

Lecture #20: Logging Schemes

15-445/645 Database Systems (Fall 2020)

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1 Crash Recovery

Recovery algorithms are techniques to ensure database consistency, transaction atomicity, and durability despite failures. When a crash occurs, all the data in memory that has not been committed to disk is at risk of being lost. Recovery algorithms act to prevent loss of information after a crash.

Every recovery algorithm has two parts:

- Actions during normal transaction processing to ensure that the DBMS can recover from a failure.
- Actions after a failure to recover the database to a state that ensures atomicity, consistency, and durability.

The key primitives that used in recovery algorithms are UNDO and REDO. Not all algorithms use both primitives.

- **UNDO:** The process of removing the effects of an incomplete or aborted transaction.
- **REDO:** The process of re-instating the effects of a committed transaction for durability.

2 Failure Classification

Because the DBMS is divided into different components based on the underlying storage device, there are a number of different types of failures that the DBMS needs to handle. Some of these failures are recoverable while others are not.

Type #1: Transaction Failures

Transactions failures occur when a transaction reaches an error and must be aborted. Two types of errors that can cause transaction failures are logical errors and internal state errors.

- **Logical Errors:** A transaction cannot complete due to some internal error condition (e.g., integrity, constraint violation).
- **Internal State Errors:** The DBMS must terminate an active transaction due to an error condition (e.g., deadlock)

Type #2: System Failures

System failures are failures in hardware that must also be accounted for in crash recovery protocols. System failures can be caused by problems in the software or the hardware.

- **Software Failure:** There is a problem with the DBMS implementation (e.g., uncaught divide-by-zero exception) and the system has to halt.
- **Hardware Failure:** The computer hosting the DBMS crashes. We assume that non-volatile storage contents are not corrupted by system crash.

Type #3: Storage Media Failure

Storage media failures are non-repairable failures that occur when the physical storage machine is damaged. When the storage media fails, the DBMS must be restored from an archived version.

- **Non-Repairable Hardware Failure:** A head crash or similar disk failure destroys all or parts of non-volatile storage. Destruction is assumed to be detectable.

3 Buffer Pool Management Policies

A *steal policy* dictates whether the DBMS allows an uncommitted transaction to overwrite the most recent committed value of an object in non-volatile storage (can a transaction write uncommitted changes to disk).

- **STEAL:** Is allowed
- **NO-STEAL:** Is not allowed.

A *force policy* dictates whether the DBMS ensures that all updates made by a transaction are reflected on non-volatile storage before the transaction is allowed to commit.

- **FORCE:** Is enforced
- **NO-FORCE:** Is not enforced

Force writes make it easier to recover since all of the changes are preserved but result in poor runtime performance.

The easiest buffer pool management policy to implement is called *NO-STEAL + FORCE*. In the NO-STEAL + FORCE policy, the DBMS never has to undo changes of an aborted transaction because the changes were not written to disk. It also never has to redo changes of a committed transaction because all the changes are guaranteed to be written to disk at commit time. An example of NO-STEAL + FORCE is show in Figure 1.

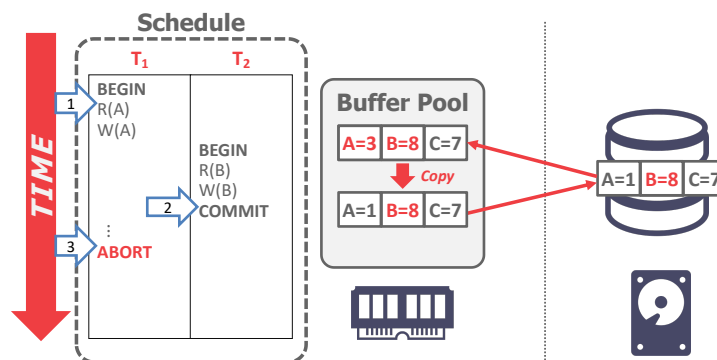


Figure 1: NO-STEAL + FORCE Example – The DBMS is using the NO-STEAL + FORCE buffer policies. All changes from a transaction are only written to disk when the transaction is committed. Once the schedule begins at Step #1, changes from T_1 and T_2 are written to the buffer pool. Because of the FORCE policy, when T_2 commits at Step #2, all of its changes must be written to disk. To do this, the DBMS makes a copy of the memory in disk, applies only the changes from T_2 , and writes it back to disk. This is because NO-STEAL prevents the uncommitted changes from T_1 to be written to disk. At Step #3, it is trivial for the DBMS to rollback T_1 since no dirty changes from T_1 are on disk.

A limitation of NO STEAL + FORCE is that all of the data that a transaction needs to modify must fit on memory. Otherwise, that transaction cannot execute because the DBMS is not allowed to write out dirty pages to disk before the transaction commits.

4 Shadow Paging

The DBMS maintains two separate *master* and *shadow* copies of the database. Updates are only made in the shadow copy. When a transaction commits, the shadow is atomically switched to become the new master. This is an example of a NO-STEAL + FORCE system. A high-level example of shadow paging is shown in Figure 2.

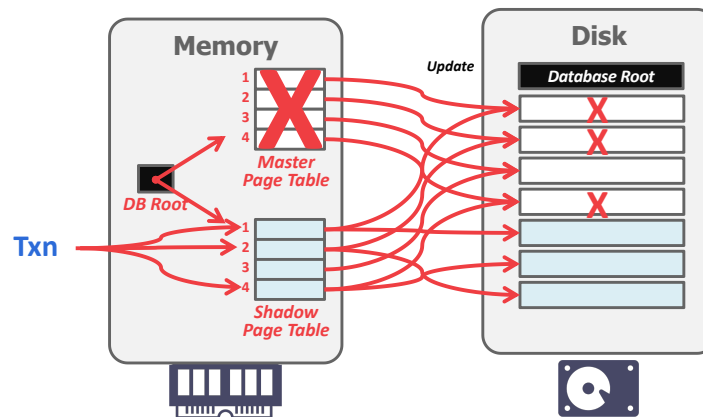


Figure 2: Shadow Paging – The database root points to a master page table which points to the pages on disk. When an updating transaction occurs, a shadow page table is created that points to the same pages as the master. Modifications are made to a temporary space on disk and the shadow table is updated. To commit, the database root pointer is redirected to the shadow table, which becomes the new master.

Implementation

The DBMS organizes the database pages in a tree structure where the root is a single disk page. There are two copies of the tree, the *master* and *shadow*. The root always points to the current master copy. When a transaction executes, it only makes changes to the shadow copy.

When a transaction wants to commit, the DBMS must install its updates. To do this, it only has to overwrite the root to make it point to the shadow copy of the database, thereby swapping the master and shadow. Before overwriting the root, none of the transaction's updates are part of the disk-resident database. After overwriting the root, all of the transaction's updates are part of the disk-resident database.

A disadvantage of shadow paging is that copying the entire page table is expensive. In reality, only paths in the tree that lead to updated leaf nodes need to be copied, not the entire tree. In addition, the commit overhead of shadow paging is high. Commits require every updated page, page table, and root to be flushed. This causes fragmented data and also requires garbage collection.

5 Write-Ahead Logging

With *write-ahead logging*, the DBMS records all the changes made to the database in a log file (on stable storage) before the change is made to a disk page. The log contains sufficient information to perform the

necessary undo and redo actions to restore the database after a crash. The DBMS must write to disk the log file records that correspond to changes made to a database object before it can flush that object to disk. An example of WAL is shown in Figure 3. WAL is also an example of a STEAL + NO-FORCE system.

In shadow paging, the DBMS was required to perform writes to random non-contiguous pages on disk. Write-ahead logging allows the DBMS to convert random writes into sequential writes to optimize performance. Thus, almost every DBMS uses write-ahead logging (WAL) because it has the fastest runtime performance. But the DBMS's recovery time with WAL is slower than shadow paging because it has to replay the log.

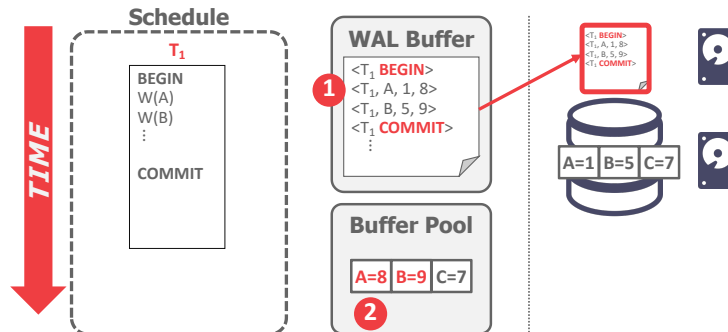


Figure 3: Write Ahead Logging – When the transaction begins, all changes are recorded in the WAL buffer in memory before being made to the buffer pool. When it comes time to commit, the WAL buffer is flushed out to disk. The transaction result can be written once the WAL buffer is safely on disk.

Implementation

All log records pertaining to an updated page are written to non-volatile storage before the page itself is allowed to be overwritten in non-volatile storage. A transaction is not considered committed until all its log records have been written to stable storage.

When the transaction starts, write a <BEGIN> record to the log for each transaction to mark its starting point.

When a transaction finishes, write a <COMMIT> record to the log and make sure all log records are flushed before it returns an acknowledgment to the application.

Each log entry contains information about the change to a single object:

- Transaction ID.
- Object ID.
- Before Value (used for UNDO).
- After Value (used for REDO).

The DBMS must flush all of a transaction's log entries to disk before it can tell the outside world that a transaction has successfully committed. The system can use the “group commit” optimization to batch multiple log flushes together to amortize overhead.

6 Logging Schemes

The contents of a log record can vary based on the implementation.

Physical Logging:

- Record the byte-level changes made to a specific location in the database.
- Example: Position of a record in a page

Logical Logging:

- Record the high level operations executed by transactions.
- Requires less data written in each log record than physical logging because each record can update multiple tuples over multiple pages. However, it is difficult to implement recovery with logical logging when there are concurrent transactions in a non-deterministic concurrency control scheme.
- Example: The UPDATE, DELETE, and INSERT queries invoked by a transaction.

Physiological Logging:

- Hybrid approach where log records target a single page but do not specify data organization of the page. That is, record the byte-level changes of a slot number in the page without specifying exactly where in the page the change is located.
- Most common approach used in DBMSs.

7 Checkpoints

The main problem with a WAL-based DBMS is that the log file will grow forever. After a crash, the DBMS has to replay the entire log, which can take a long time if the log file is large. Thus, the DBMS can periodically take a *checkpoint* where it flushes all buffers out to disk.

How often the DBMS should take a checkpoint depends on the application's performance and downtime requirements. Taking a checkpoint too often causes the DBMS's runtime performance to degrade. But waiting a long time between checkpoints can potentially be just as bad, as the system's recovery time after a restart increases.

Blocking Checkpoint Implementation:

- The DBMS stops accepting new transactions and waits for all active transactions to complete.
- Flush all log records and dirty blocks currently residing in main memory to stable storage.
- Write a <CHECKPOINT> entry to the log and flush to stable storage.