Lecture 7: Recovery (Part 1)

Crash Recovery

- Recovery algorithms are techniques to ensure database **consistency**, transaction **atomicity**, and **durability** despite failures.
- Recovery algorithms have **two parts**:
  - Actions during normal txn processing to ensure that the DBMS can recover from a failure.
  - Actions after a failure to recover the database to a state that ensures atomicity, consistency, and durability.

Logging Protocol

- Write-Ahead Logging is (almost) always the best approach to handle loss of volatile storage.
  - Use incremental updates (STEAL + NO-FORCE) with checkpoints.
  - On recovery: undo uncommitted txns + redo committed txns.

ARIES

- Algorithms for Recovery and Isolation Exploiting Semantics
- Developed at **IBM Research** in early 1990s for the DB2 DBMS.
- Not all systems implement ARIES exactly as defined in this paper but they're close enough.

ARIES – Main Ideas

- Write-Ahead Logging:
  - Any change is recorded in log on stable storage before the change is written to database on disk.
  - Must use **STEAL + NO-FORCE** buffer pool policies.
- Repeating History During **Redo**:
  - On restart, retrace actions and restore database to exact state before crash.
- Logging Changes During **Undo**:
  - Record undo actions to log to ensure action is not repeated in the event of **repeated failures**.

Today's Agenda

- Log Sequence Numbers
- Normal Commit & Abort Operations
- Checkpointing
- Recovery Algorithm

Log Sequence Numbers

Log Records

- We need to extend our log record format from last class to include additional info.
- The log is a single ever-growing sequential file (append-only).
- Every log record now includes a globally unique **log sequence number** (LSN).
- Various components in the system keep track of LSNs that pertain to them. . .

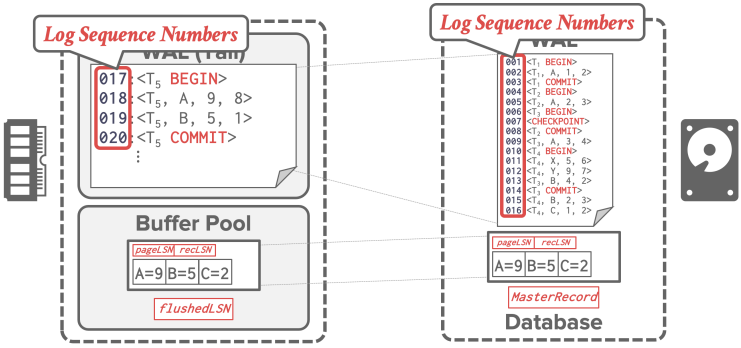
Log Sequence Numbers

LSN Type	Where	Definition
flushedLSN	Memory	Last LSN in log on disk
pageLSN	$page_x$	Newest update to $page_x$
recLSN	$page_x$	Oldest update to $page_x$ since it was last flushed
lastLSN	T_i	Latest record of txn T_i
MasterRecord	Disk	LSN of latest checkpoint

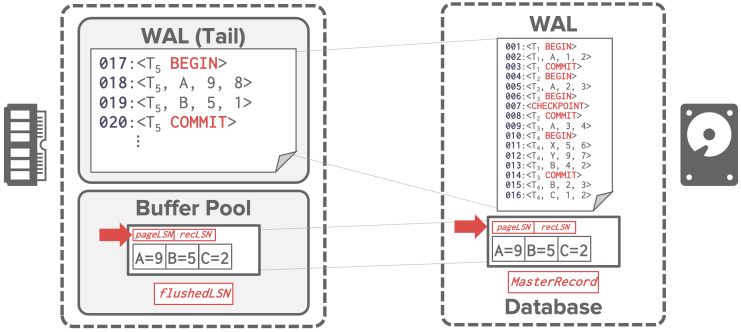
Writing Log Records

- Each data page contains a pageLSN.
  - The LSN of the most recent update to that page.
- System keeps track of flushedLSN.
  - The max LSN flushed so far.
- Before page x can be written to disk, we must flush log at least to the point where:
  - $\mathrm{pageLSN}_x <= \mathrm{flushedLSN}$

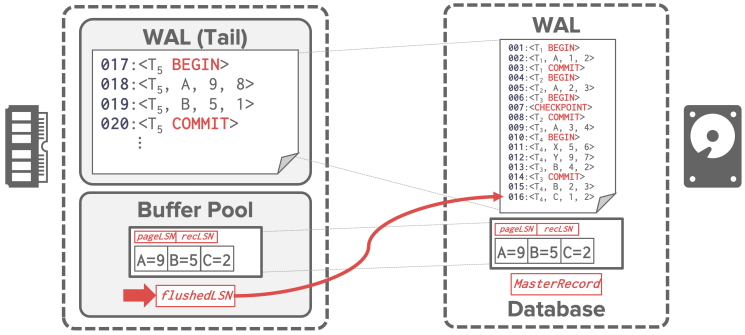
Writing Log Records



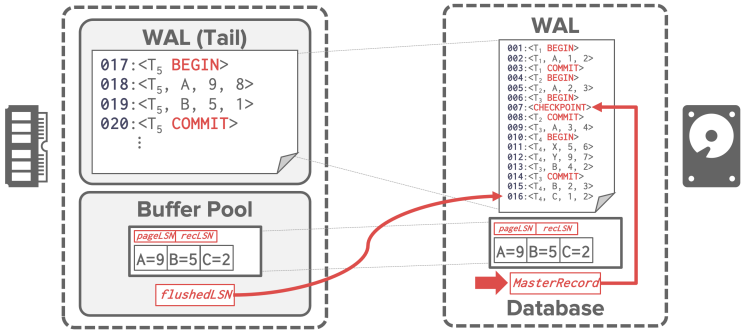
Writing Log Records



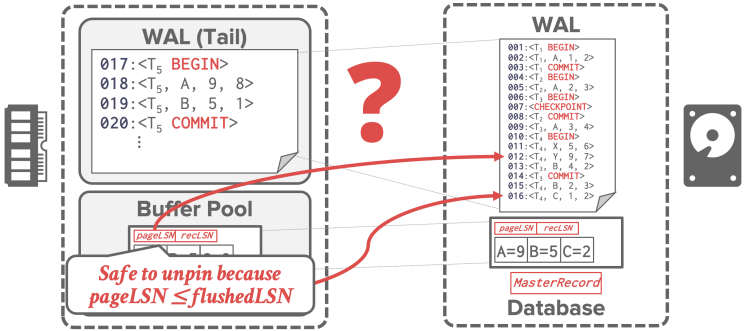
Writing Log Records



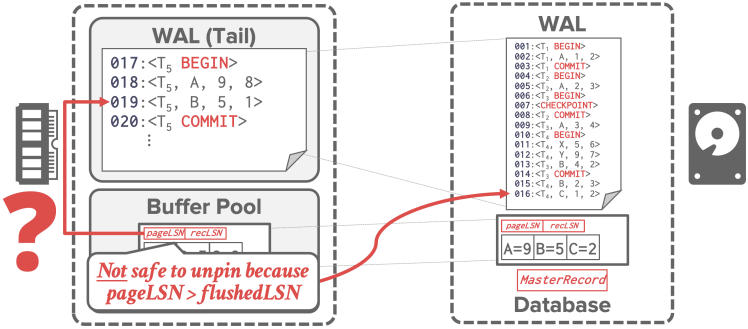
Writing Log Records



Writing Log Records



Writing Log Records



Writing Log Records

- All log records have an LSN.
- Update the *pageLSN* every time a txn modifies a record in the page.
- Update the *flushedLSN* in memory every time the DBMS writes out the WAL buffer to disk.
- Must generate the log record first before modifying the page

Normal Commit & Abort Operations

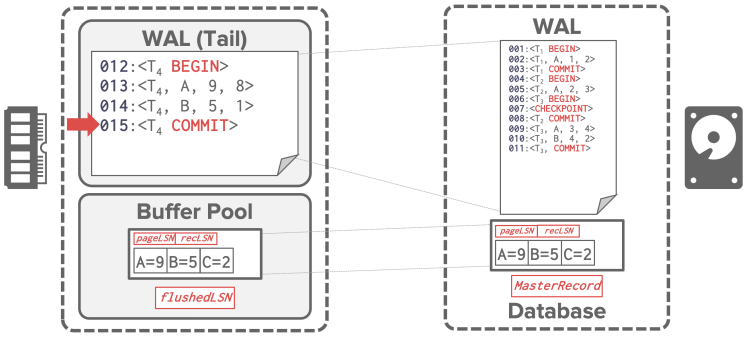
Normal Execution

- Each txn invokes a sequence of reads and writes, followed by commit or abort.
- Assumptions in this lecture:
  - All log records fit within a single page.
  - Disk writes are atomic.
  - Single-versioned tuples with **Strict Two Phase Locking**.
  - STEAL + NO-FORCE buffer management with WAL.

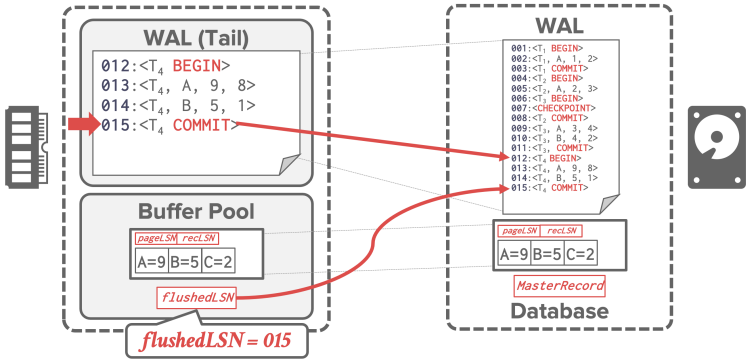
Transaction Commit

- Write **<COMMIT>** record to log.
- All log records up to txn's **<COMMIT>** record are flushed to disk.
  - Note that log flushes are sequential, synchronous writes to disk.
  - Many log records per log page.
- When the commit succeeds, write a special **<TXN-END>** record to log.
  - Now remove transaction from the **Active Transaction Table**
  - This does **not** need to be flushed immediately.

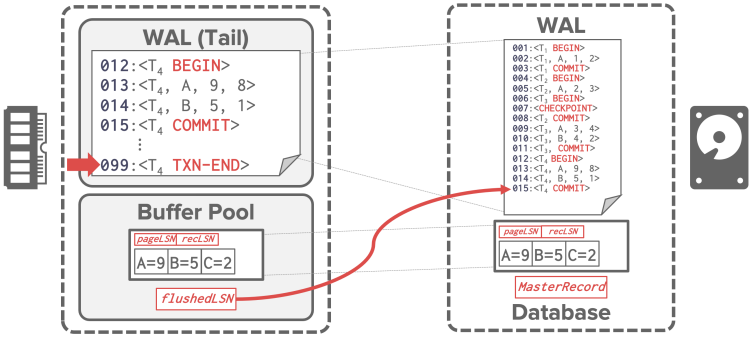
Transaction Commit



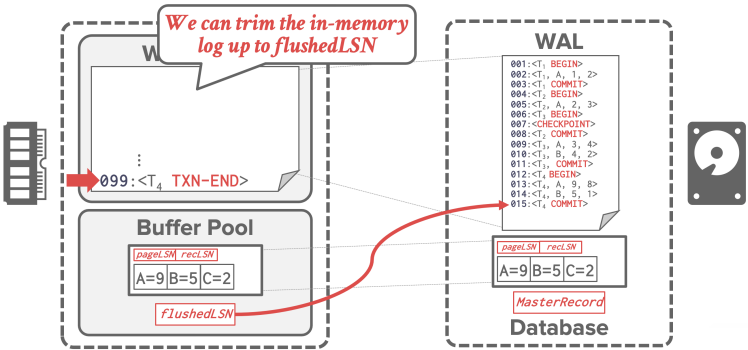
Transaction Commit



Transaction Commit



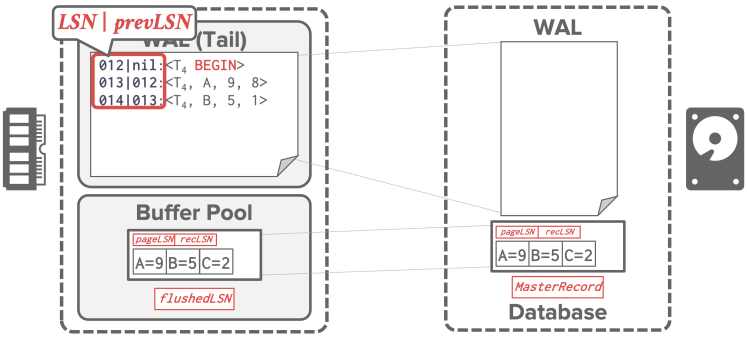
Transaction Commit



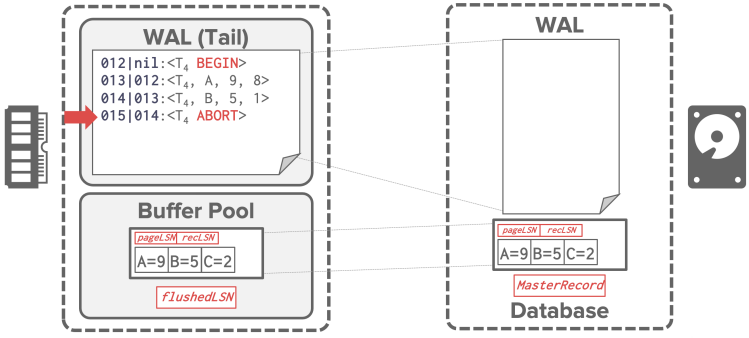
Transaction Abort

- Aborting a txn is actually a special case of the ARIES undo operation applied to only one transaction.
- We need to add another field to our log records:
  - $prevLSN$: The previous LSN for the txn.
  - This maintains a linked-list for each txn that makes it easy to walk through its records.

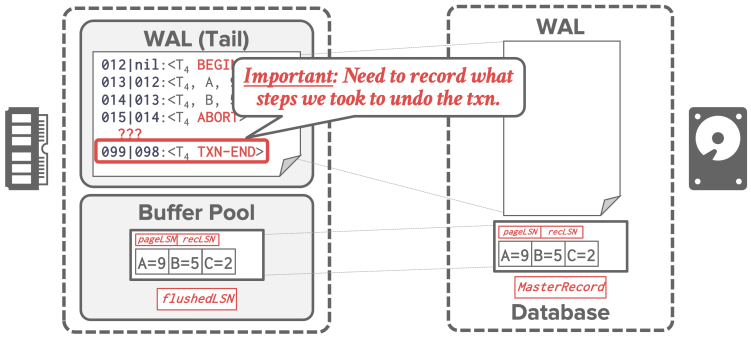
Transaction Abort



Transaction Abort



Transaction Abort



Compensation Log Records

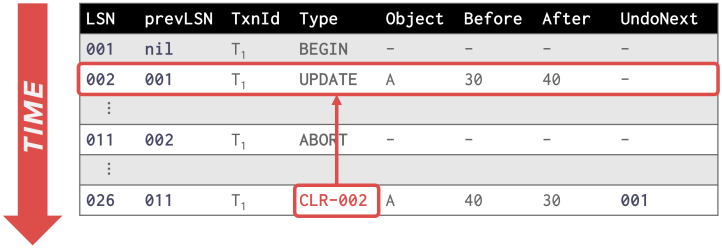
Compensation Log Records

- A **Compensation Log Record (CLR)** describes the actions taken to undo the actions of a previous update record.
- It has all the fields of an update log record plus the **undoNext** pointer (the next-to-be-undone LSN).
- CLRs are added to log like any other record.
- **Goal:** CLRs are necessary to recover the database if there is a crash during recovery.

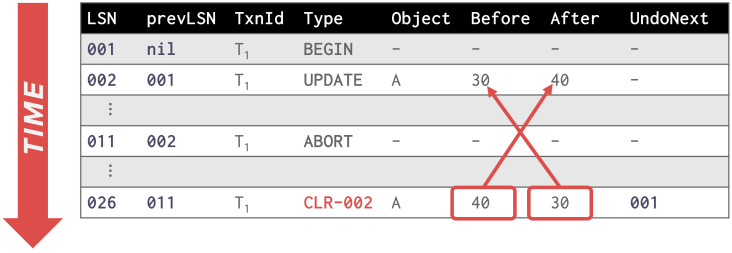
CLR Example

LSN	prevLSN	TxnId	Type	Object	Before	After	UndoNext
001	nil	T_1	BEGIN	–	–	–	–
002	001	T_1	UPDATE	A	30	40	–
⋮							
011	002	T_1	ABORT	–	–	–	–

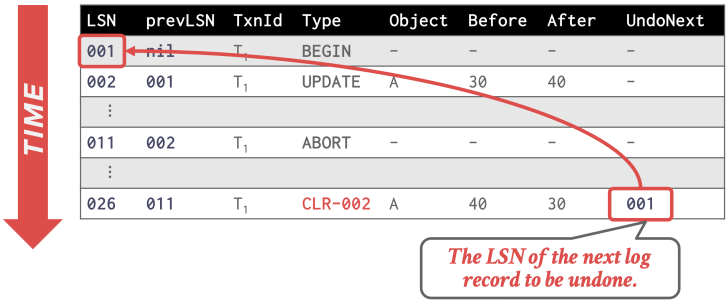
CLR Example


TIME
LSN prevLSN TxnId Type Object Before After UndoNext
001 nil T1 BEGIN - - - -
002 001 T1 UPDATE A 30 40 -
011 002 T1 ABORT - - - -
026 011 T1 CLR-002 A 40 30 001

CLR Example


TIME
LSN prevLSN TxnId Type Object Before After UndoNext
001 nil T1 BEGIN – – – –
002 001 T1 UPDATE A 30 40 –
011 002 T1 ABORT – – – –
026 011 T1 CLR-002 A 40 30 001

CLR Example


TIME
LSN
prevLSN
TxnId
Type
Object
Before
After
UndoNext
001
nil
T1
BEGIN
–
–
–
–
002
001
T1
UPDATE
A
30
40
–
011
002
T1
ABORT
–
–
–
–
026
011
T1
CLR-002
A
40
30
001
The LSN of the next log record to be undone.

CLR Example

LSN	prevLSN	TxnId	Type	Object	Before	After	UndoNext
001	nil	T_1	BEGIN	–	–	–	–
002	001	T_1	UPDATE	A	30	40	–
⋮							
011	002	T_1	ABORT	–	–	–	–
⋮							
026	011	T_1	CLR-002	A	40	30	001
027	026	T_1	TXN-END	–	–	–	nil

Abort Algorithm

- First write an **<ABORT>** record to log for the txn.
- Then play back the txn's updates in reverse order. For each update record:
  - Write a CLR entry to the log.
  - Restore old value.
- When a txn aborts, we immediately tell the application that it is aborted.
- We don't need to wait to flush the CLRs
- At end, write a **<TXN-END>** log record.
- **Notice:** CLRs never need to be undone.

Checkpointing

Checkpointing

- Log grows forever.
- Use checkpoints to limit the size of the log that the DBMS must examine.
- Checkpoint algorithms
  - Non-Fuzzy Checkpointing
  - Slight Better Checkpointing
  - Fuzzy Checkpointing

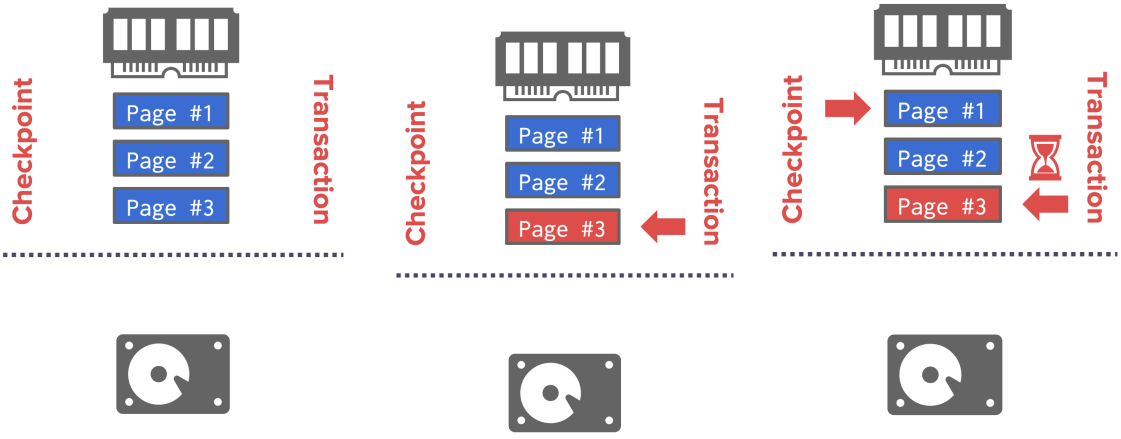
Non-Fuzzy Checkpointing

- The DBMS halts everything when it takes a checkpoint to ensure a consistent snapshot:
  - Halt the start of any new txns.
  - Wait until all active txns finish executing.
  - Flushes dirty pages on disk.
- This is obviously bad. . .

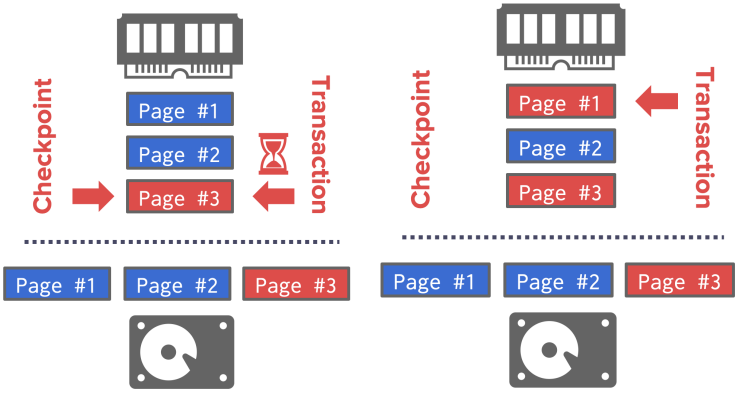
Slight Better Checkpointing

- Pause modifying txns while the DBMS takes the checkpoint.
  - Prevent queries from acquiring write latch on table/index pages.
  - Don't have to wait until all txns finish before taking the checkpoint.
- We must record internal state as of the beginning of the checkpoint.
  - **Active Transaction Table** (ATT)
  - **Dirty Page Table** (DPT)

Slight Better Checkpointing



Slight Better Checkpointing



Active Transaction Table

- Managed by the **Transaction Manager** in memory
- One entry per currently active txn.
  - `txnId`: Unique txn identifier.
  - `status`: The current "mode" of the txn.
  - `lastLSN`: Most recent LSN created by txn.
- Entry removed when txn commits or aborts.
- Txn Status Codes:
  - `R` $\rightarrow$ Running
  - `C` $\rightarrow$ Committing
  - `U` $\rightarrow$ Candidate for Undo

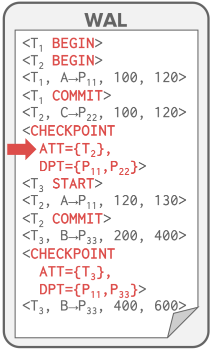
Dirty Page Table

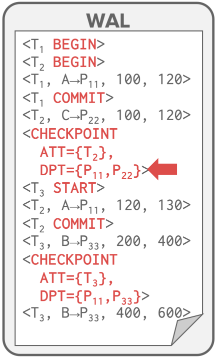
- Keep track of which pages in the buffer pool contain changes from uncommitted transactions.
- One entry per dirty page in the buffer pool:
  - recLSN: The LSN of the log record that first caused the page to be dirty.

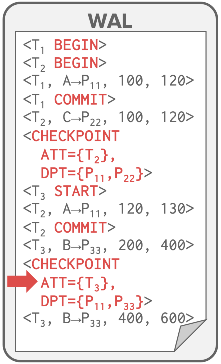
Slight Better Checkpointing

- At the first checkpoint, T2 is still running and there are two dirty pages (P11, P22).
- At the second checkpoint, T3 is active and there are two dirty pages (P11, P33).
- This still is not ideal because the DBMS must stall txns during checkpoint. . .

Slight Better Checkpointing







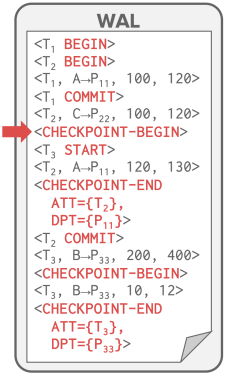
Fuzzy Checkpointing

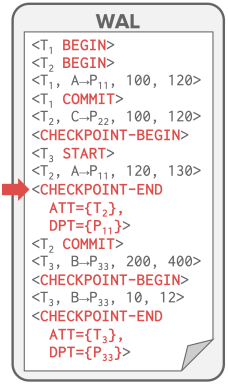
- A fuzzy checkpoint is where the DBMS allows active txns to **continue** running while the system flushes dirty pages to disk.
- New types of log records to track **checkpoint boundaries**:
  - CHECKPOINT – BEGIN: Indicates start of checkpoint
  - CHECKPOINT – END: Contains ATT + DPT.

Fuzzy Checkpointing

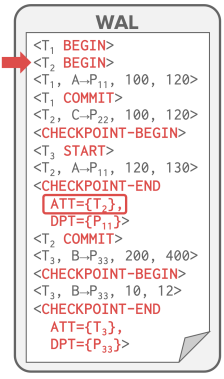
- The LSN of the **<CHECKPOINT-BEGIN>** record is written to the database's MasterRecord entry on disk when the checkpoint successfully completes.
- Any txn that starts after the checkpoint is excluded from the ATT in the **<CHECKPOINT-END>** record.

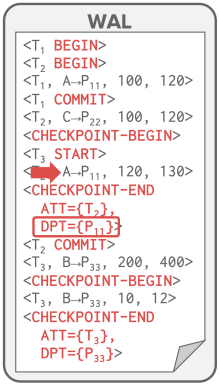
Fuzzy Checkpointing





Fuzzy Checkpointing





Conclusion

Parting Thoughts

- Log Sequence Numbers:
  - LSNs identify log records; linked into backwards chains per transaction via prevLSN.
  - pageLSN allows comparison of data page and log records.
- Mains ideas of ARIES:
  - WAL with STEAL/NO-FORCE
  - Fuzzy Checkpoints (snapshot of dirty page ids)
  - Write CLRs when undoing, to survive failures during restarts

Next Class

- Continue the ARIES protocol