CS 525: Advanced Database Organization

13: Failure and Recovery

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Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Now

- Crash recovery

Correctness (informally)

- If we stop running transactions, DB left consistent
- Each transaction sees a consistent DB

How can constraints be violated?

- Transaction bug
- DBMS bug
- Hardware failure
  - e.g., disk crash alters balance of account
- Data sharing

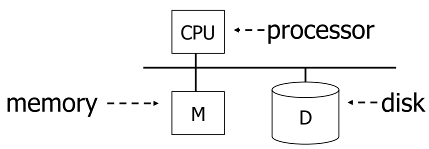
e.g.: T1: give 10% raise to programmers
T2: change programmers ⇒ systems analysts

Recovery

- First order of business: Failure Model

Events — Desired
Events — Undesired — Expected
Events — Undesired — Unexpected

Our failure model



Desired events: see product manuals….

Undesired expected events:
System crash
- memory lost
- cpu halts, resets

Desired events: see product manuals….

Undesired expected events:
System crash
- memory lost
- cpu halts, resets

that's it!!

Undesired Unexpected: Everything else!

Undesired Unexpected: Everything else!

Examples:
- Disk data is lost
- Memory lost without CPU halt
- CPU implodes wiping out universe….

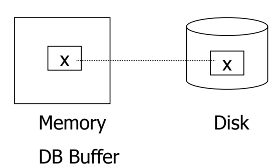
Is this model reasonable?

Approach: Add low level checks + redundancy to increase probability model holds

E.g., { Replicate disk storage (stable store)
Memory parity
CPU checks

Second order of business:

Storage hierarchy



Operations:

- Input (x): block containing x → memory
- Output (x): block containing x → disk

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- Input (x): block containing x → memory
- Output (x): block containing x → disk

- Read (x,t): do input(x) if necessary
  t ← value of x in block
- Write (x,t): do input(x) if necessary
  value of x in block ← t

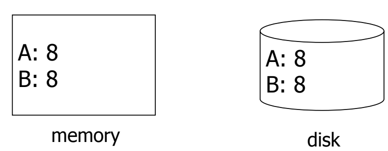
<u>Key problem</u> Unfinished transaction

Example Constraint: A=B

T1: A ← A × 2

B ← B × 2

T1: Read (A,t); t ← t×2
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
Output (B);



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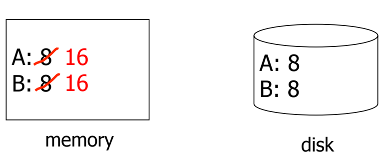
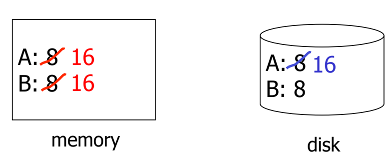


T1: Read (A,t); t ← t×2
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
failure!
Output (B);



- Need <u>atomicity:</u>
  - execute all actions of a transaction or none at all

How to restore consistent state after crash?

- Desired state after recovery:
  - Changes of committed transactions are reflected on disk
  - Changes of unfinished transactions are not reflected on disk
- After crash we need to
  - **Undo** changes of unfinished transactions that have been written to disk
  - **Redo** changes of finished transactions that have not been written to disk

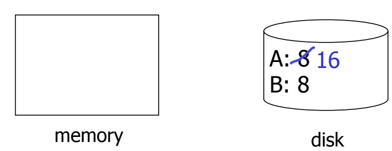
How to restore consistent state after crash?

- After crash we need to
  - **Undo** changes of unfinished transactions that have been written to disk
  - **Redo** changes of finished transactions that have not been written to disk
- We need to either
  - Store additional data to be able to Undo/Redo
  - Avoid ending up in situations where we need to Undo/Redo


```
T1:  Read (A,t);  t ← t×2
     Write (A,t);
     Read (B,t);  t ← t×2
     Write (B,t);
     Output (A);
     Output (B);
```

failure!

T_1 is unfinished -> need to undo the write to A to recover to consistent state



Logging

- After crash need to
  - **Undo**
  - **Redo**
- We need to know
  - Which operations have been executed
  - Which operations are reflected on disk
- ->**Log** upfront what is to be done

Buffer Replacement Revisited

- Now we are interested in knowing how buffer replacement influences recovery!

Buffer Replacement Revisited

- **Steal**: all pages with fix count = 0 are replacement candidates
  - Smaller buffer requirements
- **No steal:** pages that have been modified by active transaction -> not considered for replacement
  - No need to undo operations of unfinished transactions after failure

Buffer Replacement Revisited

- **Force**: Pages modified by transaction are flushed to disk at end of transaction
  - No redo required
- **No force:** modified (dirty) pages are allowed to remain in buffer after end of transaction
  - Less repeated writes of same page

Effects of Buffer Replacement

	force	No force
No steal	• No Undo • No Redo	• No Undo • Redo
steal	• Undo • No Redo	• Redo • Undo

Schedules and Recovery

- Are there certain schedules that are easy/hard/impossible to recover from?

Recoverable Schedules

- We should never have to rollback an already committed transaction (D in ACID)
- **Recoverable** (**RC**) schedules require that
  - A transaction does not commit before every transaction that is has read from has committed
  - A transaction **T** reads from another transaction **T'** if it reads an item X that has last been written by T' and T' has not aborted before the read

$T_1 = w_1(X), c_1$

$T_2 = r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

$S_1 = w_1(X), r_2(X), w_2(X), c_1, c_2$

Nonrecoverable Schedule

$S_2 = w_1(X), r_2(X), w_2(X), c_2, c_1$

Cascading Abort

- Transaction **T** has written an item that is later read by **T'** and **T** aborts after that
  - we have to also abort **T'** because the value it read is no longer valid anymore
  - This is called a **cascading abort**
  - Cascading aborts are complex and should be avoided

$S = \ldots w_1(X) \ldots r_2(X) \ldots a_1$

Cascadeless Schedules

- **Cascadeless (CL)** schedules guarantee that there are no cascading aborts
  - Transactions only read values written by already committed transactions

$T_1 = w_1(X), c_1$

$T_2 = r_2(X), w_2(X), c_2$

Cascadeless (CL) Schedule

$S_1 = w_1(X), c_1, r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

$S_2 = w_1(X), r_2(X), w_2(X), c_1, c_2$

Nonrecoverable Schedule

$S_3 = w_1(X), r_2(X), w_2(X), c_2, c_1$

$T_1 = w_1(X), a_1$

$T_2 = r_2(X), w_2(X), c_2$

Consider what happens if T1 aborts!

Cascadeless (CL) Schedule

$S_1 = w_1(X), a_1, r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

$S_2 = w_1(X), r_2(X), w_2(X), a_1, a_2$

Nonrecoverable Schedule

$S_3 = w_1(X), r_2(X), w_2(X), c_2, a_1$

Strict Schedules

- **Strict (ST)** schedules guarantee that to Undo the effect of an transaction we simply have to undo each of its writes
  - Transactions do not read nor write items written by uncommitted transactions

$T_1 = w_1(X), c_1$

$T_2 = r_2(X), w_2(X), c_2$

Cascadeless (CL) + Strict Schedule (ST)

$S_1 = w_1(X), c_1, r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

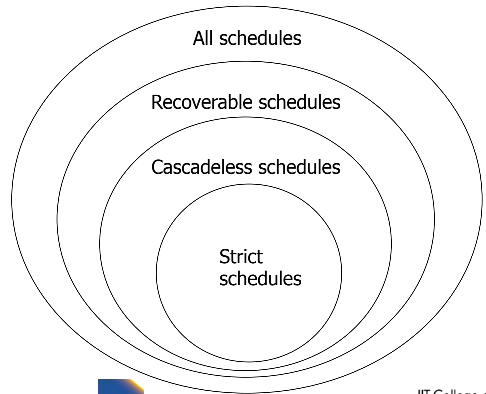
$S_2 = w_1(X), r_2(X), w_2(X), c_1, c_2$

Nonrecoverable Schedule

$S_3 = w_1(X), r_2(X), w_2(X), c_2, c_1$

Compare Classes

ST ⊂ CL ⊂ RC ⊂ ALL



Logging and Recovery

- We now discuss approaches for logging and how to use them in recovery

<u>One solution:</u> undo logging (immediate modification)

due to: Hansel and Gretel, 782 AD

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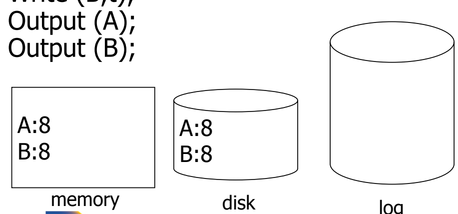
- Improved in 784 AD to durable undo logging

Undo logging (Immediate modification)

T1: Read (A,t); t ← t×2 A=B
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
Output (B);



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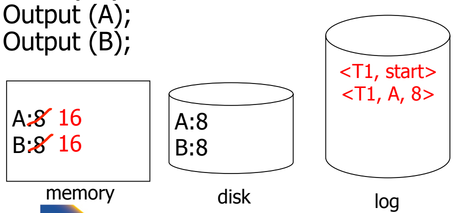

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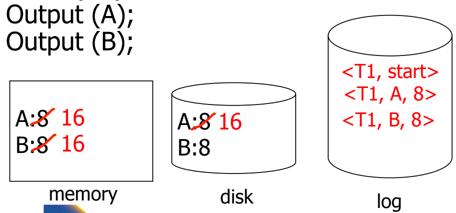

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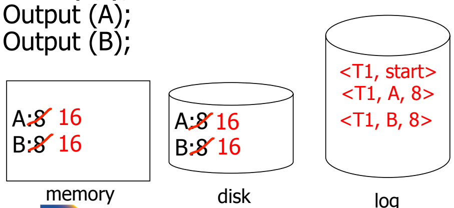

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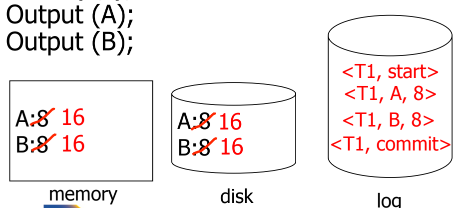
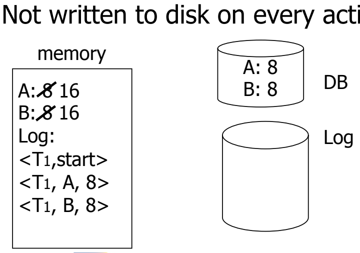


One "complication"

- Log is first written in memory
- Not written to disk on every action



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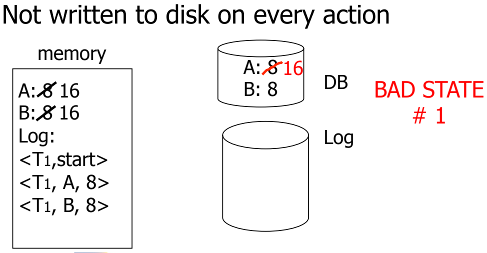

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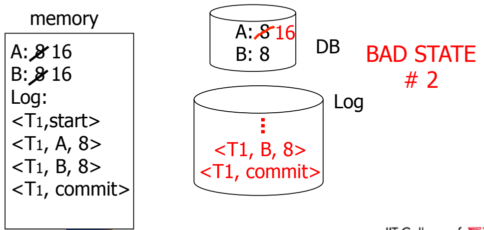

Undo logging rules

(1) For every action generate undo log record (containing old value)

(2) Before *x* is modified on disk, log records pertaining to *x* must be on disk (write ahead logging: **WAL**)

(3) Before commit is flushed to log, all writes of transaction must be reflected on disk

Recovery rules: Undo logging

- For every Ti with <Ti, start> in log:
  - If <Ti,commit> or <Ti,abort> in log, do nothing
  - Else { For all <Ti, *X*, *v*> in log:
    - { write *(X, v)*
    - output (*X*)
    - Write <Ti, abort> to log

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  - Else { For all <Ti, *X*, *v*> in log:
    - { write *(X, v)*
    - output (*X*)
    - Write <Ti, abort> to log

➧IS THIS CORRECT??

Recovery rules: Undo logging

(1) Let S = set of transactions with <Ti, start> in log, but no <Ti, commit> (or <Ti, abort>) record in log

(2) For each <Ti, X, v> in log, in reverse order (latest → earliest) do:

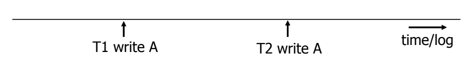
- if Ti ∈ S then { - write (X, v)
  - output (X)

(3) For each Ti ∈ S do

- write <Ti, abort> to log

Question

- Can writes of <Ti, abort> records be done in any order (in Step 3)?
  - Example: T1 and T2 both write A
  - T1 executed before T2
  - T1 and T2 both rolled-back
  - <T1, abort> written but NOT <T2, abort>?
  - <T2, abort> written but NOT <T1, abort>?



What if failure during recovery?

No problem! ✏ Undo idempotent

- An operation is called **idempotent** if the number of times it is applied do not effect the result
- For Undo:
  - Undo(log) = Undo(Undo(… (Undo(log)) …))

Undo is idempotent

- We store the values of data items before the operation
- Undo can be executed repeatedly without changing effects
  - idempotent

Physical vs. Logical Logging

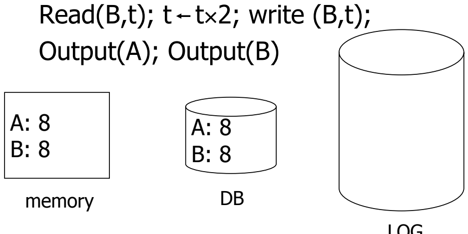
- How to represent values in log entries?
- Physical logging
  - Content of pages before and after
- Logical operations
  - Operation to execute for undo/redo
    - E.g., delete record x
- Hybrid (Physiological)
  - Delete record x from page y

To discuss:

- Redo logging
- Undo/redo logging, why both?
- Real world actions
- Checkpoints
- Media failures

Redo logging (deferred modification)

T1: Read(A,t); t← t×2; write (A,t);
Read(B,t); t←t×2; write (B,t);
Output(A); Output(B)



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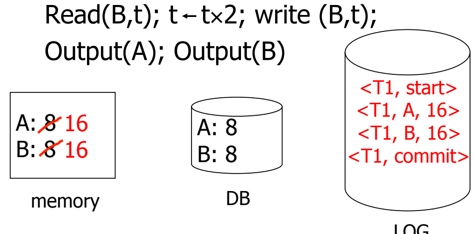

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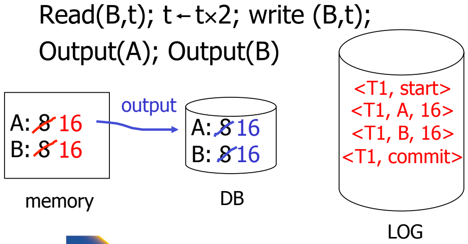

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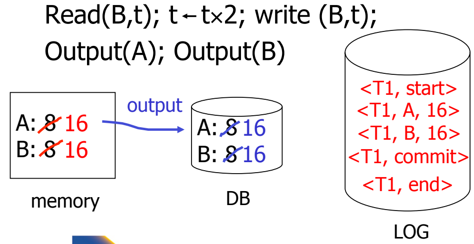

Redo logging rules

(1) For every action, generate redo log record (containing new value)

(2) Before X is modified on disk (DB), all log records for transaction that modified X (including commit) must be on disk

(3) Flush log at commit

(4) Write END record after DB updates flushed to disk

Recovery rules: Redo logging

- For every Ti with <Ti, commit> in log:
  - For all <Ti, X, v> in log:
    - Write(X, v)
    - Output(X)

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    - Output(X)

➽IS THIS CORRECT??

Recovery rules: Redo logging

(1) Let S = set of transactions with <Ti, commit> (and no <Ti, end>) in log

(2) For each <Ti, X, v> in log, in forward order (earliest → latest) do:
- if Ti ∈ S then { Write(X, v); Output(X) }

(3) For each Ti ∈ S, write <Ti, end>

Crash During Redo

- Since Redo log contains values after writes, repeated application of a log entry does not change result
  - ->idempotent

Combining <Ti, end> Records

- Want to delay DB flushes for hot objects

Say X is branch balance:
T1: ... update X...
T2: ... update X...
T3: ... update X...
T4: ... update X...

Actions:
write X
output X
write X
output X
write X
output X
write X
output X

Combining <Ti, end> Records

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Say X is branch balance:
T1: ... update X...
T2: ... update X...
T3: ... update X...
T4: ... update X...

Actions:
write X
~~output X~~
write X
~~output X~~
write X
~~output X~~
write X
output X

combined <end> (checkpoint)

Solution: Checkpoint

- no <ti, end> actions>
- simple checkpoint

Periodically:
(1) Do not accept new transactions
(2) Wait until all transactions finish
(3) Flush all log records to disk (log)
(4) Flush all buffers to disk (DB) (do not discard buffers)
(5) Write "checkpoint" record on disk (log)
(6) Resume transaction processing

Example: what to do at recovery?

Redo log (disk):

...	<T1,A,16>	...	<T1,commit>	...	Checkpoint	...	<T2,B,17>	...	<T2,commit>	...	<T3,C,21>	Crash

Advantage of Checkpoints

- Limits recovery to parts of the log after the checkpoint
  - Think about system that has been online for months
    - ->Analyzing the whole log is too expensive!
- Source of backups
  - If we backup checkpoints we can use them for media recovery!

Checkpoints Justification

- Checkpoint should be consistent DB state
  - No active transactions
    - Do not accept new transactions
    - Wait until all transactions finish
  - DB state reflected on disk
    - Flush log
    - Flush buffers

Key drawbacks:

- *Undo logging:*
  - cannot bring backup DB copies up to date
- *Redo logging:*
  - need to keep all modified blocks in memory until commit

Solution: undo/redo logging!

Update $\Rightarrow$ <Ti, Xid, New X val, Old X val>
page X

Rules

- Page X can be flushed before or after Ti commit
- Log record flushed before corresponding updated page (WAL)
- Flush at commit (log only)

Example: Undo/Redo logging what to do at recovery?

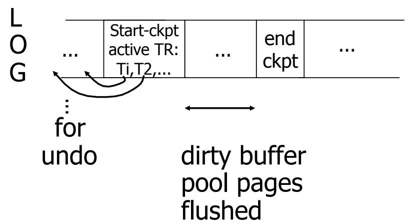
log (disk):

...	<checkpoint>	...	<T1, A, 10, 15>	...	<T1, B, 20, 23>	...	<T1, commit>	...	<T2, C, 30, 38>	...	<T2, D, 40, 41>	Crash

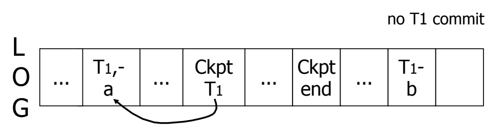
Checkpoint Cost

- Checkpoints are expensive
  - No new transactions can start
  - A lot of I/O
    - Flushing the log
    - Flushing dirty buffer pages

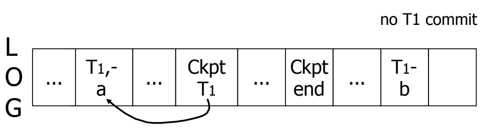
Non-quiesce checkpoint



Examples what to do at recovery time?

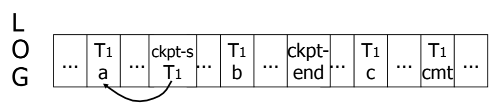


Examples what to do at recovery time?

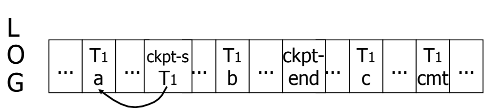


- Undo T_1 (undo a,b)

Example

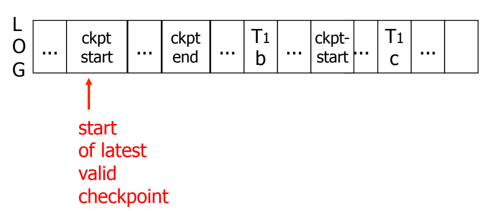


Example



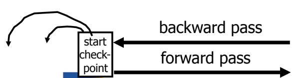
- Redo T1: (redo b,c)

Recover From Valid Checkpoint:



Recovery process:

- Backwards pass (end of log ➜ latest valid checkpoint start)
  - construct set S of committed transactions
  - undo actions of transactions not in S
- Undo pending transactions
  - follow undo chains for transactions in (checkpoint active list) - S
- Forward pass (latest checkpoint start ➜ end of log)
  - redo actions of S transactions



Real world actions

E.g., dispense cash at ATM

$Ti = a_1 a_2 \ldots\ldots a_j \ldots\ldots a_n$

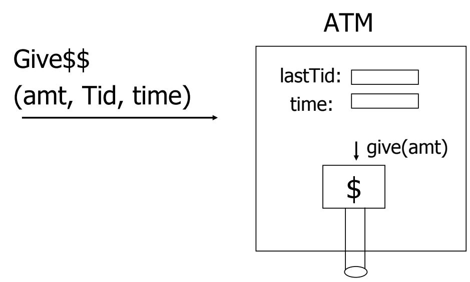
↓

$

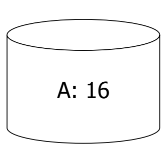
Solution

(1) execute real-world actions after commit

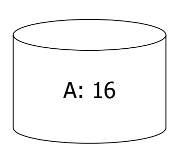
(2) try to make idempotent



Media failure (loss of non-volatile storage)



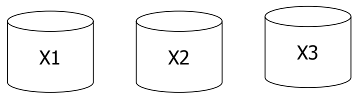
Media failure (loss of non-volatile storage)



Solution: Make copies of data!

Example 1 Triple modular redundancy

- Keep 3 copies on separate disks
- Output(X) --> three outputs
- Input(X) --> three inputs + vote

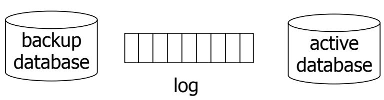


Example #2 Redundant writes, Single reads

- Keep N copies on separate disks
- Output(X) --> N outputs
- Input(X) --> Input one copy
  - if ok, done
  - else try another one

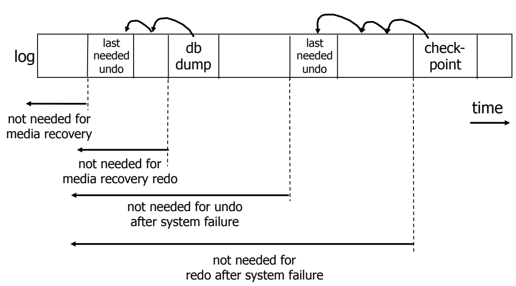
➽ Assumes bad data can be detected

Example #3: DB Dump + Log



- If active database is lost,
  - restore active database from backup
  - bring up-to-date using redo entries in log

When can log be discarded?



Practical Recovery with ARIES

- **ARIES**
  - **A**lgorithms for **R**ecovery and **I**solation **E**xploiting **S**emantics
- Implemented in, e.g.,
  - DB2
  - MSSQL

Underlying Ideas

- Keep track of state of pages by relating them to entries in the log
- **WAL**
- Recovery in **three phases**
  - Analysis, Redo, Undo
- Log entries to track state of Undo for repeated failures
- **Redo**: page-oriented -> efficient
- **Undo**: logical -> permits higher level of concurrency

Log Entry Structure

- **LSN**
  - **L**og **s**equence **n**umber
  - Order of entries in the log
  - Usually **log file id** and **offset** for direct access

- **LSN**
- **Entry type**
  - Update, compensation, commit, …
- **TID**
  - Transaction identifier
- **PrevLSN**
  - LSN of previous log record for same transaction
- **UndoNxtLSN**
  - Next undo operation for CLR (later!)
- **Undo/Redo data**
  - Data needed to undo/redo the update

Page Header Additions

- **PageLSN**
  - **LSN** of the last update that modified the page
  - Used to know which changes have been applied to a page

Forward Processing

- Normal operations when no ROLLBACK is required
  - WAL: write redo/undo log record for each action of a transaction
- Buffer manager has to ensure that
  - changes to pages are not persisted before the corresponding log record has been persisted
  - Transactions are not considered committed before all their log records have been flushed

Dirty Page Table

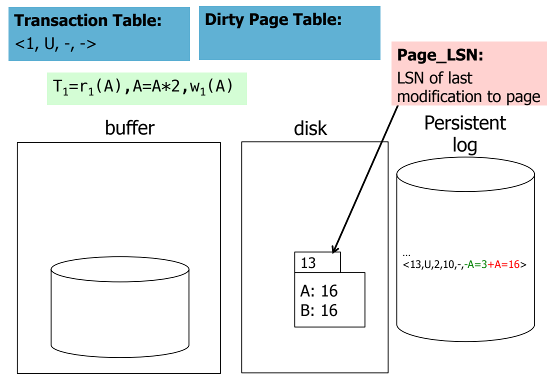
- **PageLSN**
  - Entries **<PageID,RecLSN>**
  - Whenever a page is first fixed in the buffer pool with indention to modify
    - Insert **<PageId,RecLSN>** with **RecLSN** being the current end of the log
  - Flushing a page removes it from the Dirty page table

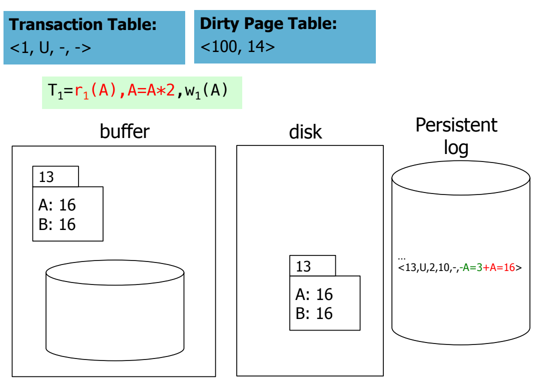
Dirty Page Table

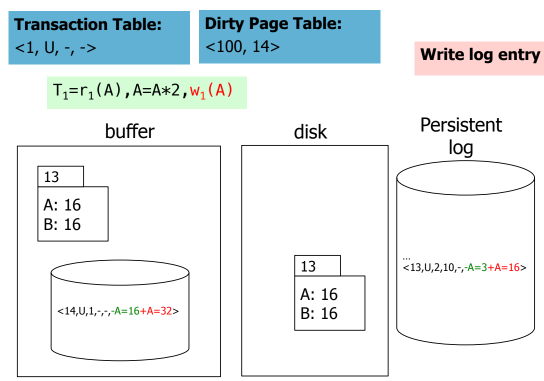
- Used for checkpointing
- Used for recovery to figure out what to redo

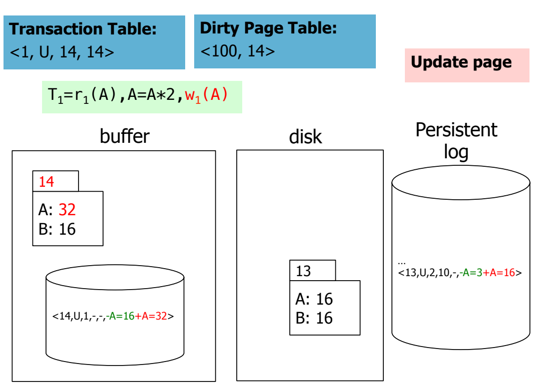
Transaction Table

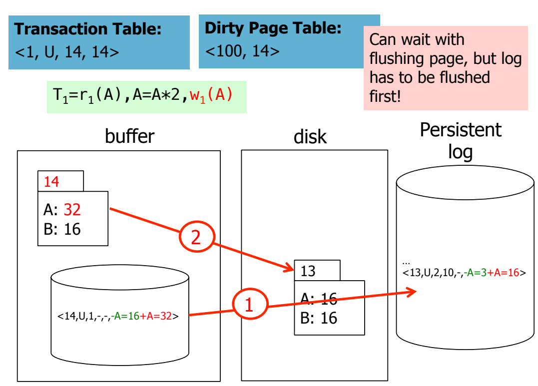
- TransID
  - Identifier of the transaction
- State
  - Commit state
- LastLSN
  - LSN of the last update of the transaction
- UndoNxtLSN
  - If last log entry is a CLR then UndoNxtLSN from that record
  - Otherwise = LastLSN











Undo during forward processing

- Transaction was rolled back
  - User aborted, aborted because of error, …
- Need to undo operations of transaction
- During Undo
  - Write log entries for every undo
  - **Compensation Log Records (CLR)**
  - Used to avoid repeated undo when failures occur

Undo during forward processing

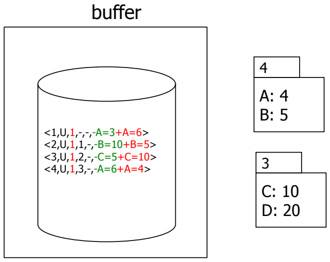
- Starting with the LastLSN of transaction from transaction table
  - Traverse log entries of transaction last to first using PrevLSN pointers
  - For each log entry use undo information to undo action
    - **<LSN, Type, TID, PrevLSN, -, Undo/Redo data>**
  - Before modifying data write an CLR that stores redo-information for the undo operation
    - **UndoNxtLSN** = **PrevLSN** of log entry we are undoing
    - **Redo data** = How to redo the undo

Transaction Table:
<1, U, 4, 4>

Undo T_1

$T_1 = w_1(A), w_1(B), w_1(C), w_1(A), a_1$

buffer

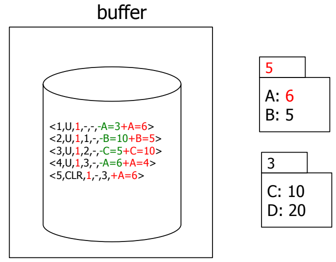


Transaction Table:
<1, U, 5, 3>

Undo T_1

$T_1 = w_1(A), w_1(B), w_1(C), w_1(A), a_1$

buffer

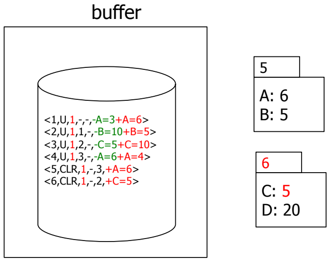


Transaction Table:
<1, U, 6, 2>

Undo T_1

$T_1 = w_1(A), w_1(B), w_1(C), w_1(A), a_1$

buffer

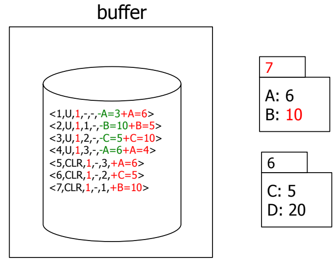


Transaction Table:
<1, U, 7, 1>

Undo T_1

$T_1 = w_1(A), w_1(B), w_1(C), w_1(A), a_1$

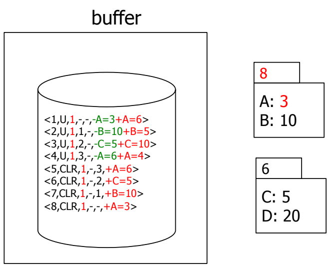
buffer



Transaction Table:
<1, U, 8, ->

Undo T_1

$T_1 = w_1(A), w_1(B), w_1(C), w_1(A), a_1$



Fuzzy Checkpointing in ARIES

- Begin of checkpoint
  - Write **begin_cp** log entry
  - Write **end_cp** log entry with
    - Dirty page table
    - Transaction table
- **Master Record**
  - LSN of begin_cp log entry of last complete checkpoint

Restart Recovery

1. Analysis Phase
2. Redo Phase
3. Undo Phase

Analysis Phase

1) Determine LSN of last checkpoint using Master Record

2) Get Dirty Page Table and Transaction Table from checkpoint end record

3) RedoLSN = min(RecLSN) from Dirty Page Table or checkpoint LSN if no dirty page

Analysis Phase

4) Scan log forward starting from RedoLSN

- Update log entry from transaction
  - If necessary: Add Page to Dirty Page Table
  - Add Transaction to Transaction Table or update LastLSN
- Transaction end entry
  - Remove transaction from Transaction Table

Analysis Phase

- Result
  - Transaction Table
    - Transactions to be later undone
  - RedoLSN
    - Log entry to start Redo Phase
  - Dirty Page Table
    - Pages that may not have been written back to disk

Redo Phase

- Start at RedoLSN scan log forward
- Unconditional Redo
  – Even redo actions of transactions that will be undone later
- Only redo once
  – Only redo operations that have not been reflected on disk (PageLSN)

Redo Phase

- For each update log entry
  – If affected page is not in Dirty Page Table or RecLSN > LSN
    - skip log entry
  – Fix page in buffer
    - If PageLSN >= LSN then operation already reflected on disk
      – Skip log entry
    - Otherwise apply update

Redo Phase

- Result
  – State of DB before Failure

Undo Phase

- Scan log backwards from end using Transaction Table
  – Repeatedly take log entry with max LSN from all the current actions to be undone for each transaction
    - Write CLR
    - Update Transaction Table

Undo Phase

- All unfinished transactions have been rolled back

Idempotence?

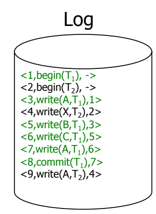
- Redo
  – We are not logging during Redo so repeated Redo will result in the same state
- Undo
  – If we see CLRs we do not undo this action again

Avoiding Repeated Work

- Redo
  - If operation has been reflected on disk (PageLSN) we do not need to redo it again
- Undo
  - If we see CLRs we do not undo this action again

$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

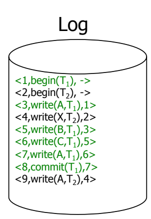
$T_2 = \quad w_1(X), \quad r(A), w(A)$



$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \quad w_1(X), \quad r(A), w(A)$

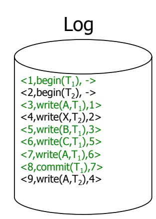
Analysis Phase:
- start at log entry 1
- add T_1 to transaction table (rec. 1)
- add T_2 to transaction table (rec. 2)
- add A to dirty page table (RecLSN 3)
- add X to dirty page table (RecLSN 4)
- add B to dirty page table (RecLSN 5)
- add C to dirtypage table (RecLSN 6)
- remove T1 from Transaction Table (rec. 8)



$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \quad w_1(X), \quad r(A), w(A)$

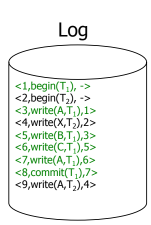
Analysis Phase Result:
- Transaction Table:
  - <T_2, 9>
- Dirty Page Table:
  - <A, 3>, <B, 5>, <C, 6>, <X, 4>
- RedoLSN = min(3,5,6,4) = 3



$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \quad w_1(X), \quad r(A), w(A)$

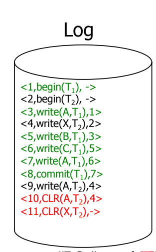
Redo Phase (RedoLSN 3):
- Read A if PageLSN < 3 apply write
- Read X if PageLSN < 4 apply write
- Read B if PageLSN < 5 apply write
- Read C if PageLSN < 6 apply write
- Read A if PageLSN < 7 apply write
- Read A if PageLSN < 9 apply write



$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \quad w_1(X), \quad r(A), w(A)$

Undo Phase (T_2):
- Undo entry 9
  - -write CLR with UndoNxtLSN = 4
  - -modify page A
- Undo entry 4
  - -write CLR with UndoNxtLSN = 2
  - -modify page X
- Done



ARIES take away messages

- Provide good performance by
  - Not requiring complete checkpoints
  - Linking of log records
  - Not restricting buffer operations (no-force/steal is ok)
- Logical Undo and Physical (Physiological) Redo
- Idempotent Redo and Undo
  - Avoid undoing the same operation twice

Media Recovery

- What if disks where log or DB is stored failes
  - ->keep backups of log + DB state

Log Backup

- Split log into several files
- Is append only, backup of old files cannot interfere with current log operations

Backup DB state

- Copy current DB state directly from disk
- May be inconsistent
- ->Use log to know which pages are up-to-date and redo operations not yet reflected

Summary

- Consistency of data
- One source of problems: failures
  - Logging
  - Redundancy
- Another source of problems:
  Data Sharing..... next