# Transaction Management Part II: Recovery

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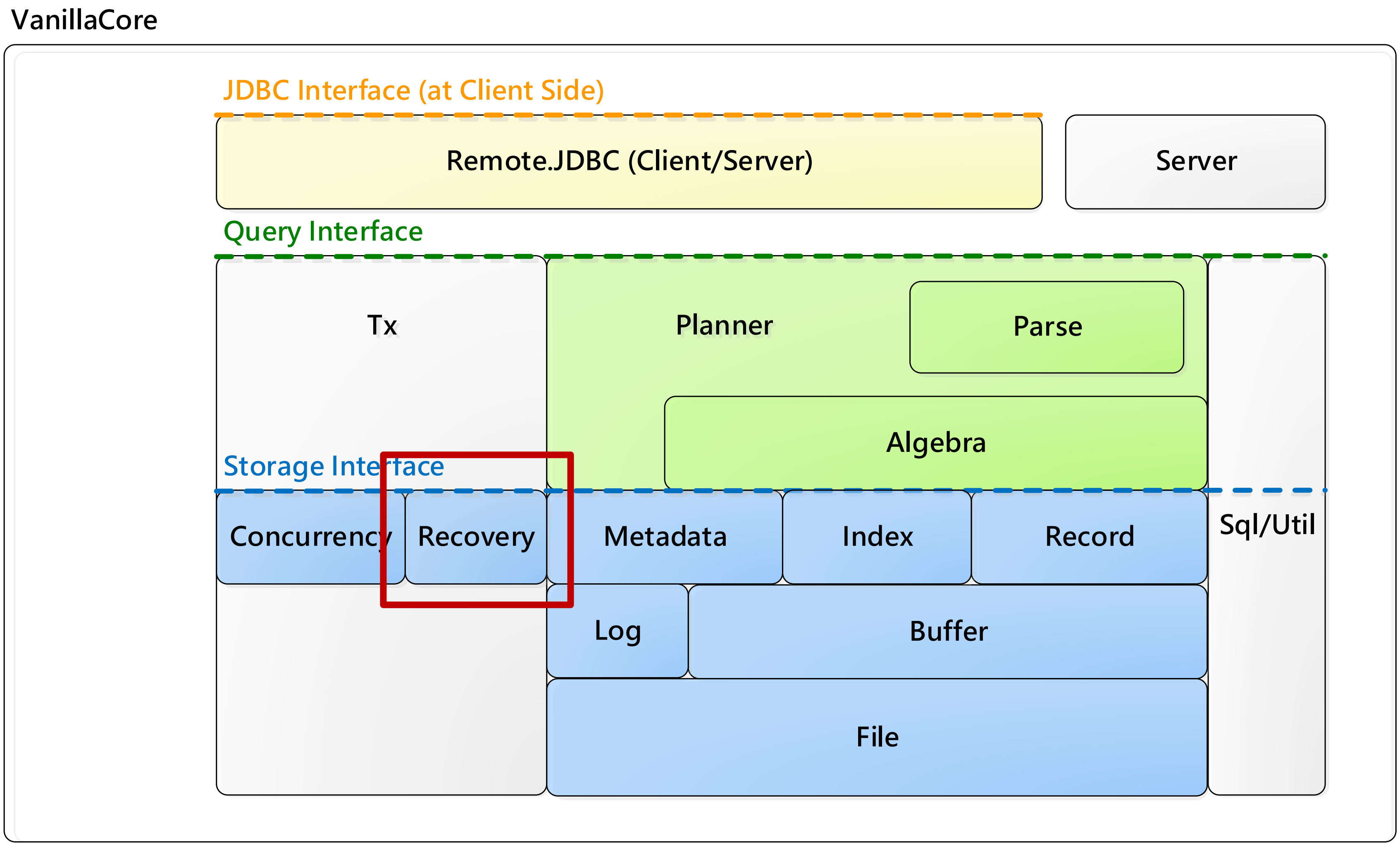
# Today’s Topic: Recovery Mgr



# 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

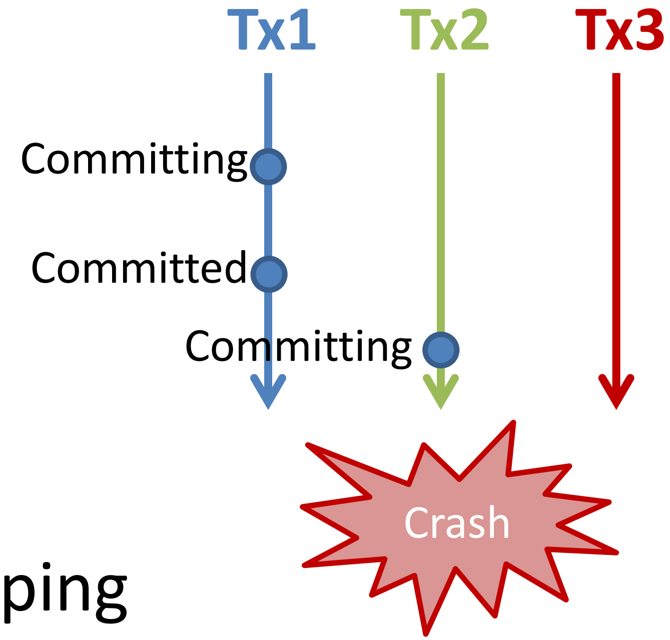
- Contents in nonvolatile storage are ***not corrupted***
  - E.g., via file-system journaling
- No Byzantine failure (zombies)
- Other types of failure will be dealt with in other ways
  - E.g., via replication, quorums, etc.

# 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***

**Txn B:**

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

- 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)

# 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

- Physical logging:
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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?

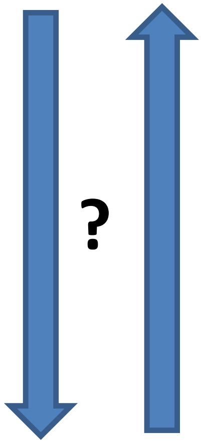
```
public void onTxCommit(Transaction tx) {
    VanillaDb.bufferMgr().flushAll(txNum);
    long lsn = new CommitRecord(txNum).writeToLog();
    VanillaDb.logMgr().flush(lsn);
}
```

- 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

# Outline

- Physical logging:
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  - Failures during recovery
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- Logical logging:
  - Early lock release and logical UNDOs
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- RecoveryMgr in VanillaCore

# Recovery

- When the DMBS restart (from crash), the recovery manager is responsible for restoring 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

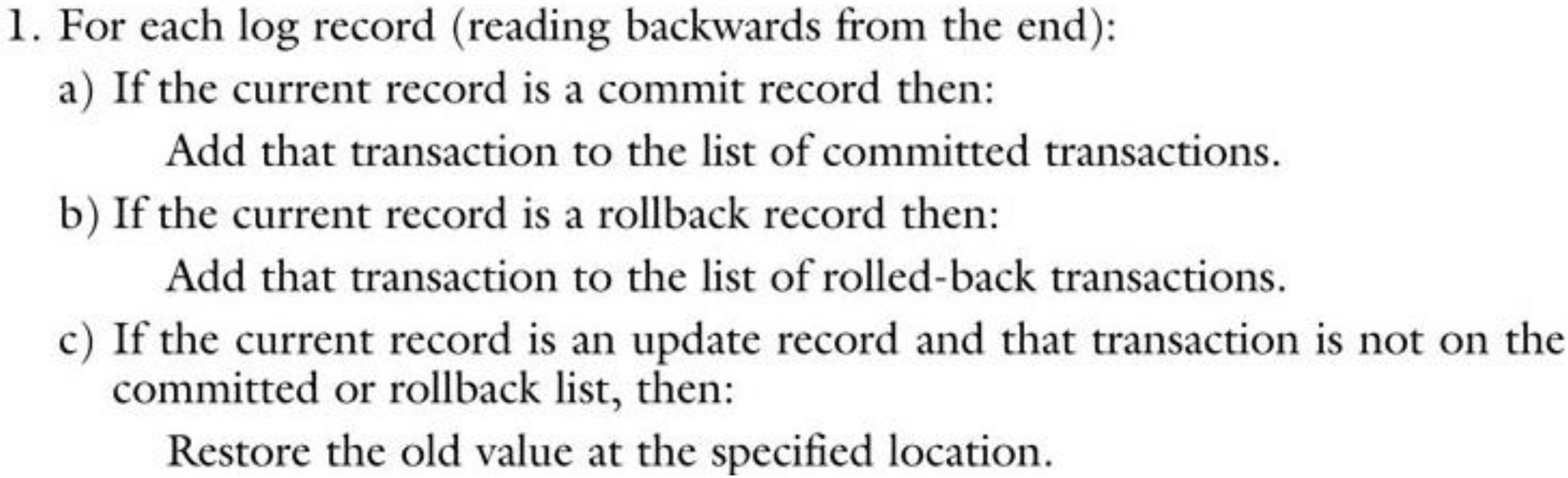
```
public void onTxCommit(Transaction tx) {
    VanillaDb.bufferMgr().flushAll(txNum);
    long lsn = new CommitRecord(txNum).writeToLog();
    VanillaDb.logMgr().flush(lsn);
}
```

```
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>
```

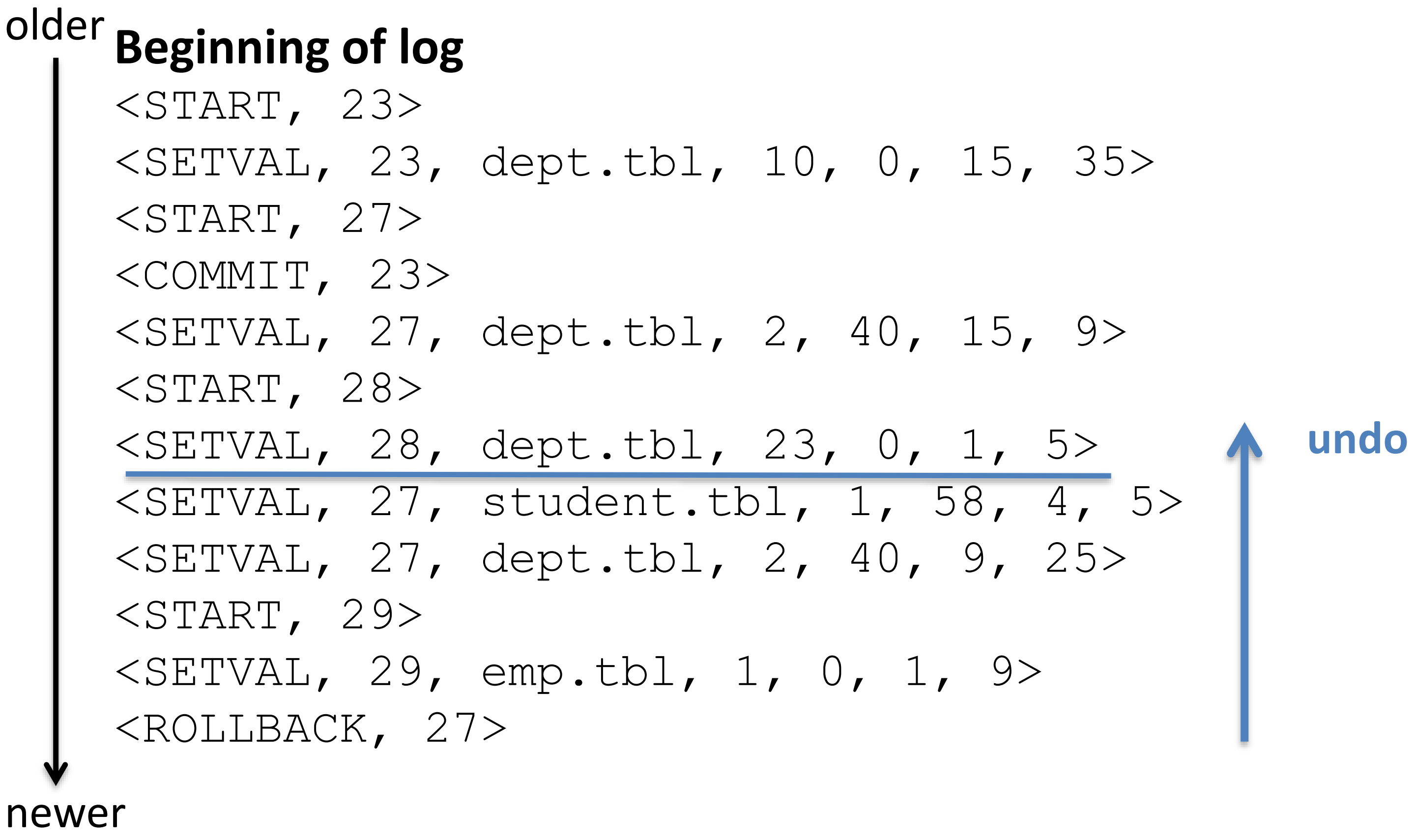
undo

newer

# Undo-Redo Recovery

- Undo and redo

**Completed Txn:**
**27**



**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-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!

# Outline

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- Logical logging:
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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**

**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 28**

newer

# 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>
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<COMMIT, 23>
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<ROLLBACK, 27>
```
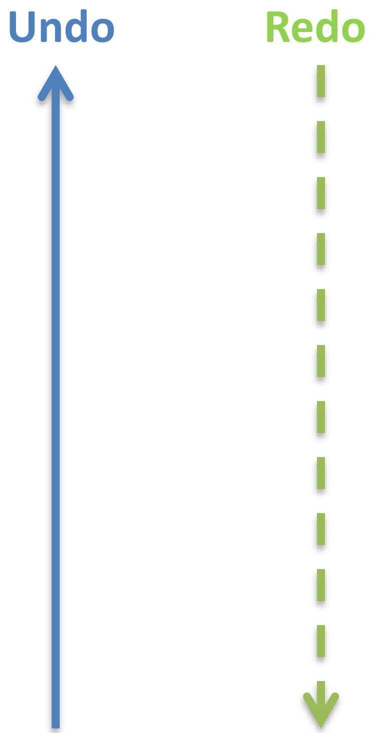

newer



# Undo-Redo Recovery

- Undo and redo

**Completed Txn:**
**27, 23**

older

**Beginning of log**

Undo

Redo

redo

```
<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, 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>
```
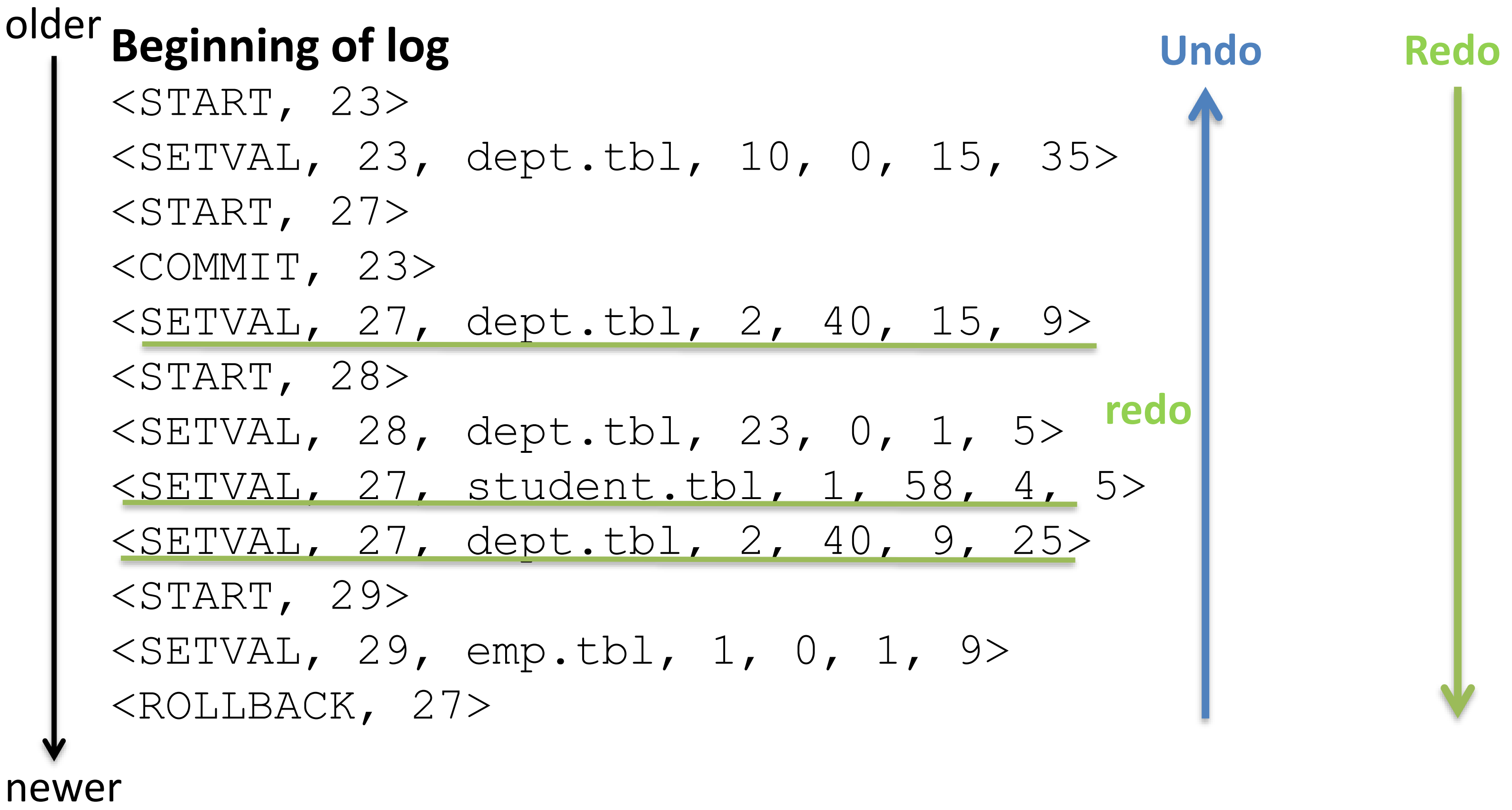

newer

# Undo-Redo Recovery

- Undo and redo

**Completed Txn:**
**27, 23**



older

**Beginning of log**

```
<START, 23>
<SETVAL, 23, dept.tbl, 10, 0, 15, 35>
<START, 27>
<COMMIT, 23>
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<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>
```
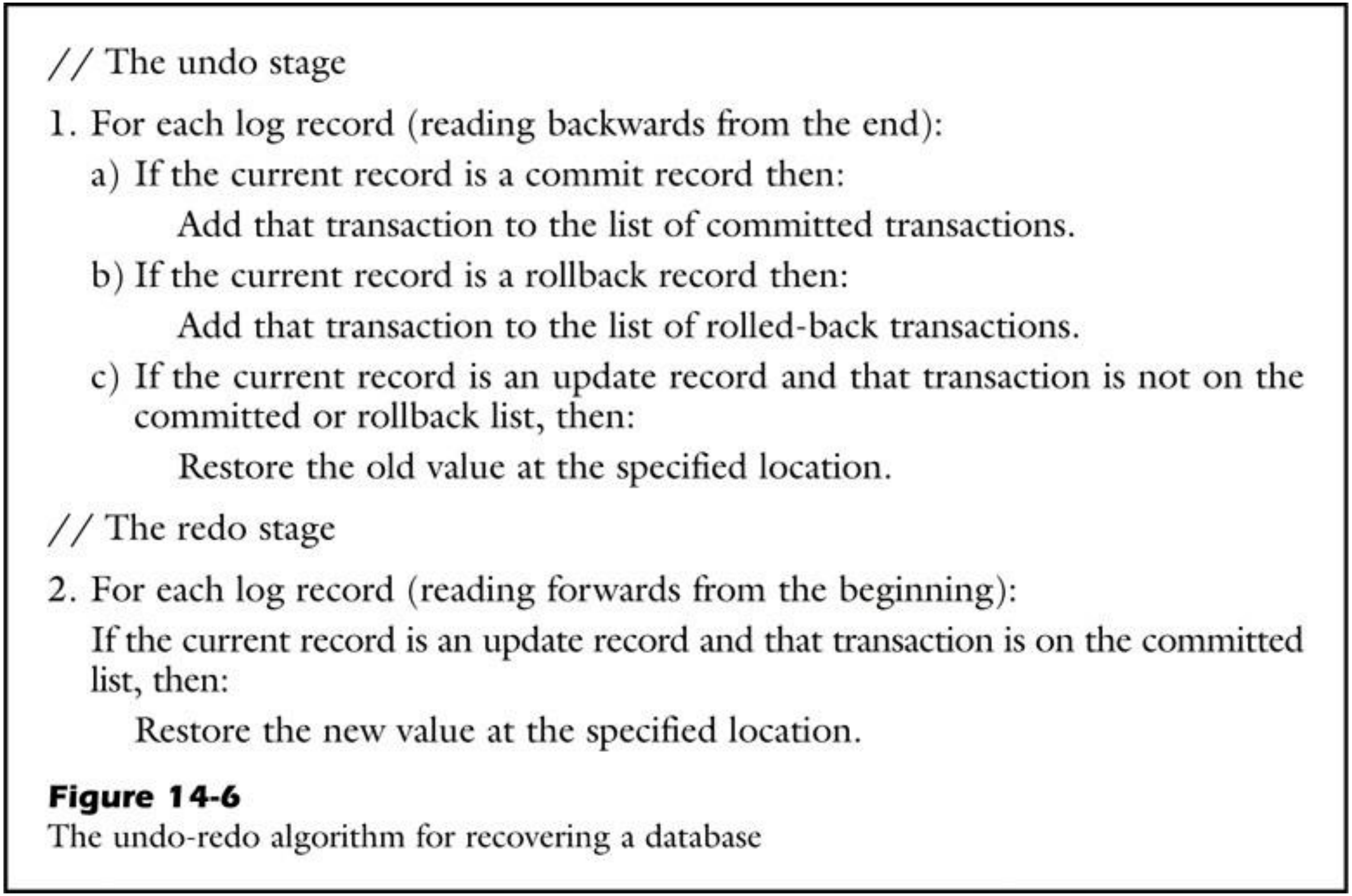

newer

# 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

```java
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

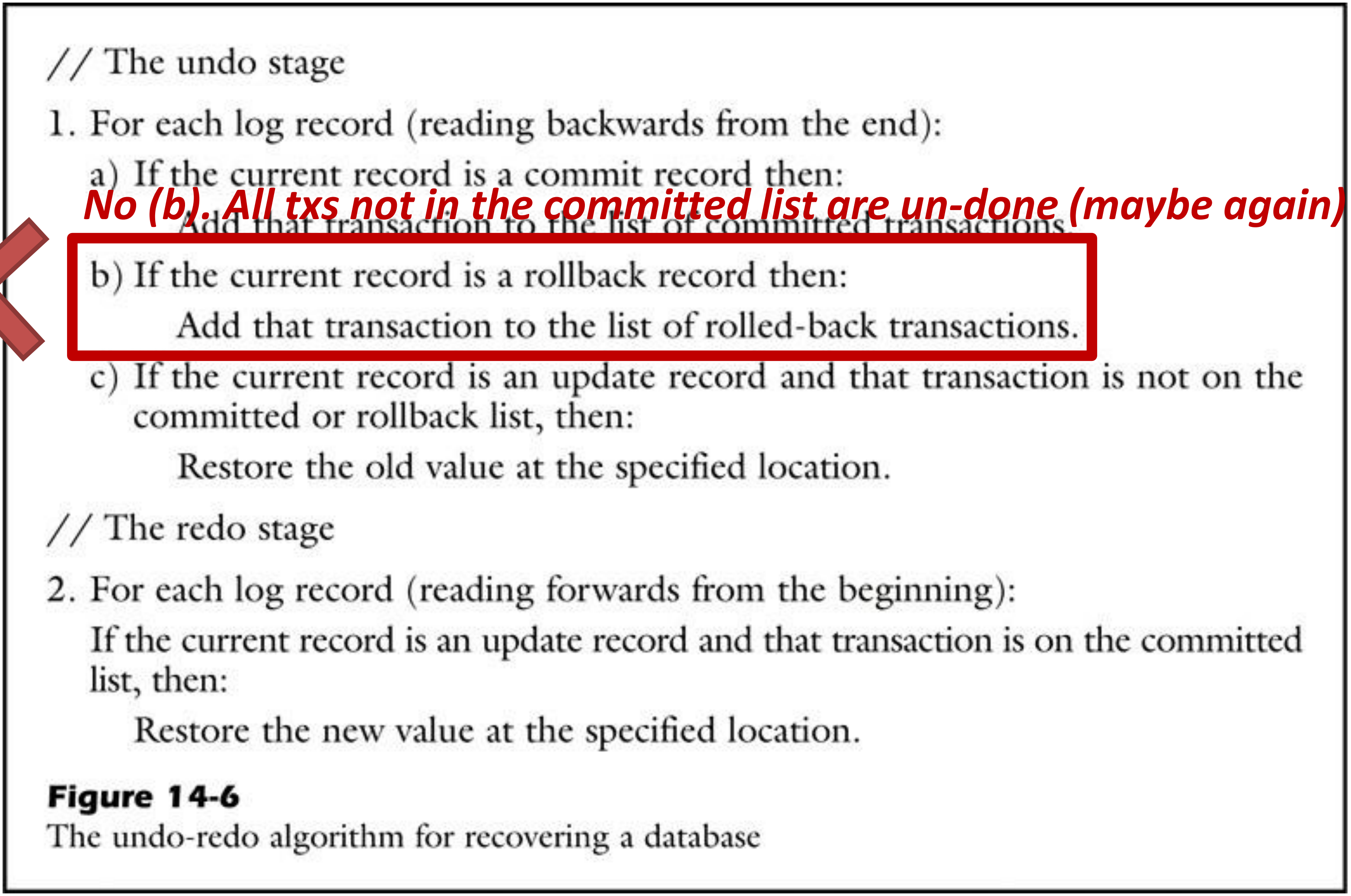
```
public void onTxRollback(Transaction tx) {
     doRollback();
     VanillaDb.bufferMgr().flushAll(txNum);
     long lsn = new RollbackRecord(txNum).writeToLog();
     VanillaDb.logMgr().flush(lsn);
}

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



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

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

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?

# 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

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()`

# 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

# Checkpointing

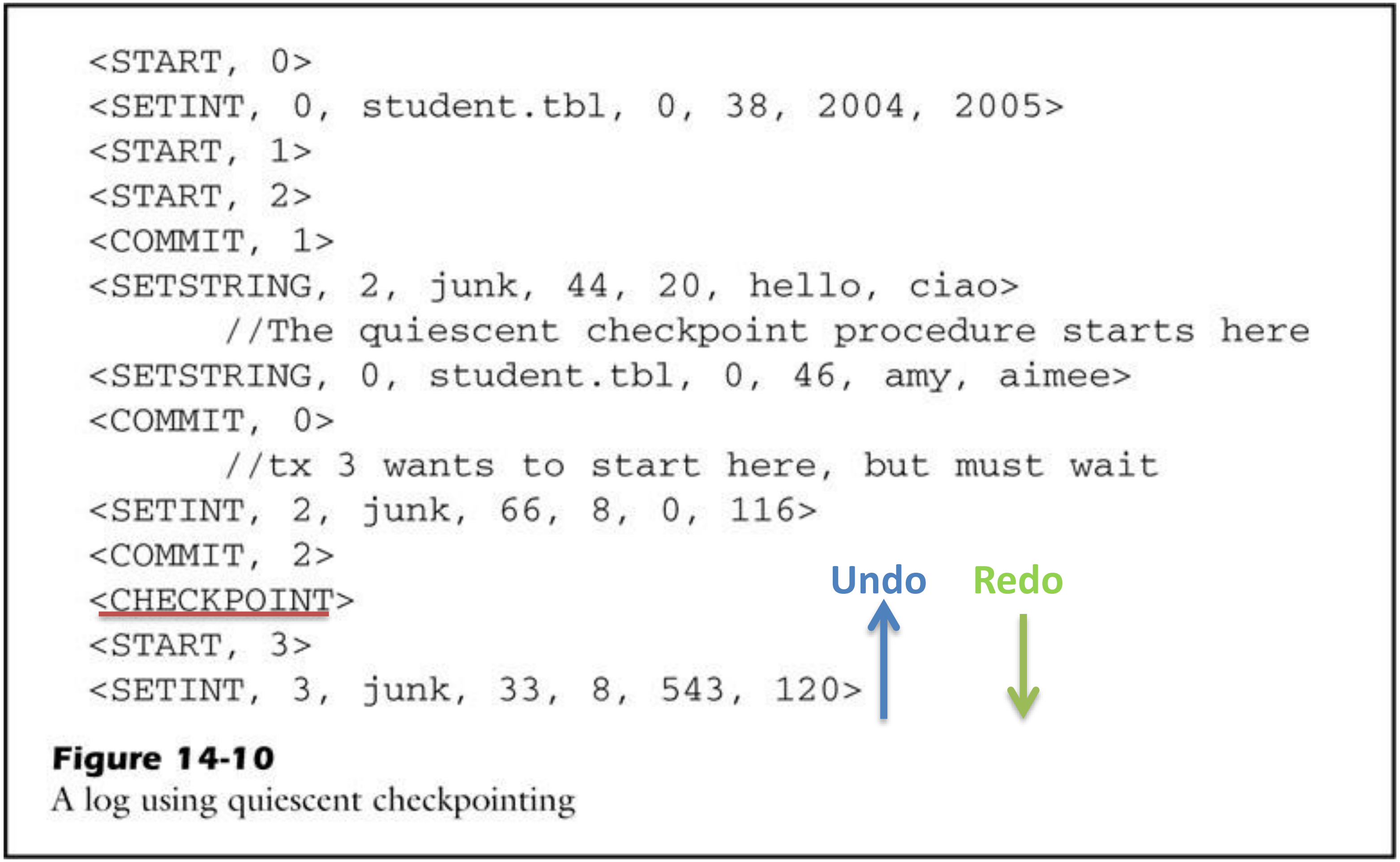
- As the system keeps processing requests, the log file may become very large
  - Running recovery process is time consuming
  - Can we just read a portion of the log?

- 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>
```

**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

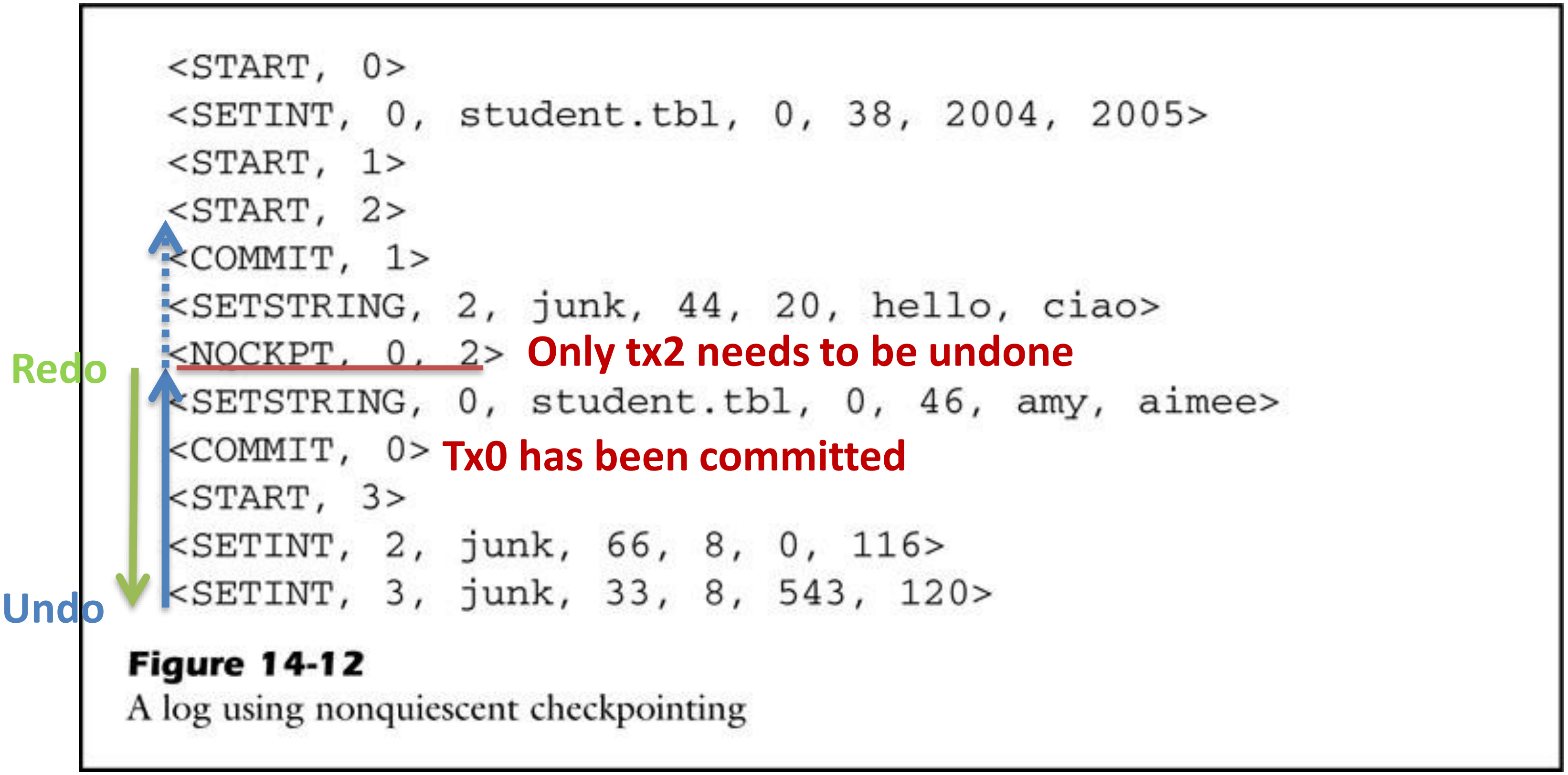
# Can we shorten the quiescent period?

# 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>
<NQCKPT, 0, 2>
<SETSTRING, 0, student.tbl, 0, 46, amy, aimee>
<COMMIT, 0>
<START, 3>
<SETINT, 2, junk, 66, 8, 0, 116>
<SETINT, 3, junk, 33, 8, 543, 120>
```

Only tx2 needs to be undone

Tx0 has been committed

**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

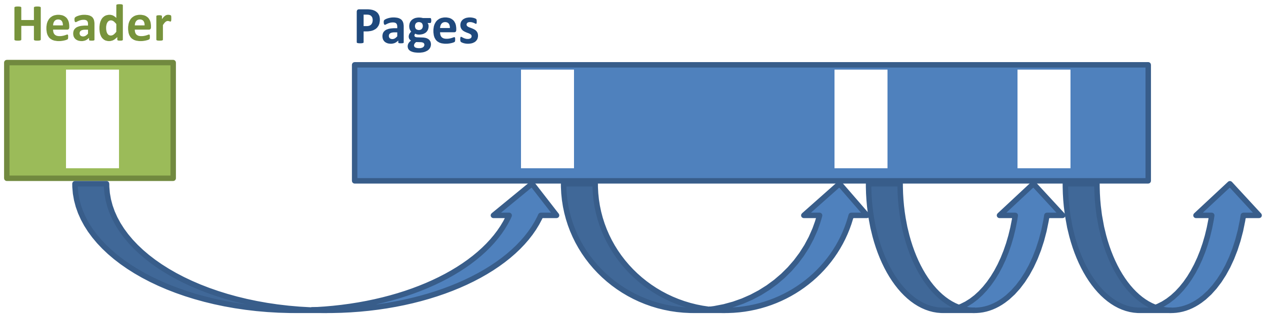
- There are meta-structures in a DBMS
  - E.g., `FileHeaderPage` in a `RecordFile`
  - Indices
- Poor performance if they are locked in strict manner
  - E.g., S2PL on `FileHeaderPage` serializes all insertions and deletions
- Locks on meta-structures are usually ***released early***

# 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)
- Better concurrency for I
- No harm to C
- Needs special care to ensure A and D

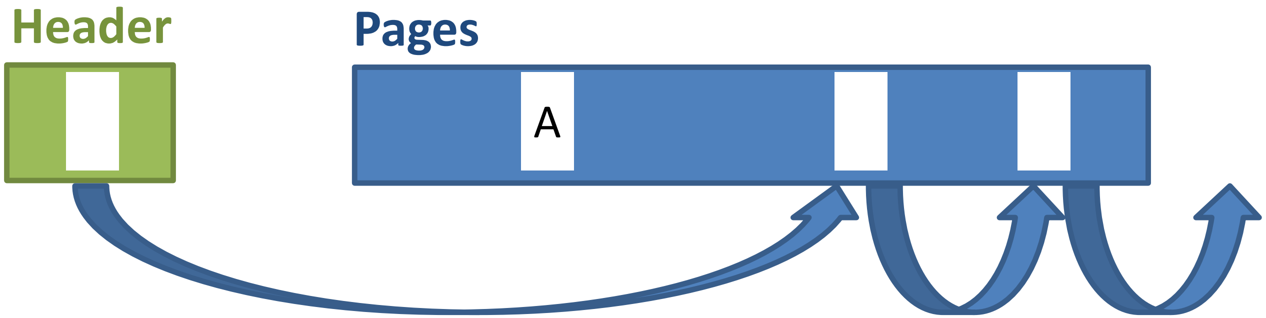
# Problems of Logical Operations

- 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!



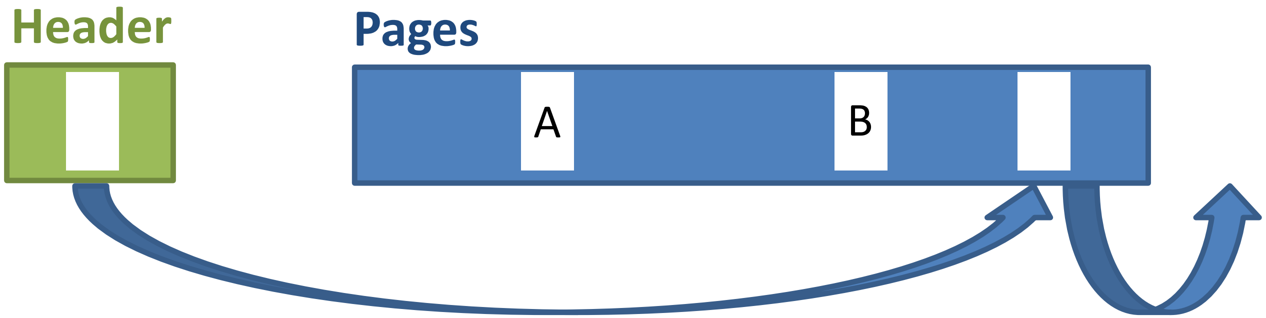
# Problems of Logical Operations

- Suppose
  1. *T1* inserts a record *A* to a table/file
     - `FileHeaderPage` and a `RecordPage` modified
  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!



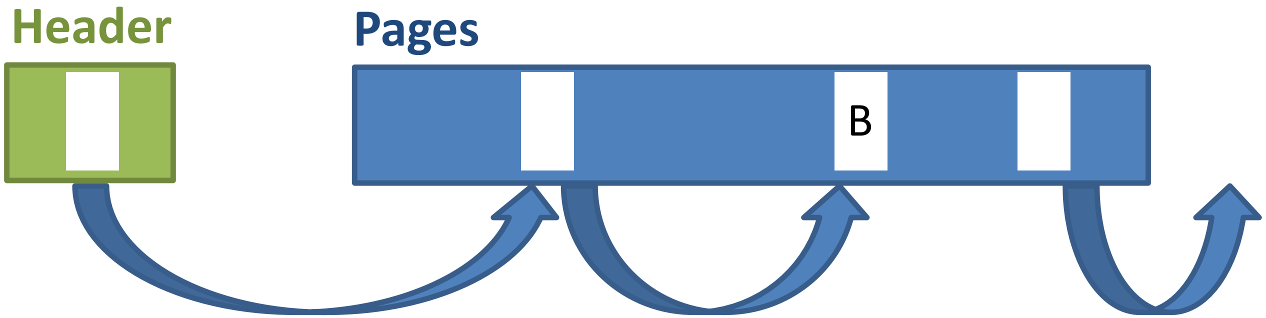
# Problems of Logical Operations

- 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*, *B* will be lost!

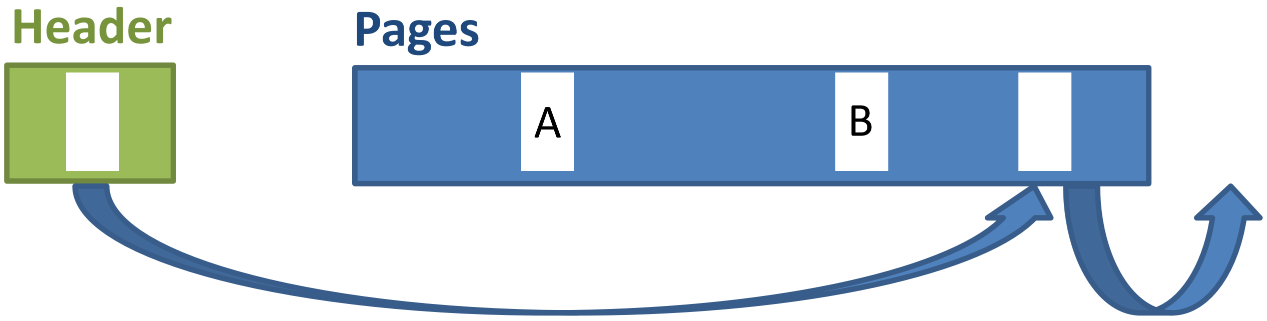


# Problems of Logical Operations

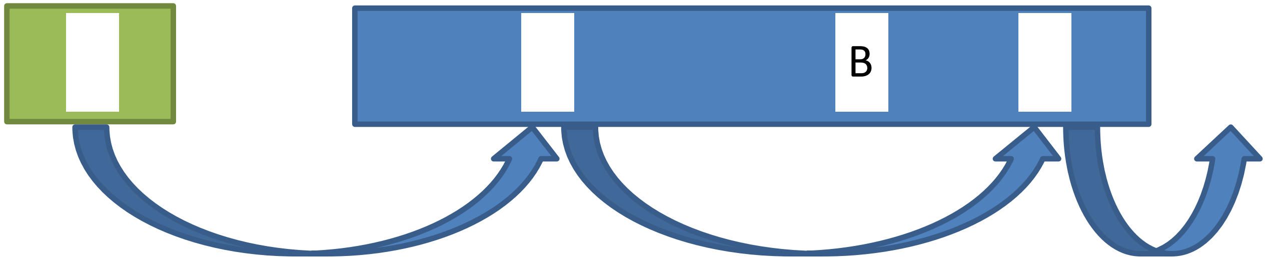
- Suppose
  1. *T1* inserts a record *A* to a table/file
     - `FileHeaderPage` and a `RecordPage` modified
  2. *T2* inserts another record *B* to the same table
     - Same `FileHeaderPage` and another `RecordPage` modified
  3. *T1* aborts
- If the physical undo record is used to rollback *T1*, free-space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

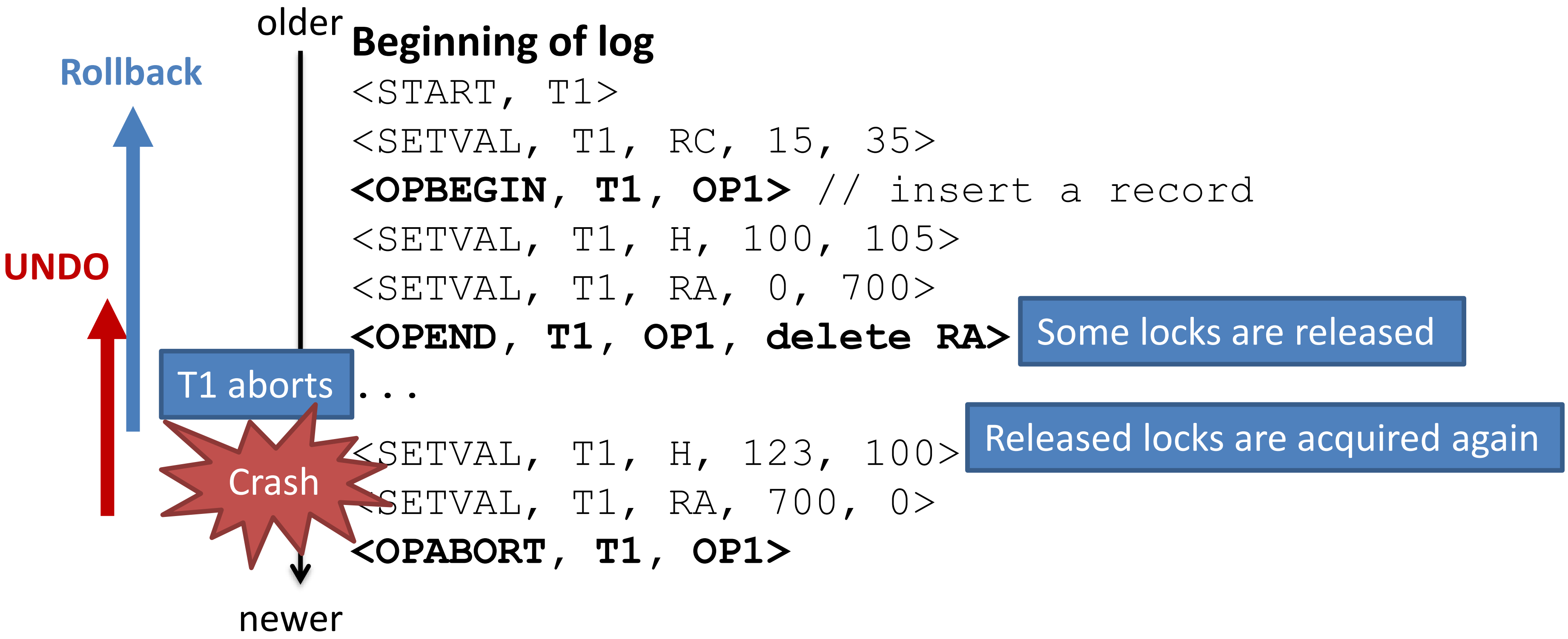
- UNDO: to roll back all uncommitted txs (and logical OPs)
- REDO: reconstruct memory state

- 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



older

Rollback

UNDO

**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>
...
<SETVAL, T1, H, 123, 100>
<SETVAL, T1, RA, 700, 0>
<OPABORT, T1, OP1>
```

Some locks are released

T1 aborts

Released locks are acquired again

Crash

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
- Logical logging:
  - Early lock release and logical UNDOs
  - Repeating history
- Physiological logging
- RecoveryMgr in VanillaCore

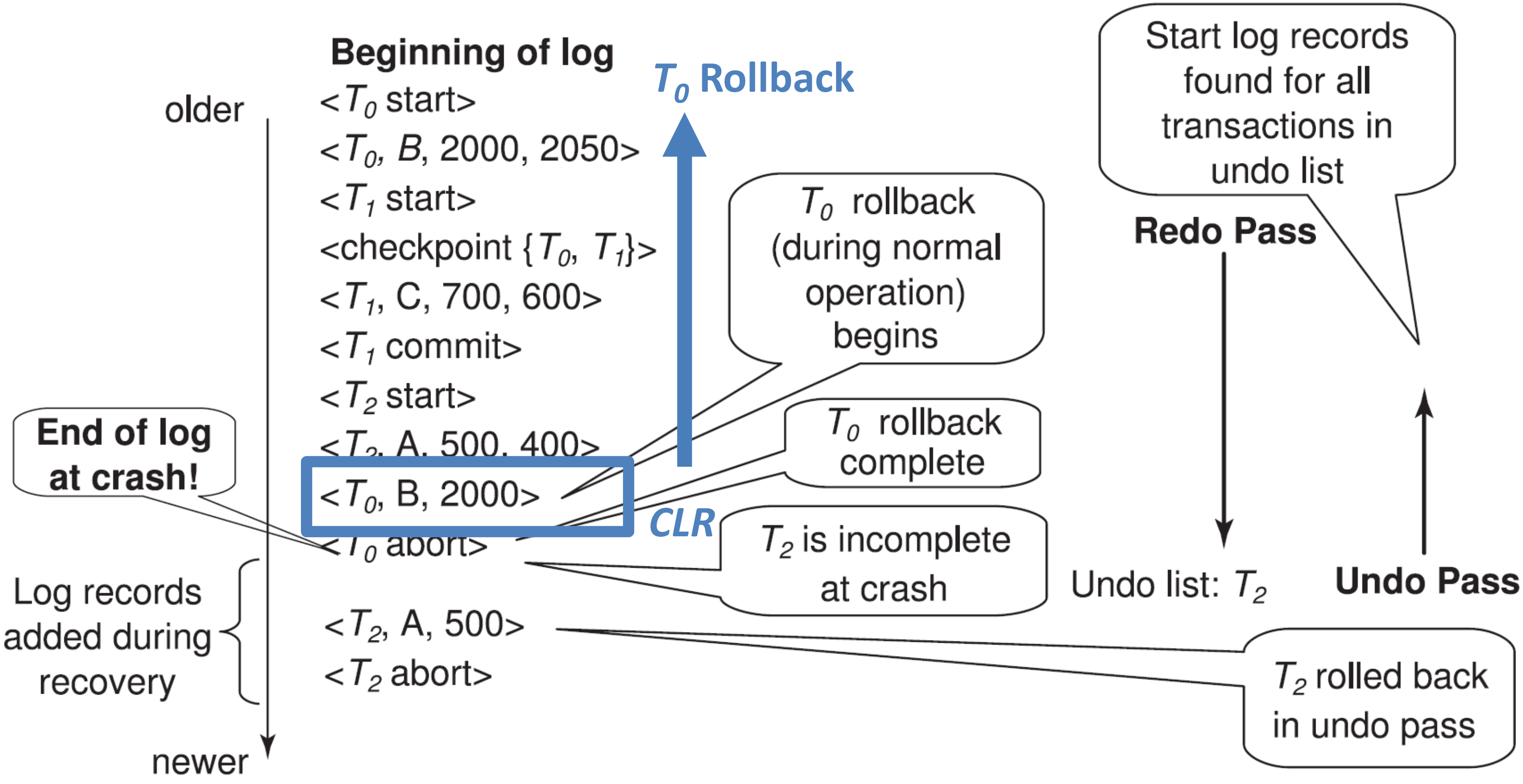
# Recovery by Repeating History

- 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



Beginning of log

older

<$T_0$ start>

<$T_0$, B, 2000, 2050>

<$T_1$ start>

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

<$T_1$, C, 700, 600>

<$T_1$ commit>

<$T_2$ start>

<$T_2$, A, 500, 400>

<$T_0$, B, 2000>

<$T_0$ abort>

<$T_2$, A, 500>

<$T_2$ abort>

newer

$T_0$ Rollback

CLR

End of log at crash!

Log records added during recovery

$T_0$ rollback (during normal operation) begins

$T_0$ rollback complete

$T_2$ is incomplete at crash

$T_2$ rolled back in undo pass

Start log records found for all transactions in undo list

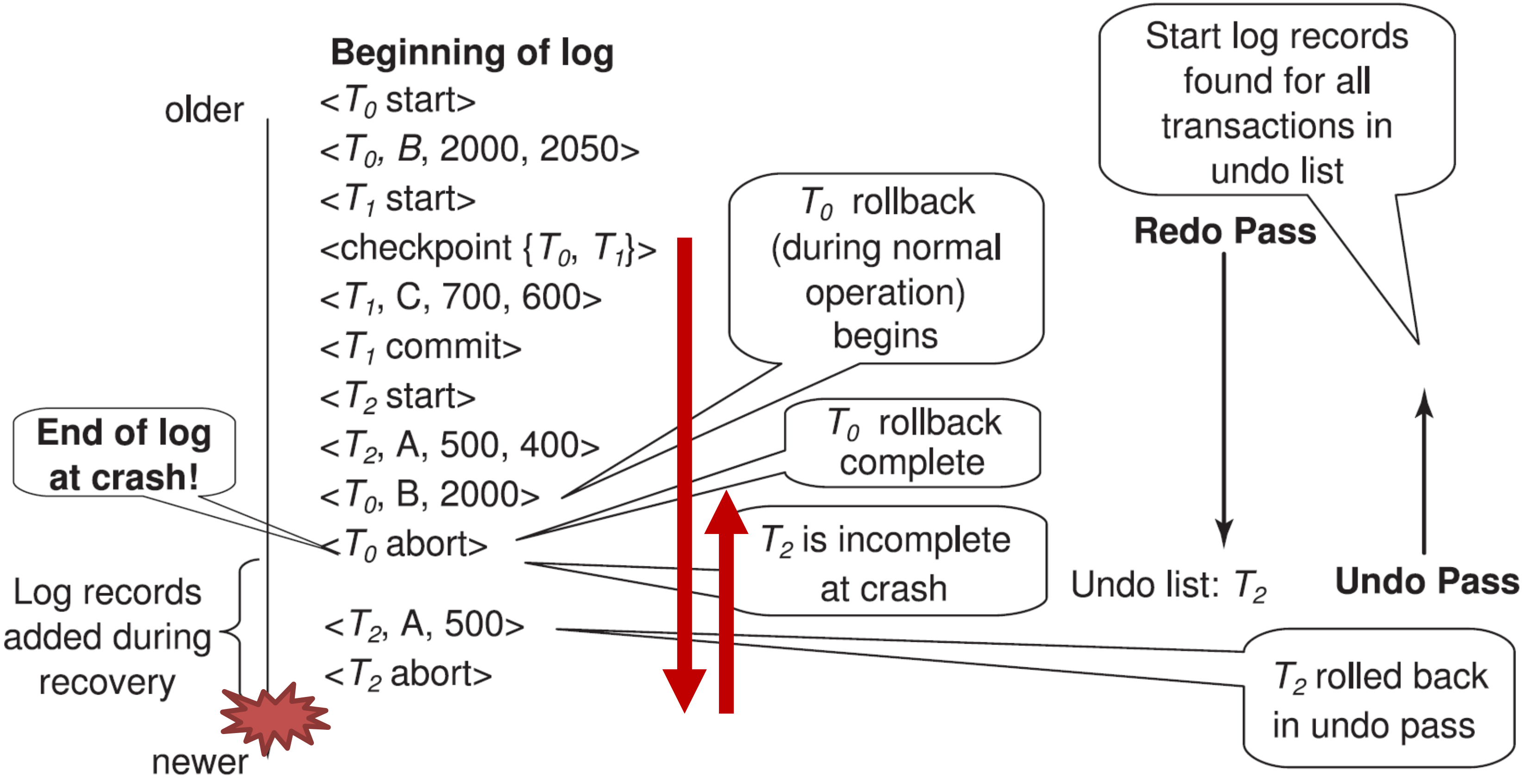
Redo Pass

Undo list: $T_2$

Undo Pass

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

# REDO-UNDO Recovery Algorithm V1



**Beginning of log**

older

<$T_0$ start>

<$T_0$, $B$, 2000, 2050>

<$T_1$ start>

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

<$T_1$, C, 700, 600>

<$T_1$ commit>

<$T_2$ start>

<$T_2$, A, 500, 400>

<$T_0$, B, 2000>

<$T_0$ abort>

<$T_2$, A, 500>

<$T_2$ abort>

newer

**End of log at crash!**

Log records added during recovery

$T_0$ rollback (during normal operation) begins

$T_0$ rollback complete

$T_2$ is incomplete at crash

$T_2$ rolled back in undo pass

Start log records found for all transactions in undo list

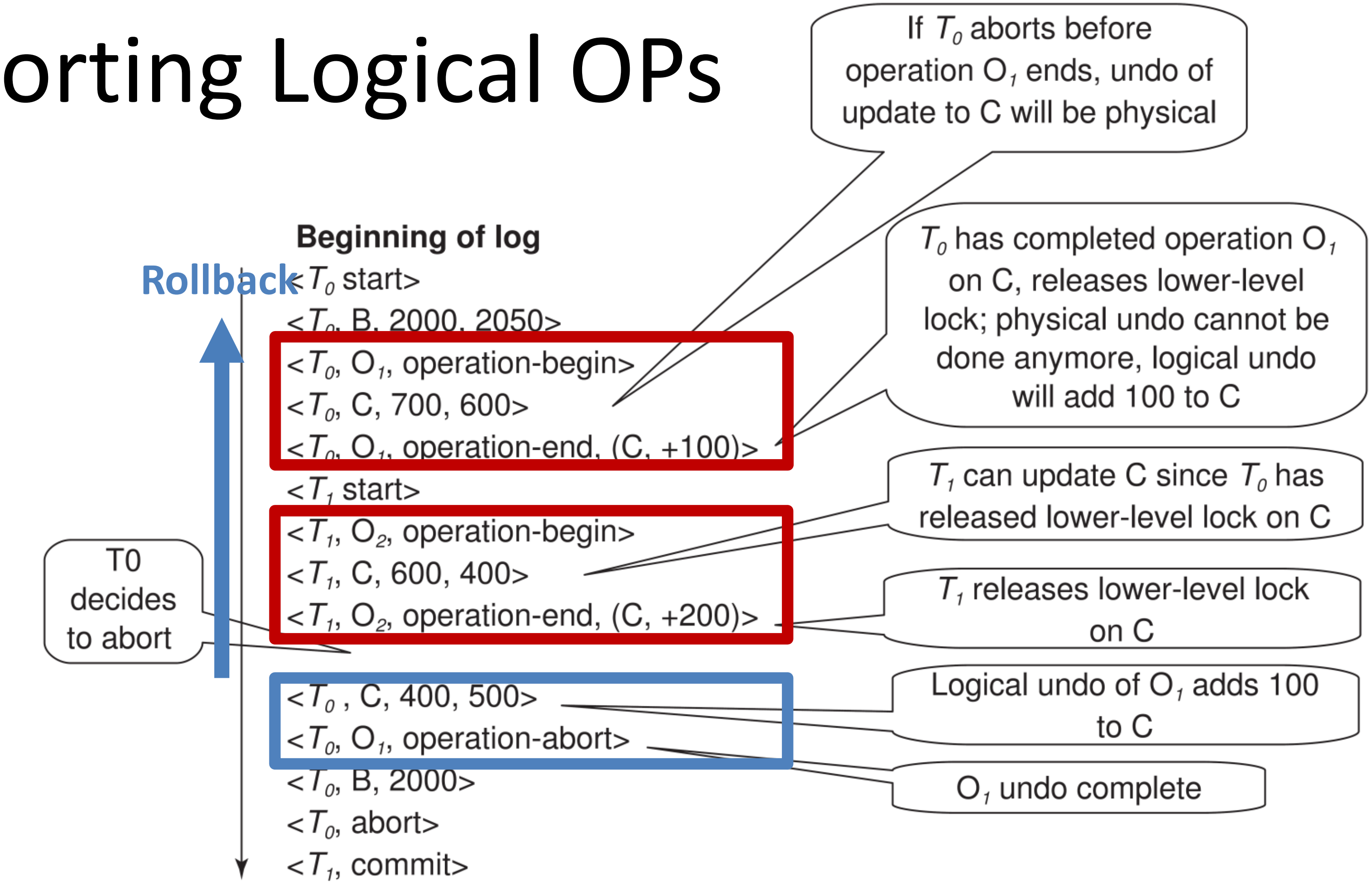
**Redo Pass**

Undo list: $T_2$

**Undo Pass**

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

# Supporting Logical OPs



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

Beginning of log

Rollback

<$T_0$ start>

<$T_0$, B, 2000, 2050>

<$T_0$, $O_1$, operation-begin>

<$T_0$, C, 700, 600>

<$T_0$, $O_1$, operation-end, (C, +100)>

<$T_1$ start>

<$T_1$, $O_2$, operation-begin>

<$T_1$, C, 600, 400>

<$T_1$, $O_2$, operation-end, (C, +200)>

<$T_0$ , C, 400, 500>

<$T_0$, $O_1$, operation-abort>

<$T_0$, B, 2000>

<$T_0$, abort>

<$T_1$, commit>

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

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

$T_1$ releases lower-level lock on C

T0 decides to abort

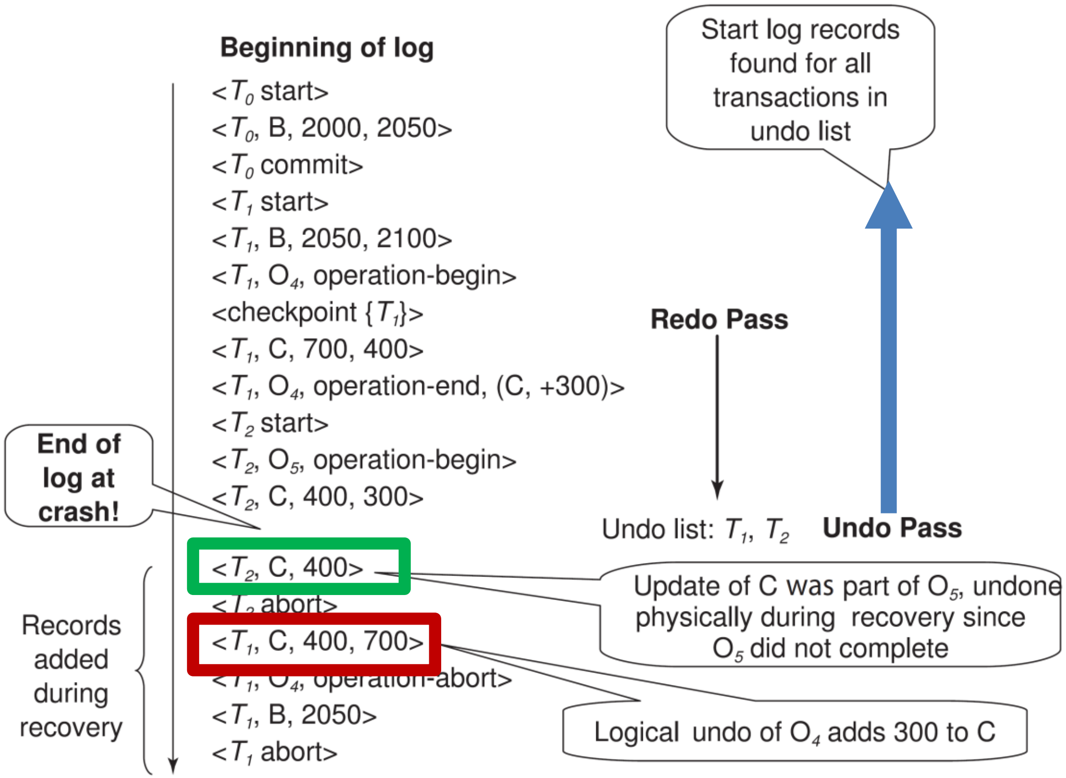
Logical undo of $O_1$ adds 100 to C

$O_1$ undo complete

- 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



**Beginning of log**

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

**End of log at crash!**

Records added during recovery

Start log records found for all transactions in undo list

**Redo Pass**

Undo list: $T_1$, $T_2$

**Undo Pass**

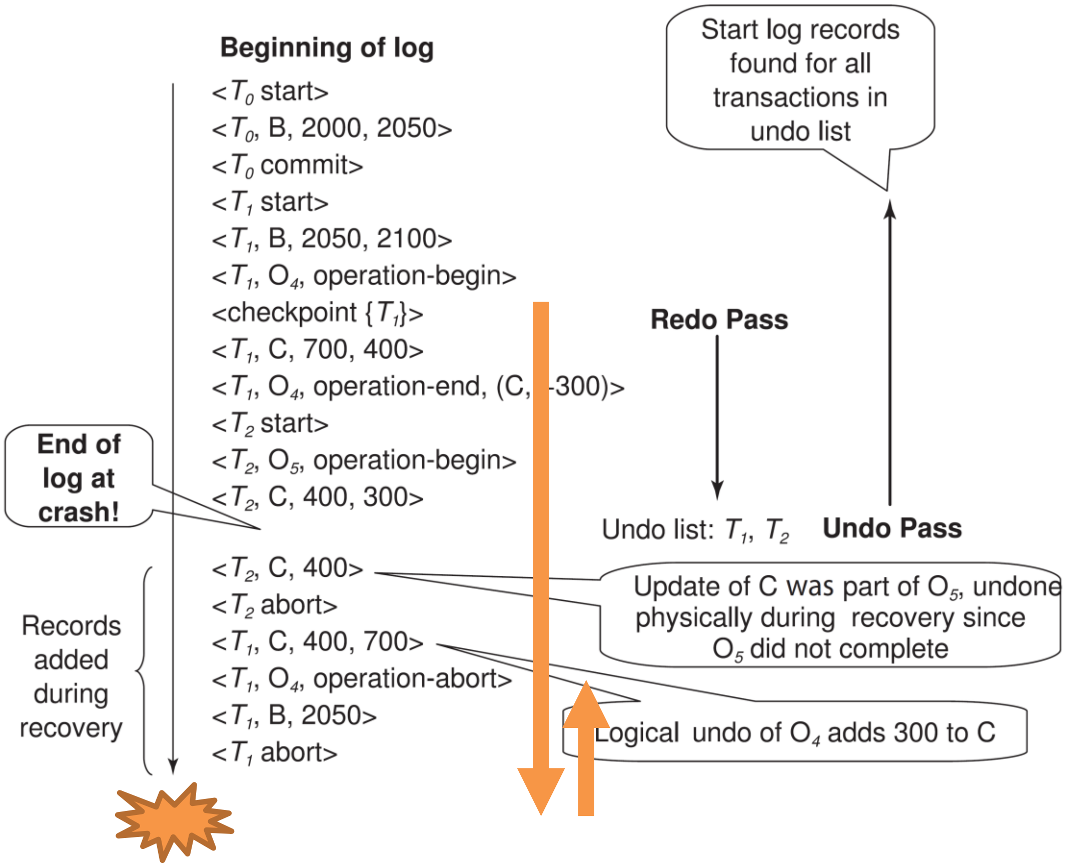
Update of C was part of $O_5$, undone physically during recovery since $O_5$ did not complete

Logical undo of $O_4$ adds 300 to C

- 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



Beginning of log

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

Start log records found for all transactions in undo list

Redo Pass

Undo list: $T_1$, $T_2$

Undo Pass

End of log at crash!

Records added during recovery

Update of C was part of $O_5$, undone physically during recovery since $O_5$ did not complete

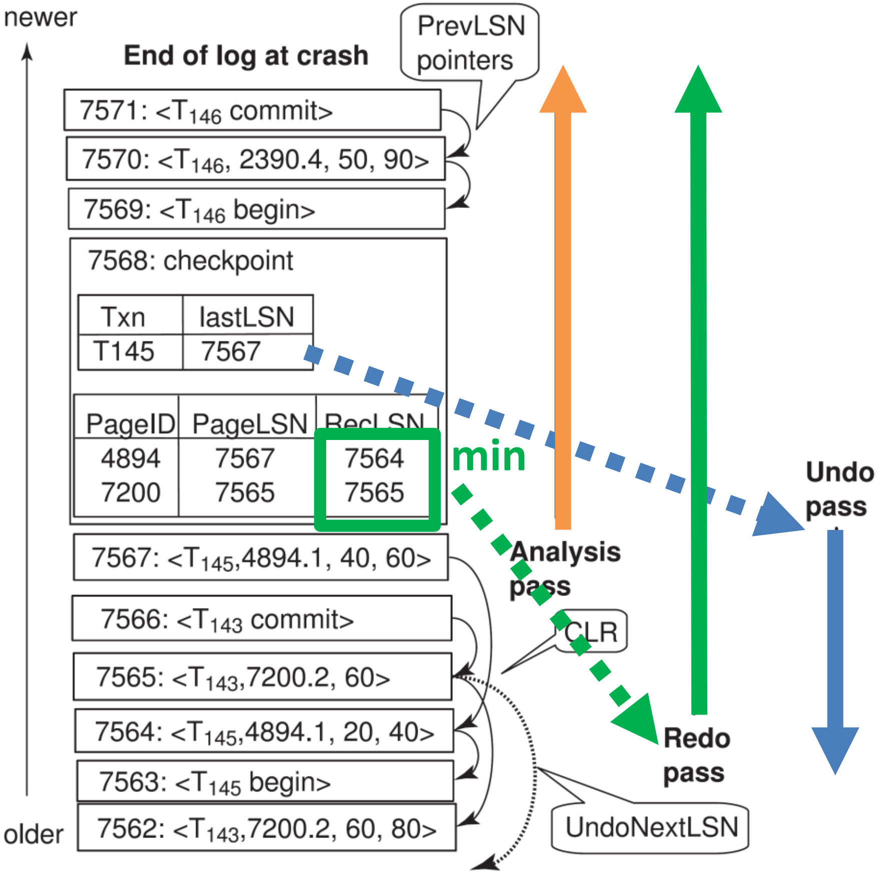
Logical undo of $O_4$ adds 300 to C

# 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



7571: <$T_{146}$ commit>

7570: <$T_{146}$, 2390.4, 50, 90>

7569: <$T_{146}$ begin>

7568: checkpoint

| Txn | lastLSN |
|---|---|
| T145 | 7567 |

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

7567: <$T_{145}$,4894.1, 40, 60>

7566: <$T_{143}$ commit>

7565: <$T_{143}$,7200.2, 60>

7564: <$T_{145}$,4894.1, 20, 40>

7563: <$T_{145}$ begin>

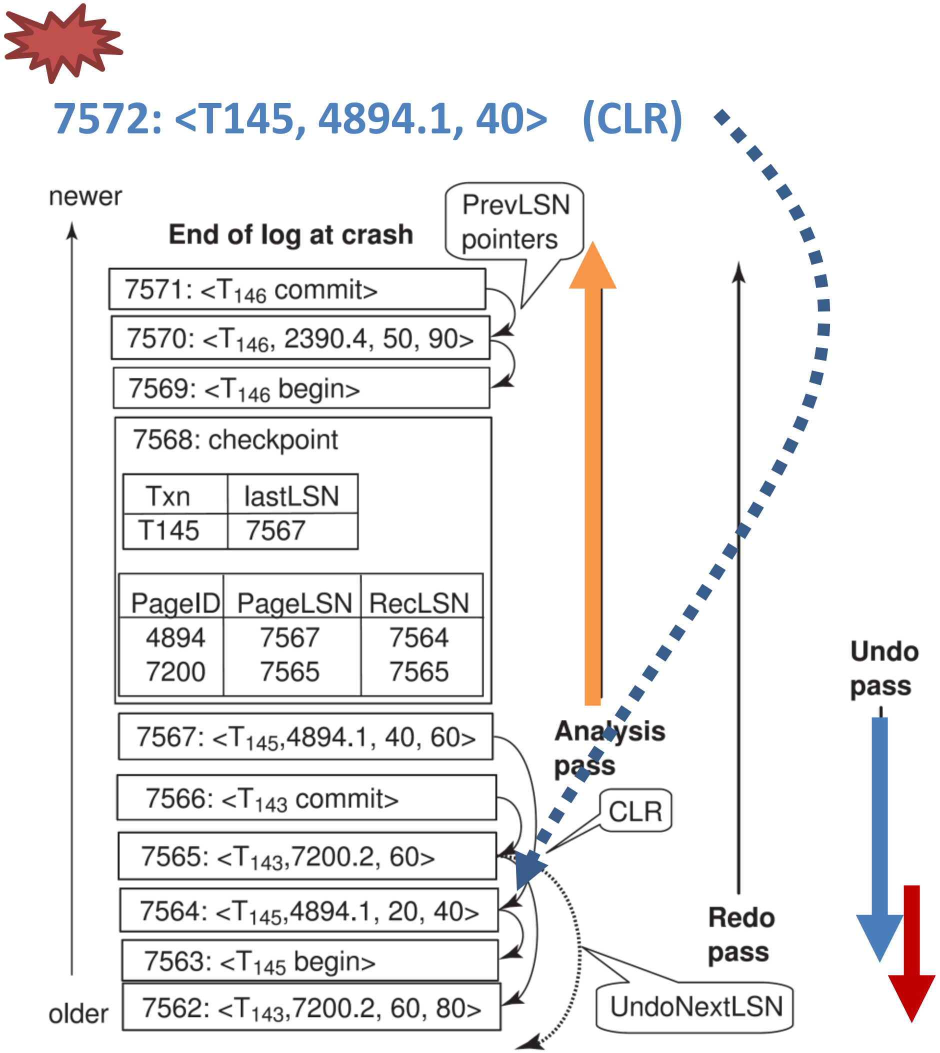
7562: <$T_{143}$,7200.2, 60, 80>

# 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



7572: <T145, 4894.1, 40> (CLR)

7571: <$T_{146}$ commit>

7570: <$T_{146}$, 2390.4, 50, 90>

7569: <$T_{146}$ begin>

7568: checkpoint

| Txn | lastLSN |
|---|---|
| T145 | 7567 |

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

7567: <$T_{145}$,4894.1, 40, 60>

7566: <$T_{143}$ commit>

7565: <$T_{143}$,7200.2, 60>

7564: <$T_{145}$,4894.1, 20, 40>

7563: <$T_{145}$ begin>

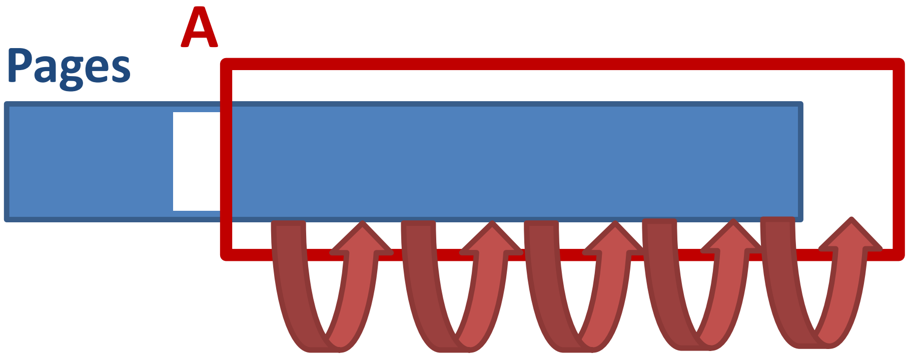
7562: <$T_{143}$,7200.2, 60, 80>

# 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

# 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

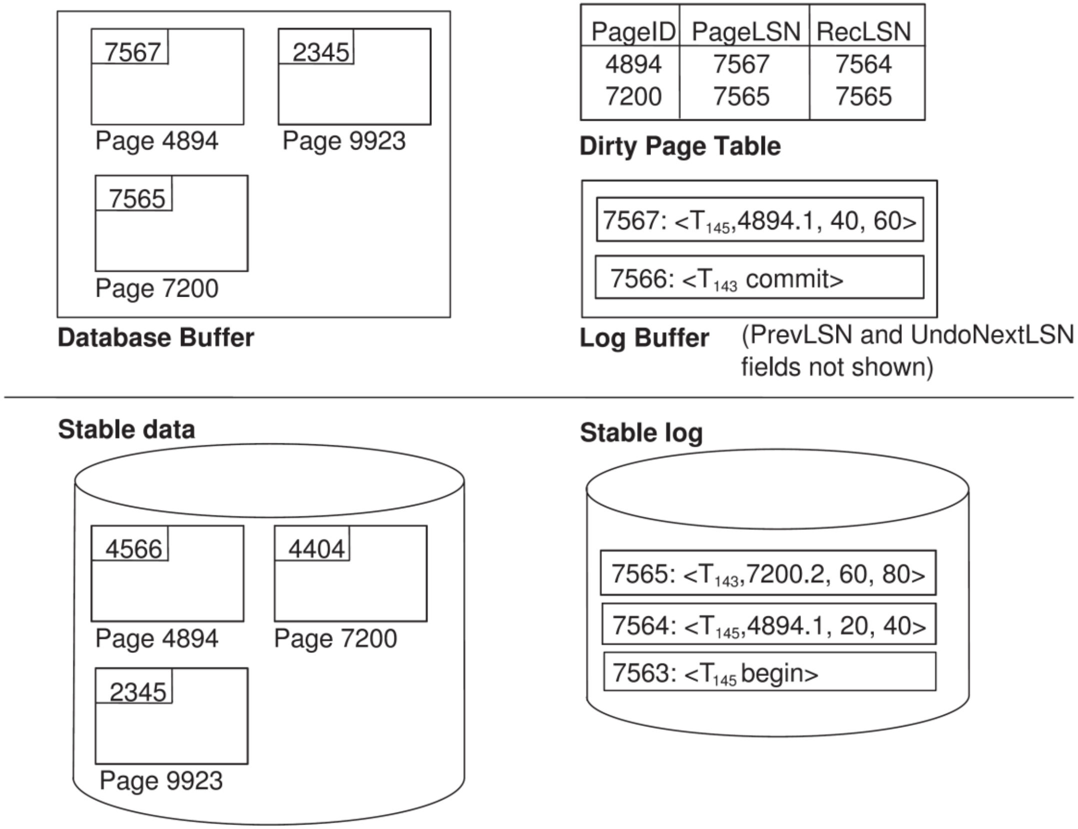
- Observe that, during a sorting op, all physical ops to the same block will be written to disk in just one flush
- Why not log all these physical ops as one logical op?
  - As long as this logical op can be undone logically
- Called ***physiological logs***, in that
  - Physical across blocks
  - Logical 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



7567

Page 4894

2345

Page 9923

7565

Page 7200

Database Buffer

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

Dirty Page Table

7567: <$T_{145}$,4894.1, 40, 60>

7566: <$T_{143}$ commit>

Log Buffer

(PrevLSN and UndoNextLSN fields not shown)

Stable data

4566

Page 4894

4404

Page 7200

2345

Page 9923

Stable log

7565: <$T_{143}$,7200.2, 60, 80>

7564: <$T_{145}$,4894.1, 20, 40>

7563: <$T_{145}$ begin>

# Outline

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