CS315: Database Systems
Query Processing

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- Query in a high-level language is first parsed and validated

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select cpi from students where cpi > 9;
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- Query code is finally generated and processed

Query Cost

- Factors that affect the runtime of the query
  - Disk accesses (weakest factor)
  - CPU time
  - Network communication
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- For s seeks and b block transfers, simply estimated as $s \times t_s + b \times t_b$

  t_s: avg seek time
  t_b: avg block transfer time
- Ignores CPU time and buffer management issues
  - ↳ CPU time
  - ↳ Buffering
  - ↳ Write verification
  - ↳ Network times.

Selection: Linear Search [Relational algebra not SQL]

- LINEAR SEARCH
- *Always* applicable

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Selection: Linear Search

Relation r
→ total size: b blocks
→ stored contiguously

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- (*) If equality on key or unique attribute, then $b/2$ transfers on average

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- Applicable for comparison on the ordering attribute [predicate]
- *Equality*

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- If one block does not contain all records, add required number of additional transfers to the cost
- *Greater than* : 1st block is identified. Everything else is scanned after that.
  - Traverse forward and add required number of additional transfers
- *Lesser than*
  - Scan from beginning till matching record
  - Reduces to *linear search*

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  where m is the total number of blocks containing matching records
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Selection: Index Search

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- B+-tree of height h [h+1 seeks] [h+1 transfers] + m transfers
- Applicable for comparison on the indexed attribute
- *Equality* using primary index
  - $h + 1$ seeks, where h is the height of B+-tree
  - $h + m$ transfers (h+1): leaf has to be searched

  where m is the total number of blocks containing matching records
- For key, $m = 1$
- *Equality* using secondary index
  - $h + n$ seeks, where h is the height of the index tree
  - $h + n$ transfers

  where n is the total number of matching records, each in a separate block
- For key, $n = 1$

Selection: Index Search (contd.)

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B+ trees are generally doubly linked.

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secondary index: good only for few record selection

Selection on Multiple Attributes

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    - For each record satisfying it, test the other attributes

⇒ Everything that matches first attr. is tested to match on other attr.

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– K-D tree / R-tree

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    - If some attribute does not have an index, then linear scan

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    - May be very inefficient

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  - Index selects leaf pointers for which corresponding records will not be retrieved

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- Negation of comparison

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  - Multiple attribute index
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  - Intersection
    - If some attribute does not have an index, test explicitly

cost: sum of cost of individual index scans + cost of retreiving records

- *Disjunction*: OR
  - Union
    - If some attribute does not have an index, then linear scan
  - Negation of conjunction
    - May be very inefficient
- *Negation* of equality
  - Linear scan
  - Index selects leaf pointers for which corresponding records will not be retrieved
- Negation of comparison is just another comparison

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- Tuples need to be *physically* sorted
- When the relation fits in memory, QUICKSORT can be used
- When it does not, external sorting algorithms are used
- EXTERNAL MERGESORT or EXTERNAL SORT-MERGE is the most used

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- Assume only *m* blocks can be put into memory
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- Merge $m-1$ runs ($(m-1)$-way merge)
  - Read in first block of $m-1$ runs
  - Output the first record to *buffer* block (m-th block in memory)
  - Continue till buffer block is full
  - Write buffer block to disk
  - When a block of a particular run is exhausted, read in the next block of the run

This may not finish in 2nd merge as m-1 runs may not be enough. There may be more than m-1 blocks produced in the 1st stage.

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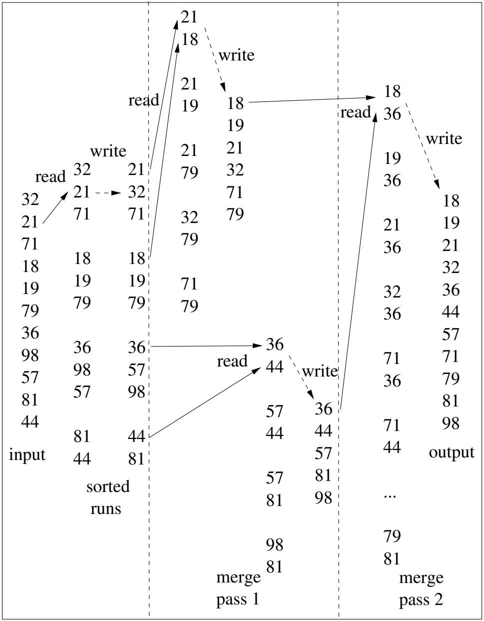
  - Write buffer block to disk
  - When a block of a particular run is exhausted, read in the next block of the run
- Continue with ($m-1$)-way merge till the number of sorted runs is *less than m*
- The last ($m-1$)-way merge sorts the relation

Example



read
write
read
write
read
write
read
write
32 21 71 18 19 79 36 98 57 81 44
input
32 21 71
18 19 79
36 98 57
81 44
21 32 71
18 19 79
36 57 98
44 81
sorted runs
21 18
21 19
21 79
32 79
71 79
18 19 21 32 71 79
36 44
57 44
57 81
98 81
merge pass 1
36 44 57 81 98
18 36
19 36
21 36
32 36
71 36
71 44
...
79 81
merge pass 2
18 19 21 32 36 44 57 71 79 81 98
output

Cost of External Mergesort

- Total number of blocks is b $(b > M)$ Memory : M
- Initial number of sorted runs is

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- In each merge pass, $m - 1$ runs are sorted
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m n

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- Therefore, total number of merge passes required is $r = \lceil \log_{m-1} n \rceil$
- During each of these passes and the first pass, all blocks are read and written
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- Hence, total number of block transfers is

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- During each of these passes and the first pass, all blocks are read and written [b + b]
- There is an initial pass of creating runs
- Hence, total number of block transfers is $2br + 2b$

  $= 2b(r+1)$

Cost of External Mergesort (contd.)

and there is only 1 seek for m blocks

- Initial pass to created sorted runs reads *m* blocks at a time
- Therefore, number of seeks is $2n$ for reading and writing

$\therefore$ for $\left\lceil \frac{b}{M} \right\rceil$ we'll have $(\cancel{1} + 1)\underbrace{\left\lceil \frac{b}{M} \right\rceil}_{n}$ seeks.

read write

Cost of External Mergesort (contd.)

- Initial pass to created sorted runs reads *m* blocks at a time
- Therefore, number of seeks is $2n$ for reading and writing
- During the merge passes, blocks from different runs may not be read consecutively
- Consequently, each read and write for another run may move the disk head away, thereby requiring a seek every time
- Hence, number of seeks for these passes is $2br$
- Therefore, total number of seeks is

For 1 pass : $2b$
For r passes: $2br$

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- Therefore, total number of seeks is $2n + 2br$

Join

- Different join algorithms
  - Nested-loop join
  - Block nested-loop join
  - Indexed nested-loop join
  - Merge join
  - Hash join
- Choice depends on cost estimates

Nested-Loop Join

- Applicable for any kind of join
- For each record $t_r \in r$ and for each record $t_s \in s$, if $t_r \bowtie t_s$ satisfies the join condition, add it to result
- Outer relation r: outer loop; inner relation s: inner loop

relation i:
- n_i: records
- b_i: blocks

$r \bowtie s$

Block transfers.

(1) t_r : b_s

[For some record $t_r \in r$, b_s blocks from s are fetched]

n_r total records, : $\boxed{b_r + n_r \times b_s}$

Seeks

t_r : $1 + 1$

$\boxed{2n_r}$

Block Nested-Loop Join

- Applicable for any kind of join
- *Disk block* aware version of nested-loop
- For each block $l_r \in r$ and for each block $l_s \in s$, test if every record $t_r \in l_r$ and $t_s \in l_s$ satisfies the join condition; if so, add to the result

Block by block join is done

block r   block s

t_r t_s

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- Seeks
  - 1 seek for records in s every time a block l_r is read
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- Smaller relation should be

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$\{ b_r + n_r \times b_s$ for NLJ $\}$

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- $m - 1$ blocks read at a time from outer relation r

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- Number of such runs is $n = \lceil b_r / (m - 1) \rceil$

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- Assume m blocks of memory to be available
- 1 left for inner relation s
- $m - 1$ blocks read at a time from outer relation r
- Number of such runs is $n = \lceil b_r/(m-1) \rceil$
- Block transfers
  - For r: b_r
  - For s: $n \times b_s$

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- Block transfers
  - For r: b_r
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- Seeks
  - For r: n = no. of runs
  - For s: n = no. of runs
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- Block transfers
  - For r: b_r
  - For s: $n \times b_s$
- Seeks
  - For r: n
  - For s: n
- Smaller relation should be outer

Example

- r: 40000 tuples at 200 per block:

Example

- r: 40000 tuples at 200 per block: 200 blocks
- s: 25000 tuples at 100 per block:

Example

b_r

- *r*: 40000 tuples at 200 per block: 200 blocks
- *s*: 25000 tuples at 100 per block: 250 blocks

b_s

Example

- r: 40000 tuples at 200 per block: 200 blocks
- s: 25000 tuples at 100 per block: 250 blocks
- Available memory is $m = 25$ for outer $\underbrace{(+1 \text{ for inner})}$

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- Available memory is $m = 25$ for outer ($+1$ for inner)
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Example

- r: 40000 tuples at 200 per block: 200 blocks
- s: 25000 tuples at 100 per block: 250 blocks
- Available memory is $m = 25$ for outer ($+1$ for inner)
- Outer should be r
- Number of runs is

Example

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- Total is 16 seeks and 2200 transfers
- If s made outer, 20 seeks and 2250 transfers

Indexed Nested-Loop Join

- Indexed version of the block nested-loop algorithm
- Applicable when inner relation has an index on the joining attribute
- For each block $l_r \in r$ and for each record $t_r \in l_r$, use index on s to locate records $t_s \in s$ that satisfies the join condition

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- Most effective when the join condition is equality

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- Therefore, total is $n + n_r \times c_s$ seeks and $b_r + n_r \times c_t$ transfers
- If index is available on both relations, like block nested-loop, smaller relation should be outer
- Generally, all levels of B+-tree are held in memory except the last
  - Then, cost of index search falls to $c_s = c_t = 1$

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Example

- r: 40000 tuples at 200 per block: 200 blocks
- s: 25000 tuples at 100 per block: 250 blocks
- Available memory is $m = 25$ for outer and enough for inner
- Outer should be s
- Number of runs is $n = \lceil 250/25 \rceil = 10$

Example

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- Number of runs is $n = \lceil 250/25 \rceil = 10$
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- Total is 25000 seeks and 25000 transfers

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- r: 40000 tuples at 200 per block: 200 blocks
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- Available memory is $m = 25$ for outer and enough for inner
- Outer should be s
- Number of runs is $n = \lceil 250/25 \rceil = 10$
- In each run, r requires $\underbrace{\text{1 seek}}_{cs}$ and $\underbrace{\text{1 transfer}}_{ct}$
- Total is 25000 seeks and 25000 transfers
- s requires $\underbrace{10}_{n}$ seeks and $\underbrace{250}_{bf}$ transfers

Example

- r: 40000 tuples at 200 per block: 200 blocks
- s: 25000 tuples at 100 per block: 250 blocks
- Available memory is $m = 25$ for outer and enough for inner
- Outer should be s
- Number of runs is $n = \lceil 250/25 \rceil = 10$
- In each run, r requires 1 seek and 1 transfer
- Total is 25000 seeks and 25000 transfers
- s requires 10 seeks and 250 transfers
- Total is 25010 seeks and 25250 transfers

Merge Join or Sort-Merge Join [only for equality join]

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- Relations need to be sorted according to the joining attribute

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- Relations need to be sorted according to the joining attribute
- Proceed in sorted order on two relations
- If records match, output; otherwise, advance to next record
- Join step is similar to merge step in mergesort
- If relations are not sorted, secondary index on attributes can be used
- HYBRID MERGE JOIN algorithm merges sorted records in one relation with B+-tree leaves of other relation

* one relation is sorted
* other is indexed (B + tree)

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  - $b_r + b_s$ transfers
  - $b_r + b_s$ seeks
- If $m = m'/2$ blocks of memory are available for each relation, cost is $\lceil b_r/m \rceil + \lceil b_s/m \rceil$ seeks and $b_r + b_s$ transfers

Example

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- Number of seeks for r is

$$= \left\lceil \frac{200}{m} \right\rceil + \left\lceil \frac{250}{m} \right\rceil \text{ seeks}$$

$$200 + 250 \text{ transfers}$$

Example

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- s: 25000 tuples at 100 per block: 250 blocks
- Available memory is $m = 13$ for each
- Number of seeks for r is $\lceil 250/13 \rceil = 20$
- Number of seeks for s is

Example

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- Available memory is $m = 13$ for each
- Number of seeks for r is $\lceil 250/13 \rceil = 20$
- Number of seeks for s is $\lceil 200/13 \rceil = 16$

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- Total is

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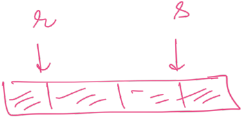
- Available memory is $m = 13$ for each
- Number of seeks for r is $\lceil 250/13 \rceil = 20$
- Number of seeks for s is $\lceil 200/13 \rceil = 16$
- Total is 36 seeks and 450 transfers

Hash Join {only on equality}

- Applicable only when the join condition is *equality*
- If record t_r and t_s match, they must hash to same value, and thus, only partitions with the same hash value need to be compared

t_r (h)

t_s



t_r & t_s must be hashed to the same position (equality join)

Partition hash join

0, ... , n − 1

H_{r_i} partition H_{s_i}

$h(t_r) = i$ $h(t_s) = i$

read in-memory hash for H_{s_i}

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- PARTITION HASH JOIN
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- s is called build input → in-memory hash
- r is called probe input → block-by-block
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- Smaller relation should be build relation

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Single Pass

- Each of the n partitions of build input s should fit into memory
- If build relation has b_s blocks, each partition has roughly b_s/n blocks

$n \geq \left\lceil \frac{b_s}{M} \right\rceil$ M: memory size

$M > n$

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- Thus, $m > n$
- Combining, $m > n > b_s/m$ or, $\boxed{m > \sqrt{b_s}}$
- If not so, then partitioning *cannot* be done in one pass

Recursive Partitioning

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- Number of passes is $p = \lfloor \log_m b_s \rfloor$
- HYBRID HASH JOIN when more memory is available
- Entire build relation s can be in memory
- Retain the first partition of build relation in memory

Example

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- Available memory is $m = 10$ blocks
  - Partitioning produces $120/10 = 12$ blocks that do not fit
  - Thus, 12 blocks are partitioned again to $12/10 = 2$ blocks each
  - This now fits
  - Thus, 2 passes are required $\rightarrow \log_m b_s$

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  - Partitioning produces $120/10 = 12$ blocks that do not fit
  - Thus, 12 blocks are partitioned again to $12/10 = 2$ blocks each
  - This now fits
  - Thus, 2 passes are required
- Available memory is $m = 4$ blocks
  - Partitioning produces $\underbrace{120/4}_{1} = 30$ and then $\underbrace{30/4}_{2} = 8$ and then 3 $\underline{8/4} = 2$ blocks
  - Thus, 3 passes are required

Cost of Hash Join

- Initial reading of a relation i requires b_i transfers

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- Total number of blocks after partitioning is at most

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- Writing them back requires

Cost of Hash Join

- Initial reading of a relation i requires b_i transfers
- Total number of blocks after partitioning is at most $b_i + n$ as each of n partitions may be partially full
- Writing them back requires $(b_i + n)$ transfers
- Reading them again during matching requires

Cost of Hash Join

- Initial reading of a relation i requires b_i transfers
- Total number of blocks after partitioning is at most $b_i + n$ as each of n partitions may be partially full
- Writing them back requires $(b_i + n)$ transfers
- Reading them again during matching requires $(b_i + n)$ transfers
- Therefore, total number of transfers is $3(b_r + b_s) + 4n$

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$\boxed{3b_i + 2n}$
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- Therefore, total number of transfers is $3(b_r + b_s) + 4n$
- Assume memory buffer of m blocks
- Partitioning requires $k_i = \lceil b_i/m \rceil$ seeks for reading and $k_i' = \lceil (b_i + n)/m \rceil$ seeks for writing
- Reading n partitions during matching requires n seeks per relation
- Therefore, total number of seeks is $k_r + k_s + k_r' + k_s' + 2n$

Reading seeks: $\overset{r}{n} + \overset{s}{n} = 2n$

For i: seeks. $\left\lceil \frac{2b_i + n}{m} \right\rceil$: (Partitioning + writing)

Total: $\left\lceil \frac{2(b_r + b_s + n)}{m} \right\rceil + 2n$

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$\left\lceil \frac{b_r}{m} \right\rceil \quad \left\lceil \frac{b_s}{m} \right\rceil$

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- Number of passes in recursive partitioning is $p = \lfloor \log_m b_s \rfloor$
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- Number of seeks during partitioning is $2p(k'_r + k'_s)$
- Matching requires $(b_r + n + b_s + n)$ transfers and $n + n$ seeks

Example

- r: 40000 tuples at 200 per block:

Example

- r: 40000 tuples at 200 per block: 200 blocks
- s: 25000 tuples at 100 per block:

Example

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- Size of each partition of r is

Example

- r: 40000 tuples at 200 per block: 200 blocks
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- Build input should be s
- Partitioning s requires

Example

Doubt

- r: 40000 tuples at 200 per block: 200 blocks
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- Available memory is 15 for partitions and $m = 10$ for buffering
- Number of partitions is $n = 15$
- Size of each partition of s is $\lceil 200/15 \rceil = 14$
- Size of each partition of r is $\lceil 250/15 \rceil = 17$
- Build input should be s
- Partitioning s requires $200 + (200 + 15) = 415$ transfers
- Number of seeks for s is

Example

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- Build input should be s
- Partitioning s requires $200 + (200 + 15) = 415$ transfers
- Number of seeks for s is $\lceil 200/10 \rceil + \lceil 215/10 \rceil = 42$

Example

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- Partitioning r requires 1 pass since it is probe input
- Number of transfers for r is $250 + (250 + 15) = 515$
- Number of seeks for r is

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- Partitioning r requires 1 pass since it is probe input
- Number of transfers for r is $250 + (250 + 15) = 515$
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- Number of transfers for r is $250 + (250 + 15) = 515$
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- Matching phase requires reading all blocks of s and r: $215 + 265 = 480$
- Number of seeks in matching phase is

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- Matching phase requires reading all blocks of s and r: $215 + 265 = 480$
- Number of seeks in matching phase is $15 + 15 = 30$
- Total is $15 + 15 + 42 + 52 = 124$ seeks and $415 + 515 + 480 = 1410$ transfers

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left - outer join

$r ⟕ S$

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s : should be build relation

Every tuple from r is probed. If it matches, we output

Even if it doesn't, the r side is output

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  - If r is the build relation, keep track of which records in hash index have been used; output all non-used records
  - If r ⟗ s, use both techniques

Hash join is generally not used for full-join

What can be done is:

Use markers on S.
(build relation)

r → S

1 } Match

0
0
0 } Don't match

At the end a pass is taken to look for 0s and output (clumsy)

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  - If relations are sorted, scan in order
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  - Use hashing to organize into groups; then apply aggregation

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  - If relations are sorted, scan in order
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  - Build hash index on one relation; test records from other relation
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  - Use hashing to organize into groups; then apply aggregation
- Duplicate detection and elimination
  - Use hashing or sorting