Crash Recovery

Chapter 18

Final Monday 12/13 @ 4pm, FB141
Study Session Sunday 12/12 @ 4:30pm, SN011
~50 questions multiple choice
Open book, notes, no computers
Review: The ACID properties

- **Atomicity**: All actions of a transaction happen, or none happen.

- **Consistency**: If each Xact is consistent, and the DB starts consistent, it ends up consistent.

- **Isolation**: Execution of one Xact is isolated from that of other Xacts.

- **Durability**: If a Xact commits, its effects persist.

- The **Recovery Manager** guarantees Atomicity & Durability.
Motivation

- Atomicity:
  - Transactions may abort ("Rollback").

- Durability:
  - What if DBMS Crashes? ("Worse case", a few unfinished Xacts are lost)

- Desired Behavior after system restarts:
  - T1, T2 & T3 should be durable.
  - T4 & T5 should be aborted (no effect).
Assumptions

- Concurrency control is in effect.
  - **Strict 2PL**, in particular.

- Updates are happening “in place”.
  - i.e. data is overwritten on (or deleted from) non-volatile disk.

- A simple scheme to guarantee Atomicity & Durability?
Handling the Buffer Pool

- **Force** every write to disk? Stall DBMS until completed
  - Poor response time.
  - But provides durability.
- **Steal** buffer-pool frames from uncommitted Xacts? (flush dirty frames, only when a new frame is needed)
  - If not, poor throughput (multiple writes to same page).
  - If so, how can we ensure atomicity?
More on Steal and Force

- **STEAL** (why enforcing Atomicity is hard)
  - What if a page, P, dirtied by some unfinished Xact is written to disk to free up a buffer slot, and the Xact later aborts?
    - Must remember the old value of P at steal time (to **UNDO** the page write).

- **NO FORCE** (why enforcing Durability is hard)
  - What if system crashes before a page dirtied by a committed Xact is flushed to disk?
    - Write as little as possible, in a convenient place, at commit time, to support **REDO**ing modifications.
Basic Idea: Logging

- Record sufficient information to REDO and UNDO every change in a log.
  - Write and Commit sequences saved to log (on a separate disk or replicated on multiple disks).
  - Minimal info (diff) written to log, so multiple updates fit in a single log page.
- **Log**: An ordered list of REDO/UNDO actions
  - Log record contains:
    - <XID, pageID, offset, length, old data, new data>
  - and additional control info (which we’ll see soon).
Write-Ahead Logging (WAL)

- The Write-Ahead Logging Protocol:
  1. Modification of a database object must first be recorded in the log, and the log updated, before any change to the object.
  2. Must write all log records of a Xact before it commits.

- #1 guarantees Atomicity.
- #2 guarantees Durability.

Exactly how is logging (and recovery!) done?
- We’ll study the ARIES algorithms.
WAL & the Log

- Each log record has a unique Log Sequence Number (LSN).
  - LSNs are always increasing.
- Each data page contains a pageLSN.
  - LSN of most recent page modification.
- System keeps track of flushedLSN.
  - Max LSN flushed from the page buffer so far.
- **WAL:** Before a page is written,
  - pageLSN ≤ flushedLSN
Log Records

Possible log record types:
- **Update**
- **Commit**
- **Abort**
- **End** (signifies end of commit or abort)
- **Compensation Log Records (CLRs)**
  - for UNDO actions

LogRecord fields:
- prevLSN
- XID
- type
- pageID
- length
- offset
- before-image
- after-image

**update**

**records only**
Other Log-Related State

- **Transaction Table:**
  - One entry per active Xact.
  - Contains XID, status (running/commited/aborted), and lastLSN due to Xact

- **Dirty Page Table:**
  - One entry per dirty page in buffer pool
  - Contains recLSN -- the LSN of the log record which first dirtied the page
### Log and Table Entries

<table>
<thead>
<tr>
<th>prevLSN</th>
<th>XID</th>
<th>type</th>
<th>pageID</th>
<th>length</th>
<th>offset</th>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1000</td>
<td>update</td>
<td>500</td>
<td>1</td>
<td>2</td>
<td>B</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td>T2000</td>
<td>update</td>
<td>600</td>
<td>3</td>
<td>1</td>
<td>DEF</td>
<td>GHI</td>
</tr>
<tr>
<td></td>
<td>T2000</td>
<td>update</td>
<td>500</td>
<td>2</td>
<td>1</td>
<td>AZ</td>
<td>MN</td>
</tr>
<tr>
<td></td>
<td>T1000</td>
<td>update</td>
<td>505</td>
<td>1</td>
<td>3</td>
<td>Q</td>
<td>R</td>
</tr>
</tbody>
</table>

#### Dirty Page Table

<table>
<thead>
<tr>
<th>pageID</th>
<th>recLSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
</tr>
<tr>
<td>505</td>
<td></td>
</tr>
</tbody>
</table>

#### Transaction Table

<table>
<thead>
<tr>
<th>transID</th>
<th>status</th>
<th>lastLSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1000</td>
<td>running</td>
<td></td>
</tr>
<tr>
<td>T2000</td>
<td>running</td>
<td></td>
</tr>
</tbody>
</table>

#### Log’s “Tail”
Normal Execution of an Xact

- Series of reads & writes, terminated by commit or abort.
  - We will assume that write is atomic on disk.
    - In practice, additional details to deal with non-atomic writes.
- Strict 2PL.
- STEAL, NO-FORCE buffer management, with Write-Ahead Logging.
**Checkpointing**

- Periodically, the DBMS creates a **checkpoint**, to minimize recovery time in the event of a system crash. What is written to log and disk:
  
  - **begin_checkpoint** record: Indicates when chkpt began.
  - **end_checkpoint** record: Contains current *Xact table* and *dirty page table*. This is a "fuzzy checkpoint":
    - Xacts continue to run; so these tables are accurate only as of the time of the **begin_checkpoint** record.
    - No attempt to force dirty pages to disk; effectiveness of checkpoint limited by oldest unwritten change to a dirty page. (So it’s a good idea to periodically flush dirty pages to disk!)
  - Store LSN of chkpt record in a safe place (**master** record).
The Big Picture: What’s Stored Where

LOG
- LogRecords
  - prevLSN
  - XID
  - type
  - pageID
  - length
  - offset
  - before-image
  - after-image

DB
- Data pages
  - each
  - with a
  - pageLSN
- master record

RAM
- Xact Table
  - lastLSN
  - status
- Dirty Page Table
  - recLSN
- flushedLSN
Simple Transaction Abort

- For now, consider an explicit abort of a Xact.
  - No crash involved.
- We want to “play back” the log in reverse order, UNDOing updates.
  - Get lastLSN of Xact from Xact table.
  - Can follow chain of log records backward via the prevLSN field.
  - Before starting UNDO, write an Abort log record.
    - For recovering from crash during UNDO!
Abort, cont.

- To perform UNDO, must have a lock on data!
- Before restoring old value of a page, write a Compensation Log Record (CLR):
  - Continue logging while you UNDO!!
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo
  - CLRIs are *never* Undone (but they might be Redone when repeating history: guarantees Atomicity!)
- At end of UNDO, write an “end” log record.
**Transaction Commit**

- Write **commit** record to log.
- All log records up to Xact’s **lastLSN** are flushed on a commit.
  - Guarantees that **flushedLSN ≥ lastLSN**.
  - Note that log flushes are sequential, synchronous writes to disk.
  - Many log records per log page.
- **Commit()** returns.
- Write **end** record to log.
Crash Recovery: Big Picture

- Start from a checkpoint (found via master record).
- ARIES 3 phases. Need to:
  - Analysis: Figure out which Xacts committed since last checkpoint, and which did not finish.
  - REDO all logged actions.
    - repeat “writing” history
  - UNDO effects of unfinished “loser” Xacts.
**Recovery: The Analysis Phase**

- Reconstruct state at checkpoint.
  - via the `end_checkpoint` record.
- Scan log forward from checkpoint.
  - *End* record: Remove Xact from Xact table because it safely completed.
  - *Other records*: Add Xact to Xact table, set `lastLSN=LSN`, change Xact status on `commit`.
  - *Update* record: If P not in Dirty Page Table,
    - Add P to D.P.T., set its `recLSN=LSN`. 
Recovery: The REDO Phase

- We *repeat History* to reconstruct state at crash:
  - Reapply *all* updates (even of aborted Xacts!), redo CLRs.
- Scan forward from log rec containing smallest recLSN in D.P.T. For each CLR or update log rec LSN, REDO the action unless:
  - Affected page is not in the Dirty Page Table, or
  - Affected page is in D.P.T., but has recLSN > LSN, or
  - pageLSN (in DB) ≥ LSN.

- To REDO an action:
  - Reapply logged changes (restore to before state).
  - Set pageLSN to LSN. No additional logging!
Recovery: The UNDO Phase

\( \text{ToUndo} = \{ l \mid l \text{ a lastLSN of a "loser" Xact} \} \)

**Repeat:**

- Choose largest LSN among ToUndo.
- If this LSN is a \text{CLR} and \text{undonextLSN} == \text{NULL}
  - Write an \text{End} record for this Xact.
- If this LSN is a \text{CLR}, and \text{undonextLSN} != \text{NULL}
  - Add \text{undonextLSN} to ToUndo
- Else this LSN is an \text{update}. UNDO the update, write a CLR, add \text{prevLSN} to ToUndo.

**Until ToUndo is empty.**
Example of Recovery

Begin_checkpoint

Update: T1 writes P5
Update: T2 writes P3
T1 abort
CLR: Undo T1 LSN 10
T1 End
Update: T3 writes P1
Update: T2 writes P5

CRASH, RESTART

LSN    LOG
00     begin_checkpoint
05     end_checkpoint
10     update: T1 writes P5
20     update T2 writes P3
30     T1 abort
40     CLR: Undo T1 LSN 10
45     T1 End
50     update: T3 writes P1
60     update: T2 writes P5

ToUndo

prevLSNs

RAM

Xact Table
  lastLSN
  status

Dirty Page Table
  recLSN
  flushedLSN

ToUndo
## Example: Crash During Restart!

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td>begin_checkpoint, end_checkpoint</td>
</tr>
<tr>
<td>10</td>
<td>update: T1 writes P5</td>
</tr>
<tr>
<td>20</td>
<td>update T2 writes P3</td>
</tr>
<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
<tr>
<td>40,45</td>
<td>CLR: Undo T1 LSN 10, T1 End</td>
</tr>
<tr>
<td>50</td>
<td>update: T3 writes P1</td>
</tr>
<tr>
<td>60</td>
<td>update: T2 writes P5</td>
</tr>
<tr>
<td>70</td>
<td>CLR: Undo T2 LSN 60</td>
</tr>
<tr>
<td>80,85</td>
<td>CLR: Undo T3 LSN 50, T3 end</td>
</tr>
<tr>
<td>90</td>
<td>CLR: Undo T2 LSN 20, T2 end</td>
</tr>
</tbody>
</table>

- **RAM**
- **Xact Table**
  - lastLSN
  - status
- **Dirty Page Table**
  - recLSN
  - flushedLSN
- **ToUndo**

**undonextLSN**
Additional Crash Issues

- What happens if system crashes during Analysis? During REDO?
- How to limit the amount of work in REDO?
  - Flush dirty pages asynchronously in the background.
  - Watch out for “hot spots”!
- How to limit the amount of work in UNDO?
  - Avoid long-running Xacts.
Summary of Logging/Recovery

- **Recovery Manager** guarantees Atomicity & Durability.
- Uses WAL to allow STEAL/NO-FORCE w/o sacrificing correctness.
- LSNs identify log records; linked into backwards chains per transaction (via prevLSN).
- pageLSN allows comparison of data page and log records.
Summary, Cont.

- **Checkpointing:** A quick way to limit the amount of log to scan on recovery.
- Recovery works in 3 phases:
  - **Analysis:** Forward from checkpoint.
  - **Redo:** Forward from oldest recLSN.
  - **Undo:** Backward from end to first LSN of oldest Xact alive at crash.
- Upon Undo, write CLRs.
- Redo “repeats history”: Simplifies the logic!