Implementing Atomicity and Durability

Chapter 22

System Malfunctions

- Transaction processing systems have to maintain correctness in spite of malfunctions
  - Crash
  - Abort
  - Media Failure

Failures: Crash

- Processor failure, software bug
  - Program behaves unpredictably, destroying contents of main (*volatile*) memory
  - Contents of mass store (*non-volatile memory*) generally unaffected
  - Active transactions interrupted, database left in inconsistent state
- Server supports atomicity by providing a *recovery procedure* to restore database to consistent state
  - Since rollforward is generally not feasible, recovery rolls active transactions back

Failures: Abort

- Causes:
  - User (*e.g.,* cancel button)
  - Transaction (*e.g.,* deferred constraint check)
  - System (*e.g.,* deadlock, lack of resources)
- The technique used by the recovery procedure supports atomicity
  - Roll transaction back

Failures: Media

- Durability requires that database state produced by committed transactions be preserved
- Possibility of failure of mass store implies that database state must be stored redundantly (in some form) on independent non-volatile devices

Log

- Sequence of records (sequential file)
  - Modified by appending (no updating)
- Contains information from which database can be reconstructed
  - Read by routines that handle abort and crash recovery
- Log and database stored on different mass storage devices
- Often replicated to survive media failure
- Contains valuable historical data not in database
  - How did database reach current state?

Log

- Each modification of the database causes an *update record* to be appended to log
- Update record contains:
  - – Identity of data item modified
  - – Identity of transaction (tid) that did the modification
  - – *Before image* (undo record) – copy of data item before update occurred
    - Referred to as *physical logging*

Log

x	*y*	*z*	*u*	*y*	*w*	*z*
T_1	T_1	T_2	T_3	T_1	T_4	T_2
17	A	2.4	18	ab	3	4.5

most recent database update

- Update records in a log

Transaction Abort Using Log

- Scan log backwards using tid to identify transaction's update records
  - – Reverse each update using before image
  - – Reversal done in last-in-first-out order
- In a strict system new values unavailable to concurrent transactions (as a result of long term exclusive locks); hence rollback makes transaction atomic
- **Problem**: terminating scan (log can be long)
- **Solution**: append a *begin record* for each transaction, containing tid, prior to its first update record

Transaction Abort Using Log

B	U	U	U	U	U	U	U
	x	*y*	*z*	*u*	*y*	*w*	*z*
T_1	T_1	T_1	T_2	T_3	T_1	T_4	T_2
	17	A	2.4	18	ab	3	4.5

abort T_1

Key:
B – begin record
U – update record

- **Abort Procedure**: Scan back to begin record using update records to reverse changes

Logging Savepoints

- *Savepoint record* inserted in log when savepoint created
  - – Contains tid, savepoint identity
- **Rollback Procedure**:
  - – Scan log backwards using tid to identify update records
  - – Undo updates using before image
  - – Terminate scan when appropriate savepoint record encountered

Crash Recovery Using Log

- Abort all transactions active at time of crash
- **Problem**: How do you identify them?
- **Solution**: *abort record* or *commit record* appended to log when transaction terminates
- **Recovery Procedure**:
  - – Scan log backwards - if T's first record is an update record, T was active at time of crash. Roll it back
    - *A transaction is not committed until its commit record is in the log*

Crash Recovery Using Log

B	U	U	U	U	U	C	U	A	U
	x	*y*	*z*	*u*	*y*		*w*		*z*
T_1	T_1	T_1	T_2	T_3	T_1	T_3	T_4	T_1	T_2
	17	A	2.4	18	ab		3		4.5

crash

Key:
- B – begin record
- U – update record
- C – commit record
- A – abort record

- T_1 and T_3 were not active at time of crash

Crash Recovery Using Log

- **Problem**: Scan must retrace entire log
- **Solution**: Periodically append *checkpoint record* to log. Contains tid's of all active transactions at time of append
  - Backward scan goes at least as far as last checkpoint record appended
  - Transactions active at time of crash determined from log suffix that includes last checkpoint record
  - Scan continues until those transactions have been rolled back

Example

← Backward scan

B2	B3	U2	B1	C2	B5	U3	U5	A5	CK	U1	U4	B6	C4	U6	U1

crash

T1
T4
T3

Key:
- U - update record
- B - begin record
- C - commit record
- A - abort record
- CK - checkpoint record

T_1, T_3 and T_6 active at time of crash

Write-Ahead Log

- When *x* is updated two writes must occur: update *x* in database, append of update log record
  - Which goes first?

…………………..update *x*; append to log …………….

crash *crash* *crash*

(no before image in log)

………………..append to log; update *x* ………………….

crash *crash* *crash*

(use before image; it has no effect)

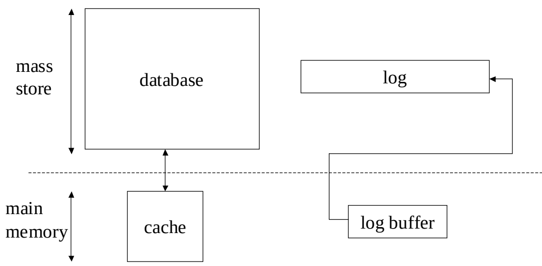
Write-Ahead Log: Performance

- **Problem**: two I/O operations for each database update
- **Solution**: log buffer in main memory
  - Extension of log on mass store
  - Periodically *flushed* to mass store
  - Flush cost pro-rated over multiple log appends
    - This effectively reduces the cost to one I/O operation for each database update

Performance

- **Problem**: one I/O operation for each database update
- **Solution**: database page cache in main memory
  - Page is unit of transfer
  - Page containing requested item is brought to cache; then a copy of the item is transferred to application
  - Retain page in cache for future use
  - Check cache for requested item before doing I/O (I/O can be avoided)

Page and Log Buffering



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Cache Management

- Cache pages that have been updated are marked *dirty*; others are *clean*
- Cache ultimately fills
  – Clean pages can simply be overwritten
  – Dirty pages must be written to database before page frame can be reused

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Atomicity, Durability and Buffering

- **Problem**: page and log buffers are volatile
  – Their use affects the time data becomes non-volatile
  – Complicates algorithms for atomicity and durability
- **Requirements**:
  – Write-ahead feature (move update records to log on mass store before database is updated) necessary to preserve atomicity
  – New values written by a transaction must be on mass store when its commit record is written to log (move new values to mass store before commit record) to preserve durability
  – Transaction not committed until commit record in log on mass store
- **Solution**: requires new mechanisms

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New Mechanism 1

- Forced vs. Unforced Writes:
  – *On database page* –
    - Unforced write updates cache page, marks it dirty and returns control immediately.
    - Forced write updates cache page, marks it dirty, uses it to update database page on disk, and returns control when I/O completes.
  – *On log* –
    - Unforced append adds record to log buffer and returns control immediately.
    - Forced append, adds record to log buffer, writes buffer to log, and returns control when I/O completes.

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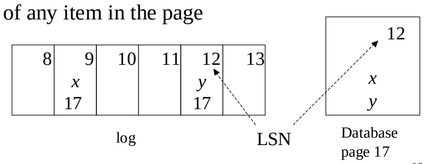
New Mechanism 2

- Log Sequence Number (LSN):
  – Log records are numbered sequentially
  – Each database page contains the LSN of the update record describing the most recent update of any item in the page



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Preserving Atomicity: the Write-Ahead Property and Buffering

- **Problem 1**: When the cache page replacement algorithm decides to write a dirty page, *p*, to mass store, an update record corresponding to *p* might still be in the log buffer.
- **Solution**: *Force* the log buffer if the LSN stored in *p* is greater than or equal to the LSN of the oldest record in the log buffer. Then *write p*. This preserves write-ahead policy.

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Preserving Durability I

- **Problem 2**: Pages updated by T might still be in cache when T’s commit record is appended to log buffer.
  - Once commit record is in log buffer, it may be flushed to log at any time, causing a violation of durability.
- **Solution**: *Force* the (dirty) pages in the cache that have been updated by T before appending T’s commit record to log buffer (*force policy*).

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Force Policy for Commit Processing

1. *Force* any update records of T in log buffer then …
2. *Force* any dirty pages updated by T in cache then …
   - (1) and (2) ensure **atomicity** (write-ahead policy)
3. *Append* T’s commit record to log buffer then …
   - *Force* log buffer for immediate commit or …
   - *Write* log buffer when a group of transactions have committed (g*roup commit*)
   - (2) and (3) ensure **durability**

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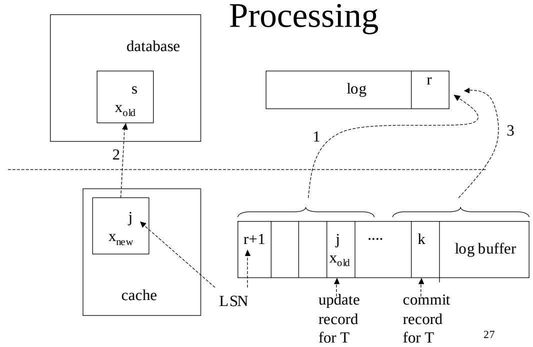
Force Policy for Commit Processing



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Force Policy

- **Advantage**:
  - Transaction’s updates are in database (on mass store) when it commits.
- **Disadvantages**:
  - Commit must wait until dirty cache pages are forced
  - Pages containing items that are updated by many transactions (*hotspots*) have to be forced with the commit of *each* such transaction …
    - but an LRU page replacement algorithm would not write such a page out

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Preserving Durability II

- **Problem 2**: Pages updated by T might still be in cache when T’s commit record is appended to log buffer
- **Solution**: Update record contains *after image* (called a *redo* record) as well as before image
  - Write-ahead property still requires that update record be written to mass store before page
  - But it is no longer necessary to force dirty pages when commit record is written to log on mass store since all after images precede commit record in log
  - Referred to as a *no-force* policy

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No-Force Commit Processing

- Append T’s commit record to log buffer
  - *Force* buffer for immediate commit
  - T’s update records precede its commit record in buffer ensuring updates are durable before (or at the same time as) it commits
- T’s dirty pages can be flushed from cache at any time *after* update records have been written
  - Necessary for write-ahead policy
- T’s dirty pages can be written before or after commit record

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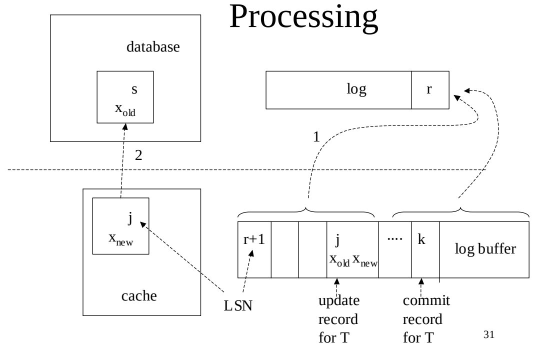
No Force Policy for Commit Processing



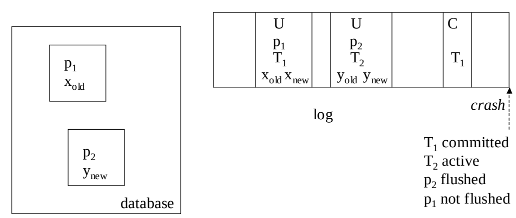
No-Force Policy

- **Advantages**:
  – Commit doesn't wait until dirty pages are forced
  – Pages with hotspots don't have to be written out
- **Disadvantage**:
  – Crash recovery complicated: some updates of committed transactions (contained in redo records) might not be in database on restart after crash
  – Update records are larger

Recovery With No-Force Policy

- **Problem**: When a crash occurs there might exist some pages in database (on mass store)
  – containing updates of uncommitted transaction: they must be rolled back
  – that do not (but should) contain the updates of committed transactions: they must be rolled forward
- **Solution**: Use a *sharp checkpoint*

Recovery With No-Force Policy



p_1 must be rolled forward using x_{new}
p_2 must be rolled back using y_{old}

Sharp Checkpoint

- **Problem**: How far back must log be scanned in order to find update records of committed transactions that must be rolled forward?
- **Solution**: Before appending a checkpoint record, CK, to log buffer, halt processing and force all dirty pages from cache
  – Recovery process can assume that all updates in records prior to CK were written to database (only updates in records after CK *might* not be in database)

Recovery with Sharp Checkpoint

- **Pass 1**: Log is scanned backward to most recent checkpoint record, CK, *to identify transactions active at time of crash.*
- **Pass 2**: Log is scanned forward from CK to most recent record. The *after images* in *all* update records are used *to roll the database forward.*
- **Pass 3**: Log is scanned backwards to begin record of oldest transaction active at time of crash. The *before images* in the update records of these transactions are used *to roll these transactions back.*

Recovery with Sharp Checkpoint

- **Issue 1**: Database pages containing items updated after CK was appended to log *might* have been flushed before crash
  - – No problem – with *physical* logging, roll forward using after images in pass 2 is *idempotent.*
    - Rollforward in this case is unnecessary, but not harmful

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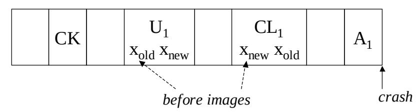
Recovery with Sharp Checkpoint

- **Issue 2**: Some update records after CK might belong to an aborted transaction, T_1. These updates will not be rolled back in pass 3 since T_1 was not active at time of crash
  - – Treat rollback operations for aborting T_1 as ordinary updates and append *compensating log records* to log



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Recovery with Sharp Checkpoint

- **Issue 3**: What if system crashes during recovery?
  - – Recovery is restarted
  - – If physical logging is used, pass 2 and pass 3 operations are idempotent and hence can be redone

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Fuzzy Checkpoints

- **Problem**: Cannot stop the system to take sharp checkpoint (write dirty pages).
  - – Use *fuzzy checkpoint*: Before writing CK, record the identity of all dirty pages (do not flush them) in volatile memory
  - – All recorded pages must be flushed before next checkpoint record is appended to log buffer

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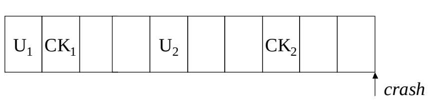
Fuzzy Checkpoints



- Page corresponding to U_1 is recorded at CK_1 and will have been flushed by CK_2
- Page corresponding to U_2 is recorded at CK_2, but *might* not have been flushed at time of crash
  - – Pass 2 must start at CK_1

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Archiving the Log

- **Problem***:* What do you do when the log fills mass store?
  - – Initial portions of log are not generally discarded since they contain important data:
    - Record of how database got to its current state
    - Information for analyzing performance
- **Solution**: *Archive* the initial portion of the log on tertiary storage. Only the portion of the log containing records of active transactions needs to be maintained on secondary store

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Logical Logging

- **Problem**: With physical logging, simple database updates can result in multiple update records with large before and after images
  - **Example** – "insert *t* in *T*" might cause reorganization of a data page and an index page for each index. Before and after images might be entire pages
- **Solution**: Log the operation and its inverse instead of before and after images
  - **Example** - store "insert *t* in *T* ", "delete *t* from *T* " in update record

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Logical Logging

- **Problem 1**: Logical operations might not be idempotent (*e.g.,* "UPDATE T SET x = x+5")
  - Pass 2 roll forward does not work (it makes a difference whether the page on mass store was updated before the crash or after the crash)
- **Solution**: Do not apply operation in update record *i* to database item in page *P* during pass 2 if $P.LSN \geq i$

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Logical Logging

- **Problem 2**: Operations are not atomic
  - A crash during the execution of a non-atomic operation can leave the database in a *physically* inconsistent state
    - **Example** - "insert *t* in *T* " requires an update to both a data and an index page. A crash might occur after *t* has been inserted in *T* but before the index has been updated
  - Applying a logical redo operation in pass 2 to a physically inconsistent state is not likely to work
    - **Example** - There might be two copies of *t* in *T* after pass 2

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Physiological Logging

- **Solution**: Use *physical-to-a-page, logical-within-a-page logging* (physiological logging)
  - A logical operation involving multiple pages is broken into multiple logical mini-operations
  - Each mini-operation is confined to a single page and hence is atomic
    - **Example -** "insert *t* in *T*" becomes "insert *t* in a page of *T*" and "insert pointer to *t* in a page of index"
  - Each mini-operation gets a separate log record
  - Since mini-operations are not idempotent, use LSN check before applying operation in pass 2

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Deferred-Update System

- *Update* - append new value to intentions list (in volatile memory); append update record (containing only after image) to log buffer;
  - write-ahead property does not apply since there is no before image
- *Abort* - discard intentions list
- *Commit* - force commit record to log; initiate database update using intentions list
- *Completion of intentions list processing* - write *completion record* to log

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Recovery in Deferred-Update System

- *Checkpoint record* - contains list of committed (not active) but incomplete transactions
- *Recovery* -
  - Scan back to most recent checkpoint record to determine transactions that are committed but for which updates are incomplete at time of crash
  - Scan forward to install after images for incomplete transactions
  - No third pass required since transactions active (not committed) at time of crash have not affected database

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Media Failure

- Durability requires that the database be stored redundantly on distinct mass storage devices
  1. Redundant copy on (mirrored) disk => high availability
     - Log still needed to achieve atomicity after an abort or crash
  2. Redundant data in log
- **Problem**: Using the log (as in 2 above) to reconstruct the database is impractical since it requires a scan starting at first record
- **Solution**: Use log together with a periodic *dump*

Simple Dump

- Simple dump
  – System stops accepting new transactions
  – Wait until all active transactions complete
  – Dump: copy entire database to a file on mass storage
  – Restart log and system

Restoring Database From Simple Dump

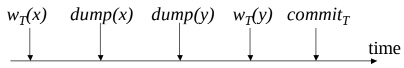
- Install most recent dump file
- Scan backward through log
  – Determine transactions that committed since dump was taken
    - Ignore aborted transactions and those that were active when media failed
- Scan forward through log
  – Install after images of committed transactions

Fuzzy Dump

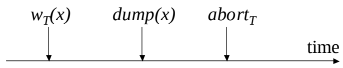
- **Problem**: The system cannot be shut down to take a simple dump
- **Solution**: Use a *fuzzy dump*
  – Write *begin dump record* to log
  – Copy database records to dump file while system active
    - Even copying records of active transactions and records that are locked

Fuzzy Dump

- Dump file might:
  – reflect incomplete execution of an active transaction that later commits



  – reflect updates of an active transaction that later aborts

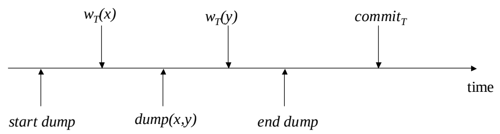


Naïve Restoration Using Fuzzy Dump

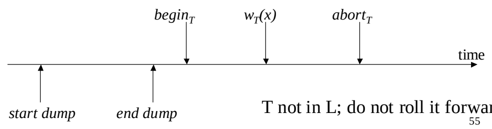
- Install dump on disk
- Scan log backwards to begin dump record to produce list, L, of all transactions that committed since start of dump
- Scan log forward and install after images in update records of all transactions in L

Naïve Restoration Using Fuzzy Dump

- It does some things correctly



T in L; roll it forward



T not in L; do not roll it forward

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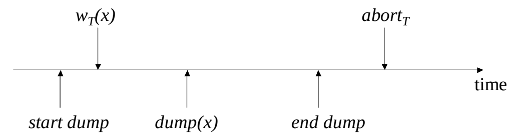
Naïve Restoration Using Fuzzy Dump

- **Problem**: Naïve algorithm does not handle two cases:
  - T commits before dump starts but its dirty pages might not have been flushed until dump completed
    - Dump does not read T's updates and T is not in L .
  - Dump reads T's updates but T later aborts:



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Taking a Fuzzy Dump

- **Solution**: Use fuzzy checkpointing and compensating log records
- Dump algorithm:
  - Write checkpoint record
  - Write begin dump record (BD)
  - Dump
  - Write end dump record (ED)

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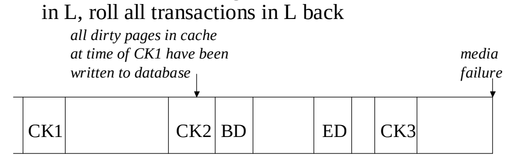
Restoration Using Fuzzy Dump

- Install dump on mass storage device
- Scan backward to CK3 to produce list, L, of all transactions active at time of media failure
- Scan forward from CK1; use redo records to roll the database forward to its state at time of media failure
- Scan backwards to begin record of oldest transaction in L, roll all transactions in L back



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