Lecture 9: ARIES from First Principles

CREATING THE NEXT®

Today's Agenda

Recap

Mains ideas of ARIES

- Mains ideas of ARIES:
  - WAL with STEAL/NO-FORCE
  - Fuzzy Checkpoints (snapshot of dirty page ids)
  - Redo everything since the earliest dirty page
  - Undo txns that never commit
  - Write CLRs when undoing, to survive failures during restarts

Mains ideas of ARIES

- **Buffer Manager**
  - PinPage, UnpinPage, ReadPage, WritePage, DirtyPageTable
- **Recovery Manager**
  - Restart, RecoverEarliestLSN, CreateLogRecord, RollbackTxn
- **Log Manager**
  - ReadNextLogRecord, AppendLogRecord, GetMasterRecord, SetMasterRecord
- **Txn Manager**
  - GetRecordInfo, SetRecordInfo, ActiveTxnTable
- **Disk Manager**
  - ReadBlock, WriteBlock

Today's Agenda

- Deriving ARIES from first principles
  - V1: Shadow Paging
  - V2: WAL–Deferred Updates
  - V3: WAL
  - V4: Commit-consistent checkpoints
  - V5: Fuzzy checkpoints
  - V6: CLRs
  - V7: Logical Undo
  - V8: Avoid selective redo

Definitions

Protocol vs Algorithm

- Protocol
  - Set of rules that govern how a system operates.
  - Rules establish the basic functioning of the different parts, how they interact with each other, and what constraints must be satisfied by the implementation.
- Algorithm
  - Set of instructions to transform inputs to desired outputs. It can be a simple script, or a complicated program. The order of the instructions is important.

f(input) => output

Protocol vs Algorithm

- Protocol
  - Logging and recovery protocol dictates how the buffer manager interacts with the recovery manager to ensure the durability of changes made by committed txns.
- Algorithm
  - A sorting algorithm may return the records in a table in alphabetical order.

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Policy vs Mechanism

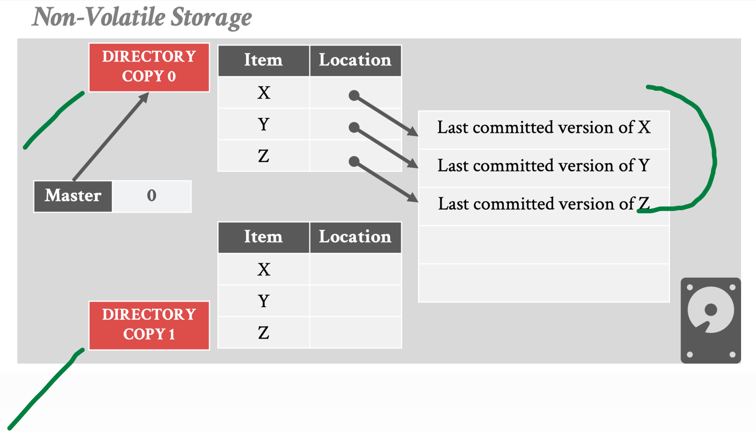
- Policy
  - Specifies the desired behavior of the system (**what**).
  - Example: Buffer manager may adopt the LRU policy for evicting pages from the buffer.
- Mechanism
  - Specifies how that behavior must be realized (**how**)
  - Example: We may implement the policy using: (1) uni-directional map + linked list, or (2) bi-directional map. Optimize the code for specific hardware technology.

Deriving ARIES

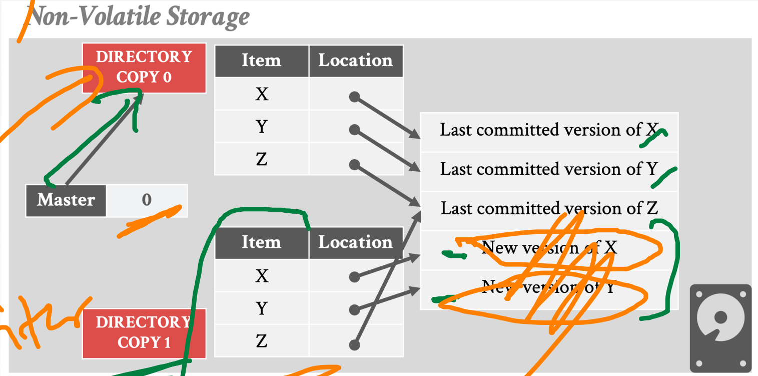
Constraints

- DRAM is volatile

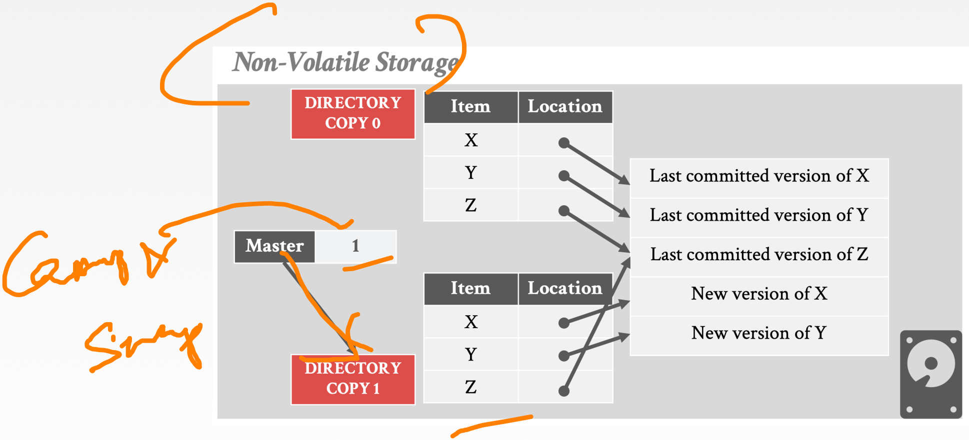
V1: SHADOW PAGING



V1: SHADOW PAGING



V1: SHADOW PAGING



V1: SHADOW PAGING

System R

- Advantages
  - No need to write log records
  - Recovery is trivial (**NO UNDO** and **NO REDO**)
- Disadvantages
  - Commit overhead is high (**FORCE** and **NO STEAL**)
  - Flush every updated page to database on disk, page table, and master page
  - Data gets fragmented over time (versioning)
  - Need garbage collection to clean up older versions.
  - Need to copy page table

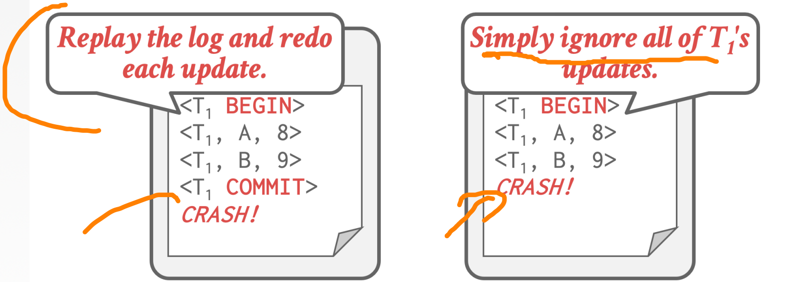
"LFS"

Constraints

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)

WAL – Deferred Updates

- If we prevent the DBMS from writing dirty records to disk until the txn commits, then the DBMS does not need to store their original values.



V2: WAL–DEFERRED UPDATES

- **Phase 1 – Analysis**
  - Read the WAL to identify active txns at the time of the crash.
- **Phase 2 – Redo**
  - Start with the last entry in the log and scan backwards toward the beginning.
  - For each update log record with a given LSN, redo the action if:
  - pageLSN (on disk) < log record's LSN

No Undo

V2: WAL–DEFERRED UPDATES

LSN Type	Where	Definition
flushedLSN	Memory	Last LSN in log on disk
pageLSN	$page_x$	Newest update to $page_x$
prevLSN	log record	LSN of prior log record by same txn

V2: WAL–DEFERRED UPDATES

- **PageLSN** (on disk – page)
  - Determine whether the log record's update needs to be re-applied to the page.
- **PrevLSN** (on disk – log record)
  - Log records of multiple transactions will be interleaved on disk
  - PrevLSN helps quickly locate the predecessor of a log record of a particular transaction
  - Facilitates parallel transaction-oriented undo

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V2: WAL–DEFERRED UPDATES

- Advantages
  - No need to undo changes (**NO UNDO** + **REDO**)
  - Flush updated pages to log on disk with sequential writes
  - Commit overhead is reduced since random writes to database are removed from the transaction commit path
- Disadvantages
  - Buffer manager cannot replace a dirty slot last written by an uncommitted transaction. (**NO FORCE** & **NO STEAL**)
  - Cannot support transactions with change sets larger than the amount of memory available

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Constraints

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)
- Support transactions with change sets > DRAM (STEAL)

V3: WAL

- **Phase 1 – Analysis**
  - Read the WAL to identify dirty pages in the buffer pool and active txns at the time of the crash.
- **Phase 2 – Redo**
  - Repeat all actions starting from an appropriate point in the log.
- **Phase 3 – Undo**
  - Reverse the actions of txns that did not commit before the crash.

V3: WAL

LSN Type	Where	Definition
flushedLSN	Memory	Last LSN in log on disk
pageLSN	$page_x$	Newest update to $page_x$
prevLSN	log record	LSN of prior log record by same txn
recLSN	DPT	Oldest update to $page_x$ since it was last flushed
lastLSN	ATT	Latest action of txn T_i

in-memory DBMS

tuple

page

V3: WAL

- **RecLSN** (in memory – Dirty Page Table)
  - Determine whether page state has not made it to disk.
  - If there is a suspicion, then page has to accessed.
  - Serves to limit the number of pages whose PageLSN has to be examined
  - If a file sync operation is found in the log, all the pages in the file are removed from the dirty page table
- **LastLSN** (in memory – Active Transaction Table)
  - Determine log records which have to rolled back for the yet-to-be-completely-undone uncommitted transactions

V3: WAL

- Advantages
  - Maximum flexibility for buffer manager
- Disadvantages
  - Log will keep growing over time thereby slowing down recovery and taking up more storage space.

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Constraints

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)
- Support transactions with change sets > DRAM (STEAL)
- Recovery time must be bounded.

V4: COMMIT-CONSISTENT CHECKPOINTS

LSN Type	Where	Definition
flushedLSN	Memory	Last LSN in log on disk
pageLSN	$page_x$	Newest update to $page_x$
prevLSN	log record	LSN of prior log record by same txn
recLSN	DPT	Oldest update to $page_x$ since it was last flushed
lastLSN	ATT	Latest action of txn T_i
MasterRecord	Disk	LSN of latest checkpoint

V4: COMMIT-CONSISTENT CHECKPOINTS

- **Phase 1 – Analysis**
  - Read the WAL starting from the **latest checkpoint**.
- **Phase 2 – Redo**
  - Repeat all actions starting from an appropriate point in the log.
- **Phase 3 – Undo**
  - Reverse the actions of txns that did not commit before the crash.

V4: COMMIT-CONSISTENT CHECKPOINTS

- Advantages
  - Recovery time is bounded due to checkpoints.
- Disadvantages
  - With commit consistent checkpointing, DBMS must stop processing transactions while taking checkpoint
  - Users will suffer long delays due to checkpointing

Constraints

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)
- Support transactions with change sets > DRAM (STEAL)
- Recovery time must be bounded.
- Users must not suffer long delays due to checkpointing.

V5: FUZZY CHECKPOINTS

- Instead of flushing **all** dirty pages, only flush those dirty pages that have not been flushed since before the **previous checkpoint**.
- This guarantees that, at any time, all updates of committed transactions that occurred before the **penultimate** (*i.e.*, second to last) checkpoint have been applied to database on disk - during the last checkpoint, if not earlier.

V5: FUZZY CHECKPOINTS

- Advantages
  - With fuzzy checkpointing, DBMS can concurrently process transactions while taking checkpoints.
- Problem
  - Repeated failures during recovery can lead to unbounded amount of logging during recovery

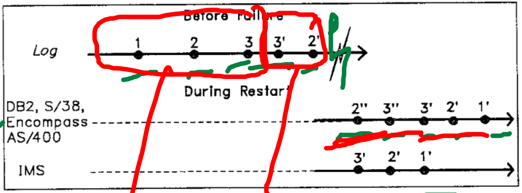
CLR

Constraints

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)
- Support transactions with change sets > DRAM (STEAL)
- Recovery time must be bounded.
- Users must not suffer long delays due to checkpointing.
- Cope with failures during recovery.

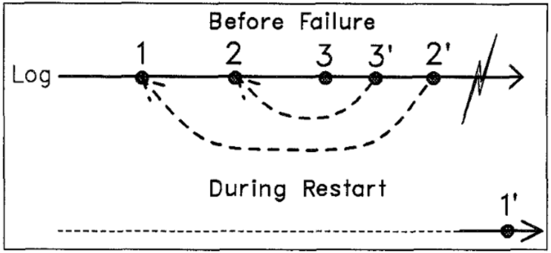
V6: COMPENSATION LOG RECORDS

- Problems: (1) compensating compensations and (2) duplicate compensations



I′ is the CLR for I and I″ is the CLR for I′

V6: COMPENSATION LOG RECORDS



I′ is the Compensation Log Record for I
I′ points to the predecessor, if any, of I

V6: COMPENSATION LOG RECORDS

LSN Type	Where	Definition
flushedLSN	Memory	Last LSN in log on disk
pageLSN	$page_x$	Newest update to $page_x$
prevLSN	log record	LSN of prior log record by same txn
recLSN	DPT	Oldest update to $page_x$ since it was last flushed
lastLSN	ATT	Latest action of txn T_i
MasterRecord	Disk	LSN of latest checkpoint
undoNextLSN	log record	LSN of prior to-be-undone record

Constraints

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)
- Support transactions with change sets > DRAM (STEAL)
- Recovery time must be bounded.
- Users must not suffer long delays due to checkpointing.
- Cope with repeated failures during recovery.
- Increase concurrency of undo.

V7: LOGICAL UNDO

- Record logical operations to be undone instead of physical offsets
  - Undo action need not be exact physical inverse of original action (*i.e.*, page offsets need not be recorded)
  - Example: Insert key X in B+tree
  - X can be initially inserted in Page 10 by T_1
  - X may be moved to Page 20 by another txn T_2 before T_1 commits
  - Later, if T_1 is aborted, logical undo (Delete key X in B+tree) will automatically remove it from Page 20

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V7: LOGICAL UNDO

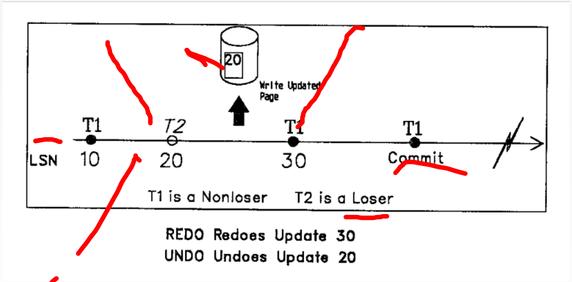
- Logical undo enables:
  - Highly-parallel **transaction-oriented logical undo**
  - Works with fast **page-oriented physical redo**
  - Hence, this protocol performs **physiological logging**
- Record logical ops for index and space management (*i.e.*, garbage collection)
  - Avoid rebuilding indexes from scratch during recovery
  - Reclaim storage space of deleted records
  - Example: Put in slot 5 (instead of Put at offset 30)

Constraints

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)
- Support transactions with change sets > DRAM (STEAL)
- Recovery time must be bounded.
- Users must not suffer long delays due to checkpointing.
- Cope with repeated failures during recovery.
- Increase concurrency of undo (logical undo).
- Support record-level locking

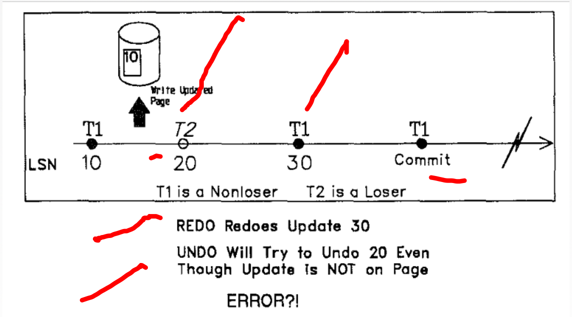
V8: AVOID SELECTIVE REDO

- Problem-free scenario



V8: AVOID SELECTIVE REDO

- Problematic scenario: **UNDOing non-existent changes**



V8: AVOID SELECTIVE REDO

- Problematic scenario:
  - Does not work with logical undo
  - Example: Consider a B+tree index with non-unique keys
  - T_1 inserted key X in Page 10 and committed
  - T_2 inserted key X in Page 10 and is not committed
  - T_3 inserted key Y in Page 10 and committed
  - Only T_1's changes make it to disk
  - While redoing T_3, we push the LSN forward
  - We must undo T_2 (since pageLSN > T_2's log record's LSN)
  - Executing Delete key X will incorrectly remove T_1's changes

V8: AVOID SELECTIVE REDO

- Solution:
  - Replay history of both committed and uncommitted transactions
  - Rather than selectively redo-ing committed transactions.
  - Then state of database guaranteed to be equivalent to that at the time of failure

Summary

- DRAM is volatile
- Avoid random writes to database on disk (NO FORCE)
- Support transactions with change sets > DRAM (STEAL)
- Recovery time must be bounded.
- Users must not suffer long delays due to checkpointing.
- Cope with repeated failures during recovery.
- Increase concurrency of undo (logical undo)
- Support record-level locking (avoid selective redo)

Conclusion

Parting Thoughts

- Protocols evolve over time to better handle user, workload, and hardware constraints.
- Deconstructing protocols will help you better appreciate the internals of complex software systems and learn the art of designing protocols.

Next Class

- Case Studies