Chapter 16 :

Recovery

Database System Concepts, 7^{th} Ed.

Recovery Algorithms

- Suppose transaction T_i transfers \$50 from account *A* to account *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

Failure Classification

- **Transaction failure** :
  - **Logical errors**: transaction cannot complete due to some internal error condition
  - **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**: system will come to a halt where there is a failure, and non-volatile storage contents are assumed to not be corrupted by system crash
- **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

Storage Structure

- **Volatile storage**:
  - Does not survive system crashes
  - Examples: main memory, cache memory
- **Nonvolatile storage**:
  - Survives system crashes
  - Examples: disk, tape, flash memory, non-volatile 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 nonvolatile media

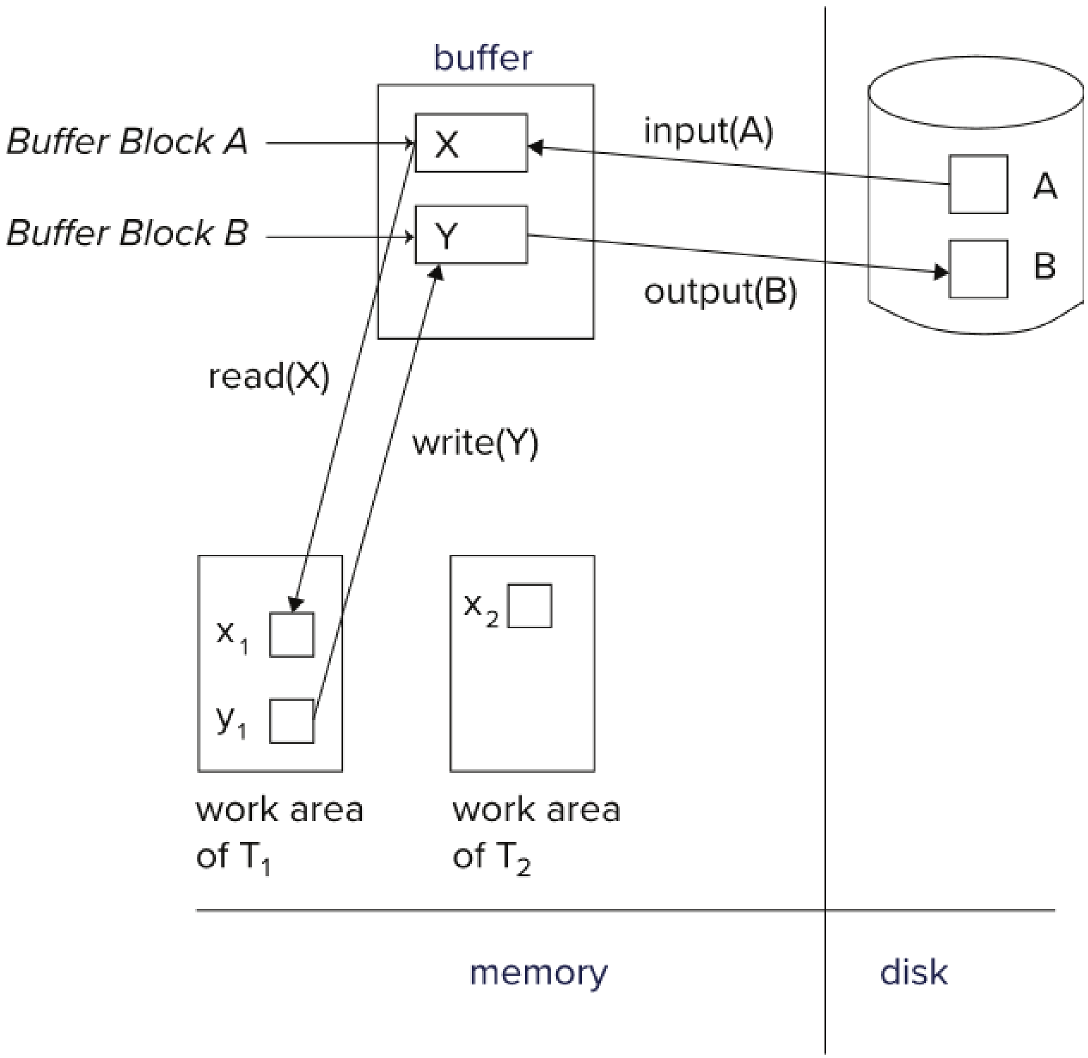
Data Access

- **Physical blocks** are those blocks residing on the disk
- **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 that each data item fits in, and is stored inside, a single block

Data Access

- Each transaction T_i has its private work-area in main memory which local copies of all data items accessed and updated by it are kept
  - T_i's local copy of a data item X is called x_i
- Transferring data items between system buffer blocks and its private work-area 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
  - Note: **output**(B_X) need not immediately follow **write**(X)
    - System can perform the **output** operation when it deems fit
- Transactions
  - Must perform **read**(X) before accessing X for the first time (subsequent reads can be from local copy)
  - **write**(X) can be executed at any time

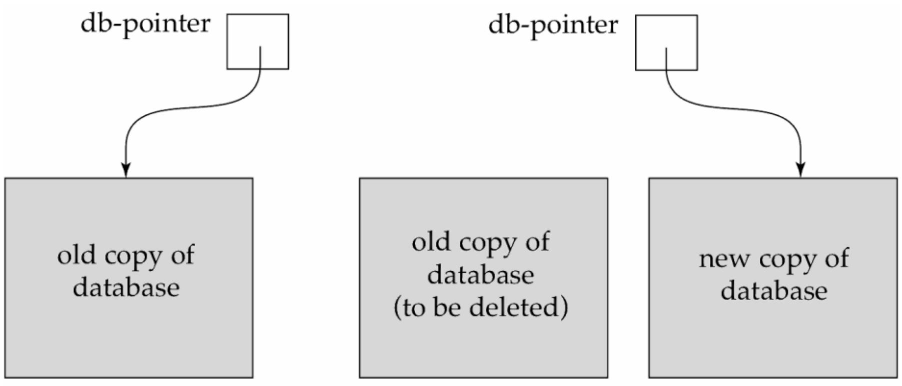
Example of Data Access



Recovery and Atomicity

- To ensure atomicity despite failures, we first output information describing the modifications to stable storage without modifying the database itself
- We shall focus on **log-based recovery mechanisms**
- Less used alternative: **shadow-copy** and **shadow-paging**

shadow-copy
(original copy)



(a) Before update (b) After update

Log-Based Recovery

- A **log** is a sequence of **log records**. The records keep information about update activities on the database
  - The **log** is kept on stable storage
- When transaction T_i starts, it registers itself by writing a

  $<T_i$ **start**$>$ log record

- 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** or **before image**), and V_2 is the value to be written to X (the **new value** or **after image**)
- When T_i finishes it last statement, the log record $<T_i$ **commit**$>$ is written

Database Modification

- We say a transaction *modifies* the database if it performs an update on a disk buffer or on the disk itself
  - Updates to the private part of main memory do not count as 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* database item is written
  - the log record is output directly to stable storage
- Output of updated blocks to disk can take place at any time before or after transaction commit
- The **deferred-modification** scheme performs updates to buffer/disk only at the time of transaction commit

Commit Point

- A transaction is said to reach its **commit point** when the effect of all the transaction operations on the database have been output to the log
- A transaction is said to have committed (beyond the commit point) when **its commit log record is output to stable storage**
  - All previous log records of the transaction must also have been output already
- Writes performed by a transaction may still be in the buffer when the transaction commits, and may be output later

Database Modification Example

Log	Write	Output
<T_0 **start**>		
<T_0, A, 1000, 950>		
<T_0, B, 2000, 2050>		
	A = 950	
	B = 2050	
<T_0 **commit**>		
<T_1 **start**>		
<T_1, C, 700, 600>		
	C = 600	
		B_B , B_C
<T_1 **commit**>		
		B_A

B_C output before T_1 commits

B_A output after T_0 commits

- Note: B_X denotes block containing X.

Undo and Redo Operations

- **Undo and Redo of Transactions**
  - **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 <T_i , X, V> is written out
    - When undo of a transaction is complete, a log record <T_i **abort**> is written out
  - **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

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 for all completed transactions if the log
    - Contains the records <T_i **start**>
    - And contains the record <T_i **commit**> *or* <T_i **abort**>

Recovering from Failure

- Suppose that failed transaction T_i was undone before system failure and the <T_i **abort**> record was written to the log, and then a system failure occurs
- On recovery from system failure, transaction T_i is redone
  - Such a **redo** redoes all the original actions of transaction T_i *including the (roll back) steps that restored old values*
    - Known as **repeating history**
    - Seems wasteful in making all the changes and then rolling them back, repeating history for failed transactions simplifies recovery

Recovery Example

Here we show the log as it appears at three instances of time preceding a failure.

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

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, and C is set to 600

Checkpoints

- Redoing/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 which have already output their updates to the database
- Streamline recovery procedure by periodically performing **checkpointing**, during which
  1. All updates are stopped while the checkpoint operation is in progress
  2. Output all log records currently residing in main memory onto stable storage
  3. Output all modified buffer blocks to the disk
  4. Output a log record < **checkpoint** *L*> onto stable storage where *L* is a list of all transactions active at the time of checkpoint

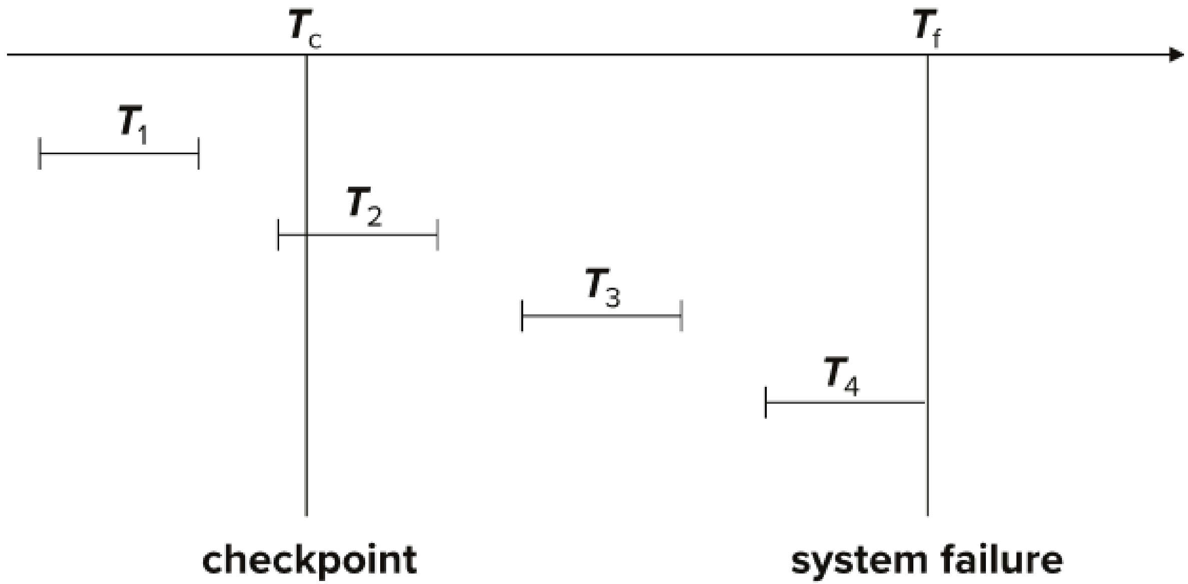
Checkpoints

- Consider a transaction T_i that completed prior to the checkpoint
- For such a transaction, the <T_i **commit**> record (or <T_i **abort**>) record appears in the log before the < **checkpoint** *L*> record
- Any database modifications made by T_i must have been written to the database either prior to the checkpoint or as part of the checkpoint itself
- Thus, at recovery time, there is no need to perform a **redo** operation on T_i

Checkpoints

- After a system crash has occurred, the system examines the log to find the last <**checkpoint** *L*> record (this can be done by searching the log backward, from the end of the log, until the first <**checkpoint** *L*> record is found)
- The redo or undo operations need to be applied only to transactions in *L*, and to all transactions that started execution after the <**checkpoint** *L*> record was written to the log. Let *T* denote this set of transactions.
  - For all transactions T_k in *T* that have no <T_k **commit**> record or <T_k **abort**> record in the log, execute undo(T_k)
  - For all transactions T_k in *T* such that either the record <T_k **commit**> or the record <T_k **abort**> appears in the log, execute redo(T_k)
- That is, we need only examine the part of the log starting with the last checkpoint log record to find the set of transactions *T* and to find out whether a commit or abort record occurs in the log for each transaction in *T*

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

Recovery Algorithm

- **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**>
  - Observe that every update action performed by the transaction or on behalf of the transaction, including actions taken to restore data items to their old value, have now been recorded in the log

Recovery Algorithm

- **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 normal log record of the form $<T_i, X_j, V_1,V_2>$, or a compensation log record of the form $<T_i, X_j, V_1>$ is encountered, the operation is redone; i.e., the value V_1 is written to data item 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 (no need to roll back an aborted T_i as by having <T_i **abort**> there, this indicates that it is already successfully aborted)

Recovery Algorithm

- **Undo phase:**

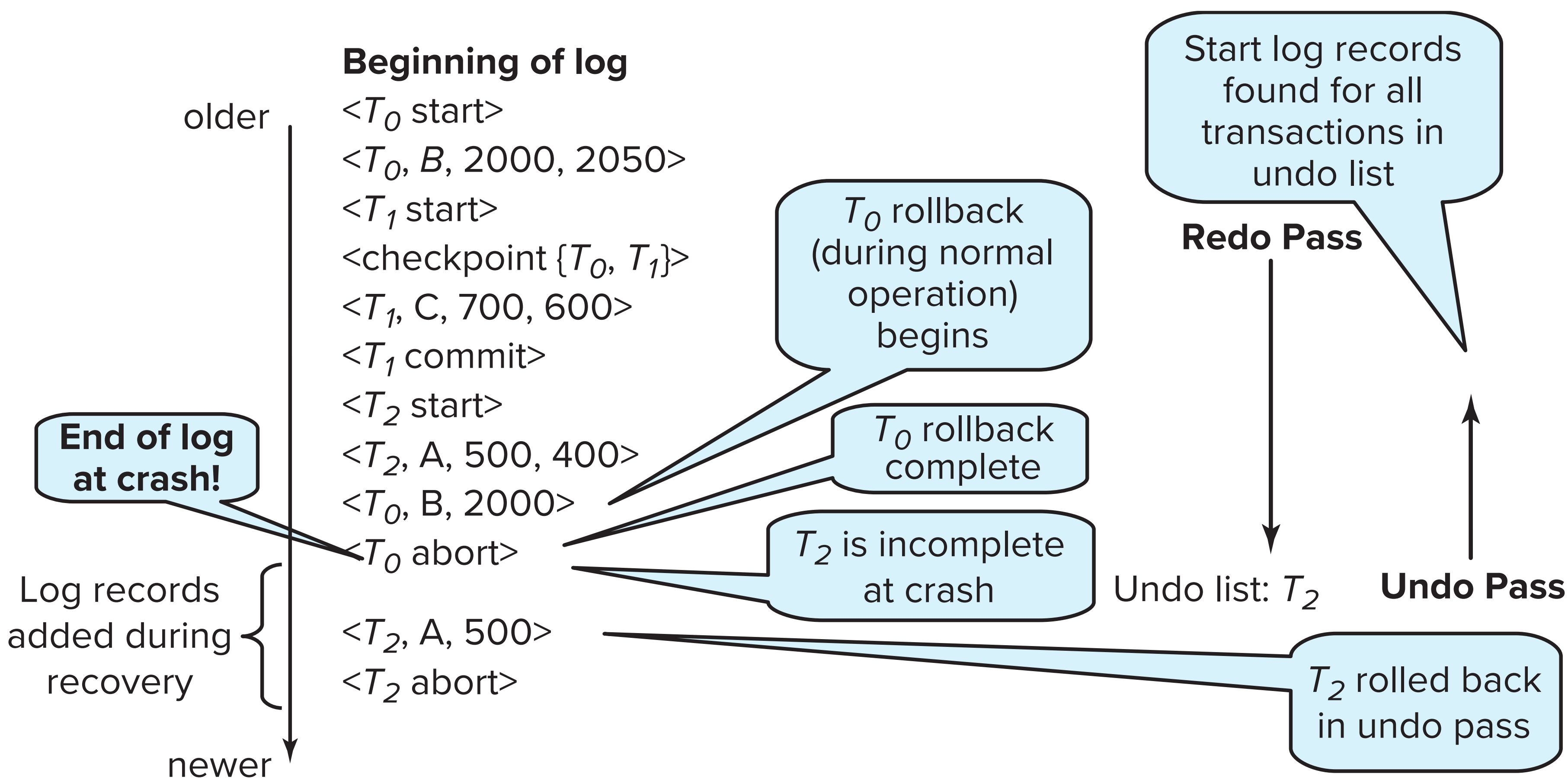
  Scan log backwards from end

  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

     (since if $<T_i$ **start**$>$ has not been found, then T_i cannot be removed from the undo-list, and the undo-list won't be empty)

- After undo phase completes, normal transaction processing can commence

Example of Recovery



Log Record Buffering

- **Log record buffering**: log records are buffered in main memory, instead 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

Log Record Buffering

- 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