CSEP544 Lecture 4: Transactions

Tuesday, April 21, 2009

HW 3

- Database 1 = IMDB on SQL Server
- Database 2 = you create a CUSTOMER db on postgres
  - Customers
  - Rentals
  - Plans

Overview

Today:

- Overview of transactions (R&G Chapter 16)
- Recovery from crashes (Ullman's book, then R&G Chapter 18)

Next week

- Concurrency control

Transactions

- **Problem**: An application must perform *several* writes and reads to the database, as a unity

- **Solution**: multiple actions of the application are bundled into one unit called *Transaction*

Turing Awards to Database Researchers

- Charles Bachman 1973 for CODASYL
- Edgar Codd 1981 for relational databases
- Jim Gray 1998 for transactions

Inconsistent Read

```
/* Client 1: move gizmo→gadget */

UPDATE Products
SET quantity = quantity + 5
WHERE product = 'gizmo'



UPDATE Products
SET quantity = quantity - 5
WHERE product = 'gadget'
```

```
/* Client 2: inventory….*/

SELECT sum(quantity)
FROM Product
```

Dirty Reads

```
/* Client 1: transfer $100  acc1→ acc2 */
X = Account1.balance
Account2.balance += 100

If (X>=100) Account1.balance -=100
else { /* rollback ! */
        account2.balance -= 100
        println("Denied !")
```

```
/* Client 2: transfer $100  acc2 → acc3 */
Y = Account2.balance
Account3.balance += 100

If (Y>=100) Account2.balance -=100
else { /* rollback ! */
        account3.balance -= 100
        println("Denied !")
```

What's wrong ?

Example: Lost Update

Client 1:

```
UPDATE Customer
SET rentals= rentals + 1
WHERE cname= 'Fred'
```

Client 2:

```
UPDATE Customer
SET rentals= rentals + 1
WHERE cname= 'Fred'
```

Two people attempt to rent two movies for Fred, from two different terminals. What happens ?

Famous anomalies

- Dirty read
  - T reads data written by T’ while T’ has not committed
  - What can go wrong: T’ writes more or aborts
  - Inconsistent read: T sees only some changes by T’
- Lost update
  - Two tasks T and T’ both modify the same data
  - T and T’ both commit
  - Final state shows effects of only T, but not of T’
- Many other anomalies exists, with or without name
  - E.g. write skew

Protection against crashes

Client 1:

```
UPDATE Accounts
SET balance= balance - 500
WHERE name= 'Fred'

UPDATE Accounts
SET balance = balance + 500
WHERE name= 'Joe'
```

Crash !

What's wrong ?

Definition of Transactions

- **A transaction** = one or more operations, which reflects a single real-world transition
  - Happens completely or not at all
- Examples
  - Transfer money between accounts
  - Rent a movie; return a rented movie
  - Purchase a group of products
  - Register for a class (either waitlisted or allocated)
- By using transactions, all previous problems disappear

Transactions in Applications

START TRANSACTION

May be omitted: first SQL query starts txn

[SQL statements]

COMMIT or ROLLBACK (=ABORT)

Default: each statement = one transaction

Revised Code

```
/* Client 1: transfer $100  acc1→ acc2 */
START TRANSACTION
X = Account1.balance;    Account2.balance += 100

If (X>=100) { Account1.balance -=100;  COMMIT }
else {println("Denied !"; ROLLBACK)
```

```
/* Client 1: transfer $100  acc2→ acc3 */
START TRANSACTION
X = Account2.balance;    Account3.balance += 100

If (X>=100) { Account2.balance -=100;  COMMIT }
else {println("Denied !"; ROLLBACK)
```

Using Transactions

Very easy to use:

- START TRANSACTION
- COMMIT
- ROLLBACK

What they mean:

- Popular culture: ACID
- Theory: serializability (next lecture)

ACID Properties

- Atomicity: Either all changes performed by transaction occur or none occurs
- Consistency: A transaction as a whole does not violate integrity constraints
- Isolation: Transactions appear to execute one after the other in sequence
- Durability: If a transaction commits, its changes will survive failures

What Could Go Wrong?

- Concurrent operations
  - Will discuss next time
- Failures can occur at any time
  - Will discuss today
- Transactions are intimately connected to the *buffer manager* (will discuss next)

The Mechanics of Disk

Mechanical characteristics:

- Rotation speed (5400RPM)
- Number of platters (1-30)
- Number of tracks (<=10000)
- Number of bytes/track(10^5)

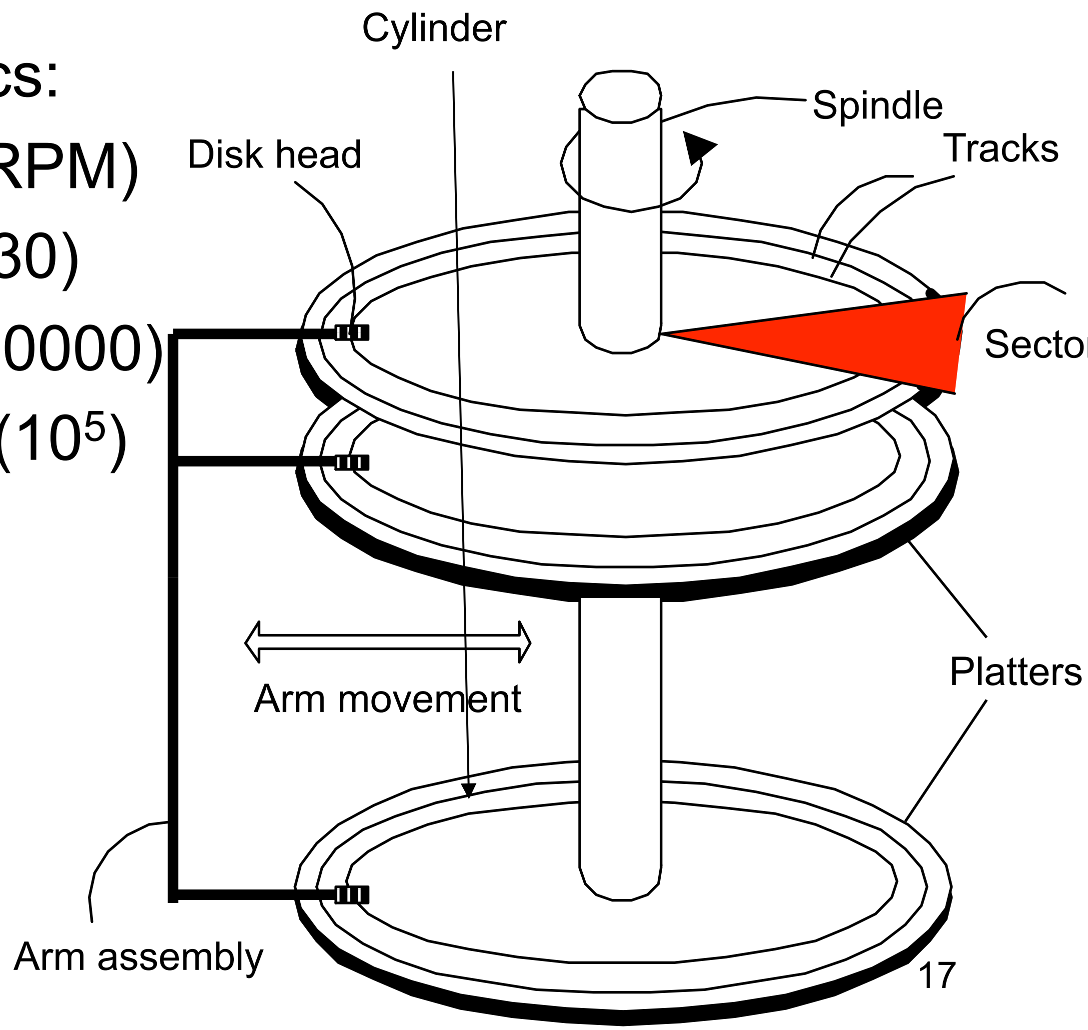
Unit of read or write:

disk block

Once in memory:

page

Typically: 4k or 8k or 16k



Disk Access Characteristics

- Disk latency = time between when command is issued and when data is in memory

- Disk latency = seek time + rotational latency
  - Seek time = time for the head to reach cylinder
    - 10ms – 40ms
  - Rotational latency = time for the sector to rotate
    - Rotation time = 10ms
    - Average latency = 10ms/2
- Transfer time = typically 40MB/s
- Disks read/write one block at a time

RAID

Several disks that work in parallel

- Redundancy: use parity to recover from disk failure
- Speed: read from several disks at once

Various configurations (called *levels*):

- RAID 1 = mirror
- RAID 4 = n disks + 1 parity disk
- RAID 5 = n+1 disks, assign parity blocks round robin
- RAID 6 = “Hamming codes”

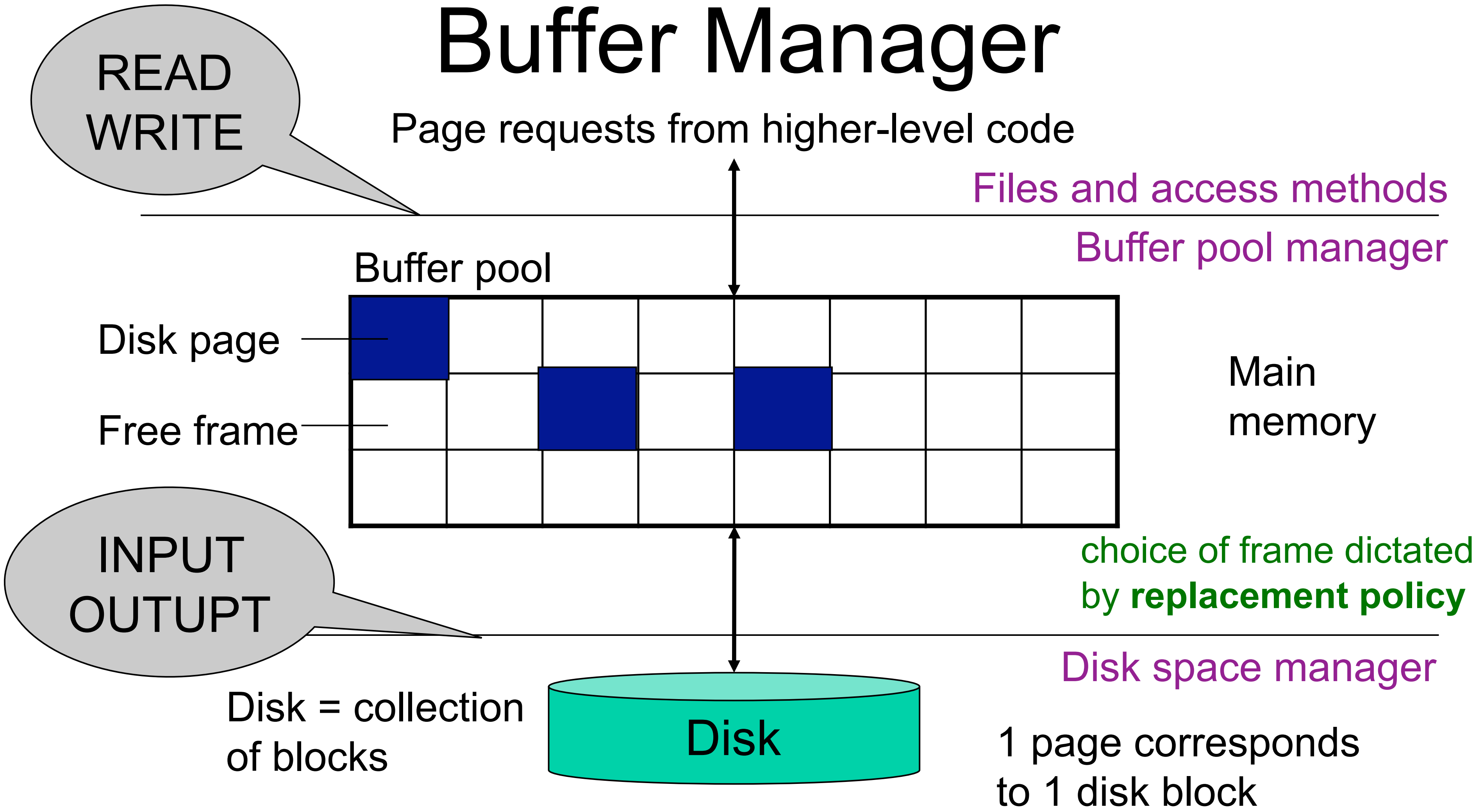
Design Question

- Consider the following query:

```
SELECT    S1.temp, S2.pressure
FROM      TempSensor S1, PressureSensor S2
WHERE     S1.location = S2.location
AND       S1.time = S2.time
```

- How can the DBMS execute this query given
  – 1 GB of memory
  – 100 GB TempSensor and 10 GB PressureSensor

Buffer Manager



- Data must be in RAM for DBMS to operate on it!
- Buffer pool = table of <frame#, pageid> pairs

Buffer Manager

- Enables higher layers of the DBMS to assume that needed data is in main memory
- Needs to decide on page replacement policy
  - LRU, clock algorithm, or other
- Both work well in OS, but not always in DB

Least Recently Used (LRU)

- Order pages by the time of last accessed
- Always replace the least recently accessed

P5, P2, P8, P4, P1, P9, P6, P3, P7

Access P6

P6, P5, P2, P8, P4, P1, P9, P3, P7

LRU is expensive (why ?); the clock algorithm is good approx

Buffer Manager

- Why not use the OS for the task??
- Reason 1: Correctness
  - DBMS needs fine grained control for transactions
  - Needs to force pages to disk for recovery purposes
- Reason 2: Performance
  - DBMS may be able to anticipate access patterns
  - Hence, may also be able to perform prefetching
  - May select better page replacement policy

Transaction Management and the Buffer Manager

Transaction manager operates on buffer pool

- **Recovery**: ‘log-file write-ahead’, then careful policy about which pages to force to disk
- **Concurrency control**: locks at the page level, multiversion concurrency control

Connection to ACID

- Recovery from crashes: ACID
  - Will discuss today
- Concurrency control: ACID
  - Will discuss next week

Recovery

From which events below can DBMS recover ?

- Wrong data entry
- Disk failure
- Fire / earthquake / bankruptcy / ….
- System failure, transaction failure:
  - Power failure
  - Rollback

Recovery

Type of Crash	Prevention
Wrong data entry	Constraints and Data cleaning
Disk crashes	Redundancy: e.g. RAID, archive
Fire, theft, bankruptcy…	Buy insurance, Change jobs…
System/transaction failures	DATABASE RECOVERY

Most frequent

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*
- Remedy: use a **<u>log</u>**
  - File that records every single action of each transaction

Problem Illustration

```
Client 1:
        START TRANSACTION
        INSERT INTO SmallProduct(name, price)
                SELECT pname, price
                FROM Product
                WHERE price <= 0.99

        DELETE Product
                WHERE price <=0.99
        COMMIT
```

Crash !

What do we do now?

Transactions

- Assumption: db composed of ***<u>elements</u>***
  - Usually 1 element = 1 block
  - Can be smaller (=1 record) or larger (=1 relation)
- Assumption: each transaction reads/ writes some elements

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

Example

```
START TRANSACTION
READ(A,t);
t := t*2;
WRITE(A,t);
READ(B,t);
t := t*2;
WRITE(B,t);
COMMIT;
```

Atomicity:
BOTH A and B
are multiplied by 2

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
READ(A,t)					
t:=t*2					
WRITE(A,t)					
INPUT(B)					
READ(B,t)					
t:=t*2					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					

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)					
t:=t*2					
WRITE(A,t)					
INPUT(B)					
READ(B,t)					
t:=t*2					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					

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)					
INPUT(B)					
READ(B,t)					
t:=t*2					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					

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)					
READ(B,t)					
t:=t*2					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					

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)					
t:=t*2					
WRITE(B,t)					
OUTPUT(A)					
OUTPUT(B)					

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)					
OUTPUT(A)					
OUTPUT(B)					

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)					
OUTPUT(B)					

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)					

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

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	[illegible]
OUTPUT(B)	16	16	16	16	16

Crash !

Crash occurs after OUTPUT(A), before OUTPUT(B)
We lose atomicity

Buffer Manager Policies

- **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 or NO-FORCE**
  - Should all updates of a transaction be forced to disk before the transaction commits?
- Easiest for recovery: NO-STEAL/FORCE
- Highest performance: STEAL/NO-FORCE

Solution: Use a Log

- **Log: append-only file containing log records**
- Enables the use of STEAL and NO-FORCE
- For every update, commit, or abort operation
  - Write physical, logical, or physiological log record
  - Note: multiple transactions run concurrently, log records are interleaved
- After a system crash, use log to:
  - Redo some transaction that did commit
  - Undo other transactions that didn't commit

Write-Ahead Log

- Rule 1: (WAL Rule) All log records pertaining to a page are written to disk before the page is overwritten on disk

- Rule 2: All log records for transaction are written to disk before the transaction is considered committed
  - Why is this faster than FORCE policy?

- **Committed transaction**: transactions whose commit log record has been written to disk

Undo Logging

Log records

- <START T>
  - Transaction T has begun
- <COMMIT T>
  - T has committed
- <ABORT T>
  - T has aborted
- <T,X,v> -- Update record
  - T has updated element X, and its *old* value was v

Action	T	Mem A	Mem B	Disk A	Disk B	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	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		
COMMIT						<COMMIT T>

Crash !

WHAT DO WE DO ?

Action	T	Mem A	Mem B	Disk A	Disk B	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 ?

After Crash

- In the first example:
  - We UNDO both changes: A=8, B=8
  - The transaction is atomic, since none of its actions has been executed
- In the second example
  - We don't undo anything
  - The transaction is atomic, since both it's actions have been executed

Undo-Logging Rules

Undo-logging Rule: If T commits, then OUTPUT(X) must be written to disk before <COMMIT T>

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

Action	T	Mem A	Mem B	Disk A	Disk B	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>

Recovery with Undo Log

After system's crash, run recovery manager

- Idea 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

- Idea 2. 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 in class:
Which updates are undone ?

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

Recovery with Undo Log

- Note: all undo commands are *idempotent*
  - If we perform them a second time, no harm done
  - E.g. if there is a system crash during recovery, simply restart recovery from scratch

Recovery with Undo Log

When do we stop reading the log ?

- We cannot stop until we reach the beginning of the log file
- This is impractical

Instead: use checkpointing

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: do we need <END CKPT> ?

Implementing ROLLBACK

- Recall: a transaction can end in COMMIT or ROLLBACK
- Idea: use the undo-log to implement ROLLBCACK
- How ?
- LSN = Log Seqence Number
- Log entries for the same transaction are linked, using the LSN's

Redo 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 *new* value is v

Action	T	Mem A	Mem B	Disk A	Disk B	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 T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

Redo-Logging Rules

Redo-logging Rule: 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*

Action	T	Mem A	Mem B	Disk A	Disk B	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 T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	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>
…
…

Nonquiescent Checkpointing

- Write a <START CKPT(T1,…,Tk)> where T1,…,Tk are all active transactions
- Flush to disk all blocks of committed transactions (*dirty blocks*), while continuing normal operation
- When all blocks have been written, write <END CKPT>

Redo Recovery with Nonquiescent Checkpointing

Step 1: look for
The last
<END CKPT>

…
<START T1>
…
<COMMIT T1>
…a
<START T4>
…
<START CKPT T4, T5, T6>
…
…
…
…
<END CKPT>
…
…
…
<START CKPT T9, T10>
…

All OUTPUTs
of T1 are
known to be on disk

Cannot
use

Step 2: redo
from the
earliest
start of
T4, T5, T6
ignoring
transactions
committed
earlier

Nonquiescent Checkpointing

- This checkpointing methods is only for the simple redo-log
- We will discuss later the checkpointing method for ARIES, which differs significantly
- The book describes ARIES only

Comparison Undo/Redo

- 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

Steal/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

No-Steal/No-Force

- 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

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 Method

- Read R&K Chapter 18
- Three pass algorithm
  - **Analysis pass**
    - Figure out what was going on at time of crash
    - List of dirty pages and active transactions
  - **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
  - **Undo pass**
    - Remove effects of all uncommitted transactions
    - Log changes during undo in case of another crash during undo

ARIES Method Illustration

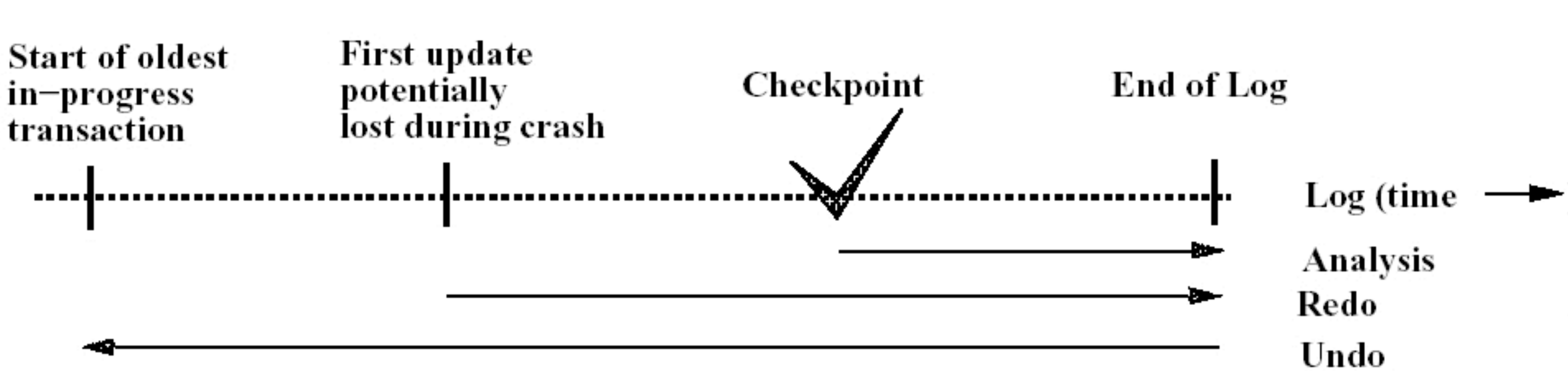


Figure 3: The Three Passes of ARIES Restart

[Figure 3 from Franklin97]

ARIES Method Elements

- Each page contains a **pageLSN**
  - **Log Sequence Number** of log record for latest update to that page
  - Will serve to determine if an update needs to be redone

- Physiological logging
  - page-oriented REDO
    - Possible because will always redo all operations in order
  - logical UNDO
    - Needed because will only undo some operations

ARIES Data Structures

- Transaction table
  - Lists all running transactions (active transactions)
  - For each txn: lastLSN = most recent update by transaction
- Dirty page table
  - Lists all dirty pages
  - For each dirty page: recoveryLSN = first LSN that caused page to become dirty
- Write ahead log contains log records
  - LSN, prevLSN = previous LSN for same transaction
  - other attributes

ARIES Data Structures

Dirty pages

pageID	recLSN
P5	2
P6	3
P7	1

Log

LSN	prevLSN	transID	pageID	Log entry
1		T100	P7	
2		T200	P5	
3		T200	P6	
4		T100	P5	

Active transactions

transID	lastLSN
T100	4
T200	3

ARIES Method Details

- Steps under normal operations
  - Add log record
  - Update transactions table
  - Update dirty page table
  - Update pageLSN

Checkpoints

- Write into the log
  - Contents of transactions table
  - Contents of dirty page table
- Enables REDO phase to restart from earliest recoveryLSN in dirty page table
  - Shortens REDO phase

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 transactions table and dirty pages table
  - Reprocess the log from the beginning (or checkpoint)
    - Only update the two data structures
  - Find oldest recoveryLSN (firstLSN) in dirty pages tables

Redo Phase

- Goal: redo all updates since firstLSN

- For each log record
  - If affected page is not in Dirty Page Table then **do not update**
  - If affected page is in Dirty Page Table but recoveryLSN > LSN of record, then **no update**
  - Else if pageLSN > LSN, then **no update**
    - Note: only condition that requires reading page from disk
  - Otherwise perform update

Undo Phase

- Goal: undo effects of aborted transactions
- Identifies all loser transactions in trans. table
- Scan log backwards
  - Undo all operations of loser transactions
  - Undo each operation unconditionally
  - All ops. logged with compensation log records (CLR)
  - Never undo a CLR
    - Look-up the UndoNextLSN and continue from there

Handling Crashes during Undo

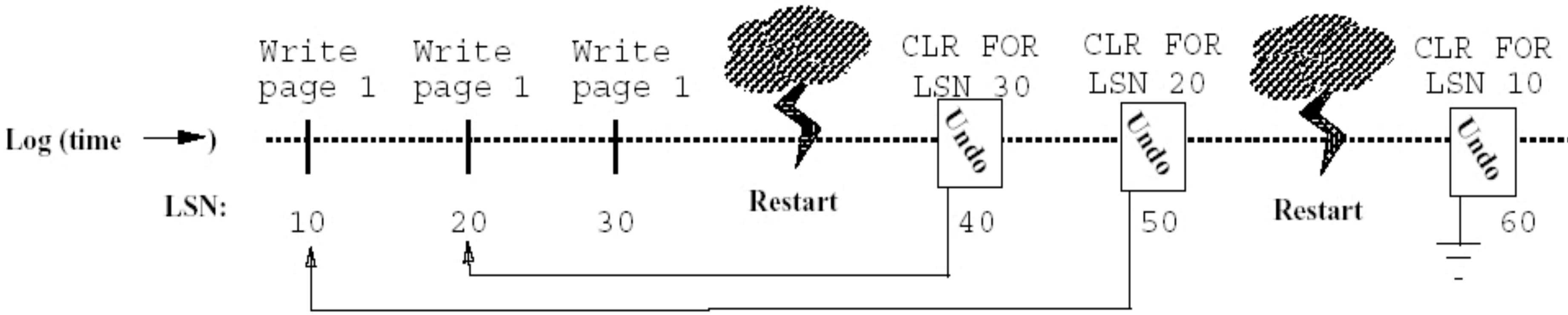


Figure 4: The Use of CLRs for UNDO

[Figure 4 from Franklin97]

Summary

- Transactions are a useful abstraction
- They simplify application development
- DBMS must maintain ACID properties in face of
  - Concurrency
  - Failures