CSE 444: Database Internals

Lectures 16-18

Transactions: Recovery

Reading Material for Lectures 16-18

Main textbook (Garcia-Molina)

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

Second textbook (Ramakrishnan)

- Ch. 16-18

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 !

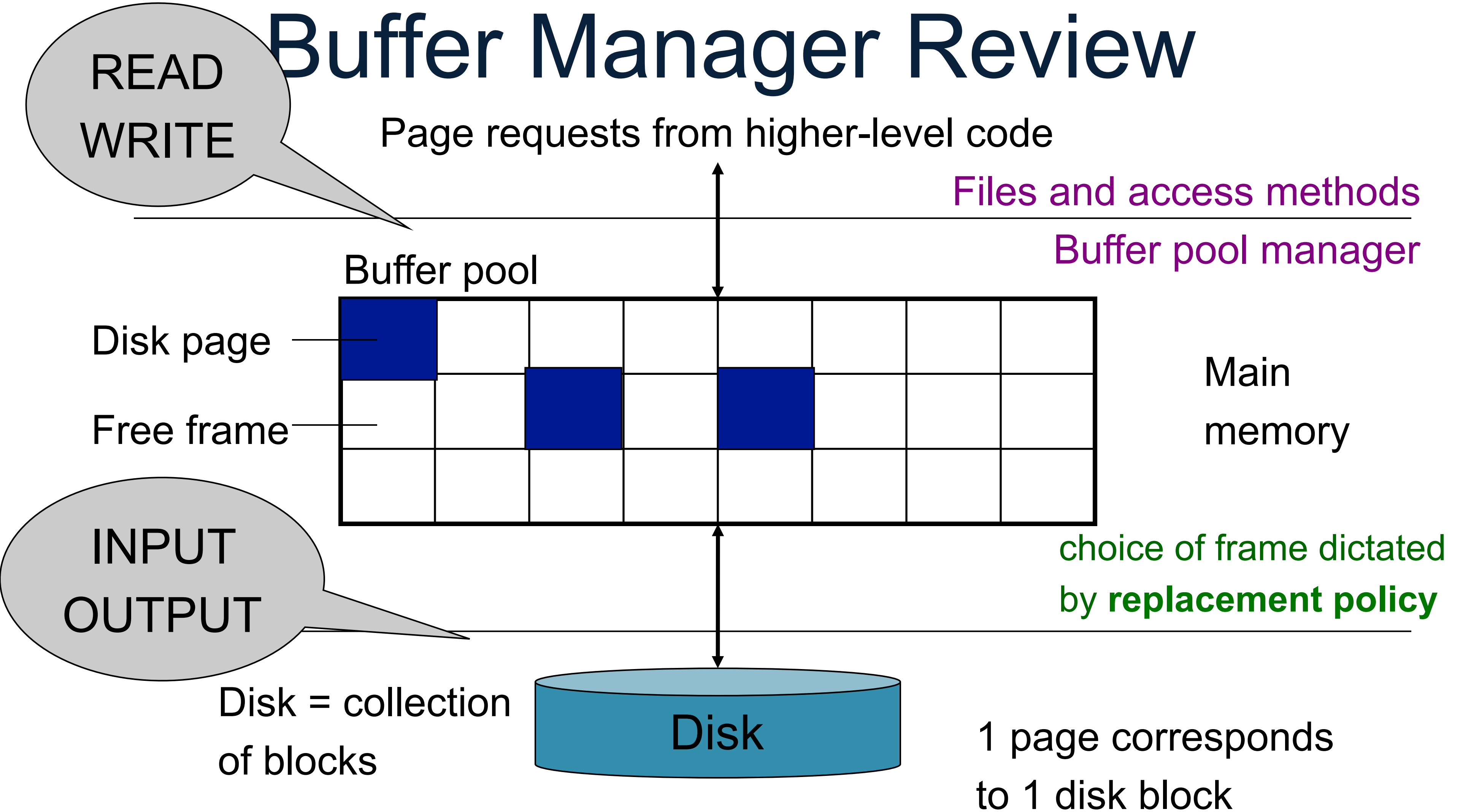
Recovery

Type of Crash	Prevention
Wrong data entry	Constraints and Data cleaning
Disk crashes	Redundancy: e.g. RAID, archive
Fire, theft, bankruptcy…	Remote backups
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



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

Transactions

- Assumption: the database is composed of ***elements***.

- 1 element can be either:
  - 1 page = physical logging
  - 1 record = logical logging
- Aries uses both (will discuss later)

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 := t*2;
WRITE(B,t)
COMMIT;
```

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.

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					

Crash !

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					

Crash !

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					

Crash !

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					

Crash !

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					

Crash !

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					

Crash !

Typically, OUTPUT is after COMMIT (why?)

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

Typically, OUTPUT is after COMMIT (why?)

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

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, Atomicity is violated; need WAL

Write-Ahead Log (WAL)

The Log: append-only file containing log records

- Records every single action of every TXN
- Force log entry to disk
- After a system crash, use log to recover

Three types: UNDO, REDO, UNDO-REDO

Aries: is an 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

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>

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

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 ?

Crash !

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

After Crash

- In the first example:
  - We UNDO both changes: A=8, B=8
  - The transaction is atomic, since none of its actions have been executed
- In the second example
  - 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

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

Crash !

Question1: Which updates are undone ?

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

Question 3:
What happens if there is a second crash, during recovery ?

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8	[illegible]	[illegible]	8	
READ(A,t)	8	[illegible]	[illegible]	[illegible]	8	
t:=t*2	16	8	[illegible]	[illegible]	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 <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>

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>

…
…
<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>

other transactions

transactions T2,T3,T4,T5

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 Recovery with Nonquiescent Checkpointing

During recovery,
Can stop at first
<CKPT>

…
…
…
…
…
…
<START CKPT T4, T5, T6>
…
…
…
<END CKPT>
…
…
…

earlier transactions plus T4, T5, T6

T4, T5, T6, plus later transactions

later transactions

Q: why do we need <END CKPT> ?

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

REDO Log

NO-FORCE and NO-STEAL

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:

- <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	
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 completed or not
  - <START T>….<COMMIT T>….   = yes
  - <START T>….<ABORT T>…….   = yes
  - <START T>………………………   = no
- Step 2. Read log from the beginning, redo all updates of *<u>committed</u>* 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>

Crash !

Show actions during recovery

Nonquiescent Checkpointing

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

Nonquiescent Checkpointing

Step 1: look for
The last
<END 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		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 <T,X,v> and <COMMIT T> must be written to disk before OUTPUT(X)

NO-STEAL

- Hence: OUTPUTs are done *late*

Comparison Undo/Redo

- Undo logging: OUTPUT must be done early:
  - Inefficient

- Redo logging: OUTPUT must be done late:
  - Inflexible

Comparison Undo/Redo

Steal/Force

- 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

No-Steal/No-Force

- 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/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

ARIES Recovery Manager

- A redo/undo log
- Physiological logging
  - Physical logging for REDO
  - Logical logging for UNDO
- Efficient checkpointing

Why ?

ARIES Recovery Manager

Log entries:

- <START T> -- when T begins
- Update: <T,X,u,v>
  - T updates X, *old* value=u, *new* value=v
  - In practice: *undo only* and *redo only* entries
- <COMMIT T> or <ABORT T>
- CLR's – 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

LSN = Log Sequence Number

- **LSN** = identifier of a log entry
  - Log entries belonging to the same TXN are linked

- 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 **<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)

- 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/aborts

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

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

ARIES Method Illustration

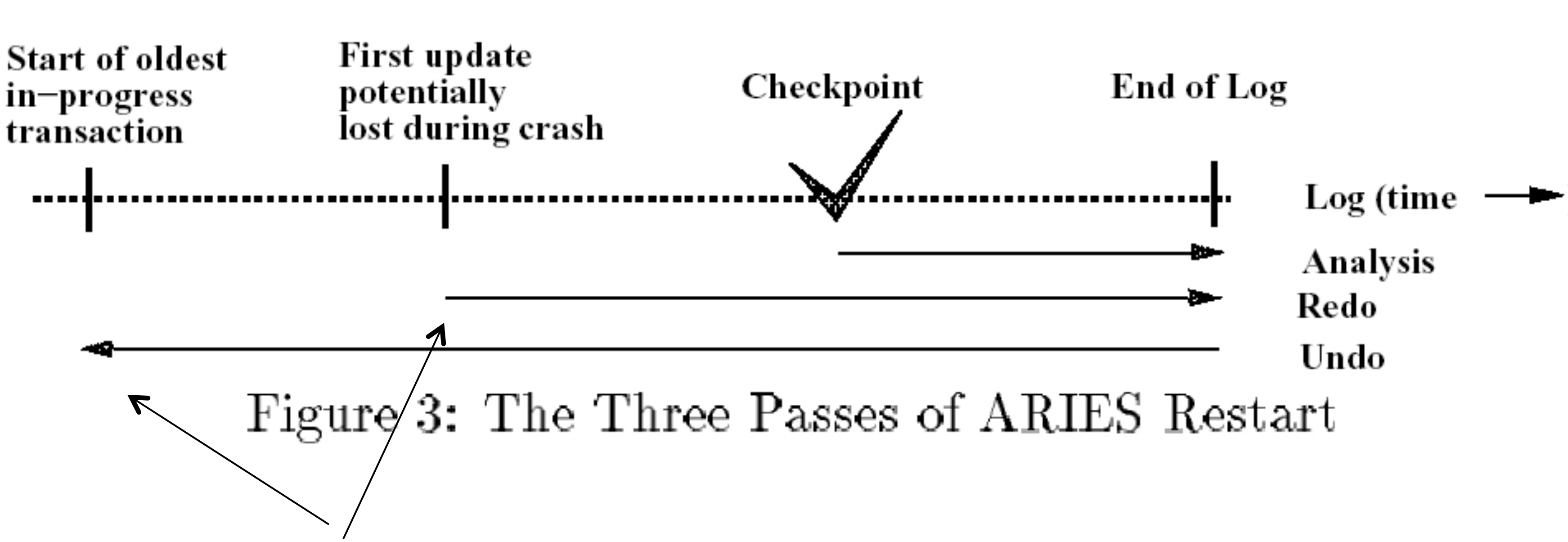


Figure 3: The Three Passes of ARIES Restart

First undo and first redo log entry might be in reverse order

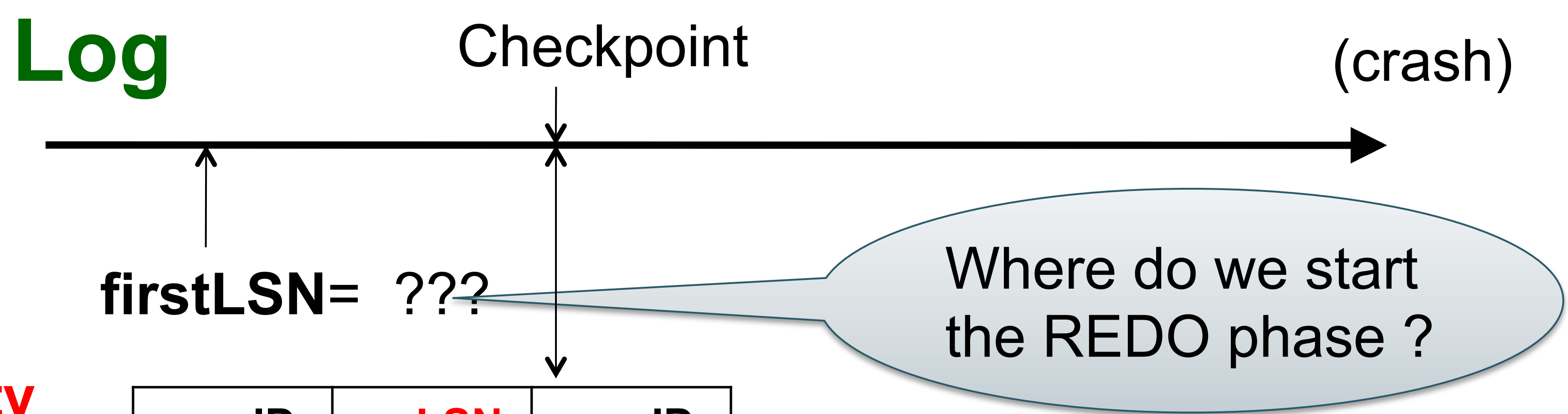
[Figure 3 from Franklin97]

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



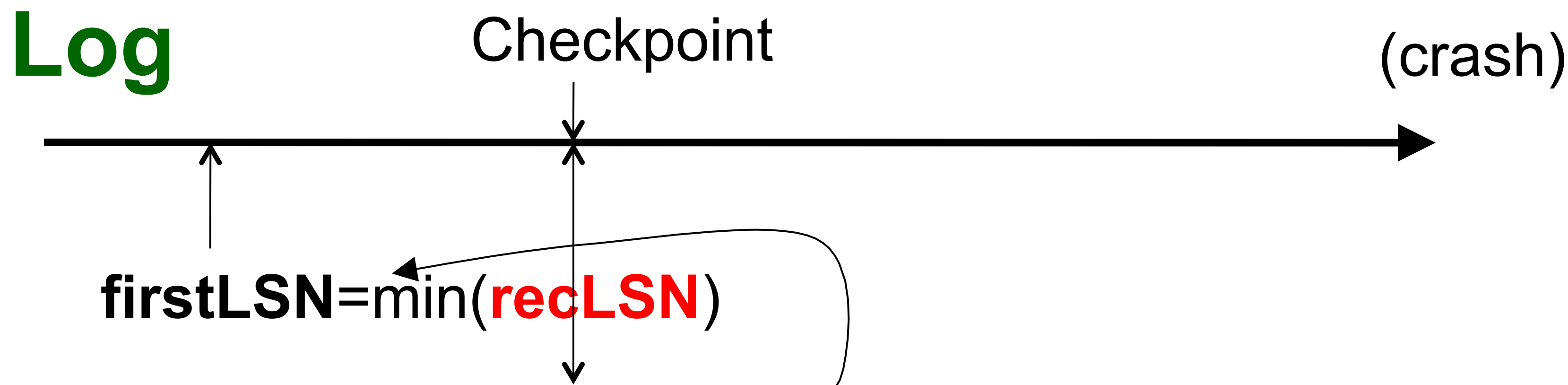
Dirty pages

pageID	recLSN	pageID

Active txn

transID	lastLSN	transID

1. Analysis Phase



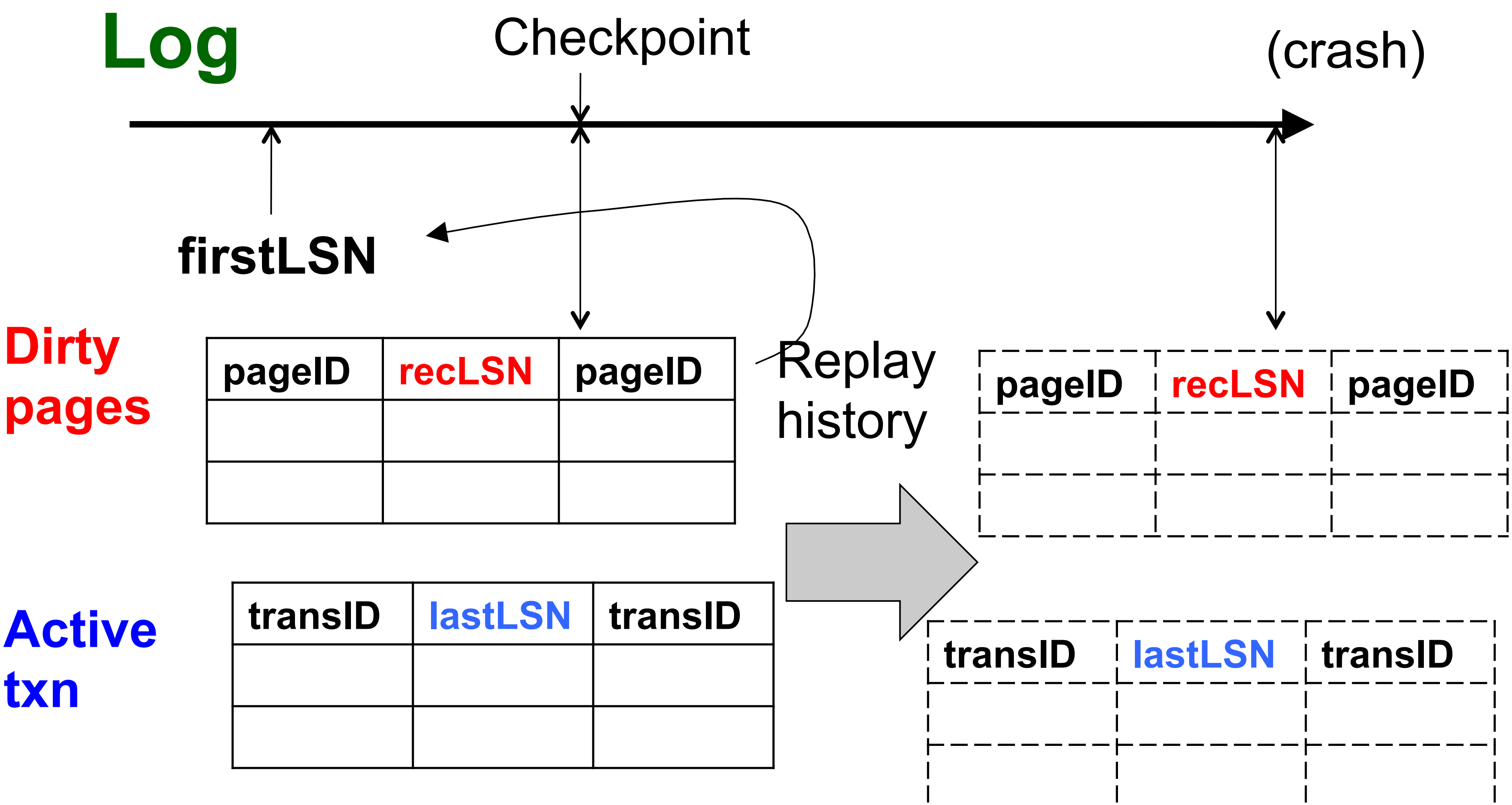
Dirty pages

pageID	recLSN	pageID

Active txn

transID	lastLSN	transID

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>**

- Re-do the action P=u and WRITE(P)
- But which actions can we skip, for efficiency ?

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 ! Each REDO operation is *idempotent*: doing it twice is the as as doing it once.

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 ?

- 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>**:
  - Undo v
  - Write a CLR where CLR.undoNextLSN = LSN.prevLSN
- If LSN = CLR record:
  - Don't undo !
- if CLR.**undoNextLSN** not null, insert in **ToUndo** otherwise, write **<END TRANSACTION>** in log

3. Undo Phase: Details

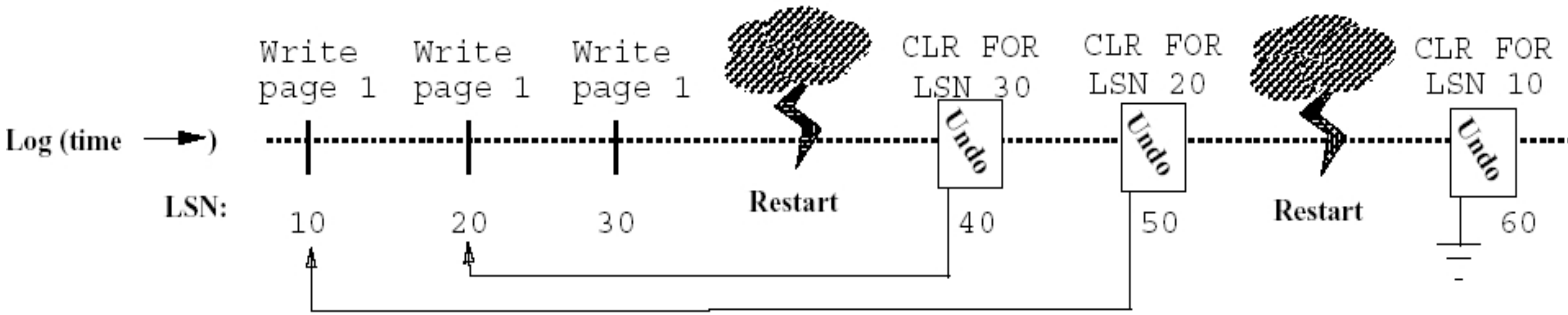


Figure 4: The Use of CLRs for UNDO

[Figure 4 from Franklin97]

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

Physical v.s. Logical Loging

Why are redo records *physical* ?

Why are undo records *logical* ?

Physical v.s. Logical Loging

Why are redo records *physical* ?

- Simplicity: replaying history is easy, and idempotent

Why are undo records *logical* ?

- Required for transaction rollback: this not "undoing history", but selective undo