Introduction to Database Systems
CSE 444

Lectures 9-10

Transactions: recovery

Outline

- We are starting to look at DBMS internals
- Today and next time: transactions & recovery
  - Disks 13.2 [Old edition: 11.3]
  - Undo logging 17.2
  - Redo logging 17.3
  - Redo/undo 17.4

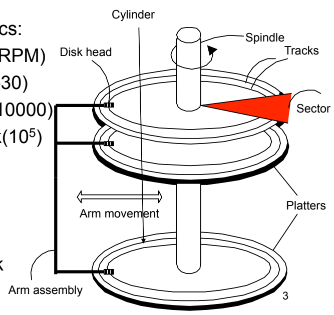
The Mechanics of Disk

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



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”

Not required for exam, but interesting reading in the book

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

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

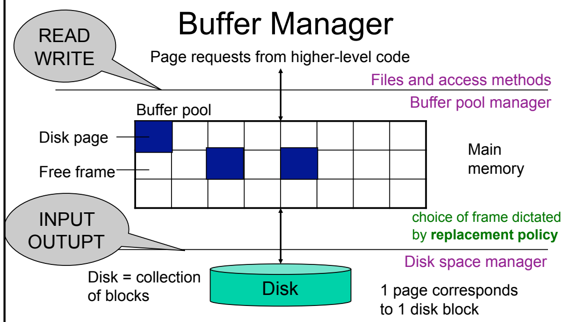
Design Question

- 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

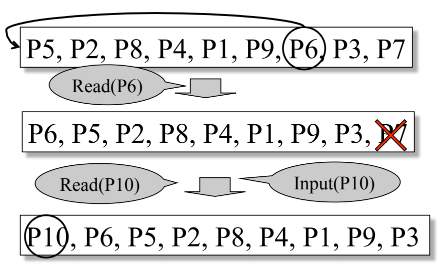


- Data must be in RAM for DBMS to operate on it!
- Buffer pool = table of <frame#, pageid> pairs

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 = expensive
  - Clock algorithm = cheaper alternative
- Both work well in OS, but not always in DB

Least Recently Used (LRU)



Buffer Manager

- DBMSs build their own buffer manager and don't rely on the OS. Why?
- 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

Will discuss details during the next few lectures

Transaction Management

Two parts:

- Recovery from crashes: ACID
- Concurrency control: ACID

Both operate on the buffer pool

Today, we focus on recovery

Problem Illustration

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

What do we do now?

Recovery

From which events below can DBMS recover ?

- Wrong data entry
- Disk failure
- Fire / earthquake / etc.
- Systems crashes
  - Software errors
  - Power failures

Recovery

Type of Crash	Prevention
Wrong data entry	Constraints and Data cleaning
Disk crashes	Redundancy: RAID, backup, replica
Fire or other major disaster	Redundancy: Replica far away
System 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 **log**
  - File that records every single action of each transaction

Transactions

- Assumption: db composed of ***elements***
  - 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	8
OUTPUT(B)	16	16	16	16	

Crash !

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

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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

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Solution: Use a Log

- Log = append-only file containing log records
- Note: multiple transactions run concurrently, log records are interleaved
- After a system crash, use log to:
  - Redo some transactions that did commit
  - Undo other transactions that did not commit
- Three kinds of logs: undo, redo, undo/redo

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>

WHAT DO WE DO ?

Crash !

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

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

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

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

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

Question 3 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: why 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
  - Read log in reverse, using LSN pointers

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

R1: If T modifies X, then both <T,X,v> and <COMMIT T> must be written to disk before OUTPUT(X)

- Hence: OUTPUTs are done ***late***

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 ***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>
…
…

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>

All OUTPUTs of T1 are known to be on disk

Cannot use

…
<START T1>
…
<COMMIT T1>
…a
<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

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>
…
…

Granularity of the Log

- Physical logging: element = physical page
- Logical logging: element = data record

- What are the pros and cons ?

Granularity of the Log

- Modern DBMS:

- Physical logging for the REDO part
  - Efficiency
- Logical logging for the UNDO part
  - For ROLLBACKs