Database Management Systems

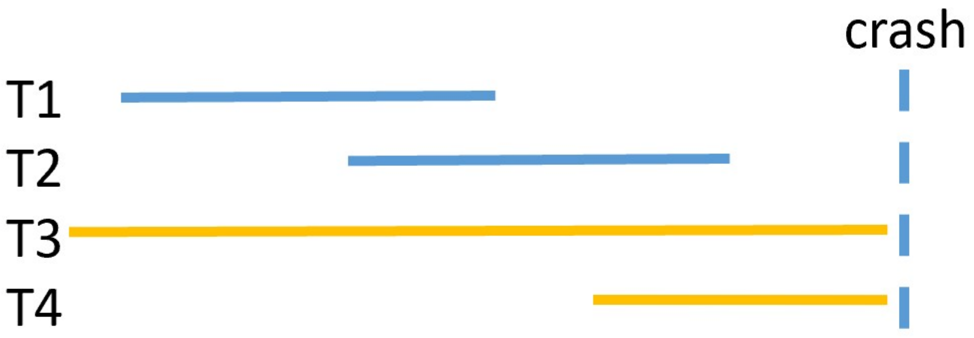
Lecture 4

Crash Recovery

Sabina S. CS

Recovery Manager

- the Recovery Manager in a DBMS ensures two important properties of transactions:
  - atomicity - the effects of uncommitted transactions are undone
  - durability - the effects of committed transactions survive system crashes



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

- 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

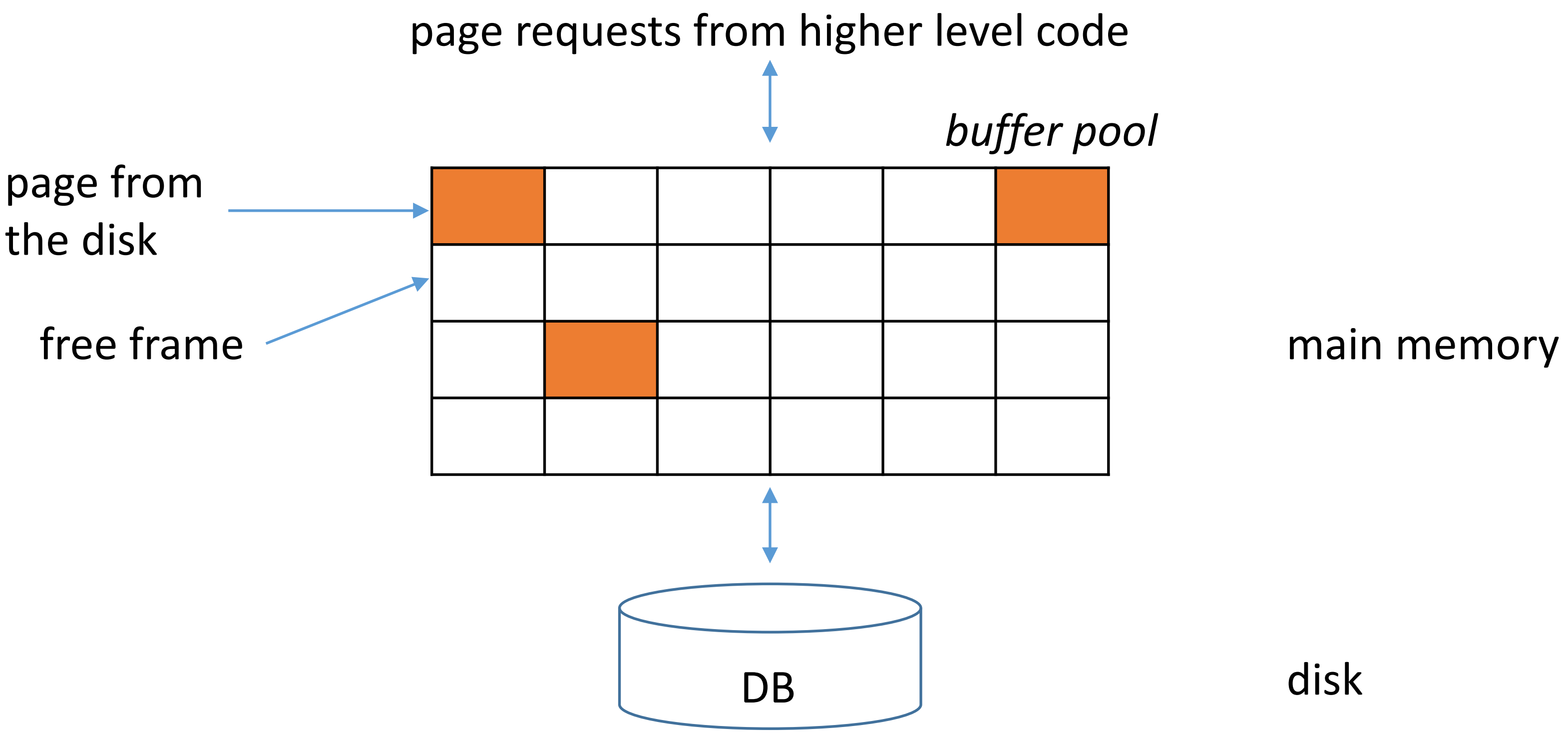
Transaction Failure - Causes

- 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*
  - 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 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

Buffer Manager*



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

Writing Objects

- options: *steal / no-steal, force / no-force*

- transaction T changes object O (in frame F in the BP)
  - *steal* approach
    - T's changes can be written to disk before it commits
    - transaction T2 needs a page; the BM chooses F as a replacement frame (while T is in progress); T2 steals a frame from T
  - *no-steal* approach
    - T's changes cannot be written to disk before it commits
  - *force* approach
    - T's changes are immediately forced to disk when it commits
  - *no-force* approach
    - T's changes are not forced to disk when it 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

Storage Media

- volatile storage
  - information doesn't usually survive system crashes (e.g., main memory)
- non-volatile storage
  - information survives system crashes (e.g., magnetic disks, flash storage)
- stable storage
  - information is never lost
  - techniques that approximate stable storage (e.g., store information on multiple disks, in several locations)

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 (in a log record LR)
  - LR must be written to stable storage 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	update: T1 writes P1
2	update: T2 writes P2
3	T2 commit
4	T2 end
5	update: T3 writes P3
6	update: T3 writes P2
crash, restart	

The Log (journal)

- history of actions executed by the DBMS
- file of records
- stored in *stable storage* (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)

The Log

- *pageLSN*
  - 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
- a log record is written for each of the following actions:
  - *update page*
  - *commit*
  - *abort*
  - *end*
  - *undo an update*

The Log

- update page P
  - add an *update type* log record ULR to the log tail (with LSN_{ULR})
  - pageLSN(P) is set to LSN_{ULR}
- transaction T commits*
  - add a *commit type* log record CoLR to the log
  - 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

* obs. committed transaction – a transaction whose log records (including the *commit log record*) have been written to stable storage

The Log

- transaction T ends
  - T commits / aborts - complete required actions
  - add an *end type* log record to the log
- undo an update
  - i.e., when the change described in an update log record is undone
  - write a *compensation log record* (CLR)

- *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

->

The Log

- *compensation log record*

* example: undo T10's update to P10

=> CLR with:

transID = T10

pageID = P10

length = 2

offset = 10

before-image = JH

undoNextLSN = LSN of 1st log record (i.e., the next record that is to be undone for transaction T10)

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

The Transaction Table and the Dirty Page Table

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

transID	lastLSN
T10	
T15	

transaction 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

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
  - example:

pageID	recLSN
P100	
P2	
P10	

dirty page table

transID	lastLSN
T10	
T15	

transaction 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

Checkpointing

- objective
  - reduce the amount of work performed by the system when it comes back up after a crash
- *checkpoints* taken periodically

- checkpointing in ARIES - 3 steps:
  - write a *begin_checkpoint* record (it indicates when the checkpoint starts)
    - LSN_{BCK} - LSN of *begin_checkpoint* record
  - write an *end_checkpoint* record
    - it includes the current Transaction Table and the current Dirty Page Table

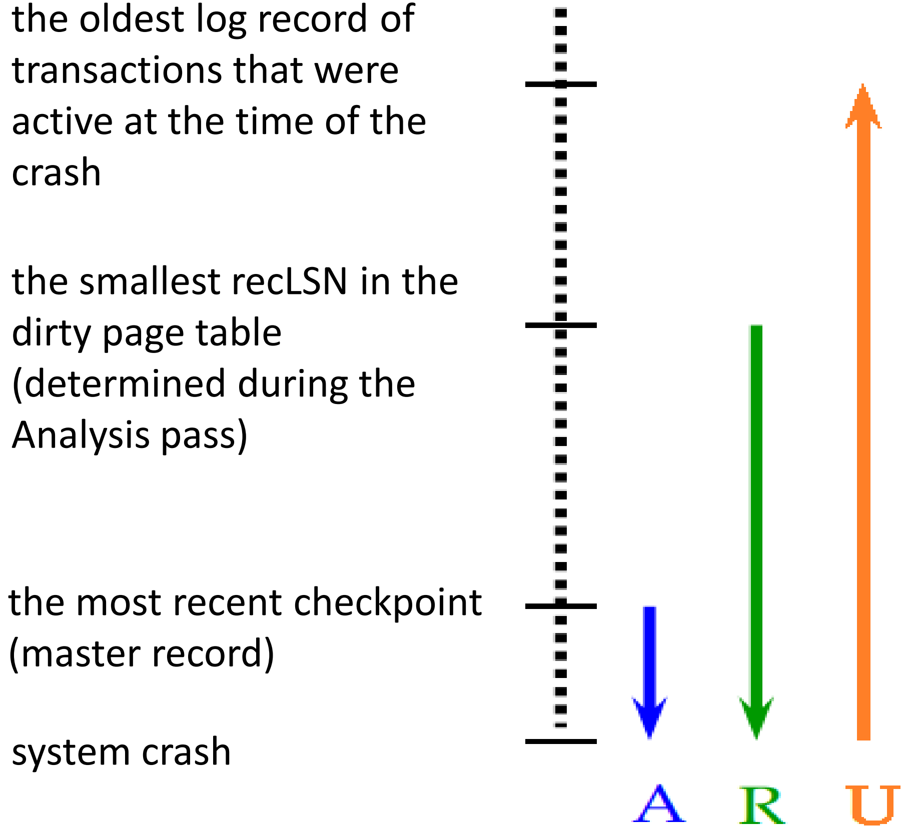
Checkpointing

- checkpointing in ARIES - 3 steps:
  - after the *end_checkpoint* record is written to stable storage:
    - write a *master* record to a known place on stable storage
    - *master* record 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



Recovery - overview

- system restart after a crash – 3 phases:
  - Redo
    - repeats history, i.e., reapplies changes to dirty pages
    - 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

- scan the log forward from the most recent checkpoint:
  - <u>transactions</u>:
    - 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)

* Analysis

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

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	2	20	GF	YT

log

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

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))

Example 1

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

<u>Analysis</u>

- 2nd log record
  - add T15 to the Transaction Table
  - add P2 to the Dirty Page Table (recLSN = LSN(2nd log record))
- 4th log record
  - add P10 to the Dirty Page Table (recLSN = LSN(4th log record))
- active transactions at the time of the crash:
  - transactions with status *U*, i.e., T10 (T15 is a committed transaction)

Example 1

Analysis

- 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 2nd log record

- log record

T10	update	P11	2	20	GF	YT

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 one of the conditions below is satisfied:
  - 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) $\geq$ 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

Example 1

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

<u>Redo</u>

- 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

Example 1

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

Redo

- 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
            - add undoNextLSN to ToUndo
    - else {LR is an update log record}
        - write a CLR
        - undo the update
        - add LR.prevLSN to ToUndo

until ToUndo is empty

Example 1

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

Undo

- active transaction at the time of the crash: T10
- lastLSN of T10: LSN of the 4th log record
- 4th log record
    - write CLR, undo update
    - add LSN of 1st log record to ToUndo

Example 1

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

Undo

- 1st log record
    - write CLR, undo update (!T15's change to P100 is lost!), write end log record for T10
- obs. if Strict 2PL is used, T15 cannot write P100 while T10 is active (T10 also modified P100)

Example 2 – system crashes during Undo

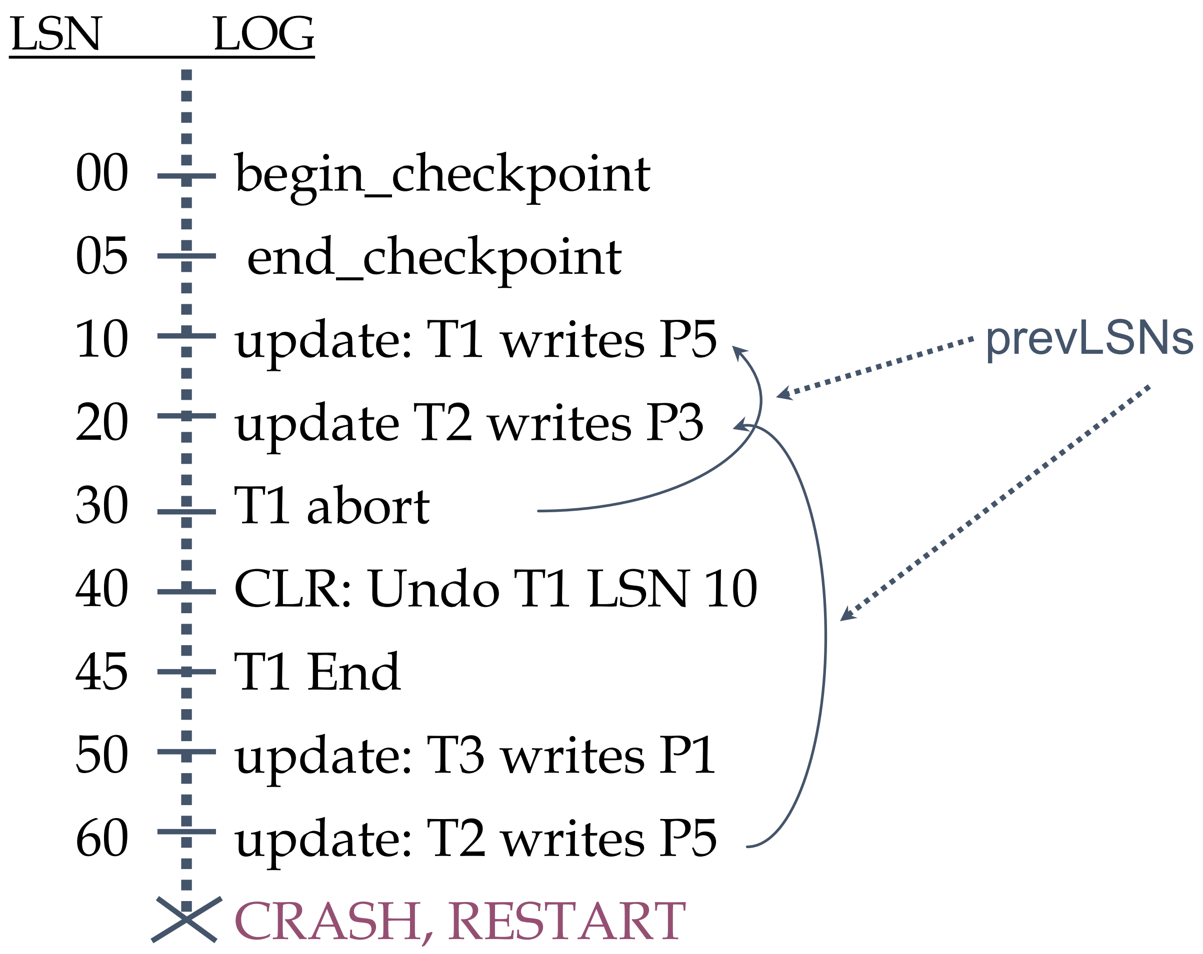
- consider the execution history below:

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)



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

References

- [Ra02] RAMAKRISHNAN, R., GEHRKE, J., Database Management Systems (3rd Edition), McGraw-Hill, 2002
- [Le99] LEVENE, M., LOIZOU, G., A Guided Tour of Relational Databases and Beyond, Springer, 1999
- [Ra02S] RAMAKRISHNAN, R., GEHRKE, J., Database Management Systems, Slides for the 3rd Edition, http://pages.cs.wisc.edu/~dbbook/openAccess/thirdEdition/slides/slides3ed.html
- [Si19] SILBERSCHATZ, A., KORTH, H., SUDARSHAN, S., Database System Concepts (7th Edition), McGraw-Hill, 2019
- [Si19S] SILBERSCHATZ, A., KORTH, H., SUDARSHAN, S., Database System Concepts, Slides for the 7th Edition, http://codex.cs.yale.edu/avi/db-book/