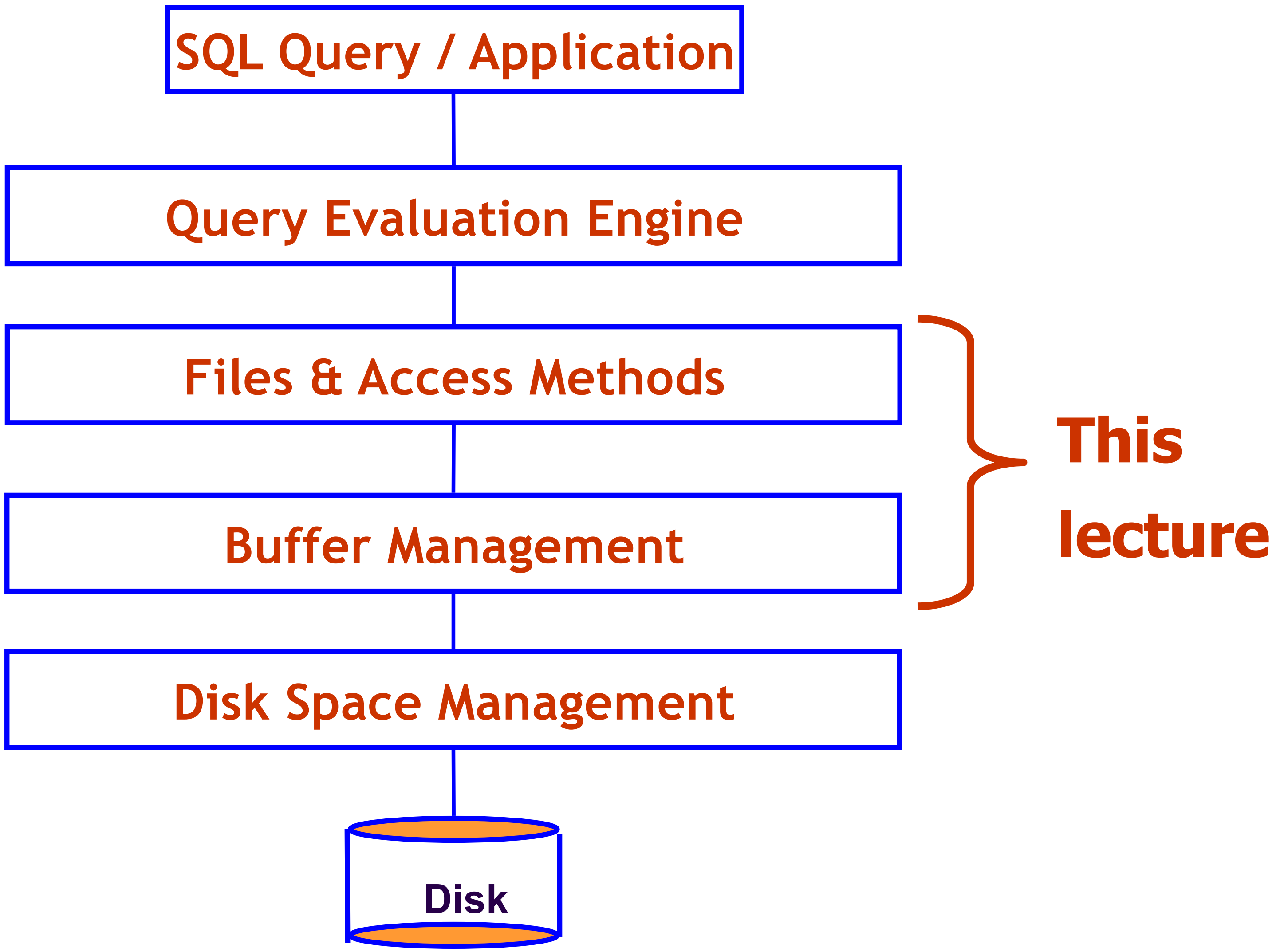
Database Recovery

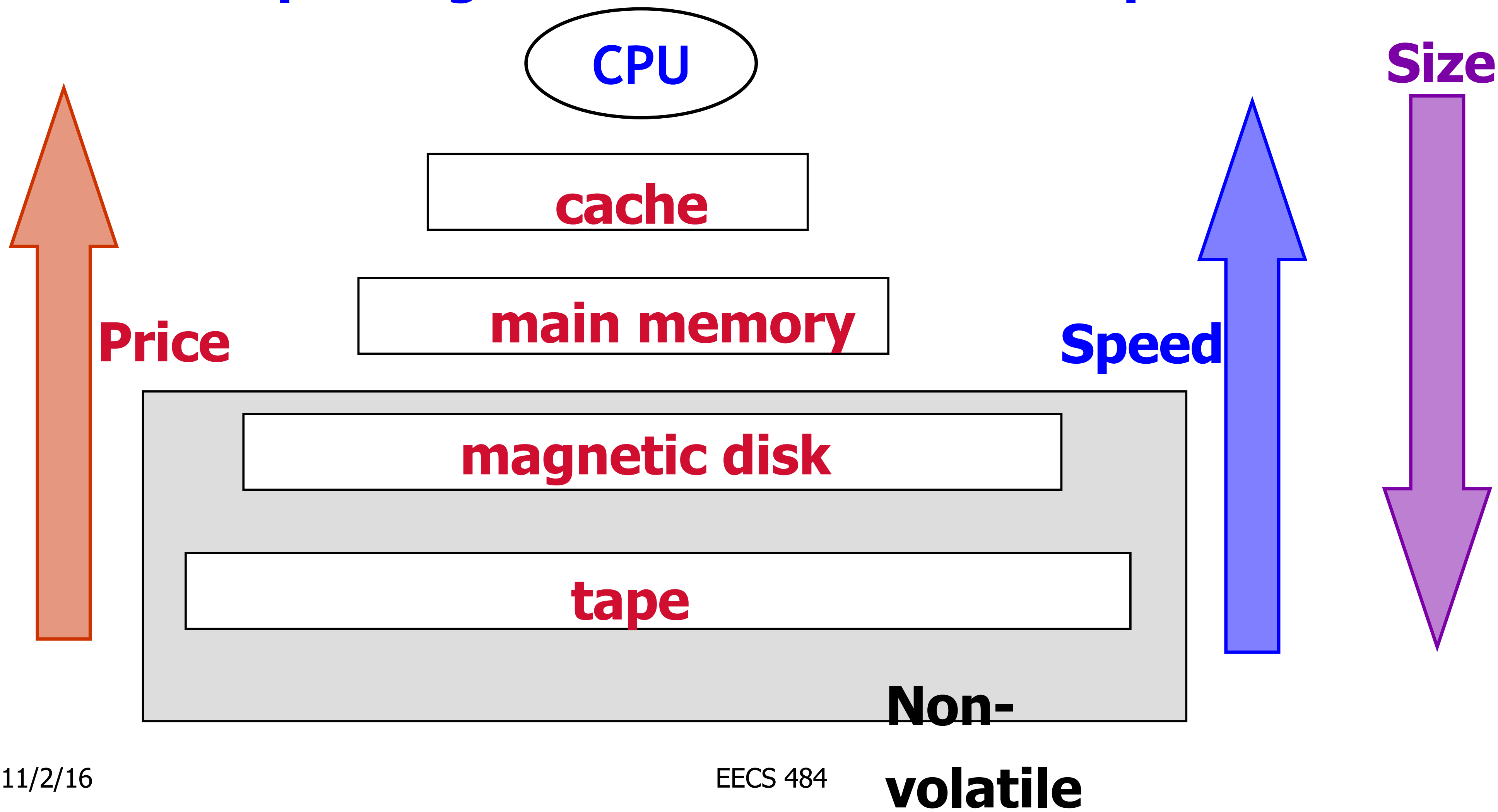
Chapter 16.7 and 18 (except 18.6 and 18.8)

DBMS Organization



The Memory Hierarchy

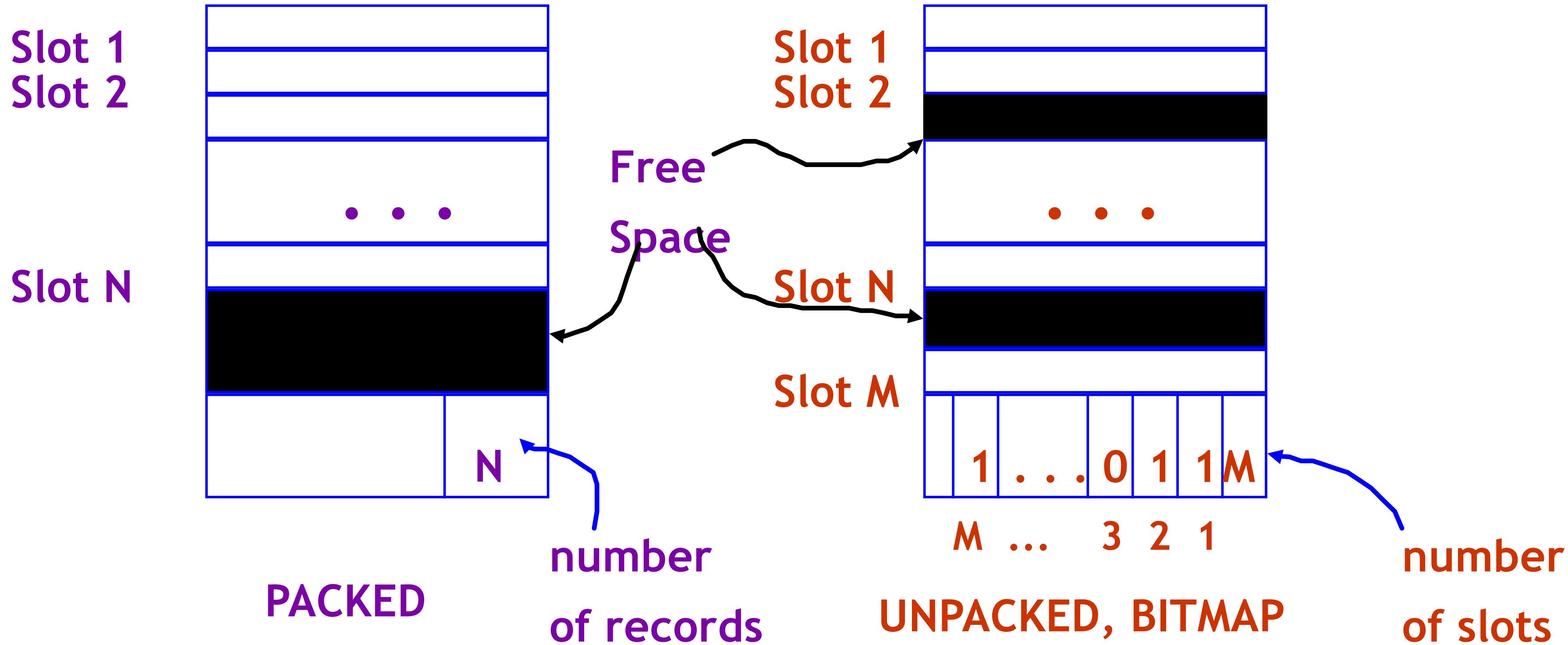
Performance of Microprocessors and Memory improving faster than disks and tapes



Why it matters?

- Unit of writing to disk:
  - Pages (512 bytes to 16K)
  - Pages contain records from a table
  - E.g., INSERT INTO Sailors VALUES(3, ‘dustin’, 23, 8);
- This requires:
  - Read a page from the database containing the Sailors records and an available slot
  - Revising the page to add a new record
  - Writing the page back to disk

Page Formats: Fixed Length Records



- Record id = <page id, slot #>
- Two alternatives for maintaining database records shown above. First requires more in-memory copying on delete of a record.

Example: INSERT

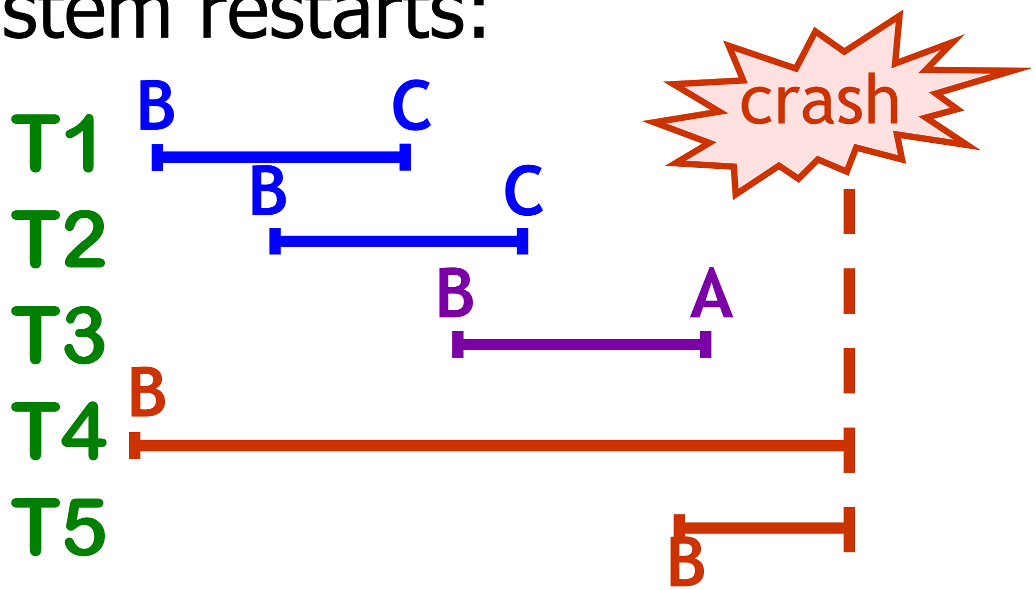
  - E.g., INSERT INTO Sailors VALUES(3, ‘dustin’, 23, 8);
- This requires:
  - READ the page from the disk containing the Sailors records and an available slot
  - Update the page in memory to add a new record
  - WRITE the page back to disk
- The disk READ and WRITE are very slow, compared to in-memory update
- Can we do better?

Challenges

- Reducing disk reads/writes
- Better strategy:
  - Keep the accessed pages cached in memory in a **buffer pool**
    - But buffer pool is limited. Thus also need to remove pages from memory
  - Delay writing pages back to disk until insufficient memory
- But, what if there is a CRASH?

Recovery

- Atomicity:
  - Transactions may abort ("Rollback").
- Durability:
  - What if DBMS stops running? (Causes?)
- Desired Behavior after system restarts:
  - T1 & T2 should be durable.
  - T4 & T5 should be aborted and any writes by them undone



What can go wrong?

- Page writes of a committed transaction:
  - If page writes only in memory (not pushed to disk) then BAD! Crash could fail to recover committed writes

- Page writes of an uncommitted transaction:
  - If uncommitted writes pushed to disk (e.g., because of memory pressure), then BAD! Crash could make uncommitted writes durable and undoable

One solution

- Try to maintain an invariant that disk has committed pages for all transactions. This requires Transaction Manager to:
  - FORCE pages of a transaction to disk upon a COMMIT.
  - NOT STEAL pages of uncommitted transactions when there is memory pressure. Stealing would require pushing uncommitted pages to disk
- Unfortunately, both would hurt performance!

Buffer Pool and ACID properties

Fortunately, alternatives exist:

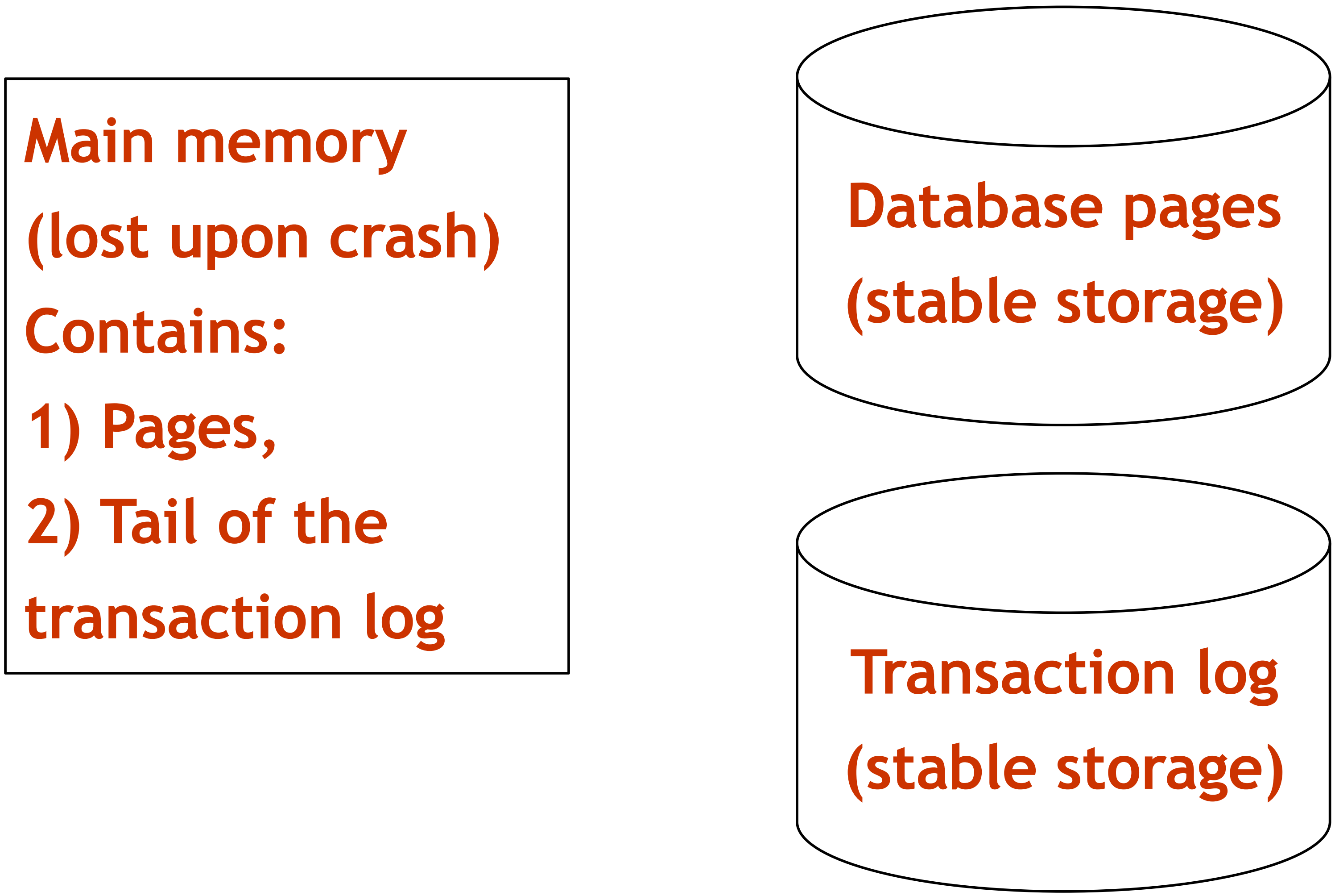
After a crash...

	No Steal	Steal
Force	Trivial, but Hurts performance	Steal is good, but undo of uncommited transactions required
No Force	No Force is good, but redo of Committed Transactions required	**Best performance! But undo/redo both required**

ARIES protocol

- ARIES (Algorithm for Recovery and Isolation Exploiting Semantics)
  - Developed by IBM researchers (1992)
- Key features:
  - Supports no force and steal
  - Every update written to two places:
    - To a database page (e.g., a record)
    - A transaction log
  - Transaction log used to help:
    - Undo stolen pages with uncommitted writes
    - Redo committed writes

Log to support undo or redo



Log allows database repair

- **LSN** **LOG**
- 10 Update: T1 writes P5 (oldval, newval)
- 20 Update: T2 writes P3 (oldval, newval)
- 30 T2 commit
- 40 T2 end
- 50 Update: T3 writes P1 (oldval, newval)
- 60 Update: T3 writes P3 (oldval, newval)
- ***BOOM!!!CRASSSHSH!H!!!***
- Upon restart, what can you tell from the log?
  - What txs were active at the time of the crash?
  - What changes should potentially be undone?
  - What changes should potentially be redone?

Log entry fields

- Record information, for every change, in a *log*.
  - Sequential writes to log (put it on a separate disk).
  - Stored in stable storage to survive system crash
  - Each log record for updates has a
    - log sequence number (LSN)
    - prevLSN, XID,
    - page#, offset, size, prev-image, new-mage
  - Log records for commits/aborts too.
  - prevLSN points to prev LSN in *same transaction*

Log Record Types

LogRecord fields:

prevLSN
XID
type

update records only:
pageID
length
offset
before-image
after-image

…

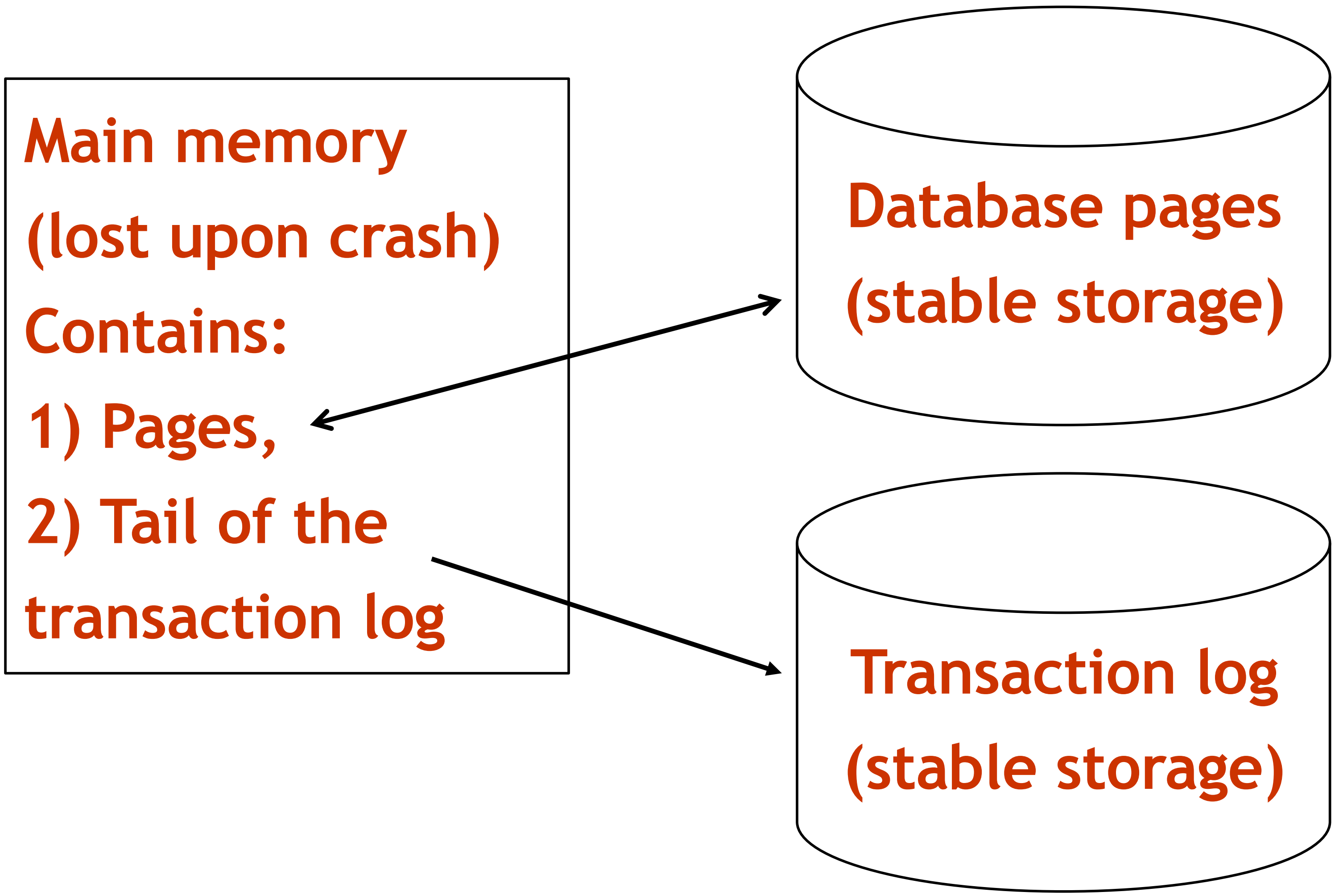
Possible log record types:

- **Update**
- **Commit**
- **Abort**
- **End** (end of commit or abort)
- Compensation Log Rec. (CLRs)
  - For UNDO actions
  - (More later)

Write-Ahead Logging (WAL)

- The Write-Ahead Logging Protocol:
  1. Force the log record for an update *before* the corresponding data page gets to disk.
  2. Must write all log records for a Xact *before commit*.
- #1 guarantees Atomicity
  - Allows undo of stolen pages
- #2 guarantees Durability
  - Allows redo of unforced but committed pages

What resides where



Write-Ahead Log (WAL)

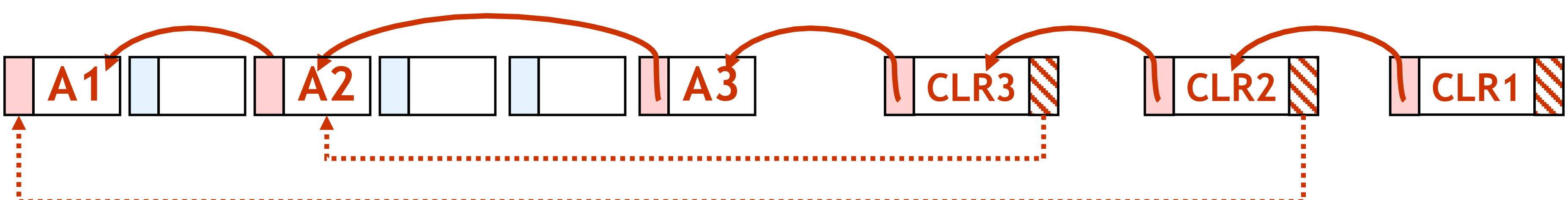
- Why is WAL faster than FORCE?
  - Both need to FORCE data to disk as transactions are committed
- Two advantages:
  - Set of WAL pages typically smaller than database data pages
  - WAL is sequential. Traditional disks are great for sequential writes

Example of update records

LSN	Txid	Type	Page	Len	Offset	Before	After	PrevLSN
10	T1000	update	P500	3	21	Abc	Def	---
20	T2000	update	P600	3	41	Hij	Klm	---
30	T2000	update	P500	3	20	Gde	Qrs	20
40	T1000	update	P505	3	21	Tuv	Wxy	10

Compensating Log Records

- Describes updates about to be undone due to abort
- Add a CLR entry to the log for every write undone
- CLR contains undoNextLSN: Reverse chain of update logs
- Contains before-image only (the value being restored). CLRs are never undone, since undone actions are due to aborts (no undo of undo)



Example: a log file with different types of record type

- 00: begin_checkpoint
- 05: end_checkpoint
- 10: update: T1 writes P5 (23, 4, "abcd", "efgh")
- 20: update: T2 writes P3 (…)
- 30: T1 aborts
- 40: CLR: Undo T1. writes P5 (23, 4, "abcd"), undoNextLSN NULL
- 45: T1 end
- 50: update: T3 writes P1 (…)
- 60: update: T2 writes P5 (…); CRASH
- 70: CLR: Undo T2 at LSN 60 (…), undoNextLSN 20
- 80: CLR: Undo T3 at LSN 50 (…), undoNextLSN NULL
- 85: T3 end
- 90: CLR: Undo T2 LSN at 20 (…), undoNextLSN NULL
- 95:T2 end

CLRs

- How many CLRs can be written to log during crash recovery?
  - Bounded by # of update log entries for active txs at time of crash

Checkpointing

- Checkpoint: (Logical) Snapshot of the database
  - Minimize recovery time by limiting log we need to examine
  - After crash, system locates most recent begin_checkpoint
- To do a Checkpoint, write to log:
  - begin_checkpoint record: Indicates when chkpt began.
  - end_checkpoint record with
    - Record Tx table and dirty page table *at time of begin_checkpoint*
    - *No attempt to force dirty pages to disk*
    - end_checkpoint can be big
    - This is a fuzzy checkpoint
  - Master record stores LSN of begin_checkpoint record in a safe place so we can jump there on restart

More Checkpointing

- Transaction table contains (txid, status, lastLSN) for each live tx
  - Points to most recent LSN for each live tx
  - Tells us “latest possible undo point” for tx
- Dirty page table contains (recLSN) for each dirty page in buffer pool.
  - Points to first log record that dirtied the page
  - Tells us “earliest possible redo point” for page
- These two tables are recovered during restart

Example

Page	recLSN
P500	
P600	
P505	

Dirty Page Table

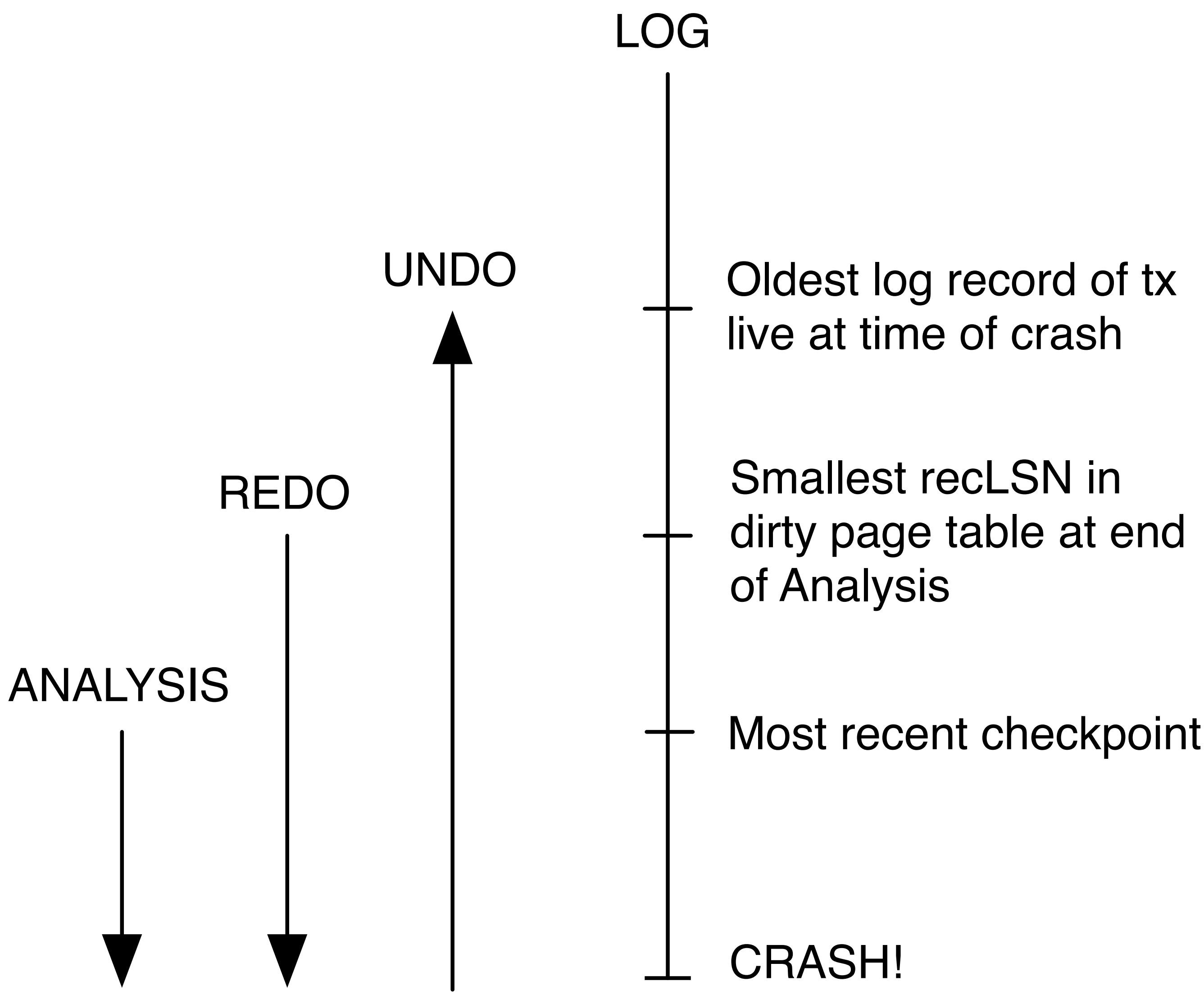
LSN	Txid	Type	Page	Len	Offset	Before	After	Prev LSN
1	T1000	update	P500	3	21	Abc	Def	
2	T2000	update	P600	3	41	Hij	Klm	
3	T2000	update	P500	3	20	Gde	Qrs	
4	T1000	update	P505	3	21	Tuv	Wxy	

Log

Txid	lastLSN	Status
T1000		U
T2000		U

Tx Table

Recovery Process



How Much Log Is Enough?

- Upon restart, how much log do you have to process?
  - What pages might be dirty and unwritten? (REDO)
  - What pages might be written but uncommitted? (UNDO)

- Undo: oldest lastLSN of txs active at crash
- Redo: oldest recLSN in dirty page table at crash

Recovery

- Three phases: Analysis, Redo, Undo
- 1. Analysis: reconstructs tables at time of crash
  - Jump to most-recent checkpoint, scan forward in log
  - If we find end-tx in log, remove it from tx table
  - If we find log entry for tx not in table, add it to table
  - If we find log entry that impacts page P, and P is not in dirty page table, add it to table
- At end of Analysis:
  - Tx table is correct
  - Dirty page table is superset of correct (for performance reasons, we don't log each page flush)

Example 1

Page	recLSN
P500	
P600	
P505	

Dirty Page Table

Txid	Type	Page	Len	Offset	Before	After
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

Txid	lastLSN	Status
T1000		U
T2000		U

Tx Table

Example 2

LSN	Log Record
10	T1: UPDATE P1 (OLD: YYY NEW: ZZZ)
15	T2: UPDATE P3 (OLD: UUU NEW: VVV)
20	BEGIN CHECKPOINT
25	END CHECKPOINT (XACT TABLE=[[T1,10],[T2,15]]; DPT=[[P1,10],[P3,15]])
30	T1: UPDATE P2 (OLD: WWW NEW: XXX)
35	T1: COMMIT
40	T2: UPDATE P1 (OLD: ZZZ NEW: TTT)
45	T2: ABORT
50	T2: CLR P1(ZZZ), undonextLSN=15
	BOOM!!!#CRASH!!!!!

Analysis phase:

- Scan forward through the log starting at LSN 20.
- LSN 25: Initialize XACT table with T1 (LastLSN 10) and T2 (LastLSN 15). Initialize DPT to P1 (RecLSN 10) and P3 (RecLSN 15).
- LSN 30: Add (T1, LSN 30) to XACT table. Add (P2, LSN 30) to DPT.
- LSN 35: Change T1 status to "Commit" and its LastLSN to 35 in XACT table
- LSN 40: Set LastLSN=40 for T2 in XACT table.
- LSN 45: Change T2 status to "Abort" and its LastLSN=45 in XACT table
- LSN 50: Set LastLSN=50 for T2 in XACT table.

Recovery

- 2. Redo: applies all updates in log
  - Start with log record of smallest recLSN of any page in dirty page table; scan forward
  - For each update/CLR encountered, check whether the update has to be applied:
    1. Is this page in the dirty page table?
    2. If yes, is the dirty page entry's recLSN ≤ current log LSN?
    3. If yes, read the actual page from disk. Is the, LSN recorded on page (called PageLSN) smaller current log LSN?
    - If yes, apply the update/CLR log to this page and set its PageLSN to the current log's LSN
    - If the answer to any of the questions above is no, move on!

Example 2

LSN	Log Record
10	T1: UPDATE P1 (OLD: YYY NEW: ZZZ)
15	T2: UPDATE P3 (OLD: UUU NEW: VVV)
20	BEGIN CHECKPOINT
25	END CHECKPOINT (XACT TABLE=[[T1,10],[T2,15]]; DPT=[[P1,10],[P3,15]])
30	T1: UPDATE P2 (OLD: WWW NEW: XXX)
35	T1: COMMIT
40	T2: UPDATE P1 (OLD: ZZZ NEW: TTT)
45	T2: ABORT
50	T2: CLR P1(ZZZ), undonextLSN=15
	BOOM!!!#CRASH!!!!!

Redo phase:

- **Scan forward through the log starting at LSN 10.**
- **LSN 10: Read page P1, check PageLSN stored in the page. If PageLSN<10, redo LSN 10 (set value to ZZZ) and set the page's PageLSN=10.**
- **LSN 15: Read page P3, check PageLSN stored in the page. If PageLSN<15, redo LSN 15 (set value to VVV) and set the page's PageLSN=15.**
- **LSN 30: Read page P2, check PageLSN stored in the page. If PageLSN<30, redo LSN 30 (set value to XXX) and set the page's PageLSN=30.**
- **LSN 40: Read page P1 if it has been flushed, check PageLSN stored in the page. It will be 10. Redo LSN 40 (set value to TTT) and set the page's PageLSN=40.**
- **LSN 50: Read page P1 if it has been flushed, check PageLSN stored in the page. It will be 40. Redo LSN 45 (set value to ZZZ) and set the page's PageLSN=50.**
- **End record is written for T1; Remove T1 from Xact.**

Recovery

- 3. Undo: Scan log backwards
  - Identify all live txs at time of crash
  - ToUndo = {the LastLSN of all uncommitted live txs}
  - While ToUndo is not empty
    - L ← Pick the max LSN in ToUndo
    - If L is an update record
      - Undo the action of L, write an CLR record to the log with undonextLSN=L.PrevLSN
      - ToUndo ← ToUndo U {L.prevLSN }
    - If L is a CLR record
      - ToUndo ← ToUndo U {L.undonextLSN}
    - Remove L from ToUndo

Example 2

LSN	Log Record
10	T1: UPDATE P1 (OLD: YYY NEW: ZZZ)
15	T2: UPDATE P3 (OLD: UUU NEW: VVV)
20	BEGIN CHECKPOINT
25	END CHECKPOINT (XACT TABLE=[[T1,10],[T2,15]]; DPT=[[P1,10],[P3,15]])
30	T1: UPDATE P2 (OLD: WWW NEW: XXX)
35	T1: COMMIT
40	T2: UPDATE P1 (OLD: ZZZ NEW: TTT)
45	T2: ABORT
50	T2: CLR P1(ZZZ), undonextLSN=15
	BOOM!!!#CRASH!!!!!

Undo phase:

- T2 must be undone. ToUndo = {50}
- LSN 50: Put LSN 15 in ToUndo. ToUndo = {15}
- LSN 15: Undo LSN 15 - write a CLR for P3 with "set P3=UUU" and undonextLSN=NULL. Write UUU into P3.
- Write an end record for T2; Remove T2 from Xact table.
- ToUndo = {}

Media Recovery

- Used for disaster recovery
  - Disk crashes, fires, alien attack, etc
- Periodically make a copy of the database
  - Similar to a "fuzzy checkpoint"
- When an object is corrupted:
  - Get potentially-outdated copy
  - Apply logs to bring it up-to-date

Summary

- Atomicity & Durability.
- WAL to allow STEAL/NO-FORCE
- 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"
- Interested in the history of ARIES:
  - http://www.almaden.ibm.com/u/mohan/ARIES_Impact.html

Announcements

- Book Exercises: 16.1, 16.3, 17.5
- Additional Review Exercise: Recall the three kinds of conflicts from last class (RW, WR, WW). For each, think of an example where the conflict occurs. How does 2PL prevent these conflicts?

Example 3 (Fig 18.5 from textbook)

- 00, 05: begin_checkpoint, end_checkpoint
- 10: update: T1 writes P5
- 20: update: T2 writes P3
- 30: T1 aborts PrevLSN
- 40, 45: CLR: Undo T1 LSN 10, T1 end
- 50: update: T3 writes P1 UndoNextLSN
- 60: update: T2 writes P5 PrevLSN
- CRASH, Restart
- 70: CLRL: Undo T2 LSN 60
- 80, 85: CLR: Undo T3 LSN 50, T3 end
- CRASH, Restart
- 90, 95: CLR: Undo T2 LSN 20, T2 end

Example 4

LSN	Log Record
0	BEGIN CHECKPOINT
5	END CHECKPOINT (EMPTY XACT TABLE AND DPT)
10	T1: UPDATE P1 (OLD: YYY NEW: ZZZ)
15	T1: UPDATE P2 (OLD: WWW NEW: XXX)
20	T1: COMMIT
	BOOM!!!#CRASH!!!!!

Analysis phase:

Scan forward through the log starting at LSN 0.

LSN 5: Initialize XACT table and DPT to empty.

LSN 10: Add (T1, LSN 10) to XACT table. Add (P1, LSN 10) to DPT.

LSN 15: Set LastLSN=15 for T1 in XACT table. Add (P2, LSN 15) to DPT.

LSN 20: Change T1 status to "Commit" in XACT table

Redo phase:

Scan forward through the log starting at LSN 10.

LSN 10: Read page P1, check PageLSN stored in the page. If PageLSN<10, redo LSN 10 (set value to ZZZ) and set the page's PageLSN=10.

LSN 15: Read page P2, check PageLSN stored in the page. If PageLSN<15, redo LSN 15 (set value to XXX) and set the page's PageLSN=15.

Redo phase:

Do nothing; no transactions to undo.

Example 5

LSN	Log Record
0	BEGIN CHECKPOINT
5	END CHECKPOINT (EMPTY XACT TABLE AND DPT)
10	T1: UPDATE P1 (OLD: YYY NEW: ZZZ)
15	T1: UPDATE P2 (OLD: WWW NEW: XXX)
20	T2: UPDATE P3 (OLD: UUU NEW: VVV)
25	T1: COMMIT
30	T2: UPDATE P1 (OLD: ZZZ NEW: TTT)
	BOOM!!!#CRASH!!!!!

Analysis phase:

- **Scan forward through the log starting at LSN 0.**
- **LSN 5: Initialize XACT table and DPT to empty.**
- **LSN 10: Add (T1, LSN 10) to XACT table. Add (P1, LSN 10) to DPT.**
- **LSN 15: Set LastLSN=15 for T1 in XACT table. Add (P2, LSN 15) to DPT.**
- **LSN 20: Add (T2, LSN 20) to XACT table. Add (P3, LSN 20) to DPT.**
- **LSN 25: Change T1 status to "Commit" and its LastLSN to 25 in XACT table**
- **LSN 30: Set LastLSN=30 for T2 in XACT table.**

Example 5

LSN	Log Record
0	BEGIN CHECKPOINT
5	END CHECKPOINT (EMPTY XACT TABLE AND DPT)
10	T1: UPDATE P1 (OLD: YYY NEW: ZZZ)
15	T1: UPDATE P2 (OLD: WWW NEW: XXX)
20	T2: UPDATE P3 (OLD: UUU NEW: VVV)
25	T1: COMMIT
30	T2: UPDATE P1 (OLD: ZZZ NEW: TTT)
	BOOM!!!#CRASH!!!!!

Redo phase:

- Scan forward through the log starting at LSN 10.
- LSN 10: Read page P1, check PageLSN stored in the page. If PageLSN<10, redo LSN 10 (set value to ZZZ) and set the page's PageLSN=10.
- LSN 15: Read page P2, check PageLSN stored in the page. If PageLSN<15, redo LSN 15 (set value to XXX) and set the page's PageLSN=15.
- LSN 20: Read page P3, check PageLSN stored in the page. If PageLSN<20, redo LSN 20 (set value to VVV) and set the page's PageLSN=20.
- LSN 30: Read page P1 if it has been flushed, check PageLSN stored in the page. It will be 10. Redo LSN 30 (set value to TTT) and set the page's PageLSN=30.
- Write end record for T1; Remove T1 from Xact table.

Example 5

LSN	Log Record
0	BEGIN CHECKPOINT
5	END CHECKPOINT (EMPTY XACT TABLE AND DPT)
10	T1: UPDATE P1 (OLD: YYY NEW: ZZZ)
15	T1: UPDATE P2 (OLD: WWW NEW: XXX)
20	T2: UPDATE P3 (OLD: UUU NEW: VVV)
25	T1: COMMIT
30	T2: UPDATE P1 (OLD: ZZZ NEW: TTT)
	BOOM!!!#CRASH!!!!!

Undo phase:

- **T2 must be undone. Put LSN 30 in ToUndo.**
- **Write Abort record to log for T2**
- **LSN 30: Undo LSN 30 - write a CLR for P1 with "set P1=ZZZ" and undonextLSN=20. Write ZZZ into P1. Put LSN 20 in ToUndo.**
- **LSN 20: Undo LSN 20 - write a CLR for P3 with "set P3=UUU" and undonextLSN=NULL. Write UUU into P3.**
- **Write 'End' record for T2; remove T2 from XACT table.**