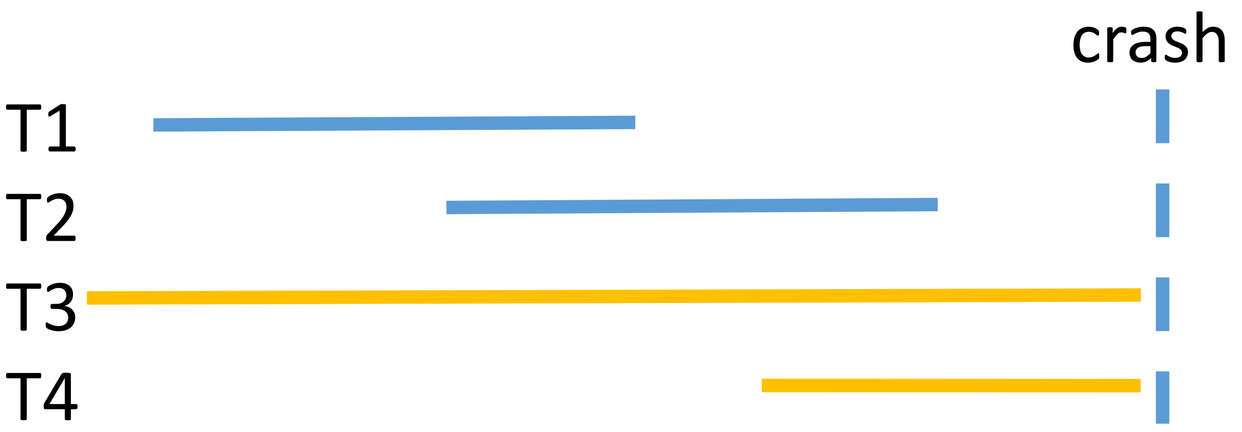
Database Management Systems

Lecture 4

Crash Recovery

Recovery - ACID

- the Recovery Manager (RM) in a DBMS ensures two important properties of transactions:
  - atomicity - the effects of uncommitted transactions (i.e., transactions that do not commit prior to the crash) are undone
  - durability - the effects of committed transactions survive system crashes



* T1, T2 commit before the crash, whereas T3 and T4 are still active when the system crashes

- when the system comes back up:
- the effects of T1 & T2 must persist
- T3 & T4 are undone (their effects are not persisted in the DB)

Transaction Failure - Causes

- system failure (hardware failures, bugs in the operating system, database system, etc)
  - all running transactions terminate
  - contents of internal memory – affected (i.e., lost)
  - contents of external memory – not affected
- application error (“bug”, e.g., division by 0, infinite loop, etc)
  - => transaction fails; it should be executed again only after the error is corrected
- action by the Transaction Manager (TM)
  - e.g., deadlock resolution scheme
  - a transaction is chosen as the deadlock victim and terminated
  - the transaction might complete successfully if executed again

Transaction Failure - Causes

- self-abort
  - based on some computations, a transaction can decide to terminate and undo its actions
  - there are special statements for this purpose, e.g., *ABORT, ROLLBACK*
  - it can be seen as a special case of *action by the TM*

Normal Execution

- during normal execution, transactions read / write database objects
- reading database object O:
  - bring O from the disk into a frame in the Buffer Pool (BP)*
  - copy O's value into a program variable
- writing database object O:
  - modify an in-memory copy of O (in the BP)
  - write the in-memory copy to disk

* see the *Databases* course in the 1st semester (lecture 8 - Buffer Manager)

Writing Objects

- options for the Buffer Manager (BM): *steal / no-steal, force / no-force*

- transaction T changes object O (in frame F in the BP)
- transaction T2 needs a page; the BM chooses F as a replacement frame (while T is still in progress)
  - *steal* approach:
    - T’s changes can be written to disk while T is in progress (T2 steals a frame from T)
  - *no-steal* approach:
    - T’s changes cannot be written to disk before T commits

- *force* approach
  - T’s changes are immediately forced to disk when T commits
- *no-force* approach
  - T’s changes are not forced to disk when T commits

Writing Objects

- *no-steal* approach
  - advantage - changes of aborted transactions don't have to be undone (such changes are never written to disk!)
  - drawback - assumption: all pages modified by active transactions can fit in the BP
- *force* approach
  - advantage - actions of committed transactions don't have to be redone
    - by contrast, when using *no-force*, the following scenario is possible: transaction T commits at time t_0; its changes are not immediately forced to disk; the system crashes at time t_1 => T's changes have to be redone!
  - drawback - can result in excessive I/O

- *steal, no-force* approach – used by most systems

ARIES

- recovery algorithm; *steal, no-force* approach
- system restart after a crash - three phases:
  - analysis – determine:
    - active transactions at the time of the crash
    - *dirty pages*, i.e., pages in BP whose changes have not been written to disk
  - redo - reapply all changes (starting from a certain record in the log), i.e., bring the DB to the state it was in when the crash occurred
  - undo - undo changes of uncommitted transactions
- fundamental principle - *Write-Ahead Logging*
  - a change to an object O is first recorded in the log (e.g., in log record LR)
  - LR must be written to disk before the change to O is written to disk

ARIES

* example

- analysis
  - active transactions at crash time: T1, T3 (to be undone)
  - committed transactions: T2 (its effects must persist)
  - potentially dirty pages: P1, P2, P3
- redo
  - reapply all changes in order (1, 2, …)
- undo
  - undo changes of T1 and T3 in reverse order (6, 5, 1)

LSN	Log
1	T1 writes P1
2	T2 writes P2
3	T2 commit
4	T2 end
5	T3 writes P3
6	T3 writes P2
crash & restart	

The Log (journal)

- history of actions executed by the DBMS
- stored in *stable storage*, i.e., keep >= 2 copies of the log on different disks (locations) - ensures the “durability” of the log
- records are added to the end of the log
- *log tail* - the most recent fragment of the log
  - kept in main memory and periodically forced to stable storage
- *Log Sequence Number* (LSN) - unique id for every log record
  - monotonically increasing (e.g., address of 1st byte of log record)
- every page P in the DB contains the *pageLSN*: the LSN of the most recent record in the log describing a change to P
- *log record* – fields:
  - prevLSN – linking a transaction’s log records
  - transID – id of the corresponding transaction
  - type – type of the log record

The Log

- each of the following actions results in a log record being written: *update page, commit, abort, end, undoing an update*
- update page P
  - add an *update type* log record ULR to the log tail (with LSN_{ULR})
  - $pageLSN(P) := LSN_{ULR}$
- transaction T commits
  - add a *commit type* log record CoLR to the log tail
  - force log tail to stable storage (including CoLR)
  - complete subsequent actions (remove T from transaction table)
- transaction T aborts
  - add an *abort type* log record to the log
  - initiate Undo for T
- transaction T ends
  - T commits / aborts - complete required actions

The Log

- transaction T <u>ends</u>
  - add an *end type* log record to the log
- <u>undoing</u> an <u>update</u>
  - i.e., when the change described in an update log record is undone
  - add a *compensation log record* (CLR) to the log
- obs. committed transaction – a transaction whose log records (including the *commit log record*) have been written to stable storage

- *update log record* – additional fields: *pageID* (id of the changed page), *length* (length of the change (in bytes)), *offset* (offset of the change), *before-image* (value before the change), *after-image* (value after the change)
  - can be used to undo / redo the change

The Log

- *compensation log record*
    - let U be an update log record describing an update of transaction T
    - let C be the compensation log record for U, i.e., C describes the action taken to undo the changes described by U
    - C has a field named *undoNextLSN*:
        - the LSN of the next log record to be undone for T
        - set to the value of prevLSN in U

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB

log

* example: undo T10's update to P10
=> CLR with *transID* = T10, *pageID* = P10, *length* = 2, *offset* = 10, *before-image* = JH and *undoNextLSN* = LSN of 1st log record (i.e., the next record that is to be undone for transaction T10)

The Transaction Table and the Dirty Page Table

- contain important information for the recovery process
- *transaction table*:
  - 1 entry / active transaction
  - fields: *transID*, *lastLSN* (LSN of the most recent log record for the transaction), *status* (in progress / committed / aborted)
  - example (*status* not displayed):

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB

log

transID	lastLSN
T10	
T15	

transaction table

The Transaction Table and the Dirty Page Table

- *dirty page table*:
  - 1 entry / dirty page in the Buffer Pool
  - fields: *pageID*, *recLSN* (the LSN of the 1st log record that dirtied the page)

pageID	recLSN
P100	
P2	
P10	

dirty page table

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB

log

transID	lastLSN
T10	
T15	

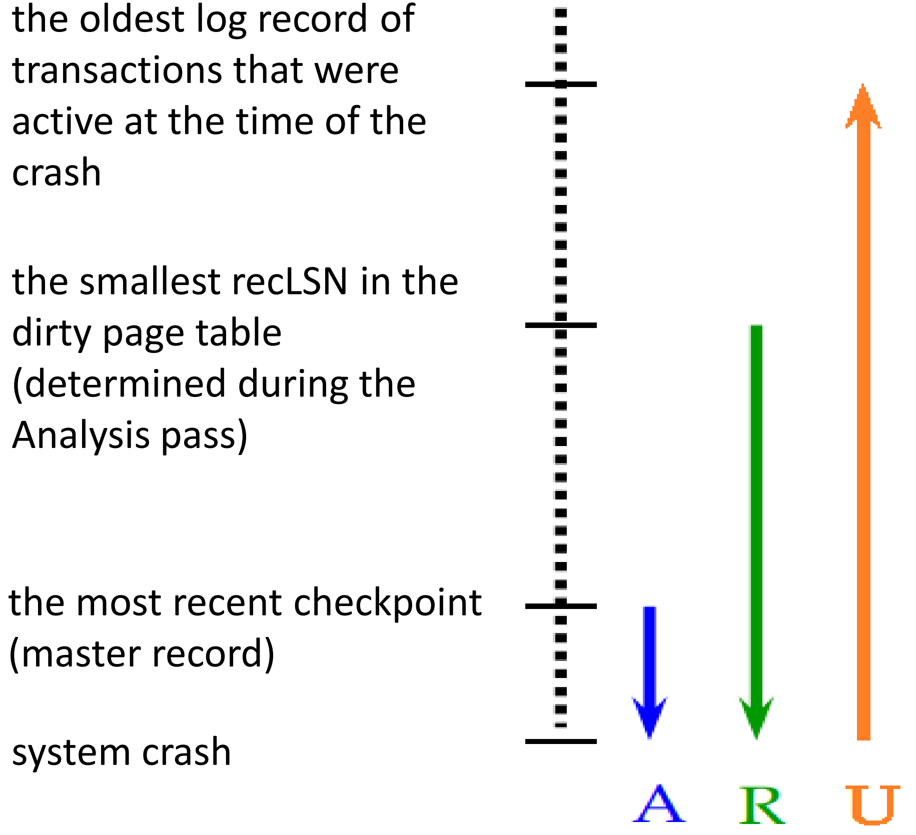
transaction table

Checkpointing

- objective: reduce the amount of work performed by the system when it comes back up after a crash
- *checkpoints* taken periodically; 3 steps:
  - write a *begin_checkpoint* record (it indicates when the checkpoint starts; let its LSN be LSN_{BCK})
  - write an *end_checkpoint* record
    - it includes the current Transaction Table and the current Dirty Page Table
  - after the *end_checkpoint* record is written to stable storage:
    - write a *master* record to a known place on stable storage
    - it includes LSN_{BCK}
- crash -> restart -> system looks for the most recent checkpoint
- normal execution begins with a checkpoint with an empty Transaction Table and an empty Dirty Page Table

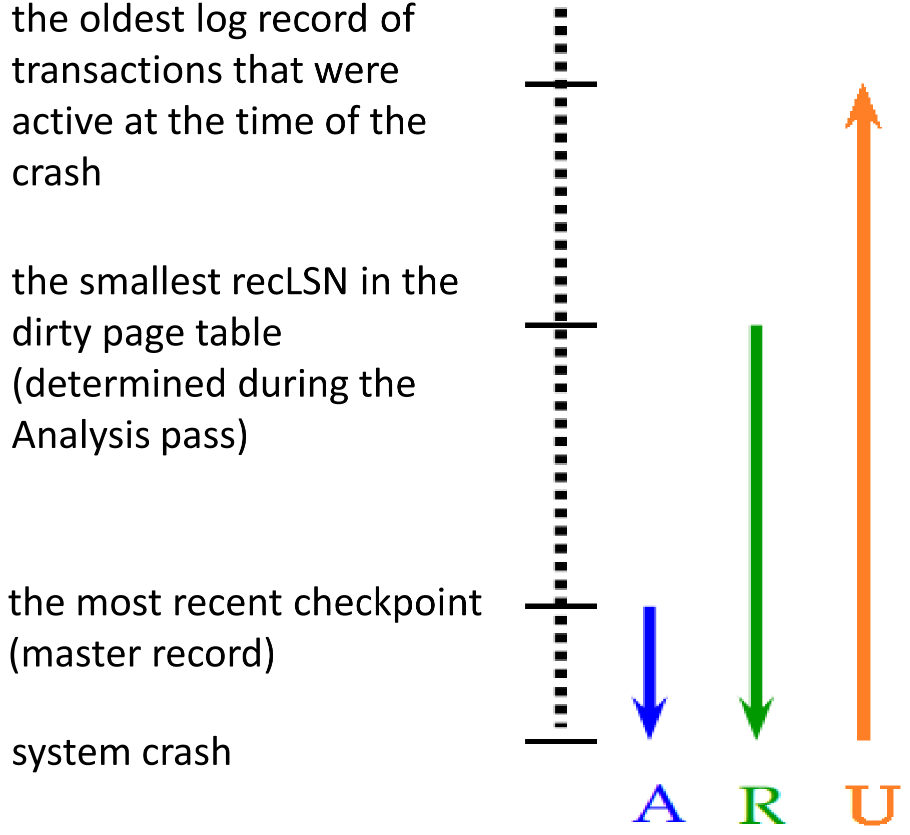
Recovery - overview

- system restart after a crash – 3 phases:
  - Analysis
    - reconstructs state at the most recent checkpoint
    - scans the log forward from the most recent checkpoint
    - identifies:
      - active transactions at the time of the crash (to be undone)
      - potentially dirty pages at the time of the crash
      - the starting point for the Redo pass
  - Redo
    - repeats history, i.e., reapplies changes to dirty pages



Recovery - overview

- system restart after a crash – 3 phases
  - Redo
    - all updates are reapplied (regardless of whether the corresponding transaction committed or not)
    - starting point is determined in the Analysis pass
    - scans the log forward until the last record
  - Undo
    - the effects of transactions that were active at the time of the crash are undone
    - such changes are undone in the opposite order (i.e., Undo scans the log backward from the last record)



* Analysis
- investigate the most recent *begin_checkpoint* log record
    - get the next *end_checkpoint* log record EC
- set Dirty Page Table to the copy of the Dirty Page Table in EC
- set Transaction Table to the copy of the Transaction Table in EC

->

* Analysis - scan the log forward from the most recent checkpoint:

- transactions:
  - encounter end log record for transaction T:
    - remove T from transaction table
  - encounter other log records (LR) for transaction T:
    - add T to Transaction Table if not already there
    - set T.lastLSN to LR.LSN
    - if LR is a commit type log record:
      - set T's status to *C*
    - otherwise, set status to *U* (i.e., to be undone)
- pages:
  - encounter redoable log record (LR) for page P:
    - if P is not in the Dirty Page Table:
      - add P to Dirty Page Table
      - set P.recLSN to LR.LSN

Example 1

- first 5 log records are written to stable storage
- system crashes before the 6th log record is written to stable storage

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB
	T15	commit					
	T10	update	P11	3	20	GFX	YTR

log

Analysis

- most recent checkpoint – beginning of execution (empty Transaction Table, empty Dirty Page Table)
- 1st log record
  - add T10 to the Transaction Table
  - add P100 to the Dirty Page Table (recLSN = LSN(1st log record))

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB
	T15	commit					

log

Analysis

- 2^{nd} log record
  - add T15 to the Transaction Table
  - add P2 to the Dirty Page Table (recLSN = LSN(2^{nd} log record))
- 4^{th} log record
  - add P10 to the Dirty Page Table (recLSN = LSN(4^{th} log record))
- active transactions at the time of the crash:
  - transactions with status *U*, i.e., T10 (T15 is a committed transaction)
- Dirty Page Table:
  - can include pages that were written to disk prior to the crash
  - assume P2's update is the only change written to disk before the crash, i.e., P2 is not dirty, but it's in the Dirty Page Table
  - the pageLSN on page P2 is equal to the LSN of the 2^{nd} log record

Analysis

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB
	T15	commit					

log

- log record

T10	update	P11	3	20	GFX	YTR

is not seen during Analysis (it was not written to disk before the crash)
- Write-Ahead Logging protocol => the corresponding change to page P11 cannot have been written to disk

* Redo
- *repeat history*: reconstruct state at the time of the crash
  - reapply *all* updates (even those of aborted transactions!), reapply CLRs
- scan the log forward from the log record with the smallest recLSN in the Dirty Page Table
- for each redoable log record LR affecting page P, redo the described action unless:
  - page P is not in the Dirty Page Table
  - page P is in the Dirty Page Table, but P.recLSN > LR.LSN
  - P.pageLSN (in DB) ≥ LR.LSN
- to redo an action:
  - reapply the logged action
  - set P.pageLSN to LR.LSN
  - no additional logging!

* Redo

- at the end of Redo:
    - for every transaction T with status *C*:
        - add an end log record
        - remove T from the Transaction Table

Redo

log

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB
	T15	commit					

- previously stated assumption: P2's update is the only change written to disk before the crash, i.e., P2 is not dirty, but it's in the Dirty Page Table
- Dirty Page Table -> smallest recLSN is the LSN of the 1st log record
- 1st log record
  - fetch page P100 (its pageLSN is less than the LSN of the current log record) => reapply update, set P100.pageLSN to the LSN of the 1st log record
- 2nd log record
  - fetch page P2
  - P2.pageLSN = LSN of the current log record => update is not reapplied
- 3rd, 4th log records – processed similarly

* Undo

- *loser transaction* – transaction that was active at the time of the crash
- ToUndo = { l | l - lastLSN of a *loser* transaction}
- repeat:
    - choose the largest LSN in ToUndo and process the corresponding log record LR; let T be the corresponding transaction
    - if LR is a CLR:
        - if undoNextLSN == NULL
            - write an end log record for T
        - else {undoNextLSN != NULL}
            - add undoNextLSN to ToUndo
    - else {LR is an update log record}
        - undo the update
        - write a CLR
        - add LR.prevLSN to ToUndo

until ToUndo is empty

Undo

- active transaction at the time of the crash: T10
- lastLSN of T10: LSN of the 4th log record
- 4th log record
  - undo update, write CLR
  - add LSN of 1st log record to ToUndo
- 1st log record
  - undo update (!T15's change to P100 is lost!)
  - write CLR
  - write end log record for T10
- obs. if Strict 2PL is used, T15 cannot write P100 while T10 is active (T10 has also modified P100)

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T10	update	P100	2	10	AB	CD
	T15	update	P2	2	10	YW	ZA
	T15	update	P100	2	9	EC	YW
	T10	update	P10	2	10	JH	AB
	T15	commit					

log

Example 2 – system crashes during Undo

- consider the execution history below:

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

prevLSNs

Example 2

- T1 aborts
  => its only update is undone (CLR with LSN 40)
  - T1 - terminated
- 1st crash:
  - Analysis:
    - dirty pages: P5 (recLSN 10), P3 (recLSN 20), P1 (recLSN 50)
    - active transactions at the time of the crash: T2 (lastLSN 60), T3 (lastLSN 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
45	T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART

prevLSNs

Example 2

- 1st crash:
  - Redo:
    - starting point
      - log record with LSN = 10 (smallest recLSN in the Dirty Page Table)
    - reapply required actions in update log records / compensation log records

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

prevLSNs

Example 2

- 1st crash:
  - Undo:
    - T2, T3 – loser transactions => ToUndo = {60, 50}
    - process log record with LSN 60:
      - undo update
      - write CLR (LSN 70) with undoNextLSN 20 (i.e., the next log record that should be processed for T2)

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

undonextLSN

Example 2

- 1st crash:
  - Undo:
    - process log record with LSN 50:
      - undo update
      - write CLR (LSN 80) with undoNextLSN *null* (i.e., T3 completely undone, write end log record for T3)
  - log records with LSN 70, 80, 85 are written to stable storage
- 2nd crash (during undo)!

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

undonextLSN

Example 2

- 2nd crash:
  - Analysis:
    - the only active transaction: T2
    - dirty pages: P5 (recLSN 10), P3 (recLSN 20), P1 (recLSN 50)
  - Redo:
    - process log records with LSN between 10 and 85

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	CLR: Undo T2 LSN 20, T2 end

undonextLSN

Example 2

- 2nd crash:
  - Undo:
    - lastLSN of T2: 70
    - ToUndo = {70}
    - process log record with LSN 70:
      - add 20 (undoNextLSN) to ToUndo
    - process log record with LSN 20:
      - undo update
      - write CLR (LSN 90) with undoNextLSN *null* => write end log record for T2

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	CLR: Undo T2 LSN 20, T2 end

undonextLSN

Example 2

- 2nd crash:
  - Undo:
    - ToUndo empty

=> recovery complete!

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	CLR: Undo T2 LSN 20, T2 end

undonextLSN

- obs. aborting a transaction
    - special case of Undo in which the actions of a single transaction are undone
- obs. system crash during the Analysis pass
    - all the work is lost
    - when the system comes back up, the Analysis phase has the same information as before
- obs. system crash during the Redo pass
    - some of the changes from the Redo pass may have been written to disk prior to the crash
    - the pageLSN will indicate such a situation, so these changes will not be reapplied in the subsequent Redo pass

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