Last Class

- Basic Timestamp Ordering
- Optimistic Concurrency Control
- Multi-Version Concurrency Control

Today’s Class

- Overview
- Write-Ahead Log
- Checkpoints
- Logging Schemes
- Recovery Protocol
- Shadow Paging

Motivation
Crash Recovery

- Recovery algorithms are techniques to ensure database consistency, transaction atomicity and durability despite failures.
- Recovery algorithms have two parts:
  - Actions during normal txn 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.
Crash Recovery

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Storage Types

- **Volatile Storage:**
  - Data does not persist after power is cut.
  - Examples: DRAM, SRAM
- **Non-volatile Storage:**
  - Data persists after losing power.
  - Examples: HDD, SDD
- **Stable Storage:**
  - A non-existent form of non-volatile storage that survives all possible failures scenarios.

Failure Classification

- Transaction Failures
- System Failures
- Storage Media Failures

Use multiple storage devices to approximate.
**Transaction Failures**

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

**System Failures**

- **Software Failure:**
  - Problem with the DBMS implementation (e.g., uncaught divide-by-zero exception).
- **Hardware Failure:**
  - The computer hosting the DBMS crashes (e.g., power plug gets pulled).
  - **Fail-stop Assumption:** Non-volatile storage contents are assumed to not be corrupted by system crash.

**Storage Media Failure**

- **Non-Repairable Hardware Failure:**
  - A head crash or similar disk failure destroys all or part of non-volatile storage.
  - Destruction is assumed to be detectable (e.g., disk controller use checksums to detect failures).
- No DBMS can recover from this. Database must be restored from archived version.

**Problem Definition**

- Primary storage location of records is on non-volatile storage, but this is much slower than volatile storage.
- Use volatile memory for faster access:
  - First copy target record into memory.
  - Perform the writes in memory.
  - Write dirty records back to disk.
Problem Definition

• Need to ensure:
  – The changes for any txn are durable once the DBMS has told somebody that it committed.
  – No changes are durable if the txn aborted.

Undo vs. Redo

• **Undo**: The process of removing the effects of an incomplete or aborted txn.
• **Redo**: The process of re-instating the effects of a committed txn for durability.

• How the DBMS supports this functionality depends on how it manages the buffer pool…

Buffer Pool Management

Schedule

T1
BEGIN R(A) W(A)
BEGIN R(B) W(B) COMMIT
ABORT

T2

Buffer Pool

Memory

Disk

BEGIN R(A) W(A)
BEGIN R(B) W(B) COMMIT
ABORT

A=1 B=99 C=7

A=3 B=99 C=7
Do we force T2’s changes to be written to disk?

Is T1 allowed to overwrite A even though it hasn’t committed?

What happens when we need to rollback T1?
Buffer Pool – Steal Policy

• Whether the DBMS allows an uncommitted txn to overwrite the most recent committed value of an object in non-volatile storage.
  – STEAL: Is allowed.
  – NO-STEAL: Is not allowed.

Buffer Pool – Force Policy

• Whether the DBMS ensures that all updates made by a txn are reflected on non-volatile storage before the txn is allowed to commit:
  – FORCE: Is enforced.
  – NO-FORCE: Is not enforced.

• Force writes makes it easier to recover but results in poor runtime performance.
开始了。“NO-STEAL + FORCE”意味着T1的更改不能写入磁盘。这意味着T2的更改必须在这一点写入磁盘。
NO-STEAL + FORCE

• This approach is the easiest to implement:
  – Never have to undo changes of an aborted txn because the changes were not written to disk.
  – Never have to redo changes of a committed txn because all the changes are guaranteed to be written to disk at commit time.
• But this will be slow…
• What if txn modifies the entire database?

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Write-Ahead Log

• Record the changes made to the database in a log before the change is made.
  – Assume that the log is on stable storage.
  – Log contains sufficient information to perform the necessary undo and redo actions to restore the database after a crash.
• Buffer Pool: STEAL + NO-FORCE

Write-Ahead Log Protocol

• 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 txn is not considered committed until all its log records have been written to stable storage.
Write-Ahead Log Protocol

- Write a `<BEGIN>` record to the log for each txn to mark its starting point.
- Log record format:
  - `<txnId, objectId, beforeValue, afterValue>`
- When a txn finishes, the DBMS will:
  - Write a `<COMMIT>` record on the log
  - Make sure that all log records are flushed before it returns an acknowledgement to application.
Write-Ahead Log – Example

-wal

-transaction begin

-transaction commit

The result is deemed safe to return to app.

WAL – Implementation Details

- When should we write log entries to disk?
  - When the transaction commits.
  - Can use group commit to batch multiple log flushes together to amortize overhead.

  - Every time the txn executes an update?
  - Once when the txn commits?

WAL – Deferred Updates

- Observation: If we prevent the DBMS from writing dirty records to disk until the txn commits, then we don’t need to store their original values.
### WAL – Deferred Updates

- **Observation:** If we prevent the DBMS from writing dirty records to disk until the txn commits, then we don’t need to store their original values.

```
WAL
<T1 begin>
<T1, A, 99, 88>
<T1, B, 10>
<T1 commit>
```

- **Replay the log and redo each update.**

- **Simply ignore all of T1’s updates.**

### WAL – Deferred Updates

- **Observation:** If we prevent the DBMS from writing dirty records to disk until the txn commits, then we don’t need to store their original values.

```
WAL
<T1 begin>
<T1, A, 88>
<T1, B, 10>
<T1 commit> CRASH!
```

- **Replay the log and redo each update.**

- **Simply ignore all of T1’s updates.**

### WAL – Buffer Pool Policies

- **This won’t work if the change set of a txn is larger than the amount of memory available.**
- **The DBMS cannot undo changes for an aborted txn if it doesn’t have the original values in the log.**
- **We need to use the STEAL policy.**

<table>
<thead>
<tr>
<th></th>
<th>NO-STEAL</th>
<th>STEAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO-FORCE</td>
<td>Slowest</td>
<td>Fastest</td>
</tr>
<tr>
<td>FORCE</td>
<td>Slowest</td>
<td>No Undo + No Redo</td>
</tr>
</tbody>
</table>

- **Runtime Performance**
- **Recovery Performance**

Almost every DBMS uses **NO-FORCE + STEAL**
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Checkpoints

• The WAL will grow forever.
• After a crash, the DBMS has to replay the entire log which will take a long time.
• The DBMS periodically takes a **checkpoint** where it flushes all buffers out to disk.

Checkpoints

• Output onto stable storage all log records currently residing in main memory.
• Output to the disk all modified blocks.
• Write a `<CHECKPOINT>` entry to the log and flush to stable storage.

```
<T1 begin>
<T1, A, 1, 2>
<T1 commit>
<T2 begin>
<T2, A, 2, 3>
<T3 begin>
<CHECKPOINT>
<T2 commit>
<T3, A, 3, 4>
⋮
CRASH!
```
Checkpoints

- Any txn that committed before the checkpoint is ignored (T1).

```
<T1 begin>
<T1, A, 1, 2>
<T1 commit>
<T2 begin>
<T2, A, 2, 3>
<T3 begin>
<T3, A, 3, 4>
<CHECKPOINT>
<T2 commit>
<T3, A, 3, 4>
```

CRASH!

Checkpoints – Challenges

- We have to stall all txns when take a checkpoint to ensure a consistent snapshot.
- Scanning the log to find uncommitted txns can take a long time.
- Not obvious how often the DBMS should take a checkpoint…

Checkpoints – Frequency

- Checkpointing too often causes the runtime performance to degrade.
  - System spends too much time flushing buffers.
- But waiting a long time is just as bad:
  - The checkpoint will be large and slow.
  - Makes recovery time much longer.
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Logging Schemes

- **Physical Logging**: Record the 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 txns.
  - Example: The `UPDATE`, `DELETE`, and `INSERT` queries invoked by a txn.

Physical vs. Logical Logging

- Logical logging requires less data written in each log record than physical logging.
- Difficult to implement recovery with logical logging if you have concurrent txns.
  - Hard to determine which parts of the database may have been modified by a query before crash.
  - Also takes longer to recover because you must re-execute every txn all over again.

Physiological Logging

- Hybrid approach where log records target a single page but do not specify data organization of the page.
- This is the most popular approach.
Logging Schemes

**INSERT INTO X VALUES(1,2,3);**

**Physical**

\(<T1, \text{Table=}\ X, \text{Page=}99, \text{Offset=}4,\ \text{Record=} (1,2,3) >\)

\(<T1, \text{Table=}X, \text{Index=}X \_PKEY,\ \text{Page=}45,\ \text{Offset=}9, \text{Key=} (1,Record1) >\)

**Logical**

\(<T1, \text{Table=}X, \text{Record=} (1,2,3) >\)

\(<T1, \text{Table=}X, \text{Index=}X \_PKEY,\ \text{IndexPage=}45,\ \text{Key=} (1,Record1) >\)

**Physiological**

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**Today's Class – ARIES**

- Algorithms for **Recovery and Isolation**
  - Exploiting Semantics
    - Write-ahead Logging
    - Repeating History during Redo
    - Logging Changes during Undo
ARIES

- Developed at IBM during the early 1990s.
- Considered the “gold standard” in database crash recovery.
  - Implemented in DB2.
  - Everybody else more or less implements a variant of it.

ARIES – Main Ideas

- **Write-Ahead Logging:**
  - Any change is recorded in log on stable storage before the database change is written to disk.
- **Repeating History During Redo:**
  - On restart, retrace actions and restore database to exact state before crash.
- **Logging Changes During Undo:**
  - Record undo actions to log to ensure action is not repeated in the event of repeated failures.

ARIES – Recovery Phases

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

- Start from last checkpoint found via *Master Record*.
- Three phases.
  - **Analysis** - Figure out which txns committed or failed since checkpoint.
  - **Redo** all actions (repeat history)
  - **Undo** effects of failed txns.

**Additional Crash Issues**

- What happens if system crashes during the Analysis Phase? During the Redo Phase?
- How do you limit the amount of work in the Redo Phase?
  - Flush asynchronously in the background.
- How do you limit the amount of work in the Undo Phase?
  - Avoid long-running txns.

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**Shadow Paging**

- Maintain two separate copies of the database (master, shadow)
- Updates are only made in the shadow copy.
- When a txn commits, atomically switch the shadow to become the new master.
- Buffer Pool: **NO-STEAL + FORCE**
Shadow Paging

- Database is a tree whose root is a single disk block.
- There are two copies of the tree, the master and shadow
  - The root points to the master copy.
  - Updates are applied to the shadow copy.

Shadow Paging – Example

- To install the updates, overwrite the root so it points to the shadow, 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.
Shadow Paging – Example

Read-only txns access the current master.

Active modifying txn updates shadow pages.

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Shadow Paging – Undo/Redo

- Supporting rollbacks and recovery is easy.
  - **Undo:**
    - Simply remove the shadow pages. Leave the master and the DB root pointer alone.
  - **Redo:**
    - Not needed at all.
Shadow Paging – Advantages

- No overhead of writing log records.
- Recovery is trivial.

Shadow Paging – Disadvantages

- Copying the entire page table is expensive:
  - Use a page table structured like a B+tree
  - No need to copy entire tree, only need to copy paths in the tree that lead to updated leaf nodes
- Commit overhead is high:
  - Flush every updated page, page table, & root.
  - Data gets fragmented.
  - Need garbage collection.

Summary

- Write-Ahead Log to handle loss of volatile storage.
- Use incremental updates (i.e., STEAL, NO-FORCE) with checkpoints.
- On recovery: undo uncommitted txns + redo committed txns.

Conclusion

- Recovery is really hard.
- Be thankful that you don’t have to write it yourself.