CAS CS 460/660
Introduction to Database Systems

Recovery

Review: The ACID properties

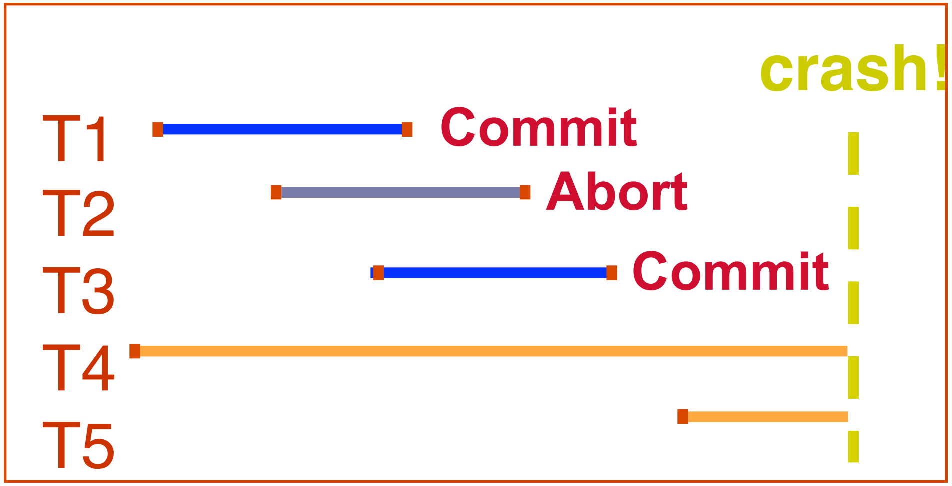
- Atomicity: All actions in the Xact happen, or none happen.
- Consistency: If each Xact is consistent, and the DB starts consistent, it ends up consistent.
- Isolation: Execution of one Xact is isolated from that of other Xacts.
- Durability: If a Xact commits, its effects persist.
- Question: which ones does the Recovery Manager help with?

Atomicity & Durability (and also used for Consistency-related rollbacks)

Motivation

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

- Desired state after system restarts:
  - T1 & T3 should be durable.
  - T2, T4 & T5 should be aborted (effects not seen).



Big Ideas

- Write Ahead Logging (WAL)
  - save it on stable storage!
  - and how it interacts with the buffer manager
- ARIES Recovery algorithm
  - “Repeats History” in order to simplify the logic of recovery.
  - Must handle arbitrary failures
    - Even during recovery!

Assumptions

- Concurrency control is in effect.
  - Strict 2PL, in particular.
- Updates are happening "in place".
  - i.e. data is overwritten on (deleted from) the actual page copies (not private copies).

Buffer Management Plays a Key Role

One possible approach – Force/No Steal:

- **Force – make sure that every updated page is written to disk before commit.**
  - Provides durability without REDO logging.
  - But, can cause poor performance.

- **No Steal – don't allow buffer-pool frames with uncommited updates to overwrite committed data on disk.**
  - Useful for ensuring atomicity without UNDO logging.
  - But can cause poor performance.

Preferred Policy: Steal/No-Force

- This combination is most complicated but allows for highest flexibility/performance.
- NO FORCE (complicates enforcing Durability)
  - What if system crashes before a modified page written by a committed transaction makes it to disk?
  - Write as little as possible, in a convenient place, at commit time, to support REDOing modifications.
- STEAL (complicates enforcing Atomicity)
  - What if the Xact that performed udpates aborts?
  - What if system crashes before Xact is finished?
  - Must remember the old value of P (to support UNDOing the write to page P).

Buffer Management summary

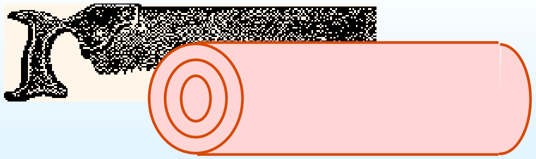
	No Steal	Steal
No Force		Fastest
Force	Slowest	

Performance Implications

	No Steal	Steal
No Force	No UNDO REDO	UNDO REDO
Force	No UNDO No REDO	UNDO No REDO

Logging/Recovery Implications

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).

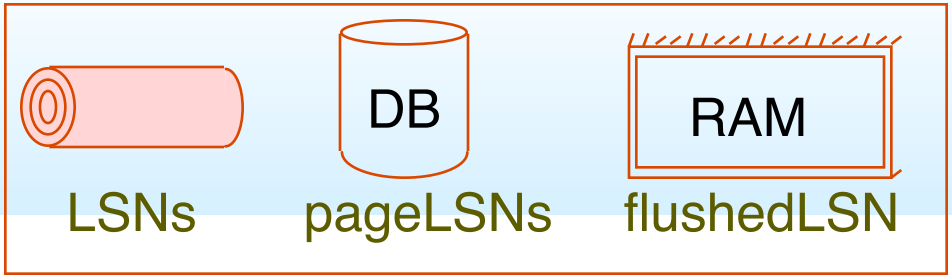
Write-Ahead Logging (WAL)

- The Write-Ahead Logging Protocol:
  1) Must force the log record for an update *before* the corresponding data page gets to disk.
  2) Must force all log records for a Xact *before commit*. (transaction is not committed until all of its log records including its "commit" record are on the stable log.)

- #1 (with UNDO info) helps guarantee Atomicity.
- #2 (with REDO info) helps guarantee Durability.
- This allows us to implement Steal/No-Force

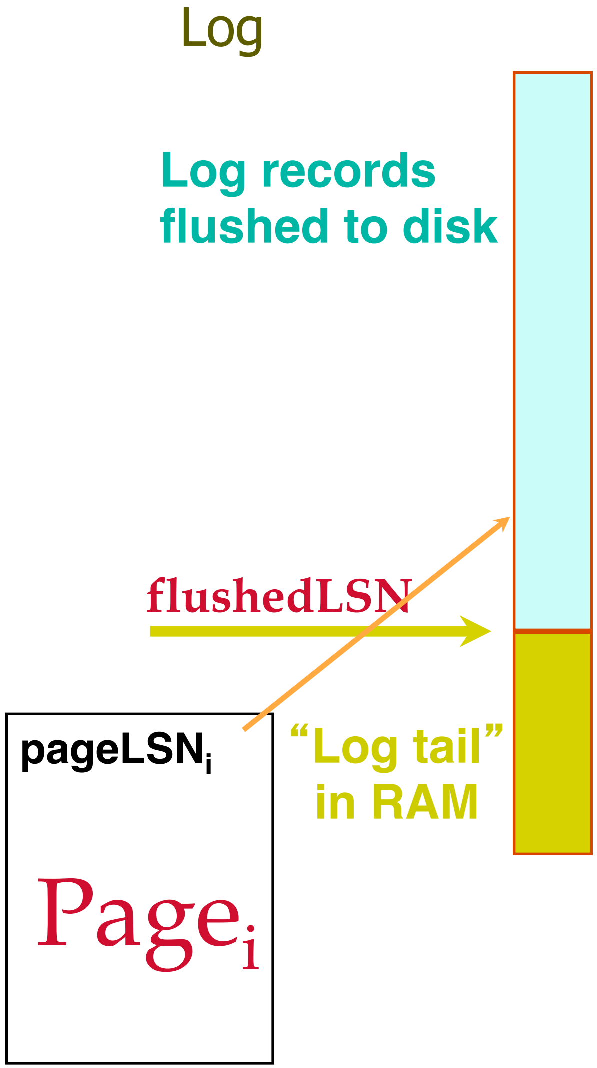
- We'll look at the ARIES algorithms from IBM.

WAL & the Log



- Each log record has a unique 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.
  - max LSN flushed to stable log so far.
- WAL (rule 1): For a page "i" to be written must flush log at least to the point where:

$pageLSN_i \leq flushedLSN$



Log Records

LogRecord fields:

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

for **update** records only

prevLSN is the LSN of the previous log record written by *this* transaction (i.e., the records of an Xact form a linked list backwards in time)

Possible log record types:

- Update, Commit, Abort
- Checkpoint (for log maintainence)
- Compensation Log Records (CLRs)
  - for UNDO actions
- End (end of commit or abort – bookkeeping only means clean-up is finished)

Other Log-Related State (in memory)

- Two in-memory tables:
- Transaction Table

  One entry per currently active transaction.

  - entry removed when Xact commits or aborts

  Contains: XID (i.e., transactionId),
  status (running/committing/aborting),
  lastLSN (most recent LSN written by Xact)

- Dirty Page Table

  One entry per dirty page currently in buffer pool.

  Contains recLSN -- the LSN of the log record that ***first*** caused the page to be dirty.

Normal Execution of an Xact

- Assume:
  - Strict 2PL concurrency control
  - STEAL, NO-FORCE buffer management, with WAL.
  - Disk writes are atomic (i.e., all-or-nothing)
- Transaction is a series of reads & writes, followed by commit or abort.
  - Update TransTable on transaction start/end
  - For each update operation:
    - create log record with LSN ℓ = ++MaxLSN and prevLSN = TransTable[XID].lastLSN;
    - update TransTable[XID].lastLSN = ℓ
    - if modified page NOT in DirtyPageTable, then add it with recLSN = ℓ
  - When buffer manager replaces a dirty page, remove its entry from the DPT

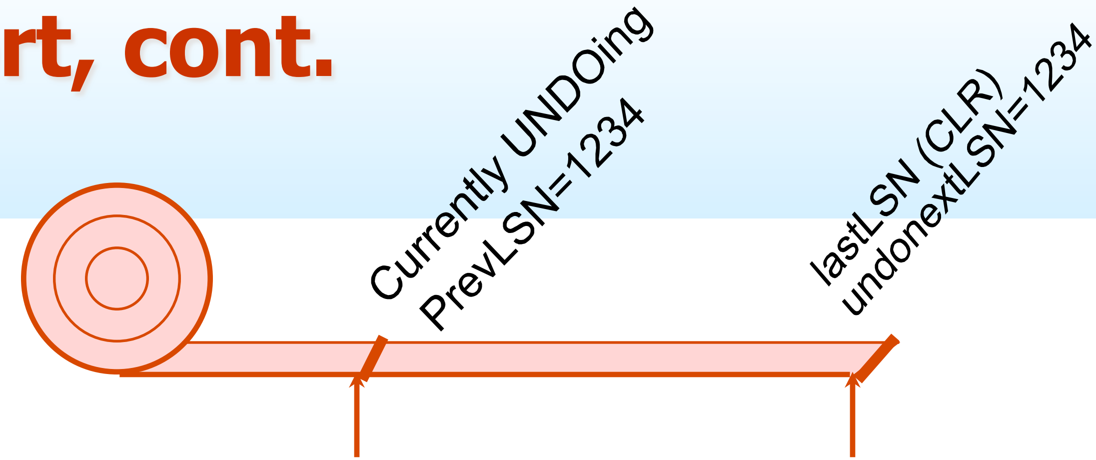
Transaction Commit

- Write commit record into log.
- Flush all log records up to and including the Xact's commit record to log disk.
  - WAL Rule #2: Ensure flushedLSN ≥ lastLSN.
    - Force log out up to lastLSN if necessary
  - Note that log flushes are sequential, synchronous writes to disk and many log records per log page.
    - so, cheaper than forcing out the updated data and index pages.
- Commit() returns.
- Write end record to log.

Simple Transaction Abort

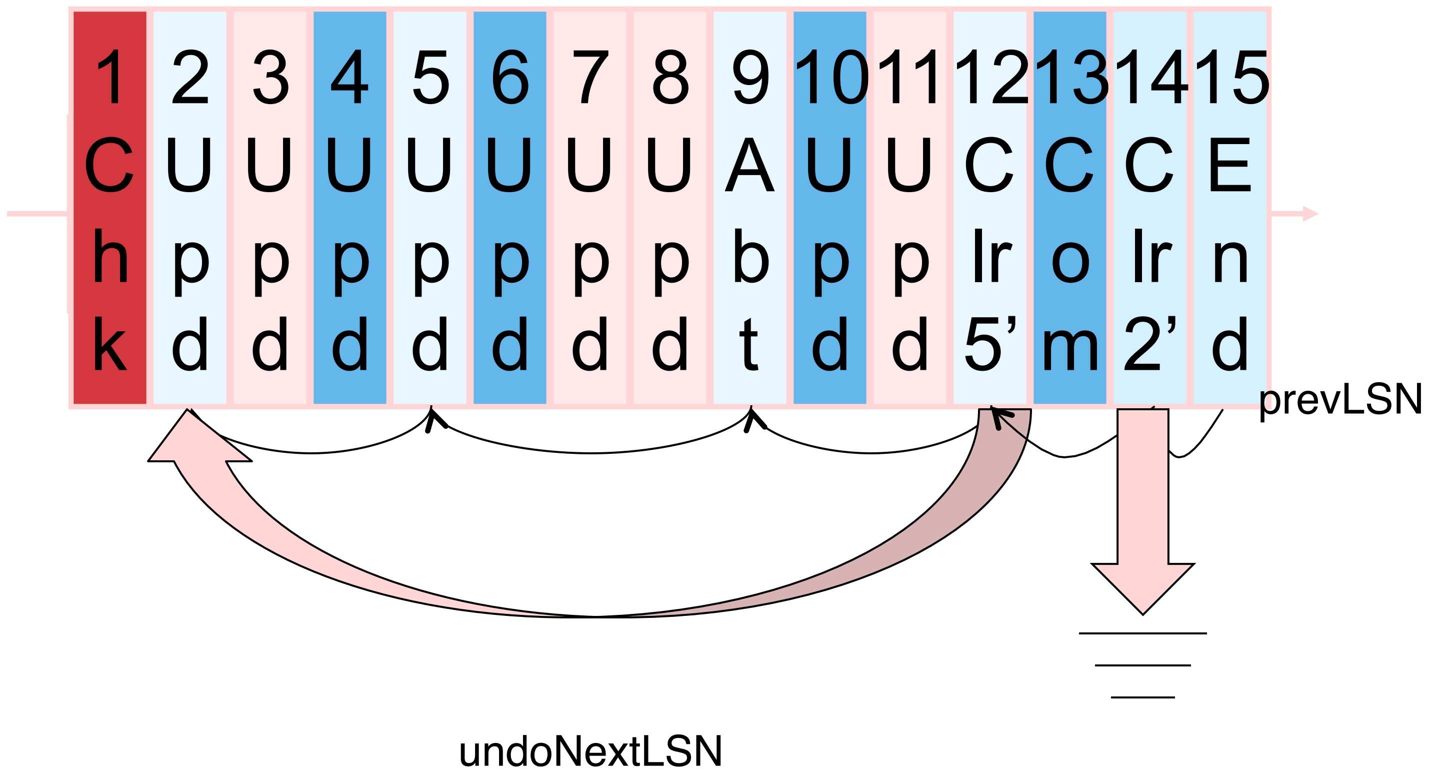
- For now, consider an explicit abort of a Xact.
  - No crash involved.
- We want to “play back” the log in reverse order, UNDOing updates.
  - Write an *Abort* log record before starting to rollback operations.
  - Get lastLSN of Xact from Transaction table.
  - Can follow chain of log records backward via the prevLSN field.
  - For each update encountered:
    - Write a “CLR” (compensation log record) for each undone operation.
    - Undo the operation (using before image from log record).

Abort, cont.



- To perform UNDO, must have a lock on data!
  - No problem (we're doing Strict 2PL)!
- 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).
  - CLRs are *never* Undone (but they might be Redone when repeating history: guarantees Atomicity!)
- At end of UNDO, write an "end" log record.

Abort Example (no crash)



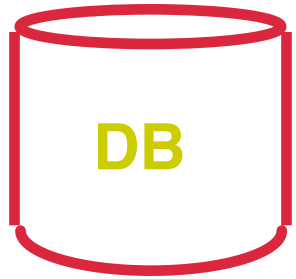
Checkpointing

- Conceptually, keep log around for all time. Obviously this has performance/implemenation problems…
- 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 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.
  - Store LSN of most recent 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

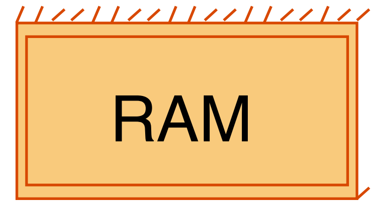


Data pages

each
with a
pageLSN

master record

LSN of
most recent
checkpoint



Xact Table

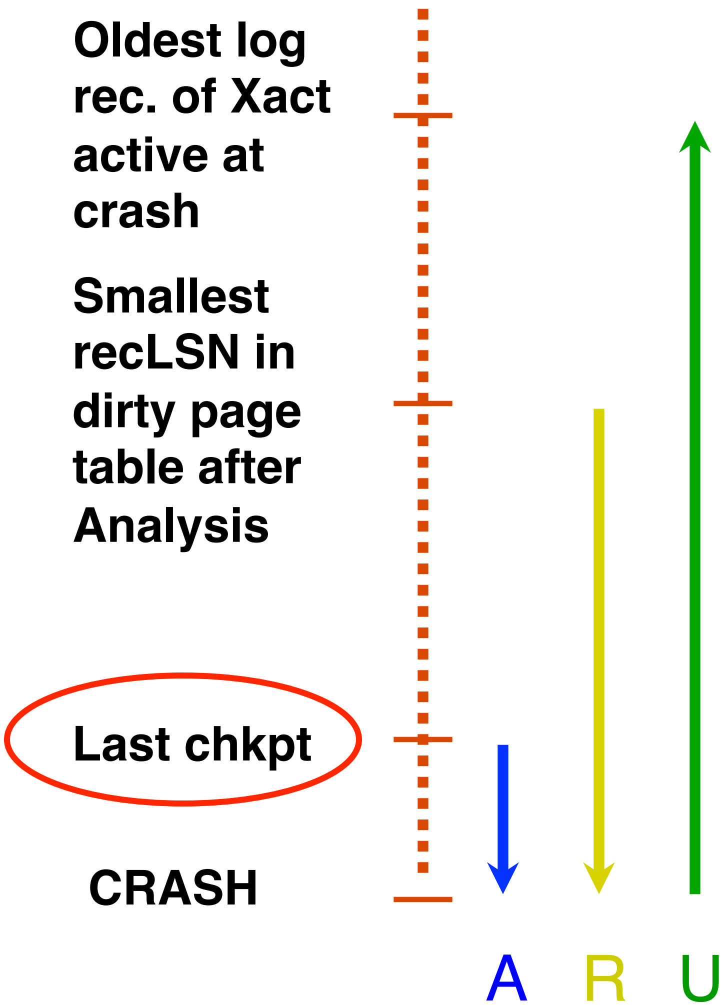
lastLSN
status

Dirty Page Table

recLSN

flushedLSN

Crash Recovery: Big Picture



- Start from a checkpoint (found via master record).
- Three phases. Need to:
  1. **Analysis** - update structures:
     - Trans Table: which Xacts were active at time of crash.
     - Dirty Page Table: which pages *might* have been dirty in the buffer pool at time of crash.
  2. **REDO** ***all*** actions.
     (repeat history)
  3. **UNDO** effects of failed Xacts.

Recovery: The Analysis Phase

- Re-establish knowledge of state at checkpoint.
  - via transaction table and dirty page table stored in the checkpoint
- Scan log forward from checkpoint.
  - End record: Remove Xact from Xact table.
  - All Other records: Add Xact to Xact table, set lastLSN=LSN, change Xact status on commit/abort.
  - also, for Update records: If page P not in Dirty Page Table, Add P to DPT, set its recLSN=LSN.
- At end of Analysis…
  - transaction table says which xacts were active at time of crash.
  - DPT says which dirty pages *might not* have made it to disk

Phase 2: 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 DPT.

  Q: why start here?
- For each update log record or CLR with a given LSN, REDO the action <u>unless</u>:
  - 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. (this last case requires I/O)
- To REDO an action:
  - Reapply logged action.
  - Set pageLSN to LSN. No additional logging, no forcing!

Phase 3: The UNDO Phase

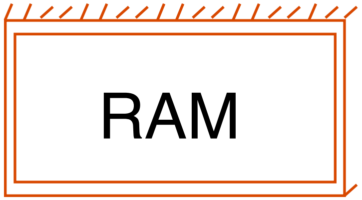
ToUndo={lastLSNs of all Xacts in the Trans Table}

Repeat:

- Choose (and remove) largest LSN among ToUndo.
- If this LSN is a CLR and undonextLSN==NULL
  - Write an End record to the log for this Xact.
- If this LSN is a CLR, and undonextLSN != NULL
  - Add undonextLSN to ToUndo
  - (note we don't do any updates to data pages to UNDO CLRs. Why?)
- Else this LSN is an update. Undo the update, write a CLR, add prevLSN to ToUndo.

Until ToUndo is empty.

Example of Recovery – (up to crash)



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, UndoNxt=Null
45	T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART

Example (cont.):Analysis & Redo

Xact Table

Trans	lastLSN	Status
T2	60	r
T3	50	r

Dirty Page Table

PageId	recLSN
P5	10
P3	20
P1	50

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, UndoNxt=Null
45	T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART

Redo starts at LSN 10;
in this case, reads P5, P3, and P1 from disk, redoes ops if pageLSN < LSN

Ex (cont.): Undo & Crash During Restart!

00 — begin_checkpoint,
05 — end_checkpoint
10 — update: T1 writes P5;Prvl=null
20 — update T2 writes P3; Prvl = null
30 — T1 abort
40 — CLR: Undo T1 LSN 10
45 — T1 End
50 — update: T3 writes P1; PrvL=null
60 — update: T2 writes P5; PrvL=20
CRASH, RESTART

After Analysis/Redo:
ToUndo: 50 & 60

ToUndo:
50 & 20

ToUndo:
20

After Analysis/Redo:
ToUndo: 70

ToUndo:
20

ToUndo:
Finished!

00 begin_checkpoint,

05 end_checkpoint

10 update: T1 writes P5;Prvl=null

20 update T2 writes P3; Prvl = null

30 T1 abort

40 CLR: Undo T1 LSN 10

45 T1 End

50 update: T3 writes P1; PrvL=null

60 update: T2 writes P5; PrvL=20

CRASH, RESTART

70 CLR: Undo T2 LSN 60; UndoNxtLSN=20

80 CLR: Undo T3 LSN 50;UndoNxtLSN=null

85 T3 end

CRASH, RESTART

90 CLR: Undo T2 LSN 20;UndoNxtLSN=null

100 T2 end

After Analysis/Redo:
ToUndo: 50 & 60

ToUndo:
50 & 20

ToUndo:
20

After Analysis/Redo:
ToUndo: 70

ToUndo:
20

ToUndo:
Finished!

Additional Crash Issues

- What happens if system crashes during Analysis? During REDO?
  - The logged action is reapplied
  - The pageLSN on the page is set to LSN of the redone log record
- At the end of REDO, write end records for all transactions with status C (why?)
- How to reduce the amount of work in Analysis?
  - Take frequent checkpoints.

Additional Crash Issues

- How do you limit the amount of work in REDO?
  - Frequent checkpoints plus
  - Flush data pages to disk asynchronously in the background (during normal operation and recovery).
    - Buffer manager can do this to unpinned, dirty pages.
- How do you limit the amount of work in UNDO?
  - Avoid long-running Xacts.

Summary of Logging/Recovery

- Transactions support the ACID properties.
- Recovery Manager guarantees Atomicity & Durability.
- Use Write Ahead Longing (WAL) to allow STEAL/NO-FORCE buffer manager without 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.
- Aries recovery works in 3 phases:
  - Analysis: Forward from checkpoint. Rebuild transaction and dirty page tables.
  - Redo: Forward from oldest recLSN, repeating history for all transactions.
  - Undo: Backward from end to first LSN of oldest Xact alive at crash. Rollback all transactions not completed as of the time of the crash.
- Redo "repeats history": Simplifies the logic!
- Upon Undo, write CLRs. Nesting structure of CLRS avoids having to "undo undo operations".

Database Architecture