Iterators, Relational Operators and Joins

R&G Chapters 12 & 14

Recall from Last Lecture

SQL Query

SELECT S.name
FROM Reserves R, Sailors S
WHERE R.sid = S.sid
AND R.bid = 100
AND S.rating > 5

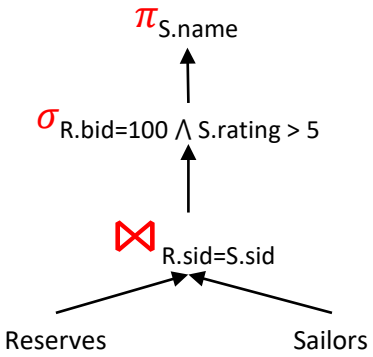
Query Parser & Optimizer

Relational Algebra

$\pi_{\text{S.name}}(\sigma_{\text{bid=100}\wedge\text{rating>5}}($ Reserves $\bowtie_{\text{R.sid=S.sid}}$ Sailors$))$

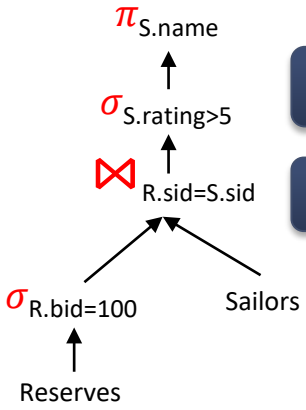
Equivalent to…

(Logical) Query Plan:



But actually will produce…

Optimized (Physical) Query Plan:



On-the-fly Project Iterator

On-the-fly Select Iterator

Indexed Nested Loop Join Iterator

Heap Scan Iterator

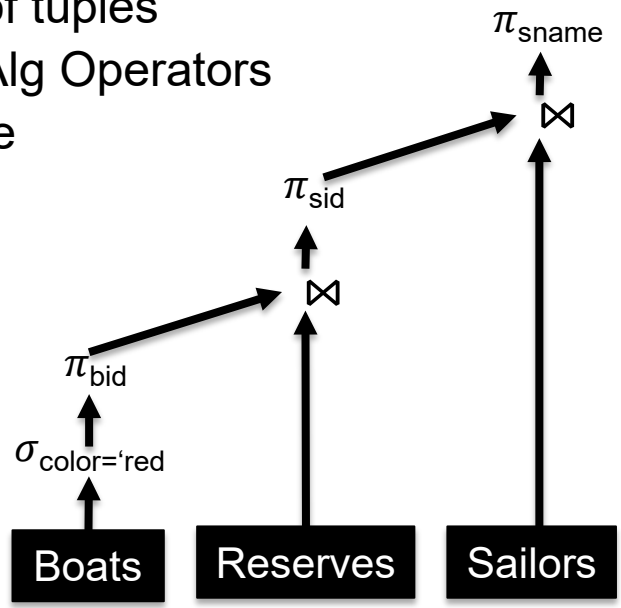
Operator Code

B+-Tree Indexed Scan Iterator

Relational Operators and Query Plans

$$\pi_{\text{sname}}(\pi_{\text{sid}}(\pi_{\text{bid}}(\sigma_{\text{color='red'}}(\text{Boats})) \bowtie \text{Res}) \bowtie \text{Sailors})$$

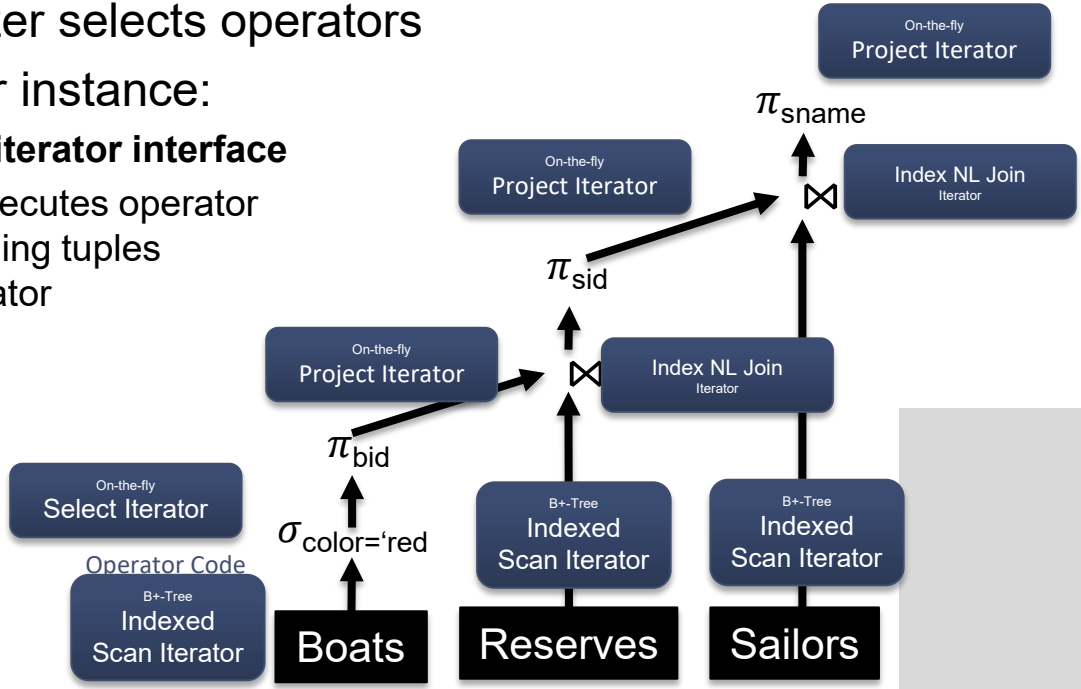
- Query plan
  - Edges encode “flow” of tuples
  - Vertices = Relational Alg Operators
  - Source vertices = table access operators …
- Also called dataflow graph



Query Executor Instantiates Operators

$$\pi_{\text{sname}}(\pi_{\text{sid}}(\pi_{\text{bid}}(\sigma_{\text{color='red'}}(\text{Boats})) \bowtie \text{Res}) \bowtie \text{Sailors})$$

- Query optimizer selects operators
- Each operator instance:
  - Implements **iterator interface**
  - Efficiently executes operator logic forwarding tuples to next operator



Iterator Interface

The relational operators implemented as subclasses of the class Iterator:

```
abstract class iterator {
      void setup(List<Iterator> inputs);
      void init(args);
      tuple next();
      void close();
}
```

Notes:

- **Pull-**based computation model
  - e.g., Console calls **init** and **next** which propagates down graph
  - *init/next* can result in either *streaming ("on-the-fly")* or *blocking ("batch")* algorithm**:**
    - streaming: small, constant amount of work per call
    - blocking: does not produce output until it consumes its entire input!
- **Encapsulation**: any iterator can be input to any other!
- **State:** iterators may maintain substantial "internal" state
  - e.g., hash tables, running counts, large sorted files …

Example: Select (on-the-fly)

- init(predicate):

```
child.init()
pred = predicate;
current = NULL;
```

- next():

```
while (current != EOF && !pred(current))
    current = child.next();
}
return current;
```

- close():

```
child.close()
```

Example: Heap Scan

- init(relation):

```
heap = open heap file for this relation;
cur_page = heap.first_page(); // first page
cur_slot = cur_page.first_slot(); // first slot on that page
```

- next():

```
if (cur_page == NULL) return EOF;  // End Of Fun
current = [cur_page, cur_slot]; // we will return this recordId
// advance the slot
cur_slot = cur_slot.next();
if (cur_slot == NULL) {
  // advance to next page, first slot
  cur_page = cur_page.next();
  if (cur_page != NULL)
     cur_slot = cur_page.first_slot();
}
return current;
```

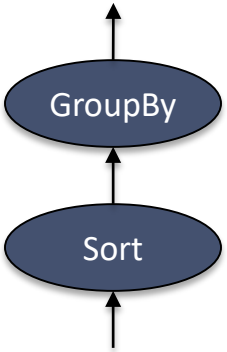
- close():

```
heap.close()
```

Example: Sort (2-pass)

- init(keys): // all of pass 0 in init, a blocking call
  child.init()
  repeatedly call child.next() and generate the sorted runs on disk, until child gives EOF
  // set up for pass 1, assumes enough buffers to merge
  open each sorted run file and load into input buffer for pass 1
- next(): // pass 1 (assumes enough buffers to merge)
  output = min tuple across all buffers
  if min tuple was last one in its buffer, fetch next page from that run into buffer
  return output (or EOF -- “End of File” -- if no tuples remain)
- close():
  deallocate the runs files
  child.close()

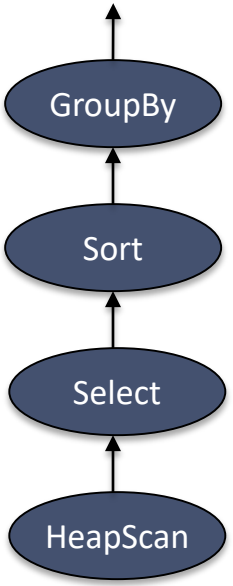
Example: Group By on Sorted input



agg_type	state	init	merge(x)	final
COUNT	count	0	count ++	count
SUM	sum	0	sum += x	sum
AVG	[count, sum]	[0, 0]	[count++, sum+=x]	sum / count
MIN	min	+infinity	min > x ? x : min	min

- init(group_keys, aggs):
  child.init()
  cur_group = NULL;
- next():
  result = NULL
  do {
  tup = child.next();
  if (group(tup) != cur_group) { // New group!
  if (cur_group != NULL) // Form a result for current group
  result = [cur_group, final() of all aggs]
  cur_group = group(tup);
  call init() on all the aggs
  }
  call merge(tup) on all the aggs
  } while (!result);
  return result;
- close():
  child.close()

A Full Query Plan



- A Query Plan is Single-threaded!
- Trace the calls:
  - Call init() on the root GroupBy
    - How does init() recurse down the chain and return?
  - call next() on root
    - How does next() recurse down the chain and return a tuple?
- Note how the blocking operator (sort) interacts with the other, streaming operators
- Note how we don’t store operator output on disk; tuples stream through the plan’s call stack
  - Some operators like Sort use disk internally

Join Operators

R&G 14.4

Schema for Examples

- Cost Notation
  - [R] : the number of pages to store R
  - p_R : number of records per page of R
  - |R| : the cardinality (number of records) of R
    - $|R| = p_R * [R]$

- Reserves (sid: int, bid: int, day: date, rname: string)
  - [R]=1000, p_R=100, |R| = 100,000
- Sailors (sid: int, sname: string, rating: int, age: real)
  - [S]=500, p_S=80, |S| = 40,000

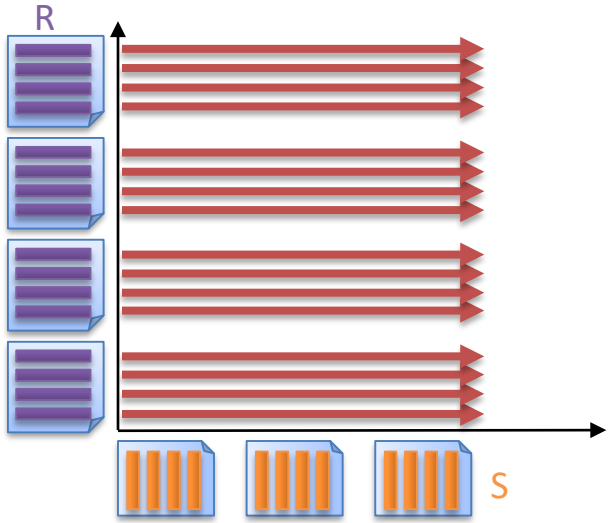
Simple Nested Loops Join

foreach **record** r in R do

  foreach **record** s in S do

    if **θ(ri, sj)** then add <ri, sj> to result buffer

Note: for simplicity we do not present iterator implementations for the join algorithms.



$[R]=1000$, $p_R=100$, $|R| = 100{,}000$

$[S]=500$, $p_S=80$, $|S| = 40{,}000$

Cost:

$[R] + |R|[S]$

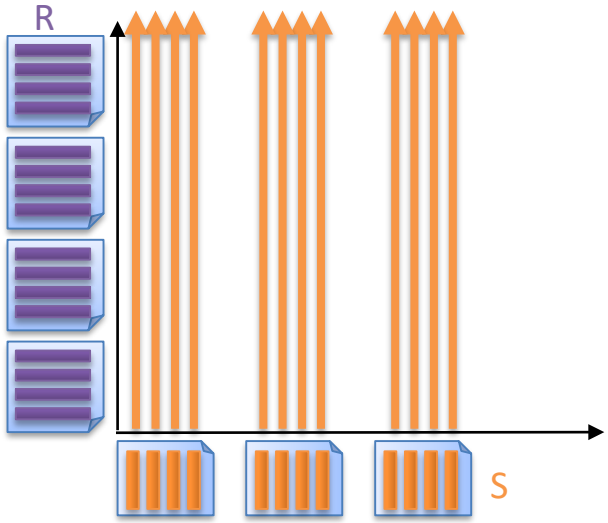
$= 50{,}001{,}000$

Changing the Join Order

foreach **record** s in S do

foreach **record** r in R do

if **θ(ri, sj)** then add <ri, sj> to result buffer



$[R]=1000$, $p_R=100$, $|R| = 100{,}000$

$[S]=500$, $p_S=80$, $|S| = 40{,}000$

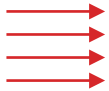
Cost:

$[S] + |S|[R]$

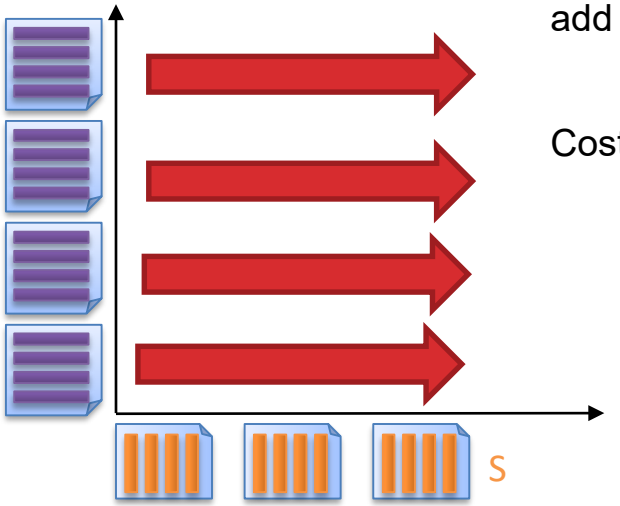
= 40,000,500

vs. 50,001,000

Page Nested Loop Join



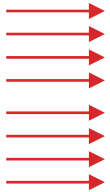
```
for each rpage in R:
    for each spage in S:
        for each rtuple in rpage:
            for each stuple in spage:
                if join_condition(rtuple, stuple):
                    add <rtuple, stuple> to result buffer
```



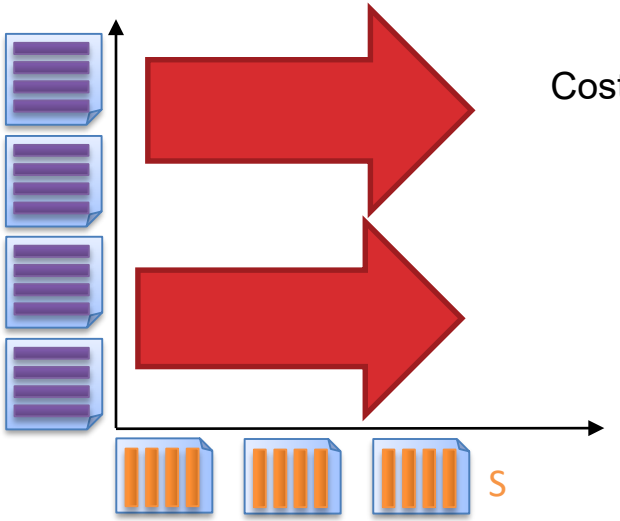
Cost = [R] + ([R] * [S])
= 501,000

"Chunk"

~~"Block"~~ Nested Loop Join




```
for each rchunk of B-2 pages of R:
    for each spage of S:
        for all matching tuples in spage and rchunk:
            add <rtuple, stuple> to result buffer
```



Cost = [R] + ⌈ [R]/(B-2) ⌉ * [S]
= 1000 + ⌈ 1000/(B-2) ⌉ * 500
= 6,000 for B=102 (~100x better than Page NL!)

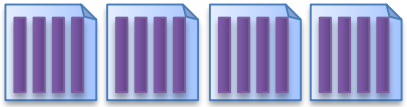
Index Nested Loops Join

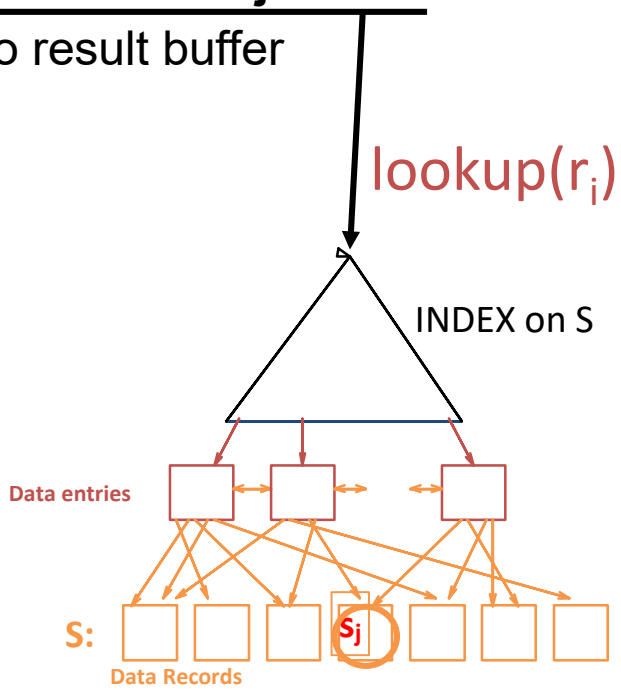
foreach **tuple** r in R do

foreach **tuple** s in S where **ri == sj** do

add <ri, sj> to result buffer

R





Index Nested Loops Join Cost

foreach **tuple** r in R do
    foreach **tuple** s in S where **ri == sj** do
        add <ri, sj> to result

Cost = [R] + |R| * cost to find matching S tuples

- If index uses Alt. 1 → cost to traverse tree from root to leaf. (e.g., 2-4 IOs)
- For Alt. 2 or 3:
  - Cost to lookup RID(s); typically 2-4 IOs for B+Tree.
  - Cost to retrieve records from RID(s)
    - Clustered index: 1 I/O per *page of matching S tuples*.
    - Unclustered: up to 1 I/O per matching S tuple

Index Nested Loops Join Cost, Part 2

- Reserves (*sid*: int, *bid*: int, *day*: date, *rname*: string)
  - [R]=1000, p_R=100, |R| = 100,000
- Sailors (***sid***: int, *sname*: string, *rating*: int, *age*: real)
  - [S]=500, p_S=80, |S| = 40,000
  - Index on sid

Index Nested Loops Join Cost, Part 3

- Unclustered Cost(R,S) = [R] + |R| * (Search + # matching tuples)
- Clustered Cost(R,S): [R] + |R| * (Search + # of matching pages)
- Here, sid is the primary key for Sailors, so there is exactly one matching sailor for each tuple in R
- Unclustered B+-Tree height 2 (3 I/Os from root to leaf):
  - R⋈S: 1000 + (100,000)*(3 + 1) = 401,000

- Clustered B+-tree height 2 (3 I/Os from root to leaf)
  - R⋈S: 1000 + (100,000)*(3 +1) = 401,000

Sort-Merge Join

- Requires equality predicate:
  - Equi-Joins & Natural Joins
- Two Stages:
  - Sort tuples in R and S by join key
    - All tuples with same key in consecutive order
    - Input might already be sorted … why?
  - Join Pass: Merge-scan the sorted partitions and emit tuples that match

Sort-Merge Join, Part 1

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

Sort-Merge Join, Part 2

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

Sort-Merge Join, Part 3

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

Sort-Merge Join, Part 4

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

Sort-Merge Join, Part 5

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

Sort-Merge Join, Part 6

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

Sort-Merge Join, Part 7

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

Sort-Merge Join, Part 8

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103

Sort-Merge Join, Part 9

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103

Sort-Merge Join, Part 10

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103

Sort-Merge Join, Part 11

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103

Sort-Merge Join, Part 12

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103

Sort-Merge Join, Part 13

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 14

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 15

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 16

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 17

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 18

```
do {
   if (!mark) {
     while (r < s) { advance r }
     while (r > s) { advance s }
     // mark start of "block" of S
     mark = s
   }
   if (r == s) {
     result = <r, s>
     advance s
     return result
   }
   else {
     reset s to mark
     advance r
     mark = NULL
   }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 19

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 20

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 21

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 22

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 23

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 24

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 25

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104

Sort-Merge Join, Part 26

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101

Sort-Merge Join, Part 27

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101

Sort-Merge Join, Part 28

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101

Sort-Merge Join, Part 29

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101

Sort-Merge Join, Part 30

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101

Sort-Merge Join, Part 31

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 32

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 33

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 34

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 35

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 36

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 37

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 38

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 39

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 40

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 41

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102

Sort-Merge Join, Part 42

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101

Sort-Merge Join, Part 43

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101

Sort-Merge Join, Part 44

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101

Sort-Merge Join, Part 45

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101

Sort-Merge Join, Part 46

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101

Sort-Merge Join, Part 47

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 48

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 49

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 50

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 51

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 52

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 53

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 54

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 55

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 56

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 57

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 57

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 58

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 59

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 60

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 61

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 62

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 63

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 64

```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102

Sort-Merge Join, Part 65

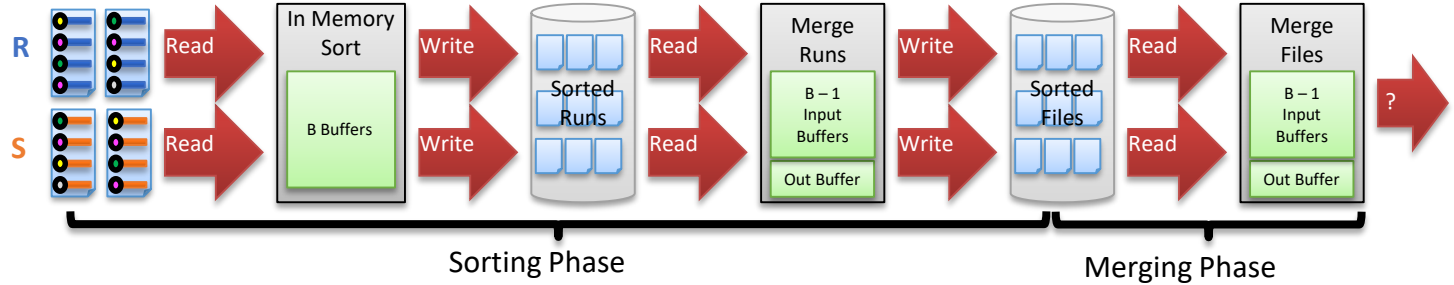
```
do {
  if (!mark) {
    while (r < s) { advance r }
    while (r > s) { advance s }
    // mark start of "block" of S
    mark = s
  }
  if (r == s) {
    result = <r, s>
    advance s
    return result
  }
  else {
    reset s to mark
    advance r
    mark = NULL
  }
}
```

sid	sname
22	dustin
28	yuppy
31	lubber
31	lubber2
44	guppy
58	rusty

sid	bid
28	103
28	104
31	101
31	102
42	142
58	107

sid	sname	bid
28	yuppy	103
28	yuppy	104
31	lubber	101
31	lubber	102
31	lubber2	101
31	lubber2	102
58	rusty	107

Cost of Sort-Merge Join



- Cost: Sort R + Sort S + ([R]+[S])
  - But in worst case, last term could be |R| *[S] (very unlikely!)
  - Q: what is worst case?
- Question: How big does the buffer have to be to sort both R and S in two passes each?
- Suppose buffer B > $\sqrt{(\max([R], [S]))}$
  - Both R and S can be sorted in 2 passes
  - 4*1000 + 4*500 + (1000 + 500) = 7500

Join First, Sort Later


```
SELECT sid, bid, sname, rname
FROM R, S
WHERE R.sid = S.sid
ORDER BY sid
```

[R]=1000, p_R=100, |R| = 100,000
[S]=500, p_S=80, |S| = 40,000
B = 102

- Reserves (*sid*: int, *bid*: int, *day*: date, *rname*: string)
- Sailors (*sid*: int, *sname*: string, *rating*: int, *age*: real)

- Block NLJ
  - Join: [S] + ([S]/(B-2))*[R]
  - Sort: ?

Join First, Sort Later Part 2


```
SELECT sid, bid, sname, rname
FROM R, S
WHERE R.sid = S.sid
ORDER BY sid
```

[R]=1000, p_R=100, |R| = 100,000
[S]=500, p_S=80, |S| = 40,000
B = 102

- Reserves (*sid*: int, *bid*: int, *day*: date, *rname*: string)
- Sailors (*sid*: int, *sname*: string, *rating*: int, *age*: real)

- Block NLJ
  - Join: [S] + ([S]/(B-2))*[R] = 5,500
  - Sort: 2 * [R]* (1 + $\log_{B-1}$ [R]/B) = 4000

Sort First, Join Later

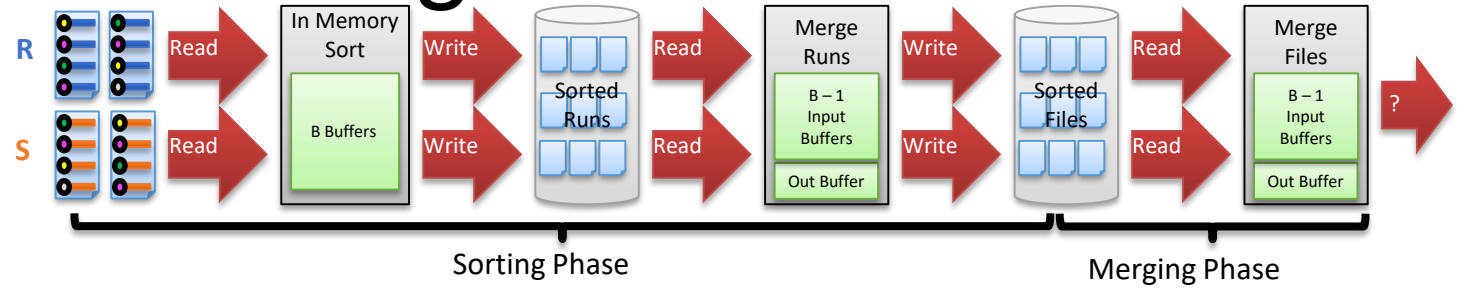

```
SELECT sid, bid, sname, rname
FROM R, S
WHERE R.sid = S.sid
ORDER BY sid
```

[R]=1000, p_R=100, |R| = 100,000
[S]=500, p_S=80, |S| = 40,000
B = 102

- Reserves (***sid***: int, ***bid***: int, ***day***: date, *rname*: string)
- Sailors (***sid***: int, *sname*: string, *rating*: int, *age*: real)

Sort R: 2*[R]*(2) = 4000
Sort S: 2*[S]*(2) = 2000
R + S = 1500
Total = 7500

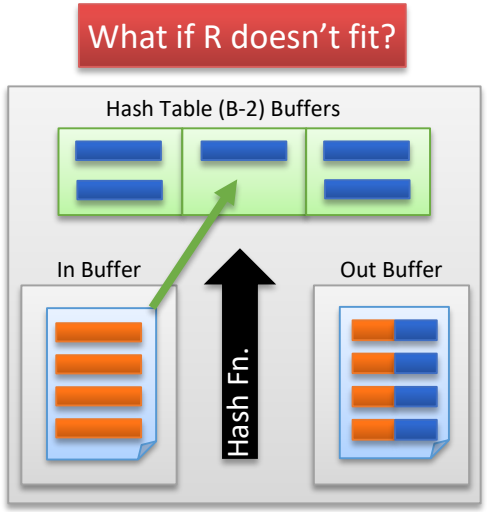
Sort-Merge Refinement



- An important refinement combines last pass of merge-sort with join pass
  - Given enough buffers to accommodate all runs in R and S on the penultimate (second-to-last) pass of sorting
  - Example for 2-pass SMJ (join during the final merging pass of sort)
    - Read R and write out sorted runs (pass 0)
    - Read S and write out sorted runs (pass 0)
    - Merge R-runs and S-runs, while finding R ⋈ S matches
  - 2-pass Cost = 3*[R] + 3*[S] = 3000+1500 = 4500

Naïve in Memory Hash Join

- Requires equality predicate:
  - Works for Equi-Joins & Natural Joins
- Assume R is smaller relation
  - Require R to fit in memory
- Simple algorithm:
  - Load all R into hash table
  - Scan S and probe R
- Memory requirements?
  - R < (B-2) * hash_fill



Properties that help

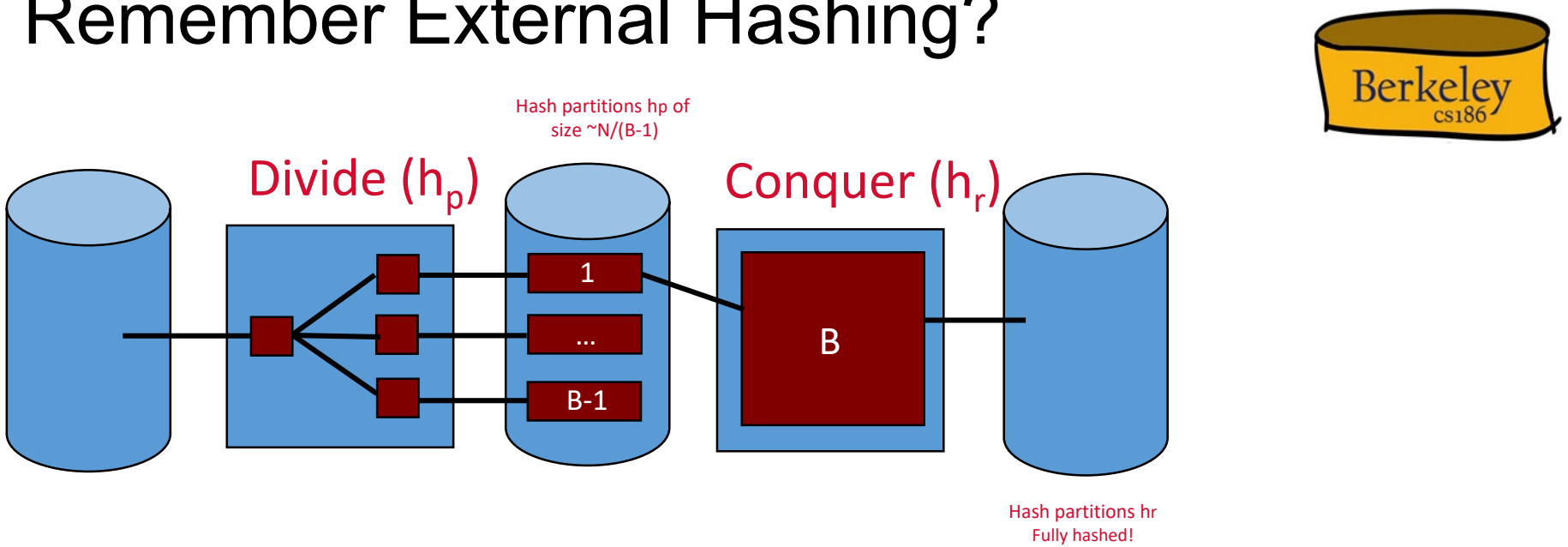
- $\sigma_{sid=4\ v\ sid=6}(R \bowtie_{sid} S) = \sigma_{sid=4}(R \bowtie_{sid} S) \cup \sigma_{sid=6}(R \bowtie_{sid} S)$

- Can Decompose Into Smaller “Partial Joins”
- $R \bowtie_{sid} S = \cup(\sigma_{hash(sid)}(R) \bowtie_{sid} \sigma_{hash(sid)}(S))$
- Pick a hash function so that $\sigma_{hash(sid)}(R)$ fits in memory!

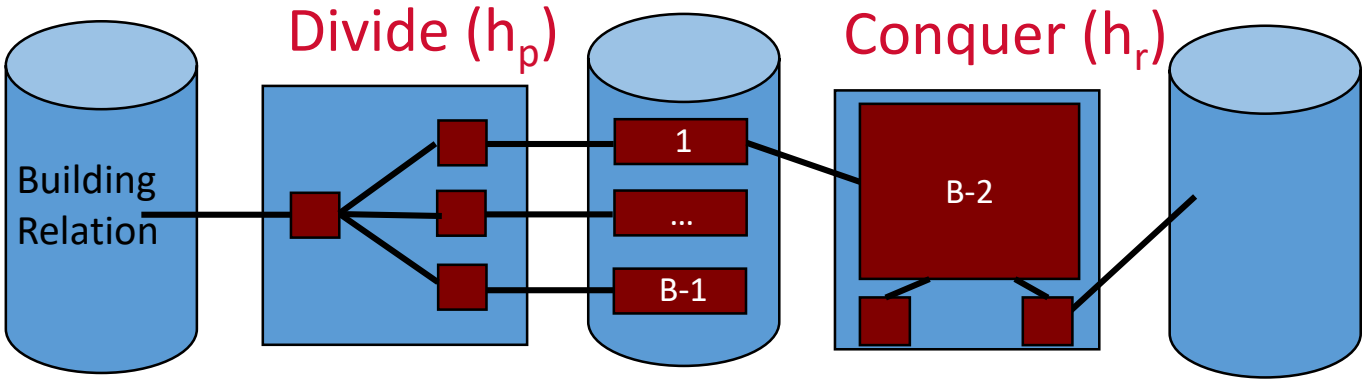
Grace Hash Join

- Requires equality predicate:
  - **Equi-Joins** & **Natural Joins**
- Two Stages:
  - **Partition** tuples from R and S by join key and store on scratch disk
    - all tuples for a given key in same partition
  - **Build & Probe** a separate hash table for each partition (like in Naïve Hash)
    - Assume **partition** of smaller rel. fits in memory
      - Recurse if necessary…

Remember External Hashing?

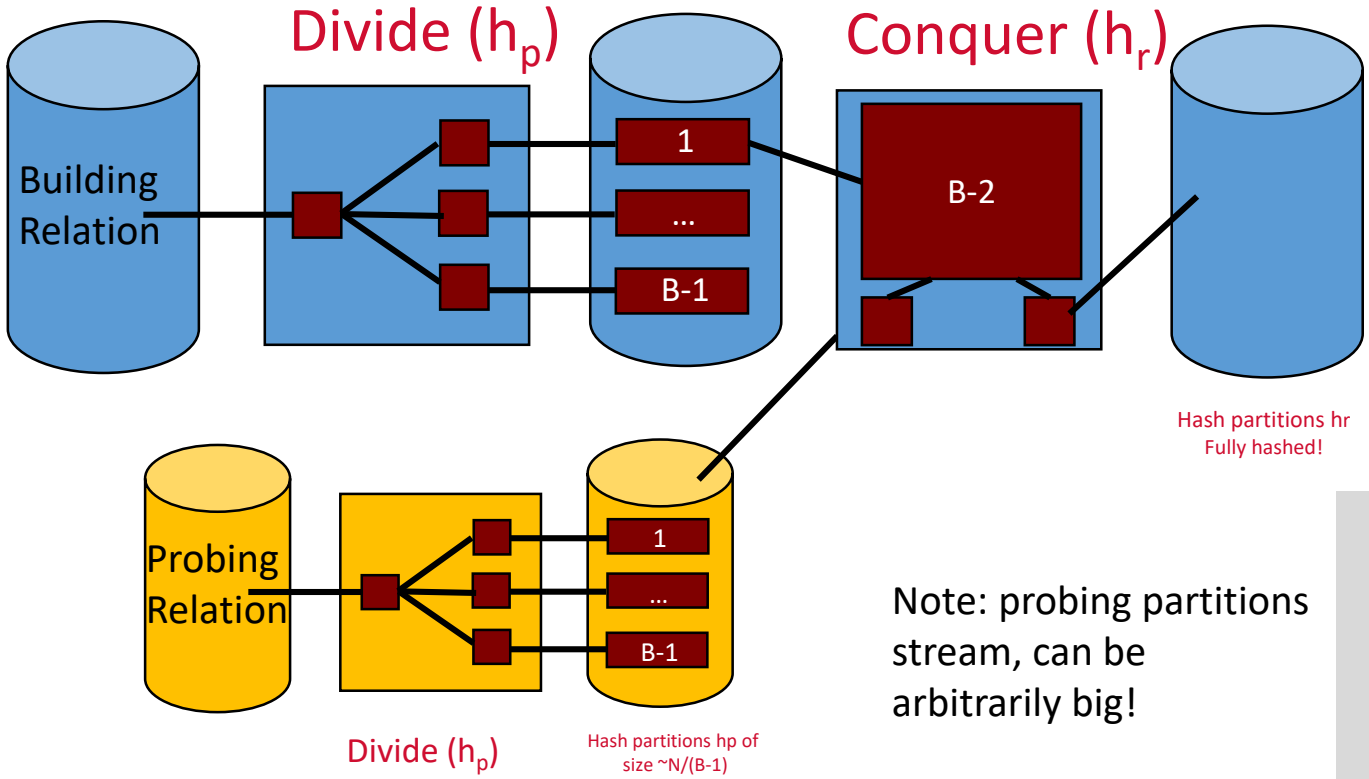


Sketch of Grace Hash Join



Hash partitions hr
Fully hashed!

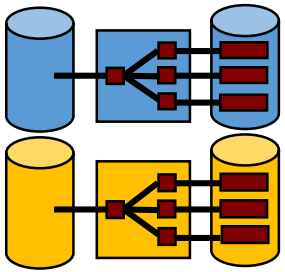
Sketch of Grace Hash Join, cont.



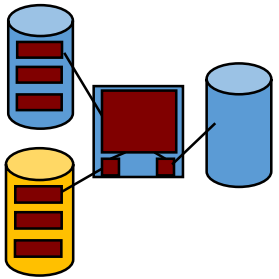
Note: probing partitions stream, can be arbitrarily big!

PsuedoCode, Grace Hash

For Cur in {R, S}
    For page in Cur
        Read page into input buffer
        For tup on page
            Place tup in output buf $hash_p$(tup.joinkey)
            If output buf full then flush to disk partition
    Flush output bufs to disk partitions



PsuedoCode, Grace Hash, cont.

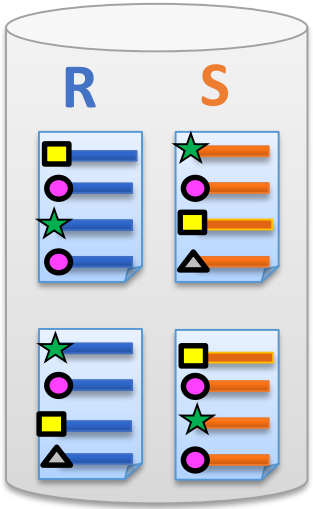


```
For Cur in {R, S}
    For page in Cur
        Read page into input buffer
        For tup on page
            Place tup in output buf hash_p(tup.joinkey)
            If output buf full then flush to disk partition
    Flush output bufs to disk partitions
For i in [0..(B-1))
    For page in R_i
        For tup on page
            Build tup into memory hash_r(tup.joinkey)
    For page in S_i
      Read page into input buffer
        For tup on page
            Probe memory hash_r(tup.joinkey) for matches
            Send all matches to output buffer
            Flush output buffer if full
```

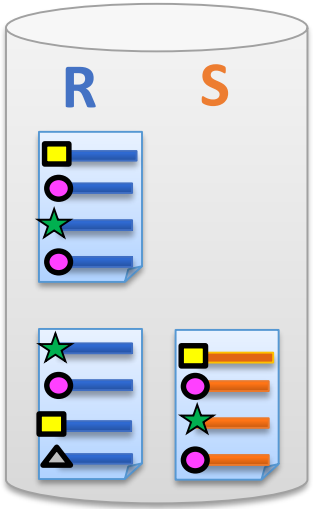
Grace Hash Join

- An animation
- Two phases:
  - Partition (divide)
  - Build & Probe hash tables (conquer)

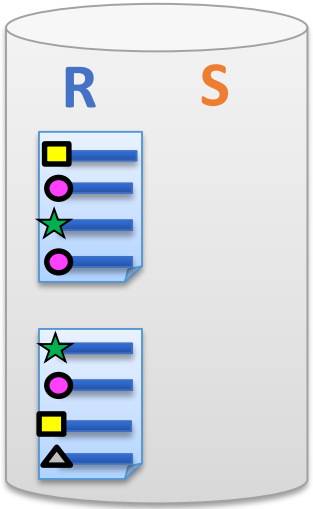
Grace Hash Join: ***Partition***

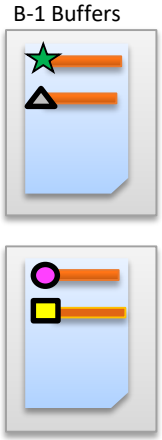


Grace Hash Join: ***Partition, Part 2***

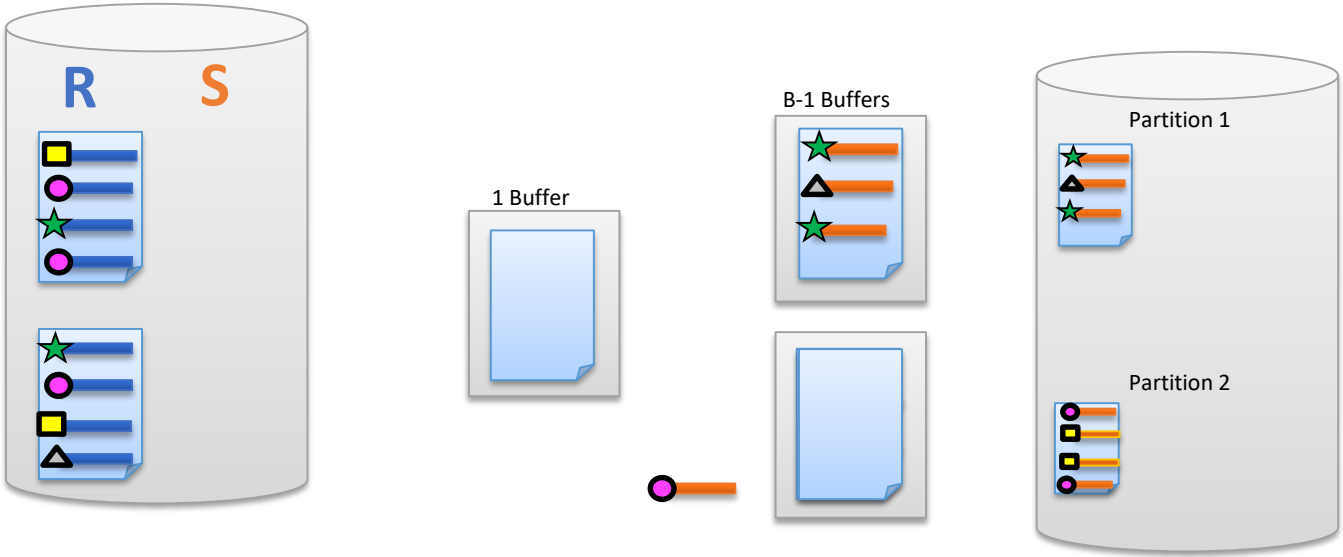


Grace Hash Join: ***Partition, Part 3***

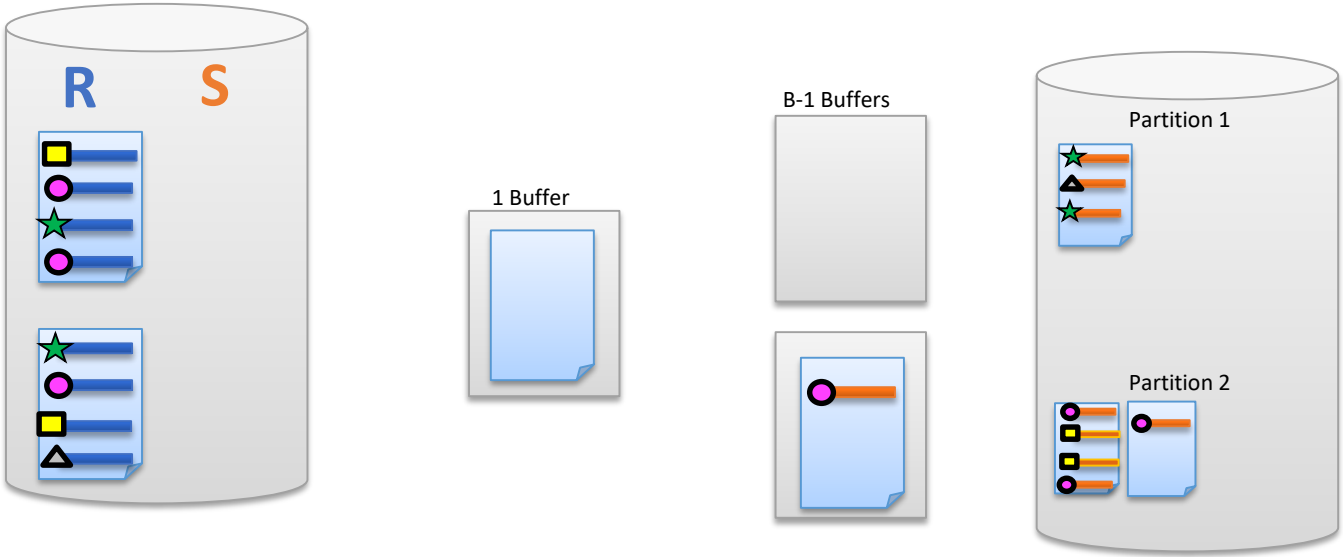




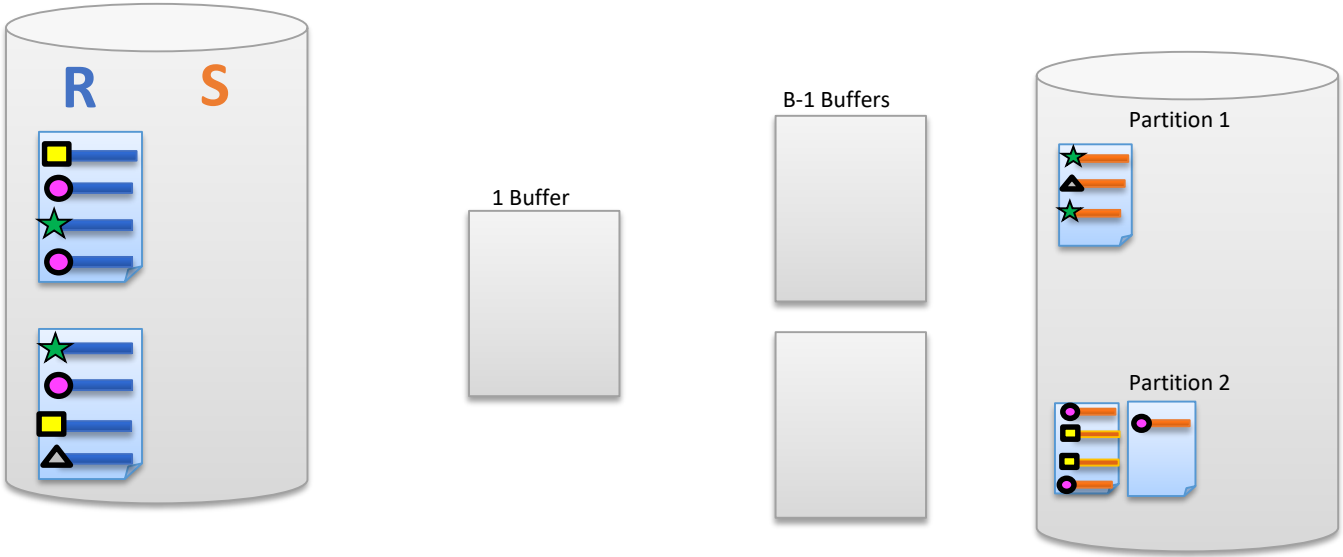
Grace Hash Join: ***Partition Part 4***



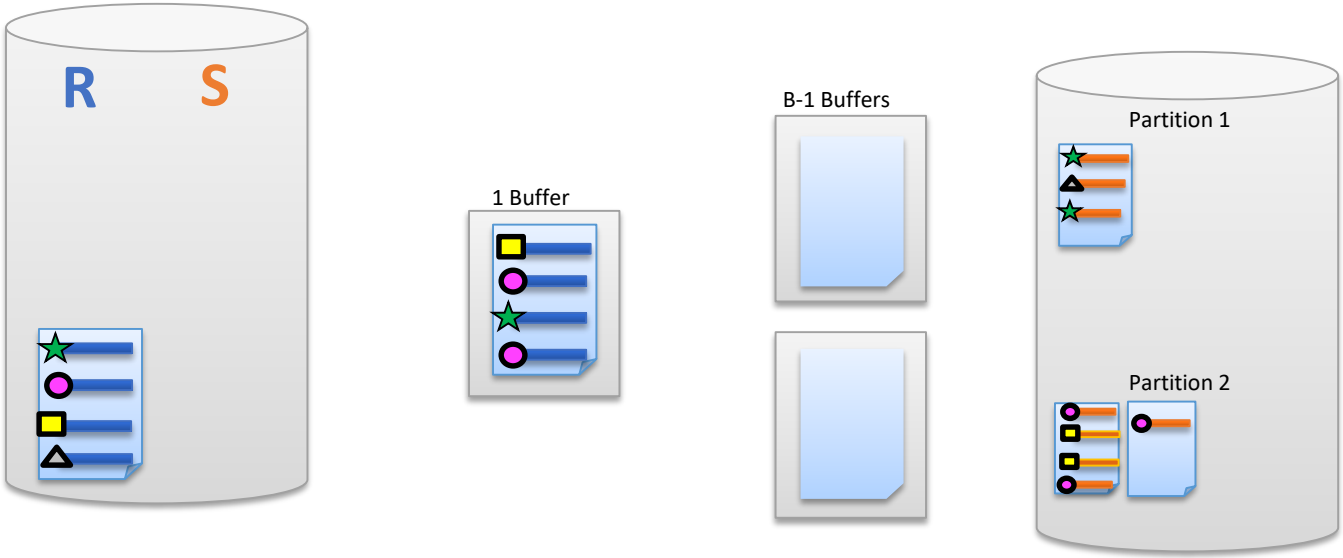
Grace Hash Join: ***Partition Part 5***



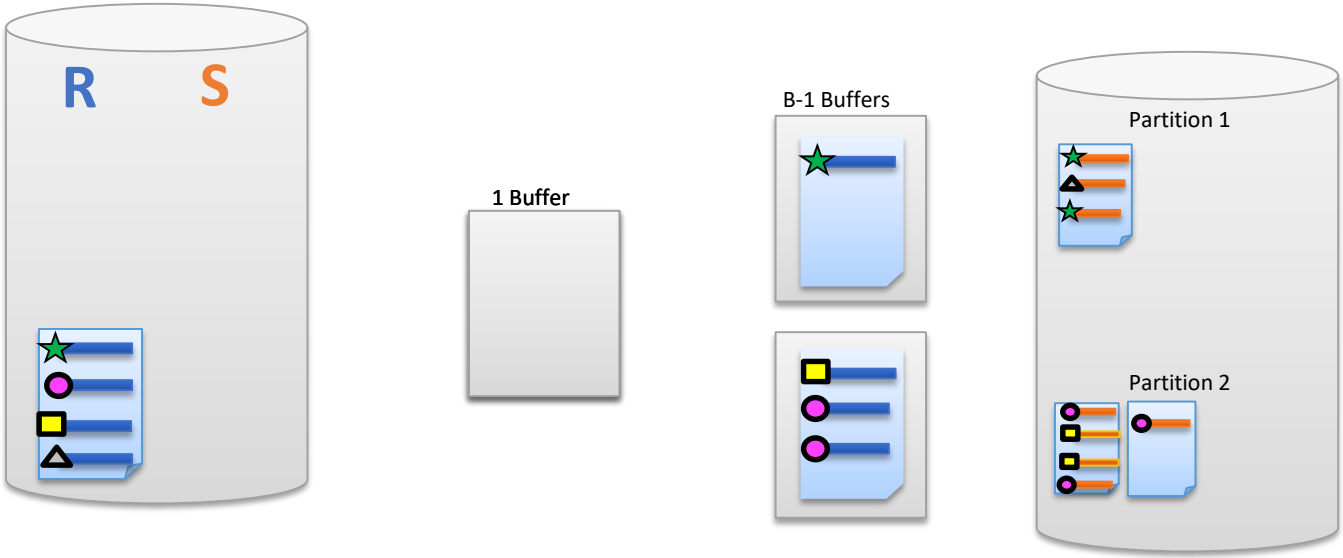
Grace Hash Join: ***Partition Part 6***



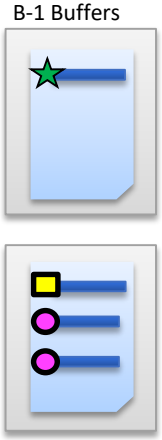
Grace Hash Join: ***Partition Part 7***

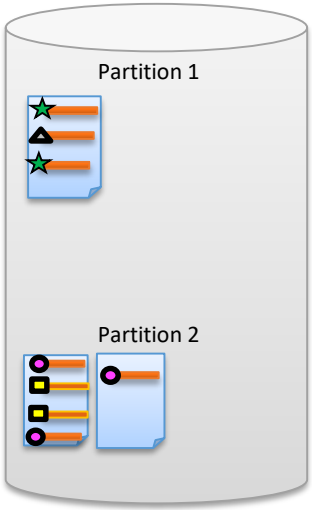


Grace Hash Join: ***Partition Part 8***

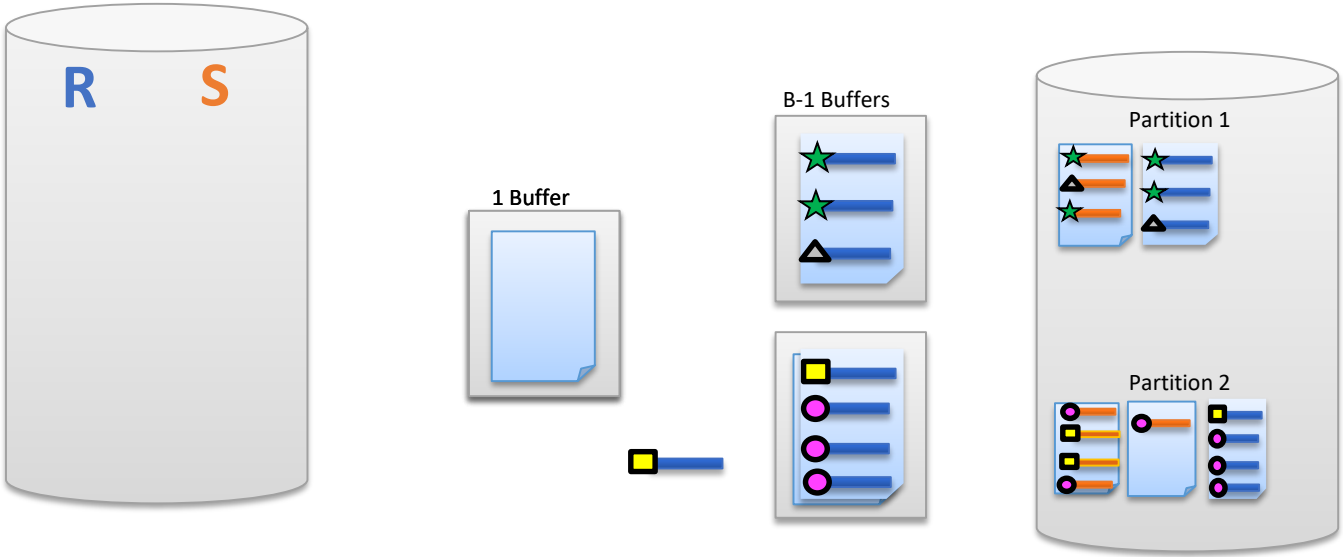


Grace Hash Join: ***Partition 9***

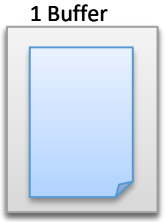


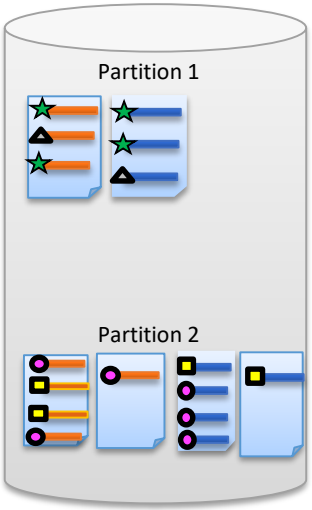


Grace Hash Join: ***Partition Part 10***



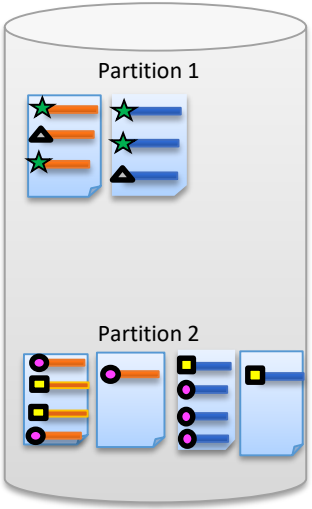
Grace Hash Join: ***Partition Part 11***



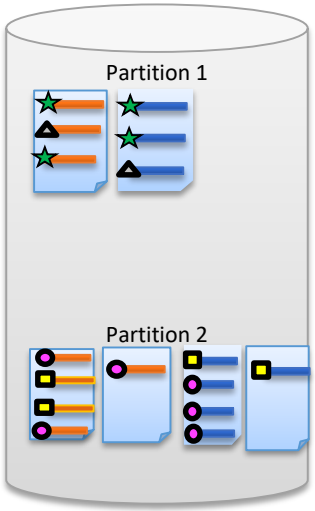


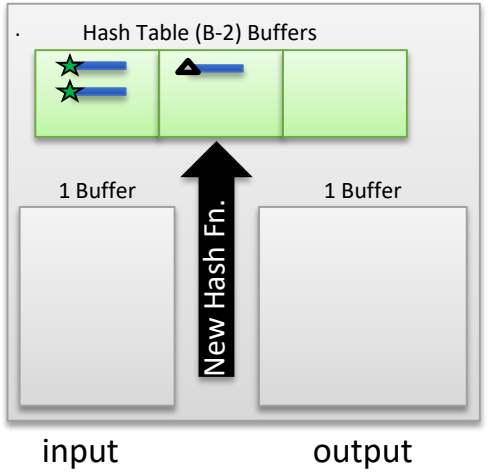
Grace Hash Join: ***Partition Part 12***

- Each key is assigned to one partition
  - e.g., green star keys only in Partition 1→
- Sensitive to key Skew
  - Fuchsia circle Key
- Each partition could be on a different disk or even different machine

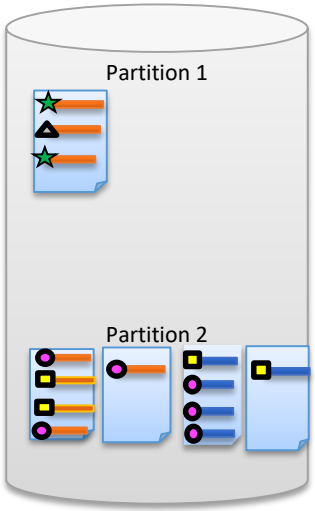


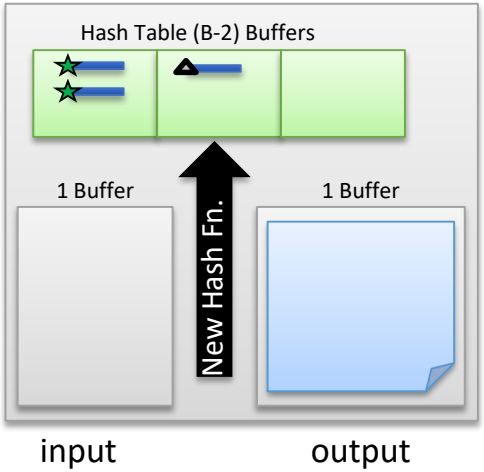
Grace Hash Join: ***Build*** **&** *Probe*



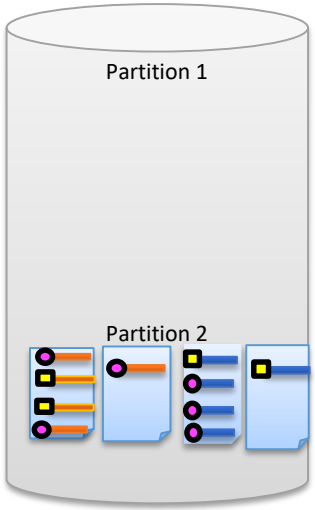


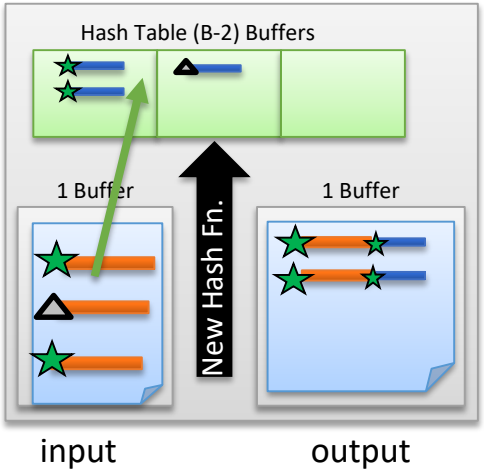
Grace Hash Join: *Build* **& *Probe Part 2***



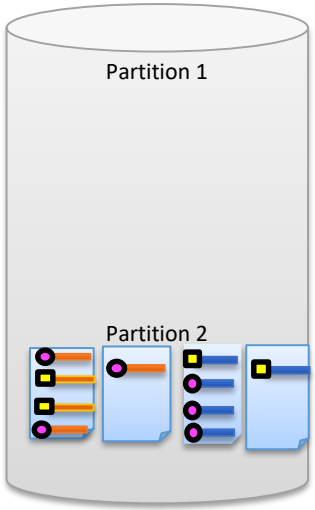


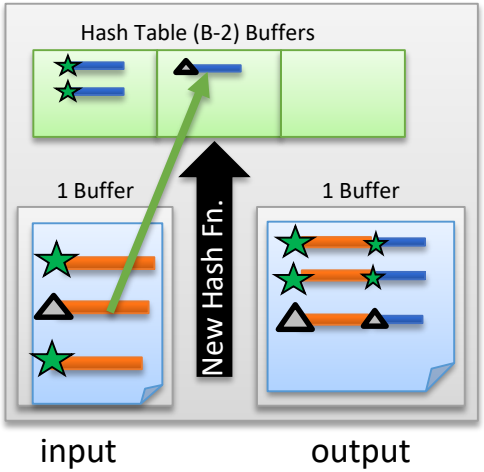
Grace Hash Join: *Build* **& *Probe Part 3***



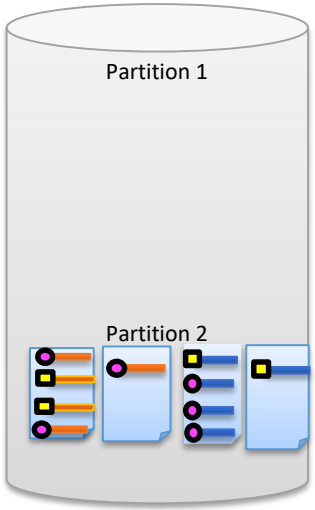


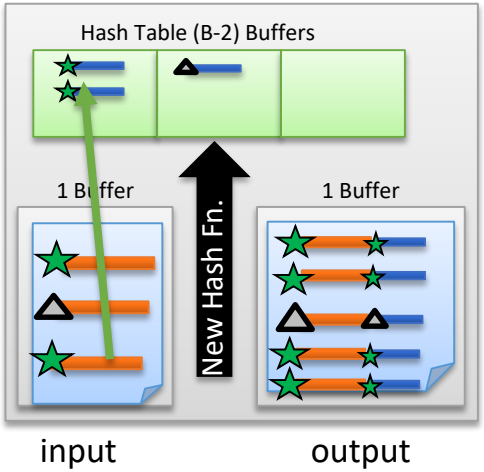
Grace Hash Join: *Build* **& *Probe Part 4***



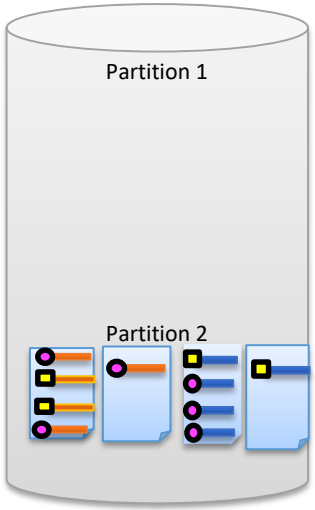


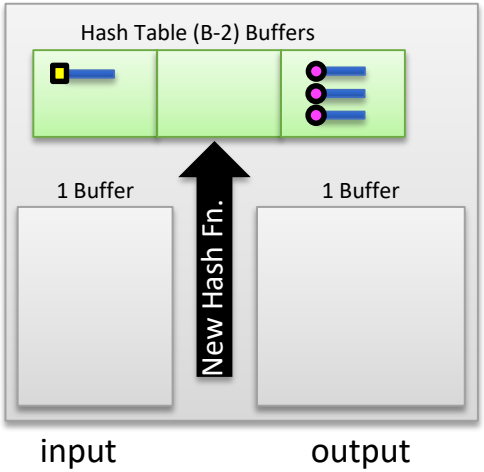
Grace Hash Join: *Build* **& *Probe Part 5***



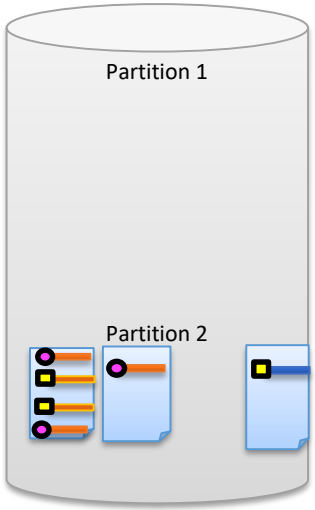


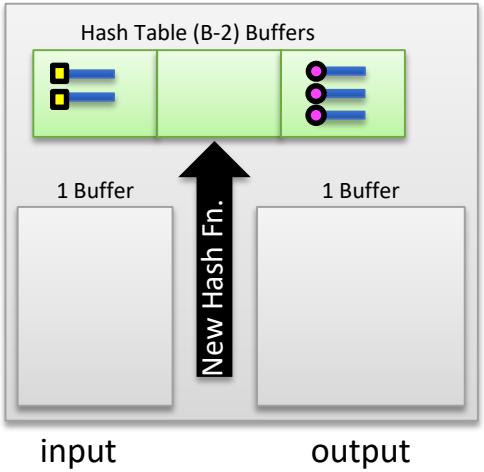
Grace Hash Join: ***Build*** *& Probe Part 6*



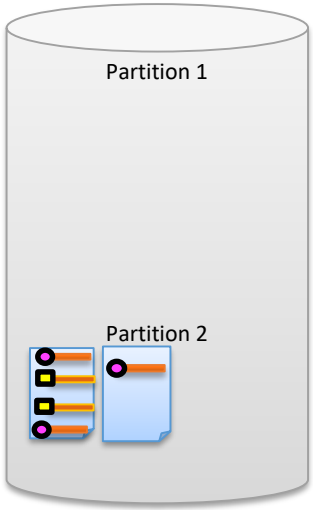


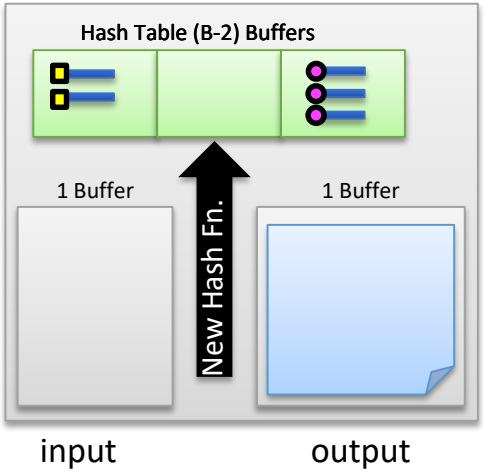
Grace Hash Join: ***Build*** *& Probe Part 7*



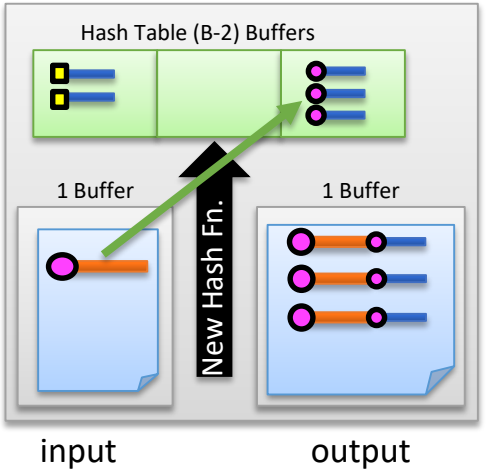


Grace Hash Join: *Build* **& *Probe Part 8***

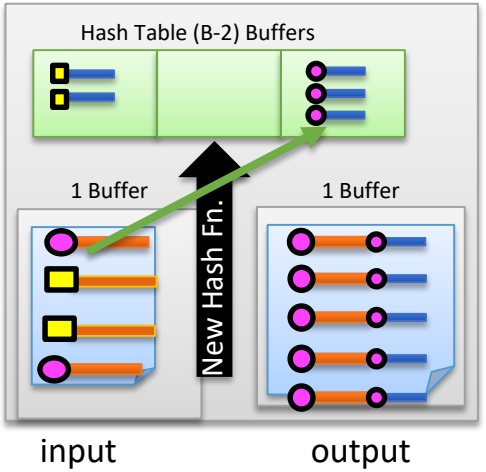




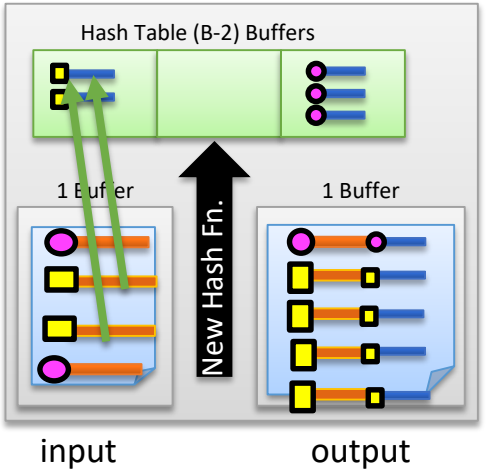
Grace Hash Join: *Build* **& *Probe Part 9***



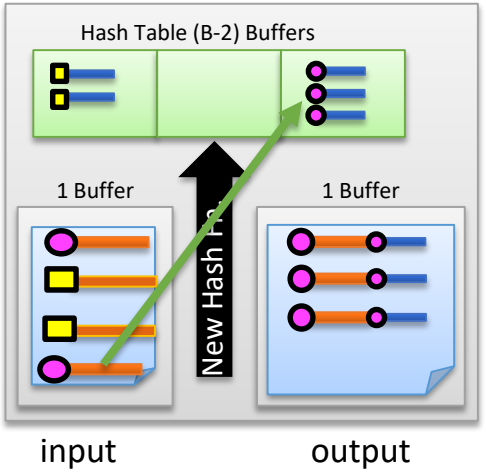
Grace Hash Join: *Build* **& *Probe Part 10***



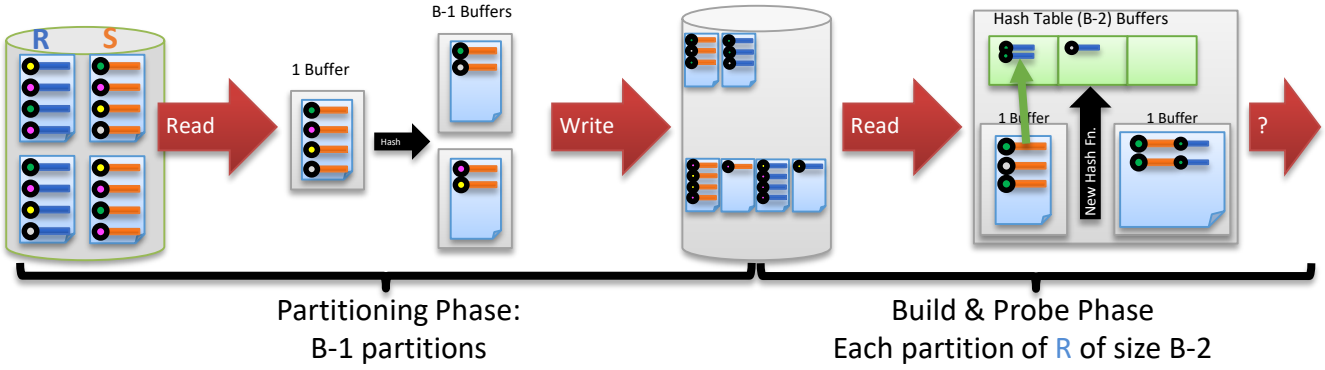
Grace Hash Join: *Build* **& *Probe Part 11***



Grace Hash Join: *Build* **& *Probe Part 12***



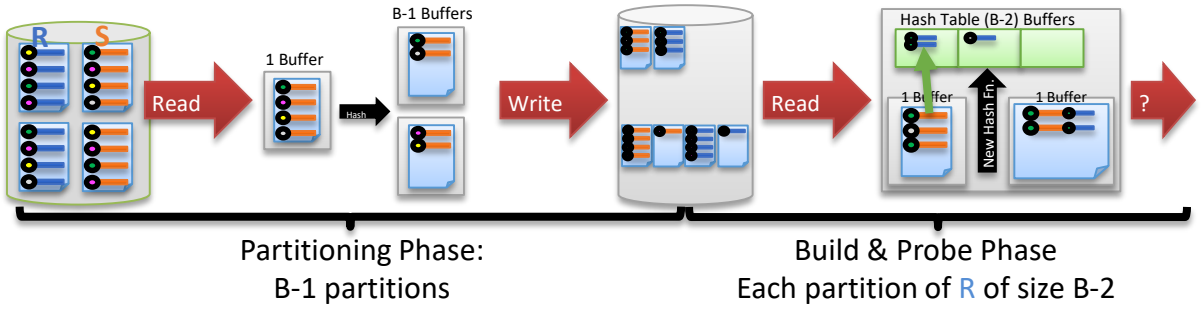
Summary of Grace Hash Join



What is the Cost?

Cost of Hash Join

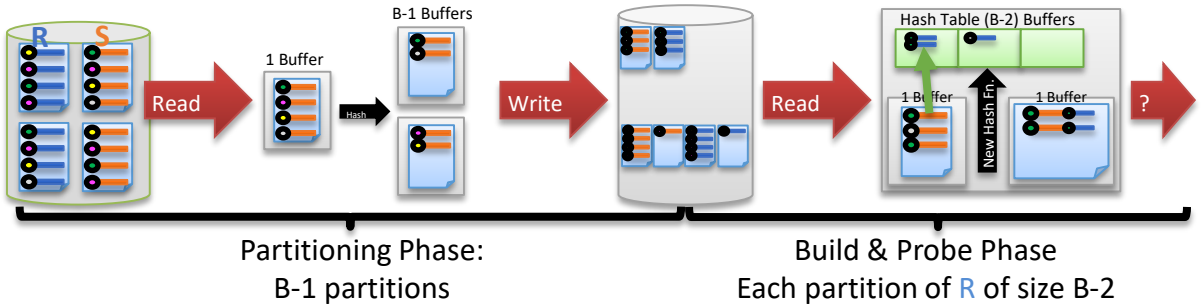
[R]=1000, p_R=100, |R| = 100,000
[S]=500, p_S=80, |S| = 40,000



- Partitioning phase: read+write both relations
  - ® 2([R]+[S]) I/Os
- Matching phase: read both relations, forward output
  - ® [R]+[S]
- Total cost of 2-pass hash join = 3([R]+[S])
  - 3 * (1000 + 500) = 4500

Cost of Hash Join Part 2

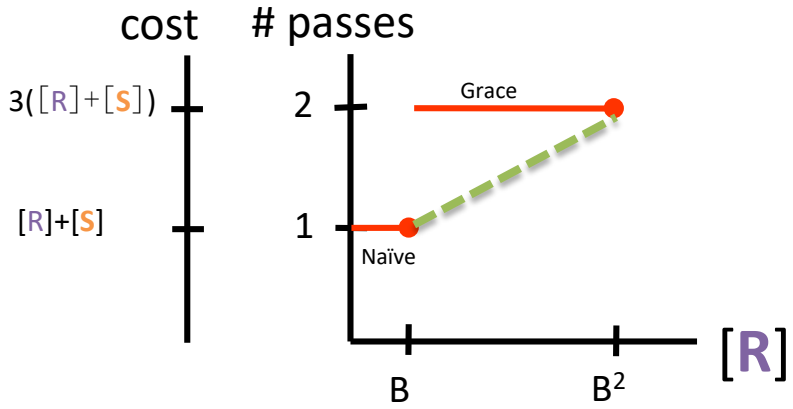
[R]=1000, p_R=100, |R| = 100,000
[S]=500, p_S=80, |S| = 40,000



- **Memory Requirements?**
- Build hash table on **R** with uniform partitioning
  - **Partitioning Phase divides R into (B-1) runs of size [R] / (B-1)**
  - **Matching Phase requires each [R] / (B-1) < (B-2)**
  - **R < (B-1) (B-2) ≈ B^2**
- Note: no constraint on size of S (probing relation)!

Cost of Hash Join Part 3

[R]=1000, p_R=100, |R| = 100,000
[S]=500, p_S=80, |S| = 40,000



- **Naïve Hash Join: *requires* [R] < B**
  - Put all of **R** in hash table
  - 1/3 the I/O cost of Grace!
- **Grace** Hash Join: 2-passes for [R] **< B^2**
- **Hybrid** Hash Join: an algorithm that adapts between the two
  - Tricky to tune

Hash Join vs. Sort-Merge Join

- Sorting pros:
  - Good if input already sorted, or need output sorted
  - Not sensitive to data skew or bad hash functions
- Hashing pros:
  - For join: # passes depends on size of smaller relation
    - E.g. if smaller relation is <B, naïve/hybrid hashing is great
  - Good if input already hashed, or need output hashed

Recap

- Nested Loops Join
  - Works for arbitrary Θ
  - Make sure to utilize memory in blocks
- Index Nested Loops
  - For equi-joins
  - When you already have an index on one side
- Sort/Hash
  - For equi-joins
  - No index required
  - Hash better if one relation is much smaller than other
- No clear winners – may want to implement them all
- Be sure you know the cost model for each
  - You will need it for query optimization!