Database Recovery

- Face it — $#!† happens
- While all systems should have some sort of *recovery scheme* in the event of failure, this is particularly important for databases
- Specifically, we want a database recovery scheme to restore a database to the most recent possible *consistent state* that existed before the failure
- We also want *high availability*: minimize the time during which the database is not usable

Failure Classification

- *Transaction failure:* Individual transactions fail
  - *Logical error:* Internal problem within the transaction
  - *System error:* External problem during transaction execution (e.g., deadlock)
- *System crash:* Problem with overall database server execution; terminates the current process
  - *Fail-stop assumption:* Data in non-volatile storage is unharmed in the event of a system crash
- *Disk failure:* Problem with storage media

Data Storage

- *Volatile storage:* Main or cache memory; very fast, but does not survive a system crash
- *Nonvolatile storage:* Disks, tapes; significantly slower due to eletromechanical element, survives system crashes
  - *Flash memory* is nonvolatile but fast — traditionally too small for databases, but that is changing
- *Stable storage:* Survives *everything*
  - Of course, this is just a theoretical ideal — the best we can do is make data loss sufficiently unlikely

- We can approximate stable storage through redundant copies, copies at different physical locations, and controlled updates of these copies
  - Write to one copy first; upon successful initial write, then write to second copy
  - Recovery involves comparing the copies, and replacing the copy with a detectable error (i.e., checksum) or replacing the copy that was written first if no detectable error
- Data access involves different layers of storage space: *physical blocks* on disk, *buffer blocks* in a designated main memory *disk buffer*, and private *work areas* for each transaction, also in main memory
  - *input(B)* and *output(B)* transfer between physical and buffer blocks
  - *read(X)* and *write(X)* transfer between buffer blocks and the work area, possibly triggering *input*(B_X) automatically
  - A *buffer manager* decides when buffer blocks should be written back to physical blocks
  - When needed, the database system can perform a *force-output* with a direct *output(B)* call

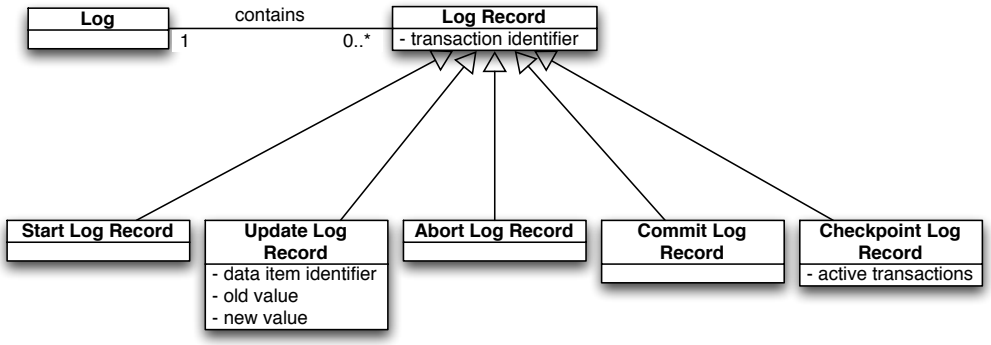
Recovery and Atomicity

- We can't perform *output(B)* in the middle of a transaction — if it fails midway, then the database will be in an inconsistent state, thus violating a transaction's atomicity property
- Rule of thumb: modify the nonvolatile database storage only after we are sure that a transaction will commit
- General approach: first record a transaction's modifications in a separate space, then transfer from that space to database blocks only after the transaction commits successfully

Log-Based Recovery

- *Logs* are the most widely-used approach for recording database modifications
- A log consists of a sequence of *log records*
- A database write is recorded in an *update log record*, which consists of:
  - *Transaction identifier* indicates the writing transaction
  - *Data-item identifier* indicates what was written (typically on-disk location of item)
  - *Old, new values* of the item before and after the write

Log Data Model



- Write the log record before modifying the database
- Undo is possible through the *old value* attribute
- Log should be written to stable storage

Deferred Database Modification

- Perform *write* operations only after the transaction partially commits (i.e., performs last action)
- Ignore log records for failed transactions
- *redo*(T_i) operation rewrites all of the data items modified by T_i (as recorded in the log) — must be *idempotent*, meaning that executing *redo*(T_i) once must have the exact effect as executing it multiple times
- To recover after a failure: perform *redo*(T_i) for T_i that have both *start* and *commit* log records

Immediate Database Modification

- Write database modifications immediately; while a transaction is active, its modifications are called *uncommitted modifications*
- Upon failure, perform *undo(T_i)* to write old values back to the database for failed transactions — again, must be idempotent
- To recover, perform *undo(T_i)* for transactions that have a *start* record but not *commit*, and perform *redo(T_i)* for transactions that have both *start* and *commit* records

Checkpoints

- Not practical to scan the *entire* log upon failure — after all, a lot of writes don't need to be redone
- So we perform a periodic *checkpoint operation*: output (1) pending log records to stable storage, (2) modified buffer blocks to disk, then (3) *checkpoint log record* to stable storage
- On failure, (1) find the most recent checkpoint, (2) find the last transaction started before that checkpoint, then (3) perform recovery for that transaction and all those after

Recovery with Concurrent Transactions

Some things to consider when multiple concurrent transactions are active (note that we still have one disk buffer and one log):

- During an undo, we should scan the log backward, to ensure the proper restoration of an item that has been written multiple times
- Any transaction that writes *Q* must either commit or be rolled back (with accompanying *undo*s from the log) before another transaction writes *Q* again — strict two-phase locking will ensure this

- Checkpoint log records must include a list of active transactions at the time of the checkpoint — otherwise, we wouldn't know how when to stop scanning the log
- Recovery algorithm then requires two passes: one to determine the transactions to undo and redo, and another to perform the actual undo and redo
  - Scan the log backward, up to the most recent checkpoint log record
  - Every committed transaction goes to the *redo-list*
  - Every started transaction not already in the redo-list goes to the undo-list
  - Transactions in the checkpoint log record not already in the redo-list go to the undo-list
- The second pass then performs the data modifications:
  - Scanning backward, undo all updates by transactions in the undo-list
  - Going forward from the most recent checkpoint log record, redo all updates made by transactions in the redo-list

Buffer Management

- Recall that the journey from main memory to disk still goes through a volatile section — the disk buffer
- Unlike main memory, the disk buffer's minimum storage matches the disk — typically *blocks*
- Since the information we read/write (log records, data items) tend to be much smaller than a disk block, it's impractical to write out entire blocks for every single logical read/write from main memory
- So we need some tweaks for efficiency's sake, without detracting from our recovery techniques

Log-Record Buffers

- Since log records are small compared to blocks, it's costly to touch stable storage for *every* log record
- So we buffer the logs too…but then, those would be lost on a system crash, so we need to make sure that log-record buffering doesn't break recoverability:
  - Transactions get the commit state only after their commit log records reach stable storage
  - The commit log record should be the last log record to reach stable storage
  - Before a data block is written to the database, all log records for data items in that block must reach stable storage
- That last rule is called the *write-ahead logging (WAL) rule* — keep that in mind, because you'll hear it again later

Database Buffers

- Database size is generally much larger than available main memory, so we sometimes need to *swap out* blocks as we read data items from the database
  - ♢ Sounds like virtual memory? That's because it is!
- With the write-ahead logging rule, we can't swap out a block until log records for that block's data are written
- While waiting on the write-ahead, we acquire a *latch* — a small, short-duration lock — on the block whose log entries are being written, so that no writes on that block can take place during the write-ahead

But What About Disk Failures?

- So far, all of these recovery techniques pertain to *system crash* errors — loss of volatile storage
- To protect against disk failures, where are our nonvolatile storage media goes bad, we perform operations that are very similar to standard file backup — we *dump* or copy the entire database to another form of nonvolatile or stable storage
- We disallow transactions during a dump, and dumps should include log records too; we can even create a new *dump log record* type so the dump goes in the log

Remote Backup

- To complete our recovery picture, we must realize that failures may have external causes — fires, floods, black holes — and so we need to have some form of physical separation for our storage devices
- We say that our main database server resides (in the real world) in the *primary site*, and we establish a *remote backup* or *secondary site* that is sufficiently separated from the primary site to protect against external disasters

- Practical synchronization can be done by sending log records from the primary to the secondary site; full replication (dumps) may occur, but less frequently
- Upon primary site failure, the secondary site (1) performs recovery as discussed previously, then (2) takes over transaction processing
- A few things to consider with remote backups:
  - Reliable detection of failure (i.e., no false alarms)
  - Transfer of control — when the primary site comes back, it can either become primary again, or become the new secondary site
  - Minimal recovery time — ideally, a secondary site should act upon the log records that it receives, making it a *hot spare* of the primary site
  - Time to commit — a tradeoff exists here between full transaction durability and commit times for a transaction: to ensure full durability, a transaction at the primary site shouldn't commit until its log records have reached the secondary site, thus requiring more time

Advanced Recovery Techniques

- Note how recovery may trade off concurrency and availability to protect against lost or inconsistent data
- While this is worthwhile, more sophisticated recovery techniques seek to have their cake and eat it too
- The state of the art in recovery is the *algorithm for recovery and isolation exploiting semantics* (ARIES) — details in the text and the literature
- While more complex, ARIES achieves less overhead and greater efficiency while maintaining recoverability

Recovery in PostgreSQL

- Again, concepts hit reality fairly directly with PostgreSQL — it uses write-ahead logging (WAL) to facilitate recovery
- Assorted parameters configure the recovery system:
  - Buffer-to-disk (*"sync"* in PostgreSQL terms) settings
  - Commit delays to allow multiple transaction log entries to reach the disk in a single call
  - Maximum "distance" between checkpoints (both in terms of log size and passage of time)