Query Optimization, part 2: query plans in practice

CS634
Lecture 13

Slides by E. O'Neil based on "Database Management Systems" 3rd ed, Ramakrishnan and Gehrke

Working with the Oracle query optimizer

- First need to make sure stats are in place in the catalog (if tables were just loaded, or indexes added)
- Analyze table on Oracle 12c is supported, but doesn't collect statistics for partitioned tables, run in parallel, etc.
- See notice in analyze doc
- To get better stats, we need to execute the following code (from class 6)

```
SQL>exec dbms_stats.gather_table_stats(
'SETQ_DB', 'BENCH',cascade=>true);
```

- Here cascade means analyze its indexes too.
- To drop stats:

```
exec dbms_stats.delete_table_stats('setq_db', 'bench');
```

Bench table

- 1M rows, 240 bytes each, so 240MB table data (30K pages)
- Data is in a heap table
  - Recall that Oracle only offers clustered index via “IOT” index-organized table.
- Column names show their cardinality:
  - k4 means 4 different values, 1,2,3,4
  - k100K means 100k different values 1, 2, …, 99999, 100000
- B-tree indexes on kseq, k4, k100, k1k, k100k, k500k columns
- No index on k5, k25, k40, k40k, k250k columns

Seeing the results of gathering stats

```
SQL>  SELECT column_name, num_distinct, num_buckets, histogram
FROM ALL_TAB_COL_STATISTICS where table_name='BENCH‘ order by num_distinct;
COLUMN_NAM NUM_DISTINCT NUM_BUCKETS HISTOGRAM
---------- ------------ ----------- ---------------
K2                    2           1 NONE
K4                    4           1 NONE       ←indexed
K5                    5           5 FREQUENCY
K10                  10           1 NONE       ←indexed
K25                  25           1 NONE
K100                100         100 FREQUENCY  ←indexed
K1K                1000           1 NONE
K10K              10000           1 NONE     ←indexed
K40K              40348           1 NONE
K100K            100816           1 NONE     ←indexed
K250K            248288           1 NONE
K500K            439200           1 NONE     ←indexed
KSEQ            1000000           1 NONE     ←indexed
```

Oracle figures that the default RF of 1/num_distinct will be good enough for k10k and up

Simple plan example, indexed column k500

SQL> alter session set current_schema = setq_db;

SQL> explain plan for select max(s1) from bench where k500k=2;

SQL> select * from table(dbms_xplan.display());

```
| Id  | Operation                    | Name    | Rows  | Bytes
---------------------------------------------------------------
|   0 | SELECT STATEMENT             |         |     1 |    14 |
|   1 |  SORT AGGREGATE              |         |     1 |    14 |
|   2 |   TABLE ACCESS BY INDEX ROWID| BENCH   |     2 |    28 |
|*  3 |    INDEX RANGE SCAN          | K500KIN |     2 |       |
--------------------------------------------------------------------------------
Predicate Information (identified by operation id):
---------------------------------------------------
   3 - access("K500K"=2)
```

- K500K index has 2 rows for each key
- Table access by those two ROWIDs extracts 28 bytes (s1 value): 2 rows of 14 bytes each
- These are aggregated and one value returned
- Same plan for k100k, k10k, but not k100…

Simple plan, indexed k100 column:

```
SQL> explain plan for select max(s1) from bench where k100=2;
SQL> select * from table(dbms_xplan.display());
| Id  | Operation          | Name  | Rows  | Bytes | Cost…
---------------------------------------------------
|   0 | SELECT STATEMENT   |       |     1 |    12 |
|   1 |  SORT AGGREGATE    |       |     1 |    12 |
|*  2 |   TABLE ACCESS FULL| BENCH | 10000 |   117K|
---------------------------------------------------
Predicate Information (identified by operation id):
   2 - filter("K100"=2)
```

- Here RF=1/100, so about 10,000 rows are produced by the filtered table scan, and each needs the s1 value, 12 bytes, so 120KB of data.
- Oracle has ignored the K100 index, preferring to do a table scan (30,000 pages) rather than do 10,000 index probes and rid lookups. Let’s see why…

Simple plan, k100 case

`select max(s1) from bench where k100=2;`

- Cost of Oracle's plan (with known histograms): read entire table, about 30,000 i/os.
- Cost of index-driven plan:
  - Here RF=1/100, so about 10,000 rows are found in the index. Maybe 100 i/os to index.
  - Each needs the s1 value, so the ROWID is used to access the table. This takes 10,000 index probes, so about 10,000 i/os (assuming buffering of upper levels of the index.)
- The difference here: sequential vs. random i/o
  - Plan 1: table scan, 30,000 sequential i/os
  - Plan 2: use index, 10,000 random accesses
- But sequential i/o uses multi-block i/o, can be 10-25x faster.
- That's assuming HDD. On SSD, use the index.

```
column column_name format a
  column column_name format a
```

Easier way to see plans:

`set autotrace on explain statistics`

- Or just **`set autotrace on exp stat`**
- Also **`set timing on`**
- Also **`set line 130`** to avoid wrapping
- Then just select …
- After this returns, you see the explain plan, plus actual statistics on the query
- The explain plan is not guaranteed to be the exact plan used

- Note: to set string column output format:

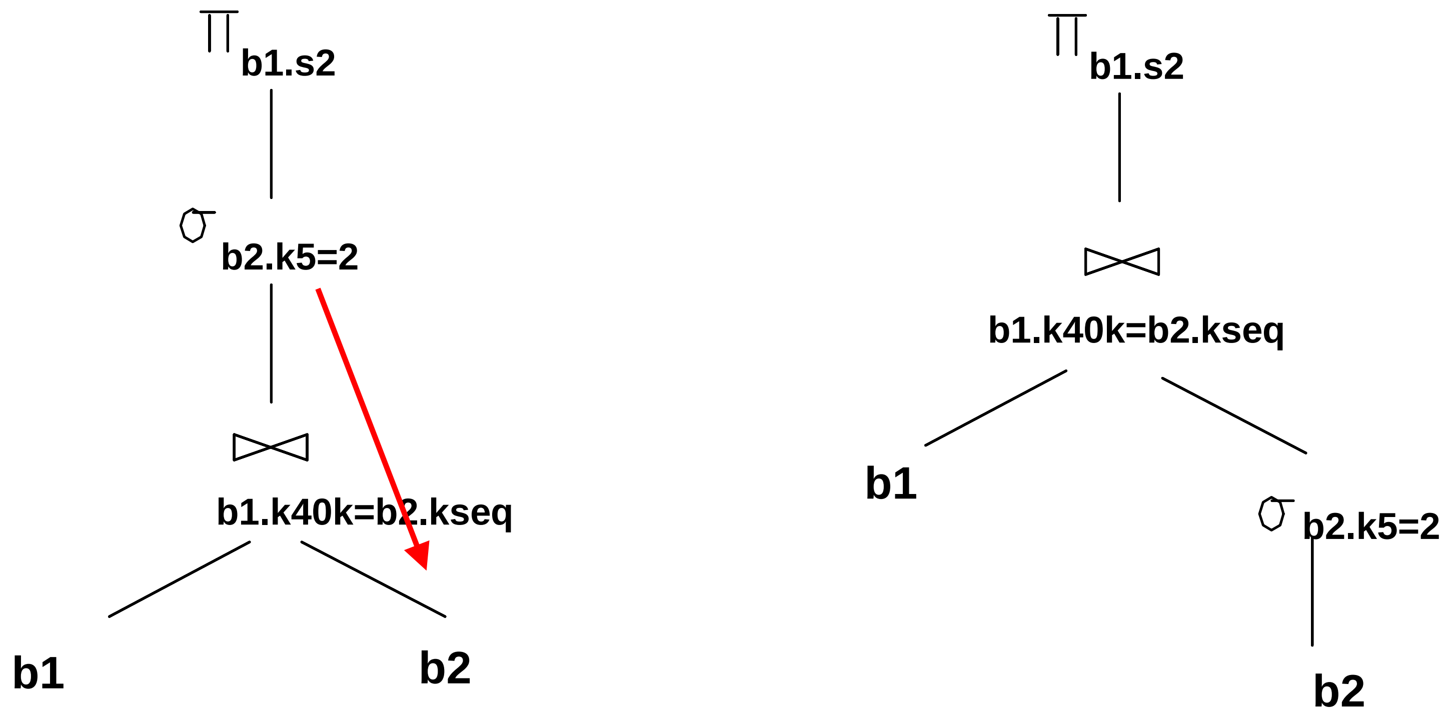
SQL> column column_name format a10

Example with set autotrace …, set timing…

```
SQL> select max(s1) from bench where k500k=2;
MAX(S1)
--------
12345678
Elapsed: 00:00:00.03

| Id  | Operation                    | Name    | Rows  | Bytes   (also Cost, Time)
---------------------------------------------------------------
|   0 | SELECT STATEMENT             |         |     1 |    14 |
|   1 |  SORT AGGREGATE              |         |     1 |    14 |
|   2 |   TABLE ACCESS BY INDEX ROWID| BENCH   |     2 |    28 |
|*  3 |    INDEX RANGE SCAN          | K500KIN |     2 |       |
---------------------------------------------------------------
Predicate Information (identified by operation id):
---------------------------------------------------
   3 - access("K500K"=2)
Statistics
----------------------------------------------------------
          1  recursive calls
          0  db block gets
          5  consistent gets
          5  physical reads  ←unfortunately, physical writes are not reported here
             …
```

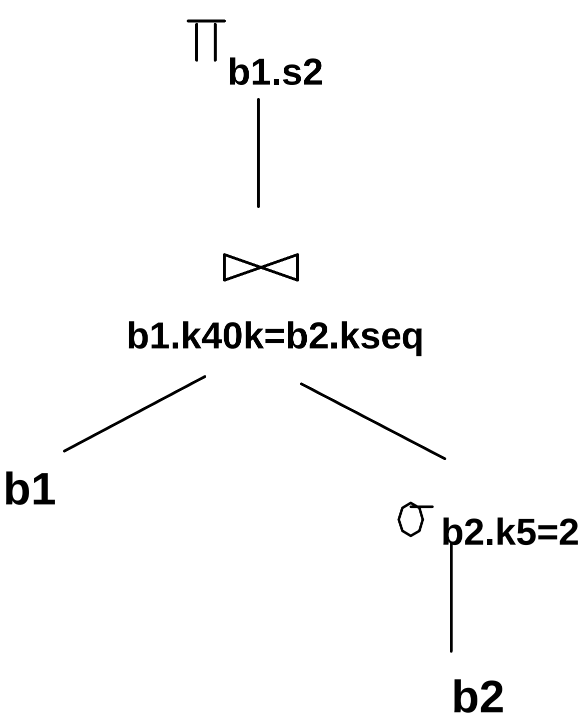
Join Example
(with index on kseq)

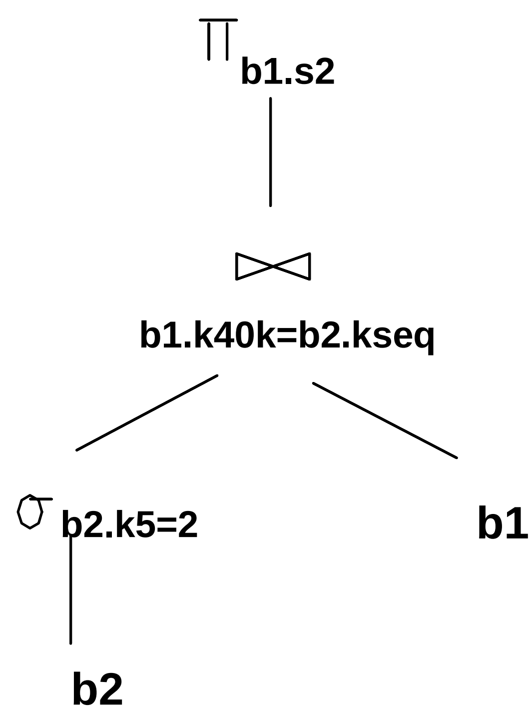
SELECT max(b1.s2)
FROM bench b1, bench b2
WHERE b1.k40k=b2.kseq AND b2.k5=2;



Join Example
(with indexes on k40k and kseq)

```
SELECT max(b1.s2)
FROM bench b1, bench b2
WHERE b1.k40k=b2.kseq AND b2.k5=2;
```





Left-deep tree (for NLJ)

```
SELECT max(b1.s2)
FROM bench b1, bench b2
WHERE b1.k40k=b2.kseq AND b2.k5=2;
```

Oracle uses Hash Join:

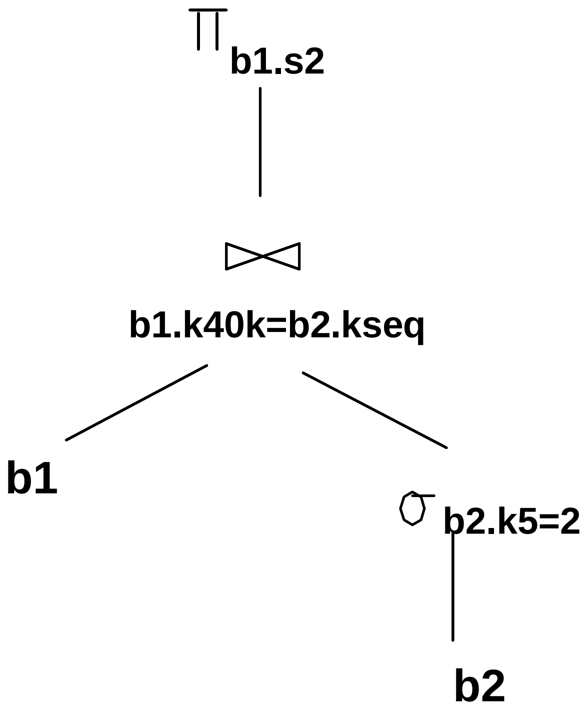
```
-----------------------------------------------------------------------------------
| Id  | Operation            | Name   | Rows   | Bytes |TempSpc| Cost (%CPU)| Time     |
-----------------------------------------------------------------------------------
|   0 | SELECT STATEMENT     |        |      1 |    34 |       | 17998   (1)| 00:00:01 |
|   1 |  SORT AGGREGATE      |        |      1 |    34 |       |            |          |
|*  2 |   HASH JOIN          |        |  1000K|    32M|  3920K| 17999   (1)| 00:00:01 |
|*  3 |    TABLE ACCESS FULL| BENCH |   200K|  1567K|       |  8002   (1)| 00:00:01 |
|   4 |    TABLE ACCESS FULL| BENCH |  1000K|    24M|       |  8003   (1)| 00:00:01 |
-----------------------------------------------------------------------------------

   2 - access("B1"."K40K"="B2"."KSEQ")
   3 - filter("B2"."K5"=2)
```

Line 3: 100000/5 = 200K rows, each with kseq, say 8 bytes, = 1600K = 1.6M bytes, OK

Line 4: all rows, drop all cols except k40k and s2, say 20 bytes = 20M bytes, OK

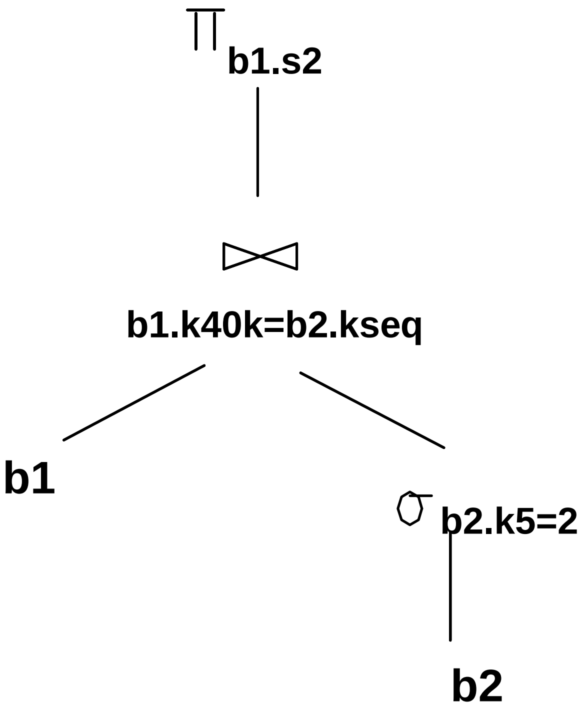
- This hash table is using the temp tablespace instead of dedicated memory, but its pages will be in memory. Here the smaller HT holds 1.6MB data, uses 3.9MB space.
- Recall the rule of thumb that a hash table should be at least twice the size of the data in it.

Hash Join Cost Analysis, case of in-memory HT, no partitioning (for small tables)



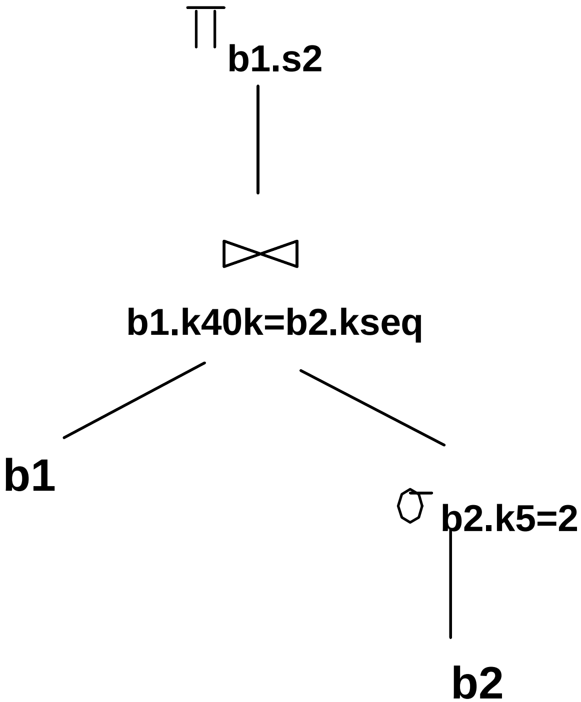
- Hash Join: 1M rows (24MB) from b1, 200K rows (1.5MB) from selection on b2
- So build hash table from b2, should fit in memory (apparently 3.9MB). If not, use partitioning.
- Hash the 1M rows of b1 and output to pipeline
- i/o Cost: read bench twice (once as b1, once as b2), about 60,000 i/os. Less if table fits in memory (our case, so only read it once)
- Mysql can’t do hash join, MariaDB can

Hash Join Cost Analysis, by textbook algorithm



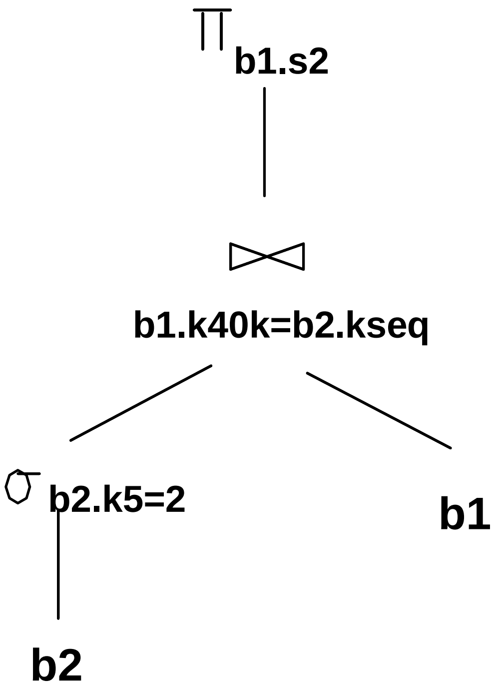
- Hash Join: 1M rows (24MB) from b1, 200K rows (1.5MB) from selection on b2 (see explain plan, slide before last)
- Book assumes partitioning needed first. Suppose only 1MB of memory available.
- So read and write all data of both tables into partitions, say 100 partitions (using 800KB of buffers, about 1MB)
  - For each partition, build hash table from b2, should fit in memory (about .01(3.8M) = 38KB)
  - Hash the 10K rows of b1 part., output to pipeline
- i/o Cost: read both tables, about 60,000 i/os. Write and read incoming tables to HJ: 24MB=3K blocks, 1.5MB = .2K blocks, total 3200 writes, 3200 reads, 6400 i/os.
- Cost = 66,400 i/os.
- Cost = $M + N + 2(M_{HJ}+N_{HJ})$, where M_{HJ} and N_{HJ} are the #pages coming into the HJ operator after selections are made and unused columns are dropped. The book ignores this effect, simplifying to 3(M+N).

Hash Join Optimization with Oracle ("hybrid hash join" of pg. 465)



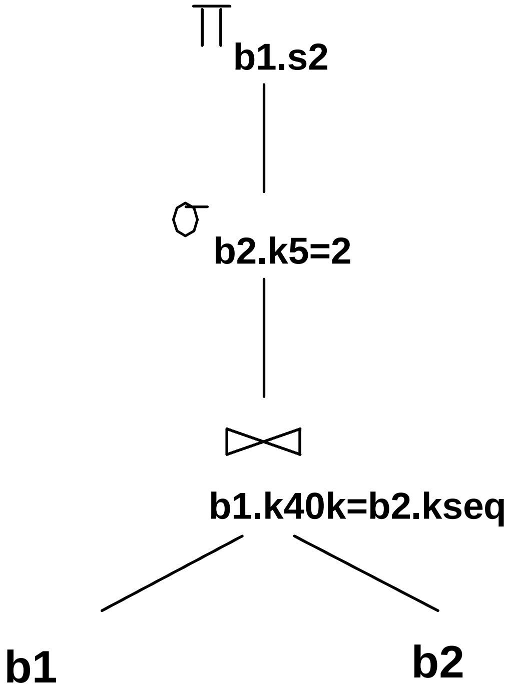
- Oracle partitions all b2 (smaller side) data and builds one or more partition's HT in memory in first pass, while writing other partitions to disk.
- While reading b1 side data, does join with in-memory b2 partition(s), writes out other b1 partitions for later processing (the ones with HTs not yet available)
- Works on processing written-out b1-partitions with next set of in-memory HTs of b2 data, etc.
- i/o Cost: read both tables, about 60,000 i/os. Write and read *parts* of smaller and larger tables.
- For small enough tables, no partition writing at all.
- This way, cost of HJ doesn't jump up as join size crosses needs-partitioning boundary.

Nested Loops Cost Analysis, b2 outer



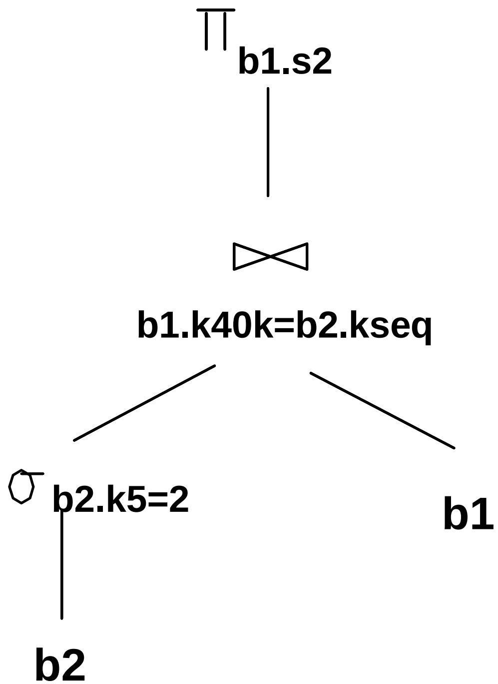
- Indexed NL Join? Not possible, no index on k40k.
- Could consider blocked NLJ.

Nested Loops Cost Analysis, b1 outer



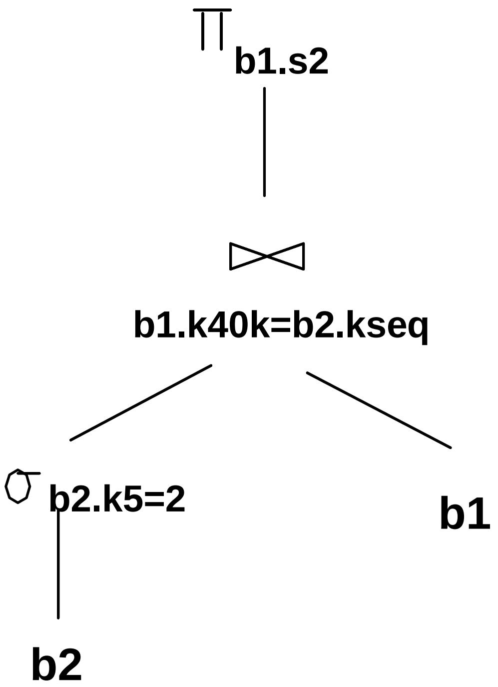
- Indexed NL Join: 1M rows in b2 with index on kseq, 1M rows (20MB) in b1
- Cost: 1 match for each k40k value, 1M index probes, but to only to the first 4% of the table (b2.kseq < 40K), so 40K i/os assuming decent buffering, plus reading b1 table (about 30,000 i/os)
- Cost = 70,000, less if table fits in memory.
- Compare to HJ costs: 60,000 (in-mem HT), 66,400 (partitioning, less if hybrid)
- HJ also benefits from using sequential i/o:
  - NLJ: 30,000 seq + 40,000 random i/os
  - HJ: 60,000-66,400 seq (much faster for HDD)

Paged Nested Loops Cost Analysis



- Paged NL Join: 200K rows (1.5 MB = 190 pages) from selection
- Then read one page of left-side input, read all of b1, then another page, read all of b1.
- Cost: read b1 190 times, b2 once, = 191*30,000 i/os. No good.

Blocked Nested Loops Cost Analysis



- Blocked NL Join: 200K rows (1.5MB) from selection, 1M rows (240MB) in b1
- Cost: assume 1MB memory available, so block = 1MB.
- Then read .75MB (half) of left-side input, read all of b1, then another .75MB, read all of b1.
- Cost: read b1 twice, b2 once, = 90,000 seq i/os.
- Only 60,000 if can use 2MB memory, and that's the same as hash join.
- Mysql v 5.6 can use this approach.

Hash Join Optimization

Since hash joins are common plans used by Oracle, how can we help make them fast?

- Raise pga_aggregate_target to maybe 10% of server memory (exact commands depend on Oracle version)
- Since the hash join speed depends on the size of the tables, be sparing with your select list: avoid select * from …
- Don't worry about indexes on the join condition columns: they won't be used!
  - Of course, if you think NLJ is possible, do use these indexes.
- Add indexes to help with selective single-table predicates: they will be used (on either or both sides) and greatly reduce the size of the join.
- Be more selective with the single-table predicates if possible.
  - Ex: instead of looking at all employees, look at one department's.

What about mysql?

- Mysql v 5.7 (our case on pe07) only joins using nested loops join, including blocked nested loops.
- MariaDB 10.1 (our case on cloud sites) uses hash join too
- Mysql has “explain”, but it is not as complete or easy to understand as Oracle’s.
- Mysql v 5.7 has new JSON-format plans for explain.

Mysql EXPLAIN

```
mysql> explain select max(s1) from bench where k500k=2 and k4=2;
--------------
explain select max(s1) from bench where k500k=2 and k4=2
--------------

+----+-------------+-------+------+---------------+---------+---------+-|
  id | select_type | table | type | possible_keys | key     | key_len | …|
+----+-------------+-------+------+---------------+---------+---------+-|
   1 | SIMPLE      | bench | ref  | k500kin,k4in  | k500kin | 4       | |
+----+-------------+-------+------+---------------+---------+---------+--+
1 row in set (0.00 sec)
```

- In this case, we see mysql chooses the one better key

Mysql can merge indexes

```
mysql>  explain select max(s1) from bench where k500k=2 and k10k=2;
--------------
explain select max(s1) from bench where k500k=2 and k10k=2
--------------
+----+-------------+-------+-------------+---------------+---------------+---------+------+
| id | select_type | table | type        | possible_keys | key           | key_len | ref  |
rows | Extra                                                     |
+----+-------------+-------+-------------+---------------+---------------+---------+------+-
|  1 | SIMPLE      | bench | index_merge | k500kin,k10kin | k500kin,k10kin | 4,4     | NULL |
1 | Using intersect(k500kin,k10kin); Using where |
+----+-------------+-------+-------------+---------------+---------------+---------+------+
```

- Shows index merge of two indexes.
- Though not really worth it: only 2 rows satisfy k500k=2
- This was mysql v5.6. Mysql v5.7 uses only the one index, a better plan

Mysql and joins

- Mysql only uses Nested Loop Joins, and left-deep plans.
- Thus it is sufficient to know the order of the joins and we know the plan tree.
- The explain output lists one line per table, leftmost table first.

Yelp_db core tables

- Review table: the big table in the middle
  - 4.5M rows in both DBs, but different storage of review text/clob (the actual texts of the submitted reviews, up to 64KB in length)
  - Oracle: 6.7GB data (840K 8KB pgs) in Oracle
    - But 1.6 GB of this is in “LOB storage”, separate from main table
    - So main table has 5.1GB data (640K pgs) 1100 bytes/row (incl. review texts < 4KB)
  - Mysql: main table has 3.7GB data (230K 16KB pgs), 820 bytes/row
    - text column data separately stored (all of it, not just bigger review texts)
  - Index on PK = id, clustered only in mysql.
  - Indexes on 2 FK cols: business_id and user_id
- Business table
  - 150K rows, 22MB data (1400 16KB pgs), so 140 bytes/row
  - Index on PK = id, clustered only in mysql.
  - Each business has 30 reviews by simple division: 4.5M/150K = 30
- Yuser table
  - 1M rows, 150MB data (9400 pgs), so 150 bytes/row on ave.
  - Index on PK = id, clustered only in mysql.

- All indexes are B+-tree indexes

Our Yelp queries: query 1

SELECT COUNT(*) FROM yelp_db.business B, yelp_db.review R
WHERE B.id = R.business_id AND R.stars = 5 AND B.state = 'NV';

- Oracle 12c on dbs3: (5.5s starting from empty buffer cache)

First run

```
  COUNT(*)
----------
    723579

Elapsed: 00:00:03.71
```

Second run

```
  COUNT(*)
----------
    723579

Elapsed: 00:00:02.08
```

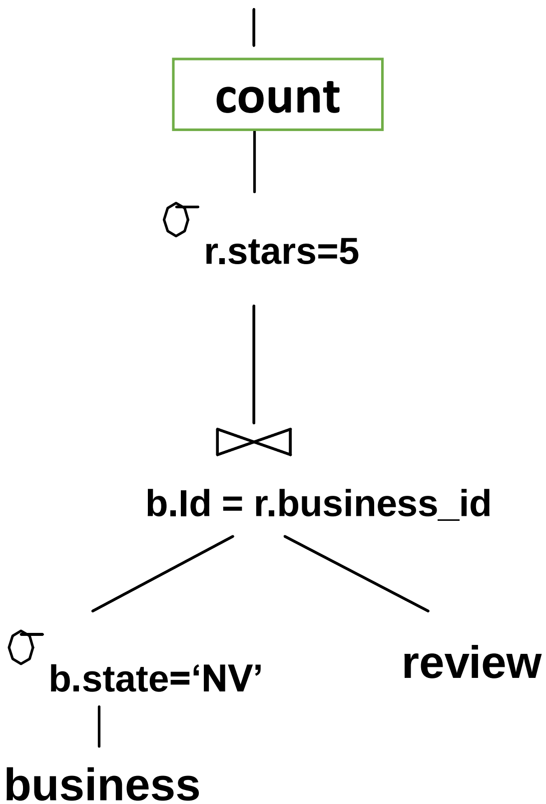
- Mysql 5.7 on pe07:

```
+----------+
| COUNT(*) |
+----------+
|   725915 |
+----------+
1 row in set (36.45 sec)
```

```
+----------+
| COUNT(*) |
+----------+
|   725915 |
+----------+
1 row in set (36.48 sec)
```

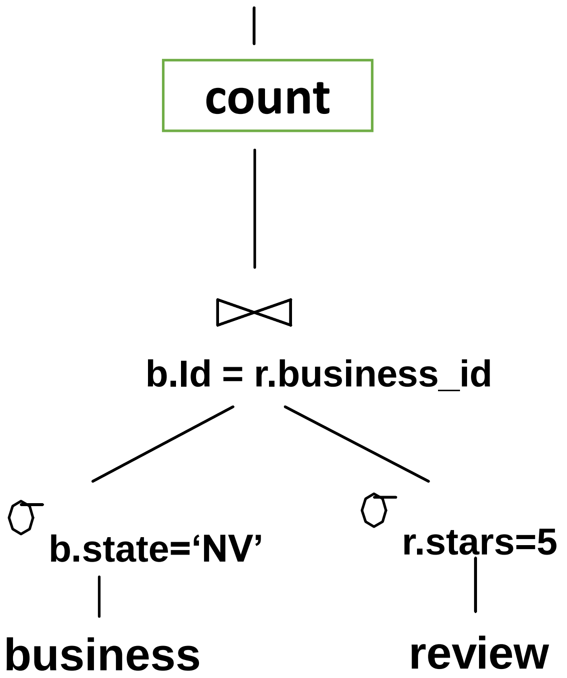
- These second runs are using cached data. How does Oracle win by factor of 17?

Nested Loops Cost Analysis, business outer



- Indexed NL Join: 4.5M rows in review with index on business_id, 150K rows in business, 30K in 'NV' (RF = 0.2)
- Cost: 30K index probes, each matching 30 reviews, then follow rid, plus reading outer table (about 1400 i/os using 16KB pages, 2800 for 8KB pgs)
- Cost = 30*30K + 1400/2800 = 900K i/os, unless table fits in memory (and it does, in effect)
- We will see this is mysql's choice.
- Note: 900K row accesses hits almost all pages in the mysql table, since it has only 230K pages.

Hash Join Cost Analysis, case of in-memory HT, no partitioning (for small smaller table)



- Hash Join: 0.8MB from selection on business, 50MB from selection on review
- So build hash table from business, should fit in memory. (If not, use partitioning.)
- Hash the rows of review and output to pipeline
- i/o Cost: read both tables, about 230K 16KB i/os. , 643K 8KB sequential i/os (Oracle tables).
- We will see this is Oracle's choice
- Mysql can't do hash join, MariaDB can

Oracle plan: Hash Join

```
SELECT COUNT(*) FROM yelp_db.business B, yelp_db.review R
WHERE B.id = R.business_id AND R.stars = 5 AND B.state = 'NV';

-------------------------------------------------------------------
| Id  | Operation             | Name      | Rows  | Bytes | Cost (%CPU)|
---------------------------------------------------------------------|
|   0 | SELECT STATEMENT      |           |     1 |    53 |   229K (1) |
|   1 |  SORT AGGREGATE       |           |     1 |    53 |            |
|*  2 |   HASH JOIN           |           |   390K|    19M|   229K  (1)|
|*  3 |    TABLE ACCESS FULL| BUSINESS | 30571 |   806K|   752   (1)|
|*  4 |    TABLE ACCESS FULL| REVIEW   |  1982K|    49M|   228K  (1)|
---------------------------------------------------------------------
   2 - access("B"."ID"="R"."BUSINESS_ID")
   3 - filter("B"."STATE"='NV')
   4 - filter("R"."STARS"=5)
```

Mysql plan: Indexed NLJ, business outer

```
mysql> explain SELECT COUNT(*) FROM yelp_db.business B,
yelp_db.review R  WHERE B.id = R.business_id AND R.stars =
5 AND B.state = 'NV';
+----+-------------+-------+------------+------+----------
| id | select_type | table | partitions | type
| possible_keys             | key                        | key_len
| ref           | rows      | filtered   | Extra       |
+----+-------------+-------+------------+------+----------
|  1 | SIMPLE      | B     | NULL       | ALL
| PRIMARY                   | NULL                       | NULL
| NULL           | 155160   |   10.00    | Using where |
|  1 | SIMPLE      | R     | NULL       | ref
|fk_reviews_business1_idx  | fk_reviews_business1_idx | 68
|yelp_db.B.id   |     36    |    10.00   | Using where |
+----+-------------+-------+------------+------+----------
```

- This report shows mysql does an indexed NLJ with business (B) the outer table (the first listed table here).

Oracle Hash Join wins over Mysql NLJ

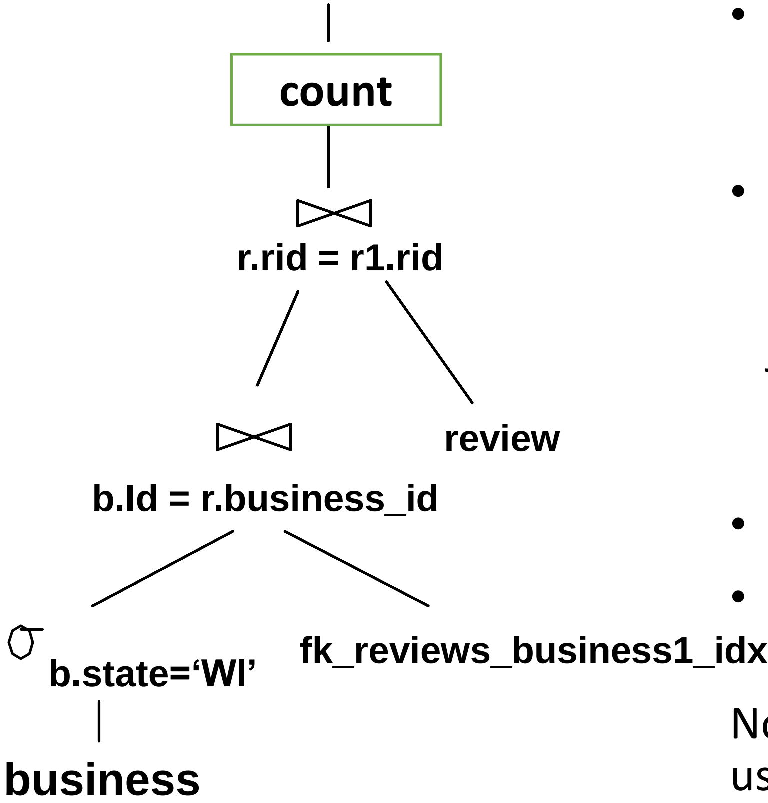
- Oracle chooses 840K seq. i/o for HJ over 900K random i/os for NLJ here, clear winner because seq. i/o is so much faster.
  - Recall we earlier estimated seq. i/o is up to 25x faster on HDD even if data is trapped in a tablespace for random i/o.
  - Of course dbs3 has much faster disk system than pe07
- Similar story for the other two queries: HJ vs. NLJ, HJ wins.
- We don't really know why Oracle is 17x faster using cached data, since no disk i/o is happening in that case.
  - Streaming data in memory is faster than random access in memory, one effect (more CPU cache traffic with random access)
  - The systems have similar CPUs, though pe07 has 2 processors vs. 1 for dbs3
  - pe07 has twice as much memory as dbs3 (128GB vs 64GB)

Oracle chooses a NLJ for state='WI'

WI has only 4190 businesses, compared to 30K for NV

```
SQL>  explain plan for SELECT COUNT(*) FROM yelp_db.business B, yelp_db.review R
WHERE B.id = R.business_id AND R.stars = 5 AND B.state = 'WI';
| Id  | Operation                    | Name                       | Rows  | Bytes
--------------------------------------------------------------------------------
|   0 | SELECT STATEMENT             |                            |     1 |    53 |
|   1 |  SORT AGGREGATE              |                            |     1 |    53 |
|   2 |   NESTED LOOPS               |                            | 53467 |  2767K|
|   3 |    NESTED LOOPS              |                            |  125K |  2767K|
|*  4 |     TABLE ACCESS FULL        | BUSINESS                   |  4190 |   110K|
|*  5 |     INDEX RANGE SCAN         | FK_REVIEWS_BUSINESS1_IDX | 30 |       |
|*  6 |    TABLE ACCESS BY INDEX ROWID| REVIEW                    |    13 |   338 |
 -------------------------------------------------------------------------------
Predicate Information (identified by operation id):
---------------------------------------------------
   4 - filter("B"."STATE"='WI')
   5 - access("B"."ID"="R"."BUSINESS_ID")
   6 - filter("R"."STARS"=5)
```

Nested Loops Cost Analysis, state='WI' (Oracle uses NLJ, twice)



- Indexed NL Join: 4.5M rows in review with index on business_id, 150K rows in business, 4K in 'WI' (RF = 0.06)
- Cost: 4K index probes in first join (which find all 30 matches together) then follow r1.rids (4.1K*30=125K est., actually 100K) in second join, check stars=5, plus reading outer table (about 1400 i/os using 16KB pages, 2800 for 8KB pgs)
- Cost = 31*4K + 1400/2800 = 125K i/os
- Cost of HJ = 640K sequential i/os, 5x this NLJ cost, but we expect seq. i/o to be much faster.

Note: Since v 11g, the rid access to review is using "vector i/o", where multiple requests are sent at once to the disk system (after sort of rids), causing it to be much faster than normal random i/o.

Oracle NLJ vs mysql NLJ: state='WI' query

Oracle: using two NLJs as shown on last slide, cost = 125K i/os

- First, after "alter system flush buffer_cache;" to clear buffer cache
  - Elapsed: 00:00:01.84 (only 0.015 ms/io, so not normal "random i/o")
- Second: table data should be in buffer cache
  - Elapsed: 00:00:00.35

Mysql time: using single NLJ as shown earlier (cost = 4K*30 = 120K i/os)

- First time (but some data in OS buffers)
  - 1 row in set (2.70 sec)
- Second time: table data should be in buffer cache
  - 1 row in set (2.69 sec)

Oracle Bitmap Indexes

```
create table emps (
  eid char(5) not null primary key,
  ename varchar(16),
  mgrid char(5) references emps,
  gender char(1), salarycat smallint, dept char(5));
create bitmap index genderx on usemps(gender); (2
values, 'M' &'F')
create bitmap index salx on usemps(salrycat);  (10
values, 1-10)
create bitmap index deptx on usemps(dept);  (12 vals, 5
char: 'ACCNT')
```

- Best for low-cardinality columns
  - Bitmap for gender='M': 0010111…
  - Bitmap for gender='F': 1101000…

Bitmap indexes, cont.

- Even with a null-value bitmap, only 3 bits/row for gender
- ORACLE uses ***compression*** for low-density bitmaps, so they don't waste space.
- Note: Call a bitmap "verbatim" if not compressed.
- Fast AND and OR of verbatim bitmaps speeds queries. Idea is: overlay unsigned int array on bitmap, loop through two arrays ANDing array (& in C), and producing result of AND of predicates. Parallelism speeds things (64 bits at a time).
- But for updates, bitmaps can cause a slowdown when the bitmaps are compressed (need to be decompressed, may recompress differently). Don't use bitmap indexes if have frequent updates (OLTP situation).

Query plan with bitmap indexes

```
EXPLAIN PLAN FOR SELECT * FROM t WHERE c1 = 2  AND c2 <>
6 OR c3 BETWEEN 10 AND 20;

SELECT STATEMENT
   TABLE ACCESS T BY INDEX ROWID
      BITMAP CONVERSION TO ROWID
         BITMAP OR
            BITMAP MINUS
               BITMAP MINUS
                  BITMAP INDEX C1_IND SINGLE VALUE
                  BITMAP INDEX C2_IND SINGLE VALUE
               BITMAP INDEX C2_IND SINGLE VALUE
            BITMAP MERGE
               BITMAP INDEX C3_IND RANGE SCAN
```

Bitmap plan discussion

- In this example, the predicate c1=2 yields a bitmap from which a subtraction can take place.
- From this bitmap, the bits in the bitmap for c2 = 6 are subtracted.
- Also, the bits in the bitmap for c2 IS NULL are subtracted, explaining why there are two MINUS row sources in the plan.
- The NULL subtraction is necessary for semantic correctness unless the column has a NOT NULL constraint.
- The TO ROWIDS operation is used to generate the ROWIDs that are necessary for the table access.

Scaling up

- Our experiments are using a single disk, so parallelism is not important.
- Serious databases use RAID, so multiple disks are working together, more or less like one faster disk.
- Huge databases use partitioning and query plans where work on different partitions proceeds in parallel.
- Will return to this when studying data warehousing.