CSE462/562: Database Systems (Spring 23)

Lecture 22: Crash Recovery

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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.

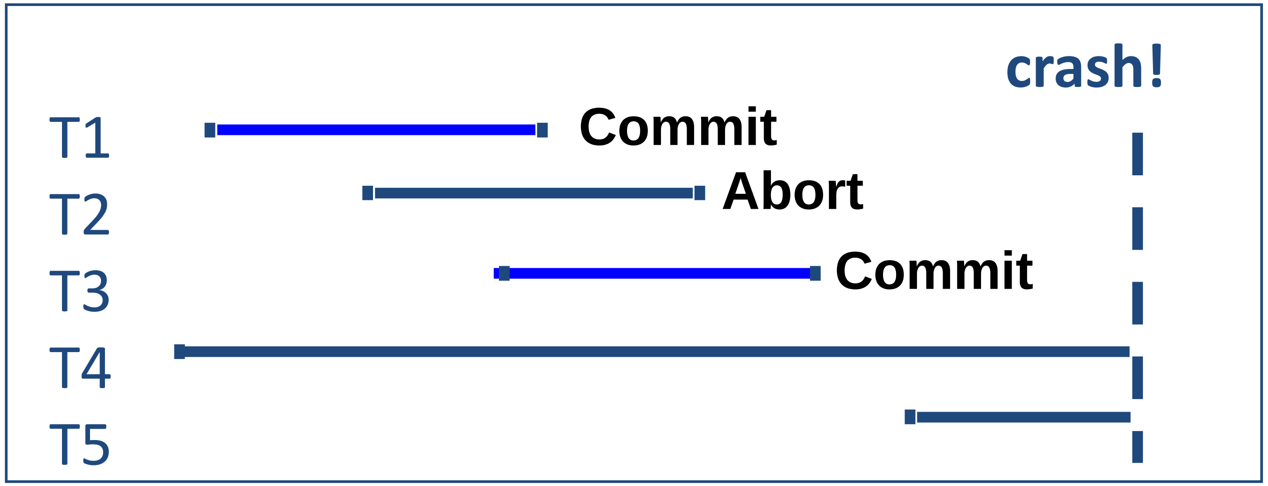
- Question: which ones does the Recovery Manager help with?

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

Motivation for crash recovery

- 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).



Assumptions

- Concurrency control is in effect.
  - Strict 2-PL, in particular.
- Updates are happening "in place".
  - i.e. data are overwritten on (or deleted from) the actual pages.

- Can you think of a *simple* scheme (requiring no logging) to guarantee Atomicity & Durability?
  - What happens during normal execution (what is the minimum lock granularity)?
  - What happens when a transaction commits?
  - What happens when a transaction aborts?

Buffer manager plays a key role

- **Force policy –** make sure that every update is on disk before commit.
  - Provides durability without REDO logging.
  - But, can cause poor performance.

- **No Steal policy –** 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 buffer management policy: steal/no-force

- This combination is most complicated but allows for highest performance.
- *NO FORCE*: do not have to flush all dirty pages of a transaction to disk before it commits
  - complicates 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:* allows buffer pool with uncommitted updates to overwrite committed data on disk
  - complicates Atomicity
  - What if the Xact that performed updates 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 policies

	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)

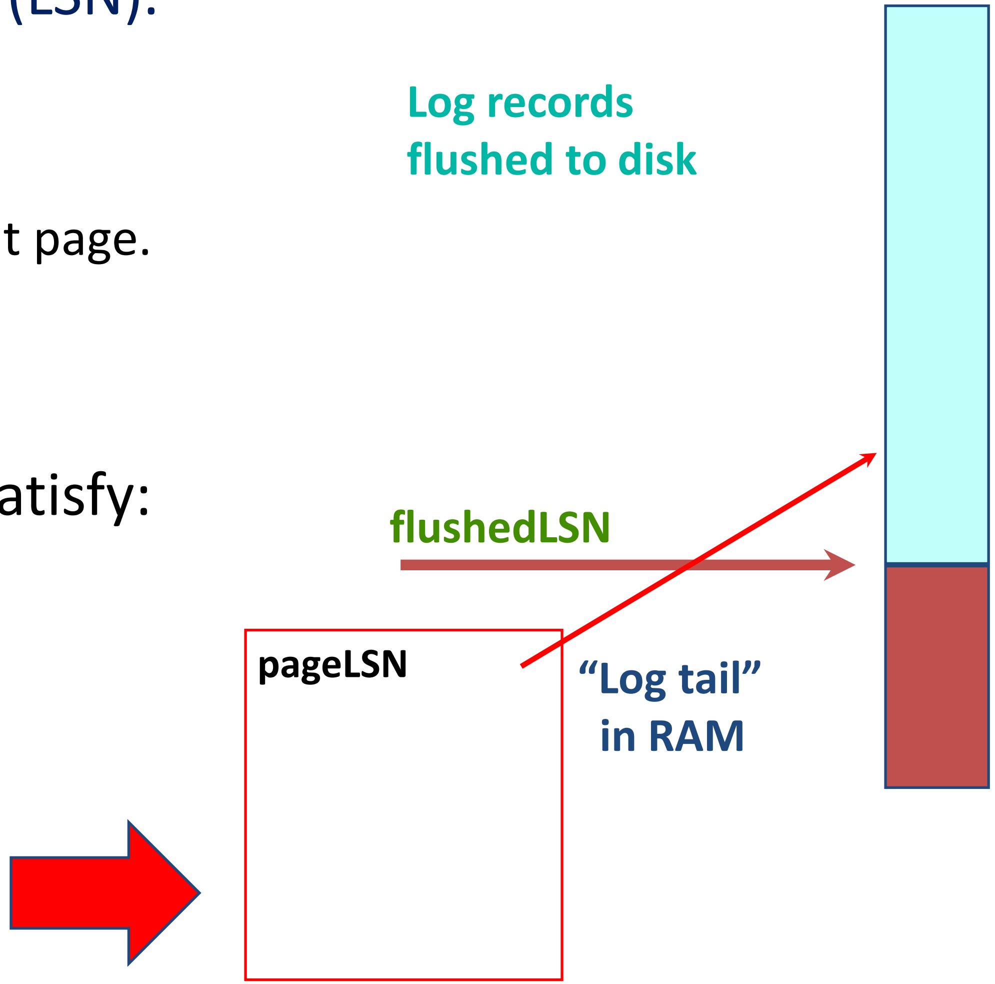
- The Write-Ahead Logging Protocol:
  - ① Must flush the log record for an update *before* the corresponding data page gets to disk.
  - ② Must flush all log records for a Xact *before commit*
    - alternatively,. transaction is not considered as committed until all of its log records including its “commit” record are on the stable log.
- #1 (with UNDO info) helps provide Atomicity.
- #2 (with REDO info) helps provide Durability.
- This allows us to employ Steal/No-Force policy

- Exactly how is logging (and recovery) done?
  - We’ll look at the ARIES algorithms.
    - Algorithms for Recovery and Isolation Exploiting Semantics

WAL & the log

- Each log record has a unique Log Sequence Number (LSN).
  - LSNs are monotonically 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: Before page i is flushed to disk, the log must satisfy:

  $pageLSN_i \leq flushedLSN$



Log Records

LogRecord fields:

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

update records only: pageID, length, offset, before-image, after-image

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

Possible log record types:

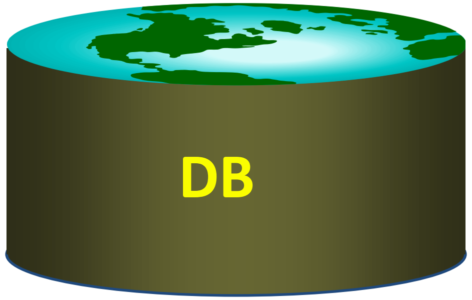
- Update
- Checkpoint (for log maintenance)
- Compensation Log Records (CLRs)
    - for UNDO actions
- Commit/Abort
- End (indicates end of commit/abort)

Other logging-related state

- Two -in-memory tables
- Transaction Table
  - One entry per currently active Xact.
    - entry removed when Xact commits or aborts
  - Contains XID, status (running/committing/aborting), and 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 which ***first*** caused the page to be dirty.
    - If a dirty page is flushed to disk, it is removed from dirty page table

The big picture: what's stored and where

LogRecords
- LSN
- 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

Normal execution of an Xact

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

Transaction Commit

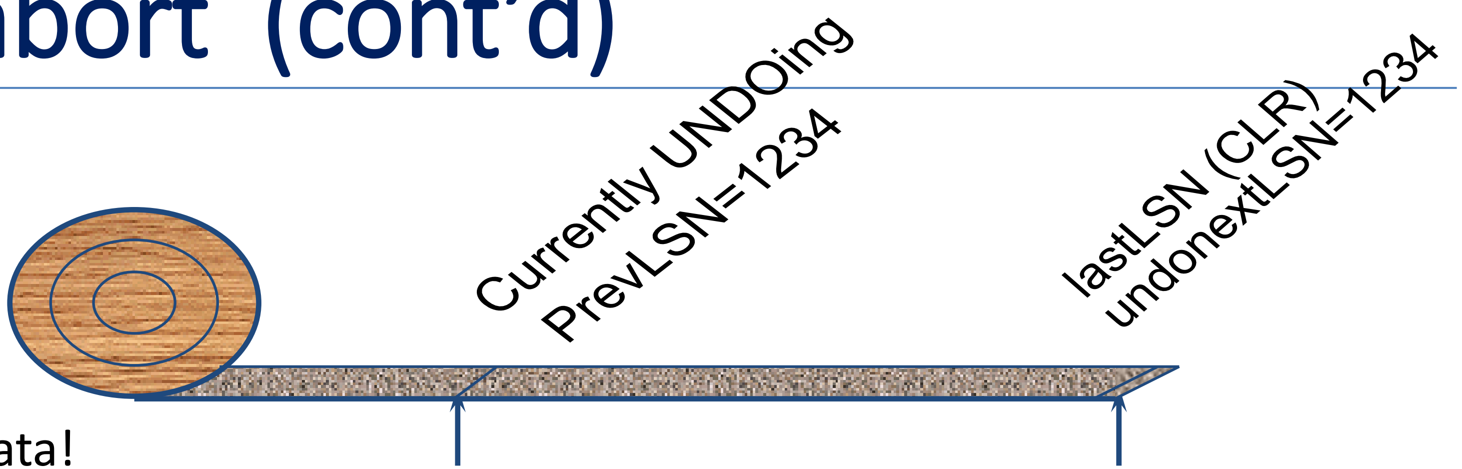
- Write commit record to log.
- All log records up to Xact's commit record are flushed to disk.
  - Guarantees that flushedLSN $\geq$ lastLSN.
  - Note that log flushes are sequential, synchronous writes to disk.
  - Many log records per log page.
- Write an end record to log (no need to flush immediately)
- Commit() returns.

- When does a transaction becomes durable in the database?
  - When its commit log record is flushed to disk, even if there are still dirty pages in bufmgr.

Simple transaction abort

- For now, consider an explicit abort of a Xact.
  - No crash involved.
- First, set the transaction state in the transaction table to aborting.
  - Write an *Abort* log record before starting to rollback operations
- 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.
  - Write a "CLR" (compensation log record) for each undone operation.
    - more details on next slide
  - Once its finished, write a transaction end log record in the disk
- Q: do we need to wait for abort, CLRs and end record to be flushed?

Simple transaction abort (cont'd)

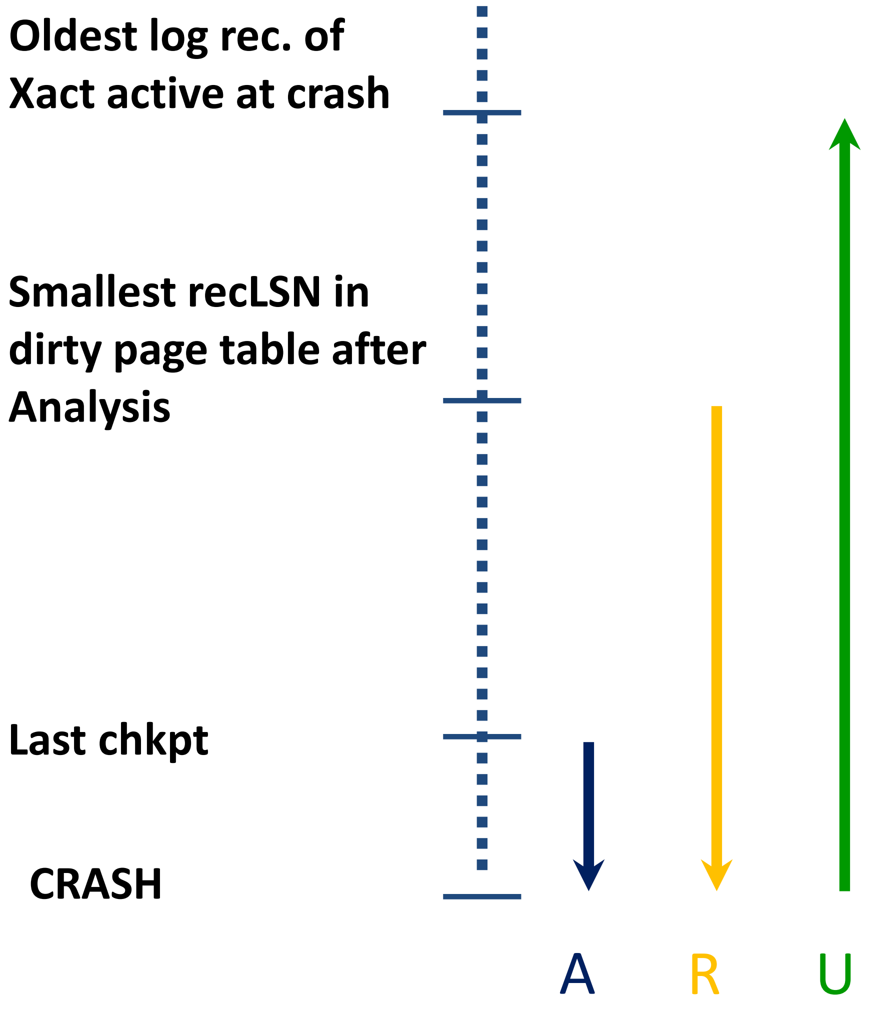


- To perform UNDO, must have a lock on data!
  - We still have the lock because of strict 2-PL.
- Before restoring old value of a page, write a CLR:
  - Must continue logging during undo in case of crash
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of the record we're currently undoing).
  - CLR contains REDO info
  - CLRs is *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.

Checkpointing

- Conceptually, we keep log around for all time. Obviously this has performance issues…
- 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 all dirty pages to disk; effectiveness of checkpoint limited by oldest unwritten change to a dirty page.
      - However, the more dirty page gets flushed, the shorter time will be needed in crash recovery
  - Store LSN of most recent chkpt record in a safe place (*master* record).

Crash Recovery: Big Picture



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

Phase 1: 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.
  - 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 (including those 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 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. (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}

i.e., last log entry of the aborted transactions

Repeat:

- Choose (and remove) 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
- Else this LSN is an update. Undo the update, write a CLR, add prevLSN to ToUndo.

Until ToUndo is empty.

Example of recovery

Xact Table

lastLSN

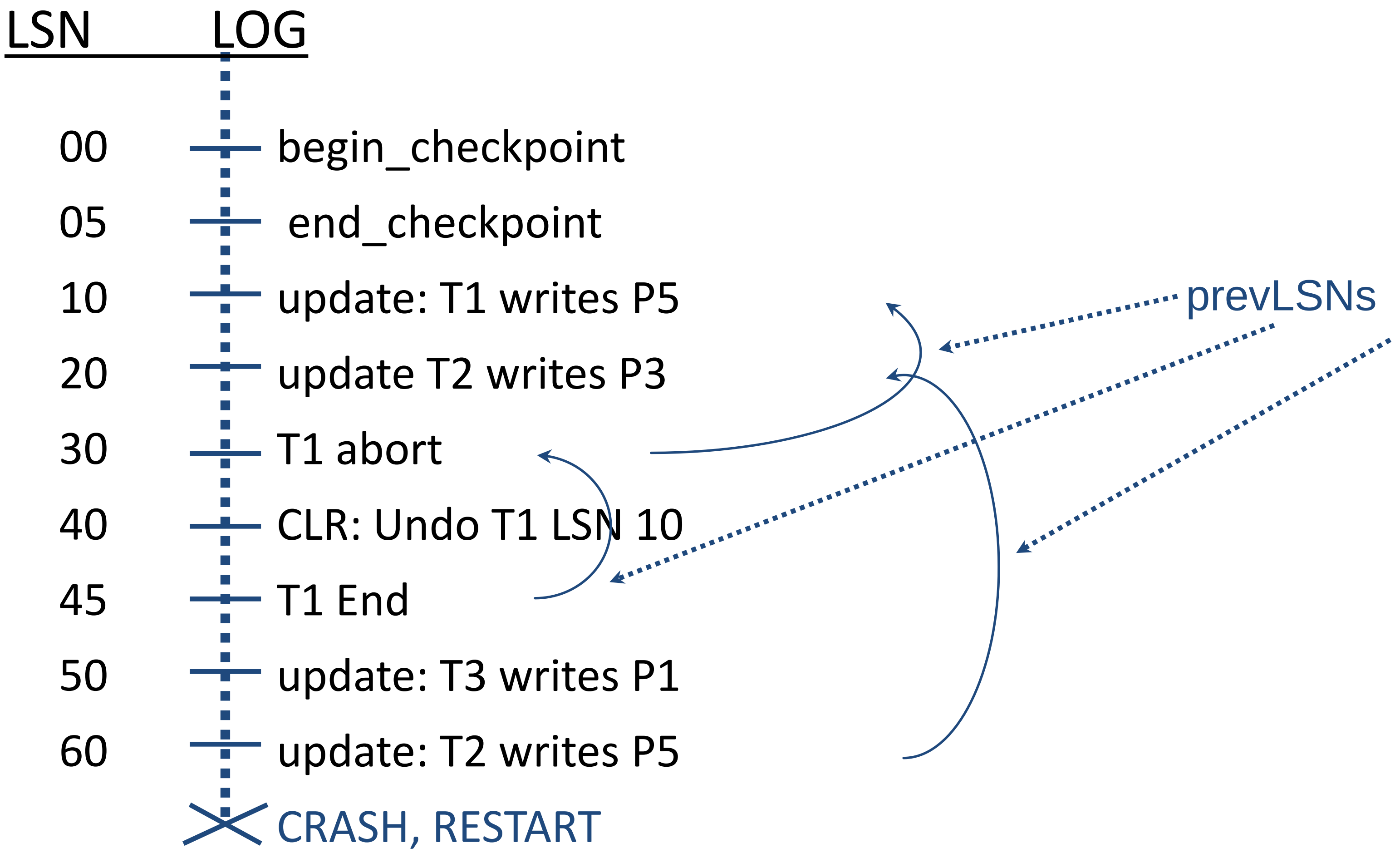
status

Dirty Page Table

recLSN

flushedLSN

ToUndo



Example: crash during recovery

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	CLR: Undo T1 LSN 10
45	T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART
70	CLR: Undo T2 LSN 60
80	CLR: Undo T3 LSN 50
85	T3 end
	CRASH, RESTART
90,95	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.

- What about schema changes/disk space management?

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.

- 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!