Transactions and Crash Recovery

CPS352: Database Systems

Simon Miner
Gordon College
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Agenda

- Check-in
- Transactions
- Design Project Presentations
- Crash Recovery

Check-in

Ensuring Data Integrity

- Issues related to preserving data integrity
  - Concurrency control
  - Crash control
- *Transactions* are a key concept at the heart of these matters
- Database is in a *consistent* state if there are no contradictions between the data within it
  - Temporary inconsistencies occur by necessity, but must not be allowed to persist
  - Example: transfer of funds between bank accounts

Transactions

Transactions are Atomic and Preserve Consistency.

- A transaction is an atomic operation (unit of work) involving a series of processing steps including:
  - One or more reads from the database (one read per item)
  - One or more writes to the database (one write per item)
  - Data computations can happen during a transaction, but the database is mostly concerned with reads and writes
- If the database is in a consistent state at the start of the transaction, it will be in a consistent state at the end of the transaction

ACID

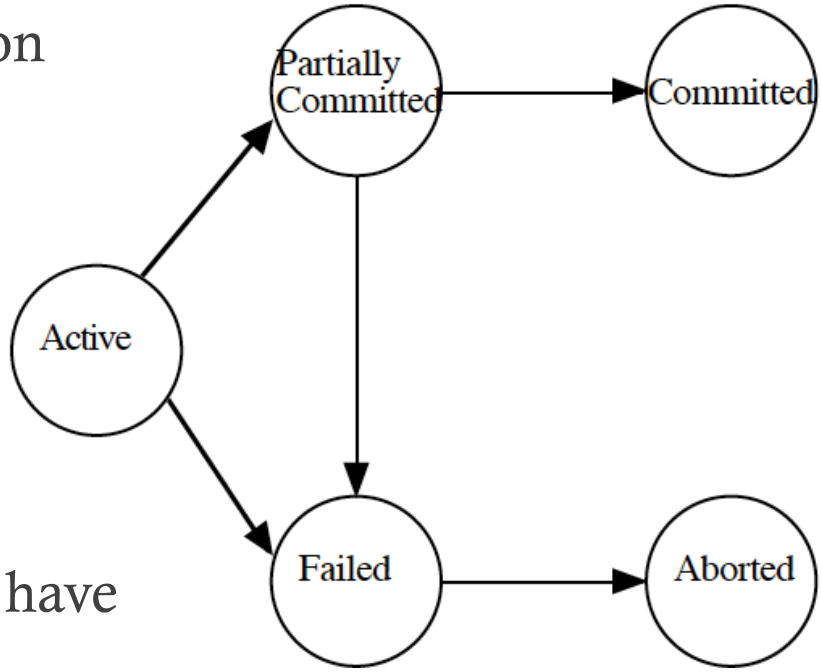
- **A**tomicity – either all of the transaction completes, or none of it completes
  - If any part of the transaction fails, all effects of it must be removed from the database
- **C**onsistency – database ends the transaction in a consistent state (provided it started that way)
- **I**solation – concurrently executing transactions must be unaware of each other (as if they ran serially)
  - It should look to one as if the other has not started or has already completed
- **D**urability – a transaction's effects must persist in the database after it completes

Explicit vs. Implicit Transactions in SQL

- Explicit (within application code)
  - begin transaction (txn)
  - end transaction (txn)
- Implicit (more common)
  - Commit – complete a transaction / write its results to the database
  - Rollback – back out all effects of the transaction
  - Transaction implicitly begins when a program or database session starts
    - Commit or rollback end this transaction and (implicitly start another one)
    - If part of a transaction fails, it must be explicitly rolled back in the code
  - Autocommit – each (DML) SQL statement in the program / session treated as an individual transaction and committed upon completion

Transaction States

- Active – from the time a transaction starts until it fails or reach its last statement
- Partially committed – last statement executed, but changes to database are not yet permanent (SQL commit)
- Committed – changes to database have been made permanent



- Failed – logic error or user abort has precluded completion, and transaction's changes must be undone (SQL rollback)
- Aborted – all effects of the transaction have been removed

Schedules

- Transaction consists of a set of read and write operations
  - Other computations as well, but reads and writes are critical, since they are the means that one transaction interacts with another
- For two or more concurrent transactions, the relative sequence of their read and write operations constitutes a *schedule*
- Example: simultaneous $50 deposit to and $100 withdrawal from a checking account
  - In SQL, these two transactions might look like this
    - update checking_account
set balance = balance + 50
where account_no = :acct
    - update checking_account
set balance = balance – 100
where account_no = :acct
  - Each update statement actually consists of a read and a write operation

Possible Schedules (1)

Schedule	Deposit (T_1)	Withdrawal (T_2)	Final Balance
S_1	read(1000) write(1050)	read(1050) write(950)	950
S_2	read(1000) write(1050)	read(1000) write(900)	900
S_3	read(1000) write(1050)	read(1000) write(900)	1050

Possible Schedules (2)

Schedule	Deposit (T_1)	Withdrawal (T_2)	Final Balance
S_4	read(900) write(950)	read(1000) write(900)	950
S_5	read(1000) write(1050)	read(1000) write(900)	1050
S_6	read(1000) write(1050)	read(1000) write(900)	900

We Want Serial or Serializable Schedules!

- The schedules which yield the correct result are both *serial*
  - One transaction is executed in its entirety before the other starts
  - Serial schedules always lead to consistent results
    - Non-serial schedules can sometimes also yield consistent results, but determining this is not always algorithmically feasible
- To preserve data integrity, ensure that a schedule of concurrent operations is *serializable* – equivalent to some serial schedule

Equivalence of Schedules

- Two schedules are considered *equivalent* if operations in one schedule can be rearranged into another schedule
  - Without altering the resulting computation
- Example:
  - S_1 can be converted to S_2
  - Swap write(A) and read(B) operations
- Note that operations in the same schedule cannot be reordered
  - Could lead to changes in transaction's computation

Schedule	T_1	T_2
S_1	read A write A	 read B write B
S_2	read A write A	 read B write B

Conflicting Operations between Transactions

- Two operations in two different transactions *conflict* if
  - They access the same data item (same column value in a single record)
    - Not same column in different records
    - Not different columns in same record
  - At least one of the operations is a write
  - Changing the relative order of two conflicting operations can result in different final outcomes
- Examples:
  - Schedules 1, 2, and 3 have conflicting operations – reordering operations would lead to different outcomes
  - Schedules 4 and 5 do not have operations in conflict – no writes

Schedule	T_1	T_2
S_1	write A	read A
S_2	read A	write A
S_3	write A	write A
S_4	read A	read A
S_5	read A	read A

Conflict Equivalence

- Two schedules S_1 and S_2 on the same set of transactions are *conflict equivalent* if one can be transformed into the other by a series of interchanges of non-conflicting operations
- Examples
  - S_1 and S_2 are conflict equivalent
    - Access different data items
  - S_3 and S_4 are not conflict equivalent
- A schedule is *conflict serializable* if there is a serial schedule to which it is equivalent

Schedule	T_1	T_2
S_1	read A write A	read B write B
S_2	read A write A	read B write B
S_3	read A write A	read A write B
S_4	read A write A	read A write B

View Equivalence

- Two schedules S_1 and S_2 on the same set of transactions are *view equivalent* if
  - Some transaction in both schedules reads the initial value of the same data item
  - If in S_1 some transaction reads a data item that was written by another transaction, the same holds for the two transactions in S_2
  - If a transaction does the last write to some data item in S_1, it also does the last write to the same data item in S_2
- This is less strict than conflict equivalence
  - Requires that two schedules have the same outcome, but don't necessarily get there the same way (conflict equivalent)
  - Conflict equivalence implies view equivalence, but not vice versa
- A schedule is *view serializable* if it is view equivalent to some serial schedule

Equivalence ≠ Producing the Same Result

- Two equivalent schedules (by either standard) will always produce the same final results
  - But not vice versa
- Example: from account deposit and withdrawal schedules
  - S_1 and S_2 produce same result, but are not equivalent

Schedule	Deposit (T_1)	Withdrawal (T_2)	Final Balance
S_1	read(1000) write (1050)	read(1050) write(950)	950
S_4	read(900) write(950)	read(1000) write(900)	950

Testing for Serializability Ensures Consistency

- To ensure correctness of concurrent operations, ensure that the schedule followed is serializable
- Want to test a schedule for serializability
  - Can be very expensive to test for view serializability,
  - More feasible to test for conflict serializability

Precedence Graph

- Construct a *precedence graph* of a schedule to test it for conflict serializability
  - Each transaction is a node on the precedence graph
  - There is a directed edge between two transactions if there are conflicting operations between them – that is, at least one of the following occurs
    - T_1 reads an item before T_2 writes it
    - T_1 writes an item before T_2 reads it
    - T_1 writes an item before T_2 writes it
- If the resulting graph contains a cycle, the schedule is not conflict serializable
- If there are no cycles, then any topological sorting of the precedence graph will give an equivalent serial schedule

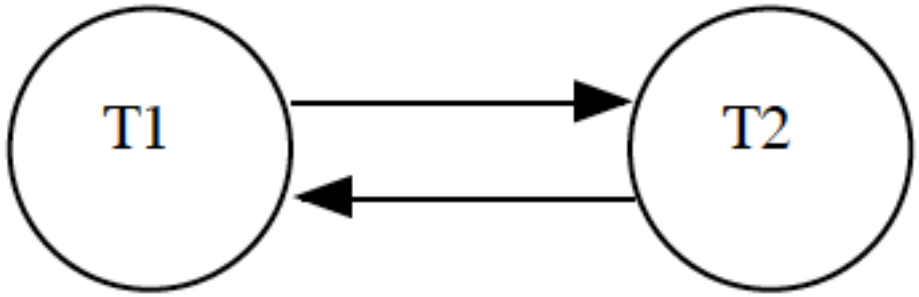
Precedence Graph Example 1

- Consider S_2 from the deposit/withdrawal schedules

Schedule	Deposit (T_1)	Withdrawal (T_2)	Final Balance
S_2	read(1000) write(1050)	read(1000) write(900)	900

  - T_1 must do its read before T_2 does its write
  - T_2 must do its read before T_1 does its write

- Yields a cyclical precedence graph
  - S_2 is not serializable



Precedence Graph Example 2

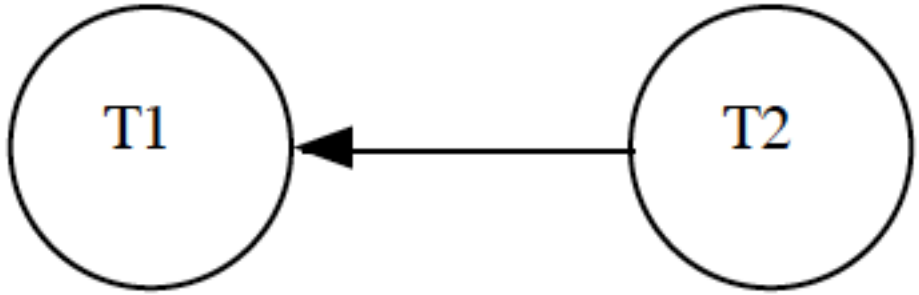
- Consider a transfer of $50 from a savings account (with a $2000 starting balance) to a checking account that occurs at the same time as a $100 checking account withdrawal via the following schedule

Transfer (T_1)	Withdrawal (T_2)	Final Balances
read savings (2000)		
	read checking (1000)	
write savings (1950)		1950 (savings)
	write checking (900)	
read checking (900)		
write checking (950)		950 (checking)

- Note the following conflicting operations in this schedule
  - T_2 must do its (checking) read before T_1 does its (checking) write
  - T_1 reads the (checking) value written by T_2

Precedence Graph Example 2 (Continued)

- Yields this precedence graph
  - Acyclic – indicates a serializable schedule
  - T_2 can be done before T_1
  - Leads to the following conflict equivalent serial schedule



Transfer (T_1)	Withdrawal (T_2)	Final Balances
	read checking (1000) write checking (900)	
read savings (2000) write savings (1950)		1950 (savings)
read checking (900) write checking (950)		950 (checking)

Transaction Recoverability

- Schedules must not only serializable, but *recoverable*
  - Unrecoverable schedules can lead to inconsistencies
  - A transaction T_2 must not commit until any transaction T_1 which produces data used by T_2 commits
    - If T_1 fails, then T_2 must also fail
- Avoid *cascading rollback* – possibility of chain of failed transactions
  - T_2 reads data from T_1, T_3 reads data from T_2 T_4 reads data from T_3
  - If T_1 fails – T_2, T_3, and T_4 must also fail
- Producing only *cascadeless schedules* is desirable
  - No transaction T_2 is allowed to read a value written by another transaction T_1 until T_1 has fully committed
    - T_2 must wait until T_1 commits or fails (in which the previous value of the uncommitted item is used)

Design Project Presentations

Crash Recovery

Causes of Data Corruption

- Logical errors related to incoming data
  - Aborted operations (both programmatic and interactive)
- Transaction failures (i.e. from rollback, deadlock, etc.)
- System crashes
  - Power failure
  - Hardware failure (i.e. failed CPU)
  - Software failure (i.e. operating system crash)
  - Network communication failure
  - Human error
  - Security breach or cyber-attack
- Disk failures that destroy the medium storing the data
- External catastrophes (i.e. fire, flood, etc.)

Storage Types and Data Loss

- Volatile storage – main memory
  - Subject to data loss at any time from many factors (i.e. power, hardware, software failure, etc.)
- Non-volatile storage – disk
  - Not as prone to data corruption
  - Still susceptible to power failures during writes, disk failures, and external catastrophes
- "Stable" storage – approaches immunity to data loss
  - Write-once media (i.e. CDs, DVDs, etc.)
  - Duplication of data (i.e. RAID, remote backup)

Approaches to Data Protection

- Regular system backups
  - Protect data against non-volatile storage failure and some inadvertent data erasure (i.e. human error)
    - Fairly rare occurrences
  - System backups are essential but not enough
    - Need fast restoration of changes since the last backup
- Crash Recovery Measures
  - Restore the system to a consistent state after an aborted operation or crash that does not involve non-volatile media failure
  - Ensure the durability property of transactions – that commits "stick"
    - Each transaction assigned a unique identifier (i.e. serial number)
    - Keep some record of incoming transactions
  - Deal with in-process transactions when the system failed

Transaction Processing Log

- Keeps track of what each transaction is doing
  - Transaction start
  - Details of changes the transaction makes to the database
  - Transaction end messages
    - Commit entry indicates successful completion of a transaction – all of its changes to the database should persist
    - Abort entry indicates the transaction failed – none of its changes should be allowed to remain
    - Neither a commit nor an abort entry will be present in the log if the system crashes while a transaction is in process
      - No changes that the transaction has made to the database should persist when the crash recovery is complete
      - If possible, the transaction can be restarted once the database is restored to a consistent state
- Can also be used for database replication

Protect the Log!

- The transaction processing log needs to be protected against corruption
  - Writing it to stable storage
  - Keep multiple copies of the log in different locations
- Ensure the log data is written before the actual changes are written to the database
  - System typically buffers log entries until a block of them can be written
    - Actual database updates written after the log buffer is flushed
  - Sometimes it might be necessary to write out data block before the logging block is full
    - This leads to a forced write of a partial log buffer
- Ensure that a crash that occurs while the log block is being written does not corrupt previous log entries

Crash Control Schemes

- Incremental Log with Deferred Updates
  - No changes are made to the database until after the transaction commits and the commit entry is written to the log
- Incremental Log with Immediate Updates
  - Changes are made to the database during the transaction, but only after a log entry is written that includes the initial values of the things changed (so they can be recovered if necessary
- Shadow Paging
  - Two copies of the relevant database data are kept during the transaction – both original and modified values. Once the transaction commits, the modified values permanently replace the original ones. (No log required.)

Incremental Log with Deferred Updates

- Example: A transaction to transfer $50 from checking to savings (with initial balances of $1000 and $2000, respectively.

SQL	Log Entries

update checking_accounts
set balance = balance – 50
where account_no = 127;
 	
update savings_accounts
set balance = balance + 50
where account_no = 253;
	T1234 starts
	T1234 writes 950 to balance of checking_accounts record 127
	T1234 writes 2050 to balance of savings_accounts record 253
	T1234 commits

- Once transaction partially commits (e.g. commit log entry is written, actual updates to the database occur
  - If the transaction fails or aborts, no changes have been made to the database

Deferred Updates and Crash Recovery

- If the system crashes during a transaction,
  - If the crash occurs before the commit log entry is written, it can be restarted or ignored when the system is restored
  - If the crash occurs after the commit log entry is written, each value specified to the log will be (re)written to the database
    - No harm in writing the same values to the database a second time
- This *redo log* approach has the following recovery algorithm
  - for each transaction with a start record in the log
    - If its commit record is also in the log
      - Write each new value for the transaction in the log to the database
- Checkpoint – periodic automated flush of buffers to disk
  - Causes committed transactions to be reflected in non-volatile storage
  - DBMS writes a checkpoint to the log
  - Only transactions after the checkpoint need to be applied after a crash

Deferred Update Tradeoffs

- Deferred update overhead
  - Transaction needs to keep local copy of modified data items
  - If a transaction needs to read an item it has written (before committing), it must read the local copy of the item
- Changes must be committed before they are available to the database
  - Simpler recovery because uncommitted transactions can be ignored

Incremental Log with Immediate Update

- Since database updates happen during the course of a transaction, log entries (written before the updates) must contain both old and new values

SQL	Log Entries

update checking_accounts
set balance = balance – 50
where account_no = 127;
 	
update savings_accounts
set balance = balance + 50
where account_no = :253;
	T1234 starts
	T1234 writes 950 to balance of
	checking_accounts record 127
	(old value was 1000)
	T1234 writes 2050 to balance of
	savings_accounts record 253
	(old value was 2000)
	T1234 commits

- If the transaction fails or aborts, all database updates must be undone by writing the original values back to the database

Immediate Update and Crash Recovery

- *Redo* and *undo* log approach to crash recovery
  - for each transaction with a start record in the log
    - if its commit record is also in the log
      - write each new value for the transaction in the log to the database (redo)
    - else
      - rewrite each old value for the transaction in the log to the database (undo)
- Order is critical here
  - Undo operations must happen first (from newest to oldest)
  - Redo operations can happen afterward (from oldest to newest)
- Checkpoints can be used to minimize undo/redo work

Incremental Update Tradeoffs

- Incremental update has more overhead than deferred update
  - Longer log entries – both old and new values stored
  - Failed transactions have to be "cleaned up"
  - Crash recovery requires processing every transaction, not just the ones that committed
  - Every database write requires the corresponding log entry to be written to disk/stable storage (not just on commit)
- Allows changes made by transactions to the database to become visible more quickly
  - Useful in bulk writes – can see updates as they occur
    - i.e. adding monthly interest to all savings accounts

Shadow Paging

- Maintain two copies of the active portion of the database
  - Current version – reflects all changes since start of current transaction
  - Shadow version – state of database before current transaction began
- If transaction fails or aborts, current version is discarded
- If transaction commits, current version replaces shadow version
- Crash recovery is automatic – since changes are only made to the current version, simply revert to the shadow version