

Database System Internals

Transactions: Recovery (part 2)

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Force/No-steal (most strict)

- **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 (least strict)

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

In both cases, 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	 Crash!
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	
COMMIT						<COMMIT T>

WHAT DO WE DO ?

We **UNDO** by setting B=8 and A=8

After Crash

- This is all we see (for example):

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

After Crash

- This is all we see (for example):

Disk A	Disk B
16	8

```
<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
16	8

```
<START T>  
<T,A,8>  
<T,B,8>
```

After Crash

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

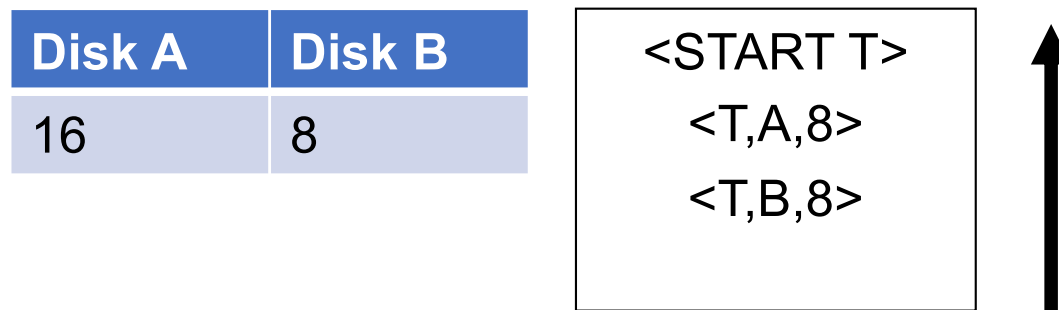
Disk A	Disk B
16	8

```
<START T>  
<T,A,8>  
<T,B,8>
```

- What direction?

After Crash

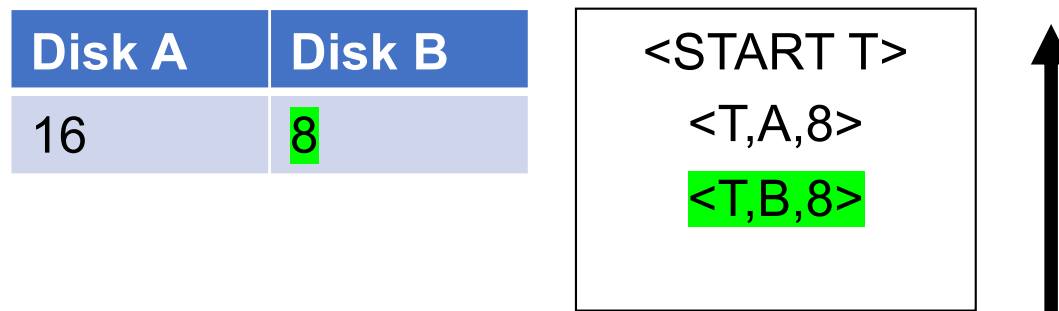
- This is all we see (for example):
- Need to step through the log



- 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

Disk A	Disk B
16	8

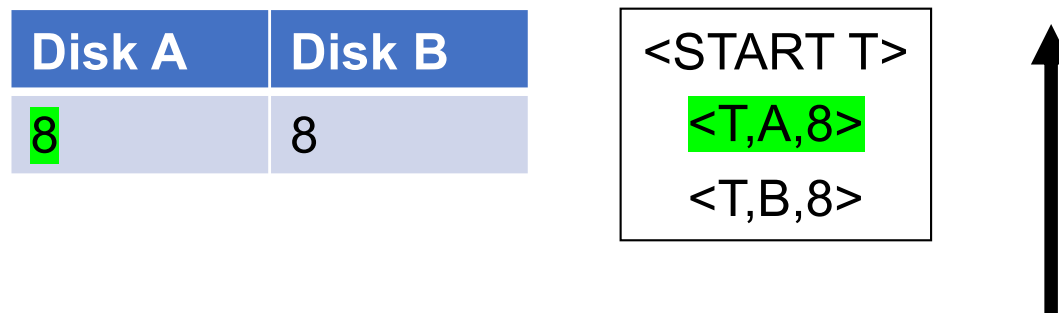
<START T>
<T,A,8>
<T,B,8>



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

After Crash

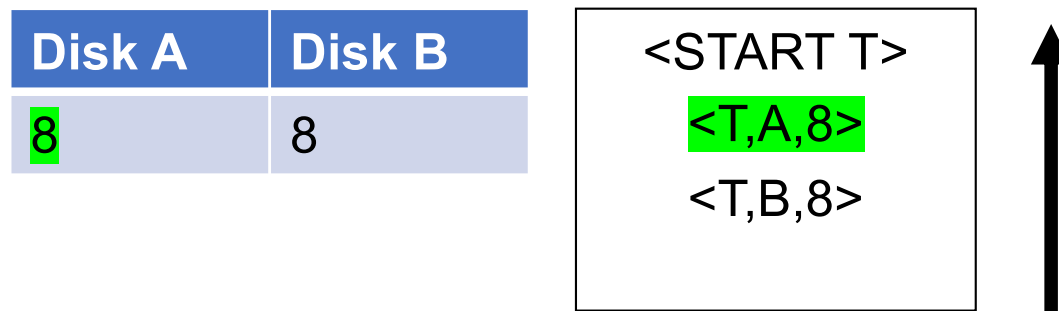
- This is all we see (for example):
- Need to step through the log



- 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 its actions have been executed

Recovery with Undo Log

After system's crash, run recovery manager

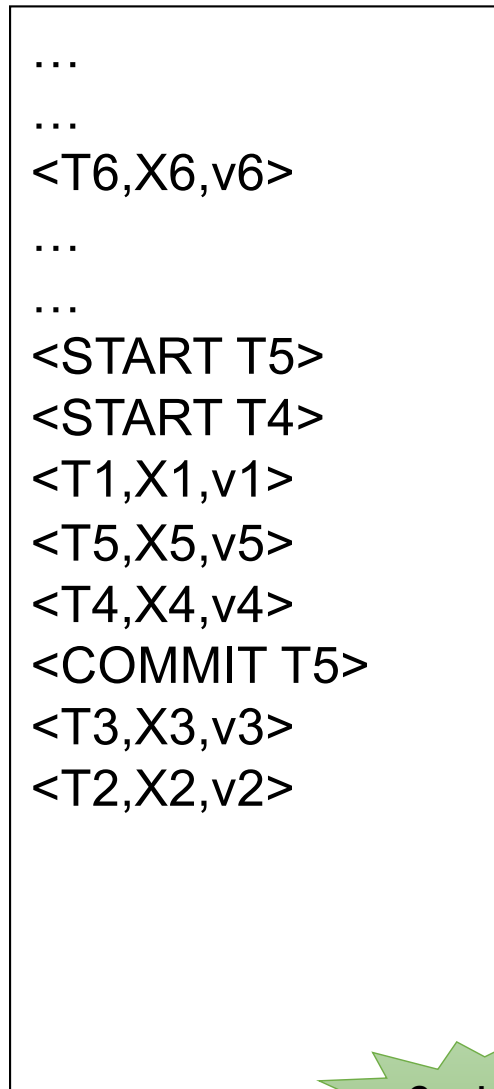
- Decide for each transaction T whether it is completed or not
 - <START T>....<COMMIT T>.... = yes
 - <START T>....<ABORT T>..... = yes (already cleaned up)
 - <START T>..... = no
- Undo all modifications by **incomplete** transactions

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

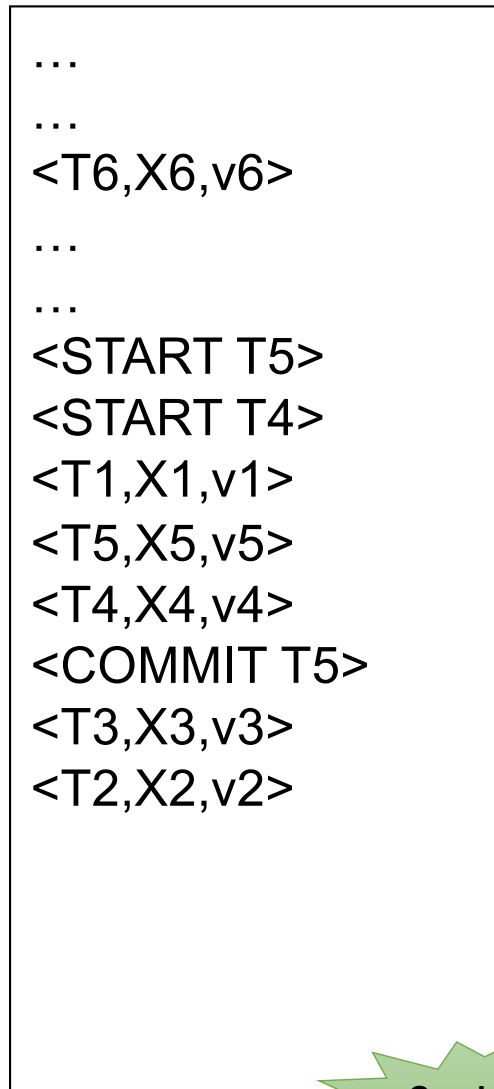


Question 1: Which updates are undone ?

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



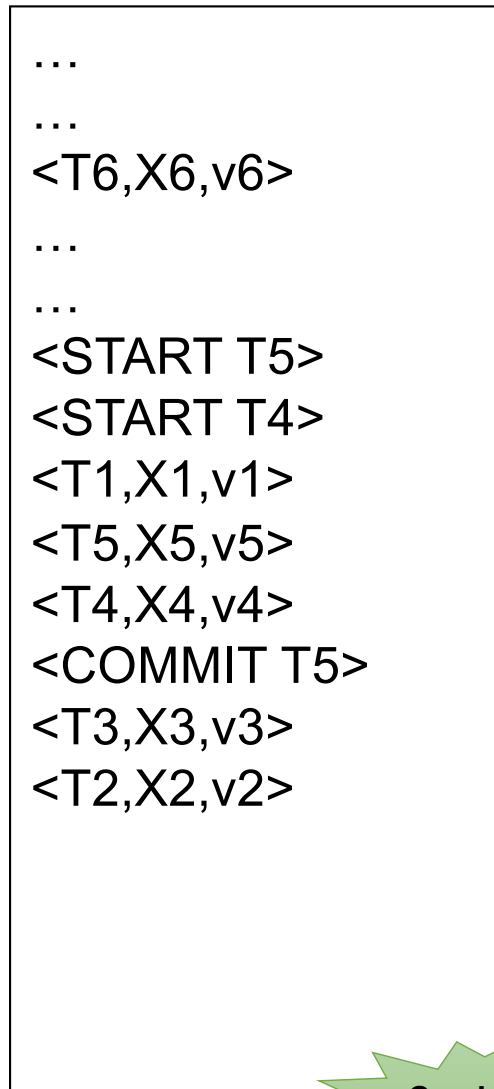
Question 1: Which updates are undone ?

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 ?

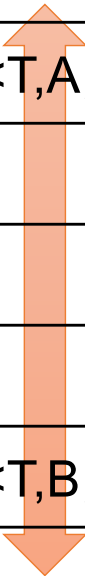
To the beginning.

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>

When must we force pages to disk ?



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>

FORCE

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 $\langle \text{COMMIT } T \rangle$

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



FORCE

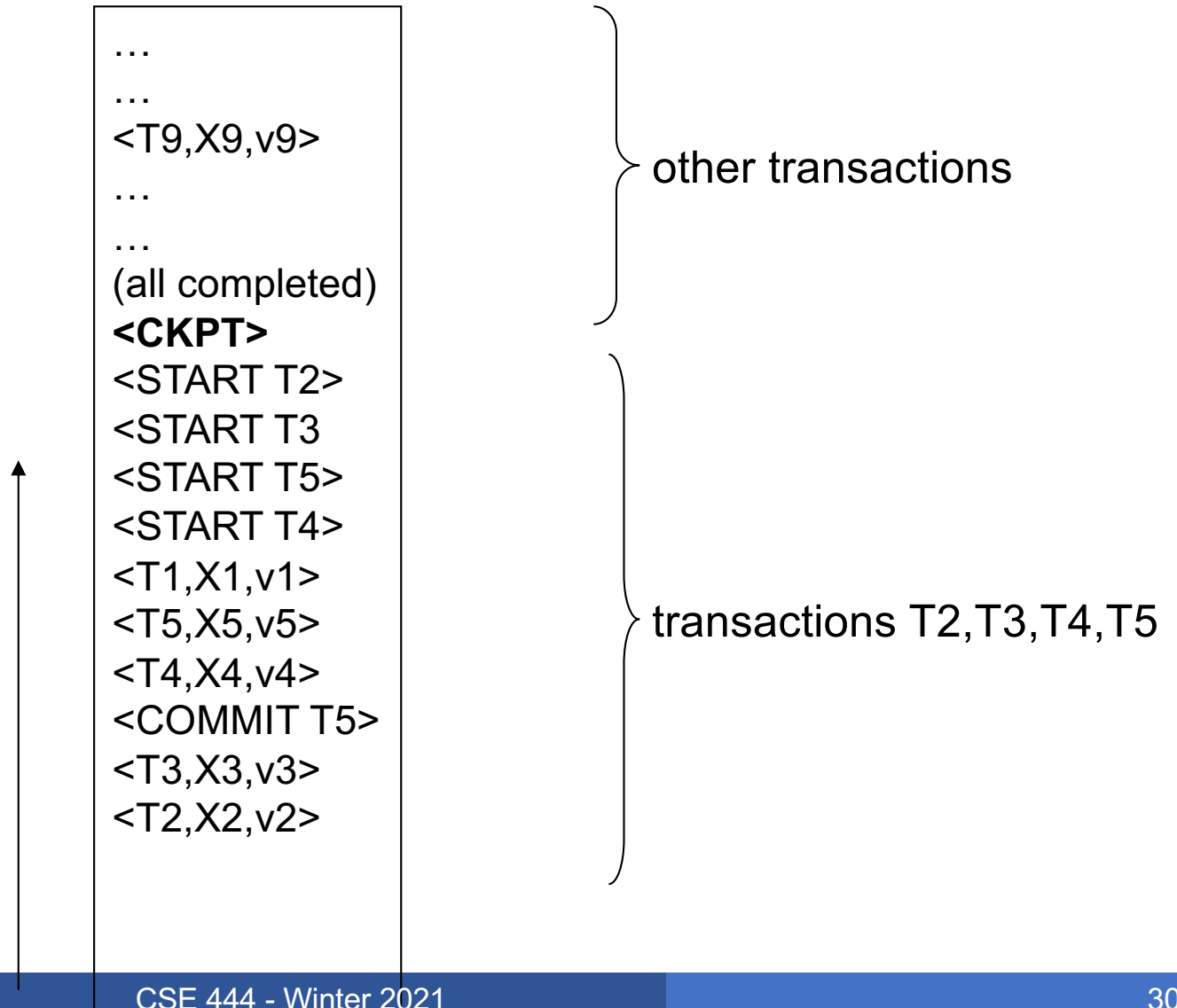
Checkpointing

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

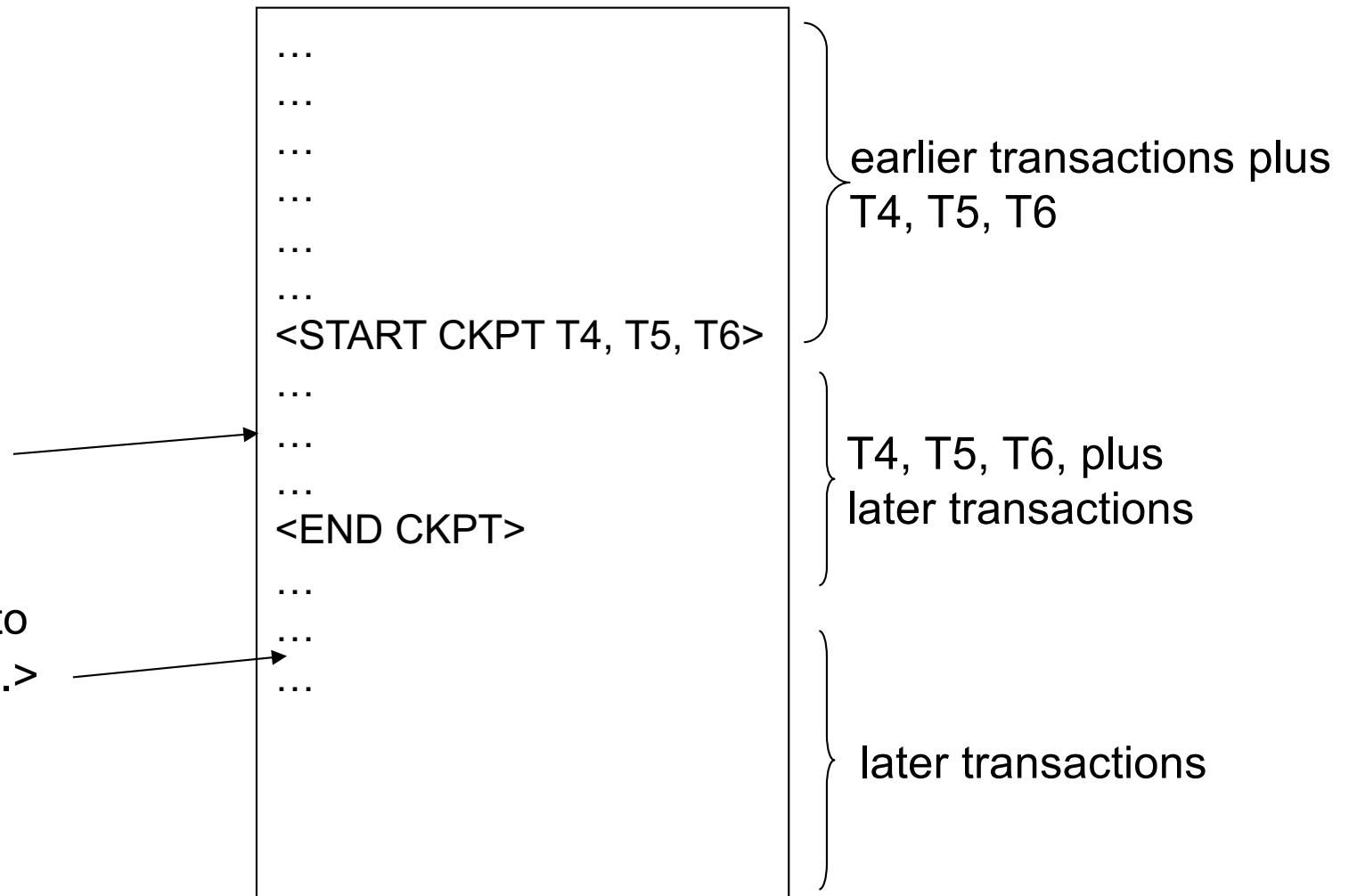
Nonquiescent Checkpointing

- Write a `<START CKPT(T1,...,Tk)>` 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 `<END CKPT>`, flush log to disk

Undo with Nonquiescent Checkpointing

If we crash here:
Need to read
Back to start of
T4, T5, T6

If we crash here:
Need to read only to
<START CKPT T4..>



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

Implementing ROLLBACK

- Rec
- RO
- Ide
- How
 -
 -
 -

```
...
...
<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>
```

CK

sing

REDO

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	

How do we recover ?

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	

How do we recover ?

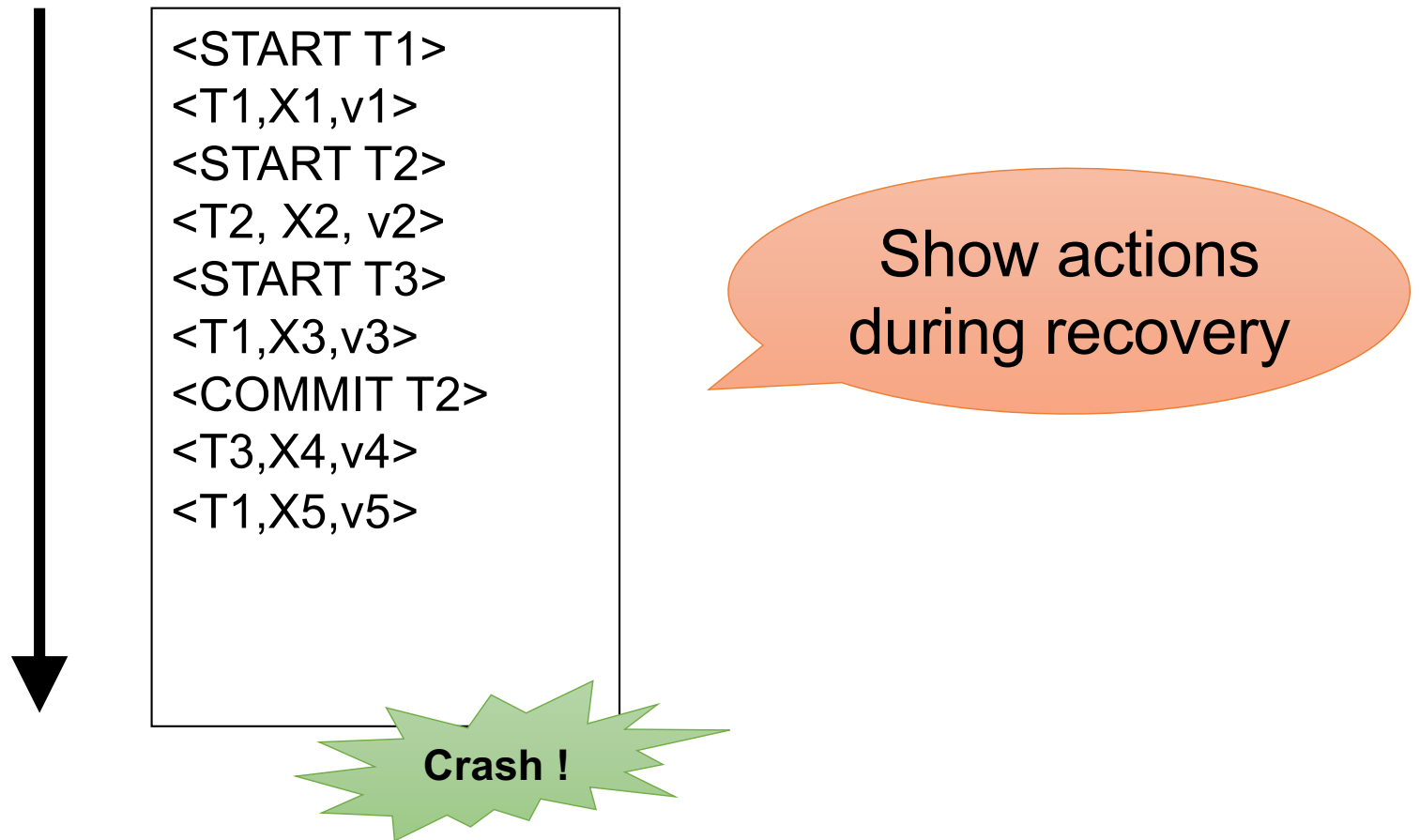
We **REDO** by setting A=16 and B=16

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(T1,...,Tk)>` where $T1, \dots, Tk$ are all active txn's
- Begin 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!
It does not mean that $T1, \dots, Tk$ are complete**

Nonquiescent Checkpointing

Step 1: look for
The last
<END CKPT> and it's
<START CKPT>

All OUTPUTs
of T1 are
known to be on disk

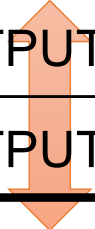
Cannot
use

```
...  
<START T1>  
...  
<COMMIT T1>  
...  
<START T4>  
...  
<START CKPT T4, T5, T6>  
...  
...  
...  
...  
<END CKPT>  
...  
...  
<START CKPT T9, T10>  
...
```

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	
t:=t*2	16	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	

When must we force pages to disk ?



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	

RULE: OUTPUT *after* COMMIT

NO-STEAL

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 $\text{OUTPUT}(X)$

- Hence: OUTPUTs are done *late*

NO-STEAL

Comparison Undo/Redo

■ Undo logging:

Steal/Force

- 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

No-Steal/No-Force

- 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/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	

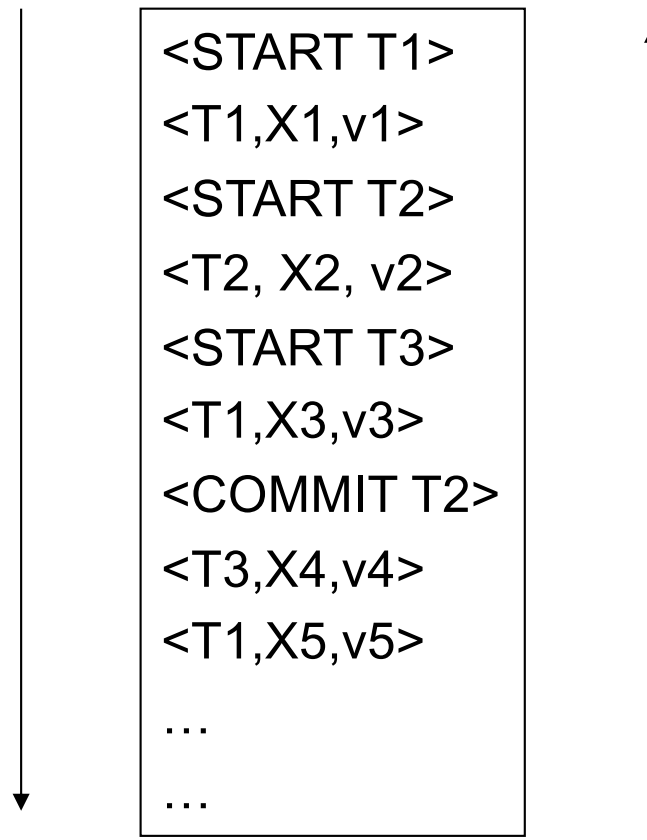
Can OUTPUT whenever we want: before/after COMMIT

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 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

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 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

Data Structures

$W_{T100}(P7)$

$W_{T200}(P5)$

$W_{T200}(P6)$

$W_{T100}(P5)$

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**
 - **pageLSN=LSN**
 - **prevLSN=lastLSN**
 - **lastLSN=LSN**
 - **recLSN**=if isNull 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

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

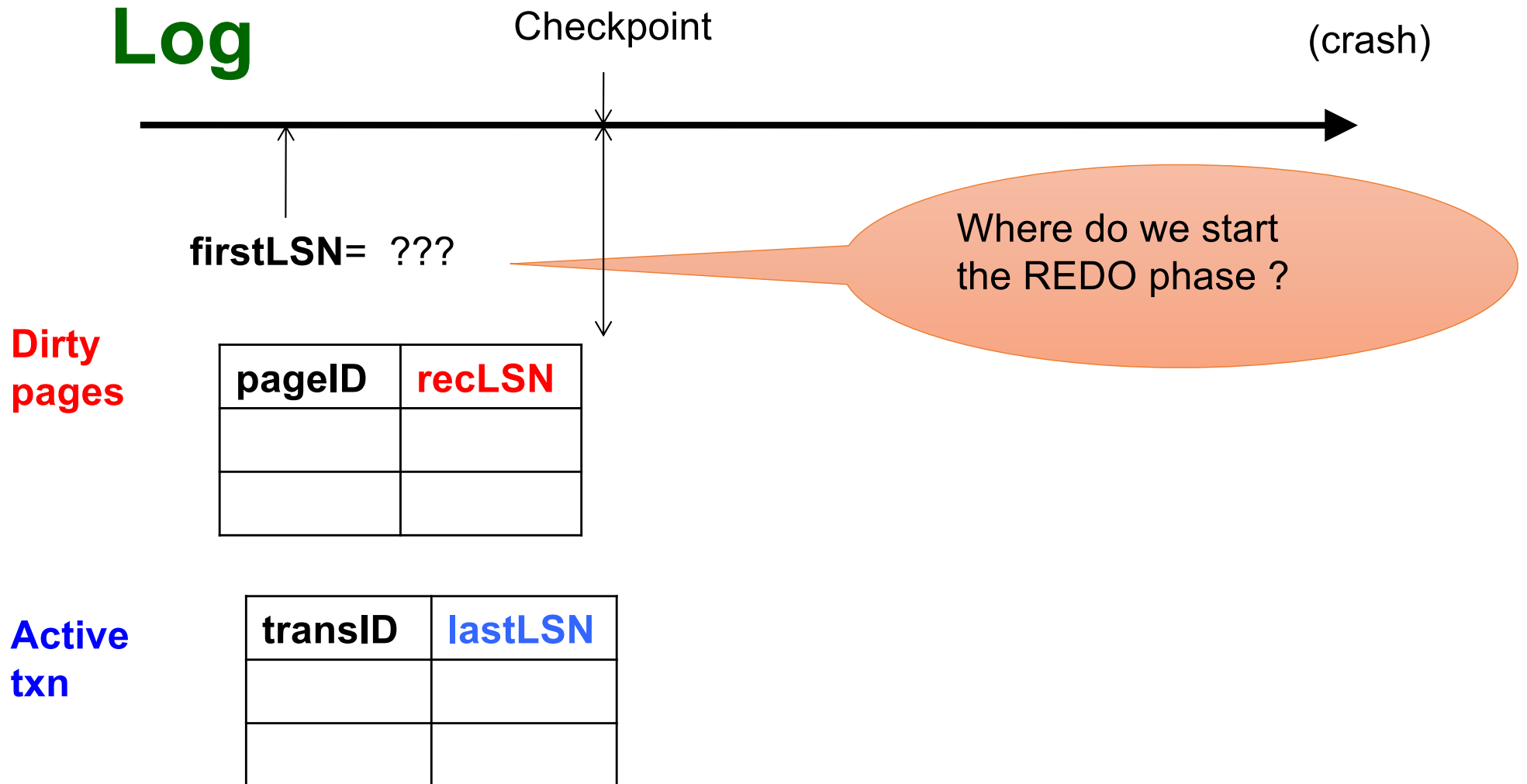
■ Goal

- 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

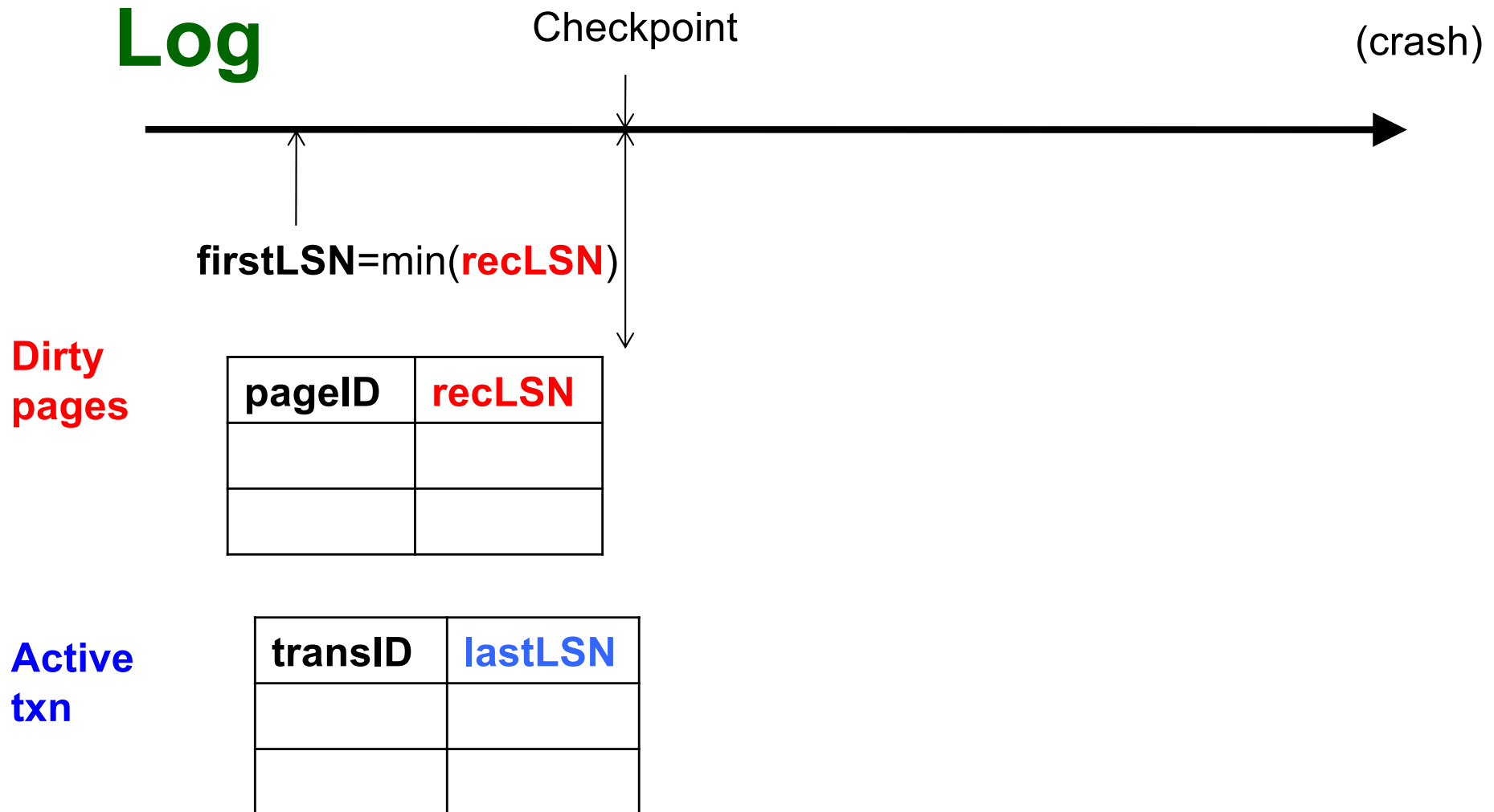
■ Approach

- 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**

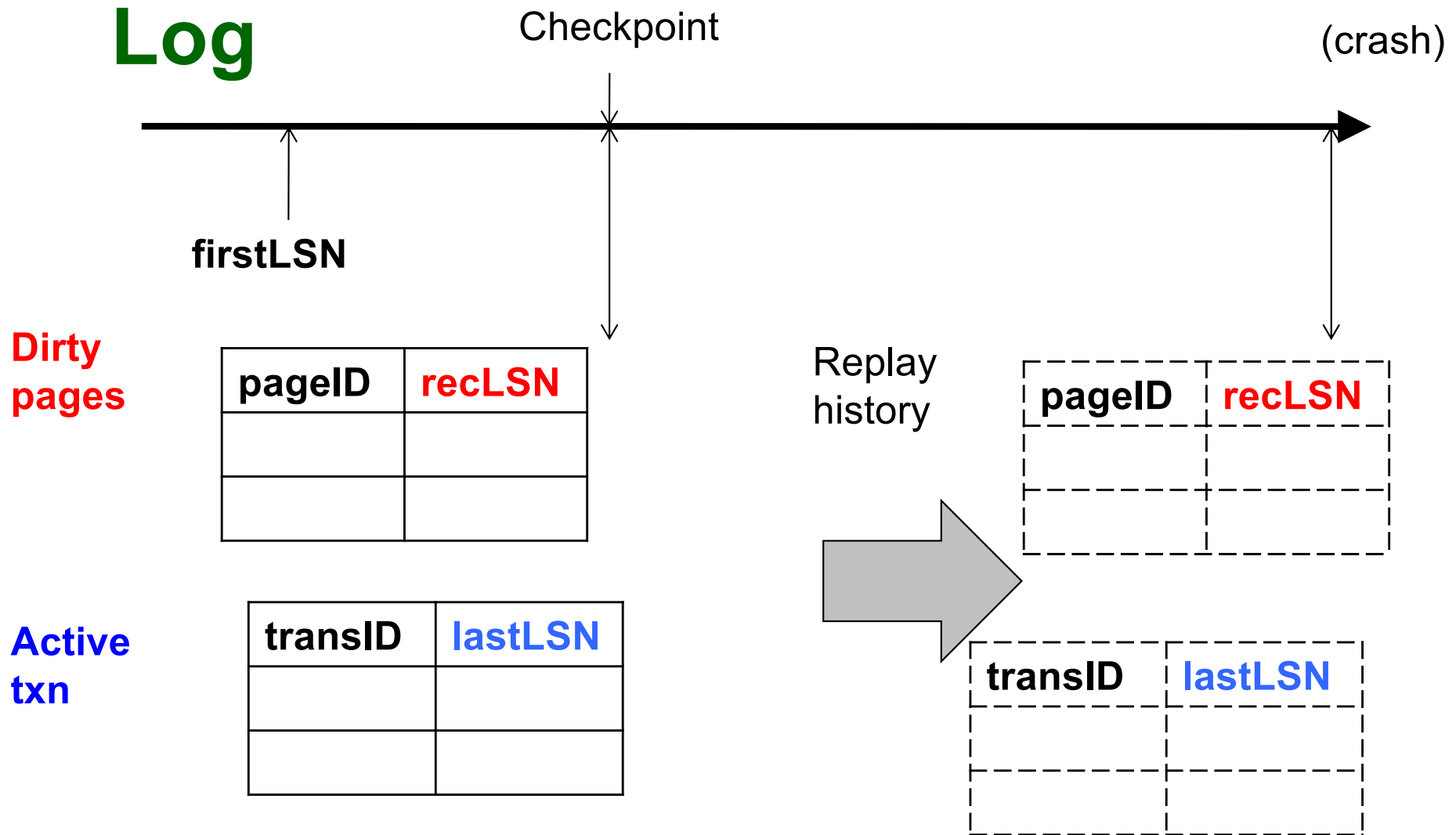
1. Analysis Phase



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 $WRITE(P)$
- Only redo actions that need to be redone

2. Redo Phase: Details

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

- 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