Transaction Management: Crash Recovery (Chap. 18), part 1

CS634
Class 17

Slides based on "Database Management Systems" 3rd ed, Ramakrishnan and Gehrke

ACID Properties

Transaction Management must fulfill four requirements:

1. Atomicity: either all actions within a transaction are carried out, or none is
   - Only actions of committed transactions must be visible
2. Consistency: concurrent execution must leave DBMS in consistent state
3. Isolation: each transaction is protected from effects of other concurrent transactions
   - Net effect is that of **some sequential execution**
4. Durability: once a transaction commits, DBMS changes will persist
   - Conversely, if a transaction aborts/is aborted, there are no effects

Recovery Manager

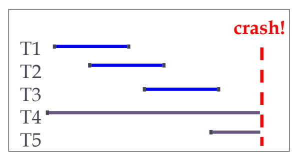
- Crash recovery
  - Ensure that atomicity is preserved if the system crashes while one or more transactions are still incomplete
  - Main idea is to keep a log of operations; every action is logged before its page updates reach disk (Write-Ahead Log or WAL)
- The **Recovery Manager** guarantees Atomicity & Durability
- "One of hardest components of a DBMS to design and implement", pg. 580
- One reason: need calls to it from all over the storage manager

Motivation

- Atomicity:
  - Transactions may abort – must rollback their actions
- Durability:
  - What if DBMS stops running – e.g., power failure?

Desired Behavior after system restarts:

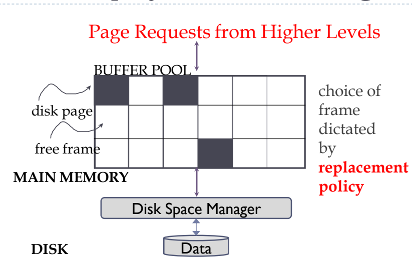
- T1, T2 & T3 should be durable
- T4 & T5 should be aborted (effects not seen)



Assumptions

- Concurrency control is in effect
  - Strict 2PL (using page locks or row locks)
- Updates are happening "in place"
  - Data overwritten on (deleted from) the disk
  - Centralized system, with one buffer pool for all system disks
  - So pages in buffer overlay those pages on disk to define the database state (see next slide)
- A simple scheme is needed
  - A protocol that is too complex is difficult to implement
  - Performance is also an important issue

A Crucial player: Buffer Manager



- The buffer pool sits in front of the disks, so determines the current view of the data for the system
- A page in the pool modified by an uncommitted transaction is a "dirty page",

Handling the Buffer Pool

- Force every write to disk?
  - Poor response time - disk is slow!
  - But provides durability
- Want to be lazy about writes to disk, but not too lazy!
- Note that one transaction can use more pages than can fit in the buffer manager, so DB needs to support spillage of active pages to disk
- So need to be able to write out a page changed by an uncommitted transaction

Stealing a page (see text, pg. 541)

- The same capability of writing a page with uncommitted data is used for "stealing" a page
- Scenario:
  - Transaction T1 has a lot of pages in buffer, with uncommitted changes
  - Transaction T2 needs a buffer page, steals it from T1 by having T1's page written to disk, then using that buffer slot
  - If row locking in use, could have T2 stealing a page from multiple other transactions, though hopefully uncommon.
- With stealing going on, how can we ensure atomicity?
- One controlling mechanism is page pinning
- Only an unpinned buffer page can be stolen…
- Another mechanism involves the log's LSNs (log sequence numbers), covered soon

Lifetime of a page: page pinning in action

- Read by T1 and pinned (see pg. 319), S lock on row (or page if page-locking)
- Read by T2 and pinned/share, S lock on row
- Read access finished by T1, unpinned by T1, still pinned by T2
- Read access finished by T2, unpinned, now fully unpinned
- Note: no logging for reads
- Write access requested by T3, page is pinned exclusive, T3 gets X lock on row C, changes row, logs action, gets LSN back, puts in page header, page unpinned
- Page now has 2 rows with S locks, one with X lock, is unpinned, so could be stolen

Steal and Force

- **STEAL**
  - Not easy to enforce atomicity when steal is possible
  - *To steal frame F:* current (unpinned) page P is written to disk; some transaction holds lock on row A of P
    - What if holder of the lock on A aborts?
    - Note the disk page holding A has the new value now, needs undoing.
    - Must remember the old value of A at or before steal time (to support UNDOing the write to row A) (remember it in the log, next slide)
- **NO FORCE (lazy page writes)**
  - What if system crashes before a modified page is written to disk?
  - Write as little as possible in a convenient place to support REDOing modifications (write it in the log)

The Log

- The following actions are recorded in the log:
  - *Ti writes an object:* the old value and the new value.
    - Log record must go to disk *before* the changed page!
  - *Ti commits/aborts:* a log record indicating this action.
  - Some other specialized records.
- Log records are chained together by Xact id, so it's easy to undo a specific Xact.
- Log is often *duplexed* and *archived* on stable storage.
- All log related activities (and in fact, all CC related activities such as lock/unlock, dealing with deadlocks etc.) are handled transparently by the DBMS.

Logging

- Essential function for recovery
  - Record REDO and UNDO information, for every update
  - Example: T1 updates A from 10 to 20
    - Undo: know how to change 20 back to 10 if find 20 in disk page and know T1 aborted
    - Redo: know how to change 10 to 20 if see 10 in the disk page and know T1 committed.
  - Updates include row inserts and deletes, but not emphasized here
  - Writes to log must be sequential, should be stored on a separate (mirrored) disk
  - Minimal information (summary of changes) written to log, since writing the log can be a performance problem

Logging

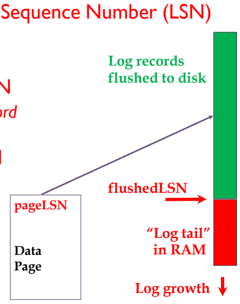
- What is in the Log
  - Ordered list of REDO/UNDO actions
  - Update log record contains:
    <prevLSN, transID, pageID, offset, length, old data, new data>
  - Old data is called the before image
  - New data called the after image
  - The prevLSN provides the LSN of the transaction's previous log record, so it's easy to scan backwards through log records as needed in UNDO processing

Write-Ahead Logging (WAL)

- The Write-Ahead Logging Protocol:
  1. Must force the log record for an update *before* the corresponding data page gets to disk
  2. Must write all log records for transaction *before commit returns*
  - Property 1 guarantees Atomicity
  - Property 2 guarantees Durability
- We focus on the ARIES algorithm
  - Algorithms for Recovery and Isolation Exploiting Semantics
  - See famous ARIES paper, also linked from class web page

How Logging is Done

- Each log record has a unique Log Sequence Number (LSN)
  - LSNs always increasing
  - Works similar to "record locator"
- Each data page contains a pageLSN
  - The LSN of the most recent *log record* for an update to that page
- System keeps track of flushedLSN
  - The largest LSN flushed so far
- WAL: *Before* a page is written, flush its log record such that
  - pageLSN ≤ flushedLSN



Log Records

LogRecord fields:

prevLSN
transID
entryType
pageID
length
offset
before-image
after-image

update records only (pageID, length, offset, before-image, after-image)

Possible log entry types:

- **Update (incl. insert, delete)**
- **Commit**
- **Abort**
- **End** (signifies end of commit or abort)
- **Compensation Log Records (CLRs)**
  - for UNDO actions

Other Log-Related State

- Transaction Table: in server memory, so volatile
  - One entry per active transaction
  - Contains transID, status (running/commited/aborted), and lastLSN (most recent LSN for transaction)
- A dirty page is one whose disk and buffer images differ
  - So a dirty page becomes clean at page write, if it stays in buffer
  - Once clean, can be deleted from dirty page table
  - And is clean if it gets read back into buffer, even with uncommitted data in it
- Dirty Page Table: in server memory
  - One entry per dirty page in buffer pool
  - Contains recLSN - the LSN of the log record which ***first*** caused the page to be dirty (spec's what part of log relates to redos for this page)
  - Earliest recLSN in table – important milestone for recovery (spec's what part of log relates to redos for whole system)

Normal Execution of Transactions

- Series of reads & writes, followed 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

Transaction Commit

- Write commit record to log for transaction T
- All log records up to lastLSN of T are flushed.
  - Guarantees that flushedLSN ≥ lastLSN
  - Note that log flushes are sequential, synchronous writes to disk
  - Does NOT mean that *page* writes are propagated to data disk!
- Commit() returns.
- Write end record to log

Example: A Committing transaction

R1(A, 50) W1(A,20) C1

- R1(A): Transaction started, entered into Transaction table, page read into buffer, pinned, data used, unpinned (no logging)
- W1(A): page found in buffer, pinned, log record written:
  - prevLSN = null, transID = 1, entryType = update, etc.
  - Before-image = 50, after-image = 20. Suppose LSN = 222
  - Page now dirty, pageLSN=222, entered into dirty page table with recLSN=222, put lastLSN = 222 in TxTable, page unpinned
- C1: Log record (LSN223) for commit has prevLSN=222, Log is pushed so LSN 223 record is on disk. Now transaction is committed.
  - Transaction status in TxTable is changed to committed
  - Log record for End (LSN224) is written, has prevLSN=223.
- Note: dirty page can still hang around in buffer pool: its content defines the database state for that page
- Sometime later, dirty page written to disk, page considered clean, dropped from dirty page table.

Checkpointing

- Periodically, the DBMS creates a checkpoint
  - minimize time taken to recover in the event of a system crash
- Checkpoint logging:
  - begin_checkpoint record: Indicates when checkpoint began
  - end_checkpoint record: Contains current *transaction table* and *dirty page table* as of begin_checkpoint time
  - So the earliest recLSN (LSN of oldest dirty page) is known at recovery time, and the set of live transactions, very useful for recovery
  - Other transactions continue to run; tables accurate only as of the time of the begin_checkpoint record – fuzzy checkpoint
    - No attempt to force dirty pages to disk at checkpoint time!
    - But good to nudge them to disk continuously, to limit recovery time.
  - LSN of begin_checkpoint written in special **master record** on stable storage

Simple Transaction Abort

- First, consider an explicit abort of a transaction
  - No crash involved, have good transaction table
- Need to "play back" the log in reverse order, UNDOing updates.
  - Get lastLSN of transaction from transaction table
  - Find that log record, undo one page change
  - 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!
- For each update UNDO, write a CLR record in the log…

The mysterious CLR log records

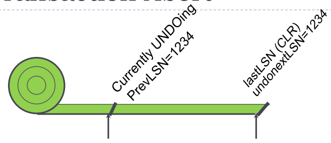
- In normal operations, a transaction may abort, partially roll back, then the system crashes.
- To recover, the system needs to know how far the rollback got, and pick up from there.
- So during the undo processing of an abort (during normal operations), the system writes CLR records to record its progress undoing the actions of the aborted transaction.
- They are "compensation" records because the system is doing actions to compensate for the work previously done by the aborted transaction.

Example: An aborting transaction

R1(A, 50) W1(A,20) A1

- R1(A): Transaction started, entered into Transaction table, page read into buffer, pinned, data used, unpinned (no logging for reads)
- W1(A): page found in buffer, pinned, log record written:
  - prevLSN = null, transID = 1, entryType = update, etc.
  - Before-image = 50, after-image = 20. Suppose LSN = 222
  - Page now dirty, pageLSN=222, entered into dirty page table with recLSN=222, put lastLSN = 222 in TxTable, page unpinned
- A1: Log record (LSN223) for abort has prevLSN=222. Then undo actions are started.
  - Undo W1(A): use lastLSN of TxTable to locate Tx's last log entry for write
  - Write CLR record to log, with LSN 224,
  - Find page in buffer, pin, apply before image (50), so A=50 again, unpin
  - Transaction status in TxTable is changed to aborted
  - Log record for End (LSN224) is written, has prevLSN=224.
- Note: dirty page can still hang around in buffer pool: its content defines the database state for that page

Simple Transaction Abort

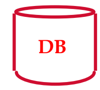


- Before restoring old value of a page, write a CLR:
  - CLR has one extra field: undoNextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of the record we're currently undoing).
    - The undonextLSN value is used only if this CLR ends up as the last one in the log for this transaction: specs which update log record to start/resume UNDOing (possibly resuming UNDO work interrupted by a crash)
  - CLRs *never* Undone (but they may be Redone when repeating history). For recovery UNDO, they just point where to start working.
- At end of transaction UNDO, write an "end" log record.

ARIES Overview

LogRecords

prevLSN
transID
type
pageID
length
offset
before-image
after-image



Data pages

Each with a pageLSN

Transaction Table

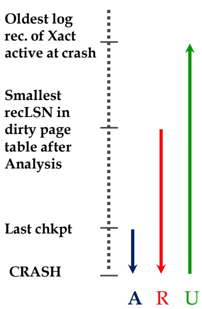
lastLSN
status

Dirty Page Table

recLSN

flushedLSN

Crash Recovery: Big Picture



Start from a checkpoint (via LSN found in DB master record)

Three phases:

- **ANALYSIS**: Find which transactions committed or failed since checkpoint
- REDO ***all*** actions (repeat history)
- UNDO effects of failed transactions