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Carnegie Mellon Univ.
Dept. of Computer Science
15-415/615 - DB Applications

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Lecture#23: Crash Recovery – Part 2

(R&G ch. 18)

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Administrivia

- HW8 is due Thurs April 24th

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Last Class

- Shadow Paging
- Write-Ahead Log
- Checkpoints
- Logging Schemes

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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.

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`fsync(2)`

- Kernel maintains a buffer cache between applications & disks.
  - If you just call `write()`, there is no guarantee that the data is durable on disk.
- Use `fsync()` to force the OS to flush all modified in-core data to disk.
  - This blocks the thread until it completes.
  - Data may still live in on-disk cache but we cannot control that.

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Buffer Pool – Steal Policy

- Whether the DBMS allows an uncommitted txn to overwrite the most recent committed value of an object in non-volatile storage.
  - **STEAL:** Is allowed.
  - **NO-STEAL:** Is not allowed.

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Buffer Pool – Force Policy

- Whether the DBMS ensures that all updates made by a txn are reflected on non-volatile storage before the txn is allowed to commit:
  - **FORCE:** Is enforced.
  - **NO-FORCE:** Is not enforced.

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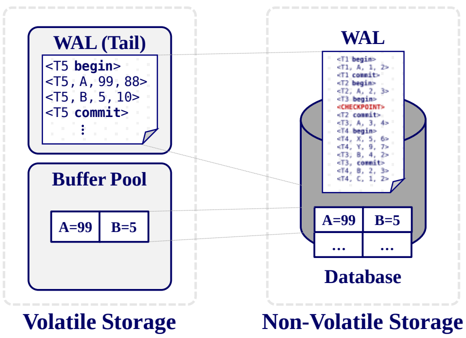
Write-Ahead Logging



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Writing Log Records

- We don't want to write one record at a time
- How should we buffer them?
  - Batch log updates (group commit).
- Page *i* can be written out only after the corresponding log record has been flushed.

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Memory Pinning

- The DBMS needs to be able restrict when pages are flushed to disk.
- “Pinning” a page means that the buffer pool manager is not allowed to flush that page.
  - Think of it like a lock.
- **NOTE:** Block == Page
  - I use these terms interchangeably.
  - They mean the same thing.

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Memory Pinning

- The DBMS un-pins a data page ONLY if all the corresponding log records that modified that page have been flushed to the log.

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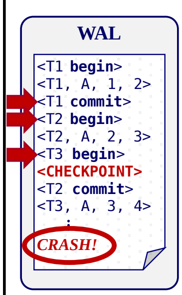
Checkpoints



- Any txn that committed before the checkpoint is ignored (T1).
- T2 + T3 did not commit before the last checkpoint.
  - Need to redo T2 because it committed after checkpoint.
  - Need to undo T3 because it did not commit before the crash.

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Summary

- Write-Ahead Log to handle loss of volatile storage.
- Use incremental updates (i.e., **STEAL**, **NO-FORCE**) with checkpoints.
- On recovery, make sure that:
  - Committed txns are atomic + durable.
  - Uncommitted txns are removed.

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Today's Class – ARIES

- **A**lgorithms for **R**ecovery and **I**solation **E**xploiting **S**emantics
  - Write-ahead Logging
  - Repeating History during Redo
  - Logging Changes during Undo

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ARIES

- Developed at IBM during the early 1990s.
- Considered the "gold standard" in database crash recovery.
  - Implemented in DB2.
  - Everybody else more or less implements a variant of it.

C. Mohan
IBM Fellow

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ARIES – Main Ideas

- **Write-Ahead Logging:**
  - Any change is recorded in log on stable storage before the database change is written to disk.
- **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.

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ARIES – Main Ideas

- Write Ahead Logging
  - Fast, during normal operation
  - Least interference with OS (i.e., **STEAL**, **NO FORCE**)
- Fast (fuzzy) checkpoints
- On Recovery:
  - Redo everything.
  - Undo uncommitted txns.

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Today's Class

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

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WAL Records

- We're going to extend our log record format from last class to include additional info.
- Every log record has a globally unique **log sequence number** (***LSN***).
- **Q:** Why do we need it?

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Log Sequence Number

Name	Where	Definition
LSN	–	Log sequence number
flushedLSN	RAM	Last ***LSN*** on log (disk).
pageLSN	@$page_i$	Latest update to $page_i$
recLSN	@$page_i$	Earliest update to $page_i$
lastLSN	T_j	Latest action of T_j
Master Record	Disk	***LSN*** of latest checkpoint

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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.
- For a page *i* to be written, must flush log at least to the point where:
  - $\boldsymbol{pageLSN_i \leq flushedLSN}$

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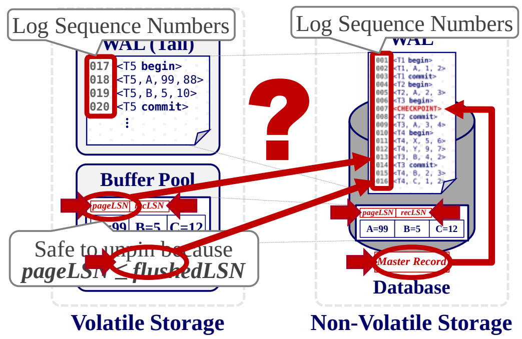
Writing Log Records



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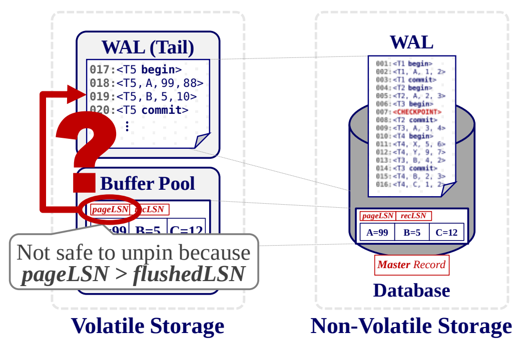
Writing Log Records



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Writing Log Records

- ***LSNs***: Written for each log record.
- ***pageLSN***: Stored in each page in database.
- ***flushedLSN***: In-Memory only.

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Today's Class

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

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Normal Execution

- Series of reads & writes, followed by commit or abort.
- Assumptions:
  - Disk writes are atomic.
  - Strict 2PL.
  - **STEAL** + **NO-FORCE** buffer management, with Write-Ahead Logging.

We do extra stuff to deal with non-atomic writes (e.g., MySQL's doublewrite).

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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 an **TXN-END** record to log.

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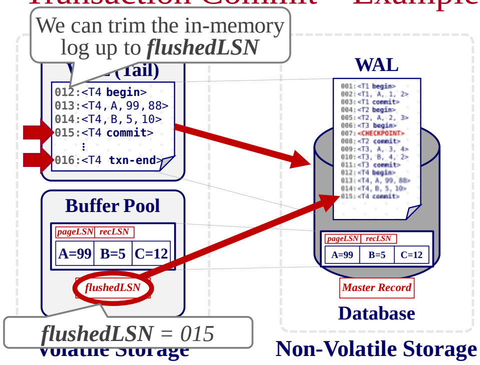
Transaction Commit – Example



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Transaction Commit

- **Q:** Why not flush the dirty pages too?
- **A:** Speed! This is why we use **NO-FORCE**
  - Example: One txn changes 100 tuples…

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Transaction Abort

- Aborting a txn is actually a special case of the ARIES **undo** operation applied to only one transaction.
- 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.

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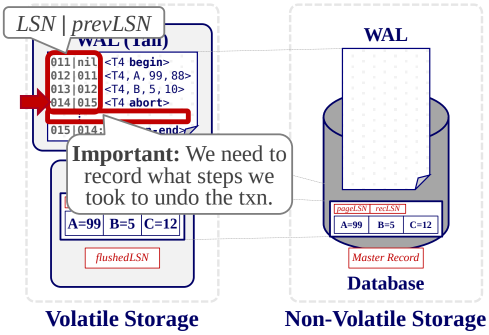
Transaction Abort – Example



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Compensation Log Records

- A 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 (i.e., the next-to-be-undone ***LSN***).
- CLRs are added to log like any other record.

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Transaction Abort – CLR Example

TIME

LSN	*prevLSN*	*TxnId*	*Type*	*Object*	*Before*	*After*
001	nil	T1	`BEGIN`	-	-	-
002	001	T1	`UPDATE`	A	30	40
⋮						
011	002	T1	`ABORT`	-	-	-

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Transaction Abort – CLR Example

TIME

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

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Transaction 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	A	40	30	001

The ***LSN*** of the next log record to be undone.

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Abort Algorithm

- First, write an **ABORT** record on log
- Play back updates, in reverse order: for each update
  - Write a **CLR** log record
  - Restore old value
- At end, write an **END** log record
- Notice: CLRs never need to be undone

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Today's Class

- Log Sequence Numbers
- Normal Execution & Abort Operations
- ➡ Fuzzy Checkpointing
- Recovery Algorithm

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(Non-Fuzzy) Checkpoints

- The DBMS halts everything when it takes a checkpoint to ensure a consistent snapshot:
  - Stop all transactions.
  - Flushes dirty pages on disk.
- This is bad…

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Better Checkpoints

- Allow txns to keep on running.
- Record internal system state as of the beginning of the checkpoint.
  - Active Transaction Table (ATT)
  - Dirty Page Table (DPT)

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Active Transaction Table (ATT)

- One entry per currently active txn.
  - ***txnId***: Unique txn identifier.
  - ***status***: The current "mode" of the txn.
  - ***lastLSN***: Most recent LSN written by txn.
- Entry removed when txn commits or aborts.
- Status Codes:
  - **R** → Running
  - **C** → Committing
  - **U** → Candidate for Undo

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Dirty Page Table (DPT)

- One entry per dirty page currently in buffer pool.
  - **recLSN**: The LSN of the log record that first caused the page to be dirty.

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Better Checkpoints

WAL

```
<T1 start>
...
<T1 commit>
...
<T2, C, 100, 120>
<CHECKPOINT
  ATT={T2},
  DPT={P10,P12}>
<T3 start>
<T2 commit>
<T3, A, 200, 400>
<CHECKPOINT
  ATT={T3},
  DPT={P10,P33}>
<T3, B, 10, 12>
```

- At the first checkpoint, T2 is still running and there are two dirty pages (i.e., P10, P12).
- At the second checkpoint, T3 is active and there are two dirty pages (i.e., P10, P33).

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Fuzzy Checkpoints

- Specifically, write to log:
  - **BEGIN-CHECKPOINT**: Indicates start of checkpoint
  - **END-CHECKPOINT**: Contains ATT + DPT.
- The "fuzzy" part is because:
  - Other txns 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;

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Fuzzy Checkpoints

WAL

```
<T1 start>
...
<T1 commit>
...
<T2, C, 100, 120>
<BEGIN-CHECKPOINT>
<T3 start>
<END-CHECKPOINT
  ATT={T2}
  DPT={P10,P12}>
<T2 commit>
<T3, A, 200, 400>
<BEGIN-CHECKPOINT>
<T3, B, 10, 12>
<END-CHECKPOINT
  ATT={T3},
  DPT={P10,P33}>
```

- The ***LSN*** of the **BEGIN-CHECKPOINT** record is written to the ***Master Record*** entry.
- Any txn that starts after the checkpoint is excluded from the txn table listing.

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Fuzzy Checkpoints

- **Q:** Why do we need store the ***LSN*** of most recent checkpoint record on disk in the ***Master Record***?
- **A:** So that we know where to start from on recovery.

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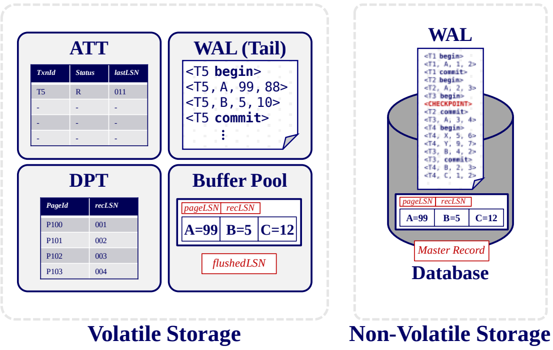
Big Picture



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- Log Sequence Numbers
- Normal Execution & Abort Operations
- Fuzzy Checkpointing
- Recovery Algorithm

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ARIES – Recovery Phases

- **Analysis:** Read the WAL to identify dirty pages in the buffer pool and active txns at the time of the crash.
- **Redo:** Repeat all actions starting from an appropriate point in the log.
- **Undo:** Reverse the actions of txns that did not commit before the crash.

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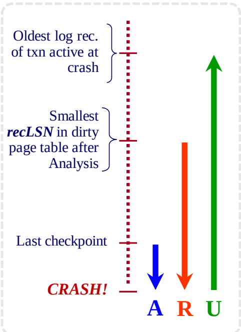
ARIES - Overview



- Start from last checkpoint found via ***Master Record***.
- Three phases.
  - **Analysis** - Figure out which txns committed or failed since checkpoint.
  - **Redo** all actions (repeat history)
  - **Undo** effects of failed txns.

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Recovery – Analysis Phase

- Re-establish knowledge of state at checkpoint.
  - Examine ATT and DPT stored in the checkpoint.

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Recovery – Analysis Phase

- Scan log forward from checkpoint.
- **END** record: Remove txn from ATT.
- All other records:
  - Add txn to ATT with status 'UNDO'
  - Set ***lastLSN=LSN***
  - On commit, change txn status to 'COMMIT'.
- For **UPDATE** records:
  - If page P not in DPT, add P to DPT, set its ***recLSN=LSN***.

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Recovery – Analysis Phase

- At end of the Analysis Phase:
  - ATT tells the DBMS which txns were active at time of crash.
  - DPT tells the DBMS which dirty pages might not have made it to disk.

Analysis Phase Example

WAL

```
010:<BEGIN-CHECKPOINT>
  ⋮
020:<T96, A→P33, 10, 15>
  ⋮
030:<END-CHECKPOINT
     ATT={T96,T97},
     DPT={P20,P33}>
  ⋮
040:<T96 commit>
  ⋮
050:<T96 end>
  ⋮
CRASH!
```

LSN	ATT	DPT
010		
020	(T96, U)	(P33)
030	(T96,U), (T97,U)	(P33), (P20)
040	(T96,C), (T97,U)	(P33), (P20)
050	(T97,U)	(P33), (P20)

(TxnId, Status)

Recovery – Redo Phase

- The goal is to repeat history to reconstruct state at the moment of the crash:
  - Reapply all updates (even aborted txns!) and redo CLRs.
  - We can try to avoid unnecessary reads/writes.

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Recovery – Redo Phase

Why start here?
All else has been flushed.

- Scan forward from the log record containing smallest ***recLSN*** in DPT.
- For each update log record or CLR with a given ***LSN***, redo the action unless:
  - Affected page is not in the DPT, or
  - Affected page is in DPT but has ***recLSN>LSN***, or
  - ***pageLSN*** (in DB) ≥ ***LSN***

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Recovery – Redo Phase

- To redo an action:
  - Reapply logged action.
  - Set ***pageLSN*** to ***LSN***.
  - No additional logging, no forcing!
- At the end of Redo Phase, write **END** log records for all txns with status 'C' and remove them from the ATT.

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Recovery – Undo Phase

- Goal: Undo all txns that were active at the time of crash ('loser txns')
- That is, all txns with 'U' status in the ATT after the Analysis phase
- Process them in reverse ***LSN*** order using the ***lastLSN's*** to speed up traversal.
- Write a CLR for every modification.

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Recovery – Undo Phase

- ***ToUndo***={***lastLSNs*** of ‘loser’ txns}
- Repeat until ***ToUndo*** is empty:
  - Pop largest ***LSN*** from ***ToUndo***.
  - If this ***LSN*** is a CLR and ***undoNext*** == nil, then write an **END** record for this txn.
  - If this ***LSN*** is a CLR, and ***undoNext*** != nil, then add ***undoNext*** to ***ToUndo***
  - Else this ***LSN*** is an update. Undo the update, write a CLR, add ***prevLSN*** to ***ToUndo***.

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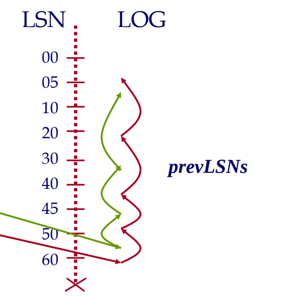
Undo Phase Example

Suppose that after end of analysis phase we have the following ATT:

TxnId	*Status*	*lastLSN*
T32	U	
T41	U	



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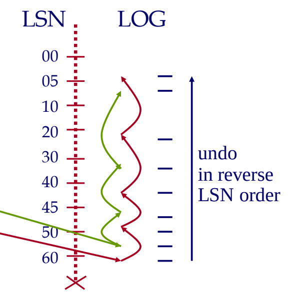
Undo Phase Example

Suppose that after end of analysis phase we have the following ATT:

TxnId	*Status*	*lastLSN*
T32	U	
T41	U	



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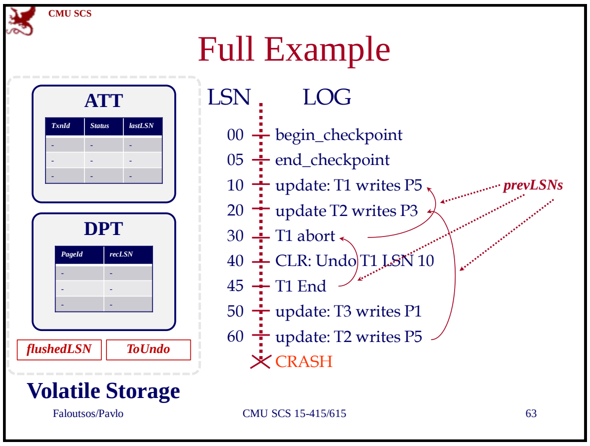
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Full Example
ATT
TxnId Status lastLSN
DPT
PageId recLSN
flushedLSN
ToUndo
Volatile Storage
LSN LOG
00 begin_checkpoint
05 end_checkpoint
10 update: T1 writes P5
20 update T2 writes P3
30 T1 abort
40 CLR: Undo T1 LSN 10
45 T1 End
50 update: T3 writes P1
60 update: T2 writes P5
CRASH
prevLSNs
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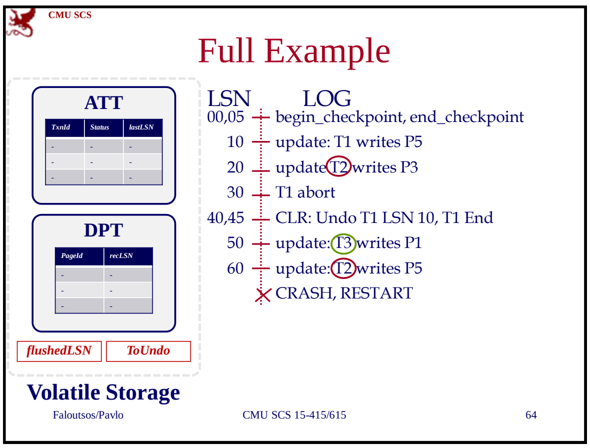
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Full Example
ATT
TxnId Status lastLSN
DPT
PageId recLSN
flushedLSN
ToUndo
Volatile Storage
LSN LOG
00,05 begin_checkpoint, end_checkpoint
10 update: T1 writes P5
20 update T2 writes P3
30 T1 abort
40,45 CLR: Undo T1 LSN 10, T1 End
50 update: T3 writes P1
60 update: T2 writes P5
CRASH, RESTART
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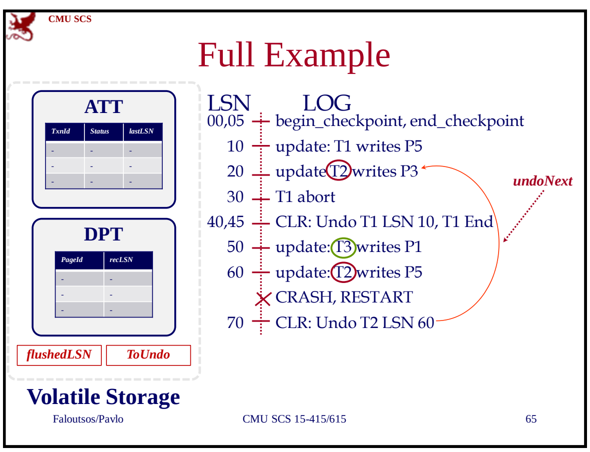
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Full Example
ATT
TxnId Status lastLSN
DPT
PageId recLSN
flushedLSN
ToUndo
Volatile Storage
LSN LOG
00,05 begin_checkpoint, end_checkpoint
10 update: T1 writes P5
20 update T2 writes P3
30 T1 abort
40,45 CLR: Undo T1 LSN 10, T1 End
50 update: T3 writes P1
60 update: T2 writes P5
CRASH, RESTART
70 CLR: Undo T2 LSN 60
undoNext
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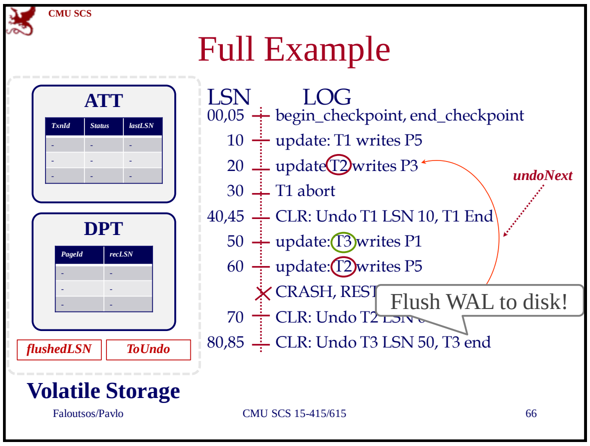
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Full Example
ATT
TxnId Status lastLSN
DPT
PageId recLSN
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ToUndo
Volatile Storage
LSN LOG
00,05 begin_checkpoint, end_checkpoint
10 update: T1 writes P5
20 update T2 writes P3
30 T1 abort
40,45 CLR: Undo T1 LSN 10, T1 End
50 update: T3 writes P1
60 update: T2 writes P5
CRASH, REST
70 CLR: Undo T2
80,85 CLR: Undo T3 LSN 50, T3 end
undoNext
Flush WAL to disk!
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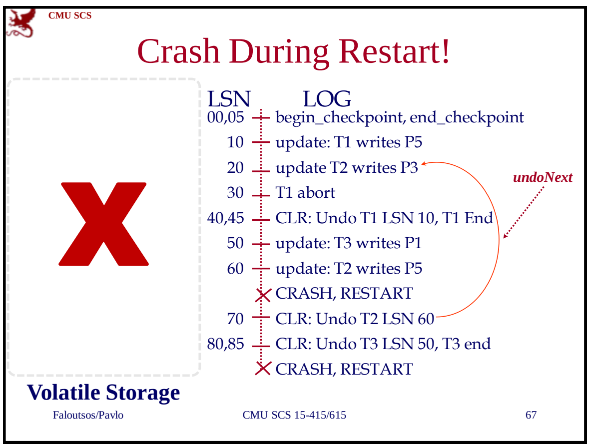
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Crash During Restart!
Volatile Storage
LSN LOG
00,05 begin_checkpoint, end_checkpoint
10 update: T1 writes P5
20 update T2 writes P3
30 T1 abort
40,45 CLR: Undo T1 LSN 10, T1 End
50 update: T3 writes P1
60 update: T2 writes P5
CRASH, RESTART
70 CLR: Undo T2 LSN 60
80,85 CLR: Undo T3 LSN 50, T3 end
CRASH, RESTART
undoNext
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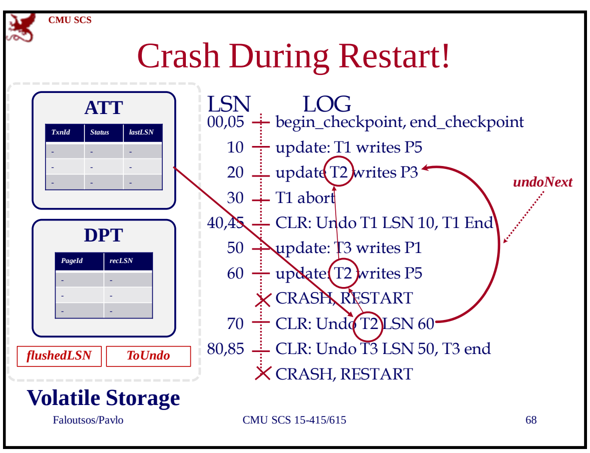
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Crash During Restart!
ATT
TxnId Status lastLSN
DPT
PageId recLSN
flushedLSN
ToUndo
Volatile Storage
LSN LOG
00,05 begin_checkpoint, end_checkpoint
10 update: T1 writes P5
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40,45 CLR: Undo T1 LSN 10, 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
undoNext
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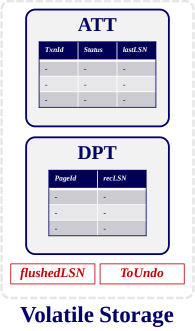
Crash During Restart!



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, 95	CLR: Undo T2 LSN 20, T2 end

undoNext

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Additional Crash Issues

- What happens if system crashes during the Analysis Phase? During the Redo Phase?
- How do you limit the amount of work in the Redo Phase?
  - Flush asynchronously in the background.
- How do you limit the amount of work in the Undo Phase?
  - Avoid long-running txns.

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Summary

- ARIES - main ideas:
  - WAL (write ahead log), STEAL/NO-FORCE
  - Fuzzy Checkpoints (snapshot of dirty page ids)
  - Redo everything since the earliest dirty page; undo ‘loser’ transactions
  - Write CLRs when undoing, to survive failures during restarts

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ARIES – Recovery Phases

- **Analysis:** Read the WAL to identify dirty pages in the buffer pool and active txns at the time of the crash.
- **Redo:** Repeat all actions starting from an appropriate point in the log.
- **Undo:** Reverse the actions of txns that did not commit before the crash.

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Summary

- Additional concepts:
  - ***LSNs*** identify log records; linked into backwards chains per transaction (via ***prevLSN***).
  - ***pageLSN*** allows comparison of data page and log records.
  - And several other subtle concepts: ***undoNext***, ***recLSN,*** etc)

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Conclusion

- Recovery is really hard.
- Be thankful that you don't have to write it yourself.

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