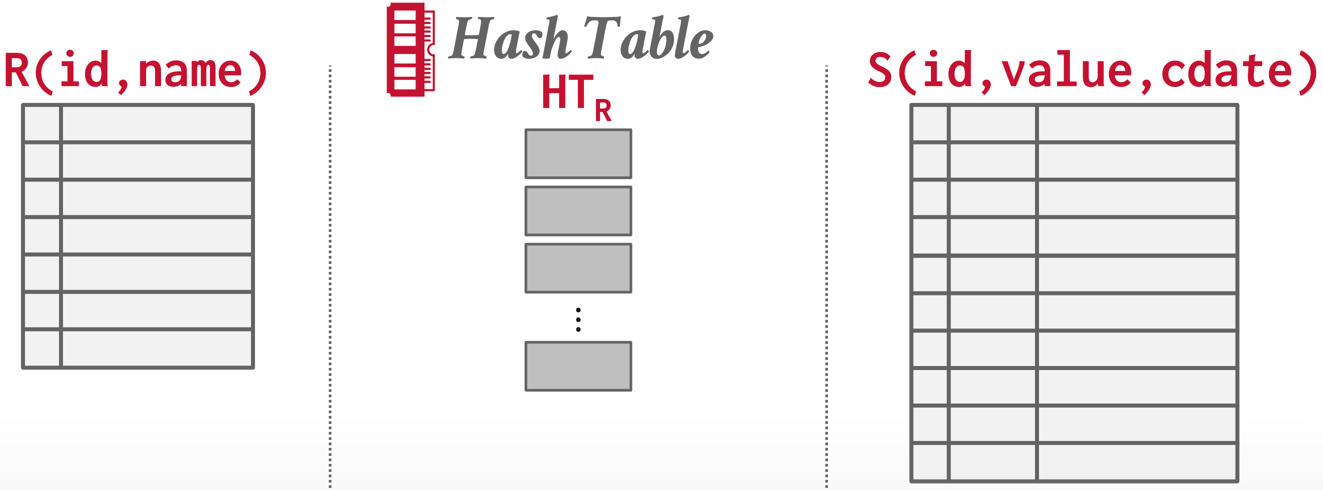
→ We can use any hash table that we discussed before but in practice linear probing works the best.

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.

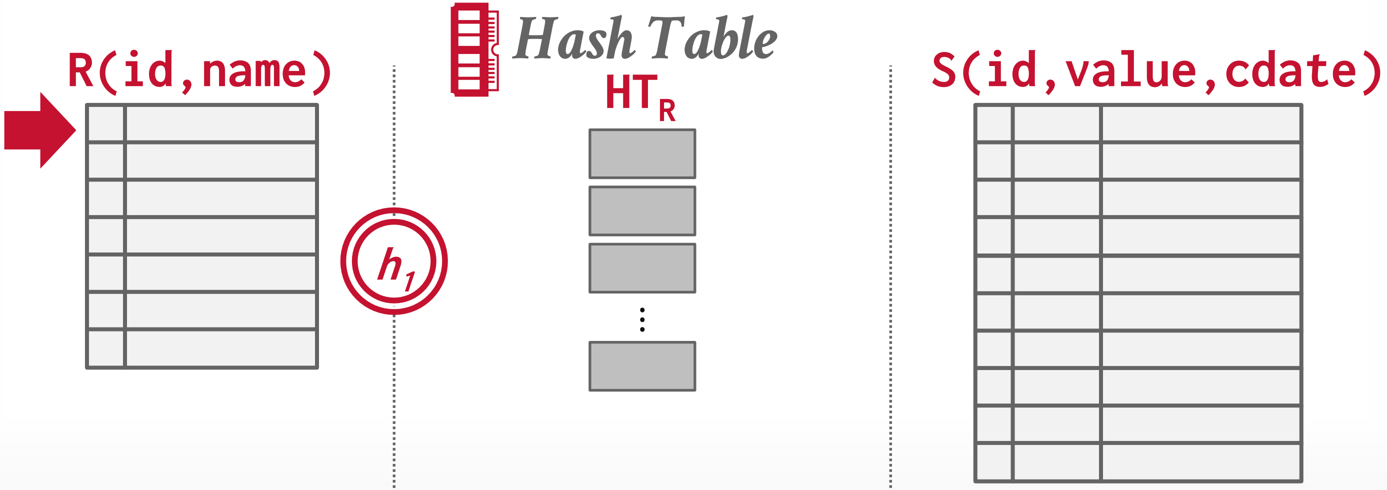
SIMPLE HASH JOIN ALGORITHM

```
foreach tuple r ∈ R:
  insert h1(r) into hash table HTR
foreach tuple s ∈ S:
  output, if h1(s) ∈ HTR
```



SIMPLE HASH JOIN ALGORITHM

foreach tuple $r \in R$:
  insert $h_1(r)$ into hash table HT_R
foreach tuple $s \in S$:
  output, if $h_1(s) \in HT_R$



SIMPLE HASH JOIN ALGORITHM

```
foreach tuple r ∈ R:
  insert h1(r) into hash table HTR
foreach tuple s ∈ S:
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```

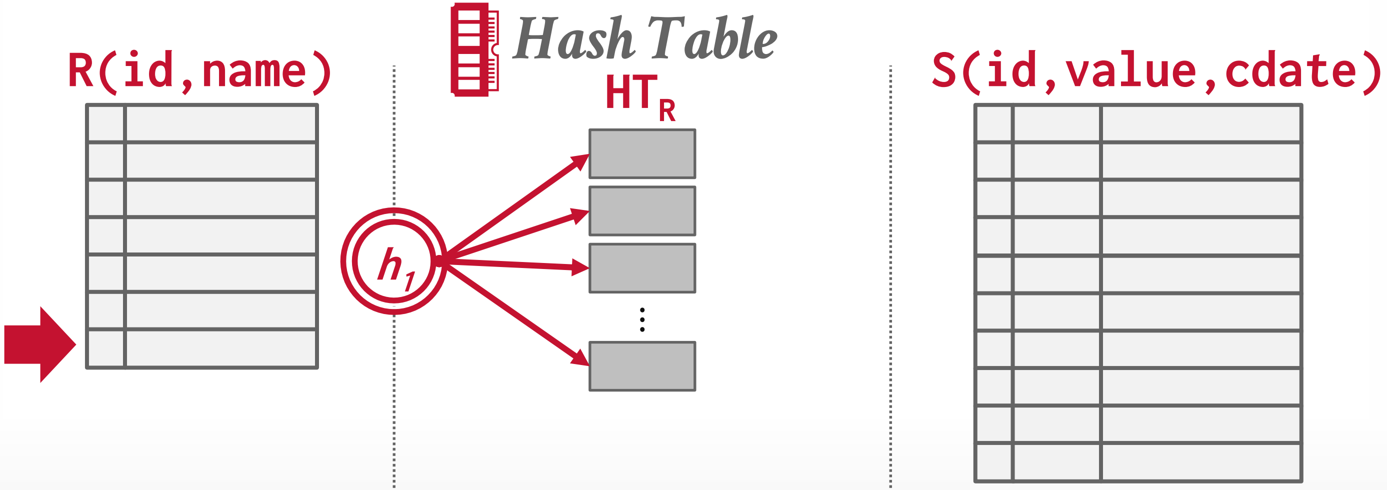

SIMPLE HASH JOIN ALGORITHM

```
foreach tuple r ∈ R:
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foreach tuple s ∈ S:
  output, if h1(s) ∈ HTR
```
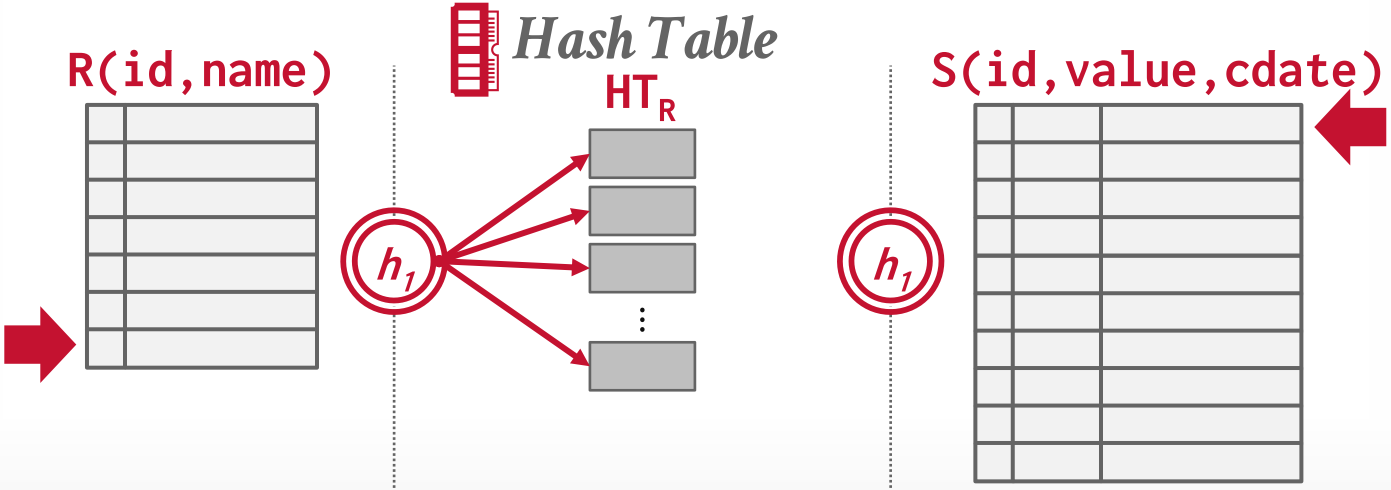
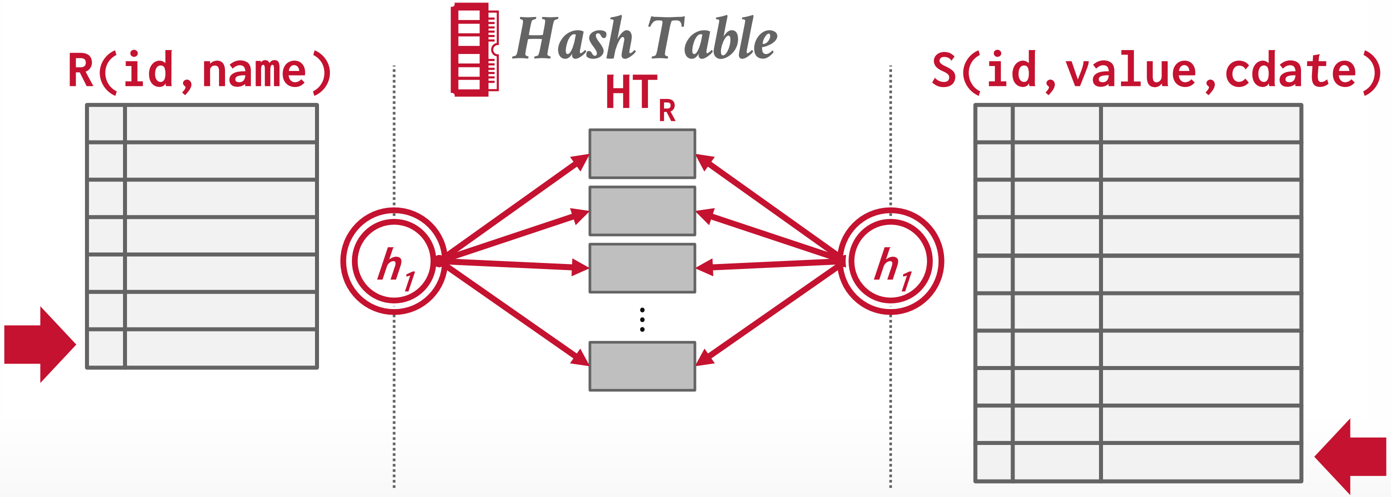



SIMPLE HASH JOIN ALGORITHM

```
foreach tuple r ∈ R:
  insert h1(r) into hash table HT_R
foreach tuple s ∈ S:
  output, if h1(s) ∈ HT_R
```



OPTIMIZATION: PROBE FILTER

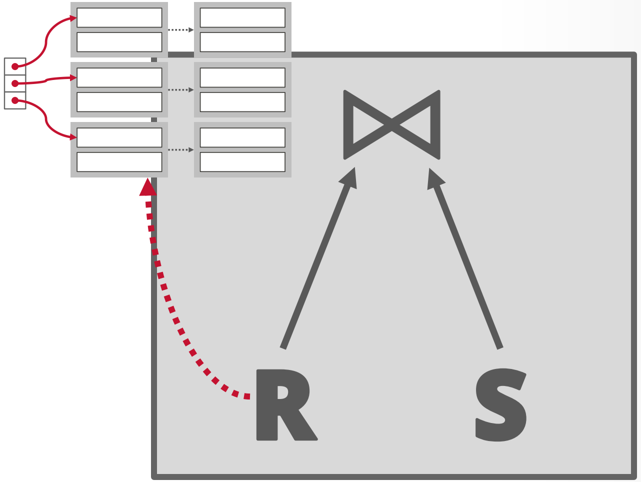
Create a probe filter (Bloom Filter) as the DBMS builds the hash table on the outer table in the first phase.

→ Always check the filter before probing the hash table.

→ Faster than probing hash table because the filter fits in CPU cache.

使用布隆过滤器探测的成本低于哈希表的探测成本.

This technique is sometimes called ***sideways information passing.***



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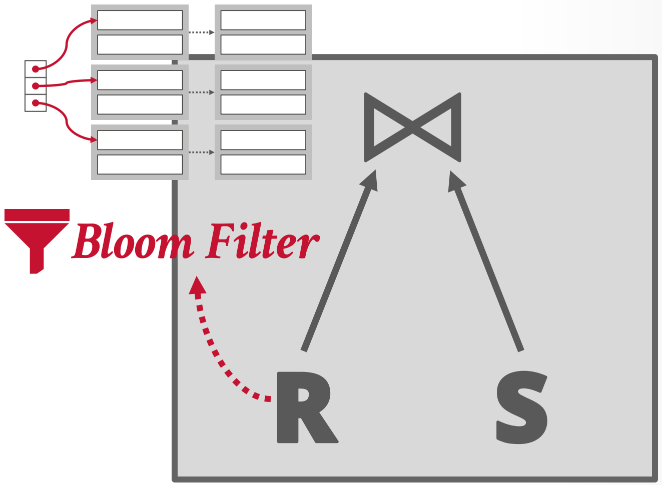

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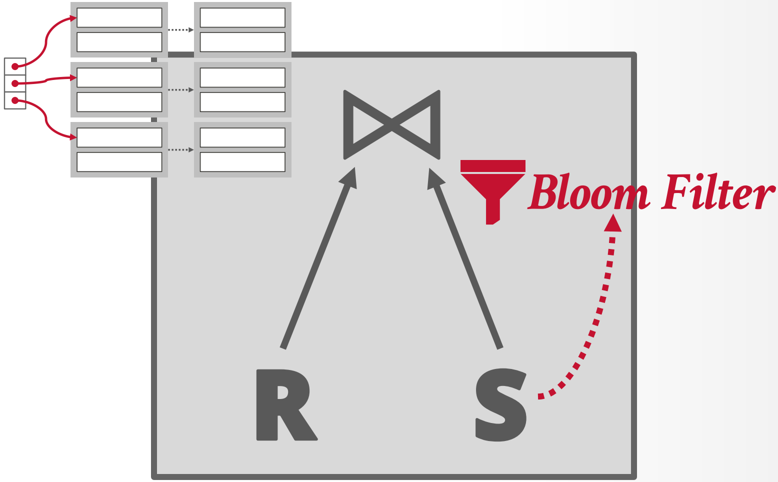


This technique is sometimes called ***sideways information passing.***

HASH JOINS OF LARGE RELATIONS

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 random.

PARTITIONED HASH JOIN

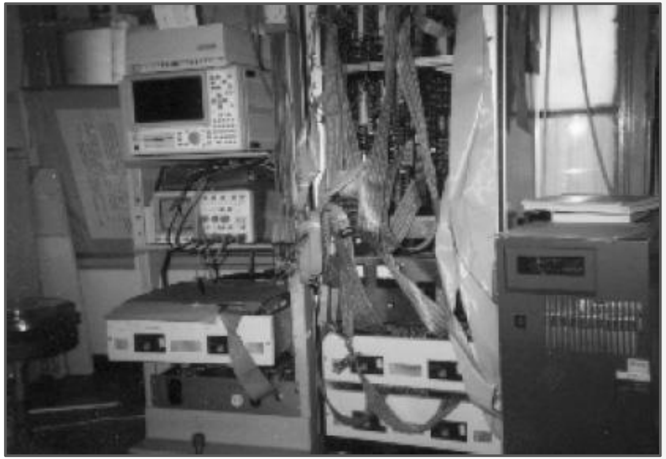
Hash join when tables do not fit in memory.

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

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

Sometimes called **GRACE Hash Join**.

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



GRACE
University of Tokyo

PARTITIONED HASH JOIN


Britton-Lee's technical achievements have created the Intelligent Data Base Machine, oriented to managers who know the value of a responsive information system. Truly user-oriented—even to people without programming knowledge—the IDM 500 provides some remarkable advantages. Imagine how the features described inside can improve YOUR company's information productivity...

NOW

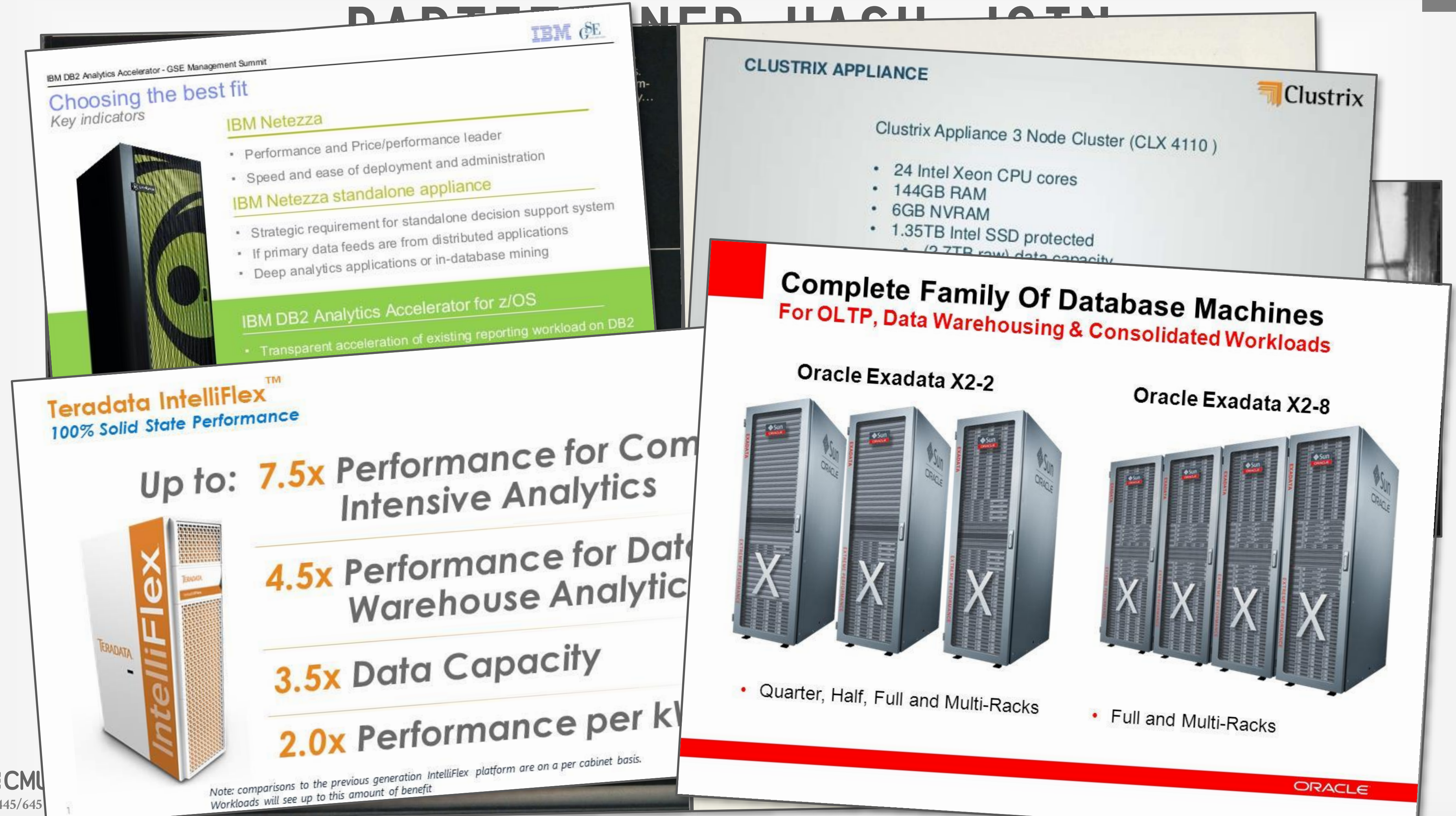
The IDM 500 A Logical Development

As data systems have evolved, the presence of special-purpose elements has become increasingly important, as these diagrams will illustrate:

In the 1960's, a single central processing unit (CPU) was required to monitor time-sharing among terminal users; to batch process computing tasks, and to control the access to stored data.

Through the development of front-end communication processors, the workload on the CPU was reduced. It was then able to perform its basic task of data processing much more efficiently. But the task of managing the data base was still imposed upon it.

Now Britton-Lee's IDM 500 special-purpose, back-end data-base processor brings full efficiency to the host computer and intelligent terminals, so that they can properly perform their correct functions.


IBM GSE
IBM DB2 Analytics Accelerator - GSE Management Summit
Choosing the best fit
Key indicators
IBM Netezza
Performance and Price/performance leader
Speed and ease of deployment and administration
IBM Netezza standalone appliance
Strategic requirement for standalone decision support system
If primary data feeds are from distributed applications
Deep analytics applications or in-database mining
IBM DB2 Analytics Accelerator for z/OS
Transparent acceleration of existing reporting workload on DB2
CLUSTRIX APPLIANCE
Clustrix
Clustrix Appliance 3 Node Cluster (CLX 4110)
24 Intel Xeon CPU cores
144GB RAM
6GB NVRAM
1.35TB Intel SSD protected
Teradata IntelliFlex™
100% Solid State Performance
Up to: 7.5x Performance for Com
Intensive Analytics
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Warehouse Analytic
3.5x Data Capacity
2.0x Performance per k
IntelliFlex
TERADATA
Note: comparisons to the previous generation IntelliFlex platform are on a per cabinet basis.
Workloads will see up to this amount of benefit
Complete Family Of Database Machines
For OLTP, Data Warehousing & Consolidated Workloads
Oracle Exadata X2-2
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Quarter, Half, Full and Multi-Racks
Full and Multi-Racks
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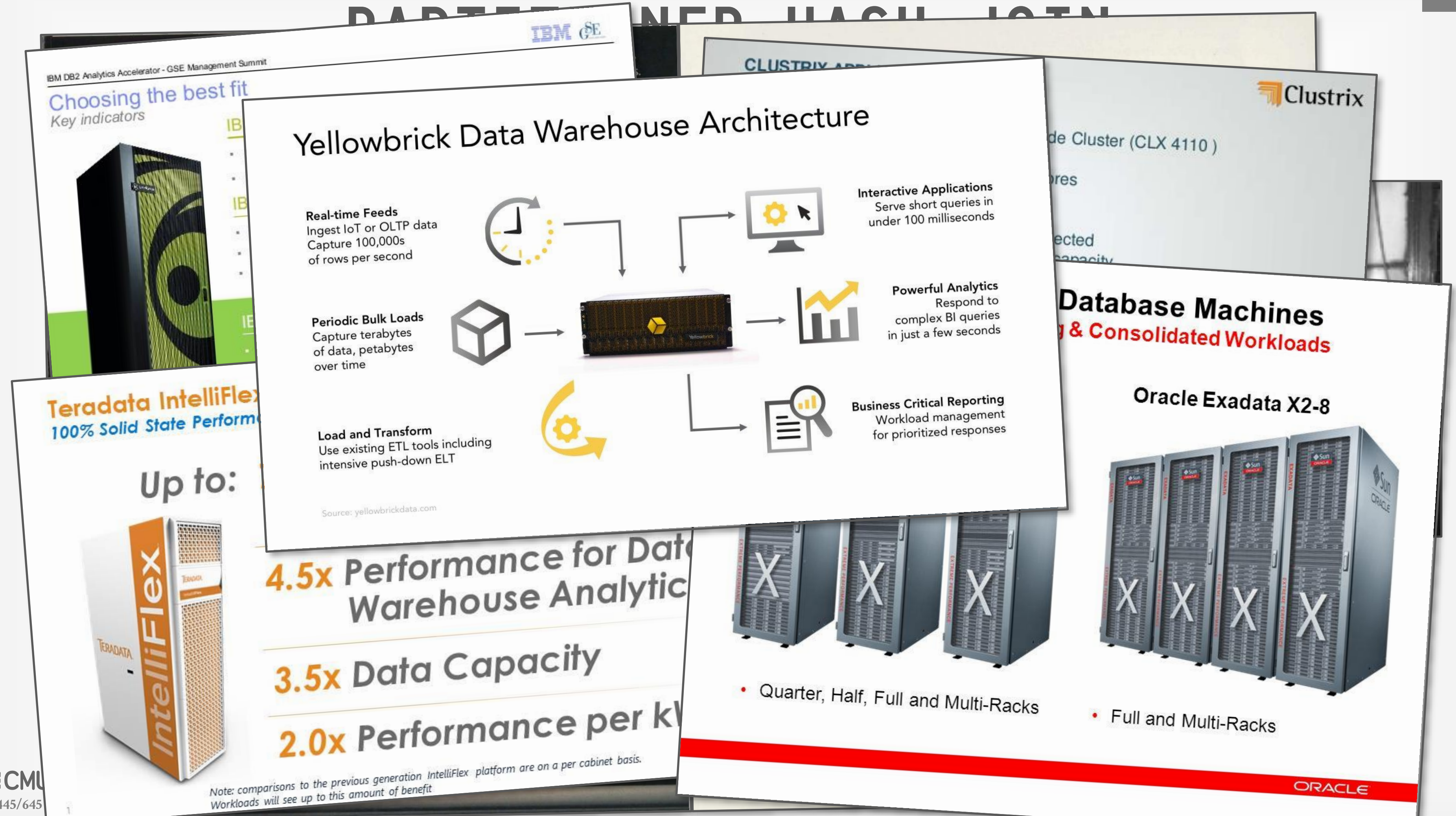
IBM GSE
IBM DB2 Analytics Accelerator - GSE Management Summit
Choosing the best fit
Key indicators
Yellowbrick Data Warehouse Architecture
Real-time Feeds
Ingest IoT or OLTP data
Capture 100,000s
of rows per second
Periodic Bulk Loads
Capture terabytes
of data, petabytes
over time
Load and Transform
Use existing ETL tools including
intensive push-down ELT
Interactive Applications
Serve short queries in
under 100 milliseconds
Powerful Analytics
Respond to
complex BI queries
in just a few seconds
Business Critical Reporting
Workload management
for prioritized responses
Source: yellowbrickdata.com
Clustrix
de Cluster (CLX 4110)
Database Machines
& Consolidated Workloads
Oracle Exadata X2-8
Quarter, Half, Full and Multi-Racks
Full and Multi-Racks
ORACLE
Teradata IntelliFlex
100% Solid State Perform
Up to:
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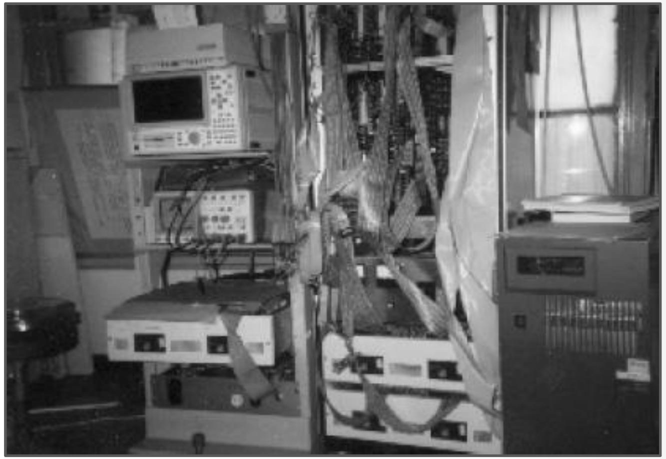


GRACE
University of Tokyo

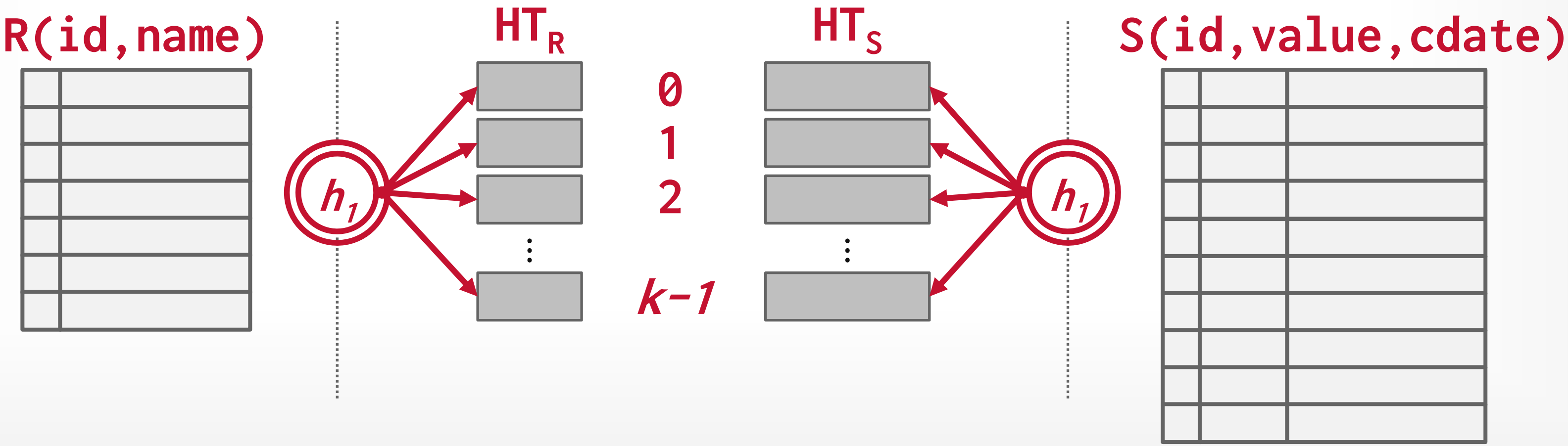
PARTITIONED HASH JOIN PARTITION PHASE

Hash **R** into *k* buckets.

Hash **S** into *k* buckets with same hash function.

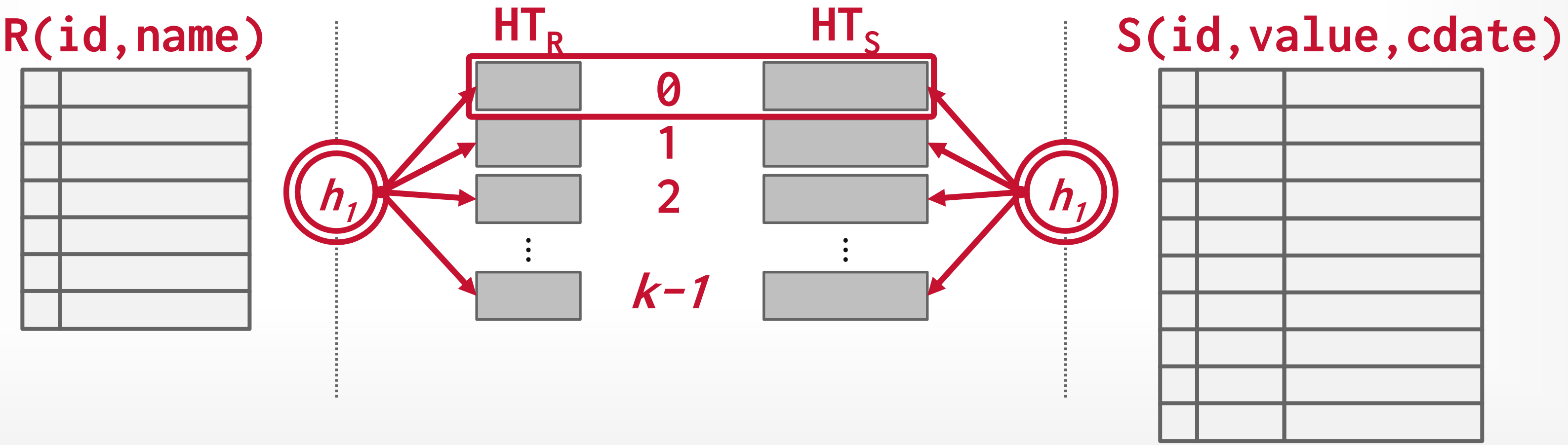
Write buckets to disk when they get full.

在同一级桶上进行 join 计算.



PARTITIONED HASH JOIN PROBE PHASE

Read corresponding partitions into memory one pair at a time, hash join their contents.



PARTITIONED HASH JOIN PROBE PHASE

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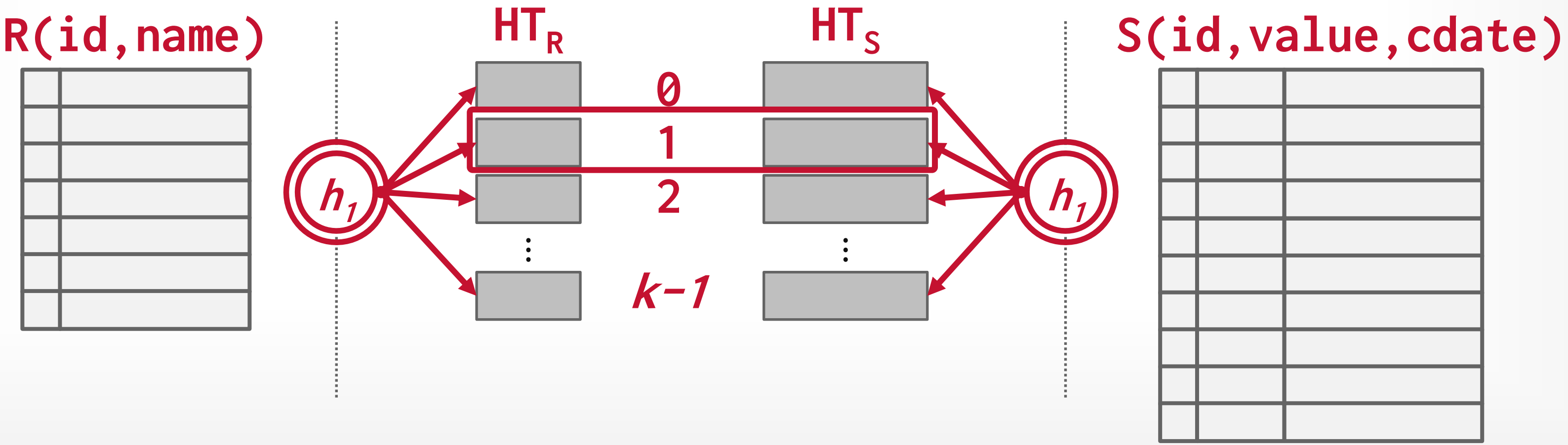

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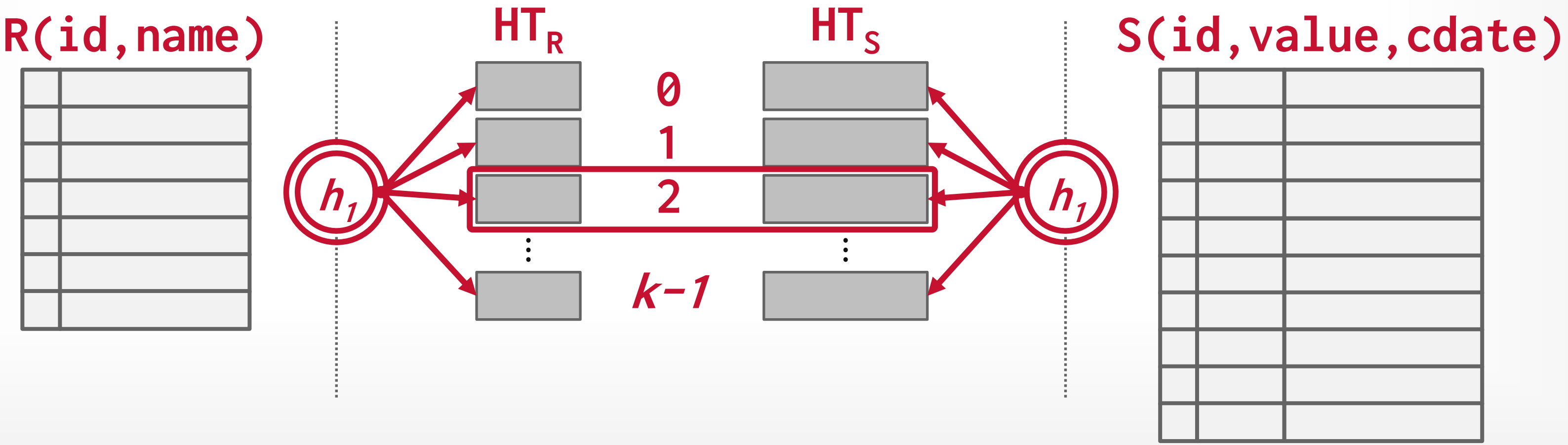
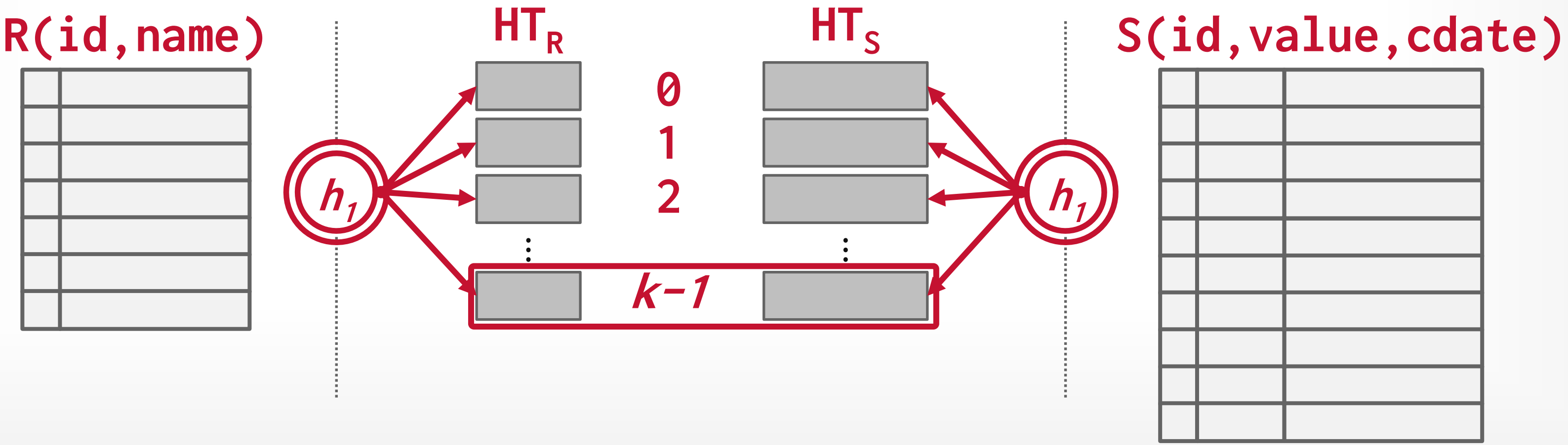


PARTITIONED HASH JOIN PROBE PHASE

Read corresponding partitions into memory one pair at a time, hash join their contents.



PARTITIONED HASH JOIN EDGE CASES

If a partition does not fit in memory, recursively partition it with a different hash function

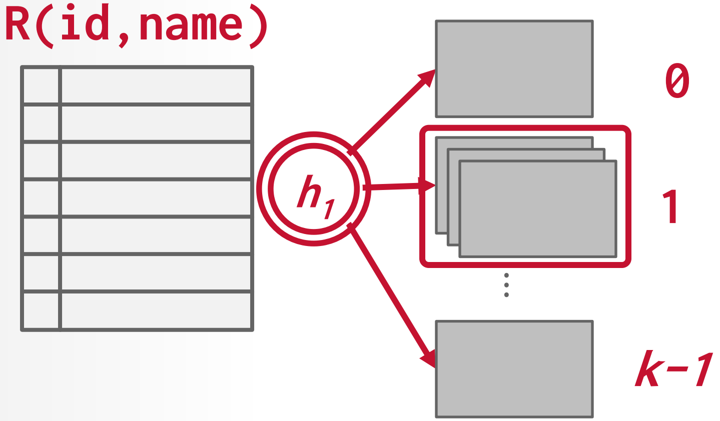
→ Repeat as needed

→ Eventually hash join the corresponding (sub-)partitions

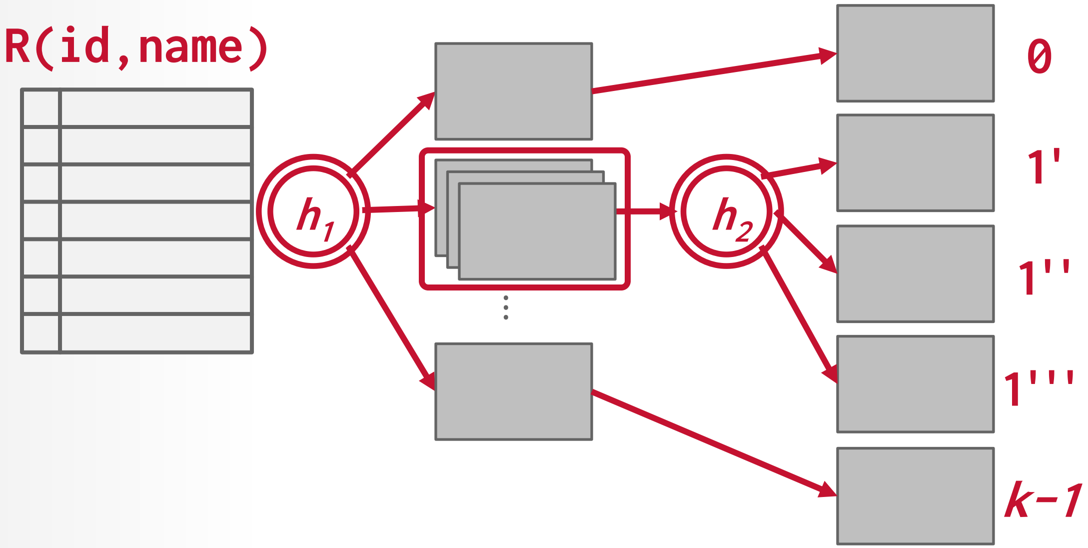
If a single join key has too many matching records that do not fit in memory, use a **block nested loop** join just for that key.

→ Avoids random I/O in exchange for sequential I/O.

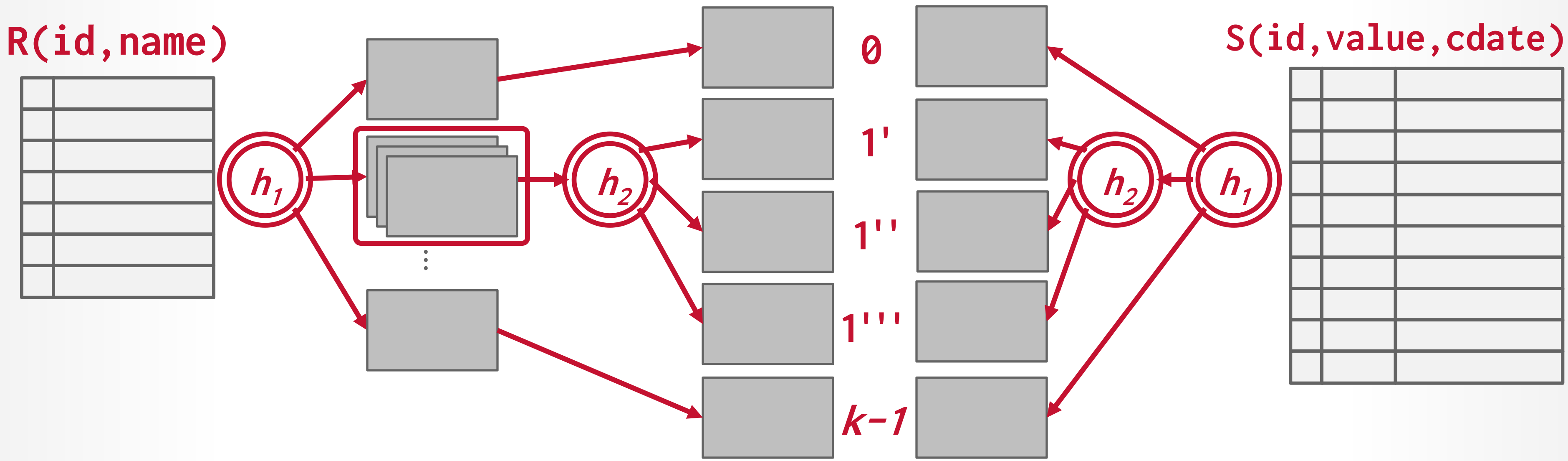
RECURSIVE PARTITIONING



RECURSIVE PARTITIONING



RECURSIVE PARTITIONING



COST OF PARTITIONED HASH JOIN

If we do not need recursive partitioning:
→ Cost: **$3(M + N)$**

Partition phase:
→ Read+write both tables
→ **$2(M+N)$** I/Os

Probe phase:
→ Read both tables (in total, one partition at a time)
→ **M+N** I/Os

PARTITIONED HASH JOIN

Example database:

- → M = 1000, m = 100,000
- → N = 500, n = 40,000

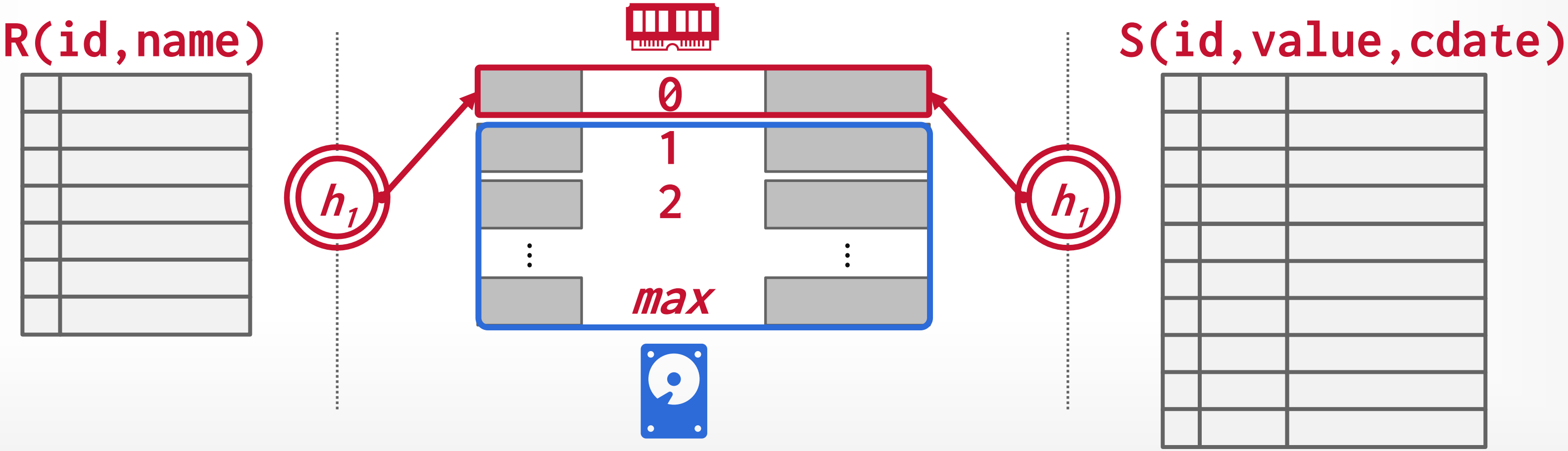
Cost Analysis:

- → $3(M + N) = 3 \cdot (1000 + 500) =$ **4,500 IOs**
- → At 0.1 ms/IO, Total time ≈ 0.45 seconds

OPTIMIZATION: HYBRID HASH JOIN

If the keys are skewed, then the DBMS keeps the hot partition in-memory and immediately perform the comparison instead of spilling it to disk.

→ Difficult to get to work correctly. Rarely done in practice.



HASH JOIN OBSERVATIONS

The inner table can be any size .
→ Only outer table (or its partitions) need to fit in memory

If we know the size of the outer table, then we can use a static hash table.
→ Less computational overhead

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
Naïve Nested Loop Join	$M + (m \cdot N)$	1.3 hours
Block Nested Loop Join	$M + (\lceil M / (B\text{-}2) \rceil \cdot N)$	0.55 seconds
Index Nested Loop Join	$M + (m \cdot C)$	Variable
Sort-Merge Join	$M + N + (\text{sort cost})$	0.75 seconds
Hash Join	$3 \cdot (M + N)$	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

Mid-Term Exam!