Crash Recovery

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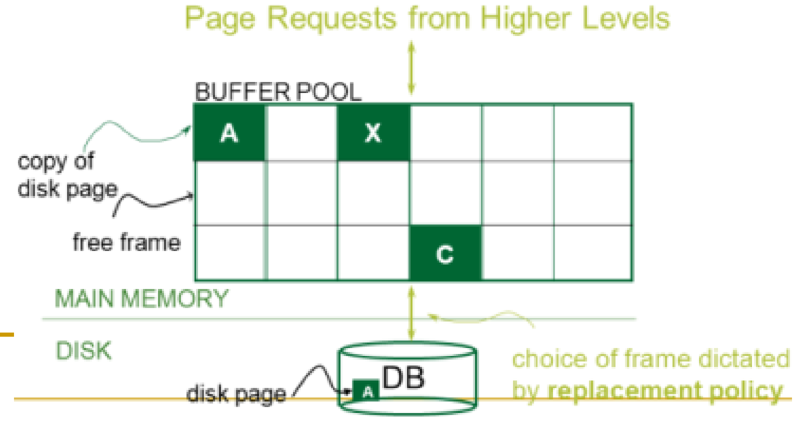
Review

- 事务的4个特性 ACID
- 事务的提交与中止
- 并发控制，严格 2PL
- Buffer Management,脏页



Review: The ACID properties

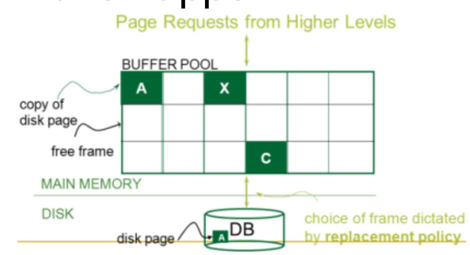
- Atomicity: All actions in the Xact (transaction) happen, or none happen.
- Consistency: If each Xact is consistent, and the DB starts consistent, it ends up consistent.
- Isolation: Execution of one Xact is isolated from that of other Xacts.
- Durability: If an Xact commits, its effects persist.

- The Recovery Manager guarantees Atomicity & Durability.

Motivation 动机

The Recovery Manager guarantees Atomicity & Durability.

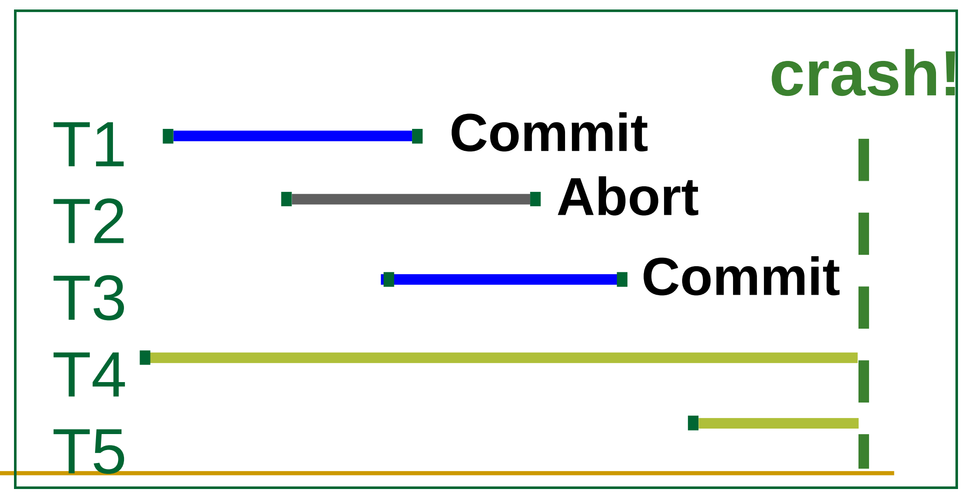
- **Atomicity:** All actions in the Xact (transaction) happen, or none happen.
  - Transactions may abort ("Rollback").
- **Durability:** If an Xact commits, its effects persist.
  - What if DBMS stops running? (Causes?)



✓ Desired state after system restarts:

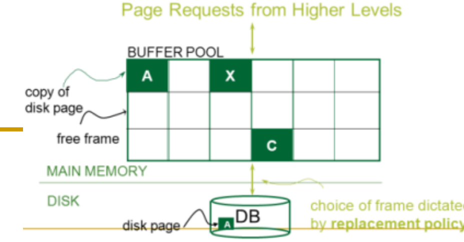
– T1 & T3 should be durable.

– T2, T4 & T5 should be aborted (effects should not be seen).



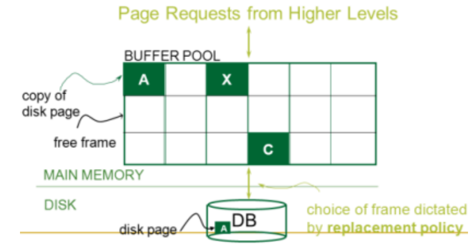
Assumptions

- Concurrency control is in effect.
  - Strict 2PL, in particular.
- Updates are happening “in place”.
  - i.e., data is overwritten on (deleted from) the disk.
- Atomic Writes: writing a page to disk is an atomic action.
  - In practice, additional details are needed to deal with non-atomic writes.



Buffer Management Policy Plays a Key Role

Crash Recovery



1、提交前写策略？

- Shall we allow "dirty pages" in the buffer pool caused by an Xact *T* to be written to disk before *T* commits?
  - If so, a second Xact *T'* can "steal" a frame from *T*. -偷帧 （提高并发度）
  - In contrast, No-Steal. （易实现UNDO ）

2、提交后不写策略？

- When an Xact *T* commits, must we ensure that all the "dirty pages" of *T* are immediately forced to disk?
  - If so, we say that a "force" approach is used. – 强制写 (易实现Durability)
  - In contrast, No-Force. 好处：降低IO开销（如：同一"脏页" 多次写）

Variants of Buffer Management Policy

1、提交前写策略？

（易实现UNDO ）　（提高并发度）

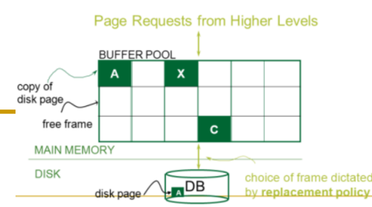
	No Steal	Steal
（降低IO开销） No Force		Fastest
2、提交后不写策略？ Force (易实现Durability)	Slowest	

Performance Implications

恢复策略？

	No Steal	Steal
No Force	No UNDO REDO	UNDO REDO
Force	No UNDO No REDO	UNDO No REDO

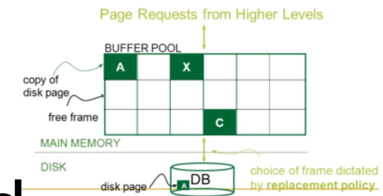
Logging/Recovery Implications



Preferred Policy: Steal/No-Force

1、提交前写策略（高并发）

2、提交后不写策略（低IO）



- STEAL (偷帧,why enforcing Atomicity is hard)
  - *To steal frame F: Current page in F (say P) is written to disk; some Xact holds lock on P.*
    - 问题:What if the Xact with the lock on P aborts?
    - 解决:Must remember the old value of P at steal time (to support UNDOing the write to page P).
- NO FORCE (非强制写,why enforcing Durability is hard)
  - 问题:What if system crashes before an updated page is written to disk?
  - 解决:Write as little as possible, in a convenient place, at commit time, to support REDOing modifications.

Basic Idea: Logging-写日志

- Record REDO and UNDO information, for every update, in a *log(日志)*.
  - Sequential writes to log (put it on a separate disk).
  - Minimal information (difference) written to log, so multiple updates fit in a single log page.
- Log: An ordered list of REDO/UNDO actions
  - Log record contains:

    <XID, pageID, offset, length, old data, new data>
  - and additional control info (which we'll see soon).

The Write-Ahead Logging (WAL) Protocol
先写日志

先写 UNDO action

#1 Must force the log record for an update to disk *before* the corresponding data page gets to disk.

- This rule helps guarantee Atomicity.
- This allows us to implement Steal policy.

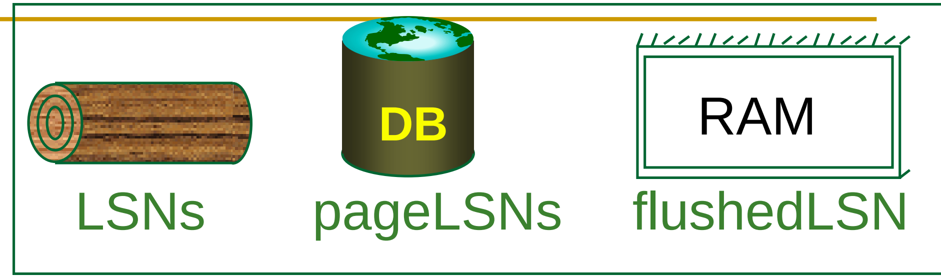
#2 Must write all log records for an Xact to disk *before commit*.

从实现角度定义"事务是否已提交？"

- I.e. transaction is not committed until all of its log records including its "commit" record are written to disk.
- This rule helps guarantee Durability.
- This allows us to implement No-Force policy.

- Exactly how is logging (and recovery!) done?
  - We'll look at the ARIES algorithms from IBM.

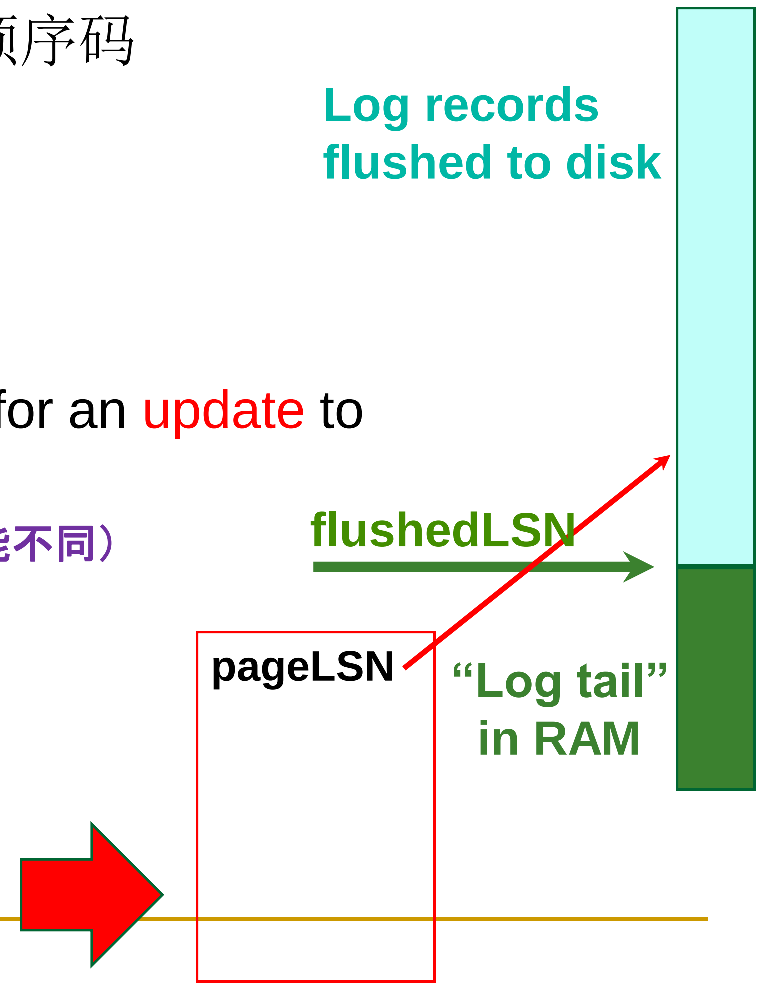
WAL & the Log



- Each log record has a unique Log Sequence Number (LSN). –日志顺序码 （使用LOG可以重构DB，即每个data page ）
  - LSNs is always increasing.
- System keeps track of flushedLSN.
  - The max LSN flushed so far.
- Each *data page* contains a pageLSN.
  - The LSN of the most recent *log record* for an update to that page.
    - 对应于LOG的某个状态，
    - 不同data page的对应状态可能不同）
- WAL: Before page i is written to disk, log must satisfy:

  $pageLSN_i \le flushedLSN$,

  i.e., the log record identified by pageLSN$_i$ must have been written to disk for page i is written to disk.



Log Records

LogRecord fields:

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

update records only

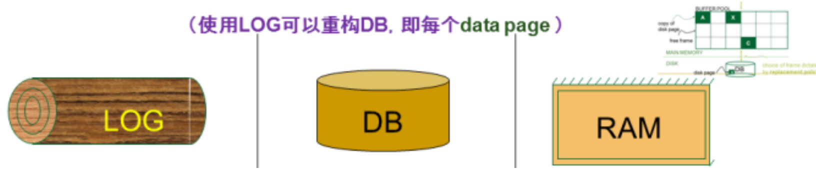
prevLSN is the LSN of the previous log record written by *this* Xact (so records of an Xact form a linked list backwards in time)

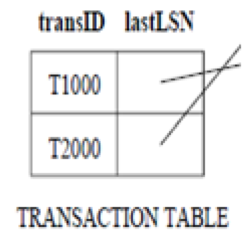
Possible log record types:

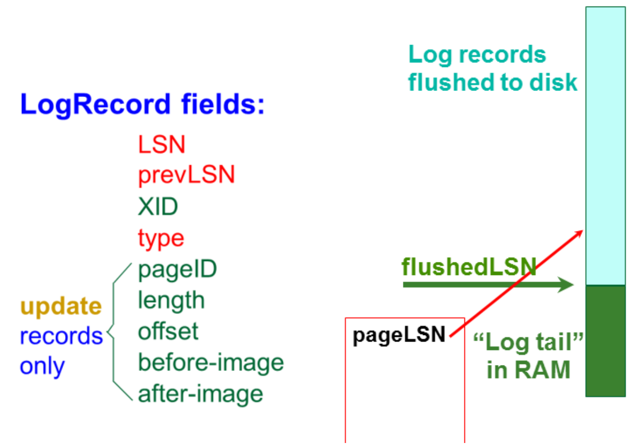
- Update, Commit, Abort
- Checkpoint (for log maintainence)
- Compensation Log Records (CLRs)
  - for UNDO actions
- End (end of commit or abort)

Other Log-Related Data Structures

（使用LOG可以重构DB，即每个data page）



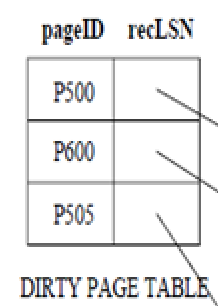




- Two in-memory tables:
- Transaction Table-事务表
  - One entry per currently active Xact.
    - entry removed when Xact commits or aborts
  - Contains XID, status (running/committing/aborting), lastLSN (most recent LSN written by Xact).

（反向链表，支持 UNDO）

- Dirty Page Table-脏页表:
  - 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. （顺序扫描，支持 REDO）



An Example

pageID	recLSN
P500	
P600	
P505	

DIRTY PAGE TABLE

transID	lastLSN
T1000	
T2000	

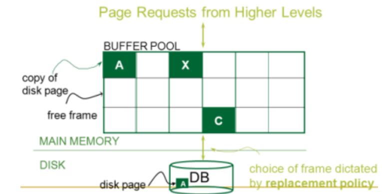
TRANSACTION TABLE

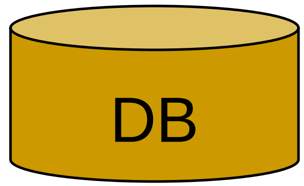
prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T1000	update	P500	3	21	ABC	DEF
	T2000	update	P600	3	41	HIJ	KLM
	T2000	update	P500	3	20	GDE	QRS
	T1000	update	P505	3	21	TUV	WXY

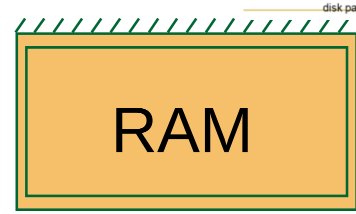
LOG

The Big Picture: What's Stored Where

（使用LOG可以重构DB，即每个data page ）

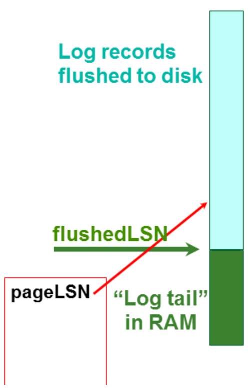






LogRecords

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



Data pages

each
with a
pageLSN

Master record

LSN
of most recent
checkpoint record

Xact Table

lastLSN
status

Dirty Page Table

recLSN

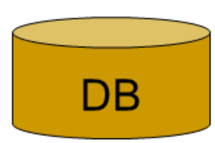
flushedLSN

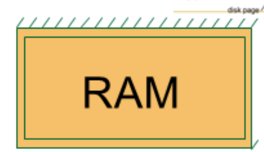
Normal Execution of an Xact

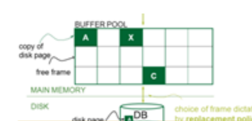
通过Log 实现崩溃恢复，要求事务的执行满足以下条件：

- Series of reads & writes, followed by commit or abort.
- Strict 2PL.
- STEAL, NO-FORCE buffer management, with Write-Ahead Logging.

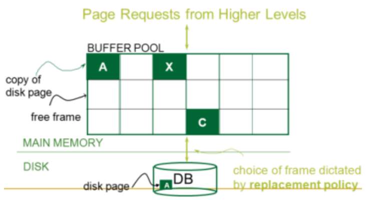
（使用LOG可以重构DB，即每个data page）

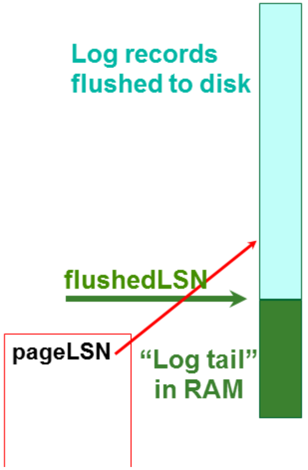






Transaction Commit





- Write *commit* record to log.
- All log records up to Xact's *commit record* are flushed to disk. 从实现角度定义“事务是否已提交？”
  - Guarantees that flushedLSN ≥ lastLSN.
  - Note that
    - log flushes are sequential, synchronous writes to disk.
    - Many log records per log page.
- Commit() returns.
- Write *end* record to log.

transID	lastLSN
T1000	
T2000	

TRANSACTION TABLE

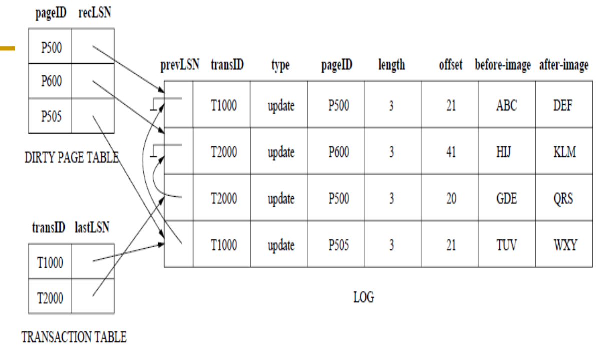
强制写日志的情况：

1. 事务提交
2. 偷帧
3. 页满？

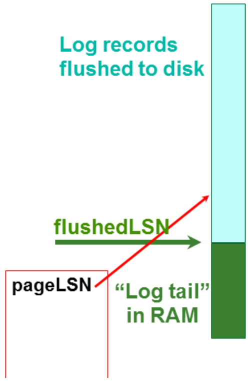
Possible log record types:

- Update, Commit, Abort
- Checkpoint (for log maintainence)
- Compensation Log Records (CLRs)
  - for UNDO actions
- End (end of commit or abort)

Simple Transaction Abort



- For now, consider an explicit abort of an Xact.
  - No crash involved.
- We want to "play back" the log in reverse order, UNDOing updates.
  - Get lastLSN of Xact from Xact table.
  - Write an *Abort* log record before starting to rollback operations
  - Can follow chain of log records backward via the prevLSN field. （反向链表，支持 UNDO）
  - Write a "CLR" (compensation log record-补偿日志记录) for each undone operation.



Abort, cont.

pageID	recLSN
P500	
P600	
P505	

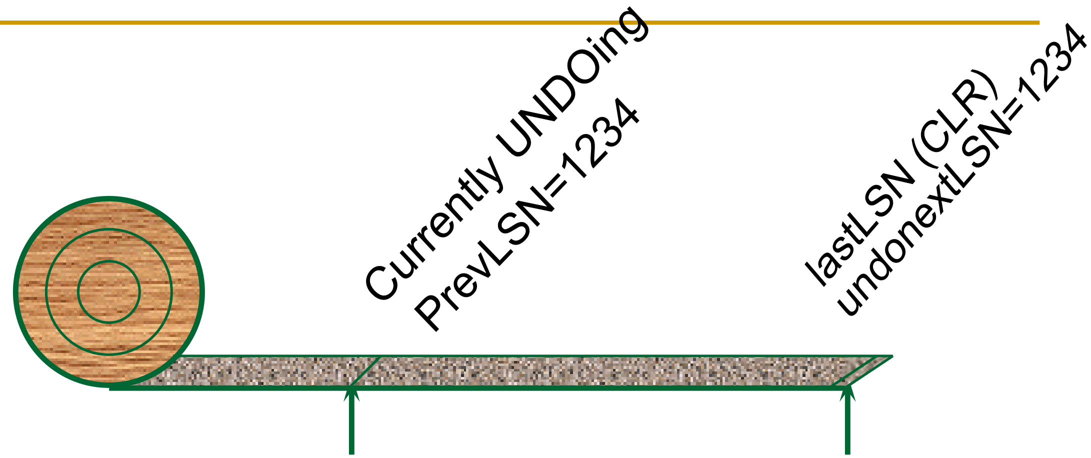
DIRTY PAGE TABLE

prevLSN	transID	type	pageID	length	offset	before-image	after-image
	T1000	update	P500	3	21	ABC	DEF
	T2000	update	P600	3	41	HIJ	KLM
	T2000	update	P500	3	20	GDE	QRS
	T1000	update	P505	3	21	TUV	WXY

LOG

transID	lastLSN
T1000	
T2000	

TRANSACTION TABLE

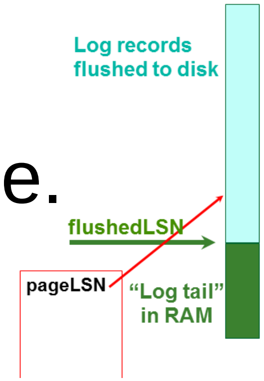


- To perform UNDO, must have a lock on data!
  - No problem! (原因:Strict 2PL.)

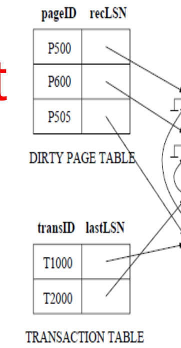
…, before-image, after-image

- Before restoring old value of a page, write a CLR:
  - You continue logging while you UNDO!!
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of the record we're currently undoing).
  - CLR contains REDO info
  - CLRs *never* Undone
    - Undo needn't be idempotent (>1 UNDO won't happen)
    - But they might be Redone when repeating history (=1 UNDO guaranteed)
- At end of all UNDOs, write an "end" log record.

Checkpointing-检查点

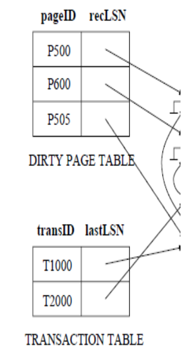


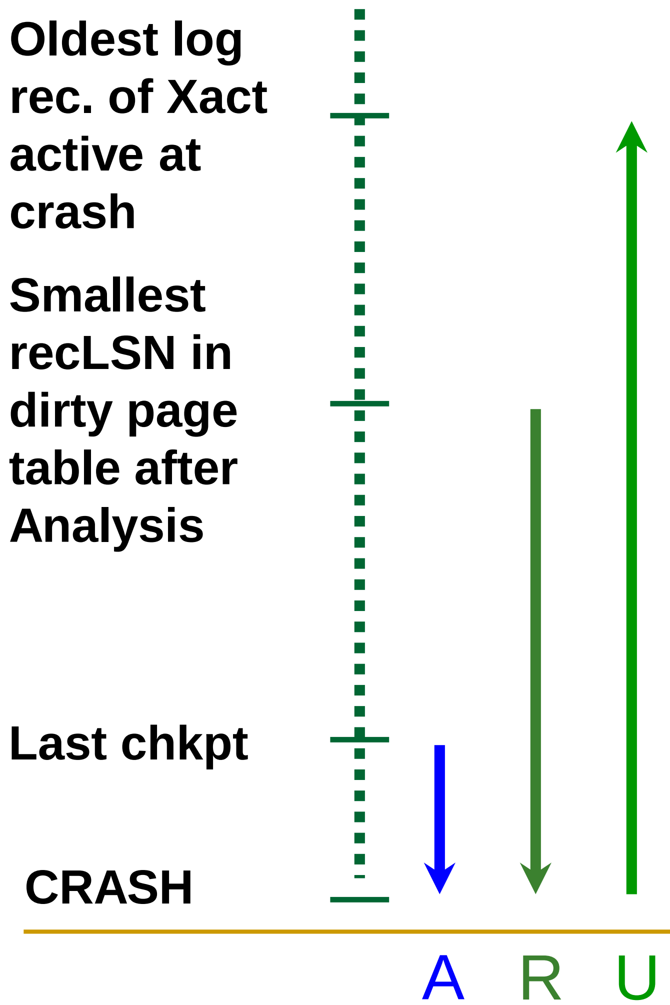
- Usually, we can not keep log around for all time.
- Periodically, the DBMS creates a checkpoint
  - Minimizes recovery time after crash.
  - Write to log:
    - begin_checkpoint record: Indicates when the checkpoint began.
    - end_checkpoint record: Contains current *Xact table* and *dirty page table*. A`fuzzy checkpoint'-模糊检查点:
      - 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.
  - Store LSN of most recent checkpoint record in a safe place (*master* record).



强制写日志的情况:
1. 事务提交
2. 偷帧
3. 页满?
4. 写 *master* record

Crash Recovery: Big Picture

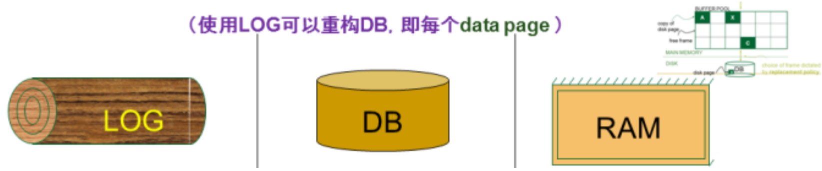




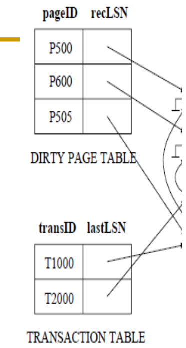
- ✓ Start from a checkpoint (found via master record).
- ✓ Three phases. Need to do:
  - – Analysis - Figure out which Xacts committed since checkpoint, which failed.
  - – REDO ***all*** actions.

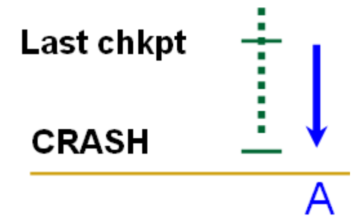
    (repeat history)
  - – UNDO effects of failed Xacts.

Recovery: The Analysis Phase

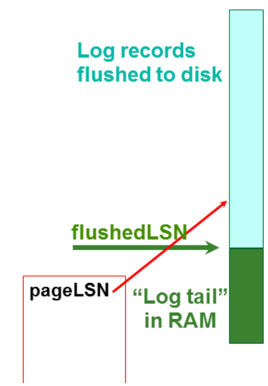


恢复事务表与脏页表





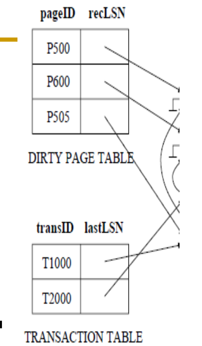
1. Re-establish knowledge of state at checkpoint.
   - via transaction table and dirty page table stored in the checkpoint
2. Scan log forward from the most recent checkpoint.
   - End record: Remove Xact from Xact table.
   - All Other records: Add Xact to Xact table, set lastLSN=LSN,
     - change Xact status on commit record.
     - also, for Update records: If page P not in Dirty Page Table (DPT), Add P to DPT, set its recLSN=LSN.



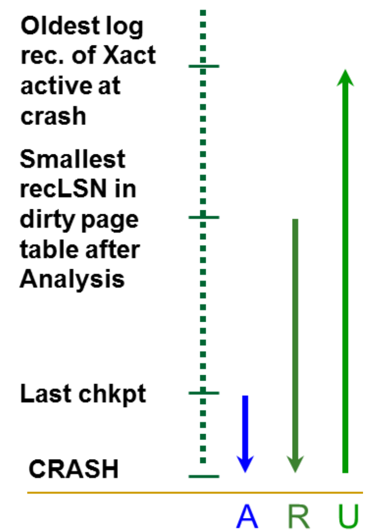
- At the end of Analysis…
  - Xact table says which xacts were active at time of crash.
  - DPT says which dirty pages *<u>might not</u>* have been written to disk.

Phase 2: The REDO Phase

恢复赃页



- We *Repeat History* to reconstruct state at crash:
  - Reapply *all* updates (even of aborted Xacts!), redo CLRs.
- Scan forward from log record containing smallest recLSN in DPT.
- For each update log record or CLR with a given LSN, REDO the action <u>unless</u>:
  - Affected page is not in the DPT, or
  - Affected page is in DPT, but has
    - recLSN > LSN, or
    - pageLSN (in DB) ≥ LSN. (this last case requires I/O)
- To REDO an action:
  - Reapply logged action.
  - Set pageLSN to LSN. No additional logging, no forcing!



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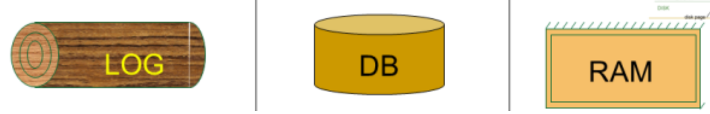
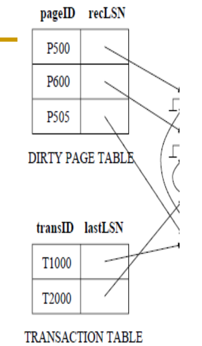
Phase 3: The UNDO Phase

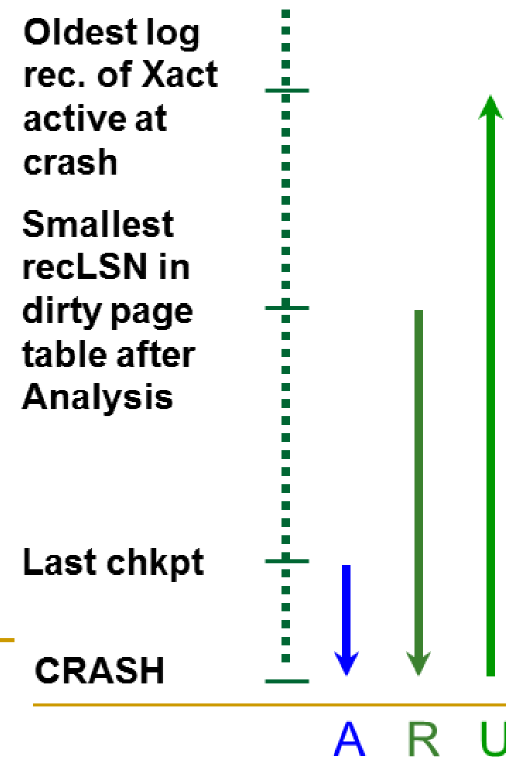
UNDO未完成事务

（使用LOG可以重构DB，即每个data page）

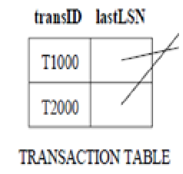


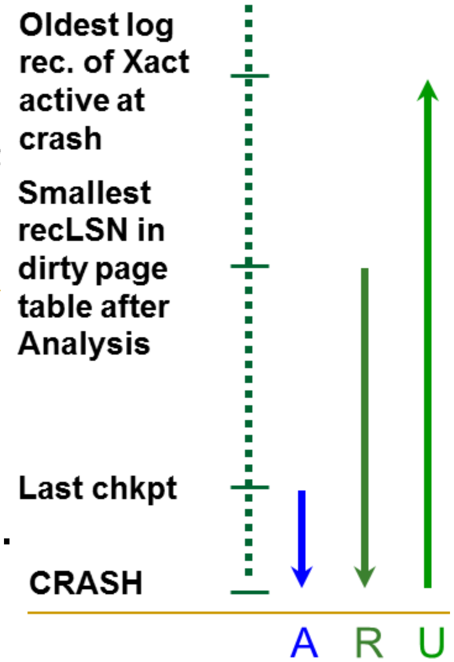


- A Naïve solution:
  - The xacts in the Xact Table are losers(失败事务).
  - For each loser, perform simple transaction abort.
  - Problems?



Phase 3: The UNDO Phase





ToUndo={lastLSNs of all Xacts in the Xact Table}
a.k.a. "losers"

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.

…, before-image, after-image

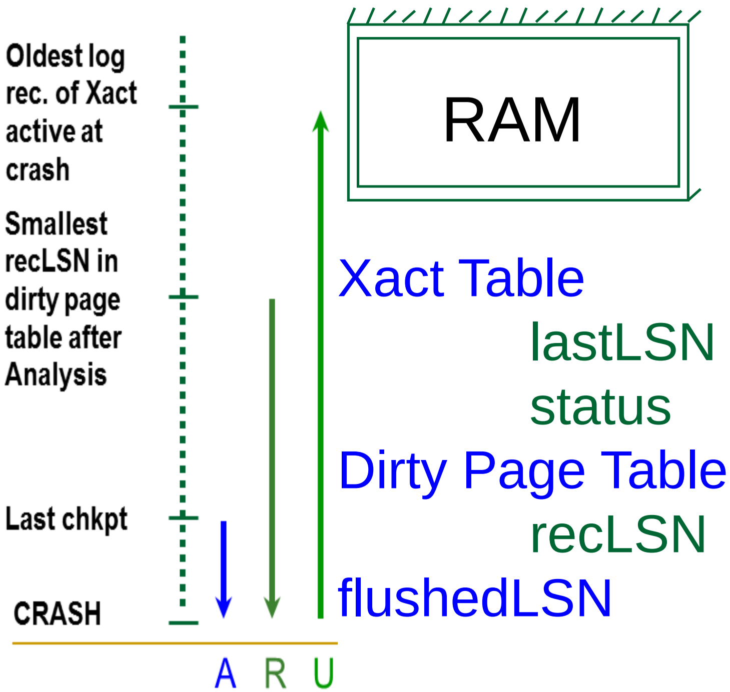
Until ToUndo is empty.

NOTE: This is simply a performance optimization on the naïve solution to do it in one backwards pass of the log!

Example of Recovery

脏页表	
pageID	recLSN
P5	10
P3	20
P1	50

事务表	
transID	lastLSN
T1	40
T2	60
T3	50



ToUndo

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

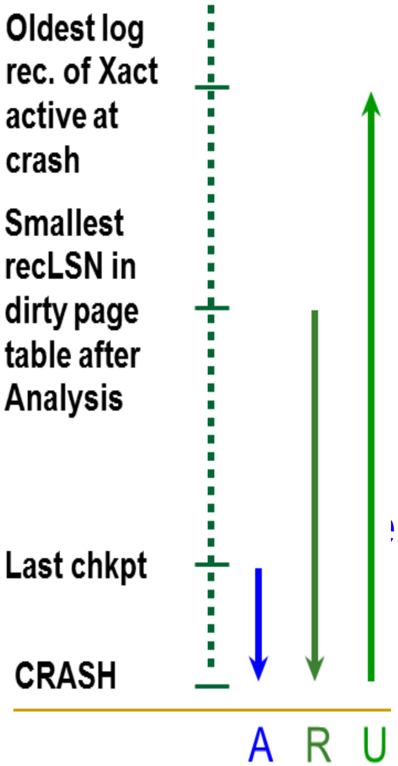
Example:
Crash During Restart!

脏页表

pageID	recLSN
P5	10
P3	20
P1	50

事务表

transID	lastLSN
T1	40
T2	70
T3	80



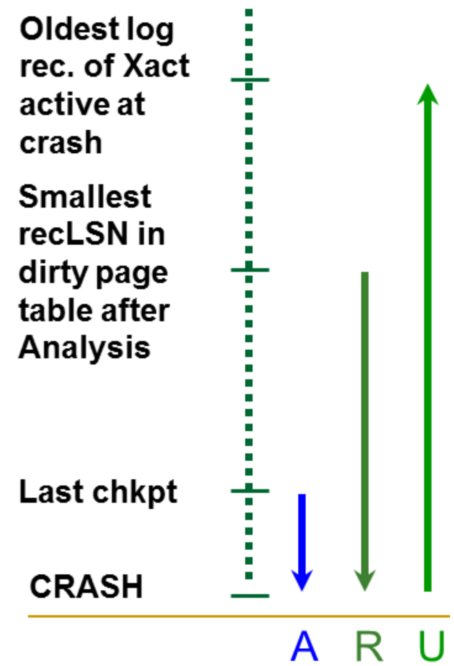
ToUndo

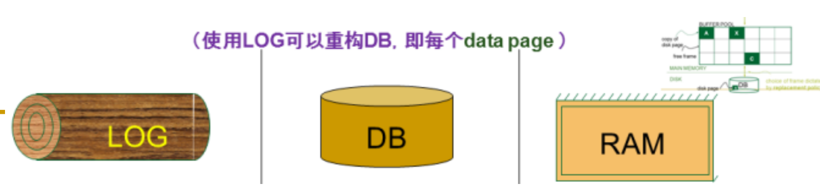
LSN	LOG
00,05	begin_checkpoint, end_checkpoint
10	update: T1 writes P5
20	update T2 writes P3
30	T1 abort
40,45	CLR: Undo T1 LSN 10, T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART
70	CLR: Undo T2 LSN 60
80,85	CLR: Undo T3 LSN 50, T3 end
	CRASH, RESTART
90	CLR: Undo T2 LSN 20, T2 end

undonextLSN

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.





1、恢复事务表与脏页表
2、恢复赃页
3、UNDO未完成事务

Summary of Logging/Recovery

- Recovery Manager guarantees Atomicity & Durability.
- Use WAL to allow STEAL/NO-FORCE w/o sacrificing correctness.
- LSNs identify log records; linked into backwards chains per transaction (via prevLSN).
- pageLSN allows comparison of data page and log records.

Summary (Contd.)

- Checkpointing: A quick way to limit the amount of log to scan on recovery.
- Recovery works in 3 phases:
  - Analysis: Forward from checkpoint.
  - Redo: Forward from oldest recLSN.
  - Undo: Backward from end to first LSN of oldest Xact alive at crash.
- Upon Undo, write CLRs.
- Redo “repeats history”: Simplifies the logic!

Summary

- 要求:
  - 理解Crash Recovery的3个阶段算法，相应的例子
  - 能够根据给定日志进行崩溃恢复，即
    - 恢复事务表、脏页表
    - 为日志添加因UNDO而生成的CLR和END日志记录