Datenbanksysteme II: Recovery

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Content of this Lecture

- Transactions
- Failures and Recovery
- Undo Logging
- Redo Logging
- Undo/Redo Logging
- Checkpointing

Transactions

- Transactions are the building blocks of operations on data
  - Sequences of SQL commands, possible embed. in a host language
- Motivation: Consistency
  - Data in a database always must be consistent
    - Inconsistency only tolerated temporarily
    - Inconsistency only tolerated in a controlled manner
- Informal definition: Given a consistent database, any transaction that runs in isolation will perform changes such that the database after executing the transaction is consistent again
  - But not necessarily in-between
- Consistent DB + TX + Synchronization $\rightarrow$ Consistent DB

Consistent States

- A database instance should be an image of a fraction of the real world
- Simple consistency rules
  - "Peter" is not an Integer
  - "Lehmann-Krause-Ufflhard-Beiersdorf" is longer than 40 characters
  - Every course at a university can have only one responsible teacher
  - A marriage is a connection between two people
  - There can be no tax rate above 100%
  - -300 ° Celsius is not a valid temperature
- Techniques
  - Data types (real, varchar, date, …)
  - Data model (cardinality of relationships)
  - Constraints: Primary key, unique, foreign key, check, …

Consistent States

- Complex consistency rules
  - If there are no purple cats, the attribute "color" of a relation "pets" must never be "purple" is the attribute "type" is "cat"
  - 29.2.2005 is not a valid date
  - Moving money from one account to another must not change the total amount of money over all accounts
    - To move X Euro from A to B, we must subtract X from account A and add X to account B
    - As things cannot happen at the very same time, in between the database is necessarily inconsistent
- Techniques
  - Trigger
  - Transactions & synchronization

Formally

- TX define consistent states
- Definition:
  A transaction T is a sequence of operations that, when executed in isolation, moves a database from one consistent state into another consistent state.
- All operations on a database must be part of a transaction
  - You might not notice, e.g., autocommit
  - Whenever a TX ends, a new one is started automatically

ACID Properties

- TX are associated with more than consistency
- Atomicity: All-or-nothing: Every TX happens entirely or not at all
- Consistency: Every TX moves a DB from a consistent state to a consistent state
- Isolation: Every TX can act on data as if there were no further TX running concurrently
- Durability: Changes performed by a TX are stable
  - Stable = preserved against failure of many (but not all) kinds

ACID Properties

- Atomicity: Every TX happens entirely or not at all
- Consistency: Every TX moves a DB from a consistent state to a consistent state
  - Recently, highly distributed protocols introduced "eventually consistent"
- Isolation: Every TX can act on data as if there were no further TX running concurrently
  - Not always achieved / achievable – see next lecture
- Durability: Changes performed by a TX are stable
  - Stable = preserved against failure of many (but not all) kinds
  - This is duty of the recovery manager

Transactional Operations

- Start T
  - Usually performed implicitly
  - Every command after an abort or a commit starts a new TX
- Commit T
  - Ends a TX; a consistent state is reached and must be preserved
- Rollback T (abort)
  - Ends a transaction; all changes must be undone
- Savepoint T (makes things easier)
  - Sets a mark in the middle of a transaction (no consistent state)
  - Allows a transaction to be roll-backed to this mark
  - One-level nested transactions

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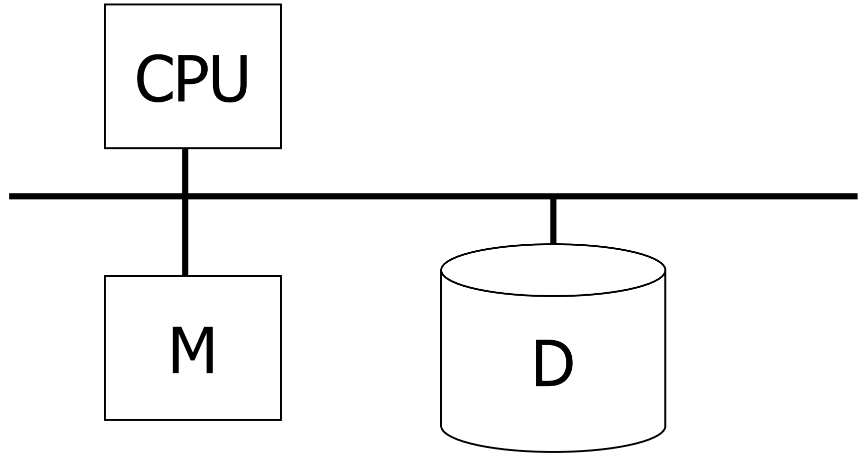
Recovery

- TX are sequences of operations that take time to execute
- If we switch off power in-between
  - No ACID: TX was not executed entirely or nor
  - No ACID: States within a TX are inconsistent by definition
  - No ACID: changes may not be durable

- Recovery: Actions that allow a database to implement transactional behavior (ACID) despite failures
  - By taking proper actions before the failure happens
  - Does only work for some types of failures
- ACID: Next lecture

Hardware Model



- Memory is volatile, disk is durable
- Assumption: Data in memory is lost, data on disk remains
- Types of events
  - Desired events
  - Undesired but expected
  - Undesired and unexpected

Types of Failures

- Undesired but expected
  - Expected and compensated by recovery manager
  - CPU stops
  - Memory is corrupted and CPU stops (CRC check, etc.)
  - RDBMS or OS crashes due to program bug
    - Hopefully not a bug in the recovery manager!
- Undesired and unexpected
  - Not expected by the recovery manager
  - Wrong program
  - Memory is corrupted and CPU does not notice / stop
  - Media failure (but RAID etc.)
  - Machine and all discs burn down (but Backup etc.)
  - Machine gets infected by malicious and clever virus

Recovery

- During DB-startup, the recovery manager must be able to
  - Recognize that there was an error
  - Restore a consistent state of the database
    - All previously committed changes are present (durability)
    - All previously uncommitted changes are not present (atomicity)
    - Hence: Must know about all TX and their states at time of failure
  - Prepare for crash during ongoing recovery
  - Move to normal operations afterwards
  - Should do this as fast as possible

Limits

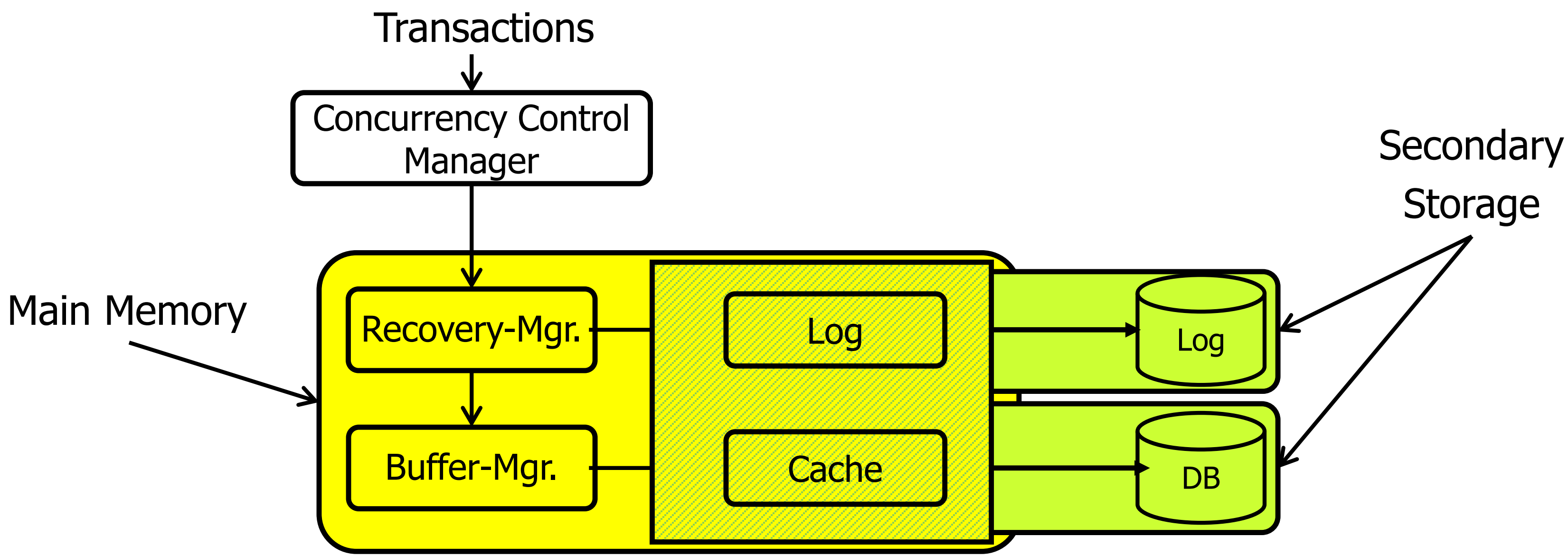
- Still, errors do happen
- Still, recovery does take time
- Still, media failures do occur

- To ensure 24x7x52 operations, use other methods on top
  - Backup, RAID, cluster with failover, hot-stand-by machine, …

First Approach

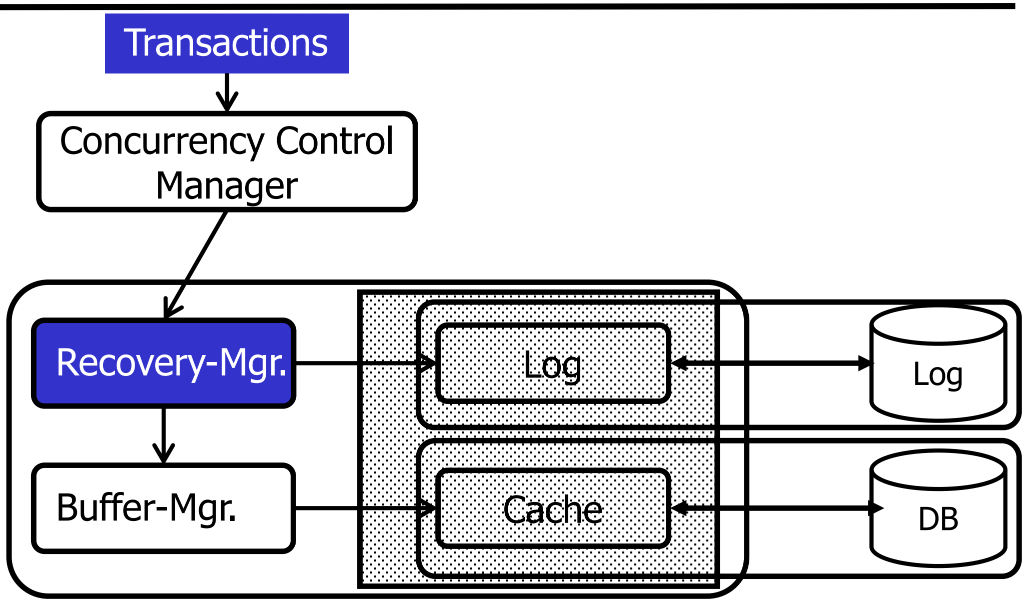
- Naïve approach
  - Phase 1: All changes within a TX are only applied in main memory
    - Never write anything to disk before COMMIT
  - Phase 2: Upon COMMIT, write all changed blocks to disk
- Crash during phase 1
  - Nothing has been written
  - Everything is fine, atomicity and durability is preserved
- Crash during phase 2
  - Some blocks/changes have been written, some not
  - We do not know which, cannot rollback – atomicity / durability hurt
- Imagine you are the recovery manager at start-up time
  - Have there been active transactions?
  - Is the DB consistent or not?

Architecture of a Recovery Manager



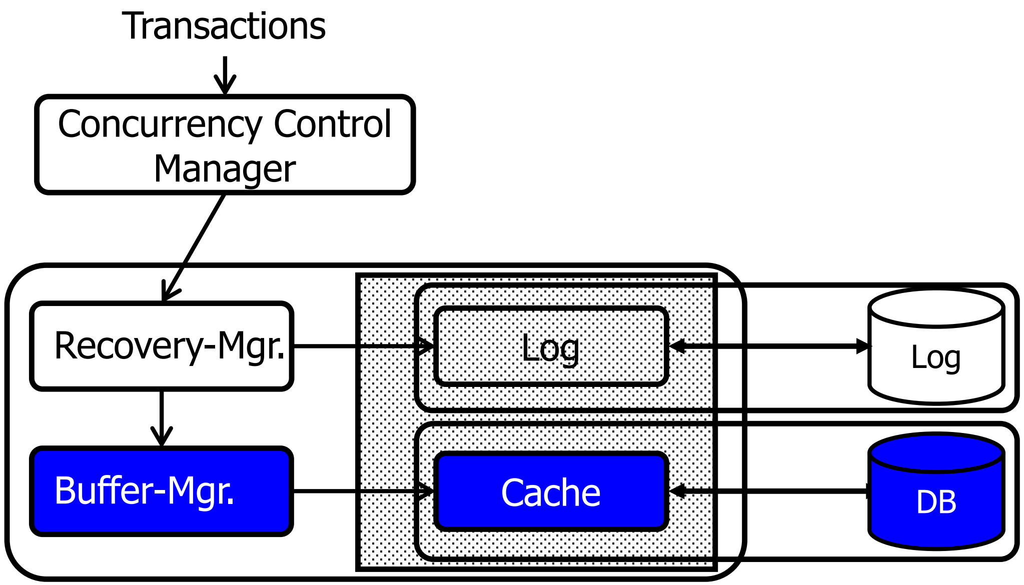
- In the following, we talk of "objects"
  - Usually means tuple (+ attribute)
  - Could also be block (more later)

Transactions



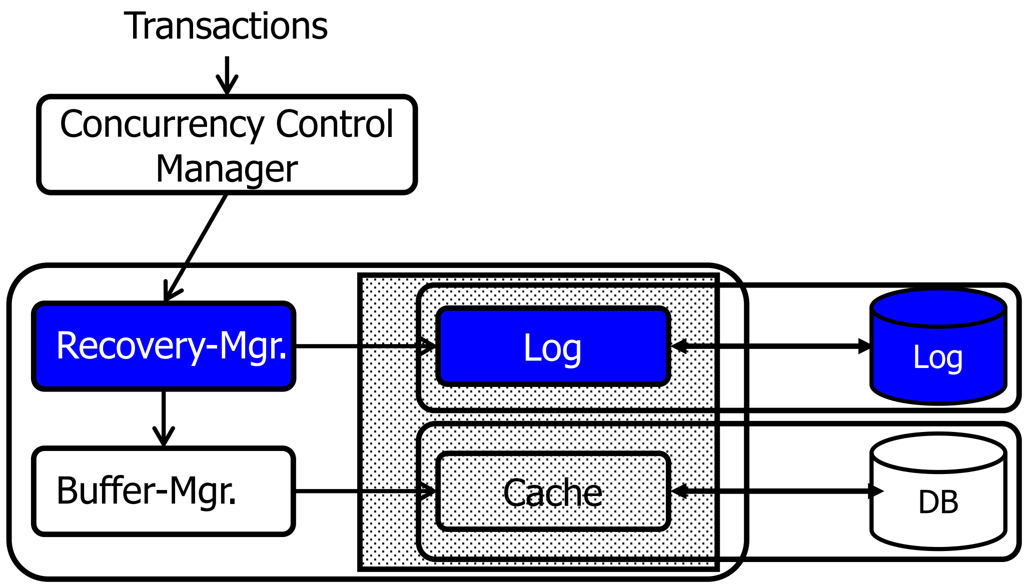
- Transactions do
  - Read(X): Read object from block X
  - Write(X): Write object into block X
  - Commit
  - Abort
- Recovery manager intercepts all commands and performs something “secretly”

Buffer Manager



- Buffer manager
  - Upon read(X): If X not in mem, load(X); give access to block to TX
    - Involves replacing blocks in cache
  - Upon write(X): Change mem, usually nothing happens on disk
- Time between change in block and writing of changed block is unpredictable for buffer manager
  - In particular, a commit does not write anything to disk per-se
  - Aim of buffer manager: Maximize performance, minimize IO

Recovery Manager

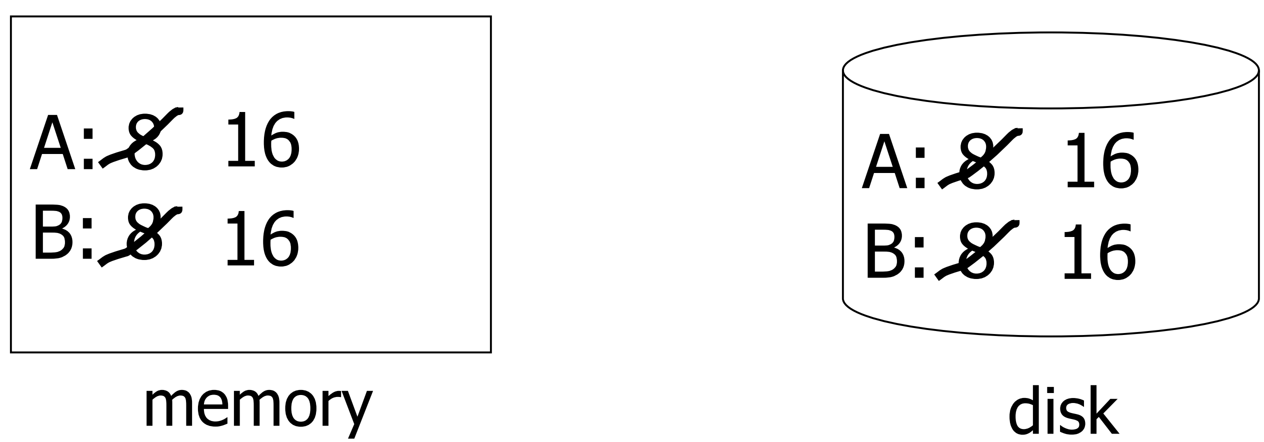


- Intercepts all TX commands
- Performs logging to ensure AC-D
- Decides when logs are written to disk
  - If possible in batches
- Decides when buffers are written to disk
  - If possible in batches

Example Failures

- Assume constraint "A=B" and a transaction T
  - T performs <start; A := A*2; B := B*2; commit;>
- Sequence of operations (assume a write-through)

```
read (A);  A := A*2
write (A);
read (B);  B := B*2
write (B);
commit;
```

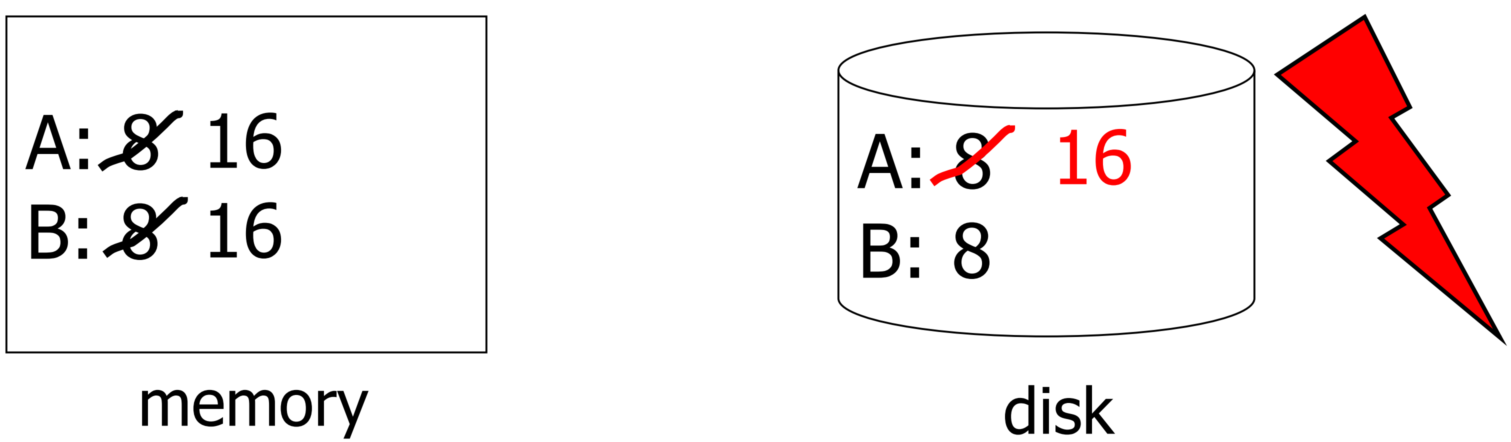


Failures

- Assume constraint A=B and transaction T
  - T performs A := A*2; B := B*2; commit;
- Sequence of operations (assume a write-through)

```
read (A);  A := A*2
write (A);
read (B);  B := B*2
write (B);
commit;
```

failure!



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Undo Logging - Idea

- Short: “Log before block, block before commit”
  - Log – block – commit
  - Old values (before update) are saved to log and written to disk before any changed blocks are written
  - Changed blocks may be written early (before commit)
  - Changed blocks must not be written too late (after commit)
- If a commit happens, new values are on disk
  - Do not allow state “committed” before all blocks have been written
- If a crash happens, old values are in log
  - At recovery, always read from logs; not sure what is in the blocks
- Undo-logging: Premature changes are undone

Detailed Rules

- During transaction processing
  - Buffer manager may write uncommitted changes to disk
    - Gives lots of freedom to write in batches
  - Old value must be in a disk-log before block is written
  - TX state changes are written to log (TX number)
    - State of a transaction can be recovered from log
  - Commits/aborts are also written to log
  - Changed blocks must be on disk before commit is flushed to disk
- During recovery
  - Identify all transactions without commit or abort in log
  - Find all log entries (=old values) of these transactions
  - Undo changes: Replay entries in reverse order

Structure of the Log

$w_{T1}(Y); w_{T1}(X); w_{T1}(Z); abort_{T1}; w_{T2}(Y); commit_{T2}; w_{T3}(Y)$

Transaction	Object	Old value
T1	Y0 → Y1	Y0
T1	X0 → X1	X0
T1	Z0 → Z1	Z0
T1	Abort	
T2	Y0 → Y2	Y0
T2	Commit	
T3	Y2 → Y3	Y2

- Records: <tID, object (tupleId+attribute), old value>
- Commits and aborts are logged

Undo Logging Rules

- Undo logging is based on three rules
  - For every changed object generate undo log record with old value
    - For on INSERT, log a DELETE; for a DELETE, log an INSERT
  - Before a block is written to disk, undo log record must be on disk
  - Before a commit in the log is flushed to disk, all blocks changed by this transaction must have been written to disk
- What does "flushing a commit" mean?
  - Log records (as data blocks) are preferably written in batches
  - Hence, there is a short period between a log operation and the point in time where this record appears on disk
  - Flushing the log = writing all not-yet-written log records to disc
- Reason for third rule
  - All committed transactions are ignored during recovery
  - Hence, if failure between log("commit") and writing of last changed block, database is inconsistent and this is not noticed

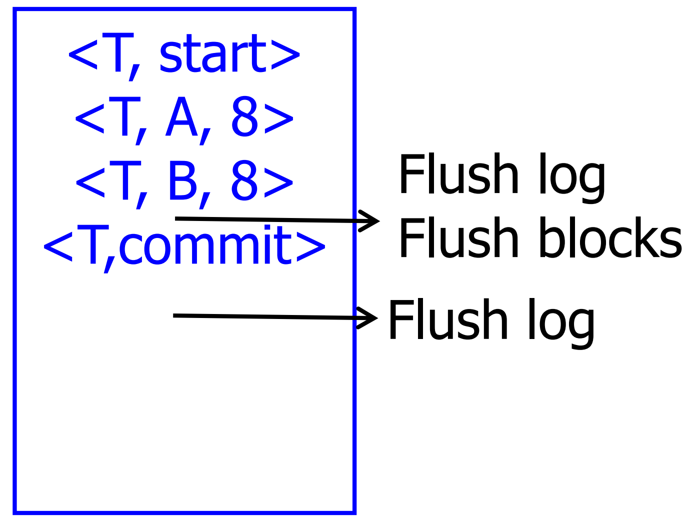
Example

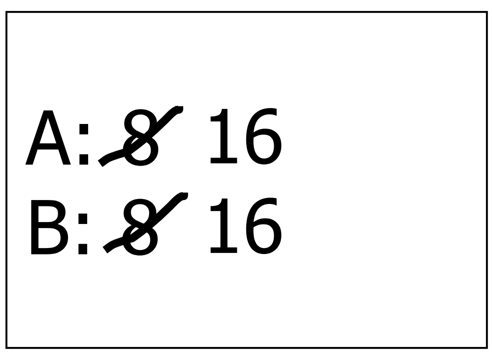
- Sequence of operations
  - `read (A);  A := A*2`
  - `write (A);`
  - `read (B);  B := B*2`
  - `write (B);`

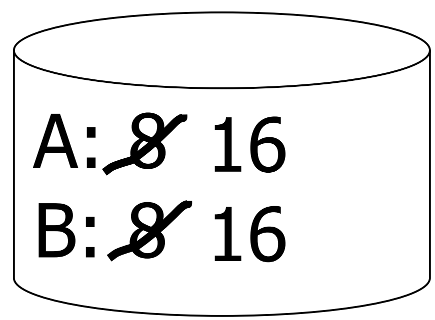
<T, start>
<T, A, 8>
<T, B, 8>

Example – Normal Commit

- Sequence of operations
  - `read (A);  A := A*2`
  - `write (A);`
  - `read (B);  B := B*2`
  - `write (B);`
  - `commit;`







Example – Failure 1

- Sequence of operations
  - **read (A); A := A*2**
  - **write (A);**
  - **read (B); B := B*2**
  - **write (B);**
  - ***read (C); C:=C-A;***
  - ***write (C);***
  - **commit;**

failure!

<T, start>
<T, A, 8>
<T, B, 8>

Flush log

  - Changes have not been written yet
    - But some log data
  - We nevertheless undo as commit not in log
    - Unnecessary undo's could be omitted in principle if block-writes were logged

A: ~~8~~ 8
B: ~~8~~ 8

Example – Failure 2

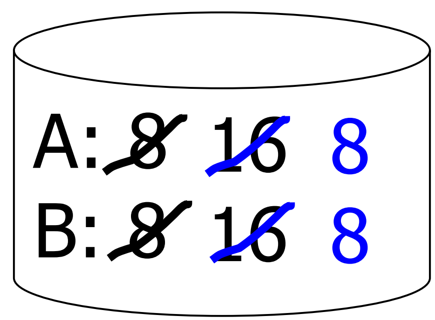
- Sequence of operations
  - **read (A); A := A*2**
  - **write (A);**
  - **read (B); B := B*2**
  - **write (B);**
  - ***read (C); C:=C-A;***
  - ~~***write (C);***~~
  - **commit;**

failure!

<T, start>
<T, A, 8>
<T, B, 8>
<T,C,4>

Flush log
Flush blocks

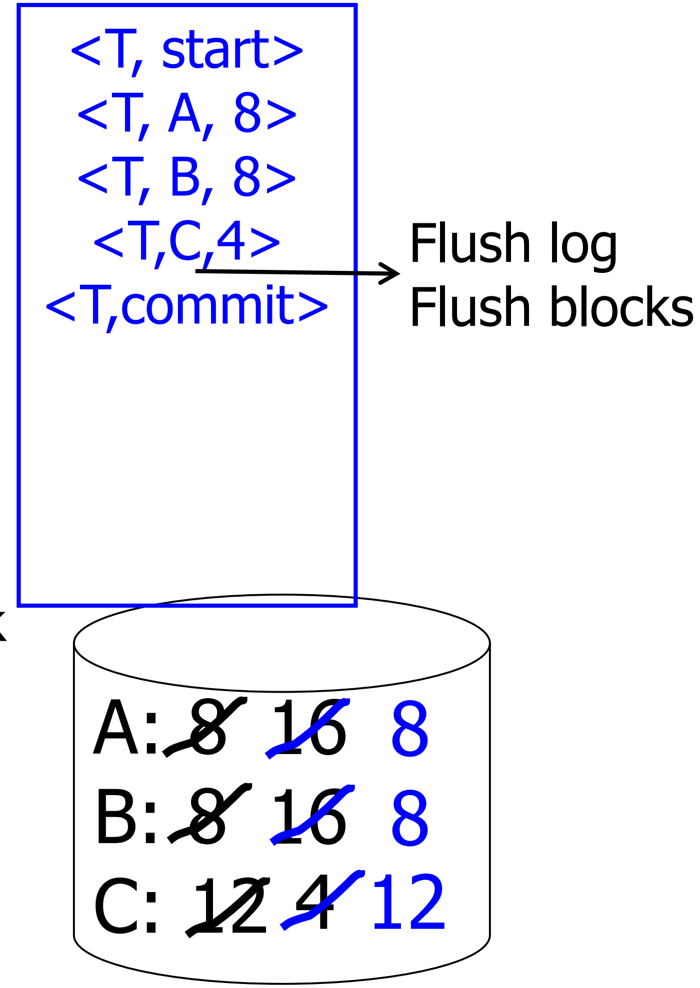
  - Some disk blocks have been written, some not; commit has not been written
  - We must undo



Example – Failure 3

- Sequence of operations
  - `read (A);  A := A*2`
  - `write (A);`
  - `read (B);  B := B*2`
  - `write (B);`
  - *`read (C); C:=C-A;`*
  - *`write (C);`*
  - `commit;`

failure!



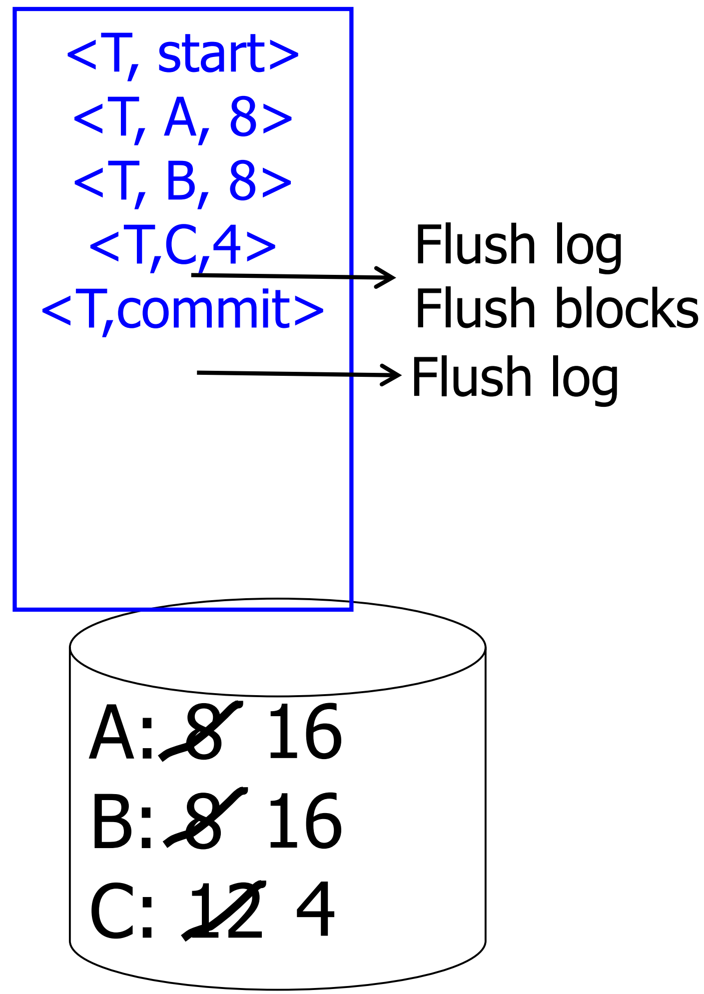
  - Commit has not been flushed to disk yet
  - We must undo all changes

Example – Failure 3

- Sequence of operations
  - `read (A);  A := A*2`
  - `write (A);`
  - `read (B);  B := B*2`
  - `write (B);`
  - *`read (C); C:=C-A;`*
  - *`write (C);`*
  - `commit;`

failure!

  - No problem, TX has finished normally
  - Nothing to do, all committed changes are on disk



Aborts

- Any transaction may abort instead of commit
  - Deliberately (rare)
  - Triggered by sync manager due to synchronization issues
- Abort is treated similar to commit
  - Perform rollback in memory, replacing old values and treating these replacements as writes in the log
    - Need not be done – later
  - Before an "abort" is flushed, all changed blocks must be on disk
    - Some blocks with wrong values might already have been written
    - Such changes of the TX must be undone
- Usage of log data to undo changes during abort
  - Problem: What if logs are already on disk – and only there?
    - Quite possible for long-running TX on heavy-write databases
  - Need to reload logs for performing the abort

Recovery using Undo Logging

- When recovery manager is evoked during start-up
  - Read log from back to front (latest first)
  - When <T,commit> or <T,abort> is encountered, mark this TX and ignore all further records regarding T
    - Updated values are certainly on disk
  - If record <T, X, Y> is encountered without T having been marked before, change X to Y in block on disk
    - That is, undo changes in reverse order
    - Updated value may be on disk
  - If record <T, start> is encountered without T having been marked before, write <T,abort> to end of log
    - Marks this transaction as undone for future recoveries
- Doing all this efficiently is a considerable problem in itself
  - We don’t want to read/write blocks for every change

Two Issues

- We must read the entire log
  - That may take a very long time
  - Checkpointing – later
- What happens if system crashes during recovery?
  - Nothing
  - "Finished recovered" transactions are not undone again (abort has been written)
  - All others are undone
  - Recovery is idempotent

Drawbacks

- Buffer manager is forced to write blocks before flushing commits to log
  - Cannot chose freely when to write to maximize sequential writes
- However, commits should be performed quickly to release locks (see synchronization)
  - Ideally, logs are flushed with every commit
  - Thus, block manager must write blocks all the time
- Trade-Off
  - Batch writes are hindered – bad performance
  - Commits are delayed – bad performance

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Redo Logging

- We twist the idea the other way round
  - Write new values, not old values, to log
  - Do not write blocks before commit, but ensure that blocks are written after commit
  - Do not undo uncommitted transactions, but ignore them
    - Blocks have not been written
  - We redo committed transactions (ignored by undo logging)
    - Blocks might have not been written
- This defers block writes
  - Bad: Long running TX consume all available memory
    - DB might need to generate temporary areas on disk
  - Good: For short running TX, buffer manager has high degree of freedom when to flush blocks

Redo Logging Rules

- Two redo logging rules
  - For every write, generate redo log record containing new value
  - Before any changed block is written to disk, transaction must have finished and all logs (including commit) must be flushed to disk
  - Short: "Log before block, commit before block"
    - Log – commit - block
- Consequence
  - No changes that might have to be reset later are written to disk
  - Good idea: Flush log with every commit to allow buffer manager to evict blocks from memory
    - Removes freedom from log manager
  - Aborts are simple, since no changes have been written to disk; aborted TX may be ignored during recovery
- How does recovery work?

Recovery with Redo Logging

- When recovery manager is evoked during start-up
  - Generate list L of all committed transactions (one scan)
  - Read log from front to back (earliest first)
  - If record <T, X, Y> is encountered with $T \in L$, set X to Y
    - That is, redo change in original order
  - Ignore all other records - uncommitted transactions
- Problem
  - Procedure is idempotent, but we always need to redo all ever committed transactions
    - Undo logging also needs to read the entire log, but not undo transactions again and again at every crash
  - That is very, very slow
  - We really need checkpointing (later)

Wrap-Up

- Undo logging forces too frequent block writes
- Redo logging forces contention in buffer manager and extremely slow recovery
- Solution: Undo/redo logging

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Best of Both Worlds

- We need only two rules
  - Upon change, write old and new value into log
  - Before writing block, always flush respective logs
    - "Respective" – all logs affecting objects of this block
    - WAL: Write ahead logging
  - Short: "Log before block"
- Having old and new values suffices to undo uncommitted transactions (undo logging) and redo committed transactions (redo logging)

Situations

- If block is on disk and commit was flushed, then crash
  - Recovery finds committed TX and redoes changes
    - Rec manager cannot be sure that blocks have been written
  - Introduces unnecessary redoing
- If block is on disk but commit not, then crash
  - Recovery finds missing commit and undoes changes
- If block is not on disk and commit was flushed, then crash
  - Recovery finds commit and redoes changes
- If neither block nor commit is on disk, then crash
  - Recovery finds missing commit and undoes changes
  - Introduces unnecessary undoing

Benefits

- Reduced dependencies between log writes and block writes
- Flushing commits is independent of flushing blocks
  - Lock/log manager can finish transactions and release locks by flushing commits without waiting for the block manager
  - Block manager may write blocks without waiting for transactions to commit (which may take a long time – user interactions, waits, …)
    - But make sure block-specific logs are written first
  - Log manager and buffer manager have more degrees of freedom to organize larger sequential writes

Recovery with Undo/Redo Logging

- When recovery manager is evoked during start-up
  - Collect list L of finished transactions and list U of unfinished transactions
  - Backward pass – read from latest to earliest and undo all changes of transactions in U
  - Forward pass – read from earliest to latest and redo all changes of transactions in L
- This performs all changes of all transactions since DB start again, but …
- … combined with checkpointing, it is very efficient
  - Still generates large log files
  - Strategy for truncation/archiving of log files required

Example

```
1.  <T1,start>
2.  <T1,A,8,16>
3.  <T1,commit>
4.  <T2,start>
5.  <T2,B,4,5>
6.  <T2,A,16,2>
7.  <T3,start>
8.  <T3,C,2,3>
9.  <T3,C,3,7>
10. <T3,commit>
11. CRASH
```

- Potentially on disk at crash: A=2, B=5, C=3
- We should have A=16, B=4, C=7
- Recovery
  - L = {T1, T3}, U = {T2}
  - Backward read
    - Find records with t∈U: entries 5 and 6
    - Undo: write(A,16), write(B,4); log(t2,abort)
  - Forward read
    - Find entries with t∈L: {2, 8, 9}
    - Redo: write(A,16), write(C,3), write(C,7)
- Will this always work?

Slighty Different Example

```
1.  <T1,start>
2.  <T1,A,8,16>
3.  <T1,commit>
4.  <T2,start>
5.  <T2,B,4,5>
6.  <T2,A,16,2>
7.  <T3,start>
8.  <T3,A,2,3>
9.  <T3,C,3,7>
10. <T3,commit>
11. CRASH
```

- What happens?
  - T1 changes A and commits
    - Change will be redone
  - T2 changes B and A and does not commit
    - Changes will be undone
  - T3 reads uncommitted change of A from T2, changes, and commits
    - Change will be redone
- Problem
  - T3 acts under false premises
  - Something is wrong
  - But: Synchronization not our business here

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Checkpointing

- Recovery may take very long
  - Undo logging: Find all uncommitted transactions and undo
  - Redo logging: Find all committed transactions and redo
  - Undo/redo logging: Do both
- But: When a transaction is committed, and all changes are written to disc and log is flushed – no need to touch this transaction any more in any future recovery
- Checkpointing: Define points in time (and in log) such that recovery only needs to go back until "roughly" there
- Notation
  A transaction is called active if it has neither committed nor aborted yet

Blocking (Quiescent) Checkpointing

- Simple way to achieve checkpointing
  - Recovery manager announces checkpoint and flushes “start ckpt” to log
  - No new transactions are allowed
  - System runs until all active transactions finish (with commit or abort) and all dirty blocks have been written
  - Recovery manager flushes “end ckpt” to log
  - DBMS resumes normal operations

Quiescent Checkpointing and Undo Logging

- At recovery time …
- Read from back to front and undo uncommitted transactions
- When the first “end ckpt” is found, recovery is finished
  - All prior transaction have committed or were aborted
  - By the undo logging rules, changes must have been written to disk before commit/abort was flushed to log
- Any “start ckpt” found before the first “end ckpt” is ignored
  - “Before” – logged later in time
  - Some transactions that were active at the “start ckpt” time might have finished before the crash – but not all of them
  - Needs recovery

Quiescent Checkpointing and Redo Logging

- At recovery time …
- Scheme doesn’t work as such – why not?
  - (… non-quiescent checkpointing is better anyway)
- We would need to ensure that all blocks are written to disk before the “end ckpt” is flushed to log
- More dependencies – “end ckpt” is almost like a database shutdown

Non-Quiescent Checkpointing

- Quiescent checkpointing essentially shuts-down DB
- None-Quiescent checkpointing
  - With start of checkpoint, write list of active TXs to log
    - DB always generates new transaction-ID during TX.start
  - When “start ckpt(17,22,23,25)” is found in log during recovery
    - All TX “older than L” had finished before
      - “Older than L”: All TX with ID<17 plus TX with ID≤25 that are not in L
    - Four transactions were active at this point in time
    - Further TX might have become active during the checkpoint (ID>25)

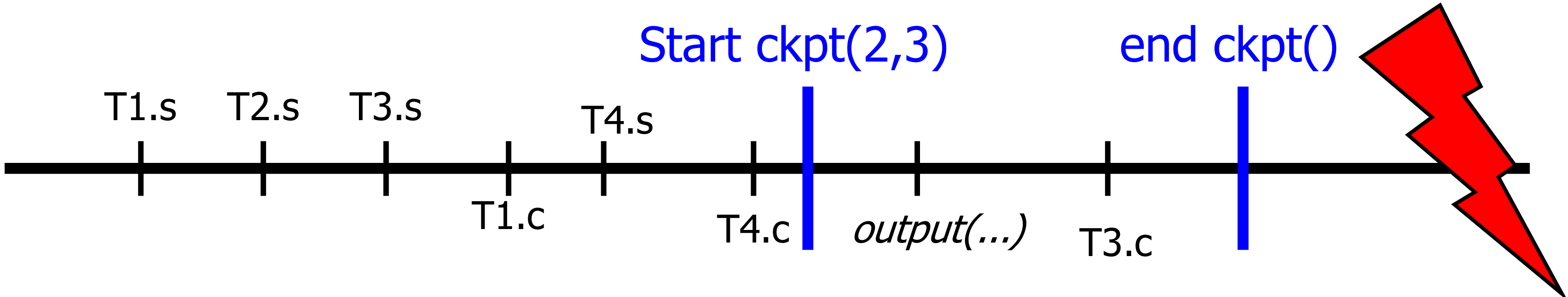
Non-Quiescent Ckpt for Undo/Redo Logging

- Recovery manager flushes “start ckpt(L)” to log
- DB operations continue normally
- All dirty blocks of TX older then L are flushed to disk
  - Need not be performed immediately
  - Advantage: More freedom when to write blocks
  - Disadvantage: Crash before “end chkp” makes checkpoint unusable
- When finished, recovery manager flushes “end ckpt” to log
  - All blocks of TX ”older than L” are certainly on disk
  - These TX can be ignored during all future recovery
- Database operations are (almost) unaffected
  - Needs some bookkeeping of affected blocks

Recovery

- Read back in log
- If a "end ckpt" is found first
  - Locate the corresponding "start ckpt(L)"
  - TX older than L can be ignored
  - Perform undo/redo only for TX in L and later
  - Note: This requires reading also prior to "start ckpt(L)"
    - Log entries for TX in L have started before checkpoint
    - These need to be inspected
    - Idea: Chain log record per TX with backward pointers to avoid scans
- If a "start ckpt(L)" is found first
  - Doesn't help
  - We don't know if all blocks have been written already
  - Read further back to next "end ckpt"

Example



- Recovery
  - Transactions older than (2,3) can be ignored (T1)
  - Transactions 2 is undone (no commit)
  - Transaction 3 is redone (commit but unclear if blocks are on disk)
  - Transaction 4 is redone (considered as newer as L)
    - This can be saves
    - Store with L the highest current transaction ID
    - Change definition of "older than L"

Again: Transactions that Abort

- Assume
  - Transaction T starts at time X
  - Later, “start ckpt(T,…)” starts
  - All blocks are flushed
  - “end ckpt” is flushed, T is still active
  - T aborts regularly
  - System crashes
- On recovery
  - T was active at start of last checkpoint, so treatment necessary
  - Some changes might have been written already (before the end of checkpoint), some not (those after the checkpoint)

Again: Transactions that Abort

- Two options
  - Transaction is considered as not committed
    - All changes are undone
  - Transaction is considered as committed
    - So changes are redone
    - This requires that before a log record “abort” is written to disk, all changes of the transaction must have been undone und this must have been logged
    - Hence, the rollback undoing is redone during recovery

TX, Values, and Blocks

- Blocks in buffer usually contain tuples changed by different transactions
- Undo log: Before commit, all changes must be on disk
  - Will include uncommitted changes – more undoing later
- Redo log: Before commit, no changes may be on disk
  - New problems for buffer manager – always waiting for some active transaction in a block
- Undo/redo logging: No dependency between commit and writing of blocks

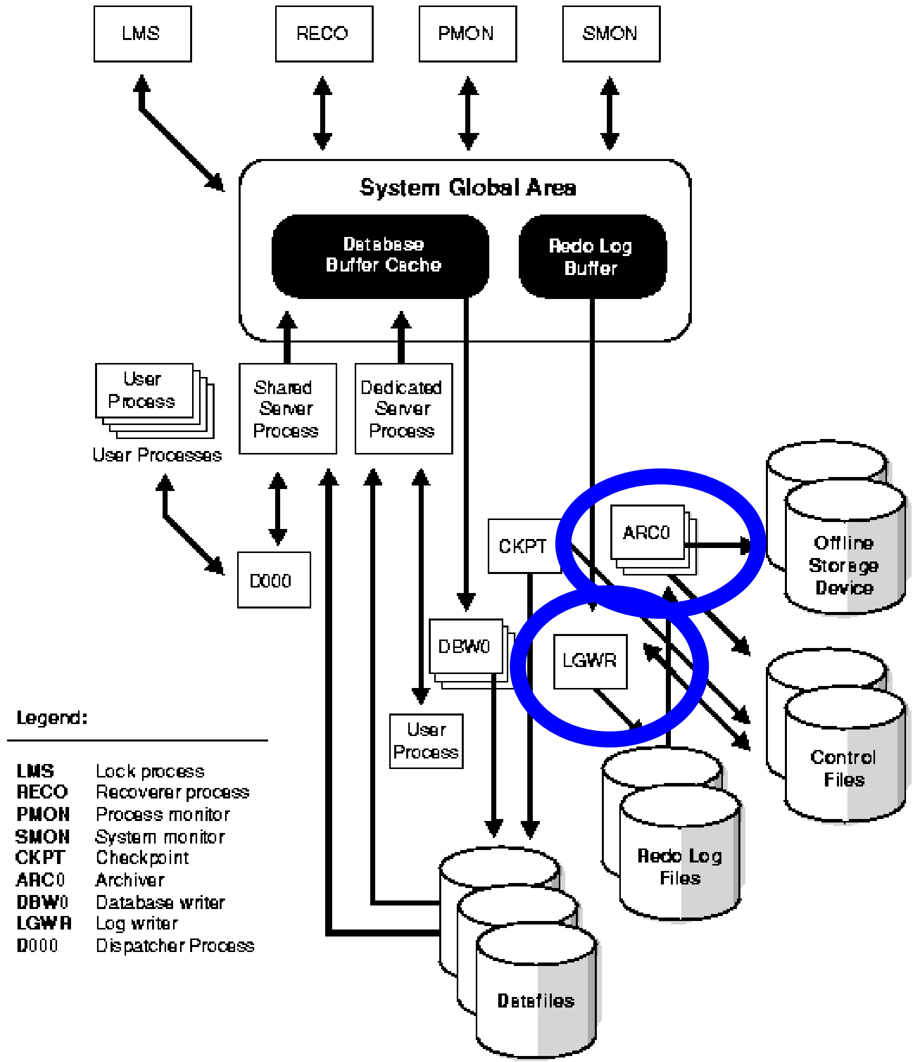
Content of this Lecture

- Transactions
- Failures and Recovery
- Undo Logging
- Redo Logging
- Undo/Redo Logging
- Checkpointing
- Recovery in Oracle

Recovery in Oracle

- Undo/redo logging with non-quiescent checkpointing
  - LGWR server process writes log in batches
  - Logs are maintained in "online redo log groups"
    - Each log is written in each group
    - Protect log from media failure - spread groups over different disks
- Each log group consists of a list of files of fixed max size
  - When last file is full, logging starts filling the first file again
  - In "archive-log" mode, log files are archived before being overwritten
  - When is it save to overwrite logs?
    - With "start ckpt(L)", keep l = "log# of oldest log of any t∈L"
    - When "end ckpt" is reached, all log records older than l can be dumped

Recall


LMS
RECO
PMON
SMON
System Global Area
Database Buffer Cache
Redo Log Buffer
User Process
User Processes
Shared Server Process
Dedicated Server Process
D000
CKPT
ARC0
Offline Storage Device
DBW0
LGWR
User Process
Control Files
Redo Log Files
Datafiles
Legend:
LMS Lock process
RECO Recoverer process
PMON Process monitor
SMON System monitor
CKPT Checkpoint
ARC0 Archiver
DBW0 Database writer
LGWR Log writer
D000 Dispatcher Process

Traveling in Time (Flashback)

- In “archive-log” mode, any point in time is reachable
  - Even committed changes can be undone in principle
- Oracle flashback queries
  - ```
    SELECT X
    FROM Y AS OF TIMESTAMP '2007-07-13 02:19:00'
    WHERE …;
    ```
- Semantics: Return data as of all TX that committed prior to timestamp
  - Implementation: Use undo logs to undo all changes on Y of TX that had not committed prior to t
  - Can rollback some DDL
  - Useful in legal issues (audit: proof what was changed when)
    ```

Total Recall

- Normal logs cannot be accessed from within database
  - No SQL query for "Give me a list of all changes applied to this table since …"
- Versioning: Track changes and make every version easily accessible
  - Linear versioning: At every point in time, there exists one version
  - Hierarchical versioning: Allow different "truths" at same time
    - "whatif analysis"
- Total recall option
  - Tracks all changes per table in immutable "history" tablespaces
  - "Retention" parameter – for how long?
  - Internal implementation: Asynchronous analysis of redo/undo logs
    - No triggers, normal operations not affected