Transaction Management Part II: Recovery

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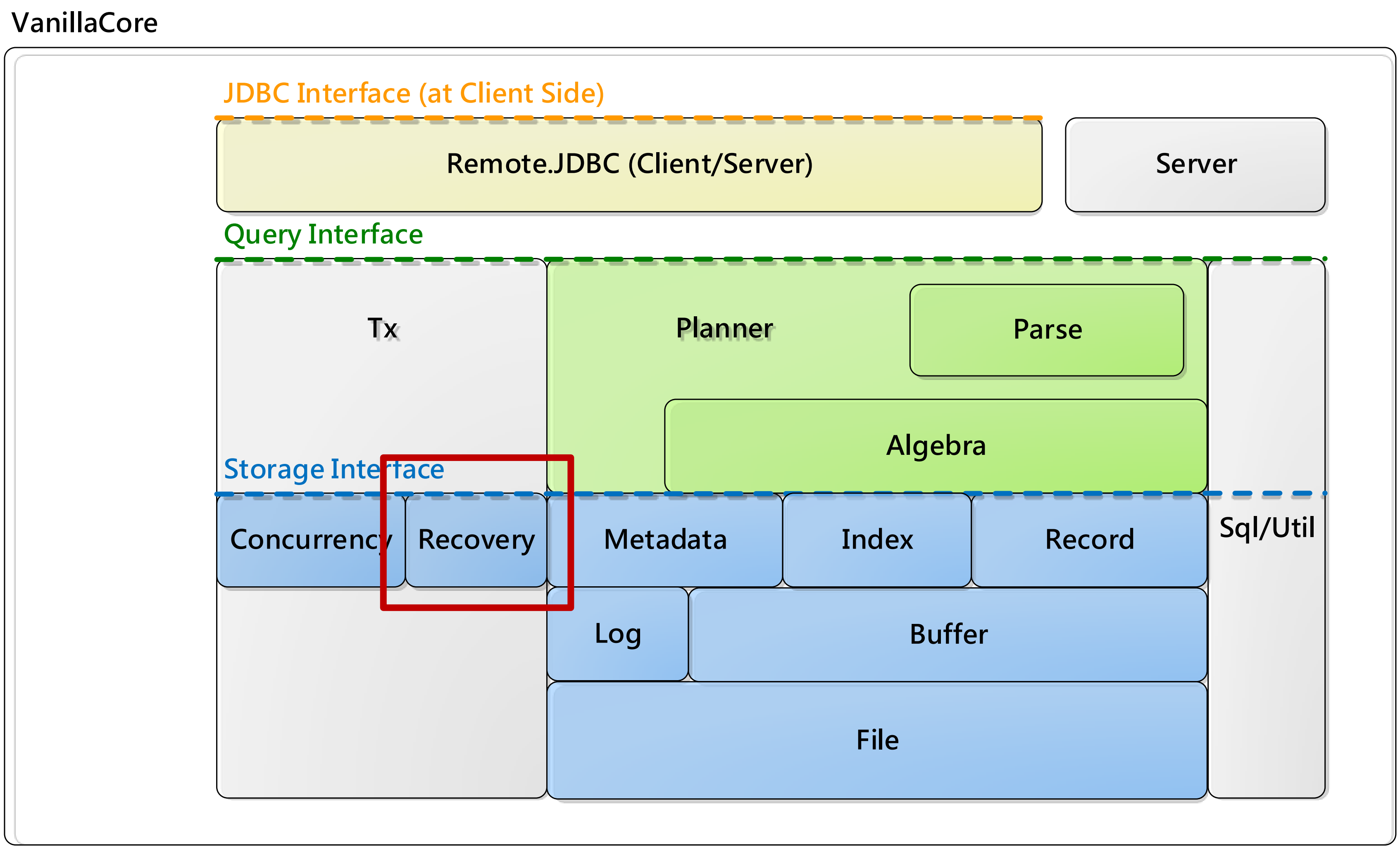
Today's Topic: Recovery Mgr



Failure in a DBMS

- Types:
  - Disk crash, power outage, software error, disaster (e.g., a fire), etc.
- In this lecture, we consider only:
  - ***Transaction hangs***
    - Logical hangs: e.g., data not found, overflow, bad input
    - System hangs: e.g., deadlock
  - ***System hangs/crashes***
    - Hardware error, or a bug in software that hangs the DBMS

Assumptions about Failure

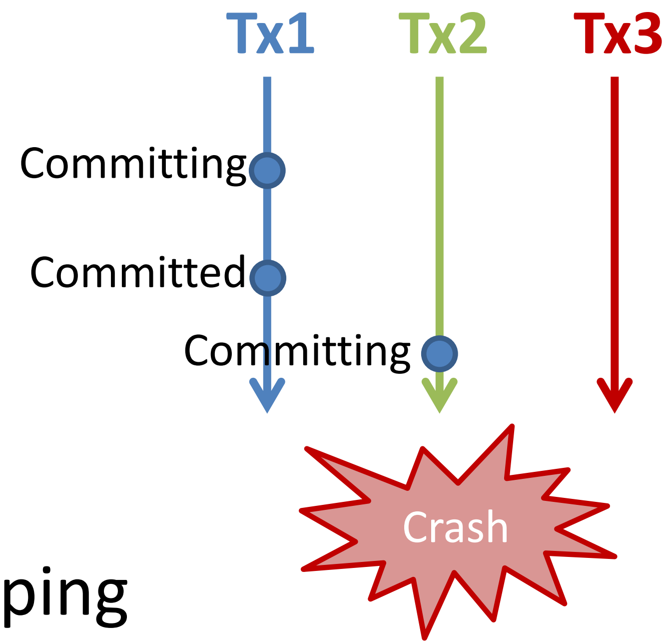
- Contents in nonvolatile storage are ***not corrupted***
  – E.g., via file-system journaling
- No Byzantine failure (zombies)
- Other types of failure will be dealt with in other ways
  – E.g., via replication, quorums, etc.

Review: Naïve A and D

- D given buffers?
- Flush all dirty buffers of a tx ***before*** committing the tx and returning to the DBMS client

Review: Naïve A and D

- What if system crashes and then restarts?
- To ensure A, DBMS needs to rollback uncommitted txs (2 and 3) at sart-up
  – Why 3? flushes due to swapping
- Problems:
  – How to determine which txs to rollback?
  – How to rollback all actions made by a tx?



Review: Naïve A and D

- Idea: ***Write-Ahead-Logging*** (***WAL***)
  - Record a ***log*** of each modification made by a tx
    - E.g., <SETVAL, <TX>, <BLK>, <OFFSET>, <VAL_TYPE>, <OLD_VAL> >
    - ***In memory*** to save I/Os
  - To commit a tx,
    1. Write all associated logs to a log file ***before*** flushing a buffer
    2. After flushing, write a <COMMIT, <TX>> log to the log file
  - To swap a dirty buffer (in BufferMgr)
    - All logs must be flushed ***before*** flushing a buffer

Review: Naïve A and D

- Which txs to rollback?
  - Observation: txs with COMMIT logs must have flushed all their dirty blocks
  - Ans: those without COMMIT logs in the log file
- How to rollback a tx?
  - Observation: each action on the disk:
  1. With log and block
  2. With log, but without block
  3. Without log and block
  - Ans: simply ***undo*** actions that are logged to disk, flush all affected blocks, and then writes a <ROLLBACK, <TX>> log

Review: Naïve A and D

- Assumption of WAL: each block-write either succeeds or fails entirely on a disk, despite power failure
  - I.e., no corrupted log block after crash
  - Modern disks usually store enough power to finish the ongoing sector-write upon power-off
  - Valid if block size == sector size or a journaling file system (e.g., EXT3/4, NTFS) is used
    - Block/physical vs. metadata/logical journals

Review: Caching Logs

- Like user blocks, the blocks of the log file are cached
  - Each tx operation is logged ***into memory***
  - To avoid excessive I/Os
- Log blocks are flushed only on either
  - Tx commit, or
  - Flushing of data buffer

System Components related to Recovery

- The ***log manager*** manages the caching for logs
  - Does not understand the semantic of logs
- The ***buffer manager*** ensures WAL for each flushed data buffer
- The ***recovery manager*** ensures A and D by deciding:
  - What to log (semantically)
  - When to flush buffers (and log tails)
  - How to rollback a tx
  - How to recover a DB from crash

Actions of Recovery Manager

- Actions during normal tx processing:
  - Adds log records to cache
  - Flushes log tail and buffers at COMMIT
  - Or, rolls back txs
    - By undoing changes made by each tx
  - On behalf of ***normal txs***
- Actions after system re-start (from a failure):
  - Recovers the database to a consistent state
  - By undoing changes made by all incomplete tx
  - In a ***dedicated recovery tx*** (before all normal txs start)

Txn B:

```
Write y = 10;
Read x;
If (x>=4)
    Write x=x+1;
else
    Rollback;
Commit;
```

Outline

- Physical logging:
  - Logs and rollback
  - UNDO-only recovery
  - UNDO-REDO recovery
  - Failures during recovery
  - Checkpointing
- Logical logging:
  - Early lock release and logical UNDOs
  - Repeating history
- Physiological logging
- RecoveryMgr in VanillaCore

Outline

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Log Records

- In order to be able to roll back a transaction, the recovery manager saves information in the log
- Recovery manager add a ***log record*** to the log cache each time a loggable activity occurs
  - Start
  - Commit
  - Rollback
  - Update record
  - Checkpoint

Log Records

Txn 27:

```
start;
getVal(blk0, 46);
setVal(blk1, 58, “abc”);
commit;
```

- The log records of txn 27:

```
<START, 27>
<SETVAL, 27, student.tbl, 1, 58, ‘kay’, ‘abc’>
<COMMIT, 27>
```

block Id — old value — offset

- In general, multiple txns will be writing to the log concurrently, and so the log records for a given txn will be dispersed throughout the log

```
<START, 27>
<ROLLBACK, 23>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, ‘kay’, ‘abc’>
<COMMIT, 27>
...
```

Why COMMIT/ROLLBACK Logs?

- Used to identify incomplete txs during recovery
- Incomplete txs?
  - E.g., those without COMMIT/ROLLBACK logs on disk
  - To be discussed later

Flushing COMMIT

- When committing a tx, the COMMIT log must be flushed ***before*** returning to the user
  - Why?

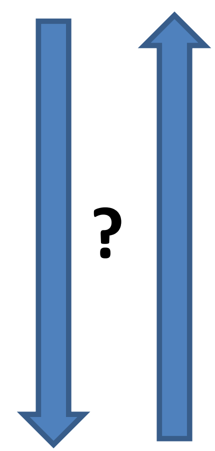
```
public void onTxCommit(Transaction tx) {
     VanillaDb.bufferMgr().flushAll(txNum);
     long lsn = new CommitRecord(txNum).writeToLog();
     VanillaDb.logMgr().flush(lsn);
}
```

- What if the system returns to the client but crashes before writing a commit log?
  - The recovery manager will treat it as an incomplete tx and undo all its changes
  - Dangers durability

Rollback

- The recovery manger can use the log to roll back a tx by ***undoing*** all tx’s modifications
- How to undo txn 27?

```
...
<START, 27>
<ROLLBACK, 23>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, ‘kay’, ‘abc’>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
...
```



Rollback

- Undo txn 27

```
...
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<ROLLBACK, 23>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 'kay', 'abc'>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<ROLLBACK, 27>
```

ensures the correctness of multiple modifications

restores old values

undo starts from log tail

The log records of *T* are more likely to be at the end of log file

Rollback

- The algorithm for rolling back txn *T*
  1. Set the current record to be the most recent log record
  2. Do until the current record is the start record for *T*:
     a) If the current record is an update record for *T*, then write back the old value
     b) Move to the previous record in the log
  3. Flush all dirty buffers made by *T*
  4. Append a rollback record to the log file
  5. Return

Codes for Rollback

```
public void onTxRollback(Transaction tx) {
     doRollback();
     VanillaDb.bufferMgr().flushAll(txNum);
     long lsn = new RollbackRecord(txNum).writeToLog();
     VanillaDb.logMgr().flush(lsn);
}

private void doRollback() {
     Iterator<LogRecord> iter = new LogRecordIterator();
     while (iter.hasNext()) {
          LogRecord rec = iter.next();
          if (rec.txNumber() == txNum) {
               if (rec.op() == OP_START)
                    return;
               rec.undo(txNum);
          }
     }
}
```

Working with Locks

- When a tx *T* that is rolling back, recovery manager requires the DBMS to prevent any access (by other txs) to the data modified by *T*
  - Otherwise, undoing an operation of *T* may override later modifications
- Can easily be enforced by, for example, S2PL

Working with Memory Managers

- ***No*** tx should be able to modify the buffer when that buffer, and its logs, are being flushed; ***and vise versa***
- How?
- For each block, pinning and flushing contend for a short-term X lock, called ***latch***

Latching on Blocks

- To modify a block:
  1. Acquire the latch of that block
  2. Log the update (in memory, done by LogMgr)
  3. Perform the change
  4. Release the latch
- To flush a buffer containing a block:
  1. Acquire the latch of that block (after pin())
  2. Flush corresponding log records
  3. Flush buffer
  4. Release the latch
- Latches have ***nothing*** to do with
  - Locks in S2PL
  - Pinning/unpinning in BufferMgr

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Recovery

- When the DMBS restart (from crash), the recovery manager is responsible to restore the database
  - All incomplete txs should be ***rolled back***
- How to identify incomplete txs?

Incomplete Txs (1)

- Recall that when committing/rolling back a tx, the CIMMIT/ROLLBACK log must be flushed before returning to the user

```
public void onTxCommit(Transaction tx) {
     VanillaDb.bufferMgr().flushAll(txNum);
     long lsn = new CommitRecord(txNum).writeToLog();
     VanillaDb.logMgr().flush(lsn);
}


public void onTxRollback(Transaction tx) {
     doRollback();
     VanillaDb.bufferMgr().flushAll(txNum);
     long lsn = new RollbackRecord(txNum).writeToLog();
     VanillaDb.logMgr().flush(lsn);
}
```

Incomplete Txs (2)

- Definition: txs without COMMIT or ROLLBACK records in the log file on disk
- Could be in any of following states when crash happens:
  1. Active
  2. Committing (but not completed yet)
  3. Rolling back

Undo-only Recovery Algorithm

1. For each log record (reading backwards from the end):
   a) If the current record is a commit record then:
      Add that transaction to the list of committed transactions.
   b) If the current record is a rollback record then:
      Add that transaction to the list of rolled-back transactions.
   c) If the current record is an update record and that transaction is not on the committed or rollback list, then:
      Restore the old value at the specified location.

Undo-Redo Recovery

- Undo and redo

Completed Txn:
27

older

Beginning of log

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

newer

undo

Undo-Redo Recovery

- Undo and redo

Completed Txn:
27

older

Beginning of log

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

undo

newer

Undo-only Recovery Algorithm

```
public void recover() { // called on start-up
    doRecover();
    VanillaDb.bufferMgr().flushAll(txNum);
    long lsn = new CheckpointRecord().writeToLog();
    VanillaDb.logMgr().flush(lsn);
}

private void doRecover() {
    Collection<Long> finishedTxs = new ArrayList<Long>();
    Iterator<LogRecord> iter = new LogRecordIterator();
    while (iter.hasNext()) {
        LogRecord rec = iter.next();
        if (rec.op() == OP_CHECKPOINT)
            return;
        if (rec.op() == OP_COMMIT || rec.op() == OP_ROLLBACK)
            finishedTxs.add(rec.txNumber());
        else if (!finishedTxs.contains(rec.txNumber()))
            rec.undo(txNum);
    }
}
```

- Flushing and checkpointing will be explained later

Working with Other System Components

- No special requirement since the recovery tx is the ***only*** tx in system at startup
  - Normal txs start only ***after*** the recovery tx finishes

The above RecoveryMgr will make system unacceptably slow!

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Why Slow?

- Slow commit
  - Flushes: undo logs, dirty blocks, and then COMMIT log
- Slow rollback
  - Flushes: dirty blocks and ROLLBACK log
- Slow recovery
  - Recovery manager need to scan the entire log file (backward from tail) every time

Force vs. No-Force

- Force approach
  - When committing tx, all modifications need to be written to disk ***before*** returning to user
- When client committing a txn
  1. Flush the logs till the LSN of the last modification
  2. Flush dirty pages
  3. Write a COMMIT record to log file on disk
  4. Return

Force vs. No-Force

- Do we really need to flush all dirty blocks when committing a tx?
- Why not just write logs?
  - No flushing data blocks ➔ faster commit
- Problem: committed txs may not be reflected to disk
  - Lost once system crashes
- Solution: a new ***redo*** phase in recovery?
  - To reconstruct buffer state in memory

Undo-Redo Recovery

- Undo and redo

older

Beginning of log

new value

<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, ***35***>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>

newer

Undo-Redo Recovery

- Undo and redo

Completed Txn:
27

older

Beginning of log

Undo

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

undo txn 29

newer

Undo-Redo Recovery

- Undo and redo

Completed Txn:
27

older

Beginning of log

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

newer

Undo

undo txn 28

Undo-Redo Recovery

- Undo and redo

Completed Txn: 27, 23

older

Beginning of log

Undo

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
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<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

newer

Undo-Redo Recovery

- Undo and redo

Completed Txn: 27, 23

older

Beginning of log

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

newer

Undo

Redo

Undo-Redo Recovery

- Undo and redo

Completed Txn:
27, 23

older

Beginning of log

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

redo

Undo

Redo

newer

Undo-Redo Recovery

- Undo and redo

Completed Txn:
27, 23

older

Beginning of log

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
<SETVAL, 27, dept.tbl, 2, 40, 15, 9>
<START, 28>
<SETVAL, 28, dept.tbl, 23, 0, 1, 5>
<SETVAL, 27, student.tbl, 1, 58, 4, 5>
<SETVAL, 27, dept.tbl, 2, 40, 9, 25>
<START, 29>
<SETVAL, 29, emp.tbl, 1, 0, 1, 9>
<ROLLBACK, 27>
```

newer

redo

Undo

Redo

The Undo-Redo Recovery Algorithm V1

// The undo stage

1. For each log record (reading backwards from the end):
   a) If the current record is a commit record then:
      Add that transaction to the list of committed transactions.
   b) If the current record is a rollback record then:
      Add that transaction to the list of rolled-back transactions.
   c) If the current record is an update record and that transaction is not on the committed or rollback list, then:
      Restore the old value at the specified location.

// The redo stage

2. For each log record (reading forwards from the beginning):
   If the current record is an update record and that transaction is on the committed list, then:
      Restore the new value at the specified location.

Figure 14-6
The undo-redo algorithm for recovering a database

From Database Design and Implementation by Edward Sciore, chapter 14.

Physical Logging

- Undo/redo operations are ***idempotent***
  - Executing same undo op multiple times = one time execution
- Some actions may be unnecessary or redundant
  - Depending on swapping state in buffer manager
  - ***No harm to C***

Can We Make Rollback Faster Too?

- Recall that when rolling back a tx, we flush dirty pages and write a rollback log

```
public void onTxRollback(Transaction tx) {
     doRollback();
     VanillaDb.bufferMgr().flushAll(txNum);
     long lsn = new RollbackRecord(txNum).writeToLog();
     VanillaDb.logMgr().flush(lsn);
}

private void doRollback() {
     Iterator<LogRecord> iter = new LogRecordIterator();
     while (iter.hasNext()) {
          LogRecord rec = iter.next();
          if (rec.txNumber() == txNum) {
               if (rec.op() == OP_START)
                    return;
               rec.undo(txNum);
          }
     }
}
```

Slow Rollback

```
public void onTxRollback(Transaction tx) {
    doRollback();
    VanillaDb.bufferMgr().flushAll(txNum);
    long lsn = new RollbackRecord(txNum).writeToLog();
    VanillaDb.logMgr().flush(lsn);
}

private void doRollback() {
    Iterator<LogRecord> iter = new LogRecordIterator();
    while (iter.hasNext()) {
        LogRecord rec = iter.next();
        if (rec.txNumber() == txNum) {
            if (rec.op() == OP_START)
                return;
            rec.undo(txNum);
        }
    }
}
```

- Why flushing dirty buffers?
  - So the recovery tx can skip txs that have been rolled back
- Can we skip it?

Fast Rollback

- No-force:
  - Do ***not*** flush dirty pages during rollback
  - In addition, there's ***no*** need to keep the ROLLBACK record in cache at all!
- Aborted txs will be rolled back again during startup recovery
  - No harm to C since undo operations are ***idempotent***

The Undo-Redo Recovery Algorithm V2

// The undo stage

1. For each log record (reading backwards from the end):

   a) If the current record is a commit record then:

   No (b). All txs not in the committed list are un-done (maybe again)

   Add that transaction to the list of committed transactions.

   b) If the current record is a rollback record then:

   Add that transaction to the list of rolled-back transactions.

   c) If the current record is an update record and that transaction is not on the committed or rollback list, then:

   Restore the old value at the specified location.

// The redo stage

2. For each log record (reading forwards from the beginning):

   If the current record is an update record and that transaction is on the committed list, then:

   Restore the new value at the specified location.

Figure 14-6
The undo-redo algorithm for recovering a database

From Database Design and Implementation by Edward Sciore, chapter 14.

Undo or Redo Phase First?

- Does not matter for the recovery algorithm V1
- But matters for V2!
  - Undo phase ***must precede*** the redo phase
  - Otherwise, C may be damaged due to aborted txs
  - E. g.,

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
// T23 rolls back (not logged) and release locks
<START, 27>
<SETVAL, 27, dept.tbl, 10, 0, 15, 40>
<COMMIT, 27>
```

  - Rolling back T23 erases the modification made by T27

Undo-Only vs. Undo-Redo Recovery

- Pros of undo-only:
  - Faster recovery
  - No redo logs
- Cons of undo-only:
  - Slower commit/rollback
- Which one?
  - Commercial DBMSs usually choose no-force approach + undo-redo recovery

Steal vs. No Steal

- Currently, dirty buffers can be flushed to disk before tx commit
  - Due to swapping
  - ***Steal*** approach
- If no steal, then we don't need undo phase!
  - Redo-only recovery
- How?
  - Pin all the modified buffers until tx ends?

No redo, no undo with force + no steal?

Redo-Only Recovery and Beyond

- No-steal is not practical
- Dirty pages still need to be flushed before commits
  - To ensure durability
- How about crash during flushing?

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  - Failures during recovery
  - Checkpointing
- Logical logging:
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- Physiological logging
- RecoveryMgr in VanillaCore

What if system crashes again during recovery?

Can we simply re-run recovery (from scratch) after restart?

Idempotent Recovery

- Yes! Since each undo/redo is idempotent
- No need to log undos/redos
  - For each data modification due to undo/redo, recovery manager passes -1 as the LSN number to the buffer manager
  - See `SetValueRecord.undo()`

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Checkpointing

- As the system keeps processing requests, the log file may become very large
  - Running recovery process is time consuming
  - Can we just read a portion of the log?

- A ***checkpoint*** is like a consistent snapshot of the DBMS state
  - All earlier log records were written by "completed" txns
  - Those txns' modifications have been flushed to disk
- During recovery, the recovery manager can ignore all the log records before a checkpoint

Quiescent Checkpointing

1. Stop accepting new transactions
2. Wait for existing transactions to finish
3. Flush all modified buffers
4. Append a quiescent checkpoint record to the log and flush it to disk
5. Start accepting new transactions

Quiescent Checkpointing

```
<START, 0>
<SETINT, 0, student.tbl, 0, 38, 2004, 2005>
<START, 1>
<START, 2>
<COMMIT, 1>
<SETSTRING, 2, junk, 44, 20, hello, ciao>
      //The quiescent checkpoint procedure starts here
<SETSTRING, 0, student.tbl, 0, 46, amy, aimee>
<COMMIT, 0>
      //tx 3 wants to start here, but must wait
<SETINT, 2, junk, 66, 8, 0, 116>
<COMMIT, 2>
<CHECKPOINT>
<START, 3>
<SETINT, 3, junk, 33, 8, 543, 120>
```

Undo ↑ Redo ↓

Figure 14-10
A log using quiescent checkpointing

Quiescent Checkpointing is Slow

- Quiescent checkpointing is simple but may make the system unavailable ***for too long*** during checkpointing process

Root Cause of Unavailability

1. Stop accepting new transactions
2. Wait for existing transactions to finish
3. Flush all modified buffers ***May be very long!***
4. Append a quiescent checkpoint record to the log and flush it to disk
5. Start accepting new transactions

Can we shorten the quiescent period?

Nonquiescent Checkpointing

1. Stop accepting new transactions
2. Let $T_1, \ldots, T_k$ be the currently running transactions
3. Flush all modified buffers
4. Write the record $<\texttt{NQCKPT}, T_1, \ldots, T_k>$ and flush it to disk
5. Start accepting new transactions

Recovery with Nonquiescent Checkpointing

- Txs not in checkpoint log are flushed thus can be neglected

```
<START, 0>
<SETINT, 0, student.tbl, 0, 38, 2004, 2005>
<START, 1>
<START, 2>
<COMMIT, 1>
<SETSTRING, 2, junk, 44, 20, hello, ciao>
<NOCKPT, 0, 2> Only tx2 needs to be undone
<SETSTRING, 0, student.tbl, 0, 46, amy, aimee>
<COMMIT, 0> Tx0 has been committed
<START, 3>
<SETINT, 2, junk, 66, 8, 0, 116>
<SETINT, 3, junk, 33, 8, 543, 120>
```

Redo

Undo

Figure 14-12
A log using nonquiescent checkpointing

Working with Memory Managers

- ***No*** tx should be able to
  1. append the log, and
  2. modify the buffer

  between steps 3 and 4
- How?
- The checkpoint tx obtains
  1. latch of log file, and
  2. latches of all blocks in BufferMgr

  before step 3
- Then release them after step 4

When to Checkpoint?

- By taking checkpoints periodically, the recovery process can become more efficient
- When is a good time to checkpoint?
  – During system startup (after the recovery has completed and before any txn has started)

```
public void recover() { // called on start-up
    doRecover();
    VanillaDb.bufferMgr().flushAll(txNum);
    long lsn = new CheckpointRecord().writeToLog();
    VanillaDb.logMgr().flush(lsn);
}
```

  – Execution time with ***low workload*** (e.g., midnight)

Outline

- Physical logging:
  - Logs and rollback
  - UNDO-only recovery
  - UNDO-REDO recovery
  - Failures during recovery
  - Checkpointing
- Logical logging:
  - Early lock release and logical UNDOs
  - Repeating history
- Physiological logging
- RecoveryMgr in VanillaCore

Early Lock Release

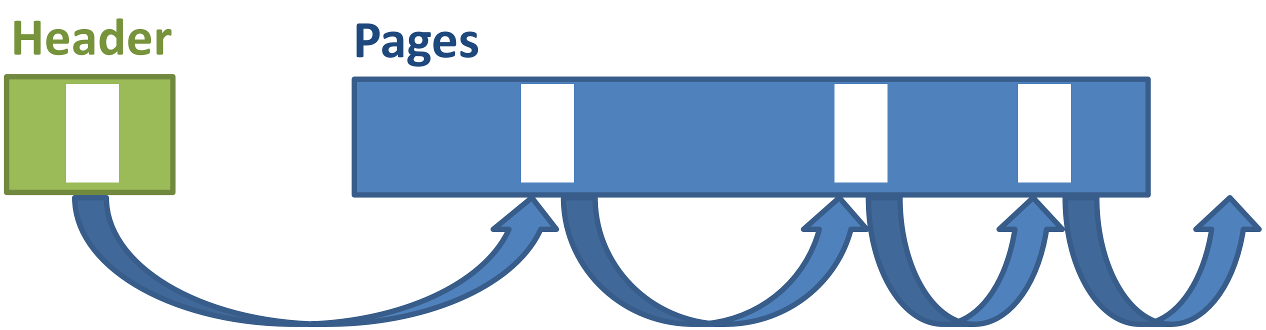
- There are meta-structures in a DBMS
  - E.g., `FileHeaderPage` in a `RecordFile`
  - Indices
- Poor performance if they are locked in strict manner
  - E.g., S2PL on `FileHeaderPage` serializes all insertions and deletions
- Locks on meta-structures are usually ***released early***

Logical Operations

- ***Logical insertions*** to a `RecordFile`:
  - Acquire locks of `FileHeaderPage` and target object (`RecordPage` or a record) in order
  - Perform insertion
  - ***Release*** the lock of `FileHeaderPage` (but not the object)
- Other examples: insertions to an index
  - Following a lock-crabbing protocol
- Better I
- No harm to C
- Needs special care to ensure A and D

Problems of Logical Operations

- Suppose
  1. *T1* inserts a record *A* to a table/file
     - `FileHeaderPage` and a `RecordPage` modified
  2. *T2* inserts another record *B* to the same table
     - Same `FileHeaderPage` and another `RecordPage` modified
  3. *T1* aborts
- If the physical undo record is used to rollback *T1*, *B* will be lost!



Problems of Logical Operations

- Suppose
  1. *T1* inserts a record *A* to a table/file
     - `FileHeaderPage` and a `RecordPage` modified
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     - Same `FileHeaderPage` and another `RecordPage` modified
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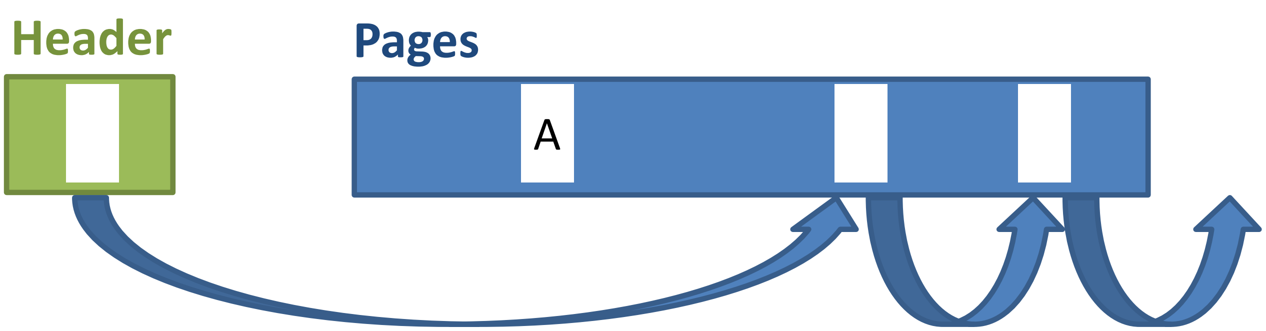
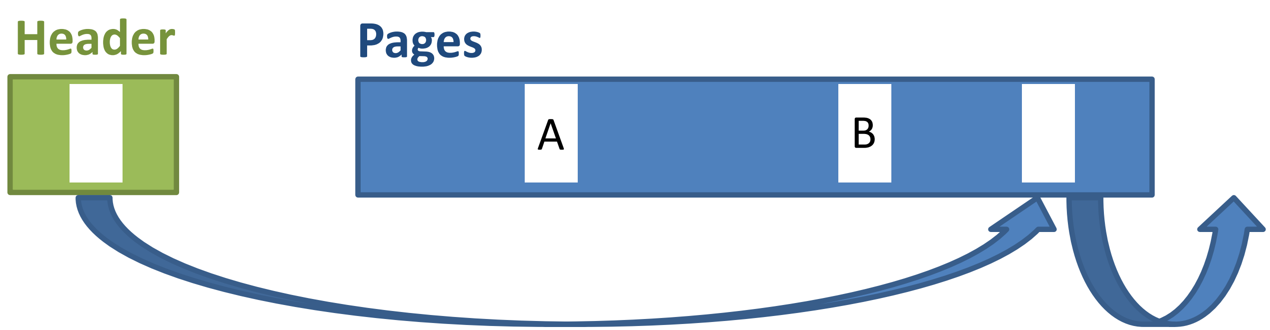
- If the physical undo record is used to rollback *T1*, *B* will be lost!



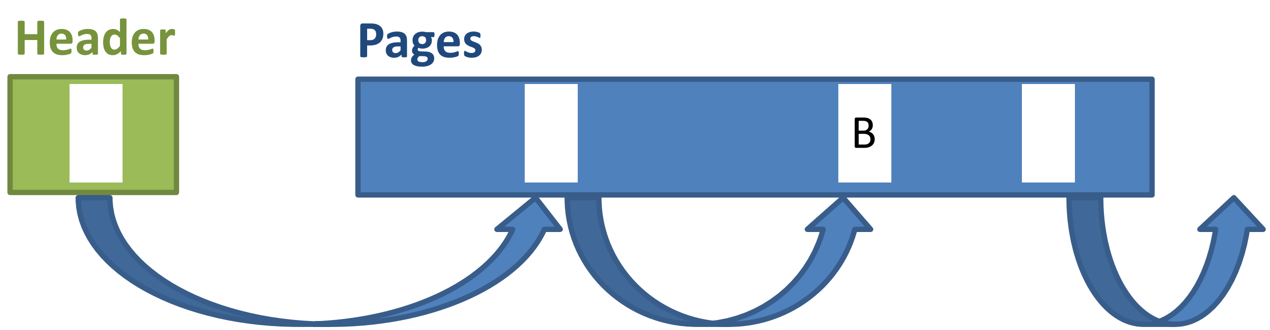
Problems of Logical Operations

- Suppose
  1. *T1* inserts a record *A* to a table/file
     - `FileHeaderPage` and a `RecordPage` modified
  2. *T2* inserts another record *B* to the same table
     - Same `FileHeaderPage` and another `RecordPage` modified
  3. *T1* aborts
- If the physical undo record is used to rollback *T1, B* will be lost!

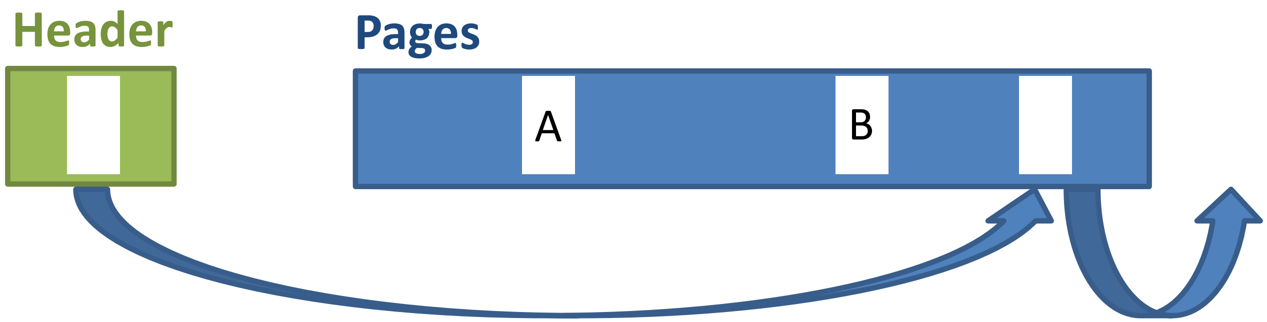


Problems of Logical Operations

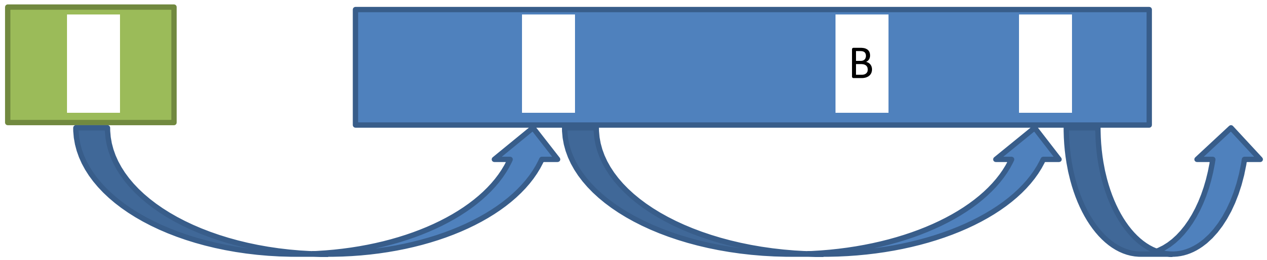
- Suppose
  1. *T1* inserts a record *A* to a table/file
     - `FileHeaderPage` and a `RecordPage` modified
  2. *T2* inserts another record *B* to the same table
     - Same `FileHeaderPage` and another `RecordPage` modified
  3. *T1* aborts
- If the physical undo record is used to rollback *T1*, free-space chain is corrupted!



Undoing Logical Operations



- How to rollback *T1*?
  - By executing a ***logical deletion*** of record *A*



- Logical operations need to be ***undone logically***

Undoing Partial Logical Ops

- What if *T1* aborts in the middle of a logical operation?
- Log each physical operation performed during a logical operation
- So partial logical operation can be undone, by undoing the physical operations

older

Beginning of log

```
<START, T1>
<SETVAL, T1, RC, 15, 35>
<OPBEGIN, T1, OP1> // insert a record
<SETVAL, T1, H, 100, 105>
<SETVAL, T1, RA, 0, 700>
<OPEND, T1, OP1, delete RA>
... // other tx can access H (early lock release)
```

newer

Identifier can be LSN

Rolling Back a Transaction

older

Beginning of log

```
<START, T1>
<SETVAL, T1, RC, 15, 35>
<OPBEGIN, T1, OP1> // insert a record
<SETVAL, T1, H, 100, 105>
<SETVAL, T1, RA, 0, 700>
<OPEND, T1, OP1, delete RA>
... // other tx can access H
```

Logical undo information

T1 aborts

- Undo *OP1* using physical logs if it is not completed yet
  - ***Locks of physical objects are not released*** so nothing can go wrong
- *OP1* must be undone logically once it is complete
  - Some locks may be released early (e.g., lock of *H*)
  - ***Must acquire the locks again during logical undo***

Let's consider crashes now...

- UNDO: to roll back all uncommitted txs (and logical OPs)
- REDO: reconstruct memory state

- Unfortunately, it’s not that simple...

Undo an Undo

- What if system crashes when *T1* is undoing a logical op?
- The "undo" is ***not*** idempotent
  - The undo needs to be undone
- How?
- The undo is itself an logical operation
- Why not log all the physical operations of such an undo?
  - The logical undo can be undone now
  - Then, at recovery time, logically undo the target logical operation again

Undo an Undo

Rollback

UNDO

older

Beginning of log

<START, T1>

<SETVAL, T1, RC, 15, 35>

<OPBEGIN, T1, OP1> // insert a record

<SETVAL, T1, H, 100, 105>

<SETVAL, T1, RA, 0, 700>

<OPEND, T1, OP1, delete RA> Some locks are released

T1 aborts ...

<SETVAL, T1, H, 123, 100> Released locks are acquired again

Crash

<SETVAL, T1, RA, 700, 0>

<OPABORT, T1, OP1>

newer

- Can we apply UNDO/REDO recovery now?

Crashes

- Two goals of restart recovery:
  - Rolling back incomplete txs
  - Reconstruct memory state
- Handled by UNDO and REDO phase respectively
- Undo-redo recovery algorithm does ***not*** work anymore!
- Why?
- Since locks may be released early, physical logs may ***depend*** on each other
- Undoing/redoing physical logs must be carried out in the order they happened to ensure C

Example

Beginning of log

```
<START, T1>
<SETVAL, T1, RC, 15, 35>
<OPBEGIN, T1, OP1> // insert a record
<SETVAL, T1, H, 100, 105>
<SETVAL, T1, RA, 0, 700>
<OPEND, T1, OP1, delete RA>
...
// T2 inserts another record (changing H),
// makes some physical changes, and then commits
...
<SETVAL, T1, H, 123, 100>
<SETVAL, T1, RA, 700, 0>
<OPABORT, T1, OP1>
```

Some locks are released

Released locks are acquired again

Rollback

T1 aborts

Crash

- To carry out the last two physical ops (i.e., "undo of undo")
  - *T2* needs to be redone physically ***first***
- Redoing *T2* requires *T1* to be redone ***partially***, even if *T1* will be rolled back eventually

Outline

- Physical logging:
  - Logs and rollback
  - UNDO-only recovery
  - UNDO-REDO recovery
  - Failures during recovery
  - Checkpointing
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  - Early lock release and logical UNDOs
  - Repeating history
- Physiological logging
- RecoveryMgr in VanillaCore

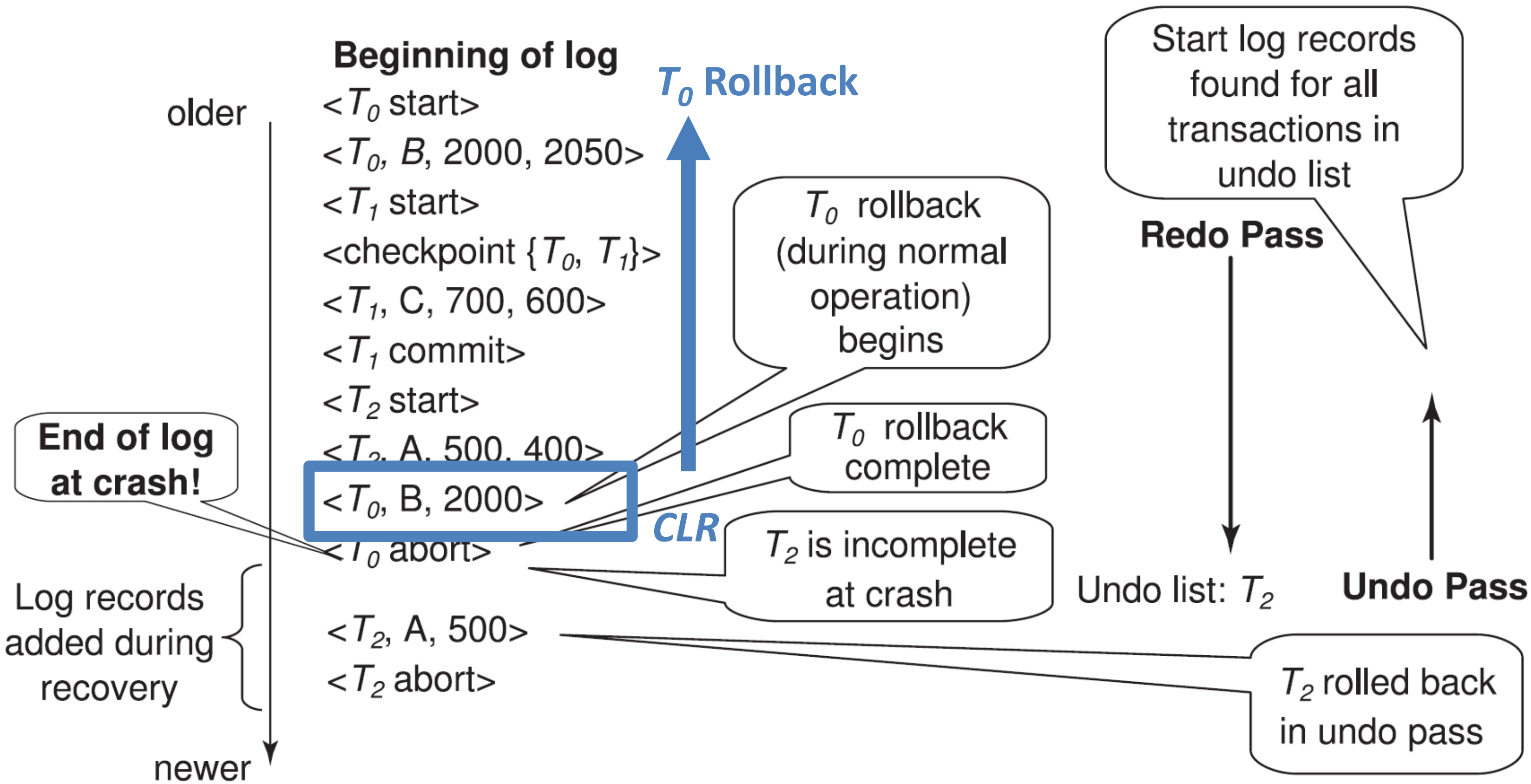
Recovery by Repeating History

- Idea:
  1. Repeat history: replay all dependent physical operations (from the last checkpoint) ***following the exact order they happened***
     - Including ongoing rollbacks/undos
     - So the memory state can be reconstructed correctly
  2. ***Resume*** rolling back all incomplete txs
     - Logically for each completed logical operation
- This leads to the state-of-the-art recovery algorithm, ***ARIES***
- Steps 1/2 are called REDO/UNDO phase in ARIES
  – Very different from REDO/UNDO phase in previous sections

Compensation Logs

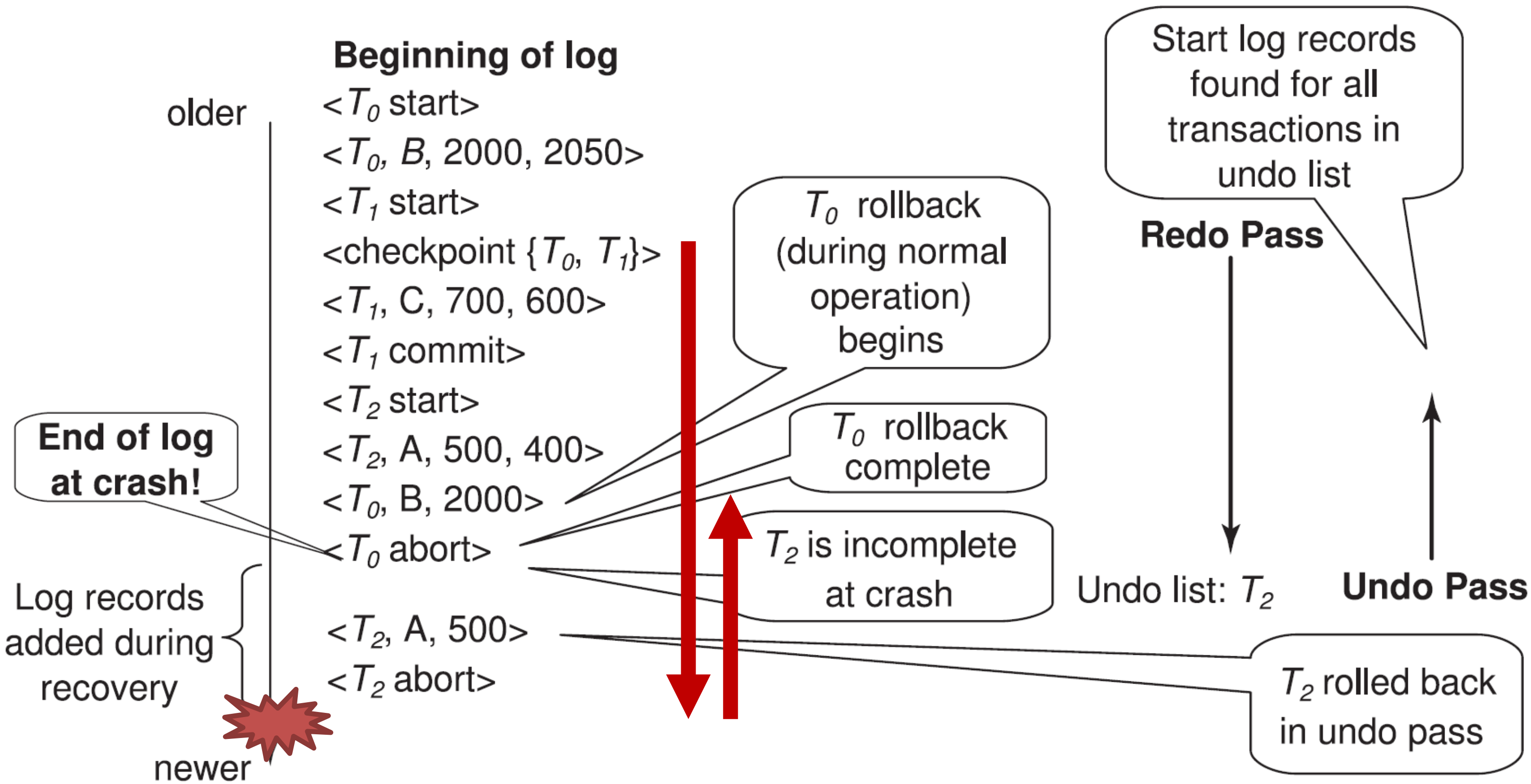
- Replaying history includes replaying previous undos
  - There may be previous ***undos for some physical ops*** (due to, e.g., tx rollbacks or crashes)
  - Need to be replayed too! But not logged currently
- How to replay history in a single phase (log scan)?
- When undoing a physical op, append an redo log, called ***compensation log***, for such undo in LogMgr
- Then, during recovery, RecoveryMgr can simply replay history by redoing ***both*** physical and compensation logs
  - In the order they appear in the log file (***from checkpoint to tail***)

REDO-UNDO Recovery Algorithm V1



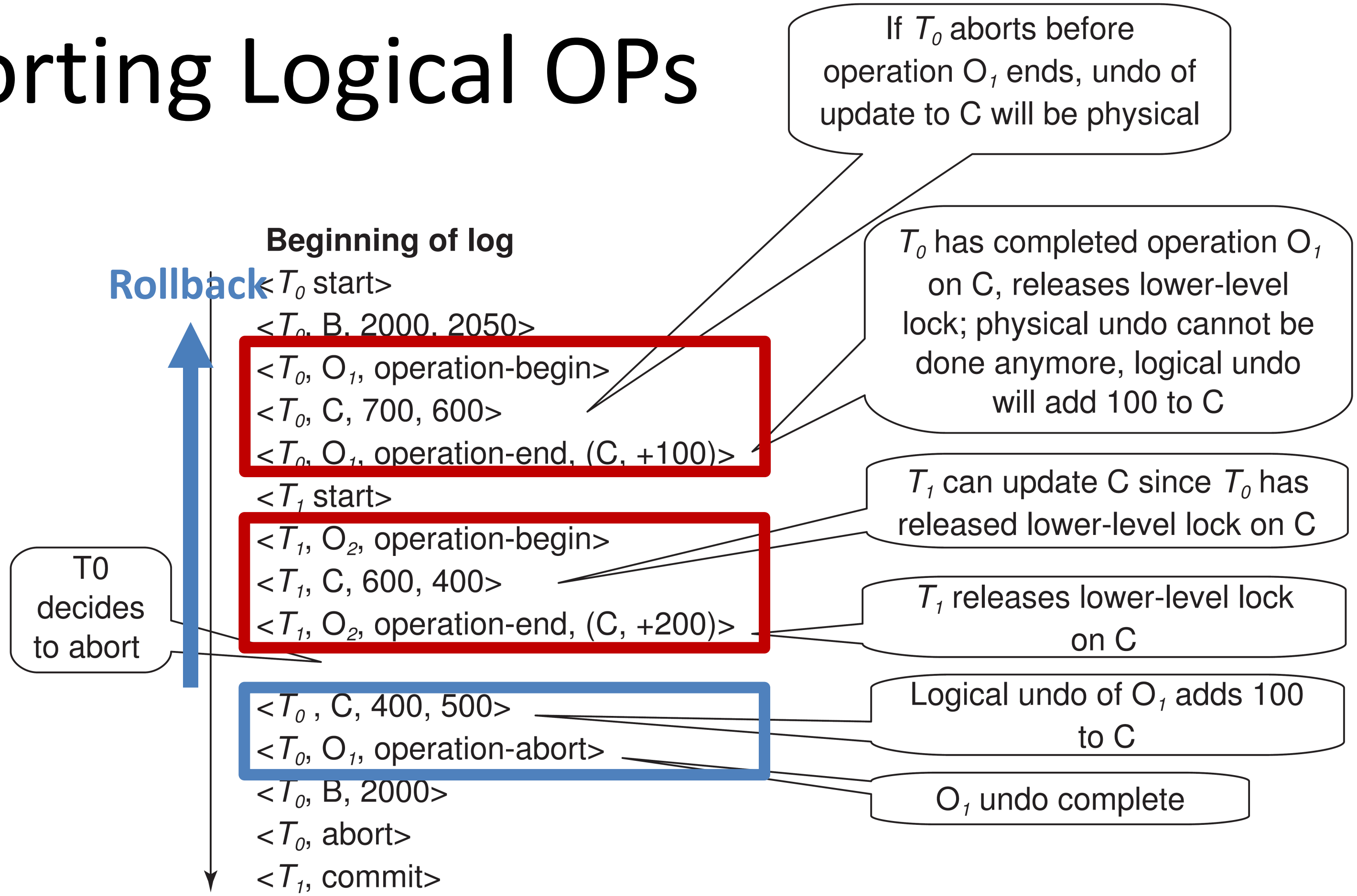
- Assuming no logical ops
- Incomplete txs are identified during the REDO phase and kept into a undo list

REDO-UNDO Recovery Algorithm V1



- Can handle repeated crashes during recovery
  - Although some redos and undos may be unnecessary

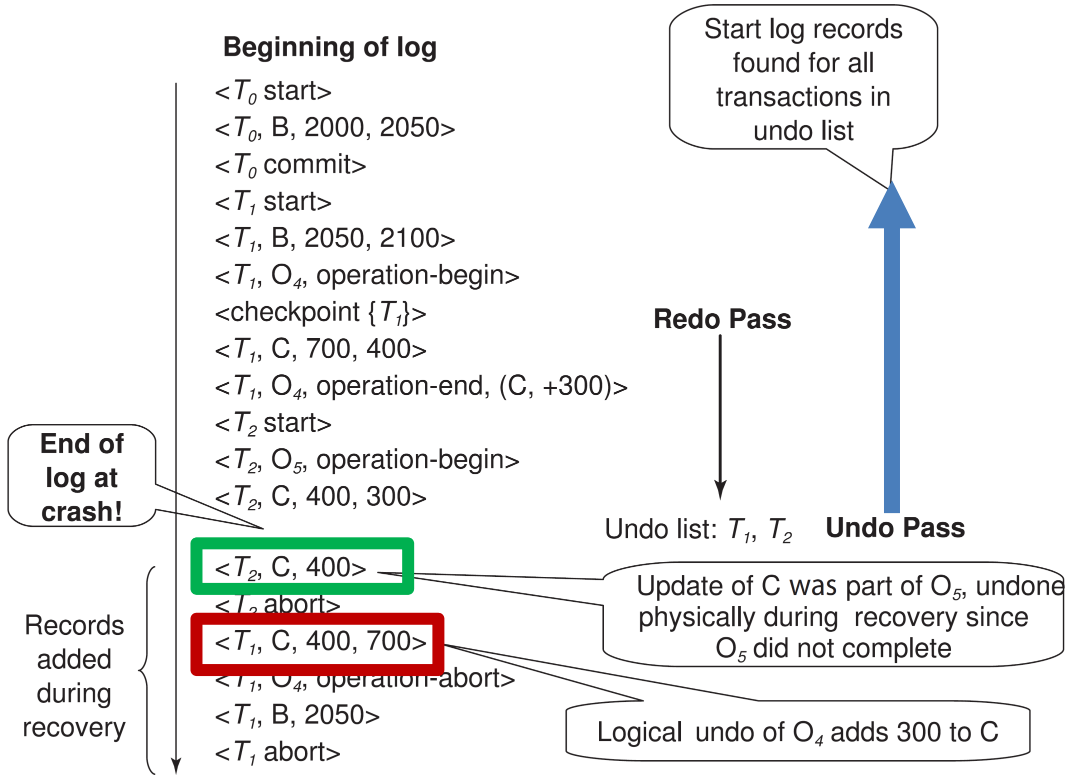
Supporting Logical OPs



- Repeating history (REDO) carries out physical ops following the exact order they happened
- Good for dependent physical ops

REDO-UNDO Recovery Algorithm V2

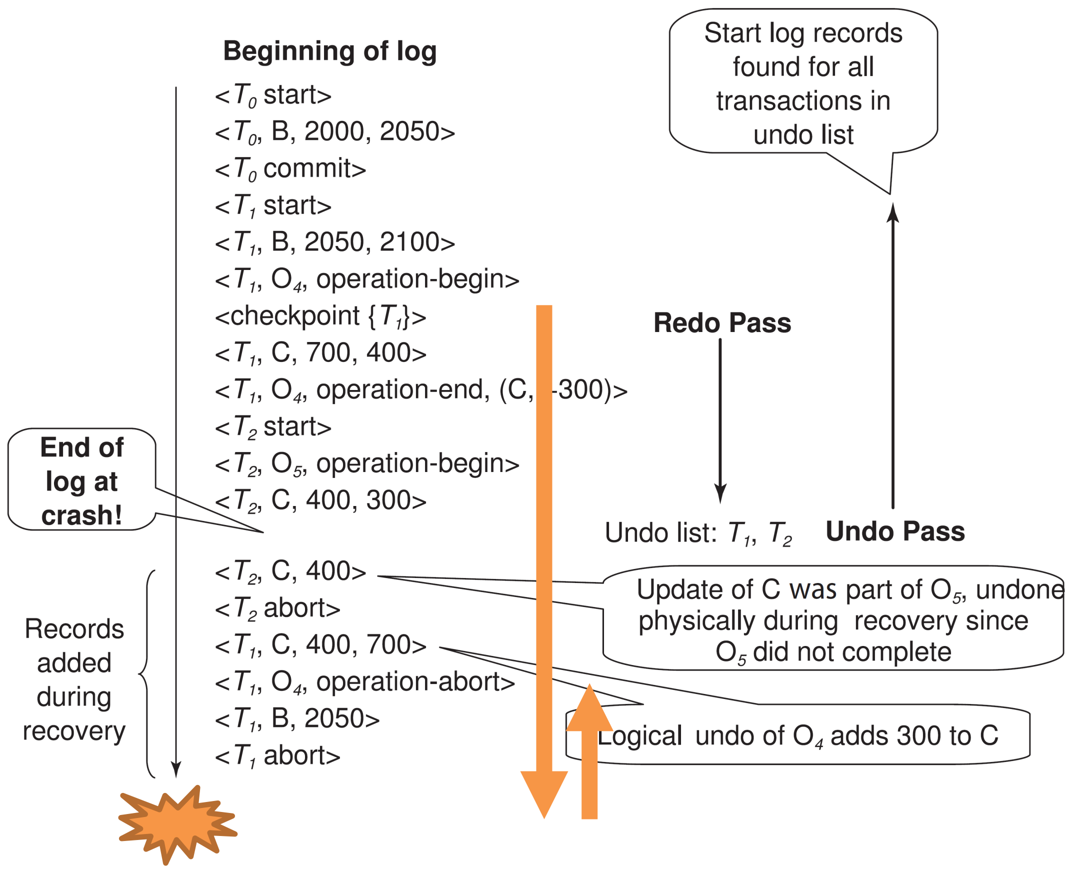
- REDO: repeat history
  - Replay ***both*** physical and compensation logs
- UNDO:
  - Physically for physical and incomplete logical ops
  - Logically for completed logical ops
  - Skip all aborted logical ops



- Keep logging in UNDO phase:
  - ***Compensation logs for physical undos***
  - ***Physical logs for a logical undos***

REDO-UNDO Recovery Algorithm V2

- REDO: repeat history
  - Replay ***both*** physical and compensation logs
- UNDO:
  - Physically for physical and incomplete logical ops
  - Logically for completed logical ops
  - Skip all aborted logical ops

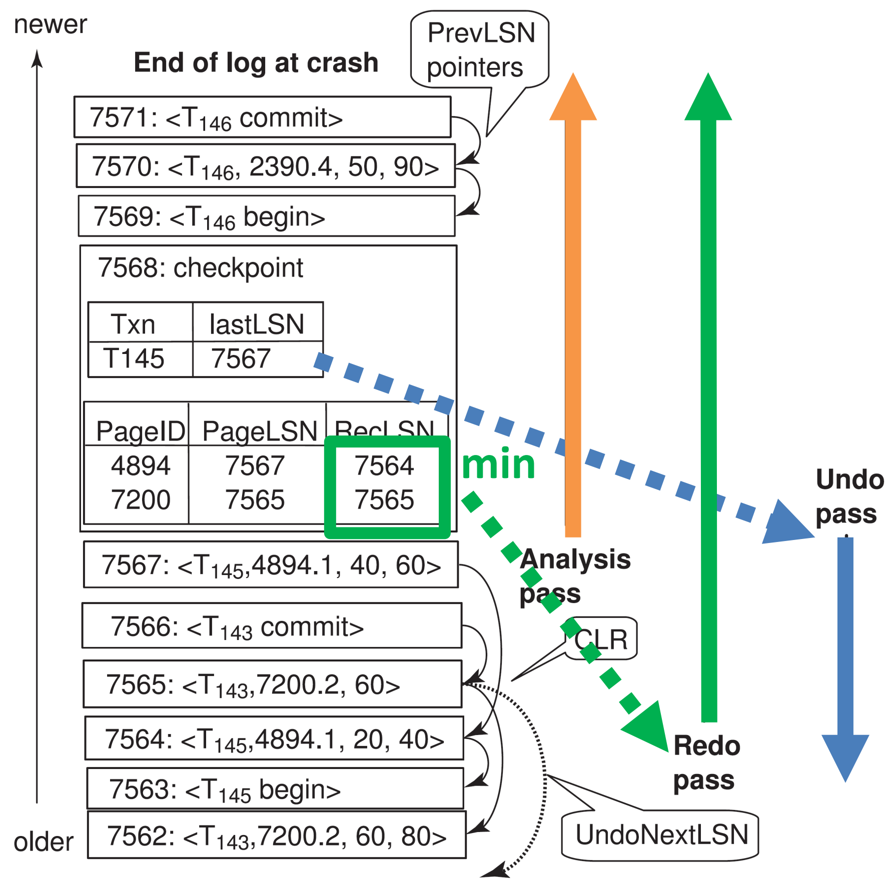


Non-Idempotent Logical OPs

- Note that logical operations, and their logical undos, are ***not*** idempotent
- Completed logical ops and logical undos are repeated ***using physical logs***
  - In REDO phase
  - “history” grows
- So, UNDO phase must skip completed logical undos
  - When rolling back a tx, we, upon finding a record <OPABORT, Ti, Oj>, need to skip all preceding records (including OPEND record for Oj) until <OPBEGIN, Ti, Oj>
  - An operation-abort log record would be found only if a tx that is being rolled back had been partially rolled back earlier

Faster Checkpointing

- Active tx list
  - Most recent LSN for each tx
- List of dirty pages
  - RecLSN: latest log reflected to disk
  - PageLSN
- No flushing pages

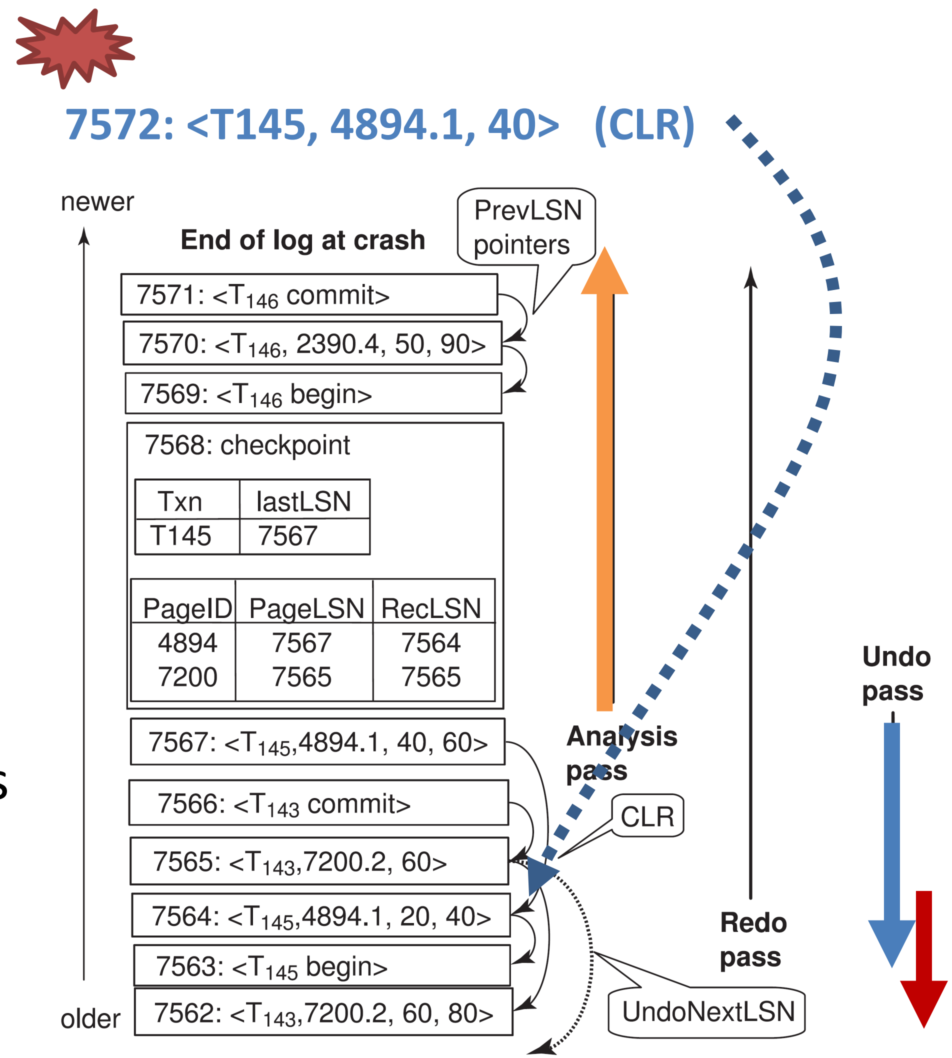


Resume Rollbacks

- How to resume rolling back all incomplete txs in UNDO phase?
- For each incomplete tx:
  - Completed logical undos must be skipped (discussed earilier)
- In addition, completed physical undos can be skipped
  - Optional; just for better performance

PrevLSN and UndoNextLSN Pointers

- Logging:
  - Each physical log keeps the PrevLSN
  - Each compensation log keeps the UndoNextLSN
- RecoveryMgr
  - Remembers the last UndoNextLSN of each tx in the undo list
  - The next LSN to process during UNDO phase is the max of the UndoNextLSNs
- Tx rollback can be resumed



Outline

- Physical logging:
  - Logs and rollback
  - UNDO-only recovery
  - UNDO-REDO recovery
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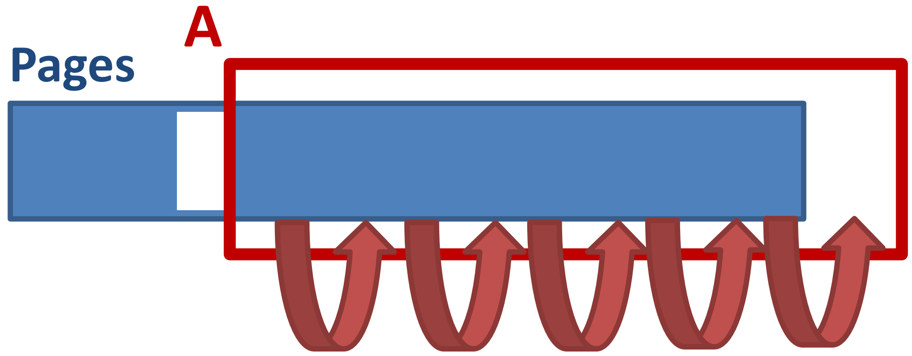
- RecoveryMgr in VanillaCore

Problems of Physical Logging

- Physical logs will be huge!
- For example, if the system wants to insert a record into a sorted file
  - Common when maintaining the indices



- How to save the number of physical logs?

Physiological logging

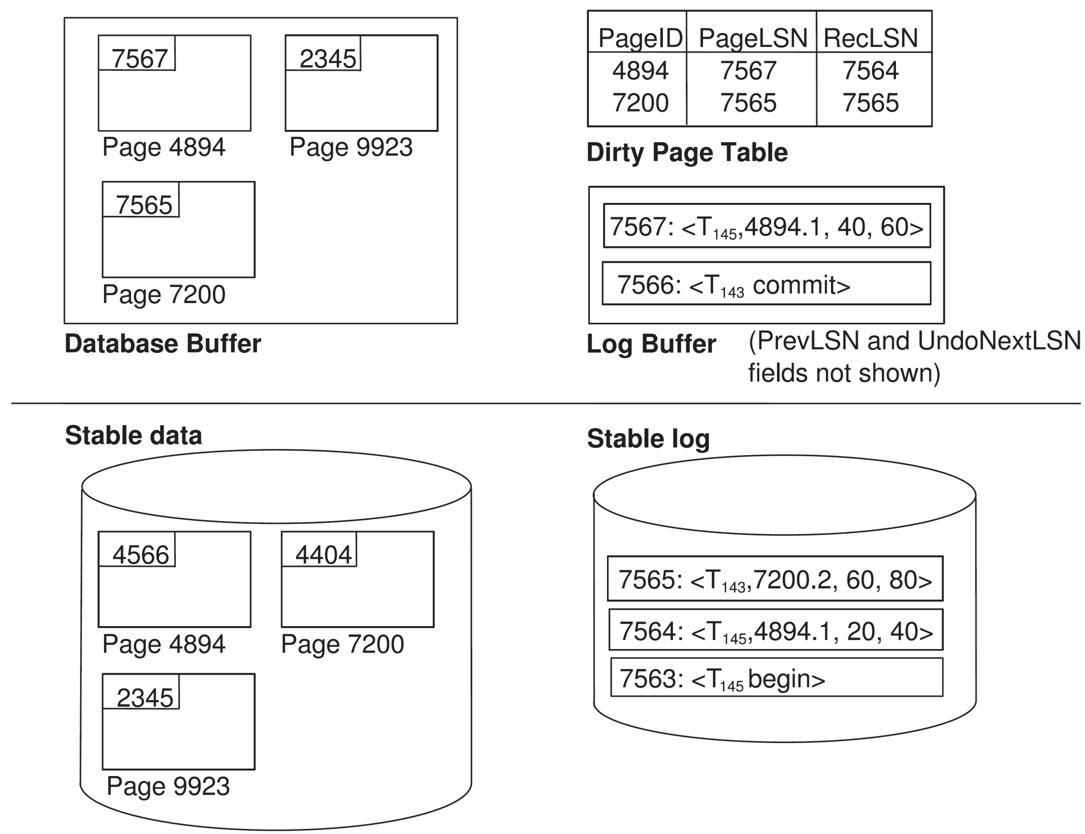
- Observe that, during a sorting op, all physical ops to the same block will be written to disk in just one flush
- Why not log all these physical ops as one logical op?
  - As long as this logical op can be undone logically
- Called ***physiological logs***, in that
  - Physical across blocks
  - Logical within each block
- Significantly save the cost of physical logging
- But complicates recovery algorithm further
  - As REDOs are ***not*** idempotent anymore
  - Need to avoid repeated replay

REDO-UNDO Recovery Algorithm V3

- During REDO, ***skip*** all physiological ops and their compensations that have been replayed previously
  - How?
- During UNDO, threat each physiological op as ***physical***
  - Write compensation log that is also a physiological op

Avoiding Repeated Replay

- Keep a PageLSN for each block
  - Most recent log for that block
- REDO phase:
  - Replay a physiological log iff its LSN is larger than the PageLSN of the target block



- Further optimized in ARIES

Outline

- Physical logging:
  – Logs and rollback
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- RecoveryMgr in VanillaCore

The VanillaDB Recovery Manager

- Log granularity: values
- Implements ***ARIES*** recovery algorithm
  - Steal and non-force
  - Physiological logs
  - No optimizations
- Non-quiescent checkpointing (periodically)
- Related package
  - `storage.tx.recovery`
- Public class
  - `RecoveryMgr`
  - Each transaction has its own recovery manager

References

- Database Design and Implementation, chapter 14. Edward Sciore.
- Database management System 3/e, chapter 16. Ramakrishnan Gehrke.
- Database system concepts 6/e, chapter 15, 16. Silberschatz.
- Hellerstein, J. M., Stonebraker, M., and Hamilton, J. Architecture of a database system. *Foundations and Trends in Databases 1*, 2, 2007