# Chapter 19: Recovery System

**Database System Concepts, 7th Ed.**

# 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.
- **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

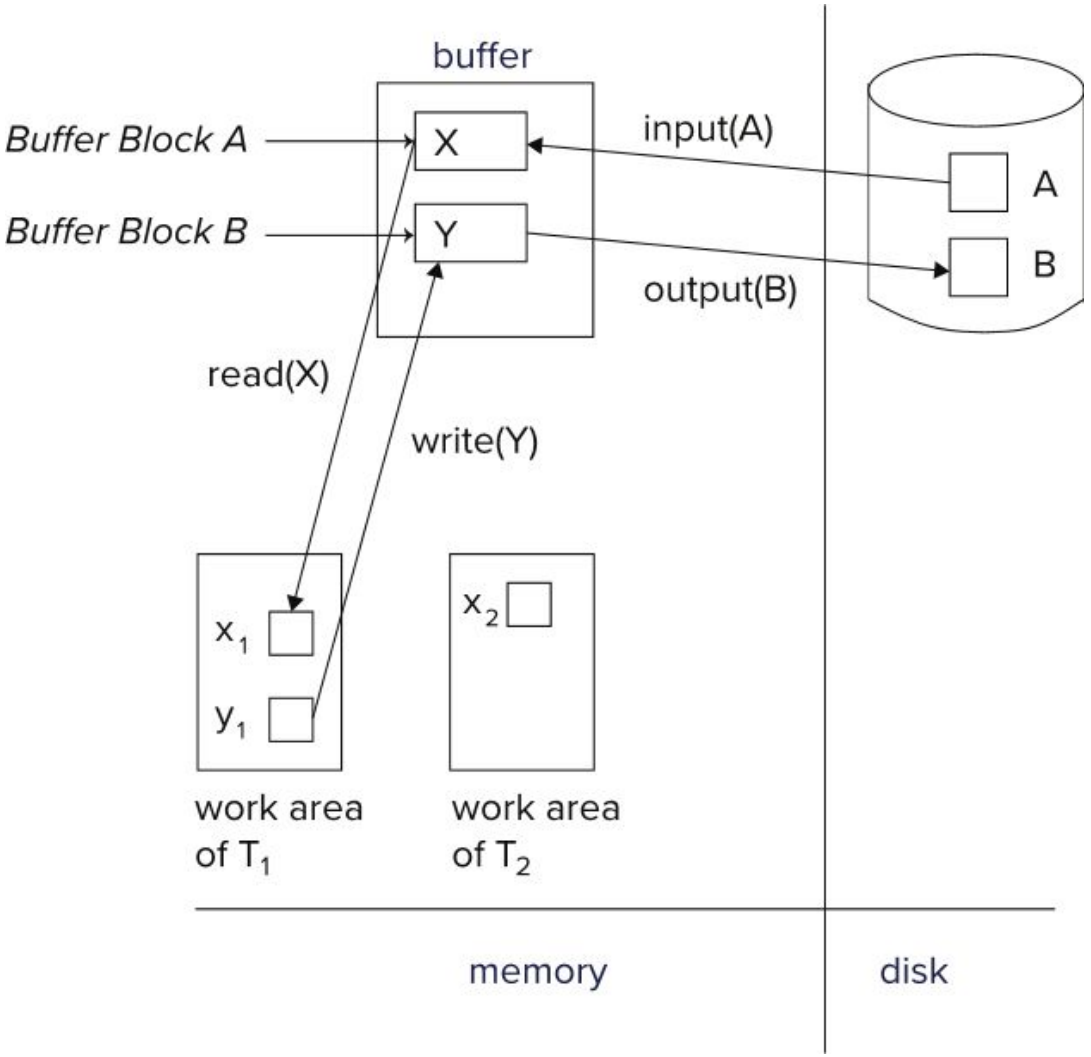
# Recovery Algorithms

- Suppose transaction $T_i$ transfers Rs50 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

# 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, for simplicity, that each data item fits in, and is stored inside, a single block.

# Example of Data Access



# 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

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

# 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 $T_i$
    - No logging is done in this case

# Immediate DB Modification Recovery Example

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

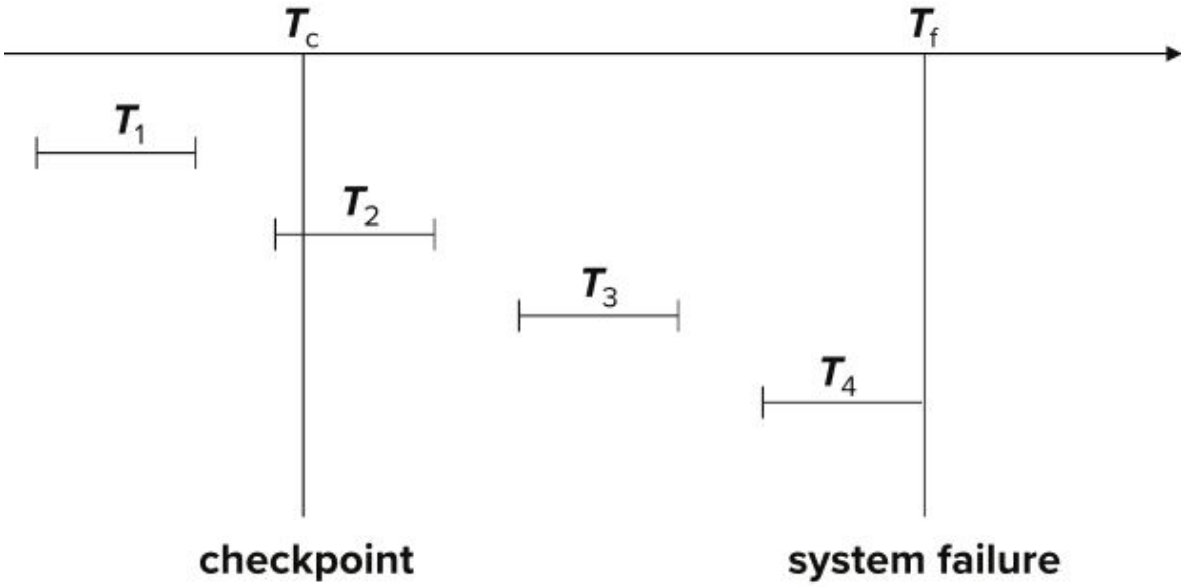
# Checkpoints

- 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**
  1. Output all log records currently residing in main memory onto stable storage.
  2. Output all modified buffer blocks to the disk.
  3. Write a log record < **checkpoint** *L*> onto stable storage where *L* is a list of all transactions active at the time of checkpoint.
  4. All updates are stopped while doing checkpointing

# Checkpoints (Cont.)

- 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.

# 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

# 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**>

# Recovery Algorithm (Cont.)

- **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

# Recovery Algorithm (Cont.)

- **Undo phase:**
  1. 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

# 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.
- Several log records can thus be output using a single output operation, reducing the I/O cost.

# Log Record Buffering (Cont.)

- 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

- 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 (Cont.)

- 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
     - 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 (Cont.)

- 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 (Cont.)

- 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.

# ARIES Recovery Algorithm

# ARIES

- 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
  1. Uses **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
     - More coming up on each of the above …

# ARIES Optimizations

- **Physiological redo**
  - Affected page is physically identified, action within page can be logical
    - Used to reduce logging overheads
      - e.g. when a record is deleted and all other records have to be moved to fill hole
        - Physiological redo can log just the record deletion
        - Physical redo would require logging of old and new values for much of the page
    - Requires page to be output to disk atomically
      - Easy to achieve with hardware RAID, also supported by some disk systems
      - Incomplete page output can be detected by checksum techniques,
        - But extra actions are required for recovery
        - Treated as a media failure

# ARIES Data Structures

- ARIES uses several data structures
  - Log sequence number (LSN) identifies each log record
    - Must be sequentially increasing
    - Typically an offset from beginning of log file to allow fast access
      - Easily extended to handle multiple log files
  - Page LSN
  - Log records of several different types
  - Dirty page table

# ARIES Data Structures: Page LSN

- Each page contains a **PageLSN** which is the LSN of the last log record whose effects are reflected on the page
  - To update a page:
    - X-latch the page, and write the log record
    - Update the page
    - Record the LSN of the log record in PageLSN
    - Unlock page
  - To flush page to disk, must first S-latch page
    - Thus page state on disk is operation consistent
      - Required to support physiological redo
  - PageLSN is used during recovery to prevent repeated redo
    - Thus ensuring idempotence

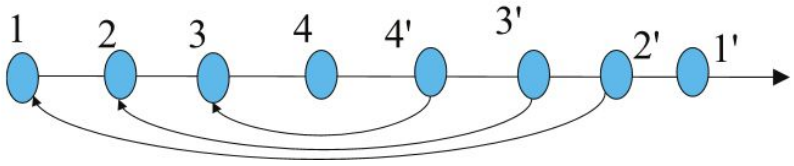
# ARIES Data Structures: Log Record

- Each log record contains LSN of previous log record of the same transaction

| LSN | TransID | PrevLSN | RedoInfo | UndoInfo |
|---|---|---|---|---|

  - LSN in log record may be implicit
- Special redo-only log record called **compensation log record (CLR)** used to log actions taken during recovery that never need to be undone
  - Serves the role of operation-abort log records used in earlier recovery algorithm
  - Has a field UndoNextLSN to note next (earlier) record to be undone
    - Records in between would have already been undone
    - Required to avoid repeated undo of already undone actions

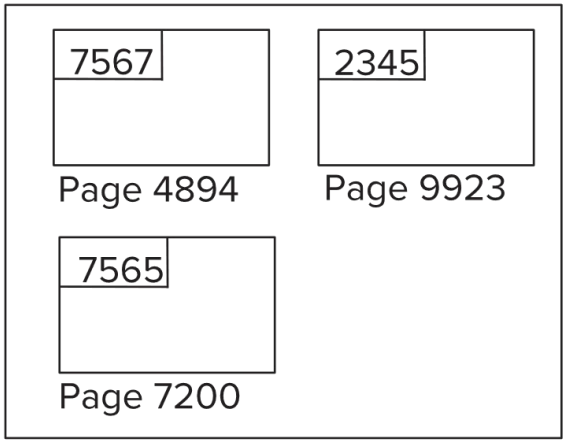
| LSN | TransID | UndoNextLSN | RedoInfo |
|---|---|---|---|



# ARIES Data Structures: DirtyPage Table

- **DirtyPageTable**
  - List of pages in the buffer that have been updated
  - Contains, for each such page
    - **PageLSN** of the page
    - **RecLSN** is an LSN such that log records before this LSN have already been applied to the page version on disk
      - Set to current end of log when a page is inserted into dirty page table (just before being updated)
      - Recorded in checkpoints, helps to minimize redo work

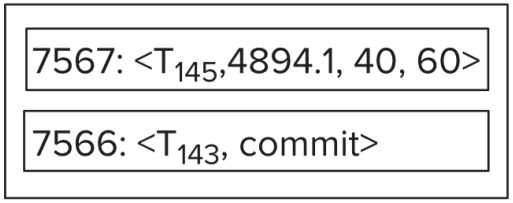
# ARIES Data Structures




**Database Buffer**

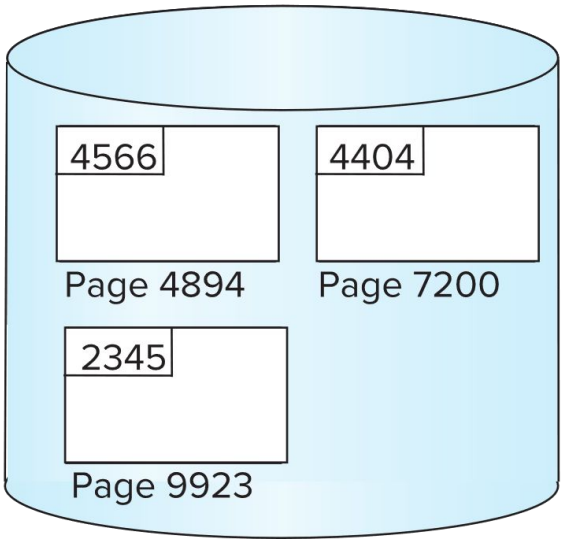
| PageID | PageLSN | RecLSN |
|---|---|---|
| 4894 | 7567 | 7564 |
| 7200 | 7565 | 7565 |

**Dirty Page Table**

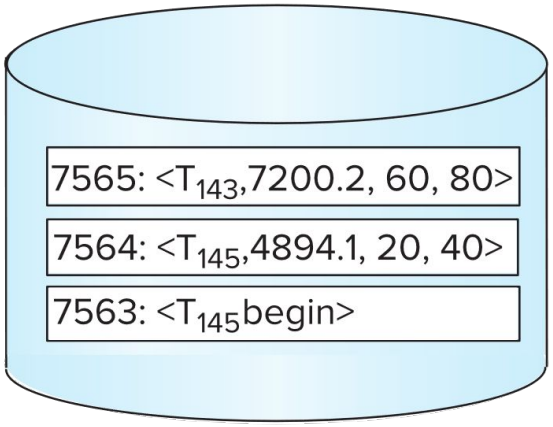



**Log Buffer** (PrevLSN and UndoNextLSN fields not shown)

**Stable data**




**Stable log**



# ARIES Data Structures: Checkpoint Log

- **Checkpoint log record**
  - Contains:
    - DirtyPageTable and list of active transactions
    - For each active transaction, LastLSN, the LSN of the last log record written by the transaction
  - Fixed position on disk notes LSN of last completed checkpoint log record
- Dirty pages are not written out at checkpoint time
    - Instead, they are flushed out continuously, in the background
- Checkpoint is thus very low overhead
  - can be done frequently

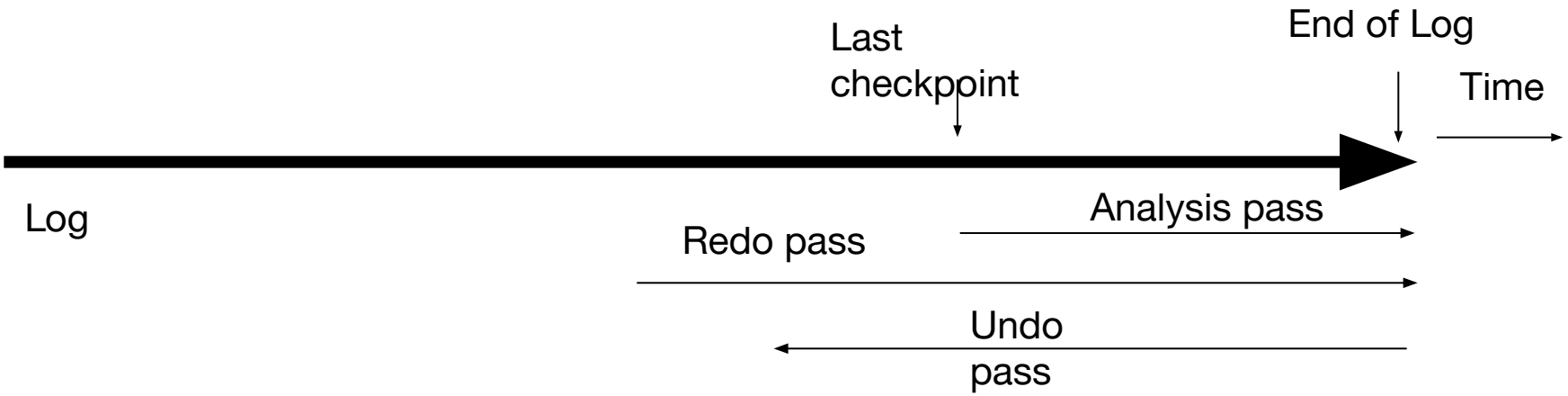
# ARIES Recovery Algorithm

ARIES recovery involves three passes

- Analysis pass: Determines
  - Which transactions to undo
  - Which pages were dirty (disk version not up to date) at time of crash
  - RedoLSN: LSN from which redo should start
- Redo pass:
  - Repeats history, redoing all actions from RedoLSN
    - RecLSN and PageLSNs are used to avoid redoing actions already reflected on page
- Undo pass:
  - Rolls back all incomplete transactions
    - Transactions whose abort was complete earlier are not undone
      - Key idea: no need to undo these transactions: earlier undo actions were logged, and are redone as required

# Aries Recovery: 3 Passes

- Analysis, redo and undo passes
- Analysis determines where redo should start
- Undo has to go back till start of earliest incomplete transaction



# ARIES Recovery: Analysis

**Analysis pass**

- Starts from last complete checkpoint log record
  - Reads DirtyPageTable from log record
  - Sets RedoLSN = min of RecLSNs of all pages in DirtyPageTable
    - In case no pages are dirty, RedoLSN = checkpoint record's LSN
  - Sets undo-list = list of transactions in checkpoint log record
  - Reads LSN of last log record for each transaction in undo-list from checkpoint log record
- Scans forward from checkpoint
- .. Cont. on next page …

# ARIES Recovery: Analysis (Cont.)

**Analysis pass (cont.)**

- Scans forward from checkpoint
  - If any log record found for transaction not in undo-list, adds transaction to undo-list
  - Whenever an update log record is found
    - If page is not in DirtyPageTable, it is added with RecLSN set to LSN of the update log record
  - If transaction end log record found, delete transaction from undo-list
  - Keeps track of last log record for each transaction in undo-list
    - May be needed for later undo
- At end of analysis pass:
  - RedoLSN determines where to start redo pass
  - RecLSN for each page in DirtyPageTable used to minimize redo work
  - All transactions in undo-list need to be rolled back

# ARIES Redo Pass

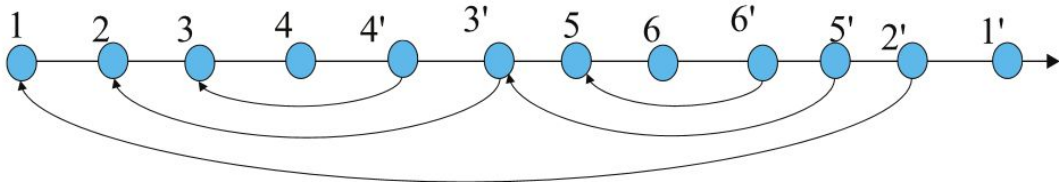
**Redo Pass**: Repeats history by replaying every action not already reflected in the page on disk, as follows:

- Scans forward from RedoLSN. Whenever an update log record is found:
  1. If the page is not in DirtyPageTable or the LSN of the log record is less than the RecLSN of the page in DirtyPageTable, then skip the log record
  2. Otherwise fetch the page from disk. If the PageLSN of the page fetched from disk is less than the LSN of the log record, redo the log record

NOTE: if either test is negative the effects of the log record have already appeared on the page. First test avoids even fetching the page from disk!

# ARIES Undo Actions

- When an undo is performed for an update log record
  - Generate a CLR containing the undo action performed (actions performed during undo are logged physicaly or physiologically).
    - CLR for record *n* noted as *n*' in figure below
  - Set UndoNextLSN of the CLR to the PrevLSN value of the update log record
    - Arrows indicate UndoNextLSN value
- ARIES supports partial rollback
  - Used e.g. to handle deadlocks by rolling back just enough to release reqd. locks
  - Figure indicates forward actions after partial rollbacks
    - records 3 and 4 initially, later 5 and 6, then full rollback

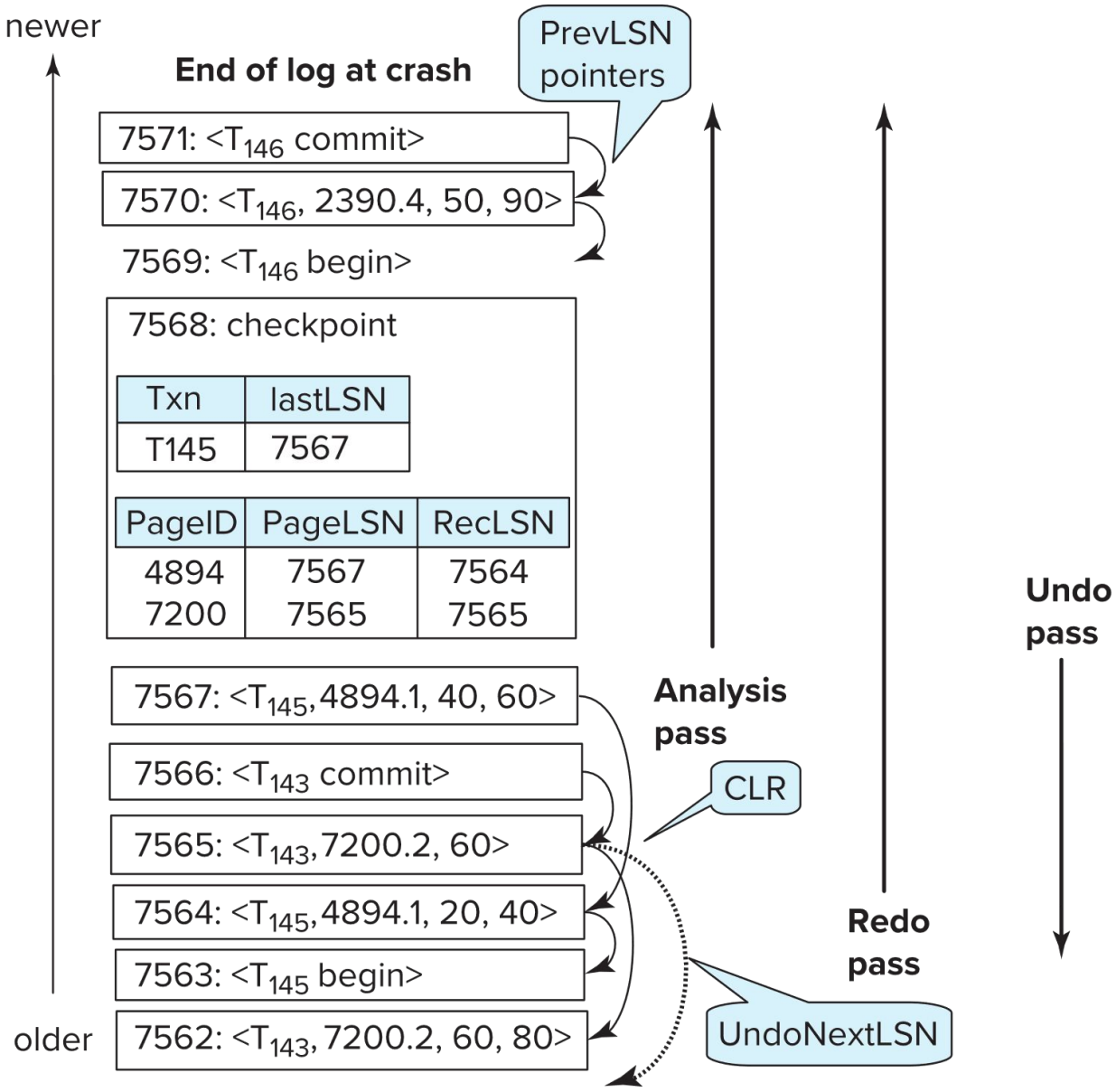


# ARIES: Undo Pass

**Undo pass**:

- Performs backward scan on log undoing all transaction in undo-list
  - Backward scan optimized by skipping unneeded log records as follows:
    - Next LSN to be undone for each transaction set to LSN of last log record for transaction found by analysis pass.
    - At each step pick largest of these LSNs to undo, skip back to it and undo it
    - After undoing a log record
      - For ordinary log records, set next LSN to be undone for transaction to PrevLSN noted in the log record
      - For compensation log records (CLRs) set next LSN to be undo to UndoNextLSN noted in the log record
        - All intervening records are skipped since they would have been undone already
- Undos performed as described earlier

# Recovery Actions in ARIES



# Other ARIES Features

- Recovery Independence
  - Pages can be recovered independently of others
    - E.g. if some disk pages fail they can be recovered from a backup while other pages are being used
- Savepoints:
  - Transactions can record savepoints and roll back to a savepoint
    - Useful for complex transactions
    - Also used to rollback just enough to release locks on deadlock

# Other ARIES Features (Cont.)

- Fine-grained locking:
  - Index concurrency algorithms that permit tuple level locking on indices can be used
    - These require logical undo, rather than physical undo, as in earlier recovery algorithm
- Recovery optimizations: For example:
  - Dirty page table can be used to prefetch pages during redo
  - Out of order redo is possible:
    - redo can be postponed on a page being fetched from disk, and performed when page is fetched.
    - Meanwhile other log records can continue to be processed

# Recovery in Main Memory Databases

- Normal recovery algorithms can be used with main-memory databases
- But optimizations are possible
  - No redo-logging for indices: indices can be rebuilt quickly in-memory on recovery
  - No undo logging if only committed data is written to disk
  - Parallel recovery is important to load large amounts of data in-memory and perform recover with minimum delay

# End of Chapter 19