UNIVERSITÄT MANNHEIM

Database Technology
Recovery

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Flashback to First Lecture

- We already stumbled upon transactions

```
Delete from file: active lecturers

Add to file: retired lecturers
```

Computer crashes here

File: active lecturers

Prof. Smith
Dr. Stevens
Prof. Miller

File: retired lecturers

Dr. Hawkins
Prof. Brown
Prof. Wilson

Recap: ACID Properties

- **Atomicity:** Either all operations of the transaction are properly reflected in the database, or none
- **Consistency:** Execution of a full transaction preserves the consistency of the database
- **Isolation:** Although multiple transactions may execute concurrently, each transaction must be unaware of other concurrently executing transactions
  - Intermediate transaction results must be hidden from other concurrently executed transactions
  - i.e., for every pair of transactions T_i and T_j, it appears to T_i that either T_j, finished execution before T_i started, or T_j started execution after T_i finished
- **Durability:** After a transaction completes successfully, the changes it has made to the database persist, even if there are system failures

Outline

- Failure Classification
- Storage Structure
- Recovery and Atomicity
- Log-Based Recovery
- Recovery Algorithm
- Remote Backup Systems

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**: non-volatile storage contents are assumed to not be corrupted as result of a system crash
    - Database systems have numerous integrity checks to prevent corruption of disk data
- **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 a transaction that transfers $50 from account A to account B
  - Two updates: subtract 50 from A and add 50 to B
- Transaction 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
  - not 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
  - Actions taken *during normal transaction processing* to ensure enough information exists to recover from failures
  - Actions taken *after a failure* to recover the database contents to a state that ensures atomicity, consistency, and durability

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 (battery backed up) RAM
  - but may still fail, losing data
- **Stable storage**:
  - a mythical form of storage that survives all failures
  - approximation: maintaining multiple copies on distinct nonvolatile media

Stable Storage Approximation

- Maintain multiple copies of each block on separate disks
  - copies can be at remote sites to protect against disasters such as fire or flooding
- Failure during data transfer can still result in inconsistent copies:
  - Block transfer can result in
    - Successful completion
    - Partial failure: destination block has incorrect information
    - Total failure: destination block was never updated
- Protecting storage media from failure during data transfer (one solution):
  - 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 Approximation

- 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:
  - First find inconsistent blocks
    - Expensive solution: Compare the two copies of every disk block
    - Better solution:
      - 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
    - Used in hardware RAID systems
  - 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

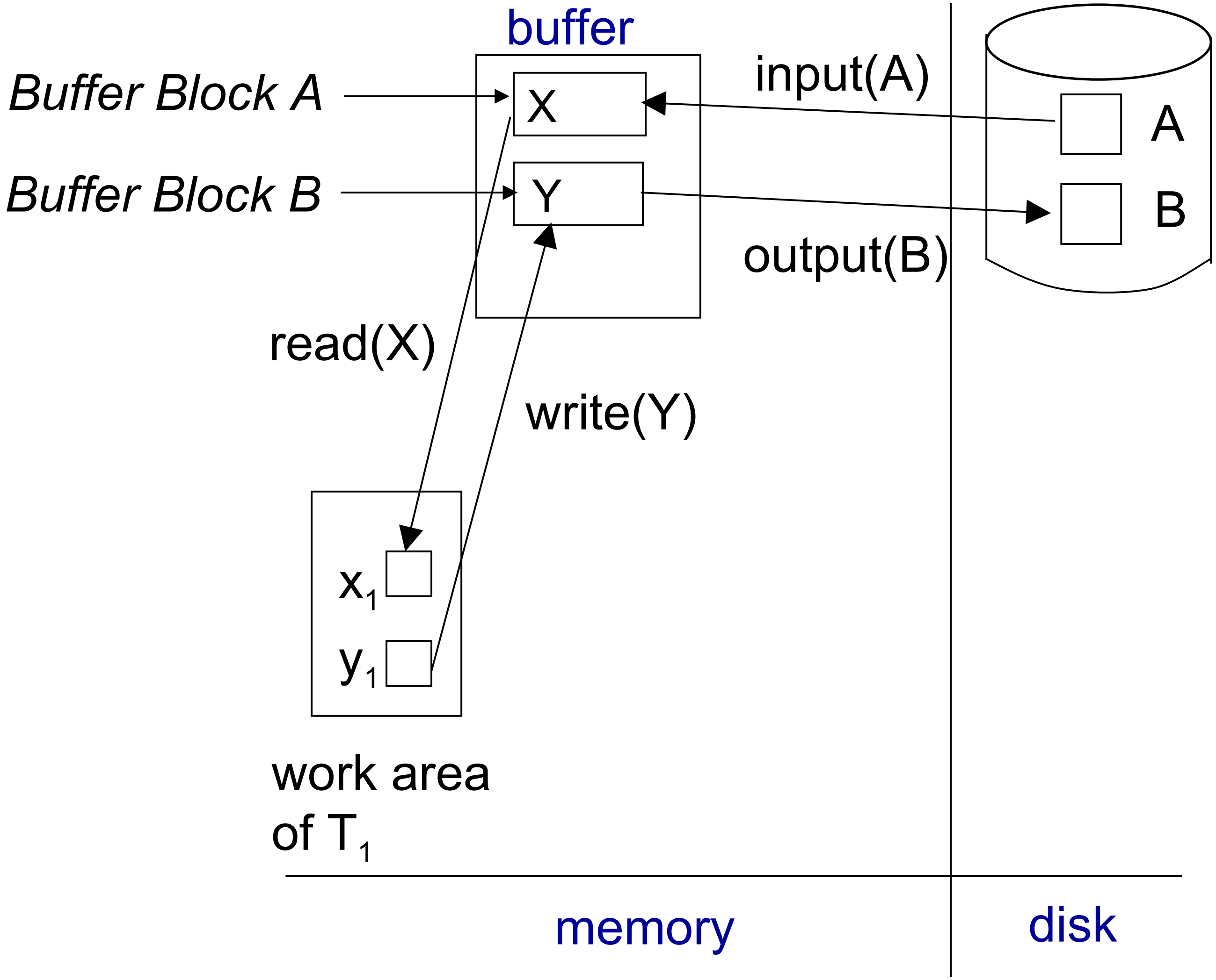
Data Access and Buffering

- **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
- Simplifying assumption:
  - each data item fits in, and is stored inside, a single block

Data Access and Buffering

- Each transaction T_i has its private work-area in 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 denoted by x_i.
  - B_X denotes block containing X
- 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
- Transactions
  - Must perform **input**(X) before accessing X for the first time (subsequent reads can be from local copy)
  - The **write**(X) can be executed 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 deems fit

Data Access and Buffering



Recovery and Atomicity

- How can we ensure atomicity despite failures?
  - *first* output information describing the modification to stable storage
  - *then* modify the database itself
- This is called a **log-based recovery mechanism**
- For the moment, we assume serial execution for simplicity
  - parallel variants exist

Log-based Recovery

- A **log** is kept on stable storage
  - sequence of **log records**
  - 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 is written

  <T_i, X, V_1, V_2>

  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 it last statement, the log record <T_i **commit**> is written.
- Two approaches using logs
  - Immediate database modification
  - Deferred database modification

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 immediately to stable storage
    - however, it is possible 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
- 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 the moment, we only consider 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 **start**>		
<T_0, A, 1000, 950>		
<T_o, 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** of a log record <T_i, X, V_1, V_2> writes the **old** value V_1 to X
- **Redo** of a log record <T_i, X, V_1, V_2> writes the **new** value V_2 to X
- **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 (called **redo-only**) <T_i , X, V> is written out
    - When undo of a transaction is complete, a log record <T_i **abort**> is written out (to indicate that the undo was completed)
  - **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

- **undo** and **redo** operations are used in several different circumstances:
- **undo** is used
  - for *transaction rollback* during normal operation (in case a transaction cannot complete its execution due to some logical error)
- **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

- 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**>

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**>
- Why redo transaction T_i if the case of <T_i **abort**>?
  - for <T_i **abort**>, there are also redo-only records for the undo operation
  - the end result will be to undo T_i's modifications in this case
  - redo *all* original actions including the steps that restored the old value
    - known as *repeating history*
  - simplifies the recovery algorithm, enables faster overall recovery time

Examples for Immediate Recovery

- Below we show the log as it appears at points in time:

(a)	(b)	(c)
<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>

- 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

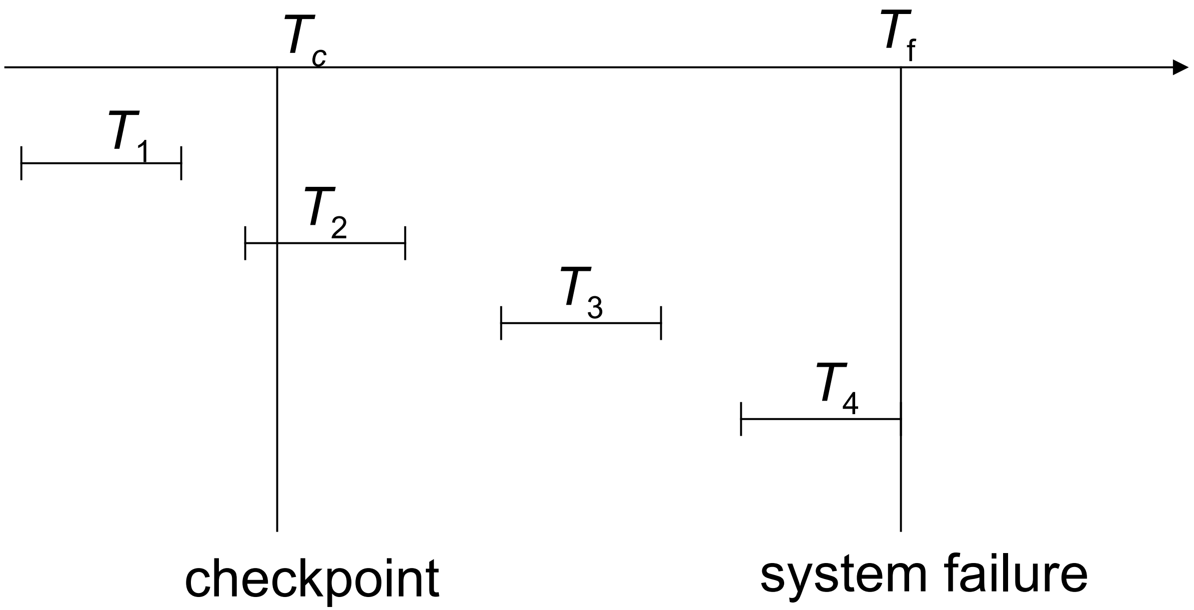
- Redoing/undoing all transactions recorded in the log can be very slow
  - Processing the entire log is time-consuming if the system has run for a long time
  - We might unnecessarily redo transactions which have already output their updates to the database
- Streamline recovery procedure by periodically performing checkpointing
  - All updates are stopped while doing checkpointing
    - Output all log records currently residing in main memory onto stable storage
    - Output all modified buffer blocks to the disk
    - Write a log record <checkpoint L> onto stable storage where L is a list of all transactions active at the time of checkpoint

Checkpoints

- During recovery we need to consider only the most recent transaction T_i that started before the checkpoint, and transactions that started after T_i
  - Scan backwards from end of log to find the most recent <checkpoint L> record
  - Only transactions that are in L 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 whenever desired

Checkpoints

- T_1 can be ignored
  - updates have already been output to disk due to checkpoint
- T_2 and T_3 are redone
- T_4 is undone



The 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>
    - write a log record <T_i , X_j, V_1>
    - perform the undo by writing V_1 to X_j,
    - 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**>

The 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

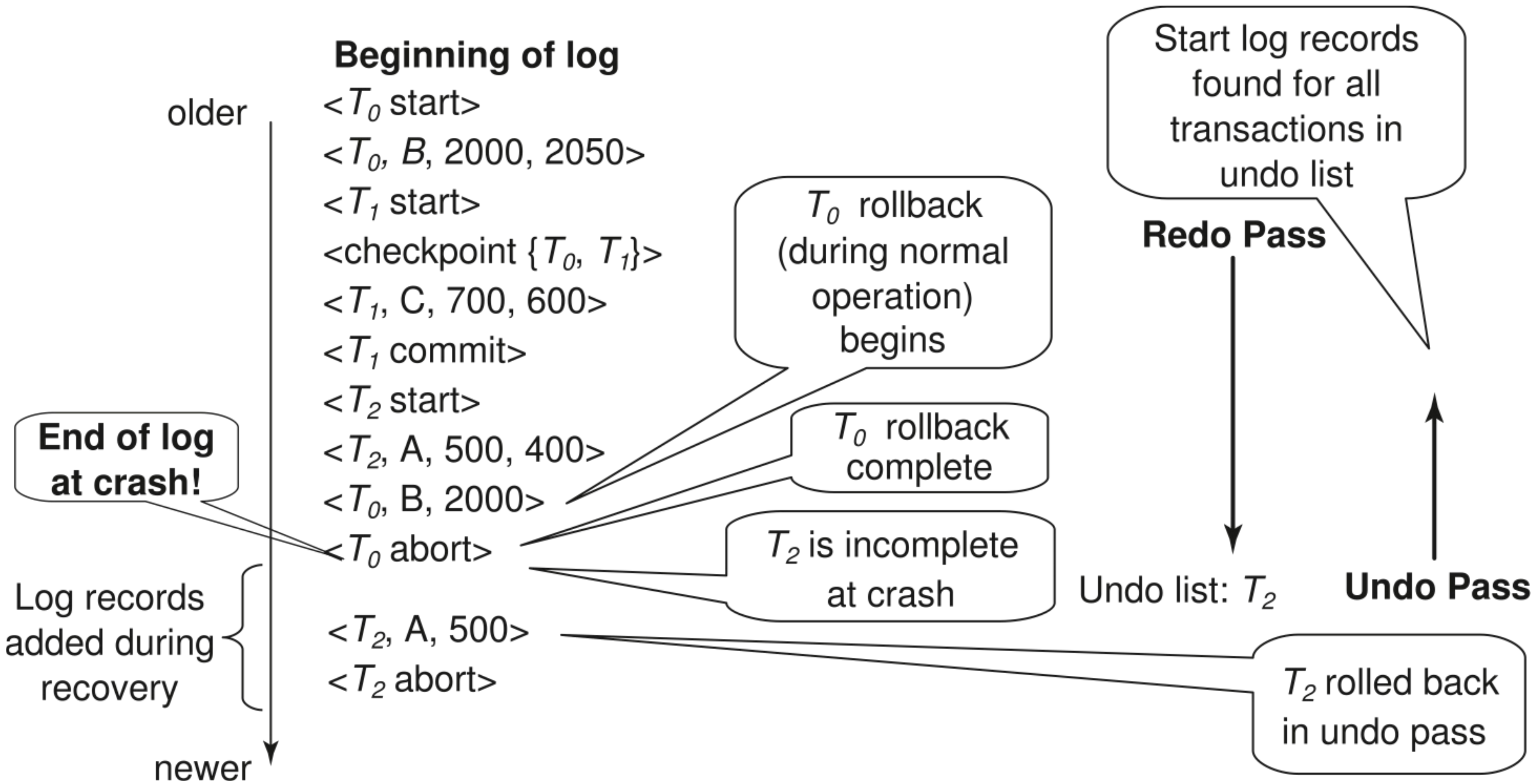
The Recovery Algorithm

- **Redo phase**:
  - Find last <**checkpoint** *L*> record, and set undo-list to *L*.
  - Scan forward from above <**checkpoint** *L*> record
    - Whenever a record $<T_i, X_j, V_1, V_2>$ is found,
      - redo it by writing V_2 to X_j
    - Whenever a log record $<T_i$ **start**$>$ is found
      - add T_i to undo-list
    - Whenever a log record $<T_i$ **commit**$>$ *or* $<T_i$ **abort**$>$ is found
      - remove T_i from undo-list

The Recovery Algorithm

- **Undo phase:**
  - Scan log backwards from end
  - When 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:
      - perform undo by writing V_1 to X_j.
      - write a log record <T_i , X_j, V_1>
  - When a log record <T_i **start**> is found where T_i is in undo-list
    - Write a log record <T_i **abort**>
    - Remove T_i from undo-list
  - Stop when undo-list is empty
    - i.e.,<T_i **start**> has been found for every transaction in undo-list
- After undo phase completes, normal transaction processing can commence

Recovery Example



Log Record Buffering

- **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 & Write-Ahead Logging

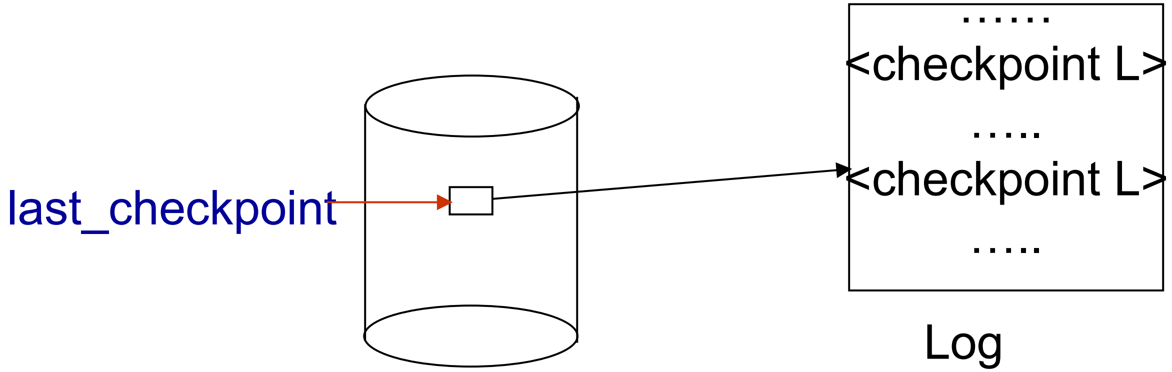
- The rules below must be followed if log records are buffered:
  - Log records are output to stable storage in the order of creation
  - Transaction T_i enters the commit state only when the log record <T_i **commit**> has been output to stable storage
  - Before a block of data in main memory is output 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

Fuzzy Checkpointing

- To avoid long interruption of normal processing during checkpointing, allow updates to happen during checkpointing
- Fuzzy checkpointing is done as follows:
  - Temporarily stop all updates by transactions
  - Write a <checkpoint L> log record and force log to stable storage
  - Note list M of modified buffer blocks
  - Now permit transactions to proceed with their actions
  - 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
  - Store a pointer to the checkpoint record in a fixed position last_checkpoint on disk

Fuzzy Checkpointing

- 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



Failure with Loss of Non-volatile Storage

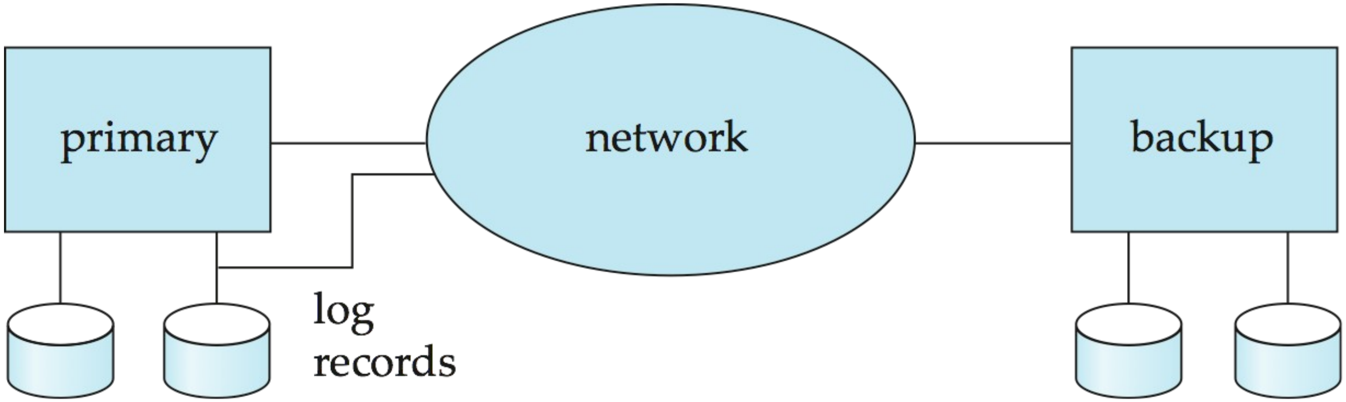
- So far we assumed no loss of non-volatile storage
- Technique similar to checkpointing used to deal with loss of non-volatile storage
  - Periodically **dump** the entire content of the database to stable storage
  - No transaction may be active during the dump procedure
  - a procedure similar to checkpointing must take place
- Output all log records currently 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

Recovery from Failure of Non-volatile 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

Remote Backup Systems

- Risk minimization:
  - allowing transaction processing to continue even if the primary site is destroyed



Remote Backup Systems

- **Detection of failure**:
  - Backup site must detect when primary site has failed
  - to distinguish primary site failure from link failure: maintain *several* communication links in between
  - Heart-beat messages
- **Transfer of control**:
  - To take over control backup site first performs recovery using its copy of the database and all the log records it has received from the primary
    - i.e., completed transactions are redone and incomplete transactions are rolled back
  - When the backup site takes over processing it becomes the new primary
  - To transfer control back to old primary when it recovers
    - old primary must receive redo logs from the old backup and apply all updates locally

Remote Backup Systems

- **Time to recover** – reduce delay in takeover
  - backup site periodically processes the redo log records
    - i.e., performs recovery from previous database state
  - performs a checkpoint, and can then delete earlier parts of the log
- Hot-Spare configuration permits very fast takeover:
  - Backup continually processes redo log records as they arrive
    - applying the updates locally
  - When failure of the primary is detected
    - the backup rolls back incomplete transactions
    - and is ready to process new transactions
- Alternative to remote backup: distributed database with replicated data
  - Remote backup is faster and cheaper, but less tolerant to failure

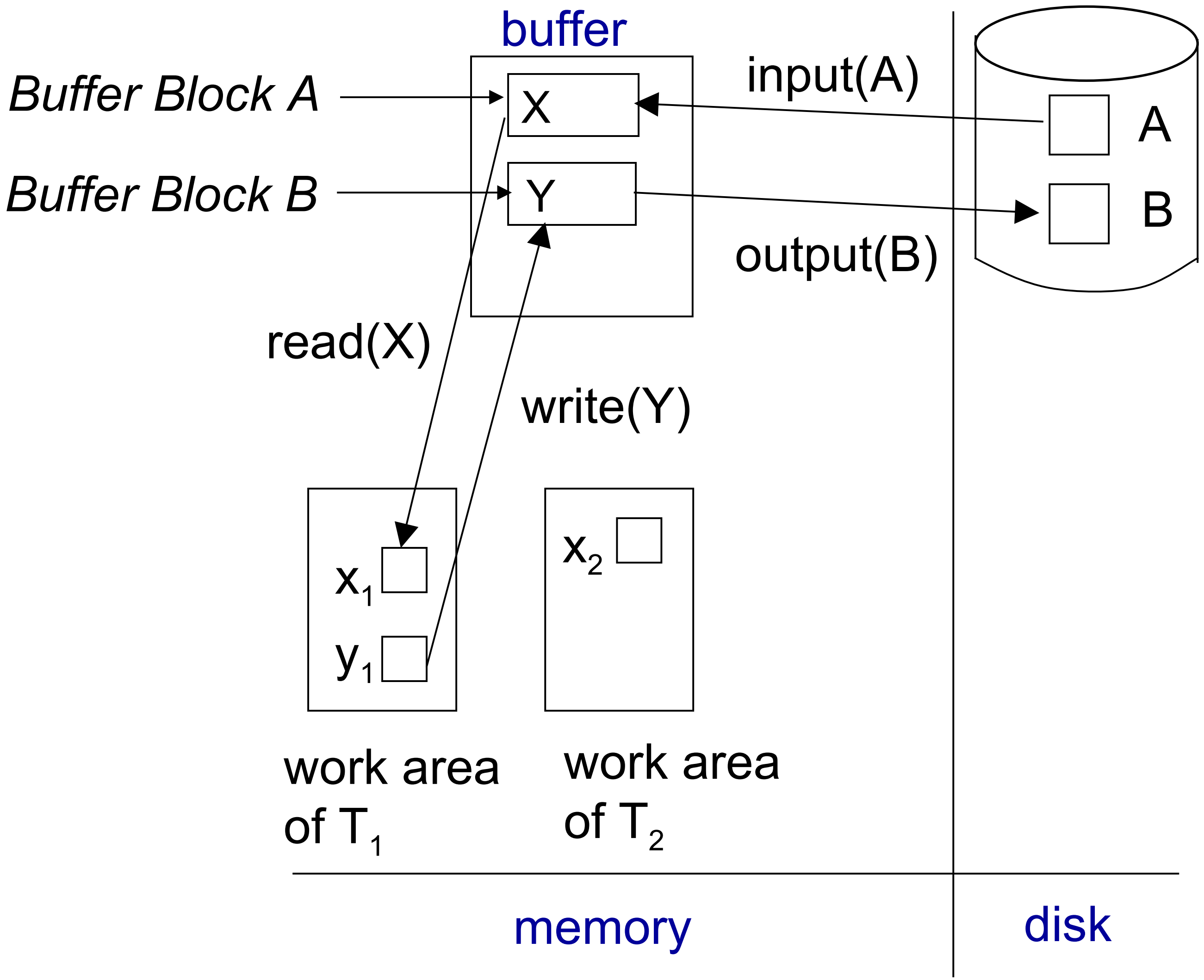
Remote Backup Systems

- Ensure durability of updates by delaying transaction commit
  - until update is logged at backup
  - avoid this delay by permitting lower degrees of durability
- One-safe: commit as soon as transaction’s commit log record is written at primary
  - Problem: updates may not arrive at backup before it takes over
- Two-very-safe: commit when transaction’s commit log record is written at primary and backup
  - Reduces availability since transactions cannot commit if either site fails
- Two-safe: proceed as in two-very-safe if both primary and backup are active
  - If only the primary is active, the transaction commits as soon as its commit log record is written at the primary
  - Better availability than two-very-safe
  - avoids problem of lost transactions in one-safe

Concurrency Control and Recovery

- All transactions share a single disk buffer and a single log
  - A buffer block can have data items updated by one or more transactions
- Log records of different transactions may be interspersed in the log
- We assume that *if a transaction T_i has modified an item, no other transaction can modify the same item until T_i has committed or aborted*
  - i.e. the updates of uncommitted transactions should not be visible to other transactions
    - 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 obtaining exclusive locks on updated items and holding the locks till end of transaction (strict two-phase locking)

Data Access and Buffering (revisited)



Summary

- Recovery ensures consistency of the database
  - handles rollbacks
  - takes care of setting the database back to operation after failures
- Mechanisms
  - Logs: write ahead (write log first, then write data)
  - Checkpoints
- Trade off between normal and recovery performance
  - e.g., by using fuzzy checkpoints
- Remote backup
  - distribution of risk
- Recovery and Concurrency

Questions?