# CSE 444: Database Internals

Lectures 17-19

Transactions: Recovery



## The Usual Reminders

- HW3 is due on Wednesday
- Lab3 is due on Friday



## Readings for Lectures 17-19

Main textbook (Garcia-Molina)

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

Second textbook (Ramakrishnan)

- Ch. 16-18

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



## Transaction Management

Two parts:

- Concurrency control: ACID
- Recovery from crashes: ACID

We already discussed concurrency control

You are implementing locking in lab3

Today, we start recovery



## System Crash

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

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



## Recovery

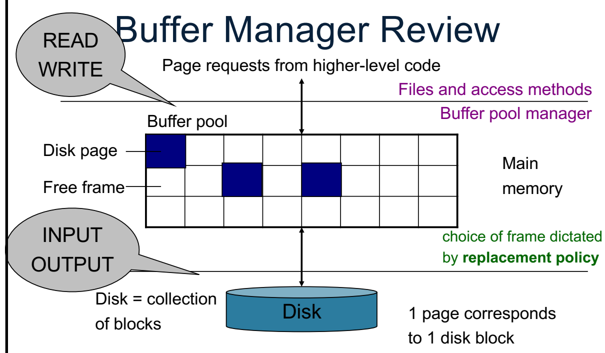
| Type of Crash | Prevention |
|---|---|
| Wrong data entry | Constraints and Data cleaning |
| Disk crashes | Redundancy: e.g. RAID, archive |
| Data center failures | Remote backups or replicas |
| System failures: e.g. power | DATABASE RECOVERY |

## System Failures

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



## Buffer Manager Review




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 physiological logging
  - (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 | | | | | |

3

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 !

4

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 !

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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 !

6

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 !

8

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 !



OUTPUT can also happen after COMMIT (details coming)

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



OUTPUT can also happen after COMMIT (details coming)

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

Crash !



# Atomic Transactions

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



# Force/No-steal

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

Easy to implement (how?) and ensures atomicity



# No-Force/Steal

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

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

## Write-Ahead Log (WAL)

**The Log**: append-only file containing log records

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

Three types: UNDO, REDO, UNDO-REDO

Aries: is an UNDO-REDO log



## Policies and Logs

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



## UNDO Log

FORCE and STEAL



## Undo Logging

Log records

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



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



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


WHAT DO WE DO ?

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

# 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 second crash during recovery?

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# 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 ? To the beginning.

Question 3: What happens if second crash during recovery? No problem! Log records are idempotent. Can reapply.

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| 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 ?

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| 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

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# 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

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## 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: do we need <END CKPT> ?



## 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: do we need <END CKPT> Not really



## 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 |
| Crash ! | | | | | |
| OUTPUT(B) | 16 | 16 | 16 | 16 | 16 |



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 |
| Crash ! | | | | | |
| 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 | | | | | |
| Crash ! | | | | | |
| 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 | | | | | |
| Crash ! | | | | | |
| 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 |
| Crash ! | | | | | |
| COMMIT | | | | | |
| OUTPUT(A) | 16 | 16 | 16 | 16 | 8 |
| OUTPUT(B) | 16 | 16 | 16 | 16 | 16 |

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 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>

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 | M[illegible] | [illegible]k A | Disk B | REDO Log |
|---|---|---|---|---|---|---|
| | | | | | | <START T> |
| READ(A,t) | 8 | 8 | [illegible] | [illegible] | 8 | |
| t:=t*2 | 16 | 8 | [illegible] | [illegible] | 8 | |
| WRITE(A,t) | 16 | 16 | [illegible] | 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 | |

NO-STEAL

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

- 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



## Granularity in ARIES

- *Physiological logging*
  – Log records refer to a single page
  – But record logical operation within the page
- Page-oriented logging for REDO
  – Necessary since can crash in middle of complex op.
- Logical logging for UNDO
  – Enables **tuple-level locking**!
  – Must do logical undo because ARIES will only undo loser transactions (this also facilitates ROLLBACKs)



## 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



## 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
- 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

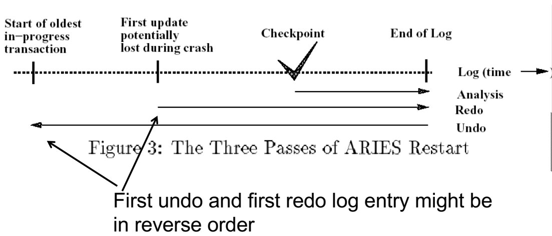
Background process periodically flushes dirty pages to disk



## 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

## ARIES Method Illustration




[Figure 3 from Franklin97]

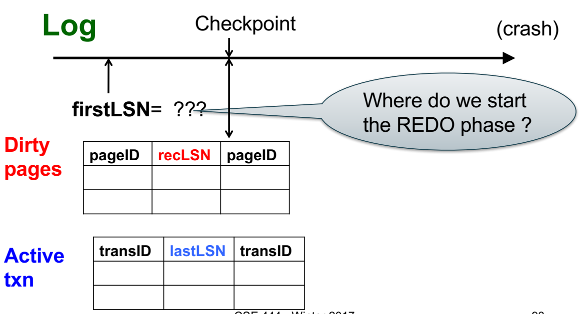


## 1. Analysis Phase

- 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

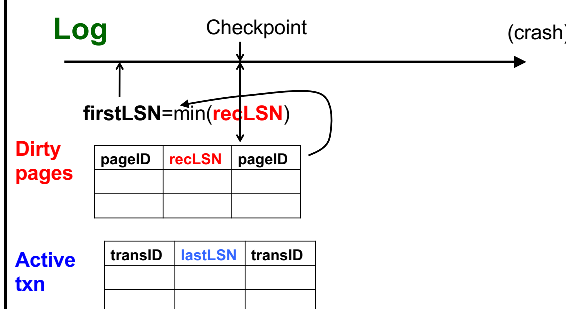


## 1. Analysis Phase



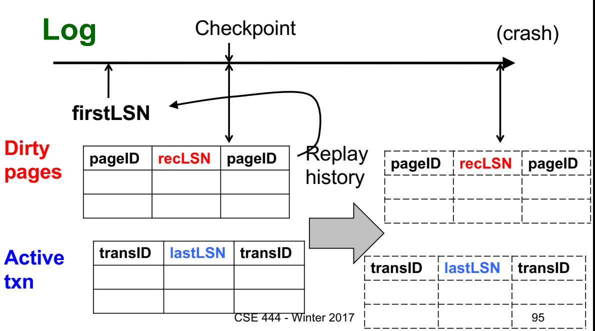



## 1. Analysis Phase






## 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: **<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>**:
  - 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>** in log



## 3. Undo Phase: Details

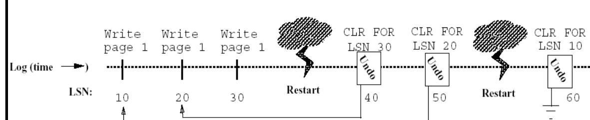



Figure 4: The Use of CLRs for UNDO

[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