Recovery

Lecture 15

Outline

1. Issues and Models
   - Transaction Properties
   - Storage Hierarchy
   - Failure Mode
   - System Log
2. UNDO Logging
   - (Quiescent) Checkpoints
3. REDO Logging
4. UNDO/REDO Logging
5. Closing Notes

Transaction Properties

This lecture focuses on how to support transactions in the context of certain types of failures

- **Atomicity**: need to UNDO writes from partially completed transactions
- **Consistency**: need to make sure that after failure, new transactions have a consistent start state
- **Durability**: need to REDO writes from committed transactions

Side Note: Consistency

- Most of the time we think of consistency from the DBMS standpoint
  - Often in context of failure, concurrency
- But it may be the case that transactions themselves are poorly written w.r.t. database constraints
  - And thus are legitimately aborted

Checkup

- Assume a database has the following asserted constraint: A > B > 0

- Which transactions will NOT necessarily preserve consistency of the database?
  - Provide an example

i. A = 2A; B = 2B
ii. A = 2A; B = A - 1

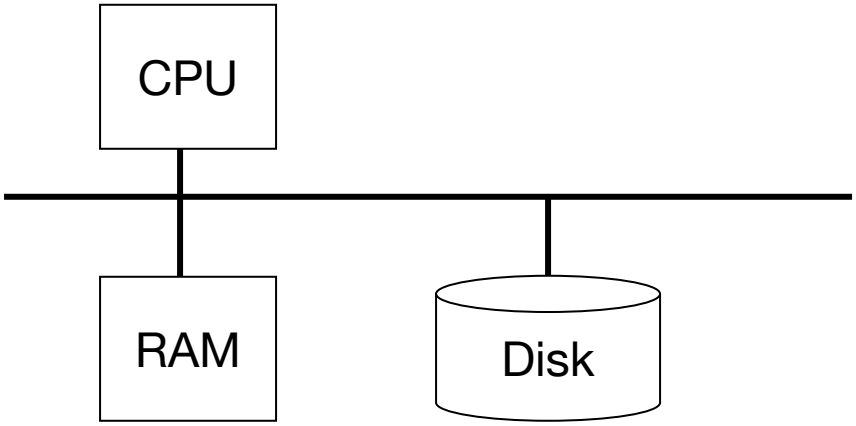
Answer (A > B > 0)

i. A = 2A; B = 2B
   - WILL preserve
   - If both started > 0, will remain so under multiplication
   - If A > B, 2A > 2B

ii. A = 2A; B = A – 1
   - WILL NOT (always) preserve
   - Start: A=0.5, B=0.4
     - Result: A=1, B=0

Storage Hierarchy

Assume the following computational abstraction…



where RAM is volatile (contents do not durably persist unless directed by CPU to disk)

Operational Sequence

1. Input(X): Disk -> Memory

2. Read(X, t): Memory -> Variable
   - Necessary for any computation via CPU
   - Assumed to perform Input(X) if necessary

3. Write(X, t): Variable -> Memory

4. Output(X): Memory -> Disk

Failure Modes

- User error (e.g. bad data entry)
  - Some handled via (application) constraints
  - Not discussed here
- Media failure (e.g. bad HD/SSD)
  - Briefly touched on at the end
- Catastrophic (e.g. fire, flood)
  - Briefly touched on at the end
- System failure (e.g. OS/application crash)
  - What happens when RAM doesn't make it to disk?
  - **Our focus**

System Log

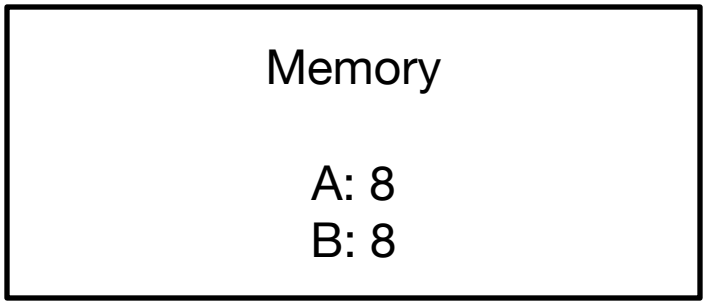
- AKA transaction log, recovery log, …
- Think of it as an append-only file on disk
  - Known format (sequence of “records”)
  - Maintained by the DBMS
  - As with actual DB data, buffered in RAM to improve efficiency (but only disk contents survive failure)
- **Main question**: what set of rules can we put in place to ensure correct transaction processing in the face of system failure, while not severely impacting performance?

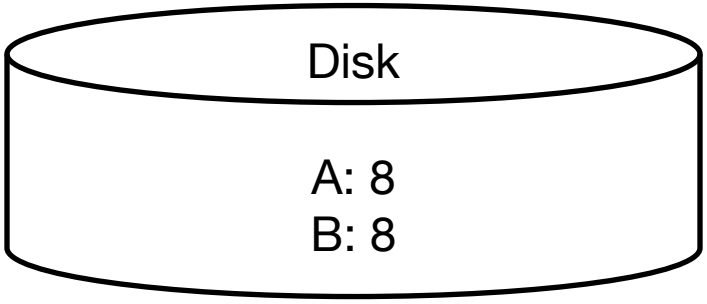
Example

- Constraint: A=B
- T1: A=2A; B=2B
  - Transaction consistent?

T1

1. Read(A, t)
2. t = 2*t
3. Write(A, t)
4. Read(B, t)
5. t = 2*t
6. Write(B, t)
7. Output(A)
8. Output(B)



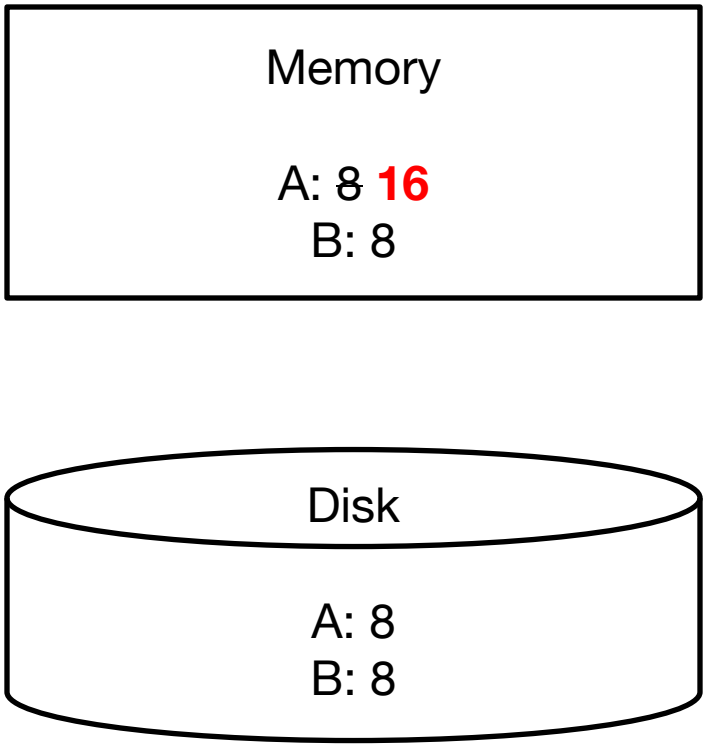


Example

- Constraint: A=B
- T1: A=2A; B=2B
  - Transaction consistent?

T1

1. Read(A, t)
2. t = 2*t
3. **Write(A, t)**
4. Read(B, t)
5. t = 2*t
6. Write(B, t)
7. Output(A)
8. Output(B)

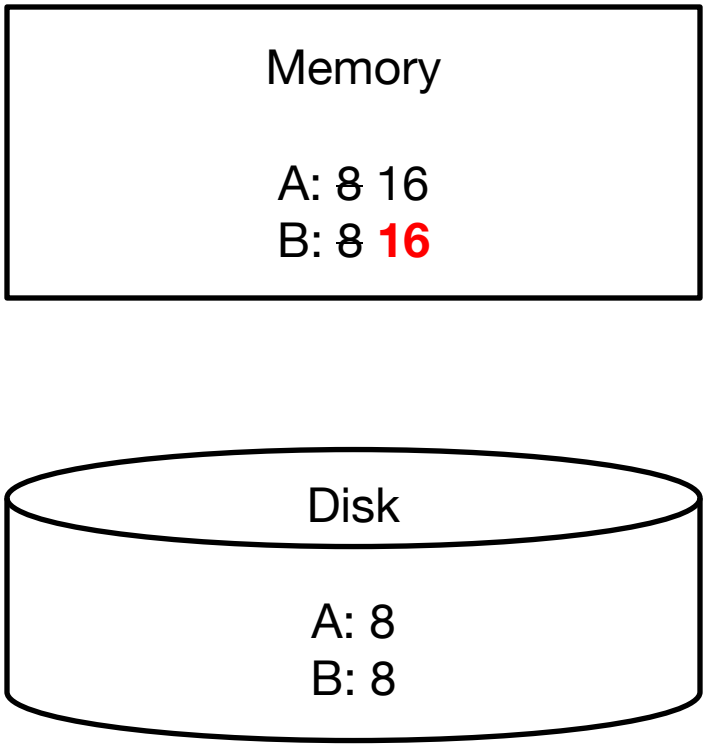


Example

- Constraint: A=B
- T1: A=2A; B=2B
  - Transaction consistent?

T1

1. Read(A, t)
2. t = 2*t
3. Write(A, t)
4. Read(B, t)
5. t = 2*t
6. **Write(B, t)**
7. Output(A)
8. Output(B)

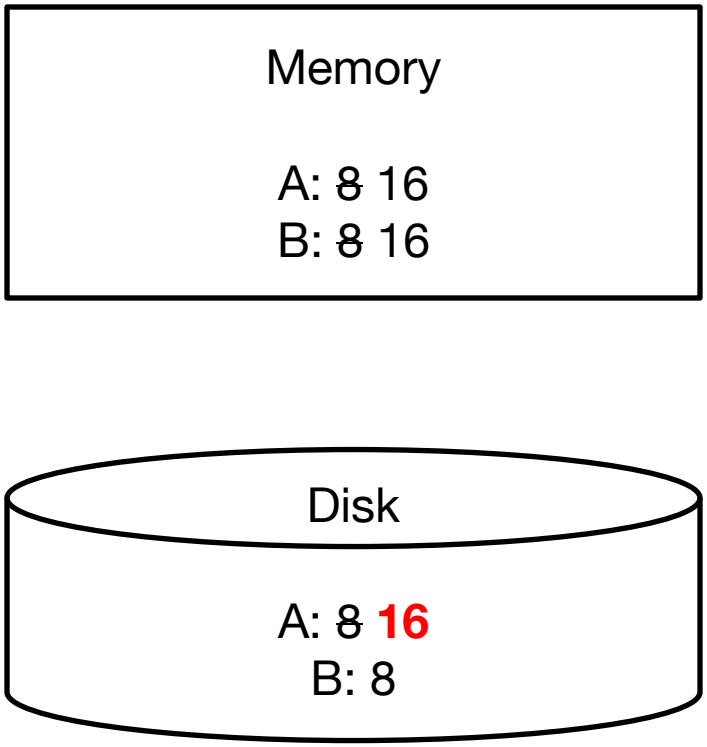


Example

- Constraint: A=B
- T1: A=2A; B=2B
  - Transaction consistent?

T1

1. Read(A, t)
2. t = 2*t
3. Write(A, t)
4. Read(B, t)
5. t = 2*t
6. Write(B, t)
7. **Output(A)**
8. Output(B)



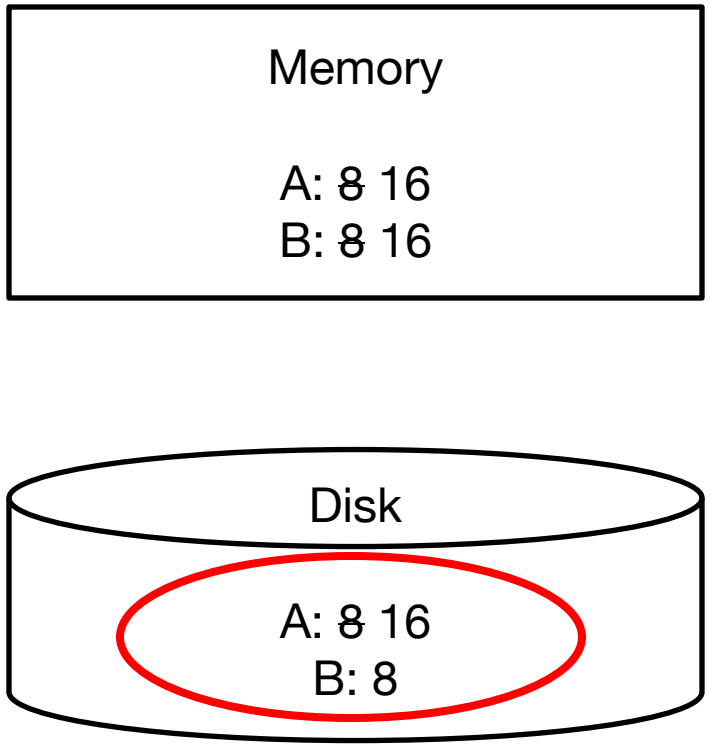
Example

- Constraint: A=B
- T1: A=2A; B=2B
  - Transaction consistent?

T1

1. Read(A, t)
2. t = 2*t
3. Write(A, t)
4. Read(B, t)
5. t = 2*t
6. Write(B, t)
7. Output(A)

8. Output(B)



Consistency Fail – Now What!!??

Map from Here

Log Format

- Approach #1: UNDO
  - Write data before COMMIT
- Approach #2: REDO
  - All modifications in RAM until log on disk
- Approach #3: UNDO/REDO
  - Fat log records

Long-Term Strategy

- Approach #1: None
  - Good luck with that…
- Approach #2: Checkpoint
  - Stops all transactions
- Approach #3: Non-Quiescent Checkpoint
  - Need more history

UNDO Logging

- At the beginning of a transaction
  `<Ti, START>`
- For every action generate undo log record containing old value
  `<Ti, X, v>`
- Before x is modified on disk, log records pertaining to x must be on disk
  - Write-Ahead Logging (WAL)
  - FLUSH LOG
- Before commit is flushed to log, all writes of transaction must be reflected on disk
  `<Ti, COMMIT>`

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log

- M-* = Value * in memory
- D-* = Value * on disk

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>
8	FLUSH LOG	16	16	16	8	8	

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>
8	FLUSH LOG	16	16	16	8	8	
9	OUTPUT(A)	16	16	16	16	8	

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>
8	FLUSH LOG	16	16	16	8	8	
9	OUTPUT(A)	16	16	16	16	8	
10	OUTPUT(B)	16	16	16	16	16	

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>
8	FLUSH LOG	16	16	16	8	8	
9	OUTPUT(A)	16	16	16	16	8	
10	OUTPUT(B)	16	16	16	16	16	
11		16	16	16	16	16	<T1, COMMIT>

Example

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>
8	FLUSH LOG	16	16	16	8	8	
9	OUTPUT(A)	16	16	16	16	8	
10	OUTPUT(B)	16	16	16	16	16	
11		16	16	16	16	16	<T1, COMMIT>
12	FLUSH LOG	16	16	16	16	16	

UNDO Recovery

- For all transactions that did not COMMIT/ROLLBACK…
  - Remember, if these log entries made it to disk, so did the corresponding value operations
- From **latest to earliest** of **`<Ti, X, v>`**
  - WRITE(X, v)
  - OUTPUT(X)
- Write **`<Ti, ABORT>`**
  - Note, system failure during recovery doesn't hurt, because operations **idempotent**

Example Failure (UNDO)

Step	Action	t	M-A	M-B	D-A	D-B	Log
							<T1, START>
							<T1, A, 8>
							<T1, B, 8>
							<T1, COMMIT>

Example Failure (UNDO)

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>
8	FLUSH LOG	16	16	16	8	8	
9	OUTPUT(A)	16	16	16	16	8	
10	OUTPUT(B)	16	16	16	16	16	
11		16	16	16	16	16	<T1, COMMIT>
12	FLUSH LOG	16	16	16	16	16	

Do nothing! Commit on disk!

Example Failure (UNDO)

Step	Action	t	M-A	M-B	D-A	D-B	Log
							<T1, START>
							<T1, A, 8>
							<T1, B, 8>

Example Failure (UNDO)

Step	Action	t	M-A	M-B	D-A	D-B	Log
1					8	8	<T1, START>
2	READ(A, t)	8	8		8	8	
3	t=2*t	16	8		8	8	
4	WRITE(A, t)	16	16		8	8	<T1, A, 8>
5	READ(B, t)	8	16	8	8	8	
6	t=2*t	16	16	8	8	8	
7	WRITE(B, t)	16	16	16	8	8	<T1, B, 8>
8	FLUSH LOG	16	16	16	8	8	
9	OUTPUT(A)	16	16	16	16	8	
10	OUTPUT(B)	16	16	16	16	16	

UNDO all T1!
Unsure if any OUTPUTS finished :(

Checkup

Given the following UNDO log, what ***could*** be the values of A and B on disk?

- R: A=A+1; B=B-1
- S: A=2*A; B=B+1
- T: A=A+1; B=3*B

1. <S, START>
2. <T, START>
3. <S, A, 5>
4. <S, B, 10>
5. <S, COMMIT>
6. <T, A, 10>
7. <T, B, 11>
8. <R, START>
9. <T, COMMIT>
10. <R, A, 11>
11. <R, B, 33>

Answer

Given the following UNDO log, what ***could*** be the values of A and B on disk?

- R: A=A+1; B=B-1
- S: A=2*A; B=B+1
- T: A=A+1; B=3*B

1. <S, START>
2. <T, START>
3. <S, A, 5>
4. <S, B, 10>
5. <S, COMMIT>
6. <T, A, 10>
7. <T, B, 11>
8. <R, START>
9. <T, COMMIT>
10. <R, A, 11>
11. <R, B, 33>

COMMIT made it to disk for S & T, so their modifications certainly made it to disk.

Last known values (@9): A=11, B=33

COMMIT didn't make it to disk for R, so unsure if any changes made it to disk. Also aren't unsure of OUTPUT order in R, so…

A=11, B=33; A=12, B=32
A=12, B=33; A=11, B=32

In the Long Run…

- Even if average number of records remains the same, the log will grow monotonically
  - As will the time to recover!

- Hence the need for checkpointing
  - Identify a point past which log is unnecessary (for recovery)

Basic Checkpoint

1. Stop accepting new transactions
2. Wait until all active transactions COMMIT or ROLLBACK (in the log!)
   - Termed: **quiescence**
3. FLUSH the log
4. Write <CKPT> to the log, FLUSH
   - Point to stop checking for unfinished transactions in future recovery – hence, could delete before!
5. Resume accepting transactions

Nonquiescent Checkpoint

- Step 1 (stop all incoming transactions) might not be reasonable in all work loads
  - Basically takes the database offline :(

- SO…
  1. Write **<START CKPT(T1, … Tk)>**
     - Includes transactions that have started, but not yet completed
  2. When T1…Tk have completed, **<END CKPT>** and flush the log

Recovery

- What happens if we hit a CKPT END?
  - Scan back only as far as START: any incomplete started after that point
- What happens if we hit a CKPT START?
  - Failure must have happened during checkpointing :(
  - BUT, we know exactly which incomplete transactions (T1…Tk), so go back as far as their START
- Win: we only need to go back as far as START CKPT since the last END CKPT

REDO Logging

- A weakness of UNDO: need to write to disk before COMMIT

- REDO protocol (via **Deferred Update**)
  - For every action, generate redo log record (containing new value)
  - Before X is modified on disk, all log records for the transaction that modified X (including COMMIT) must be on disk

REDO Recovery

- For all transactions that did COMMIT…
  - Remember, if these log entries made it to disk, the whole transaction committed

- From **earliest to latest** of <Ti, X, v>
  - WRITE(X, v)
  - OUTPUT(X)
    - Technically, optional (why?)

REDO Checkpoints

1. START(…), FLUSH LOG
2. Write DB changes for committed transactions
3. END, FLUSH LOG

- Note: requires that the DBMS keep track of changes to memory by committed transactions that have not yet been written to disk

Checkup

Assume that initially A=5, B=10. Given the following REDO log, what ***could*** be the values of A and B on disk?

1. <S, START>
2. <S, A, 20>
3. <S, B, 30>
4. <S, COMMIT>
5. <R, START>
6. <R, B, 25>
7. <T, START>
8. <R, A, 50>
9. <T, B, 2>
10. <T, COMMIT>

Answer

Assume that initially A=5, B=10. Given the following REDO log, what ***could*** be the values of A and B on disk?

1. <S, START>
2. <S, A, 20>
3. <S, B, 30>
4. <S, COMMIT>
5. <R, START>
6. <R, B, 25>
7. <T, START>
8. <R, A, 50>
9. <T, B, 2>
10. <T, COMMIT>

COMMIT made it to disk for S & T, so their modifications *could* have made it to disk.

COMMIT for R did not make it to disk, so new values certainly could not.

So… {5, 20} x {10, 30, 2}

A=5, B=10; A=5, B=30; A=5, B=2
A=20, B=10; A=20, B=30; A=20, B=2

UNDO vs REDO

- UNDO: write all before COMMIT
  - High I/O :(
- REDO: in RAM till COMMIT
  - Higher memory footprint, greater need for recovery in case of failure :(
- Solution: combine as UNDO/REDO!

UNDO/REDO Logging

- Before X is modified on disk, flush corresponding log record

  `<Ti, X, old, new>`

- Flush log on commit

- Full flexibility as to when non-log data is written to disk
  - At the cost of fatter log entries

Recovery

- Backwards pass (UNDO)
  - Start at the end of the log, go backwards to the most recent checkpoint start
  - UNDO actions of uncommitted transactions
    - Including ABORT entry
- Forward pass (REDO)
  - Start at the most recent checkpoint start, go forward to the end of the log
  - REDO actions of committed transactions

UNDO/REDO Checkpoints

1. START(…), FLUSH LOG
2. Write all DB changes (committed or not)
3. END, FLUSH LOG

Checkup

Given the following UNDO/REDO log, what ***could*** be the values of A and B on disk?

1. <S, START>
2. <S, A, 10, 20>
3. <S, B, 15, 30>
4. <S, COMMIT>
5. <T, START>
6. <T, A, 20, 30>
7. <START CKPT(T)>
8. <T, B, 30, 10>
9. <T, COMMIT>
10. <R, START>
11. <R, A, 30, 50>
12. <END CKPT>
13. <R, B, 10, 1>
14. <R, COMMIT>

Answer

Given the following UNDO/REDO log, what ***could*** be the values of A and B on disk?

1. <S, START>
2. <S, A, 10, 20>
3. <S, B, 15, 30>
4. <S, COMMIT>
5. <T, START>
6. <T, A, 20, 30>
7. <START CKPT(T)>
8. <T, B, 30, 10>
9. <T, COMMIT>
10. <R, START>
11. <R, A, 30, 50>
12. <END CKPT>
13. <R, B, 10, 1>
14. <R, COMMIT>

At the end of the checkpoint, last memory values were on disk (A=30, B=30).

Any other log entries *could* have been mirrored to disk by a delayed update.

SO… {30, 50} x {30, 10, 1}

A=30, B=30; A=30, B=10; A=30, B=1
A=50, B=30; A=50, B=10; A=50, B=1

Checkup

Given the following UNDO/REDO log, what are the values of A/B **in the database at the end of recovery**?

1. <S, START>
2. <S, A, 10, 20>
3. <S, B, 15, 30>
4. <S, COMMIT>
5. <T, START>
6. <T, A, 20, 30>
7. <START CKPT(T)>
8. <T, B, 30, 10>
9. <T, COMMIT>
10. <R, START>
11. <R, A, 30, 50>
12. <END CKPT>
13. <R, B, 10, 1>
14. <START CKPT(P, R)>
15. <P, START>
16. <R, COMMIT>
17. <P, A, 50, 60>

Answer

Given the following UNDO/REDO log, what are the values of A/B **in the database at the end of recovery**?

1. <S, START>
2. <S, A, 10, 20>
3. <S, B, 15, 30>
4. <S, COMMIT>
5. <T, START>
6. <T, A, 20, 30>
7. <START CKPT(T)>
8. <T, B, 30, 10>
9. <T, COMMIT>
10. <R, START>
11. <R, A, 30, 50>
12. <END CKPT>
13. <R, B, 10, 1>
14. <START CKPT(P, R)>
15. <P, START>
16. <R, COMMIT>
17. <P, A, 50, 60>

All transactions but P have committed via the log, so look to last result values…

A=50
B=1

Closing Notes

- Still need database/log copies to protect against media failure
  - RAID, remote backup (full vs incremental)

- The log will likely grow faster than the database
  - So typical to regularly delete what isn't necessary (when depends on logging type)