

CSE 444: Database Internals

Lectures 17-19
Transactions: Recovery

The Usual Reminders

- HW3 is due tonight
- Lab3 is due May 18
- Quiz grades are out on Gradescope
- HW4 is out – material covered this week

Readings for Lectures 17-19

Main textbook (Garcia-Molina)

- Ch. 17.2-4, 18.1-3, 18.8-9

Second textbook (Ramakrishnan)

- Ch. 16-18

Also: M. J. Franklin. Concurrency Control and Recovery. The Handbook of Computer Science and Engineering, A. Tucker, ed., CRC Press, Boca Raton, 1997.

Transaction Management

Two parts:

- Concurrency control: ACID
- Recovery from crashes: ACID

We already discussed concurrency control

You are implementing locking in lab3

Today, we start recovery

System Crash

Client 1:

BEGIN TRANSACTION

UPDATE Account1

SET balance= balance – 500

UPDATE Account2

SET balance = balance + 500

COMMIT



Crash !

Recovery

Type of Crash	Prevention
Wrong data entry	Constraints and Data cleaning
Disk crashes	Redundancy: e.g. RAID, archive
Data center failures	Remote backups or replicas
System failures: e.g. power	DATABASE RECOVERY

System Failures

- Each transaction has *internal state*
- When system crashes, internal state is lost
 - Don't know which parts executed and which didn't
 - Need ability to *undo* and *redo*

Buffer Manager Review

READ
WRITE

Page requests from higher-level code

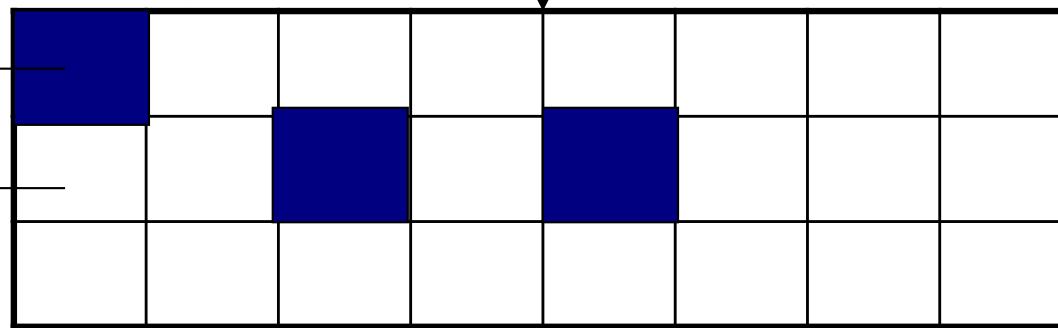
Files and access methods

Buffer pool manager

Disk page

Buffer pool

Free frame



INPUT
OUTPUT

choice of frame dictated
by **replacement policy**

Disk = collection
of blocks



1 page corresponds
to 1 disk block

Data must be in RAM for DBMS to operate on it!

Buffer pool = table of <frame#, pageid> pairs

Buffer Manager Review

- Enables higher layers of the DBMS to assume that needed data is in main memory
- Caches data in memory. Problems when crash occurs:
 - If committed data was not yet written to disk
 - If uncommitted data was flushed to disk

Primitive Operations of Transactions

- **READ(X,t)**
 - copy element X to transaction local variable t
- **WRITE(X,t)**
 - copy transaction local variable t to element X
- **INPUT(X)**
 - read element X to memory buffer
- **OUTPUT(X)**
 - write element X to disk

Running Example

BEGIN TRANSACTION

READ(A,t);

$t := t^*2;$

WRITE(A,t);

READ(B,t);

$t :=$ ~~110~~

WR

CO

Initially, A=B=8.

Atomicity requires that either
(1) T commits and A=B=16, or
(2) T does not commit and A=B=8.

Will look at various crash scenarios

What behavior do we want in each case?

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)					
$t:=t^*2$					
WRITE(A,t)					
INPUT(B)					
READ(B,t)					
$t:=t^*2$					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					
COMMIT					3

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^*2$					
WRITE(A,t)					
INPUT(B)					
READ(B,t)					
$t:=t^*2$					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					
COMMIT					4

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)					
INPUT(B)					
READ(B,t)					
$t:=t^2$					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					
COMMIT					5

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)					
READ(B,t)					
$t:=t^2$					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					
COMMIT					

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)					
$t:=t^2$					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					
COMMIT					

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t:=t^2$					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					
COMMIT					

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t:=t^2$	16	16	8	8	8
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					
COMMIT					

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t:=t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)					
OUTPUT(B)					
COMMIT					0

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t:=t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)					
COMMIT					

```

READ(A,t); t := t*2; WRITE(A,t);
READ(B,t); t := t*2; WRITE(B,t)

```

Transaction		Buffer pool		Disk	
Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t:=t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Yes it's bad: A=16, B=8....

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Yes it's bad: A=B=16, but not committed

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t:=t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t:=t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16
COMMIT					

Is this bad ?

No: that's OK

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16
COMMIT					

OUTPUT can also happen **after** COMMIT (details coming)

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t := t^*2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t := t^*2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

OUTPUT can also happen **after** COMMIT (details coming)

Action	t	Mem A	Mem B	Disk A	Disk B
INPUT(A)		8		8	8
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
INPUT(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Atomic Transactions

- **FORCE or NO-FORCE**
 - Should all updates of a transaction be forced to disk before the transaction commits?
- **STEAL or NO-STEAL**
 - Can an update made by an uncommitted transaction overwrite the most recent committed value of a data item on disk?

Force/No-steal

- **FORCE**: Pages of committed transactions must be forced to disk before commit
- **NO-STEAL**: Pages of uncommitted transactions cannot be written to disk

Easy to implement (how?) and ensures atomicity

No-Force/Steal

- **NO-FORCE**: Pages of committed transactions need not be written to disk
- **STEAL**: Pages of uncommitted transactions may be written to disk

In either case, need a Write Ahead Log (WAL) to provide atomicity in face of failures

Write-Ahead Log (WAL)

The Log: append-only file containing log records

- Records every single action of every TXN
- Forces log entries to disk as needed
- After a system crash, use log to recover

Three types: UNDO, REDO, UNDO-REDO

Aries: is an UNDO-REDO log

Policies and Logs

	NO-STEAL	STEAL
FORCE	Lab 3	Undo Log
NO-FORCE	Redo Log	Undo-Redo Log

UNDO Log

FORCE and **STEAL**

Undo Logging

Log records

- <START T>
 - transaction T has begun
- <COMMIT T>
 - T has committed
- <ABORT T>
 - T has aborted
- <T,X,v>
 - T has updated element X, and its old value was v
 - *Idempotent, physical* log records

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
$t := t * 2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A, 8 >
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
$t := t * 2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
$t := t * 2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
$t := t * 2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

WHAT DO WE DO ?

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
$t:=t*2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
$t:=t*2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	 Crash !
COMMIT						<COMMIT T>

WHAT DO WE DO ?

ES

We UNDO by setting B=8 and A=8

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
$t:=t*2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
$t:=t*2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

What do we do now ?



Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
$t:=t*2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
$t:=t*2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

What do we do now ?

Nothing: log contains COMMIT

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
$t := t * 2$	16	8		8	8	
WRITE(A,t)	16	16	16	8	8	<T,A,8>
INPUT(B)						
READ(B,t)						
$t := t * 2$				8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						

Crash !

After Crash

- This is all we see (for example):

Disk A	Disk B
8	16

<START T>

<T,A,8>

<T,B,8>

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
8	16

<START T>

<T,A,8>

<T,B,8>

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
8	16

<START T>

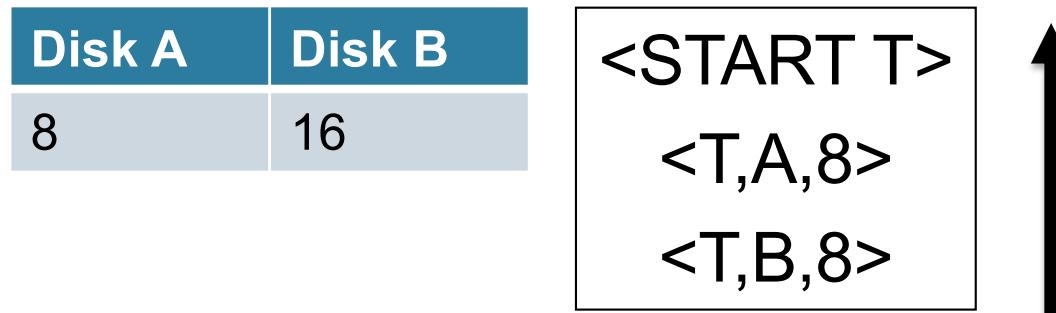
<T,A,8>

<T,B,8>

- What direction?

After Crash

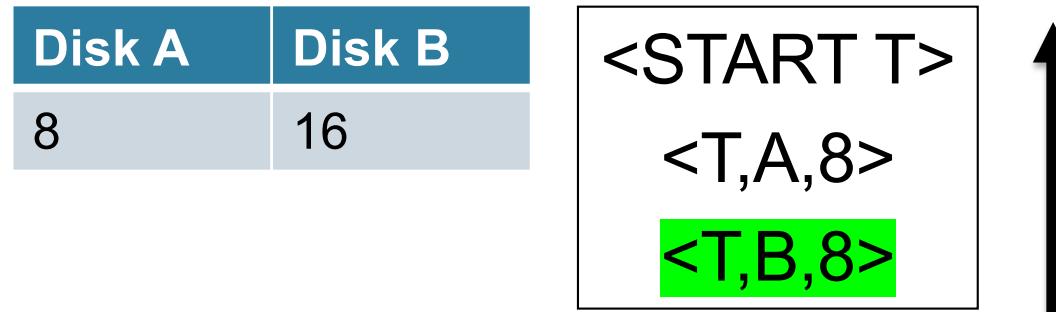
- This is all we see (for example):
- Need to step through the log



- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

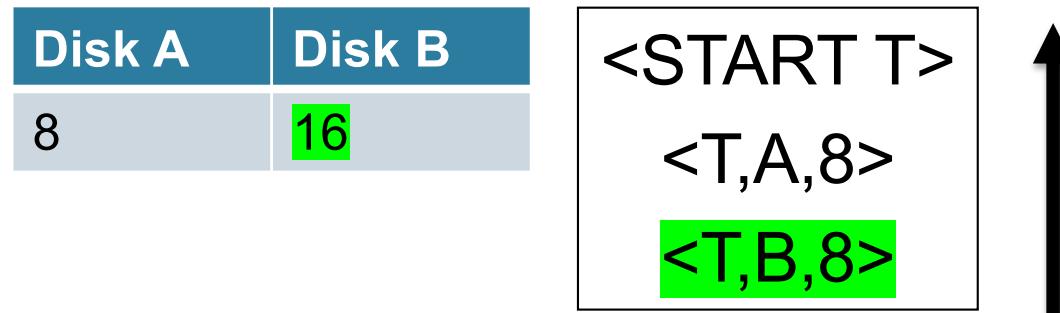
- This is all we see (for example):
- Need to step through the log



- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

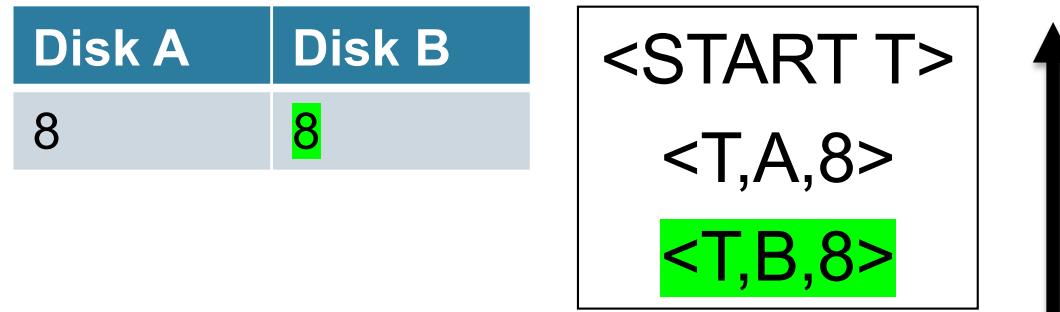
- This is all we see (for example):
- Need to step through the log



- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

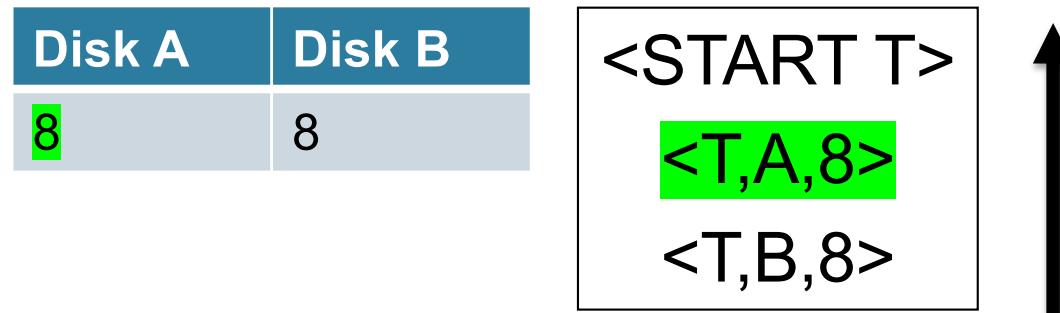
- This is all we see (for example):
- Need to step through the log



- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

- This is all we see (for example):
- Need to step through the log



- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

- If we see NO Commit statement:
 - We UNDO both changes: A=8, B=8
 - The transaction is atomic, since none of its actions have been executed
- In we see that T has a Commit statement
 - We don't undo anything
 - The transaction is atomic, since both it's actions have been executed

Recovery with Undo Log

After system's crash, run recovery manager

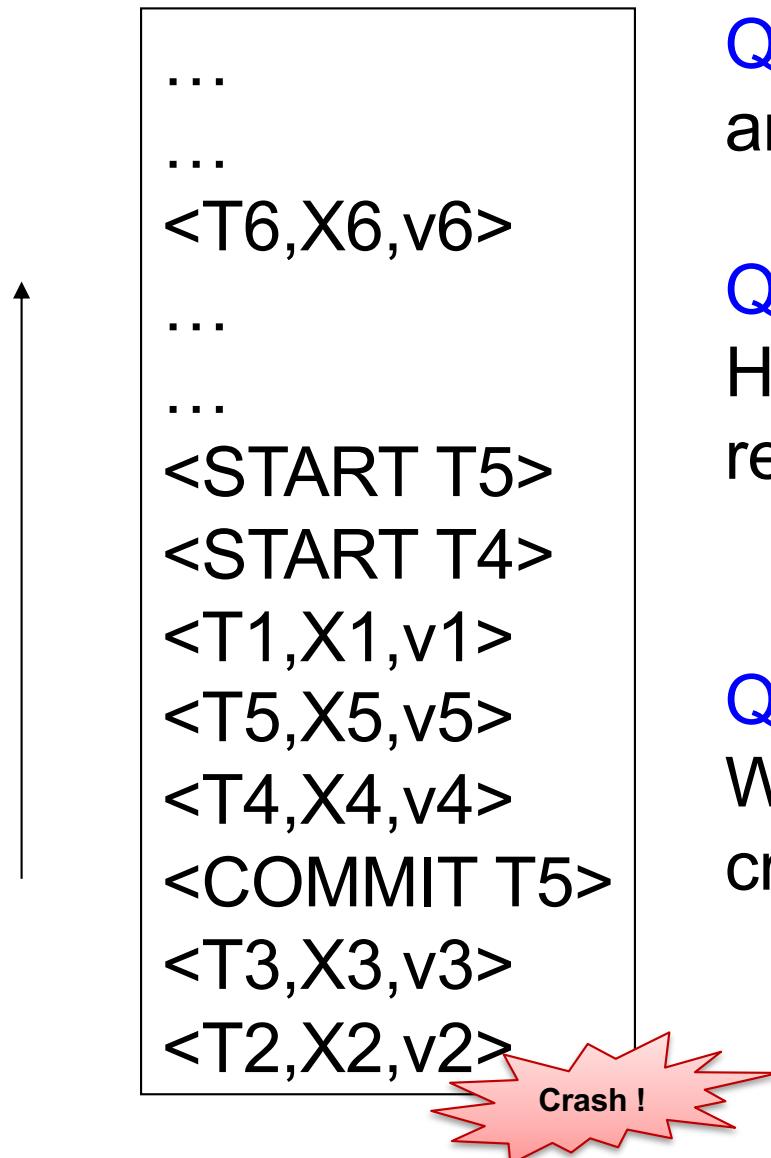
- Decide for each transaction T whether it is completed or not
 - <START T>....<COMMIT T>.... = yes
 - <START T>....<ABORT T>..... = yes
 - <START T>..... = no
- Undo all modifications by incomplete transactions

Recovery with Undo Log

Recovery manager:

- Read log from the end; cases:
 - <COMMIT T>: mark T as completed
 - <ABORT T>: mark T as completed
 - <T,X,v>: if T is not completed
 - then write X=v to disk
 - else ignore
 - <START T>: ignore

Recovery with Undo Log

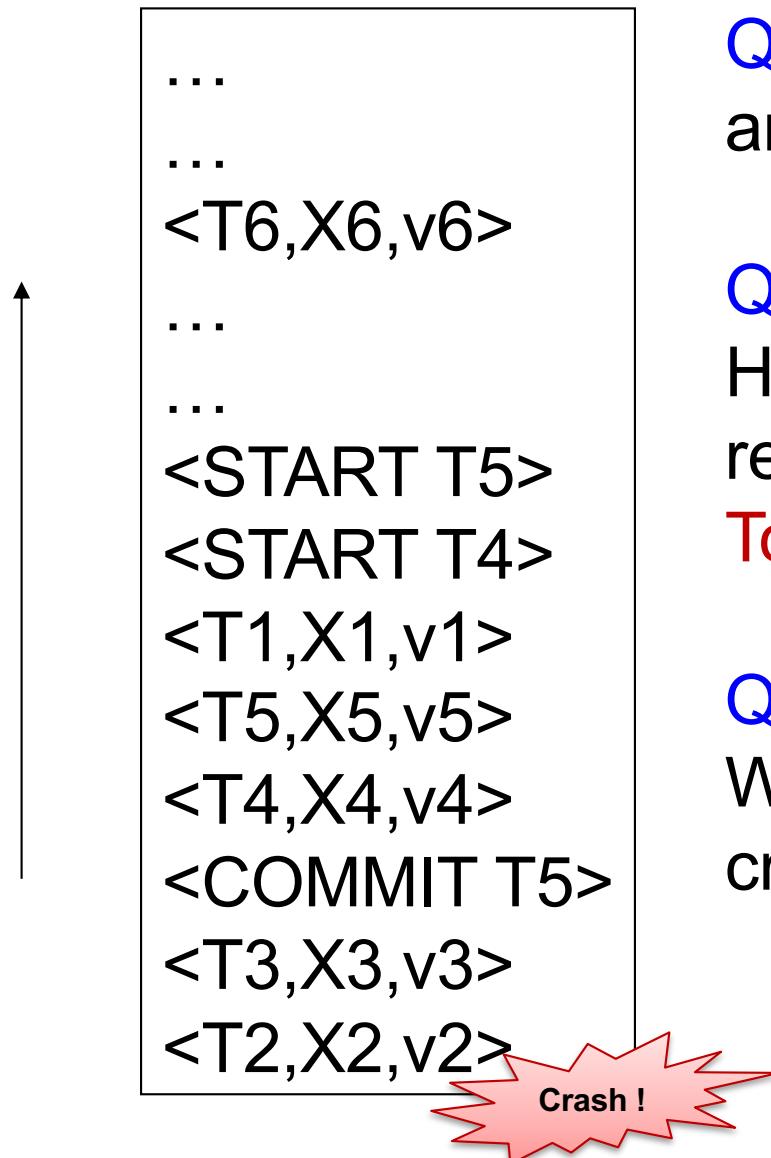


Question 1: Which updates are undone ?

Question 2:
How far back do we need to read in the log ?

Question 3:
What happens if second crash during recovery?

Recovery with Undo Log



Question 1: Which updates are undone ?

Question 2:

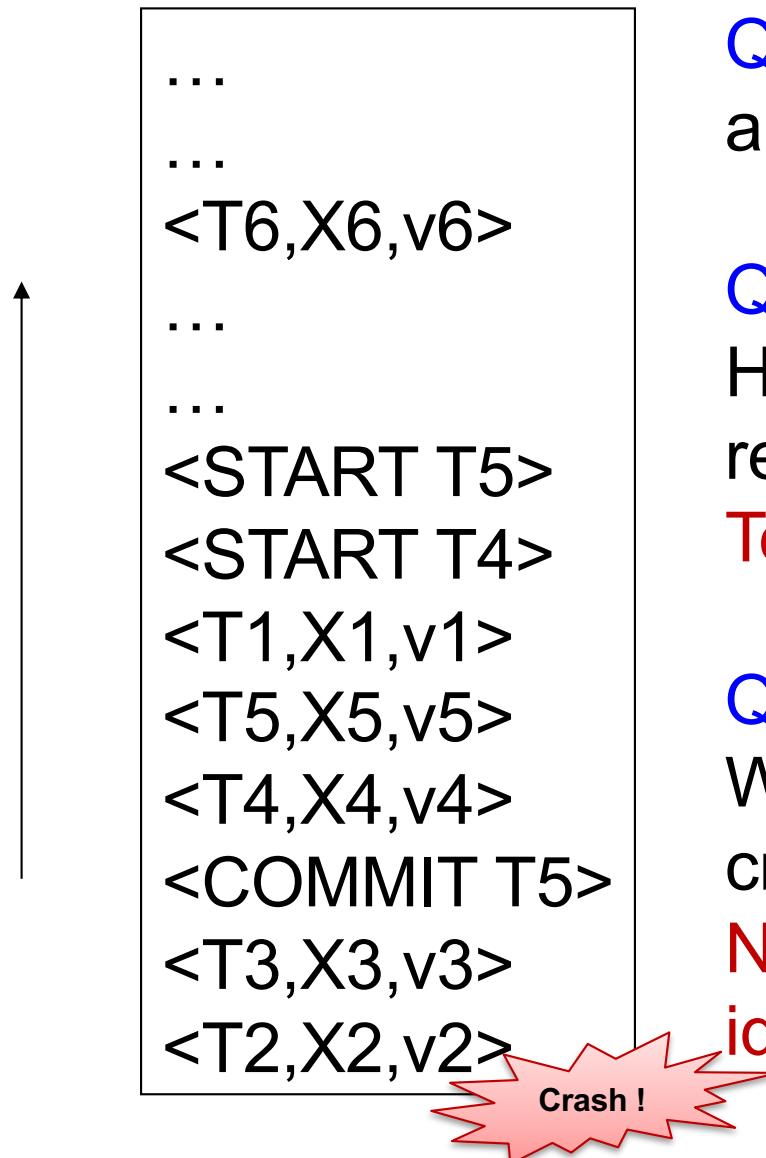
How far back do we need to read in the log ?

To the beginning.

Question 3:

What happens if second crash during recovery?

Recovery with Undo Log



Question 1: Which updates are undone ?

Question 2:

How far back do we need to read in the log ?

To the beginning.

Question 3:

What happens if second crash during recovery?

No problem! Log records are idempotent. Can reapply.

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)					8	
READ(A,t)	8				8	
$t := t * 2$	16	8			8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	?
$t := t * 2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	?
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
$t := t * 2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
$t := t * 2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT				FORCE		<COMMIT T>

RULES: log entry before OUTPUT before COMMIT

Undo-Logging Rules

U1: If T modifies X, then $\langle T, X, v \rangle$ must be written to disk before $\text{OUTPUT}(X)$

U2: If T commits, then $\text{OUTPUT}(X)$ must be written to disk before $\langle \text{COMMIT } T \rangle$

FORCE

- Hence: OUTPUTs are done *early*, before the transaction commits

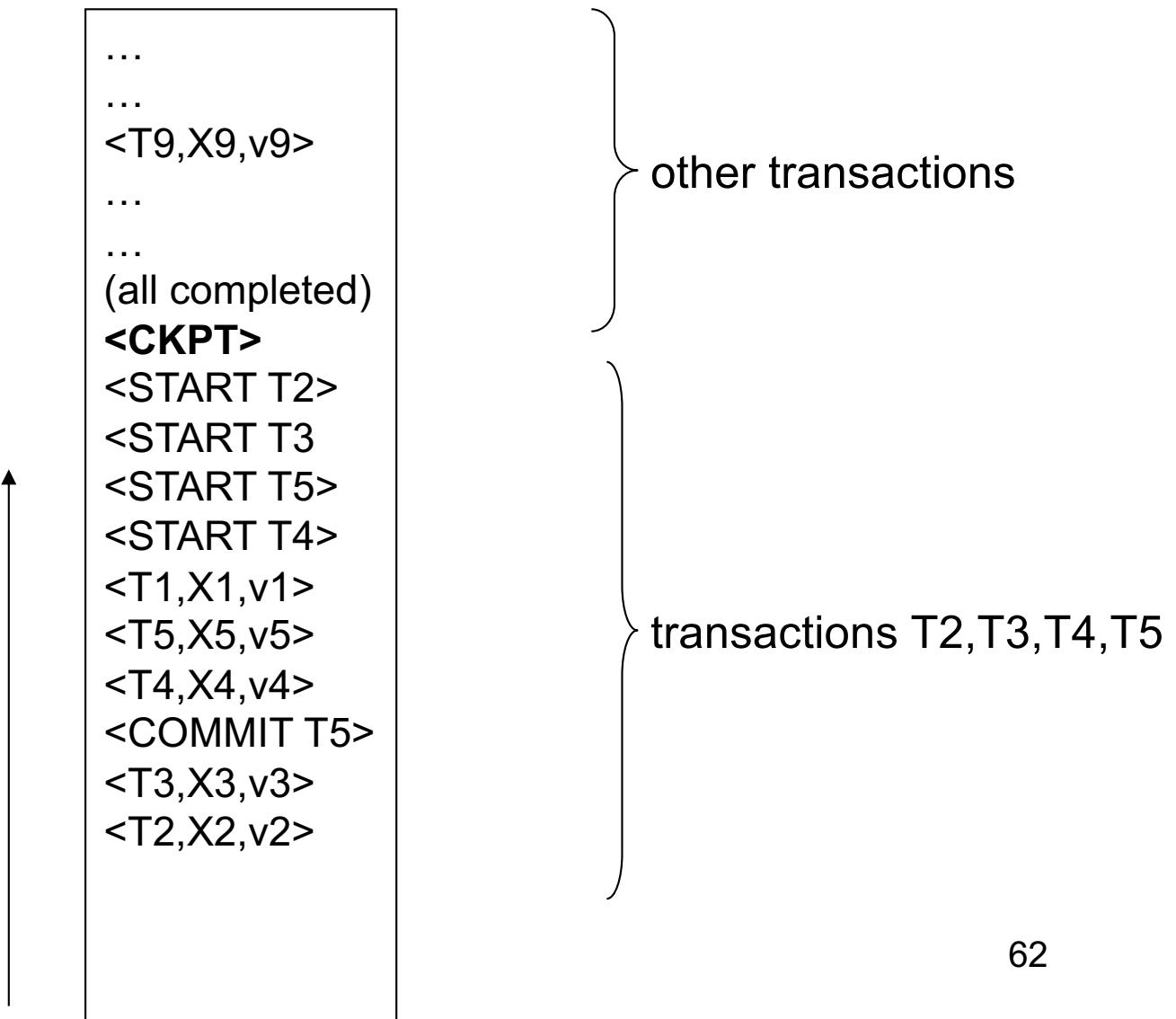
Checkpointing

Checkpoint the database periodically

- Stop accepting new transactions
- Wait until all current transactions complete
- Flush log to disk
- Write a <CKPT> log record, flush
- Resume transactions

Undo Recovery with Checkpointing

During recovery,
Can stop at first
<CKPT>



Nonquiescent Checkpointing

- Problem with checkpointing: database freezes during checkpoint
- Would like to checkpoint while database is operational
- Idea: nonquiescent checkpointing

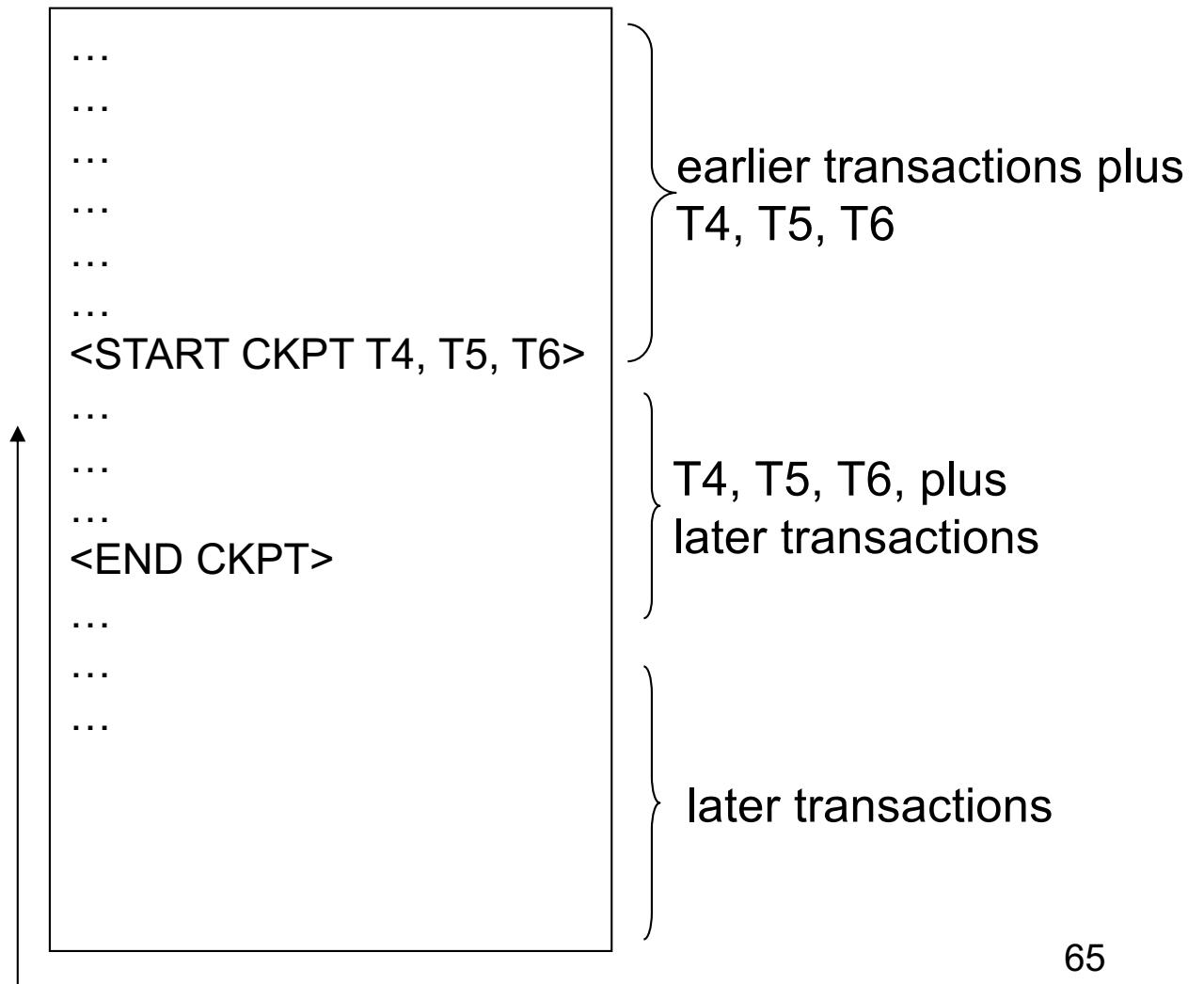
Quiescent = being quiet, still, or at rest; inactive
Non-quiescent = allowing transactions to be active

Nonquiescent Checkpointing

- Write a $\langle \text{START CKPT}(T_1, \dots, T_k) \rangle$ where T_1, \dots, T_k are all active transactions. Flush log to disk
- Continue normal operation
- When all of T_1, \dots, T_k have completed, write $\langle \text{END CKPT} \rangle$, flush log to disk

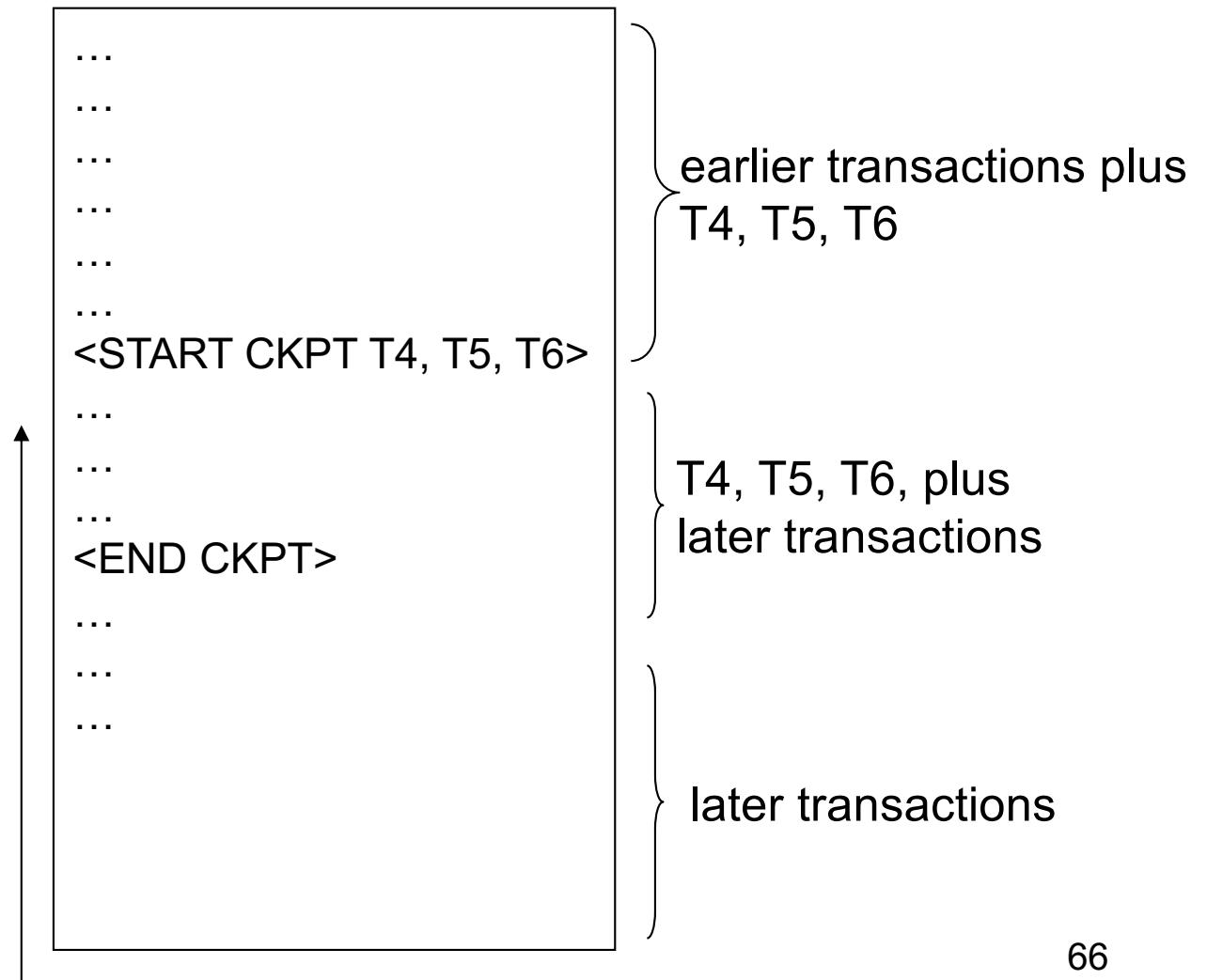
Undo Recovery with Nonquiescent Checkpointing

Need to read
Back to start of
T4, T5, T6



Undo Recovery with Nonquiescent Checkpointing

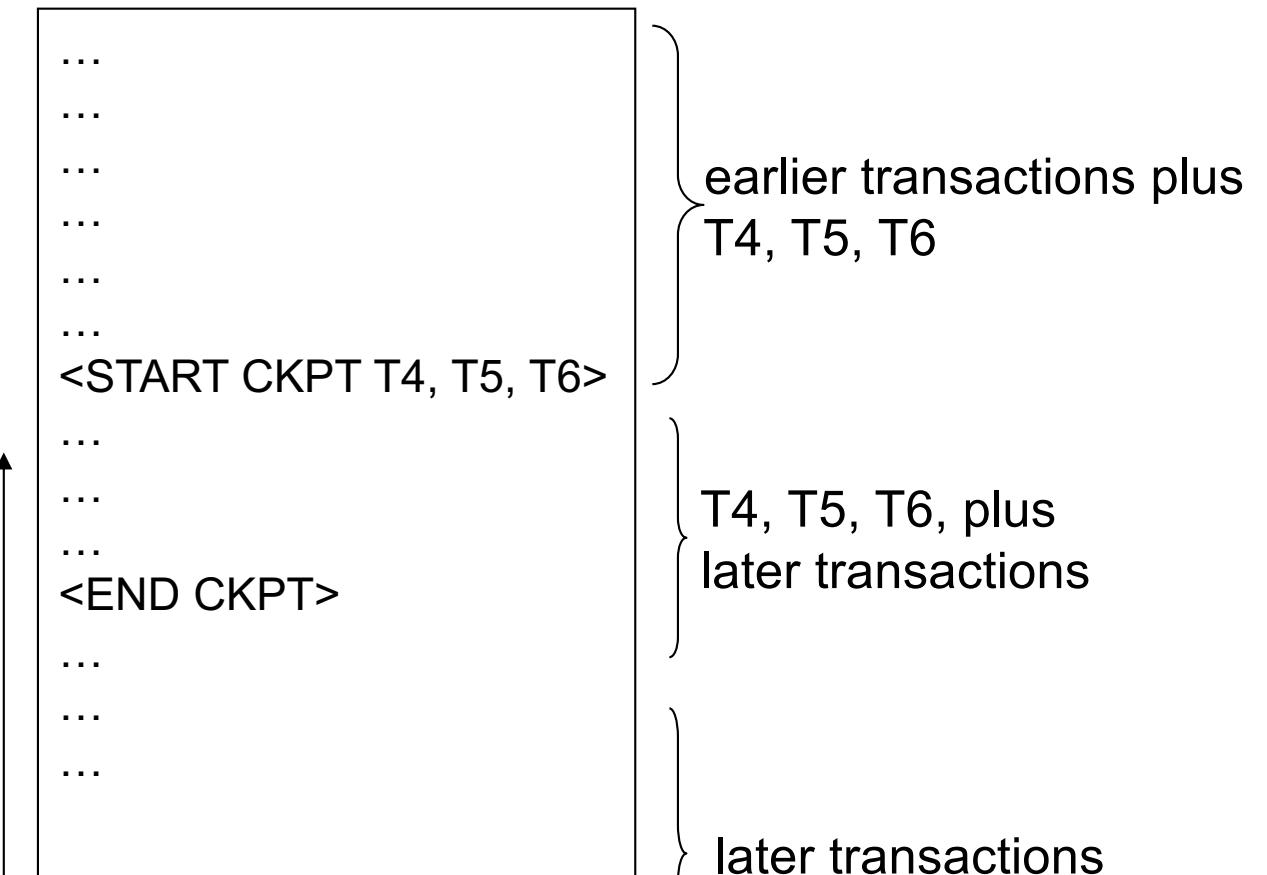
Need to read
Back to start of
T4, T5, T6



Q: do we need
<END CKPT> ?

Undo Recovery with Nonquiescent Checkpointing

Need to read
Back to start of
T4, T5, T6

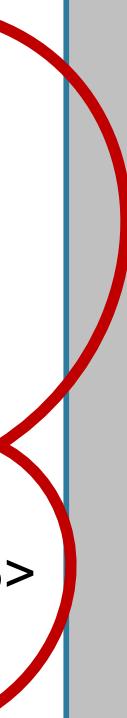


Q: do we need

<END CKPT> Not really, it's implicit in seeing T4,T5,T6 commits

Implementing ROLLBACK

- Recall: a transaction can end in COMMIT or ROLLBACK
- Idea: use the undo-log to implement ROLLBACK
- How ?
 - LSN = Log Sequence Number
 - Log entries for the same transaction are linked, using the LSN's
 - Read log in reverse, using LSN pointers

- Recovery
Order
List
 - Identify
Recovered
Transactions
 - Hold
Backlog
- ...
...
<T9,X9,v9>
...
...
(all completed)
<CKPT>
<START T2>
<START T3>
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T2,X1,v2>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>
- 

REDO Log

NO-FORCE and NO-STEAL

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
$t := t^* 2$	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
$t := t^* 2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

Yes, it's bad: A=16, B=8

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16



Crash !

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

Yes, it's bad: lost update

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16



Crash !

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

No: that's OK.

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
$t := t^2$	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
$t := t^2$	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16



Crash !

Redo Logging

One minor change to the undo log:

- $\langle T, X, v \rangle =$ T has updated element X, and its new value is v

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
$t := t^* 2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
$t := t^* 2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
$t := t^2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
$t := t^2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	 Crash !

How do we recover ?

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Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
$t := t^2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
$t := t^2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	 Crash !

How do we recover ?

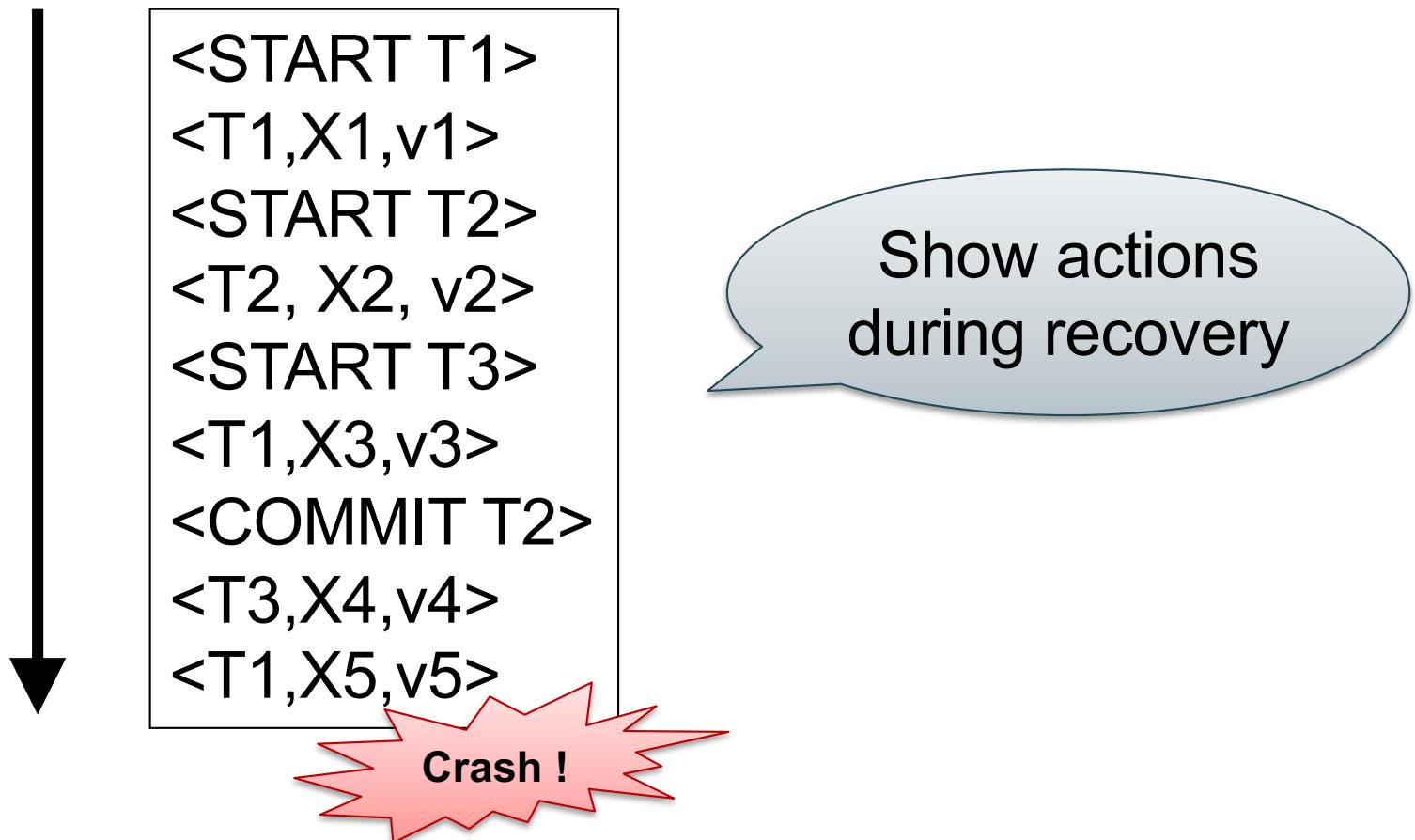
We **REDO** by setting A=16 and B=16

Recovery with Redo Log

After system's crash, run recovery manager

- Step 1. Decide for each transaction T whether it is committed or not
 - <START T>....<COMMIT T>.... = yes
 - <START T>....<ABORT T>..... = no
 - <START T>..... = no
- Step 2. Read log from the beginning, redo all updates of committed transactions

Recovery with Redo Log



Nonquiescent Checkpointing

- Write a <START CKPT(T_1, \dots, T_k)>
where T_1, \dots, T_k are all active txn's
- Flush to disk all **blocks of committed transactions** (*dirty blocks*)
- Meantime, continue normal operation
- When **all blocks have been written**, write <END CKPT>

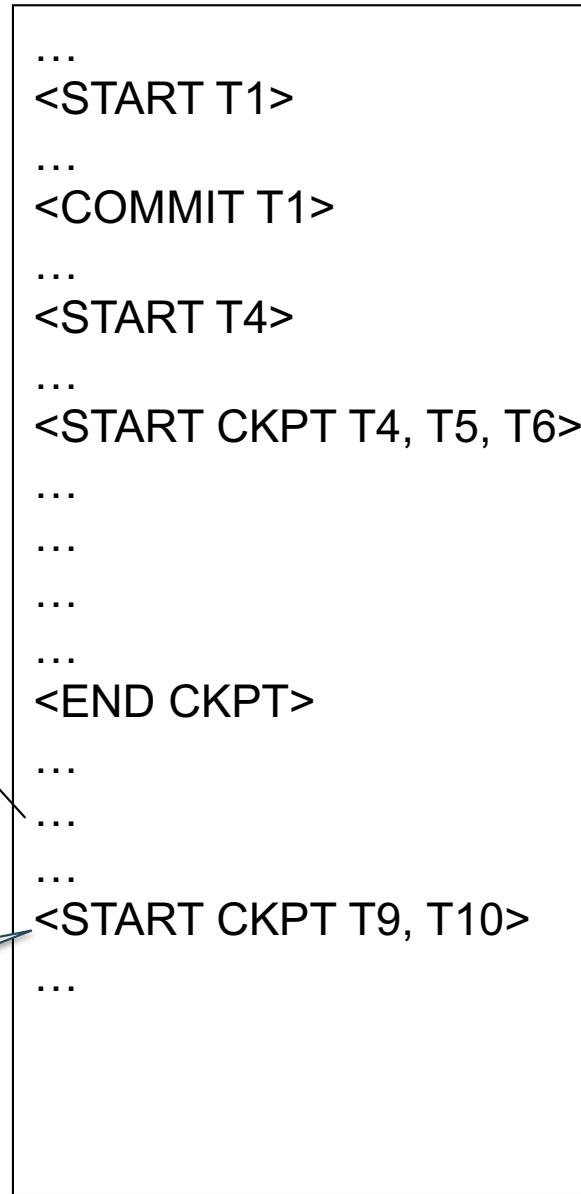
END CKPT has different meaning here than in Undo log

Nonquiescent Checkpointing

Step 1: look for
The last
<END CKPT>

All OUTPUTs
of T1 are
known to be on disk

Cannot
use



Step 2: redo
from the
earliest
start of
T4, T5, T6
ignoring
transactions
committed
earlier

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
$t := t^* 2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
$t := t^* 2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
$t := t^* 2$	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
$t := t^* 2$	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT		NO-STEAL				<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

RULE: OUTPUT after COMMIT

Redo-Logging Rules

R1: If T modifies X, then both $\langle T, X, v \rangle$ and $\langle \text{COMMIT } T \rangle$ must be written to disk before $\text{OUTPUT}(X)$

NO-STEAL

- Hence: OUTPUTs are done late

Comparison Undo/Redo

- Undo logging:
 - OUTPUT must be done early
 - If <COMMIT T> is seen, T definitely has written all its data to disk (hence, don't need to redo) – inefficient
- Redo logging
 - OUTPUT must be done late
 - If <COMMIT T> is not seen, T definitely has not written any of its data to disk (hence there is not dirty data on disk, no need to undo) – inflexible
- Would like more flexibility on when to OUTPUT:
undo/redo logging (next)

Steal/Force

No-Steal/No-Force

Steal/No-Force

Undo/Redo Logging

Log records, only one change

- $\langle T, X, u, v \rangle = T$ has updated element X , its *old* value was u , and its *new* value is v

Undo/Redo-Logging Rule

UR1: If T modifies X, then $\langle T, X, u, v \rangle$ must be written to disk before $\text{OUTPUT}(X)$

Note: we are free to OUTPUT early or late relative to $\langle \text{COMMIT } T \rangle$

Action	T	Mem A	Mem B	Disk A	Disk B	Log
						<START T>
REAT(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8,16>
OUTPUT(A)	16	16	16	16	8	
						<COMMIT T>
OUTPUT(B)	16	16	16	16	16	

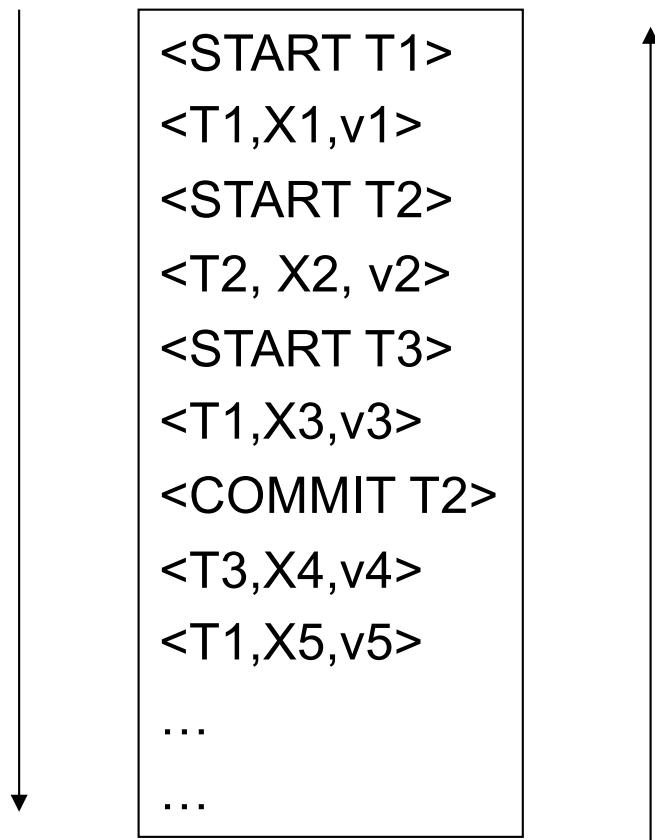
Can OUTPUT whenever we want: before/after COMMIT 93

Recovery with Undo/Redo Log

After system's crash, run recovery manager

- Redo all committed transaction, top-down
- Undo all uncommitted transactions, bottom-up

Recovery with Undo/Redo Log



ARIES

Aries

- ARIES pieces together several techniques into a comprehensive algorithm
- Developed at IBM Almaden, by Mohan
- IBM botched the patent, so everyone uses it now
- Several variations, e.g. for distributed transactions

Log Granularity

Two basic types of log records for update operations

- **Physical log records**
 - Position on a particular page where update occurred
 - Both before and after image for undo/redo logs
 - Benefits: Idempotent & updates are fast to redo/undo
- **Logical log records**
 - Record only high-level information about the operation
 - Benefit: Smaller log
 - BUT difficult to implement because crashes can occur in the middle of an operation

ARIES Recovery Manager

Log entries:

- <START T> -- when T begins
- Update: <T,X,u,v>
 - T updates X, *old* value=u, *new* value=v
 - Logical description of the change
- <COMMIT T> or <ABORT T> then <END>
- <CLR> – we'll talk about them later.

ARIES Recovery Manager

Rule:

- If T modifies X, then $\langle T, X, u, v \rangle$ must be written to disk before $\text{OUTPUT}(X)$

We are free to OUTPUT early or late w.r.t commits

LSN = Log Sequence Number

- **LSN** = identifier of a log entry
 - Log entries belonging to the same TXN are linked with extra entry for previous LSN
- Each page contains a **pageLSN**:
 - LSN of log record for latest update to that page

ARIES Data Structures

- **Active Transactions Table**
 - Lists all active TXN's
 - For each TXN: **lastLSN** = its most recent update LSN
- **Dirty Page Table**
 - Lists all dirty pages
 - For each dirty page: **recoveryLSN** (**recLSN**)= first LSN that caused page to become dirty
- **Write Ahead Log**
 - LSN, prevLSN = previous LSN for same txn

W _{T100} (P7)
W _{T200} (P5)
W _{T200} (P6)
W _{T100} (P5)

ARIES Data Structures

Dirty pages

pageID	recLSN
P5	102
P6	103
P7	101

Log (WAL)

LSN	prevLSN	transID	pageID	Log entry
101	-	T100	P7	
102	-	T200	P5	
103	102	T200	P6	
104	101	T100	P5	

Active transactions

transID	lastLSN
T100	104
T200	103

Buffer Pool

P8	P2	...
	...	
P5 PageLSN=104	P6 PageLSN=103	P7 PageLSN=101

ARIES Normal Operation

T writes page P

- What do we do ?

ARIES Normal Operation

T writes page P

- What do we do ?
- Write $\langle T, P, u, v \rangle$ in the Log
- $\text{pageLSN} = \text{LSN}$
- $\text{prevLSN} = \text{lastLSN}$
- $\text{lastLSN} = \text{LSN}$
- $\text{recLSN} = \text{if } \text{isNull} \text{ then LSN}$

ARIES Normal Operation

Buffer manager wants to OUTPUT(P)

- What do we do ?

Buffer manager wants INPUT(P)

- What do we do ?

ARIES Normal Operation

Buffer manager wants to OUTPUT(P)

- Flush log up to **pageLSN**
- Remove P from **Dirty Pages** table

Buffer manager wants INPUT(P)

- What do we do ?

ARIES Normal Operation

Buffer manager wants to OUTPUT(P)

- Flush log up to **pageLSN**
- Remove P from **Dirty Pages** table

Buffer manager wants INPUT(P)

- Create entry in **Dirty Pages** table
recLSN = NULL

ARIES Normal Operation

Transaction T starts

- What do we do ?

Transaction T commits/aborts

- What do we do ?

ARIES Normal Operation

Transaction T starts

- Write **<START T>** in the log
- New entry T in Active TXN;
lastLSN = null

Transaction T commits

- What do we do ?

ARIES Normal Operation

Transaction T starts

- Write <START T> in the log
- New entry T in Active TXN;
lastLSN = null

Transaction T commits

- Write <COMMIT T> in the log
- Flush log up to this entry
- Write <END>

Checkpoints

Write into the log

- Entire **active transactions table**
- Entire **dirty pages table**

Recovery always starts by analyzing latest checkpoint

Background process periodically flushes dirty pages to disk

Announcements

- Lab 4 out tomorrow
- Lab 5 due dates extended
 - No late days allowed (will take that into consideration when setting deadline)
- HW 6 released tomorrow
 - On parallel database concepts

ARIES Recovery

1. Analysis pass

- Figure out what was going on at time of crash
- List of dirty pages and active transactions

2. Redo pass (repeating history principle)

- Redo all operations, even for transactions that will not commit
- Get back to state at the moment of the crash

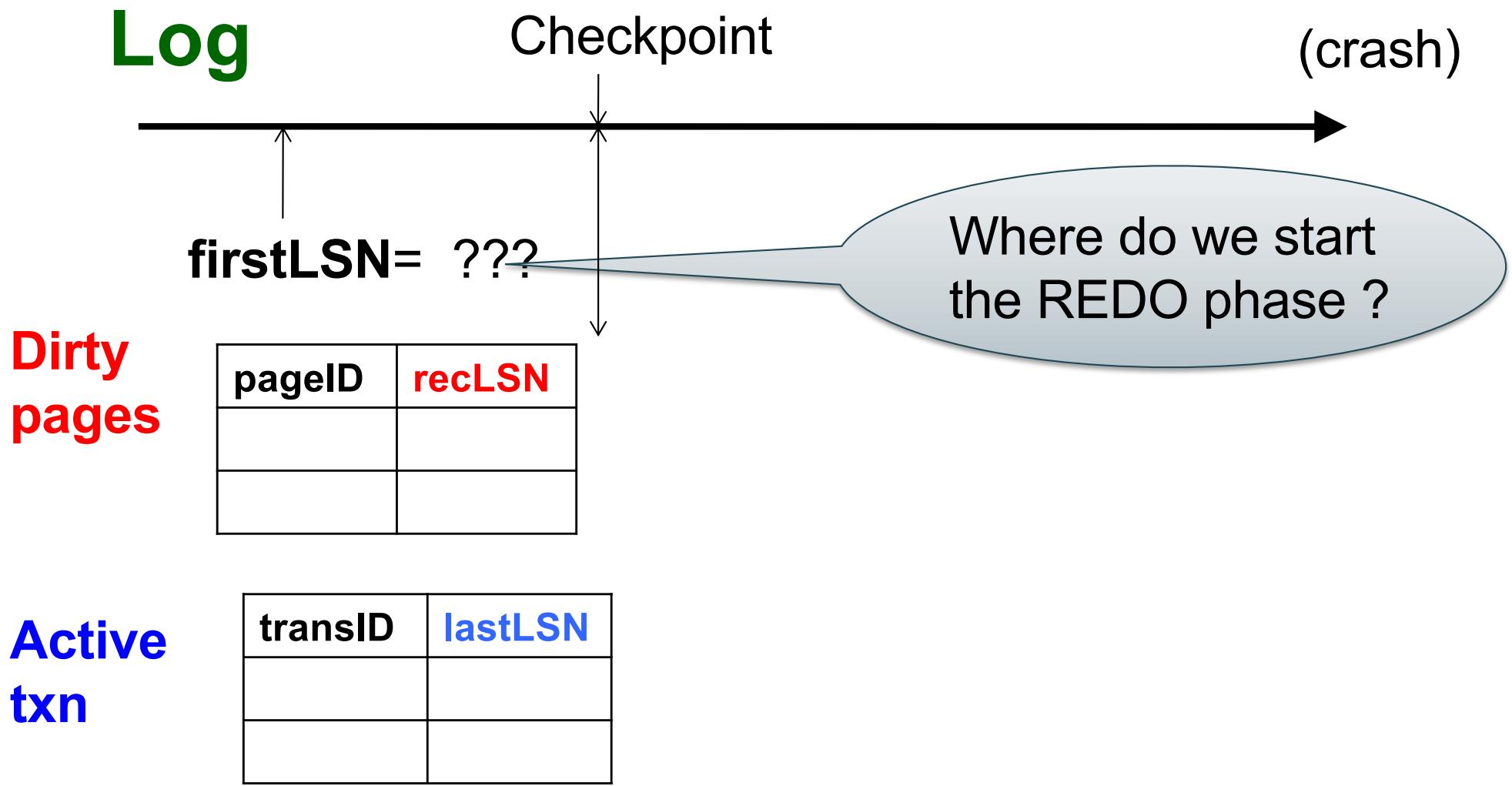
3. Undo pass

- Remove effects of all uncommitted transactions
- Log changes during undo in case of another crash during undo

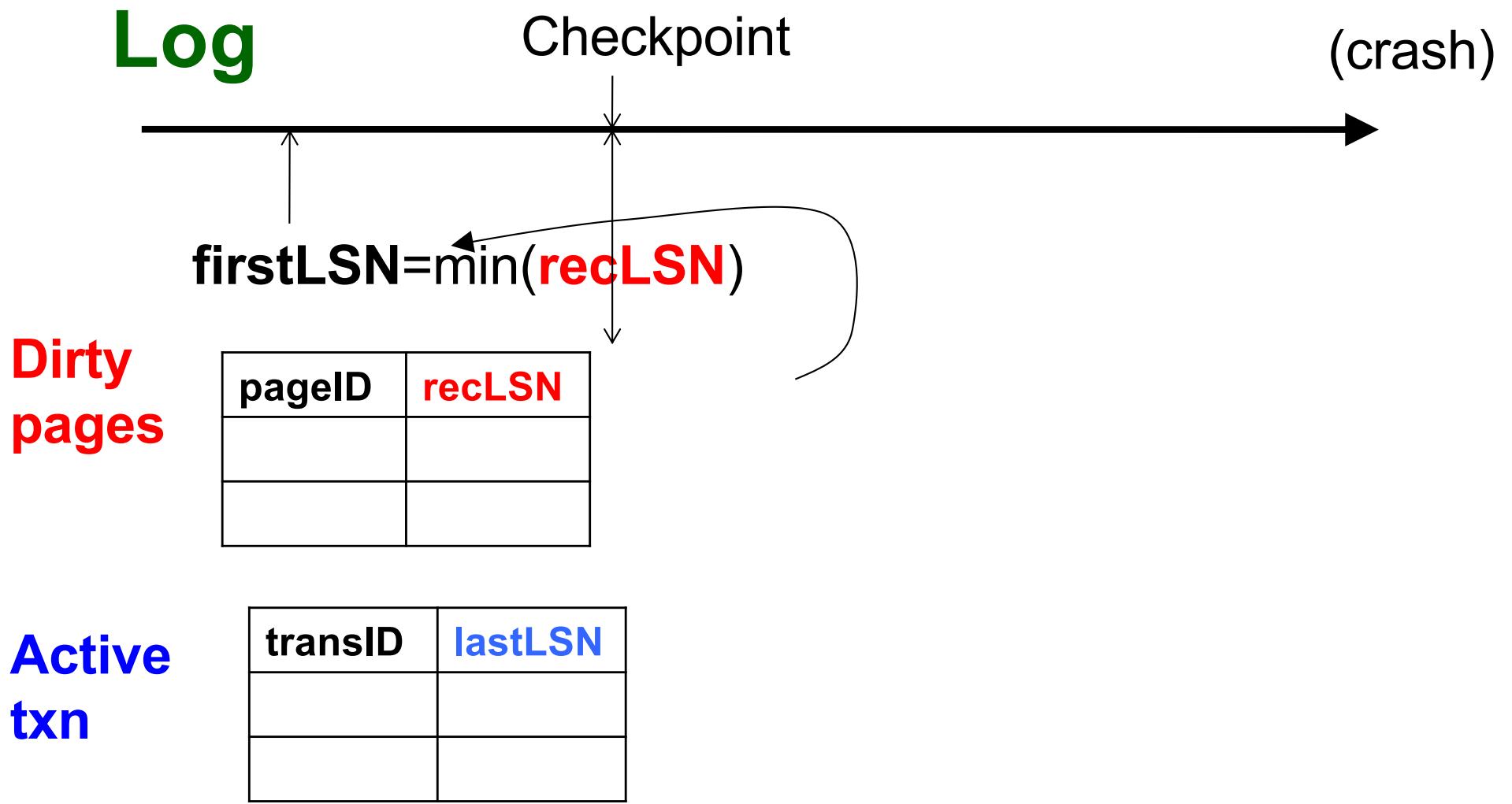
1. Analysis Phase

- Goal
 - Determine point in log where to start REDO
 - Determine set of dirty pages when crashed
 - Conservative estimate of dirty pages
 - Identify active transactions when crashed
- Approach
 - Rebuild **active transactions table** and **dirty pages table**
 - Reprocess the log from the checkpoint
 - Only update the two data structures
 - Compute: **firstLSN** = smallest of all **recoveryLSN**

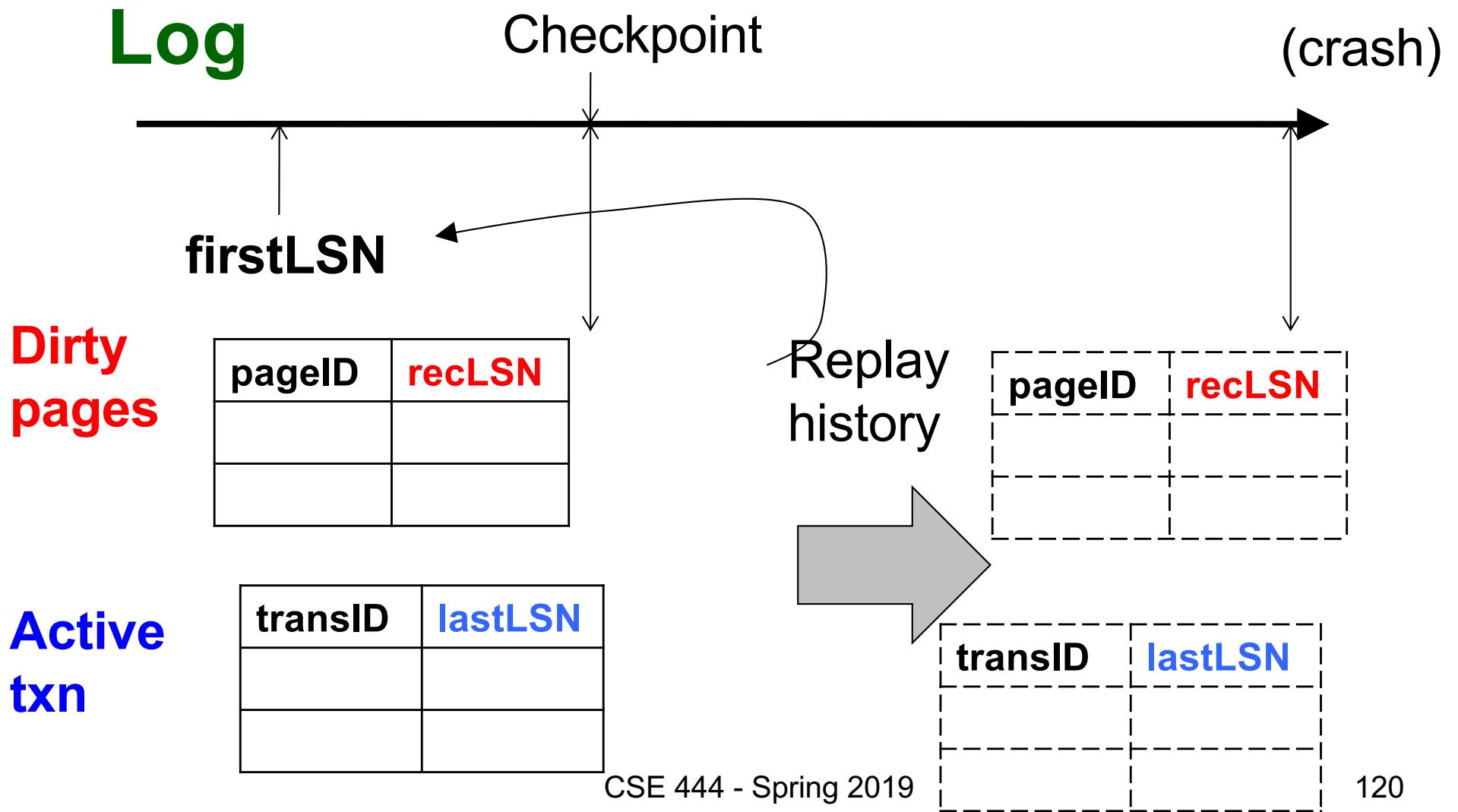
1. Analysis Phase



1. Analysis Phase



1. Analysis Phase



2. Redo Phase

Main principle: replay history

- Process Log forward, starting from **firstLSN**
- Read every log record, sequentially
- Redo actions are not recorded in the log
- Needs the **Dirty Page Table**

2. Redo Phase: Details

For each Log entry record LSN: $\langle T, P, u, v \rangle$

- Redo the action $P=u$ and $\text{WRITE}(P)$
- Only redo actions that need to be redone

2. Redo Phase: Details

For each **Log** entry record **LSN: <T,P,u,v>**

- If P is not in **Dirty Page** then **no update**
- If **recLSN** > **LSN**, then **no update**
- Read page from disk:
If **pageLSN** \geq **LSN**, then **no update**
- Otherwise perform update

2. Redo Phase: Details

What happens if system crashes during
REDO ?

2. Redo Phase: Details

What happens if system crashes during REDO ?

We REDO again ! The pageLSN will ensure that we do not reapply a change twice

3. Undo Phase

- Cannot “unplay” history, in the same way as we “replay” history
- WHY NOT ?

3. Undo Phase

- Cannot “unplay” history, in the same way as we “replay” history
- WHY NOT ?
 - Undo only the loser transactions
 - Need to support ROLLBACK: selective undo, for one transaction
- Hence, *logical* undo v.s. *physical* redo

3. Undo Phase

Main principle: “logical” undo

- Start from end of Log, move backwards
- Read only affected log entries
- Undo actions are written in the Log as special entries: CLR (Compensating Log Records)
- CLRs are redone, but never undone

3. Undo Phase: Details

- “Loser transactions” = uncommitted transactions in **Active Transactions Table**
- **ToUndo** = set of **lastLSN** of loser transactions

3. Undo Phase: Details

While **ToUndo** not empty:

- Choose most recent (largest) **LSN** in **ToUndo**
- If **LSN** = regular record **<T,P,u,v>**:
 - Write a **CLR** where **CLR.undoNextLSN** = **LSN.prevLSN**
 - Undo v
- If **LSN** = **CLR** record:
 - Don't undo !
- if **CLR.undoNextLSN** not null, insert in **ToUndo**
otherwise, write **<END>** in log

3. Undo Phase: Details

What happens if system crashes during UNDO ?

3. Undo Phase: Details

What happens if system crashes during UNDO ?

We do not UNDO again ! Instead, each CLR is a REDO record: we simply redo the undo