Advanced Databases

Recovery System

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Outline

1. Failure Classification
2. Storage Structure
3. Log-Based Recovery
4. Recovery Algorithm
5. Early Lock Release and Logical Undo
6. ARIES

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Failure Classification

- Transaction failure:
  - Logical errors: transaction cannot complete due to some internal error condition (e.g., bad input)
  - System errors: the database system must terminate an active transaction due to an error condition (e.g., deadlock)
- System crash: a power failure or other hardware or software failure causes the system to crash.
  - Fail-stop assumption: errors bring system to hold
  - Non-volatile storage contents are assumed to not be corrupted
- Disk failure: a head crash or similar disk failure destroys all or part of disk storage.
  - Destruction is assumed to be detectable: disk drives use checksums to detect failures.

Recovery Algorithms

- Consider transaction T_i that transfers \$50 from account A to B
  - Two updates: subtract 50 from A and add 50 to B
- Transaction T_i requires updates to A and B to be output to the database.
  - A failure may occur after one of these modifications have been made but before both of them are made.
  - Modifying the database without ensuring that the transaction will commit may leave the database in an inconsistent state.
  - Not modifying the database may result in lost updates if failure occurs just after transaction commits.
- Recovery algorithms have two parts:
  1. Actions taken during normal transaction processing to ensure enough information exists to recover from failures.
  2. Actions taken after a failure to recover the database contents to a state that ensures atomicity, consistency, and durability.

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Storage Structure

- Volatile storage:
  - does not survive system crashes
  - examples: main memory, cache memory
- Non-volatile storage:
  - survives system crashes
  - examples: disk, tape, flash memory, non-volatile (battery backed up) RAM
  - but may still fail, losing data
- Stable storage:
  - a mythical form of storage that survives all failures
  - approximated by maintaining multiple copies on distinct non-volatile media

Stable-Storage Implementation/1

- Maintain multiple copies of each block on separate disks
  - copies at remote sites to protect against disasters such as fire or flooding
- Failure during block transfer can still result in inconsistent copies.
  - successful: destination block successfully updated
  - partial failure: destination block has incorrect information
  - total failure: destination block was never updated
- To protect storage media from failure during data transfer execute output operation as follows (assuming two copies of each block):
  1. Write the information onto the first physical block.
  2. When the first write successfully completes, write the same information onto the second physical block.
  3. The output is completed only after the second write successfully completes.

Stable-Storage Implementation/2

Protecting storage media from failure during data transfer (cont.):

- Copies of a block may differ due to failure during output operation. To recover from failure:
  1. Find inconsistent blocks:
     Expensive solution:
     - Compare the two copies of every disk block.

     Better solution (used in hardware RAID systems):
     - Record in-progress disk writes on non-volatile storage (non-volatile RAM or special area of disk).
     - Use this information during recovery to find blocks that may be inconsistent, and only compare copies of these.
  2. If either copy of an inconsistent block is detected to have an error (bad checksum), overwrite it by the other copy. If both have no error, but are different, overwrite the second block by the first block.

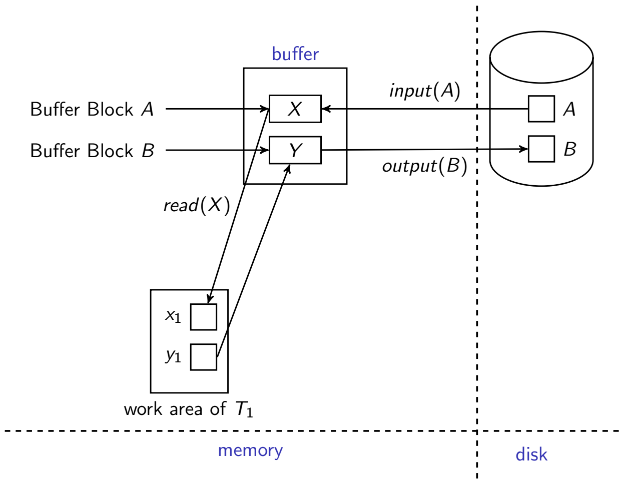
Data Access/1

- Physical blocks are those blocks residing on the disk.
- System buffer blocks are the blocks residing temporarily in main memory.
- Block movements between disk and main memory are initiated through the following two operations:
  - **input(B)** transfers the physical block B to main memory.
  - **output(B)** transfers the buffer block B to the disk, and replaces the appropriate physical block there
- We assume, for simplicity, that each data item fits in, and is stored inside, a single block.

Data Access/2

- Each transaction T_i has its private work-area in which local copies of all data items accessed and updated by T_i are stored.
  - T_i's local copy of a data item X is denoted by x_i
  - B_X denotes block containing X
- Transferring data items between system buffer blocks and the private work-area of T_i are done by:
  - **read**(X) assigns the value of data item X to the local variable x_i
  - **write**(X) assigns the value of local variable x_i to data item X in the buffer block
- Transactions
  - must perform **read**(X) before accessing X for the first time (subsequent reads can be from local copy);
  - can execute **write**(X) at any time before the transaction commits.
- Note that output(B_X) need not immediately follow **write**(X). System can perform the output operation when it seems fit.

Data Access/2



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Recovery and Atomicity

- To ensure atomicity despite failures, we first output information describing the modifications to stable storage without modifying the database itself.
- We study log-based recovery mechanisms in detail:
  - We first present key concepts,
  - then present the actual recovery algorithm.
- Less used alternative: shadow-copy and shadow-paging
- For now we assume serial execution of transactions and extend to the case of concurrent transactions later.

Log-Based Recovery

- A log is kept on stable storage.
  - The log is a sequence of log records, which maintains information about update activities on the database.
- When transaction T_i starts, it registers itself by writing a record $< T_i$ **start** $>$ to the log.
- Before T_i executes **write**(X), a log record $< T_i, X, V_1, V_2 >$ is written, where V_1 is the value of X before the write (the old value), and V_2 is the value to be written to X (the new value).
- When T_i finishes, the log record $< T_i$ **commit** $>$ or $< T_i$ **abort** $>$ is written.
- Two approaches using logs
  - immediate database modification
  - deferred database modification

Immediate Database Modification

The immediate-modification scheme allows updates of an uncommitted transaction to be made to the buffer, or the disk itself, before the transaction commits.

- Update log record must be written before a database item is written
  - we assume that the log record is output directly to stable storage
  - will see later how to postpone log record output to some extent
- Output of updated blocks to disk storage can take place at any time before or after transaction commit.
- Order in which blocks are output can be different from the order in which they are written.

Deferred Database Modification

The deferred-modification scheme performs updates to buffer/disk only at the time of transaction commit:

- simplifies some aspects of recovery
- but has overhead of storing local copy for all updated data items

We cover here only the immediate-modification scheme.

Transaction Commit

- A transaction is said to have committed when its commit log record is output to stable storage.
  - all previous log records of the transaction must have been output already
- Writes performed by a transaction may still be in the buffer when the transaction commits, and may be output later.

Immediate Database Modification Example

Log	Write	Output
$< T_0, \textbf{start} >$		
$< T_0, A, 1000, 950 >$		
$< T_0, B, 2000, 2050 >$		
	$A = 950$	
	$B = 2050$	
$< T_0, \textbf{commit} >$		
$< T_1, \textbf{start} >$		
$< T_1, C, 700, 600 >$		
	$C = 600$	
		B_B, B_C
$< T_1, \textbf{commit} >$		
		B_A

- Note: B_X denotes block containing X.
- B_C output before T_1 commits
- B_A output after T_0 commits

Undo and Redo Operations/1

- Undo of log record $< T_i, X, V_1, V_2 >$ writes the old value V_1 to X
- Redo of log record $< T_i, X, V_1, V_2 >$ writes the new value V_2 to X
- Undo transaction: **undo**(T_i) restores the value of all data items updated by T_i to their old values, going backwards from the last log record for T_i:
  - Each time a data item X is restored to its old value V a special log record (called redo-only) $< T_i, X, V >$ is appended to the log.
  - When undo of a transaction is complete, a log record $< T_i$ **abort** $>$ is appended to the log (to indicate that the undo was completed).
- Redo transaction: **redo**(T_i) sets the value of all data items updated by T_i to the new values, going forward from the first log record for T_i
  - No logging is done in this case

Undo and Redo Operations/2

- The undo and redo operations are used in several different circumstances:
  - The undo is used for transaction rollback during normal operation (e.g., when a transaction must abort due to some logical error).
  - The undo and redo operations are used during recovery from failure.
- We need to deal with the case where during recovery from failure another failure occurs prior to the system having fully recovered.

Transaction rollback (during normal operation)

- Let T_i be the transaction to be rolled back.
- Scan log backwards from the end, and for each log record of T_i of the form $< T_i, X_j, V_1, V_2 >$:
  - perform the undo by writing V_1 to X_j,
  - write a redo-only log record $< T_i, X_j, V_1 >$ (also called compensation log record)
- Once the record $< T_i$ **start** $>$ is found stop the scan and write the log record $< T_i$ **abort** $>$.

Undo and Redo on Recovering from Failure

When recovering after failure:

- Transaction T_i needs to be undone if the log
  - contains the record $< T_i$ **start** $>$,
  - but does not contain either the record $< T_i$ **commit** $>$ or $< T_i$ **abort** $>$.
- Transaction T_i needs to be redone if the log
  - contains the records $< T_i$ **start** $>$
  - and contains the record $< T_i$ **commit** $>$ or $< T_i$ **abort** $>$.

Repeating History

- Repeating history: recovery redoes all the original actions including the steps that restored old values (redo-only log records).
- It may seem strange to redo transaction T_i if the record $< T_i$ **abort** $>$ record is in the log.
- Why does this work?
  - if $< T_i$ **abort** $>$ is in the log, so are the redo-only records written by the undo operation
  - thus, the end result will be to undo T_i's modifications
- This slight redundancy simplifies the recovery algorithm and enables faster overall recovery time.

Immediate Modification Recovery Example

Below we show the log as it appears at three instances of time.

$< T_0,$ **start** $>$	$< T_0,$ **start** $>$	$< T_0,$ **start** $>$
$< T_0,\ A,\ 1000,\ 950 >$	$< T_0,\ A,\ 1000,\ 950 >$	$< T_0,\ A,\ 1000,\ 950 >$
$< T_0,\ B,\ 2000,\ 2050 >$	$< T_0,\ B,\ 2000,\ 2050 >$	$< T_0,\ B,\ 2000,\ 2050 >$
	$< T_0,$ **commit** $>$	$< T_0,$ **commit** $>$
	$< T_1,$ **start** $>$	$< T_1,$ **start** $>$
	$< T_1,\ C,\ 700,\ 600 >$	$< T_1,\ C,\ 700,\ 600 >$
		$< T_1,$ **commit** $>$
(a)	(b)	(c)

Recovery actions in each case above are:

- (a) **undo**(T_0): B is restored to 2000 and A to 1000, and log records $< T_0,\ B,\ 2000 >$, $< T_0,\ A,\ 1000 >$, $< T_0,$ **abort** $>$ are written out
- (b) **redo**(T_0) and **undo**(T_1): A and B are set to 950 and 2050 and C is restored to 700. Log records $< T_1,\ C,\ 700 >$, $< T_1,$ **abort** $>$ are written out.
- (c) **redo**(T_0) and **redo**(T_1): A and B are set to 950 and 2050, respectively. Then C is set to 600.

Checkpoints/1

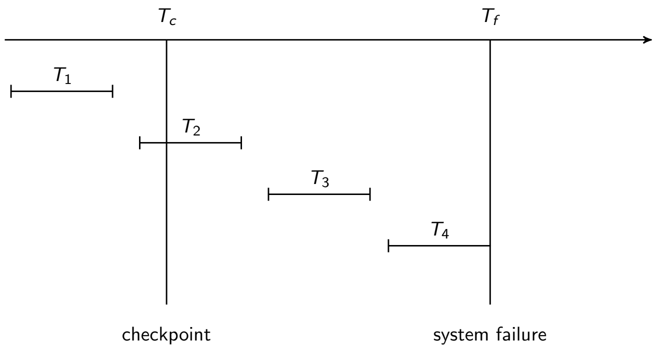
- Re-/undoing all transactions recorded in the log can be very slow:
  - Processing the entire log is time-consuming if the system has run for a long time.
  - We might unnecessarily redo transactions that have already output all their updates.
- Checkpoints streamline the recovery procedure:
  1. Stop all updates while doing checkpointing.
  2. Output all log records currently residing in main memory onto stable storage.
  3. Output all modified buffer blocks to the disk.
  4. Write a log record $<$ **checkpoint** $L >$ onto stable storage where L is a list of all transactions active at the time of checkpoint.

Checkpoints/2

- Recovery with checkpoints:
  - Scan backwards from end of log to find the most recent $<$ **checkpoint** $L >$ record.
  - Only transactions that
    - are in L (i.e., were active at the time of the checkpoint), or
    - started after the checkpoint

    need to be redone or undone.
  - Transactions that committed or aborted before the checkpoint already have all their updates output to stable storage.
- Some earlier part of the log may be needed for undo operations
  - Continue scanning backwards till a record $< T_i$ **start** $>$ is found for every transaction T_i in L.
  - Parts of log prior to earliest $< T_i$ **start** $>$ record above are not needed for recovery, and can be erased.

Example of Checkpoints



- T_1 can be ignored (updates already output to disk due to checkpoint)
- T_2 and T_3 redone.
- T_4 undone

Concurrency Control and Recovery

- So far we assumed serial execution.
- With concurrent transactions:
    - All transactions share a single disk buffer and a single log.
    - Multiple transactions may update data items on a single buffer block.
- Assumptions:
    - The updates of uncommitted transactions are not visible to other transactions (cascadeless schedules).
    - If a transaction T_i has modified an item, no other transaction can modify the same item until T_i has committed or aborted.
    - Otherwise, how do we perform undo if T_1 updates A, then T_2 updates A and commits, and finally T_1 has to abort?
    - Can be ensured by strict two-phase locking: obtain exclusive locks on updated items and hold the locks till end of transaction.
- Log records of different transactions may be interspersed in the log.

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Recovery Algorithm/1

- Logging (during normal operation):
    - $< T_i$ **start** $>$ at transaction start
    - $< T_i,\ X_j,\ V_1,\ V_2 >$ for each update, and
    - $< T_i$ **commit** $>$ at transaction end
- Transaction rollback (during normal operation)
    - Let T_i be the transaction to be rolled back
    - Scan log backwards from the end, and for each log record of T_i of the form $< T_i,\ X_j,\ V_1,\ V_2 >$
        - perform the undo by writing V_1 to X_j,
        - write a log record $< T_i,\ X_j,\ V_1 >$ — such log records are called compensation log records
    - Once the record $< T_i$ **start** $>$ is found stop the scan and write the log record $< T_i$ **abort** $>$

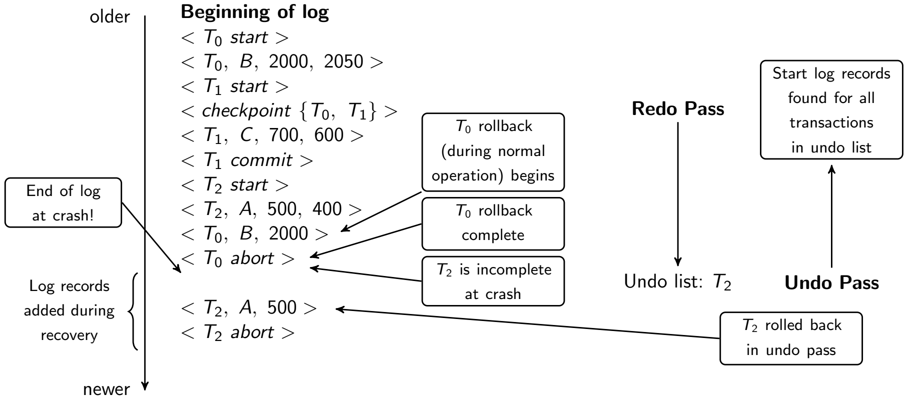
Recovery Algorithm/2

- Recovery from failure: Two phases
    - Redo phase: replay updates of all transactions, whether they committed, aborted, or are incomplete
    - Undo phase: undo all incomplete transactions
- Redo phase:
    1. Find last $<$ **checkpoint** $L >$ record, and set undo-list to L.
    2. Scan forward from above $<$ **checkpoint** $L >$ record
        1. whenever a record $< T_i,\ X_j,\ V_1,\ V_2 >$ or $< T_i,\ X_j, V_2 >$ is found, redo it by writing V_2 to X_j
        2. whenever a log record $< T_i$ **start** $>$ is found, add T_i to undo-list
        3. whenever a log record $< T_i$ **commit** $>$ or $< T_i$ **abort** $>$ is found, remove T_i from undo-list
- After redo: database is in the same state as at time of crash

Recovery Algorithm/2

- Undo phase: Scan log backwards from end
  1. Whenever a log record $< T_i, X_j, V_1, V_2 >$ is found where T_i is in undo-list perform same actions as for transaction rollback:
     1. perform undo by writing V_1 to X_j.
     2. write a log record $< T_i, X_j, V_1 >$
  2. Whenever a log record $< T_i$ **start** $>$ is found where T_i is in undo-list,
     1. write a log record $< T_i$ **abort** $>$
     2. remove T_i from undo-list
  3. Stop when undo-list is empty
     1. i.e., $< T_i$ **start** $>$ has been found for every transaction in undo-list
- After undo phase completes, normal transaction processing can commence

Example of Recovery



Beginning of log

$< T_0$ *start* $>$

$< T_0, B, 2000, 2050 >$

$< T_1$ *start* $>$

$<$ *checkpoint* $\{T_0, T_1\} >$

$< T_1, C, 700, 600 >$

$< T_1$ *commit* $>$

$< T_2$ *start* $>$

$< T_2, A, 500, 400 >$

$< T_0, B, 2000 >$

$< T_0$ *abort* $>$

$< T_2, A, 500 >$

$< T_2$ *abort* $>$

older
newer
End of log at crash!
Log records added during recovery
T_0 rollback (during normal operation) begins
T_0 rollback complete
T_2 is incomplete at crash
T_2 rolled back in undo pass
Redo Pass
Undo list: T_2
Undo Pass
Start log records found for all transactions in undo list

Log Record Buffering/1

- Log record buffering: log records are buffered in main memory, instead of of being output directly to stable storage.
  - Log records are output to stable storage when a block of log records in the buffer is full, or a log force operation is executed.
- Log force is performed to commit a transaction by forcing all its log records (including the commit record) to stable storage.
- Several log records can thus be output using a single output operation, reducing the I/O cost.

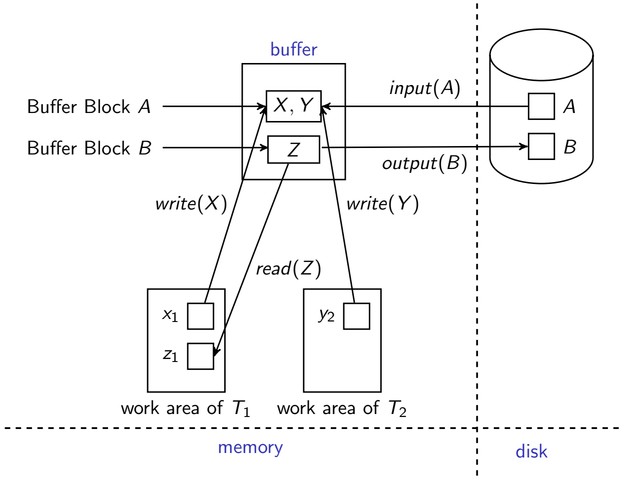
Log Record Buffering/2

- The rules below must be followed if log records are buffered:
  - Log records are output to stable storage in the order in which they are created.
  - Transaction T_i enters the commit state only when the log record $< T_i$ **commit** $>$ has been output to stable storage.
  - Before a block of data in main memory is output to the database, all log records pertaining to data in that block must have been output to stable storage.
    - This rule is called the write-ahead logging or WAL rule
    - Strictly speaking WAL only requires undo information to be output

Database Buffering/1

- Database maintains an in-memory buffer of data blocks
    - When a new block is needed, if buffer is full an existing block needs to be removed from buffer
    - If the block chosen for removal has been updated, it must be output to disk
- The recovery algorithm supports the no-force policy: i.e., updated blocks need not be written to disk when transaction commits
    - force policy: requires updated blocks to be written at commit
        - More expensive commit
- The recovery algorithm supports the steal policy: i.e., blocks containing updates of uncommitted transactions can be written to disk, even before the transaction commits

Database Buffering/2



- Both T_1 and T_2 write a data item (X resp. Y) on block A

Database Buffering/3

- If a block with uncommitted updates is output to disk, log records with undo information for the updates are output to the log on stable storage first
    - (Write ahead logging)
- No updates should be in progress on a block when it is output to disk. Can be ensured as follows.
    - Before writing a data item, transaction acquires exclusive lock on block containing the data item
    - Lock can be released once the write is completed.
        - Such locks held for short duration are called latches.
- To output a block to disk
    1. First acquire an exclusive latch on the block
        1. Ensures no update can be in progress on the block
    2. Then perform a log flush
    3. Then output the block to disk
    4. Finally release the latch on the block

Buffer Management/1

- Database buffer can be implemented either
    - in an area of real main-memory reserved for the database, or
    - in virtual memory
- Implementing buffer in reserved main-memory has drawbacks:
    - Memory is partitioned before-hand between database buffer and applications, limiting flexibility.
    - Needs may change, and although operating system knows best how memory should be divided up at any time, it cannot change the partitioning of memory.

Buffer Management/2

- Database buffers are generally implemented in virtual memory in spite of some drawbacks:
  - When operating system needs to evict a page that has been modified, the page is written to swap space on disk.
  - When database decides to write buffer page to disk, buffer page may be in swap space, and may have to be read from swap space on disk and output to the database on disk, resulting in extra I/O!
    - Known as dual paging problem.
  - Ideally when OS needs to evict a page from the buffer, it should pass control to database, which in turn should
    1. Output the page to database instead of to swap space (making sure to output log records first), if it is modified
    2. Release the page from the buffer, for the OS to use

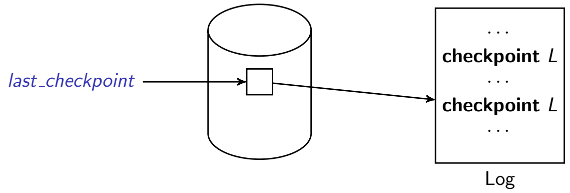
    Dual paging can thus be avoided, but common operating systems do not support such functionality.

Fuzzy Checkpointing/1

- To avoid long interruption of normal processing during checkpointing, allow updates to happen during checkpointing
- Fuzzy checkpointing is done as follows:
  1. Temporarily stop all updates by transactions
  2. Write a < **checkpoint** L > log record and force log to stable storage
  3. Note list M of modified buffer blocks
  4. Now permit transactions to proceed with their actions
  5. Output to disk all modified buffer blocks in list M
     - blocks should not be updated while being output
     - follow WAL: all log records pertaining to a block must be output before the block is output
  6. Store a pointer to the checkpoint record in a fixed position last_checkpoint on disk

Fuzzy Checkpointing/2

- When recovering using a fuzzy checkpoint, start scan from the checkpoint record pointed to by last_checkpoint
  - Log records before last_checkpoint have their updates reflected in database on disk, and need not be redone.
  - Incomplete checkpoints, where system had crashed while performing checkpoint, are handled safely



Disk Crash

- What happens if the disk crashes and the data on it is gone?

Failure with Loss of Nonvolatile Storage

- So far we assumed no loss of non-volatile storage
- Technique similar to checkpointing used to deal with loss of non-volatile storage
  - Periodically dump the entire content of the database to stable storage
  - No transaction may be active during the dump procedure; a procedure similar to checkpointing must take place
    - Output all log records currently residing in main memory onto stable storage.
    - Output all buffer blocks onto the disk.
    - Copy the contents of the database to stable storage.
    - Output a record $<$ **dump** $>$ to log on stable storage.

Failure with Loss of Nonvolatile Storage

- To recover from disk failure
  - restore database from most recent dump.
  - Consult the log and redo all transactions that committed after the dump
- Can be extended to allow transactions to be active during dump; known as fuzzy dump or online dump
  - Similar to fuzzy checkpointing

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Recovery with Early Lock Release

- Some low-level locks should be released early to increase concurrency.

- Early lock release violates the assumptions of our recovery algorithm:
  - The updates of uncommitted transactions are not visible to other transactions (cascadeless schedules).
  - If a transaction T_i has modified an item, no other transaction can modify the same item until T_i has committed or aborted.

- Logical logging fixes this issue.

Examples for Early Lock Release

- Crabbing protocol: B$^+$-tree insert and delete release locks early.
  - Cannot be undone by restoring old values (physical undo): once the lock on a node is released, other transactions may updated the node.
  - Instead, insertions (resp. deletions) are undone by executing a deletion (resp. insertion) operation (known as logical undo).
- Frequently accessed data structures that track, e.g., the free blocks in a database, free space in a block, blocks in a relation.

Logical Undo Logging

- For operations with early lock release
  - instead of storing the old value (physical logging)
  - store the undo operation to be executed to undo the update
- Undo operations for some examples of logical operations:
  - insert key into B$^+$-tree: undo by deleting key from B$^+$-tree
  - deletion of a tuple: undo by inserting the tuple
  - add deposited amount to account: undo by subtracting amount

Physical Redo

- Redo information is logged physically (i.e., log new value for each write) even for operations with logical undo:
  - Logical undo requires operation consistent state when recovery starts, i.e., there must be no partial effects of an operation.
  - For example, inserting key into B$^+$-tree not possible if B$^+$-tree is in an operation inconsistent state (i.e., does not have a valid structure).
  - Physical redo logging does not conflict with early lock release.

Operation Logging/1

- Operation logging is done as follows:
  1. When operation starts, log $< T_i,\ O_j,\ \textit{operation-begin} >$. Here O_j is a unique identifier of the operation instance.
  2. While operation is executing, normal log records with physical redo and physical undo information are logged.
  3. When operation completes, $< T_i,\ O_j,\ \textit{operation-end},\ U >$ is logged, where U contains information needed to perform a logical undo.

  Example: insert of $(\textit{key},\ \textit{record-id})$ pair $(K5,\ RID7)$ into index $I9$

$$
\begin{array}{l}
< T_1,\ O_1,\ \textit{operation-begin} > \\
\ldots \\
\left.\begin{array}{l} < T_1,\ X,\ 10,\ K5 \\ < T_1,\ Y,\ 45,\ RID7 \end{array}\right\} \text{Physical redo of steps in insert} \\
< T_1,\ O_1,\ \textit{operation-end},\ (\textit{delete}\ I9,\ K5,\ RID7) >
\end{array}
$$

Operation Logging/2

- If crash/rollback occurs before operation completes:
  - the operation-end log record is not found, and
  - the physical undo information is used to undo operation.
- If crash/rollback occurs after the operation completes:
  - the operation-end log record is found, and in this case
  - logical undo is performed using U; the physical undo information for the operation is ignored.
- Redo of operation (after crash) still uses physical redo information.

Transaction Rollback with Logical Undo/1

Rollback of transaction T_i: Scan the log backwards:

1. If a log record $< T_i,\ X,\ V_1,\ V_2 >$ is found: perform the undo and log a redo-only record $< T_i,\ X,\ V_1 >$.
2. If a $< T_i,\ O_j,\ \textit{operation-end},\ U >$ record is found:
   - Rollback the operation logically using the undo information U.
   - Updates performed during rollback are logged physically using log records of the form $< T_i,\ X,\ V_1,\ V_2 >$.
   - At the end of the operation rollback, instead of logging an *operation-end* record, generate a record $< T_i,\ O_j,\ \textit{operation-abort} >$.
   - Skip all preceding log records for T_i until the record $< T_i,\ O_j,\ \textit{operation-begin} >$ is found
3. If a redo-only record of T_i is found: ignore it.
4. If a $< T_i,\ O_j,\ \textit{operation-abort} >$ record is found: skip all preceding log records for T_i up to the record $< T_i,\ O_j,\ \textit{operation-begin} >$.
5. Stop the scan when the record $< T_i,\ \textit{start} >$ is found
6. Add a $< T_i,\ \textit{abort} >$ record to the log

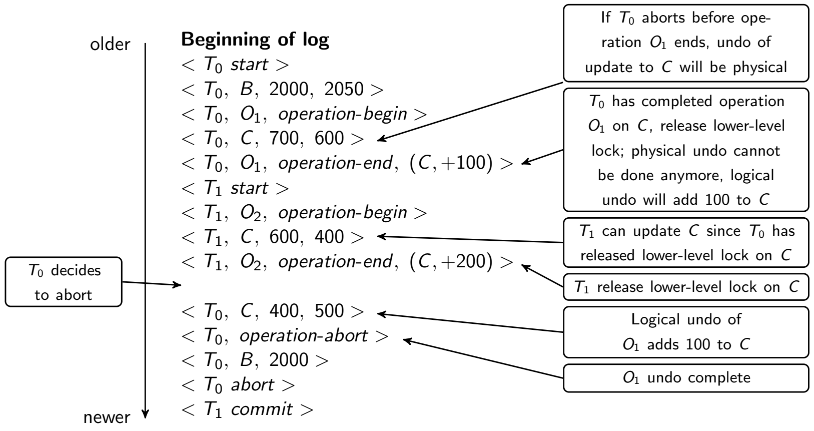
Transaction Rollback with Logical Undo/2

Some points to note:

- Cases 3 and 4 above can occur only if the database crashes while a transaction is being rolled back.
- Skipping of log records as in case 4 is important to prevent multiple rollback of the same operation.

Transaction Rollback with Logical Undo

- Transaction rollback during normal operation



Beginning of log

$< T_0\ \textit{start} >$
$< T_0,\ B,\ 2000,\ 2050 >$
$< T_0,\ O_1,\ \textit{operation-begin} >$
$< T_0,\ C,\ 700,\ 600 >$
$< T_0,\ O_1,\ \textit{operation-end},\ (C,+100) >$
$< T_1\ \textit{start} >$
$< T_1,\ O_2,\ \textit{operation-begin} >$
$< T_1,\ C,\ 600,\ 400 >$
$< T_1,\ O_2,\ \textit{operation-end},\ (C,+200) >$
$< T_0,\ C,\ 400,\ 500 >$
$< T_0,\ \textit{operation-abort} >$
$< T_0,\ B,\ 2000 >$
$< T_0\ \textit{abort} >$
$< T_1\ \textit{commit} >$

If T_0 aborts before operation O_1 ends, undo of update to C will be physical

T_0 has completed operation O_1 on C, release lower-level lock; physical undo cannot be done anymore, logical undo will add 100 to C

T_1 can update C since T_0 has released lower-level lock on C

T_1 release lower-level lock on C

Logical undo of O_1 adds 100 to C

O_1 undo complete

Transaction Rollback: Another Example

- Example with a complete and an incomplete operation

$< T_1\ start >$
$< T_1,\ O_1,\ operation\text{-}begin >$
...
$< T_1,\ X,\ 10,\ K5 >$
$< T_1,\ Y,\ 45,\ RID7 >$
$< T_1,\ O_1,\ operation\text{-}end,\ (delete\ I9,\ K5,\ RID7) >$
$< T_1,\ O_2,\ operation\text{-}begin >$
$< T_1,\ Z,\ 45,\ 70 >$
← T_1 Rollback begins here
$< T_1,\ Z,\ 45 >$ ← redo-only log record during physical undo (of incomplete O_2)
$< T_1,\ Y,\ \ldots,\ \ldots >$ ← Normal redo records for logical undo of O_1
...
$< T_1,\ O_1,\ operation\text{-}abort >$ ← What if crash occurred immediately after this?
$< T_1\ abort >$

Recovery Algorithm with Logical Undo/1

Recovery from crash: same as physical algorithm, except that transaction rollback with logical undo is used.

1. (Redo phase): Scan log forward from last $<$ **checkpoint** $L >$ record till end of log
    1. Repeat history by physically redoing all updates of all transactions.
    2. Create an *undo-list* during the scan as follows:
        - *undo-list* is set to L initially
        - whenever $< T_i\ start >$ is found, T_i is added to *undo-list*
        - whenever $< T_i\ commit >$ or $< T_i\ abort >$ are found, T_i is deleted from *undo-list*

    This brings database to state as of crash, with committed as well as uncommitted transactions having been redone.

    Now *undo-list* contains transactions that are incomplete, that is, have neither committed nor been fully rolled back.

Recovery Algorithm with Logical Undo/2

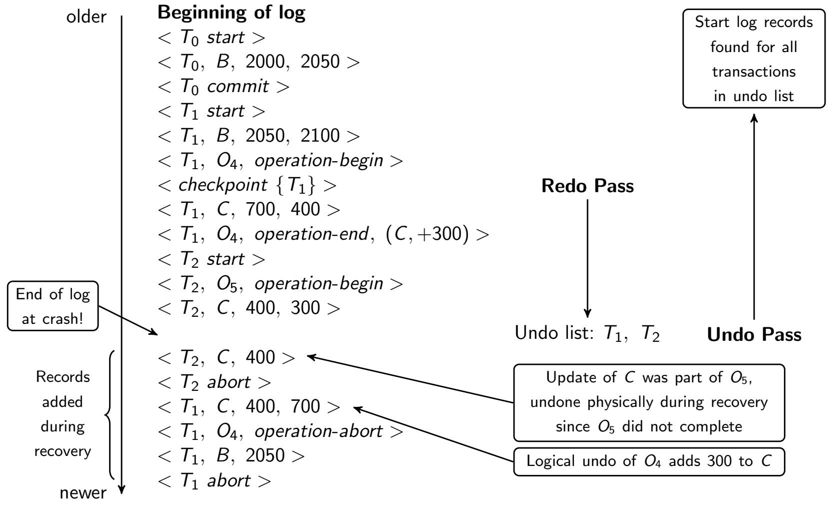
Recovery from system crash (cont.)

2. (Undo phase): Scan log backwards, performing undo on log records of transactions found in *undo-list*.
    - Do a single shared scan for all transactions being undone.
    - Log records of transactions being rolled back are processed as discussed earlier (including logical undo).
    - When $< T_i\ start >$ is found for a transaction T_i in *undo-list*, write a $< T_i\ abort >$ log record.
    - Stop scan when $< T_i\ start >$ records have been found for all T_i in *undo-list*.

    This undoes the effects of incomplete transactions (those with neither commit nor abort log records).

Recovery is now complete.

Failure Recovery with Logical Undo



Beginning of log
$< T_0\ start >$
$< T_0,\ B,\ 2000,\ 2050 >$
$< T_0\ commit >$
$< T_1\ start >$
$< T_1,\ B,\ 2050,\ 2100 >$
$< T_1,\ O_4,\ operation\text{-}begin >$
$< checkpoint\ \{T_1\} >$
$< T_1,\ C,\ 700,\ 400 >$
$< T_1,\ O_4,\ operation\text{-}end,\ (C, +300) >$
$< T_2\ start >$
$< T_2,\ O_5,\ operation\text{-}begin >$
$< T_2,\ C,\ 400,\ 300 >$
$< T_2,\ C,\ 400 >$
$< T_2\ abort >$
$< T_1,\ C,\ 400,\ 700 >$
$< T_1,\ O_4,\ operation\text{-}abort >$
$< T_1,\ B,\ 2050 >$
$< T_1\ abort >$

older
newer
End of log at crash!
Records added during recovery
Redo Pass
Undo list: T_1, T_2
Undo Pass
Start log records found for all transactions in undo list
Update of C was part of O_5, undone physically during recovery since O_5 did not complete
Logical undo of O_4 adds 300 to C

Outline

1. Failure Classification
2. Storage Structure
3. Log-Based Recovery
4. Recovery Algorithm
5. Early Lock Release and Logical Undo
6. ARIES

ARIES – Algorithms for Recovery and Isolation Exploiting Semantics

- ARIES is a state of the art recovery method
  - Incorporates numerous optimizations to reduce overheads during normal processing and to speed up recovery
  - The recovery algorithm we studied earlier is modeled after ARIES, but greatly simplified by removing optimizations
- Unlike the recovery algorithm described earlier, ARIES uses:
  1. Log sequence number (LSN) to identify log records
     - Stores LSNs in pages to identify what updates have already been applied to a database page
  2. Physiological redo
  3. Dirty page table to avoid unnecessary redos during recovery
  4. Fuzzy checkpointing that only records information about dirty pages, and does not require dirty pages to be written out at checkpoint time
- Savepoints are used for partial rollbacks.