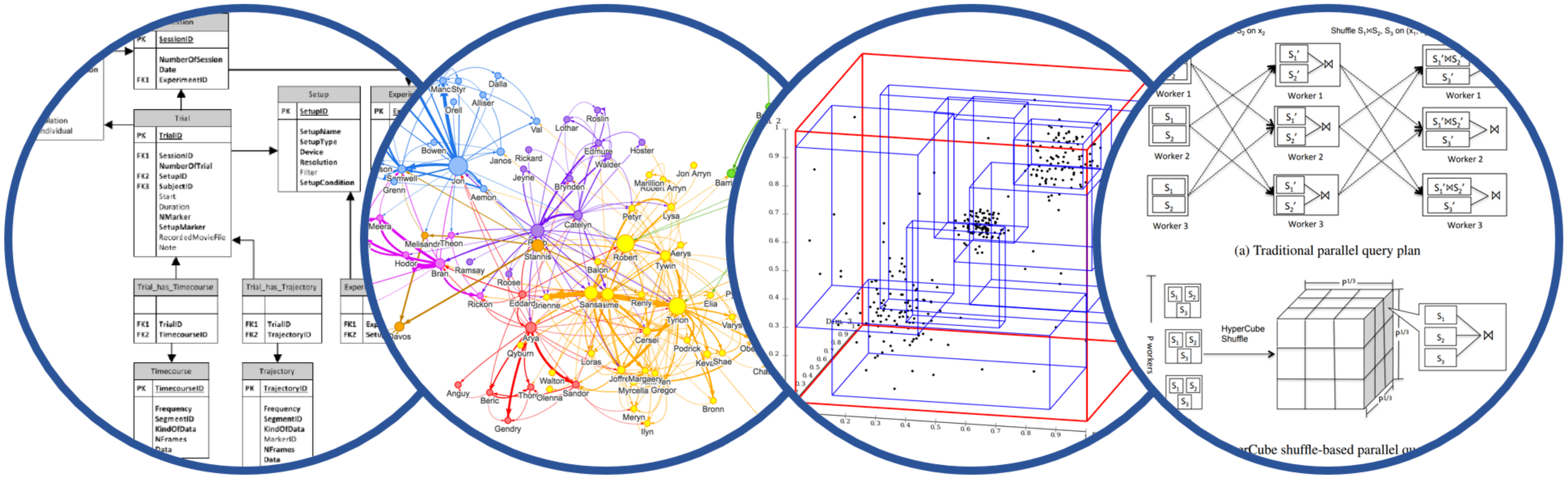

Database System Internals

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	
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

Crash !

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 ?

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

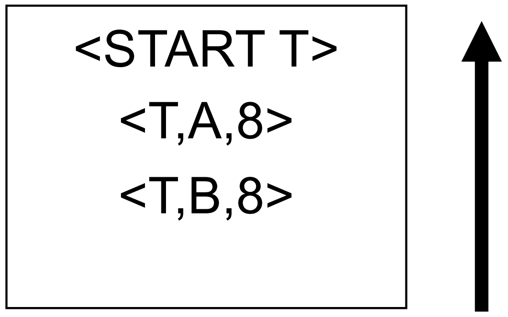
```
<START T>
<T,A,8>
<T,B,8>
```

- What direction?

After Crash

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

Disk A	Disk B
16	8



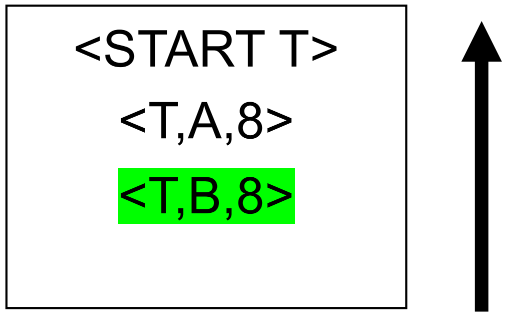
```
<START T>
<T,A,8>
<T,B,8>
```

- 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

Disk A	Disk B
16	8



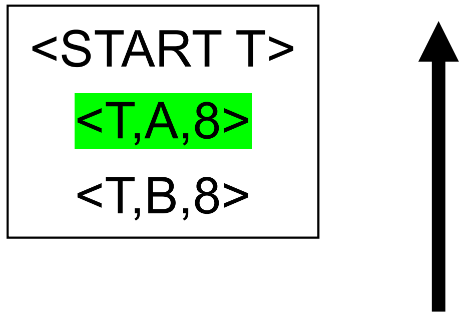
```
<START T>
<T,A,8>
<T,B,8>
```

- 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

Disk A	Disk B
16	8



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

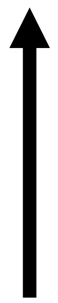
- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

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

Disk A	Disk B
8	8

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

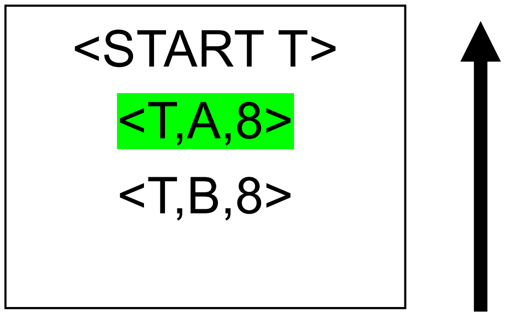


- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

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

Disk A	Disk B
8	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

- 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

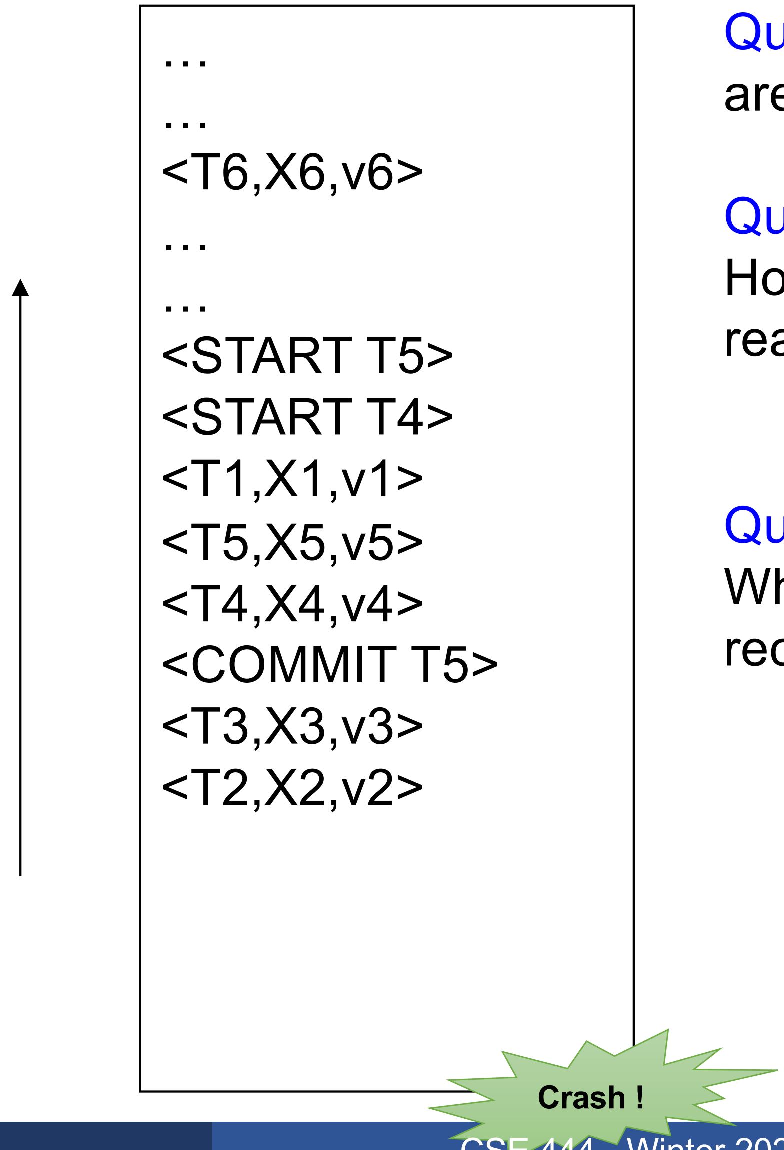
Recovery with Undo Log

Recovery manager:

- Read log <u>from the end</u>; 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



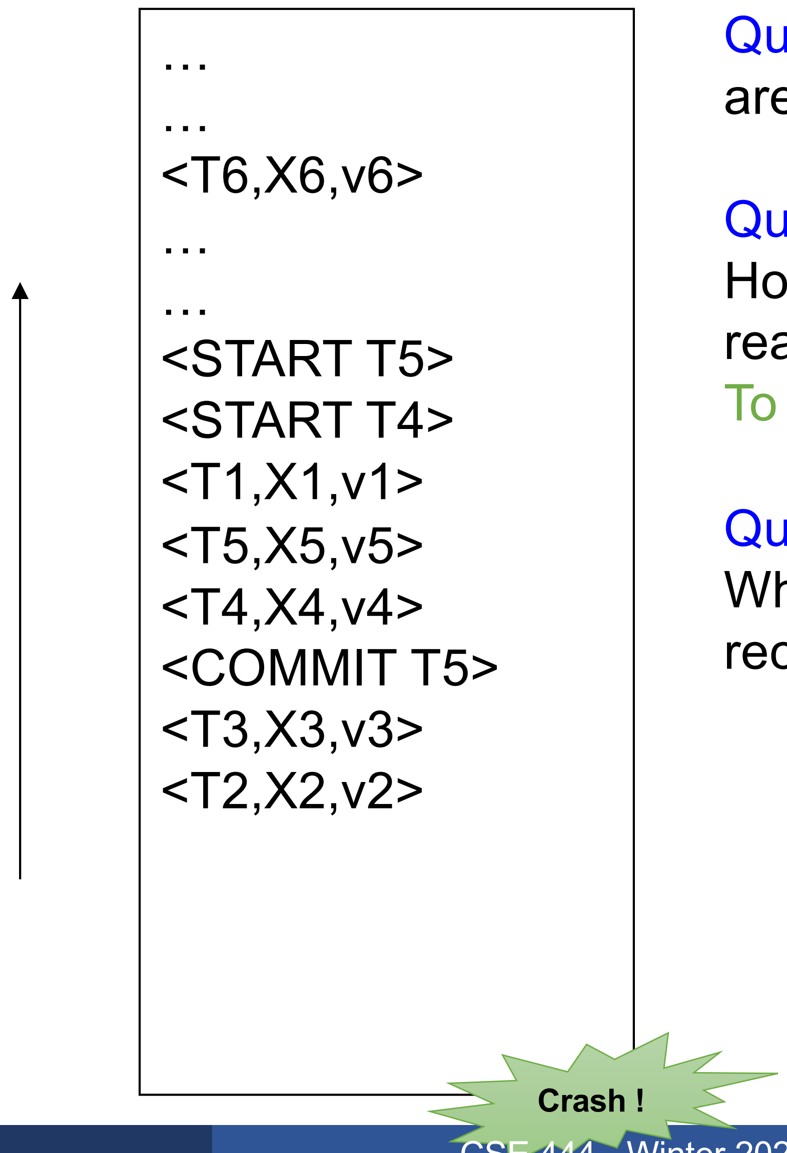
```
…
…
<T6,X6,v6>
…
…
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>
```

Question1: 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



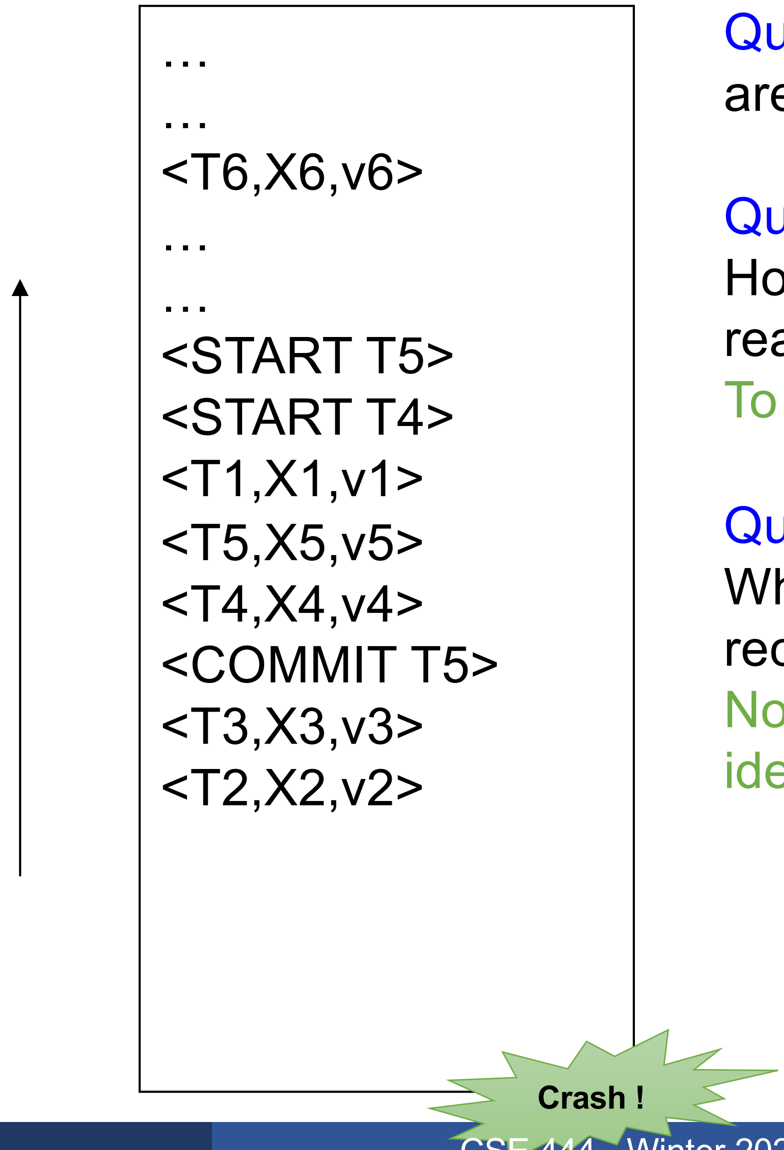
```
…
…
<T6,X6,v6>
…
…
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>
```

Question1: 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



```
…
…
<T6,X6,v6>
…
…
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>
```

Question1: 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			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				FORCE		<COMMIT T>

RULES: log entry *before* OUTPUT *before* COMMIT

Undo-Logging Rules

U1: If T modifies X, then <T,X,v> must be written to disk before OUTPUT(X)

U2: If T commits, then OUTPUT(X) must be written to disk before <COMMIT T>

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

FORCE

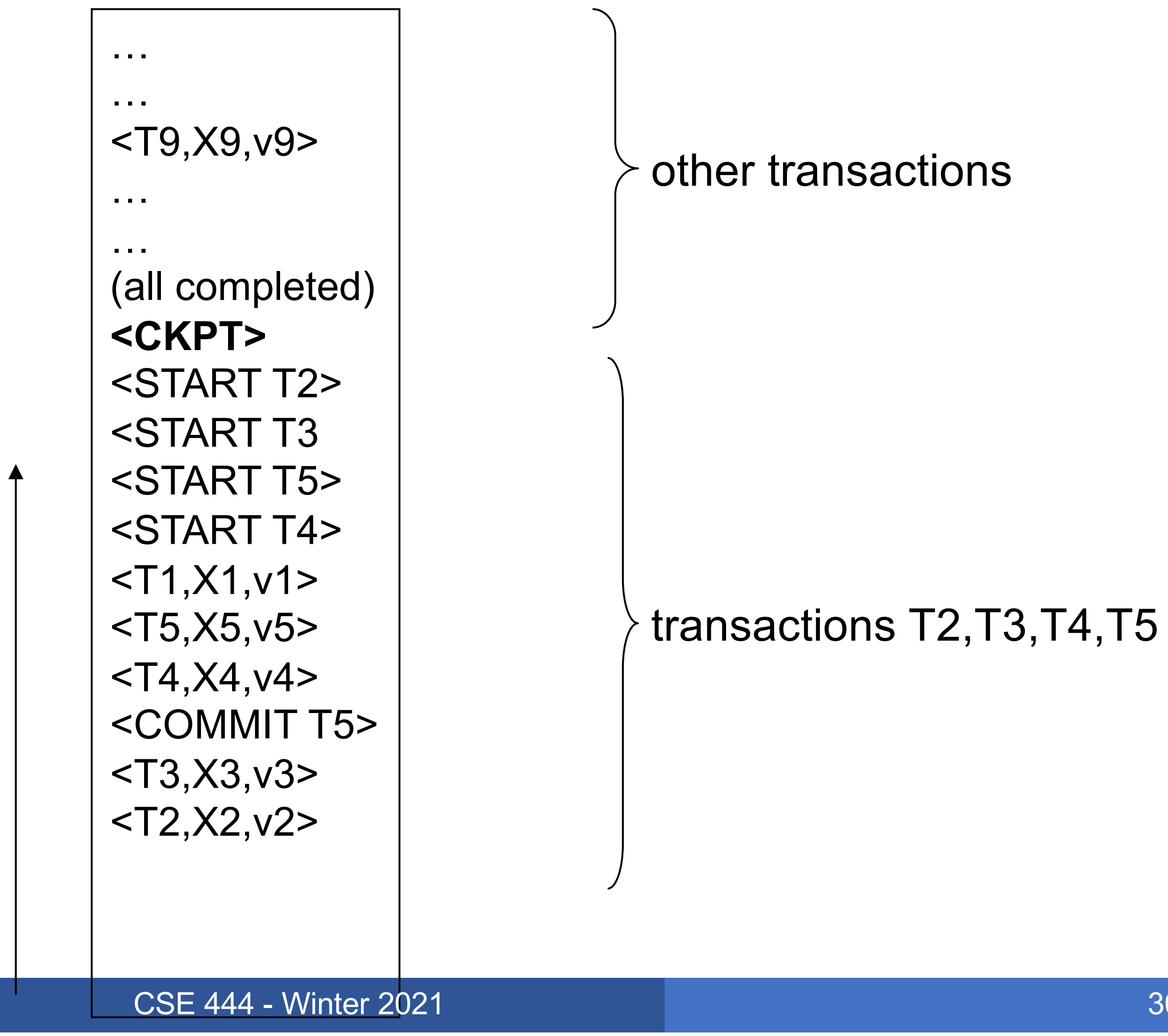
Checkpointing

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>



```
…
…
<T9,X9,v9>
…
…
(all completed)
<CKPT>
<START T2>
<START T3
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>
```

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

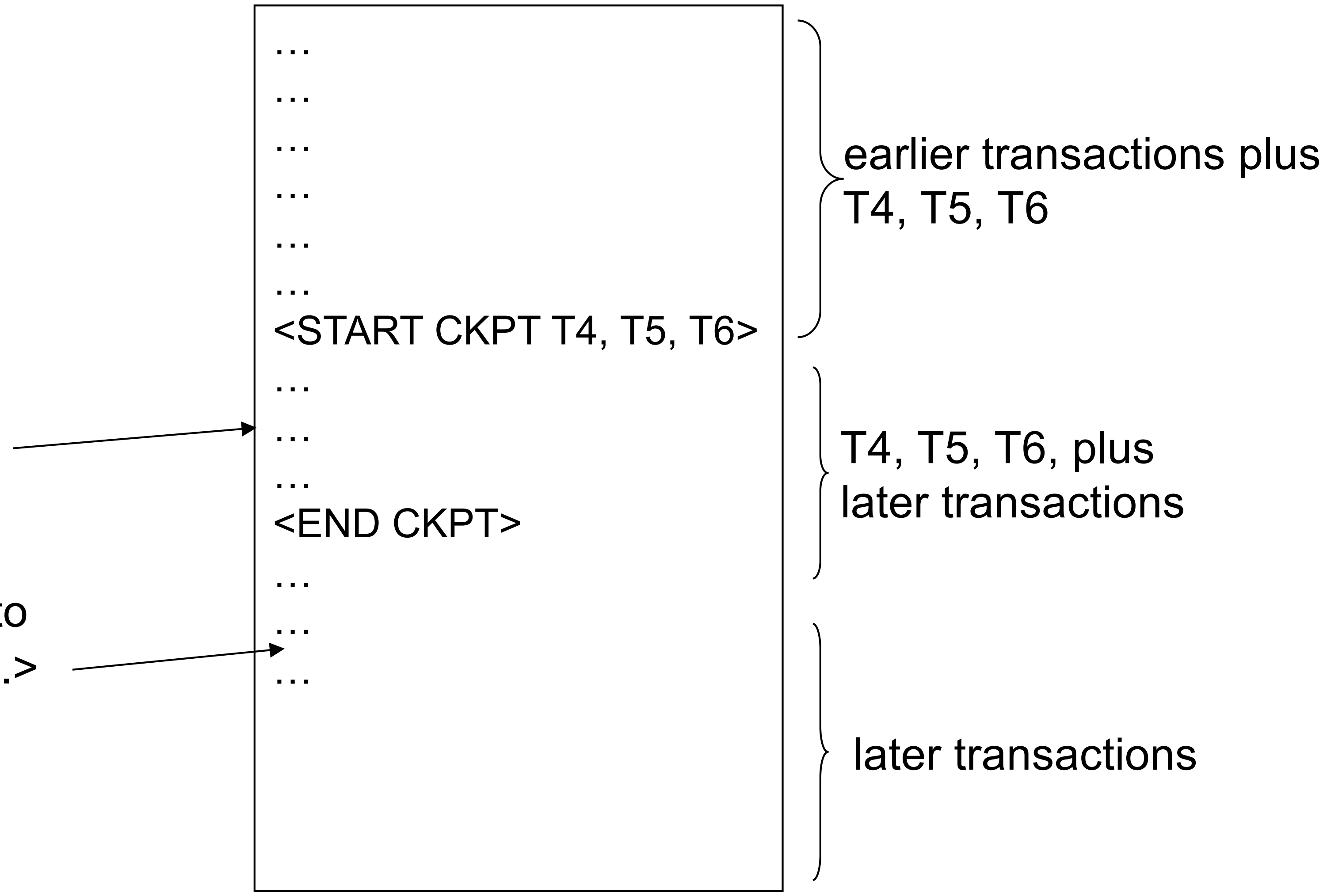
Nonquiescent Checkpointing

- Write a <START CKPT(T1,…,Tk)> where T1,…,Tk are all active transactions. Flush log to disk
- Continue normal operation
- When all of T1,…,Tk 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..>


…
…
…
…
…
…
<START CKPT T4, T5, T6>
…
…
…
<END CKPT>
…
…
…
earlier transactions plus T4, T5, T6
T4, T5, T6, plus later transactions
later transactions

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 ACK
- Hov
  - L
  - L sing
    t
  - F

```
…
…
<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

NO-FORCE and NO-STEAL

Announcements

- HW 5 released, due March 2
- Lab 4 out tonight

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 ?

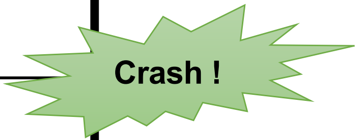
Yes, it's bad: A=16, B=8

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



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:

- <T,X,v>= 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 ?

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	Crash !
OUTPUT(B)	16	16	16	16	16	

How do we recover ?

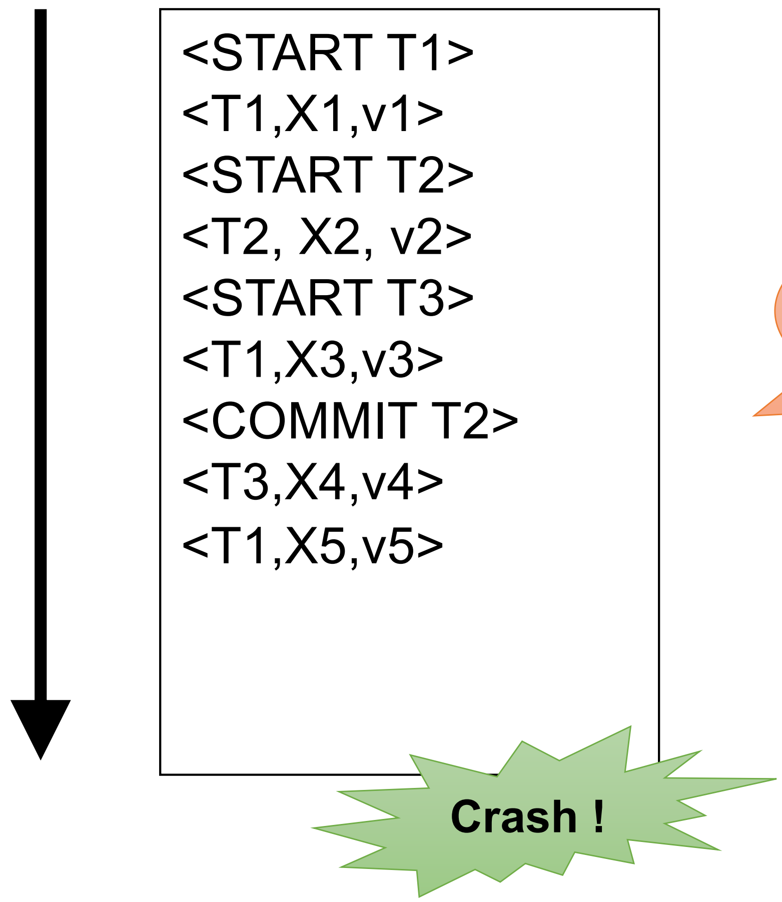
We REDO by setting A=16 and B=16

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



```
<START T1>
<T1,X1,v1>
<START T2>
<T2, X2, v2>
<START T3>
<T1,X3,v3>
<COMMIT T2>
<T3,X4,v4>
<T1,X5,v5>
```

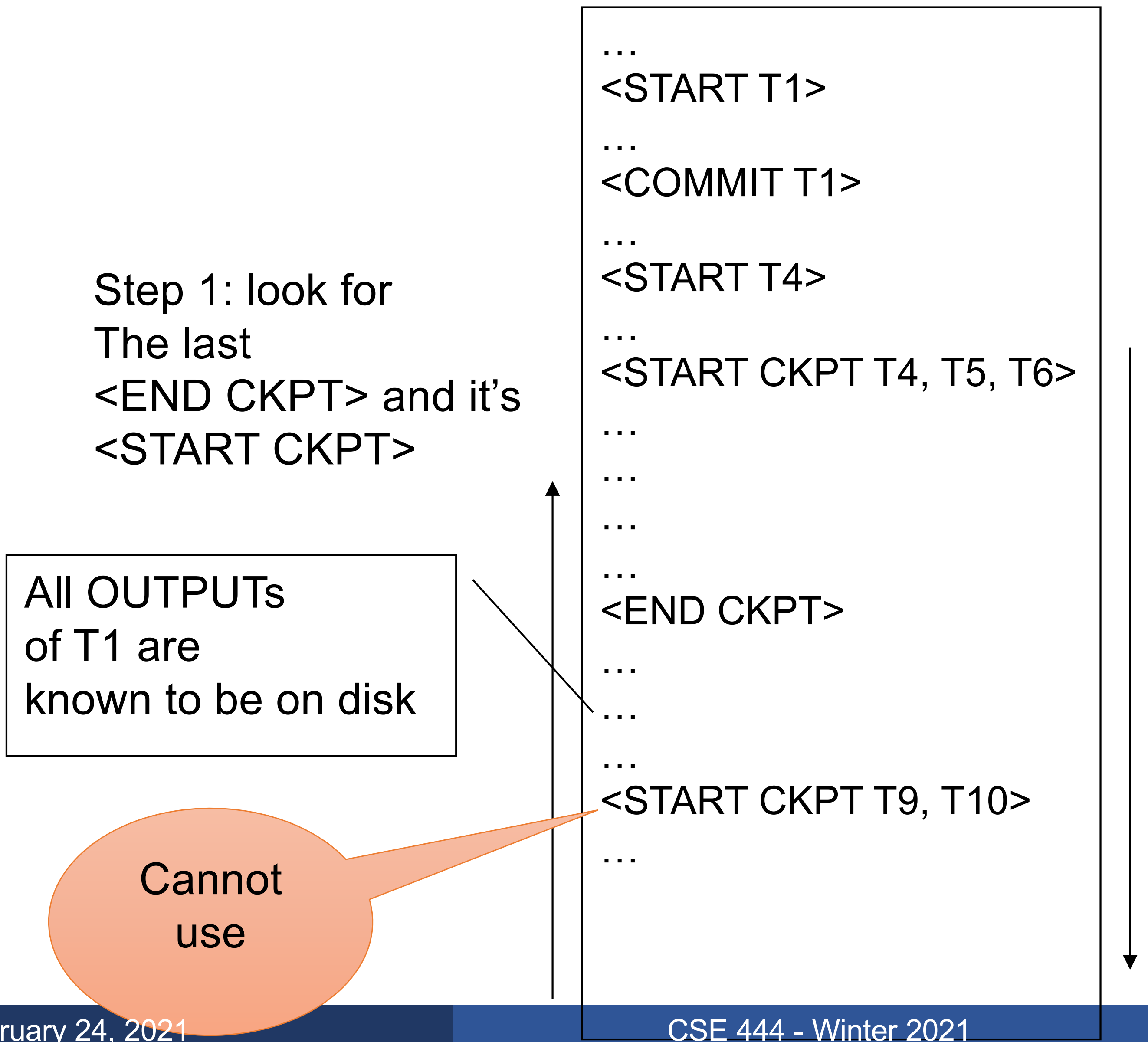
Show actions during recovery

Nonquiescent Checkpointing

- Write a <START CKPT(T1,…,Tk)> where T1,…,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,…,Tk are complete

Nonquiescent Checkpointing



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

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 <T,X,v> and <COMMIT T> must be written to disk before 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

- <T,X,u,v>= 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 <T,X,u,v> must be written to disk before OUTPUT(X)

Note: we are free to OUTPUT early or late relative to <COMMIT T>

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	

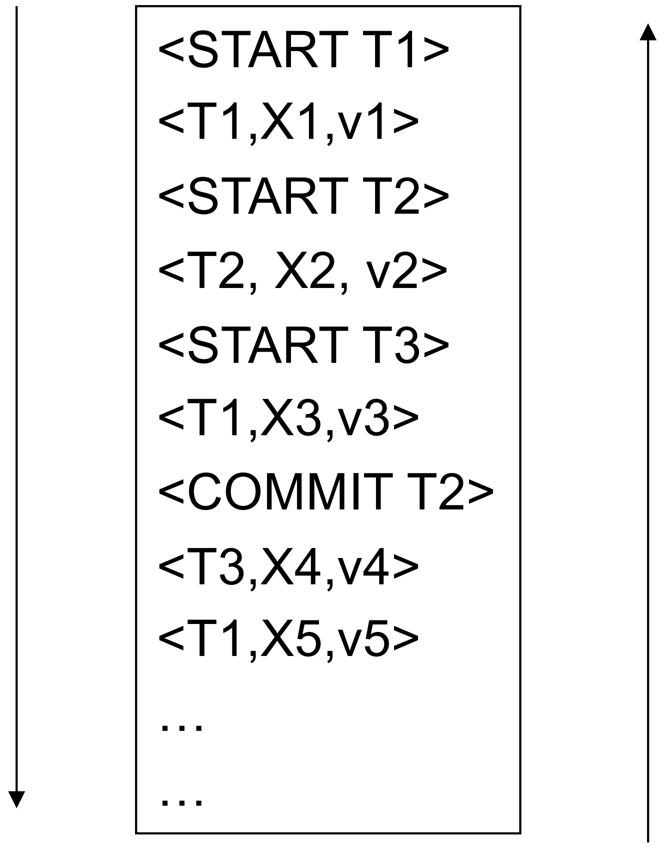
Can OUTPUT whenever we want: before/after COMMIT

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



```
<START T1>
<T1,X1,v1>
<START T2>
<T2, X2, v2>
<START T3>
<T1,X3,v3>
<COMMIT T2>
<T3,X4,v4>
<T1,X5,v5>
…
…
```

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 <T,X,u,v> 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

$W_{T100}(P7)$
$W_{T200}(P5)$
$W_{T200}(P6)$
$W_{T100}(P5)$

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 **<T,P,u,v>** 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

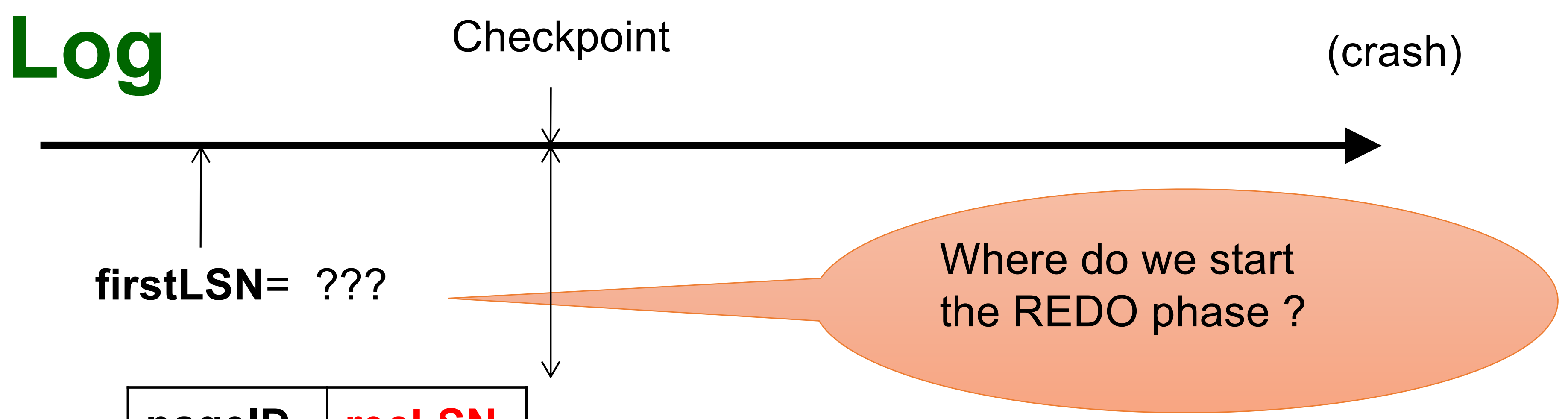
ARIES Recovery

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



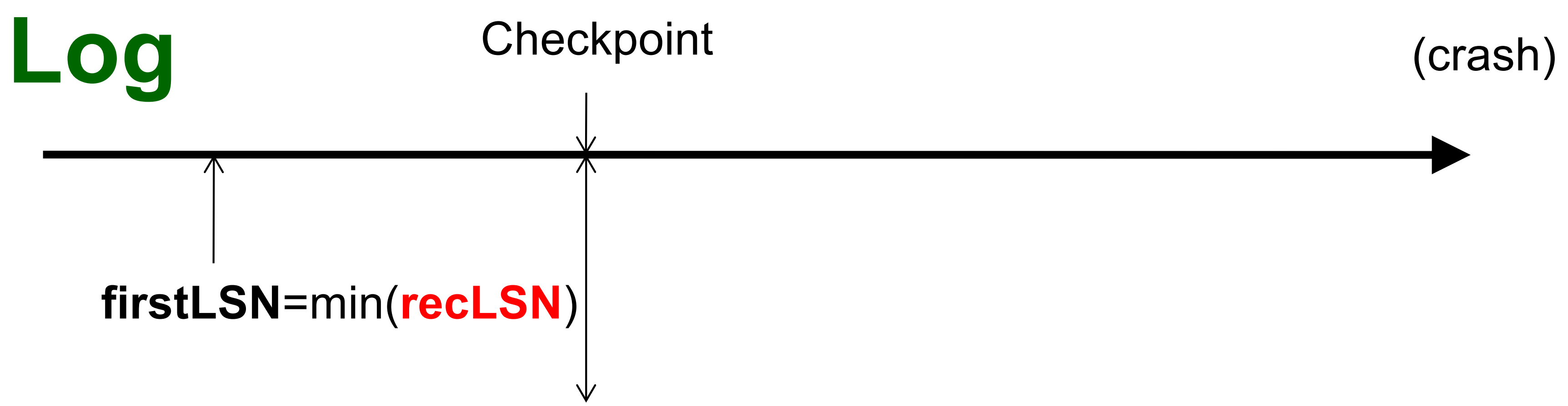
Dirty pages

pageID	recLSN

Active txn

transID	lastLSN

1. Analysis Phase



Dirty pages

pageID	recLSN

Active txn

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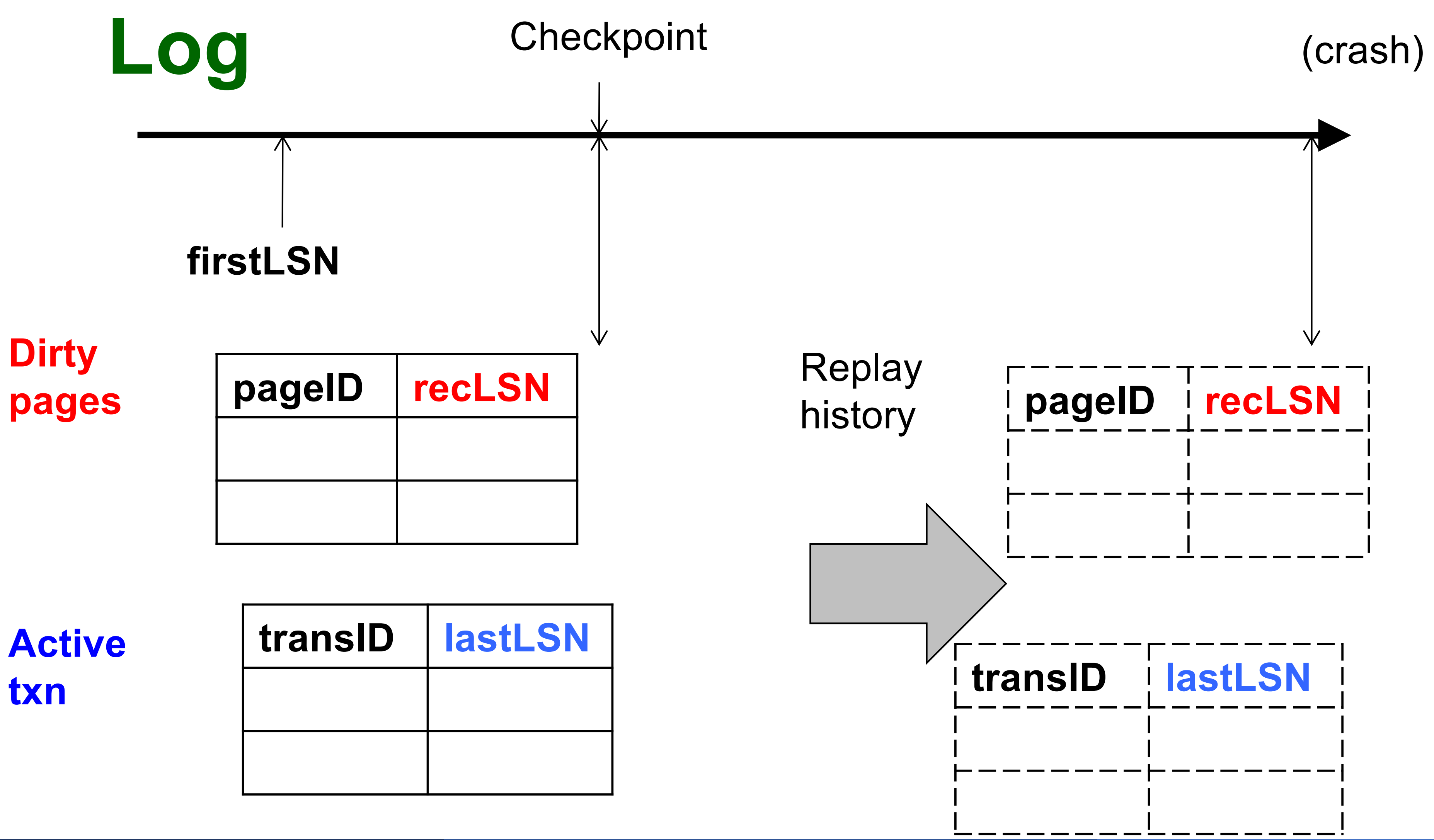
1. Analysis Phase



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: **<T,P,u,v>**

- 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: **<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** >= 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