CS 5614: (Big) Data Management Systems

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Lecture #9: Logging and Recovery 2:
  ARIES
Motivation

- **Atomicity:**
  - Transactions may abort ("Rollback").

- **Durability:**
  - What if DBMS stops running? (Causes?)

- Desired state after system restarts:
  - T1 & T3 should be **durable**.
  - T2, T4 & T5 should be **aborted** (effects not seen).
General Overview

- Preliminaries
- Write-Ahead Log - main ideas
- (Shadow paging)
- Write-Ahead Log: ARIES
Main ideas so far:

- Write-Ahead Log, for loss of volatile storage,
- with incremental updates (STEAL, NO FORCE)
- and checkpoints
- On recovery: **undo** uncommitted; **redo** committed transactions.
Today: ARIES

With full details on
  – fuzzy checkpoints
  – recovery algorithm

C. Mohan (IBM)
Overview

- Preliminaries
- Write-Ahead Log - main ideas
- (Shadow paging)
- Write-Ahead Log: ARIES

- LSN’s
  - examples of normal operation & of abort
  - fuzzy checkpoints
  - recovery algo
LSN

- Log Sequence Number
- every log record has an LSN
- Q: Why do we need it?
LSN

A1: e.g, undo T4 - it is faster, if we have a linked list of the T4 log records
A2: and many other uses - see later

~~~~ CRASH ~~~~
Types of log records

Q1: Which types?
A1:

Q2: What format?
A2:

<T1 start>
<T2 start>
<T4 start>
<T4, A, 10, 20>
<T1 commit>
<T4, B, 30, 40>
<T3 start>
<T2 commit>
<T3 commit>

~~~~~ CRASH ~~~~~
Types of log records

Q1: Which types?
A1: Update, commit, checkpoint, …

Q2: What format?
A2: x-id, type, (old value, …)

<T1 start>
<T2 start>
<T4 start>
<T4, A, 10, 20>
<T1 commit>
<T4, B, 30, 40>
<T3 start>
<T2 commit>
<T3 commit>

~~~~ CRASH ~~~~
Possible log record types:
- **Update**, **Commit**, **Abort**
- **Checkpoint** (for log maintenance)
- **Compensation Log Records** (CLRs)
  - for UNDO actions
- **End** (end of commit or abort)

LogRecord fields:
- prevLSN
- XID
- type
- pageID
- length
- offset
- before-image
- after-image
Overview

- Preliminaries
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- Write-Ahead Log: ARIES
  - LSN’s
    - examples of normal operation & of abort
    - fuzzy checkpoints
    - recovery algo
Writing log records

- We don’t want to write one record at a time – (why not?)
- How should we buffer them?
Writing log records

- We don’t want to write one record at a time
  - (why not?)
- How should we buffer them?
  - Batch log updates;
  - Un-pin a data page ONLY if all the corresponding log records have been flushed to the log.
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.

**WAL**: For a page $i$ to be written must flush log at least to the point where:

$$
\text{pageLSN}_i \leq \text{flushedLSN}
$$
Can we un-pin the gray page?
Can we un-pin the gray page?
A: yes
WAL & the Log

- Can we un-pin the blue page?

Log records flushed to disk

flushedLSN

"Log tail" in RAM

pageLSN

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Can we un-pin the blue page?
A: no
WAL & the Log

Q: why not on disk or log?

Log records flushed to disk

"Log tail" in RAM
Overview

- Preliminaries
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    - recovery algo
Normal Execution of an Xact

- Series of reads & writes, followed by commit or abort.
  - We will assume that disk write is atomic.
    - In practice, additional details to deal with non-atomic writes.

- Strict 2PL.

- STEAL, NO-FORCE buffer management, with Write-Ahead Logging.
Normal execution of an Xact

- Page ‘i’ can be written out only after the corresponding log record has been flushed
Transaction Commit

- Write **commit** record to log.
- All log records up to Xact’s **commit record** are flushed to disk.

**Q:** why not flush the dirty pages, too?
Transaction Commit

- Write `commit` record to log.
- All log records up to Xact’s `commit record` are flushed to disk.
  - Note that log flushes are sequential, synchronous writes to disk.
  - Many log records per log page.
- `Commit()` returns.
- Write `end` record to log.
### Example

<table>
<thead>
<tr>
<th>LSN</th>
<th>prevLSN</th>
<th>tid</th>
<th>type</th>
<th>item</th>
<th>old</th>
<th>new</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>NULL</td>
<td>T1</td>
<td>update</td>
<td>X</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>T1</td>
<td>update</td>
<td>Y</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>50</td>
<td>T1</td>
<td>commit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68</td>
<td>63</td>
<td>T1</td>
<td>end</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DBMS flushes log records + some record-keeping
Overview

- Preliminaries
- Write-Ahead Log - main ideas
- (Shadow paging)
- Write-Ahead Log: ARIES
  - LSN’s
  - examples of normal operation & of abort
    - fuzzy checkpoints
    - recovery algo
Abort

Actually, a special case of the up-coming ‘undo’ operation,
applied to only one transaction - e.g.:
## Abort - Example

<table>
<thead>
<tr>
<th>LSN</th>
<th>prevLSN</th>
<th>tid</th>
<th>type</th>
<th>item</th>
<th>old</th>
<th>new</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>NULL</td>
<td>T2</td>
<td>update</td>
<td>Y</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>10</td>
<td>T2</td>
<td>abort</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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## Abort - Example

<table>
<thead>
<tr>
<th>LSN</th>
<th>prevLSN</th>
<th>tid</th>
<th>type</th>
<th>item</th>
<th>old</th>
<th>new</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>NULL</td>
<td>T2</td>
<td>update</td>
<td>Y</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>10</td>
<td>T2</td>
<td>abort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>63</td>
<td>T2</td>
<td>CLR</td>
<td>(LSN 10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>72</td>
<td>T2</td>
<td>end</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The compensating log record is indicated by the LSN 10 (CLR) and LSN 10 (end).
## Abort - Example

<table>
<thead>
<tr>
<th>LSN</th>
<th>prevLSN</th>
<th>tid</th>
<th>type</th>
<th>item</th>
<th>old</th>
<th>new</th>
<th>undoNextLSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>NULL</td>
<td>T2</td>
<td>update</td>
<td>Y</td>
<td>30</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>10</td>
<td>T2</td>
<td>abort</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>63</td>
<td>T2</td>
<td>CLR</td>
<td>Y</td>
<td>40</td>
<td>30</td>
<td>NULL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>72</td>
<td>T2</td>
<td>end</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CLR record - details

- a CLR record has all the fields of an ‘update’ record
- plus the ‘undoNextLSN’ pointer, to the next-to-be-undone LSN
Abort - algorithm:

- First, write an ‘abort’ record on log and
- 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: CLR records never need to be undone
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(non-fuzzy) checkpoints

- they have performance problems - recall from previous lecture:
We assumed that the DBMS:
- stops all transactions, and
- flushes on disk the ‘dirty pages’

Both decisions are expensive.

Q: Solution?
(non-fuzzy) checkpoints

Q: Solution?

*Hint1*: record state as of the beginning of the ckpt

*Hint2*: we need some guarantee about which pages made it to the disk

```plaintext
<T1 start>
...
<T1 commit>
...
<T499, C, 1000, 1200>
<checkpoint>
<T499 commit>
<T500 start>
<T500, A, 200, 400>
<checkpoint>
<T500, B, 10, 12>
```

crash
checkpoints

Q: Solution?
A: write on the log:
- the id-s of active transactions and
- the id-s (ONLY!) of dirty pages (rest: obviously made it to the disk!)

<T1 start>
...
<T1 commit>
...
<T499, C, 1000, 1200>
<checkpoint>
<T499 commit>
<T500 start>
<T500, A, 200, 400>
<checkpoint>
<T500, B, 10, 12>

before

crash
(Fuzzy) checkpoints

Specifically, write to log:

- `begin_checkpoint` record: indicates start of ckpt
- `end_checkpoint` record: Contains current *Xact table* and *dirty page table*. This is a `fuzzy checkpoint`:
  - Other Xacts 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; effectiveness of checkpoint limited by oldest unwritten change to a dirty page.
(Fuzzy) checkpoints

Specifically, write to log:

- `begin_checkpoint` record: indicates start of ckpt
- `end_checkpoint` record: Contains current Xact table and dirty page table. This is a `fuzzy checkpoint`:
  - Other Xacts 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; effectiveness of checkpoint limited by oldest unwritten change to a dirty page.

solved both problems of non-fuzzy ckpts!!
(Fuzzy) checkpoints - cont’d

And:

– Store LSN of most recent chkpt record on disk (master record)
  • Q: why do we need that?
(Fuzzy) Checkpoints

More details: Two in-memory tables:

#1) Transaction Table

Q: what would you store there?
(Fuzzy) Checkpoints

More details: Two in-memory tables:

#1) Transaction Table

- One entry per currently active Xact.
  - entry removed when Xact commits or aborts

- Contains
  - XID,
  - status (running/committing/aborting), and
  - lastLSN (most recent LSN written by Xact).
(Fuzzy) Checkpoints

#2) Dirty Page Table:

– One entry per dirty page currently in buffer pool.
– Contains recLSN -- the LSN of the log record which first caused the page to be dirty.
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  - fuzzy checkpoints
- recovery algo
The Big Picture: What’s Stored Where

LogRecords
- prevLSN
- XID
- type
- pageID
- length
- offset
- before-image
- after-image

update
CLR

CLR
- undoNextLSN

Xact Table
- lastLSN
- status

Dirty Page Table
- recLSN

flushedLSN

Data pages each with a pageLSN

master record
- LSN of most recent checkpoint

LOG

DB

RAM
Crash Recovery: Big Picture

- **Start from a checkpoint** (found via master record).

- **Three phases.**
  - **Analysis** - Figure out which Xacts committed since checkpoint, which failed.
  - **REDO** all actions (repeat history)
  - **UNDO** effects of failed Xacts.
Crash Recovery: Big Picture

- Oldest log rec. of Xact active at crash
- Smallest recLSN in dirty page table after Analysis
- Notice: relative ordering of A, B, C may vary!
Recovery: The Analysis Phase

- Re-establish knowledge of state at checkpoint.
  - via transaction table and dirty page table stored in the checkpoint
Recovery: The Analysis Phase

- Scan log forward from checkpoint.
  - **End** record: Remove Xact from Xact table.
  - All **Other records**:
    - Add Xact to Xact table, with status ‘U’ (=candidate for undo)
    - set lastLSN=LSN,
    - on *commit*, change Xact status to ‘C’.
  - also, for **Update** records: If page P not in Dirty Page Table (DPT),
    - add P to DPT, set its recLSN=LSN.
Recovery: The Analysis Phase

- At end of Analysis:
  - transaction table says which transactions were active at time of crash.
  - DPT says which dirty pages might not have made it to disk.
Phase 2: REDO

Goal: repeat *History* to reconstruct state at crash:
   – Reapply *all* updates (even of aborted Xacts!), redo CLRs.
   – (and try to avoid unnecessary reads and writes!)

Specifically:

- Scan forward from log rec containing smallest *recLSN* in DPT. **Q: why start here?**
Phase 2: REDO (cont’d)

- ...

- For each update log record or CLR with a given LSN, REDO the action unless:
  - Affected page is not in the Dirty Page Table, or
  - Affected page is in D.P.T., but has $\text{recLSN} > \text{LSN}$, or
  - $\text{pageLSN}$ (in DB) $\geq \text{LSN}$. (this last case requires I/O)
Phase 2: REDO (cont’d)

- ...

- To **REDO** an action:
  - Reapply logged action.
  - Set pageLSN to LSN. No additional logging, no forcing!
Phase 2: REDO (cont’d)

- ...
- at the end of REDO phase, write ‘end’ log records for all xacts with status ‘C’,
- and remove them from transaction table
Phase 3: UNDO

Goal: Undo all transactions that were active at the time of crash (‘loser xacts’) 

- That is, all xacts with ‘U’ status on the xact table of the Analysis phase
- Process them in reverse LSN order
- using the lastLSN’s to speed up traversal
- and issuing CLRs
Phase 3: UNDO

ToUndo = {lastLSNs of ‘loser’ Xacts}

Repeat:
  – Choose (and remove) largest LSN among ToUndo.
  – If this LSN is a CLR and undonextLSN == NULL
    • Write an End record for this Xact.
  – If this LSN is a CLR, and undonextLSN != NULL
    • Add undonextLSN to ToUndo
  – Else this LSN is an update. Undo the update, write a CLR, add prevLSN to ToUndo.

Until ToUndo is empty.
suppose that after end of analysis phase we have:
xact table

<table>
<thead>
<tr>
<th>xid</th>
<th>status</th>
<th>lastLSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>T32</td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>T41</td>
<td>U</td>
<td></td>
</tr>
</tbody>
</table>
Phase 3: UNDO - illustration

suppose that after end of analysis phase we have:

<table>
<thead>
<tr>
<th>xid</th>
<th>status</th>
<th>lastLSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>T32</td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>T41</td>
<td>U</td>
<td></td>
</tr>
</tbody>
</table>

undo in reverse LSN order
Example of Recovery

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>begin_checkpoint</td>
</tr>
<tr>
<td>05</td>
<td>end_checkpoint</td>
</tr>
<tr>
<td>10</td>
<td>update: T1 writes P5</td>
</tr>
<tr>
<td>20</td>
<td>update T2 writes P3</td>
</tr>
<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
<tr>
<td>40</td>
<td>CLR: Undo T1 LSN 10</td>
</tr>
<tr>
<td>45</td>
<td>T1 End</td>
</tr>
<tr>
<td>50</td>
<td>update: T3 writes P1</td>
</tr>
<tr>
<td>60</td>
<td>update: T2 writes P5</td>
</tr>
</tbody>
</table>

Xact Table
- lastLSN
- status

Dirty Page Table
- recLSN
- flushedLSN

ToUndo

RAM

prevLSNs
Questions

- Q1: After the Analysis phase, which are the ‘loser’ transactions?

- Q2: UNDO phase - what will it do?
Questions

- Q1: After the Analysis phase, which are the ‘loser’ transactions?
  - A1: T2 and T3
- Q2: UNDO phase - what will it do?
  - A2: undo ops of LSN 60, 50, 20
Example: Crash During Restart!

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td>begin_checkpoint, end_checkpoint</td>
</tr>
<tr>
<td>10</td>
<td>update: T1 writes P5</td>
</tr>
<tr>
<td>20</td>
<td>update: T2 writes P3</td>
</tr>
<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
<tr>
<td>40,45</td>
<td>CLR: Undo T1 LSN 10, T1 End</td>
</tr>
<tr>
<td>50</td>
<td>update: T3 writes P1</td>
</tr>
<tr>
<td>60</td>
<td>update: T2 writes P5</td>
</tr>
</tbody>
</table>

CRASH, RESTART
## Example: Crash During Restart!

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td><code>begin_checkpoint, end_checkpoint</code></td>
</tr>
<tr>
<td>10</td>
<td>update: T1 writes P5</td>
</tr>
<tr>
<td>20</td>
<td>update T2 writes P3</td>
</tr>
<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
<tr>
<td>40,45</td>
<td>CLR: Undo T1 LSN 10, T1 End</td>
</tr>
<tr>
<td>50</td>
<td>update: T3 writes P1</td>
</tr>
<tr>
<td>60</td>
<td>update: T2 writes P5</td>
</tr>
<tr>
<td>70</td>
<td>CLR: Undo T2 LSN 60</td>
</tr>
</tbody>
</table>

- **Xact Table**
  - lastLSN
  - status
- **Dirty Page Table**
  - recLSN
  - flushedLSN
- **ToUndo**

**RAM**
Example: Crash During Restart!

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td>begin_checkpoint, end_checkpoint</td>
</tr>
<tr>
<td>10</td>
<td>update: T1 writes P5</td>
</tr>
<tr>
<td>20</td>
<td>update T2 writes P3</td>
</tr>
<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
<tr>
<td>40,45</td>
<td>CLR: Undo T1 LSN 10, T1 End</td>
</tr>
<tr>
<td>50</td>
<td>update: T3 writes P1</td>
</tr>
<tr>
<td>60</td>
<td>update: T2 writes P5</td>
</tr>
<tr>
<td>70</td>
<td>CLR: Undo T2 LSN 60</td>
</tr>
<tr>
<td>80,85</td>
<td>CLR: Undo T3 LSN 50, T3 end</td>
</tr>
</tbody>
</table>

RAM

Xact Table
- lastLSN
- status

Dirty Page Table
- recLSN
- flushedLSN

ToUndo

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Example: Crash During Restart!

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td>begin_checkpoint, end_checkpoint</td>
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<tr>
<td>10</td>
<td>update: T1 writes P5</td>
</tr>
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<td>20</td>
<td>update T2 writes P3</td>
</tr>
<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
<tr>
<td>40,45</td>
<td>CLR: Undo T1 LSN 10, T1 End</td>
</tr>
<tr>
<td>50</td>
<td>update: T3 writes P1</td>
</tr>
<tr>
<td>60</td>
<td>update: T2 writes P5</td>
</tr>
<tr>
<td></td>
<td>CRASH, RESTART</td>
</tr>
<tr>
<td>70</td>
<td>CLR: Undo T2 LSN 60</td>
</tr>
<tr>
<td>80,85</td>
<td>CLR: Undo T3 LSN 50, T3 end</td>
</tr>
<tr>
<td></td>
<td>CRASH, RESTART</td>
</tr>
</tbody>
</table>
Questions

- Q3: After the Analysis phase, which are the ‘loser’ transactions?

- Q4: UNDO phase - what will it do?
Questions

- Q3: After the Analysis phase, which are the ‘loser’ transactions?
- A3: T2 only
- Q4: UNDO phase - what will it do?
- A4: follow the string of $prevLSN$ of T2, exploiting $undoNextLSN$
Example: Crash During Restart!

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td>begin_checkpoint, end_checkpoint</td>
</tr>
<tr>
<td>10</td>
<td>update: T1 writes P5</td>
</tr>
<tr>
<td>20</td>
<td>update T2 writes P3</td>
</tr>
<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
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<tr>
<td>80,85</td>
<td>CLR: Undo T3 LSN 50, T3 end</td>
</tr>
</tbody>
</table>

Xact Table

- lastLSN
- status

Dirty Page Table

- recLSN
- flushedLSN

ToUndo

RAM

undonextLSN
Questions

- Q5: show the log, after the recovery is finished:
### Example: Crash During Restart!

<table>
<thead>
<tr>
<th>LSN</th>
<th>LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td>begin_checkpoint, end_checkpoint</td>
</tr>
<tr>
<td>10</td>
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<td></td>
<td><strong>CRASH, RESTART</strong></td>
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<td>70</td>
<td>CLR: Undo T2 LSN 60</td>
</tr>
<tr>
<td>80,85</td>
<td>CLR: Undo T3 LSN 50, T3 end</td>
</tr>
<tr>
<td></td>
<td><strong>CRASH, RESTART</strong></td>
</tr>
<tr>
<td>90, 95</td>
<td>CLR: Undo T2 LSN 20, T2 end</td>
</tr>
</tbody>
</table>

---

**RAM**

**Xact Table**
- lastLSN
- status

**Dirty Page Table**
- recLSN
- flushedLSN

**ToUndo**
Additional Crash Issues

- What happens if system crashes during Analysis? During REDO?
- How do you limit the amount of work in REDO?
  - Flush asynchronously in the background.
- How do you limit the amount of work in UNDO?
  - Avoid long-running Xacts.
Summary of Logging/Recovery

- Recovery Manager guarantees Atomicity & Durability.

Atomicity
Consistency
Isolation
Durability
Summary of Logging/Recovery

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

let OS do its best

idempotency
Summary of Logging/Recovery

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: undoNextLSN, recLSN etc)