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)

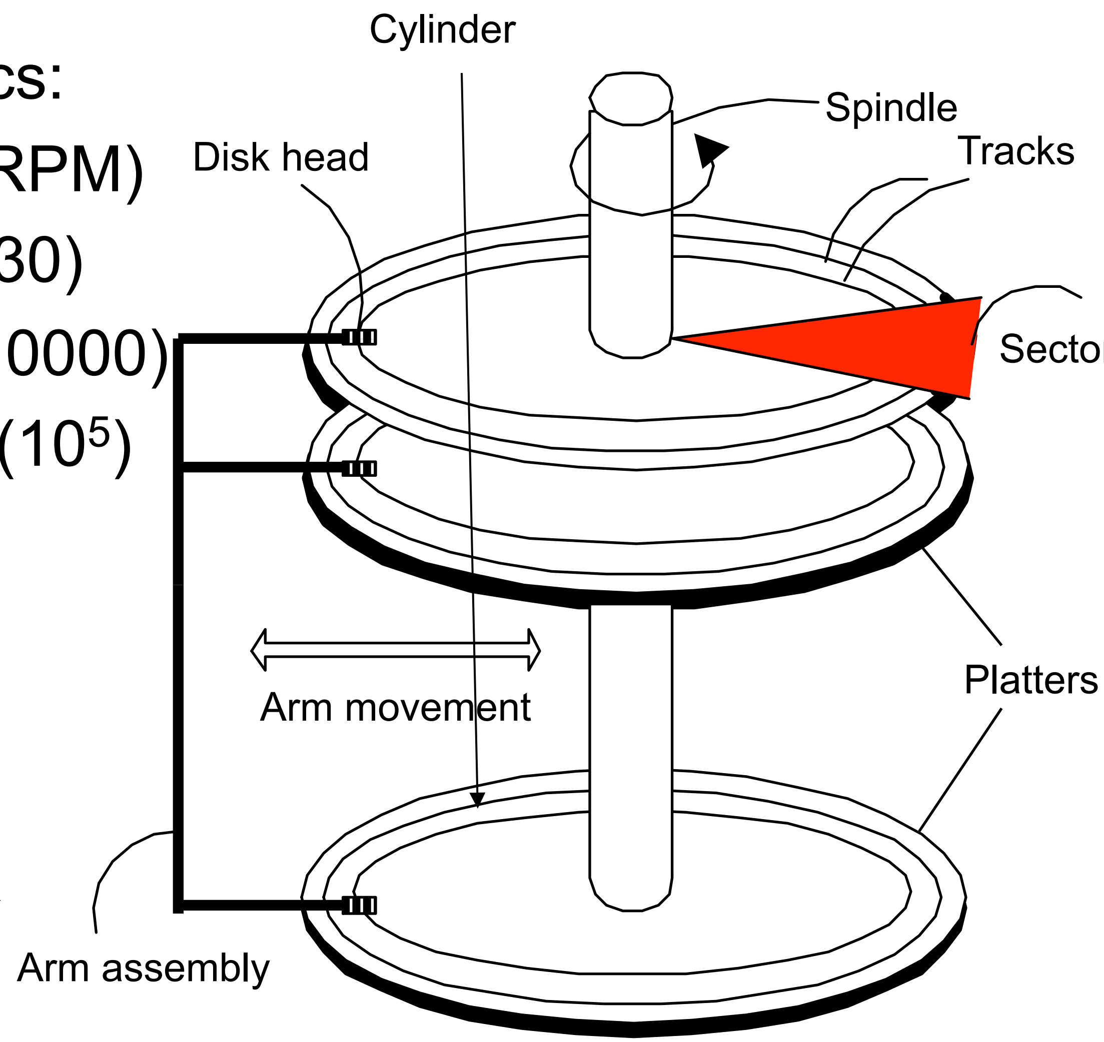
Unit of read or write:

disk block

Once in memory:

page

Typically: 4k or 8k or 16k



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”

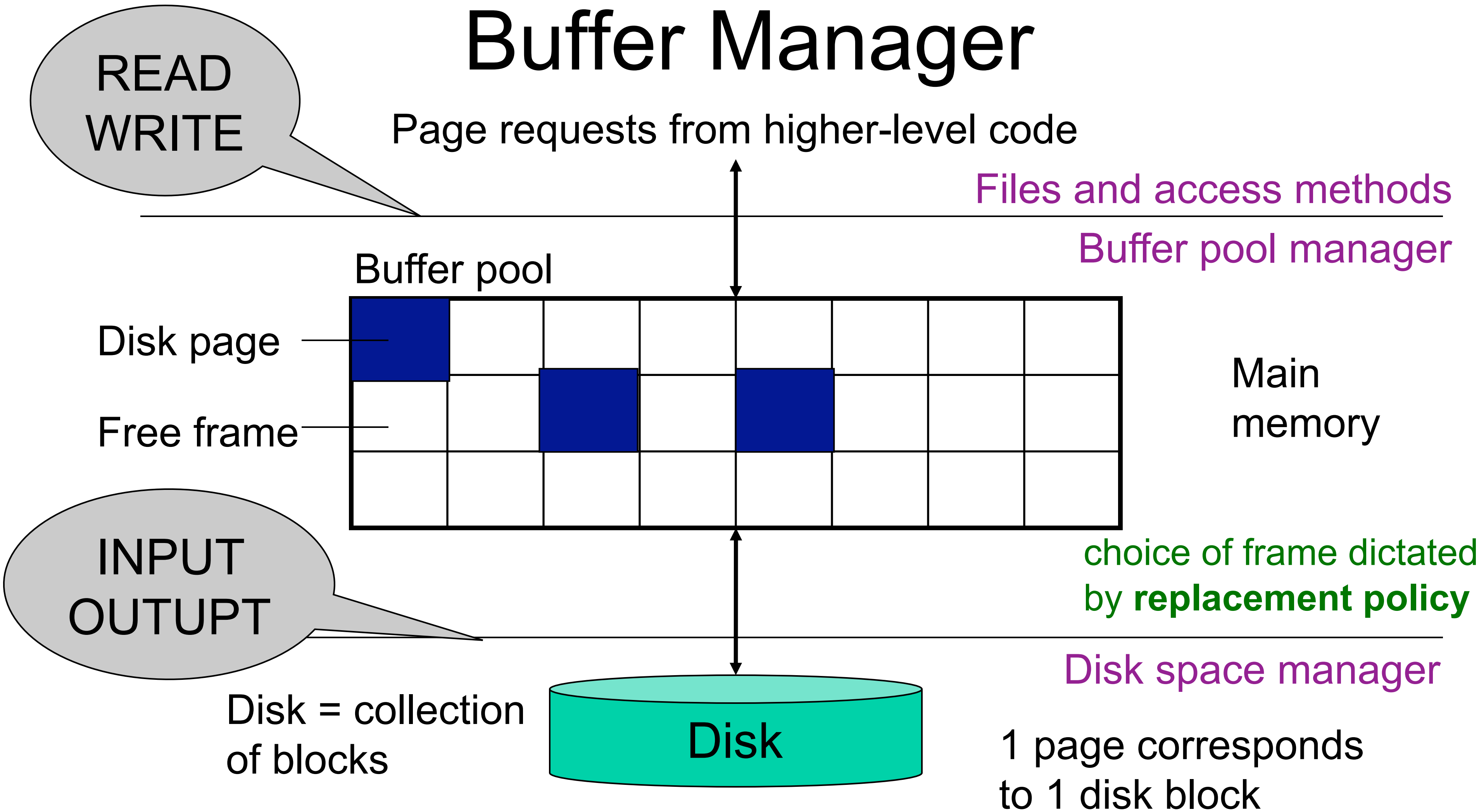
Design Question

- 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

Will discuss details during the next few lectures

Transaction Management

Two parts:

- Recovery from crashes: <u>A</u>CI<u>D</u>
- Concurrency control: AC<u>I</u>D

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

        DELETE Product
                WHERE price <=0.99
        COMMIT
```

Crash !

What do we do now?

Recovery

From which events below can DBMS recover ?

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

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

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
- 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>

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

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 <u>from the end</u>; 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: 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

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>

…
<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

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

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