WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

CS 564: Database Management Systems

Lecture 34: ARIES Recovery

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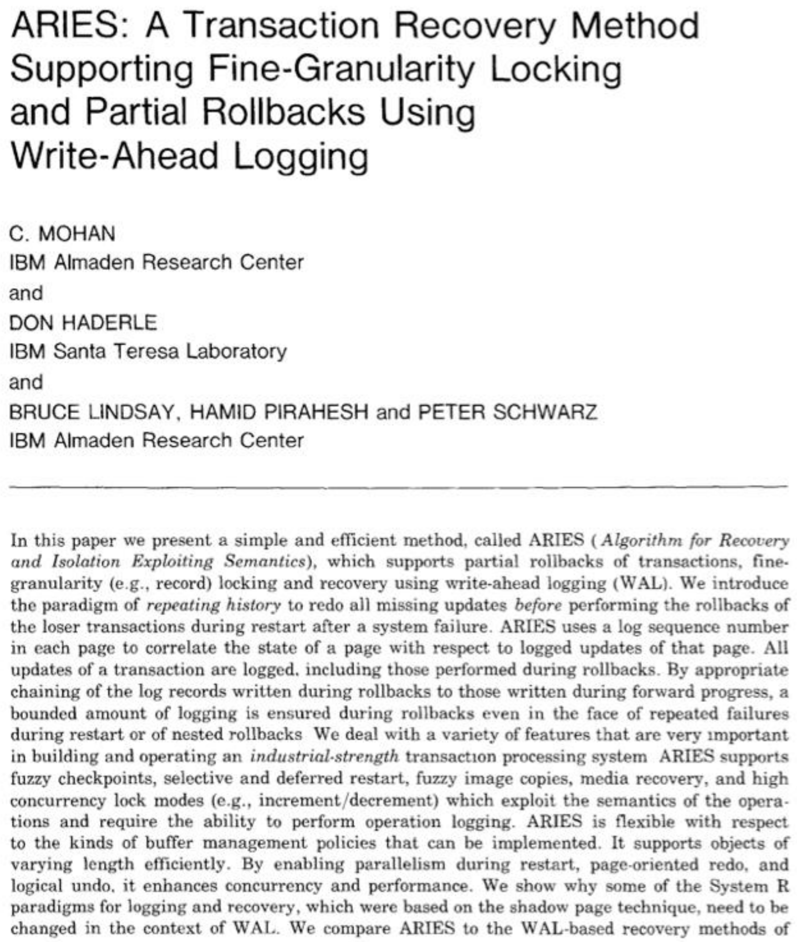
ARIES Logging and Recovery



ARIES: A Transaction Recovery Method Supporting Fine-Granularity Locking and Partial Rollbacks Using Write-Ahead Logging

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IBM Almaden Research Center

In this paper we present a simple and efficient method, called ARIES (*Algorithm for Recovery and Isolation Exploiting Semantics*), which supports partial rollbacks of transactions, fine-granularity (e.g., record) locking and recovery using write-ahead logging (WAL). We introduce the paradigm of *repeating history* to redo all missing updates *before* performing the rollbacks of the loser transactions during restart after a system failure. ARIES uses a log sequence number in each page to correlate the state of a page with respect to logged updates of that page. All updates of a transaction are logged, including those performed during rollbacks. By appropriate chaining of the log records written during rollbacks to those written during forward progress, a bounded amount of logging is ensured during rollbacks even in the face of repeated failures during restart or of nested rollbacks We deal with a variety of features that are very important in building and operating an *industrial-strength* transaction processing system ARIES supports fuzzy checkpoints, selective and deferred restart, fuzzy image copies, media recovery, and high concurrency lock modes (e.g., increment/decrement) which exploit the semantics of the operations and require the ability to perform operation logging. ARIES is flexible with respect to the kinds of buffer management policies that can be implemented. It supports objects of varying length efficiently. By enabling parallelism during restart, page-oriented redo, and logical undo, it enhances concurrency and performance. We show why some of the System R paradigms for logging and recovery, which were based on the shadow page technique, need to be changed in the context of WAL. We compare ARIES to the WAL-based recovery methods of

ACM Trans. Database Syst. 1992.

Logging Recap

	Steal	No Steal
Force	**UNDO** only	No REDO nor UNDO
No Force	**REDO and UNDO** logging (ARIES [2])	**REDO** only

REDO and UNDO

- Log combined REDO/UNDO record before each update to database
- Log COMMIT record when a transaction finishes execution
- Modified data pages can be written to disk any time after the corresponding REDO/UNDO record (the most flexible)
- **Recovery**: UNDO uncommitted transactions and REDO committed transactions

Baseline REDO/UNDO Design

Write: Flush REDO/UNDO to log; update the page

Commit: Write COMMIT to log

Recovery:

- Forward scan of entire log: redo all records
- Backward scan of entire log: undo uncommitted transactions

Baseline REDO/UNDO Design

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Data structures

Log entry

- (LSN), txnID, pageID, data

Data page

- Tuple data

LSN: Log Sequence Number

Baseline REDO/UNDO Design

Write: Flush REDO/UNDO to log; update the page

Commit: Write COMMIT to log

Recovery:

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- Backward scan of entire log: undo **uncommitted** transactions

Data structures

Log entry

- (LSN), txnID, pageID, data

Data page

- Tuple data

LSN: Log Sequence Number

How to identify transactions that did not commit before crash?

- Those that do not have a commit record

Baseline REDO/UNDO Design

Write: Flush REDO/UNDO to log; update the page

Commit: Write COMMIT to log

Recovery:

- Forward scan of entire log: redo all records; **keep a table for active transactions**
- Backward scan of entire log: undo uncommitted transactions

Data structures

Log entry

- (LSN), txnID, pageID, data

Data page

- Tuple data

(Active) **Transaction Table**

- txnID

LSN: Log Sequence Number

If see transaction T’s log record, add T to **Transaction Table**; if see T’s commit record, remove T from **Transaction Table**

- In the backward scan, undo only transactions in the Transaction Table

Limitation of the Baseline Design

Inefficiency in the REDO process

- Unnecessary to redo all records
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Lack of checkpointing

- Unnecessary to start from the beginning of log
- Start with the first log record that is not reflected in data pages

Optimize REDO Process

Inefficiency in the REDO process

- Unnecessary to redo all records
- Need to redo only records that are not reflected in the data page

Data structures

Log entry

- (LSN), txnID, pageID, data

Data page

- Tuple data

(Active) Transaction Table

- TransID

Optimize REDO Process

Inefficiency in the REDO process

- Unnecessary to redo all records
- Need to redo only records that are not reflected in the data page

Solution: add a version number to each page

- **pageLSN**: LSN of the log record that describes the latest update to the page.
- **REDO scan**: Apply REDO only if record.LSN > page.pageLSN
- **Write**: update pageLSN for the page in buffer pool for each write

Data structures

Log entry

- (LSN), txnID, pageID, data

Data page

- Tuple data
- **pageLSN**

(Active) Transaction Table

- TransID

Optimize UNDO Process

Inefficiency in the UNDO process

- Unnecessary to scan the entire log
- Can skip records that do not belong to uncommitted transactions

Data structures

Log entry

- (LSN), txnID, pageID, data

Data page

- tuple data
- pageLSN

(Active) Transaction Table

- transID

Optimize UNDO Process

Inefficiency in the UNDO process

- Unnecessary to scan the entire log
- Can skip records that do not belong to uncommitted transactions

Solution: link records from the same transaction

- **prevLSN**: preceding log record written by the same transaction
- **lastLSN**: LSN of the last log record written by the transaction
- **UNDO scan**: Follow lastLSN and prevLSN to undo records
- **REDO scan**: update lastLSN in Transaction Table based on the last update of the transaction

Data structures

Log entry

- (LSN), txnID, pageID, data
- **prevLSN**

Data page

- tuple data
- pageLSN

(Active) Transaction Table

- transID
- **lastLSN**

Checkpoint

Lack of checkpointing

- Unnecessary to start from the beginning of log
- Start with the first log record that is not reflected in data pages

Data structures

Log entry

- (LSN), txnID, pageID, data
- prevLSN

Data page

- tuple data
- pageLSN

(Active) Transaction Table

- transID
- lastLSN

Checkpoint

Lack of checkpointing

- Unnecessary to start from the beginning of log
- Start with the first log record that is not reflected in data pages

Solution: Maintain a dirty page table

- **pageID**: ID of the dirty page
- **recLSN**: LSN of the first log record since when the page is dirty
- **Fuzzy Checkpoint:** log DPT and TT asynchronously
- **REDO scan**: start from the smallest LSN in DP

Data structures

Log entry

- (LSN), txnID, pageID, data
- prevLSN

Data page

- tuple data
- pageLSN

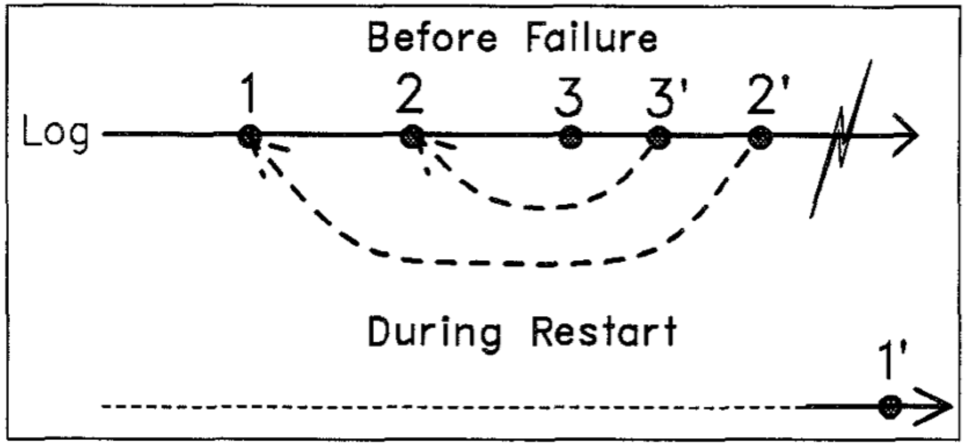
(Active) Transaction Table

- transID
- lastLSN

Dirty Page Table

- **pageID**
- **recLSN**

Compensation Log Record (CLR)



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

The action of applying UNDO leads to a CLR

- In undo scan, do not reapply UNDO if CLR exists
- **UndoNxtLSN**: LSN of the next record to be processed during undo scan

Data structures

Log entry

- (LSN), txnID, pageID, data
- prevLSN
- **UndoNxtLSN**

Data page

- tuple data
- pageLSN

(Active) Transaction Table

- transID
- lastLSN
- **UndoNxtLSN**

Dirty Page Table

- pageID
- recLSN

ARIES – Big Picture

Goal: Bring the database to the state before the crash (REDO phase) and rollback uncommitted transactions (UNDO phase)

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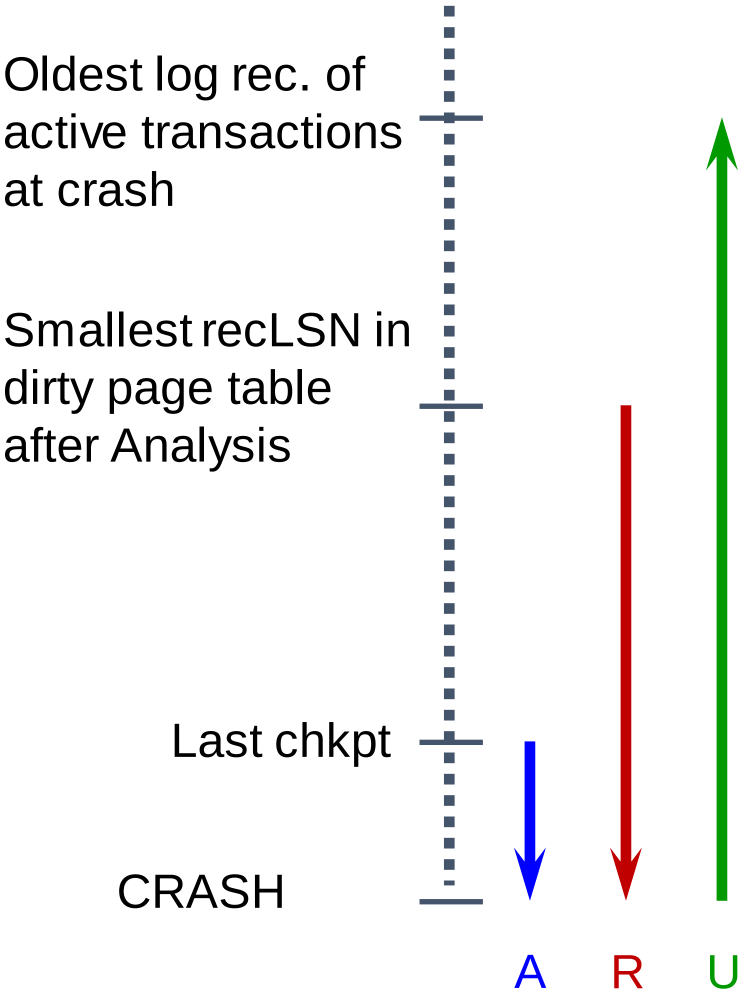
Start from the last complete checkpoint

- **Analysis phase**: rebuild transaction table (for undo phase) and dirty page table (for redo phase)
- **REDO phase**: redo transactions whose effects may not be persistent before the crash
- **UNDO phase**: undo transactions that did not commit before the crash

ARIES – Big Picture


Oldest log rec. of active transactions at crash
Smallest recLSN in dirty page table after Analysis
Last chkpt
CRASH
A
R
U

Goal: Bring the database to the state before the crash (REDO phase) and rollback uncommitted transactions (UNDO phase)

Start from the last complete checkpoint

- **Analysis phase**: rebuild transaction table (for undo phase) and dirty page table (for redo phase)
- **REDO phase**: redo transactions whose effects may not be persistent before the crash
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Crash Recovery – Analysis Phase

Goal: Rebuild transaction table (for undo phase) and dirty page table (for redo phase) based on the ones in the last checkpoint

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(update transaction table) For each log record:

- If ‘update’ or ‘CLR’: insert to transaction table if not exists
- If ‘end’: delete from transaction table

Crash Recovery – Analysis Phase

Goal: Rebuild transaction table (for undo phase) and dirty page table (for redo phase) based on the ones in the last checkpoint

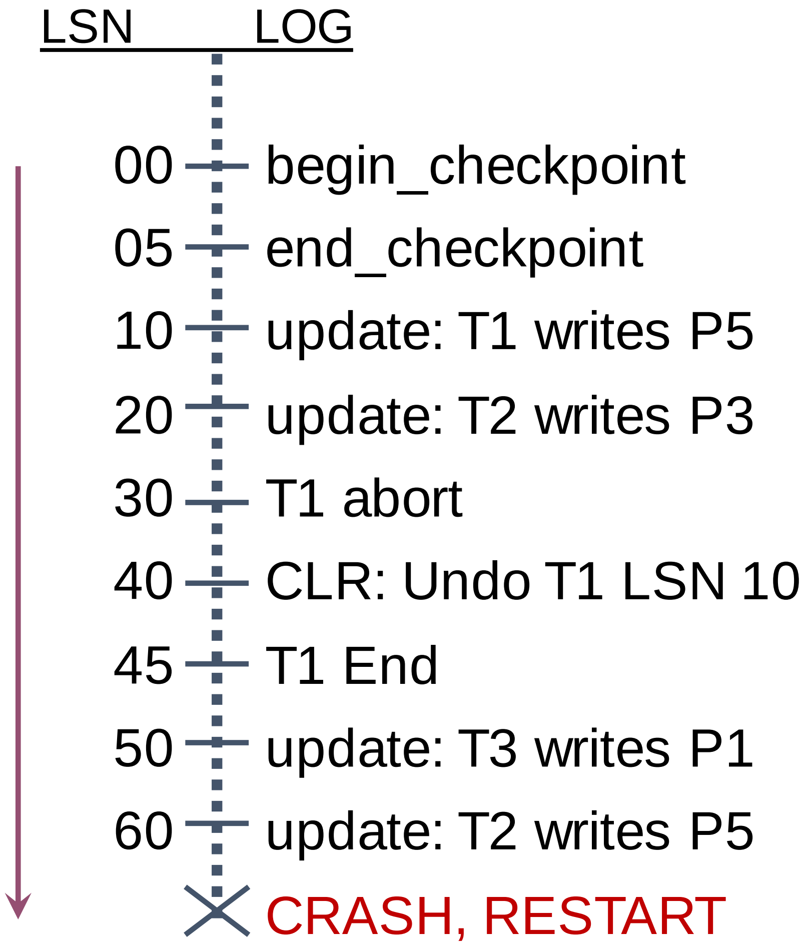
(update transaction table) For each log record:

- If ‘update’ or ‘CLR’: insert to transaction table if not exists
- If ‘end’: delete from transaction table

(update dirty page table) For each log record:

- If ‘update’ or ‘CLR’: insert to dirty page table if not exists (PageID, RecLSN)

Analysis Phase – Example



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

Transaction Table

TransID	LastLSN

Dirty page table

PageID	RecLSN

Analysis Phase – Example

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✕	CRASH, RESTART

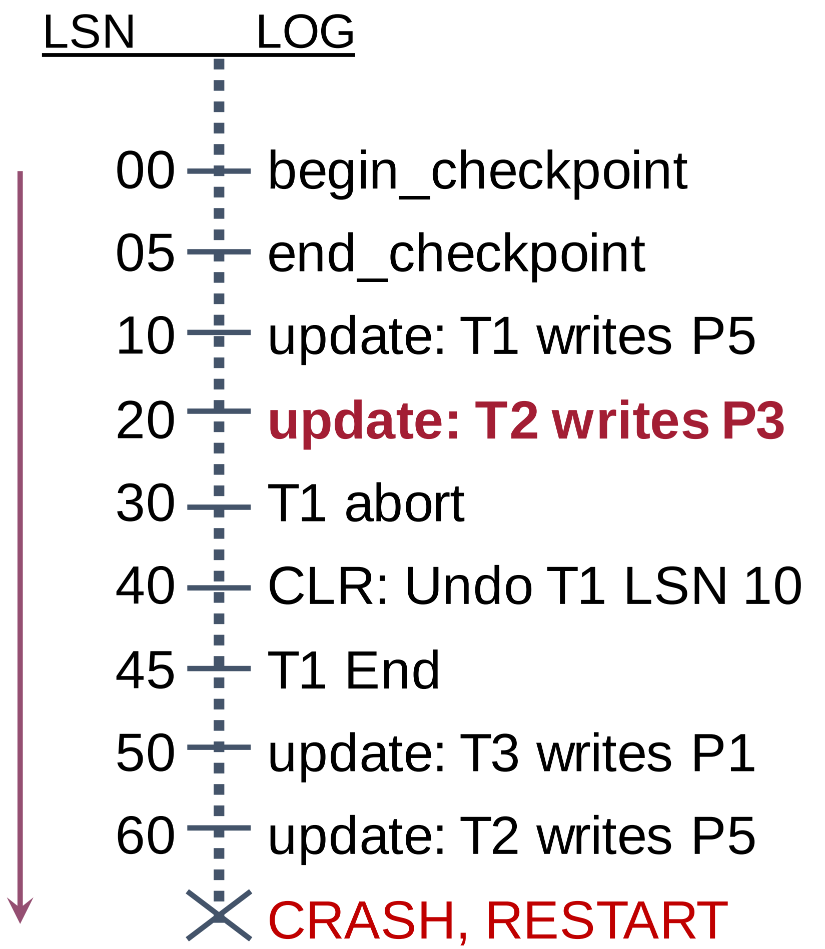
Transaction Table

TransID	LastLSN
T1	**10**

Dirty page table

PageID	RecLSN
P5	**10**

Analysis Phase – Example



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	CRASH, RESTART

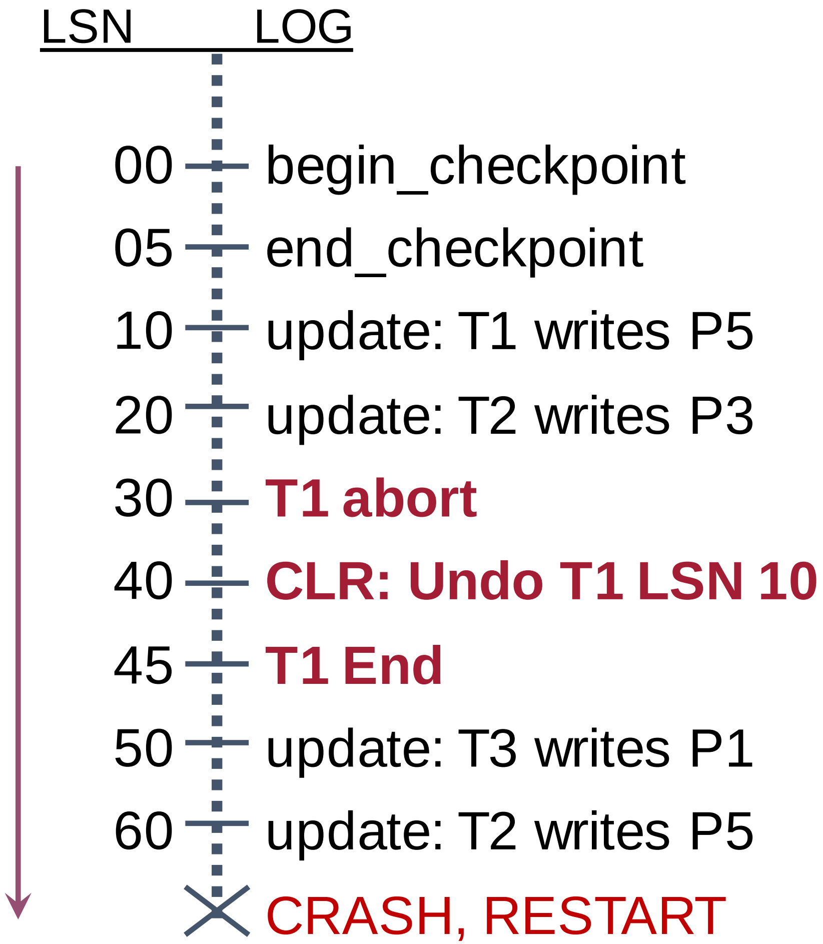
Transaction Table

TransID	LastLSN
T1	10
T2	**20**

Dirty page table

PageID	RecLSN
P5	10
P3	**20**

Analysis Phase – Example



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45	**T1 End**
50	update: T3 writes P1
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	CRASH, RESTART

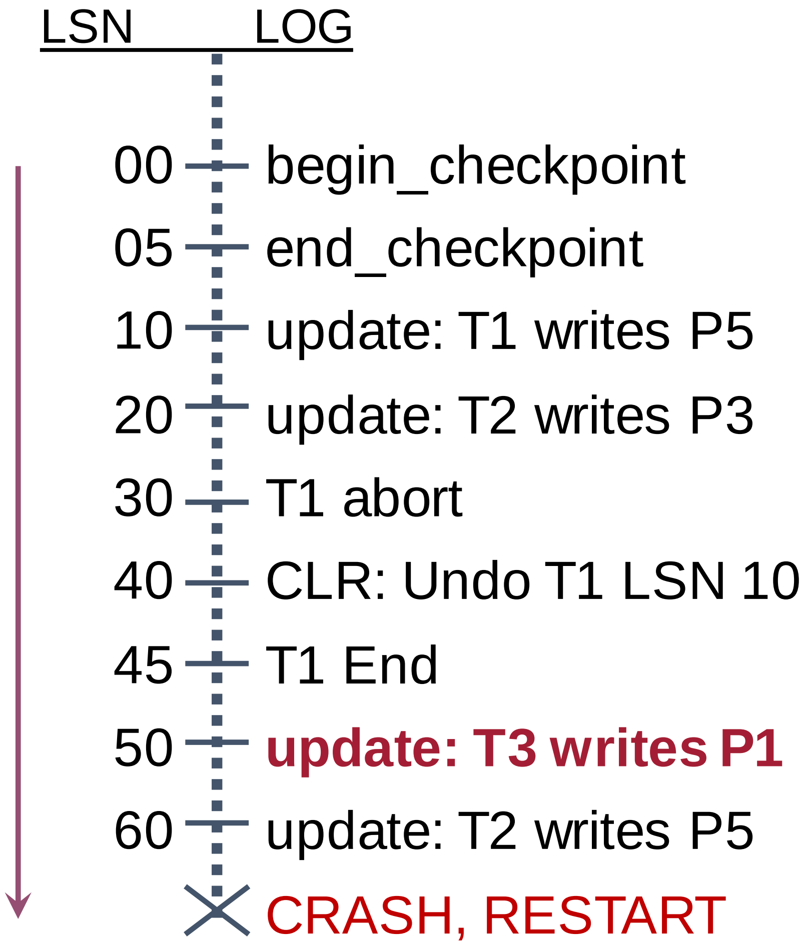
Transaction Table

TransID	LastLSN
~~T1~~	~~10~~
T2	20

Dirty page table

PageID	RecLSN
P5	10
P3	20

Analysis Phase – Example



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45	T1 End
50	**update: T3 writes P1**
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	CRASH, RESTART

Transaction Table

TransID	LastLSN
T3	**50**
T2	20

Dirty page table

PageID	RecLSN
P5	10
P3	20
P1	**50**

Analysis Phase – Example

LSN	LOG
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10	update: T1 writes P5
20	update: T2 writes P3
30	T1 abort
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45	T1 End
50	update: T3 writes P1
60	**update: T2 writes P5**
	CRASH, RESTART

Transaction Table

TransID	LastLSN
T3	50
T2	**60**

Dirty page table

PageID	RecLSN
P5	10
P3	20
P1	50

Crash Recovery – REDO Phase

Repeat history to reconstruct state at crash

- Reapply all updates (even of aborted transactions), redo CLRs

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Where to start?

- From log record containing **smallest RecLSN** in the dirty page table
- Before this LSN, all redo records have been reflected in data pages on disk

Crash Recovery – REDO Phase

Repeat history to reconstruct state at crash

- Reapply all updates (even of aborted transactions), redo CLRs

Where to start?

- From log record containing **smallest RecLSN** in the dirty page table
- Before this LSN, all redo records have been reflected in data pages on disk

Observation: can **skip a redo record** for the following cases where the corresponding page has already been flushed before the crash

- The page is not in dirty page table (DPT)
- The page is in DPT but redo_record.LSN < DPT[page].recLSN
- After fetching the data page, redo_record.LSN ≤ page.page_LSN

REDO Phase – Example

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60	update: T2 writes P5
✕	CRASH, RESTART

Transaction Table

TransID	LastLSN
T3	50
T2	60

Dirty page table

PageID	RecLSN
P5	10
P3	20
P1	50

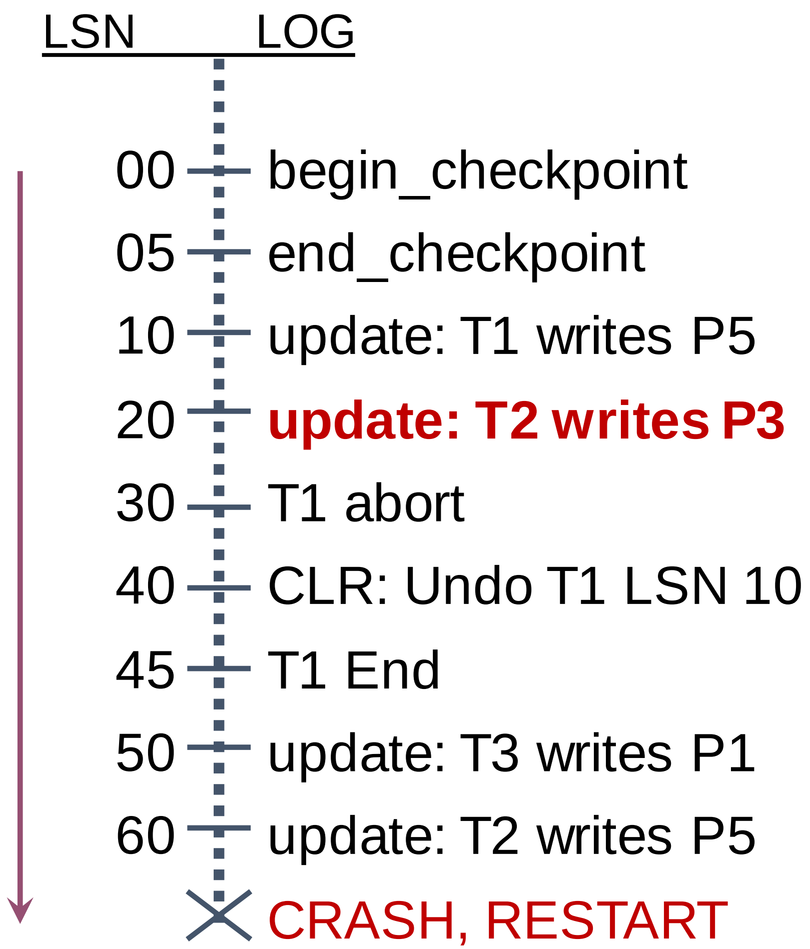
No need to update

Write already reflected on disk

Data pages

PageID	Page_LSN
P5	40
P3	0
P1	0

REDO Phase – Example



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45	T1 End
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	CRASH, RESTART

Transaction Table

TransID	LastLSN
T3	50
T2	60

Dirty page table

PageID	RecLSN
P5	10
P3	20
P1	50

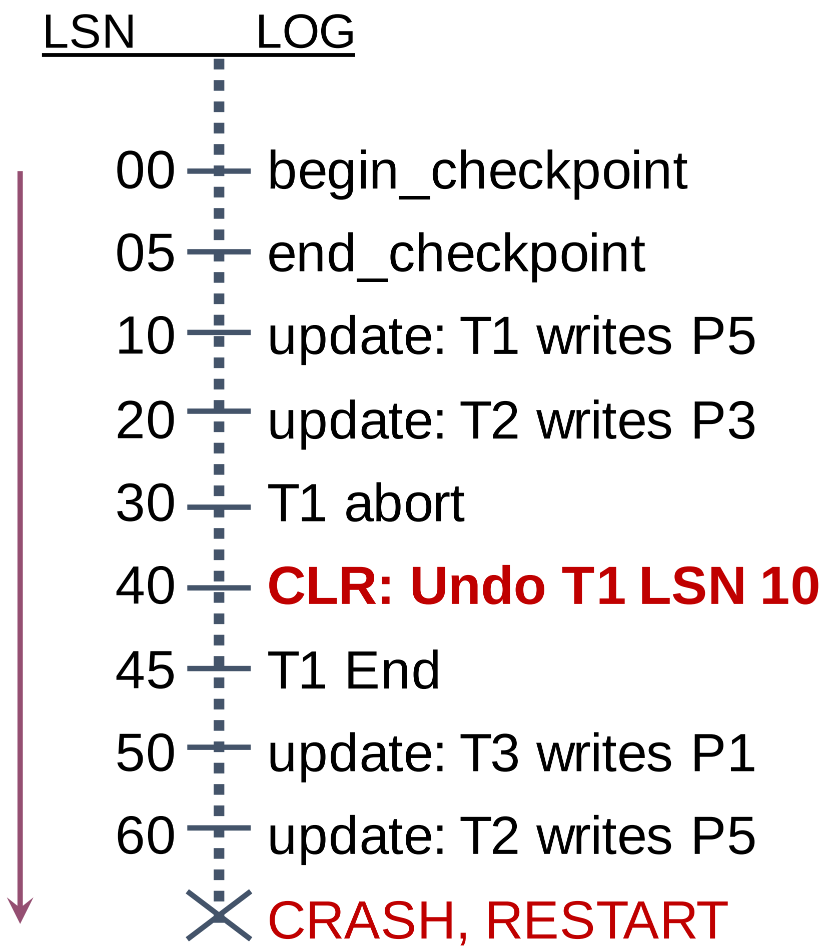
Update P3 in buffer pool

No need to flush P3 now

Data pages

PageID	Page_LSN
P5	40
P3	0
P1	0

REDO Phase – Example



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Transaction Table

TransID	LastLSN
T3	50
T2	60

Dirty page table

PageID	RecLSN
P5	10
P3	20
P1	50

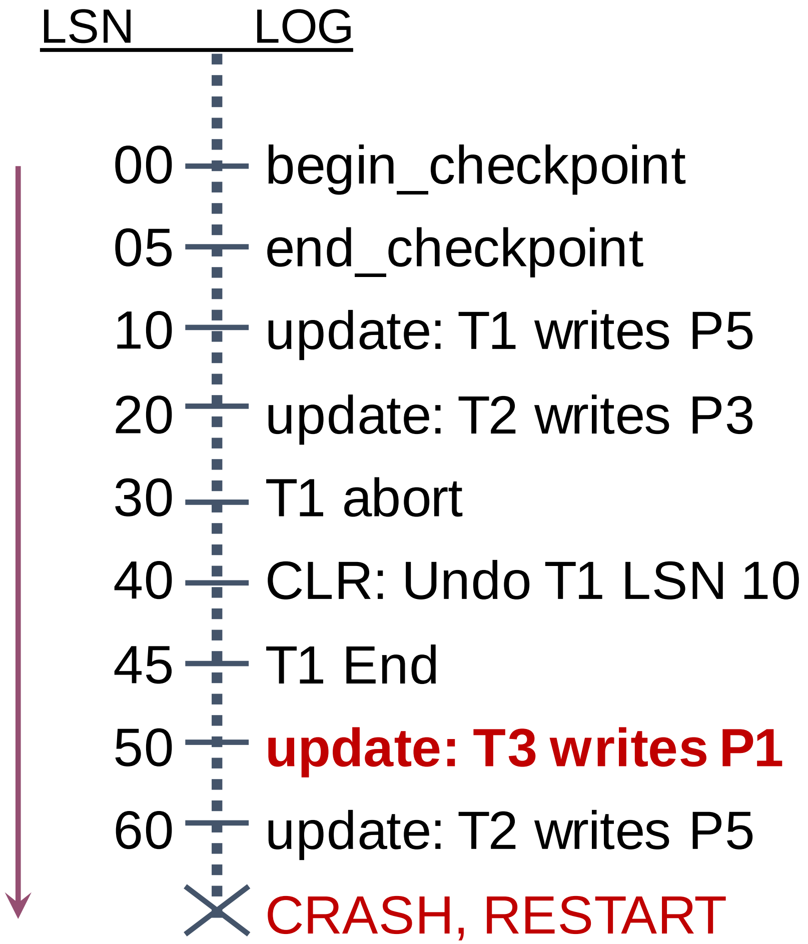
No need to update

Write already reflected on disk

Data pages

PageID	Page_LSN
P5	40
P3	0
P1	0

REDO Phase – Example



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Transaction Table

TransID	LastLSN
T3	50
T2	60

Dirty page table

PageID	RecLSN
P5	10
P3	20
P1	50

Update P1 in buffer pool

No need to flush P1 now

Data pages

PageID	Page_LSN
P5	40
P3	0
P1	0

REDO Phase – Example

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
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✕	CRASH, RESTART

Transaction Table

TransID	LastLSN
T3	50
T2	60

Dirty page table

PageID	RecLSN
P5	10
P3	20
P1	50

Update P5 in buffer pool

No need to flush P5 now

Data pages

PageID	Page_LSN
P5	40
P3	0
P1	0

Crash Recovery – UNDO Phase

Rollback uncommitted transactions

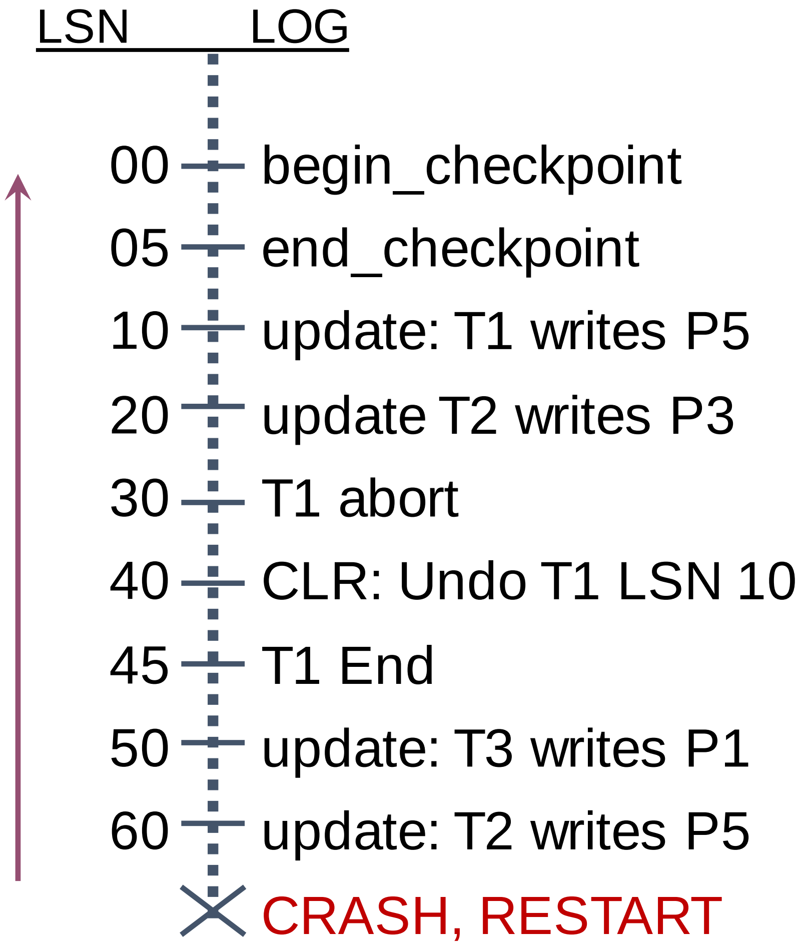
Crash Recovery – UNDO Phase

Rollback uncommitted transactions

Repeat until transaction table is empty:

- Choose largest LastLSN among transactions in the transaction table
- If the log record is an ‘update’: Undo the update, write a CLR, add record.prevLSN to transaction table
- If the log record is an ‘CLR’: add CLR.UndoNxtLSN to transaction table
- If prevLSN and UpdoNxtLSN are NULL, remove the transaction from transaction table

UNDO Phase – Example



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

Transaction Table

TransID	LastLSN	UndoNxtLSN
T3	50	50
T2	60	60

UNDO Phase – Example

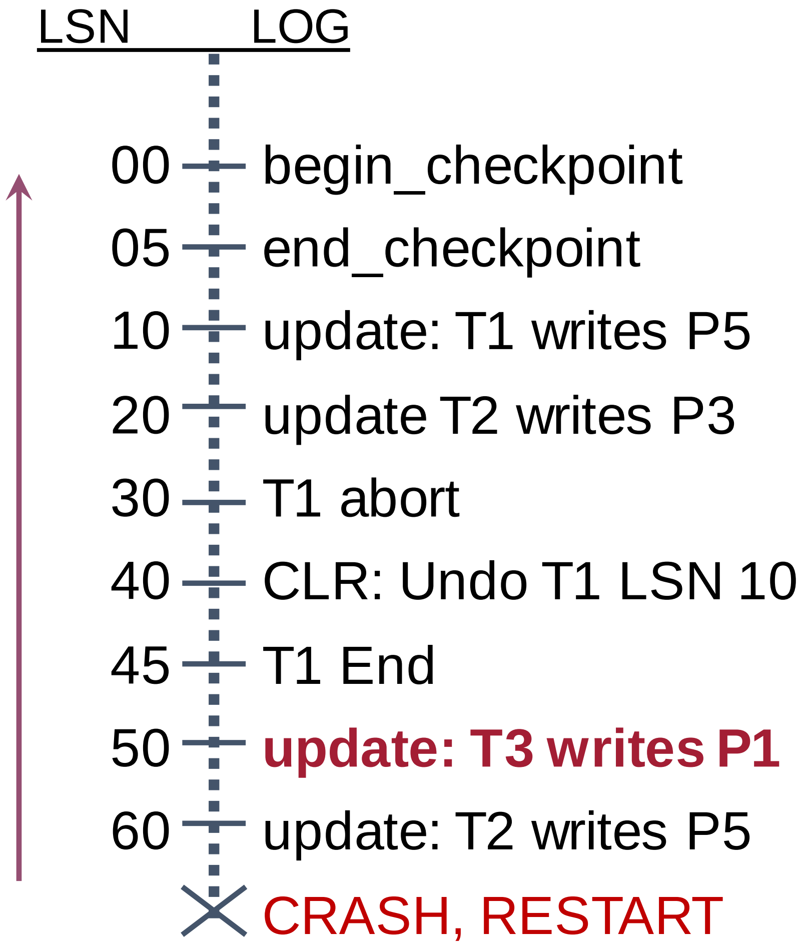
LSN	LOG
00	begin_checkpoint
05	end_checkpoint
10	update: T1 writes P5
20	update T2 writes P3
30	T1 abort
40	CLR: Undo T1 LSN 10
45	T1 End
50	update: T3 writes P1
60	**update: T2 writes P5**
	CRASH, RESTART

Transaction Table

TransID	LastLSN	UndoNxtLSN
T3	50	50
T2	~~60~~ 70	~~60~~ 20

LSN	LOG	(undoNextLSN)
70	CLR: Undo T2, LSN 60,	(20)

UNDO Phase – Example



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

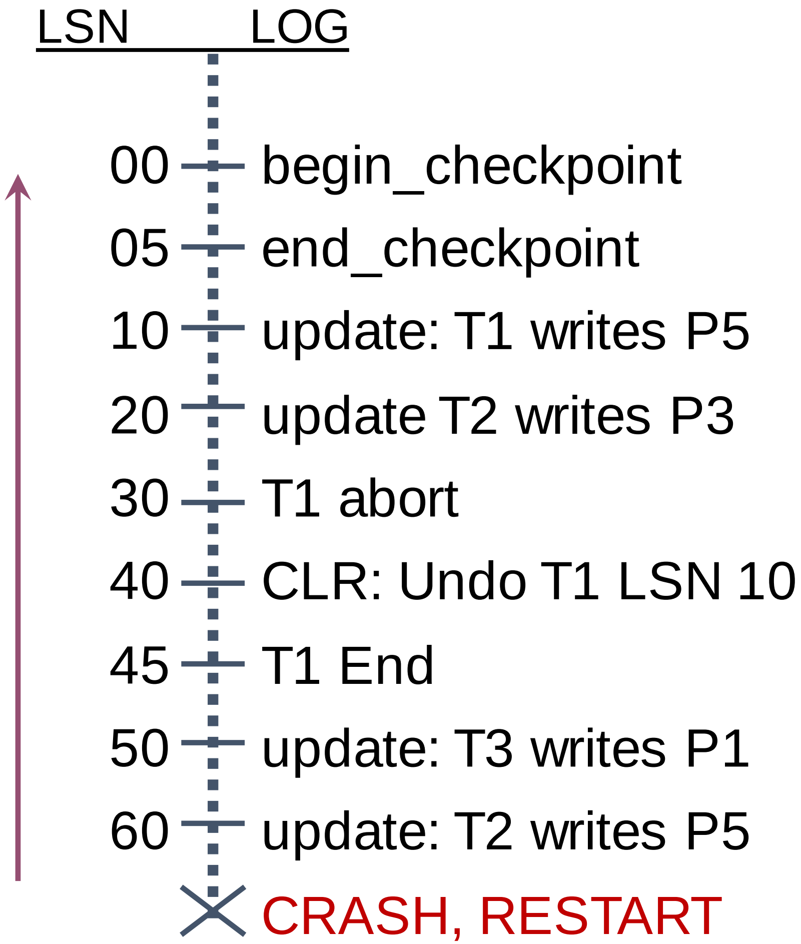
CRASH, RESTART

Transaction Table

TransID	LastLSN	UndoNxtLSN
T3	~~50~~ 80	~~50~~ null
T2	70	20

LSN	LOG	(undoNextLSN)
70	CLR: Undo T2, LSN 60,	(20)
80	CLR: Undo T3, LSN 50,	(null)

UNDO Phase – Example



LSN LOG

00 begin_checkpoint

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30 T1 abort

40 CLR: Undo T1 LSN 10

45 T1 End

50 update: T3 writes P1

60 update: T2 writes P5

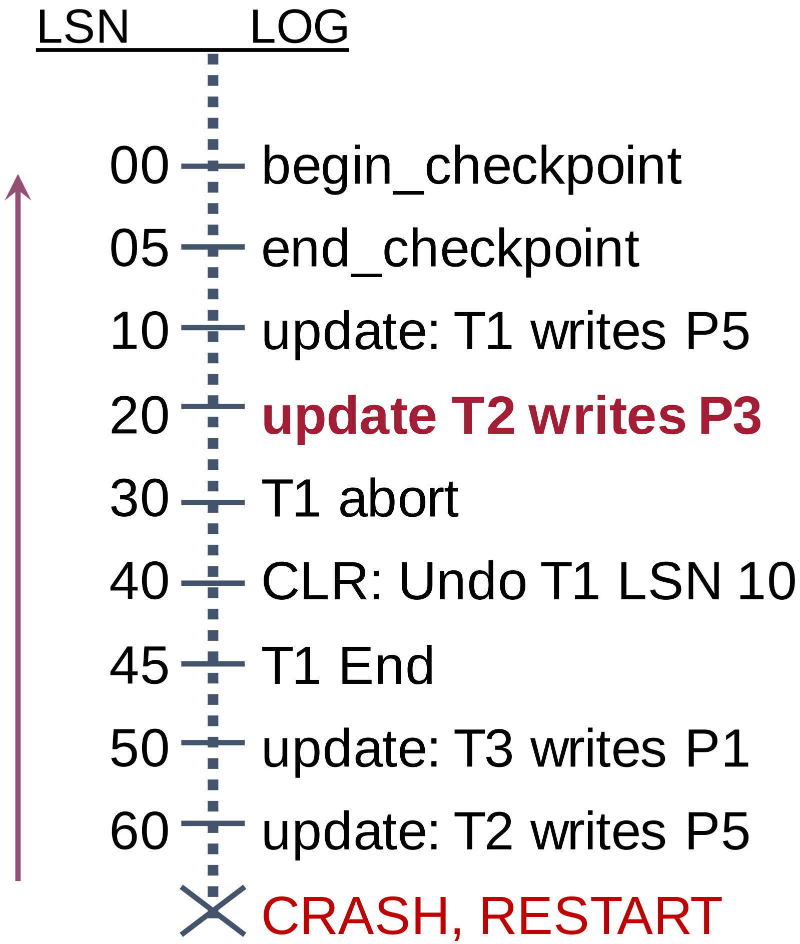
CRASH, RESTART

Transaction Table

TransID	LastLSN	UndoNxtLSN
~~T3~~	~~80~~	~~null~~
T2	70	20

LSN	LOG	(undoNextLSN)
70	CLR: Undo T2, LSN 60,	(20)
80	CLR: Undo T3, LSN 50,	(null)
85	T3 End	

UNDO Phase – Example



LSN LOG

00 begin_checkpoint

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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

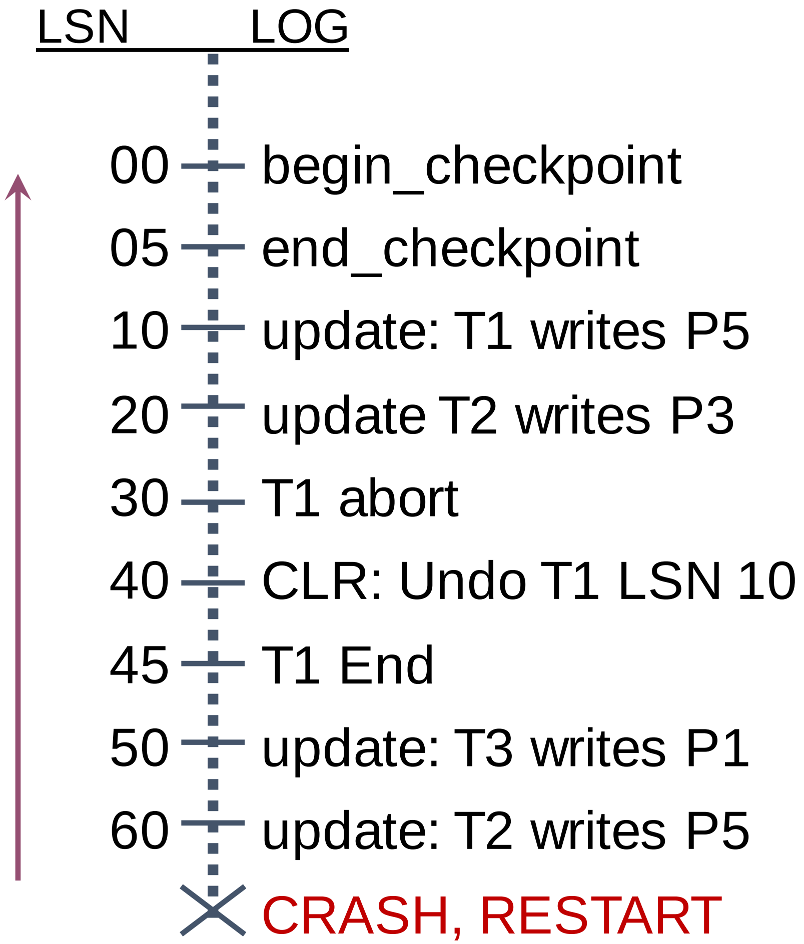
CRASH, RESTART

Transaction Table

TransID	LastLSN	UndoNxtLSN
T2	~~70~~ 90	~~20~~ null

LSN	LOG	(undoNextLSN)
70	CLR: Undo T2, LSN 60,	(20)
80	CLR: Undo T3, LSN 50,	(null)
85	T3 End	
90	CLR: Undo T2, LSN 20,	(null)

UNDO Phase – Example



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30	T1 abort
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45	T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART

Transaction Table

TransID	LastLSN	UndoNxtLSN
~~T2~~	~~90~~	~~null~~

LSN	LOG	(undoNextLSN)
70	CLR: Undo T2, LSN 60,	(20)
80	CLR: Undo T3, LSN 50,	(null)
85	T3 End	
90	CLR: Undo T2, LSN 20,	(null)
95	T2 End	

Summary

ARIES Logging

- Analysis phase
- REDO phase
- UNDO phase