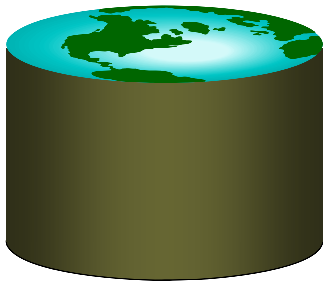
ARIES: Logging and Recovery

Slides derived from Joe Hellerstein; Updated by A. Fekete

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*



Review: The ACID properties

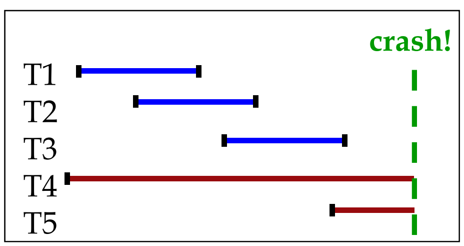
- **A tomicity: All actions in the Xact happen, or none happen.**
- **C onsistency: If each Xact is consistent, and the DB starts consistent, it ends up consistent.**
- **I solation: Execution of one Xact is isolated from that of other Xacts.**
- **D urability: If a Xact commits, its effects persist.**

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

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).



Intended Functionality

- **At any time, each data item contains the value produced by the most recent update done by a transaction that committed**

Assumptions

- **Essential concurrency control is in effect.**
  - For read/write items: Write locks taken and held till commit
    - Eg Strict 2PL, but read locks not important for recovery.
  - For more general types: operations of concurrent transactions commute
- **Updates are happening "in place".**
  - i.e. data is overwritten on (deleted from) its location.
    - Unlike multiversion approaches
- **Buffer in volatile memory; data persists on disk**

Challenge: REDO

Action	Buffer	Disk
Initially		0
T1 writes 1	1	0
T1 commits	1	0
CRASH		0

- **Need to restore value 1 to item**
  - Last value written by a committed transaction

Challenge: UNDO

Action	Buffer	Disk
Initially		0
T1 writes 1	1	0
Page flushed		1
CRASH		1

- **Need to restore value 0 to item**
  - Last value from a committed transaction

Handling the Buffer Pool

- **Can you think of a simple scheme to guarantee Atomicity & Durability?**
- **Force write to disk at commit?**
  - Poor response time.
  - But provides durability.
- **No Steal of buffer-pool frames from uncommited Xacts ("pin")?**
  - Poor throughput.
  - But easily 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**
  - Log record contains:

    <XID, pageID, offset, length, old data, new data>
  - and additional control info (which we'll see soon)
  - For abstract types, have operation(args) instead of old value new value.

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 a Xact *before commit*.
- **#1 (undo rule) allows system to have Atomicity.**
- **#2 (redo rule) allows system to have Durability.**

ARIES

- **Exactly how is logging (and recovery!) done?**
  - Many approaches (traditional ones used in relational systems of 1980s);
  - ARIES algorithms developed by IBM used many of the same ideas, and some novelties that were quite radical at the time
    - Research report in 1989; conference paper on an extension in 1989; comprehensive journal publication in 1992
    - 10 Year VLDB Award 1999

Key ideas of ARIES

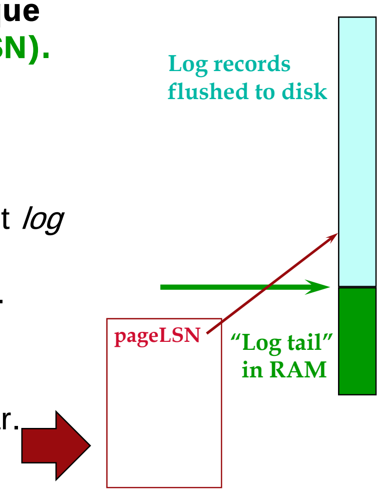
- **Log every change (*even undos during txn abort*)**
- **In restart, *first* repeat history without backtracking**
  - *Even redo the actions of loser transactions*
- ***Then* undo actions of losers**

- **LSNs in pages used to coordinate state between log, buffer, disk**

Novel features of ARIES *in italics*

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 constraints

- ***Before* a page is written,**
  - pageLSN ≤ flushedLSN
- **Commit record included in log; all related update log records precede it in log**

Log Records

LogRecord fields:

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

(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.
    - In practice, additional details to deal with non-atomic writes.
- **Strict 2PL (at least for writes).**
- **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!)
  - Store LSN of chkpt record in a safe place (*master* record).

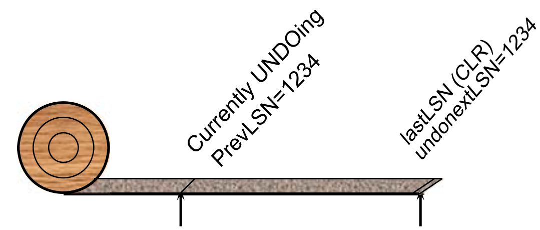
The Big Picture: What's Stored Where

LOG	DB	RAM
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.

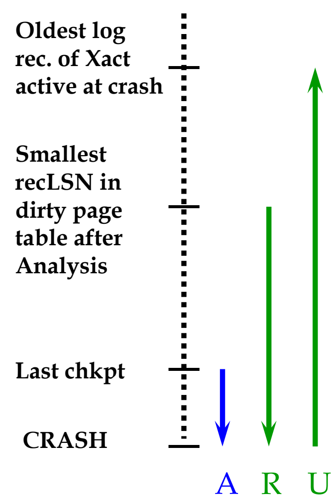


- **To perform UNDO, must have a lock on data!**
  - No problem!
- **Before restoring old value of a page, write a CLR:**
  - You continue logging while you UNDO!!
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of the record we're currently undoing).
  - 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 $\geq$ 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.

This phase could be skipped;
information can be regained in REDO pass following

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 page is already more uptodate than this record:**
  - REDO when Affected page is in D.P.T., and has pageLSN (in DB) < LSN. [if page has recLSN > LSN no need to read page in from disk to check pageLSN]
- **To REDO an action:**
  - Reapply logged action.
  - Set pageLSN to LSN. No additional logging!

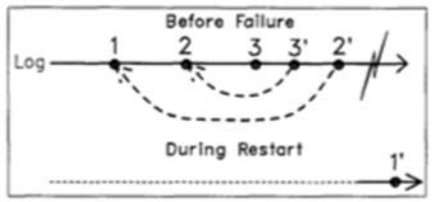
Invariant

- **State of page P is the outcome of all changes of relevant log records whose LSN is <= P.pageLSN**
- **During redo phase, every page P has P.pageLSN >= redoLSN**
- **Thus at end of redo pass, the database has a state that reflects exactly everything on the (stable) log**

Recovery: The UNDO Phase

- **Key idea: Similar to simple transaction abort, for each loser transaction (that was in flight or aborted at time of crash)**
  - Process each loser transaction's log records backwards; undoing each record in turn and generating CLRs
- **But: loser may include partial (or complete) rollback actions**
- **Avoid to undo what was already undone**
  - undoNextLSN field in each CLR equals prevLSN field from the original action

UndoNextLSN



I' is the Compensation Log Record for I
I' points to the predecessor, if any, of I

Fig. 5. ARIES' technique for avoiding compensating compensations and duplicate compensations.

From Mohan et al, TODS 17(1):94-162

Recovery: The UNDO Phase

ToUndo={ / | /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
  - (Q: what happens to other CLRs?)
- Else this LSN is an update. Undo the update, write a CLR, add prevLSN to ToUndo.

Until ToUndo is empty.

Example of Recovery

RAM

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

prevLSNs

Example: Crash During Restart!

RAM

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

undonextLSN

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.

Parallelism during restart

- **Activities on a given page must be processed in sequence**
- **Activities on different pages can be done in parallel**

Log record contents

- **What is actually stored in a log record, to allow REDO and UNDO to occur?**
- **Many choices, 3 main types**
  – PHYSICAL
  – LOGICAL
  – PHYSIOLOGICAL

Physical logging

- **Describe the bits (optimization: only those that change)**
- **Eg**
  – OLD STATE: 0x47A90E....
  – NEW STATE: 0x632F00...
  – So REDO: set to NEW; UNDO: set to OLD
- **Or just delta (OLD XOR NEW)**
  – DELTA: 0x24860E...
  – So REDO=UNDO=xor with delta
- **Ponder: XOR is not idempotent, but redo and undo must be; why is this OK?**

Logical Logging

- **Describe the operation and arguments**
- **Eg Update field 3 of record whose key is 37, by adding 32**
- **We need a programmer supplied inverse operation to undo this**

Physiological Logging

- **Describe changes to a specified page, logically within that page**
- **Goes with common page layout, with records indexed from a page header**
- **Allows movement within the page (important for records whose length varies over time)**
- **Eg on page 298, replace record at index 17 from old state to new state**
- **Eg on page 35, insert new record at index 20**

ARIES logging

- **ARIES allows different log approaches; common choice is:**
- **Physiological REDO logging**
  - Independence of REDO (e.g. indexes & tables)
    - Can have concurrent commutative logical operations like increment/decrement ("escrow transactions")
- **Logical UNDO**
  - To allow for simple management of physical structures that are invisible to users
    - CLR may act on different page than original action
  - To allow for escrow

Interactions

- **Recovery is designed with deep awareness of access methods (eg B-trees) and concurrency control**
- **And vice versa**
- **Need to handle failure during page split, reobtaining locks for prepared transactions during recovery, etc**

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!**

Further reading

- **Repeating History Beyond ARIES,**
  - C. Mohan, Proc VLDB'99
  - Reflections on the work 10 years later
- **Model and Verification of a Data Manager Based on ARIES**
  - D. Kuo, ACM TODS 21(4):427-479
  - Proof of a substantial subset
- **A Survey of B-Tree Logging and Recovery Techniques**
  - G. Graefe, ACM TODS 37(1), article 1