CS 4604: Introduction to Database Management Systems

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Lecture #18: 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
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 ~~~~
Log Records

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

update records only
Overview

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  - 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.
WAL & 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:
  $$\text{pageLSN}_i \leq \text{flushedLSN}$$
WAL & the Log

- 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

• LSNs
• pageLSNs
• flushedLSN

“Log tail” in RAM

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Overview

- Preliminaries
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  - examples of normal operation & of abort
    - fuzzy checkpoints
    - 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>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>

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>
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>

compensating log record
## 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>T2</td>
<td>abort</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>10</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>T2</td>
<td>end</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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  - recovery algo
(non-fuzzy) checkpoints

- they have performance problems - recall from previous lecture:
(non-fuzzy) checkpoints

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 theckpt

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

<T1 start>
...
<T1 commit>
...
<T499, C, 1000, 1200>
<checkpoint>
<T499 commit> before
<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!)
(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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- Write-Ahead Log: ARIES
  - LSN’s
  - examples of normal operation & of **abort**
  - fuzzy checkpoints
- recovery algo
The Big Picture: What’s Stored Where

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

- **DB**
  - Data pages each with a pageLSN
  - master record LSN of most recent checkpoint

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

- **CLR**
  - undoNextLSN

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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.

Oldest log rec. of Xact active at crash

Smallest recLSN in dirty page table after Analysis

Last chkpt

CRASH
Crash Recovery: Big Picture

- Oldest log rec. of Xact active at crash
- Smallest recLSN in dirty page table after Analysis
- Last chkpt

CRASH

A     R     U

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 xacts 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 recLSN > LSN, or
  - pageLSN (in DB) $\geq$ 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.
Phase 3: UNDO - illustration

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>

prevLSNs
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>

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>
Example of Recovery

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

Xact Table
lastLSN
status
Dirty Page Table
recLSN
flushedLSN

ToUndo
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>
<tr>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

**Xact Table**
- lastLSN
- status

**Dirty Page Table**
- recLSN
- flushedLSN

**ToUndo**
### Example: Crash During Restart!

<table>
<thead>
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<th>LSN</th>
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</tr>
</thead>
<tbody>
<tr>
<td>00,05</td>
<td>begin_checkpoint, end_checkpoint</td>
</tr>
<tr>
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<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>70</td>
<td>CLR: Undo T2 LSN 60</td>
</tr>
</tbody>
</table>

**Xact Table**
- lastLSN
- status

**Dirty Page Table**
- recLSN
- flushedLSN

**ToUndo**
Example: Crash During Restart!

<table>
<thead>
<tr>
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</thead>
<tbody>
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<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></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>
</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>
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<tr>
<td>30</td>
<td>T1 abort</td>
</tr>
<tr>
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<td>CLR: Undo T1 LSN 10, T1 End</td>
</tr>
<tr>
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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>
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RAM

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Prakash 2018

VT CS 4604
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>
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<tr>
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**CRASH, RESTART**

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**CRASH, RESTART**
Questions

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

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</tr>
<tr>
<td>90, 95</td>
<td>CLR: Undo T2 LSN 20, T2 end</td>
</tr>
</tbody>
</table>

**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
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)