CS3223
AY22/23 Sem 2
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L4: Query Evaluation - Sort, Select

Sorting - External Merge Sort

Projection, join, bulk loading etc all require sorting

- Uses B number of buffer pages
- Pass 0: Creation of sorted runs
  - Read in and sort B pages at a time
  - Number of sorted runs created = $\lceil N/B \rceil$
  - Size of each sorted run = B pages (except possibly for last run)
- Pass i, $i \geq 1$: Merging of sorted runs
  - Use $B-1$ buffer pages for input & one buffer page for output
  - Performs (B-1)-way merge
- Analysis:
  - N_0 = number of sorted runs created in pass 0 = $\lceil N/B \rceil$
  - Total number of passes = $\lceil \log_{B-1}(N_0) \rceil + 1$
  - Total number of I/O = $2N(\lceil \log_{B-1}(N_0) \rceil + 1)$
    - Each pass reads N pages & writes N pages

# of merges needed

first pass

N because we only write back N pages

External Merge Sort - Bocked I/O

- Read and write in blocks of **b** buffer pages (replace b with 1 for unoptimised)
- $\lfloor \frac{B-b}{b} \rfloor$ blocks for input, 1 block for output
- Can merge at most $\lfloor \frac{B-b}{b} \rfloor$ sorted runs in each merge pass
- $F = \lfloor \frac{B}{b} \rfloor - 1$ runs can be merged at each pass
- Num passes = $\log_F N_0$

B+ tree sort

- B+ Tree is sorted by key
- Format 1 (clustered): Sequential Scan
- Format 2/3:Retrieve data using RID for each data entry
- Unclustered implies more I/Os

Access Path refers to the different ways to retrieve tuples from a relation. It is either a **file scan** or a **index plus matching selection condition**. The more **selective** the access paths, the fewer pages are read from the disk.

- Table scan: scan all data pages
- Index scan: scan all index pages
- Table intersection: combine results from multiple index scans (union, intersec). Find RIDs of each predicate and get the intersection

Query: Selection Covering Index

- I is a covering index of $query_Q$ if I contains all attributes of Q
- No RID lookup is needed, Index-only plan
- If data is unclustered, unsorted, no index $\rightarrow$ best way is to collect all entries and sort by RID before doing I/O

CNF Predicate

- Find RIDs of each predicate and get the intersection
- Conjuncts are in the form (R.A op c V R.a op R.b)
- CNF are conjucts (or terms) connected by $\wedge$

Matching Predicates - B+ Tree

- Non-disjunctive CNF (no $\vee$)
- At most one non-equality comparison operator which must be on the **last attribute in the CNF**
- $(k_1 = c_1) \wedge (k_2 = c_2) \wedge ...k_i op c_i | I = (k_1, k_2 ... k_n)$
- The order of k matters, and there cannot be missing K_i in the middle of the CNF
- Having inequality operator before equality operator makes the query to be less selective

Matching Predicates - Hasing

- No inequality operators $(k_1 = c_1) \wedge ...k_i = c_n | I = (k_1, k_2 ... k_n)$
- Unlike B+ tree, **all predicates must match**

I=(age, weight, height), p=($age \geq 20 \wedge age \geq 18 weight = 50 \wedge height = 150 \wedge level = 3$)

Primary Conjuncts : The subset of conjuncts in p that I matches

Primary Conjuncts: $age \geq 20 \wedge age \geq 18$

Covered Conjuncts : The subset of conjuncts in p that I covers (conjuncts that appear in I). Primary conjunct $\subseteq$ covered conjunct

Covered Conjuncts: $age \geq 20 \wedge age \geq 18 \wedge height = 150$

Cost Notation

Notation	Meaning
r	relational algebra expression
$\|\|r\|\|$	number of tuples in output of r — data records
$\|r\|$	number of pages in output of r
b_d	number of data records that can fit on a page σ [d+1, 2d+1]
b_i	number of data entries that can fit on a page
F	average fanout of B$^+$-tree index (i.e., number of pointers to child nodes)
h	height of B$^+$-tree index (i.e., number of levels of internal nodes)
	$h = \lceil \log_F(\lceil \frac{\|\|R\|\|}{b_i} \rceil) \rceil$ if format-2 index on table R
B	number of available buffer pages

Cost of B+-tree index evaluation of p

Let p'=primary conjuncts of p (**matching**) — p_c=covered conjuncts of p

1. Navigate internal nodes to locate the first leaf page

$$Cost_{internal} = \begin{cases} \lceil log_F(\lceil \frac{||R||}{b_d} \rceil) \rceil | Format1 \\ \lceil log_F(\lceil \frac{||R||}{b_i} \rceil) \rceil | Otherwise \end{cases}$$

1.1 This is traversing the height of B+ tree

2. Scan leaf pages to access all qualifying data entries

$$Cost_{leaf} = \begin{cases} \lceil \frac{||\sigma_{p'}(R)||}{b_d} \rceil | Format1 \\ \lceil \frac{||\sigma_{p'}(R)||}{b_i} \rceil | Otherwise \end{cases}$$

- This is the cost of reading qualifying conjuncts
- Using p_c would be wrong since covering conjuncts may be non-matching which results in more reads from the leaves.
- Conversely, non-matching (but covered) conjuncts cannot be derived from the B+ tree and needs to be read from disk
- Retrieve qualified data records using RID lookups. 0 if I is covering OR format 1 index. $||\sigma_{p_c}(R)||$ otherwise
- includegraphics[width=5cm, height=1.3cm]optimisation.png

Cost of Hash index evaluation of p (all covered index are matched)

- Format 1: cost to retrieve **data entries** is at least $\lceil \frac{||\sigma_{p'}(R)||}{b_d} \rceil$
- Format 2: cost to retrieve **data entries** is at least $\lceil \frac{||\sigma_{p'}(R)||}{b_i} \rceil$
- Format 2: Cost to retrieve **data records** is 0 if it is a covering index (all information in data entry) OR $||\sigma_{p'}(R)||$ otherwise

L5:Query Evaluation - Projection and Join

- $\pi^*(R)$ refers to projection without removing duplicates
- $\pi(R)$ involves 1.Removing unwanted attributes 2. Removing duplicates
- Sorting is better if we have many duplicates or if hte distribution is nonuniform(overflow more likely for hashing paritions)
- Sorting allows results to be sorted
- If $B > \sqrt{|\pi^*_L(R)|}$, then both sorting and hashing has similar I/O costs ($\lceil \frac{\lceil R \rceil}{B} \rceil \rightarrow |R| + 2 * |\pi^*_L(R)|$)

Approach 1: project based on sorting

- **Naive**: Extract attributes L from records $\rightarrow \pi^*_L(R) \rightarrow$ Sort attributes $\rightarrow$ Remove duplicates
- Cost: Cost to scan records ($|R|$) + Cost to output to temporary result ($|\pi^*_L(R)|$) $\rightarrow$ cost to sort records ($2|\pi^*_L(R)| \log_m(N_0) + 1$) $\rightarrow$ Cost to scan data records $|\pi^*_L(R)|$
- **Optimisation**: Create Sorted runs with attributes L only (Pass 0) $\rightarrow$ Merge sorted runs and remove duplicates $\rightarrow \pi_L(R)$

Approach 2: project based on hashing

- Build a main-memory hash table to detect and remove duplicates. Insert to the hashtable if then entry is not already in it.
- 1. Partition R into $R_1, R_2 ... R_{B-1}$, hash on $\pi_L(t)$ for $t \in R \leftarrow (\pi^*_L(R_i)$ does not intersect $\pi^*_L(R_j), i! = j)$

1.1 Use 1 buffer for input and (B-1) for output

1.2 Read R 1 page at a time, and hash tuples into B-1 partitions

1.3 Flush output buffer to disk when full

- 2. Eliminate duplicates in each partition $\pi^*_L(R_i)$
- $\pi_L(R) = \cup_i^{B-1}(\pi_L(R_i))$

2.1 For each partition, Initialise an in-memory hash table and insert each tuple into B_j if $t \notin B_j$

Parition overflow: Hash table $\pi^*_L(R_i)$ is larger than available memory buffers.

Solution: Recursively apply hash-based partitioning to overflowed partitions.

Analysis: Effective (no overflow) when B $> \frac{|\pi^*_L(R)|}{B-1} * f \approx \sqrt{f * \pi^*_L(R)|}$

If no partition overflow: (partition)$|R| + \pi^*_L(R)|$ + (duplicate elimination)$|\pi^*_L(R)|$

Join

$R \bowtie_\theta S$, where R is the outer relation and S is the inner relation

Optimal join

- Cost: $|R| + |S|$
- load smaller relation into memory
- requires: $|S| + 2$ buffers

Tuple-based

- Cost: $|R| + ||R|| * |S|$
- for each tuple r in R
- for each tuple s in S
- if (r matches s) then output (r, s)4 to result

Page-based

- Load P_R and P_S to main memory
- Cost: $|R| + |R| * |S|$
- for each page P_R in R
- for each page P_S in S
- for each tuple $r \in P_R$
- for each tuple $s \in P_S$
- if (r matches s) then output (r, s)4 to result

Block nested-loop

- Allocate 1 page for S, 1 for output, B-2 for R $|R| \leq |S|$
- Cost: $|R| + (\lceil \frac{|R|}{B-2} \rceil * |S|)$
- $|R| \leq |S|$
- while Scanning R
- read next (B-2) pages of R to buffer
- for P_S in S
- read P_S into Buffer
- for $r \in buffer \wedge s \in P_S$
- if (r matches s) then output (r, s)4 to result
- Without materialisation: $\lceil \frac{|R|}{B-2} \rceil * |T|$

Index Nested Loop Join

- There is an index on the join attributes of S
- Uniform distribution: r joins $\lceil \frac{||S||}{||\pi_{B_j}(S)||} \rceil$ tuples in S
- format 1 B+Tree:$|R| + ||R|| * J$
- Assuming unclustered:
- J = height of tree + reading leaf pages + RID Look up
- J = $\log_F(\lceil \frac{||S||}{b_d} \rceil)$ (tree traversal)+$\lceil \frac{||\pi_{p'}(S)||}{b_i} \rceil$ (search leaf nodes) + RID lookup
- for $r \in R$
- use r to probe S's index to find matching tuples

Sort-Merge Join

- Sort R and S on join attributes and merge
- Cost: $2|\pi^*_L(R)|(\log_{B-1}(\frac{|R|}{B}) + 1)$ + $2|\pi^*_L(S)|(\log_{B-1}(\frac{|S|}{B}) + 1)$ + $|\pi^*_L(R)| + |\pi^*_L(S)|$
- merging cost is $|R| + ||R|| * |S|$ if each tuple of R requires a full scan of S
- Optimisation: $B \geq N(R, i) + N(S, i) + 1 \geq \sqrt{|R| + |S|}$
- We can choose which relation to partition again if this is not met
- Cost: cost of getting R, S + k(write out ($|R| + |S|$)) + m(merge ($|R| + |S|$))
- If sorted on join column: $|R| + |S|$

Grace Hash Join

- Partition into $B - 1$ partitions
- If no partition overflow ($B > \sqrt{f * |S|}$):
- k(Cost to partition R, S) + Cost of probe phase
- Partition cost = cost of getting R + cost to write partitions($|R|$)
- Probe cost = $|R| + |S|$

L6: Query Optimisation

1. Search space: Queries considered

- **Search Place** Queries being considered
- **Linear** if at least one operand for each join is a base relation, bushy otherwise
- **Left-deep** if every right join operand is a base relation
- **Right-deep** if every left join operand is a base relation

2. Plan enumeration - for joins between 2 tables

- Basic DP is not always Optimal since it goes for lowest current cost and ignores the sorted property of outputs
- **Enhanced DP:** left-deep only, avoids cross products, considers early selection and projections, considers order of output

SPJ = SELECT , PROJECT, JOIN

Dynamic programming formulation NP Hard :(. Normally there is a limit to how many tables are needed. PSQL sets it to 12, any larger we wont use DP

```
Input: A SPJ query q on relations R_1, R_2, ..., R_n
Output: An optimal query plan for q
for i = 1 to n do// consider 1 relation plan --> best plan for accessing that table
    optPlan({R_i}) = best access plan for R_i
for i = 2 to n do  i// consider all subset of relations of size 1
    for each S ⊆ {R_1, ..., R_n}, |S| = i do      // subsets
        bestPlan = dummy plan with cost(bestPlan) = ∞
        for each S_j, S_k, |S_j| ∈ [1, i), S = S_j ∪ S_k do  // ways to form this subset
            p = best way to join optPlan(S_j) and optPlan(S_k)
            if (cost(p) ≤ cost(bestplan)) then  // use the optimal plan identified in previous iterations
              bestPlan = p
        optPlan(S) = bestPlan   // best plan for subset is updated
return optPlan({R_1, ..., R_n})
```

3. Cost Model

- **Uniformity:** uniform distribution of all values
- **Independence:** Independent distribution of values in different attributes
- **Inclusion:** for $R \bowtie S, if ||\pi_A(R)|| \leq ||\pi_B(S)||$ then $\pi_A(R) \subseteq \pi_B(S)$

Plans-no join, 1 table

- **Table scan** Scan the entire table. Cost: $|R|$
- **Index scan** Scan the index. Cost: 2 + $|$leaf pages satisfying the predicate$|$ + $||$entries satisfying predicate$||$ (unclustered)
- **Index intersection with** I_a I_b Cost to find relevant entries from index and materialise(R and s) + cost to intersect partitions 1,2 (block nested, grace hash, sort merge)+ cost to RID lookup (if more attributes are needed)
- cost to partition: Scan index for matching pages + cost to write partitions from matching entries

Histogram

- **Equiwidth** Each bucket has equal number of values
- Estimate: $\frac{1}{|bucket|}$ * $||bucket||$
- **Equidepth** Each bucket has equal number of tuples
- Sub-ranges can overlap, tuples of the same value can be in 2 adjacent buckets
- $\frac{1}{|bucke_A|}$ * $||bucket_A||$ + $\frac{1}{|bucke_B|}$ * $||bucket_B||$ + ...
- **MCV** Separately track the top-k MCV and exclude them from the bucket

Size of query

- **Join** $||R|| * ||S|| * \frac{1}{max(||\pi_b(R)||, ||\pi_b(S)||)}$
- **Select - OR** $(1 - (p(\ a! = x) * p(\ b! = y)) * ||R||)$
- **Select - AND** $p(a = x) * p(b = y) * ||R||$

L7: Transaction Management

View Equivalent

- If R_i reads A from one write W_j in S, then R_i must also read A from the same write W_j in S'
- For each data object A, Xact (if any) that performs final write on A in S must also perform final write on A in S'

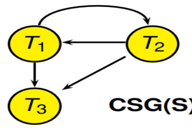
Conflicting actions - WW, WR

- **Dirty Read-WR** T2 read uncommited write from T1
- **Unrepeatable Read-WR** T2 updates an object that T1 has previously read and T2 commits while T1 is still in progress $\rightarrow$ T1 can get a different value from read
- **Lost Update-WW** T2 overwrites the value of an object that has been modified by T1 while T1 is still in progress
- **View serializable - view equivalent to some serial S** cannot be view serializable if the above anomalies occur. Conversely, no anomalies occur if view serializable.
- **Blind write** $R_1(X), W_2(Y), W_1(X)$ Blind write: $W_2(Y)$
- **Conflict Serializable** Conflict equivalent to serial schedule, view serializable and not blind write
- **Non Conflict Serializable** find conflicting action pairs(R1(x) W2(x)), (R2(x) W1(x))
- Conflicting actions does not mean not serializable, there needs to be a cycle
- $CSS \subsetneq VSS \subsetneq MVSS$. The more restrictive, the less concurrent and less resources are needed to check serializability

Conflict Serializability Graph

- V contains a node for each committed Xact in S
- E contains (T_i, T_j) if an action precedes and conflicts with one of T_j's actions

$R_1(A)$, $W_2(A)$, $Commit_2$, $W_1(A)$, $Commit_1$, $W_3(A)$, $Commit_3$



CSG(S)

ACID

- **Atomicity** Either all actions of a transaction are committed or none are
- **Consistency** Each transaction is consistent and DB begins in a consistent state $\rightarrow$ DB ends in a consistent state
- **Isolation** Execution of one xact is isolated from other Xacts
- **Durability** Once a transaction is committed, its effects persists
- Concurrency control ensures isolation
- Recovery manager ensures atomicity and durabilitt
- Consistency is ensured by constraints, cascades and triggers

Schedules

- **Cascading aborts** T_i read from $T_j \rightarrow T_j$ aborts $\rightarrow T_i$ aborts. This requires high book keeping efforts, so we turn to recoverable schedules instead.
- **Recoverable** $\forall T \in S$ T2 must commit after T1 if T2 reads from T1 (or T2 aborts before T1). Can still have cascading aborts. Is compulsory.
- **Cascadeless** Whenever T_i reads from T_j in S, Commit must precede this action. This is desirable, not compulsory.
- Theorem 4: Cascadeless $\rightarrow$ Recoverable (not iff)
- **Recovery with before image** Store the before image before write, restore this before image if write aborts. This can lead to **lost update** anomaly if the before image overwrites another Xact's write.
- **Strict** to use before-images, $\forall W_i(O) \in S$, O is not read or written by another Xact until Ti either aborts or commits. This ensures no lost update anomaly during recovery.
- Strict schedules allows recovery using before images to be more efficient but restricts concurrency
- Theorem 5: Strict $\rightarrow$ Cascadless (not iff)

2PL

- To read an object O, a Xact must hold a S-lock or X-lock on O
- To write to an object O, a Xact must hold a X-lock on O
- Once a Xact releases a lock, the Xact can't request any more locks
- Theorem 1: 2PL is conflict serializable

L8: Concurrency Control

Lock based concurrency control

- If lock request is not granted, then T becomes blocked and gets added to O's request queue

Strict 2PL

- A Xact must hold on to locks until Xact commits or aborts
- Theorem 2: Strict 2PL is strict and conflict serializable
- Strict 2PL prevents cascading rollback and deadlock and ensures recoverability

Detect deadlocks

- Waits-for graph (WFG) → Deadlock is detected if WFG has a cycle. $(V_i, V_j \rightarrow T_i waits - for T_j)$
- Breaks a deadlock by aborting a Xact in cycle

Deadlock Prevention

- Each Xact is assigned a timestamp when it starts
- Assume older (smaller time stamp) Xacts have higher priority than younger Xacts
- Tie between blocked/restarted xact brokered by priority, priority is maintained after abort
  - Suppose T_i requests for a lock that conflicts with a lock held by T_j
  - Two possible deadlock prevention policies:
    - Wait-die policy: lower-priority Xacts never wait for higher-priority Xacts
    - Wound-wait policy: higher-priority Xacts never wait for lower-priority Xacts

Prevention Policy	T_i has higher priority	T_i has lower priority
Wait-die	T_i waits for T_j	T_i aborts
Wound-wait	T_j aborts	T_i waits for T_j

Multi Version Serializable Schedle (MVSS)

- **multiversion view equivalent** if S and S' have the same set of read-from relationships
- i.e. Ri (xj) occurs in S iff Ri (xj) occurs in S'
- **Monoversion Schedule** each read action returns the most recently created object version
- **MVSS** if there exists a serial Monoversion schedule that is multiversion view equivalent to S
- Note that a MVSS is not necessarily conflict serializable schedule if it is not a valid monoversion schedule
- E.g. W1(x1), R2(x0), R2(y0), W1(y1), C1, C2 is MVSS with (T2, T1) but contains conflicting actions W1(x1) and R2(X0)

Snapshot Isolation (SI)

- Each Xact has a snapshot of the database at the start of the Xact and sees only versions from that snapshot and **its own writes**
- **FUW** T needs to acquire X-lock on O (if not - wait), and if O has been updated by a concurrent T' then T aborts
- **FCW** (no locks) before commiting T checks if O has been updated, abort if it has been updated
- **Write-skew anomaly**, not MVSS: $R_1(X_0), R_2(X_0), R_1(Y_1), R_2(Y_2), W_1(X_1), Commit1, W_2(Y_2), Commit2$
- **Read-only anomaly**,not MVSS: $R_1(b), R_2(a), W_1(b), C_1, R_2(b), W_2(a), R_3(a), R_3(b), C_3$

Transaction Dependencies

- **WW** from T1 to T2: T1 commits some version of X and T2 writes the immediate successor
- **WR** from T1 to T2: T1 commits some version of X which is read by T2
- **RW** from T1 to T2: T1 reads some version of X and T2 commits the immediate successor
- **DSG** V = xacts, E = Dependencies, use $-->$ for concurrent transactions and $\rightarrow$ for non-concurrent

Lock Requested	Lock Held: -	IS	IX	S	X
IS	✓	✓	✓	✓	×
IX	✓	✓	✓	×	×
S	✓	✓	×	✓	×
X	✓	×	×	×	×

L10-Recovery

Policies

- **Steal:** Allows dirty pages to be written to disk before commit
- **Force:** Requires all dirty pages to be written to disk when commit
- No-steal: no undo, Force: no redo. Pgsql uses steal and no-force

Restart: analysis, redo, undo

- Analysis: identifies dirtied pool pages and active Xacts at time of crush
- Redo: redo actions to restore db to pre-crush
- Undo: undo actions of Xacts that did not commit

Analysis: Xact table

1. When the first log record is created, create a new entry T with status U
2. Update lastLSN for T to be r's LSN
3. Remove T if end log is seen

Analysis: Dirty Page Table

1. New dirtied page will be added to the DPT with recLSN=r.LSN
2. Remove entry when it is flushed to disk

LOG

	prevLSN	XactID	type	pageID	length	offset	before image	after image
10	-	T_1	update	P500	3	21	ABC	DEF
20	-	T_2	update	P600	3	41	HIJ	KLM
30	20	T_2	update	P500	3	20	GDE	QRS
40	10	T_1	update	P505	3	21	TUV	WXY

DIRTY PAGE TABLE

pageID	recLSN
P500	10
P600	20
P505	40

XACT TABLE

XactID	lastLSN	status
T_1	40	U
T_2	30	U

Redo Phase (DPT)

1. Redo LSN = min(recLSNs), then fetch page LSN,
2. if r.LSN $>$ pageLSN and Page is in DPT, redo
3. Update pageLSN to r.LSN

Undo Phase (TT)

1. Start from largest LSN from L
2. if update, create CLR with undoNextLSN=r's prevLSN, update-L-TT(r.prevLSN)
3. if CLR, update-L-TT(r.undoNextLSN)
4. update-L-TT(lsn): add lsn to L if lsn not null, else add end log record for T and remove it from TT

Checkpointing

- Normal(no ECPLR): CPLR's TT, empty DPT
- Fuzzy: BeginCPLR's TT and BCPLR's DPT