Recovery I

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Reading: R&G - Chapter 16,18

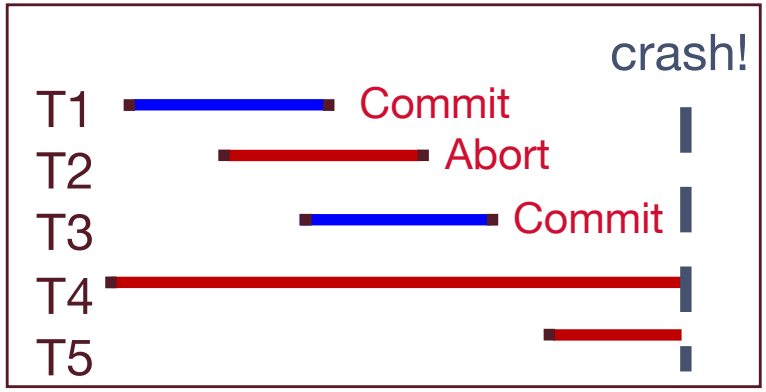
Review: The ACID properties

- **Atomicity:** All actions in the txn happen, or none happen.
- **Consistency**: If the DB starts consistent before the txn…
  it ends up consistent after.
- **Isolation**: Execution of one txn is isolated from that of others**.**
- **Durability:** If a txn commits, its effects persist.

- Recovery Manager
  - **Atomicity** & **Durability**
  - Also to rollback transactions that violate **Consistency**

Motivation

- Atomicity: Algorithm for rollback?
  - Transactions may abort ("Rollback").
- Durability:
  - What if DBMS stops running?
- Desired state after system restarts:
  - T1 & T3 should be durable.
  - T2, T4 & T5 should be aborted (effects not seen).
- Questions:
  - Why do transactions abort?
  - Why do DBMSs stop running?



Atomicity: Why Do Transactions Abort?

- User/Application explicitly aborts
- Failed Consistency check
  - Integrity constraint violated
- Deadlock
- System failure prior to successful commit

Durability: Why Do Databases Crash?

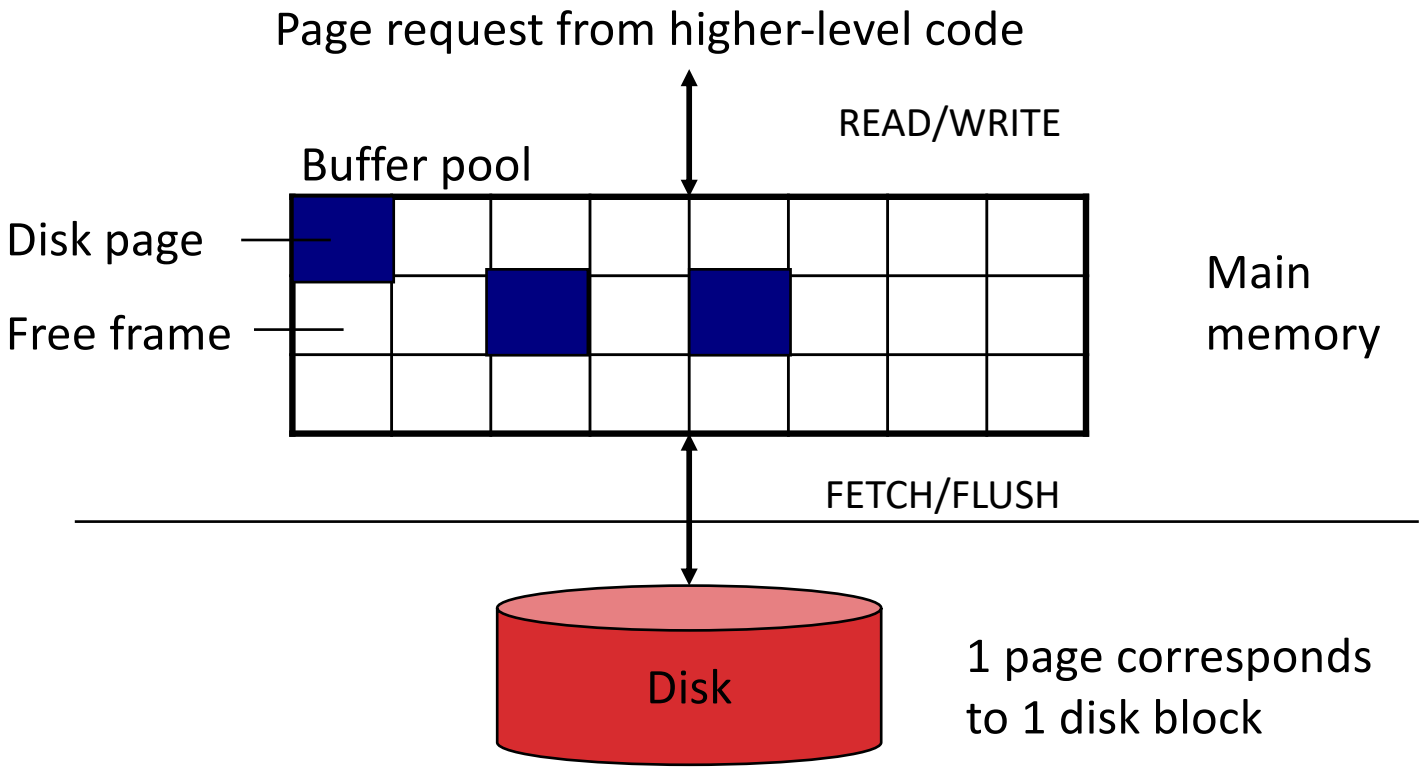
- These days:
  - FIRE! PANDEMIC! APOCALYPSE!
- Operator Error
  - Trip over the power cord
  - Type the wrong command
- Configuration Error
  - Insufficient resources: disk space
  - File permissions, etc.
- Software Failure
  - DBMS bugs, security flaws, OS bugs
- Hardware Failure
  - Media or Server

Starting our Recovery Discussion

- Assumption: Concurrency control is in effect.
  - **Strict 2PL**, in particular.
- Assumption: Updates are happening “in place”.
  - i.e., data is modified in buffer pool and pages in DB are overwritten
    - Transactions are not done on “private copies” of the data

- Challenge: Buffer Manager
  - Changes are performed in memory
  - Changes are then written to disk
  - This *discontinuity* complicates recovery

Impact of Buffer Manager (Recap)



Primitive Operations

- READ(X,t)
  - copy value of data item X to transaction local variable t
- WRITE(X,t)
  - copy transaction local variable t to data item X

- FETCH(X) New
  - read page containing data item X to memory buffer
- FLUSH(X) New
  - write page containing data item X to disk

from memory buffer

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)

A = 8
B = 8

	Transaction	Buffer pool		Disk	
Action	**t**	**Mem A**	**Mem B**	**Disk A**	**Disk B**
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Yes it's bad: A=16, B=8….

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

Is this bad ?

Yes it's bad: A=B=16, but not committed

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

(User may try again)

Crash !

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

Is this bad ?

No: that's OK

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

Crash !

disk not changed, transaction did not go thru

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

Problematic Crashes!

disk got updated but not committed

(so when crash, we try to run transaction again since we did not commit)

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16
COMMIT					

What if we delayed FLUSH to after commit?

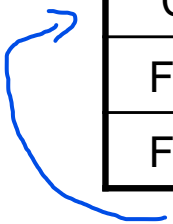
Only “dirtied” disk when COMMIT is complete?

Problematic Crashes!

OK, let's try this …

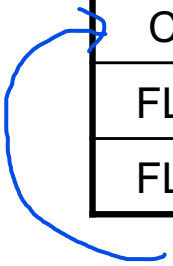
Any problematic crashes?

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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					
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16



No such luck!

Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(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
FETCH(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					
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16



Problematic Crashes!

No such luck!

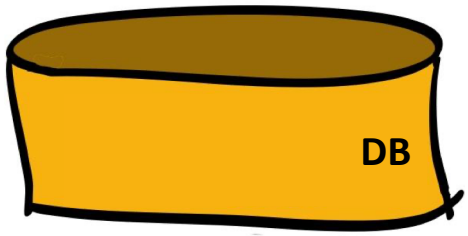
Action	t	Mem A	Mem B	Disk A	Disk B
FETCH(A)		8		8	8
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
FETCH(B)	16	16	8	8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
FLUSH(A)	16	16	16	16	8
FLUSH(B)	16	16	16	16	16

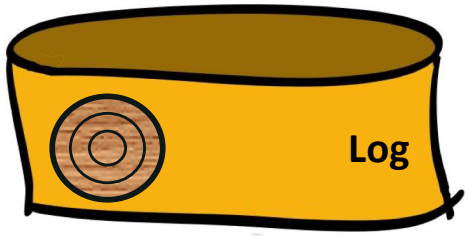
Solution:
Write things down!

Problematic Crashes!

Solution: Write-Ahead Log

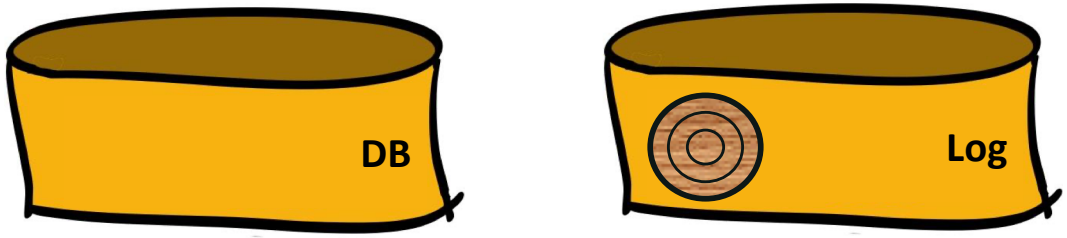
- **Log: append-only file containing log records**
  - This is usually on a different disk, separate from the data pages, allowing recovery
- For every update, commit, or abort operation
  - Write a log record
  - Multiple transactions run concurrently, log records are interleaved
- After a system crash, use log to:
  - Redo transactions that did commit
    - Redo ensures Durability
  - Undo transactions that didn't commit
    - Undo ensures Atomicity



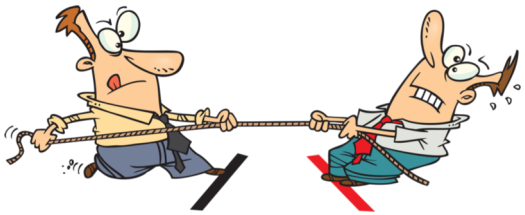


Solution: Write-Ahead Log

- **Log: append-only file containing log records**
- Also performance implications:
  - Log is sequentially written (faster) as opposed to page writes (random I/O)
  - Log can also be compact, only storing the "delta" as opposed to page writes (write a page irrespective of change to the page)
    - Pack many log records into a log page



Two Important Logging Decisions



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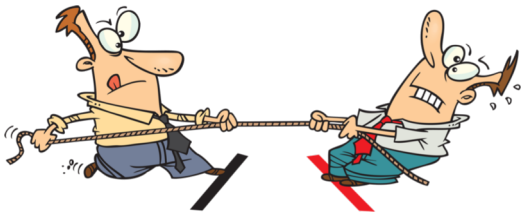
- **Decision 1: STEAL or NO-STEAL**
  - Impacts ATOMICITY and UNDO
  - Steal: allow the buffer pool (or another txn) to "steal" a pinned page of an uncommitted txn by flushing to disk
  - No-steal: disallow
  - If we allow "Steal", then need to deal with uncommitted txn edits appearing on disk
    - To ensure Atomicity we need to support UNDO of uncommitted txns
  - OTOH "No-steal" has poor performance (pinned pages limit buffer replacement)
    - But no UNDO required. Atomicity for free.

Two Important Logging Decisions



- **Decision 2: FORCE or NO-FORCE**
  - Impacts DURABILITY and REDO
  - Force: ensure that all updates of a transaction is "forced" to disk prior to commit
  - No-force: no need to ensure
  - If we allow "No-force", then need to deal with committed txns not being durable
    - To ensure Durability we need to support REDO of committed txns
  - OTOH, "Force" has poor performance (lots of random I/O to commit)
    - But no REDO required, Durability for free.

Buffer Management summary

Performance Implications

Logging/Recovery Implications

Next, will talk about UNDO logging (Force/Steal), REDO logging (No Steal/No Force), then finally UNDO-REDO (ARIES!)

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

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
FETCH(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>
FETCH(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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
FETCH(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>
FETCH(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>
FLUSH(A)	16	16	16	16	8	
FLUSH(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>
FETCH(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>
FETCH(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>
FLUSH(A)	16	16	16	16	8	
FLUSH(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>
FETCH(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>
FETCH(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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

What do we do now ?

Crash !

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
FETCH(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>
FETCH(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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

Crash !

What do we do now ?

Nothing: log contains COMMIT

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

When must we force pages to disk ?

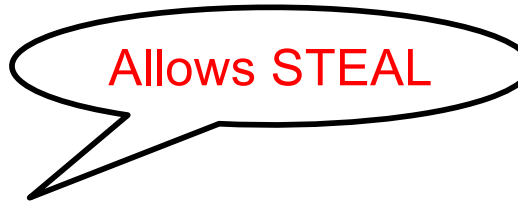
?

?

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
FETCH(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>
FETCH(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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	
COMMIT					FORCE	<COMMIT T>

RULES: log entry *before* FLUSH *before* COMMIT

Undo-Logging (Steal/Force) Rules

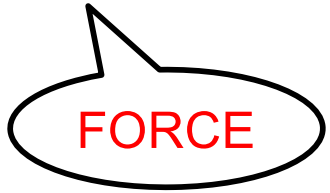


U1: If T modifies X, then <T,X,v> must be written to disk before FLUSH(X)

>> Want to record the old value before the new value replaces the old value permanently on disk.

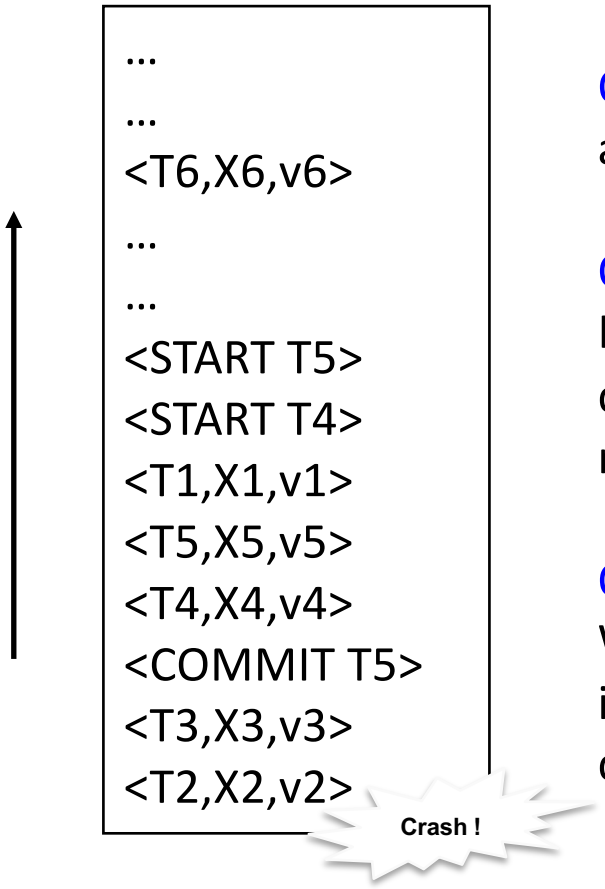
U2: If T commits, then FLUSH(X) must be written to disk before <COMMIT T>

>> Want to ensure that all changes written by T have been reflected before T is allowed to commit.



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

Recovery with Undo Log

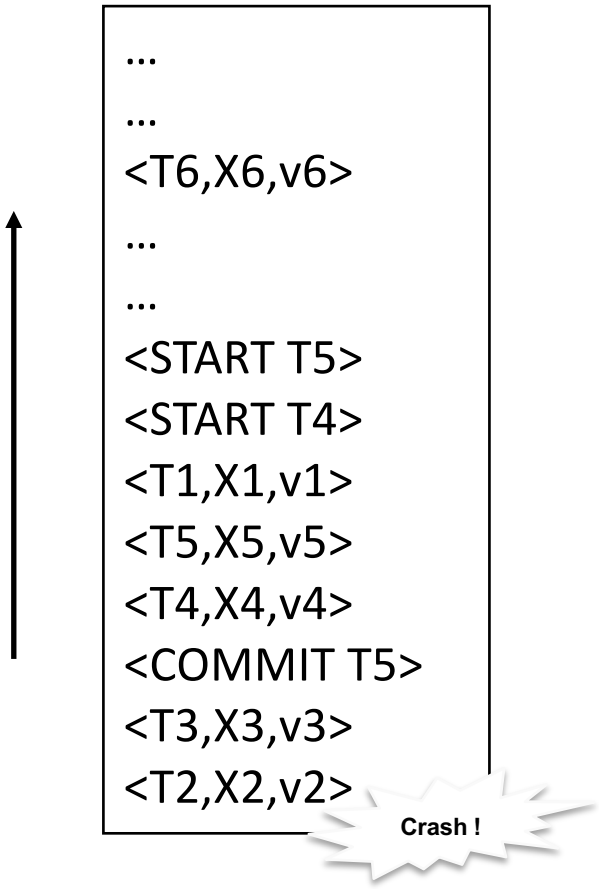


Question1: Which updates are undone ?

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



Question1: Which updates are undone ?

All uncommitted txns

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

Start of earliest uncommitted txn

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

OK: undos are idempotent

However, perf implications fixed by ARIES

Recovery with Undo Log

After system 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

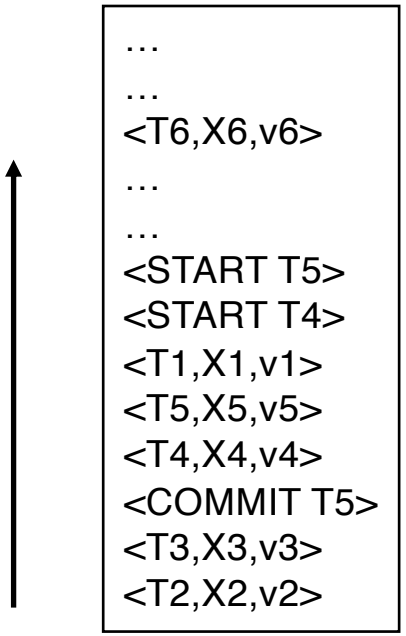
Recovery with Undo Log

Recovery manager:

- Read log from the end; cases:
  - <COMMIT/ABORT T>: mark T as completed
  - <T,X,v>: if T is not completed
    then write X=v to disk
    else ignore /* *committed or aborted txn.* */
  - <START T>: ignore

- How far back do we need to go?
  - All the way to the earliest uncommitted txn!
  - Could have a very long txn
  - Fixed by checkpointing

Recovery with Undo Log



- Write v6 to X6 on disk
- Write v1 to X1 on disk
- Write v4 to X4 on disk
- Mark T5 as completed
- Write v3 to X3 on disk
- Write v2 to X2 on disk

REDO Log

NO-FORCE and NO-STEAL

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>
FLUSH(A)	16	16	16	16	8	
FLUSH(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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	

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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	

How do we recover ? We REDO by setting A=16 and B=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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	

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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	

How do we recover ? Nothing to do!

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8				
t:=t*2	16	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>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	

When must we force pages to disk ?

?

?

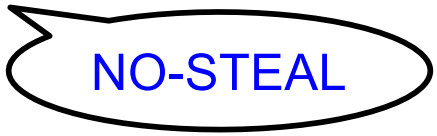
Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
FLUSH(A)	16	16	16	16	8	
FLUSH(B)	16	16	16	16	16	

NO-STEAL

RULE: FLUSH *after* COMMIT

Redo-Logging Rules

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



- Hence: FLUSHes are done *late*

Recovery with Redo Log

After system crash, run recovery manager

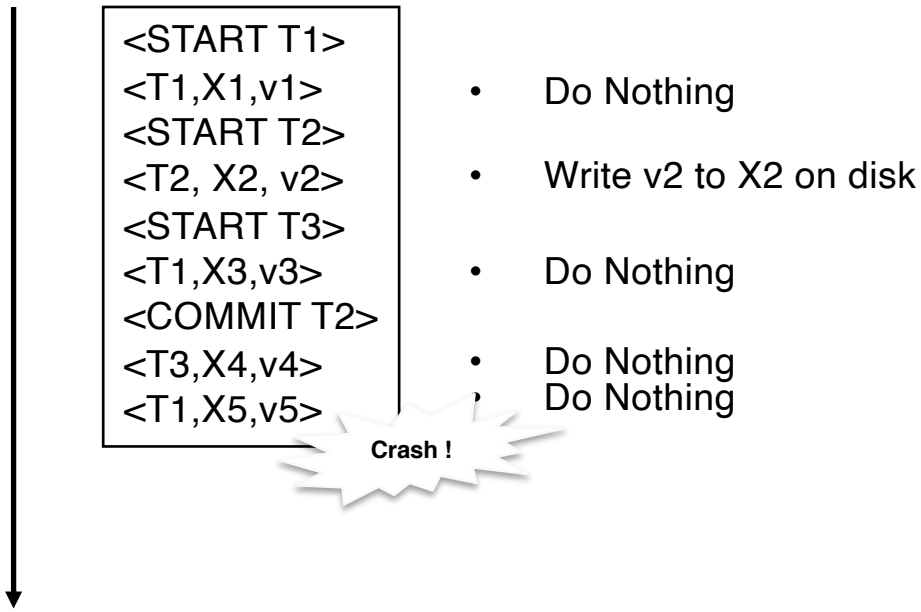
- Step 1. Decide for each transaction T whether it is completed or not
  - <START T>….<COMMIT T>…. = yes
  - <START T>….<ABORT T>……. = yes
  - <START T>…… = no
- Step 2. Read log from the *beginning*, redo all updates of *committed* transactions

(as opposed to: Undo all modifications by incomplete transactions)

Again, this could be slow! Fix with checkpointing (later)

Recovery with Redo Log

Committed transactions: T2



Comparison Undo/Redo

- Undo logging:
  - Data page FLUSHes must be done early
  - If <COMMIT T> is seen, T definitely has written all its data to disk (hence, don't need to undo)

- Redo logging
  - Data page FLUSHes must be done late
  - If <COMMIT T> is not seen, T definitely has not written any of its data to disk (hence there is no dirty data on disk)

Pro/Con Comparison Undo/Redo

- Undo logging: (Steal/Force)
  - Pro: Less memory intensive: flush updated data pages as soon as log records are flushed, only then COMMIT.
  - Con: Higher latency: forcing all dirty buffer pages to be flushed prior to COMMIT can take a long time.

- Redo logging: (No Steal/No Force)
  - Con: More memory intensive: cannot flush data pages unless COMMIT log has been flushed.
  - Pro: Lower latency: don't need to wait until data pages are flushed to COMMIT