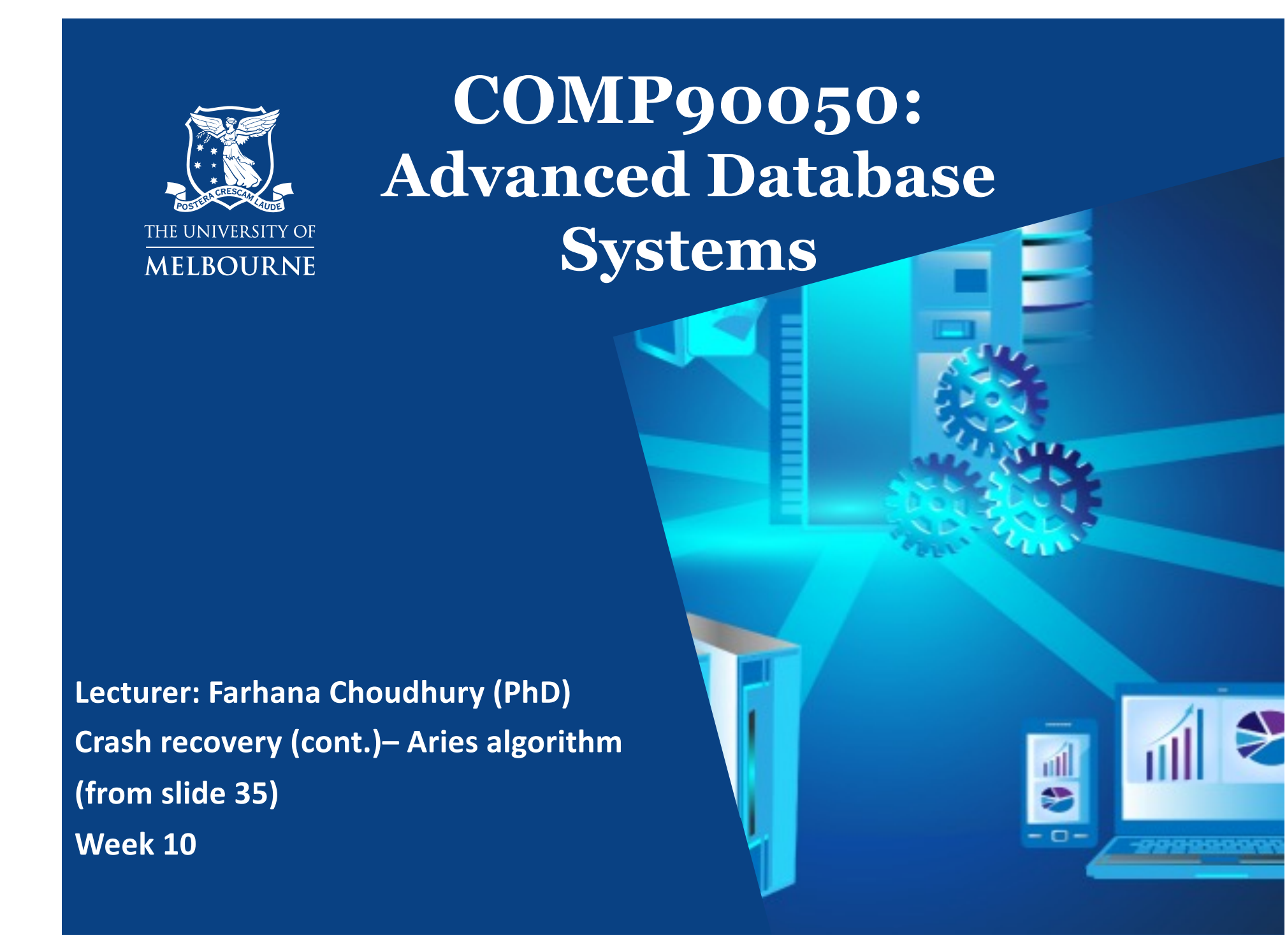


COMP90050: Advanced Database Systems

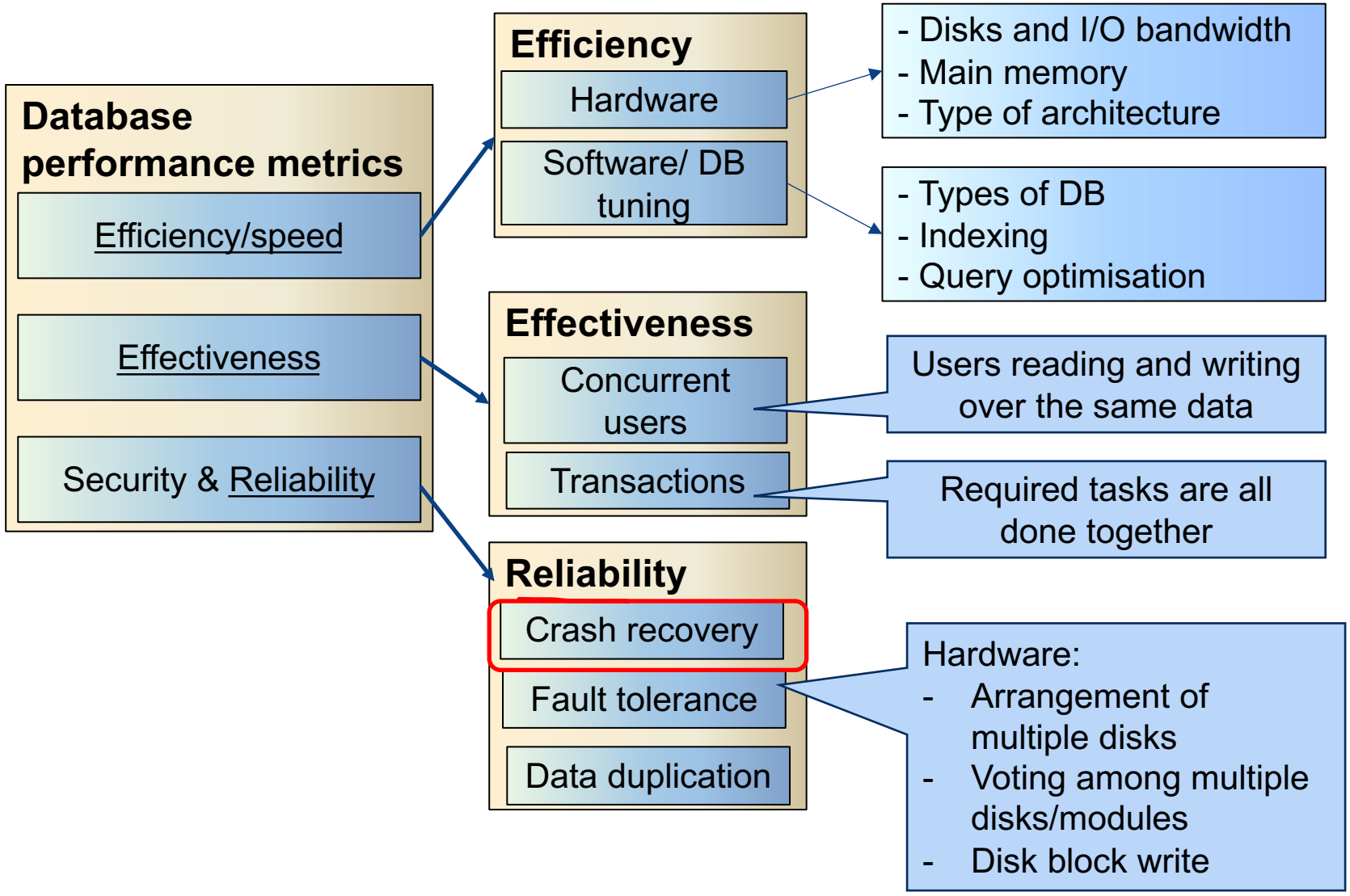
Lecturer: Farhana Choudhury (PhD)

Crash recovery (cont.)– Aries algorithm

(from slide 35)

Week 10

Core Concepts of Database management system



Crash recovery

Recover from a failure either when a single-instance database crashes or all instances crash.

Crash recovery is the process by which the database is moved back to a consistent and usable state after a crash. This is done by making the committed transactions durable and rolling back incomplete transactions.

*The following slides are from Berkeley, Hammoud and Wang with modifications - http://redbook.cs.berkeley.edu/redbook3/**aries**/**aries**.ppt*

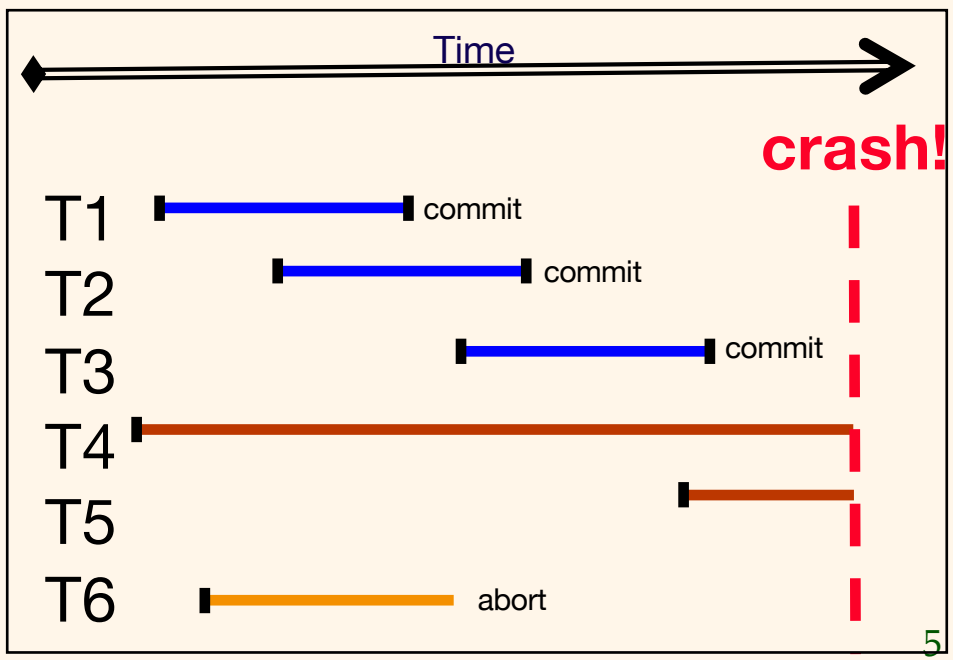
Review: The ACID properties

- **A**tomicity: All actions in the Xact happen, or none happen.
- **C**onsistency: If each Xact is consistent, and the DB starts consistent, it ends up consistent.
- **I**solation: Execution of one Xact is isolated from that of other Xacts.
- **D**urability: If a Xact commits, its effects persist.

- The Recovery Manager guarantees Atomicity & Durability.

Motivation

- Atomicity:
  - Transactions may abort ("Rollback"). E.g. T6
- Durability:
  - What if DBMS stops running? (Causes?)
- Desired Behavior after system restarts:
  - T1, T2 & T3 should be durable as they are committed before the crash.
  - T4, T5, T6 should be aborted (effects not seen).



Assumptions

- Concurrency control is in effect.
  - Strict 2PL (Two Phase Locking), in particular.
- Updates are happening “in place”.
  - i.e. data is overwritten on (deleted from) the disk.
- A simple scheme to guarantee Atomicity & Durability?

Buffer Caches (pool)

1. Data is stored on disks
2. Reading a data item requires reading the whole page of data (typically 4K or 8K bytes of data depending on the page size) from disk to memory containing the item.
3. Modifying a data item requires reading the whole page from disk to memory containing the item, modifying the item in memory and writing the whole page to disk.
4. Steps 2 & 3 can be very expensive and we can minimize the number of disk reads and writes by storing as many disk pages as possible in memory (buffer cache) – this means always check in buffer cache for the disk page of interest if not copy the associated page to buffer cache and perform the necessary operation.
5. When buffer cache is full we need to evict some pages from the buffer cache in order fetch the required pages from the disk .

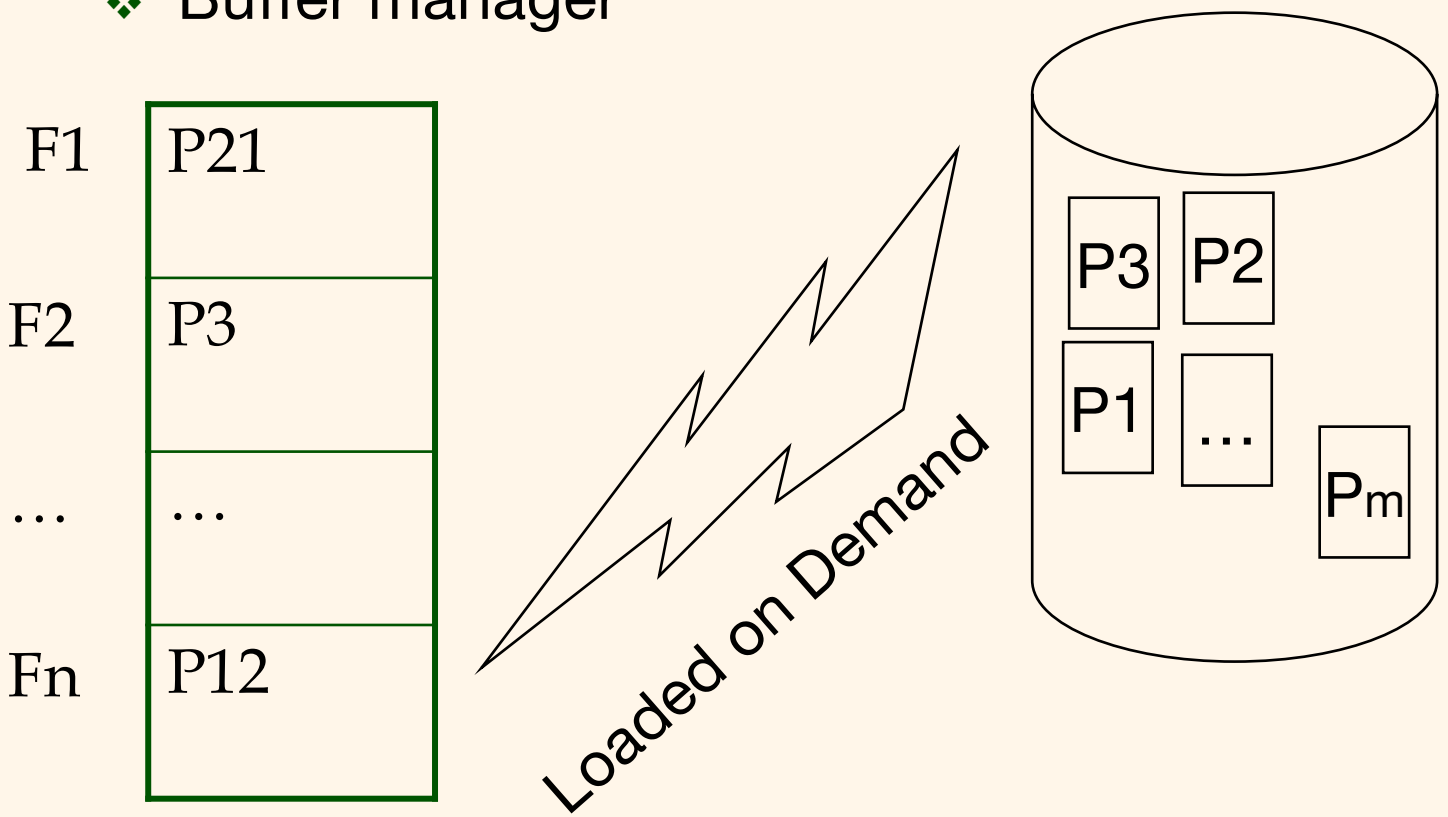
Buffer Caches (pool)

6. **Eviction needs to make sure that no one else is using the page and any modified pages should be copied to the disk.**
7. Since several transactions are executing concurrently this requires additional locking procedures using latches. These latches are used only for the duration of the operation (e.g. READ/WRITE) and can be released immediately unlike record locks which have to be kept locked until the end of the transaction.

- fix(pageid)
  - reads pages from disk into the buffer cache if it is not already in the buffer cache
  - fixed pages cannot be dropped from the buffer cache as transactions are accessing the contents
- unfix(pageid)
  - The page is not in use by the transaction and can be evicted as far as the unfix calling transaction is concerned. (We need to check to see that no one else wants the page before it can be evicted)

Main components of a Database System

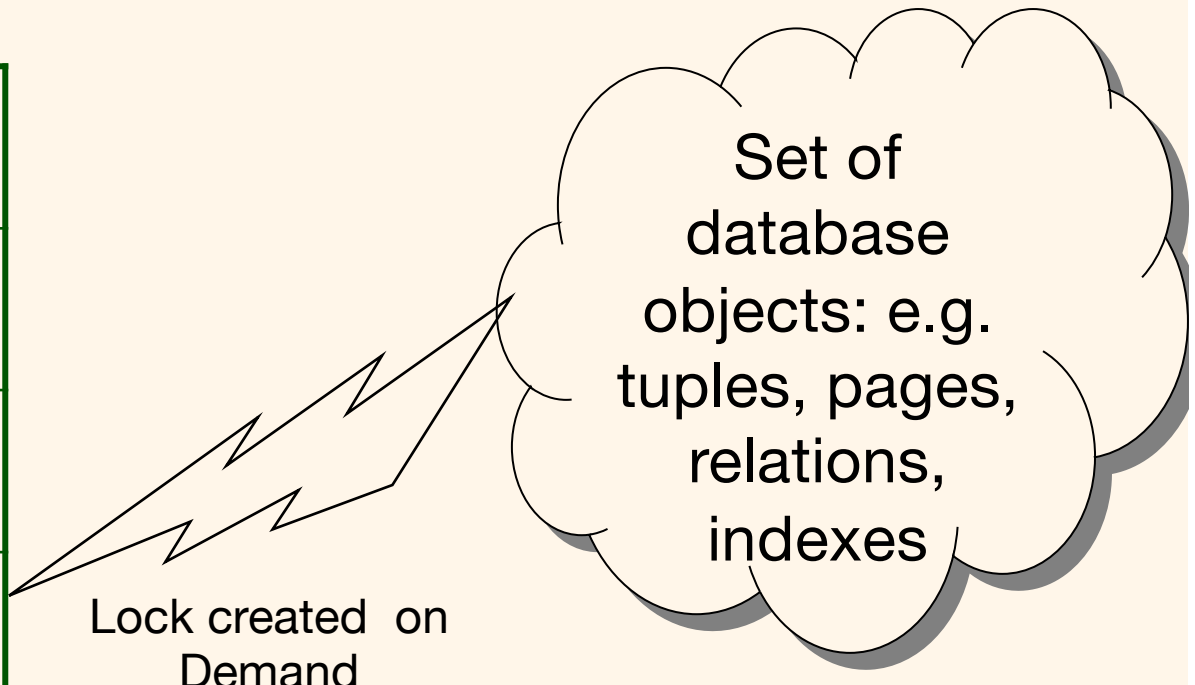
- Buffer manager



Main components of a Database System

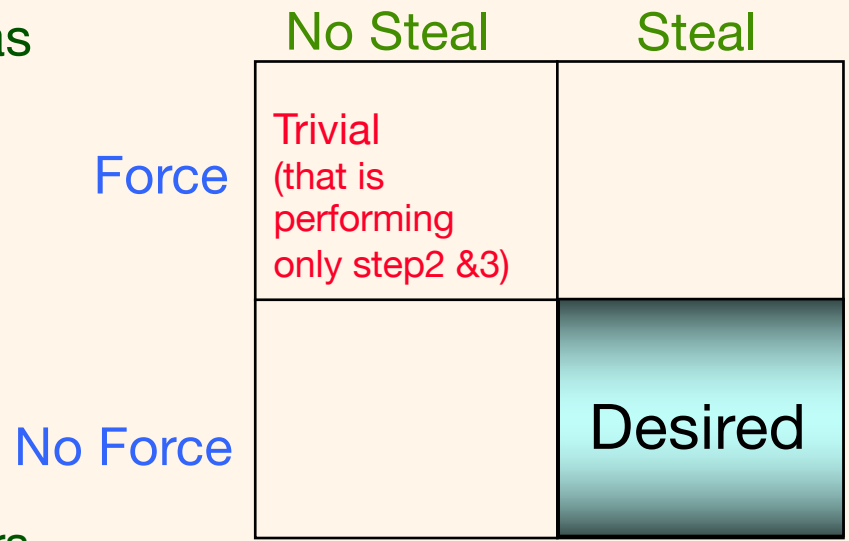
Lock manager

Object Id	Ref to lock details
Tuple A	
…	
Relation X	
Page P7	



Handling the Buffer Pool (cache)

- Force write to disk at commit?
  - Poor response time.
  - But provides durability.
- NO Force leave pages in memory as long as possible even after commit without modifying the data on the disk.
  - Improves response time and efficiency as many reads and updates can take place in main memory rather than on disk.
  - Durability becomes a problem as update may be lost if a crash occurs
- Steal buffer-pool frames from uncommitted Xacts?
  - If not, poor throughput.
  - If so, how can we ensure atomicity?



That is a page modified by a transaction is written to disk but the transaction decides to abort!

More on Steal and Force

- STEAL (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.
    - What if the Xact with the lock on P aborts?
    - Must remember the old value of P at steal time (to support UNDOing the write to page P).
- NO FORCE (why enforcing Durability is hard)
  - What if system crashes before a modified page is written to disk?
  - Write as little as possible, in a convenient place, at commit time, to support REDOing modifications.

Basic Idea: Logging

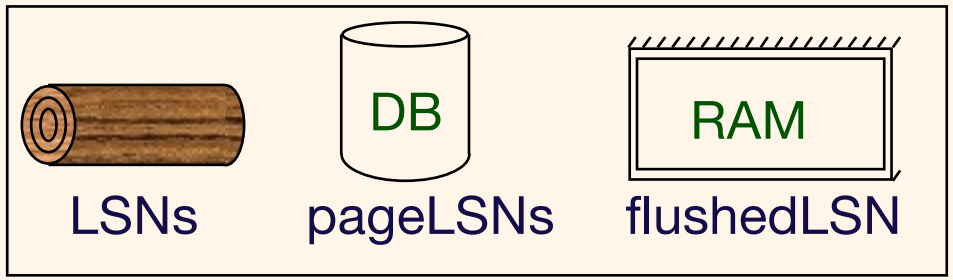
- Record REDO (new value) and UNDO (old value) information, for every update, in a *log.*
  - Sequential writes to log (put it on a separate disk).
  - Minimal info (diff) written to log, so multiple updates fit in a single log page.
- Log: An ordered list of REDO/UNDO actions
  - Log record contains:

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

Write-Ahead Logging (WAL)

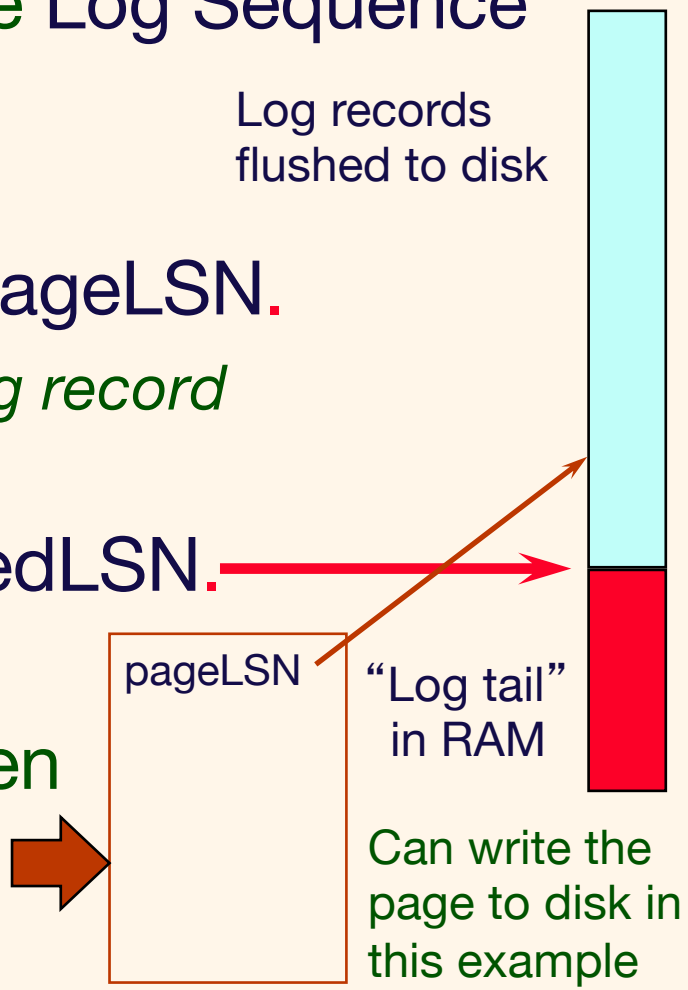
- The Write-Ahead Logging Protocol:
  1. Must force the log record which has both old and new values for an update *before* the corresponding data page gets to disk (stolen).
  2. Must write all log records to disk (force) for a Xact *before commit*.
- 1. guarantees Atomicity because we can undo updates performed by aborted transactions and redo those updates of committed transactions.
- 2. guarantees Durability.
- Exactly how is logging (and recovery!) done?
  - We study the ARIES algorithms.

WAL & the Log

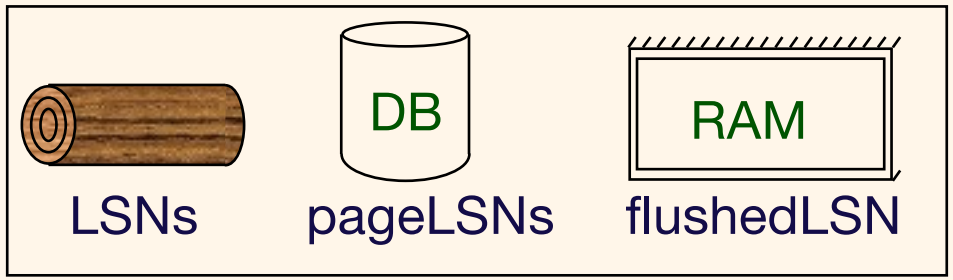


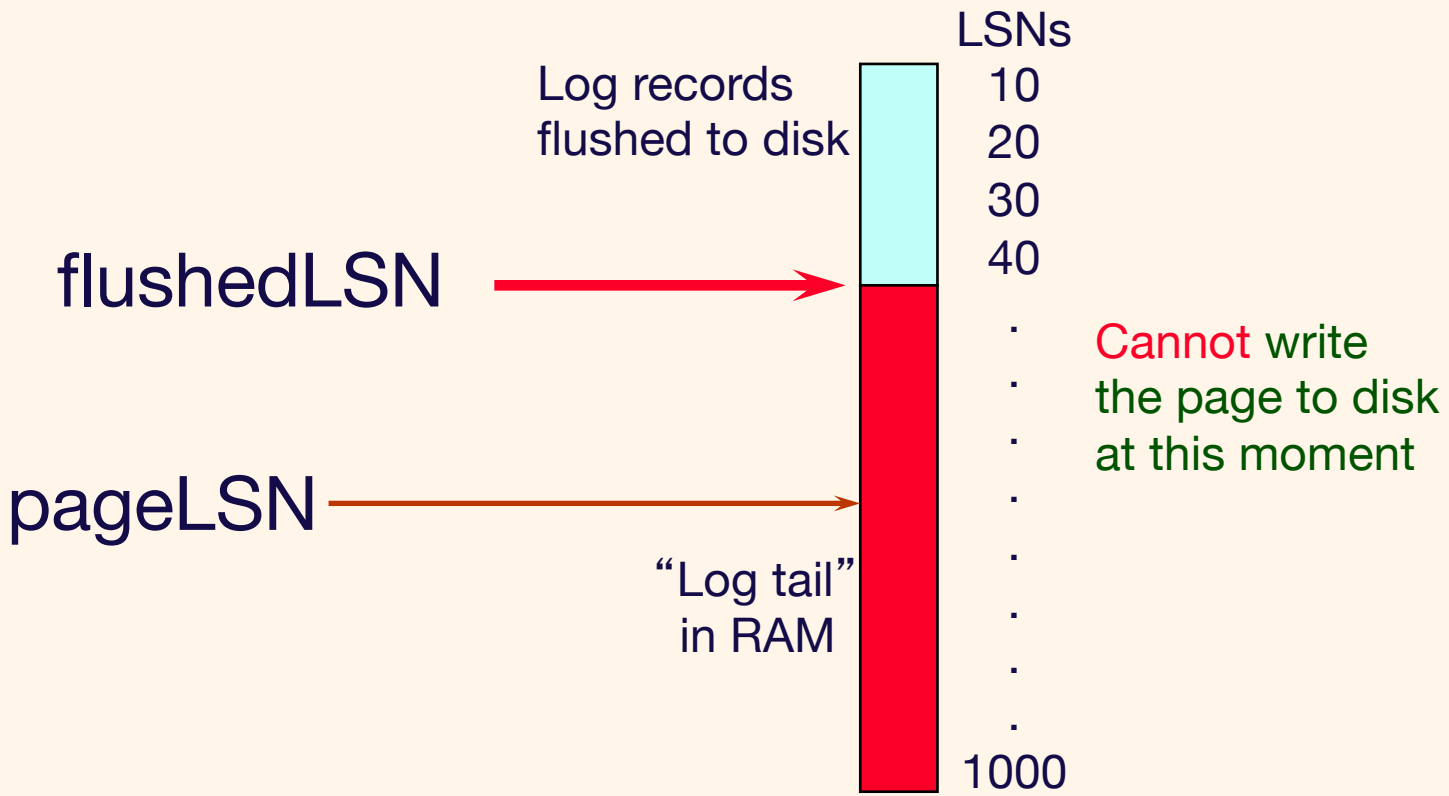
- Each log record has a unique Log Sequence Number (LSN).
  - LSNs always increasing.
- Each *data page* contains a pageLSN.
  - The LSN of the most recent *log record* for an update to that page.
- System keeps track of flushedLSN.
  - The max LSN flushed so far.
- WAL: *Before* a page is written to disk make sure

  pageLSN <= flushedLSN

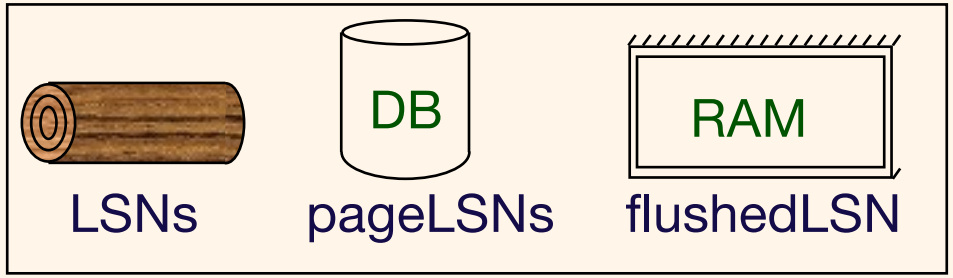


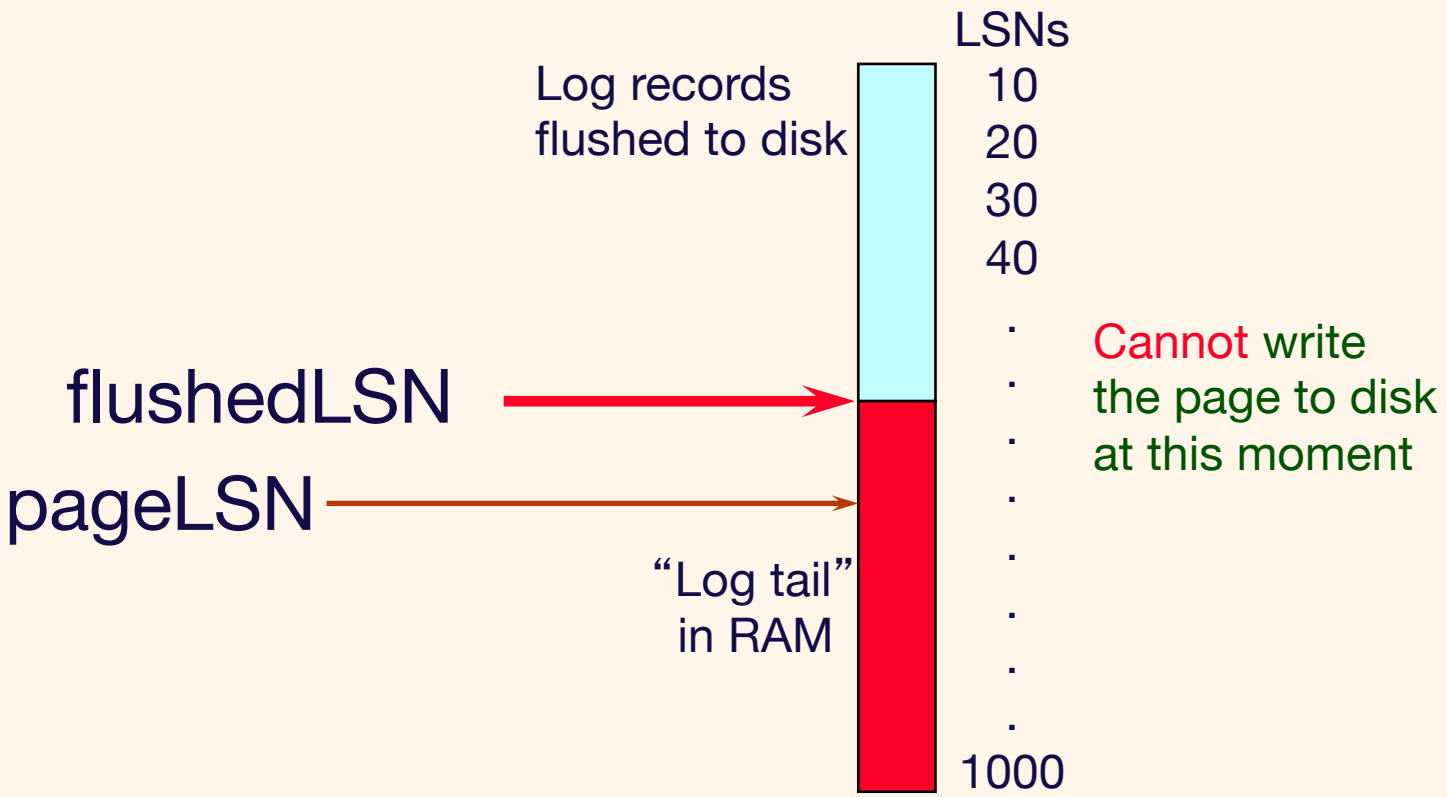
WAL & the Log


DB
RAM
LSNs
pageLSNs
flushedLSN


LSNs
Log records
flushed to disk
10
20
30
40
flushedLSN
pageLSN
Cannot write
the page to disk
at this moment
"Log tail"
in RAM
1000

WAL & the Log


DB
RAM
LSNs
pageLSNs
flushedLSN


LSNs
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the page to disk
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"Log tail"
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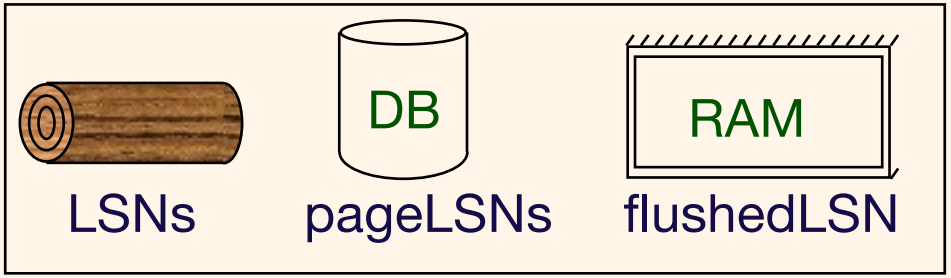
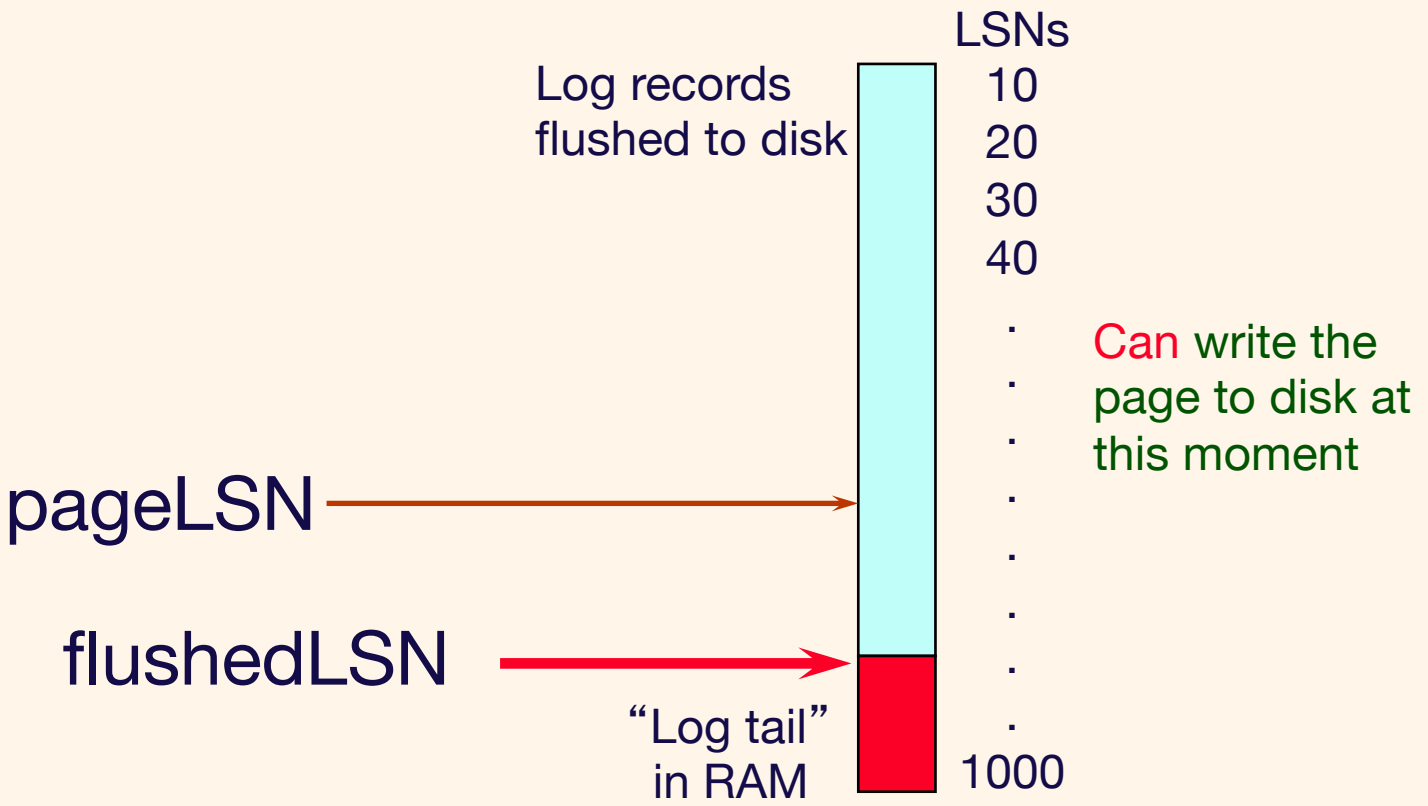
WAL & the Log


DB
RAM
LSNs
pageLSNs
flushedLSN


LSNs
Log records
flushed to disk
10
20
30
40
Can write the
page to disk at
this moment
pageLSN
flushedLSN
"Log tail"
in RAM
1000

Log Records

LogRecord fields:

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

update records only

Possible log record types:

- Update
- Commit
- Abort
- End (signifies end of commit or abort)
- Compensation Log Records (CLRs)
  - for UNDO actions

Other Log-Related State

- Transaction Table:
  - One entry per active Xact.
  - Contains XID, status (running/committed/aborted), and lastLSN.
- Dirty Page Table:
  - One entry per dirty page in buffer pool.
  - Contains recLSN -- the LSN of the log record which *first* caused the page to be dirty since loaded into the buffer cache from the disk.

Instance of Log, Transaction and Page tables

Dirty Page table

Page #	**Oldest LSN (Recent LSN)**

X-table

Xid	**Status**	**Last LSN**

Log

Prev LSN	Tid	Type	Page	Length	Offset	Old Value	New Value

Instance of Log, Transaction and Page tables

Dirty Page table

Page #	Oldest LSN (Recent LSN)
P5	

X-table

Xid	Status	Last LSN
T1	R	

Log

Prev LSN	Tid	Type	Page	Length	Offset	Old Value	New Value
	T1	U	p5	4	20	abcd	ABCD

Instance of Log, Transaction and Page tables

Dirty Page table

Page #	Oldest LSN (Recent LSN)
P5	
P6	

X-table

Xid	Status	Last LSN
T1	R	
T2	R	

Log

Prev LSN	Tid	Type	Page	Length	Offset	Old Value	New Value
	T1	U	p5	4	20	abcd	ABCD
	T2	U	p6	4	40	efgh	EFGH

Instance of Log, Transaction and Page tables

Dirty Page table

Page #	Oldest LSN (Recent LSN)
P5	
P6	

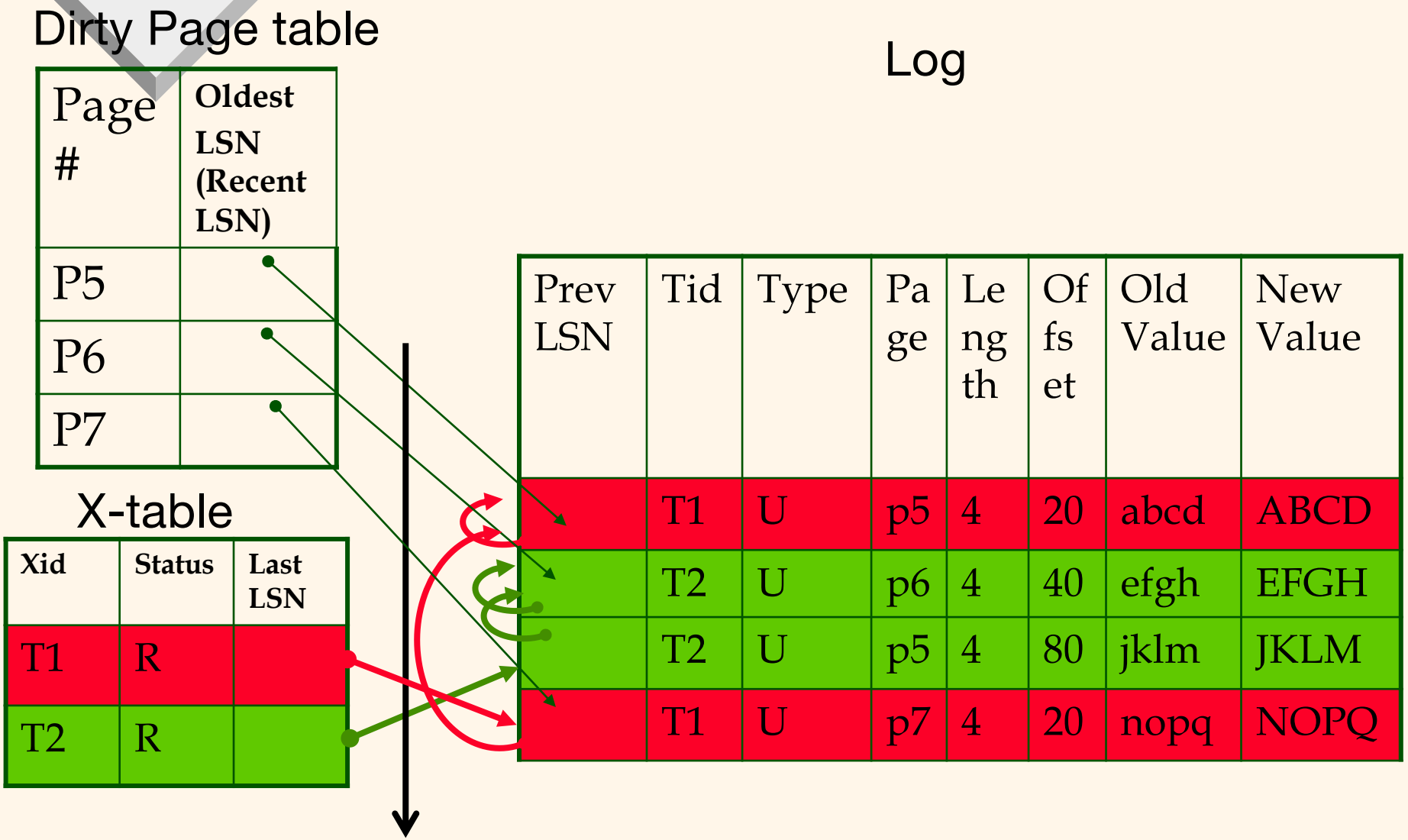
X-table

Xid	Status	Last LSN
T1	R	
T2	R	

Log

Prev LSN	Tid	Type	Page	Length	Offset	Old Value	New Value
	T1	U	p5	4	20	abcd	ABCD
	T2	U	p6	4	40	efgh	EFGH
	T2	U	p5	4	80	jklm	JKLM

Instance of Log, Transaction and Page tables



Normal Execution of an Xact

- Series of reads & writes, followed by commit or abort.
  - We will assume that write is atomic on disk.
    - In practice, additional details to deal with non-atomic writes. We discussed how we do this earlier.
- Strict 2PL.
- STEAL, NO-FORCE buffer management, with Write-Ahead Logging.

Checkpointing

- Periodically, the DBMS creates a checkpoint, in order to minimize the time taken to recover in the event of a system crash. Write to log:
  - Begin checkpoint record: Indicates when chkpt began.
  - 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 is limited by the oldest unwritten change to a dirty page. (So it's a good idea to periodically flush dirty pages to disk!)
  - Store LSN of chkpt record in a safe place (*master* record).

The Big Picture: What's Stored Where

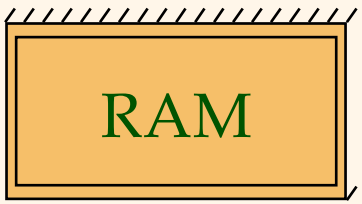
LogRecords

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

master record

Data pages

each
with a
pageLSN



Xact Table

lastLSN
status

Dirty Page Table

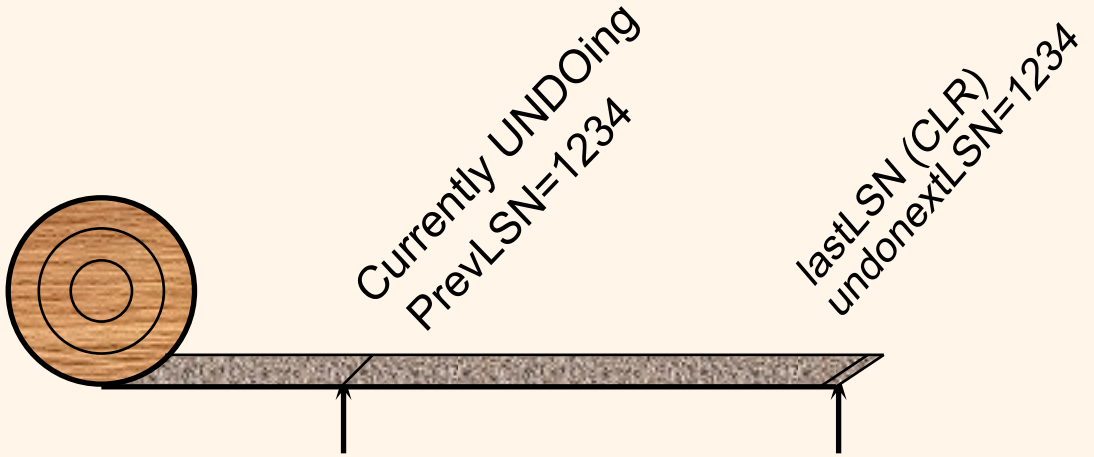
recLSN

flushedLSN

Simple Transaction Abort

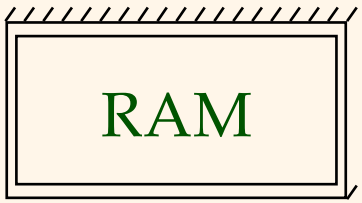
- For now, consider an explicit abort of a Xact.
  - No crash involved.
- We want to "play back" the log in reverse order, UNDOing updates.
  - Get lastLSN of Xact from Xact table.
  - Can follow chain of log records backward via the prevLSN field.
  - Before starting UNDO, write an *Abort* log record.
    - For recovering from crash during UNDO!

Abort, cont.



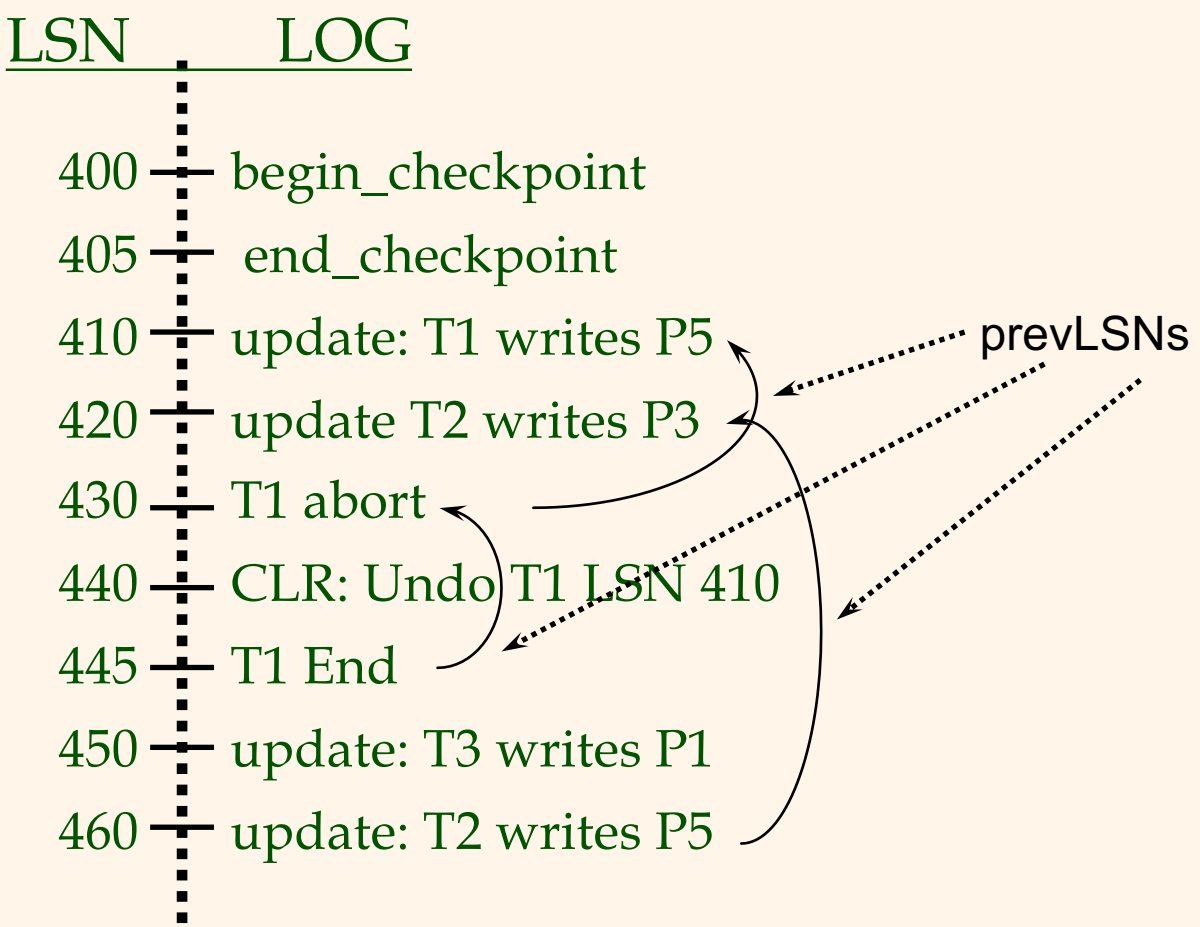
- To perform UNDO, must have a lock on data!
  - No problem!
- Before restoring old value of a page, write a CLR (Compensation Log Record):
  - You continue logging while you UNDO!!
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of the record we're currently undoing).
  - CLRs *never* Undone (but they might be Redone when repeating history: guarantees Atomicity!)
- At end of UNDO, write an "end" log record.

Example of Transaction Abort



Xact Table
lastLSN
status
Dirty Page Table
recLSN
flushedLSN

ToUndo



Transaction Commit

- Write commit record to log.
- All log records up to Xact's lastLSN are flushed.
  - Guarantees that flushedLSN ≥ lastLSN.
  - Note that log flushes are sequential, synchronous writes to disk – (very fast writes to disk).
  - Many log records per log page – (very efficient due to multiple writes).
- Commit() returns.
- Write end record to log.

Instance of Log, Transaction and Page tables

Dirty Page table

Page #	Oldest LSN (Recent LSN)
P5	
P6	
P7	

X-table

Xid	Status	Last LSN
T1	R	
T2	R	

Log

PrevLSN	Tid	Type	Page	Length	Offset	Old Value	New Value
	T1	U	p5	4	20	abcd	ABCD
	T2	U	p6	4	40	efgh	EFGH
	T2	U	p5	4	80	jklm	JKLM
	T1	U	p7	4	20	nopq	NOPQ
	T2	Commit					

We have to flush the log to this point because of commit of T2 and making T2 durable.

Instance of Log, Transaction and Page tables

Dirty Page table

Page #	Oldest LSN (Recent LSN)
P5	
P6	
P7	

X-table

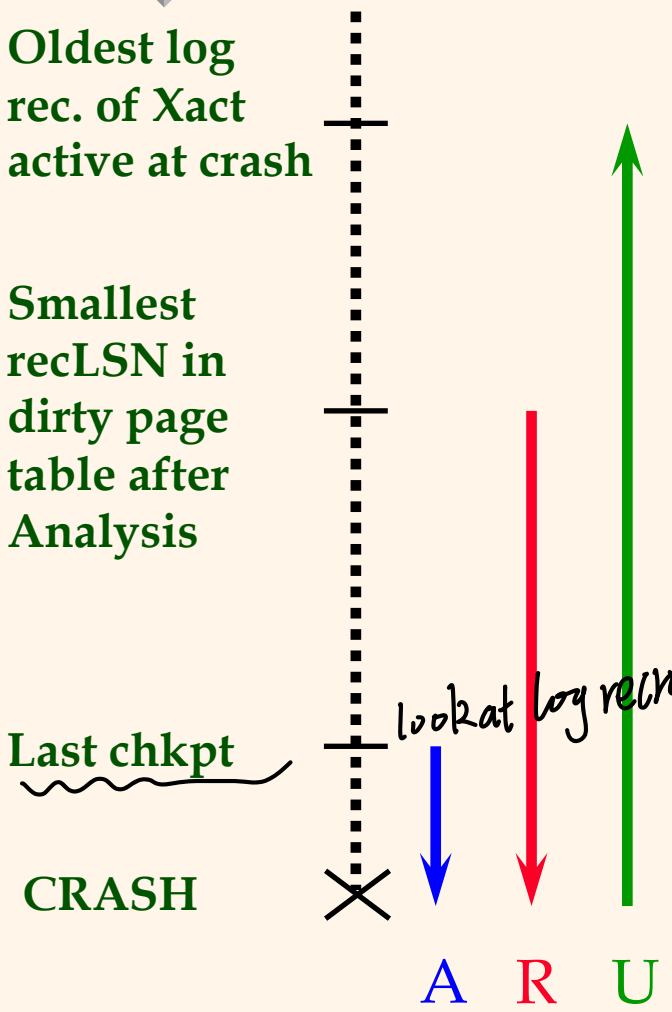
Xid	Status	Last LSN
T1	R	

Log

PrevLSN	Tid	Type	Page	Length	Offset	Old Value	New Value
	T1	U	p5	4	20	abcd	ABCD
	T2	U	p6	4	40	efgh	EFGH
	T2	U	p5	4	80	jklm	JKLM
	T1	U	p7	4	20	nopq	NOPQ
	T2	Commit					

We have to flush the log to this point because of commit of T2 and making T2 durable.

Crash Recovery: Big Picture



crash recovery make sure durability and atomicity maintains.

- Start from a checkpoint (found via master record).
- Three phases. Need to:
  - Figure out which Xacts committed since checkpoint, which failed (Analysis).
  - REDO *all* actions.
    - (repeat history)
  - UNDO effects of failed Xacts.

look at log records at checkpoint this

Recovery: The Analysis Phase

system creats checkpoints for durable storage from time to time (checkpoints: store what was the transaction table and dirty page table information at that time of that checkpoint)

- Reconstruct state at checkpoint.
  - via end_checkpoint record.
- Scan log forward from checkpoint.
  - End record: Remove Xact from Xact table.
  - Other records: Add Xact to Xact table, set lastLSN=LSN, change Xact status on commit.
  - Update record: If P not in Dirty Page Table,
    - Add P to D.P.T., set its recLSN=LSN.

The transaction has committed if it has end record.

X-table

Xid	Status	Last LSN
T1	R	
T2	R	

Dirty Page table

Page #	Oldest LSN (Recent LSN)
P5	
P6	
P7	

If an action done on particular page ⇒ that page is not in the dirty table ⇒ add that page id to the dirty page table ⇒ set the oldest LSN = LSN

Recovery: The REDO Phase

- We *repeat History* to reconstruct state at crash:
  - Reapply *all* updates (even of aborted Xacts!), redo CLRs.
- Scan forward from log rec containing smallest recLSN in D.P.T. For each CLR or update log rec 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) ≥ LSN.
- To REDO an action:
  - Reapply logged action.
  - Set pageLSN to LSN. No additional logging!

redo all the the actions by following the log records
get same situation for the pages and transactions (doesn't matter it is aborted or running)
가장 작은 recLSN 찾기 in dirty page table
the page has been evicted before crush
all the changes in that page are made durable.

Affected page is not in the Dirty Page Table, or

If a page is removed from DPT all logs are flushed for eviction => written back to disk => not in dirty page table

It's safe to not redo the action because all those actions that are done on that particular page already made durable before crash happen

Affected page is in D.P.T., but has recLSN > LSN,

Dirty page table LSN # < ~~LSN~~ recLSN
(the smallest one) in D.P.T

Recovery: The UNDO Phase

ToUndo={ *l* | *l* is a lastLSN of a "loser" Xact}

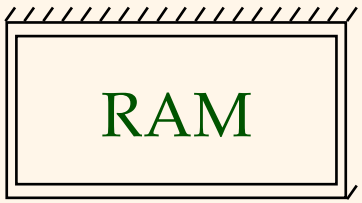
We can form this list from Xtable.

Repeat:

- Choose the 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
  - (Q: what happens to other CLRs?)
- Else this LSN is an update. Undo the update, write a CLR, add prevLSN to ToUndo.

Until ToUndo is empty.

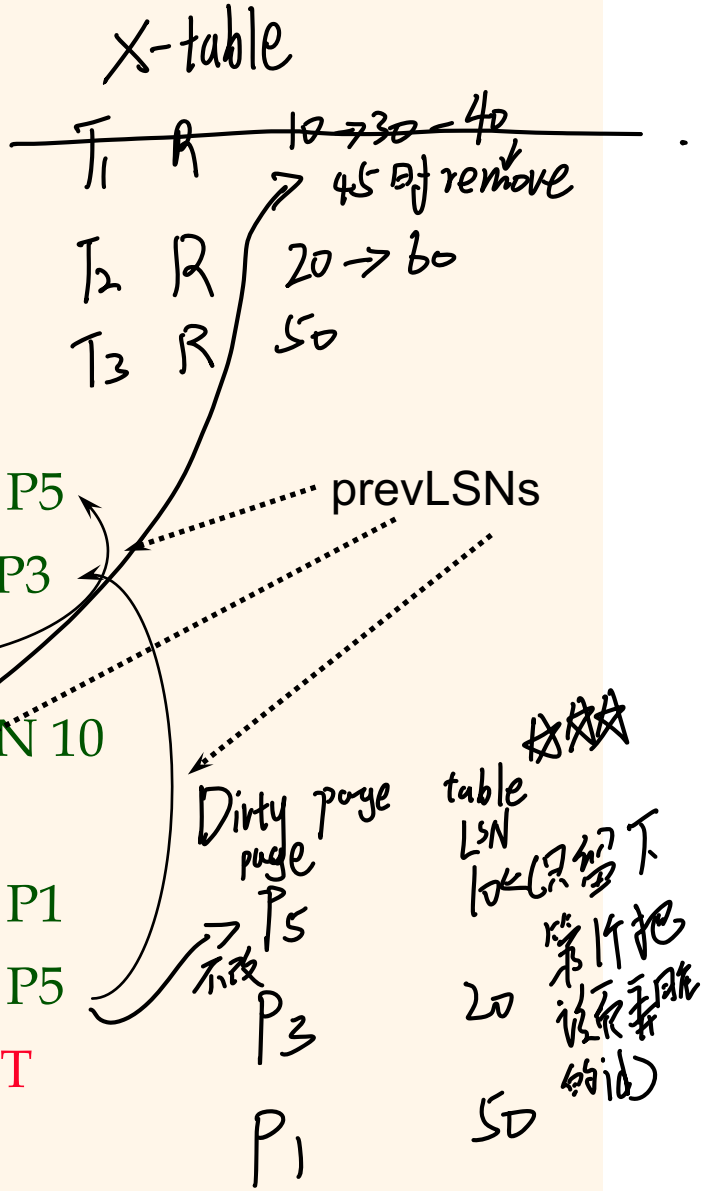
Example of Recovery



Xact Table
lastLSN
status
Dirty Page Table
recLSN
flushedLSN

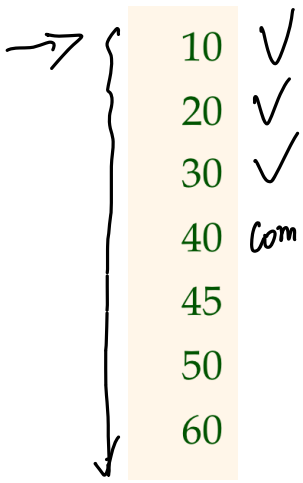
ToUndo

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

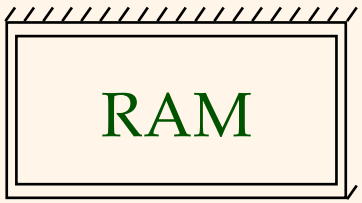


redo phase start with lowest LSN in D.P.T : 10

from the log We need to sequentially scan the log records ⇒ redo actions



Example: Crash During Restart!



Xact Table
lastLSN
status
Dirty Page Table
recLSN
flushedLSN

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.
  - Watch "hot spots"!
- How do you limit the amount of work in UNDO?
  - Avoid long-running Xacts.

Summary of Logging/Recovery

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

Summary, Cont.

- 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!