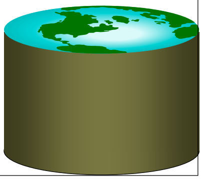
Logging and Recovery

If you are going to be in the logging business, one of the things that you have to do is to learn about heavy equipment.

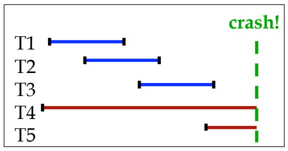
~ Robert VanNatta,
Logging History of Columbia County



Motivation

- **Atomicity:**
  - Transactions may abort ("Rollback").
- **Durability:**
  - What if DBMS stops running? (Causes?)

- 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, in particular.
- **Updates are happening in DIRECT mode**
  - i.e. data is overwritten on (deleted from) the disk.

- **A simple scheme to guarantee Atomicity & Durability?**

Handling the Buffer Pool

- **Force write to disk at commit?**
  - Poor response time (& throughput)
  - But provides durability.
- **Steal buffer-pool frames from uncommited Xacts?**
  - If not, poor throughput.
    - Among other problems!
  - If so, how can we ensure atomicity?

	No Steal	Steal
Force	Trivial	
No Force		Desired

More on Steal and Force

- STEAL **(why enforcing Atomicity is hard)**
  - *To steal frame F:* Current page in F (say P) is written to disk; some Xact holds lock on P.
    - What if the Xact with the lock on P aborts?
    - Must remember the old value of P at steal time (to support UNDOing the write to page P).
- NO FORCE **(why enforcing Durability is hard)**
  - What if system crashes before a modified page is written to disk?
  - Write as little as possible, in a convenient place, at commit time,to support REDOing modifications.

Basic Idea: Logging

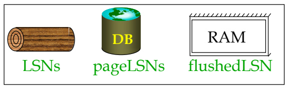
- **Record REDO and UNDO information, for every update, in a *log*.**
  - Sequential writes to log (put it on a separate disk).
  - Minimal info (diff) written to log, so multiple updates fit in a single log page.
- **Log: An ordered list of REDO/UNDO actions**
  - A simple (physical) log record contains:
    <XID, pageID, offset, length, old data, new data>
  - and additional control info (which we'll see soon).

Write-Ahead Logging (WAL)

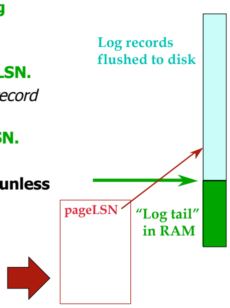
- **The Write-Ahead Logging Protocol:**
  - ❶ Must force the log record for an update *before* the corresponding data page gets to disk.
  - ❷ Must write all log records for a Xact *before commit*.
- **#1 guarantees Atomicity.**
- **#2 guarantees Durability.**

- **Exactly how is logging (and recovery!) done?**
  - We'll study the ARIES protocol.

WAL & the Log



- **Each log record has a unique Log Sequence Number (LSN).**
  - LSNs always increasing.
- **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 max LSN flushed so far.
- **WAL: Cannot flush a data page unless**
  - pageLSN ≤ flushedLSN



Log Records

LogRecord fields:

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

update records only

Possible log record types:

- Update
- Commit
- Abort
- End (signifies end of commit or abort)
- Compensation Log Records (CLRs)
  - for UNDO actions
  - (and some other tricks!)

Other Log-Related State

- **Transaction Table:**
  - One entry per active Xact.
  - Contains XID, status (running/commited/aborted), and lastLSN.
- **Dirty Page Table:**
  - One entry per dirty page in buffer pool.
  - Contains recLSN -- the LSN of the log record which *first* caused the page to be dirty.

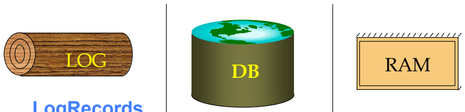
Normal Execution of an Xact

- **Series of reads & writes, followed by commit or abort.**
  - We will assume that page write is atomic on disk.
- **Strict 2PL.**
- **STEAL, NO-FORCE buffer management, with Write-Ahead Logging.**

Checkpointing

- **Periodically, the DBMS creates a checkpoint, in order to minimize the time taken to recover in the event of a system crash. Write to log:**
  - begin_checkpoint record: Indicates when chkpt began.
  - end_checkpoint record: Contains current *Xact table* and *dirty page table*. This is a \`fuzzy checkpoint':
    - Other Xacts continue to run; so these tables only known to reflect some mix of state *after 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! Recall when we said that NO STEAL had other problems? This is one.)
  - Store LSN of chkpt record in a safe place (*master* record).

The Big Picture: What's Stored Where



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

Data pages
each
with a
pageLSN

master record

Xact Table
lastLSN
status

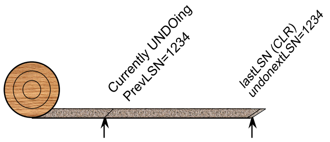
Dirty Page Table
recLSN

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.
  - Note: before starting UNDO, could write an *Abort* log record.
    - Why bother?

Abort, cont.

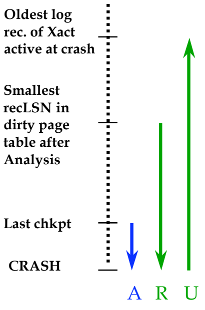


- **To perform UNDO, must have a lock on data!**
  - No problem!
- **Before restoring old value of a page, write a CLR:**
  - You continue logging while you UNDO!!
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of the record we're currently undoing).
  - CLR contains REDO info
  - CLRs *never* Undone
    - Undo needn't be idempotent (>1 UNDO won't happen)
    - But they might be Redone when repeating history (=1 UNDO guaranteed)
- **At end of all UNDOs, write an "end" log record.**

Transaction Commit

- **Write commit record to log.**
- **All log records up to Xact's lastLSN are flushed.**
  - Guarantees that flushedLSN ≥ lastLSN.
  - Note that log flushes are sequential, synchronous writes to disk.
  - Many log records per log page.
- **Make transaction visible**
  - Commit() returns, locks dropped, etc.
- **Write end record to log.**

Crash Recovery: Big Picture



- Start from a checkpoint (found via master record).
- Three phases. Need to:
  - Figure out which Xacts committed since checkpoint, which failed (Analysis).
  - REDO *all* actions.
    - (repeat history)
  - UNDO effects of failed Xacts.

Recovery: The Analysis Phase

- **Reconstruct state at checkpoint.**
  - via end_checkpoint record.
- **Scan log forward from begin_checkpoint.**
  - End record: Remove Xact from Xact table.
  - 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.
- **At end:**
  - the Xact table contains all "loser" xacts
  - the DPT contains a superset of dirty data pages

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. (requires an I/O)
- **To REDO an action:**
  - Reapply logged action.
  - Set pageLSN to LSN. No additional logging!

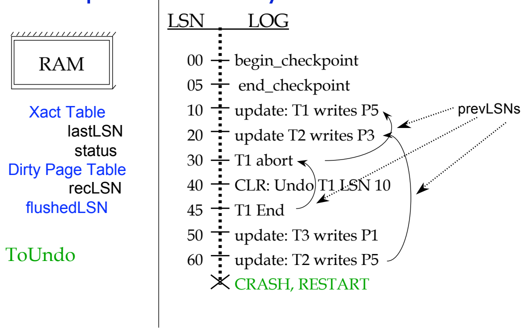
Recovery: The UNDO Phase

ToUndo={ *l* | *l* a lastLSN of a "loser" Xact}

```
Repeat:
    – Choose largest LSN among ToUndo.
    – If this LSN is a CLR and undonextLSN==NULL
        • Write an End record for this Xact.
    – If this LSN is a CLR, and undonextLSN != NULL
        • Add undonextLSN to ToUndo
        • (note: we may have skipped a number of other CLRs!)
    – Else this LSN is an update.  Undo the update, write a CLR,
      add prevLSN to ToUndo.
Until ToUndo is empty.
```

Note: could do this one xact at a time; the above is a minor optimization that does them all at once.

Example of Recovery

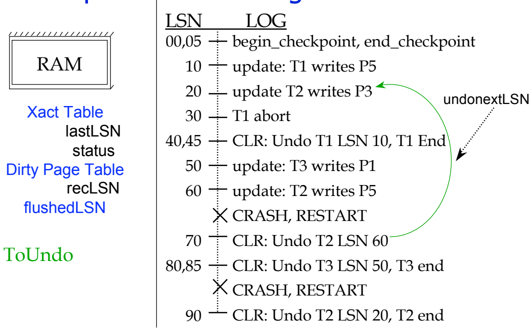


Xact Table
lastLSN
status
Dirty Page Table
recLSN
flushedLSN

ToUndo

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
	CRASH, RESTART

Example: Crash During Restart!



Xact Table
lastLSN
status
Dirty Page Table
recLSN
flushedLSN

ToUndo

LSN	LOG
00,05	begin_checkpoint, end_checkpoint
10	update: T1 writes P5
20	update T2 writes P3
30	T1 abort
40,45	CLR: Undo T1 LSN 10, T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART
70	CLR: Undo T2 LSN 60
80,85	CLR: Undo T3 LSN 50, T3 end
	CRASH, RESTART
90	CLR: Undo T2 LSN 20, T2 end

Additional Crash Issues

- **What happens if system crashes during Analysis? During REDO?**
- **How do you limit the amount of work in REDO?**
  - Flush asynchronously in the background.
  - Watch "hot spots"!
- **How do you limit the amount of work in UNDO?**
  - Avoid long-running Xacts.

Logical vs. Physical Logging

- **Roughly, ARIES does:**
  - Physical REDO
  - Logical UNDO
- **Why?**

Logical vs. Physical Logging, Cont.

- **Page-oriented REDO logging**
  - Independence of REDO (e.g. indexes & tables)
    - Simplifies things enormously
    - Allows for optimizations (reordering/parallelization in Recovery)
  - Not quite physical, but close
    - Can have logical operations like increment/decrement ("escrow transactions")
- **Logical UNDO**
  - To allow for simple management of physical structures that are invisible to users
  - To allow for logical operations

Nested Top Actions

- **Trick to support physical operations you do not want to ever be undone**
  - Example?
- **Basic idea**
  - At end of the nested actions, write a dummy CLR
    - Nothing to REDO in this CLR
  - Its UndoNextLSN points to the step before the nested action.

Summary of Logging/Recovery

- **Recovery Manager guarantees Atomicity & Durability.**
- **Use 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!**