CSE544
Lecture 17

Transactions (Recovery)

Project Presentations

Friday, June 7th, 9:30-2:30, in CSE 405 (details TBA)

What to include:

- Describe the problem:
  - why is it important, why is it non-trivial
- Overview prior approaches,
  - related work
- Your approach
- Your results
  - theoretical, empirical, experimental
- Discuss their significance
  - do they work ? do they solve the problem you set out to do ? do they improve over existing work ?
- Conclusions

Rule of thumb: 1 slide / minute, less slack. 15’ ➔ 12 slides.

Outline

- Transaction basics
- Recovery
- Concurrency control (next lecture)

Textbook (Ramakrishnan): Ch. 16, 17, 18

Read BOTH the slides and the book!

Transaction

Definition: a transaction is a sequence of updates to the database with the property that either all complete, or none completes (all-or-nothing).

BEGIN TRANSACTION

[SQL statements]

COMMIT or ROLLBACK (=ABORT)

May be omitted: first SQL query starts txn

In ad-hoc SQL: each statement = one transaction

Implementing Transactions

- System crash
  - Software failure (e.g. division by 0
  - Hardware failure (e.g power failure)

- Interferences with other users
  - "Anomalies" – 3 have famous names

System Crash

```
Client 1:
BEGIN TRANSACTION
UPDATE Account1
SET balance= balance – 500


UPDATE Account2
SET balance = balance + 500
COMMIT
```

Crash !

1st Famous Anomaly: Lost Update

Client 1:
BEGIN TRANSACTION
  UPDATE Account1
  SET balance= balance+$100
COMMIT

Client 2:
BEGIN TRANSACTION
  UPDATE Account1
  SET balance=balance-$100
COMMIT

<u>Lost update</u>: two TXN's update the same element, but only one succeeds.

2^{nd} Famous Anomaly: Inconsistent Read

```
Client 1: transfer $100
BEGIN TRANSACTION
  UPDATE Account1
  SET balance= balance+$100

  UPDATE Account2
  SET balance= balance+$100
COMMIT
```

```
Client 2: check total balance
BEGIN TRANSACTION
  SELECT sum(balance)
  FROM All_Accounts
COMMIT
```

<u>Inconsistent read</u>: TXN sees some updates by another TXN, but not all updates.

3rd Famous Anomaly: Dirty Reads

```
-- Client 1:
BEGIN TRANSACTION
  UPDATE Account1
  SET balance= balance+$100


  . . .
  ROLLBACK
```

```
-- Client 2: get cash $100
BEGIN TRANSACTION
X = Account1.balance
If (X>=100)
     { …dispense money…
       COMMIT }
. . .
```

<u>Dirty read</u>: TXN reads a value written by another transaction that later aborts.

ACID Properties

- Atomic
  - State shows either all the effects of txn, or none of them
- Consistent
  - Txn moves from a state where integrity holds, to another where integrity holds
- Isolated
  - Effect of txns is the same as txns running one after another (ie looks like batch mode)
- Durable
  - Once a txn has committed, its effects remain in the database

Outline

- Recovery from failures (the A in ACID)
  - Today
- Concurrency Control (the C in ACID)
  - Next lecture

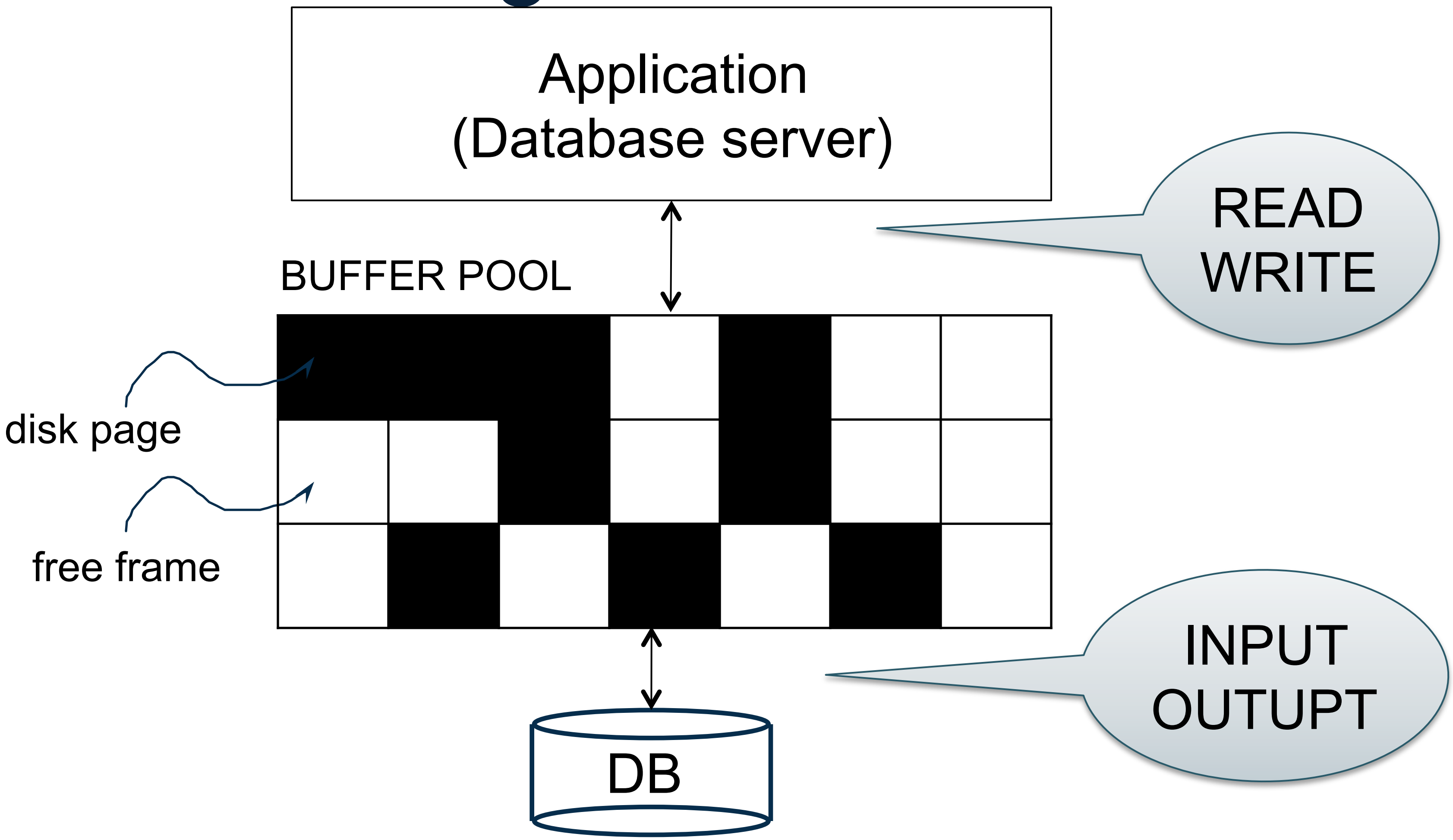
Log-based Recovery

Basics (based on Garcia-Molina Ch. 17.2, 17.3, 17.4)

- Undo logging
- Redo logging

Aries: (Ramakrishnan Ch. 18)

Buffer Management in a DBMS



Large gap between disk I/O and memory → Buffer pool

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

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, Atomicity is violated; need WAL

Write-Ahead Log

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

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	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	Crash !
OUTPUT(B)	16	16	16	16	16	
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>

Crash !

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

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			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>

FORCE

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

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

<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

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

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

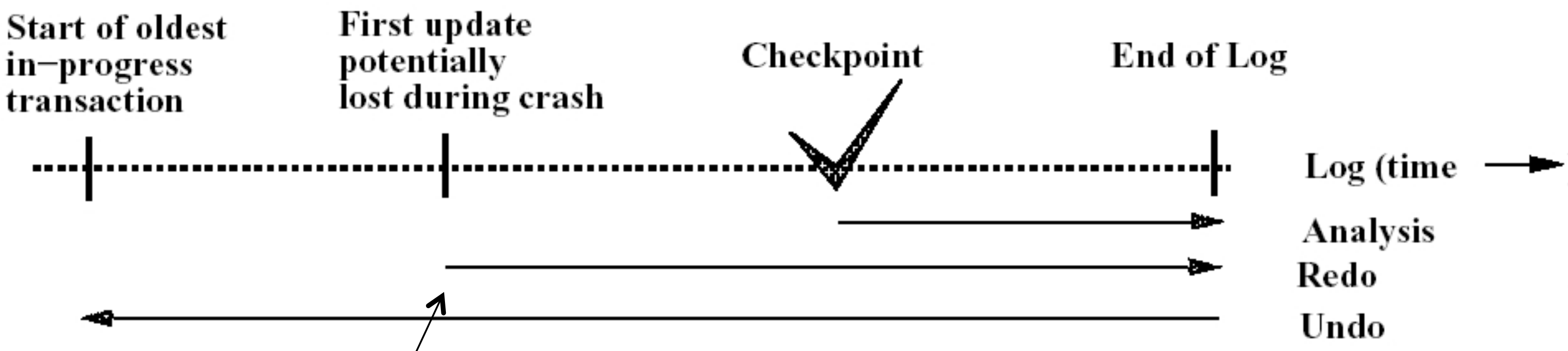


Figure 3: The Three Passes of ARIES Restart

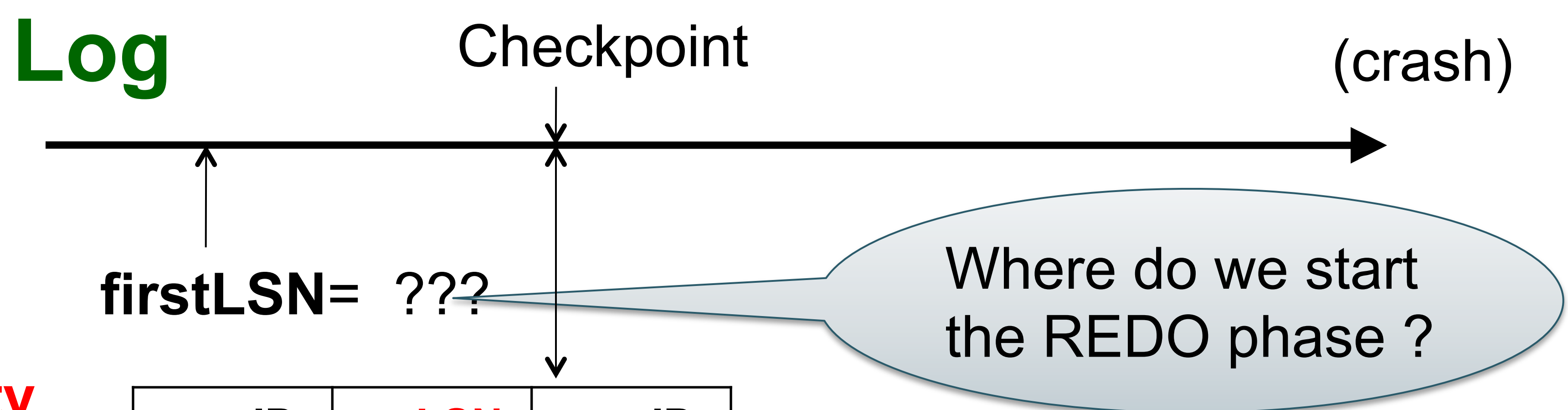
First undo and first redo log entry might be in reverse order

[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

Log Checkpoint (crash)

firstLSN=min(**recLSN**)

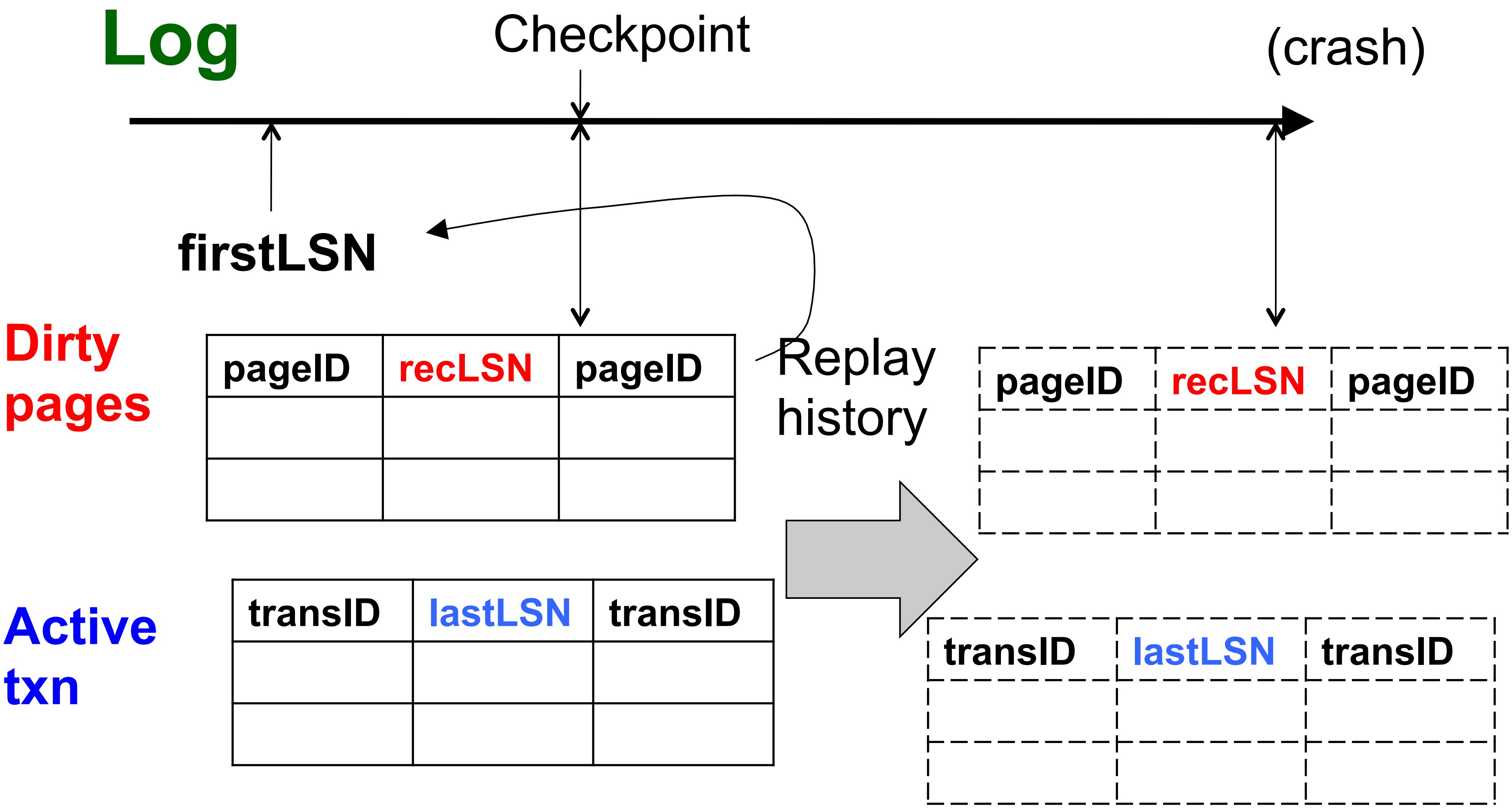
Dirty pages

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

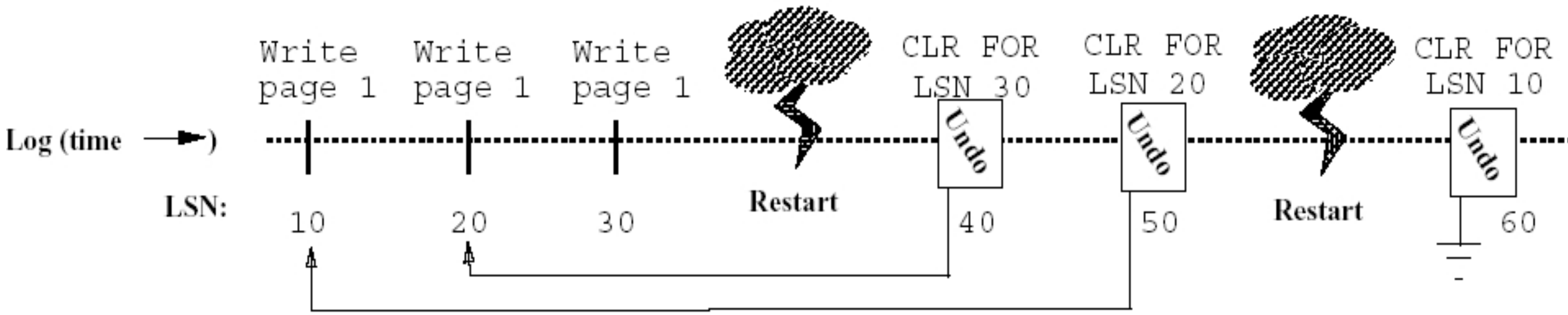


Figure 4: The Use of CLRs for UNDO

[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