Introduction to Database Systems
CSE 444

Lectures 9-10

Transactions: recovery

Outline

- We are starting to look at DBMS internals

- Next pair of lectures: transactions & recovery
  - Disks 13.2
  - Undo logging 17.2
  - Redo logging 17.3
  - Redo/undo 17.4

The Mechanics of Disk

Mechanical characteristics:

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

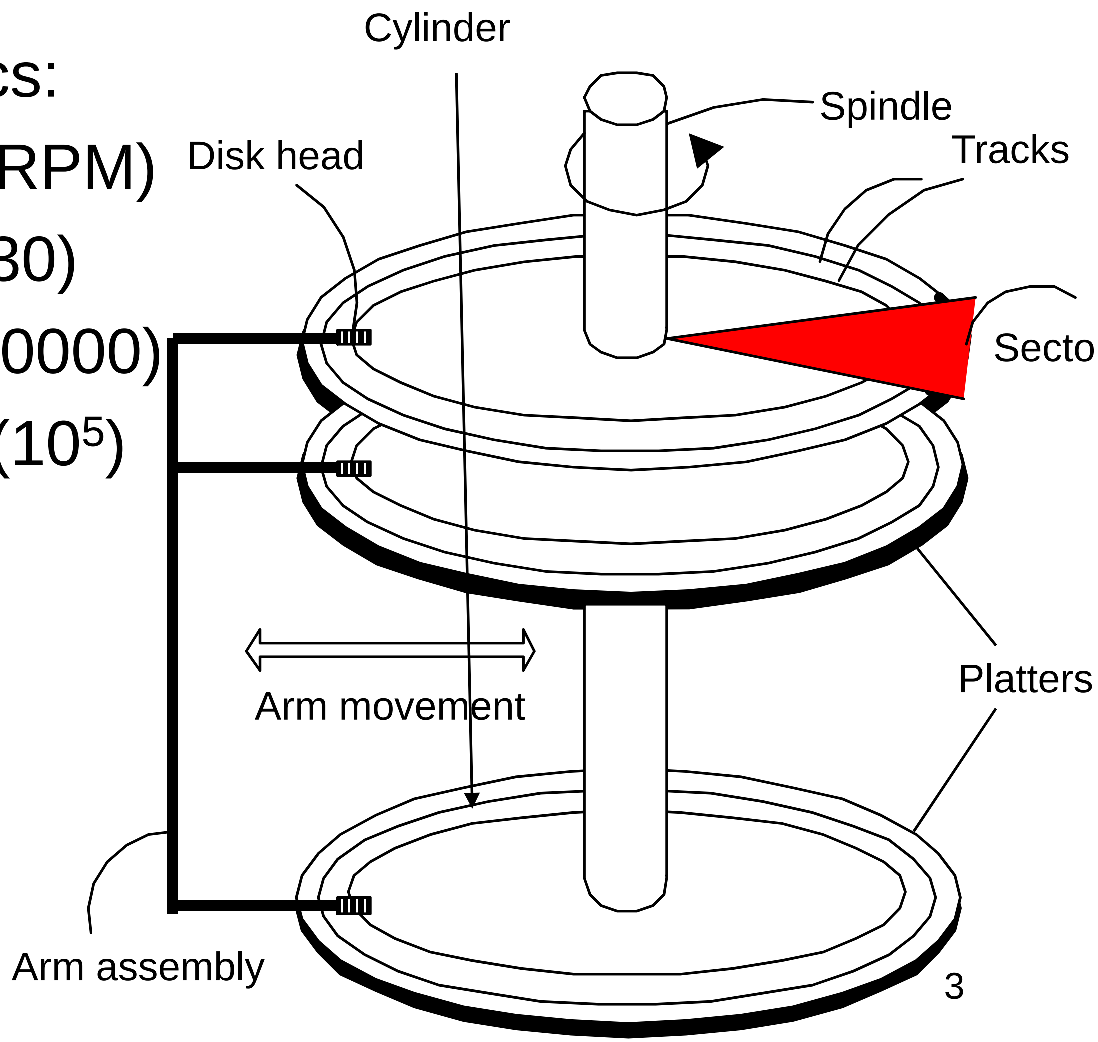
Unit of read or write:

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*):

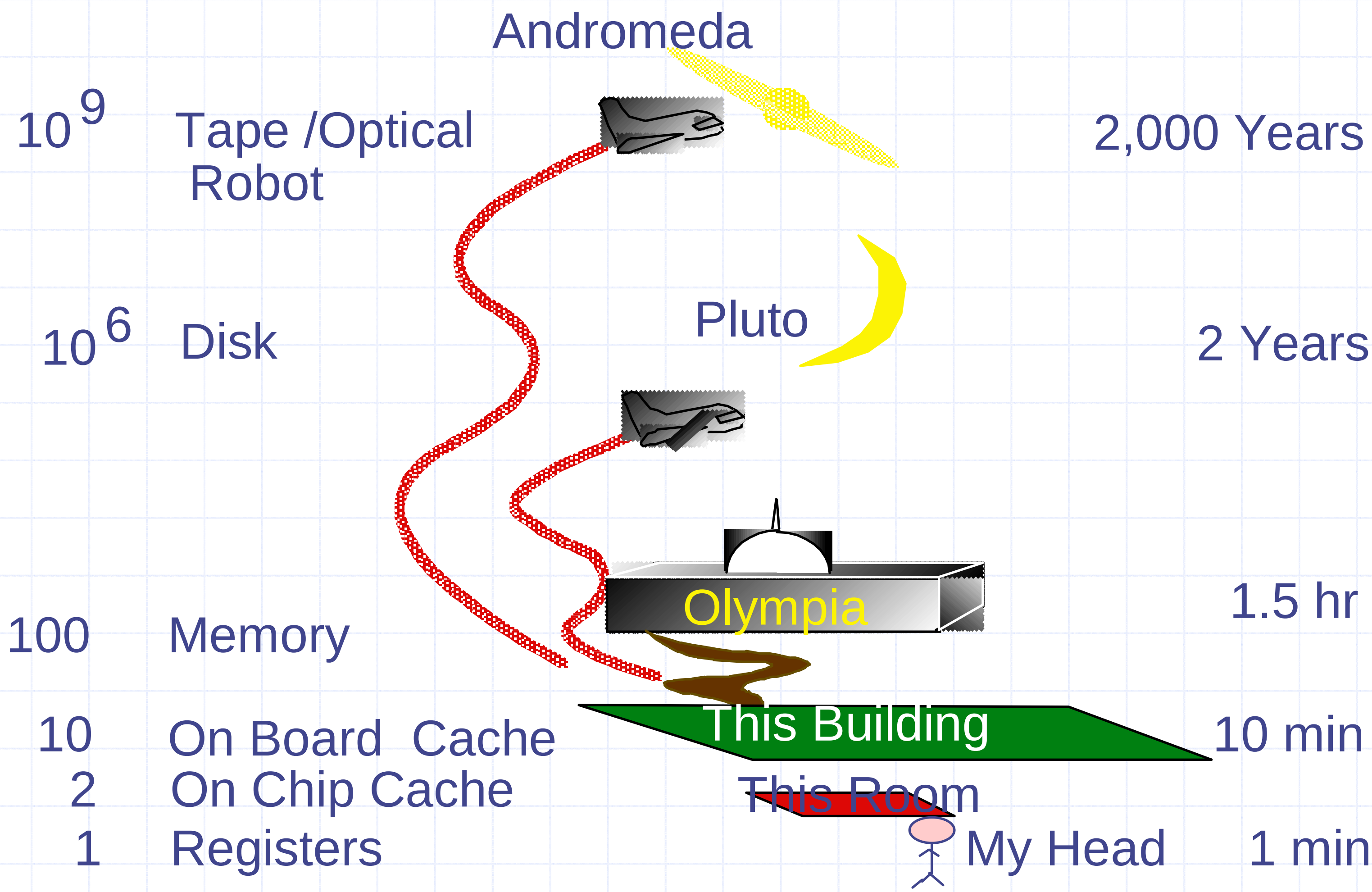
- RAID 1 = mirror
- RAID 4 = n disks + 1 parity disk
- RAID 5 = n+1 disks, assign parity blocks round robin
- RAID 6 = “Hamming codes”

Disk Access Characteristics

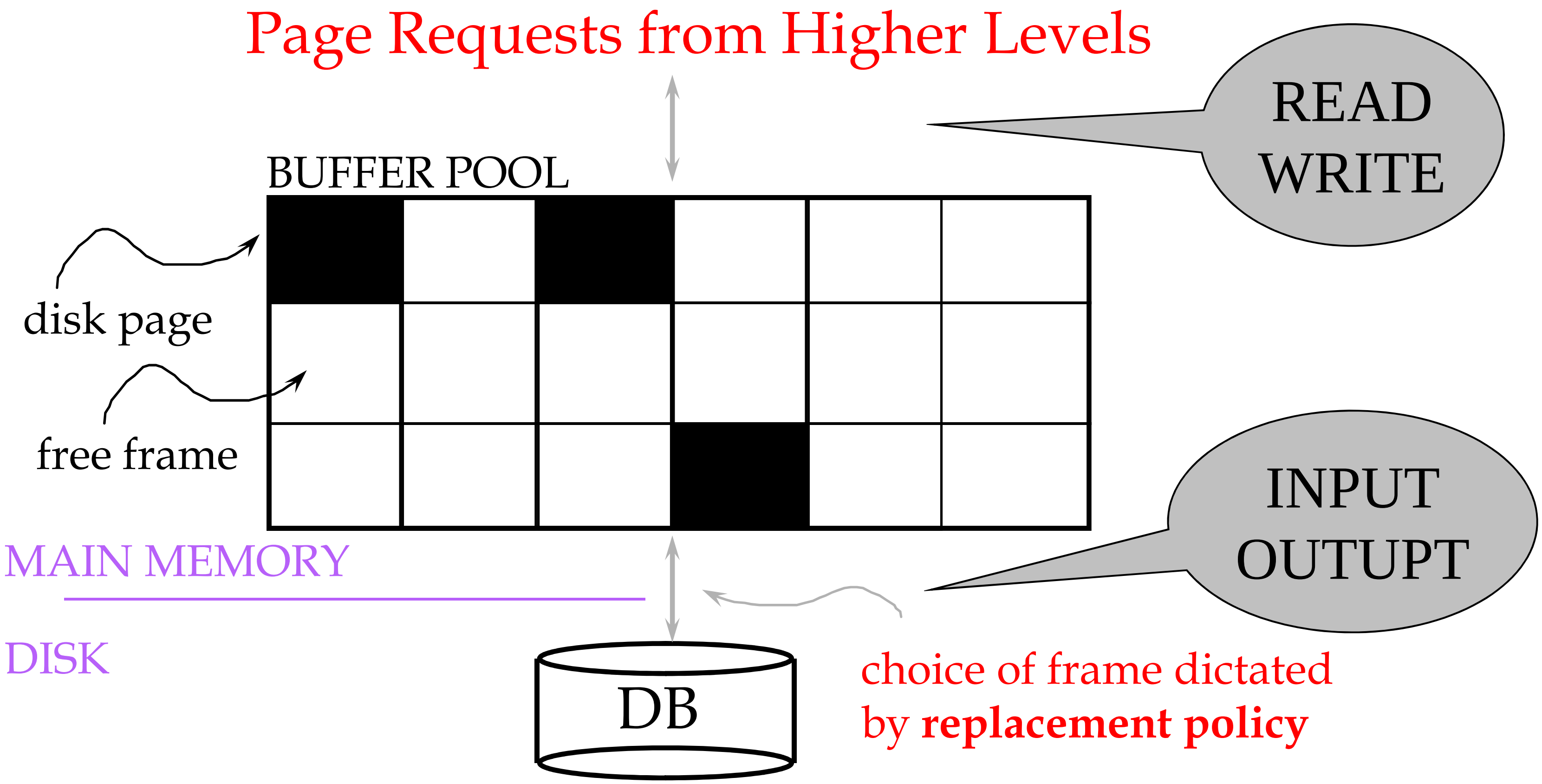
- Disk latency = time between when command is issued and when data is in memory

- 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

Storage Latency: How Far Away is the Data?



Buffer Management in a DBMS



- Data must be in RAM for DBMS to operate on it!
- Table of <frame#, pageid> pairs is maintained

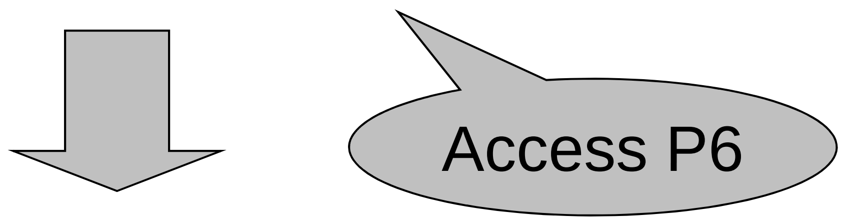
Buffer Manager

- 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



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
  - May want to pin pages in the buffer

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

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

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

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

Main Idea for Recovery

- 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 all running transactions
  - After a crash, transaction manager reads the log to find out exactly what each transaction did or did not do

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);
```

Action	t (Transaction)	Mem A (Buffer pool)	Mem B (Buffer pool)	Disk A (Disk)	Disk B (Disk)
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	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

The Log

- Log = append-only file containing log records
- 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

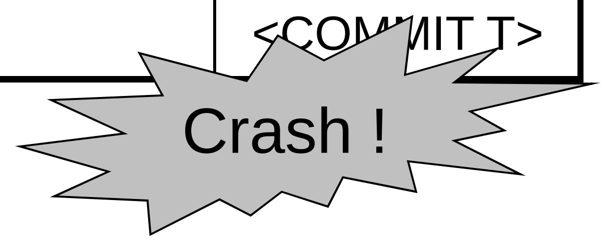
Action	T	Mem A	Mem B	Disk A	Disk B	Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						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

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:

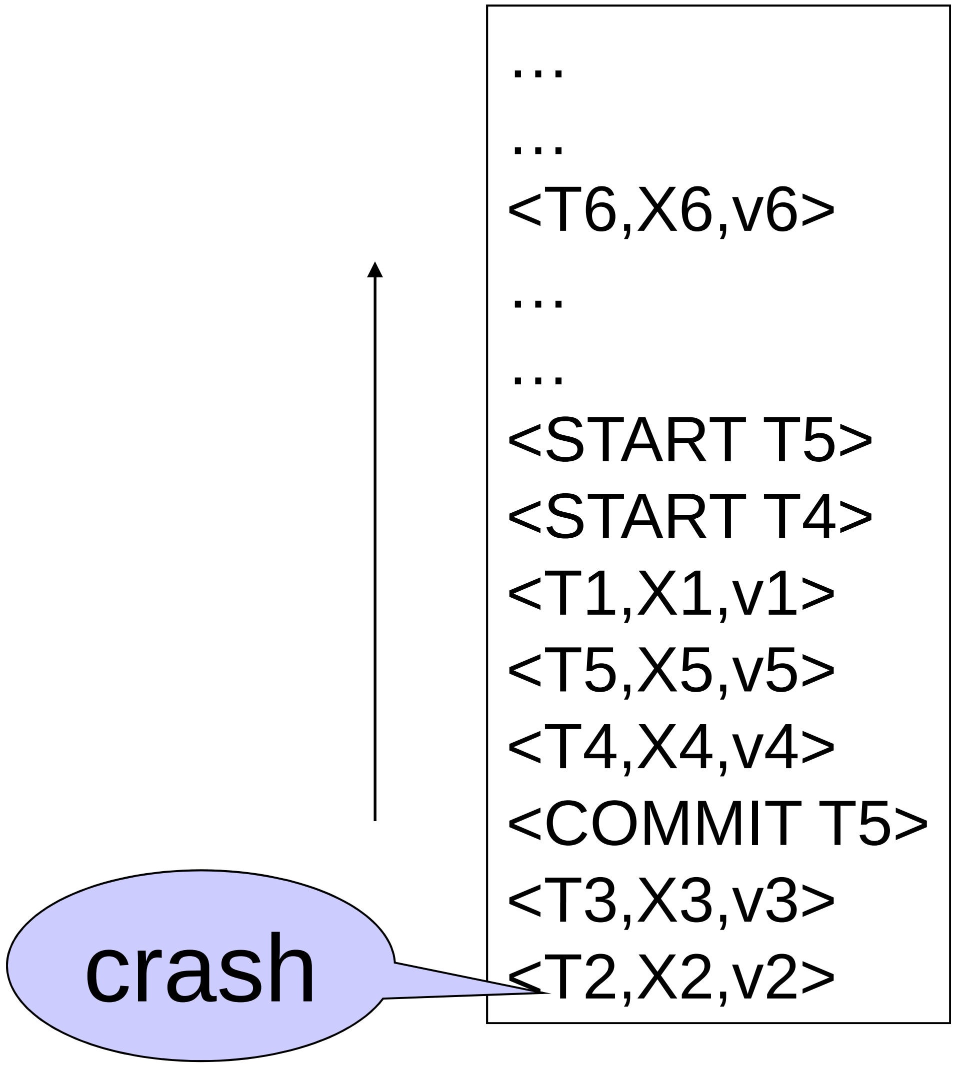
  <COMMIT T>: mark T as completed

  <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



Question 1: Which updates are undone?

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

Question 3: What happens if there is a second crash during recovery?

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.

- Continue normal operation

- When all of T1,…,Tk have completed, write <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> ?

Implementing ROLLBACK

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

Undo Logging Critique

- Works!
- But….
  - Requires physical OUTPUT before transaction can commit
    - Can cause unnecessary I/O ops if more updates will be done on the same buffer page soon
    - What if two transactions share the same buffer page and only one is ready to commit? (this one is subtle – more later…)

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:
  - 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